FELIX
A Full Acceptance Detector at the LHC
Letter of Intent

FELIX Collaboration

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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F E L I X

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Abstract

The FELIX Collaboration proposes the construction of a full acceptance detector for the LHC, to be located at Intersection Region 4, and to be commissioned concurrently with the LHC. The primary mission of FELIX is the study of QCD: to provide comprehensive and definitive observations of a very broad range of strong-interaction processes. This document contains a description of the detector concept including details of the individual detector elements and their performance characteristics, an extensive discussion of the physics menu, and the plans for integration of FELIX into the collider lattice and physical environment.

Spokespersons:

K. Eggert
(Karsten.Eggert@cern.ch)
C. Taylor
(cct@po.cwru.edu)

FELIX Collaboration

**Institute of Chemical Physics and Biophysics, Estonian Academy of Science, Tallin,
ESTONIA**

E. Lippmaa, R. Ostonen, M. Raidal, J. Subbi

Tel Aviv University, ISRAEL

L. Frankfurt

Institute for High Energy Physics, Protvino, RUSSIA

A. Ageev, I. Britvich, A. Derevschikov, V. Gridasov, E. Kashtanov, A. Inyakin, A. Medvedkov,
K. Myznikov, V. Ouvarov, V. Polyakov, R. Shuvalov, V. Sytnik, A. Toukhtarov, V. Vasilchenko,
A. Vasiliev, L. Vasiliev, O. Yushchenko, S. Zinchenko

**Institute of Superconductivity and Solid State Physics RRC "Kurchatov Institute",
Moscow, RUSSIA**

I.D. Karpushov, E.Yu. Klimenko, V.A. Mokhnatuk, S.I. Novikov

Institute for Nuclear Research, Moscow, RUSSIA

M.N. Gotra, A.B. Krasulin, V.D. Laptev, U.A. Matveev, V.E. Postoev, G.N. Rybkin, A.S. Sadovsky,
M.D. Sergienko

Institute of Nuclear Physics of Moscow State University, Moscow, RUSSIA

A.V. Kubarovsky, A.K. Leflat, V.M. Manankov, V.S. Murzin, E.K. Shabalina, L.A. Tikhonova,
N.P. Zotov.

Joint Institute for Nuclear Research, Dubna, RUSSIA

K. Akhobadze, M. Bondila, S. Goloskokov, V. Djordjadze, O. Kozlov, V. Nikitin, P. Nomokonov,
I. Roufanov, O. Selyugin, V. Smirnov, G. Shabratova

European Laboratory for Particle Physics (CERN), Geneva, SWITZERLAND

V.Avati¹, L.Dick, K. Eggert, G. Karapetian¹, V. Karapetian¹, H. Riege, F. Sauli

Case Western Reserve University, Cleveland, OH, USA

N. Rubin, C. Taylor

Penn State University, University Park, PA, USA

L. Alvero, J. Collins, M. Strikman, J. Whitmore

Stanford Linear Accelerator Center, Stanford, CA, USA

J.D. Bjorken

University of Michigan, Ann Arbor, MI, USA

H.R. Gustafson, L. Jones

University of Wisconsin, Madison, WI, USA

F. Halzen

¹Visitor at CERN.

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Figure II: Expanded view of the forward part of FELIX

1 Introduction and Overview

FELIX will be the first full acceptance detector at a hadron collider. It will be optimized for studying the structure of individual events over all of phase space (see Figure 1.1). FELIX will observe and measure all charged particles, from the central region all the way out to diffractive protons which have lost only 0.2% of their initial energy. It will even see elastic protons which have a momentum transfer of at least 10^{-2} GeV². This comprehensive, precision tracking is accompanied by equally superb electromagnetic and hadronic calorimetry. FELIX will observe and measure photons and neutrons down, literally, to zero degrees, giving it an unparalleled ability to track the energy flow. In contrast, the other LHC detectors are sensitive over only a fraction of phase space and see less than 10% of the typical energy flow. FELIX is thus uniquely able to pursue physics complementary to that of the other detectors planned for the LHC.

The FELIX design involves the coordinated arrangement of three distinct systems: the magnetic architecture responsible for getting the beams through the I4 straight section, the tracking system, and the calorimetry. Each system must be complete in its own right, without compromising the characteristics of the other systems. The magnetic apertures must not be limiting apertures of either the tracking or calorimeter systems. There must be sufficient physical space for both tracking and calorimetry. The calorimeters must be physically large enough to have good resolution, and must not interfere with either the tracking or the magnetic systems.

All of this requires a lot of space, and the detector must be carefully integrated into the design of the machine. Full acceptance cannot be achieved by “adding on” to central detectors optimized for high p_T physics. Here FELIX is fortunate. The decision to split the RF cavities at I4, moving them to ± 140 m from the interaction point (IP), combined with the fact that FELIX’s “low” luminosity permits the focusing quadrupoles to be moved more than 120 m from the IP, provides the necessary longitudinal space. I4 is also ideal from the point of view of transverse space. The beams are separated by 42 cm at the location of the RF cavities, providing room for zero degree calorimetry. Since the existing infrastructure, including the ALEPH solenoid, can be re-used with minimal modifications, I4 is clearly a superb location for a full acceptance detector. (See

Figures I and II).

Nevertheless, the task of integrating a detector with genuinely full acceptance into the available space at I4 is not trivial. This Letter of Intent outlines how it can be done, using well-understood magnets and compact detectors, for a comparatively modest price. We estimate a cost of about 25 MCHF for the machine magnets and the infrastructure, and about 50 MCHF for the detector presented here.

Figure 1.1. The pseudorapidity distribution of charged particles and of the energy-flow at $\sqrt{s} = 14$ TeV.

1.1. The FELIX detector

We now introduce the major features of the FELIX design.

1.1.1. A tunable insertion at I4

A full acceptance detector must be able to analyze global structure event-by-event. This means that it should run at a luminosity no greater than $\mathcal{L} \sim 10^{32}$ cm⁻² s⁻¹; that is, with less than about one interaction per crossing. This luminosity can be achieved at I4 by means of an insertion which can be tuned from $\beta^* = 23$ m to $\beta^* = 900$ m without changing the magnetic elements.

There are two significant features of this insertion. First, the final-focus quadrupoles can be placed

Figure 1.2. The top view of the FELIX detector. The different magnets, calorimeters, tracking stations and the beam trajectories in the horizontal plane are indicated.

more than 120 m from the IP, providing the space needed to accommodate the FELIX dipoles. Second, it is economical. The necessary quadrupoles are already in the LHC baseline design.

The ability to tune the insertion also has several nice features. At $\beta^* = 900$ m, FELIX is optimized for the study of low- t elastic scattering. At $\beta^* = 110$ m, where FELIX's luminosity is about $4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ when the LHC is at design luminosity, the beam size in the heart of FELIX detector (± 120 m) is minimized, permitting the Roman pot detectors in these locations to come as close as 3 mm to the beam. Finally, $\beta^* = 23$ m permits FELIX to reach luminosities as high as $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

1.1.2. Well-understood magnets

FELIX will implement a "kissing scheme" in which the two beams are brought together at 0° in the horizontal plane and then returned to the same inner or outer arc (See Figure 1.2). To accomplish this, we need some 67 T-m to first bring the beams together (D2 magnets), and then another 67 T-m (D1 magnets) to make them parallel. This has to be accomplished within the 120 m available. Both sets of magnets must be superconducting machine dipoles. The D1 magnets must also have large bores, both to accommodate both beams and to provide acceptable tracking and calorimetry apertures.

FELIX is fortunate that Brookhaven National Laboratory (BNL) has designed large aperture superconducting dipole magnets for use at RHIC. With a coil aperture of 18 cm and a design field of 4.28 T (FELIX will use them at 3.62 T), these magnets are suitable for use as D1 magnets. While prototypes will not be tested until the fall of 1997, BNL is committed to producing these magnets for RHIC and thus will be able to supply well-understood magnets on the FELIX time scale.

The constraints on the D2 magnets are somewhat less severe, and several options are available. Of these, FELIX proposes existing superconducting dipoles constructed as prototypes for UNK. While these are single aperture magnets, the 42 cm beam separation permits two UNK cold masses to be assembled in a common cryostat for use as D2 magnets.

In order to avoid parasitic beam-beam interactions and long-range tune shift effects, the beams will collide with a vertical crossing angle of ± 0.5 mrad. To do this while optimizing the match of the magnetic architecture to tracking and calorimetry, we propose to re-use the existing UA1 magnet, split longitudinally into two halves and equipped with new coils. We will also build two 5 meter long, 1.5 T warm dipole (D0) magnets.

The magnetic architecture is completed by the re-

use of the existing ALEPH solenoid, which is well-matched with the use of the UA1 magnet.

An important feature of this overall design is that the strengths of the magnetic fields increase in the forward direction, always well-matched to the typical momenta of the particles, resulting in momentum resolution which is reasonably uniform over all of phase space.

Finally, we note that all magnets can be accommodated in the existing Aleph collision hall and adjacent tunnels without any significant civil construction.

1.1.3. Compact, precise tracking

Figure 1.3. A schematic view of a tracking station based on Si pixel detectors and a micro-TPC. Note that several large-area GEM chambers have been removed to improve visibility of the micro-TPC.

Some 50 tracking stations, located as far as 430 m from the IP, are needed to ensure full acceptance and uniform resolution. The positions of most of the stations are indicated in Figure 1.2.

FELIX will instrument radially outward, emphasizing compact, near-beam tracking. How close we will approach the beams depends on the location. In general, we will use Roman pot detectors to aggressively approach the beams wherever the location is accessible and the pot mechanical structure does not interfere with other tracking or calorimetry. Elsewhere, we propose to use fixed-radius tracking, approaching to within 2.5 cm of the beams.

An important consideration is the occupancy within the tracking detectors. High particle densities close to the beam pose a significant pattern recognition problem. Each tracking station should

thus have sufficient resolution and redundancy to be able to locally reconstruct track segments. Track segments are then matched, station-to-station, resulting in a very powerful spectrometer.

These considerations lead to a common conceptual design for most FELIX tracking stations, based on two technologies: Si pixel detectors out to radii of about 8 cm, supplemented by Gas Electron Multiplier (GEM) chambers at larger radii. We are also exploring the possibility of using GEM as the basis for very compact micro-TPC's. Conceptual designs for a "standard" fixed-radius tracking station are shown in Figure 1.3. The same technologies will be used for a compact microvertex detector.

1.1.4. Forward calorimetry

FELIX proposes four calorimeters on each side of the IP to provide complete electromagnetic and hadronic calorimetry for angles $\theta < 0.2$ radian, that is, for $|\eta| > 2.3$. The coverage of the calorimeters is illustrated in Figure 1.4. The interplay with the magnets and tracking systems is illustrated in Figures I and II.

The calorimeters must have superb energy and spatial resolution, and must provide the information needed to identify neutrons, electrons and gammas. This must be done in limited space, and in a high-radiation environment. These considerations determine the structure of the calorimeters, the choice of sampling materials and the kinds of photodetectors and front end electronics which can be used for the readout.

The UA1 endwall calorimeter, which is expected to have a radiation dose of less than 5 Mrad for 10 years running, is a sampling calorimeter based on plastic scintillators and wavelength shifting fibers. The very forward (D0, D1 and Zero Degree calorimeters) see much higher radiation levels, and will thus be "spaghetti"-type calorimeters, based on either thin capillaries filled with liquid scintillator or on quartz fibers. All three very forward calorimeters are similar in construction, differing only in their overall dimensions. Each consists of a preshower detector, an EM calorimeter, and two hadron calorimeter sections.

Figure 1.4. Schematic view of FELIX forward calorimetry.

1.2. Physics Overview

1.2.1. The primary physics menu for FELIX is QCD

Full-acceptance data sets in hadron collisions, most of them from bubble chambers, have typically contained no more than a million events. To this day these data sets remain the principal basis of our knowledge of the basic properties of high energy hadron-hadron collisions. The initial operation of FELIX, with just a minimum-bias trigger, should increase this ten to a hundredfold. The quality of information per event, thanks to revolutions in technology, will be superior in many respects to what was attained in the past. Without question, this initial agenda will grow into new, data-driven directions difficult to predict in advance.

The heart of the FELIX physics agenda is QCD. FELIX will be the ultimate QCD detector at the LHC. Many of the new opportunities in QCD physics at the LHC are not well known, and we have accordingly placed high priority in this document in providing a description of them.

1.2.2. QCD is universal

Omitting QCD from experimental elementary particle physics nowadays is unthinkable. Take away quarks, gluons, and all other conjectured colored particles and there is very little left. True, what is left is most simple and beautiful. But the remainder consists of the bulk of existing and proposed experimental programs. And while the search for, say, the gluino is not motivated by the desire to understand QCD better, it is clear that a better understanding of QCD is important in making such a

search. Furthermore, in almost every phenomenon where QCD issues enter, be it old physics or new, there are some non-perturbative features of QCD which are involved. Consequently it is vital that there be close interplay between experiments and QCD theory/phenomenology.

1.2.3. Dedicated study of QCD at the LHC is essential

In the case of electron-positron collisions, close interplay between theory and experiment has in general been attained. The cleanliness of the process, together with the low event rate and full-acceptance capability of the detectors, has led to an especially fruitful interaction between the QCD aspects of that experimental program with the remainder.

The case of hadron-hadron collider physics is quite different. The high- p_T , low cross section physics is accessed by highly selective triggers. The phase-space acceptance of the detectors is limited to the central rapidity region. Full acceptance has not been attained since the bubble-chamber era of fixed-target physics. Therefore the basic data base is much more limited.

This situation is all the more serious because of the great variety in event classes for hadron-hadron collisions. There are soft collisions with large impact parameters; angular momenta of tens of thousands instead of the unique $J = 1$ of the e^+e^- world. Central collisions produce much higher multiplicities than are seen in e^+e^- annihilation. There are the diffraction classes of events, with and without jet activity, that comprise several to tens of percent of typical subsamples (if seen in full acceptance) and which present a major challenge to theory. There

are poorly understood strong Bose-Einstein-like correlations seen at very low p_T and low relative p_T in hadron-hadron collisions which do not occur in e^+e^- collisions. But at collider energies this is only based on one sample of low- p_T data from UA1, because until now no other detector has had the measurement capability. Finally, there is little if any data in the forward fragmentation regions, where cosmic ray experiments insistently claim that anomalies exist.

Given this richness of phenomena, and given the importance of QCD to the interpretation of the new-physics data expected to emerge from the LHC, it is clearly very important to improve the data-base with an LHC detector and experimental group fully dedicated to the observation and interpretation of as broad a range of QCD phenomena as possible. This is of course the mission of the FELIX initiative.

1.2.4. Minijet production in hadron-hadron collisions is strongly energy dependent

The need for a vastly improved QCD data-base for hadron-hadron collisions is made even more urgent by the fact that qualitative changes are expected even in the structure of generic events because of the rapid increase with energy of gluon parton densities in the primary protons. Thanks to the measurements at HERA, this is not only the theoretical expectation but also a data-driven one. The parton densities at a 5–10 GeV scale become so large that minijet production in central collisions may become commonplace, with minijet p_T large enough for reasonably clean observability. These very high parton densities create, at a perturbative short distance scale, “hot spots” in the spacetime evolution of the collision process within which there may be thermalization or other nonperturbative phenomena not easy to anticipate in advance of the data. Particle spectra themselves may evolve to something quite distinct from what has been so far observed, with strangeness, heavy flavors, and/or baryon and antibaryon production enhanced. Especially in central proton-ion collisions, where the total gluon-gluon luminosity per collision is maximized, and where the evolution of a single proton fragment is followed, one can expect this class of phenomena to be most prominent and surprises most probable.

1.2.5. Parton densities can be measured to extremely small x , below 10^{-6}

The parton densities at small x are themselves a very important thing to measure. Up to now

HERA has provided data down to x values of order 10^{-4} for Q^2 in the perturbative domain of several GeV^2 . FELIX will have the capability to extend these measurements to x values below 10^{-6} via observation of dileptons, low-mass dijets, and low-mass jet-photon systems carrying large longitudinal momenta. In this regime one expects (again, especially for proton-ion collisions) the breakdown of the usual DGLAP/BFKL evolution-equation formalism and significant nonlinear effects to be observed.

1.2.6. Diffractive final states are endemic, many are important, and some are spectacular

Diffractive final states will comprise almost 50% of all final states at the LHC. The soft diffraction at very large impact parameter, which perhaps sheds light on pion-cloud or glueball physics, is at one extreme, and hard diffraction, where rapidity gaps coexist with jets, is at the other. As we will discuss below, there are a large variety of hard diffraction processes, including some with two and three rapidity gaps, which are of basic interest to study. In this class there are expected to be, for example, an extraordinary class of events where the complete event consists of a coplanar dijet accompanied by the two unfragmented beam protons detected in Roman pots, and absolutely nothing else in the detector. Certainly ATLAS and CMS can also detect such events, provided they sacrifice a luminosity factor of about 30 relative to their hard-earned peak luminosity. However, to really understand this event class, one will need, at the very least, to examine the t -distribution of the Roman-pot protons, as well as to study the generalizations of this process to the cases where one or both of the protons undergoes soft diffraction dissociation to a low mass resonance or a high mass continuum, or to a high- p_T system containing a tagging jet. Only FELIX would have such a capability.

In addition to this class of hard diffraction and very soft diffraction processes, there is another very interesting class of semihard diffractive phenomena associated with the conjectured fluctuation of the initial-state projectile into a transversely compact configuration, which therefore interacts with an unusually small cross section. Evidence for this is seen in vector-meson photoproduction at HERA, especially J/ψ production, which exhibits the expected rapid increase of cross section with energy. Also at Fermilab, diffraction dissociation of a high energy pion into dijets, with all the initial pion energy going into the dijet system, is being studied by experiment

E791. As will be discussed below, exactly the same process is available at the LHC with FELIX, as well as a similar process where one beam proton dissociates diffractively into three jets, one for each quark. The A dependence of these processes is remarkable, roughly $A^{4/3}$, because this diffractive process should occur even in central collisions, thanks to the small size of the initial configuration.

1.2.7. Particle production from deep within the light cone may exist and deserves careful searches

The existence of events with a very high final-state multiplicity of minijets and their associated hadrons has other implications. The products of such interactions for the most part can be expected to explode from the initially compact collision volume in all directions at the speed of light. Because of the high multiplicity density, the time of hadronization of all these degrees of freedom will be lengthened from the usual low-energy value of 1-2 fm to several fm. Up to this time of hadronization, the expanding “fireball” containing most of the partonic collision products is arguably a rather thin spherical shell, of thickness of order a fm. So even before hadronization there is a large interior volume of hundreds of fm³, isolated from the exterior vacuum, which may evolve toward a chirally disordered vacuum. Consequently in such events there might be a large pulse of semiclassical, coherent pions of relatively low p_T emitted when this false vacuum eventually decays: disoriented chiral condensate. This is at present only a speculative possibility, although experimental searches, especially in the context of ion-ion collisions, are underway.

More generally, one may ask: if disoriented vacuum is not what is in the interior of this quasi-macroscopic fireball, what is? If the interior “vacuum” is broken into domains of various chiral orientations, then topological obstructions might lead to production of (Skyrmionic) baryons and antibaryons of unusually low p_T . And if there is activity deep inside the light cone, no matter what it is, then this activity has eventually to be turned into emission of particles; hence a new particle production mechanism which deserves to be studied. It would seem that the only alternative available for the *absence* of new phenomena emergent from the deep interior of the light cone under these circumstances is that that region relaxes back to the true vacuum, despite its being isolated from the true vacuum by a fireball shell and despite there not being enough elapsed time for chiral orientation to be distinguished ener-

getically from chiral disorientation.

1.2.8. Collisions with very high impact-parameter may probe the chiral vacuum structure

In general, the chiral vacuum condensate is distorted in the neighborhood of impurities such as an isolated proton. This is just the long-range pion cloud surrounding it. The pion-cloud structure can be probed especially well in high energy pp collisions at very large impact parameters, say 2 to 3 fm. These interactions are, because of the larger radii of interaction at the LHC, a bigger component of the cross section, and can lead to larger final-state multiplicities than found at lower energies. Perhaps here too there may be coherence in the structure of the pion emission, and this class of events may turn out to be of special interest. Again a detection capability at very low p_T , 100 MeV and less, as possessed by FELIX, is important for such studies.

1.2.9. New opportunities exist for tagging event classes

Together with these many novel phenomena, there will be new methods for experimentally tagging different kinds of events. The impact parameter of the collision is obviously of importance to determine event-by-event. This is done routinely in ion-ion collisions via zero degree measurements of nuclear fragments and by the amount of transverse energy produced. At the LHC, the FELIX instrumentation in the forward direction allows a data-driven approach for attacking the problem by the former method. The large yield of minijets, strongly dependent upon impact parameter, may allow the latter method, based upon transverse energy production, to be used more effectively at the LHC (by all detector groups) because of the stronger correlation of multiplicity with impact parameter than at lower energy. A combination of both methods, unique to FELIX, is likely to be the best of all.

A second important tag available to FELIX is the choice of beam. By tagging on a leading neutron or Δ^{++} at very low t , one can reasonably cleanly isolate the one-pion-exchange contribution, and thereby replace the LHC pp collider with a somewhat lower energy, lower luminosity πp collider. In a similar spirit, and including Λ tags, one can study collisions of any combination of π , K , or p with each other. The beam-dependence of phenomena has historically been of considerable importance, and it may find important applicability, especially with respect to questions of valence-parton structure, at the LHC

energy scale.

A special case of these tags is that of a photon tag in ion-ion collisions, via forward detection of the undissociated ions. The luminosity for $\gamma\gamma$ collisions is very high, and the capability of FELIX to exploit this luminosity is also very high.

Another class of tags which has been underutilized is the diffractive tag, where leading protons are detected via Roman-pots. As discussed above, this leads to a very rich stratum of up-to-now poorly-measured, poorly understood, but potentially important physics.

Finally, there may be pattern tags. The event structure in final states containing jets is dependent upon the color flow. Typically, neighboring jets in phase space are connected by a partonic color line (antenna). For quarks, one antenna line emerges from the jet, for gluons two. Along these antenna lines in phase space, hadronization and minijet production is enhanced. Recently the Tevatron collider experiments have observed these effects. In principle this technique might allow one in the future to identify in an individual multijet event quarks versus gluons, and even fully classify the event structure according to the color flow. Clearly such a pattern-analysis technique is very difficult, and needs to be data-driven. FELIX, with full acceptance, will be optimal for making the attempt.

2 Physics Objectives

(We acknowledge contributions by: G. Amelino-Camelia, R. Baier, J. Bartels, G. Baur, M. Beneke, A. Berera, A. Capella, F. Close, C. Costa, J.-R. Cudell, Yu. Dokshitzer, A. Donnachie, R. Engel, K. Geiger, A. Giovannini, K. Goulianos, K. Hencken, M.M. Islam, A.B. Kaidalov, Y. Kharlov, V. Khoze, S. Klein, K. Kowalski, P.V. Landshoff, A.H. Mueller, G. Marchesini, R. Orava, E. Papageorgiou, D. Rainwater, J. Ranft, G.P. Salam, S. Sadovsky, D. Schiff, D. Treleani, R. Ugoccioni, A. White, Z. Wlodarczyk, V. Yakovlev, D. Zeppenfeld, M. Zhalov.)

2.1. New hard QCD phenomena at the LHC

2.1.1. Motivations for hard, small x physics at the LHC

2.1.1.1. Large parton densities and a new QCD regime

Recent data from HERA show that the proton's quark and gluon distributions grow fairly rapidly with decreasing x -values for a fixed value of Q^2 , in qualitative agreement with expectations. This means that the number of partons, quarks and gluons, in a high energy proton becomes remarkably large at very small values of x . Present indications are that the number of gluons per unit rapidity having spatial transverse size $\Delta x_\perp \propto 1/Q$, is around 25 for moderate $Q^2 \sim 20 \text{ GeV}^2$ at the smallest $x \sim 10^{-4}$ available at HERA. Parton densities cannot grow indefinitely at small x at fixed Q^2 , since this violates unitarity for hard processes. Exactly how this contradiction is resolved is currently the subject of vigorous study by theorists. But clearly new mechanisms beyond the standard hard-scattering picture are necessary. Why this is a fundamental and exciting question is not hard to see [1]. Gluons having longitudinal momentum fraction x and transverse size $\Delta x_\perp \propto 1/Q$ may give a contribution to the typical QCD field strength in the light cone wave function of the proton so large that perturbation theory ceases to be reliable and a new nonperturbative regime of QCD is reached. This is a regime where α_s is small, and so the usual nonperturbative effects of QCD associated with gluon and/or chiral condensates should be unimportant. Nevertheless, the field strengths are so large that

interactions are highly nonlinear.

Although parton number densities at HERA and Fermilab energies are large, they do not appear to be large enough to reach a truly high density regime where perturbation theory breaks down while α_s is still small. Deep inelastic scattering on nuclei at HERA may allow one to reach saturation in the $Q^2 \approx 3\text{-}6 \text{ GeV}^2$ region [2] but studies of very high density, small x partonic systems where α_s is clearly small can only be done at the LHC both for pp and for pA collisions using a forward detector. Such a detector would allow one to extend the previously studied x range by three orders of magnitude.

The consequences for LHC collisions are enormous: at the perturbative QCD scale of 5-10 GeV, literally many thousands of gluon pairs from the projectiles are available for semi-hard collisions. As discussed later, visible jets at this scale may become commonplace even in typical minimum-bias interactions.

2.1.1.2. The BFKL regime; high energy scattering of small color dipoles

For conventional hard-collision processes, the Q^2 evolution is the basic phenomenon. The hard scale is supplied by the virtuality of jets, while there is a soft scale determined by the proton size of $\approx 1 \text{ fm}$.

For the total cross-section of deep inelastic scattering and for typical hadron-hadron hard collisions, the well-known DGLAP equations describe the evolution of the hard-collision rate from the large Q^2 scale to the scale of soft QCD processes. Soft physics then enters in terms of the boundary conditions for these equations. On the other hand, the consideration of the growth of parton densities with energy at fixed Q^2 is attacked within perturbative theory via a different kind of evolution equation, the BFKL formalism [3]. A prototypical process here is the high-energy scattering of two small objects, such as "onium-onium" scattering. For such processes, the strong coupling α_s has a fixed momentum scale Q which is defined by the transverse size of the colliding objects. If the onia are sufficiently small, then α_s is small and this justifies the use of perturbation theory. However, in spite of the smallness of the coupling constant, the lowest order approximation in α_s is still insufficient at very large energies $\sqrt{s}$ and relatively small momentum transfers $|t| = Q^2$. For example, within the leading logarithmic $\alpha_s(Q) \ln s$ approximation, the forward elastic scattering am-

plitude of the two small-size colorless objects, and thus the total cross-section, increases strongly with energy [3]:

$$T_{el}(s, 0) \sim i s^{1+\omega} \quad (2.1)$$

where

$$\omega = \omega_{BFKL} = \frac{4N_c \ln 2}{\pi} \alpha_s \approx 0.5 \quad \text{for } \alpha_s = 0.19. \quad (2.2)$$

Next to leading order corrections are being calculated, and these corrections may reduce substantially the growth of $T_{el}(s, 0)$, see e.g. [4].

The Feynman diagrams that contribute to this approximation can be represented as gluon ladder diagrams. This means that, roughly speaking, the growth in energy of the onium-onium interaction is created by multiregge-like production of gluon jets, of typical transverse momentum scale Q or larger. This multijet structure requires extremely large energies and very large acceptance to become manifest experimentally, and will be a major object of study for FELIX.

2.1.1.3. Quark-quark scattering at very large values of s

To clearly study the BFKL process, one ideally wants to maximize the sub-energy $\sqrt{s}$, keeping the transverse scale $p_T \sim Q \geq 5 - 10$ GeV in order to clearly identify parton jets in the final state. An optimal choice for doing this at the LHC is by studying the interaction of valence quarks, with $\sqrt{s} \sim 5 - 10$ TeV. At $p_T \geq 10$ GeV, this implies production angles of 2 - 4 mrad.

The naive expectation for the BFKL enhancement mechanism over the one-gluon-exchange process is the associated emission of the multiregge “ladder” of gluons. The cross-section enhancement might be crudely expected (Eqns.(2.1,2.2)) to be $(s/t)^\omega \sim 30$, with the average number of emitted gluons being

$$\bar{n} \sim \omega \ln \frac{s}{t} \sim 3 - 4. \quad (2.3)$$

This implies that the original quark dijet coplanarity will be destroyed by the presence of the intermediate gluons. It will, of course, be important to measure the acoplanarity as well as the yield of these multijet configurations in full acceptance. This again requires the FELIX detector.

In addition to this inelastic process the naive expectation for *elastic* quark-quark scattering via color-singlet two-gluon exchange is that it should be enhanced by the square of the BFKL factor $\sim (s/t)^{2\omega} \approx 10^3$.

At moderate energies this two-gluon cross-section is suppressed by two powers of α_s (but enhanced by a factor $\ln s$), and is only a ten percent contribution. However its rapid energy dependence could make it comparable to the inelastic contribution for the above conditions at FELIX. This elastic contribution consists of coplanar dijets occasionally accompanied by a rapidity gap, and is therefore distinguishable from the inelastic contribution. Note that if the elastic contribution does overtake the inelastic, this signals the onset of a “blackness” of the “pointlike” quarks of perturbative QCD physics.

Unfortunately, at present there are no reliable, well-normalized predictions available for these cross-sections. Some detailed estimates, taking into account realistic kinematic effects omitted in the leading order analytic calculations, greatly reduce the naive expectations. Nevertheless a significant enhancement over lowest-order estimates can be anticipated. The measurement of the scattering of valence quarks as a function of angle, at the highest $\sqrt{s}$, therefore is a fundamental empirical probe of this new regime of nonperturbative short-range QCD.

2.1.1.4. Resolving the theoretical uncertainties

While the physics of the BFKL enhancement originates within perturbative QCD, it should be already clear that its role in phenomenology, present and future, remains uncertain. The normalization problem alluded to in the previous section may in time be solved by more detailed calculations. But there are other uncertainties. One is that the quarks of the previous section are not onia or small color dipoles (although arguably such configurations will exist within the valence-parton wave functions of the projectiles), so the applicability of the enhancement factor to quark-quark scattering may not be completely justified.

But the most serious problem is more fundamental, and it is called diffusion in p_T . With increasing energy, the relevant phase space of the gluons inside the BFKL ladder spreads out into both the infrared and the ultraviolet region. So even if the external transverse momentum scale is chosen to be very large, there is a contribution due to the infrared part of the internal phase space which will become important at sufficiently high energy. In other words, in contrast to the DGLAP calculations, the BFKL ladder has no strict separation of short and large distance physics. By choosing sufficiently small sizes of the external particles one can suppress the infrared effects, but with increasing energy these

contributions will always grow. At some high energy the perturbative QCD approximation becomes inapplicable. This transition from perturbative to non-perturbative physics defines a *new frontier* in QCD which already is moving into the center of theoretical and experimental interest. It should be clear that to make progress, one will need a large and comprehensive experimental data base.

2.1.1.5. Event structure in the high parton-density regime

The above perturbative QCD ideas should be applicable in the p_T range of 1 - 2 GeV to 10 GeV; however in this regime it will not be easy to clearly isolate gluon jets. This is the “minijet” region, where hadronization effects partially (but not completely) obscure what is happening at the parton level. The phenomena discussed above will have very strong effects on phenomenology in this region of p_T scales at the LHC, and in particular lead to average large dispersion in the multiplicity.

Although BFKL contributions to semi-hard collisions, producing jets of about 5 GeV transverse momentum, occur with a cross-section of only 1 mb or so at LHC energies (including its rapid increase with energy), the parton densities at small x are so large that there can be a large probability for producing several pairs of jets via multiple pair-wise interactions of the partons of the colliding protons. This probability for multiple parton interactions remains high up to $p_T^{min} \sim 10$ GeV/c [5]. Moreover, when the gluon densities become high, the pairwise interaction of small color dipoles (or partons with large virtualities) leads by itself to enhanced multiplicities of produced secondaries [1]. Finally, soft “spectator” interactions may also become much stronger, as discussed in the next section. This is yet another source of large dispersion in multiplicity.

Therefore one can expect that *typical events* at the LHC will be characterized by a significant average density of minijets per unit of rapidity, by large fluctuations in the number of such minijets, and by fluctuations in the multiplicity of soft particles, both for central and for forward rapidities. Long-range correlations even stronger than those seen at the $SppS$ and Tevatron are expected for the whole rapidity range at the LHC. Correlations between the multiplicity in the fragmentation regions and the central regions should in particular be strong. The pattern of these correlations should be highly sensitive to the pattern of parton correlations in the nucleons and the parton evolution at high densities. Thus even the basic phenomenology of generic central collisions may be quite different at the LHC.

Besides having a lot of jets contained in several units of rapidity, other signals can be expected from such high field strength “hot spots”. For example, there may be a significant amount of charm and bottom quark production associated with the gluon jets, with bottom production perhaps only mildly suppressed compared to charm. All of this is a subject still in its infancy and one can expect new ideas and experimental signatures to emerge in the course of the theoretical development of the subject, a development which is receiving impetus also from the importance of understanding the earliest stages of heavy ion collisions [6].

2.1.1.6. Hard coherent phenomena in small x processes

Hard processes at moderate x correspond to small space-time intervals $1/Q$ and to small distances ≤ 1 fm. With decreasing x , the transverse space-time intervals remain small but typical longitudinal distances, l_c , in the target rest frame become extremely large [7,8], proportional to the beam energy or equivalently x^{-1} . At the LHC when $x = 10^{-6}$, the value of l_c in the proton rest frame is $l_c = 10^5$ fm. Thus the wave function of a fast projectile is built up over macroscopic distances (on the scale of hadron physics), and is “frozen”, due to time dilation, during the collision.

Sometimes the incident-projectile configuration may be a small, colorless wave packet. The interaction of such a configuration with hadronic media is analogous to Fraunhofer diffraction in optics. This limit is different from the BFKL limit discussed above where both objects are small, and has a closer connection to DGLAP evolution. The total cross-section for such “onium”-hadron interactions is still small (color transparency). This follows from the fact that hard high energy processes are dominated by gluon exchanges, and that the cross-section for a small $q\bar{q}$ configuration is proportional to b^2 , its size in impact parameter space [9,10]:

$$\sigma^{q\bar{q}}(inel) = \alpha_s(\mu^2) \frac{\pi^2 b^2}{3} xG(x, \mu^2). \quad (2.4)$$

Here $G(x, \mu^2)$ is the gluon distribution in the target, and the hard scale μ^2 to be used in the above formula is related to b^2 at the energy scale $x \in 10^{-2} - 10^{-4}$ by the relation $b^2 \mu^2 \approx 9$ and $x = \mu^2/s$. The decrease of the cross-section with b is partly compensated by the increase of the gluon density. At fixed size b and at very high energy, when the number of gluons becomes very large, Eq.(2.4) leads to large interaction cross sections and what may be

called perturbative color opacity.

An important consequence of color transparency is that, in the region of its applicability, initial and final state interactions are suppressed and cross-sections for hard diffractive processes are calculable in terms of parton densities in a model independent way. So such processes can be used to investigate the three-dimensional distribution of color within hadrons rather than the one-dimensional distribution of deep inelastic scattering.

A number of such processes have been studied at HERA: $\gamma_L^* + p \rightarrow \rho(\phi) + p$, $\gamma(\gamma^*) + p \rightarrow J/\psi + p$ [11]. These studies find the expected strong increase of the cross-sections for hard diffractive processes $\propto [xG(x, Q^2)]^2$ and a tendency for restoration of the flavor SU(3) symmetry at large Q^2 . FELIX will be able to extend substantially the energy range of measurements for J/ψ photoproduction and also measure Υ photoproduction in a large energy range via AA collisions. Related hard pp and pA processes calculable in perturbative QCD, only possible to study with a forward detector such as FELIX, include diffraction of a proton into three high p_T jets and diffraction dissociation of a pion into two jets in baryon-tagged processes (see Section 2.1.5.2, page 25). In such hard diffractive processes it may also be possible to measure the part of the wave function of a proton relevant for proton decay calculations.

2.1.2. Measurement of parton distributions at small x

2.1.2.1. Kinematics of hard processes to be measured at FELIX

HERA measurements of parton distributions in nucleons have greatly expanded our knowledge about perturbative QCD in the new domain of very small x and large Q^2 . They confirm the predicted rapid increase of the parton densities. However the kinematic range available at HERA barely touches the domain where linear QCD evolution equations are expected to break down (see discussion in Section 2.1.1, page 9). A program aimed at measuring parton densities over a wide range of small x and over a range of virtualities Q will be necessary to probe the non linear, high density regime described in Section 2.1.1, page 9; the onset of the regime is signaled by a failure in the consistency of the parton density measurements.

In principle, studies of hard processes at the LHC will allow one to cover a very large x, Q^2 region

$$x_1 \geq \frac{4p_T^2}{x_2 s}, \quad Q^2 \sim p_T^2. \quad (2.5)$$

Here x_1 and x_2 are the momentum fractions of the colliding partons, and p_T is the transverse momentum of the produced jets. In a dijet event, with two jets at large positive rapidities y_1 and y_2 , the momentum fractions of the initial partons can be approximately reconstructed as

$$x_1 = \frac{p_T}{\sqrt{s}} (e^{y_1} + e^{y_2}), \quad (2.6)$$

$$x_2 = \frac{p_T}{\sqrt{s}} (e^{-y_1} + e^{-y_2}). \quad (2.7)$$

For $p_T^{min} \sim 10$ GeV, Eq. (2.5) indicates that at the LHC the range in x can be extended by at least three orders of magnitude down from the HERA limit to $x \sim 10^{-6}$.

However, the detector should meet at least three requirements:

- The detector should have good acceptance in as large a rapidity interval as possible. Losing two units of rapidity is approximately equivalent to losing one order of magnitude in the x -range.
- The detector should have fine enough angular and momentum resolution to resolve and to measure these jets in the forward region down to $p_T \sim 10$ GeV to ensure that one can probe parton distributions at sufficiently small virtualities.
- To discriminate between quark and gluon densities, the detector should be able to detect prompt photons and preferably also heavy flavor particles as well as electrons and muons.

All of these requirements are satisfied for FELIX. There are several reactions which can be used for the measurements of the parton densities and studies of the related physics:

$$\begin{aligned} pp &\rightarrow \text{jet}_1 + \text{jet}_2 + X, \\ &\rightarrow \text{jet} + \gamma + X, \\ &\rightarrow Q + \bar{Q} + X, \\ &\rightarrow l^+ + l^- + X, \\ &\rightarrow Z(W) + X, \\ &\rightarrow \gamma + \gamma + X, \end{aligned} \quad (2.8)$$

where $Q(\bar{Q})$ denotes a heavy quark (antiquark), and l stands for an electron or muon. The cross-sections for these processes are straightforward convolutions over parton densities of elementary hard-collision cross-sections $d\sigma/dt$. Details of the cross-sections in lowest order may be found in [12] and relevant parton distributions may be found in [13,14].

Figure 2.1. A plot of the number of events in (p_T, x) bins for jet + γ production.

To probe the parton distributions at the smallest x possible, it is necessary to choose highly asymmetric kinematics: $x_1 \gg x_2$ (or $x_2 \gg x_1$). In this case the hard subsystem is produced in the nucleon fragmentation region at very large rapidities y . An important advantage of these kinematics is that, for such large y (especially for y corresponding to $|y - y_{max}| \leq 3$), soft interactions result in substantially smaller backgrounds than for $y \sim 0$. Hence we chose $p_T^{min} = 10$ GeV in our estimates. In this case, for $\sqrt{s} = 14$ TeV, the momentum fractions x_i obey $x_1 x_2 \geq 2 \times 10^{-6}$. In fact, for the production of heavy flavors one can probably take p_T^{min} even smaller. For Drell-Yan dileptons, one may go all the way down to $p_T \geq 2 - 3$ GeV, allowing a probe of considerably smaller x . We find that the various reactions in (2.8) allow the measurement of both quark and gluon distributions with a number of cross checks.

2.1.2.2. Jet plus photon

For $p_T \sim p_T^{min}$, one of the safest probes is the production of a jet plus photon. In this case the uncertainties in the reconstruction of a jet of relatively low p_T are minimized. Since we are interested in probing the small x behavior of parton densities, we can consider the cross-section in bins of p_T and x_1 , with the parameter x_2 integrated up to 0.8.

Fig. 2.1 shows the number of events in bins of (p_T, x_1) calculated for an integrated luminosity of

100 pb^{-1} where the color bar on the right gives the number of events. One readily observes that large counting rates are expected over the entire range of x_1 with $10 \text{ GeV} \leq p_T \leq 50 \text{ GeV}$. This will guarantee the statistical accuracy of the measurements to be better than 1%. The cross-section (solid curve)

Figure 2.2. The cross-section $\sigma(x)$ for $pp \rightarrow \text{jet} + \gamma + X$ as a function of $x = x_1$. It is integrated over $p_T > 10$ GeV, $\max(x_1, x_2) < 0.8$, and $x/\Delta < \min(x_1, x_2) < x\Delta$ where $\Delta = 10^{1/20}$. The choice of Δ corresponds to 10 bins per decade of x .

in bins of x_1 is shown in Fig. 2.2, where the separate contributions from the gq (dashed curve) and $q\bar{q}$ (dot-dashed curve) channels are also shown. The cross-section is dominated by the gq channel, which is at least 10 times larger than the contribution of the $q\bar{q}$ channel over the entire x_1 range. Using large x quark distributions which are known from HERA experiments with an accuracy of better than 10%, it would be possible to extract the gluon density for $x \geq 2.6 \times 10^{-6}$ from this process, (Fig. 2.3). The information from the angular distribution of the jet- γ system for fixed x_1 and x_2 is also of importance for the separation of the gluon and quark contributions [15].

2.1.2.3. Heavy quarks

We next consider the cross-section for the production of charm quarks for the same cut in p_T . As mentioned above, this may be somewhat too conser-

Figure 2.3. The gluon momentum distribution with error bars as determined from the jet + γ cross-section.

vative, since the leading particle effect in charm production may allow one to define jets adequately at smaller transverse momenta. We need not consider separately b -particle production, since for $p_T^{min} = 10$ GeV the cross-sections for the production of $b\bar{b}$ and $c\bar{c}$ are comparable. Fig. 2.4 shows a plot of the number of events in bins of (p_T, x_1) , with x_2 integrated up to 0.8 for an integrated luminosity of 100 pb^{-1} .

Again, one observes that large counting rates are expected in the entire range of x_1 and $p_T \leq 50$ GeV, as well as for parts of the x_1 range up to $p_T \leq 500$ GeV. In analogy with the jet- γ process, the dominant contribution is given by the $gg \rightarrow Q\bar{Q}$ channel, with the $q\bar{q} \rightarrow Q\bar{Q}$ channel generally giving less than a 10% correction.

However, in the region $2.5 \times 10^{-6} \leq x \leq 4 \times 10^{-6}$ the $q\bar{q}$ contribution dominates (Fig. 2.5). In this bin the counting rate is about 10^5 events per year, with the $q\bar{q}$ contribution being twice that of gg . Hence, using gluon densities obtained from other reactions as well as from the study of charm at smaller x_2 it should be possible to determine quark densities at $x \leq 10^{-5}$ with a reasonable accuracy.

2.1.2.4. Two jets

The cross-section for two jet production is about 100 times larger than $Q\bar{Q}$ production. At $p_T \geq 20 - 30$ GeV [16], uncertainties in the determination of the jet p_T become small enough so that this

Figure 2.4. A plot of the number of events in (p_T, x) bins for charm quark production.

Figure 2.5. The cross-section $\sigma(x)$ for $pp \rightarrow Q\bar{Q} + X$ as a function of $x = x_1$. It is integrated over $p_T > 10$ GeV, $\max(x_1, x_2) < 0.8$, and $x/\Delta < \min(x_1, x_2) < x\Delta$ where $\Delta = 10^{1/20}$. The choice of Δ corresponds to 10 bins per decade of x

process can be used to study gluon parton densities with only a small correction from the gq process. Obviously this would allow a measurement of the gluon density at small x for much larger virtualities than via the other processes considered above. For $p_T \leq 100$ GeV this process will also provide an independent consistency check of the gluon distributions obtained from the other processes (Fig. 2.6).

Figure 2.6. A contour plot showing the region in $(E = p_T, x)$ where measurements of the gluon density in the proton can be made to within 20% accuracy. The regions marked with vertical, horizontal and slanted lines correspond to jet plus γ , charm quark and dijet production, respectively.

2.1.2.5. Drell-Yan lepton pair production and production of W and Z bosons

The ability of FELIX to identify events with heavy-flavor production should allow a measurement of the Drell-Yan process down to rather small invariant masses – probably down to dilepton masses ~ 4 GeV. Dilepton backgrounds from heavy-flavor processes, in general very serious, are expected to be substantially reduced for the forward kinematics. Consequently it appears possible to probe quark distributions down to $x \sim 2 \times 10^{-7}$ and cover a broad range of x, Q^2 (Fig. 2.7). A study of W and Z boson production will allow one to probe a rather large range of $x_1 \geq 5 \times 10^{-5}$ (Fig. 2.8).

Note also that a measurement of the W^-/W^+

Figure 2.7. The $\bar{u}$ antiquark momentum distribution with error bars as calculated from the Drell-Yan cross-section.

Figure 2.8. The cross-section $\sigma(x)$ for $pp \rightarrow W^\pm + X$ as a function of $x = x_1$. It is integrated over $\max(x_1, x_2) < 0.8$, and $x/\Delta < \min(x_1, x_2) < x\Delta$ where $\Delta = 10^{1/20}$. The choice of Δ corresponds to 10 bins per decade of x .

Figure 2.9. A contour plot showing the region in $(E = p_t, x)$ where measurements of the anti-quark densities in the proton can be made to within 20% accuracy. The region marked with cross-hatch shading corresponds to the Drell-Yan process. The dashed horizontal line is where W production dominates. The small triangle with horizontal shading shows where charm production is dominated by the $q\bar{q} \rightarrow c\bar{c}$ subprocess.

ratio at large x_F would allow a measurement of the $d(x, Q^2)/u(x, Q^2)$ ratio for $x \geq 0.5$, where current determinations are affected by uncertainties from nuclear effects.

Summary

To summarize, we find that due to its unique forward acceptance and to its capability for lepton and heavy-flavor identification, FELIX offers an excellent opportunity for the measurement of quark and gluon parton densities in nucleons down to $x \sim 10^{-7}$ and 10^{-6} . This can be done in several independent ways, with a number of cross checks for the perturbative QCD interpretation of the measurements - (see Fig. 2.6 for gluons and Fig. 2.9 for anti-quarks). These measurements will be able to establish the presence of nonlinear effects in QCD evolution at extremely small x by seeing the breakdown of the predictions of cross-sections via the DGLAP evolution equations.

2.1.3. Diffractive hard scattering at FELIX

By definition, diffraction is the set of phenomena associated with nonexponentially suppressed rapidity gaps. In high-energy collisions, hadrons appear to be fragile objects, their breakup typically resulting in high final-state particle multiplicities. Nevertheless, about half of all hadronic collisions should be diffractive (elastic scattering + inelastic diffraction-dissociation).

In the two decades since QCD was discovered, there has been a noticeable lack of interest in diffraction. This can be perhaps ascribed to the difficulty of relating the phenomena to the fundamental microscopic theory. But now this situation is changing. Diffraction processes represent a primary challenge to theorists: how to understand the phenomena from first principles.

A new subject of active investigation is that of hard diffraction: diffractive processes that contain a hard (short-distance) collision, with visible jets in the final state. Experiments at $p\bar{p}$ colliders and at HERA have provided first evidence of the existence of these processes. This opens up new possibilities for experimentally probing the space-time structure of hadronic scattering.

There are a large variety of basic hard diffractive processes to be studied. There can be more than one rapidity gap in the final state; the most common example is “double Pomeron exchange”. A single gap can reside between high- p_T jets (“perturbative Pomeron exchange”). Also, dijet final states can be found in single diffraction dissociation. Each of these basic processes has variants, exhibited in Fig. 2.10. They are all linked logically together, irrespective of how one views the underlying dynamics. How this works will be mentioned again in Section 2.1.4.2, page 22. But to begin we restrict our attention to the relatively well-studied case of single, hard diffractive dissociation.

We will use the variables x_F and t to describe diffractive processes ($p + p \rightarrow p + X$). x_F is the fractional energy loss of the proton, and t is the invariant momentum transfer from the proton to the rest of the system. The squared mass of the rest of the system is then $x_F s$. The momentum fraction of the diffracted proton is $x_F = 1 - x_P$.

The same definitions can be used if an excited state $n\pi^+, p\pi^+\pi^-$ or ΛK^+ is detected instead of a final proton. It is important to realize that when x_F is small it can be measured from the structure of rapidity gap events (e.g. the location in rapidity of the edge of the gap) without using information

Figure 2.10. Lego plots for the basic class of hard-diffraction events containing jets plus rapidity-gaps. The top row illustrates (a) the generic HERA nondiffractive, high Q^2 final state, (b) the diffractive final state with an undissociated proton, and (c) the diffractive final state with the proton dissociated into a soft, high mass final state. The next row illustrates hard single diffraction for pp collisions, in a hopefully clear notation. Note that the final state in process (f) corresponds to diffraction off a parton in the proton with large p_T , leading to a tagging-jet, and a subsystem similar to the generic HERA final state. The next two rows illustrate the same categories for double-Pomeron-exchange. Finally, the last four rows, beginning with the basic hard process (p) with a gap between jets, adds gaps to the left - and/or right-moving subsystems in a way analogous to the previous cases. Note also that, for example, processes (n) and (y) are closely related. Many other such relationships can be identified.

about the momentum of the leading nucleon (or the diffractively excited system).

The kinematics alone suggests a possible description in which there is an exchange of an entity, the soft Pomeron, between the proton and the system X . Regge-pole theory makes this possibility manifest: the amplitude for the diffractive process factors into 3 pieces: the t -dependent coupling of the Pomeron Regge-pole to the proton, the “propagator” of the Reggeon, containing an energy dependent factor $\left(\frac{s}{M_X^2}\right)^{\alpha(t)}$, and finally the amplitude for the Pomeron to be “absorbed” by the other nucleon and produce the system X .

While this language is widely used in hard-diffraction phenomenology, it is far from established as an appropriate one. As discussed in Section 2.2.2.1, page 35, soft diffraction and elastic scattering may not be simply described by Regge-pole theory at all. In addition it should be remembered that there are two distinct uses for the word *factorization*. One is in the sense of Regge factorization as used above, and the other one is in the sense of hard-scattering factorization. Diffractive hard-scattering is concerned with both kinds of factorization, and one must be careful to distinguish them. As mentioned above and discussed in Section 2.2.2.5, page 38, experimental data appear to show a breakdown of Regge factorization in single diffraction excitation [17,18]. Nevertheless, despite these reservations, the concept of Pomeron-exchange is widely used to describe hard-diffraction processes. In the present case, following the pioneering theoretical work of Ingelman and Schlein and of the UA8 experimental program, one considers the diffractive dijet process as occurring via a Pomeron-proton collision, within which a parton in the Pomeron interacts with another in the proton, producing the dijets in the final state. This picture provides an operational definition of the parton distribution of the Pomeron, although it is not at all guaranteed that the parton distribution so defined can be successfully applied to a different process. It also implies a Regge factorization for the single hard diffraction process itself, again something which needs experimental verification.

In any case, irrespective of the language used, FELIX would allow a systematic study and extension of the studies carried out by UA8 and now extended at CDF and D0 to a broader range of single diffractive processes, containing the hard final states of the nondiffractive processes of Eq.(2.8), as discussed in Section 2.1.2, page 12.

2.1.3.1. Diffractive hard factorization

A generic property of most of the current models for hard diffraction is the assumption of factorization of hard scattering from the soft processes [19–29], see summary in [30]. For example, one writes for nondiffractive dijet production the familiar formula

$$\frac{d\sigma}{dp_T^2 d\eta_1 d\eta_2} = \sum_{i,j} f_{i/A}(x_a, \mu) f_{j/B}(x_b, \mu) \frac{d\hat{\sigma}_{ij}}{dp_T^2 d\eta_1 d\eta_2}, \quad (2.9)$$

where the momentum fractions x_a, x_b are determined from the kinematics of the collision, i.e. the rapidities η_1 and η_2 of the observed jets. $f_{i/A}$ is the ordinary parton density in the non-diffracted hadron, and μ is the usual renormalization/factorization scale.

For the diffractive process one writes a direct generalization:

$$x_P \frac{d\sigma}{dx_P dt dp_T^2 d\eta_1 d\eta_2} = \sum_{i,j} f_{i/A}(x_a, \mu) \frac{x_P df_{j/B}^D}{dx_P dt} \left(\frac{x_b}{x_P}, x_P, t, \mu \right) \frac{d\hat{\sigma}_{ij}}{dp_T^2 d\eta_1 d\eta_2} \quad (2.10)$$

The ratio of these two cross-sections is the (differential) probability for finding the single-diffractive final state, or differential gap fraction r :

$$x_P \frac{dr}{dx_P dt} = \frac{1}{\sum_j f_{j,b}(x_b, \mu)} \sum_j x_P \frac{df_{j,b}^D}{dx_P dt} (x_b/x_P, x_P, t, \mu). \quad (2.11)$$

The hard factorization hypothesis is that this quantity is indeed dependent only on the properties of the diffracted proton B and not on those of the undiffracted proton A or on hard the collision parameters η_1, η_2, p_T^2 .

An even simpler expression can be written down for a gap fraction appropriate to HERA electroproduction, and experimentally this gap fraction, integrated over t , is found to be about 5% (per unit rapidity). The corresponding quantity for UA8 and Fermilab single hard-diffraction data appears to be considerably smaller, of order (0.5 – 1)%.

For processes like this, where both colliding particles are hadrons, one indeed expects such a substantial reduction of the hard diffractive cross section relative to the hard factorization predictions, given

diffractive densities from fits to deep inelastic electroproduction processes. The physics of the reduction is simply the possibility for spectator partons in the hadron projectiles to interact via soft collisions. A necessary condition for the diffractive final state to survive is that no inelastic spectator collisions occur. This obviously leads to a strong reduction of the diffractive cross-section. Indeed in this case factorization can be proven [31] not to hold, at least as a statement about perturbation theory. But it may be possible to prove hard-scattering factorization [27,28] for the class of diffractive hard processes in which there is only one hadron in the final state e.g., diffractive deep inelastic scattering [32]. Hence it is natural to use these processes as a benchmark for determining diffractive quark and gluon distributions [33].¹

Figs. 2.11 and 2.12 show the cross-sections calculated from Eq. (2.10) for diffractive dijet and W production, respectively, at the LHC using diffractive densities obtained from fits to HERA diffractive DIS data.

It is convenient to represent the measured cross-section as a factorizing cross-section times a suppression factor:

$$\sigma_{\text{true}} = \sigma_{\text{fact}} \times S(x_P, t, s). \quad (2.12)$$

Estimates of the value of S typically give a value $S \sim \frac{1}{10}$.

S may actually be a slowly varying, but rather complicated function of initial energy, x_P , t , and x_B . For example, one can expect that it will decrease with an increase of $\sigma_{\text{tot}}(pp)$ (stronger spectator effects), increase with increasing $|t|$ (selection of more weakly interacting configurations in the intact nucleon [39]), and increase as x_B becomes large (due to a selection of smaller size configurations in B).

It would be also interesting to study diffraction to inelastic low-mass final states B in the process:

$$p(p_1) + p(p_2) \rightarrow (\text{jet}_1 + \text{jet}_2 + X) + B \quad (2.13)$$

which may select configurations with an interaction strength rather different from the average one. Several examples of the channels feasible with FELIX include the aforementioned $B = n\pi^+, p\pi^+\pi^-$ and ΛK^+ , each of which can be studied as a function of

p_T of the produced jets for fixed $t \sim 0$. A hard factorization combined with Regge factorization would lead to

$$\frac{\sigma(p(p_1) + p(p_2) \rightarrow (\text{jet}_1 + \text{jet}_2 + X) + B)}{\sigma(p(p_1) + p(p_2) \rightarrow (\text{jet}_1 + \text{jet}_2 + X) + p)} = \frac{\sigma(p(p_1) + p(p_2) \rightarrow p + B)}{\sigma(p(p_1) + p(p_2) \rightarrow p + p)} \quad (2.14)$$

It is natural to expect that at least for large enough p_T this factorization would be broken, with the cross-section of diffractive jet production in the inelastic diffraction channel substantially enhanced compared to the expectations of Eq.(2.14).

2.1.3.2. The super-hard Pomeron

One of the striking features of the UA8 diffractive jet data [40] is that in a substantial proportion of the events almost all of the momentum associated with the Pomeron exchange goes into the jet system. The H1 collaboration [37] has presented a fit to their diffractive-electroproduction data in which a similar peak appears in the gluon distribution in the Pomeron.

If the diffractive process is modeled in terms of color-singlet two-gluon exchange, then this contribution can be interpreted as exchange of configurations where almost all the momentum is carried by one or the other of the gluons, but not both. It is even possible that the soft gluon is really nonperturbative in character, perhaps better described as a color-octet system of gluon degrees of freedom which is exchanged. On the other hand, such super-hard terms might be accountable within a perturbative QCD framework [39], especially at reasonably large t and at not too large p_T .

In any case, the phenomenology and theory of these super-hard terms is in its infancy. One should look for them under as large a range of conditions as possible (large and small t , large and small jet p_T). Any experiment that is capable of seeing the kinds of cross-section predicted by factorization will also be able to investigate the super-hard terms. As data from CDF and D0 are analyzed over the next year or two, it should become apparent whether or not they confirm UA8's measurement of a super-hard component to diffractive hard processes.

2.1.4. Rapidity gaps between jets

2.1.4.1. One gap events

An important characteristic of scattering events at the LHC is the color flow in the underlying partonic process. In forward scattering, where the t -

¹A number of theorists and experimentalists are actively involved in fitting diffractive parton densities to data and in predicting further cross-sections (e.g., [28,34–37]). Coordination of the diffractive physics between the HERA, the Tevatron and the FELIX experiments ensures that predictions made for other processes (e.g., [36,38]) are properly normalized, and known QCD effects (particularly evolution) are taken into account.

Figure 2.11. The cross-section $\sigma(x, \beta)$ for diffractive dijet production at the LHC for different values of $\beta = |t|/(M_X^2 + |t|)$. The solid (dashed) curves correspond to the fits to the current diffractive data assuming that the Pomeron structure function is dominated by gluons (quarks) at $Q_0^2 = 4 \text{ GeV}^2$ [38,36]. The cross-section is given as a function of $x = x_2$ and is integrated over $p_T > 10 \text{ GeV}$, $\beta/\Delta < x_1 < \beta\Delta$, $x/\Delta < x_2 < x\Delta$ and $0.002 < x_{pom} < 0.03$, with $\Delta = 10^{1/40}$. Here, x_1, x_2 are the longitudinal momentum fractions of the dijet relative to the Pomeron and the nondiffracted proton, respectively.

Figure 2.12. The cross-section $\sigma(x, \beta)$ for diffractive W production at the LHC for different values of β . The curves correspond to the same model as in Fig. 2.11. The cross-section is given as a function of $x = x_2$ and is integrated over $\beta/\Delta < x_1 < \beta\Delta$, $x/\Delta < x_2 < x\Delta$ and $0.002 < x_{pom} < 0.03$, with $\Delta = 10^{1/40}$. Here, x_1, x_2 are the longitudinal momentum fractions of the W relative to the Pomeron and the nondiffracted proton, respectively.

Figure 2.13. Dependence of the dijet cross-section on (a) the rapidity distance η_c between the jet cones and (b) the rapidity range covered by the detector. Curves are for minimal jet p_T 's of 10 (solid), 20 (dashed), 30 (dotted), and 50 GeV (dash-dotted lines).

channel exchange of light quanta dominates, color-octet exchange of gluons versus color-singlet exchange of electroweak bosons or Pomerons is expected to lead to very different hadronization patterns. In t -channel color-singlet exchange, color coherence between initial and final state gluon radiation leads to soft gluon emission preferentially into the region between the beam and the forward scattered parton. This leaves the central region (between the two jets in a dijet event) free of gluons and their hadronization products. In t -channel color-octet exchange, on the other hand, gluon radiation into the central region is preferred. Consistently t -channel color-singlet exchange can lead to a rapidity gap, *i.e.* a rapidity region of exceptionally low hadronic activity, for the fraction of pp collisions which produce no underlying event containing soft inelastic spectator interactions.

An excess of dijet events with rapidity gaps has already been observed at the Tevatron [41]. About 1% of all dijet events with rapidity separations $|\eta_{j1} - \eta_{j2}| \geq 4$ exhibit anomalously low hadronic activity in the rapidity region between the jet cones. At the LHC, FELIX, with its unique angular coverage, can continue and extend these studies of rapidity gaps in dijet events and, among other things, study the energy dependence of the gap survival

probability. Within the DGLAP and BFKL approximations, it is expected that the probability of the hard subprocess would increase with the length of the rapidity interval. On the other hand, since $\sigma_{tot}(pp)$ is expected to increase by nearly 50% between the Tevatron collider and the LHC, one may expect a substantial decrease of the gap survival probability at the LHC for the same η_{j1}, η_{j2} .

Fig. 2.13 shows the dijet cross-section as a function of the separation of jet definition cones, $\eta_c = |\eta_{j1} - \eta_{j2}| \sim 1.4$, and as a function of the maximal jet rapidity η_{max} , for p_T thresholds defining a jet of $p_T > 10, 20, 30$, and 50 GeV. For an integrated luminosity of 100 pb^{-1} and a 1% fraction of rapidity gap events, the dijet cross-section in pb corresponds to the total number of rapidity gap events. From Fig. 2.13 it is then clear that FELIX can record meaningful samples of gap events with gaps which are 8 or even 10 units of rapidity wide. What is perhaps more important, FELIX can study the continuous transition from soft diffraction, mediated by Pomeron exchange with $|t|$ in the 1 GeV^2 range or below, to the hard gap events considered here, with a momentum transfer $|t|$ in excess of $t \approx p_{Tj}^2 \geq 100 \text{ GeV}^2$. Symmetric events with $x_1 \approx x_2$ will be dominated by the scattering of valence quarks for $x_1 \geq 0.3$ and by glue-glue

scattering for $x_1, x_2 \ll 0.01$. Asymmetric events with large x_1 but small x_2 on the other hand will be dominated by quark-gluon scattering. The large acceptance in rapidity of the FELIX detector will be vital in separating these samples. Such a study will allow measurements of the fraction of rapidity gap events separately for quark-quark, quark-gluon and gluon-gluon scattering, an issue which is crucial for distinguishing different models of hard rapidity gap events. A model [42] based upon perturbative, color-singlet two-gluon exchange predicts, due to the stronger coupling of the gluons to the color-octet charge of the scattered gluons, an enhanced rapidity gap fraction in glue-gluon scattering. A color evaporation model, on the other hand, makes it more difficult for the color-octet charge of scattered gluons to be “bleached” and implies that the rapidity gap fraction is largest for quark-quark scattering [43]. Another possibility considered in [44] is the suppression of the gap survival probability by Sudakov type form factors. FELIX will be able to discriminate in great detail these possibilities. The preliminary evidence from D0 [45] appears to favor the latter mechanism, implying that, even when the momentum transfer is tens of GeV, nonperturbative effects are of great importance.

We also emphasize the importance of investigating the gap-survival probability in the situation when one of the jets is generated by a quark or gluon with $x \geq 0.4 - 0.5$. In this situation relatively compact, weakly interacting configurations in the colliding hadron may be preferentially selected. This could lead to an increase in the gap survival probability to a level closer to what is observed at HERA for γp collisions [46].

2.1.4.2. Multigap events

Hard diffraction events containing more than one rapidity gap should occur and, thanks to the very large FELIX rapidity acceptance, be readily observable. The most familiar example of this class is double-Pomeron exchange, with both undissociated beam protons being detected in Roman pots. This process will be discussed in the next subsection. However, as already illustrated in Fig. 2.10, there are a variety of other quite fundamental processes to be considered.

A convenient starting point for considering these is the hard double-diffraction process discussed above, and observed at the Tevatron, consisting of a rapidity gap between jets. As discussed in the previous section, about 1% of all coplanar dijet events contain such a gap. Theoretically, one expects that there is a 10% chance per event that the hard pro-

cess be color-singlet exchange, with the remaining 10% factor being due to the requirement that spectator degrees of freedom at other locations in the impact plane do not interact inelastically. This is essentially the factor S in Eq.(2.12).

The event structure in such events is closely related to what is seen in ordinary deep inelastic events at HERA. In particular the left-moving system looks like the entire HERA hadron final state, with the right-moving hadron system being a reflected copy which replaces the single positron in the HERA right-moving system. Since these final states are so similar, it is not at all unreasonable to expect that in the pp or $p\bar{p}$ reactions there will also be a diffractive component. Furthermore, in terms of the gap fractions introduced in Section 2.1.3.1, page 18, it is also reasonable that the fraction of events which contain the extra gaps will be similar to what is seen at HERA, namely 5% per unit rapidity. Therefore of order 10^{-3} dijet events should have an extra rapidity gap. These are by definition a subclass of single-diffraction dijet events which contain a rapidity gap between the jets. A more quantitative estimate is simply found by multiplying 1% by 5%, and by the rapidity interval over which the second gap edge can occur (a number which will be between 3 and 10 in practice). There is of course another factor of two from choosing which of the incident protons is diffractive.

If both left- and right-moving systems choose to be diffractive, then the final state system contains three rapidity gaps. This is a special case of a hard double-Pomeron process. Multiplication of 1%, $(5\%)^2$, and a factor 10 for the rapidity acceptance of the two new gap edges, gives for the fraction of dijet events with this rich topology a number of order 3×10^{-4} . Note that now one can remove the central gap, and obtain an estimate for the number of ordinary double-Pomeron hard-diffraction coplanar dijet events of the order of 3×10^{-3} . Again, a more precise prediction would be in terms of a gap fraction differential in the locations of the two gap edges; this number is evidently $1\% \times (5\%)^2 \times 10 = 3 \times 10^{-4}$. Likewise, one can remove the central gap in the double-gap, hard-single diffraction example, and get for the gap fraction, differential in the location of the gap edge, the value $1\% \times 5\% \times 10 = 5 \times 10^{-3}$. This number is quite consistent with what is observed, as quoted in Section 2.1.3.1, page 18.

It is very important to recognize that this line of argument, based in large part on the HERA phenomenology, is only appropriate for the hard collision process being a quark-quark interaction; there is little doubt that this is what generates the “quark-

jet" in the HERA final state. Furthermore, the diffracted mass at HERA at a given Q^2 is typically of order Q or more; the contribution with $M_X^2 \ll Q^2$ is higher-twist. What this means kinematically is that, in the HERA laboratory-frame, the diffractive gap edge cannot be too close to the quark-jet seen in the final state. The distance in the lego plot from gap edge to jet core is bounded below by $\ln Q$. This feature should persist, for quark-quark processes, in the FELIX context as well.

However we already noted in Section 2.1.4.1, page 19, that both from experiment and theory there are expected to be important differences between quark-initiated processes and gluon-initiated ones. The gap fraction for quarks may be larger than that for gluons. However, in the case of gluons there is the evidence from UA8 that, in the Pomeron-exchange language, there is a super-hard component to the Pomeron structure function. What this means in practice is that kinematically the Pomeron exchange acts as if it is a single-gluon exchange. This is just what is in fact observed in the Tevatron hard double-diffraction process. The rapidity-gap edges are seen to be at the edge of the jet cores (0.7 units away), and the final state is as if there were photon exchange between the left-moving and right-moving systems.

This is also the phase-space signature of the super-hard Pomeron contribution to hard single-diffraction production of dijets as observed by UA8. The superhard contribution puts the rapidity gap at the edge of the dijet system. So, in summary, for quark-induced hard collisions the gap edge is separated from the quark jet by at least $\ln p_T$, but for gluon-induced hard collisions, there need not be such a constraint. In terms of the microscopic dynamics, this distinction has to do with the fact that when color triplets are produced in distant parts of phase space (as in electron-positron annihilation), rapidity gap production in the intermediate phase-space region is exponentially suppressed. For color-octet systems, however, extra (possibly nonperturbative) soft gluon exchanges allow the screening of the octet color and therefore allow larger rapidity gaps to form. However, the systematic theoretical development of these ideas is still in its infancy. And if nonperturbative mechanisms are involved (as the recent D0 data suggest [45]; cf Section 2.1.4.1, page 19) it may take some time as well as considerable data to create the full picture.

Experimentally, it will be important to systematize the gap-fraction contributions from the quarks and from the gluons and, in the case of the gluons, to determine what fraction of their contribution is

superhard. At present there are only the rough beginnings of this phenomenology.

For FELIX, even the triple-gap process fits rather comfortably into its acceptance. If the dijets are produced at 50 mrad with a p_T of 20 GeV, then the central gap extends from +100 mrad to -100 mrad, an interval of six units of rapidity. If the process is quark induced, the gap edge must be roughly at least 3 units of rapidity beyond the jet-core rapidity, namely at an angle of 2.5 mrad. So the study of the distribution of the gap edges should be possible over a broad range relative to this central value.

There are clearly a variety of lines of generalization for this approach. An important one is to vary the momentum transfer to the diffracted proton; there may be a distinctly different behavior in the soft region of $|t| < 0.4 \text{ GeV}^2$ and the semihard region $|t| > 1 \text{ GeV}^2$. One may also see what happens when the proton is softly dissociated into a low mass system like $p\pi^+\pi^-$, $n\pi^+$, ΛK^+ , etc. (This is probably a small fraction of the gap events, perhaps of order 1%.) Next, one should look at what happens when the proton dissociates softly into a high-mass system. This is harder experimentally, although do-able. Theoretical expectations based on existing data from HERA and the Tevatron suggest that this component is perhaps 5 – 20% of the contribution from undissociated protons. Finally there is the contribution from very high momentum transfers, high enough to create a tagging-jet in the diffracted-proton system. This subprocess should of course have a much smaller cross-section (for fixed kinematics of the central dijet, etc., system). It should be estimated by taking the perturbative cross-section calculation for the full multijet system without gaps (including the aforementioned tagging jets), and then appending the differential gap-fraction estimates for each rapidity gap, with one final factor of the gap survival-probability S . It is important to note that the survival probability factor S is applied once, and only once, since it once and for all requires all spectators not to interact inelastically.

From a practical point of view, the gap-fraction approach allows one to estimate cross-sections and construct simulations from the existing theoretical Monte-Carlo data base. One may simulate in general the hard processes without gaps, and then analytically estimate the fraction of those processes which will contain the gaps of interest. Also, from the point of view of triggering, it is clear that one will take as primary trigger the jet structure (p_T , existence of jet cores, etc). Certainly in many if not most cases, this will give a low enough trigger rate

that the gap search can be done offline or at Level 2. In the remaining cases, lack of activity at very large rapidities, or existence of a Roman pot tag, should easily suffice to reduce the trigger rate to a reasonable value.

2.1.4.3. Double-Pomeron exchange

The ideas applied to single diffractive hard scattering and to single gap events can be applied to double-Pomeron induced processes as well:

$$pp \rightarrow p + X + p, \quad (2.15)$$

with a large rapidity gap on opposite sides of the central system X , i.e., between X and each of the two diffracted beam particles. Because of the information obtainable from the Roman-pots, this process is especially accessible to detailed experimental scrutiny. Recently, first evidence for the occurrence of such processes, with dijets in the central system X , has been reported by D0 [45]. The gap fraction, however, is quite low, and it is not yet clear whether the yield is consistent with the estimates made in the previous subsection.

More detailed estimates of cross-sections for this class of processes exist, but at present the spread in the predictions covers several orders of magnitude. The basic underlying mechanism assumed in most calculations is perturbative color-singlet two-gluon exchange, something which itself is not above suspicion. But even so, estimation of the cost of suppression of soft gluon radiation, etc., creates major uncertainties.

If super-hard Pomeron collisions occur, then they will result in a spectacular signature in double-Pomeron exchange events: the final state consists of a proton going down each beam pipe plus a central two-jet system and absolutely nothing else. The shadowing effects already observed for single diffraction probably strongly reduce the rate as compared to the expectations based on perturbative QCD, without taking shadowing into account. It is not yet clear whether the hard double-Pomeron-exchange processes seen at the Tevatron contain superhard contributions. The next collider run at Fermilab should create a much improved data base.

2.1.5. Hard exclusive diffraction

2.1.5.1. Diffraction into three jets

It is possible that a nucleon (meson) has a significant amplitude to be in a configuration where valence partons are localized in a small transverse area together with the rest of the partons. These configurations are usually referred to as *minimal* Fock space

configurations - $|3q\rangle$ ($|q\bar{q}\rangle$). Strong evidence for the importance of such configurations in the wave function of vector mesons has been obtained recently at HERA from the observation of the rather rapid increase with energy of the cross-sections for exclusive electroproduction of ρ , ϕ and especially J/ψ -mesons at small x . Hadrons in such a configuration occupy a small transverse area with a larger probability than in the case of nonminimal configurations, because, e.g. the long range pion field is very weak. Therefore, such initial configurations are expected to interact with other hadrons, even at high energy, with a small cross-section. In the case of the “elastic scattering” of such a proton configuration off another proton, this three-quark system with large relative momenta should preferentially diffractively dissociate into a system of three jets with large transverse momenta $p_{Ti} \sim \pi b^{-1}$, where b is the transverse size of the minimal configuration. The production cross-section for the three jets can be estimated [47] to leading order in $(\alpha_s \ln M_{3jet}^2)$. As in the case of diffractive vector meson production in deep inelastic scattering, the cross-section is proportional to the square of the gluon density in the nucleon at $x \approx M_{3jets}^2/s$, and virtuality $\sim p_{T,jet}^2$. The distribution over the fractions of the momentum carried by the jets is proportional to the square of the light cone wave function of the $|3q\rangle$ configuration. Hence the diffraction of a proton into three jets provides important information about the short-distance quark structure of the proton, and also provides unique information about the longitudinal momentum distribution in the $|3q\rangle$ configuration. From an analysis of diffraction data [47,48], numerical estimates lead to a value of the cross-section integrated over everything except a $p_{T,jet}$ threshold for one jet,

$$\sigma_{3jets} \sim (10^{-4} - 10^{-5}) \left(\frac{5 \text{ GeV}}{p_{T,jet}} \right)^8 \text{ mb}. \quad (2.16)$$

The probability of the $|3q\rangle$ configuration is estimated using a phenomenological fit to the probability of configurations of different interaction strengths in a nucleon (cf. [47,48]). One can see from the estimate (2.16) that FELIX should be able to collect more than 10^7 events/year in this interesting kinematic regime. Studies of this reaction in pA collisions (Section 2.3, page 43) will allow one to enhance this signal.

Another interesting group of hard processes is proton diffraction into 2 high p_T jets and one collinear jet. These processes are dominated by parton configurations when only 2 quarks in the projectile proton are close to each other, i.e., have large transverse momenta. Such quark configura-

tions are relevant for estimates of proton decay rates. The wave function describing such a configuration can be measured in the double-diffraction process where each of the protons fragments into 3 high p_t jets: $pp \rightarrow jet(k_t) + jet(-k_t - q_t) + jet(q_t) + jet(l_t) + jet(-l_t - r_t) + jet(r_t)$. Note that to measure the cross-section for such diffractive processes, both arms of the FELIX spectrometer are needed.

2.1.5.2. Tagged-pion diffraction dissociation

Reactions containing a very forward neutron or a Δ -isobar can be dominated by the scattering off the pion cloud of the nucleon. In this way the proton beam is effectively converted into a pion beam; the leading baryon is effectively a pion tag. A necessary condition that one-pion exchange dominates this process is that the transverse momentum of the forward baryon be small compared to 300 MeV and, in the case of the Δ , that its x_F exceed 0.9. The precise condition is

$$|t| = \left(\frac{M_B^2}{x_F} - m_N^2 \right) (1 - x_F) + \frac{k_t^2}{x_F} \leq 0.1 \text{ GeV}^2. \quad (2.17)$$

One must still deal with absorptive corrections due to the simultaneous interactions of the projectile with a nucleon and a pion. These are expected to be corrections no larger than a factor two.

Two types of processes would be of special interest:

Pion diffraction into two jets:

In analogy with the process of nucleon diffraction into three jets it is expected that a pion can dissociate into two jets in the process $\pi + p \rightarrow jet_1 + jet_2 + p$ [49,50] (Fig. 2.14).

Figure 2.14. Illustrative diagram for hard diffractive production of jets when an incident pion dissociates into a $q\bar{q}$ pair before hitting the nucleon. The exchanged gluons are represented by wavy lines.

The cross-section for this process has a similar structure [50,51]: due to the rapid increase of the

Figure 2.15. Diagram corresponding to large $|t|$ elastic scattering off the pion cloud.

gluon density with energy one expects the cross-section for pion diffraction into two jets to be much larger than in the case of the fixed target experiment E791 at FNAL which has just reported first evidence for this effect [52].

Two $\rightarrow$ three hard reactions:

It is also interesting to study large $|t|$ elastic scattering off the pion cloud in a number of reactions [53] like (Fig. 2.15):

$$pp \rightarrow B(p_{T\,B}) + \pi(p_{T\,\pi}) + p(p_{T\,p}), \quad (2.18)$$

for $B = N, \Delta$, $x_F(B) \geq 0.9$, $p_{T\,B} \sim 0$, and $p_{T\,\pi} \sim -p_{T\,p} \gg 1$ GeV, which corresponds to the proton elastic scattering off the pion cloud. Although the flux of such pions in the proton is only $\sim 1\%$, at large $|t| \approx p_{T\,p}^2$ the cross-section for elastic πp scattering is expected to be substantially larger than the cross-section for elastic pp scattering.² Hence the cross-sections for reaction (2.18) and elastic pp scattering at $|t|$ larger than 10 GeV² should be comparable.

One may also consider elastic scattering of two pions in processes like

$$pp \rightarrow B(p_{T\,B}) + \pi(p_{T\,\pi}) + \pi(p_{T\,\pi'}) + B'(p_{T\,B'}) \quad (2.19)$$

for $B, B' = N, \Delta$, $x_B, x_{B'} \geq 0.9$, $p_{T\,B} \sim p_{T\,B'} \sim 0$, and $p_{T\,\pi} \sim -p_{T\,\pi'} \gg 1$ GeV. Again the much slower decrease of the $\pi\pi$ elastic scattering with $|t|$ helps to compensate the small probability of finding both nucleons in configurations with pions.

Many generalizations of such processes can be estimated. These include channels with strange par-

²The high-energy data on large $|t|$ πp elastic scattering [54] are consistent with this expectation.

ticles in the final state like

$$pp \rightarrow (\Lambda K^+, \Sigma^+ K^0) + p$$

as well as kinematics for which the transverse momentum of the proton is balanced by a baryon, not a meson. Such processes are of interest, both for the study of high-energy scattering and for the structure of color correlations in hadrons, especially in relation to the question of intrinsic strangeness in nucleons, see e.g. [55]. Note that at sufficiently large $|t|$, where the colliding-hadron configurations are sufficiently small for the applicability of perturbative QCD, new factorization relations are expected to be valid. The ratio of elastic cross-sections at large $|t|$ should be equal to the ratio of the probabilities for small configurations in the colliding hadrons. For example

$$\frac{\frac{d\sigma^{el}}{dt}(Kp)}{\frac{d\sigma^{el}}{dt}(\pi p)} \rightarrow \left(\frac{f_K}{f_\pi}\right)^4 \sim 3. \quad (2.20)$$

Here f_π, f_K are the leptonic decay constants of the π^- and K^- -mesons.

2.1.6. Quarkonium physics with FELIX

2.1.6.1. Problems with the theory of quarkonium production

There is of course a long history of quarkonium production in hadron-hadron collisions, with quite a rich data base, especially for the S -wave spin-triplet states $J/\psi, \psi', \Upsilon(nS)$. Because these states are made of heavy degrees of freedom, it is expected that their production properties will reveal important information on an underlying hard production process. However, the mechanism of quarkonium formation has stubbornly resisted the theoretical interpretations based upon the simplest perturbative QCD mechanisms. Even after twenty years of development, until recently theory and experiment on high- p_T charmonium hadroproduction differed by one to two orders of magnitude.

However, there have been promising recent developments in the theory. In particular, aside from the question of how to describe in detail the underlying dynamics, it has been explicitly recognized that the ratio of bound-charm production to low-mass open-charm production for the same external kinematics, e.g. pseudorapidity and p_T , is a slow function of such variables and typically of order 10 percent. This feature is a central element of the color-evaporation model of charmonium production, but is not limited to this theoretical description. For recent reviews of the theoretical and experimental

situation see [56–58].

2.1.6.2. Probing gluon densities

It is not clear, however, whether this 10% ratio of bound charm to low-mass open charm will extrapolate into the LHC kinematic domain, especially in the very-small- x regime, where novel nonlinear effects are anticipated. If it changes, this in itself is a strong indicator of new phenomena occurring. And if the ratio of hidden to open charm production does not markedly change, then the hidden-charm production should be a faithful indicator, for whatever reason, of the nature of the physics of the more-difficult-to-measure, but more-easy-to-calculate, open charm production. In this regard, it is important to recognize that the J/ψ production process is distinguished by offering the largest reach as far as probing the gluon density at small x is concerned. The kinematic limit, realized in very forward J/ψ production at the LHC, is given by $x \approx 5 \cdot 10^{-8}$. At such small values of x the effect of saturation of the gluon density should manifest itself in terms of a failure of naive extrapolations of total production cross-sections from fixed target and Tevatron energies. It might correspond to an increase of these cross-sections by a factor of ~ 100 .

The usefulness of such a measurement to precisely determine the gluon density is probably limited, because the nonperturbative parameters that describe quarkonium formation cannot be completely eliminated by normalizing the cross-section to low-energy data. Nevertheless, the qualitative behavior of the gluon distribution should be clearly visible. The main uncertainties which arise from energy-dependent perturbative QCD effects as well as from nonperturbative effects can be investigated through the x_F dependence of the production cross-section.

The situation could be improved at the expense of losing some of the reach in small x by measuring the p_T distribution at large transverse momentum ($p_T \approx 20$ GeV, say), where quarkonium production is for sure dominated by color-octet fragmentation of a virtual gluon as the initiating process. In this case, in the framework of nonrelativistic QCD, the only unknown is a single nonperturbative parameter which can be eliminated by normalizing the rate to Tevatron data.

There is more that can be done to elucidate the detailed mechanism of the quarkonium formation. The comparison of quarkonium and open charm (beauty) production close to threshold over a wide range of transverse and longitudinal momenta, as already indicated above, would be very revealing.

Would this ratio stay the same as simple color evaporation models suggest? Polarization measurements are of special importance, since polarization yields information on the nature of quarkonium binding from a heavy quark-antiquark pair, and, to a lesser extent, also on the underlying heavy quark production mechanism.

Direct J/ψ polarization at large transverse momentum, in particular, can discriminate between the color evaporation model and other ideas, such as the nonrelativistic QCD approach [57], which is diagrammatic, but includes Coulomb-like enhancements due to the low velocity of the heavy quarks. The former mechanism assumes an important role of soft (transverse) gluons being emitted and absorbed during the formation of the quarkonium bound state, such that no information on the spin of the heavy quark pair is preserved. In this case an isotropic angular distribution of decay muons in the J/ψ rest frame is expected. In the nonrelativistic QCD approach a significant fraction of transverse polarization is predicted and it should increase with increasing p_T . As soft gluons should couple to bottomonium more weakly than to charmonium, a comparison of the angular distributions in direct Υ and J/ψ production would be especially interesting.

With good photon identification and energy resolution, a polarization measurement of P -wave χ_{cJ} states, something which has not been done to date, may become feasible via their radiative decays. The χ_{c2} polarization is of special interest here, because at leading order (integrated over all p_T) χ_{c2} is produced with helicity 2, provided color-singlet production dominates the rate. The polarization measurement will clarify the relative importance of alternative production mechanisms, such as color-octet production.

Such measurements are certainly difficult. But for sure the best chance is to search for these states when they are produced at large energies, where the radiative γ at least has a relatively high energy. For a χ_{c2} produced with 700 GeV laboratory momentum, the γ will have a typical energy of 90 GeV.

The bottomonium system has not been explored very well in hadron-hadron collisions so far, mainly because of either lack of statistics or lack of photon identification. For example, it has not been possible so far to separate the indirect contribution to $\Upsilon(nS)$ production through χ_b production and their subsequent radiative decays. Again, such a measurement, while difficult, would add another important piece to our understanding of quarkonium production mechanisms, and in particular to their scaling with the heavy quark mass. For example, the ob-

served ratio of χ_{c1} to χ_{c2} production cross-sections can only be explained by invoking a large contribution from color-octet production to both states. Observation of this ratio for bottomonium states would not only test this explanation, but also probe the coupling of soft gluons to $b\bar{b}$ pairs. If these couplings are described by the nonrelativistic QCD formalism, then the χ_1/χ_2 -ratio is predicted to decrease significantly as compared to charmonium. In the color-evaporation model, the ratio would stay constant. Again, in the forward kinematics, the photons from the χ decays carry relatively large momenta and the energy and angular resolutions of the calorimeters may be sufficient for such measurements.

A measurement of the energy dependence of the ratio of the yields of Υ and J/ψ production at large fixed x_F would be of special interest. This ratio is expected to increase with incident energy due to a more rapid increase of gluon density with x at larger virtualities. This effect may be amplified due to nonlinear effects for gluon densities (saturation effects) which should be much more important for smaller virtualities relevant for J/ψ production.

The observation of $\Upsilon(3S)$ at a rate comparable to $\Upsilon(2S)$ at fixed-target and the Tevatron is a difficulty for the nonrelativistic QCD picture, which suggests the existence of an as yet unobserved $\chi_b(3P)$ state. Verifying or excluding this state by direct observation would yield another constraint on the nonrelativistic QCD description of quarkonium production. Besides P -wave states, potential models predict many bottomonium states below threshold that have not been observed so far. Of particular interest would be the observation of D wave states and the observation of η_b in its $\gamma\gamma$ decay.

2.1.7. Searching for BFKL effects in hard processes

As already discussed in Section 2.1.1.2, page 9, a strong growth of the scattering amplitudes is expected in the high-energy limit for the interaction of small color dipoles such as onia. In the BFKL model for the interaction of two dipoles of the size of the J/ψ one expects the total cross-section to increase $\approx s^{0.5}$, see Eq.(2.1). In other models a somewhat smaller increase is expected [4,59].

2.1.7.1. Mueller-Navelet jets

For FELIX, a basic measurement is that proposed by Mueller and Navelet, namely the inclusive measurements of two jets with as large a rapidity interval between them as possible (Mueller-Navelet jets [60]).

This is essentially the quark-quark process already discussed in Section 2.1.1.3, page 10. At present the attempts to find BFKL effects are rather ambiguous. At HERA, extra jet activity in the proton direction is a possible signal, as well as the behavior of F_2 itself. At Fermilab, the evidence from hard double diffraction (rapidity-gap between jets) and small-angle dijet production remains inconclusive.

Mueller and Navelet emphasize the importance of comparing the production cross-sections of the 2 jets at different energies, but the same x_i and p_T . The ratio of the yields is then simply

$$\frac{\sigma_1}{\sigma_2} \sim \left(\frac{s_1}{s_2} \right)^\omega, \quad (2.21)$$

where ω is given by Eq.(2.2). This is one of the most important reasons, from the point of view of the FELIX program, for running the LHC at a reduced energy. If this is done, the analysis of data becomes much less theory dependent. In this respect the planned studies at the Tevatron will benefit the proposed program, although the limited rapidity coverage of CDF and D0 remains a limitation. But, in general, reduced-energy running at the LHC is desirable for most any new physics and/or standard physics for which there is a substantial application of perturbative QCD phenomenology.

Other important distinguishing features of the BFKL mechanism for the production of two jets with a large rapidity separation would be the dependence of the transverse momenta of particles produced between the jets, because characteristic virtualities in the BFKL ladder are $\sim p_{T,jet}^2$ and a different pattern of azimuthal decorrelations of the jets will occur. As mentioned above, attempts to study these effects were recently performed at the Tevatron. The results for the rapidity dependence of the cross-section are not yet compelling [61]. A more refined test is the azimuthal correlation of the two jets [45,62], and this looks more promising.

2.1.7.2. High multiplicities in events with Mueller-Navelet jets

In the two-jet production with Mueller-Navelet kinematics, multiple interactions of the two colliding partons are possible. Mueller and Salam [1] have recently estimated these in a simple analytic model, as well as numerically. Their expansion is in the “number of cut BFKL Pomerons”, k , which is in rough proportion to the number of associated jets produced. The results are shown in Fig. 2.16.

The number of jets produced per unit rapidity is $(\alpha_P - 1) \cdot k \approx \frac{1}{2}k$. Such events would be quite striking. Over a few units of rapidity there would be, for $k = 10$, about 5 jets per unit rapidity. For jets

having $k_\perp$ on the order of 5 GeV this should be right around the saturation regime where one can expect the jets to interact strongly. It is also where our present ability to calculate in perturbation theory breaks down so that one should regard this at best as a rough estimate when k is as large as 10. It must be emphasized that this mechanism of multiple minijet production is distinct from that to be discussed in the next subsection.

2.1.7.3. Elastic (or diffractive) proton-proton scattering at large momentum transfer $|t|$

Another place where the BFKL calculation might be used is the pp large- $|t|$ elastic or diffractive scattering : $pp \rightarrow X + p$ [39,63,64]. Here the large scale which justifies the use of perturbative QCD is given by the momentum transfer t to the final proton, and the hadronic scales at the two ends of the ladder do not spoil the BFKL prediction. The main signatures of the BFKL calculation are the BFKL-like energy dependence of the cross-section at fixed t and the slope of the t -dependence which is predicted to be smaller than in typical soft hadronic processes. For detailed discussion of elastic pp scattering see Section 2.2.2, page 35.

2.1.8. Multiple minijets at the LHC

Everyone knows that, for the purposes of hard-collision phenomenology, a high-energy proton may be regarded as a beam of (temporarily) non-interacting partons with a phase-space distribution depending upon the hard-collision scale. Enormous effort has been invested in learning about the distribution in longitudinal momentum of these partons. However, the relevant phase space is not one-dimensional, but three-dimensional. The other two coordinates are most conveniently taken to be the transverse impact plane coordinates.

Very little is known about the transverse distribution of partons, or how they are correlated transversely or longitudinally. For example, in a constituent quark picture we are not yet able to tell whether the infinitely many wee partons associated with an infinite-momentum proton are correlated with the valence system (Fig. 2.17a), whether they are correlated with the distribution of the vacuum chiral condensate, i.e. “pion cloud” (Fig. 2.17b), or whether they are correlated at all. The reason for this profound level of ignorance is that in most processes which are studied experimentally the transverse information is integrated out. One of the most promising sources of impact-plane infor-

Figure 2.16. Probability of the “number of cut Pomeron”, roughly one half the jet multiplicity per unit rapidity, according to the calculations of Mueller and Salam.

Figure 2.17. Where are the infinite number of primordial “sea” partons in the infinite-momentum state of the proton: inside the constituent quarks (a)—or outside (b)?

Figure 2.18. A view of double scattering in the transverse plane.

mation is in double- or multiple-parton interactions. Double-parton scattering [65], the simplest example, consists of two different pairs of partons interacting independently in the same inelastic hadronic event, with a momentum transfer larger than some lower cutoff which establishes the onset of a semi-hard regime. The scale in p_T of the semi-hard interaction should correspond to a much smaller distance in coordinate space than the hadronic radius. In the case of a double-parton collision the two interaction regions are therefore well separated in transverse space and, as a consequence, the two-parton processes add incoherently in the cross-section (Fig. 2.18).

The nonperturbative input to the theoretical estimations is the joint parton distribution D_2 , which is a function both of the fractional momenta and of the transverse distance b between the two partons: $D_2 = D_2(x, x'; b)$. It is a well-defined convolution of parton densities of projectiles, the simplest measure available for the study of impact-plane structure. Evidently the simplest possibility is one where all multiparton distributions are uncorrelated. In that case $D_2(x, x'; b) = f_{eff}(x)f_{eff}(x')F(b)$ with $f_{eff}(x)$ being the effective parton distribution (namely the gluon plus 4/9 of the quark and anti-quark parton distributions) and $F(b)$, the convolution in the transverse plane of the matter distribution of the two hadrons, is normalized to one. In this case the double scattering process measures σ_{eff} which is defined as

$$\frac{1}{\sigma_{eff}} = \int d^2b F^2(b). \quad (2.22)$$

Until recently, the measurements of σ_{eff} have been sparse and not very consistent. But recently quite a large number of double-parton collisions have been observed by CDF [66]; their measurement gives $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb. This number is small enough to indicate in fact that some nontrivial transverse-plane correlation structure does exist. On the other hand, by looking at the dependence of σ_{eff} on x , CDF has found no correlation in x in the limited range of values of x available.

In any case, the measurement of multiparton distributions via triple, quadruple etc. scattering processes would test the noncorrelation hypothesis. If valid these processes measure the integral in transverse space of corresponding powers of $F(b)$. The measure of all multiparton scattering cross-sections would therefore allow one to take literally the picture of the projection in transverse space of the matter distribution of the two colliding hadrons. If the noncorrelation hypothesis is invalid, one will learn about nontrivial impact-plane substructure of the projectiles.

From this hypothesis of uncorrelated multiparton distributions, one may estimate the rate of multiparton collisions and extrapolate to LHC energies. The extrapolation suggests that at least 50% of all inelastic events should be characterized by the presence of minijets with transverse momenta larger than 7 GeV. In an inelastic event with minijets, the semi-hard component of the interaction corresponds to the presence of several partonic collisions localized at different points in the transverse plane. Given the noncorrelation hypothesis the distribution in the number of collisions is Poissonian with the average number depending on the impact parameter [67]. One expects therefore that the number distribution of minijets will be characterized by a very large dispersion, corresponding to the differing impact parameters for the reaction. Indeed the number of produced minijets can be used to give an estimate, event by event, of the impact parameter of the hadronic interaction. One expects in fact that the main source of the large event-by-event variation in the number of minijets expected at the LHC is the variation of the number of partonic collisions as a function of the impact parameter.

The rising importance of multiple parton semi-hard collisions with increasing hadron c.m. energy is in fact related to the larger parton densities which are accessible at higher energies. Larger parton densities give larger parton fluxes and growing probabilities for having multiple parton collisions. At the

LHC, the parton distributions at small x are very large. At the p_T scale of 8 – 10 GeV, the number of candidate pair interactions is between five and ten thousand per pp collision. It is therefore reasonable that multiple parton collisions, leading to visible minijets, should become a common feature of most of the inelastic events and therefore affect substantially many global characteristics of typical events.

At the LHC energy scale, if one represents the partonic interaction by the exchange of a BFKL Pomeron, one may obtain for the average number of partonic collisions in each hadronic interaction with minijets a number as big as 8 for $p_T^{min} = 7$ GeV and 3 for $p_T^{min} = 9$ GeV. The actual normalized distribution in the number of partonic collisions is shown in Fig. 2.19 for two different values of the lower threshold for the production of minijets: $p_T^{min} = 7$ GeV and $p_T^{min} = 9$ GeV. The large number of parton-parton collisions is not strongly dependent on the enhancement of the partonic cross-section at large rapidity distances, which characterizes the BFKL approach. The average rapidity difference between two minijets resulting from the same partonic interaction is, in fact, not too large. It depends slightly on the value of p_T^{min} and typically it is between five and six units. A different approach to the partonic interaction, which is normalized to the UA1 data on the minijet cross section [68], does not change the qualitative features. The actual distribution shown in the figure is obtained by assuming a Gaussian shape for the parton structure in the transverse plane. Although the distribution depends on the specific form of $F(b)$, different functional forms of $F(b)$ do not induce major changes. So far only uncorrelated multiparton distributions have been considered. The main reason of interest in multiple parton collisions is however in the actual measurement of the multiparton correlations. The noncorrelation hypothesis is surely untenable when x is large. To measure the multiparton correlations of the hadron structure one has to look for multiparton processes at large values of x , which corresponds to large rapidities [5]. Combining such measurements with corresponding pA data, the inclusive cross-section to produce minijets at large rapidities would allow one to probe the transverse separation of valence quarks in the proton.

An interesting quantity to study is the long-range rapidity correlation in events with multiple minijet production. One can expect significant deviations from the minimum bias events. The reason is that the multijet trigger predominantly selects central pp collisions with a higher density of soft partons. In

Figure 2.19. A normalized distribution of the number of partonic collisions per hadronic pp interaction at the LHC for two different p_T^{min} thresholds.

such events the long-range correlations are likely to change. In this case the transverse energy and entropy densities are so high that it is even possible that a qualitatively different class of final states is attained, with a new, distinct correlation structure.

2.1.9. QCD structure of jets

Studying the detailed structure of final hadronic states produced in high energy hard collisions is of primary importance for QCD. Not only will this allow one to verify well established perturbative QCD predictions concerning the gross features of hadron jets, but also to study the impact of the color structure of underlying parton processes on the distributions of final hadrons, that is to shed light on the dynamics of confinement. A central feature of the final hadron states in hard processes which follows from QCD is the fractal structure of jets. This means that a large jet consists of smaller jets, which after rescaling have the same partonic substructure [69]. Although the fractal structure of jets is a well-known consequence of QCD evolution, it requires rather large energies to clearly reveal itself. So this is an example of a hard phenomenon where the LHC has evident advantages. The main strength of FELIX for such studies is that it can study the interior structure of jets of laboratory momentum ≥ 3 TeV as a function of p_T over a very broad range of production

angles.

2.1.9.1. Mean jet characteristics

Measuring the momenta of all (or all charged) hadrons with transverse momenta $p_T > Q_0$ in an event, allows one to apply the so-called p_T (Durham) jet finding algorithm to unambiguously select hard processes producing parton jets at a given hardness scale p_T and then to study the internal structure of preselected jets, with a variable resolution $Q_0 \ll p_T$. This includes studying

- Mean subjet multiplicities as a function of the resolution scale Q_0 , for a given overall hardness p_T ,
- Subjet multiplicity fluctuations (KNO distributions),
- Energy spectra of subjets within a given primary jet,
- Angular profiles of relatively soft particles and subjets around the main jet direction.

The latter should reveal (yet unobserved) coherent effects which are sensitive to an overall color structure of the primary parton ensemble, $AB \rightarrow CD$, and cause azimuthal asymmetries of the final jets C, D (lopsided jets).

For these gross features of intrajet structure, well elaborated theoretical predictions are available, derived at the perturbative QCD level [69,70]. Decreasing Q_0 down to the hadronic scale may allow one to probe intimate details of the hadronization (confinement) mechanism. Along the way, in particular, one could hope to resolve a long standing problem of the comparative properties of quark *vs.* gluon jets.

The above program should also be carried out imposing an additional angular cone restriction on the particles (subjets) within a given jet. By doing so, one suppresses the contamination from interjet particles and assures a cleaner environment for testing the details of the coherent QCD parton branching picture, hump-backed energy plateau etc.

2.1.9.2. Interjet particle flows

Of importance is a series of studies of the pattern of *interjet* flows of (relatively) soft accompanying particles/subjets. Soft particle flows are driven by the color structure of the hard parton system (“antenna”) and exhibit the so-called string/drag effects, see review in [69]. They can be used, in principle, on an event-by-event basis, as an additional trigger for new physics searches.

At least two major open questions can be raised here:

- Studying the ratios of averaged particle flows in different interjet valleys for different colliding partons (qq, qg, gg);
- Visualizing two distinctive patterns of final particle flows accompanying gluon-gluon fusion, $gg \rightarrow gg$, a process in which two different color antennae contribute.

Such “color antenna” effects are seen at CDF and D0 already, on a statistical basis [71]. An event-by-event capability for analyzing the pattern of color flow would be especially important to attain. It would have implications, not only for QCD itself, but possibly also for new-particle searches. This challenging goal may become more practical at the LHC because of the higher yields of minijets via BFKL effects, and because of the larger phase-space region into which they can go. On the other hand, there will have to be, at the very least, application of sophisticated techniques of pattern analysis, along with a detailed understanding of underlying-event structure, especially with respect to the role of spectator minijets, to be able to succeed. The subclass of events which have large impact parameter, hence low global multiplicity, and which contain one and only one hard-collision “hot spot” will be important to isolate. If the hard process has a large subenergy, the search for the color flows across the lego plot should be optimal for such an event class.

It should be clear that a close interplay of theory, of good simulation, and of comprehensive experimental data is a necessary condition in exploring this potentially very important topic. The large acceptance of FELIX and its dedicated QCD mission will be extremely valuable assets [72].

2.2. Soft QCD at the LHC

2.2.1. General issues

2.2.1.1. The need to understand soft QCD

The study of generic soft strong interaction processes is sometimes carelessly considered as “not even QCD.” This is nothing but denial. Soft QCD is, almost by definition, the part of the theory not readily calculable by perturbative means. However this does not mean that it is uninteresting or unimportant. If for no other reasons than to certify and/or optimize the Monte-Carlo simulations which underlie all of the LHC detector design and physics agenda, it is important to pay attention to the input

angles.

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2.2.1. General issues

2.2.1.1. The need to understand soft QCD

The study of generic soft strong interaction processes is sometimes carelessly considered as “not even QCD.” This is nothing but denial. Soft QCD is, almost by definition, the part of the theory not readily calculable by perturbative means. However this does not mean that it is uninteresting or unimportant. If for no other reasons than to certify and/or optimize the Monte-Carlo simulations which underlie all of the LHC detector design and physics agenda, it is important to pay attention to the input

physics at the most fundamental level possible. In particular, to model reliably the responses of detectors to several simultaneous inelastic pp interactions during single collisions between proton bunches (at LHC ≈ 20 simultaneous interactions for high luminosity operation), it is necessary to measure not only the average characteristics of hadronic collisions but also the event-to-event fluctuations.

At present the physics of hadroproduction in hadron-hadron collisions is much less understood than in electron-positron or even electron-proton collisions. Even the most fundamental question, the choice of suitable degrees of freedom for a sensible description, is uncertain. At intrinsic energy scales smaller than 500–1000 MeV, a description utilizing the chiral effective action is widely used. In such a picture the basic degrees of freedom are constituent quarks and pions, while gluons are of secondary importance. All other hadrons are treated as composite objects, built out of these basic degrees of freedom. On the other hand, a considerable number of theorists aggressively extrapolate the calculational methods and ideology of partonic QCD far into the realm of soft physics. There have been many successful results from this approach. Nevertheless, one still must seriously question their meaningfulness.

The difference between hadron-hadron and, say, electron-positron collisions is evident already upon looking at the initial conditions. In the latter, one begins with only a pair of point-like quarks in a state of $J = 1$ which evolves into the final system of hadrons. But two LHC protons have a typical initial-state J (the product of beam momentum and impact parameter) of about 30,000. At the arrival at the collision point, they are structured objects with internal motions frozen, but with internal configurations which can vary greatly from event-to-event. Are the three valence quarks of an incident projectile close together or far apart? Does the meson field around a nucleon depend on the distance between valence quarks? What happens when quarks shadow each other? The nature of the final state certainly depends upon such parameters, but it has not been easy to isolate them experimentally. Theoretical ideas for doing so exist, but they are inhibited by lack of data, and by the generally gloomy prospects for acquiring such data at collider energies.

2.2.1.2. Event classes: soft Pomerons vs. perturbative gluons

We have already identified some of the most important event classes in the preceding sections.

They include

- Very large impact parameter: peripheral col-

lisions.

- Small impact parameter: central collisions.
- Unusual configurations of the internal states of the protons on arrival at the collision point, especially small-size or even point-like configurations.
- Diffractive final states.
- Final states containing leading-particle tags.

This variety of event classes will, as argued already in the overview, become more extreme at LHC energies. Therefore, it will become less and less relevant to consider final-state properties which have been averaged over these—and probably other—event classes. This feature has implications for theory as well as for experiment.

At low energies, with the distinctions between event classes less prominent, and with less than complete absorption of incident beam protons occurring even for central impact parameters, it did make sense for theorists to do the average, and thereby create a global description of soft processes. A variety of theoretical approaches of this sort exist and are in use. One important class is nonperturbative, based on the string picture of QCD confinement, especially as developed by the Lund group [73]. Others introduce the concept of the soft Pomeron, a pure Regge-pole with intercept near unity [74]. It is an appropriate tool, in principle, for the description of elastic scattering, soft diffraction, and multiparticle production—provided short-range correlations in rapidity dominate the final-state structure. However, corrections, hopefully small and controllable at moderate energies, are anticipated within this framework itself to grow with energy. They must be treated via “multiple Pomeron exchange” contributions, for which there is an elaborate formalism involving Reggeon calculus, AGK cutting rules, etc. [75] This soft-Pomeron formalism by itself generates at sufficiently high energies long range rapidity correlations in multiparticle production, as well as shadowing (absorption) effects in elastic and diffractive scattering.

On the other hand, we have seen that there is another very strong source of such effects from the perturbative, semi-hard interactions of the many small- x gluons, as seen at HERA. It is possible, but less than convincing, to relate this rise in F_2 seen at HERA directly to multiple-soft-Pomeron-exchange effects. The simpler alternative is to recognize the wee perturbative gluons as an independent source of this rapid rise in F_2 , with the appropriate implications for $\bar{p}p$ and pp collisions at Tevatron and LHC

energies. As we discuss in Section 2.2.3.1, page 39, there are already indications in existing data that the partonic contribution is a distinct component of soft-QCD phenomenology.

Consequently, at the LHC it is likely that there will be applied a hybrid description of the soft collisions. Descriptions of central collisions probably must include a formalism emergent from perturbative-QCD considerations, in addition to the nonperturbative mechanisms extrapolated from lower energies. Very peripheral collisions may be more aptly described by something closer to the stringy or soft-Pomeron methodology used at lower energies, although perturbative-QCD “hot spots” may still occur. The boundary separating the two extremes will probably need to be determined in good part by experiment and phenomenology. And to do this, the separation of the phenomenology into distinct event classes will be vital. Furthermore, it should be clear that the full-acceptance capability of FELIX will be a very strong asset in accomplishing this quite nontrivial task.

In the next subsections we briefly discuss some of the soft-physics topics which can be strongly identified with the aforementioned event classes, and conclude with some brief comments on more generic processes which have been extensively studied and which are of interest.

2.2.1.3. Monte-Carlo codes and soft QCD at the LHC.

One indicator of the theoretical status of soft-collision phenomenology, perhaps the most important from a practical point of view, is how well existing Monte-Carlo codes for soft hadron-hadron collisions identify the above event classes and anticipate the problems which must be faced at the LHC energy scale.

The Monte Carlo models for high-energy proton-proton collisions may be roughly divided into the two broad categories identified above. The first category is based on perturbative QCD, involving the parton densities of the colliding protons, which are convoluted with the hard cross-section of two partons, and supplemented with associated initial-state and final-state parton shower evolution. It is most appropriate for central collisions and extremely high energies.

The second category is built on the Regge theory, viewing the colliding protons in terms of constituent valence quarks and diquarks which interact via soft Pomeron exchange. It is most appropriate for peripheral collisions and relatively low energies. For both categories, the nonperturbative

hadronization dynamics of converting the final-state color charges into white hadrons is modelled phenomenologically. Again two models are mainly used; either some version of *string fragmentation* (e.g., Lund, Feynman-Field), or of *cluster formation and decay* (e.g., Marchesini-Webber).

Some event generators of the first, partonic category are:

- (i) PYTHIA, probably the most versatile generator, includes high- p_T jet production, low- p_T Pomeron-type gg interactions, a model for multiple parton interactions, and options to trigger on elastic, single-diffractive and double-diffractive events according to the corresponding cross-sections parametrized from data. Hadronization is effected via the Lund string model.
- (ii) HERWIG, the most refined and accurate event generator on the perturbative-QCD level, includes high- p_T jet production, resummation of soft, small- x gluon evolution, and next-to-leading order contributions. Hadronization is implemented via the Marchesini-Webber cluster model.
- (iii) ISAJET is similar to PYTHIA in its overall structure. But it is much more limited on the QCD sector, since its emphasis lies on new-particle searches and supersymmetry. It incorporates high- p_T jet production, as well as options for triggering on elastic, single-diffractive and double-diffractive events. Hadronization is implemented via independent string fragmentation.
- (iv) VNI also utilizes, in addition to the commonly employed momentum-space description, the space-time structure of events. It includes high- p_T jet production, low- p_T soft parton interactions, multiple parton collisions and mini-jet production, as well as the possibility to study spatial fluctuations (e.g. color transparency), and to extract impact-parameter dependence. The Ellis-Geiger cluster model (a space-time extension of the Marchesini-Webber approach) is used for hadronization.

Omitted from all these event generators is the only-recently-observed phenomenon of hard diffraction. This is now being remedied via the introduction of POMPYT, a variant of PYTHIA, based upon a pure Regge-pole interpretation of the soft Pomeron. Only PYTHIA includes soft diffraction.

Only VNI, and to some extent PYTHIA, has the ability to classify events in terms of impact parameter or initial-state configuration, and only PYTHIA and VNI include multiple minijet production.

Examples of event generators of the second, Reggeonic category are:

- (v) DPM describes soft interactions among the protons by single and double-Pomeron-exchange, and incorporates a (relatively) simple hard component in terms of quark-quark Born scattering. It includes diffractive and elastic scattering. Hadronization is implemented via string fragmentation.
- (vi) FRITIOF is another Lund product, essentially PYTHIA with none of the perturbative-QCD ingredients, and is based solely on string excitation and fragmentation.
- (vii) VENUS is a hybrid of FRITIOF and PYTHIA using string degrees of freedom and soft-Pomeron exchange for soft interactions. But it does include a hard component by means of hard-Pomeron exchange, via a perturbative-gluon ladder. This code employs space-time variables in addition to the momentum-space description. For hadronization, Lund string fragmentation is used.

None of these “soft” codes incorporates hard diffraction, minijet production, or parton evolution. At present, none, except VENUS, can address the impact-parameter or initial-state-configuration dependence of the phenomenology.

These quite sophisticated codes incorporate many required features of high energy collisions and are absolutely invaluable practical tools. But it is fair to say that not one of them encompasses the full range of phenomena discussed in this LOI, and that none of them can be expected to describe, for example, the leading-particle behavior and its correlation with phenomena in the central rapidity region. This has to be the case for no other reason than that a proper data base does not exist at collider energy scales.

Likewise, for the description of diffractive phenomena and of correlations induced by impact-parameter and initial-state-configuration dependence, there is again every reason to suspect that these codes will be deficient. There is simply an insufficient data base to provide a reliable calibration.

2.2.2. Large impact parameters

2.2.2.1. Small- t elastic scattering and the soft Pomeron

Much of the interest in large-impact parameter collisions centers on elastic scattering and soft inelastic diffraction. Small- t elastic scattering in fact serves to define the impact-parameter region (via the Fourier transform of the elastic amplitude) for which inelastic diffraction occurs. This is the “gray” impact-parameter region, where absorption is neither complete nor absent. These events, containing rapidity gaps, are customarily described in terms of the exchange of a Reggeon, the soft Pomeron. The problem of the structure of the soft Pomeron, and indeed even the question of whether it is the most appropriate descriptive language, is central to the problem of understanding high energy soft interactions.

A very appealing, and in many respects very successful, picture of the soft Pomeron has been proposed by Donnachie and Landshoff [74]. Their soft Pomeron is a pure Regge pole, implying that the energy dependence of the total cross-section is a pure power, s^ϵ . Their predictions of elastic scattering, in terms of Pomeron-pole exchange between constituent quarks with Regge-intercept $\epsilon = 0.07 - 0.11$, give an excellent description of the data [74].

Most fits to the existing data predict a cross-section at the LHC energy not far from 110 – 120 mb. For example, the recent fit of Ref. [76] leads to

$$\sigma_{\text{tot}}(pp)(\sqrt{s} = 14 \text{ TeV}) = 113.9^{+8.3}_{-7.4} \text{ mb.}$$

This value agrees with a cosmic-ray measurement [77]. Note that the conflict between the two Tevatron data points [78] leads to substantial uncertainty in these fits.

At the LHC, the nucleon will look more like a black disk and less like the Gaussian density seen thus far. Thus competing viewpoints, which do not assume Regge-pole dominance even at low energy, may be more favorable at the LHC energy scale. Existing data can be fitted either in terms of the above Pomeron Regge-pole exchange [74], which corresponds to small shadowing corrections, or in terms of exchange of a Pomeron with $\alpha_P(0)$ much higher, $\epsilon \approx 0.2$, implying large shadowing corrections described by multiple Pomeron exchanges [75].

Fits [74] to elastic scattering data suggest that the effective Pomeron trajectory is linear in t for moderate t :

$$\alpha(t) = 1 + \epsilon + \alpha' t .$$

The value $\alpha' = 0.25 \text{ GeV}^2$ was extracted from data more than 20 years ago [79]. It has a direct effect on the forward exponential slope $B(s)$ in elastic scattering: if single-Pomeron exchange alone is included then

$$B(s) = B_0(s_0) + 2\alpha' \ln \left(\frac{s}{s_0} \right).$$

On the contrary, in the Froissart limit where the proton behaves as a black disc, $B(s) \propto \ln^2 s$.

The increase of $B(s)$ with energy implies that the mean impact parameters in pp scattering also increase with energy, i.e. that at sufficiently large energies the total cross-section is dominated by peripheral collisions, instead of central collisions, as is the case at medium energies. The value of the slope B found at the FNAL collider implies mean impact parameters in pp scattering $\langle b^2 \rangle \approx 1.4 \text{ Fm}^2$. Extrapolation to LHC energies leads to $\langle b^2 \rangle \approx 1.6 \text{ Fm}^2$. These impact parameters become comparable with average internucleon distances in nuclei. So a description of pA and AA collisions at LHC energies in terms of multiple Pomeron exchanges becomes doubtful.

The universality of the slope of this effective Pomeron trajectory on the choice of the projectile has not been checked experimentally thus far above $\sqrt{s} = 25 \text{ GeV}$. As discussed in Sections 1.2.9, page 6, and 2.2.4.2, page 42, the FELIX program includes the measurement of the absolute value and the energy dependence of the slope $B(s)$ in the elastic, diffractive pp scattering, in meson(photon)-proton, and meson-meson scattering.

2.2.2.2. Elastic scattering—medium t

Even if the exchange of two Pomerons is a small contribution to the total cross-section, and therefore also to elastic scattering at very small t , this will not be so at larger $|t|$; the distribution is flatter than for single-Pomeron exchange. As s increases, the double-Pomeron contribution increases only half as rapidly with energy. On the other hand, at $t = 0$ it rises more rapidly than single-Pomeron exchange.

Therefore, as s increases, the value of t for which the two contributions are equal moves downward.

One consequence of this is that the shape of the differential cross-section, as a function of t , changes with increasing energy. It happens that, at the Tevatron energy, the two contributions combine in such a way that an exponential fit $e^{-b|t|}$, with b independent of t , is quite good [74], although this is not true for either lower or higher energies. At lower energies $d\sigma/dt$ is concave up in a log/linear plot, while at very high energies it should be concave down. This

Figure 2.20. Elastic scattering differential cross-section at $\sqrt{s} = 14 \text{ TeV}$ in an impact-picture calculation [80].

behavior is also what is expected from the optical-model picture. The interplay of single and double scattering allows one to explain the presence of the dip in the elastic cross-section at ISR energies at $|t| = 1.4 \text{ GeV}^2$, and its conversion to a shoulder at the CERN $p\bar{p}$ collider. Estimates [74] suggest that at the LHC the minimum may reappear at $|t| \sim 0.5 \text{ GeV}^2$.

2.2.2.3. Elastic scattering—high t

At ISR energies, the pp elastic differential cross-section has a strikingly simple behavior for $|t|$ greater than about 3 GeV^2 : it is energy independent and behaves as $|t|^{-8}$ (Fig. 2.21). This is consistent with the three valence quarks from one nucleon scattering independently and simultaneously from the three valence quarks from the other nucleon. It may be a simple one-gluon exchange [20], or a color-singlet exchange mechanism [81], between the quarks. It will be interesting to see whether this energy-independence at large $|t|$ survives at the LHC.

In particular, the regime of large spacelike $|t|$ is associated with small interquark transverse

Figure 2.21. The differential cross-section for pp elastic scattering, with the fit $0.09|t|^{-8}$.

distances within a proton, and may be linked with perturbative-QCD phenomena, in particular the BFKL energy dependence discussed in Section 2.1.1.2, page 9. If the energy dependence of the elastic cross-section is parametrized by an effective Regge trajectory $\alpha_{eff}(t)$, then this approach predicts a minimum value for this trajectory in the spacelike region. At small $|t|$, $\alpha_{eff}(t) \geq 1$, it is known to decrease with increasing $|t|$, becoming significantly smaller than 1. But at sufficiently large energies and large $|t|$, according to the BFKL approximation [82], the differential cross-section would rise rapidly with $\sqrt{s}$, again implying an effective Regge trajectory above unity.

It is intriguing that UA8 has observed some non-linearity of the effective Pomeron trajectory, as suggested by perturbative-QCD [39], in the differential cross-section for single soft diffraction: $pp \rightarrow Xp$. They find

$$\alpha(t) = 1.08 - 0.25|t| + 0.07|t|^2 \quad (2.23)$$

with $|t|$ measured in GeV^2 . This form of the effective trajectory suggests that $|t| \geq 3 \text{ GeV}^2$ is necessary for the onset of such a new perturbative-QCD

regime.

On the other hand, it may be that the cross-section at large $|t|$ is smaller at FELIX than at lower energies. This is anticipated in the impact-picture approach [80], as a consequence of a purely absorptive energy-dependent interaction. A variety of other predictions exist, and are summarized by Islam in his FELIX Note [83]. This includes a survey of interpretations of the structure of the differential cross-section in the “dip” region, containing a minimum and secondary maximum of the t -distribution (at ISR energies), which separates the regions of intermediate and large $|t|$. This interference region is different for pp and $p\bar{p}$ interactions, so the extrapolation of expectations to the LHC energy scale is difficult.

In summary, the estimates of cross-sections in the large- $|t|$ region, a region which some theorists insist is controlled in principle by short-distance, perturbative-QCD dynamics, are in practice uncertain, and vary over orders of magnitude.

2.2.2.4. Flavor dependence of hadron elastic collisions

If single-Pomeron exchange dominates two-body processes, there will be factorization relations between total and differential cross-sections for interactions of different beam particles [84]. FELIX should provide measurements of total cross-sections of pp , γp and $\gamma\gamma$ collisions, as well as a variety of others (πp , $\pi\pi$, Kp , $K\pi$, ...) using forward tags. There should also be measurements of various exclusive channels like $\gamma\gamma \rightarrow V_1 V_2$ where $V_i \equiv \rho, \omega, \phi, J/\psi$ -meson (cf. Section 2.4.4, page 59). The ability to measure a broad range of processes will provide a good probe of the interaction of large size hadrons, where the s and $|t|$ dependences are nearly universal, to the perturbative-QCD regime of scattering of a small object on a large object (e.g. $\gamma\gamma \rightarrow \rho + J/\psi$), where one expects a much faster energy dependence, similar to that observed in the $\gamma p \rightarrow J/\psi + p$ reaction at HERA. In general, a weak energy dependence of the $|t|$ -slope of the cross-section is expected. But there may be BFKL effects in onium-onium interactions, such as the two J/ψ mesons in $\gamma\gamma$ collisions. This process, in the BFKL approximation, would increase with energy, approximately proportional to s . Processes involving elastic photoproduction of one or two ϕ 's may provide especially valuable interpolation points.

2.2.2.5. Soft single diffraction

From elastic scattering information, the impact-parameter region where absorption goes from 90% to 10% is roughly 1.5 ± 0.7 fm. It is here where most inelastic diffraction should occur. Larger impact parameters may of course contribute as well, with reduced yields. And because the nucleons will look more like black disks at LHC energies and less like the Gaussian density distributions seen so far, the sum of elastic, single diffractive, and double-diffractive cross-sections should saturate at nearly 50% of the total cross-section, with the elastic portion taking a larger share than at Tevatron energies. Thus the ratio of diffractive to elastic scattering should decrease with energy. This is because inelastic diffraction, an edge effect, should disappear in the black disc limit.

On the other hand, a pure single-Regge-pole exchange predicts that the ratio of inelastic diffraction (to a given, fixed range of final states) to elastic scattering should be independent of energy. Experimentally, a measure of this is the ratio of inelastic

diffraction to the elastic pp cross-sections at $t = 0$:

$$R(s) \equiv \left[\frac{d\sigma_{\text{inel. diff.}}/dt}{d\sigma_{\text{el}}/dt} \right]_{|t|=0}$$

At $\sqrt{s} \geq 100$ GeV this ratio decreases with increasing energy, from about 0.3 – 0.35 at $\sqrt{s} \sim 60$ GeV, to 0.15 at the Tevatron. Extrapolation to the LHC [85] gives $R(\sqrt{s} = 14\text{TeV}) = 0.06 - 0.07$. On the other hand, in the Pomeron-pole picture this ratio is expected to *increase* with energy, because of the increasing range of diffractive masses available with increasing energy.

2.2.2.6. Double diffractive dissociation and double-Pomeron exchange

From both the theoretical and experimental sides, there is more uncertainty for the expected LHC rate of double inelastic diffraction (both protons dissociated; one central rapidity gap) and soft double-Pomeron exchange (neither proton dissociated; central hadron production only). Double diffraction dissociation can occur via scattering of subsystems of the proton projectiles (e.g. single scattering of constituent quarks), so a much broader t -distribution is anticipated. Consequently, an estimate of the cross-section for double diffraction is rather large, about 5 mb for the LHC [86]. Shadowing effects should manifest themselves in long-range rapidity correlations between the two diffractive states for large diffracted mass.

This distinctive experimental feature, the slow decrease of cross-section with momentum transfer, is seemingly in variance with the fact that diffractive processes are more peripheral than elastic scattering. It has been suggested [87] that the amplitudes of diffractive processes should contain significant contributions of amplitudes with spin flip, which become zero at zero scattering angle. With FELIX, it should be possible to study spin alignment effects for selected channels.

Final states in soft double-Pomeron exchange may help to distinguish different pictures of soft diffraction. If the Pomeron is a Regge pole, then it is arguable that the $J = 2$ “recurrence” on its trajectory ought to be preferentially produced: is this state a glueball? Or is soft-diffraction simply the collisions of pion clouds, i.e. soft excitation of the chiral vacuum? If so, the coherent production of pion clusters, especially at low p_T and relative p_T , may be a possible alternative.

Hints of the latter behavior may exist in UA1 correlation data. As mentioned in the overview, strong Bose-Einstein effects seem to be present under these conditions, and are strongest when the associated

multiplicity is *low*, suggesting it originates in the periphery of the colliding systems. Therefore it is appropriate that extensions of such correlation studies be done on nondiffractive and diffractive subsystems having relatively low rapidity density dN/dy .

The phase-space region $3 < \eta < 6$ (5–100 mrad) can be used as an alternative to a “barrel” detector to see (boosted) products of Pomeron-Pomeron collisions. For low-mass quasi-isotropic systems, this rapidity acceptance is already reasonably good for seeing all the secondaries, and “endcap” information (100–200 mrad; 2–5 mrad) is available too. The photon and charged particle coverage is on endwalls in this region, and granularity and resolution is excellent. This comment of course also applies to the study of $\gamma\gamma$ collisions. Double-Pomeron-exchange processes leading to low mass final states are, as is also the case for $\gamma\gamma$ collisions, a rich source of spectroscopic information. The implications are discussed in Section 2.4.6. The cross-section for double-Pomeron production of states of large mass M can be estimated roughly from factorization

$$M^2 \frac{d\sigma_{DPE}}{dM^2 d\eta} \sim \frac{1}{\sigma_{\text{inel}}} \left(\frac{d\sigma_{DD}}{d\eta_{\text{gap}}} \right)^2 \approx 5 \mu\text{b}$$

where η is the central rapidity of the diffractively produced state. This suffices to produce an enormous, high-quality sample in FELIX.

2.2.2.7. Bose-Einstein correlations and very large impact parameters

Meson radiation by any source should obey Bose-Einstein statistics. How this occurs in detail is a much more complex problem, not completely explored to this day [88]. The interest in Bose-Einstein correlations is due to their sensitivity to the hadron formation region and to the possible formation of new forms of hadron matter. The unmistakable signal that the Bose-Einstein effect is at work is the observation of like-sign two-pion correlations (known as the Hanbury Brown-Twiss effect), namely the strong enhancement of the correlation function at low four-momentum differences, Q ; for recent reviews see [89]. This correlation function is defined as the ratio of the double inclusive cross-section to the product of single inclusive cross-sections, with proper normalization.

At LHC energies, several new phenomena may lead to a substantial change of the picture of the Bose-Einstein correlations. These include

1. The increase with energy of the effective transverse size of the area where hadrons are produced.

2. The large increase of hadron densities at the central rapidities resulting in an increase of the radius of the last collision.
3. The change of composition of primary particles (increase of the fraction of heavy resonances) due to the high entropy densities at early times in the collision process.
4. The presence of large long-range rapidity correlations, and of fluctuations of multiplicity in minimum bias events.
5. the possible formation of large, long lived objects such as disoriented chiral condensates or related phenomena.

As a result one can expect a relatively strong dependence of the radius and the coherence parameter of the Bose-Einstein correlations on rapidity, on the associated hadron multiplicity, on the presence of leading particles in the events, etc.

2.2.3. Central collisions

2.2.3.1. Hidden minijet phenomena

It is in soft and semi-soft central collisions that there is the greatest potential for real surprises. In Sections 2.1.1, page 9, and 2.1.8, page 28, it was emphasized that the gluon densities become so large that visible minijet activity, at a p_T scale of 5 to 10 GeV, is expected to become a feature of the generic central collision. While all the nonperturbative phenomena present at lower energy will still be present, this new mechanism at the very least will greatly enrich the phenomenology. In addition, for the p_T scale of 1 to 5 GeV, the microscopic dynamics probably still originates within the perturbative quark-gluon QCD regime, and the gluon-gluon luminosities will be even higher. However, the difference is that real minijets cannot be manifestly seen in the final state. At best, only clusters of low- p_t hadrons will mark the approximate locale of an underlying parent gluon.

Nevertheless, high multiplicity in the final state should characterize this class of events, and they may already be a significant component of existing event samples from the $S\bar{p}\bar{p}S$ and Tevatron. In particular, the shape of the multiplicity distributions has an appearance suggesting a two-component structure. This feature has been modelled [97] in terms of a sum of two independent negative-binomial contributions, with energy-dependent normalizations, means, and dispersions (see Fig. 2.22). What is found is a rapid growth with energy of the high-multiplicity component, presumably to be

Figure 2.22. Charged particle multiplicity distributions at c.m. energies 200 GeV, 546 GeV and 900 GeV. Data (open dots) are from the UA5 Collaboration; the solid line is the fit in terms of two negative-binomial distributions whose components are given by the dashed lines. The solid dots show the result of Monte Carlo calculations (PYTHIA).

identified with the perturbative-QCD minijets. How to extrapolate in detail this model to the much higher LHC energy scale is fraught with great uncertainties. But the conclusion that this “minijet” contribution will dominate the global multiplicity distribution is robust.

2.2.3.2. Can thermalization occur?

At a more speculative level, it may be that the gluon densities at this lower scale, say $p_T = 1 - 2$ GeV, may be so large as to create a class of novel final states, characterized by a partial or complete thermalization of first-generation produced partons. If so, the initial energy densities and temperatures could be extraordinarily high, especially for shadowed, small-size initial-state configurations colliding at small impact parameter. There is here a clear link to the similar speculations for A - A collisions. We again note that it is in central pA collisions, in the (large) rapidity region free of ion fragmentation products, that the relevant gluon-gluon luminosity per collision is maximized.

The search for such “thermalized” final states can follow the leads suggested by the heavy-ion community: enhanced p_T , existence of transverse flow, enhancement of strangeness and heavy-flavor production, enhancements in soft dilepton production, unusual event texture, etc. One would look for such novel transitions as function of associated multiplicity, or perhaps of minijet activity.

2.2.3.3. Are there novel leading-particle effects?

The nature of the leading fragment distribution may also be dramatically modified under these circumstances. Imagine boosting the LHC process to a frame of reference where one has a 7 PeV beam colliding with a 7 GeV beam. There may be such a dense wall of gluons in the 7 PeV beam that all partons in the 7 GeV beam are swept forward via gluon-Compton scattering. If that happens, the secondaries, moving forward in this reference frame at nearly the speed of light, will be stuck to the Lorentz-contracted 7-PeV gluon wall, and leave behind a piece of “vacuum” with no memory of the initial valence quanta of the 7 GeV beam. The large-angle decay products of this space-time region (as viewed in this reference frame) may therefore be novel and interesting, and approach a new limiting distribution obeying approximate Feynman scaling. This may also be a good region for a disoriented-chiral-condensate search, as described in the next subsection. The pseudorapidity region of interest is roughly 5-7, and a detailed examination of it, as well

as the even more forward region, is best done by the FELIX detector.

2.2.3.4. Is disoriented chiral condensate produced?

In the overview it was already mentioned that the decay products of a disoriented chiral vacuum (DCC) might be a component of the final state hadron distribution, perhaps seen best at low p_T or in low-mass clusters of pions. The main signature for this behavior is an unusually large dispersion in the distribution of the fraction f of pions, appropriately sampled, which are neutral. In the ideal case, instead of a binomial distribution peaked at $1/3$, one finds an inverse-square-root distribution.

This subject is still a young one, and a quite speculative one. There is no compelling argument that DCC must exist, but there is no compelling argument that it does not exist. There have been two experimental searches, one at the Fermilab collider, and the other in heavy ion beams at CERN. No evidence in favor of the presence of DCC has been found. These experimental initiatives are stimulating the theoretical development, which is still in too primitive a condition to deliver realistic simulations of DCC production.

Nevertheless, the search phenomenology and strategy has been refined. Useful tools, the factorial moments of multiplicity distributions, well known in the multiparticle-dynamics community, appear to allow a sensitive search strategy for DCC in small phase-space intervals. From the joint multiplicity distribution of pions and gammas, one constructs robust measures [90] for detecting the presence of DCC. At present there is activity, especially with regard to exploiting wavelet analysis techniques [91], in generalizing these methods to large phase space regions, in order to search for unusual pattern structure created by this mechanism. It is not understood what the correlation structure (in lego phase space) of the disoriented chiral order parameter is likely to be, although a correlation length of order 1 - 2 lego units is the natural expectation.

This subject is related closely to that of Bose-Einstein correlations and to other possible mechanisms of producing hadrons coherently. It is becoming integrated into the general phenomenology of multiparticle dynamics, and can be expected to develop considerably between now and the commissioning of the LHC.

The specifications for good experimental searches are mainly the ability to count gammas and charged pions event by event with momentum analysis, especially at low p_T (below 100 MeV in particular), and

with the inclusion of the forward region of phase-space, where cosmic-ray evidence for DCC-like phenomena occurs. In these respects, FELIX is an especially good detector.

2.2.4. Special initial-state configurations

2.2.4.1. Small-size colorless configurations

In Section 2.1.5, page 24, we have already considered the diffractive excitation of point-like configurations into final states containing jets. These processes should have analogues at lower p_T scales, which however may be consequences of more non-perturbative features of hadron structure. For example, such fluctuations arise naturally for constituent quark models of a hadron. For string models, the interaction cross-section is minimal for an initial state string configuration oriented along the momentum vector of the projectile and is maximal for strings oriented in the transverse plane. Thus color-coherent phenomena (color transparency in the perturbative domain, and color-opacity effects in the nonperturbative domain) can lead to large fluctuations of the average characteristics of high energy processes, which go well beyond the optical-model approximation. The cross-section of small configurations increases rapidly with energy, and thus the role of color-transparency effects in the average characteristics of pp collisions may decrease with the increase of the energy. However important effects should persist for the special hard processes already discussed in Section 2.1.5, page 24.

2.2.4.2. Leading particle tags

Another set of special initial-state configurations are those associated with the leading-particle tags mentioned in the overview, Section 1.2.9, page 6. For example, the one-pion exchange tag using a leading neutron ($x \gtrsim 0.8$), neglecting absorption corrections, is

$$\frac{d\sigma_{pp}}{d\Gamma dx_\pi dp_T^2} = \frac{1}{2\pi} \left(\frac{g^2}{4\pi} \right) \frac{x_\pi}{x_N} \frac{p_T^2}{(p_T^2 + m_\pi^2)^2} \frac{d\sigma_{\pi p}}{d\Gamma}$$

with $x_\pi = 1 - x_N$ and p_T the transverse momentum of the neutron. The system Γ detected by FELIX can be any final state of the πp system.

At low impact parameters this formula is likely to be wrong. Absorption corrections can be applied; they will modify the p_T^2 distribution and lower the rate somewhat. However the fraction of pp triggers into the system Γ that can be ascribed to the one-pion exchange πp process, after appropriate cuts on neutron energy and p_T in the zero-degree, forward

calorimeter, should be greater than 10^{-3} .

Similar calculations can be set up for Δ and Λ tags. In all cases, if the subprocess cross-sections are at all reasonable, the estimated rates will be comfortably high. The real problem will be separating the desired signal from the continuum background. The physics of that background, hence its importance, is quite uncertain, due to the nearly nonexistent leading-particle-production data base.

2.2.5. Generic collisions

The average behavior of particle production is also, of course, important. This is too broad and too mature a field to properly summarize here. The best way of surveying those issues of current interest which have not been covered here is to refer to the sequence of recent conferences on multiparticle dynamics [92,93] and hadron-collision phenomenology. What one finds there, first, is the search for a suitable description able to encompass what is known about generic multiparticle-production phenomenology. In addition, of course, there is the search for interesting correlation structures in the data.

In e^+e^- annihilation, some correlations are seen and are largely understood in terms of jet production, parton-level branching processes, and a reasonable phenomenology of hadronization and resonance production. This is expressed in terms of event-generators that reproduce well the observed correlations, as well as analytic techniques expressing the event-generator physics reasonably faithfully.

But, as repeatedly emphasized already, this happy state of affairs does not exist in hadron-hadron collisions. Correlation structures appear which are much less understood. Important tools used for the study of correlations and fluctuations are the factorial moments and cumulant moments of multiplicity distributions, measured usually in limited regions of phase-space, of variable size. It is found that the dependence of the factorial moments on the phase-space size is that of a power law, over a remarkably large range of sizes [94]. This dependence, known as intermittency, is evocative of self-similarity and fractality, as found in branching processes. It is not at all clear whether this is the correct interpretation, and further study and more data are for sure needed.

As already mentioned in Section 2.2.2.7, page 39, there are also strong Bose-Einstein-like correlations seen at low p_T and low cluster masses [96]. They also are not well understood, and may be related to the intermittency phenomenon. There are also persistent reports of anomalous bremsstrahlung at

very low p_T , and this deserves being followed up.

The factorial and cumulant moments of multiplicity distributions, central objects of interest for the study of intermittency, Bose-Einstein effects, and DCC searches, are phase-space integrals over the correlation functions. The correlation functions themselves show rich structure and energy dependence. Of particular importance are the strong long-range rapidity correlations which emerge at collider energies [98], but are largely absent at fixed-target energies. In all models of multiparticle production, soft or hard, it is anticipated that these correlations will on average further strengthen at the LHC energy scale. In the soft, Reggeon picture, it is multiple-Pomeron-exchange (or, more simply, multiple sources per event in the transverse impact plane for secondary particle production [99–102]). In the hard, perturbative-QCD picture, the long-range rapidity correlations are simply induced by the gluon-exchange itself. However, as the particle and/or minijet density gets extremely high, there may appear a new regime with *less* correlation structure. This, for example, happens in central ion-ion collisions, where only short range correlations survive.

Therefore the continuation of all these studies of correlations and fluctuations may lead to evidence of a new distinct regime of conditions to be faced by multihadron production phenomenology. It should be especially interesting to study long-range correlations between *four* distinct phase-space regions: the two beam fragmentation regions ($x \geq 0.03$; $|\eta| \geq 7$) and the left-moving and right-moving “central” regions (e.g. $2 \leq \eta \leq 5$).

We have already emphasized the importance of inclusive-distribution measurements in all these phase-space regions, in particular with respect to flavor and baryon-number composition. Without supplementary particle-identification capability, this is nontrivial to do with FELIX. However a variety of species, such as K_S , Λ , ϕ , ω , η , π^0 , ... will be accessible.

Complementary to all these “local” samplings of the multiparticle final states will be the “global” methods which search for event-by-event textures or patterns in complete phase space. In addition to the well-established textures created by jets, resonance clusters, and rapidity gaps, there have been hints in data of the existence of other structures in the phase-space. There have been sightings of narrow spikes in the rapidity distribution [103], and of highly coplanar multijet final states [104]. The systematic search for such effects is at present hampered by limited statistics. Serious pattern-analysis methodologies are also a necessity, and the intro-

duction of wavelet techniques may be a useful tool in the future.

In summary, a large array of techniques and body of experience is available for the analysis and interpretation of new data from the LHC. It must be kept in mind that this expertise, and the present description of multiparticle production, has in large part been built upon experiments done in full acceptance at fixed target energies, along with some collider data from the ISR, and from UA5 and UA1, with event samples no larger than 10^6 per experiment. The first round of data from FELIX would immediately improve that situation hundredfold, in an entirely new energy regime.

2.3. Hard and soft QCD in pA collisions

2.3.1. Physics motivations

2.3.1.1. Ions are really black at the LHC energy scale

There are many motivations for the study of proton-ion collisions at the LHC, but the most basic is that it simply has not been done at all at modern collider energies. Use of nuclear targets at fixed target energies has been commonplace and of great use in elucidating production dynamics. And, as argued repeatedly in the preceding material, the conditions at LHC collider energies will be quite different even for pp collisions. So big surprises in pA collisions are to be expected. For most of the topics we have already considered, having the capability of studying their A -dependence is, as we discuss in more detail below, an important asset. But in still more general terms, there are major differences to be expected from what is seen at fixed-target energies. The mean free path of the proton projectile in nuclear matter is diminished by a factor of about 3, and thus there are many more obstacles placed in the way of the incident proton. At fixed-target energies the mean number of “wounded” nucleons in a central pPb collision is about 6, while at the LHC this is replaced by about 20. The impact parameters typical for pp scattering increase by a factor ≈ 1.5 between 100 GeV and LHC kinematics. So the proton will often interact simultaneously with nucleons which have essentially the same longitudinal coordinate but which have large transverse separations.

Obviously this corresponds to a dramatic departure from the space-time picture of pA interactions at intermediate energies. Consequently the proton may be more easily excited into exotic high-mass or

very low p_T , and this deserves being followed up.

The factorial and cumulant moments of multiplicity distributions, central objects of interest for the study of intermittency, Bose-Einstein effects, and DCC searches, are phase-space integrals over the correlation functions. The correlation functions themselves show rich structure and energy dependence. Of particular importance are the strong long-range rapidity correlations which emerge at collider energies [98], but are largely absent at fixed-target energies. In all models of multiparticle production, soft or hard, it is anticipated that these correlations will on average further strengthen at the LHC energy scale. In the soft, Reggeon picture, it is multiple-Pomeron-exchange (or, more simply, multiple sources per event in the transverse impact plane for secondary particle production [99–102]). In the hard, perturbative-QCD picture, the long-range rapidity correlations are simply induced by the gluon-exchange itself. However, as the particle and/or minijet density gets extremely high, there may appear a new regime with *less* correlation structure. This, for example, happens in central ion-ion collisions, where only short range correlations survive.

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Obviously this corresponds to a dramatic departure from the space-time picture of pA interactions at intermediate energies. Consequently the proton may be more easily excited into exotic high-mass or

high-rapidity-density final states than in a collision with a single nucleon. The changes are so great that the conventional Gribov-Glauber picture of nuclear cascading may require fundamental modifications.

2.3.1.2. Gluon densities of heavy ions are definitely saturated, and the possibility for novel phenomena is maximized

Given that the gluon densities of the projectile and ion are both so high, there may well be new classes of strong-interaction phenomena which occur within the short-distance, near-the-light-cone space-time region one associates with perturbative QCD. It is even more probable in pA collisions than in pp collisions that, as discussed in Sections 2.1.1, page 9 and 2.1.8, page 28, the densities of partons, and of energy-momentum, may be high enough to “burn away” the nonperturbative QCD vacuum structure in these “hot spots”, leaving behind only a dense partonic fluid in principle governed by perturbative dynamics but in practice involving short-distance strong couplings. If there is a large enhancement of hard-collision, gluon-induced processes, then there could be an enhancement of heavy-flavor production as well. The study of the x and A -dependence of forward J/ψ and Υ production (in the direction of the fragmenting proton) should be especially accessible and incisive.

Conventional hard-collision phenomenology such as dilepton production, direct photon production, and dijet production allow by definition the introduction of a distribution of partons in the ion. However, the relation between this parton distribution, the nucleon’s parton distribution and the distribution of the nucleons within the ion is not at all straightforward. Even for single nucleons the gluon densities rise with x so strongly that saturation effects are anticipated. The gluon densities for ions are much, much higher and the perturbative saturation phenomena should be manifest.

In general, the A -dependence of DGLAP-BFKL type hard-collision phenomenology will shed much light on the nature of the dynamics. And in all cases, it will be important to compare the A -dependence of the yield of hard-collision products in the direction of the fragmenting proton with the particle production in the direction of the fragmenting ion: the A -dependences in the two regions may be expected to differ significantly.

With regard to soft, nonperturbative physics, even what to expect for the A -dependence of the generic, minimum-bias particle production is very uncertain. Will there be “Feynman scaling” of the leading fragments of the nucleon, especially when

the collision is a central one? Existing data are very sparse. What do exist indicate that leading-particle production is suppressed quite strongly in central proton-nucleus collisions already at fixed target energies. If so, does this trend continue with energy? And if the trend does continue rather strongly, so that no leading particles are seen, what does this imply for the multiplicity distribution, $dN/d\eta$, at large rapidities in the proton hemisphere? Just energy conservation would suggest that it must grow rapidly for central as opposed to peripheral collisions. Indeed can the amount of absorption be so large that “thermalization” occurs?

2.3.1.3. What happens to soft and hard diffraction in pA collisions?

Soft rapidity-gap processes are not very well understood, and A -dependence studies will be of considerable value. What is the A -dependence of inelastic diffraction and double-Pomeron exchange processes? The nucleus is nearly black at the LHC for all but the fringe impact parameters. Soft inelastic diffraction is believed to be determined by fluctuations in the amplitude for absorption of the projectile wave packet, and is expected to be strongly suppressed at the LHC, in comparison to lower energies. As a result, at LHC energies the nucleus may serve as a very effective filter, enhancing the contributions of semi-hard diffraction originating from the scattering of protons in weakly interacting configurations, as discussed in Section 2.1.5, page 24.

However, it is not out of the question that even in central pA collisions, high-mass inelastic soft diffraction might occur at some level. The time at which a diffractive rapidity-gap “edge” is formed is in general quite large: it can be many tens or hundreds of fermi later than the collision time (in typical reference frames). In the intervening time interval, there is a lot of particle emission from the candidate diffractive system moving down the beam axis, and it may be that this system “forgets” its past as it evolves. If so, there could be the possibility that it evolves into a state which is not orthogonal to a single nucleon, and therefore some of the time will produce the diffractive final system, no matter what its condition at early times. While this scenario may seem unlikely, it would not seem so were the data to show that such a phenomenon exists. It will be important to look.

Such gaps if present would most likely lie completely within the phase-space region of the fragmenting proton (the “coherent” phase-space region (b) discussed below in Section 2.3.2.1, page 46), and would provide extremely important information on

the nature of the “soft” Pomeron.

Hard diffraction, even more than soft, is expected theoretically to be peripheral. The number of multiple interactions with the nucleons at the edge of the nucleus should be small, and consequently the Glauber-Gribov picture should be the standard of reference. Nevertheless, as discussed in Section 2.1.4.1, page 19, it appears that even hard diffraction has important nonperturbative features, with perhaps a relatively close relationship to the poorly-understood mechanisms of soft diffraction. Therefore, it again will be important to look for central hard diffraction in pA collisions.

2.3.1.4. Impact-parameter dependence is accessible and important

As is already apparent from the preceding discussion, the proton-ion processes emphasize the importance of thinking in terms of the transverse structure of the process, especially on the impact-parameter dependence of the phenomenology. This way of thinking is commonplace in the heavy-ion community already; the determination event-by-event of the impact-parameter (angular momentum), and even the orientation of the collision plane, of the colliding ions is an essential tool [105]. It is implemented for example via measurement of leading fragments, as well as via the distribution of transverse energy and entropy. On the other hand, in hadron-hadron or lepton-hadron collisions the dependence of the phenomenology on transverse coordinates has been almost completely neglected, although as discussed in Sections 2.1.5, page 24 and 2.2.4.1, page 42, the opportunities for doing this at LHC energies with FELIX are more promising.

Proton-ion collisions interpolate between the extremes. We have already mentioned that the impact-parameter dependence of generic particle production provides vital information. This is also the case for ion parton distributions, and for the frequency of occurrence of diffraction or rapidity-gap processes.

It should be possible to determine the impact parameter event-by-event. The technique differs from what we have discussed for pp collisions. As discussed in Section 2.3.2.2, page 46, the nuclear fragment distribution should be a good discriminant.

2.3.1.5. Proton-ion collisions probe transverse nucleon structure

As already discussed in Sections 1.2.6, page 5, 2.1.5, page 24, and 2.2.4.1, page 42, one supposes that in some subclass of events the distribution of constituents in the initial proton may

be unusually local in the transverse, impact plane when the proton collides with the ion. If this is so, its effective cross-section per nucleon will be greatly reduced, perhaps all the way to the perturbative-QCD level. If the effective cross-section of such a point-like configuration goes below 20 mb, there will be an appreciable probability that it can penetrate through the center of a Pb ion and survive. This would lead to a highly enhanced yield of diffractive production of the products of the point-like configuration in collisions with heavy ions.

Not only might the properties of the final-state collision products depend upon the nature of the transverse structure of the proton primary at arrival at the collision point, but even the conventional parton distributions may also be affected. For example, again consider, as in Section 2.2.4.1, page 42, a nucleon as a small quark and small diquark connected by a narrow QCD flux-tube. It should be clear that if the flux-tube is at right angles to the collision axis at arrival, then the valence partons will have comparable longitudinal momentum or x . On the other hand, if the flux tube is parallel to the direction of motion, then one of the valence systems will have very large x , and the other very small. This happens because in this case the internal longitudinal momenta of the valence systems, in the rest frame of the projectile proton, are in opposite directions. Therefore the smallness of the configuration is correlated with the joint x -distribution of its constituents. This kind of nonfactorization may be determined by the study of the perturbative-QCD processes of dilepton, direct-photon, or dijet production as a function of the centrality of the collision.

2.3.1.6. Proton-ion collisions “calibrate” ion-ion and cosmic-ray phenomenology

An extremely important reason for the study of proton-ion collisions is that it provides fundamental input information necessary for the interpretation of ion-ion collisions. Especially with respect to the hard-collision processes, determination of the ion parton distributions experimentally in pA collisions appears to be an absolute prerequisite. In addition, the study of energy losses for secondary partons propagating through nuclear matter, of the energy and baryon-number flow from the proton projectile into the central rapidity region, and of the presence already in pA collisions of unusual forms of the produced hadron system, would have a strong influence on the phenomenology of ion-ion collisions.

As discussed in Section 2.5, page 70, the measurement of the basic parameters of proton-ion collisions for $A = 14 - 16$ is very relevant for the interpreta-

tion of ultra-high-energy cosmic-ray extensive-air-shower data. In addition, data from heavier ions will be important in comparing LHC data with cosmic-ray data from emulsion-chamber experiments such as JACEE or Chacaltaya-Pamir.

2.3.1.7. The FELIX detector has special advantages

While many of the above topics will be accessible to all detectors at the LHC, and while it is hoped that all collaborations take the above physics issues seriously, it is clear that the FELIX detector has special advantages. Not only is the study of leading proton fragments paramount for many of the above issues, but also the study of ion-fragments for the impact-parameter tagging. Indeed in all of the items above, it is easy to see that the capabilities provided by FELIX are extremely advantageous. In particular, as emphasized already in the context of pp collisions, the capability of FELIX to study in detail the parton distributions at extremely small x , down to values smaller than 10^{-6} , together with the impact-parameter-tagging feature, makes many of the above studies unique to FELIX.

2.3.2. Generic features of pA collisions

2.3.2.1. Basic subregions of final-state phase space

In terms of the phase space of produced hadrons, we may divide the particle production mechanisms into at least three distinct regions:

a) The soft fragments, mainly pions, nucleons, and spallation products, produced more or less isotropically in the rest frame of the ion, are an important indicator of the centrality of the proton-ion collision, as discussed in more detail in the next subsection. In the collider frame, these fragments will typically carry transverse momenta of hundreds of MeV at most, and longitudinal momenta in the TeV range; hence their pseudorapidities will be in excess of 8-9.

b) Produced hadrons, as seen in the ion rest frame, which are so energetic that their production angles are small compared to 1 fm divided by the nuclear diameter (60 mrad in Pb), will have formation lengths large compared to the nuclear diameter. Taking a factor 10 for safety (6 mrad instead of 60), this defines roughly the boundary of what may be called, somewhat inaccurately, the “coherent” phase-space region in the collider reference frame. This boundary is roughly at a pseudorapidity of 3-4 in the ion direction, and this phase-space region then extends through central pseudorapidities all the way

to the leading-proton fragments. In this phase-space region the production amplitude for those produced particles depends on the interaction of the projectile with all the “wounded” nucleons in the ion, via a nontrivial quantum cascade mechanism.

c) The remaining phase-space region, which is in the ion-hemisphere and extends from pseudo-rapidities of about 3-4 to 8-9, should have enhanced secondary-particle multiplicity due to fairly conventional, classical cascading mechanisms within the nuclear matter. However, as we discuss in Section 2.3.4.2, page 53, even in this phase-space region what to expect is quite uncertain. But the features of this part of the final state may again be of much use in tagging the impact parameter of the incident proton.

It is the phenomenology in the “coherent” phase space region (b) which impacts most directly upon both perturbative hard-QCD phenomenology and the soft-QCD nonperturbative processes. The phenomenologies of the remaining regions are essential, however, especially in their potential for providing tags of impact-parameter and of the initial-state configuration of the proton.

2.3.2.2. Triggers for centrality of pA collisions

Studies of interactions with nuclei at energies $\sqrt{s} \leq 40$ GeV have established a correlation between the centrality of the collisions and the multiplicity of nucleons produced in the nucleus fragmentation region. This correlation has been observed in fixed target experiments [106] both for the production of slow fragments with momenta ≤ 300 MeV/c, and for the production of protons with momenta $700 > p_N > 300$ MeV/c emitted backward and forward in the nucleus rest frame (black and grey particles in the terminology of emulsion studies). The black particles are predominantly produced in pre-evaporation and in evaporation of the residual nuclear system. (This category should include soft neutrons, which are not detected in the emulsion experiments and which for heavy nuclei are the major channel of evaporation.) The gray particles are predominantly produced via two mechanisms. The first is emission of short-range-correlated nucleon pairs hit by the projectile, together with their secondary hadrons. (These contribute to both forward and backward hemispheres in the nucleus rest frame.) The second mechanism is the production of secondaries into the forward direction (in the nucleus rest frame) by “wounded” nucleons [107]. The number of gray particles grows approximately linearly with the number of wounded nucleons. FELIX will be able to observe these fragments and

hence distinguish central from peripheral collisions. Note that all these fragments to good approximation move with the same velocity as the incident ion, and are therefore found in the far-forward phase-space region (a) discussed in the previous subsection.

Similarly the total multiplicity of fast hadrons (shower particles) was found to depend linearly on the number of wounded nucleons. The dependence of the number of black, gray, and shower particles on centrality is likely to be different, due to the larger elementary cross-section of the pN interaction at LHC energies. Nevertheless the qualitative pattern is likely to be preserved.³ Another option to select more central collisions (especially for heavy nuclei), easily available for collider experiments, is the study of event structure as a function of the multiplicity of the neutrons with very small energies in the nucleus rest frame. In collider kinematics these neutrons are emitted at very small laboratory angles and are absorbed by the forward zero-degree calorimeter. Since all these neutrons have energies close to E_A/A the energy detected in the calorimeter measures the soft neutron multiplicity. Thus we conclude that FELIX will have several handles for determining the centrality of collisions. To calibrate these “gauges” a systematic study of soft processes with a variety of nuclei will be necessary.

2.3.3. Hard QCD phenomena in pA scattering

2.3.3.1. Parton densities of nuclei

Nuclear parton distributions at small x : nuclear shadowing phenomena

We discussed in Sections 2.1.1, page 9, and 2.1.2, page 12, that in the small x region one can probe nonlinear QCD effects and explore the fundamental question of what kind of dynamics slows down and eventually stops the rapid growth of the cross-section (or the structure functions $F_2(x)$ and $xG(x)$) at small x . The use of nuclei allows one to enhance these effects. Indeed, in the small x regime a hard collision of a parton of the projectile nucleon with a parton of the nucleus occurs coherently with all the nucleons at a given impact parameter. The coherence length by far exceeds the nuclear size: in the kinematic regime accessible for FELIX it can reach up to 10^5 fm (in the nucleus rest frame). In the

rest frame of the nucleus this can be visualized in terms of the propagation of a parton in high density gluon fields over much larger distances than is possible with free nucleons. In the Breit frame it corresponds to the fact that small x partons cannot be localized longitudinally to anything close to the Lorentz-contracted thickness of the nucleus. Thus low x partons from different nucleons overlap spatially, creating much larger parton densities than in the free nucleon case. This leads to a large amplification of the nonlinear effects expected in QCD at small x ; see e.g. [108,109].

Constraints from unitarity [110] indicate that nonlinear effects (i.e. effects not accounted for by the standard evolution equations) should become significant at much larger values of x for the nuclear parton densities than for the nucleon parton densities. It has been estimated [108–112] that the x -range where nonlinear effects become significant differs for a heavy nucleus and for a nucleon by more than one to two orders of magnitude, assuming its gluon density $xG(x, Q^2)$ is proportional to x^{-n} with $n \sim (0.2 - 0.4)$.

The analysis of Section 2.1.2, page 12, has shown that in the case of pp scattering FELIX is able to probe gluon as well as quark structure functions at very small x , see Figs. 2.6, 2.9. In the case of nuclei a very similar range can be probed:

$$x_{\min}(A) = \sqrt{\frac{A}{2}} x_{\min}(pp)^4.$$

It is worth emphasizing that for these measurements it is again necessary to study the jets, leptons and photons at rapidities close to the nucleon rapidity. In this y -range, the accompanying soft hadron multiplicities are relatively small, leading to a soft particle background comparable to that in pp scattering. In fact, for $|y_{\max} - y| \leq (2 - 3)$ the background level may even be smaller than in pp collisions.

Thus the arguments presented in Section 2.1, page 9, for using a relatively low minimum- p_T cutoff for the jets should hold in this case as well. Since the cross-sections for hard processes increase roughly linearly with A , even short runs with nuclear beams will produce data samples sufficient to measure parton distributions with *statistical* accuracy better than 1% practically down to the smallest x which is kinematically allowed. The systematic errors for the ratios of nuclear and nucleon structure functions are also expected to be small since most of these errors cancel in the ratios of the cross-sections, cf [109].

³One example of a possible change is a significant reduction of the probability for a spectator to survive in the interaction with the projectile nucleon, leading to a reduction of the ratio $E \frac{d\sigma^{p+A \rightarrow p+X}}{d^3p} / \sigma_{\text{inel}}(NN)$ with an increase of $\sigma_{\text{inel}}(NN)$. Here the nucleon is in the nucleus fragmentation region, carrying a fraction of the nucleus momentum $\geq 1/A$.

⁴The factor $\sqrt{\frac{A}{2}}$ is due to the difference of maximal energy per nucleon for the acceleration of a nucleon as compared to a proton.

Nuclear parton distributions at large x

FELIX will have sufficient luminosity to measure production of W and Z bosons at $0.4 > x_A > 0.1$, in the ion hemisphere. Even for such forward production, their decay products typically emerge at angles $\geq 20 - 100$ mrad, and can be reliably distinguished from ion-fragmentation debris. In this kinematic regime, the A -dependence of the ion's structure function $F_2(x, Q^2)$, as measured in Z^0 production and charge-averaged $W^\pm$ production, should be independent of A with an accuracy of 1-2%. Hence, these distributions can be used to measure nuclear shadowing effects with an accuracy better than $\sim 5\%$ down to $x \sim 3 \cdot 10^{-7}$ for quarks, and to $x \sim 4 \cdot 10^{-6}$ for gluons.

Centrality dependence for parton distributions

A simple but very important application of centrality triggers would be a study of the dependence of the shape of the parton distribution on the impact parameter. As described above, it should be possible to normalize the parton distributions at small x to the values of the quark distributions at $x_A \sim 0.1 - 0.2$, where nuclear effects on quark distributions are small, for all nuclear densities.

Naturally one expects larger gluon shadowing for central impact parameters. It is expected to be accompanied by an enhancement of the gluon densities ("anti-shadowing") at $x \sim 0.1 - 0.2$ (up to 20% for the case of Pb) [113] which could be probed by comparing gluon-dominated to quark-dominated cross-sections. This enhancement follows from the necessity to satisfy momentum and baryon charge sum rules and from the lack of nuclear enhancement in the data on the antiquark distribution in nuclei [114]. Note that it is just these effective gluon distributions which one needs for the calculation of the minijet production in the central AA collisions at the LHC.

2.3.3.2. Multi-jet production

Multiparton distributions

As already pointed out in Section 2.1.8, page 28, the large number of gluon-pairs available for semi-hard scattering at the LHC energy scale may saturate the unitarity limit already at the level of perturbative interactions. This interesting feature allows the possibility of describing, within the perturbative approach, global features of the typical inelastic event. If this is possible, the domain of understanding of strong interactions would be greatly extended. But this achievement would not come

without a price. One is in fact forced to introduce into the perturbative picture of the interaction new nonperturbative quantities. They are the multiparton distributions, which in fact represent our present lack of knowledge of the nonperturbative structure of the hadron.

But the experimental opportunity at the LHC energy is in fact the actual measurement of these multiparton distributions. In this respect the use of nuclear targets is of great help. The interesting feature of semihard interactions with a nuclear target is represented by the large number of partons of the target as compared with the proton case and by the combined possibility of varying the number of partons both by choosing different values for the minimum jet p_T , and also by varying the nuclear atomic mass number. These two possibilities allow one to use the interaction on a nucleus as a very efficient tool to investigate the nonperturbative structure of the proton.

Nuclear enhancements

The advantage with the nuclear target is that the large enhancement in the number of parton collisions allows one to have sizeable rates of interactions at significantly larger values of transverse momenta. Indeed the problem with the unitarity limit is twofold. One faces it at the hadronic (or nuclear) level and one faces it also at the partonic level. When the unitarity problem is present at the hadronic level one is in the regime where the presence of many scattering centers has to be taken into account. When the problem appears at the level of parton-parton interactions, the structure of the single interaction itself shows up in a non-trivial way. Although this represents a rather interesting possibility for the understanding of perturbative QCD, it is very important to be able to have a clear distinction between the two different regimes. One has a much cleaner access to the information on multiparton distributions in the regime where the partonic interaction is elementary. The larger the momentum transfer, the simpler and better understood is the structure of the partonic interaction.

The relevant quantity is the dependence with A of the probability for multiple parton interactions. The cross-section for production of two pairs of coplanar jets due to the interaction of two partons of each projectile is [115]:

$$\sigma = \sigma_1 \cdot A + \sigma_2 \quad (2.24)$$

where the first term is due to interactions where two partons of the nucleus belong to the same nucleon and the second term is due to interactions with par-

tons of two different nucleons.

In contrast to σ_1 , which we discussed in Section 2.1.8, page 28, the term σ_2 in Eq.2.24 does not depend on the transverse separation between partons “1” and “2” in the proton. Hence it *directly measures* the correlated parton density in the nucleon: $f(x_1, x_2)$. Using information from the CDF double scattering experiment[116] on the mean transverse separation of partons in a nucleon, one expects that the contribution of the second term is dominant for heavy nuclei:

$$\begin{aligned} \frac{\sigma_2}{\sigma_1 \cdot A} &\approx \frac{(A-1)}{A^2 \cdot 1.4 \text{ fm}^2} \int T^2(b) d^2b \approx \\ &\approx 0.45 \cdot \left(\frac{A}{10}\right)^{0.5}_{A \geq 10}. \end{aligned} \quad (2.25)$$

Here the quantity

$$T(b) = \int_{-\infty}^{\infty} dz \rho(z, b) \quad (2.26)$$

is the nucleon density per unit area, the so-called optical thickness, with $\rho(\vec{r})$ the nuclear density, normalized so that $\int d^3\vec{r} \rho(\vec{r}) = A$.

In Eq.(2.25) nuclear shadowing effects are approximately taken into account if the momentum fraction x_A of at least one of the partons belonging to the nucleus is large enough ($x_A \geq 0.02$).

Other opportunities with multi-jets include

- Probing correlations between partons in the nucleus at high densities, i.e. for $x_{1A}, x_{2A} \ll 10^{-3}$, which would provide qualitatively new information about the dynamics of nuclear shadowing.
- Studying the accompanying soft hadron production (cf. the discussion in Section 2.3.4.1, page 52), which would allow measurement of the transverse size of a proton configuration containing partons x_1, x_2 . In particular, the production of 4 jets with two jets at large x in the proton fragmentation region $x_1 + x_2 \geq 0.5$ may provide another way to look for point-like configurations in nucleons; see Section 2.1.5, page 24.
- Investigating three- and four-parton correlations in protons and nuclei.

2.3.3.3. Propagation of partons through nuclear matter

Studies at fixed-target energies have established an interesting pattern of nuclear effects for high- p_T inclusive particle production. The ratio of inclusive

production on nuclei to the same process on a nucleon, $A^{f(x, p_t)}$, shows an effective exponent $f(x, p_t)$ exceeding 1 at $p_T \geq 1.5$ GeV, the so-called Cronin effect [117]. Analogous studies of the A -dependence of jet production have been inconclusive, to large extent because the transverse momenta of the jets are small.

Recent work [118–121] on the energy loss of high energy partons in a finite QCD medium, including cold nuclear matter, leads to the expectation that the energy losses of partons propagating through nuclear media should depend relatively weakly on their energy, and in fact may be quite small. They also indicate that energy losses in hot matter should be much larger than in cold matter, making jet quenching a probe of the state of the matter produced at early times in AA collisions. This adds importance to the experimental studies of parton propagation effects.

The medium-induced gluon radiation of a very energetic incident quark or gluon propagating through matter is found to be independent of energy provided the initial jet energy is large enough, typically ≥ 30 GeV (for quarks) in the rest frame of the medium. For a quark jet [119,120], the medium-induced energy loss increases *quadratically* with the length L and is independent of E for $E \rightarrow \infty$. For $L = 5$ fm, the asymptotic ΔE is estimated to be less than 1 GeV in a cold nuclear medium, making it difficult to check experimentally this remarkable dependence on the length L .

However, the smallness itself has implications. If leading partons suffer no significant energy degradation in traversing the center of a Pb nucleus, then the inclusive distribution of the leading secondaries can be expected to obey approximate Feynman scaling. This goes against the trend seen in fixed-target experiments, as well as against some of the arguments made in preceding sections of this document. But even if the scaling is there, the inclusive distributions and particle ratios may be quite distinct from what is found at low energies, because there is no suppression of short-distance multiple scattering effects.

The QCD prediction for transverse-momentum broadening due to multiple scattering is similar to the ordinary multiple-scattering result: a quark (gluon) from a projectile proton collides with the various target nucleons exchanging transverse momentum $\vec{p}_\perp$ at each collision before forming e.g. a Drell-Yan pair (J/ψ). The expression is

$$\langle p_\perp^2 \rangle = \frac{\alpha_s C_F \pi^2}{2} (xG) \rho L \simeq 0.5 \alpha_s \left(\frac{L}{5\text{fm}} \right) \text{GeV}^2 \quad (2.27)$$

This effect of the transverse-momentum broadening

of jets due to initial-state multiple scattering is easier to measure. Recent analysis of Drell-Yan data [122] and of J/ψ data [123] in pA collisions, agrees with the estimate in Eq.(2.27) with $\alpha_s \simeq 1/3$, when it is assumed that the broadening is entirely due to initial state interactions.

There are several options for probing parton propagation with FELIX:

- The A dependence of p_T broadening in the production of Drell-Yan pairs as a function of the energy of the parton (x_F), its virtuality (M_{l+l-}^2) can be studied at FELIX in a extremely wide kinematic range from $E_q \sim 20$ GeV to $E_q \sim 5 \cdot 10^7$ GeV in the nucleus rest frame. This would allow one to check the expectation of [119] that p_T broadening is energy independent.
- The A dependence of dijet acoplanarity and of individual jet shapes can be studied for high p_T jets which are moving relatively slowly in the ion rest frame, something which can be seen only in a FELIX type detector, as well as for jets with very high energies in the ion rest frame. The γ -jet sample would allow an especially clean interpretation.
- The ability of FELIX to detect both quarkonium production and open heavy quark production in similar kinematics would provide unique opportunities for the comparison of propagation of color singlet and color octet systems through nuclear media. For example, would the production of $J/\psi, \psi', D\bar{D}, \Upsilon, B\bar{B}$ at $x_A \sim 0.5$ have the same A -dependence? Would the rate of production of charm particles with $x_A \sim 1$ increase with A faster than A due to slowing down of c -quarks and/or re-interactions of charmed hadrons in nuclear media? Such measurements would be a challenging task for FELIX, due to the larger multiplicities of hadrons produced in the nucleus fragmentation region. However at least some of the channels like $J/\psi, \Upsilon$, and $e\mu$ pairs from open-charm decays may be accessible.

2.3.3.4. Search for color transparency effects

Interaction of point-like configurations with nuclei

We discussed in Sections 1.2.6, page 5, and 2.1.5, page 24, that hadrons are thought to occasionally fluctuate to small size, point-like configurations, within which color is localized in a small transverse area. In case of the scattering off nuclei, this

physics leads to many coherent phenomena. Some of them have been observed in fixed target experiments; for a review, see references [48]. Because the gluon densities are high at the ultra-high energies of the LHC, many formerly point-like configurations may interact with rather larger cross-sections. Nevertheless these cross-sections are likely to be substantially smaller than the average cross-section, as discussed in Section 2.1.5, page 24.

Transverse mapping of the nucleon

As mentioned in Section 2.3.1.5, page 45, the use of nuclear targets with a hard trigger allows one to address the question of correlations between the longitudinal distribution of partons in a nucleon and the strength of the interaction of such configurations with the target (roughly speaking with the transverse size of the configuration). Since the presence of a parton with large $x \geq 0.6$ requires three quarks to exchange rather large momenta, one may expect that these configurations have a smaller transverse size and hence interact with the target with a smaller effective cross-section $\sigma_{eff}(x)$. Suggestions for such a dependence of the size on x are widely discussed in the literature; see e.g. [124]. Using as a guide a geometric (eikonal type) picture of pA interactions and neglecting (for simplicity) shadowing effects for nuclear parton densities one can estimate the number of wounded nucleons $\nu(x, A)$ in events with a hard trigger (Drell-Yan pair, γ -jet, dijet,...) as a function of σ_{eff} [125]:

$$\nu(x, A) = 1 + \sigma_{eff}(x) \frac{A-1}{A^2} \int T^2(b) d^2b, \quad (2.28)$$

where the nuclear density per unit area $T(b)$ is defined in Eq.(2.26), Section 2.3.3.2, page 48. For average inelastic pPb collisions, $\sigma_{eff} \sim \sigma_{inel}(pp)$, and $\nu \approx 10$ at the LHC. This is somewhat larger than the average number of wounded nucleons in pA collisions, due to the selection of more central impact parameters in events with a hard trigger.

A decrease of the effective cross-section for large x , say, by a factor of 2, would result in a comparable drop of the number of “shower” particles, and perhaps “gray” and “black” particles (cf. Section 2.3.2.2, page 46) as well, produced in the collision along with a significant drop of the total multiplicity.

Another interesting quantity to study in coincidence with the hard trigger is the number of leading particles in the nucleon fragmentation region. If the fragmentation process does not remember the removal of one fast parton one may expect a stronger drop of the forward ($z_h \geq 0.3$) multiplicity with A than in the inclusive processes $p+A \rightarrow h+X$, where

scattering off the edge of the nucleus gives a significant contribution (see the discussion in Section 2.3.4.2, page 53). On the other hand, if a large x_p trigger selects a small size configuration, the pattern could be reversed, leading to a nearly A -independent multiplicity of accompanying forward particles.

Semihard coherent diffraction.

Ultimately for the processes dominated by the scattering of a proton in a point-like configurations the A -dependence of the total coherent diffractive cross-section would be proportional to $A^{4/3}$ (modulo nuclear shadowing effects for parton densities which may reduce the A -dependence to about $A^{(1-1.1)}$). This should be compared to the $A^{0.25}$ dependence, which is expected for soft processes at the LHC energies. Thus the observation of a rapid increase with A of a particular channel of diffraction would provide a clear signature of the importance of point-like configurations in the process.

Theoretically the cleanest process is the diffraction of a proton into three high p_T jets, which was discussed for the pp case in Section 2.1.5, page 24. The expected rapid growth of this cross-section with A leads to sufficient rates even for short pA runs. Other possible channels include production of two high p_T jets carrying a large fraction of the nucleon momentum. This may originate from the scattering of a proton in a configuration where two quarks came close together, leading to a reduction of the size of the projectile. Another suggested channel is diffraction to $B_c + D_s$ originating from small configurations in a nucleon containing a $c\bar{c}$ pair [126].

Survival probability in rapidity-gap events

In the geometric, Gribov-Glauber picture of nucleon propagation through the nucleus the gap survival probability decreases with A as

$$R_A = \frac{\sigma_{in}(pp)}{\sigma_{in}(pA)} \int d^2b T(b) (1 - \sigma_{in}(pp) T(b))^{A-1}, \quad (2.29)$$

where again $T(b)$ is the optical thickness defined in Eq. (2.26). Eq. (2.29) predicts a very strong suppression of the gap events for scattering off nuclei: for example by a factor of $\sim 4(12)$ for scattering from $^{16}O(Pb)$. Obviously if the parton of the nucleon belongs to a point-like configuration, the survival probability will be much larger. Ultimately, if one would be able to select scattering off configurations interacting with $\sigma_{eff} \leq 15$ mb, the probability would start to increase with A .

Hard diffraction dissociation of the Pomeron by the nuclear medium

To get a better understanding of the parton structure of the Pomeron it would be interesting to measure large $|t|$ diffraction of the projectile proton into an exclusive state (p, N^*) , together with high p_T dijets in the nucleus fragmentation region. An especially interesting case is for “superhard” Pomeron kinematics, when the jets carry practically all the momentum of the Pomeron (see discussion in Section 2.1.3.2, page 19). If such a process is due to the scattering of the proton in a point-like configuration, the cross-section should be approximately proportional to A . To understand the role of soft rescatterings in such a process it would be instructive to compare this process with large $|t|$ diffraction, with the jets carrying a smaller fraction of the Pomeron momentum, and also with the case where no jets are produced.

Color transparency in quasielastic processes

We discussed in Section 2.2.2.3, page 36, that at sufficiently large $|t|$ elastic pp scattering also may be dominated by the scattering of smaller than average-size configurations. Thus it is natural to ask whether these configurations are absorbed by the target with the same cross-section as a generic proton. The study of the quasielastic reaction $p + A \rightarrow p + p(N^*) + (A-1)'$ at $t \sim \text{few GeV}^2$ would allow addressing this question. Measurements for $|t| \leq 10 \text{ GeV}^2$ would require only a few days of FELIX running in a pA mode. The triggering would be similar to what is done for elastic pp scattering. In addition, it would be possible to use the forward acceptance of FELIX to suppress background processes containing pion production.

Such large $|t|$ color transparency experiments have been carried out at $E_{inc} \sim 6 - 15 \text{ GeV}$, with complicated results. But most of those complexities of interpretation should be absent at the much higher FELIX energy.

It should be possible to detect a relatively small decrease of the effective cross-section σ_{eff} from $\sigma_{tot} \approx 120 \text{ mb}$; see Fig. 2.23. Note also that it should be possible to study the change of the A dependence from rather small $|t|$, where a geometric approximation is likely to work, up to quite large $|t|$. Since the cross-section for absorption of a low-momentum nucleon which is formed close to the interaction point (in the nucleus rest frame) weakly depends on this momentum the only significant source of the change of the A dependence as a function of t would be a change in the transparency of the projectile.

Figure 2.23. A dependence of the nuclear transparency in the $pA \rightarrow pp(A-1)$ reaction at large $|t|$, as a function of the effective interaction cross-section of the projectile proton.

2.3.4. Basic characteristics of soft pA collisions

We already discussed in Section 2.3.1.1, page 43, that soft pA physics at LHC energies may dramatically differ from low energies, $\sqrt{s} \leq 40$ GeV, where most available data exist, if for no other reason than that the effective radius of a proton becomes comparable to the internucleon distances in nuclei and that the mean free path becomes smaller than the average internucleon distance. Consequently, although a black disc model will still reasonably describe total and perhaps elastic cross-sections of pA interactions as for pre-LHC energies, the underlying dynamics may be quite different. This is especially the case, given in addition the emergence of minijet phenomena at the LHC energy scale.

2.3.4.1. Total and elastic cross-sections

Due to the large value of the cross-section of the elementary pp interaction, the proton-nucleus interaction at all impact parameters except near the edge is practically black. As a result the total cross-sections for pA scattering depend very weakly on the nucleon-nucleon total cross-section, the ratio of real to imaginary part of the forward nucleon-nucleon scattering amplitude, and on inelastic shadowing effects. For example, variation of $\sigma_{tot}(pN)$ between

Figure 2.24. cross-section of elastic and quasielastic pPb scattering

100 and 120 mb and Re/Im between 0.00 and 0.15 leads to an increase of the cross-section of pA scattering by 4-8%, while inelastic shadowing effects reduce the cross-section by only 1-2%.

The study of elastic scattering, which constitutes nearly half the total cross-section, may provide a somewhat more sensitive test of the dynamics of the soft interaction. In particular, the study of the diffraction pattern of the minima and maxima of elastic scattering may allow one to probe in detail the picture of multiple interactions of the projectile with nuclei.

FELIX will be able to study elastic scattering off nuclei in two ways. For the lightest nuclei, such as ^4He , the acceptance in the nuclear arm ($t_{min}(pA) = Z^2 t_{min}(pp)$) should be good enough to measure elastic scattering through a direct coincidence measurement.

For heavier nuclei, to avoid backgrounds from beam gas interactions it seems only possible to study processes with nuclear excitations. These have huge cross-sections up to $|t| \gg 1 \text{ GeV}^2$ (see Fig. 2.24). To select these processes one would use the forward calorimeter to select events for which the nucleus was excited and emitted photons with average energy ~ 5 GeV and $\theta \sim 0.2$ mrad, or for which the nucleus decayed with the emission of neutrons.

2.3.4.2. Inelastic soft diffraction by nuclei

The very strong absorption present at central impact parameters results in the expectation that inelastic diffraction predominantly occurs from scattering of the proton off the nuclear edge. This gives only a very slow increase with A of the inelastic diffractive cross-section $\propto A^{0.25}$. However it is natural to expect that the production of different final states is determined by configurations with different average interaction cross-section - e.g. states with charm, minijets, etc. For these states one expects a much more rapid increase of the cross-section with A (see the discussion in section 2.3.3.4, page 50). Hence the study of the A -dependence of various channels of inelastic diffraction, without nuclear breakup, can again shed new light on the fluctuations of the interaction strength at ultra-high energies. The beam-gas background in this case is a difficulty, but one can hope to suppress it by an accurate determination of vertex position. Alternatively one can analyse incoherent diffractive processes where nuclear decay products are observed in the forward detector.

Again, the standard of reference for the treatment of these processes should be Glauber-Gribov theory, since the number of multiple interactions with nucleons in the nucleus should be small.

2.3.4.3. A -dependence of the particle production

Particle production in the proton fragmentation region

The A -dependence of hadron production in the proton fragmentation region remains one of the least understood aspects of hadron-nucleus interactions. Practically all available data are inclusive. They indicate that the cross-section is dominated by the production of leading particles at large impact parameters, where the projectile interacts with only one or two nucleons of the nucleus. As a result very little information is available about hadron production at the central impact parameters which are most crucial for the study, for example of AA collisions. Theoretical predictions for this region are also rather uncertain.

In eikonal type models, where the energy is split between several soft interactions, one may expect a very strong decrease of the yield of the leading particles. The dependence is expected to be exponential with path length in the nucleus; their mean energy is attenuated exponentially. On the other hand, if the valence partons of the projectile do not lose a significant amount of their initial momentum, as sug-

gested by perturbative QCD [118,119] and already discussed in Section 2.3.3.3, page 49, the spectrum of leading particles may approach a finite limit for large A [127]. However, this limit may differ even qualitatively relative to what is seen in pp collisions at low energy. Another open question is the change of the A -dependence due to the increase of the total pp cross-section by nearly a factor of three from fixed target energies. If the probability of leading particle production is determined by collisions with one or two nucleons, the spectrum of forward particles would be suppressed much more strongly at LHC energies than at fixed target energies.

FELIX will be able to measure the A -dependence of the production of a variety of leading hadrons: neutrons, protons, Δ -isobars, hyperons, K_S 's, and π^0 's. Use of impact-parameter tags, as discussed in Sections 1.2.9, page 6, and 2.2.4.2, page 42, will be very important in disentangling the dynamics. The very limited data now available do not contradict the idea of a limiting distribution for the hadron fragmentation when averaged over impact parameter; see [127].

Particle production in the central region

The Gribov-Glauber model including inelastic screening effects, but neglecting the final state interactions between the hadrons produced in different Pomeron exchanges, as well as neglecting the interactions of these hadrons with the nuclear target, leads to a prediction that at high energies and rapidities y , such that $|y_p - y| \gg 1$ (the fragmentation region (b) of Section 2.3.2.1, page 46), the inclusive spectrum of produced hadrons should be proportional to that in the inclusive cross-section of hN scattering:

$$\frac{d\sigma^{p+A \rightarrow h+X}(y, p_T)}{dy \, d^2p_T} = A \frac{d\sigma^{p+N \rightarrow h+X}(y, p_T)}{dy \, d^2p_T}. \quad (2.30)$$

Since $\sigma_{inel}(pA)/\sigma_{inel}(pN) \propto A^{2/3}$, Eq. (2.30) implies that the multiplicity of particles produced in the inelastic pA collisions should increase with A , roughly as $A^{1/3}$. Data at fixed target energies do not contradict this relation, but the energy is too low for an unambiguous interpretation.

The opposite extreme is to assume that the effects of multiple semihard interactions of the projectile hadron are the main mechanism of particle production. Multiple short range scatterings between partons (minijet production) together with associated QCD radiation (gluon bremsstrahlung) then are assumed to produce the major part of the total entropy and transverse energy. Such a model has been developed by Geiger, with an eye to appli-

Figure 2.25. Comparison of the prediction of the Glauber-Gribov model with the quark-parton cascade model of [128] for the A -dependence of hadron production.

cation to AA collisions [128]. For pA collisions, this model predicts an A -dependence of hadron production which differs very substantially from the expectations of the Gribov-Glauber model, see Fig. 2.25.

Particle production in the ion fragmentation region

For rapidities close to the nucleus rapidity, (fragmentation region (c) of Section 2.3.2.1, page 46) there are indications of the contribution of slow hadron re-interactions, which lead to an increase of the multiplicity of nucleons with momenta $1.0 \geq p_N \geq 0.3$ GeV, as compared with expectations neglecting final state re-interactions (a factor of ~ 2 for heavy nuclei) [107]. As we have repeatedly discussed, it is doubtful that the Gribov-Glauber picture is correct at LHC energies, so one may expect significant deviations from the expectations based on Eq. (2.30).

This actually is the case in the model of Geiger, mentioned in the previous subsection, as can be seen in Fig. 2.25. It must be emphasized that a quantitative understanding of the physics of particle production in pA collisions in this phase-space region is a prerequisite for understanding the corresponding phenomenology in AA collisions.

2.4. Two photon physics in pp and AA collisions

2.4.1. Overview

The large fluxes of quasi-real photons associated with the Coulomb fields of ultrarelativistic heavy ions at the LHC will lead to $\gamma\gamma$ collisions with cross-sections which scale roughly as Z^4 . Effective luminosities in a broad range of $\gamma\gamma$ mass intervals will be orders of magnitude higher than achieved at present e^+e^- colliders.

The physics interest in $\gamma\gamma$ collisions at the LHC is centered on QCD processes at moderate center-of-mass energies, with a primary goal being light and heavy quark spectroscopy. The high luminosity and high quality of the FELIX tracking make this an especially attractive option. Another advantage is that the rapidity range from 2 to 6, which is covered by the UA1 and D0 portions of the FELIX detector, is an especially practical phase-space region for accepting the products of the $\gamma\gamma$ collisions. In particular, the boosted secondary photons will be detected with percentage resolutions in energy and angle comparable, at the same p_T , to what is attained in a good e^+e^- detector such as CLEO.

It may seem strange at first that a collider operating at many TeV in the center of mass should

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It may seem strange at first that a collider operating at many TeV in the center of mass should

be used for light-quark spectroscopy. Nevertheless, this subject is today and almost certainly will continue to be a serious frontier of QCD research. The nonperturbative sector of QCD remains the greatest challenge to theory. And there are many fundamental unanswered questions still open in light quark spectroscopy.

A central issue is whether states beyond those built from $q\bar{q}$ and qqq exist. Gluon degrees of freedom are endemic in perturbative QCD, but there is no deep understanding of their role in the non-perturbative regime. Glueball spectroscopy is predicted by lattice-QCD and related models. There is some consensus that the lightest state is 0^{++} and has a mass of about 1.5 GeV, while 0^{-+} and 2^{++} are just above 2 GeV. Hybrid states, where gluonic degrees of freedom are excited in the presence of the $q\bar{q}$ “seed”, are also predicted to lie around 2 GeV. Here the 0^{-+} and 2^{++} are accessible to the $\gamma\gamma$ process. An additional array of states (with $C = +1$ all accessible to the $\gamma\gamma$ process) up to 4 GeV and beyond are anticipated. Also predicted is an exotic 1^{-+} state, which is not possible for the simple $q\bar{q}$ classification. It is accessible to $\gamma\gamma^*$, but unfortunately not to $\gamma\gamma$. Somewhat less fundamental but nonetheless interesting are possible multiquark $qq\bar{q}\bar{q}$ or meson “molecules” such as $K\bar{K}$.

In addition, at the LHC there is enough luminosity to access, in principle, the spectroscopy of single $C = +1$ heavy quarkonia such as η_c , χ_c , η_b and their radial excitations. Unlike LEP 200, the two photon processes in heavy ion collisions at LHC enable studies of the final states with b-quarks.

One may ask why $\gamma\gamma$ channels are so special for such investigations. The γ couples to the charge and spin of the constituents. Historically it has been the case that γ -induced processes were very important in establishing the quark model itself:

- Deep inelastic γ (and ν) interactions established the u and d charges of partons; recent polarized- γ studies show that the spin structure of partons in hadrons is more profound than hitherto suspected.
- Nonperturbative studies in photoproduction and in $e^+e^- \rightarrow \rho : \omega : \phi : \psi$ revealed the $(u\bar{u} \pm d\bar{d}) : s\bar{s} : c\bar{c}$ structure of the vector mesons from the squared charge of the constituents. This “gift” of nature that produced ideally mixed vector mesons in flavor was an essential piece of information that pointed the way toward the quark model in the early 1960’s. The $\gamma\gamma$ channels may provide similar impetus in the $C = +1$ channels that these

pioneering studies did for the $C = -1$ channels.

The capabilities for $\gamma\gamma$ physics at the LHC are not, however, limited to spectroscopy. Already at present energies a variety of processes have been studied, for which the parton structure of the photon is important [129]. Multijet production is an especially attractive LHC process [130]; the two photon mass region, $M < 150$ GeV, is accessible.

In addition, heavy ion collisions at the LHC provide the possibility to observe a variety of important diffractive processes, both hard and soft. One example of such processes is the diffractive dissociation of one photon into dijets, either light flavors at high p_T , or heavy flavors at any p_T : $\gamma\gamma \rightarrow jet + jet + V$. Diffractive production of two vector mesons, $\gamma\gamma \rightarrow V + V$, is also important. When the vector mesons are made of the light quarks, a “soft” behavior is expected. When at least one of the vector mesons is built from heavy-flavor quarks, this process is ideal for probing high energy meson-onium and onium-onium scattering. As discussed in Sections 2.1.1.2, page 9, and 2.1.1.6, page 11, the cross-sections for such processes are predicted to increase strongly with energy.

Photoproduction physics, similar to what is done at HERA, is also accessible at the LHC at much larger center-of-mass energies. On the one hand, coherent photoproduction processes constitute a potential background for the $\gamma\gamma$ physics, and must be understood. This background problem will be discussed in the next subsection. On the other hand, the photoproduction process is interesting in its own right. As already discussed in Section 2.1.1.6, the study of vector-meson photoproduction, especially in the comparison of energy dependence for light mesons like ρ and ϕ with heavy onia, ψ and Υ , is important for the study of small-size initial-state configurations (color transparency) and of the gluon distributions in the ions. In addition, the spectroscopy of higher mass systems produced in γ -Pomeron collisions is essentially unexplored and will be, like it or not, available for study in FELIX. This is also the case for the products of Pomeron-Pomeron collisions, another potential source of background. However, the physics of double-Pomeron exchange is probably best addressed in pp running, with the AA data constituting a useful supplementary source of information.⁵

⁵In ion-ion collisions, it should be understood that the phrase “Pomeron exchange” must be interpreted broadly; the idea of Regge-pole amplitudes dominating such a complex process is too simplistic. Here we only imply that the process has the same diffractive, rapidity gap structure as the extreme case of simple exchange of a Pomeron Regge-pole.

One aspect of pp double-Pomeron-exchange physics not emphasized in the previous sections is that of spectroscopy. The basic physics issues which are addressed are very similar to those expressed above for $\gamma\gamma$ collisions. But of course the nature of the incident Pomeron “beams” is still very enigmatic: are they to be viewed mainly as pion cloud or mainly as gluon degrees of freedom? If it is the latter, then the Pomeron-induced processes can be expected to be especially rich in glueball spectroscopy. But since the places in the detector that the products of double-Pomeron-exchange go are the same as for the $\gamma\gamma$ process, since the trigger is essentially the same, and since the choice of channels to be studied is the same (essentially everything with $C = +1$), the experimental problems have a very large (but not complete) overlap. We return to this subclass of processes in Subsection 2.4.6.

The very large $\gamma\gamma$ luminosities lead to very large cross-sections for QED processes such as dilepton pair production. Besides being vital for monitoring purposes, the production of τ pairs may be interesting in its own right [131], in particular, in measuring anomalous magnetic and electric dipole moments with good precision.

Finally the $\gamma\gamma$ luminosities are so high that it is not out of the question to search for particles beyond the standard model, especially light Higgs particles, new leptons, or SUSY sleptons [132–134], produced in a relatively clean environment. Higgs decays into $b\bar{b}$ pairs are a candidate for study. Furthermore, the low production rate for non-strongly interacting particles (sleptons, charginos, neutralinos) in Drell-Yan and gg -fusion processes may make the two photon processes preferable to pp for their observation [135].

2.4.2. Isolating $\gamma\gamma$ processes in ion-ion collisions

Even leaving aside for now the pure electromagnetic processes, some of which have truly huge cross-sections, the strong ion-ion cross-sections are orders of magnitude larger than the $\gamma\gamma$ hadroproduction cross-sections of interest. Of course most of these lead to easily distinguishable final states. What is left to consider are essentially strong double-Pomeron-exchange processes at the ion-ion level, as well as diffractive photoproduction, “ γ -Pomeron fusion”. The primary signature of these backgrounds, as is the case for the $\gamma\gamma$ signal, is large rapidity gaps in both directions along the beams.

The triggering for these channels is the same as discussed for double-Pomeron exchange processes in pp collisions, namely activity (hit density in tracking

systems, transverse-energy deposition in calorimetry, pulse-heights in trigger scintillator) in specified regions of the lego plot (where one envisages the products of the gamma-gamma collisions to lie), and no activity in the remainder of the lego plot, except possibly in the zero degree calorimeter. By “no activity” is meant no activity induced by primary particles from the collision. In practice, of course, one will define this in a more operational way as the absence of activity above noise thresholds, and with obvious backgrounds rejected.

Since the basic trigger is identical to a double-Pomeron-exchange trigger for pp collisions, it will evidently accept at this level all the double-Pomeron-exchange processes which occur for AA collisions. As we will discuss in detail below, the estimated total cross-section for the double-Pomeron exchange process is competitive with that of the signal. The estimates are not fully reliable, if for no other reason than that double-Pomeron exchange cross-sections for pp collisions are nearly nonexistent. In addition the question of how to extrapolate from low energies to the LHC energy scale is likewise very uncertain.

However, the situation is much better than this, because the bulk of this background process will be incoherent on the nucleus, unlike the $\gamma\gamma$ signal of interest. The typical recoil transverse momenta of the nucleons participating in the primary double-Pomeron-exchange collision will be hundreds of MeV and will in general lead to nuclear excitation. Thanks to the large Lorentz boost of the ions at the LHC, the decay products of such excitations carry a large amount of energy and will almost always be visible in the forward part of the FELIX detector. Evaporation neutrons will produce a well-defined 3 TeV signal in the zero-degree calorimeter (ZDC). Even a 10 MeV gamma ray will leave a 10 GeV electromagnetic shower in the forward calorimeter. Protons and pions from nuclear breakup will be swept into the forward tracking system of the FELIX detector. These and other such signatures, such as the very low total p_T of fully reconstructed final states, can be used offline to reject the incoherent Pomeron-induced processes. The actual efficiency which can eventually be achieved will depend on the details of the nuclear breakup and the forward geometry, and on performance parameters of the FELIX detector. (Beam-gas backgrounds are also a serious concern, but are beyond the scope of the considerations here.) Given the paucity of primary input data, it is premature to try to estimate the exact level of purity of the $\gamma\gamma$ signal which will be achieved.

Nevertheless, there will be a residual coherent

‘background’, involving both exchanged photons and Pomerons, that couples to the entire nuclei. This includes two-photon, photon-Pomeron and double-Pomeron interactions that can closely mimic the reactions of interest. These interactions will exhibit similar rapidity gaps and nuclear form-factor-imposed kinematic constraints. Consequently, they can only be separated from the signals of interest by conventional high energy physics analysis cuts, and by their distinctively different A and Z dependences.

In any case, it is undeniably very important to have a good estimate of the fraction of these double-Pomeron-exchange events for which the ion does not break up. Highly detailed estimates do not yet exist. But the probability that the recoil given to the nucleon is small enough that it can be absorbed coherently by the nucleus is arguably proportional to the ratio of the square of the proton size to the nuclear size, namely $\propto A^{-2/3}$ (per ion). In principle this gives nearly two orders of magnitude suppression of this background for the $CaCa$ collisions of greatest interest, and of course an even greater suppression for $PbPb$ collisions.

Further study, especially primary data on the systematics of double-Pomeron-exchange processes at collider energies, is needed to determine how serious these backgrounds will be. One promising source of information may be the program at RHIC, where there is interest in accessing this physics. There are already detailed studies under way by the STAR collaboration. Monte Carlo simulations of most of these background processes have been performed. Detailed numerical estimates of the backgrounds are not yet available. Although these studies correspond to a much lower beam energy, in a considerably less hermetic detector, it is found that selecting on a specific final state, with nothing else in the detector, together with cuts on the p_T of the produced hadron system, is sufficient to yield a good signal to noise ratio for a number of analyses of interest [136]. FELIX, being a full acceptance detector should have a much easier time than STAR, despite the increased beam energy, with correspondingly better signal to noise ratios. However, for the case of poorly defined final states, such as jets, the analysis may be much tougher, and the feasibility remains to be determined.

But no matter how this issue evolves, the full acceptance in the forward direction of FELIX is clearly of critical importance in the discrimination of the $\gamma\gamma$ signal from such strong-interaction diffractive backgrounds, making it a uniquely powerful instrument at the LHC for the investigation of this interesting class of processes. And as mentioned in the previ-

ous section, the backgrounds will also be classified and available for study; they contain very interesting physics as well.

The two photon processes themselves are also classified according to the nature of the excitation of the ion, if any, after the collision: incoherent, semi-coherent or coherent. In incoherent processes, the ion, as discussed above, is broken up. The semi-coherent processes are electromagnetic-dissociation processes, where one or both of the ions is excited by the Weizsacker-Williams Coulomb field of the other, for example into the giant dipole resonance. Coherent processes leave the nucleus in the ground state.

At the LHC, the secondary ion in a coherent process cannot be directly detected after the interaction, because its recoil is so small that it remains within the phase-space of the circulating beam. Therefore it is the rejection of generic forward activity which has to be the primary signature of the $\gamma\gamma$ process.

The squared four-momentum of each photon is small, as coherent emission from the whole nucleus limits its value to $q^2 < 1/R^2$, with R the radius of the nucleus. Both photons are therefore quasi-real. In the Weizsacker-Williams approximation the cross-section is expressed in the form [137]:

$$\frac{d\sigma_{AA \rightarrow AAX}}{dM dY} = \sigma_{\gamma\gamma \rightarrow X}(M^2) \cdot \frac{dL_{\gamma\gamma}}{dM dY}, \quad (2.31)$$

where $\sigma_{\gamma\gamma \rightarrow X}(M^2)$ is the cross-section of X-system production in $\gamma\gamma$ -collisions, M is the invariant mass of the $\gamma\gamma$ -system, and Y its rapidity. The last factor, $dL_{\gamma\gamma}/dM dY$, is the differential effective $\gamma\gamma$ -luminosity. It is proportional to the ion beam luminosity L_{AA} (as the photons are emitted coherently), to the fourth power of the ion charge Z^4 for symmetric collisions, and to $Z_1^2 Z_2^2$ for asymmetric collisions. Due to this coherence factor, heavy ion collisions are clearly more favorable for the study of two-photon processes. However the larger cross-section of electromagnetic processes in a heavy ion beam (for example, $\simeq 300$ barn in the case of Pb beams) reduces the lifetime of the heavy ion beams for very large Z . This favors the use of lighter ions, which yield a beam-luminosity larger than for the heaviest ions. Consequently, the highest two-photon luminosities are achieved with Ca beams [138].

The estimates of luminosity using the Weizsacker-Williams approximation may be questioned when the Z becomes as large as for lead. However the conclusion that $CaCa$ collisions is optimal does not depend upon this feature, and the relatively low value of Z for Ca should not lead to large corrections.

Another important variable is the average running time per year which is anticipated for the different

ion species. Because pp collisions have an exposure time larger by an order of magnitude than for ions, they may also be of interest for two-photon physics. The expected ion luminosities, running times and beam energies for different ion species (cf. Section 4.2, page 102) are shown in Table 2.1.

2.4.3. Luminosities for $PbPb$, $CaCa$ and pp collisions

The effective $\gamma\gamma$ luminosity is a complicated function depending on the two-photon invariant mass, the beam energy and the type of ion one uses. When the two ions overlap, the strong interaction leads to a large number of forward-produced particles in the final state, and the two-photon processes in these collision will be totally lost. In the black disc approximation, we therefore have to exclude collisions with impact parameter $b < 2R$ (with R the ion radius).

In addition, if the final state is produced within one of the nuclei they can interact strongly, again making the detection of such an event as a two-photon process impossible. Therefore we must also restrict the individual impact parameters b_1, b_2 of the $\gamma\gamma$ system, relative to the ions, to be larger than R .

These restrictions lead to essential modifications of the effective $\gamma\gamma$ luminosity, compared with what is calculated for e^+e^- collisions [139]. These effects lead to an adiabatic cut-off of the photon energy spectrum, and therefore to a related cut-off of the luminosity at an invariant $\gamma\gamma$ mass

$$M_{\gamma\gamma}^{max} \simeq 2\gamma_A/R, \quad (2.32)$$

where $\gamma_A = \gamma_p Z/A$ is the Lorentz factor of the ions in the laboratory frame and $R \simeq r_0 A^{1/3}$, with $r_0 \simeq 1.2$ fm. In the case of proton collisions we have taken as proton radius its charge rms value of 0.8 fm. Thus the accessible $\gamma\gamma$ mass range, $M \leq M_{\gamma\gamma}^{max}$, increases for the case of light ions and of protons, due to the favorable γ_A and R factors in comparison to heavy ions.

The effective $\gamma\gamma$ -luminosity for different ion species can be expressed in terms of a universal function [140–142] $\xi(x)$:

$$dL_{\gamma\gamma}/dx = \frac{\alpha^2 Z^4}{\pi^2} \frac{16}{3x} \xi(x) \quad (2.33)$$

where x is the normalized $\gamma\gamma$ -mass $x = M/M_{\gamma\gamma}^{max}$. Therefore we expect an extension of the accessible $\gamma\gamma$ mass range, for example, in $CaCa$ collisions by about a factor of two (i.e. up to ~ 450 GeV) compared with that in $PbPb$ collisions, mainly due to the smaller radius of Ca ions. For pp collisions

this reduction of the luminosity appears only at $M_{\gamma\gamma}^{max} = 4$ TeV. The differential $\gamma\gamma$ -luminosities versus two-photon mass for pp , $CaCa$ and $PbPb$ collisions, as well as for e^+e^- collisions at LEP 200, are shown in Fig. 2.26. These luminosities have been calculated for integrated luminosities of the primary ion collisions as quoted in Table 2.1. For e^+e^- collisions, an integrated luminosity of $\mathcal{LT} = 100$ pb $^{-1}$ was used.

Figure 2.26. The differential $dL_{\gamma\gamma}/dM$ luminosities for different ion species at LHC and for e^+e^- at LEP 200 normalized for integrated luminosities of the primary collisions over the expected run times per year TL_{coll} , which are equal to 10^3 pb $^{-1}$, 4 pb $^{-1}$, 10^{-4} pb $^{-1}$ and 100 pb $^{-1}$ for pp , $CaCa$, $PbPb$ and e^+e^- collisions respectively.

It is clearly shown in Fig. 2.26 that $CaCa$ collisions are most favorable for two photon physics in heavy ion collisions. The effective $\gamma\gamma$ luminosity in $PbPb$ collisions is more than two orders of magnitude smaller than in $CaCa$ collisions. For LEP 200 the $\gamma\gamma$ -luminosity per year is comparable to the estimated luminosity for $PbPb$ collisions, but extends only up to 200 GeV for the effective $\gamma\gamma$ masses.

At fixed values of the $\gamma\gamma$ mass M , the effective luminosity $dL_{\gamma\gamma}/dM dY$ is a Gaussian like function of the rapidity with mean value $Y_0 = 0$. As an example, in Fig. 2.27 the Y -dependence of the $\gamma\gamma$ -luminosity is shown at several values of the $\gamma\gamma$ -mass in the case of $PbPb$ collisions. A half-width of the

Table 2.1. Luminosities of ion collisions, for the FELIX run scenario.

Collision	Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	Bunch spacing (ns)	Run time (s/year)	CM Energy (TeV)
pp	$10^{29} - 10^{31}$	25	10^7	14
$PbPb$	10^{26}	25, 125	10^6	1148
$CaCa$	$4 \cdot 10^{30}$	25	$10^5 - 10^6$	280
pPb	10^{30}	25, 125	10^5	126
pCa	10^{31}	25	10^5	63

Y -distributions can be roughly characterized by the value

$$Y_{\gamma\gamma}^{max} = \ln \frac{M_{\gamma\gamma}^{max}}{M}, \quad (2.34)$$

where $M_{\gamma\gamma}^{max}$ is defined by Eq. (2.32). Thus the rapidity interval increases with the Lorentz factor of the ions and decreases with the radius of the ions as well as logarithmically with the mass of the $\gamma\gamma$ -system. In particular for $\gamma\gamma$ -masses comparable with $M_{\gamma\gamma}^{max}$ the rapidity distribution is concentrated around zero values of the rapidity, see Fig. 2.27, and therefore heavy systems are produced in $\gamma\gamma$ -collisions almost at rest in the laboratory frame. As

$q^2 < R^{-2}$. Therefore the maximum transverse momentum of a system produced in a coherent ion-ion collision is $p_T^{max} \approx \sqrt{2}R^{-1}$. But in most events the $\gamma\gamma$ system has a transverse momentum even smaller, of order [137].

$$p_T \sim M/\gamma_A, \quad (2.35)$$

Hence in a typical mass range, say $M < 100$ GeV, one has $p_T \sim 30$ MeV in $PbPb$ -collisions and ~ 25 MeV in $CaCa$ collisions.

2.4.3.1. Luminosity monitoring

In the light of the inherent uncertainties in the luminosity estimates, it is clearly vital to have ways of checking the theoretical calculations of the luminosity by an appropriate $\gamma\gamma$ luminosity monitor. A good process for this purpose is the production of $\mu^+\mu^-$ pairs. The expected rates for $PbPb$, $CaCa$ and pp collisions in the FELIX geometry ($|\eta| > 2.25$) are shown in Fig. 2.28. From the figure one can see that during a standard one-month run the statistical accuracy which can be reached for this dimuon monitoring process is of the order of 1% in the mass range up to 10 GeV in $PbPb$ collisions and up to 50 GeV in $CaCa$ collisions.

The use of e^+e^- pair production for $\gamma\gamma$ luminosity monitoring does not substantially improve the statistical precision. There is also greater uncertainty in the accuracy of the theoretical calculations than in the dimuon case. Nevertheless the 5% statistical level in the precision of the $\gamma\gamma$ luminosity monitoring can be extended up to 130 GeV in $CaCa$ and up to 30 GeV in $PbPb$ collisions.

2.4.4. Cross-sections, rates, and triggers

2.4.4.1. Cross-sections

Events in ion collisions are classified according to the value of the impact parameter and the nature of the ion interaction:

Figure 2.27. The differential $dL_{\gamma\gamma}^2/dM dY$ luminosities at $M = 1, 5, 25, 125, 250$ GeV for $PbPb$ collisions at LHC.

for the transverse momentum of the $\gamma\gamma$ system, its value is limited by the condition of photon virtuality,

Figure 2.28. Detection rates of $\mu^+\mu^-$ pairs in $PbPb$, $CaCa$ and pp collisions at the LHC in the forward-backward geometry of FELIX.

- Strongly inelastic ion-ion interactions, occurring when the impact parameter of the ions b is less than the sum of ion radii, $b < R_1 + R_2$.
- Diffractive interactions in “grazing” ion collisions, when $b \sim R_1 + R_2$. The strong interactions between the ions are in this case mainly caused by single and double Pomeron exchange at the LHC energy scale.
- Peripheral interaction of the ions, when $b > R_1 + R_2$.

The first class can be excluded by FELIX by requiring both ions to remain (almost) intact. The processes of interest are two-photon, photon-Pomeron and double Pomeron processes. As already discussed above, the momentum transfer in the Pomeron interactions is much larger than in the photon interactions. Therefore the requirement that the ions not break up strongly suppresses the double Pomeron contribution in coherent collisions of heavy ions. Nevertheless, as already emphasized above, this contribution is not demonstrably negligible, and is not under good theoretical control.

The cross-section of the strong, inelastic interaction of ions is reasonably described in the framework of a hard-sphere overlapping model [143]. For collisions of identical ions

$$\sigma_{nucl} = \sigma_0 (2A^{1/3} - \Delta R)^2, \quad (2.36)$$

Figure 2.29. The P_t distribution of the system produced in central diffraction processes obtained with the PHOJET event generator [148].

where $\sigma_0 \simeq 70 \text{ mb}$, A is the ion mass number and $\Delta R = 1.3$. For more accurate cross-section calculations, the semiclassical optical model [144] or the Gribov-Glauber model [145] can be used.

For the cross-sections for double-Pomeron processes, which are actually peripheral nuclear interactions, simple geometrical considerations suggest a scaling with the ion radius $\sim A^{1/3}$. In the context of simple single-Pomeron-exchange phenomenology [146], the differential cross-section of hadron production in the double Pomeron processes can be roughly estimated:

$$\frac{d\sigma_{DP}}{dm_X^2} = \frac{\sigma_{DP}}{m_X^2} (A^{1/3} + \delta) \ln \frac{s_{NN}}{(m_X m_N R)^2} \quad (2.37)$$

where $\sigma_{DP} = 1.3 \mu\text{b}$, m_X is the effective mass of the hadron system in the central rapidity region, $\sqrt{s_{NN}}$ is the CM energy in the corresponding nucleon collisions, m_N is the nucleon mass, $R = r_0 A^{1/3}$ is the ion radius, and $\delta = 1.5a/r_0$ is connected with the width of the nuclear surface. After integration of Eq. (2.37) over dm_X in a range up to $m_X^{max} = \sqrt{s_{NN}}/m_N R$, the total cross-section of the double Pomeron processes can be estimated. The results are shown in Table 2.2 as the cross-section of the reaction $AA \rightarrow AAX(DP)$. A more refined description of the double-Pomeron as well as Pomeron-photon processes can be performed in the framework of the two-component Dual Parton

Model (DPM), cf. for example [147]. The corresponding cross-sections of central diffractive (mainly double Pomeron) processes obtained with the PHOJET event generator [148] are shown in Table 2.2, reaction $AA \rightarrow \bar{A}\bar{A} X(CD)$. But the PHOJET generator does not distinguish the final states of the colliding ions. Therefore the generated processes combine the coherent diffractive interactions of the ions (i.e. when the ions after interaction are intact) with excitation and even full disintegration of the ions. Note again that the average transverse momentum of the hadron system in the central rapidity region is of the order of 450 MeV (cf. Fig. 2.29), which is an order of magnitude higher than that in two photon processes (Eq. 2.35). This feature can help to distinguish the two processes whenever the final state produced by the photons is fully reconstructed. The cross-sections for the coherent two photon processes can be obtained by folding the effective $\gamma\gamma$ luminosities in the Weizsacker-Williams approximation with the corresponding cross-sections for the two photon interactions, as expressed in Eq. (2.31). In particular, for an estimation of the total cross-section of $\gamma\gamma$ processes we have used the parametrization of Schuler and Sjostrand:

$$\sigma_{\gamma\gamma}^{tot}(s) \simeq 211 (s/s_0)^\epsilon + 297 (s/s_0)^{-\eta} \text{ nb}, \quad (2.38)$$

where, $\epsilon \simeq 0.0808$, $\eta \simeq 0.4525$ and $s_0 = 1 \text{ GeV}^2$ [149].

The pure electromagnetic processes of e^+e^- and $\mu^+\mu^-$ pair production are needed for luminosity monitoring. The cross-section for low-mass e^+e^- pair production can be estimated according to the approximate formula [150]:

$$\sigma_{e^+e^-} = \frac{28}{27\pi} \frac{(Z\alpha)^4}{m_e^2} \ln^3 \gamma_A, \quad (2.39)$$

where m_e is the electron mass and γ_A is the Lorentz factor of the ions in the laboratory frame. A highly accurate determination will take a lot of work, due to nontrivial coherent effects in nuclei, which are sensitive to the multiple scattering of the pair as it traverses the nuclear matter. However, these effects are far less important for the $\mu^+\mu^-$ process.

The probability of ion excitation in two-photon processes has been studied recently in a semiclassical impact parameter approach [139]. Particularly important is the excitation of the Giant Dipole Resonance (GDR). The probability of ion excitation as a function of the impact parameter of the collision can be approximately expressed in the form [139]:

$$P_{GDR}(b) = 1 - \exp\left(-\frac{3\alpha Z^2}{16\pi^2 b^2} \frac{(A-Z)Z}{A^{2/3}} \text{ mb}\right). \quad (2.40)$$

Similarly the total probability for the electromagnetic dissociation of the ion, including the GDR, has been given for $PbPb$ collisions as [151]

$$P_{Dis}(b) = 1 - \exp\left(-\frac{303 \text{ fm}^2}{b^2}\right) \quad (2.41)$$

The probability of the GDR excitation is about 40% per Pb ion, and about 1% per Ca ion, at an impact parameter of $b = 2R$. As each of the ions can be excited, the excitation probability for at least one ion is about 65% and about 2% for $PbPb$ and $CaCa$ collisions respectively.

The electromagnetic dissociation of ions in the one photon processes are also subdivided into excitation into the GDR and into electromagnetic dissociation above the GDR excitation. The cross-section for ion dissociation at the GDR can be estimated [138,139] as:

$$\sigma_{GDR} \simeq 67.5 \frac{(A-Z)Z^3}{A^{2/3}} \mu\text{b}, \quad (2.42)$$

The cross-section of the ion electromagnetic dissociation above the GDR can be approximated by the formula [138,139]:

$$\sigma_{ED} \simeq 108 A^{0.9} Z^2 \mu\text{b}. \quad (2.43)$$

The cross-sections of all these processes as well as the expected event rates are shown in Table 2.2 for $PbPb$, $CaCa$ and pp collisions.

2.4.4.2. Rates

We have already noted that the cross-section for hadroproduction by two photons is only a small fraction of the inelastic ion-ion hadroproduction cross-section; cf. Table 2.2. In the case of $PbPb$ collisions the cross-section ratio of $\gamma\gamma$ to nuclear interactions is of the order of 2%, whereas this ratio falls to 5×10^{-3} in $CaCa$ and to 2×10^{-7} in pp collisions ($W_{\gamma\gamma} > 1 \text{ GeV}$). Most of this background is easily rejected, the remaining double-Pomeron-exchange piece being the most serious remnant.

The semicoherent, electromagnetic-dissociation processes lead to excitation of ions. Especially important is the Giant Dipole Resonance excitation, which leads to the emission of a soft neutron in the ion rest frame [141]. In the laboratory frame the emitted neutron will have an energy of about 3 TeV (due to the Lorentz factor of the excited ion) and will strike the zero degree calorimeter, providing a very clean signature of the GDR excitation. In $PbPb$ collisions the electromagnetic-dissociation cross-section is large, $\sigma_\gamma = 230 \text{ barn}$, even compared with that of the nuclear ion interaction ($\sigma_{nucl} = 7.8 \text{ barn}$). In the case of $CaCa$ collisions this cross-section, $\simeq 2 \text{ barn}$, is almost the same as the nuclear

Table 2.2. Cross-sections ($M_X > M_{cut}$) and event rates of the main processes in $PbPb$, $CaCa$ and pp collisions with luminosities 10^{26} , 4×10^{30} and $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ respectively.

Reaction	M_{cut} GeV	PbPb-collision		CaCa-collision		pp-collision	
		σ , b	rate, Hz	σ , b	rate, Hz	σ , b	rate, Hz
$AA \rightarrow X$ (Nuclear)	–	7.8	$7.8 \cdot 10^2$	2.1	$8.4 \cdot 10^6$	0.1	$1.0 \cdot 10^7$
$AA \rightarrow AA X$ (DP)	–	$1.0 \cdot 10^{-3}$	0.1	$0.8 \cdot 10^{-3}$	$3.2 \cdot 10^3$	$0.5 \cdot 10^{-3}$	$5.0 \cdot 10^4$
$AA \rightarrow \tilde{A}\tilde{A} X$ (CD)	2.0	$7.3 \cdot 10^{-3}$	0.7	$5.1 \cdot 10^{-3}$	$2.0 \cdot 10^4$	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^5$
$AA \rightarrow AA X$ (CD) ¹⁾	2.0	$4.7 \cdot 10^{-5}$	$4.7 \cdot 10^{-3}$	$3.3 \cdot 10^{-5}$	$1.3 \cdot 10^2$	$6.5 \cdot 10^{-6}$	$6.5 \cdot 10^2$
$AA \rightarrow AA_{GDR}^*$	–	130	$1.3 \cdot 10^4$	0.9	$3.6 \cdot 10^6$	–	–
$AA \rightarrow AA_{ED}^*$	–	90	$0.9 \cdot 10^4$	1.2	$4.8 \cdot 10^6$	–	–
$AA \rightarrow AA e^+e^-$	–	$2.3 \cdot 10^5$	$2.3 \cdot 10^7$	800	$3.2 \cdot 10^9$	$6.3 \cdot 10^{-3}$	$6.3 \cdot 10^5$
$AA \rightarrow AA e^+e^-$	1.0	0.5	$0.5 \cdot 10^2$	$2.8 \cdot 10^{-3}$	$1.1 \cdot 10^4$	$5.0 \cdot 10^{-8}$	5
$AA \rightarrow AA \mu^+\mu^-$	–	2.2	$2.2 \cdot 10^2$	$1.2 \cdot 10^{-2}$	$4.8 \cdot 10^4$	$1.3 \cdot 10^{-7}$	13
$AA \rightarrow AA \mu^+\mu^-$	1.0	0.15	15	$8.0 \cdot 10^{-4}$	$3.2 \cdot 10^3$	$1.4 \cdot 10^{-8}$	1.4
$AA \rightarrow AA \gamma\gamma \rightarrow X$	2.0	0.03	3	$6.0 \cdot 10^{-4}$	$2.4 \cdot 10^3$	$1.3 \cdot 10^{-8}$	1.3
$AA \rightarrow AA_{GDR}^* \gamma\gamma \rightarrow X$	2.0	0.05	5	$1.2 \cdot 10^{-5}$	$4.8 \cdot 10^2$	–	–

¹⁾ $p_T(X) < 50 \text{ MeV}/c$

cross-section, see Table 2.2. Thus we can expect important contributions from these processes in the zero degree calorimeters. The corresponding event rates are shown in Table 2.2.

As shown in Table 2.2, the inclusive cross-section for e^+e^- pair production in heavy ion collisions is huge ($2.3 \cdot 10^5$ barn in $PbPb$ and 800 barn in $CaCa$). It is so large that for central collisions the probability of pair emission per event is large compared to unity. A significant fraction of the electrons and positrons are emitted in the forward and backward directions. Although most of the produced pairs have very small mass, $m_{e^+e^-} \sim 3m_e$, and very small energies, the cross-section for production of energetic electrons, say greater than several GeV, is not small. Direct calculations [152] give the numbers shown in Table 2.3. These events produce an intense background mainly for the UA1 electromagnetic calorimeters. However, because the pairs are swept overwhelmingly into the bending plane of the detector (actually a bending surface), they will occupy at worst only a very small portion of the acceptance.

2.4.4.3. Triggers

As mentioned in Section 2.4.2, the basic triggers for the $\gamma\gamma$ processes are essentially the same as for the double-Pomeron-exchange processes in pp collisions, and are based on the pattern of activity in all of phase space seen by FELIX. It is anticipated that the detailed trigger thresholds in the various phase-space regions and the correlations between them for an effective $\gamma\gamma$ trigger is “programmable”, so that

Table 2.3. Cross-sections and event rates for e^+e^- pair production when both electron and positron, have energy higher than a given threshold, E_{thr} , for $PbPb$ and $CaCa$ collisions with luminosities 10^{26} and $4 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ respectively.

E_{thr} GeV	$\sigma(AA \rightarrow AA + e^+e^-)$		Event rate, MHz	
	$PbPb$	$CaCa$	$PbPb$	$CaCa$
0.25	3.5 kb	12 b	.35	48.
0.50	1.5 kb	5.5 b	.15	22.
1.0	0.5 kb	1.8 b	.05	7.2
2.5	0.08 kb	0.3 b	.008	1.2
5.0	0.03 kb	0.1 b	.003	0.4

no separate discussion is needed here; cf. Chapter 9. The development of these detailed trigger strategies will be mostly driven by the program of diffractive, rapidity-gap physics in pp collisions, likely to precede in time high-luminosity $CaCa$ running.

Examination of Table 2.3 shows that the rate of double-Pomeron plus $\gamma\gamma$ events in $CaCa$ collisions approaches 10 kHz at design luminosity. This is probably one to two orders of magnitude higher than what will be written to tape, so additional rejection will be needed. For spectroscopy, one can tighten the pattern requirements, so that the produced low mass system is directed toward the rapidity region of interest for the detailed analysis, say $2 < \eta < 6$, with rapidity gaps required elsewhere in the phase space. For the diffractive photoproduction channels there

will be an extra rapidity gap which can be put into the pattern trigger. And of course the design run would be preceded by an early “minimum bias” run at lower luminosity, where these refinements need not even be considered. In all cases it will be in offline analysis, not in the trigger, where the problems of separating the double-Pomeron, diffractive-photoproduction, and true $\gamma\gamma$ processes must be faced.

2.4.5. Basic QCD phenomena

2.4.5.1. The $\gamma\gamma$ total cross-section and event structure

Minimum-bias event rates in two photon processes are high enough to study soft and semihard interactions of photons at $\gamma\gamma$ cms energies up to 450 (200) GeV in $CaCa$ ($PbPb$) collisions. This is 4 (2) times larger than the energy range accessible at LEP 200 (cf. Table 2.2).

The energy dependence of the $\gamma\gamma$ total cross-section is of special interest, inasmuch as the hadronic composition of a real, energetic photon contains, in addition to a soft “vector-dominant” hadronic portion (60%-80%), a more-or-less point-like $q\bar{q}$ piece which acts as a relatively small color dipole. Therefore the energy dependence may contain a component which has the rapid rise characteristic of the BFKL dynamics discussed in Section 2.1.1.2. In photoproduction there is no evidence of such a rise, but there could be an enhancement in $\gamma\gamma$ collisions due to the occasional presence, with $\sim 10\%$ probability, of two small dipoles in the initial-state configuration.

To measure the total cross-section, it is very advantageous to have large enough acceptance to see the entire final state and the rapidity gaps beyond. The final state structure in $\gamma\gamma$ collisions is like generic hadron-hadron collisions at comparable cms energy W ; the energy flow in the final state is mainly in the forward and backward directions. In the experiments at LEP 200, much information about two photon events disappears down the beam directions [154]; 30% to 50% of the hadronic energy is lost in the forward-backward directions.

The measurement accuracy of the total hadron cross-section in two photon processes at LEP is not so much limited by event statistics as by the need for a precise description of competing reactions such as beam-gas or beam-wall scattering, annihilation reactions etc. [154]. This is probably not the problem for FELIX, nor is statistical accuracy or efficiency in detection of the $\gamma\gamma$ processes. Instead, the accurate determination of coherent-photoproduction

and double-Pomeron-exchange contaminations may be the most important limitation. As discussed in previous subsections, this limitation is very difficult to assess at present.

2.4.5.2. Exclusive vector-meson pair production

The study of exclusive vector-meson pair production in two photon processes allows the study of Pomeron-exchange factorization relations at high energies, and to study various color-coherent phenomena. Given the assumption that single Pomeron exchange dominates these two-body processes, factorization relations [84] among total cross-sections for pp , γp and $\gamma\gamma$ collisions are predicted

$$\sigma_{tot}(\gamma p)^2 = \sigma_{tot}(pp) \sigma_{tot}(\gamma\gamma), \quad (2.44)$$

as well as among the differential cross-sections:

$$\frac{d\sigma(\gamma p \rightarrow V_1 p)}{dt} \frac{d\sigma(\gamma p \rightarrow V_2 p)}{dt} = \frac{d\sigma(\gamma\gamma \rightarrow V_1 V_2)}{dt} \frac{d\sigma(pp \rightarrow pp)}{dt}, \quad (2.45)$$

$$\frac{d\sigma(\gamma\gamma \rightarrow V_1 V_1)}{dt} \frac{d\sigma(\gamma\gamma \rightarrow V_2 V_2)}{dt} = \frac{d\sigma(\gamma\gamma \rightarrow V_1 V_2)^2}{dt}. \quad (2.46)$$

Perturbative-QCD predicts that the energy dependence of the cross-sections for vector mesons built of light quarks: $V_1, V_2 = \rho, \omega, \phi$ should be close to that for soft QCD two-body processes, while the energy dependence of the cross-sections for the combined production of V_1 and hidden heavy-flavor V_2 like J/ψ or Υ (and their excited states) should be proportional to the square of the gluon distribution in V_1 , i.e. to be as strong as what is observed at HERA for the photoproduction of J/ψ . The cross-section for the production of two hidden charm or beauty vector mesons would resemble onium-onium scattering. As discussed in Sections 2.1.1.2, page 9, and 2.1.1.6, page 11, the BFKL dynamics may well apply in this case, leading to a large enhancement for production of such onium states compared to the expectations of Eqs. (2.44-2.46). In particular, estimates [155] indicate that Eq.(2.45) may underestimate the cross-section for the of $J/\psi + J/\psi$ channel by a factor $\sim 10^2$ for $W \sim 100$ GeV. In addition, it is not evident that the shrinking with energy of the diffraction peak will be the same for photoproduction of J/ψ and Υ than, say, for the ρ meson, since in the BFKL limit very little shrinkage is expected.

The $\gamma\gamma \rightarrow V_1 V_2$ cross-sections have been calculated from Eq. (2.46) on the basis of data for

vector meson photoproduction at HERA and for pp elastic scattering. The differential cross-sections $d\sigma(\gamma\gamma \rightarrow V_1 V_2)/dt$ can be parameterized in the form:

$$\frac{d\sigma}{dt}(\gamma\gamma \rightarrow V_1 V_2) = A_{V_1 V_2} \left(\frac{W}{W_0} \right)^{C_{V_1 V_2}} \exp \left(t B_{V_1 V_2} + 4t \alpha'_{V_1 V_2} \ln \frac{W}{W_0} \right), \quad (2.47)$$

where t is the squared transfer momentum in the reaction $\gamma\gamma \rightarrow V_1 V_2$, W is the effective mass of the vector pair, and $W_0 = 50$ GeV. Other cross-section parameters and cross-sections, at a 2-photon mass $W > 20$ GeV, are shown in Table 2.4.

Figure 2.30. Mass spectrum of K^+K^- systems of detected process $\gamma\gamma \rightarrow \omega\phi \rightarrow 3\gamma K^+K^-$ and $\pi^+\pi^-$ system of detected process $\gamma\gamma \rightarrow \omega\rho^0 \rightarrow 3\gamma\pi^+\pi^-$, if pions are misidentified as kaons.

As typical examples we consider below the detection of several specific $V_1 V_2$ channels, including ω and J/ψ production in combination with ρ , ω and ϕ mesons detected in the forward and backward portions of the FELIX detector. For the ω identification we use its 3γ decay, i.e. $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$, which can be effectively detected and triggered by the electromagnetic calorimeters. For detection of the J/ψ we use its decays into lepton pairs: e^+e^- and $\mu^+\mu^-$. Both decay channels can be triggered by the electromagnetic calorimeters or muon chambers. The

Figure 2.31. Mass spectrum of the detected $\gamma\gamma \rightarrow V_1 V_2$ events during 10^6 sec run with $CaCa$ in the FELIX geometry. The branching ratios of the decays, $\omega \rightarrow \pi^0\gamma$, $\phi \rightarrow K^+K^-$, $J/\psi \rightarrow e^+e^-$ are taken into account.

$\phi \rightarrow K^+K^-$ decay may be detected without identification of charged kaons if there is only one unidentified hadron pair in an event (Fig.2.30). In Fig.2.31 the $V_1 V_2$ mass distributions expected for the $\gamma\gamma \rightarrow V_1 V_2$ events are shown for $CaCa$ collisions, for several choices for the produced vector mesons. The detection efficiencies in the forward/backward geometry, as well as branching ratios of the vector meson decays ($\omega \rightarrow \pi^0\gamma$, $\phi \rightarrow K^+K^-$, $J/\psi \rightarrow e^+e^-$), have been taken into account.

The number of events expected in $PbPb$ collisions is marginal for studies of the $\rho\omega$, $\omega\phi$, $\rho J/\psi$ (and therefore $\rho\rho$ and $\rho\phi$) systems. As one can see from Fig. 2.31, in $CaCa$ collisions the mass range for these processes up to 150 GeV is attainable, due to the higher $\gamma\gamma$ -luminosity. The detection efficiency for the $\omega J/\psi$ and $\omega\omega$ systems can probably be improved by using the 3π decay of the ω . A study of the $\phi\phi$ system in its $2K^+2K^-$ decay mode may be performed if identification of charged kaons exists in the FELIX detector. But a study of $\phi J/\psi$ and say $J/\psi J/\psi$ is not possible with FELIX if the above factorization estimates hold. However, if the BFKL dynamics is valid, there will be a chance to observe these processes.

Table 2.4. Parametrization of $\gamma\gamma \rightarrow V_1 V_2$ cross-sections and corresponding cross-sections of the meson pair production in two photon processes of ion collisions at $M_{\gamma\gamma} > 20$ GeV.

Meson pair	$A_{V_1 V_2}$ nb	$B_{V_1 V_2}$ (GeV/c) ⁻²	$C_{V_1 V_2}$	$\alpha'_{V_1 V_2}$ (GeV/c) ⁻²	$\sigma_{tot}(AA \rightarrow AA_{\gamma\gamma \rightarrow V_1 V_2})$	
					PbPb, μ b	CaCa, nb
$\rho\rho$	150	6	0.22	0.25	230	$3.2 \cdot 10^3$
$\rho\omega$	33	6	0.22	0.25	51	700
$\rho\phi$	17	4	0.22	0.25	41	560
$\omega\phi$	1.9	4	0.22	0.25	4.5	62
$\phi\phi$	0.5	2	0.22	0.25	2.1	30
$\rho J/\psi$	1.1	2.5	0.80	0.0	3.0	47
$\omega J/\psi$	$1.3 \cdot 10^{-1}$	2.5	0.80	0.0	0.35	5.6
$\phi J/\psi$	$6.8 \cdot 10^{-2}$	1.5	0.80	0.0	0.3	4.9
$J/\psi J/\psi$	$3.1 \cdot 10^{-4}$	1.5	1.38	0.0	$1.2 \cdot 10^{-3}$	0.02
$J/\psi J/\psi^*)$	$0.16/\ln(W/M_\psi)$	1.5	2.00	0.0	0.2	4.6

*) BFKL approximation

2.4.5.3. Diffractive photoproduction of heavy quarkonia

Diffractive vector meson photoproduction is a valuable window on the interface between perturbative QCD and hadronic physics. While elastic processes are commonly described through non-perturbative, phenomenological methods, hard exclusive photoproduction of heavy mesons is calculable in perturbative QCD. It has been shown [156] that the cross-sections of hard diffractive processes off a hadronic target are proportional to the square of the gluon distribution in the nucleon. The x at which the gluon density is probed is given by $x \approx m_V^2/W^2$ where m_V is the mass of the vector meson and W denotes the invariant mass of the photon-nucleon system. Initial HERA data on photoproduction of J/ψ mesons [157] confirms the rapid increase of the cross-section with energy W , predicted by perturbative QCD.

At FELIX, hard diffractive vector meson photoproduction can be investigated especially well in AA collisions. In comparison to previous experiments, the very large photon luminosity should allow observation of processes with quite small γp cross-sections, such as Υ photoproduction. Measurements to much higher energies than available up to now will also be possible. At HERA, for example, diffractive J/ψ photoproduction has been measured up to $W \sim 160$ GeV, while with FELIX this should be possible up to $W \sim 1$ TeV. The cross-section for diffractive J/ψ and Υ production has been estimated using the color dipole formalism [158]. The cross-sections for diffractive photon-nucleon scatter-

Figure 2.32. Differential cross-section for exclusive diffractive J/ψ production in photon-pomeron collisions.

ing are folded with the photon flux calculated in the quasi-classical approximation, and the shadowing effects are calculated within the Gribov-Glauber approximation [145]. In Figs. 2.32, 2.33 the expected differential cross-sections $d\sigma/dW$ for exclusive production of J/ψ and Υ mesons are shown. The calculations have been done for $W > 20$ GeV, and a pseudorapidity of the mesons of $|\eta| < 4$. This ensures that the beam remnants are well separated from the diffractively produced mesons. In Table 2.5 the integrated cross-sections are given for several W -cuts.

The efficiencies of J/ψ and Υ detection in the

Table 2.5. Cross-sections for exclusive diffractive photoproduction of vector mesons in various pA and AA collisions at the LHC.

Meson / Energy	σ_{pCa} , nb	σ_{CaCa} , nb	σ_{pPb} , nb	σ_{PbPb} , nb
J/ψ ($W > 20$ GeV)	5400	$21 \cdot 10^3$	$67 \cdot 10^3$	$400 \cdot 10^3$
J/ψ ($W > 200$ GeV)	3100	$10 \cdot 10^3$	$33 \cdot 10^3$	$150 \cdot 10^3$
J/ψ ($W > 500$ GeV)	1100	$2.2 \cdot 10^3$	$9 \cdot 10^3$	$16 \cdot 10^3$
Υ ($W > 20$ GeV)	4.9	17	55	280
Υ ($W > 200$ GeV)	3.8	11	37	150
Υ ($W > 500$ GeV)	1.7	3.3	12	20

Figure 2.33. Differential cross-section for exclusive diffractive Υ production in photon-Pomeron collisions.

e^+e^- and $\mu^+\mu^-$ decay modes are almost zero in the rapidity interval $|Y| < 1.5$. Beyond this range the efficiencies become large. During a 10^6 sec run we expect the detection of 3×10^6 and 800 J/ψ in the e^+e^- decay mode for $CaCa$ and $PbPb$ runs respectively. For Υ we expect the detection of 600 events in $CaCa$ collisions in the same decay channel, while the event number in the $PbPb$ run is negligible. The differential cross-section of the J/ψ photoproduction can be measured up to $W = 1000$ GeV with a statistical accuracy better than 3%, whereas the cross-section of the Υ production can be measured up to $W = 800$ GeV with a 20% accuracy if the two leptonic decay modes (e^+e^- and $\mu^+\mu^-$) are combined.

2.4.6. Hadron spectroscopy

2.4.6.1. Light quark spectroscopy

In the overview it was stressed that photon-photon collisions provide an independent view of the QCD world of meson and baryon spectroscopy. The states which are produced resonantly in the s -channel will have $C = +1$, opposite to what is obtained from e^+e^- annihilation reactions. This in turn leads to quite distinctive features of the systematics. In particular,

- There will be a characteristic flavor dependence for the production of the various states comprising a $q\bar{q}$ nonet with ideal mixing:

$$\Gamma_{\gamma\gamma} \left(\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}} : \frac{(u\bar{u} - d\bar{d})}{\sqrt{2}} : s\bar{s} \right) = 25 : 9 : 2$$

So the relative widths, as given above, establish the pattern of flavor mixing. The question of which J^{PC} nonets are ideally flavor-mixed (like ρ , ω , and ϕ , or a_2 , f_2 , f_2' for the 2^{++} nonet), and which are not (like the 0^{-+} nonet), is critical to the understanding of the nature of the dynamics of flavor mixing. A systematics is needed, but at present little is known. The $\gamma\gamma$ reaction provides unique information.

- The J^{PC} dependence of the production ratios is also an important characteristic. Within a 3L_J multiplet, one has in a nonrelativistic approximation

$$\Gamma(^3P_2 : ^3P_1 : ^3P_0) = 1 : 0 : 15/4 \quad (2.48)$$

whereas as $m_q \rightarrow 0$, $\Gamma(^3P_0) \rightarrow 0$. The $\Gamma_{\gamma\gamma}(^3P_2)$ width is known; determining the remaining $\Gamma(^3P_J)$ will provide new insight on

the enigma of how to relate the small, partonic current-quark masses to the constituent-quark masses of spectroscopy. For example, is $\Gamma(^3P_0) > \Gamma(^3P_2)$, as the constituent-mass limit implies, or is it the other way around, as implied in the current-quark limit?

Relations similar to Eq. 2.48 exist for the higher multiplets, and enable, for example, separation of the 2^{++} radial excitation of the $^3P_2(1270)$, expected at ~ 1800 MeV, from the 3F_2 state expected to lie in the same mass region [159]. The 3P_2 is predicted to be entirely produced in $\gamma\gamma$ collisions in the $J_z = 2$ substate. This is an exact selection rule nonrelativistically, and should be tested in $\gamma\gamma \rightarrow \chi_c$ or χ_b ; it is still robust when relativistic corrections are included [160]. It is also good empirically for $f_2(1270) \rightarrow \gamma\gamma$. In contrast, a 3F_2 is predicted to have a $\gamma\gamma$ width from $J_z = 0$ roughly 1/3 to 1/2 of that from $J_z = 2$. So observation of a significant $J_z = 0$ contribution for a 2^{++} around 1800 MeV, say, can help to distinguish the 3F_2 from the radial excitation of $f_2(1270)$, 3P_2 . (These remarks are also true for the $b\bar{b}$ system, where the radial $^3P(\chi_2)$ and the $^1F(\chi_2)$ are possibly below $B\bar{B}$ threshold.)

The general conclusion from this particular example is that the $\gamma\gamma$ process provides powerful information on both the flavor and the spin/angular-momentum internal structure of hadrons.

The 3P_0 states are pivotal also, because the lightest glueball is predicted to be $\cong 1.6$ GeV, which is in the vicinity of the 3P_0 nonet. Hence mixing will occur [161,162], with the $f_0(1370)$, $f_0(1500)$, and $f_{(J=0?)}(1710)$ as the physical states of interest. The couplings to the $\gamma\gamma$ system can disentangle the pattern of the 0^{++} states and clarify the role of $f_0(1500)$ and $f_{(J=0?)}(1710)$ in the glueball- $q\bar{q}$ mixing. There is much attention paid to this question at present, because lattice QCD predicts $M \cong 1.6 \pm 0.1$ GeV for the 0^{++} glueball mass in the quenched approximation. The implications for $\gamma\gamma$ processes [163] is that $\gamma\gamma \rightarrow \pi^+\pi^-$ or $\pi^0\pi^0$ should give $f_0(1370)$ with $\Gamma(\gamma\gamma) \cong 3 - 5$ KeV, while $f_0(1500)$ is predicted to have $\Gamma(\gamma\gamma) \cong 0.05 - 0.3$ KeV [160]. The Aleph collaboration is searching for this state, and they are already at an interesting level of sensitivity [164].

The $f_J(1710)$ may be accessed best in $\gamma\gamma \rightarrow K\bar{K}$, or in $\eta\eta$, as its $q\bar{q}$ content is expected to be dominantly $s\bar{s}$. The 4π state in $\gamma\gamma$ collisions is also good for accessing the $f_0(1370)$ and $f_0(1500)$. The $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ states are also very nice “strategic” channels and, with good endwall calorimetry in FELIX, may well be very accessible. The $\gamma\gamma$ system obviously couples preferentially to charged constituents, while it is believed that the η and η'

couple strongly to glueballs. It would therefore be interesting to see what the spectrum of states looks like in these channels; it would sensitively probe the mixing structure between $q\bar{q}$ channels and gg channels.

The $f_0(980)$ and $a_0(980)$ states remain enigmatic. These states couple strongly to $K\bar{K}$, even though they are near or even below $K\bar{K}$ threshold. Are they $K\bar{K}$ bound states [165] or $q\bar{q}$ states shifted by couplings to hadronic channels [166], or multi-quark states? If they are $K\bar{K}$ “molecules”, one expects [167]

$$\Gamma(f_0, a_0 \rightarrow \gamma\gamma) \cong 0.6 \text{ KeV} \quad (2.49)$$

In contrast, $q\bar{q}$ states at this mass would be expected to have widths (computed by using $f_2 \rightarrow \gamma\gamma$ as input)

$$\begin{aligned} \Gamma(f_0 \rightarrow \gamma\gamma) &\cong 2.5 \text{ KeV} \\ \Gamma(a_0 \rightarrow \gamma\gamma) &\cong 1.0 \text{ KeV}. \end{aligned} \quad (2.50)$$

These numbers are driven by the 25:9 ratio for $(u\bar{u} + d\bar{d}) : (u\bar{u} - d\bar{d})$ in relative size—assuming this flavor content by the similarity in the $f_0:a_0$ masses.

Experimental widths appear quite small for these channels; they each have a central value of 0.25 KeV with 30-40% error ranges. This suggests that the $\gamma\gamma$ coupling is driven by $K\bar{K}$, although with the large errors, one cannot yet rule out a 25:9 ratio favoring the f_0 over the a_0 .

2.4.6.2. Double Pomeron exchange in pp collisions: opportunities for spectroscopy

Double-Pomeron-exchange processes in pp collisions, leading to low to moderate masses, are an important potential resource for spectroscopy. These processes have been considered in this subsection as a possibly annoying background for the $\gamma\gamma$ physics. And it is certainly the case that they are best studied in pp collisions, where one has the information on the momentum transferred to the leading protons, positively detected in the FELIX Roman-pot system.

The discussion in Section 2.2.2.6 of spectroscopy issues for the double-Pomeron-exchange processes was deferred to this subsection, in order that the direct comparison with the corresponding $\gamma\gamma$ physics, both experimentally and theoretically, could be made. It should be abundantly clear that in terms of physics goals and experimental technique, there is a great overlap. But there is an extra dimension present in the case of double-Pomeron exchange. As always, one would like to search for

as many resonant states as possible and determine masses, widths, branching ratios, etc. However, the physics of the production mechanism has not the relative simplicity possessed by the $\gamma\gamma$ initial state. Understanding the dynamics associated with Pomeron exchange is a very important goal in itself, and the spectroscopic information on Pomeron structure complements the information coming from the systematics of hard and soft diffraction at the much higher p_T and mass scales which were discussed at length in Sections 2.1.3, page 16, 2.1.4, page 19, 2.2.2.5, page 38, 2.2.2.6, page 38. As an example of the importance of the detailed Roman-pot information, it should be noted that a strong dependence of the produced resonant systems on the magnitude of the *difference* of the recoil transverse-momenta imparted to the two leading protons has been recently observed [168]. Empirically it appears that well-established P and D wave $q\bar{q}$ states (such as $f_1(1285)$, $f_1(1420)$, $f_2(1525)$, and $\eta_2(1700)$) are strongly suppressed when this transverse-momentum difference dp_T is small. On the other hand, they become prominent when dp_T is large [169]. At small dp_T the remaining states include the glueball candidates $f_0(1500)$ and $f_J(1710)$. There also appears in this limit a broad tensor state $f_2(1900)$ that has a mass consistent with the 2^{++} state on the Pomeron trajectory. The implications of these results for the nature of these mesons and/or diffractive scattering phenomenology are not yet understood. A detailed comparison of their production in Pomeron-Pomeron *versus* $\gamma\gamma$ collisions, especially when done with the same detector and under very similar conditions, offers intriguing prospects.

2.4.6.3. Heavy quark spectroscopy

The C-even states of heavy quarkonium cannot be produced in e^+e^- collisions directly, but only through the subsequent radiative decays of the C-odd vector states. Two photon processes provide the opportunity to produce these states *directly*. In the narrow width approximation, the production cross-section of a resonant state in $\gamma\gamma$ collisions is given by the formula [170]:

$$\sigma_{\gamma\gamma \rightarrow R}(M_{\gamma\gamma}^2) = 8\pi^2(2J+1) \Gamma_{\gamma\gamma} \delta(m_{\gamma\gamma}^2 - M_R^2)/M_R, \quad (2.51)$$

where J is the spin of the state and $\Gamma_{\gamma\gamma}$ is its two-photon width.

For charmonium production, the $\Gamma_{\gamma\gamma}(\eta_c)$ is known from experiment [171]. But the two photon widths of P -wave charmonium states have been measured with only moderate accuracy. Here for the cross-section calculations we use theoretical estimates of

these widths based on perturbative QCD [172]. Similar predictions of two photon widths for bottomonium states can be found elsewhere [173,174].

In Table 2.6 the cross-sections for quarkonium production in the rapidity range $|Y| < 7$ for the two-photon processes, as well as the expected numbers of events, are presented for the 10^6 sec runs with ion luminosities as shown in Table 2.1. As background processes, marked in the Table as $\gamma\gamma \rightarrow X$, we consider minimum-bias two photon processes in the mass range $M \pm \Delta M$, where ΔM is the expected mass resolution for the hadron system produced in $\gamma\gamma$ collisions. In the FELIX forward-backward geometry, $\Delta M \approx 40$ MeV. The minimum-bias cross-section has been calculated according to equations (2.31) and (2.38).

As one sees from Table 2.6, millions of C-even charmonium states will be produced in coherent two photon processes during a standard 10^6 sec heavy ion run at the LHC. The detection efficiency of charmonium events has been estimated as 5% for the forward-backward FELIX geometry. On this basis, we expect detection of about 5×10^3 charmonium events in $PbPb$ and about 10^6 events in $CaCa$ collisions. This is two to three orders of magnitude higher than what is expected during 5 years of LEP 200 operation [154]. The ratio of the minimum-bias background to the charmonium events is of the order of 2-9 if no specific decay modes are taken into account. By selecting distinctive charmonium decays, we expect to reduce the background level by a large factor, as already achieved at LEP experiments [175].

In Fig. 2.34 the expected mass spectrum of charmonium states is shown for a 10^6 sec $CaCa$ run, in the mass range up to 4.5 GeV for the forward/backward geometry of FELIX and with the assumption of charged-kaon identification. The minimum-bias background was generated with the TPHIC generator [176]. For all events the cut $P_t < 30$ MeV/c was applied to select the exclusive final states. The same spectrum without charged kaon identification is shown in Fig.2.35. As one sees from these figures, if no special η_c decay channels are taken into account, the signal to background ratio for the η_c is expected to be at the level of about 1/3. But if no particle identification for charged kaons exists in the forward/backward regions of the FELIX detector, the relative background level is 4 times worse.

The study of C-even bottomonium states in two photon processes in the forward/backward FELIX geometry is rather doubtful due the small detection efficiency (of order of 0.2%) and a high value, ~ 300 ,

Table 2.6. Production cross-sections and event numbers for heavy quarkonia produced in 10^6 sec run in $PbPb$ and $CaCa$ collisions with luminosities 10^{26} and $4 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$.

State	Mass, MeV	$\Gamma_{\gamma\gamma}$ keV	$\sigma(AA \rightarrow AA + X)$		Events for 10^6 sec	
			$PbPb$	$CaCa$	$PbPb$	$CaCa$
η'	958	4.2	22 mb	125 μb	$2.2 \cdot 10^6$	$5.0 \cdot 10^8$
η_c	2981	7.5	590 μb	3.8 μb	$5.9 \cdot 10^4$	$1.5 \cdot 10^7$
χ_{0c}	3415	3.3	160 μb	1.0 μb	$1.6 \cdot 10^4$	$4.0 \cdot 10^6$
χ_{2c}	3556	0.8	160 μb	1.0 μb	$1.6 \cdot 10^4$	$4.0 \cdot 10^6$
$\gamma\gamma \rightarrow X$	2950	—	1.4 mb	9.0 μb	$1.4 \cdot 10^5$	$3.6 \cdot 10^7$
η_b	9366	0.43	370 nb	3.0 nb	37	12000
χ_{0b}	9860	$2.5 \cdot 10^{-2}$	18 nb	0.14 nb	2	560
χ_{2b}	9913	$6.7 \cdot 10^{-3}$	23 nb	0.19 nb	2	760
$\gamma\gamma \rightarrow X$	9400	—	140 μb	1.0 μb	$1.4 \cdot 10^4$	$4.0 \cdot 10^6$

Figure 2.34. Mass spectrum of secondary particles with identification of charged kaons from all decays of η_c , χ_{0c} and χ_{2c} states produced in two photon processes during 10^6 sec runs with $CaCa$, the total transverse momentum of the system, $P_t < 30 \text{ MeV}/c$.

Figure 2.35. The same as in the previous figure but without charged kaon identification.

of the background to bottomonium event ratio already for the η_b (Table 2.6). But if FELIX is upgraded with central detectors which include particle identification for charged kaons, we can expect detection of some several thousands of the η_b decays. Isolation of them from the minimum-bias events via looking for η_b in special decay modes, as already achieved in the case of η_c at LEP [175], may be attained.

2.5. The astroparticle connection

FELIX, a full acceptance LHC detector with the capability of observing events over the full range of pseudorapidity at LHC energies, can contribute significantly to cosmic ray astrophysics and to the resolution of some of its outstanding problems, and it will open previously inaccessible regions of parameter space to quantitative study where cosmic ray experiments have hinted at unusual physics.

- The modeling of particle interactions is an essential, integral part of operating and extracting results from cosmic ray, high energy gamma ray and neutrino detectors. As far as possible, it is highly desirable to replace the conjectured models with experimental data. FELIX is unique in covering the energy and rapidity range explored by high energy cosmic ray detectors and relevant to observations of cosmic ray muons and neutrinos. Its data will remove the ambiguity of results extracted from the data of current and future non-accelerator experiments.
- Unlike conventional central detectors, FELIX can search for a variety of unusual phenomena associated with the production of very forward particles in cosmic ray interactions with collision energy in excess of $\sim 10^3$ TeV (one PeV), i.e. $\sqrt{s}$ larger than 1 TeV. Proton-nucleus and nucleus-nucleus interactions will be studied as well as p-p collisions. Cosmic ray experimentalists have, for many years, reported observations at these energies and at large η which appear inconsistent with known and expected strong-interaction particle physics. A statement heard often at conferences and repeated in the conclusions of papers is that "There is persuasive evidence that there is a fundamental change in the character of strong interactions above 10^{16} eV" (4.3 TeV c.m.) [177]. Certainly, to date, there are no hard accelerator data to contradict that statement! The reason

is simply that high energy particle detectors cover only the central region of pseudorapidity ($\eta - \phi$) phase space and, to date, even this only at lower energies.

2.5.1. Forward physics and energy flow: accelerators and cosmic rays

Cosmic ray observations are dominated by the energy flow in nucleon-nucleon collisions, as energy-sensitive detectors of nuclear and electromagnetic cascades are critical in triggering and analyzing cosmic ray data. The energy flow, in turn, very strongly weights the most forward-produced particles. The number distribution as a function of pseudorapidity η (in effect equivalent to rapidity y), $dN/d\eta$, when weighted by energy ($E dN/d\eta$) is approximately $e^y dN/d\eta$. The LHC c.m. energy of 14 TeV corresponds to a proton of about 100 PeV on a stationary nucleon target, with rapidity ranging up to 19.2 for forward nucleons. The flux of cosmic rays falls very rapidly with energy; the differential flux dN/dE falling approximately as E^{-3} above a PeV. A plot of the integral flux is shown in Fig. 2.36.

Direct observations of interactions of primary cosmic rays via balloon or satellite payloads have been limited to exposures measured in square meter-days, and hence to energies below a PeV. Knowledge of strong interactions from cosmic rays of energies greater than this comes primarily from mountain top observations, under 5 to 7 nuclear interaction mean free paths of atmospheric overburden, and from observations of the electromagnetic cascades (air showers) and muons at about sea level or (for muons) underground.

2.5.2. The origin of cosmic rays

The energy spectrum and composition of cosmic rays can be understood, up to perhaps a PeV, in terms of acceleration by the blasts of supernova shocks exploding into the interstellar medium of our galaxy. Although the slope of the cosmic ray spectrum increases above a PeV, particles with energies in excess of 10^{20} eV have been observed. The break in the spectrum above a PeV is believed to be related to the onset of a different acceleration mechanism. Where and how cosmic rays with energy well in excess of 1 PeV are accelerated is one of the most interesting problems in cosmic ray astrophysics.

The difficulty in formulating convincing models for the acceleration of charged particles with energies well above a PeV has inspired speculations wherein the highest energy cosmic rays are produced

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The difficulty in formulating convincing models for the acceleration of charged particles with energies well above a PeV has inspired speculations wherein the highest energy cosmic rays are produced

Figure 2.36. The integral flux of high energy cosmic rays. Note the change in slope of the spectrum near 10^{15} eV. The equivalent nucleon-nucleon energies of hadron colliders is noted on the abscissa.

in a “top-down” mechanism, e.g. the decay of X-particles[178]. Sources of these particles would be topological defects formed in the early universe at the time of GUT phase transitions. Energy is no longer a problem: the characteristic energy scale associated with such a scenario is the GUT scale (10^{13} TeV).

Topological defects illustrate how cosmic ray experiments may probe aspects of particle physics which cannot be addressed with accelerators. It is therefore reasonable to argue that the question of the origin of the highest energy particles in the universe is of sufficient importance to merit the support of accelerator experiments which are able to resolve ambiguities in the interpretation of the cosmic ray observations. FELIX, more than any other accelerator experiment, has the capability to provide measurements directly relevant to the analysis of cosmic ray experiments.

2.5.3. Understanding cosmic rays: particle physics beyond the reach of accelerators

Above energies of a few hundred TeV, the mix of atomic weights in primary cosmic rays is not known, and almost surely changes with energy. The simulation models used to understand observations deep in the atmosphere generally assume Feynman scaling and nearly constant inelasticity; over a wide range of energies, these assumptions are subject to logarithmic corrections as embodied, for instance, in “QCD-inspired” models[179].

In almost any model of particle interactions, over 90% of the primary cosmic ray energy eventually appears in the electromagnetic component. This electromagnetic part of the cascade can be modeled with considerable confidence and therefore yields a robust lower limit to the particle energies. (The “Long Flying Component” could lead to a significant underestimate of the primary energy, as discussed below.)

It is, of course, necessary to understand the physics of the first interactions, including effects due to nuclear primaries, in order to unambiguously model air showers in their entirety and to separate the effects of primary composition from interaction dynamics. Proponents of new particle thresholds [180] have a collection of unusual phenomena; so-called “anomalies”, to bolster their claims. The critical point is that an LHC detector sensitive to all (including very large) rapidities will provide the critical particle physics information required to more unambiguously extract the cosmic ray composition and energy from air shower experiments.

2.5.4. New particle thresholds and “anomalies”

There is a spectrum of remarkable anomalies reported in the cosmic ray literature. These hint at unusual physics, not anticipated by the Standard Model, and observed at energies and/or regions of η outside the range of existing accelerator observations. These anomalies may be divided into two groups; inclusive phenomena - wherein inclusive distributions of certain cosmic ray data conflict with expectations based on existing accelerator data, and anomalous individual events - smaller numbers of exotic events containing unexpected features.

It must be pointed out that exaggerated claims or experimental mistakes have rarely been the source of cosmic ray anomalies. The possible fates of an anomaly are that: i) it is the first hint of new physics, (like the discovery of charm in cosmic rays) ii) it is eventually understood in terms of known

physics (puzzling observations are scattered over the cosmic ray literature which, after their identification at accelerators, are understood as manifestations of parton jets) or iii) it reflects an insufficient understanding of the measurements which are often very indirect. Because of the characteristic millibarn cross-sections associated with many of these "anomalies", they should be readily observed by FELIX; luminosity and running time will not be limitations.

One should not forget that, in 1971, Niu, et al. reported cosmic ray observations from balloon-borne emulsion chambers of unstable, decaying hadrons which were clearly not hadrons containing the S quark or other known particles [181]. After the discovery of Charm in 1974, Gaisser and Halzen showed clearly that Niu's particles were D mesons (containing the Charm quark) [182]; Niu's masses, lifetimes, and other properties had by then been confirmed from accelerator experiments.

The first set of anomalies are those which appear as inclusive phenomena, and which therefore are apparent in the distributions of all events in certain classes (e.g., above a given energy).

- Anomalous Mean Free Path, the Long Flying Component:

The Russians have operated a lead/ionization chamber calorimeter of 36 square meters area at a mountain station on Tien-Shan at an elevation of 3340 meters. A high-energy hadron entering the calorimeter will interact at some depth; neutral pions produced in this interaction will initiate EM cascades resulting in a prompt build-up of ionization and permitting identification of the initial interaction depth. Secondary hadrons then interact at greater depths, each initiating its own EM and hadronic cascade. The resulting ionization *vs.* depth shows a peak followed by an exponentially falling ionization with depth, where the slope is a function of the interaction mean free path and the inelasticity of the produced secondaries. From calculations and models, this exponential slope should be only a weak function of the energy of the incident hadron.

The observations show that the exponential characterizing the ionization *vs.* depth of the cascade from a cosmic ray hadron becomes flatter (the attenuation length greater) as the incident hadron becomes more energetic, for energies above about 10 TeV [183]. A compilation of results of attenuation length *vs.* incident energy is in Fig. 2.37. The group ar-

Figure 2.37. Compilation of the ionization attenuation length, $L(E)$, data for the Russian lead calorimeter [183]. The Monte Carlo simulation based on established lower-energy models is plotted as open circles.

gues that the explanation for this phenomenon could be the production of charmed hadrons in the forward direction at high energies. At low energy, the charmed particle decay length is short compared to the characteristic cascade development, and there is little effect on cascades. However, for energies well above 10 TeV, the charmed hadron decay length becomes comparable to the depth of a Pb calorimeter, and this would lead to the observed lengthening of the cascade profile and large energy depositions deep in the calorimeter.

They conclude that the data can be explained by forward (high- x) production of charmed hadrons with a probability of 30% per interaction above about 10 TeV. The Russian-Japanese emulsion chamber group working at the Pamirs site has published data from their chambers supporting the Tien-Shan results

Figure 2.38. Emulsion chamber observation of the associated production of heavy quarks. Event (A) appears to show the decay of 5 quarks. One of the quarks, presumably a b , undergoes a b to c cascade decay. Event (B) shows an event wherein four γ conversions point to a decay in flight. Note in both figures a 100:1 (approximately) transverse-longitudinal scale difference. Only tracks relating to the decay processes are shown; other secondaries are not shown in the interest of clarity.

[184]. Yakovlev and White have also interpreted certain observed anomalies in the observations of extensive air showers in support of the 'long-flying component' [180].

- Anomalous Heavy Flavor Production:

There have been numerous other indications that the production of heavy flavors (charm and bottom quark states) are enhanced at high energies in the far forward direction. The strongest evidence for this comes from the JACEE collaboration. In recent publications [185], they report the analysis of a subset of 15 events with incident energies of over a TeV per nucleon wherein the number of secondaries was less than 50 per event (at energies of tens of TeV, a heavy primary cosmic ray may produce hundreds of secondaries in a collision with an emulsion nucleus). Within these 15 events, they observed 64 secondary vertices (kinks, vees, 3-prong vertices, etc.) within their chamber. Two events are especially striking, each showing a kink (decay in flight) of a secondary with 4 gamma vertices pointing back to the kink. As the chambers are only a fraction of a radiation length in depth, the observed gammas are compatible with a total of about 10 gammas produced at each vertex. The observed gammas do not

pair to fit π^0 s. These decays do not match any known charm or bottom hadrons. A diagram of the relevant tracks from one of the events is shown in Fig. 2.38(B). An interesting event with 5 (apparently) heavy quarks produced and containing no γ 's from the decay vertices is also reproduced in Fig. 2.38(A). One must appreciate that these, as well as other observed cosmic ray events, must be produced with cross-sections of millibarns, which makes exotic explanations such as WW production followed by $t\bar{t}$ decay, in the context of the Standard Model, quite irrelevant. However White [180] suggests just this mechanism and events such as this in support of his "color sextet" model.

- Anomalous Attenuation of Secondary Hadrons

The Chacaltaya-Pamir Collaboration has reported hadrons with anomalously short mean free path in their emulsion chambers [186]. The interaction length, ΔT , is defined as the distance between the top of the chamber and the initiation of an electromagnetic cascade deeper than 6 radiation lengths into the chamber, which signals the vertex of a hadronic interaction.

From the study of γ -initiated cascades, the group can determine the distance between the

Figure 2.39. Correlation between air shower size, $N(e)$, and visible energy in emulsion chamber families, ΣE_γ . The left graph is from the Chacaltaya results and the right graph from the Tien-Shan experiment. Filled circles are data and open circles are Monte Carlo simulations.

observed maximum of the electromagnetic cascade and its initiating vertex. The distribution of ΔT is then exponential. However the slope of this exponent is significantly greater than that for single unaccompanied hadrons seen in the same chambers and corresponds to a cross section in lead much larger than known from accelerator experiments. The attenuation length is 170 g/cm^2 , whereas 252 g/cm^2 is expected.

- Energy Fraction of Air Showers in Emulsion Chamber Families:

The Japanese emulsion chamber group working at Mt. Chacaltaya has reported that, for extensive air showers produced by incident cosmic rays of over 10 PeV, the energy visible in families in their emulsion chambers is not proportional to the incident energy as determined by the air shower array. They show that the visible energy in electromagnetic cascades (from incident electrons and γ 's as well as incident hadrons) increases less rapidly than the total number of electrons in the air shower. Their results are summarized in Fig. 2.39, where results from the Russian HADRON experiment at Tien-Shan, which reached the same conclusions, are also presented [187].

- Scaling and Inelasticity

The inelasticity, K , is defined as $K = (1 - E_l/E_o)$, where E_l is the energy of the leading final-state hadron, and E_o is the incident energy. At energies below a TeV (laboratory), $\langle K \rangle \simeq 0.5$, and Feynman scaling of the forward-produced particles holds. At energies at and above a PeV, however, the situation is much less clear. Costa and Halzen[188] have shown that the inclusive distribution of hadrons *vs.* energy observed at mountain elevations can be reproduced with a Monte Carlo simulation using the known primary spectrum, Feynman scaling, inelasticity only slowly increasing (as predicted by QCD), and a reasonable mass spectrum of primaries ($\langle A \rangle = 7.3$) (see Fig. 2.40). Ohsawa and Wlodarczyk[189], on the other hand, argue that the cosmic ray data support a fall in inelasticity with energy (see Fig. 2.41), and that the data from UA-7, as well as cosmic ray data, demonstrate a departure from scaling. The particular inclusive distributions referenced above, in the case of the anomalous fraction of air shower energy in observed emulsion chamber families, also suggest new physics. This discussion ignores the ambiguities associated with nuclear effects. These are usually finessed by using the superposition model for air shower simulations: the interaction of a primary cosmic ray nucleus with A constituent nucleons and energy E , is modeled as A independent nucleons,

Figure 2.40. Integral energy spectra of electromagnetic showers ($\diamond$) detected at Mt. Chacaltaya compared to a calculation assuming Feynman scaling for the productions of neutral pions in the very forward direction [188]. These gamma rays initiate a cascade with the photon energy distribution shown in the figure. Dashed lines: $\langle A \rangle = 1$ (proton) and 56 (iron); solid line: $\langle A \rangle = 7.3 \pm 0.9$, dotted lines: calculated from uncertainties in A and γ .

Figure 2.41. Energy dependence of average inelasticity, $\langle K \rangle$, in hadron-air nucleus collisions. (a) evaluated from hadronic flux measured at different depths in the atmosphere, (b) from $h-^{12}\text{C}$ collisions from analysis of Pamir emulsion chambers, (c) from zenith-angle distribution of hadrons, (d) from fluctuations in the depth of air shower maxima, and (e) and (f) from the joint analysis of the Akeno and Fly's Eye data respectively. The solid line is a calculated 'valon-gluon model' [189].

each with energy E/A . Whereas the model is likely to adequately reproduce average properties of the shower, it almost certainly underestimates fluctuations. The LHC will be able to accelerate nuclei and will provide FELIX with the relevant data on nucleus-nucleus as well as proton-nucleus collisions, to both better interpret the cosmic ray data and study this area of physics which is also of great intrinsic interest.

The phenomena noted below are observed in a fraction of high energy cosmic ray interactions studied and (with the exceptions noted) do not impact inclusive distributions.

- Centauros and Anti-Centauros:

Several events have been reported from the Brazilian-Japanese Collaboration, first about 25 years ago, wherein an interaction in the air 50 to about 500 meters above the detector gave rise to a large number of charged hadrons and zero or very few γ 's (or electrons). The separation between the electromagnetic component (γ 's and electrons) and charged hadrons is quite clean, based on the depth of initiation of the electromagnetic cascade in the lead of the chamber[190]. In one particularly striking Centauro event, 49 hadrons are observed to interact in the detector but only 1 γ or electron. From estimates of the hadrons which penetrated without interaction and interactions in the air above the chamber, the authors estimate that 74 hadrons were produced and (probably) no neutral pions. By particle physics standards these events are not rare; an estimate of the probability of producing a Centauro in an interaction of one PeV or above is about 1%.

The Japanese - American Cooperative Emulsion - chamber Experiment, JACEE, has flown emulsion chambers with balloons near the top of the atmosphere. At least two events have been observed which have been referred to as "Anti-Centauros". Here a region of η - ϕ phase space is seen containing an anomalous number of γ -induced showers and a dearth of charged particles. In one such event, 32 γ cascades are observed within a circle of radius 0.7 in η - ϕ space with only 1 charged track. Another event (reported in 1993), has 27 γ 's with $\eta > 6$ (and these from conversions in only 0.8 radiation lengths), while only 6 charged tracks fall in the same kinematic range [191].

These Centauro and Anti-Centauro events have been interpreted as manifestations of

Disoriented Chiral Condensates[192]. Another interpretation of the Chacaltaya Centauro events suggests that they are due to fragments of heavy primary cosmic rays. However the survival probability of heavy primary nuclei to this depth in the atmosphere appears much too low to account for the number of Centauros reported.

Another suggested source of these phenomena are "Strangelets" (hadronic matter containing comparable fractions of up, down, and strange quarks). Were they a component of primary cosmic rays, they could penetrate deeply into the atmosphere and decay, evaporating into nucleons [193].

- Chirons, Halo Events, and Mini-Clusters:

For some years the Brazilian-Japanese collaboration, working with emulsion chambers on Mt. Chacaltaya, have reported a class of events they refer to as "Chirons" [194]. The two best examples are events where the event vertex is found by triangulation to be in the air within 500 meters above the chambers. These events are characterized by clean hadronic cascades (not clustered among E-M cascades from atmospheric showering of γ 's in the intervening atmosphere) with average transverse momenta of 2 to 3 GeV/c. This is interesting in itself. Even more unusual is the fact that about half of these hadronic cascades are seen, on close inspection, to contain two or more internal cascades, clearly identified as initiated by hadrons. The relative transverse momenta within each minicluster are anomalously small: 20 or 30 MeV/c. They are also said to have an anomalously high hadron/ γ ratio.

Events are also often observed which are characterized by a dense blackening of the emulsion over a small area (due to an electromagnetic cascade which had begun development in the air above the chamber) containing within it several hadronic cores, again spaced very closely together. These authors suggest again that the relative transverse momenta of the hadrons within these miniclusters are in the 20-30 MeV/c range, as in the Chirons. These are called "Halo" events [195].

The cosmic ray community has been very intrigued with the observation that in many of these multi-halo events, the halos are aligned. Halos are electromagnetic showers produced by the most energetic π^0 in jets. Parton-parton scattering naturally leads to the align-

ment of the final state nucleon fragment with two or more parton jets [196]. However the Russian Group reports that the observed alignment is significantly greater than can be accommodated by the QCD theory. It is intriguing that the data discussed here pertain to the highest energy parton jets ever observed.

- Muon Bundles

Events have been reported wherein bundles of muons are observed with very small lateral separation, as if produced in a process with very small relative transverse momenta (as in the Chiron miniclusters). In one event, 5 parallel muons are observed within a radius of 10 cm. If produced at an elevation of 10 km above the detector, they have an angular spread of only 10 μ -radians [197].

This list of anomalies is incomplete. The anomalies are all associated with very high energy data and, even where they overlap with existing collider energies, they represent very far forward phenomena which have not been studied by existing detectors. Because the target (or possibly both beam and target) is a nucleus, there is also the possibility that cosmic ray anomalies are associated with nuclear effects. The FELIX detector is the only instrument that can thoroughly explore these claims.

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3 Magnetic Architecture

Figure 3.1. The top view of the FELIX detector, showing the different magnets, calorimeters and tracking stations.

3.1. Design considerations

The aim of the FELIX detector is to detect and momentum analyze every charged particle produced in LHC pp collisions. As such, several different magnetic spectrometers are combined in such a way as to cover the complete solid angle and momentum range accessible at LHC energies. Owing to the desire to measure diffractively scattered protons and other high momentum particles produced at small scattering angles, and the presence of the noninteracting proton beams, the FELIX magnets will serve in two capacities: as machine magnets and as the experimental spectrometer analysis magnets. Hence, it is important that the magnets be fully integrated into the design of the machine lattice. Much work has gone in to ensuring this, thanks to the considerable efforts and the enthusiastic cooperation of the LHC machine group. Furthermore, care has been taken to make sure that each of the planned components fit into the present I4 interaction hall without major civil construction.

The layout (top view) of the FELIX detector is

shown in Fig. 3.1 which shows one half of the completely symmetric arrangement. The interaction point (IP) is surrounded by the central ALEPH solenoidal magnet, complemented on both sides by dipole magnets with horizontal (UA1 and D0) and vertical (D1 and D2) fields (of opposite directions in the otherwise identical arms). The ALEPH and UA1 magnets serve complementary functions in terms of the acceptance for detecting charged particles. Clearly, there is a large saving of money as well as time and personnel effort from designing the detector around these existing components which, in addition, are ideally suited for their proposed function. We do not expect any big interference in the simultaneous operation of the ALEPH and UA1 magnets.

As indicated above, many of the magnetic elements must perform dual roles in FELIX. UA1 and D0, conventional dipole magnets, with their horizontal fields also provide the vertical crossing-angle of ± 0.5 mrad at the IP. The two sets of dipoles D1 (each split into five magnets to provide good acceptance for forward-going particles) and D2 (each consisting of three magnets) have vertical fields and serve, on the one hand, to provide the bending power needed to separate the noninteracting proton beams to $\pm$

Figure 3.2. A cutaway drawing of the ALEPH magnet (on the left) and one-quarter of the UA1 magnet next to it (on the right). A similar section of the UA1 magnet will be placed on the left side of the ALEPH magnet.

21 cm, horizontally, at the exit of the D2 magnets, a distance of 118 m from the IP (see the trajectories shown in Fig. 3.1). The D1 magnets provide a p_T -kick to the beams of the order of 20 GeV, corresponding to an integrated field strength of $\int B \cdot dl \sim 67$ T-m. On the other hand, the D1 magnets must also serve as the basis for the magnetic analysis of all charged particles produced with longitudinal momentum fraction, $x_L > 0.06$. The D1 and D2 dipoles will also serve as a leading proton spectrometer for the larger $|t|$ diffractive scattering, $|t| \sim 0.1$ GeV² and $\xi = \frac{\Delta p}{p} \approx 1\% - 10\%$.

3.2. The ALEPH solenoid magnet

The ALEPH magnet [1] provides a uniform solenoidal field of 1.5 T parallel to the beam direction. It consists of a superconducting solenoid and a 2580 tons iron yoke, which serves a dual function as a return for the magnetic flux and as a possible hadron calorimeter which could be instrumented later. The iron yoke consists of a dodecagonal central "barrel" part of ~ 9.4 m diameter and 7.24

m length and two end-caps, each of 1.684 m axial length and 8.7 m outer diameter. The presently existing cylindrical end-cap hole of 0.9 m diameter will have to be increased and made into a conical shape, to match the UA1 aperture, to allow an acceptance angle of $\pm 9^\circ$ from the IP. The superconducting solenoid is in a cryostat 7 m long and 5.84 m in diameter and, at a current of 5000 A, provides a nominal field (with the yoke) of 1.5 T. Fig. 3.2 shows a cutaway drawing of the ALEPH magnet.

3.3. The UA1 dipole magnet

(In collaboration with W. Flegel PPE/EC)

The central ALEPH magnet is complemented on both sides by a dipole magnet with a horizontal field of $B = 0.7$ T orthogonal to the beam. We propose to re-use the flux return yoke of the UA1 magnet for these two magnets, see Fig. 3.2. The magnets will be arranged as the existing UA1 magnet, but each with half of the available number of yokes. To adapt to the required length of the new magnet, two short flux return yokes have to be added. This requires completely new windings which, in addition,

have to provide a large opening of 1.8 m diameter around the beam axis at the end closest to the interaction point (see Fig. 3.3). At the opposite end, the beam pipe is of ~ 20 cm diameter, it fits between the two halves (see Fig. 3.3) and needs no special shaping of the winding. A support and moving system similar to the one for the UA1 magnet has to be constructed for each magnet.

Figure 3.3. A view of one-half of the UA1 magnet, which will be located next to the central ALEPH magnet.

3.3.1. Mechanical arrangement of the magnet system

The new magnets will consist of two halves which are mirror symmetric about a vertical plane containing the beam axis, as is the case for the UA1 magnet. Each half consists of 4 rectangular, C-shaped flux return yokes of UA1 plus an additional one to adapt to the length of the new magnets. The opening of the C-shaped yoke is facing the beam. Each yoke is constructed of 16 low-carbon steel plates of 50 mm thickness and separated by 17 mm gaps. For UA1 they were instrumented with scintillators for hadron calorimetry, but they will not be so equipped for FELIX. Each magnet will be placed onto a support system which permits one to horizontally separate the two magnet halves orthogonal to the beam, in order to gain access to the magnet volume for detector installation without dismantling the beam pipe. In addition, in its open position it has to allow for the axial displacement of the ALEPH end caps.

3.3.2. Winding and coil partition

The new coils were calculated and designed to obtain the required acceptance angle and the necessary bending field. In order to avoid a strong saturation of the iron in the return yoke, a field value of $B = 0.7$ T is envisaged. For reasons of cost, aluminium is proposed as the conductor material with an acceptable current density of $s = 3.2$ A/mm². Finally, the pressure drop of the cooling water in the underground hall of ALEPH has to be kept well below 10 bar. These considerations then lead to a similar conductor cross-section as in UA1. Each magnet half will contain two coils with the same number of turns. The coils near the beam axis on the side facing the interaction point provide a large opening of 1.8 m diameter for particle acceptance. Fig. 3.2 shows in a perspective view the C-shaped return yokes of one-half of a magnet half and its pair of coils in its position next to the ALEPH magnet. Each coil is built of 7 pancakes, each with two layers of 5 turns. A list of the parameters of the proposed magnet layout is given in Table 3.1.

3.3.3. Coil optimization

One way to reduce the cost of the magnet is to re-use the existing material and equipment from the UA1 magnet. Additional iron is, however, needed to adapt to the required length of the new magnets. Because of their complex shape, the coils will be a major cost item. A first optimization of the costs for coil manufacture versus operation cost has been performed. The resulting current density determined the choice of the conductor cross section. The following costs were assumed for this calculation:

- coil material and manufacture: 30 CHF/kg
- electricity: 40 CHF/MWh
- magnet operation: 100 days p.a. for 5 years.

In addition, the actual cross section chosen takes into account the space constraints given by the iron yoke and the required magnet aperture. Further optimization of the design will follow through consultation with industry.

3.3.4. Field calculations with TOSCA

The combined field of the ALEPH solenoid and the UA1 dipole magnet at nominal current has been calculated with the TOSCA [2] programme. For these calculations, the main field component of the dipole magnet is in the x -direction, that is in the

Table 3.1. Parameters of the proposed UA1 magnet.

Overall external magnet dimensions without support (length $\times$ width $\times$ height):	$4.4 \times 5.8 \times 6.2 \text{ m}^3$
weight of magnetic iron:	490 tons
weight of winding:	28 tons
upstream / downstream aperture:	$1.8 / 0.2 \text{ m } \varnothing$
conductor material:	aluminium
conductor dimensions	$55 \times 48 \text{ mm}^2$
diameter cooling hole:	21 mm
total current	
in Ampere-turns (4 coils):	$NI = 2\,000 \text{ kA}$
number of turns in each coil:	$N = 70$
number of pancakes per coil:	$n = 7$
number of turns per pancake:	2×5
current density in aluminium:	$s = 3.2 \text{ A/mm}^2$
nominal current:	7.2 kA
approx. upstream / downstream field at axis:	$B = 0.7 \text{ T}$
field integral along axis:	$F = 2.5 \text{ Tm}$
direction of magnetic field:	horizontal
magnetized volume (length $\times$ width $\times$ height):	$3.22 \times 3.60 \times 3.41 \text{ m}^3$
total dissipated power:	$P = 3.1 \text{ MW}$
total resistance:	$R = 60 \text{ m } \Omega$
inductance of the magnet:	$L = 160 \text{ mH}$
total stored magnetic energy:	$W = 8.0 \text{ MJ}$
flux of cooling water ($\Delta T = 30^\circ \text{C}$):	$1.45 \text{ m}^3/\text{min}$
expected pressure drop:	5 bar

horizontal direction orthogonal to the beam axis. The main field component of the ALEPH solenoid is in the z -direction, that is the beam axis. Fig. 3.4 shows the horizontal component of the field. In the dipole region, the asymmetry in the field is due to the coil asymmetry between upstream and downstream currents. The interference between the ALEPH solenoid and the UA1 dipole has also been checked. Figs. 3.4 and 3.5 show the x and z field components, respectively, resulting from both magnets. In the region of "ALEPH cap & UA1 coils" the main fringe field effect in the z -component is from the dipole, while in the horizontal direction, the biggest effect is due to the radial component of the field in the solenoid. In this simulation, the shims and grooves, currently made in the ALEPH end-cap in order to reduce the field inhomogeneity, have not been taken into account [1].

3.4. The D0 dipole magnet

(In collaboration with E.V. Arkipov, V.I. Datskov, Y.A. Shishov, A.S. Vodopianov, and G.P. Tsineva, JINR, Dubna.)

The D0 magnet system will consist of two conventional dipole magnets. The main parameters and dimensions of each dipole are presented in Fig. 3.6 and in Table 3.2.

The aperture of the magnet will be $0.5 \times 2.0 \text{ m}^2$ and each magnet will have a weight of about 220 tons.

The iron yoke has a rectangular shape with poles. It can be constructed either from iron slabs or from plates. Coils are placed vertically on both the left and right sides of the iron yoke. The yoke is split into two parts, which are symmetric about the vertical plane and which can be moved apart horizontally. The conductor is composed of 99.5% aluminium and has a rectangular shape with a water channel inside to provide cooling. The conductor is isolated with

Figure 3.4. B_x component for the total field: the dotted curves correspond to different emittance angles from the interaction point in the horizontal plane; the solid curve is the field along the z -axis.

Figure 3.5. B_z component for the total field: the dotted curves correspond to different emittance angles from the interaction point in the horizontal plane ; the solid curve is the field along the z -axis.

Figure 3.6. The D0 magnet.

Table 3.2. Main parameters of the D0 magnet.

Items	Unit	Value
Aperture	m	0.5×2.0
Total length of magnet	m	5.0
Cross section of winding	m	0.35×0.65
Pole gap	m	0.5
Central field ($x=y=z=0$)	T	1.5
Operating current	kA	1.84
Overall current density	A/mm ²	1.55
Total Amp × turns	MA	0.7
Stored energy	MJ	3.0
Consumed energy	MW	0.46
Al conductor mass	t	10.4
Yoke mass	t	205
Total magnet mass	t	220
Features	flat rectangular winding	
Cooling method	water	
Cooling water supply	ℓ/s	3.7
Water heating	°C	30
Al (99.5%) conductor cross section	mm ²	32×32
Central channel dia.	mm	10
Total length of conductor	km	4.08
Insulation : 4 layers of kapton film 0.075 mm and 4 layers of glass tape of 0.25 mm impregnated with epoxy resin

Figure 3.7. Field map of the D0 magnet (a quarter).

Figure 3.8. DX magnet and cryostat as designed for RHIC.

a kapton foil and a fiberglass tape and impregnated with an epoxy resin.

Two-dimensional magnetic field calculations have been performed at Dubna (Fig. 3.7). These field calculations, for different geometries of the magnetic aperture and poles, have shown that the optimal value of the power consumption could be reached with the aperture of $0.5 \times 2.0 \text{ m}^2$ and a current density of 1.55 A/mm^2 . The power consumption is then expected to be about 0.5 MW.

3.5. RHIC DX magnets as D1 dipoles

(We would like to acknowledge the assistance of M. Anerella, D. Fisher, R. Grandinetti, M. Harrison, H. Hseuh, G. Morgan, J. Sondericker, and D. Weiss, of Brookhaven National Laboratory in preparing this section.)

3.5.1. Design requirements of D1 dipoles

As discussed earlier, the D1 dipoles must play a dual role in FELIX. On the one hand, they must serve as machine dipoles. On the other hand, the D1 magnets must also serve as a magnetic spectrometer. In order to have full acceptance, it is thus important that the aperture of the D1 dipoles be as large as possible. Fortunately, magnets which appear to be suitable for this purpose have been designed for the Relativistic Heavy Ion Collider

(RHIC) at Brookhaven National Laboratory. In order to bring the beams into collision, RHIC needs 12 large-aperture superconducting dipoles. These so-called DX dipoles have a magnetic length of 3.7 m, a nominal field of 4.28 T, and a coil inside-diameter of 18 cm. This magnet, including the RHIC cryostat, is shown in Fig. 3.8.

The field strength and bore size of the RHIC DX magnet will result in larger mechanical forces than in any accelerator magnet yet built. While the magnet has not yet been demonstrated at the time of writing, a prototype will be tested in the fall of 1997. Since RHIC is committed to building the 12 DX magnets for RHIC, they will be able to provide FELIX with what will by then be well-understood magnets. We propose to use magnets of the RHIC DX design for the FELIX D1 magnets. More specifically, we propose to use 10 DX cold masses. We have investigated the possibility of changing some of the DX design parameters. Any change in the diameter or length of the cold mass would significantly increase the cost of these magnets. However, in developing the design for the FELIX magnetic architecture we have assumed that we will operate the magnets at a somewhat lower field strength (3.625 T) than will be used at RHIC. Furthermore, we envisage building a cryostat optimized for the FELIX applications. In particular, in FELIX design studies we have assumed that the physical length of the magnet plus cryostat is 5.5 m, and that the aperture is 16 cm. These issues are discussed below.

Table 3.3. RHIC DX magnet field harmonics.

I,kA	B_0 ,T	B_{pk} ,T	b_2	b_4	b_6	b_8	b_{10}	b_{12}
2.0	1.3435	1.6163	0.00	0.12	-0.20	-0.03	0.05	-0.04
3.0	2.0148	2.4242	-0.35	0.09	-0.18	-0.03	0.05	-0.04
4.0	2.6805	3.2271	-1.17	0.20	-0.11	-0.05	0.05	-0.04
5.0	3.3295	4.0132	0.00	0.11	0.08	-0.07	0.06	-0.04
6.0	3.9467	4.7667	0.00	0.16	0.14	-0.08	0.05	-0.04
7.0	4.5111	5.4699	-1.36	0.41	-0.09	-0.07	0.05	-0.05
8.0	5.0318	6.1331	-8.38	0.25	-0.22	-0.05	0.04	-0.04
9.0	5.5338	6.7776	-13.7	0.25	-0.30	-0.03	0.04	-0.05

3.5.2. Physical characteristics

The RHIC DX magnetic length is 3.7 m. The cold mass length is 4.15 m. End boxes increase this to 5.06 m. The cryostat as designed for RHIC is approximately 5.64 m in length. The DX magnet has a coil diameter of 18 cm. As used at RHIC, the DX magnet has a cold bore tube with inside diameter of 16.28 cm and a warm bore with inside diameter of 14.3 cm. The difference in these two diameters includes space for heaters and insulation sufficient for a 250° C bakeout, as well as the beam-tube (1.6 mm thick walls). It is important to note that the first DX magnet is not scheduled for testing until October, 1997. Many important parameters such as heat load, operating margin and field margin will not be known until several magnets have been tested. These are necessary inputs before we know what the limits of the design for FELIX will be.

There may be some limited possibility for decreasing the length of the magnet plus cryostat assembly. It is important to note that the design for RHIC is optimized for their configuration (in which there is a 12.7 cm beam-pipe entering on one end and a 30.48 cm diameter beam-pipe on the other end). These issues, including the detailed design of the cryogenics, require further study.

The question of the maximum attainable radius is also rather complicated. Increasing the coil diameter would be extremely expensive. Important considerations include baking scenarios, vacuum quality and heat load on the magnet. Final numbers will require further study.

3.5.3. Field quality

Since the D1 magnets are machine magnets, with significant $\int B \cdot dl$ and with beam separation ± 4.7 cm at the end of the D1 string, a critical issue is the uniformity of the magnetic field. Field quality for a dipole is usually defined in terms of field harmonics,

b_n , as measured at a reference radius equal to 2/3 of the coil inside diameter (6 cm for the DX magnets), expressed in terms of 10^{-4} of the central field.

For the RHIC DX magnets, the central field B_0 , the peak field B_{pk} (which occurs at the second block from the pole) and the harmonics b_n have been calculated as a function of the current at a radius of 6 cm [3]. The results are tabulated in Table 3.3. Note that these are straight section harmonics not including harmonics due to superconductor magnetization and not including end harmonics. The harmonics b_2 , b_4 and b_6 are plotted as a function of field in Fig. 3.9 [3].

Figure 3.9. DX magnet field harmonics (in units of 10^{-4} of central field).

3.5.4. Manufacturing considerations

Any changes in either the bore or the length of the cold mass would entail significant additional costs arising from tooling modifications. BNL has significant reservations about any proposal to increase the bore of the magnet, and does not believe that it would be cost effective for them to do so. FELIX thus proposes to use the BNL design for the RHIC DX cold masses unchanged.

While the lead time for the cold masses may be as much as two years from “agreement to build” to “shipment” [4], the Brookhaven Superconducting Magnet Facility foresees no problems with producing the magnets FELIX needs on the relevant time scale. Brookhaven also welcomes this opportunity to further support the LHC accelerator and experimental programs [5].

3.6. UNK magnets as D2 magnets

(In collaboration with N.I. Andreev, P.N. Chirkov, V.A. Sychev, V.V. Sytnik, L.M. Tkachenkov, S.V. Trofimov, Institute for HEP, Protvino, Moscow Region, Russian Federation)

The D2 dipoles of the FELIX experiment are double aperture magnets which are assembled in two short sections, with three magnets per section. They will be placed between 100 and 120 m from the IP, close to the quadrupoles Q2. These magnets must work together with the main machine magnets of the LHC during proton beam acceleration. The magnet can be easily placed inside the LHC tunnel since the external radius of the vacuum vessel of D2 is only 10 cm larger than the LHC dipole cryostat.

3.6.1. Conceptual design of D2 dipole short-section for FELIX

The proposed design of the D2 dipole for FELIX is based on the UNK Superconducting (SC) dipole which is a single aperture magnet. The D2 FELIX dipole is a double aperture magnet and could be assembled from the cold masses of the existing UNK SC dipole, shown in Fig. 3.10. Each cold mass has an individual helium vessel and is connected to the other one by outside supporting structures. Vertical and horizontal titanium suspensions will go through these supporting structures and would keep the cold masses inside a common vacuum vessel. A common thermal shield with a superinsulation surrounds the cold masses and is cooled by a 50-70 K helium flow.

The cold masses with the SC coil are cooled by a 4.4-4.6 K single-phase helium flow. Helium lines with these parameters will exist in the LHC cryogenic system and could be used for cooling the FELIX D2 short sections. The main parameters of the D2 dipole based on the UNK magnets are given in Table 3.4. A detailed description of the UNK dipole and results from their tests can be found in Ref. [6]. The main features of this design are a two-layer coil which is preloaded by a stainless-steel collar and a cold-iron yoke. The iron yoke has a vertical split and is assembled around the collared coil. The position of the collared coil inside the yoke is fixed by two vertical and two horizontal lugs.

3.6.2. Performance of the UNK magnets

In 1991-2, a pre-production batch of 25 SC dipoles for the UNK accelerator was produced and successfully tested. The results of the study of this pre-production batch of the SC dipoles showed that all major parameters of the UNK magnets ensured operation of the dipoles in both normal and emergency modes in a manner which satisfied the UNK requirements [7]. Table 3.5 presents the measured mean values and rms spread of the normal and “skew” integral field nonlinearities for these 25 SC dipoles at 4 kA on the reference radius 35 mm. The mean values of the nonlinearities are not large and are within the tolerances, except for a skew gradient, S_2 . Its systematic value is 1.6 times larger than the tolerance. However, a selection from among the existing dipoles can be made in order to minimize S_n for the FELIX 3-magnet section.

The rms spread of the majority of the nonlinearities is within tolerances.

Fig. 3.11 presents a schematic view of the D2 dipole short-section which is comprised of three magnets, a feed box and a return box. The length of this short section is about 21 m. The feed box should contain current leads and all connections of the helium pipe lines, as well as a cold-warm transition for the bore tubes of the D2 dipole. The return box will contain interconnections between the single UNK dipoles: both for the SC cables as well as for the helium pipes. A safety current lead or a quench stopper could also be placed in this box if it is necessary for the quench protection system. A cold-warm transition for the bore tubes of the D2 dipole will be made in this box as well. The interconnections between the magnets will have safety releasing valves which will open during a quench and keep the pressure inside the helium vessel of the magnets at less than 20 bar. The cooling scheme of the D2 dipoles

Figure 3.10. The D2 magnet, consisting of two UNK-magnets in a common cryostat.

Figure 3.11. The D2 dipole short-section with three magnets in a common cryostat.

Table 3.4. Main parameters of the D2 dipole magnet.

Operational field:	4-5 T
Magnetic length	5664 m
Nominal field integral at 5 T	29 T-m
Operating current	4100-5140 A
Critical current	6500 A
Operating Temperature	4.4-4.6 K
Temperature margin	2.5-1.4 K
Inner coil diameter	80 mm
Cold bore diameter	68 mm
Minimal distance between dipole axis	380 mm
Distance between magnets axis is changed according to the beam trajectory	
Length	6.42 m
Magnet weight	12000 kg

Table 3.5. Mean values (C_n, S_n) and rms spread ($\langle C_n \rangle, \langle S_n \rangle$) for the UNK magnets at 4 kA. All values are expressed in terms of 10^{-4} of the central field.

n	2	3	4	5	6	7	8	9	10
C_n	-0.1	-0.7	0.0	0.8	0.1	-0.5	-0.1	-0.5	-0.1
$\langle C_n \rangle$	0.6	2.9	0.5	2.4	0.2	1.3	0.3	1.2	0.7
S_n	1.6	-0.2	0.6	-0.1	0.3	-0.2	0.3	0.0	0.1
$\langle S_n \rangle$	3.7	0.4	2.8	0.4	1.1	0.4	0.9	0.4	1.3

Table 3.6. Preliminary heat load budget.

Temperature level	@T=50-70 K	@T=4.5 K
Suspensions,safety valves and cryostat superinsulation	180 W	30 W
Interconnections and boxes	60 W	10W
Current leads		10W + 15 l/hr
Total	240 W	50 W +15 l/hr

short-section will be determined by:

- the heat load;
- the necessary flow rate and thermodynamic conditions of the helium flow; and
- the cryogenic resources in this region that are available from the LHC main cryogenic system.

The preliminary heat load budget from the construction elements of the D2 short section for FELIX is given in Table 3.6.

An additional heat load will arise from particle irradiation, synchrotron radiation, and RF losses due to image currents. These losses should be determined during further analysis. A large heat load of

up to 240 W (nominal) at the 4.7 K level will be deposited in the cold mass of the SC magnets located close to the high-luminosity experimental areas (in the beam separation and recombination dipoles).

Originally the helium channels of the UNK dipole were sized for 60-100 g/s of helium flow rate to cool a string of about 100 magnets connected in series. It would be preferable to keep these single phase flow parameters (60 g/s, 4.5 K, 3 bar). In this case, the so-called "fish-bone" channels are effective enough because the helium fluid will circulate between the coil layers and the large helium flow rate will keep a stable temperature level (4.5 K) in the magnet.

The LHC superfluid helium cooling scheme could also be used in the event that the particle irradiation losses are very high (6000 W in ultimate condi-

tions) [8]. An increase of the temperature margin up to $\Delta T = 4-5$ K should give stable operating conditions for the SC magnets under this radiation. Further analysis will give more realistic heat loads and define the interface with the LHC cryogenic system.

A string test facility of 4 UNK SC dipoles has been assembled and investigated during a program of the UNK magnet structure development [9]. The feed box and return box for the single aperture dipole were tested. Parameters of the quench protection system elements – a quench stopper, safety leads, by-pass switches, safety valves – were checked. The first string test demonstrated good operation performances of the UNK SC dipoles as well as all other elements of the string. The design of these elements could be used as a prototype for elements of the FELIX D2 short-section. The operating status of the string test facility was monitored by the quench monitor system which was developed and tested during this program as a prototype of the UNK quench protection system. This quench monitor system could also be used for the FELIX D2 magnet system.

3.6.3. Preliminary cost estimates

UA1 cost estimate

Estimation of the total costs for one dipole magnet:

- iron for the additional yokes at end of the magnet (2×33 tons @ 3 CHF/kg): 200 kCHF
- two pairs of Al coils (28 tons @ 30 CHF/kg): 850 kCHF
- magnet support and movement system (mechanics, rollers, hydraulic jacks, advancement system, motors, control): 350 kCHF
- **total costs for one magnet: 1400 kCHF**

D0 cost estimates

Estimation cost for one D0 magnet is 800kCHF; the cost of two magnets is 1400kCHF.

D1 cost estimates

Brookhaven National Laboratory has provided estimates [4,10] for the cost of constructing 10 DX cold masses.⁶

⁶This includes collared coil assemblies installed into yokes and helium support shells, with end plates, electrical connections and flex joints, inside end volumes which complete the pressure vessel, but not including support posts, or the heat shield of vacuum vessel.

All costs are in constant FY98 US dollars. A 15% contingency is added for unknowns such as future overhead rate and work scope changes. If there are no changes in the length or bore of the RHIC DX magnet design, the costs are:

Labor:	\$ 400K
Material:	\$ 2,780K
Overhead:	\$ 1,110K
Contingency:	\$ 640K
Total:	\$ 4,930K

Brookhaven National Laboratory has also prepared an estimate [11] for the cost of supplying 10 DX cryostats. This estimate is provisional and final numbers will depend upon the details of the LHC cryogenic, electrical and tunnel utility system not known to Brookhaven. The estimate is:

Estimated design time for changes to adapt RHIC to LHC	\$ 200K
For the fabrication 10 Assemblies - Material and Manufacturing	\$ 1,100K
Cold Mass/Cryostat Assembly	\$ 800K
Total	\$ 2,100K

3.6.3.1. D2 cost estimates

A preliminary estimate of the cost of the short-section elements is presented in Table 3.7. It is relatively cheap because the UNK dipoles already exist and all of the other elements already have working prototypes.

Table 3.7. Preliminary cost estimate (in k\$).

Cold mass of the existing UNK dipole:	100
Cryostat with final assembling of the D2 magnet:	70
Assembled D2 magnet (2x100+70):	270
Feed and return boxes:	80
Magnet interconnections (including safety valves):	60
Quench protection system (hardware and software):	80
Total for FELIX D2 short section, 3 magnets (3x270+80+60+80):	1030

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4 Beam Line and Run Conditions

4.1. A tunable insertion for IP4

(In collaboration with A. Verdier/SL)

Intersection point IP4 will house the radio frequency (RF) and feedback systems for the LHC. It is also an ideal place for FELIX which will run at reduced luminosities and hence can accept larger β^* values at the IP. As a consequence, the beam focusing quadrupoles are placed behind the beam separating dipoles as already foreseen in the layout topology of the LHC design report [1]. This arrangement has two major advantages for the FELIX experiment: it leaves the necessary longitudinal space to accommodate the forward arms which extend up to 120 m into the machine tunnel, and the larger beam separation of 42 cm, needed for the RF, gives sufficient transverse space to place the zero degree calorimeter between the beams.

A preliminary optics involving only minimal changes to [1], and using the existing quadrupoles, has been proposed for FELIX by A. Verdier [2]. In order to make the beams collide and to leave sufficient space for detectors close to the interaction point, a long dipole system has to be used due to the larger beam separation of 42 cm needed for the RF. The central orbit of the left half part of the insertion

in the horizontal plane is sketched in Fig. 4.1.

The dipole system D2, consisting of 3 magnets originally foreseen for the UNK collider in Russia (see Section 3.6, page 93), bends the beams towards the IP. The dipole system D1, made out of 5 RHIC dipoles (see Section 3.5, page 91), causes the beams to interact with zero degree horizontal crossing angle in a kissing scheme. This is imposed by the fact that the two rings do not cross in this insertion. In order to avoid parasitic beam-beam interactions and long range tune shift effects, particularly at large β^* values, a vertical crossing angle of ± 0.5 mrad is foreseen. It is accomplished by the two spectrometer magnets, UA1 and D0, with their horizontal dipole fields. Since these two magnets are close to the intersection region, the vertical closed orbit distortion is limited to ± 7 mm. Further upstream the beams are bent back into the horizontal plane by means of a localized vertical closed orbit correction. This scheme, which uses the FELIX spectrometer magnets for the beam optics and vice versa, leaves sufficient space in the two forward arms to place the charged particle detectors and calorimeters. There is limited space left for the quadrupole doublet sitting between D2 and the RF system. Nevertheless, an economical optics can be made by using this

Figure 4.1. Central orbit (horizontal plane) in the left half part of the insertion, from QT8 on the left to IP4 on the right, to make collisions in IP4. The full boxes are dipoles, the half boxes are quadrupoles. The feedback system lies around the RF cavities.

doublet instead of a triplet for the final focus. The maximum values of the β -functions inside a doublet are larger than inside a triplet. However, due to the constraints associated with the RF system, these maximum values are limited anyway so that a doublet is quite satisfactory. It has the advantage of being cheaper than a triplet and it can be made with standard arc quadrupoles, provided the distance between the two elements of the doublet is large enough.

The optics proposed in [2] has the virtue that β^* values between 23 m and 900 m can be achieved by changing the magnet settings, but without the need for any changes in the positions of the optical elements. This has two advantages for FELIX. Firstly, since the luminosity at FELIX scales with the inverse of the β^* value, it means that we can easily tune our luminosity over a wide range of values. Secondly, the proposed optics provides the freedom to optimize the beam line for different kinds of physics.

A special consideration is the measurement of elastically scattered protons with scattering angles between $10 \mu\text{rad}$ and 1 mrad and of diffractive protons with relative momentum losses between 10^{-3} and 10^{-1} . To accomplish this requires careful matching of the experiment to the LHC machine lattice. Measurements of other particles can be accomplished with detectors within $\pm 100 \text{ m}$ of the IP, and are described elsewhere in this Letter.

In order to obtain a uniform acceptance for the above protons, detectors should ideally be placed in as many locations in the forward arms as possible. However, the only locations for particle detectors available without serious disturbances to the LHC design are up to 120 m upstream from the IP and at Q11 (about 420 m upstream) where a free space of about 10 m exists. Detectors must be placed out of the beam halo, i.e. at a transverse distance larger than 10σ from the beam center. Hence the beam profile should be minimized and the particle displacement maximized for the possible detector positions. Optimizing the acceptances for forward protons in the above range of scattering angles and momentum losses implies different β^* values at the IR.

4.1.1. Optics for small angle elastic scattering ($\beta^* = 900 \text{ m}$)

A measurement of the elastic proton scattering at the lowest scattering angles requires the largest possible β^* value at the IP (in our case 900 m , imposed by the RF) while optimizing the phase advance at the detector location. (This is discussed in more detail in Section 11.4) The goal is the de-

tection of protons scattered with angles down to $10 \mu\text{rad}$, corresponding to a momentum transfer squared $|t| = 0.5 \times 10^{-2} \text{ GeV}^2$. The measurement is best done in the vertical plane where the dispersion of the machine is not important. Hence the optics is designed to maximize the vertical amplitude at Q11 of a trajectory starting at the IP with an angle and no displacement. The vertical phase between the IP and Q11 should be close to $3/2 \pi$ for the ideal situation which is parallel to point focusing. With the present dispersion suppressor it is possible to obtain a phase of 1.42π which is satisfactory. This optics can be made with standard quadrupoles in the quadruplet and a maximum normalized gradient of 0.0051 m^{-2} in the trim quadrupoles of the dispersion suppressor. The associated β -functions (vertical and horizontal) around the insertion are shown in Fig. 4.2 together with the machine dispersion.

4.1.2. High luminosity optics ($\beta^* = 23 \text{ m}$)

Since the final focusing quadrupoles are behind the beam separating dipoles, the lowest achievable β^* at the IP is 23 m , still producing luminosities at the highest acceptable level for FELIX of around $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. This lower limit of the β^* value is imposed by the maximal allowed β value in the RF system. This optics needs quadrupoles stronger than the standard quadrupoles for the doublet close to D2 and a maximum normalized gradient at the limit of the trim quadrupoles of the dispersion suppressor. Solutions with standard quadrupoles exist, e.g. doubling the strongest ones or making the distance between the doublet larger by increasing the field in D2 and D1 or using a special quadrupole between D1 and D2. Fig. 4.3 shows the β -functions for this optics.

4.1.3. Optics for an intermediate β^* value ($\beta^* = 110 \text{ m}$)

An intermediate value is not only needed for covering a wide range of luminosities, but it also serves to minimize the beam size in the region between the D1 and D2 magnets. This will also permit the measurement of elastic scattering with intermediate t -values and of diffractive protons with $1 - 10\%$ momentum losses. The minimal beam size at a distance s is obtained if β^* at the IP equals s . The optics functions associated with $\beta^* = 110 \text{ m}$ are given in Fig. 4.4. The beam size at the end of D2 is 0.3 mm at 7 TeV . Thus a 10σ amplitude corresponds to an angle of 0.03 mrad ($|t| = 0.05 \text{ GeV}^2$).

Figure 4.2. β -functions and dispersion around IP4 for the largest β^* of 900 m. The dispersion is zero at the crossing point.

Figure 4.3. β -functions and dispersion around IP4 for the possibly lowest β^* of 23 m. The dispersion is zero at the crossing point.

Figure 4.4. β -functions and dispersion around IP4 for an intermediate β^* of 110 m. The dispersion is zero at the crossing point.

Summary

An insertion in IP4 can be designed which includes a physics experiment with moderate luminosity in IP4, while minimizing the changes to the design foreseen in the LHC Conceptual Design Report [1]. Obtainable β^* -values range from 23 to 900 m, fully compatible with the needs for FELIX. There is enough flexibility to include this insertion into the standard LHC optics.

4.2. Run scenarios

4.2.1. pp collisions

The wide range of β^* -values permits the adjustment of the luminosity for FELIX almost independently of the luminosities given to the other experiments. During the first years of the LHC operation the luminosities at ATLAS and CMS will be steadily increasing from 10^{32} to 10^{33} $\text{cm}^{-2} \text{sec}^{-1}$, starting with about 10% of the maximum beam current and, if possible, with reduced emittances [3]. FELIX will run at the beginning with a large β^* -value (luminosity: 10^{29} to 10^{30} $\text{cm}^{-2} \text{s}^{-1}$), mainly taking minimum bias events to study the detector performance and also to accumulate a large unbiased data sample for optimizing the trigger strategies.

We will also take advantage of the reduced emittances at the LHC start-up to measure forward protons at the lowest momentum transfers and momentum losses. Measuring the forward scattering amplitude, extrapolated to $t=0$, together with the inelastic rate, will determine the total cross-section in a luminosity independent manner via the optical theorem. These measurements should be done in short dedicated runs which also help to understand the machine.

Once the detector and trigger performances are well under control we will proceed towards larger luminosities, with an upper limit of about 10^{32} $\text{cm}^{-2} \text{s}^{-1}$ to keep the number of overlapping events small. We note, however, that our maximum luminosity may in fact be determined by the radiation environment and the radiation hardness of our pixel detectors. At the present time we expect that most of our running will be done with a β^* of about 110 m and a moderate luminosity of 10^{31} $\text{cm}^{-2} \text{s}^{-1}$.

4.2.2. AA collisions

FELIX will also take data with heavy ion collisions ($PbPb$ and $CaCa$) to study $\gamma\gamma$ collisions. The maximum achievable luminosity is principally limited by the short beam lifetimes which are a consequence of the large beam-beam cross-section [4].

Table 4.1. FELIX running scenarios.

beam particles	$\sqrt{s}/\text{nucleon}$ (TeV)	$\sqrt{s}$ (TeV)	$\mathcal{L}$ ($\text{cm}^{-2} \text{sec}^{-1}$)	β^* (m)	bunchstruct (nsec)
pp	14	14	10^{29}	900	25
			10^{29-30}	110, 900	25
			10^{31-32}	23, 110	25
$Pb Pb$	5.5	1148	10^{26}	23	25, 125
$Ca Ca$	7	280	$4 \cdot 10^{30}$	23	25
$p Pb$	8.8	126	10^{30}	23	25, 125
$p Ca$	9.9	88	10^{31}	23	25

The two main contributions to this cross-section are the electromagnetic dissociation of the ions, and the creation of an electron-positron pair with subsequent electron capture. Both processes have a strong dependence on the ion charge Z . While the total cross-section for $Pb Pb$ collisions is 336 b it drops to 5.2 b for $Ca Ca$ collisions. The luminosity depends inversely on the square of this cross-section. Hence three orders-of-magnitude larger luminosities can be achieved with Ca collisions. Assuming a luminosity lifetime of 10 hours and two running experiments the initial luminosity is about $3 \cdot 10^{26}$ for Pb with a bunch structure of 125 nsec and $4 \cdot 10^{30}$ for Ca with 25 nsec. A summary of the maximum luminosities for different heavy ion running schemes is given in [4] where a low β^* at the IP of 0.5 m was assumed.

For the optics of FELIX the smallest possible β^* value (23 m) will reduce the luminosities in [4] by a factor 46. With a new accumulation scheme for Pb ions, a bunch structure of 25 nsec could regain a factor 5 in the luminosity and perhaps more if larger Pb currents could be accumulated. In the case of Ca , larger beam currents may be envisaged with an optimized accumulation scheme, thus balancing the loss in luminosity due to the larger β^* value. However, the maximum beam current has to respect the limit arising from the emittance increase from intra-beam scattering. The enhanced luminosities and the smaller size of the ion make beams with light ions, like Ca , more efficient for $\gamma\gamma$ interactions compared to Pb ions, over compensating the Z^4 dependence of the $\gamma\gamma$ cross-section. Luminosities larger than $4 \cdot 10^{30}$ would lead to multiple interactions per bunch, which should be avoided in order to have clean $\gamma\gamma$ events.

4.2.3. $p A$ collisions

The decision to separate the RF cavities into two, each acting on one beam, permits collisions of any nuclei. For FELIX $p Pb$ and $p Ca$ collisions are of special interest. In contrast to AA collisions, the

above mentioned electromagnetic processes which disintegrate the beams can be neglected in $p A$ collisions because of their strong Z -dependence. It was demonstrated in [5] that the luminosity lifetime is limited by the emittance blow-up of the ion beam due to intra beam scattering and the total nuclear cross-section. Asymmetric beam intensities, with the proton beam being several orders of magnitude more intense than the Pb (Ca) beam, maximize the luminosities. The higher β^* value for FELIX can be fully compensated by more intense proton beams. In such a scenario, a luminosity of about 10^{30} can be obtained for $p Pb$ collisions with a bunch structure of 125 nsec or even better with 25 nsec, if possible. For $p Ca$, the largest achievable luminosity could be as high as 10^{32} with the usual bunch structure of 25 nsec but at the expense of several events per bunch. If multiple events ought to be avoided the luminosity should not exceed 10^{31} .

Summary

The running scenarios for FELIX with pp , $p A$ and AA collisions are summarized in Table 4.1.

pp running will form the heart of the FELIX program of physics. FELIX will start with large β^* values (110 m and 900 m) to take minimum bias data and with special runs to measure low- t elastic scattering and total cross-section. Once the events and triggers are understood the usual run luminosity will be around 10^{31} and perhaps up to $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ if radiation and background conditions are acceptable.

FELIX will also participate in AA runs to study two-photon physics. For $Pb Pb$ collisions the luminosity will be rather small and could only be increased if a bunch structure of 25 nsec were possible. Using a dedicated accumulation scheme for Ca ions could lead to a few 10^{12} Ca ions per beam and luminosities around $4 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. This value is close to the limit where radiation damage might become important and where multiple interactions

will occur which makes a bunch structure of 25 nsec mandatory. On the other hand, Ca collisions at high luminosities are ideal for the exploration of two photon physics at large center-of-mass energies.

FELIX is particularly interested in pA ($A = Pb, Ca$) runs since many of the physics subjects studied in pp find a natural extension in pA . The luminosity for pPb collisions is modest but it can be large ($10^{31} \text{ cm}^{-2} \text{ s}^{-1}$) for pCa , again if large Ca currents are obtainable.

It is worth mentioning that FELIX, as a fifth experiment, will have only a very small impact on the luminosity of the other experiments, consuming less than 1% of the protons. There is however the concern that a limitation could arise at the highest LHC luminosities from the tune shift limit, to which FELIX will contribute. We have chosen a larger crossing angle ($\pm 0.5 \text{ mrad}$) to reduce the long-range tuneshift to practically zero, but the head-on tuneshift, being independent of the β^* value, will still remain. In the event of a tuneshift limitation at the top luminosities, we propose to delay colliding beams at I4 during each run until after the luminosity has dropped. In such a way, we can guarantee that the loss in luminosity will never exceed 5% and would be less in most of the runs.

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5 Tracking

5.1. Introduction

The goal of the FELIX tracking system is Full Acceptance: we want to see every charged particle and measure its momentum. In order to achieve this goal, we need approximately 50 tracking stations, located as much as 430 m from the IP. The locations of the stations assumed in the design studies are indicated in Table 5.1. Fig. 5.1 indicates the locations of the tracking stations within about 20 m of the IP, and illustrates the delicate interplay between tracking, magnets and calorimetry.

Station	z: from (m)	to (m)	comments
1	vertex		
2	0.15	0.35	In Aleph solenoid
3	2.2	2.7	
4	5.7	5.9	In UA1 dipole
5	6.3	6.7	
6	7.5	7.8	
7,8	10.9	11.4	
9	12.45	12.55	In D0 dipole
10	13.45	13.55	
11	14.45	14.55	
12	15.45	15.55	
13	16.5	16.6	Region D1 dipoles
14	18.9	19.1	
15	24.6	31.2	
16	25.6		
17	31.1		
18	39.1		
19	40.1		
20	45.6		
21	46.6		
22	52.1		Region D2 dipoles
23	74.1		
24	94.0		
25	119.0		
26	120.5		
27	420		Q11
28	430		

Table 5.1. Locations of the FELIX tracking stations assumed in design studies. All entries represent two locations, one on either side of the IP.

Despite the large number of tracking stations, there are a number of considerations which are com-

mon to many or all of them.

The first is physical size. In order to ensure full acceptance and reasonably uniform momentum coverage, FELIX emphasizes near-beam tracking, instrumenting radially outward. This means that much of the tracking in FELIX is necessarily rather compact and needs to have extremely high resolution.

A second consideration is thickness. In general, tracking stations shadow other stations further away from the IP, as well as the calorimeters. In order to minimize gamma conversions in the tracking stations, and to minimize multiple scattering of charged particles, all tracking stations should be as thin as possible.

A third consideration is chamber occupancy. (We use the term "chamber" to denote a generic tracking device, without presupposing any particular technology). The chambers very far upstream, at Q11 and past D2, will see no more than a single charged particle from the collision in any event. Occupancies increase as one approaches the vertex, enhanced (even dominated) by the "splash" from particles interacting in upstream material. Occupancies are in fact high enough that both radiation damage and pattern recognition are serious concerns. While radiation damage is related to the luminosity we run at, occupancies are not. This last observation leads to the demand that each tracking station have sufficient resolution and redundancy to be able to locally reconstruct track segments. This then allows us to match track segments through magnets, resulting in a very powerful spectrometer.

Taken together, these considerations lead to a common conceptual design for most FELIX tracking stations, based on two basic technologies: silicon pixel detectors and Gas Electron Multiplication (GEM) chambers [1-3]. We propose to use the GEM detectors in two fashions: as chambers, and as the basis for a micro-Time Projection Chamber (μ -TPC). While the latter idea is as yet untested, it is extremely promising. Thus the preferred option for the "standard" FELIX tracking station is illustrated in Fig. 5.2. It consists of two planes of Silicon pixels, reaching to an outer radius of approximately 8 cm, with a μ -TPC in between. The Si tracking planes are continued by GEM chambers at radii greater than about 8 cm. Fig. 5.3 represents a more conventional alternative, based on three tracking planes, with inner Si tracking supplemented at larger distances by GEM chambers.

Figure 5.1. The FELIX tracking system involves careful interplay between the tracking stations, the magnets and the calorimeters.

Figure 5.2. A schematic view of a tracking station based on Si pixel detectors and a micro-TPC. Note that several large-area GEM chambers have been removed to improve the visibility of the μ TPC.

Figure 5.3. Schematic design of a tracking station with both Si pixel and GEM detectors.

Modifications of this strategy are required in two regions of the detector.

At the IP, where we look at particles at large production angles ($|\eta| < \sim 1.5$), we propose a microvertex detector, based on two barrels of Si pixel detectors reaching to $z = \pm 14.0$ cm at radii of 4.9 cm and 7.9 cm, complemented by cylindrical GEM chambers at radii of 12.2 cm and 20 cm, with the generic FELIX tracking planes as endcaps.

In the extreme forward region (past the D2 magnets and at Q11), occupancies are lower and the area to be covered ($\Delta x = \pm 2.5$ cm, $\Delta y = \pm 1.8$ cm) is smaller. It may be useful to supplement the Si detectors with a detector based on scintillating fibers or liquid scintillator-filled capillaries, in order to be able to get a fast signal which can be used in the Level I trigger.

How close we can come to the beams depends on the location of the detector. In general, we propose to use Roman pot detectors to aggressively approach the beams wherever (a) the location is reasonably accessible; and (b) the material of the mechanical part of the pot is in the shadow of a calorimeter or magnet. Such arrangements will allow us to approach as close as 10σ to the beam. In areas where Roman pots are not feasible, we will make a transition to a small, fixed radius beampipe of diameter ~ 2.5 cm.

The beampipe in general presents some formidable problems. A simple straight pipe is clearly unacceptable in the forward direction: at angles of 10 mrad, photons, for example, would see material equivalent to 100 times the thickness of the pipe, and would thus always shower in the pipe. We thus propose a rather intricate pipe which ensures that all tracking stations look through comparatively thin windows. The bulk of the material of the pipe is placed at large radii, either hidden behind magnets or calorimeters, or, where unavoidable, aligned so that it obscures a small region of phase space in the middle of calorimeter acceptances, thus avoiding propagating showers downstream. The detailed design of this beampipe involves significant mechanical, vacuum and radio frequency considerations. We have thus devoted substantial effort to establishing credible approaches to solving the various problems.

5.2. The silicon micropattern pixel detectors in FELIX

(In collaboration with E.H.M. Heijne CERN/ECP, M. Campbell CERN/ECP, W. Snoeys CERN/ECP, of the RD19 collaboration, Micropat-

tern Pixel Detector Development.)

5.2.1. Introduction

The hybrid version of a micropattern pixel detector consists of a readout chip that is bump-bonded directly to a matrix-segmented semiconductor particle sensor. At the present time, this semiconductor particle sensor is often a high resistivity Si detector, but GaAs has also been employed successfully, and other materials are also being considered. The Omega2 [4] and LHC1/Omega3 detectors [5] have been developed in the LHC-detector R&D collaboration RD19 as initial demonstrations of this technology. They have also been the first active pixel detectors that were installed in an experiment. The heavy ion physics experiment WA97 in the Omega spectrometer was a particularly suitable environment because of the high instantaneous particle density in the $PbPb$ interactions: several tens of tracks per cm^2 have been reached. 12 planes, $5 \times 5 \text{ cm}^2$, each comprising 97,536 pixels, are now being installed in NA57.

Further development is underway in RD19, mainly for ALICE and LHC-B, while ATLAS and CMS continue independently, but with exchange of experience. For the FELIX pixel detectors one expects to use readout chips that will become available as a result of these various efforts, while the detector geometry and operational conditions will be adapted to the specific situation.

5.2.2. Detector module geometry

Figure 5.4. Ladders of 6 and 8 chips.

Figure 5.5. An array of 5 ladders. The figure to the right shows the overlap of the active area of the ladders when two arrays are assembled back to back and staggered to ensure full coverage.

Both the sensor matrix and the readout chip have cells of similar shape and size; the pixel dimensions are $50\ \mu\text{m} \times 500\ \mu\text{m}$ in the LHC1 chip. While these dimensions would be adequate for FELIX, it is more likely that the basic cell will have $50\ \mu\text{m} \times 300\ \mu\text{m}$ because both ALICE and ATLAS are aiming for this size. The LHC2 readout chip is currently planned as a matrix of 128 rows by 32 columns so that with a peripheral area of 3.6 mm width the total chip will be $10 \times 9.9\ \text{mm}^2$. An active sensor area of $6.4 \times 10.2\ \text{mm}^2$ is read out by this chip. Either 8 or 6 readout chips of approximately $120\ \mu\text{m}$ thickness are to be assembled in a row on a common 'ladder' substrate as shown in Figure 5.4.

This ladder, with a length of 83 mm (resp. 63 mm), will serve both as sensor and as support for the data bus and the electrical connections to the readout chips. RD19 and ATLAS, in collaboration with the IMEC institute in Leuven, have undertaken the development of integrated MCM-D (Deposited Multi-Chip-Module) technology on high resistivity detectors. The IMEC process allows $20\ \mu\text{m}$ copper bus lines at $50\ \mu\text{m}$ pitch. A sandwich of 5 interconnect layers then adds $60\ \mu\text{m}$ thickness to the sensor wafer. Via contacts through such a sandwich have already been demonstrated. At the end of each ladder, a ceramic substrate carries a pilot chip, connected to the MCM-D bus lines for raw data compression, line driver and local bias management.

A sensitive thickness of $120\ \mu\text{m}$ of Si is sufficient for the required signal/noise performance. Such a small thickness allows the use of Si with a reduced resistivity of e.g. $300\ \Omega\text{-cm}$ with an initial depletion voltage of 230 V. The overall thickness of the high

resistivity sensor-substrate will then depend essentially on the mechanical constraints of the assembly. An overall thickness of $400\ \mu\text{m}$ Si-equivalent ($120\ \mu\text{m}$ sensor + $120\ \mu\text{m}$ readout + $60\ \mu\text{m}$ interconnect + $100\ \mu\text{m}$ mechanical reserve) is assumed.

Because of the 3.6 mm wide inactive strip on each ladder, it is necessary to overlap ladders in order to ensure complete coverage. Our basic arrays are constructed of two layers of 5 ladders each. In each layer, the ladders are separated by 1.9 mm. Using carbon fiber supports, the two layers are mounted back-to-back, and staggered so that the active areas overlap by 0.444 mm. The resulting double-layer arrays have sensitive areas of $83\ \text{mm} \times 60\ \text{mm}$ and $63\ \text{mm} \times 60\ \text{mm}$, respectively. This construction is illustrated in Figure 5.5.

5.2.3. A full detector plane

Figure 5.6. Isovlew of full detector plane.

The drawing of a full detector plane is shown in Fig. 5.6. The overall coverage is $250\ \text{cm}^2$. 4 double-arrays with 83 mm ladders and 2 double-layer arrays with 63 mm ladders are needed, in total carrying 440 readout chips. These chips contain 1.8 million pixels and, with a power consumption of $50\ \mu\text{W}$ per pixel, they use 90 W of power. Cooling should be performed by a forced flow of cold nitrogen. It is assumed that the operating temperature can be in the $10\text{-}20\ ^\circ\text{C}$ region. The average effective material thickness is about 0.77 mm of Si, not including the small amount of carbon-composite for support.

5.2.4. Electronics in each pixel cell

The overall block diagram of the circuit in the existing LHC1 pixel cell is illustrated in Figure 5.7.

Figure 5.7. Block diagram of the LHC1 pixel cell.

The front-end amplifier and latched comparator are operating asynchronously. After 150 ns the binary signal is fed into a delay line which can be adjusted in duration in two complementary ways over a range of 1 to 5 μ s. The electronic noise of this system has been measured to be 175 e⁻ r.m.s. The threshold for the discriminator in the LHC1 chip has a 400 e⁻ standard deviation at a value of 4000 e⁻. For the more recent chip, LHC2-test, a preliminary result of 2000 e⁻ with 250 e⁻ rms deviation has been obtained. This value would allow operation of the electronics at 120 μ m sensor thickness, which gives a typical signal of 9000 e⁻. The comparator provides a fast-OR and it can be masked, i.e. inhibited to operate if the preamp or the comparator prove to be too noisy or defective. This fast-OR signal is transmitted directly to the bottom of the column, and might be used for timing or trigger purposes. This LHC1 architecture is designed so that zero data suppression, encoding and chip bias adjustments can be done in a local pilot chip for each ladder. This 'COOP' chip [6] has recently been shown to perform as intended, and a prototype module is now under construction.

5.2.5. Radiation hardness

The thin detector construction with lower-than-usual resistivity Si helps to increase the radiation hardness of the detector. Following recent results by Dezillie [7] one can expect another improvement by using epitaxial Si detector substrates. One intends to avoid operation temperatures below 0 C so that forced nitrogen gas cooling is possible. The LHC2 readout chip is being designed in deep sub-micron technologies in order to achieve a moderate radiation hardness (up to 2-3 Mrad) while using relatively cheap, normal CMOS suppliers.

5.2.6. Detector cost

The overall area for the 46 tracking stations within 100 m of the IP, each with two planes, amounts to 2.7 m² with 40,480 readout chips. Using the cost estimates originally developed for ATLAS (400 CHF/cm²) one arrives at an estimated cost of 10.8 MCHF. The remaining stations (past D2 and at Q11, on each side) will in total cost only approximately 100 kCHF because the beampipe limits the area to be covered to only about 18 cm².

5.3. Gas Electron Multiplier detectors

5.3.1. Introduction

The recently introduced Gas Electron Multiplier (GEM) [1-3] amplifies electrons released in a gas by ionizing radiation. Amplifications of about two hundred have been demonstrated with a single GEM mesh 50 μ m thick, and of several thousand with two GEMs in cascade or with a "thicker" mesh obtained by overlapping two GEMs in electrical contact [8]. This permits the detection of minimum ionizing tracks directly on a printed circuit board with strips. The main results obtained with a Double-GEM and Super-GEM are summarized here. We assume that developments under way will permit the fabrication of a single GEM 100 μ m thick with similar characteristics.

5.3.2. The basic GEM detector

The basic detector is shown schematically in Fig. 5.8. It consists of an upper electrode, delimiting a 3 mm thick conversion and drift region, of one GEM amplifying mesh, and of an induction gap 1 mm thick terminating with a printed circuit board with parallel pick-up strips 150 μ m wide at 200 μ m pitch. The GEM meshes are manufactured on metal

Figure 5.8. Schematic view of a GEM detector. The drift space is 3 mm and the induction gap is 1 mm thick.

clad kapton foils 100 μm thick, etched with a high density of holes (typically 120 μm in diameter at 200 μm pitch) using the photo-lithographic process described in the references. With the application of suitable potentials, electrons released by ionization in the upper gas layer drift into the open channels of GEM, multiply in avalanche in the high field and transfer to the second gap. Signals are induced on the pick-up strips by the electron swarm leaving GEM, with an amplitude corresponding to the total drifting charge. As discussed in Ref [3], use of this drift mode for signal induction and absence of cancellations due to the presence of opposite polarity pulses result in larger effective signals, given the total gain, than in a conventional avalanche mode. The detector is, moreover, remarkably safer than a micro-strip chamber due to the absence of high voltages on the readout plane. Fig. 5.9 shows the typical charge gain curve for the Super-GEM detector, as a function of the voltage difference across the electrodes.

Exposing the detector to a ^{90}Sn source, and triggering on external scintillation counters to select minimum ionizing electrons, one obtains the pulse height spectrum shown in Fig. 5.10, and the efficiency plateau given in Fig. 5.11 as a function of potential.

Measurements have been realized on 16 adjacent strips equipped with a fast multiple amplifier circuit [8] followed by ADCs; the signal to noise ratio in the middle of the plateau is around 100. The rise-time of the signal in the ionization mode, corresponding to the drift time of electrons across the last gap (about 20 ns) is a priori slower than in the avalanche mode; both are however faster than the rise-time of currently available amplifiers (30-40 ns) and are therefore indistinguishable. Moreover, as there is no slow ion component, signals are effectively shorter in duration implying a higher intrinsic rate capability. A time resolution of 30 ns

Figure 5.9. Charge gain curve for the Super-GEM detector as a function of the voltage difference across the electrodes.

Figure 5.10. Pulse height spectrum of minimum ionizing electrons.

fwhm has been measured, but can be certainly improved by a different choice of operating conditions (higher drift fields and faster gas). In each event, signals are induced on two or three adjacent strips; although the position resolution has not yet been measured, it is expected to be comparable with the one obtained with micro-strip chambers, dominated by energy loss statistics and diffusion.

5.3.3. A four-coordinate GEM detector

A thin, double-sided printed circuit with perpendicular strips for the read-out can achieve two-dimensional localization. The low mass and the operation in non-flammable gases makes the use of the

Figure 5.12. A basic double-gap, four-coordinate GEM detector(left); a schematic view of a GEM chamber indicating readout location (center) and the fiberglass frame (right).

Figure 5.11. Efficiency as a function of potential.

GEM detector particularly attractive in the FELIX environment. A basic double-gap, four-coordinate GEM detector is shown in Fig. 5.12.

A common central plane (thin polymer foil metal clad on both sides) constitutes the drift electrode for the two detection volumes. One Super-GEM on each side and the read-out circuit completes the detector. Structural support is provided by two thin expanded polyurethane plates, 3 mm thick, on each side of the double detector. A fiberglass frame few mm wide (not shown in the figure) holds the foils and provides gas tightness. With the use of a double-sided printed circuit made on thin polymer foil, two coordinates per gap can be read-out: two perpendicular (X and Y) and two inclined (U and V). Table 5.2 gives an indicative list of materials used for a double, four-coordinate detector (a "4C Module") and of their thickness (not including the frame and the electron-

ics). We have also assumed that a development of the technology will allow the use of aluminum (as opposed to copper) for the various electrodes.

A set of four 4C Modules, edge to edge, constitutes a detection layer, and we assume that for each measurement station two detection layers will be used. The geometry and size of the modules depend on the tracking station. The figures illustrate rectangular GEM chambers 30 cm x 40 cm, but other shapes, such as annuli, are also possible. The construction of the pick-up strips by etching PC boards also permits their size and orientation to be optimized. The electronics is mounted on the two outer edges (see Fig. 5.12). As shown in the detail of Fig. 5.12, frames are made of fiberglass about 3x3 mm² in section, except on the angle facing the beam pipe, where it is realized with a thin (100 μm) polymer foil to reduce scattering and interactions.

A tentative layout of a measuring station, inserted between two bellows in the vacuum tube, is shown in Fig. 5.3. It consists of three layers of 4-C GEMs, separated by the available space, with the sensitive region starting 7.5 cm from the center of the beam. A set of silicon pixel detectors (described in the previous subsection) cover the inner region, in contact with the beam pipe.

5.3.4. A μ -TPC based on GEM

A very promising alternative solution is based on a cylindrical GEM detector, functionally equivalent to a radial Time Projection Chamber (GEM μ -TPC). The setup for one station is schematically shown in Fig. 5.2, and the μ -TPC geometry is given in more details in Fig. 5.13. Fig. 5.14 shows a hypothetical detected event. A cylindrical drift electrode, consisting of a thin polymer foil in contact with the beam

Table 5.2. Material budget in the active area for a 4C Module.

ELEMENT	MATERIALS	THICKNESS	NUMBER	X ₀ (cm)	X/X ₀
Structural plate	Kapton	25 μm	2	25	$2 \cdot 10^{-4}$
	Rohacell	3 mm	2	1000	$6 \cdot 10^{-4}$
Double-sided printed circuit readout board	Aluminum	2 μm	2	9	$5 \cdot 10^{-5}$
	Kapton	25 μm	2	25	$2 \cdot 10^{-4}$
	Aluminum	2 μm	2	9	$5 \cdot 10^{-5}$
Super-GEM	Aluminum	2 μm	2	9	$5 \cdot 10^{-5}$
	Kapton	100 μm	2	25	$8 \cdot 10^{-4}$
	Aluminum	2 μm	2	9	$5 \cdot 10^{-5}$
Drift plane	Aluminum	2 μm	1	9	$2.5 \cdot 10^{-5}$
	Kapton	25 μm	1	25	$1 \cdot 10^{-4}$
	Aluminum	2 μm	1	9	$2.5 \cdot 10^{-5}$
TOTAL					$2.2 \cdot 10^{-3}$

Figure 5.13. Details of the μ -TPC geometry.

Figure 5.14. A hypothetical event as seen in the μ -TPC.

pipe, is used to drift ionization trails generated by small angle tracks through the cylindrical GEM amplifier and to readout electrode, realized on a flexible printed circuit. The basic idea of the GEM μ -TPC is to allow detection of tracks produced at shallow angles, as soon as they emerge from the beam pipe; no other known detector can approach this region with full sensitivity. Depending on expected rates and multiplicity, the readout electrode could be realized with pads (the more powerful but more expensive choice), or with sets of radial and longitudinal strips; in this case, the multi-track resolution will be reduced due to overlapping signals.

Figure 5.15. Schematic view of GEM readout electronics.

GEM readout and cost estimates

The planar GEM detectors have individual strip readout at a $200\ \mu\text{m}$ pitch; a 4-coordinates chamber of $30 \times 30\ \text{cm}^2$ needs 1500 readout channels per plane, or 6000 channels in total. Each strip is instrumented with a fast amplifier followed by a shaper and an analogue pipelined buffer memory (Fig. 5.15); typical amplifier shaping times are 50 ns, and clocking frequency 40 MHz to cope with the collision rates. The analogue memory is 128 cells deep, storing the sampled input information for $3.2\ \mu\text{s}$; this is the maximum time for trigger selection. A deconvolution circuit unfolds the shaped output pulses to extract on line the cluster charge and crossing time. Signals are read-out sequentially after the trigger selection; data are transmitted through optical fibers to remote digitizers. Typical integrated circuits for the readout have 32 channels; the size of a 512 channels card (complete with readout ancillaries and cooling) is about $100 \times 20\ \text{mm}^2$ and the thickness between 0.1 and $0.25\ \text{g/cm}^2$ depending on design. Typical power dissipation for a card is 0.5 W. The estimated cost for the rad-hard version is 1300 CHF/card or $\sim 5\ \text{kCHF/plane}$ (2.4 CHF/channel) including data transmission and digitization. For the cylindrical micro-TPC GEM detector, the above circuit is suitable for recording the analogue strip or pad information, but an improved time resolution is necessary to record the radial coordinate (drift time). This could be obtained by an increase of the clocking frequency (if possible) or by the use of fast multi-hit time digitizers (such as the Lecroy Fastbus 1877). Another possibility would be to sample each input on two or more pipelines with an additional delay at the input, followed by a suitable deconvolution.

5.3.5. Electronics

(These considerations are based upon the present development of integrated electronics for silicon strips and MSGC readout in CMS [9]).

5.4. The FELIX microvertex detector

Figure 5.16. A schematic view of one half of the FELIX microvertex detector. 1) cylindrical GEM chamber at $r=20$ cm; 2) cylindrical GEM chamber at $r=12.2$ cm; 3) $r=4.7$ cm beampipe; 4) $r=7.9$ cm Si barrel; 5) $r=4.9$ cm Si barrel; 6) annular GEM chamber at $z=31.75$ cm; 7) Si detector plane at $z=31.5$ cm; 8) μ TPC. The Si plane at $z=15.82$ cm is obscured by the Annular GEM at $z=15.8$ cm.

A schematic view of the FELIX microvertex detector is indicated in Figs. 5.16 and 5.17. It consists of two barrels of Si pixel detectors, at radii of 4.9 cm and 7.9 cm with an active area reaching to ± 14 cm. These barrels are made out of the standard FELIX arrays. From 15 cm to 30 cm, a standard FELIX tracking station, with two Si planes and a μ -TPC, serves as an end-cap for the Silicon pixel barrels.

GEM chambers are used at larger radii. Two barrels of GEM chambers, of radius 12.2 cm and 20 cm, and 15 cm in length, are envisaged. Annular GEM chambers, reaching from 8 cm to 20 cm, located at $z=15$ cm and at $z=30$ cm complete the endcap of the central inner tracker. All chambers are segmented azimuthally as indicated in the figures. All GEM chambers are of the standard 4-C construction, providing four coordinate readout. There are a total of about 216,000 channels in the GEM chambers.

The total Si channel count is about $17.2 \cdot 10^6$ in the two barrels, and an additional $1.8 \cdot 10^6$ for each of the four transverse planes in the standard FELIX stations serving as endcaps. Taken together, these will generate about 1.6 kW of heat, which will require cooling.

The total cost of the Si barrels is 1.1 MCHF. The

Figure 5.17. A view along the beam axis of one-half of the FELIX micro-vertex detector. The azimuthal segmentation of the annular GEM chamber at $z=15$ cm is indicated. The annular window in the beampipe at $z=15$ cm has been removed so that the Si detector plane is visible.

total cost of the GEM barrels is 270 kCHF. The cost for each of the two "standard" FELIX tracking stations serving as endcaps, already included in the earlier summary of the cost of the forward tracking stations, is about 236 kCHF for the two Si pixel planes and about 122 kCHF for the GEM chambers in each station.

5.5. Roman-pot detectors

(In collaboration with C. Avila (Universidad de Los Andes), A. Brandt (FNAL), and H. da Motta (LAFEX).)

Very forward tracking is typically done using detectors located in Roman pots, which are stainless steel containers that allow the detectors to function close to the beam but outside the machine vacuum. Particles traverse thin steel windows at the entrance and exit of each pot. The pots are remotely controlled and can be moved close to the beam (within a few mm) during stable beam conditions and retracted otherwise. Roman pots have been successfully used in many experiments such as UA4, UA8, CDF, E710, and ZEUS, and have typically been used as a leading proton tagger and momentum spectrometer. They make use of machine magnets along with points measured on the track of the scattered proton to calculate the proton momentum and angle ($\theta \sim \sqrt{t}$).

Roman pots and their associated detectors do not require major research and development as they use existing technologies. All that is required is some optimization for the specific beam optics at the different pot locations. Since Roman pot spectrometers have typically been concerned with protons carrying a large fraction of the beam momentum, the associated track multiplicities for these detectors are usually very small (≤ 2), care should be taken in the detector design to account for the higher track multiplicities expected at certain locations in the FELIX layout.

5.5.1. Roman pot hardware

A conceptual diagram of a Roman pot is shown in Fig. 5.18. The bellows allow for movement of the pot close to the beam. Thin stainless steel windows bracketing the active area of the pot reduce multiple scattering. Pressure compensation is necessary to combat the forces caused by the imbalance in pressure between the vacuum and the inside of the pot which is at atmospheric pressure. The final positions of the pot which should be accurate to about 20 microns.

Figure 5.18. A conceptual diagram of a Roman pot.

5.5.2. Roman pot locations

The current scheme envisages some 16 Roman pots in each arm, distributed between 20 and 430

m from the interaction point. They would be located just after UA1, at D1¹ (with 1 in front + 1 behind), D1² (1+1), D1³ (0+1), D1⁴ (1+1) and D1⁵ (1+1 followed by 1 to provide a longer lever arm) situated between 20 and 50 m from the IP. At D2, there would be (1+2). The two final pots would be located in the free space near Q11 at 420 m and 430 m (see Table 5.1). The role of the pots is somewhat different in the various locations, and so there may be differences in construction and detector technology.

Figure 5.19. A schematic view of the "bay" design.

5.5.3. Roman pot options

Roman pots have typically been used either with pressure compensation as in Fig. 5.18 (E710-type Roman pot), or with a large brute force motor (CDF approach). An alternative approach, which could be less costly than either of these two methods, involves reducing the pressure imbalance by minimizing the area of the detector and keeping the bulk of the pot within vacuum. This design involves a "bay" for the detector when it is in the retracted position, as illustrated in Fig. 5.19. The combination of the smaller bellows and reduced forces should result in a significantly less expensive apparatus. Such a design is currently being studied by the DØ collaboration [10].

5.5.4. Position detectors

Each Roman pot contains a position detector, which is used to determine the (x, y) coordinate of the deflected proton at the pot position. These detectors should be very reliable as they will be located in the tunnel and consequently difficult to access.

The demands on the detectors depend on the location. The Roman pots at Q11 or D2 will see clean events, with no more than a single track from the collision. On the other hand, it is important to be able to have signals from these detectors which can be used in the Level 1 or Level 2 triggers to tag elastic and diffractive protons. Closer to the IP, the multiplicity of tracks of interest will rise, and so will backgrounds from splash from particles interacting in the beampipe or calorimeters.

Silicon pixel detectors

Roman pots in the D1 region or closer are essentially standard tracking stations. As such, the detectors will be planes of Si pixels, similar to those described in Section 5.2.

Scintillating fiber detectors

We consider the use of scintillating fiber detectors in the D2 and Q11 regions. In addition to the fast response, the sensitive area can be brought closer to the beam than may be the case with Silicon detectors. We will, however, supplement the scintillating fiber detectors with Si strips in order to improve resolution. It may also turn out that economies of scale again dictate that these silicon planes should be pixel detectors.

A particular option is a scintillating fiber detector with a multi-anode photo-multiplier tube (MAPMT) as shown in detail in Fig. 5.20. This simple detector is comprised of stacked ribbons of four fibers oriented so that the scattered proton will pass through all four fibers to maximize the light output. Each detector will have two views rotated by 90° relative to each other, with each view consisting of two sets of 20 parallel ribbons⁷. The ribbons in each set have a one-third ribbon width spacing and the sets are displaced from each other by two-thirds of the ribbon width, in order to minimize the resolution. The use of 0.8×0.8 mm square scintillator fibers would allow a theoretical resolution of about $80 \mu\text{m}$.

The scintillating fibers are connected to clear fibers that are bundled together in groups of four

Figure 5.20. Details of the position detector and MAPMT described in the text.

and connected to one channel of the MAPMT as shown in the bottom of Fig. 5.20. Four fibers/channel will give about 10 photoelectrons and fit comfortably within the pixel size of the MAPMT. The upper right side of Fig. 5.20 shows a front view of the 16 channel HAMAMATSU H6568 MAPMT. This MAPMT presents good gain uniformity among its 16 anodes and has a pitch of 4.5 mm.

The MAPMT's can be read out by a simple trigger board, with one trigger board required for each of the spectrometers. The Level 1 trigger logic is formed in gate array chips which combine the (x, y) coordinates in the pots along with a lookup-table incorporating the transport matrix equations to give bins of ξ and $|t|$ which can be used in a Level 1 trigger. The total time required for the decision is only a couple of hundred nanoseconds longer than the sum of the proton transit time and the time for the return of the signal to the interaction region.

Other options

A number of variations on the Scintillating fiber design are being considered. One which should be mentioned is the possibility of using capillary bundles filled with liquid scintillator instead of plastic

⁷This assumes an active area of about $2 \times 2 \text{ cm}^2$. This design is easily scaled for a larger detector.

Table 5.3. Estimated cost per Roman pot.

Item	Quantity	Unit Cost (\$)	Total Cost (\$)
Bellows	2	1,000	2,000
Flanges	2	2,000	4,000
Pipe	1	1,000	1,000
Window	2	250	500
Pressure Compensation	1	3,000	3,000
Rough Control	1	1,000	1,000
Fine Control	1	4,000	4,000
Machine Costs	-	-	5,000
Assembly Costs	-	-	2,000
Miscellaneous	-	-	2,500
Total	-	-	25,000

scintillating fibers.

New types of photodetectors (APD, HPD [12], etc.) will also be tested for this application because they may permit a reduction of the readout cost.

5.5.5. Costs

A rough estimate of the cost per pot is shown in Table 5.3 (see also Fig. 5.18). The costs of Si pixel detectors has been reviewed in Subsection 5.2.6. Si strip detectors are somewhat cheaper, about 60 CHF/cm².

The cost of the scintillating fiber detector is dominated by the MAPMT which is about \$100 per channel. The fiber and scintillator costs are minimal. Other costs including cables, trigger boards and high voltage would bring the estimated cost to about \$150 per channel.

5.6. Beampipe

5.6.1. Vacuum chambers: mechanics

(In collaboration with: T. Kurtyka CERN/EST; J. Kruzelecki, Cracow University of Technology, Poland; P. Lepeule CERN/LHC; A. Lugan CERN/EST; E. Morin CERN/EST; B. Skoczen CERN/EST; R. Veness CERN/LHC)

Mechanical requirements

The proposed scheme of the forward detector results in a complex layout of the beampipe system, shown schematically in Fig. 5.21. Mechanically, it has several specific features: first, the whole system is large. It consists of two halves, each 109 m long, extending symmetrically from the interac-

tion point and passing through different detector elements. (These elements also serve as possible supporting points.) Secondly, central subsections, each 16.5 m long, contain several large diameter conical and cylindrical chambers connected by a small diameter (50 mm) tube. Sudden transitions of the diameters over limited length must be provided here in order to ensure a small angle of acceptance for near-beam detector elements without presenting unacceptable amounts of material to larger angle tracks. Thus the entry and exit walls of each chamber must be designed as transparent windows, as thin as possible.

The main goal of the mechanical design may thus be summarized as a minimization of the thickness of the windows, while the thickness of the side walls of the chambers and the total volume of the material of the beampipe system should be kept at a reasonable level.

Further, in view of the beampipe dimensions, the material and manufacture cost of individual segments of the beampipe should be minimized. This can be accomplished by the use of aluminum alloys as basic materials for the beampipe system. They provide a good compromise between transparency requirements, mechanical properties and cost. Such alloys as A. A. 5754 or A. A. 5083 (in quarter-hard or half-hard tempers) are considered as candidate materials. They are well verified for UHV applications and combine good mechanical strength with acceptable formability and weldability. Inside surfaces of aluminum vacuum chambers will need a surface coating to suppress secondary electron emission.

Figure 5.21. The FELIX vacuum chamber.

Influence of vacuum conditioning on mechanical design

The vacuum in the beampipe specified in FELIX will require vacuum conditioning or bakeout of the chamber (see the next subsection). For an aluminum beampipe this means that entire lengths of a chamber between 2 valves must be heated for 24 hours to either 150°C (for aluminum segments), 300°C (for stainless steel segments), or 350°C (for stainless steel segments with NEG pumps). This implies removable heater elements and thermal insulation, which requires access and adds extra mass to supports. Bellows will also be required to compensate for the thermal expansion of beampipe segments. In addition, the mechanical design must take into account the loss of mechanical strength at elevated temperatures.

Influence of RF on mechanical design

Preliminary calculations of the heat deposited in the vacuum chamber by coherent and incoherent RF losses have shown that beam screens will be required in certain subsections of the beampipe (see the subsection on RF considerations later in this chapter). These screens will need to be electrically conducting cylindrical sleeves at a radius of 80 mm, maintaining electrical continuity whilst allowing vacuum pumping of the exterior volumes. Calculations for similar screens for the HERA-B experiment show that stretched wires, foil strips and perforated tubes can all be acceptable from the point of view of RF[13].

Installing such screens will present a significant engineering challenge. They must be as transparent as possible, but sufficiently well supported to avoid excessive sag. They must ensure a good electrical contact at each end. In addition, some heat will be deposited in the screens due to RF losses. Technical solutions should be found for the removal of this heat.

Preliminary estimates of the wall thickness of beampipe segments

Lateral walls

The thickness of the vacuum chambers walls will strongly depend on design solutions adopted for each individual chamber and for the supporting system of the beampipe as a whole. While a more detailed design analysis is under way, only preliminary thickness estimations may be given at present. Such estimates are obtained by first considering each individual chamber as an independent unit calculated from the conditions of elastic stability and strength under external atmospheric pressure. The thickness

of the side walls of the chambers estimated in this way should be included within the range of 1.0 to 1.4% of their respective diameters (or equivalent average diameters for conical chambers). This means that for the large chambers with diameters in the range of 200 to 850 mm (this latter being the equivalent diameter of the largest conical chamber) the thickness of the walls will be in the range of 2.0 to 8.5 mm for the lower estimate or within 2.8 to 12 mm for the upper one. The lower estimate corresponds to favorable boundary conditions, with the design of the chambers requiring circumferential reinforcing ribs (placed at the ends of short chambers or spaced along long ones at the intervals of approximately 4 diameters), essentially rigidifying the structure, while the upper one corresponds to a conservative estimation of the buckling pressure for an infinite, non-reinforced tube. Both these estimates are based on the safety factor on buckling pressure equal to 4, as commonly applied for preliminary dimensioning of experimental vacuum chambers, and take into account a weakening of the material during bakeout of the beampipe. Since the thickness of the chamber walls is less critical than the thickness of the windows for the FELIX beampipe, the use of reinforcing ribs, restricting the transparency for certain angles, should be avoided.

The thickness of beampipe tubes with smaller diameters, up to 200 mm, must usually be assumed higher than given by the above estimates, in order to compensate for higher thickness tolerances of such tubes and bending interactions between the segments.

Windows

A preliminary analysis [14] has been made to investigate various design options for the windows (i.e. entry and exit walls of the vacuum chambers), since these are the critical elements with respect to transparency requirements. Three design solutions have been compared in more detail: 1) conical windows, 2) convex spherical windows, and 3) concave spherical windows.

From this analysis it follows that the relation between the minimum achievable thickness for these three types windows is approximately 1 to $\frac{1}{2}$ to $\frac{1}{4}$, where the thickness of the conical windows, taken here as a reference, is usually of the same order (or slightly lower) as the wall thickness of the respective chambers. This would mean that for the chambers with larger diameters the use of conical or convex spherical windows must be practically excluded, as this would require the thickness of several millimeters, probably prohibitive for the transparency,

and would result in a serious limitation of the active length of the chambers, since such windows cannot be made too flat.

Clearly, at least at the present stage of the design, the concave windows seem to be the only acceptable solution for the large diameter chambers. While the design of the conical and convex spherical windows is governed by stability requirements under compressive stress, the concave spherical windows are subject to predominantly tensile stress, and their thickness may be much lower, since it is determined from a more favorable strength condition. Tentative estimates show that for the FELIX chambers it may be possible to maintain the thickness of such windows in the range of 1.2 to 1.8 mm, or even below, with the radii of the windows not exceeding 800 to 1500 mm, respectively. An example of a possible form of such a concave window applied to the largest conical chamber is shown in Fig. 5.22.

Concave windows also have a drawback, since the chambers with such windows must be equipped with carefully designed supports protecting the chamber against lateral, column-type buckling. Such a phenomenon of overall instability of the beampipe, as distinguished from the local buckling of chamber walls, is enhanced by the presence of windows, which form flexible joints with relatively low lateral flexural rigidity, and which are loaded by the longitudinal resultants of pressure forces in the chain of beampipe elements.

The application of concave windows to vacuum chambers of large dimensions has not yet been verified in practice. Thus, even though the idea is quite promising, a more detailed study must be made before judging its feasibility.

The estimates given above for the wall thickness and windows should be treated as first approximations, valid for separate vacuum chambers. They may be considerably modified in the next stage of stability and strength analysis which should take into account the interaction between the beampipe segments, real support conditions, deflections under own weight, possible misalignment forces and manufacturing imperfections of the chambers.

Remarks on the support system

The supports of the beampipe should ensure alignment and re-alignment of beampipe elements with a given, possibly high precision. They carry the weight of the beampipe while minimizing its deflection (which negatively influences both the aperture and buckling behavior) and protect it against overall instability, as discussed above. It must also be designed to allow for possible thermal deforma-

tion of the beampipe. This will be particularly important if it turns out from the analysis of vacuum requirements that the beampipe must undergo periodic in-situ vacuum re-conditioning.

The supports of the FELIX beampipe must be quite strong. The beampipe will be heavy, with the mass of some chambers exceeding 100 kg and with the specific average mass estimated at 40 to 50 kg per metre of length for the segments exceeding 400 mm in diameter, not counting the equipment such as pumps, valves, etc.

From the point of view of the support requirements, the beampipe has two distinct parts. The first part, up to 18.9 m, containing 10 large diameter chambers connected by small diameter tubes ($\varnothing 50$, $\varnothing 94$, $\varnothing 86/97$ mm) has highly varying flexural rigidity. In this region, either each individual chamber must be supported separately (with obvious harmful consequences on alignment precision and economy of design) or some chambers should be mechanically connected into longer segments (5 to 6 m long) with sufficient flexural rigidity. The latter solution, decreasing the number of necessary supports, would be also beneficial for decreasing the risk of the column-type instability, particularly for the chambers with concave windows.

The second remaining part of the beampipe, is composed of the sequence of tubes with uniform diameters ($\varnothing 160$, $\varnothing 200$, $\varnothing 420$ mm) and thus more uniform flexural rigidity. As it covers, however, the length of nearly 90 meters, multiple supports are necessary for this part. The layout and the design of the supports will strongly depend on whether the in-situ bakeout is applied to the beampipe.

The distribution and the type of supports also strongly influence the layout of expansion bellows; these flexible elements must be introduced between some segments of the beampipe in order to compensate their possible misalignments and absorb thermal elongation, particularly during the bakeout. In this last case they should be designed to compensate elongation of the order of 3 mm per meter of beampipe length. For reasons of strength, availability and corrosion resistance stainless steel bellows with standard steel/aluminum transition parts are considered as a basic design option. They may be joined with the beampipe either via vacuum flanges or welded (see remarks on Installation and access).

Installation and access

Following vacuum conditioning and testing at CERN, the beampipe must be transported and installed in the tunnel. Experience with installation of the ALEPH beampipe in the same area has shown

Figure 5.22. Possible form of a large conical vacuum chamber with a thin concave window. See text for thickness estimates.

that 6 to 7 m is the practical maximum length of a beampipe that can be lowered down the access shaft and maneuvered in the area. The FELIX beampipe will therefore need to be installed in a number of segments, connected together in situ with UHV connections.

Two possibilities exist for these connections. The first, vacuum flanges, offers the advantage of quick access (perhaps necessary in radioactive areas), repeated openings and closings, and easy capping of vacuum chamber segments for cleanliness. Many standard flanges exist, in aluminum alloy and stainless steel and a development is underway to minimize the mass of flanges in experimental areas. As a second option, vacuum chamber segments could be welded in situ. This is the lowest mass connection. However, access times are long, there are limited possibilities for opening and re-welding and it will be difficult to ensure straightness tolerances. In-situ welding of stainless steel has been developed for the LHC machine and is under way in aluminum for the experiments.

Alignment

The alignment requirements of the experiment for the beampipe are yet to be defined. The main requirement from the machine side is clearly the beam aperture. This means that where its diameter is small the beampipe must be aligned relative to the beam axis. This should be relatively straightforward in the very forward parts of the experiment, in the tunnel. However, in the experimental cavern, far from fixed reference points, it will be more complex.

The minimum diameter of the beampipe to allow sufficient beam aperture will depend both on static errors, such as alignment precision and mechanical tolerances on beampipe segments, and on dynamic errors, such as movement of detectors under magnetic forces, slow movement with time of the cavern and detector structures, and movement of the beam during the year.

Detector and beampipe envelopes must be defined to ensure that sufficient space is available for re-alignment. In areas where relative movements of support structures are possible, such as between de-

tector elements, and between the cavern and the tunnel, sets of double bellows must be installed on the beamline.

5.6.2. Vacuum considerations

(In collaboration with J. M. Laurent [15]/LHC-VAC and O. Grobner/LHC-VAC)

FELIX proposes a base pressure of 10^{-10} Torr, dominated by hydrogen, with heavier gases, such as CO_2 , held to 10^{-11} Torr. These pressures will keep the beam gas rate in the FELIX collision area to ~ 1 kHz/m. Using standard estimates for fixed-target cross sections for 7 TeV protons [16], (94 mb for H_2 and 1.3 b for CO_2), one finds beam gas rates of about 100 Hz/m for interactions with H_2 and 140 Hz/m for interactions with CO_2 for each beam when the LHC is at design luminosity.

The beampipe is composed of a series of large chambers connected by low conductance (30 to 50 l/s) tubes. It follows that the vacuum chamber must be baked, high-temperature treated and each section must be independently pumped. The proposed pumping system is a combination of getter pumps (for hydrogen) and sputter ion pumps (for the remaining non-getterable gas). These pumps must be integrated into the vacuum chambers.

The vacuum system is divided into several sectors in order to allow for the installation and repair, for the testing, the bake-out and for safety. The sector valves must be all-metal, remotely controlled and equipped with an RF screen. In each sector roughing valves are installed for pump-down and leak detection. Space must be reserved to connect the pumping stations to these valves (primary pump and turbomolecular pump with associated gauges and gas analyzers) during the pump-down, bake-out or leak detection procedures.

Hence, the vacuum chamber must be all-metallic and baked out at a temperature of at least 200 °C (preferably 300 °C) to achieve a good pumping efficiency and a low outgassing rate of less than 10^{-12} torr l s $^{-1}$ cm $^{-2}$ (consisting mainly of hydrogen). The surfaces of the different large chambers lie between 1 and 4 m 2 and require pumping speeds between 100 and 500 l s $^{-1}$ to obtain 10^{-10} torr.

This is possible with titanium sublimation getter pumps and NEG pumps for the hydrogen and with sputter ion pumps (SIP) for the other gases. The SIPs must have a minimum pumping speed matching the getter pump speed in order to keep the proportion of heavier gases below 10 %. Getter pumping can take place with lumped Ti sublimators wherever compatible with available space, or

with non-evaporable getter ribbons in spatially restricted areas. Getter ribbons or a gettering alloy can be deposited on the chamber walls, where they can be activated during bake-out. SIP pumping is achieved with discrete triode sputter ion pumps with permanent magnets or with integrated pumps inside the magnetic field of the experiment. The required pumping speeds of 400 l s $^{-1}$ can be obtained by 10 small-size standard pumping elements mounted around the vacuum chamber parallel to the magnetic field. Locations of these pumps are indicated schematically on Fig. 5.21. During shutdown of the magnets of the experiment and beam-off conditions permanent magnets must be installed around the SIPs. The drawn SIP current is a measure of the vacuum level for safety purposes.

5.6.3. RF considerations

(In collaboration with O. Brüning, SL/AP, CERN.)

Introduction

Beam pipes of complicated geometry can have significant interaction with the beam. Two types of problems must be considered. First, sudden changes in the radius of a beampipe will in general lead to energy losses as a bunch passes through the region. This energy loss can lead to heating of the beampipe and is characterized by an incoherent loss factor. Second, cavity-like structures can trap higher order modes. For large Q-values, each higher order mode is associated with a narrow band impedance that can drive collective instabilities.

Two additional considerations are important. For a broad band impedance the wake fields extend only over a short range behind the bunch and the wake fields of two consecutive bunches can not interfere. Thus, for a broad band impedance, the total power loss of all bunches is given by the product of the number of bunches and the power loss per bunch. For a narrow band impedance, the wake fields extend over a long range behind each bunch and the wake fields of successive bunches can overlap. Depending on the distance of the successive bunches, this overlap of the wake fields can lead to a coherent power loss which is proportional to the square of the total number of bunches.

A preliminary analysis of the FELIX beampipe to ± 20 m (expected to be the most serious region) has been carried out [17]. The calculations have been made both for the case in which an RF screen is located a distance of 8 cm from the beam, and for the case of no RF screen. The detailed geometry of the RF screen is not essential for the purpose of these calculations, which is merely to determine

if it is feasible to reduce the RF loads generated in the vacuum chamber to an acceptable level by means of an RF-screen. Mechanical design of the RF screen will require further work. Assuming for the moment a screen with an copper surface one needs at least a copper thickness of $17.5 \mu\text{m}$ in order to screen frequencies above 40 MHz (bunch frequency for the nominal bunch separation). Mechanical considerations, including the need to dissipate the small amount of heat still generated with an RF screen will probably dictate the details of the final design.

Incoherent losses

The wake function for the FELIX pipe has been calculated with and without an RF screen, and this has then been used to calculate the incoherent power losses, obtaining a total incoherent power loss of

$$P_{\text{incoh.}} = 16.32 \text{ kW} \quad (5.1)$$

for the structure without RF-screen,

$$P_{\text{incoh.}} = 97.93 \text{ W} \quad (5.2)$$

for a structure with RF-screen and

$$P_{\text{incoh.}} = 41.62 \text{ W} \quad (5.3)$$

for a structure with RF-screen and tapering.

There is no resonance condition associated with the incoherent losses and in all cases the vacuum chamber/RF-screen must be capable to dissipate the heat of the incoherent losses. The values given in Eqs. (5.1), (5.2) and (5.3) are per beam. Thus, during luminosity operation, the chamber must dissipate twice the values.

The incoherent losses for a vacuum chamber without RF-screen reach intolerable values of more than 16 kW. Compared to these large losses, the vacuum chamber with RF-screen has rather moderate incoherent losses of less than $2 \times 100 \text{ W}$. However, the RF-screen will be in vacuum and it can dissipate the accumulated heat only at the end points where it is connected to the outer vacuum chamber. It still remains to be examined whether a heat load of about 200 W can be tolerated in such an environment and whether the resulting temperature increase on the screen can be tolerated by the vacuum requirements. In any case, the required minimum thickness of the screen will probably be determined by the heat load produced.

Coherent losses

The coherent power loss associated with a narrow band impedance can be calculated analytically assuming a simple form for the resonator impedance

which are satisfied by the higher order mode (HOM) spectrum of the FELIX chamber.

Assuming that the resonance frequency of the impedance is right on a frequency line of the bunch spectrum, the vacuum chamber without RF-screen has a rich spectrum of HOM with a coherent power loss of approximately

$$P_{\text{coh.}} > 500 \text{ kW}. \quad (5.4)$$

For a structure with RF-screen there are 13 HOM with a coherent power loss of

$$P_{\text{coh.,MAFIA}} > 200 \text{ W}. \quad (5.5)$$

Both values are rather large and one either has to avoid that the resonance frequency of the trapped modes lies right on one of the frequency lines of the bunch spectrum or one has to reduce the shunt resistance of the trapped modes in the FELIX vacuum chamber. The first method seems to be very difficult for a variety of reasons. The second method, referred to as 'de-Qing', involves putting a resistive material or an antenna into the structure. One can thus reduce the shunt resistance and the Q -values of the trapped modes while keeping the ratio R_S/Q constant. Unfortunately, resistive materials have a small free path length for particles penetrating through the material. Thus, the introduction of resistive materials into the vacuum chamber is excluded due to restrictions from the experiment. The introduction of antennas in the experimental chamber does not require resistive materials and thus is a feasible option. It does, however, imply a non-uniform distribution of objects inside the experimental chamber and additional components and cabling outside the experimental chamber. Furthermore, a large number of HOM modes might also require a large number of antennas, each optimized for one mode. A reduction of the coherent loss to less than 10 W per trapped mode requires a 'de-Qing' to the point that $Q \sim 250$ and a scenario using antennas for this purpose requires further studies.

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6 Calorimetry

6.1. Introduction

Calorimetry in the FELIX experiment covers the complete pseudorapidity range $|\eta| > 2.3$ in both the forward and backward directions by the use of four different calorimeters (see Fig. 6.1). Their main tasks will be:

- measurements of the energy and position of single particles (photons, electrons, charged and neutral hadrons);
- particle identification, especially the separation of electrons and hadrons, particles and jets, electrons and photons in the very forward direction;
- reconstruction of the energy and direction of jets;
- reconstruction of the topology of the event so that it can be used at the trigger level.

The main performance requirements for FELIX calorimetry in the forward direction are summarized in Table 6.1.

As is well-known, the energy resolution for sampling calorimeters is given (with E in GeV) by:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (6.1)$$

where

- the first term, $a = \sigma_{\text{samp}} \oplus \sigma_{\text{p.e.}}$ is determined by the sampling fluctuations and by photostatistics with $\sigma_{\text{p.e.}} = 1/\sqrt{N_{\text{p.e.}}}$, where $N_{\text{p.e.}}$ is the number of photoelectrons
- the second term, b is determined by the ratio of the electronics noise to the light yield (number of photoelectrons per GeV of absorbed energy): $b = \sigma_{\text{noise}} = \frac{ENC \times \sqrt{N_{\text{ch}}}}{N_{\text{p.e.}} \times G}$, where ENC is the electronic noise, G is the photodetector gain, and N_{ch} is the number of towers; and
- the third term c arises from the nonuniformity of light collection, inaccuracy of calibration, etc., with best values of $c \sim 0.5\%$ for an electromagnetic (EM) calorimeter and a few times larger for hadronic calorimeters (HC).

The required energy resolution in the low energy range from a few GeV up to 50 GeV is such that one needs to keep the sampling term (a) less than

8% for $|\eta| < 5$ and less than 12% for $|\eta| > 5$ for the electromagnetic calorimeters and less than 50% for the hadron calorimeters. These requirements dictate that the total thickness should not be less than $27 X_0$ for the EM calorimeters and $10-12 \lambda$ for the hadron calorimeters. A similar statement holds for the linearity response of the calorimeters, including the electronics readout chain, which should have a nonlinearity of less than 0.5%. The dynamic range of 10^5 is defined, at the lower end, by the electronic noise level of 30 to 50 MeV for the EM calorimeter, and 100 to 200 MeV for the hadron calorimeter, and by the desire to detect a isolated muon in the calorimeter cells. The upper end is determined by the detection of electrons with a few TeV from W and Z decays.

The fast time response of less than 25 ns is very important for reducing the “pile-up” noise from overlapping events from neighboring crossings. Rejection of the background from beam-gas interactions is achieved at the trigger level by using a time coincidence of the calorimeter signals from the two arms of the experiment. The need to remove the single background showers inside an event sets the requirement on the time resolution of about 1 ns.

The lateral size of each detector is designed to partially overlap the preceding calorimeter, see Fig. 6.1. Each of the D0, D1 and ZD calorimeters consists of a preshower detector and EM and HC sections.

The calorimeters will see high levels of radiation, neutron flux, and the high charged particle multiplicities. These conditions will determine the choice of sampling and the structure of the calorimeters as well as the kinds of photodetectors and front-end electronics used in the readout. In the pseudorapidity range $2.3 < |\eta| < 5$, where the radiation dose is expected to be less than 5 Mrad for 10 years running, it is possible to use a sampling calorimeter based on plastic scintillators and wavelength shifting fibers (WLS). In the very forward direction $|\eta| > 5$ where the level of radiation is higher, we will need to implement a “spaghetti”-type of calorimeter based either on thin capillaries filled with liquid scintillator or quartz fibers. These designs are expected to work well even after doses of a few hundred Mrad without any significant degradation of their performance characteristics.

Table 6.1. Performance requirements for the forward electromagnetic and hadron calorimeters.

Electromagnetic calorimeters				
	UA1	D0	D1	ZD
Energy resolution				
stochastic a, %	6.5	11.	11.	11.
constant c, %	0.5	0.5	0.5	0.5
noise b, GeV	< 0.05	< 0.05	< 0.05	< 0.05
Z position, m	7.9	16.6	31.15	95.0
Rapidity coverage				
$ \eta _{min}$	2.33	4.76	6.05	6.45
$ \eta _{max}$	4.94	6.64	7.15	11.
Angular coverage				
$ \theta _{min}$	0.81°	0.15°	0.09°	0.0°
$ \theta _{max}$	11.1°	1.03°	0.27°	0.18°
Granularity, $\Delta\eta \times \Delta\varphi$	0.1×0.1	0.15×0.15	0.15×0.15	0.25×0.25
Threshold, GeV	0.2	0.2	0.2	0.2
Dynamic range	10^5	10^5	10^5	10^5
Time resolution, ns	< 1	< 1	< 1	< 1
Timing, ns	< 25	< 25	< 25	< 25
Dose, Mrad/year	~ 0.5	~ 3.	~ 10.	~ 30.
Hadron calorimeters				
Energy resolution				
stochastic a, %	55	50	50	50
constant c, %	~ 2	1 – 2	1 – 2	1 – 2
noise b, GeV	< 0.2	< 0.2	< 0.2	< 0.2
Z position, m	8.3	16.9	31.45	95.3
Rapidity coverage				
$ \eta _{min}$	2.33	4.76	6.05	6.45
$ \eta _{max}$	4.94	6.64	7.15	11.
Angular coverage				
$ \theta _{min}$	0.81°	0.15°	0.09°	0.0°
$ \theta _{max}$	11.1°	1.03°	0.37°	0.18°
Granularity, $\Delta\eta \times \Delta\varphi$	0.2×0.2	0.45×0.45	0.45×0.45	0.75×0.75
Threshold, GeV	0.5	0.5	0.5	0.5
Dynamic range	10^5	10^5	10^5	10^5
Timing, ns	< 25	< 25	< 25	< 25
Dose, Mrad/year	~ 0.2	~ 1.	~ 3.	~ 10.

Figure 6.1. The geometric positions, showing the angular and pseudorapidity coverage, of the four forward calorimeters in FELIX. This layout displays one of the two identical arms.

6.1.1. UA1 calorimeter

The UA1 calorimeters cover the pseudorapidity range $2.33 < |\eta| < 4.94$, see Fig. 6.1, and must have good energy and spatial resolution, good hermeticity, fine lateral granularity, and be able to work in a magnetic field. The high multiplicity of charged and neutral particles incident on the calorimeter (~ 100 particles per event) sets the requirements on the lateral segmentation, radiation length and Moliere radius of these calorimeters. The EM calorimeter must have a transverse granularity no worse than $\Delta\eta \times \Delta\varphi \sim 0.1 \times 0.1$ to obtain the good spatial resolution necessary to achieve the separation of two nearby showers. The hadron calorimeter can have a factor of two coarser granularity.

The UA1 magnet has a thick coil which closes the rear aperture of the magnet (Fig. 3.3, page 87). The coil thickness is 45 cm (or $\sim 0.3 \lambda$) on average. The structure of the UA1 magnet dictates that we place the EM calorimeter section and the first section of the hadron calorimeter (HC1, about 2λ thick) inside the magnetic field. In this case, the effect of the inactive material of the coil on the energy and spatial resolutions of the UA1 calorimeter will be insignificant. Hence we will need to use non-magnetic materials and a readout which is insensitive to the magnetic field. In a magnetic field, the light yield of scintillators is increased [4,6] so the influence of a magnetic field on the calorimeter parameters needs to be studied carefully.

We only have about 1 m free space inside the magnet and 1.4 m outside for the UA1 calorimeters. The remaining hadronic section, HC2, will therefore lie outside the coil.

The granularity requirements can be most economically satisfied by constructing the calorimeter in three separate radial pieces called “parts”. The requirements on the thicknesses of the EM and hadron calorimeters given above define the choice of absorbers: tungsten and lead for the inner/middle and the outer parts of the EM calorimeter, respectively, and copper for the hadron calorimeter.

Our primary choice for the UA1 calorimeter is the Bayan-type with plastic scintillator and tungsten/lead/copper absorber, see below.

6.1.2. D0 and D1 calorimeters

The D0 and D1 calorimeters are located between the very forward magnets after the D0 wide aperture dipole and the D1² dipole. The available space (of less than 2.4 m) for the calorimeters again defines the choice of absorber. Only tungsten allows enough room for a hadron calorimeter with more than 12λ , as needed for the complete absorption of TeV hadrons. Because of the higher radiation dose the photodetectors and front-end electronics must be placed on the sides of calorimeters with additional shielding.

The choice for the D0 and D1 calorimeters is based on capillary tubes containing liquid scintillator as the active material. The attenuation length of the capillaries with liquid scintillator and the requirement to achieve a low constant term (c) dictate a longitudinal segmentation of the hadron calorimeters into two sections. The segmentation is also useful for particle identification.

6.1.3. Zero degree calorimeter

The ZD calorimeter (ZDC) covers the very forward direction so as to really make FELIX a full acceptance detector for neutral particles. This calorimeter will function as a precision detector and is very important for studying proton diffraction, the spectra of leading particles and other very forward processes. The ZDC is designed to measure the integrated flow of energy and jets and also to measure the coordinates and the energy of very forward particles with a sufficient accuracy to reconstruct well the masses of unstable particles (π^0 , Λ , K_s , Σ etc.). Further details of the reconstruction may be found in the section on calorimeter performance, see Section 11.2, page 181. At a distance of 95 m from IP4, the beams are separated in the horizontal plane by 34 cm. The ZDC will be placed between and around the two vacuum pipes with two holes for the beampipes.

6.1.4. Preshowers

Because of the very small angles of the incident particles, we require a very high spatial resolution (no worse than $100\ \mu\text{m}$ for 100 GeV photons) to obtain a good two-shower separation (about 2-3 mm). To achieve this goal, a preshower detector with a strip size of about 1 mm is placed in front of each very forward calorimeter. The particle occupancies permit us to build preshower detectors with this projective geometry.

6.2. UA1 forward calorimeter

6.2.1. Choice of calorimeter

A novel, sandwich-type of electromagnetic calorimeter, named the Bayan calorimeter, has recently been developed at IHEP, Protvino [3,7]. In this calorimeter, thin absorbers interleaved with scintillators are either bent along the beam axis or are tilted at a small angle (see Fig. 6.2). The wavelength shifting fibers that are used for light collection are placed along the narrow edges of the scintillator sheets. A hadron calorimeter with a similar structure has been built and tested in the U-70 accelerator at IHEP, Protvino [3,8].

A calorimeter with this structure is assembled from continuous absorber plates and smaller scintillating elements. The fibers of these elements are joined together in bundles in the process of forming single towers. In this case there exist no boundaries between towers, and the dimensions of the absorber plates are defined only by the dimensions of

Figure 6.2. The two basic designs of a Bayan electromagnetic calorimeter.

the complete calorimeter or by the need for convenient assembly. Note that lead plates can be glued together with a very thin steel plate (0.05-0.1 mm thick) between them. This sandwich has good mechanical properties and is a detector which can be built with a self-supporting structure without any dead zones.

In comparison with other calorimeter structures, this approach has the following advantages:

- good energy resolution;
- high light yield and low noise;
- simple manufacturing with low cost; and
- good uniformity and minimum dead zones.

6.2.2. Mechanical design

The front face of the UA1 calorimeter is located 7.9 m from IP4 and covers the angular range from 14 mrad to ~ 200 mrad. The UA1 calorimeter is divided longitudinally into three sections (EM, HC1 and HC2), as discussed above (see Fig. 6.1).

The lateral dimensions of the EM calorimeter are $3.12 \times 3.12\ \text{m}^2$. The gap between the calorimeter and the interior surface of the magnet is used for the support structure and for cable routing of the monitoring system and the UA1 chambers.

A three-dimensional view of the first (EM + HC1) section of the UA1 calorimeter is presented in Fig. 6.3. The section consists of 896 modules with dimensions $104 \times 104\ \text{mm}^2$. The requirements on the granularity dictate a radial partitioning of the EM calorimeter into three parts with different cell-size: inner, near the central hole ($R < 208\ \text{mm}$), middle ($208\ \text{mm} < R < 624\ \text{mm}$) and outer ($624\ \text{mm} <$

Figure 6.3. A 3-D view of the electromagnetic and first section (HC1) of the hadron UA1 calorimeters. (All dimensions are in mm.)

$R < 1560$ mm). At the center of the inner part is a wedge-shaped beam pipe hole with dimensions 224×224 mm² at the front and 244×244 mm² at the back of the calorimeter.

The main parameters of the UA1 calorimeters are summarized in Table 6.2.

Inner part of EM and HC1

The inner part (Fig. 6.3), placed around the central beam hole of the calorimeter, consists of 12 nonstandard modules, which must form the wedge-shape beam pipe hole. These modules will have a coarse sampling of 1 mm tungsten and 1 mm scintillator to reduce the background on the very forward calorimeters and chambers caused by the lat-

eral leakage of the EM showers. We will also build the inner wall of the hole of the calorimeter with 2-3 mm tungsten. The inner part is divided into 6×6 cells with size 17.3×17.3 mm². The radiation length of the structure is 7 mm and the Moliere radius is about 20 mm. The energy resolution of the calorimeter is about $10\%/\sqrt{E}$. We will have a granularity $\Delta\eta \times \Delta\phi$ for the inner part varying from 0.13×0.14 to 0.09×0.08 . The total number of cells is 432. The hadron section of the inner part consists of 2×2 cells with dimensions 52×52 mm².

Middle and outer parts of EM and HC1

The middle and outer parts have a similar structure (a three-dimensional view of the single (EM +

Table 6.2. Main parameters of the UA1 calorimeters.

	EM	HC1	HC2
distance from IP4	790 cm	830 cm	935 cm
angular coverage	$\pm 11^\circ$	$\pm 11^\circ$	$\pm 11^\circ$
thickness	40 cm	40 cm	120 cm
	1.35λ	2.2λ	6.6λ
cell size, inner	$17.3 \times 17.3 \text{ mm}^2$	$52 \times 52 \text{ mm}^2$	$52 \times 52 \text{ mm}^2$
middle	$26 \times 26 \text{ mm}^2$	— " —	— " —
outer	$52 \times 52 \text{ mm}^2$	$104 \times 104 \text{ mm}^2$	$104 \times 104 \text{ mm}^2$
Moliere radius	35 mm	18 mm	18 mm
inner	20 mm	— " —	— " —
radiation length	15 mm	17 mm	17 mm
inner	7 mm	17 mm	17 mm
radiation thickness	$27 X_0$	—	—
weight	24.6 t	38 t	114 t
number of cells	5504	1316	1872
photodetector	Phototetrodes/APD	PMT/HPD	PMT/HPD
weight of tungsten	4.7 t	—	—
weight of lead	16 t	—	—
weight of copper	—	37 t	112 t
weight of scintillator	3.2 t	0.6 t	1.8 t
scintillator thickness	1 mm	1 mm	1 mm
absorber, inner	1.0 mm W	5.5 mm Cu	5.5 mm Cu
middle	0.3 mm W	— " —	— " —
outer	0.6 mm Pb	— " —	— " —

HC1) module is shown in Fig. 6.4). The module has a transverse size of $104 \times 104 \text{ mm}^2$ and a length of 856 mm not including the space needed for the readout system and the fiber bundles, an additional 140 mm.

In the middle part, each module is divided into 4×4 cells with $26 \times 26 \text{ mm}^2$. The granularity $\Delta\eta \times \Delta\phi$ is equal to 0.12×0.13 , at a radius $R \sim 210 \text{ mm}$ and 0.04×0.04 , when $R \sim 620 \text{ mm}$. Each module is assembled from 80 alternating layers of 0.3 mm tungsten and 1.0 mm scintillator. A single layer consists of a continuous tungsten plate and four scintillator elements (see "section A" in Fig. 6.4). The scintillation light is collected and shifted by WLS fibers of diameter 0.8 to 1.0 mm. The scintillator sheet together with the WLS fiber is wrapped in white paper or aluminized mylar for light insulation from nearby elements. The 20 elements are joined into a single cell, each with an independent readout. The total radiation thickness of the EM part of calorimeter is $27 X_0$ with a radiation length of 15 mm. A GEANT simulation of the structure of the EM calorimeter shows that the expected energy resolution is $6.5\% \sqrt{E} \oplus 0.5\%$. Results of the simu-

lation are described in the section on calorimeter performance, see Section 11.2, page 181.

The hadronic section of the module is assembled from copper plates with thickness 5.5 mm and scintillator sheets with a thickness of 1 mm. Each hadron module is divided into 4×4 cells with dimensions $52 \times 52 \text{ mm}^2$. 16 layers form the hadronic section of the module. The scintillating elements in the hadronic section are formed from two scintillator sheets and one WLS fiber placed between them. A single scintillator sheet has dimensions $24.5 \times 400 \times 1.0 \text{ mm}^3$, about the same as in the EM section of the module. This makes it possible to use the same molded form for the manufacture of the scintillator sheets, and the same equipment for quality control, assembly, etc.

A single hadron layer is well-matched with 5 EM layers, and ten EM fibers are formed into a bundle and are inserted in a small groove in the copper plate (see "Section B" in Fig. 6.4). This structure of modules permits a reduction of the gap between the EM and hadron calorimeters to 25 mm. This is very important for the energy resolution and two-shower separation in the hadronic section. This distance

Figure 6.4. A view of the single combined module of the electromagnetic and first hadron sections of the UA1 calorimeters. (All dimensions are in mm.)

is needed for the interior support structure and for fiber bundle formation, since the minimum radius of curvature for which the light loss is negligible is about 50 mm for plastic fibers with this diameter.

The total weight of the module is 55 kg, where 33.5 kg is the weight of the hadronic section and 21.5 kg is the weight of the electromagnetic section. Thin tapes of stainless steel close the module on the sides and improve the mechanical rigidity.

The total numbers of cells in the middle part are 2048 in the EM section and 512 in the hadronic section.

The outer part of the calorimeter has a similar structure, but in the EM section we plan to use lead as the absorber with thickness 0.6 mm. The dimensions of the cells in the EM and hadronic sections are again $52 \times 52 \text{ mm}^2$ and $104 \times 104 \text{ mm}^2$, respectively. The radiation length and Moliere radius of the outer electromagnetic section are essentially the same as for the middle part.

The total numbers of cells in the outer part are 3024 in the EM section and 756 in the hadronic section.

tion.

HC2 section

The second section of the hadron calorimeter is placed immediately after the UA1 coil, at a Z position of 9.35 m. The section also covers the angular range $\pm 11^\circ$ and has transverse dimensions $3.75 \times 3.75 \text{ m}^2$ with a wedge-shaped hole, having an angular aperture of 14 mrad. The structure, design and segmentation are practically the same as the first hadronic section with one difference: the total length of this section is 120 cm. The total numbers of cells are 768 in the inner part and 1104 in the outer part, which is well matched to the same parts of the front section of the hadron calorimeter (HC1).

6.2.3. Photodetector, front-end electronics and readout considerations

It is well known that an electromagnetic shower in a calorimeter generates on average about 10^4 pho-

tons/incident particle (of 1 GeV). This large light output allows one to use simple devices with low gain readout systems, such as vacuum phototetrodes and avalanche photodiodes (APD).

Both of these photodetectors function in magnetic fields and have small dimensions, which is important because of the lack of space inside the UA1 magnet. The light output from the hadron calorimeter is less than that of the EM. For this reason we will probably use hybrid photodiodes (HPD), working inside the magnetic field, or photomultipliers, but in the latter case we would need to transport the light from the hadronic cells to the outside of the magnet by clear fibers.

The energy dependence of the energy resolution for a sampling EM calorimeter with σ_{sampl} of 6.0% is shown in Fig. 6.5 for various types of photodetectors. The following values were used:

- PMT: $N_{p.e.} = 2000$ p.e. per GeV, $\sigma_{\text{noise}} = 0$;
- PIN diode: $N_{p.e.} = 8000$ p.e. per GeV, ENC = 500 e^- , $G = 1$;
- phototetrode: $N_{p.e.} = 2000$ p.e. per GeV, ENC = 500 e^- , $G = 30$; and
- APD: $N_{p.e.} = 4000$ p.e. per GeV, ENC = 2000 e^- , $G = 100$.

The most promising candidates are vacuum phototetrodes. The avalanche photodiodes (APD) might also be used despite existing problems with long-term and temperature stability.

Vacuum phototetrodes

One of the possibilities for an EM readout is to use vacuum phototetrodes. At the normal operating point the gain of the phototetrode is in the range 30-50 [9]. The reduced amplification (in an axial magnetic field of ~ 1 T) of the phototetrode is about 15-20 (see Fig. 6.6) but it has the following advantages: radiation hardness, lack of "nuclear counter" effect, low intrinsic electric capacitance, and thermal and temporal stability [10].

The constraints of the low energy shower's position resolution and the moderate light yield of scintillator calorimeters result in a low-noise amplifier implementation in the readout. The scheme of such an amplifier [11] is based on the current sensitive configuration with a JFET head transistor. The three stages of the amplification exclude the need for a post-amplifier in the control room and diminish the influence of electromagnetic interference on the signal transferred by cable. The hybrid is designed on a ceramic nonmagnetic substrate and coated in

diamagnetic plastic. The dimensions of the design are $24 \times 10.5 \times 2$ mm³. The measurements of the equivalent noise charge (ENC) were made for the peak detection of the delta-response, and they show that ENC equals $\sim 600 e^-$ for base-to-base duration 60 to 70 ns and 0 pF detector capacity.

Avalanche photodiodes

In recent years avalanche photodiodes have come into wide use in HEP [12,13]. Recently Hamamatsu and EG&G (Optoelectronics, Vaudreuil, Canada) have produced a new model with the following characteristics:

- Capacitance of 120-130 pF;
- SiO₂ entrance windows;
- Sensitive area of 0.2cm²;
- Quantum efficiency (at 530nm) of $\sim 75\%$

These devices have achieved gains of 100-200 with low bias voltage (180-190 Volts) and dark currents (2-20 nA). An attractive feature of such solid state devices is their relative insensitivity to magnetic fields, although they are highly sensitive to temperature changes. To achieve the results listed above the detector temperature must be stable to 0.5 deg C.

Hybrid photodiodes

Hybrid photodiodes (HPD) are a relatively new class of hybrid photomultiplier tubes [13-15]. They consist of a photocathode, followed by a gap (of several mm) over which a potential of $U=6-10$ kV is applied. The quantum efficiency of this device is determined by the type of photocathode used but for a multi-alkaline type it is about 20% at a wavelength of 420 nm (and 12% at a wavelength of 530 nm). The electric field accelerates the photoelectrons onto a silicon target. The gain of such a device is determined by the relation: $\text{gain} = U/3.6$ (V) and is about $1 - 3 \times 10^3$. The HPD is rapidly developing for hodoscope and calorimetry applications in high energy physics. Their popularity has led to a decrease in their price.

6.3. Very forward calorimeters (D0, D1, ZD)

6.3.1. Choice of calorimeter

The spaghetti-type of calorimeter based on capillaries filled with liquid scintillator is the primary option for the FELIX very forward calorimetry. Calorimeters based on scintillating fibers are

Figure 6.5. The energy resolution of a scintillating sampling calorimeter *vs* energy for various photodetectors with σ_{simpl} of 6.0%.

well-known detectors [16,17] and have been studied in detail over the past ten years. They have a good energy resolution, especially for hadrons ($35\text{--}50\%/\sqrt{E}$), high light yield (500 to 2000 p.e. per GeV depending on the sampling), and a small radiation length and Moliere radius. Replacing fibers by capillaries filled with liquid scintillator should improve the parameters of this type of calorimeter, although the first attempts have not been a great success [18]. The light yield of liquid scintillators is higher, as is its attenuation length (the properties of various liquid scintillators are presented below). A lead-liquid scintillator calorimeter has been used in a Fermilab experiment [19].

6.3.2. Mechanical design

All three very forward calorimeters have a similar structure and differ only in their dimensions and in the construction of the region where the beampipes pass through the calorimeter. They each consist of a preshower detector, EM and two hadron sections. The main parameters of the very forward FELIX calorimeters are listed in Table 6.3.

Figure 6.6. The response variation as a function of the magnetic field intensity, normalized to the value at $B = 0$ T, for a sample of 15 tubes. The upper (solid dots) represent the average of the 15 tubes, while the lower set (open boxes, open circles and solid triangles) represent 3 individual tubes, multiplied by 0.5 for clarity.

D0 and D1 calorimeters.

D0 and D1 each have a central hole with a square shape and dimensions $90 \times 90 \text{ mm}^2$ and $96 \times 96 \text{ mm}^2$, respectively. They are placed around the beam pipe, which requires a segmentation into two sections: left and right.

In this case we would have the possibility to assemble it without dismounting the beampipe.

A three-dimensional view of the D0 calorimeter is shown in Fig. 6.7. The D0 EM calorimeter has lateral dimensions of $60 \times 60 \text{ cm}^2$, the D0 hadron calorimeter has a lateral dimension 10 cm larger.

The length of the electromagnetic section is 20 cm, approximately equal to $40 X_0$. The hadron calorimeter is divided into two sections with lengths 85 cm (6.1λ) and 75 cm (5.3λ). Taking into account the electromagnetic section (1.4λ), the total thickness of the calorimeter is equal to 12.8λ , which is sufficient for full absorption of 1 TeV hadron showers.

Gaps of about 100 mm between parts of the calorimeter are designed for the preparation of capillary bundles, placement of light guides (which have a reduction factor near 5) and for transporting the

Table 6.3. The main parameters of the very forward calorimeters.

	D0		D1		ZD	
	EM	HC	EM	HC	EM	HC
distance from IP4	1660 cm	1690 cm	3115 cm	3145 cm	9500 cm	9530 cm
thickness	20 cm	160 cm	20 cm	160 cm	20 cm	160 cm
	1.4λ	11.4λ	1.4λ	11.4λ	1.4λ	11.4λ
dimension, cm^2	60×60	70×70	30×30	40×40	60×40	60×40
number of cells	1036	464	364	110	760	240
cell size, mm^2	14×14	42×42	15×15	45×45	15×15	45×45
Moliere radius	14 mm	14 mm	14 mm	14 mm	14 mm	14 mm
radiation length	5 mm	5 mm	5 mm	5 mm	5 mm	5 mm
radiation thickness	$40 X_0$	—	$40 X_0$	—	$40 X_0$	—
weight, t	0.8	6.5	0.2	1.6	0.5	4.2
ratio tungsten/capillaries	1.5:1	1.5:1	1.5:1	1.5:1	1.5:1	1.5:1
diameter of capillaries	0.5 mm	1 mm	0.5 mm	1 mm	0.5 mm	1 mm
photodetector	PMT/APD	PMT	PMT/APD	PMT	PMT/APD	PMT
length of capillary, km	180	305	45	75	120	205

bundles of clear quartz fibers. GEANT simulations of these calorimeters have shown that the stochastic term of the energy resolution is 12% for the EM and 50% for the hadron sections. Estimates of the light yield for these calorimeters are about 2000 p.e./GeV for the EM and a few hundred photoelectrons for the hadron section when photomultipliers are used for the readout. Even with a reduction of the light yield due to inefficiencies, the contribution of the photostatistics to the resolution will be negligible.

A drawing of a single cell of the EM section is shown in Fig. 6.8. The EM and hadronic sections are assembled from thin tungsten layers with 0.5 mm and 1 mm thickness, respectively. On the surface of each layer there is a semi-circular groove to hold the capillaries of diameter 0.5 mm in the EM section and 1 mm in the hadronic sections. The step size between capillaries is equal to twice their diameter and the centers of the capillaries in each successive layer are shifted by a half step. This staggered alignment of the capillaries provides a superior transverse uniformity in the response and consequently improves the energy and spatial resolutions.

The radiation length and Moliere radius for this type of calorimeter are $X_0 = 5$ mm and $R_M = 14$ mm, respectively. These values and the diameter of the beam holes in the calorimeters determine a minimum cell size of $14 \times 14 \text{ mm}^2$ for D0 and $15 \times 15 \text{ mm}^2$ for D1. The hadronic cells have a factor of three larger dimensions.

For the outer part of the D0 EM calorimeter, the distance to the beam axis is more than 200 mm and

it is possible to increase the lateral cell size by a factor of two. In this case we would have the following granularities $\Delta\eta \times \Delta\varphi$: at $R = 50$ mm: 0.25×0.3 ; at $R = 100$ mm: 0.14×0.15 ; at $R \sim 200$ mm: 0.07×0.08 ; and at $R = 300$ mm: 0.1×0.1 . The numbers of cells in the EM calorimeter are 748 in the inner part and 288 in the outer part. In each hadron section we have 232 cells, and so the total number is 464 cells.

The D1 EM calorimeter is smaller with lateral dimensions of $30 \times 30 \text{ cm}^2$, the hadron calorimeter has a lateral dimension 10 cm larger. The total number of cells is 364 in the EM section and 110 in the hadronic section.

Zero degree calorimeter

The ZDC is placed between and around the two vacuum pipes which go through holes of size $40 \times 60 \text{ mm}^2$. The ZD calorimeter itself has a rectangular shape with dimensions of $60 \times 40 \text{ cm}^2$. The design, structure and composition of the ZDC at this moment is the same as for the D0 and D1 very forward calorimeters of FELIX, i.e., it is a spaghetti-type. The square central part of $40 \times 40 \text{ cm}^2$ consists of 676 electromagnetic cells, with cell size of $15 \times 15 \text{ mm}^2$. The cell size in the outer part is twice as large and the number of channels is 84. The cell size is $45 \times 45 \text{ mm}^2$ and the number of cells in the hadronic section is equal 240.

The total length of the ZDC (12.8λ) could be increased by an additional 2-3 λ , as we have enough free space for it. However, we need to perform de-

Figure 6.7. A 3-D view of the D0 and D1 calorimeters. (All dimensions are in mm.)

Figure 6.8. A drawing of the electromagnetic module of the very forward calorimeters.

Figure 6.9. The principal structure of the D0 and D1 preshower detectors.

tailed GEANT simulations and beam tests of prototypes in order to minimize the opposing effects of longitudinal leakage and light attenuation lengths, which contribute to the constant term in the energy resolution of the hadron calorimeter.

Preshower detectors (PD)

The preshower detectors, placed in front of each of the very forward calorimeters, consist of four capillary planes and four tungsten sheets with a thickness of 3 mm. The total PD thickness is equal $3.6 X_0$, including the material of the support plates for the capillaries. It provides for an approximate 95% efficiency for photon conversion.

The structure of the preshower detector is shown in Fig. 6.9 and the parameters are given in Table 6.4. The first plane is positioned in front of a tungsten sheet. This plane is used for the coordinate measurement for charged particles.

Each capillary plane is assembled from four independent quarters with projective geometry. The

first plane consists of two double quarter layers, in which the capillaries are aligned along the X-direction and V_1 or U_1 is rotated with respect to the X-axis by 55° or -55° , respectively. The capillaries in the next plane have a similar placement, but V_2 and U_2 are rotated with respect to the Y-axis by the same angles. The next two planes are copies of the first and second planes.

The structure of the capillary planes and 3D-views of the D0 and ZD preshower detectors are shown in Figs. 6.10 and 6.11, respectively. The ZD preshower detector has two holes and is assembled in two halves. The capillaries in this detector are not aligned along the X-axis; the four planes have the following orientations: first – V_1 and U_1 ; second – Y and V_1 ; third – Y and U_1 ; and fourth – V_1 and U_1 .

The capillaries, of 1 mm diameter, are located at intervals 1.2 mm, and the diameter of the core is 0.7-0.8 mm. The dead zone between adjacent strips amounts to 0.4-0.5 mm and is overlapped by the

Table 6.4. The main parameters of the preshower detectors.

	D0	D1	ZD
thickness	10 cm	10 cm	10 cm
	$3.6 X_0$	$3.6 X_0$	$3.6 X_0$
dimension, cm ²	60×60	30×30	60×40
total number of strips	18976	9472	15880
X strips/plane	2000	1000	—
Y strips/plane	2000	1000	2000
U strips/plane	2744	1368	1980
V strips/plane	2744	1368	1980
strip size, mm	0.7	0.7	0.7
diameter of capillaries	1 mm	1 mm	1 mm
photodetector	VLPC/APD	VLPC/APD	VLPC/APD
length of capillary, km	11	5	9

next layer, in which the capillaries are shifted by a half step. The gaps between adjacent capillaries are needed for bending the $U_{1,2}$ and $V_{1,2}$ capillaries along the X- or Y-axis. In this case we have a simpler construction for the connection of the capillaries to the clear quartz transport fibers, (see “Section B-B” in Figs. 6.10 and 6.11).

A single plane is mounted in an air-tight box, assembled from thin, stainless steel plates. Each capillary layer fits between the two composite plates with semi-circular grooves. The composite plates are interleaved with thin, stainless steel plates for mechanical rigidity. A thin glass or quartz window separates the volume with capillaries and liquid scintillator from the transport fibers. The distance between the edge of the capillary and the fiber may be made about 0.3-0.4 mm and in this case the light loss in the connector will be about 30-40%.

A minimum ionization particle passing through the capillary, filled with liquid scintillator (1MN type), produces 70-80 photons. Taking into account the loss at the light connection and the efficiency of the Visible Light Photon Counter (VLPC) [20] or the APD [21] of $\sim 70\%$ for blue light, we have about 40 photoelectrons, more than enough for a 100% measurement efficiency.

6.3.3. Photodetector and front-end electronics

For the very forward calorimeters we propose to use the same type of photodetectors and front-end electronics as in the UA1 calorimeters (see Section 6.2.3). The photodetectors and front-end electronics are placed at a distance of 0.5 to 1.0 m from the beam axis, behind additional radiation shielding to reduce the radiation dose and the neutron fluxes

to permissible levels (see Section 6.6).

We consider two options of photodetectors for the preshower detectors: avalanche photodiodes based on a metal-resistor semiconductor structure [21] and Visible Light Photon Counters (VLPC) [20].

New avalanche photodiodes have a high gain 10^4 to 10^5 and a high (60 to 70%) efficiency for visible light. Their small size and low cost make them good candidates for the capillary preshower detector. However, they will require careful monitoring and control of the temperature and bias voltage with a precision better than 0.1° and 0.01 V, respectively.

The upgrade of the D0 experiment plans to use about 10^5 channels of VLPC for their scintillating tracker and fiber preshower detectors [22]. The VLPC are arsenic-doped silicon diodes. The VLPC chips are produced by Rockwell and are supplied as a 1×8 pixel array with individual pixels of 1 mm diameter. Measurements are usually carried out at an operating temperature between 5.5 K and 7.0 K, with the VLPC bias between 5.9 and 7.1 V and low power requirements of $\leq 1 \mu\text{W}$. At the normal operating point, the gain is about 10^4 . The nonuniformity of the signal gain and the variation among pixels is $\leq 10\%$. The relative quantum efficiency (from pixel to pixel) is about 60-70% at a wavelength of 530 nm. The VLPCs have a fast rise time ≤ 10 ns [23] and a dark pulse rate of about 10 kHz. Note that such devices are insensitive to magnetic fields.

6.4. A quartz ZD calorimeter option

In spite of the fact that the ZDC is situated about 95 m from IP4, it must work in a high radiation

Figure 6.10. A 3-D view of the D0 preshower detector with a drawing showing one quarter of the detector.

environment. A simple estimate for each minimum bias event for a 7 TeV $\times$ 7 TeV pp collision is that an average energy of 700 GeV is deposited in each arm of the ZDC. In the central part of the ZDC the dose will be of the order of 0.25×10^3 Gy per day, at the highest FELIX luminosity of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$. Thus, the high radiation conditions may not permit the use of conventional plastic scintillation fibers.

At this moment we envisage two options for the ZDC. The first is a calorimeter where capillaries with liquid scintillators are used as the active material. In the event that the radiation environment is too harsh for this type of detector, our second option would be a calorimeter with quartz fibers as the active material where the shower particles produce Cherenkov light. Recently there have been extensive studies performed on this type of calorimeter [24–27]. It has been shown that calorimeters with quartz core and quartz cladding are extremely radiation

Figure 6.11. A 3-D view of the ZD preshower detector with a drawing showing one-half of the detector.

hard and show no change in response for up to 1–2 Gigarad. Two LHC collaborations, CMS and ALICE, have made this type of calorimeter their choice for their Very Forward Calorimeters and ZDC, respectively (see the Technical Proposals of CMS and ALICE [24,25]). These calorimeters have a resistance to Gigarad level, a very quick response and a very narrow transverse size of hadron showers [26–29].

The FELIX quartz fiber ZDC would also be a “spaghetti” type where the quartz fibers are used as the active material instead of the scintillating fibers. To compare with the previous option of the ZDC we have simulated the same geometry and structure that has been described above in Section 6.3. The fiber-to-absorber filling ratio (quartz to tungsten) is also similar to that for the scintillating fibers option of the ZDC. The diameter of the active part of the quartz fibers is $300 \mu\text{m}$, the thickness of the

inactive part (cladding + coating) is $20\text{ }\mu\text{m}$ and the distance between neighboring fibers is $485\text{ }\mu\text{m}$. The radiation issues for quartz fibers will be discussed in Section 6.6.

A GEANT simulation of this calorimeter shows that the energy resolution for electrons and photons is $25\%/\sqrt{E} \oplus 0.2\%$, while for hadrons it is $80\%/\sqrt{E} \oplus 5\%$. These values are obtained for a ratio of tungsten/quartz of 1.5:1.0 and for a very high quantum efficiency for the photomultipliers (20% in the wavelength range 300 to 650 nm). The calorimeter is extremely noncompensating [29] and this is the main reason for the large constant term in the hadronic energy resolution. The stochastic term is primarily defined by the photostatistical fluctuations, in this instance we only have 20 photoelectrons per GeV for photons. This number may be increased by a factor of 2 to 3 times with the use of photomultipliers with quartz windows and by the evaporation of a mirror on to the far end of the fibers. The amount of Cherenkov light could be increased by 2 – 2.5 times if the angle of the fibers would be about 45° .

In order not to degrade the spatial resolution it is best to bend the fibers in a spiral form with a small diameter. Electromagnetic showers consist mainly of relativistic electrons and positrons. So the energy dependence of the response of this calorimeter is very linear for photons and electrons.

The number of channels for the quartz version of the ZDC is the same as for the liquid scintillator option. The quartz fiber version is 1.5-2 times more expensive because of the additional cost of the quartz and the need to use more expensive photodetectors.

6.5. Calibration and monitoring

Calibration and monitoring are very important for maintaining good performance throughout the lifetime of a detector. In order to meet the needs of the FELIX experiment the calibration constants must be known within 0.2-0.5%.

The calibration includes the measurement of each cell in a high-energy electron test beam at several energy points and also an *in situ* calibration during a run using isolated electrons. For this goal e^+e^- pairs, from conversion photons in the chambers placed in front of the calorimeters may be used. It is expected that, for the FELIX luminosity, the number of isolated electrons coming from the decays of W and Z bosons will not be sufficient for this task.

The monitoring process includes the following tasks:

- monitoring of each electronics chain, including

the photodetector and amplifier, using a light source system based on a laser;

- monitoring of the light yield and attenuation length of the plastic scintillator using muon signals. For the calorimeters with PMT read-out, radioactive sources can also be used;
- measurement of the light yield and attenuation length of liquid scintillator by laser or some other light system;
- measurement of the radiation dose at several different points in the calorimeters;
- monitoring and control of the temperature and bias voltage for the APD and VLPC; and the high voltage for the PMT and HPD.

Good uniformity of the FELIX calorimeter system requires excellent quality control in the production phase of all the components for the calorimeters. This will be developed and improved upon in the future.

6.6. Radiation hardness

Scintillators

One of the principle design constraints on the EM calorimeter in the UA1 detector is the extreme radiation environment. It is well known that the scintillating plates and WLS fibers which have been selected for this detector are susceptible to degradation due to both natural aging and radiation effects. The damage due to aging is expected to reduce the light output from the plates and WLS fibers by $< 1-2\%/yr$ [30]. This will be acceptable for FELIX. The damage to the detector due to the radiation environment at the LHC is expected to be substantially greater than that due to aging. The radiation will effect both the light output and the attenuation length of the scintillating plates and WLS. Changes in the attenuation lengths will cause an increase in the constant term of the energy resolution. The usual contribution of the attenuation for WLS fibers to the energy resolution of an EM calorimeter is less than 0.1-0.2% before irradiation. After a radiation dose of 2-3 Mrad it may increase by a factor of 2. The main contribution of the attenuation length of the scintillator sheets is a transverse nonuniformity of the calorimeter response, which can be corrected through the calibration system. Small losses of the intrinsic light output (eg a light loss of $\sim 15\%$) lead to an increase in the constant term ($\sim 1.5\%$) of the energy resolution [31]. The strictest requirements

Figure 6.12. The relative light yield of thin scintillator plates *vs* radiation dose. The black points are taken immediately and the open points 1 day after the irradiation.

Figure 6.13. Normalized light attenuation length l/l_0 and conversion efficiency $I(0)/I_0(0)$ for Y-7 curves (1,3) and BCF-92a curves (2,4) WLS fibers as functions of the dose D (in Gy).

Table 6.5. Scintillation and radiation hardness properties of some blue light emitting scintillators.

Type	Thickness mm	Light yield %, anthracene	Wavelength nm	Radiation dose D_{max} , Mrad
SCSN-81	4	40	430	2.0
PSM-115(A)	4	40	420	1.0
NE-110	4	60	434	0.8
PSM-115(A)	1	53	420	2.5

Table 6.6. Efficiency and radiation hardness properties of some green WLS fibers.

Type	Efficiency %, anthracene	Wavelength nm	Radiation dose D_{max} , Mrad
Y-7	100	~510	2.0
Y-8	100	~530	3.6
BCF-91a	103	~500	2.0

on the light output losses are imposed for the EM calorimeters. For the expected lifetime of the experiment (~ 10 yr) the total light output losses due to radiation damage should be less than 10% [32]. We will use this design constraint to define a dose level (D_{max}) at which the light output will be about 90% of the output prior to irradiation as our standard of radiation hardness. Note that for a given material the level of radiation hardness is very sensitive to the specific features of the detector (eg material thickness, wavelength region of operation, and the plastic production techniques used. An important consideration arises from the influence of atmospheric oxygen on the process of irradiation and recuperation. The thinner the scintillating plates and WLS, the better is their radiation hardness.

Polystyrene scintillators (PS) based on granulated polystyrene of the PSM-115 trade mark,¹ manufactured by injection into the mold technique² and bulk-polymerized SCSN-81³ are the most radiation resistant (see Table 6.6) [33–36].

The results of radiation damage measurements for blue light emitting, thin scintillating plates containing 2% PTP + 0.05% POPOP are presented in Fig. 6.12. These data show that taking into account the post-radiation recuperation process thin (~ 1 mm) scintillating sheets have their light output reduced by 10% at doses $D_{max}=2.5$ Mrad.

A comparative study showed that such bulk-polymerized plates based on Kuraray-3HF³ scintillators had ~ 2 -6 times, depending on their thickness, higher levels of radiation hardness compared to the above blue scintillator [34].

Similar to the blue plates, some green light emitting WLS fibers are also radiation resistant. WLS fibers such as Y-7, Y-8³ and BCF-91a⁴ have radiation resistances of $D_{max}=2.0$ -3.6 Mrad (see Table 6.6) [34,35]. The normalized light attenuation length and efficiency of the WLS fibers (Y-7 type) [35] with the best radiation resistance are presented in Fig. 6.13.

Note that the highest level of radiation resistance of thin scintillating plates (≤ 1 mm) is very close to the level of the radiation resistance for the best WLS fibers.

We are also considering another possibility for improving the radiation hardness of our EM calorimeter through the use of a combination containing green light emitting plastic scintillating plates and orange light emitting WLS fibers. This is possible

due to the lower levels of the transmission losses after irradiation in plastic materials at the longer wavelength regions [36]. Data indicate that a combination of green Kuraray-3HF scintillating plates and new orange O-2.³

WLS fibers can provide a radiation resistance up to $D \leq 10$ Mrad with a 25% loss of the light output [37].

Some detectors in the FELIX experimental setup will use clear fibers for light transmission to the photoreceivers. Because of this, their radiation hardness is important. The radiation resistance of clear-PSM (double-clad, Kuraray) plastic fibers in the green wavelength region is about 0.16 Mrad [38]. However some of them have shown up to a 300 times lower level of radiation resistance compared to the normal ones. Hence the radiation resistance of double-clad clear fibers requires careful monitoring and study.

The EM calorimeter will be exposed to a periodic type of irradiation with a maximum dose/period of irradiation D less than a certain critical dose D_{cr} . Each period of irradiation is accompanied by a time break for the full recovery of plastic materials. Taking into account that the recovery times for some scintillating plates are rather short (~ 0.5 -3 days) [33–35] such a working mode for the whole experimental setup looks possible. Obviously, such a mode will improve the radiation hardness up to several times [39].

The above data on the radiation damage studies can be used here as preliminary results for estimating the calorimeter radiation hardness. Its exact value can only be determined after the calorimeter module undergoes radiation damage tests with actual low dose rate irradiation. R&D on the radiation damage of the plastic materials to be employed will be vigorously pursued by the FELIX Collaboration.

Liquid scintillators (LS)

Among the various organic materials tested, liquid scintillators in neutral atmospheres or in vacuum have shown the maximum levels of radiation resistance [41]. They display more than an order of magnitude higher level of radiation resistance in comparison with the best plastic scintillators. Some results of this investigation are presented in Fig. 6.14. In order to determine the radiation resistance level which capillaries, filled with the best liquid scintillators, can provide we should consider that the most irradiated parts in electromagnetic calorimeters occupy only a small region (from 10 to 15 cm) near the maxima of the electromagnetic shower development. This constitutes about 20% of their whole volume. Liquid scintillors are widely available from well

¹KNK, Moscow, Russian Federation.

²IHEP, Protvino, Russian Federation.

³Kuraray Corp., Japan.

⁴Bicron corp., USA.

Figure 6.14. A comparison of the light attenuation in 500 μm unirradiated capillaries filled with LSs based on 1MN and Bicron LSs. 1 - 0 Mrad 1MN + R45 ($l=313$ cm); 2 - 0 Mrad BC-599-13G ($l=225$ cm); 3 - 0 Mrad BC-599-13B ($l=129$ cm); 4 - 48 Mrad 1MN + R45 ($l=102$ cm); 5 - 48 Mrad BC-599-13G ($l=88$ cm); 6 - 48 Mrad BC-599-13B ($l=84$ cm).

Figure 6.15. The influence of air on the light yield and attenuation length of the liquid scintillator based on 1MN solvent with R6 dopant during the irradiation. The diameter of the capillaries is 110 μm . 1 - attenuation length $l = 118$ cm, no irradiation; 2 - attenuation length $l = 101$ cm, 12.5 Mrad irradiation in vacuum; 3 - attenuation length $l = 30$ cm, 13.3 Mrad irradiation in air.

Table 6.7. Optical and scintillation properties of the liquid scintillators. In the table, IPN is a derivative of methylnaphthalene, IPB is isopropylbiphenyl, and m.o. is a mineral oil.

Solvent + Dye	λ_{em} , nm	Light Yield, %, anthracene	Decay time, ns	Light attenuation length, m
1MN + R6	485	58	7.6	1.9
IPN + R6	485	58	6.3	2.0
IPB + R6	485	46	6.2	2.0
m.o. (BC-517S)	420	66	2-3	4-5

known firms around the world. Properties which are typical of LS's are:

- light output is 55 – 65% of anthracene
- attenuation lengths of 3-5 m
- decay time constants of 2-3 ns for the blue wavelength (420-440 nm) region and 6-8 ns for the green wavelength (~ 500 nm) region.
- refractive index, $n = 1.58-1.63$

Of all the LSs, the FELIX collaboration is most interested in LSs based on mineral oils, viscous silica-organic liquids (having phenyl or benzene groups in their structure), etc. which are characterized by a low level of evaporation, low inflammability, low potential for leakage (high viscosity), etc. Some efficient LSs with a light output of up to 66% of anthracene (about 11000 photons/MeV) based on mineral oils (BC-517S) are manufactured, for example, by Bicron. For details, see Table 6.7.

Here again we take the 10% level for permissible losses of the light output due to irradiation in these scintillators. According to such rough estimates, capillaries filled with liquid scintillators based on 1-methylnaphthalene (1MN) and some radiation resistant scintillating dopants R6, R39 (pyrazoline derivatives), etc. emitting light in the green wavelength region would provide a radiation hardness of about 60-100 Mrad.

Note that these LSs have a high level of radiation resistance in a neutral atmosphere or in vacuum. One can see from Fig. 6.15 that the radiation resistance of the LSs, based on 1MN + R6, is much smaller in air due to their solvent oxidization by O_2 under irradiation.

The influence of the darkening of the glass walls on the attenuation length in a capillary turns out to be relatively small, especially for capillaries of a large diameter (> 0.5 mm), because the scintillating light trapped in a capillary by the total internal reflection from the liquid scintillator - glass wall interface penetrates only a few wavelengths deep into the glass. The radiation resistance of a capillary filled with a liquid scintillator is mainly limited by the liquid scintillator radiation resistance rather than the capillary glass, and the radiation resistance of the whole detector could be significantly improved by the periodic renovation of the liquid scintillator.

Quartz fibers

The radiation resistance of quartz fibers in the visible wavelength region (400-600 nm) for a calorimetry application has been studied recently [40]. It was

shown that the radiation resistance of quartz-quartz (quartz-polymer) fibers has reached a level of about 1 Grad (200-400 Mrad) for γ -quanta irradiation.

The light trapping efficiency ε of a fiber is determined by the formula:

$$\varepsilon = 1/2 \times (1 - n_{cl}^2/n_{core}^2)$$

for short distances ($\leq 1-2$ m), and for long distances ($\geq 1-2$ m) by

$$\varepsilon = 1/2 \times (1 - n_{cl}/n_{core}).$$

Here n_{cl} and n_{core} are the refractive indices of the fiber's cladding and core, respectively. Possible core material are quartz ($n_{core} = 1.46$) and ordinary boron-silicate glass ($n_{core} = 1.51$ to 1.53). The polymer used as cladding in some quartz-polymer fibers has $n_{cl} = 1.42$. As is clear from the above, in FELIX some glass-polymer light guides are needed because they have the maximum level of the trapping efficiency $\varepsilon = 7\%$ which is needed in order to transmit light from capillary fibers filled with LSs and have $\varepsilon = 6-9\%$ to photodetectors with minimal light losses (up to 40 %) at the connector. According to our measurements, the light attenuation length in ordinary quartz-polymer fibers at a wavelength length of 500 nm is about 50 dB/km.

Some characteristics of different types of quartz fibers are presented in Table 6.8.

Radiation hardness of the photodetectors

In the FELIX experimental setup some photoreceivers must work in a severe radiation environment. Hence it is important that they are radiation resistant. Photomultipliers and vacuum phototetrodes have a high level of radiation resistance. In fact, no noticeable changes were registered in signals from a PMT FEU (manufactured by MELZ, Moscow, Russia) with an entrance window based on a radiation resistant glass (SO96-1) and a multi-alkaline photocathode for accumulated doses up to 35 Mrad of γ -irradiation [42].

For other types of photodetectors such as VLPC, APD, HPD and for front-end electronics, their levels of radiation resistance are determined mainly by their content of silicon elements. At the moment such elements can tolerate integral doses of γ -irradiation up to a few Mrad and fluxes of fast neutrons $10^{13}-10^{14}$ n/cm² [43]. The recent progress in the improvement of the radiation resistance of both photodetectors and front-end electronics is connected to the use of As/Ga [44]. The elements of electronics based on As/Ga can provide up to an order of magnitude higher level of radiation resistance to both γ -quanta and neutron fluxes, i.e. up

Table 6.8. Some characteristics of quartz fibers. Here fquartz is a fluorinated quartz. Note that the values of ϵ in this table are calculated with the short distance formula.

Type	Production	Core, μm ; type	Cladding, μm ; type	ϵ , %	D_{max} Mrad
quartz-quartz	SeramOptec	500; quartz	500; fquartz	< 1	≥ 1000
quartz-polymer	SeramOptec	500; quartz	600; polymer	2.8	200-400
quartz-polymer	IGP, Moscow	50; quartz	25; polymer	2.8	10-30

to 10 Mrad γ -irradiation and $\geq 10^{14}$ n/cm² in comparison with silicon types of electronics. Note that the radiation resistance of multicomponent devices is determined by the most radiation-sensitive element.

6.7. R&D studies for FELIX

6.7.1. Results of previous R&D

The results of beam studies of a prototype Bayan sandwich-type electromagnetic calorimeter have been described elsewhere [7]. A planar version of this calorimeter was tested in electron beams with energies from 1 GeV to 100 GeV using the test beams of the PS and SPS CERN accelerators. This prototype consisted of 9 towers assembled in a 3×3 matrix. The lateral tower size is 70×70 mm² and the length is 60 cm ($\sim 23 X_0$). The tilt angle of the tower axis towards the beam direction is $\theta = 120$ mrad. Each tower consists of 37 layers of lead and 37 scintillating elements. The prototype is comprised of 210×600 mm² lead plates, 0.37 ± 0.02 mm thick, and of 70×600 mm² scintillating elements.

A scintillating element consists of thin scintillator strips with WLS fibers placed along the longest narrow edge of a scintillator strip. We used 1.0-1.5 mm thick scintillator and 1.1 and 1.2 mm diameter fibers. The scintillators, together with the fibers, are wrapped in aluminized mylar. The front end of the fiber has been polished and a thin layer of Al has been evaporated on to it to provide an 80% reflection efficiency. The polystyrene scintillator was doped with 1.5% PTP (para-terphenil) + 0.001% POPOP (1.4-bis-[2-(5phenyloxazolyl)]-benzene). The WLS fibers (polystyrene core with K-27 dopant, cladde - fluorinated PMMA) were used. The fibers were glued with epoxy into bundles and were coupled to the photodetector by an air light-guide. The light attenuation length has been measured for these scintillating elements to be better than 3 m. This value guarantees a high longitudinal uniformity and a constant term in the Bayan energy resolution which is smaller than 0.5%.

The prototype provided good energy resolution (Fig. 6.16), high light yield ($N_{p.e.} = 1000$ per 1 GeV electron) and low lateral nonuniformity (less than 1%). The use of molded scintillators, for which a cheap mass production technology now exists, is a great advantage.

The beam tests at higher energies show a low constant term in the energy resolution: $\sigma_E/E = 0.78\%$ (1.1%) has been achieved in a 100 GeV (50 GeV) electron beam. The dependence of the energy resolution on the incident angle of the electron beam is shown in Fig. 6.17. Significant degradation of the energy resolution is not observed except for angles of 10 - 20 mrad.

The beam tests with a low energy electron beam, and a phototetrode readout (Hamamatsu R2149) show an equivalent noise level of about 30 MeV/cell.

6.7.2. A future R&D program

The Felix Collaboration is considering an R&D program with the aim of optimizing the calorimeter design, studying prototypes and improving some of vital parameters of materials used for the experimental setup application. There are several directions for this research:

- We will build and study a calorimeter with as fine a sampling as possible within the limits of technological and mechanical problems: $\sigma_E/E = (5 - 7)\%/\sqrt{E} \oplus 10\%/E \oplus 0.5\%$, $X_o \sim 15$ mm, $R_m \sim 30$ mm.
- We would like to have as compact a calorimeter as possible, i.e one with a small Moliere radius. This means that the scintillator sheets must be as thin as possible and/or a scintillator with a smaller radiation length than usual is desirable: $\sigma_E/E = (6 - 8)\%/\sqrt{E} \oplus 5\%/E \oplus 0.5\%$, $X_o \sim 7$ mm, $R_m \sim 15$ mm.
- We will study a preshower and calorimeter prototype based on glass and quartz capillaries filled with liquid scintillator, and will study

Figure 6.16. The energy resolution of a Bayan prototype (open points) *vs* electron energy. The solid line is the result of a fit yielding $\sigma_E/E = 8.1\%/\sqrt{E} \oplus 0.3\%$.

Figure 6.17. The energy resolution *vs* the angle between the direction of the incident electrons and the scintillator sheets.

possible new structures for high radiation resistant calorimeters;

- We plan to perform a detailed computer simulation of the shower development within the calorimeters to optimize the structure, light collection and longitudinal sampling. A detailed Monte-Carlo simulation should reveal the effects of irradiation on the parameters of calorimeters (such as the spatial and energy resolutions) in order to formulate the permissible levels for the losses in calorimeter light output. This will make our prediction of the radiation resistance of the materials more accurate.
- We are going to investigate new radiation resistant blue light emitting polystyrene scintillating plates, i.e. materials doped with so-called antiradiation dopants.
- We should find a method to stabilize the radiation resistance for delicate double-clad fibers. A quality control procedure for double-clad fibers should also be found.
- Experimental data indicate that a combination of green scintillating plates and orange WLS fibers can provide a higher level of radiation resistance [37]. We intend to investigate

the possibilities of using these materials for the FELIX forward calorimetry.

- There is little information on the levels of the radiation hardness of optical materials under high energy hadron irradiation. This type of irradiation will play a significant role in the FELIX experimental setup including optical materials, electronics (low noise amplifiers, etc.), photoreceivers, etc.
- The main problem with calorimetry based on liquid scintillators is the threat of leakage and evaporation. Because of this, we are going to search for new liquid scintillators which have a lower level of evaporation and a higher viscosity, such as mineral oils, silica-organic liquids, etc.
- The radiation hardness of the final versions of the electromagnetic and hadron prototype calorimeters should be investigated for both γ -quanta and high energy hadron irradiation.

6.8. Cost estimates

The estimates for the production costs are shown in Tables 6.9, 6.10, and 6.11.

6.8.1. Cost estimates for a QFC

The most expensive features this type of calorimeter are the quartz fibers which are costly. The remaining component and construction costs are approximately the same as for the scintillating fiber calorimeter. The cost for the quartz is about \$3 million for both arms. The cost of the tungsten (including the machining) is about \$470,000. The price of the photomultipliers (\$200 per unit) is \$450,000. So the total cost of the ZDC (ADCs not included) is \$3.92 million. This price is large, however by decreasing the packing fraction of the quartz, we could reach a compromise between the acceptable quality and the cost.

Table 6.9. Cost estimate of the D0, D1 and ZD calorimeters (per side).

	Western	Russian
D0		
capillary, 550 km	1670 kCHF	1110 kCHF
tungsten, 8.4 t	1680 kCHF	1265 kCHF
support	100 kCHF	70 kCHF
assemble	150 kCHF	120 kCHF
Detector	3.6 MCHF	2.56 MCHF
APD, 1500 p.	115kCHF	
Total	3.7 MCHF	2.7 MCHF
D1		
capillary, 180 km	540 kCHF	360 kCHF
tungsten, 2.7 t	540 kCHF	400 kCHF
support	80kCHF	60kCHF
assemble	120kCHF	100 kCHF
Detector	1.28 MCHF	0.92 MCHF
APD, 474 p.	35 kCHF	
Total	1.3 MCHF	0.95 MCHF
ZD		
capillary, 325 km	975 kCHF	650 kCHF
tungsten, 4.7 t	940 kCHF	710 kCHF
support	100 kCHF	70 kCHF
assemble	150 kCHF	120 kCHF
Detector	2.16 MCHF	1.55 MCHF
APD, 1000 p.	80 kCHF	
Total	2.24 MCHF	1.63 MCHF

Table 6.10. Cost estimate of the preshowers detectors (per side).

	D0, D1 and ZD preshowers	
	Western	Russian
capillary, 25 km	100 kCHF	75 kCHF
quartz fibers, 25 km	200 kCHF	150 kCHF
support	150 kCHF	100 kCHF
assemble	250 kCHF	200 kCHF
Detector	0.7 MCHF	0.525 MCHF
VLPC/APD, 44328 p.	450 kCHF	450 kCHF
Total	1.15 MCHF	0.97 MCHF

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Table 6.11. Cost estimate of the UA1 electromagnetic and hadron calorimeters (per side).

	Western	Russian
Electromagnetic calorimeter		
scintillator, 3.2 t	290kCHF	190kCHF
fibers, 100 km	150kCHF	
tungsten, 4.7 t	705kCHF	560kCHF
lead, 13.4t	130kCHF	90kCHF
support	320kCHF	250kCHF
assemble	450kCHF	350 kCHF
Detector	2045kCHF	1690kCHF
APD, 5504 p.	470kCHF	
low noise amplifiers, 5576 p.	160kCHF	110kCHF
Total	2.67 MCHF	2.27 MCHF
Hadron calorimeter		
scintillator, 2.4 t	215kCHF	140kCHF
fibers, 120 km	180kCHF	
copper, 152t	1370kCHF	1070kCHF
support	440kCHF	290kCHF
assemble	450kCHF	400 kCHF
Detector	2650kCHF	2080kCHF
HPD, 3188 p.	320kCHF	
Total	2.97 MCHF	2.4 MCHF

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7 Muon Detection

7.1. General considerations

Muons, like electrons, are essential in FELIX. The standard sources for prompt muons are the decays of heavy flavours (charm, beauty and top), W and Z decays and Drell-Yan processes. In addition, some more speculative muon sources, e.g. multi-muon bundles, are of particular interest to FELIX.

Muons are identified by their ability to pass through calorimeters and absorbers without strong interactions. The identification is therefore based on a comparison of the track direction before and after the absorber, which should differ only by the multiple scattering undergone in the absorber. As compared to electrons, the muon identification is easier in particular in the presence of hostile strong activities, like jets. The background, which is very dependent on the experimental set-up, can in principle be divided into two sources: muons arising from pion and kaon decays in the free space before the absorber and leakage from hadron-initiated cascades through the absorber. Muon identification and backgrounds in an LHC experimental environment have been discussed in detail in Ref. [1]. Extensive studies have been made in the RD5 experiment with the goal towards optimizing the absorber thickness [2] and

testing suitable muon chambers with trigger capabilities [3]. Relying on the extensive R&D experience, we will only mention in the following details specific to our set-up. We will not discuss details of the muon chamber construction.

7.2. Forward muon detection

We will concentrate on the muon identification in the two forward arms at production angles below 9° . The muon stations are naturally located just behind the three forward calorimeters at 10.65 m, 18.95 m and 33.25 m (see Fig. 7.1). The three stations are considered independently, i.e. muons traversing the absorber of the first station will not be followed through the subsequent stations, even if they fall into their acceptances. However, it is a good feature of our set-up that a sizeable fraction of muons passing the first calorimeter will be measured again in the D0 spectrometer. The thickness of the first calorimeter amounts to about 2 m Fe equivalent, which reduces the punchthrough probability of a typical 10 GeV hadron to some 10^{-3} [2]. At this level the particle leakage is driven by muons originating from the hadron cascade in the absorber.

Figure 7.1. Detailed view of the forward part of FELIX: the muon stations are indicated.

Figure 7.2. The pseudorapidity distributions of pions and kaons decaying into muons observed in each of the three muon stations. Also shown is the effect of a pointing cut of 1° , 2° and 4° .

This can be concluded from the slope change of the absorption curve at about 2 m Fe equivalent. To account for the higher particle energy (about 30 GeV) at the second station, the D0 calorimeter is thicker (2.5 m Fe equivalent).

While it is easy to raise the threshold of an electron calorimeter trigger, it is very demanding to determine the muon momentum with sufficient precision in the first or even second level trigger. The muon trigger is based on the existence of a track behind the absorber which is pointing within a given angular accuracy to the vertex. Hadronic leakage and muons originating from the absorber will rarely produce a pointing track. Since the muons are bent by the magnetic field before the calorimeter, an angular cut represents also a momentum cut, however with a less sharp threshold behaviour compared to the electron trigger. The precise muon momentum can eventually be determined in the third level trigger by reconstructing the muon track in the spectrometer in front of the absorber and by matching it with the track behind the calorimeter.

The muon chambers and related electronics have to permit a fast reconstruction of a track element and a fast decision on the pointing angle, which is the angle between the muon track and a straight line connecting the muon hits with the vertex. Each of the muon stations consists therefore of two position detectors separated by about 0.5 m to obtain a large enough lever arm for the track angle measure-

ment. This provides already on the trigger level, where only a crude position measurement of ~ 1 cm is obtainable, an angular resolution of the order of 1° .

We believe that a sharp pointing cut will eliminate leakage through the absorber and also background muons arising from upstream beam-gas interactions. The major background to prompt muons from the collision will therefore come from pion and kaon decays in the free space before the absorber. We have simulated these decays with particles from minimum bias events, generated by PYTHIA. Fig. 7.2 shows the pseudorapidity distribution of the decaying particles (pion or kaon) which produced muons in one of the three stations. The vertical scale is the number of muons per bin and event. There is an overlap in the pseudorapidity acceptances of these stations which arises from the bending in the magnets. 35% of all events have at least one muon in the first station, 13% and 0.4 % in the second and third station, respectively. The momentum distribution of these decay muons is shown in Fig. 7.3. Low momentum muons are bent into the acceptance of the first station, whereas the third station accepts only very high momentum muons. Due to the Lorentz-boost, there are less decays the more forward the particles are emitted and the background therefore becomes smaller. Nevertheless, each second event will have at least one decay muon which makes it obvious that further cuts have to be applied on the trigger level.

Figure 7.3. The momentum distributions of muons from pion and kaon decays for each of the three stations.

To obtain the efficiency we traced muons with different momenta through the detector and applied the pointing cut in the bending plane. The result is shown in Fig. 7.4 where the muon efficiency is plotted versus the momentum for the two first stations which suffer from the largest background. Most of the muons in the first station behind the UA1 calorimeter are below 10 GeV and will be removed by a 2° cut. The appropriate cut for the second station is between 2° and 4° . Because of multiple scattering in the absorber, the efficiency curves are not very steep, in particular for the small angle cuts. The effect of the pointing cuts of 1° , 2° and 4° on the pseudorapidity distribution can be seen in Fig 7.2.

7.3. Background rates

By applying the appropriate cuts in the first two stations and no cut in the third one, we can calculate the one and two muon rates arising from the background. The result for different cuts is summarized in Table 7.1 for the individual stations and for the complete event. In the case of a one muon trigger, the event rejection varies between a factor of 5 and 15, depending on the cuts. The two muon requirement yields a rejection factor of about 100. In comparison, it is worth mentioning that the fraction of events with at least one prompt muon is of the order of 10^{-3} . The above cuts can probably be done in the first or second level trigger, whereas a track reconstruction in the spectrometer with a more pre-

cise momentum cut has to wait for the third level trigger.

Table 7.1. Fraction (in percent) of minimum bias events containing 0, 1, >1 muons from pion and kaon decays. Numbers are given for the different stations individually and also for all stations.

1° station	No cut	4°	2°	1°
No muon	65.4	82.6	92.1	97.2
1 muon	26.4	15.5	7.5	2.8
>1 muon	8.2	1.9	0.4	$< 10^{-1}$
2° station	No cut	4°	2°	1°
No muon	86.5	93.1	96.8	98.8
1 muon	12.3	6.6	3.2	1.2
>1 muon	1.2	0.3	$< 10^{-1}$	$< 10^{-1}$
3° station	No cut			
No muon	99.6			
1 muon	0.4			
>1 muon	$< 10^{-1}$			
All stations	No cut	$4^\circ + 4^\circ$	$2^\circ + 4^\circ$	$1^\circ + 2^\circ$
No muon	56.3	76.6	85.4	93.7
1 muon	31.0	20.1	13.4	6.1
>1 muon	12.7	3.3	1.2	0.2

Figure 7.4. The efficiency of the angular pointing cut as a function of the muon momentum for the first and the second station.

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8 Backgrounds and Radiation

(In collaboration with N. Mokhov and A. Drozhdan, Fermi National Accelerator Laboratory)

The overall FELIX performance at the Large Hadron Collider (LHC) is strongly dependent on the background particle rates in detector components. Three sources can be identified as the major components of this background:

- Particle production at the interaction point (IP) and cascades initiated by them in the detector components (pp -background)
- Local beam losses
- Beam - gas interactions.

The contributions of these sources to the total detector load are not the same as for the high-luminosity detectors ATLAS and CMS. The contribution from the second and third sources should be relatively more important for FELIX, since the machine background depends on the beam current but the pp background depends on the luminosity.

In this chapter the results of the pp background simulation and estimations for the machine background, on the basis of extrapolations of simulation data for the high-luminosity experiments[1], are presented.

8.1. Simulation of the pp background

8.1.1. Simulation tools

The DPMJET-II event generator [2], based on the Dual Parton formalism [3], has been used to simulate pp collisions. It has the virtue that it treats both soft (low p_T) and hard (minijet, large p_T) processes in a unified and consistent way. 2000 minimum bias proton-proton interactions at $\sqrt{s}=14$ TeV have been generated. They include elastic and single diffractive events.

The multipurpose, multiparticle transport code FLUKA [4,5] was used for the description of the FELIX geometry and the cascade propagation through detector media. The kinetic energy cuts for the transport of the secondary particles have been set as follows:

- thermal for neutrons,

- 50 Mev for antineutrons and neutral kaons, and
- 10 Mev for other particles.

The charged particle cuts in the FLUKA simulation need some explanation. When the energy of the charged particles drops below the cutoff, and when this cut-off is lower than 100 MeV (as in our case), the particles are not stopped, but are transported in straight lines until they come to rest.

The radial dimensions of the ALEPH, UA1 and D0 magnets were reduced by up to one nuclear collision length in order to save CPU time. This reduction did not strongly affect the radiation load on the main detector components. The total energy deposition, neutron fluences, and charged particle fluences were recorded.

8.1.2. Results

Figures IV and VI map the energy deposition and neutron fluence in one half of FELIX up to 20 m from the IP. Figures V and VII plot the charged particle and neutron fluence at the location of selected tracking stations. The plots are scaled to an integrated luminosity of $\int \mathcal{L} dt = 10^{39} \text{ cm}^{-2}$, corresponding to one year (10^7 sec) of exposure at $\mathcal{L} = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

Figure 8.1 indicates the radiation dose in the various calorimeters as a function of radial and longitudinal position. The distribution of the radiation load in the calorimeters can be clearly seen. The maximal radiation dose increases from the $5.1 \cdot 10^2$ Gy for the portion of the UA1 hadron calorimeter outside the magnet up to $9.6 \cdot 10^5$ Gy for the zero degree calorimeter. Plots are not displayed for the electromagnetic and hadronic parts of the calorimeter inside the UA1 magnets. The maximum radiation dose in these calorimeters is $1.9 \cdot 10^3$ Gy and $1.2 \cdot 10^3$ Gy, respectively. Note that we have normalized all of these results to an integrated luminosity of $\int \mathcal{L} dt = 10^{38} \text{ cm}^{-2}$, corresponding to one year (10^7 sec) of exposure at $\mathcal{L} = 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$.

Of particular importance in detector design is the radiation dose level and neutron fluence in the tracking stations. The maximum dose levels for selected chambers and Roman pots are presented in Table 8.1.

The chambers in Table 8.1 are listed in order of increasing distance from the interaction point. One

Figure 8.1. The dose maps of the calorimeters after the UA1 magnet for $\int \mathcal{L} dt = 10^{38} \text{ cm}^{-2}$.

Table 8.1. Maximum dose levels and neutron fluences for selected chambers and Roman pots.

Characteristics	Chamber 5	Chamber 11	Roman pot 16	Roman pot 23
Dose level [Gy]	$8.3 \cdot 10^3$	$3.7 \cdot 10^3$	$2.3 \cdot 10^3$	$1.72 \cdot 10^2$
Fluence [n/cm^2]	$1.8 \cdot 10^{12}$	$1.4 \cdot 10^{12}$	$2.9 \cdot 10^{12}$	$1.1 \cdot 10^{13}$

Figure IV: The map of energy deposited in one half of the FELIX detector at $\int \mathcal{L} dt = 10^{39} \text{ cm}^{-2}$.

Figure V: The charged particle fluence at $\int \mathcal{L} dt = 10^{39} \text{ cm}^{-2}$ for the chamber at the face of the ECAL in the UA1 magnet and the last chamber of the D0 magnet.

Figure VI: The map of neutron fluence in one half of the FELIX detector at $\int \mathcal{L} dt = 10^{39} \text{ cm}^{-2}$.

Figure VII: The neutron fluence at $\int \mathcal{L} dt = 10^{39} \text{ cm}^{-2}$ for the chamber at the face of the ECAL in the UA1 magnet and the last chamber of the D0 magnet.

can see that, while the dose level decreases with the distance from the IP, the value of the neutron fluence increases. The largest neutron fluence is expected at the face of the zero degree calorimeter, and is near 10^{13} neutrons per cm^2 .

8.2. Estimation of the machine background

Accelerator related backgrounds in the detector are induced by beam losses at limiting apertures of the lattice and by beam interactions with the residual gas nuclei inside the vacuum pipe. The expected beam loss rates are given in [1,6] for all the envisaged loss-inducing processes: inelastic and elastic beam-gas scattering, inelastic, single diffractive and elastic pp collisions, and machine imperfections. With two high-luminosity experiments operating simultaneously diffractive protons from IP1 and IP5 can be lost in the IP4 region. The studies [1] show that with a beam cleaning system embedded into the lattice the beam loss source term in the IP vicinity is composed of three components:

- beam-gas inelastic interactions in the warm and cold sections of the IR and adjacent arc sections.
- quasi-local interactions of the beam halo tails from the beam cleaning system with the IR components.
- quasi-local interactions of diffractive protons from another IP with the IR components.

Using results of recent studies of the LHC vacuum system [7,8], the following beam-gas inelastic interaction rates in the vicinity of IP4 can be used [1]:

- $500 \text{ m}^{-1}\text{s}^{-1}$ in warm and cold straight sections.
- $2 \times 10^4 \text{ m}^{-1}\text{s}^{-1}$ in cold arcs.

Analysis shows that the beam losses in the $\pm 700 \text{ m}$ region from the IP can be a source of background in the FELIX straight section [1,9]. As a result, many particles are generated in the accelerator components. Some of them can reach the detector. Especially dangerous are high energy muons, which are produced mainly in π , K or heavy flavour decays following the interaction of beam particles with machine elements or residual gas in the vacuum pipe. A full Monte-Carlo in a complete FELIX geometry with the final IP4 lattice is required to obtain detailed background distributions in the detector.

Positioning of the Roman Pots with respect to the beam is a critical issue. Monte Carlo simulations for the Tevatron forward detector at DØ [12] have shown that the number of halo particle trajectories which pass through the Roman Pot detectors is decreased by a factor of three if the Roman Pots are placed at $9\sigma_{x,y}$ from the beam rather than at $8\sigma_{x,y}$. The required geometric aperture in the LHC is about 10σ [6]. The LHC secondary collimators are positioned at 8σ from the beam axis at collisions. The aperture studies [13–15] have shown that for the optimized LHC collimation system the positioning of the FELIX Roman Pots at $\geq 10\sigma_{x,y}$ is required to avoid their irradiation, the generation of additional background in FELIX, and the creation of an additional limiting aperture in the machine. There is, in addition, motion of the beam in the LHC due to ground motion and power supply ripples on various time scales, from days to tenths of milliseconds. Slow displacements may be compensated using orbit measurements. Fast orbit displacement at the Roman Pot locations will result in an uncertainty of the particle angle in the IP, as calculated from the Roman Pot measurements.

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9 Triggering and Data Acquisition

9.1. Design issues for the trigger and DAQ system

9.1.1. The multi-level triggering scheme

The DAQ system for FELIX will be designed in a way similar to the ATLAS [1] and CMS [2] systems, in order to utilize as much of the R and D work carried out for those programs as possible. Its basic structure is a multi-level triggering scheme, which must reduce the trigger rate from 40 MHz to a rate acceptable for data recording. A schematic of how this is done is exhibited in Fig. 9.1[3].

The initial Level 1 triggering must be done for each bunch crossing. It must establish clean evidence of the presence of an event from the triggering constituents and produce a constituent-based trigger decision. This is achieved with simple algorithms based upon the topology of the elements of the detectors which fired, or upon special trigger counters and energy deposited therein. These local trigger decisions are produced near the detector front-end electronics by special circuitry. Compilation of these in the Global Trigger System (GTS) produces the global Level 1 trigger[4]. The processing is deadtimeless, and the decision to collect data related to a given bunch crossing is taken after a fixed latency of around 3 μ sec. During the Level 1 latency, the sampled data of all channels of all detectors are stored in data pipelines.

After a positive Level 1 trigger decision, the output data are associated with specific bunch crossings, formatted into event fragments, and stored for subsequent filtering by the Level 2 trigger. The output rate from Level I is estimated to be around 100 kHz.

The Level 2 system performs a fast decision on the event quality, based upon data from separate detectors or portions thereof, using more sophisticated algorithms. These may be realized by a set of dedicated hardware [5] or software [6] processors. The output rate from Level 2 is estimated to be roughly 10 KHz.

The Level 2 filtered data are combined into complete events by the event builder [3], and are filtered by the Level 3 computer farm [7]. Level 3 produces the complete event-based decision, and its task is to reduce the trigger rate from 10 KHz to one acceptable for data recording (around 100

MBytes/sec). We estimate the mean FELIX event size to be around 0.5 MBytes. Therefore the Level 3 rate might be around 200 Hz.

9.1.2. Basic subdivisions of the detector for DAQ and trigger algorithms

We assume a full-acceptance capability for at least tracking and triggering at the commissioning stage of detector and machine. An important consideration is how one triggers in the central region. Calorimetry will be continued into the central region if sufficient resources can be found. In the absence of central calorimetry, trigger signals for γ 's from the central rapidity region can originate in a modest extension of the microvertex detector, consisting of additional GEM chambers behind converter. The cost of such an extension is modest compared to the overall cost of the detector.

It will turn out that for the class of processes we have considered, nothing very exotic seems to be needed at the trigger level in order to select most of the processes of interest. There will be cases where one needs to trigger on an isolated lepton or photon of considerable p_T . And in many cases the trigger will be on hadronic and/or electromagnetic transverse energy, or on track multiplicity. This latter class of triggers we will lump together with the generic word "activity".

Especially in this latter class, there will be a large variety of processes whose characteristic signature is a *pattern* of activity: large amounts in some regions of phase space and very little in others. Hard diffractive processes (cf. Fig. 2.10) are an extreme example. Therefore there will be the demand that the phase space of the detector be subdivided and the activity in each subdivision be separately determined, with programmable patterns of activity distribution of the many subunits being available for selection at the trigger level.

The natural subdivision in the lego plot is that the basic subunit relevant for pattern triggers has a lego acceptance of $\sim 0.7 \times 0.7$, because most phase-space textures are of this scale or larger. Since the total phase-space lego area, excluding the special zero-degree endwall regions, is $\sim 16 \times 6 \approx 100$ lego units, this implies that there are about 200 subunits whose individual activities are interrogated at trigger level. This means that the information within

Figure 9.1. The FELIX triggering and DAQ scheme.

these basic cells is first compactified into a manageably small message. Alternatively, the data flow might be a continual merging of information from initially small pixels, say 0.1×0.1 in lego variables, via an inverted-tree structure, with local cluster and pattern algorithms applied at each stage of combination to provide the required compactification of information. In what follows we shall, for definiteness, only consider the former option.

9.1.3. Summary of trigger constituents

Modularity and local preprocessing will be an important element of the overall trigger strategy. At the local level, within an elementary 0.7×0.7 cell in the lego plot, a compactified set of information must be provided to the GTS in order to provide candidate trigger constituents.

The generic classes of such input information can include the following:

- Level of activity. Again, by the word “activity”, we simply mean the amount of hadronic or electromagnetic transverse energy, or the multiplicity of track candidates.
- Jet candidates (extremely large activity in a lego cell).
- Gap candidates (extremely low activity in a lego cell).
- Lepton candidates.
- Isolated photon candidates.
- Isolated hadron candidates, especially in the zero degree calorimeter.
- Isolated track candidates, in particular from the Roman-pots.
- Track segments (as input for higher level track triggers).
- Displaced-vertex candidates from the inner tracking system (Heavy flavors).

9.1.4. The delay problem

The distances between FELIX detectors and the GTS (100 m for the Zero Degree Calorimeter and 430 m for the most distant Roman pot type detectors, in both directions) are large. Therefore the time-delay for transmitting signals from the most distant Roman-pots to the central triggering system makes it rather tight to implement that information within a Level 1 trigger decision. The nearby

Roman-pots appear to be available, because the delay is less than $1 \mu\text{sec}$. Therefore fast preprocessing and a shorter pipeline may suffice. This option is, however, more problematic for the distant Roman pots.

9.2. Evolution in time of the FELIX data sets

9.2.1. Run scenarios

The first major data set containing inelastic events used for serious physics analyses is assumed to be of order 10^8 pp collisions, taken with essentially a minimum-bias trigger. The only selectivity provided at trigger level would address the rejection of bunch crossings with no interactions (or more than one interaction), and rejection of candidate events seriously contaminated with beam-gas background.

After such a minimum-bias run, an intermediate-luminosity run could be naturally implemented using only the Level 2 trigger strategy and a choice of interaction rate compatible with the lack of rejection that Level 1 would provide. Such a strategy would seem to maximize the flexibility of choice of detailed triggers, and leave to a minimum the amount which is hard-wired into the front end of the DAQ system. We assume here that this intermediate-luminosity run might yield of order 10^8 recorded events for 10^{11} pp interactions in the FELIX detector, i.e. have a rejection of order 10^3 .

Finally, the design run, fully implementing the Level 1 and Level 2 triggers, should be expected to yield 10^8 recorded events per 10^{14} interactions in the detector.

The detailed choice of the trigger algorithms should probably be deferred for as long as possible, for at least two reasons. One is technological; the rate of change is so large that one should opt for as modern hardware (and software) as possible. The other is the physics itself, which is evolving and will continue to evolve rather rapidly with time. It is not easy to anticipate in detail what will be the highest-priority QCD physics to address at the time of LHC commissioning.

9.2.2. The minimum bias data set

The topics which are accessible already at the minimum bias level are large in number, and include most of multiparticle production dynamics: e.g., multiplicity distributions and their factorial and cumulant moments, inclusive distributions including composition dependence, correlation functions, cor-

relation moments and factorial correlators, wavelet analyses of final-state texture, and leading-particle “tags” for “meson beams”. These topics are defined by the nature of the diagnostic tool, rather than the nature of a specific physical phenomenon of interest. They can and should be first applied to the most commonplace, generic, relatively featureless class of final states. However, in event subclasses requiring a trigger, these techniques are still applicable and should be applied.

The minimum-bias menu can also be classified according to the physical phenomena of interest. One broad classification is minijet production due to the high parton densities or to the BFKL mechanism within the primary subprocesses. A corollary of this is the search for exotic effects such as thermalization, exotic new structures in the forward fragmentation region, intermittency, or creation of disoriented chiral condensate via the baked-Alaska mechanism, or of coherent pion production in large-impact-parameter collisions. These processes will have signatures, some of which may be triggerable, and some of which by definition will be as unpredictable as the basic phenomena themselves. There is an important design criterion implicit here on the structure of the triggering/DAQ system. It is *flexibility*.

Multijet physics and soft diffraction are also accessible at the minimum bias level. There should be a clean dijet sample, with size $\sim 10^{5-6}$, just from the minimum-bias running. Even after removing a factor 100 to isolate an extra rapidity gap, the sample is still of respectable size. In the same way, multijet final states, with all jets at the same p_T scale as the above-mentioned dijets, can be accessed up to a total multiplicity of 4 or 5, because addition of each jet costs no more than a factor $\geq 3\alpha_s/2\pi \sim 0.1$ in rate. However, the main studies of jets and/or hard diffraction will benefit greatly by specialized triggering, to which we now turn.

9.2.3. The intermediate data set

Any feature of generic events which occurs at the part per thousand level is a prime candidate for thousandfold enhancement in statistics in the intermediate data set, provided an efficient trigger for such events can be found. Diffractive triggers using the Roman pot information would open up a very large class of processes for study. In hard diffraction, even without the Roman pots, two extra rapidity gaps in an accessible minimum-bias sample of jet events is another example. The trigger can be on pattern, as already alluded to in Section 9.1.2. Other examples would be the presence of a leading-

particle tag. In the case of a leading neutron, a signal and pattern in the zero degree calorimeter might already suffice; for Δ^{++} or Λ a more sophisticated track trigger would be needed. Drell-Yan dilepton and direct photon triggers for the small- x physics fall into this category, as well as secondary-vertex triggers for determining the fraction of an event sample containing heavy flavors. Many of the BFKL physics applications imply an enhanced heavy-flavor ratio in the phenomenology, so that there will be most likely no shortage of theoretical motivation for doing this. Of course this class of physics goals also enhances the desirability of having very good lepton triggers, with displaced-vertex capability built in.

9.2.4. The design-level data set

There are not too many processes which were explicitly discussed in the physics overview which *require* the design level of luminosity for their first observations. Among the ones that do require this are the spectroscopy of charmonia or bottomonia in either Pomeron-Pomeron, γ -Pomeron, or $\gamma\gamma$ collisions, coherent semihard diffraction dissociation of proton or pion into jets, observation of W , Z , and Y production in various processes, and double superhard Pomeron exchange. Again, this clearly does not exhaust the list of processes which require the design-level trigger rejection. All pairwise combinations of the intermediate-level triggers are in this category.

It therefore seems especially premature to go into detail into the specific physics motivations for this design-level trigger now. Instead, the general criteria, including flexibility most of all, need to be addressed first.

9.2.5. Benchmark processes

Because there are so many topics in QCD which can be pursued within the FELIX program, it is very desirable to select a few for detailed study in order to obtain some focus on the real-life problems in implementing the general guidelines. A preliminary selection of a number of processes has been made. It will take time and more resources to assess how these processes are accessed by a FELIX DAQ system. We enumerate these below, roughly in increasing level of difficulty, with some brief commentaries:

- **Elastic scattering of protons at large t :** This process was done at the ISR, but truly large t has not been attained since. It requires special run conditions and evidently exercises the Roman-pot capability of FELIX.

- **Spectra of leading particles:** This is an important minimum-bias measurement, straightforward in principle. In practice it exercises comprehensively the performance of the detector in the far-forward D1 and ZDC regions.
- **Mueller-Navelet jets:** This process is characterized by jet detection at very forward angles (a few milliradians), together with study of the associated activity between them (jets, rapidity gaps, quiet underlying event structure, etc.) It is interesting technically because the jet reconstruction and trigger algorithms may be not completely conventional, because the jet products are so close to the beam axis, are in strong magnetic fields, and are often shared between different FELIX detector elements.
- **Parton distributions at small x :** The relevant processes are forward production of dileptons, dijets, and jet + γ . These processes especially exercise the $e/\mu/\gamma$ forward acceptance and trigger capability of FELIX.
- **Hard double-Pomeron exchange:** This process, consisting of four jets and two or three rapidity gaps in full acceptance, (cf. Fig. 2.10, panels (n) and (y)), will have a small cross section but a very rich pattern structure. It therefore exercises strongly the capability of the global pattern trigger.
- **Tagged pion dissociation into dijets:** This process, discussed in Section 2.1.5.2, is a low cross-section, soft single diffraction process, which may require putting Roman-pot signals into the trigger, as well as strongly suppressing beam-gas backgrounds.
- **Proton diffraction into three jets from nuclei:** The physics, discussed in Section 2.1.5.1, is related to the previous case, but the triggering (cf. Section 2.3.2.2) involves how the products of a dissociated ion are seen in the FELIX forward acceptance. It is a different and perhaps more difficult observation than the preceding case, where there is a clean Roman-pot diffractive proton as part of the tag/trigger.
- **Vector meson production in $\gamma\gamma$ collisions:** This process addresses the problems, discussed at length in Section 2.4.2, of separating $\gamma\gamma$ signals from double-Pomeron exchange and coherent photoproduction backgrounds.

Summary

One conclusion following from the above discussion is that, first, the initial complement of FELIX physics is not highly dependent upon the development of sophisticated trigger algorithms. It will however depend upon the successful management of the very large, very fast data flow. Here the experience of the other LHC enterprises will be of great help.

However, in the long run a sophisticated collection of triggers will be essential. An important corollary is that the trigger strategy and architecture should be as flexible as possible. The trigger cannot only focus upon a limited class of processes. It must provide well defined tools for programming into the DAQ system the many selection criteria of interest.

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10 Integration into the LHC Environment

(In collaboration with K. Potter EST/LEA & E. Sabin EST/LEA)

The proposed layout of the LHC has horizontal beam cross-overs at P1, P2, P5 and P8 (see Fig. 10.1). All four zones are allocated to one of the four experiments which are either approved or already under consideration. In order to create a fifth experimental region at the LHC, a different crossing scheme is necessary. Fortunately, at the time of the decision to cross the LHC beams only four times rather than eight (a decision taken in the interests of economy), it was established that a "beam kissing" scheme would be feasible. Thus it is possible to bring the two beams together, returning them to the same outer or inner arc. Such a scheme is possible in particular at P4 where it was decided to install the RF cavities at the extreme ends of the straight section leaving the central region available for a future experiment. Point 4 is in fact the only reasonable point where FELIX could be installed. Point 6, the only other LEP experimental cavern not already al-

located to an experiment, will be used for the LHC beam dump equipment. This requires a double septum magnet in the center of the insertion and is thus unsuitable for an experiment.

Point 4 has an available underground cavern of the standard LEP type, that is a roughly cylindrical cavern 21.4 m in diameter and 70 m long, placed orthogonal to the machine tunnel, as shown in Fig. 10.2. This cavern (UX45) and the other facilities for experiments at P4 are presently used by the LEP experiment ALEPH. Since FELIX proposes to reuse the ALEPH solenoid, it is natural that it should stay in UX45 with the additional forward detectors of FELIX installed around it. It follows that the very forward detectors in the adjacent straight sections and dispersion suppressors must be integrated into the special machine insertion designed around the requirements of the RF cavities [1]. The details of the magnetic optics which will provide LHC collisions at the center of point 4 are described elsewhere in this Letter of Intent. The LHC beams will be 300 mm above those of LEP with the collision points

Figure 10.1. Schematic layout of the LHC.

Figure 10.2. FELIX Experimental Hall, isometric view.

directly above the present LEP interaction regions. Hence to obtain LHC collisions in the center of the ALEPH solenoid it will be necessary to raise the magnet by 300 mm. This can be done without great difficulty, but attention will have to be paid to potential interference with the overhead bridge cranes.

The LEP caverns are equipped with a telescopic shielding which can be moved out from the machine tunnels on each side of the detectors to assure the shielding link between the detectors and the cavern walls. This self-shielding property of LEP experiments will be inadequate for the LHC and the "mobile shielding" can be dismantled to allow room for the forward magnets of FELIX, as seen in Fig. 10.3. In addition to the easily removable blocks of the mobile shielding, it will be necessary to remove a part of the supporting rampart on each side. However, this mass of concrete was added to the normal cavern shell and its partial removal should create no special problems.

The UA1 magnets will be largely outside the transverse range of the 40 tons hooks of the existing bridge cranes. However these magnets open to give access to their inner detectors. They could then be reached with an existing counter-balanced extension to the crane hook of limited capacity. The UA1 magnets will be installed by assembling them in the

central region of the cavern garage, raising them to beam height, sliding them out to the sides, using airpads for example and then along the side of the cavern on rails, making maximum use of the existing rails and support structures (Fig. 10.4). This procedure should be entirely feasible given their relatively modest size and weight (less than 600 tons).

The equipment access shaft (PX45) has a diameter of 10 m and is equipped with an 80 ton crane. While the diameter of the shaft would allow the UA1 magnets to be pre-assembled and tested on the surface, and then lowered complete, the crane capacity would be totally inadequate. A temporary heavy lifting device operating through the roof of the SX assembly hall could however be used. This type of operation is foreseen by CMS for their 2000 ton modules and could also be used on a smaller scale for FELIX. Alternatively, though less desirably, the magnets could be assembled from pieces of 80 tons or less in the UX cavern.

Access for personnel into the LEP caverns is possible during LEP operations via the PZ shafts. This is acceptable from a radiation point of view because the self-shielding of the detectors and additional mobile shielding provides the equivalent of 1m of concrete. With LHC beams the minimum personnel shielding is more than three meters of concrete. A

Figure 10.3. Available space for the FELIX central magnets.

Figure 10.4. FELIX central magnets as installed.

Figure 10.5. FELIX Experimental Hall, top view.

scheme has been worked out, illustrated in Fig. 10.5, which would allow the use of the PZ lift during LHC operation and allow access to a shielded zone behind a two to three meter thick concrete wall. If this wall is constructed on the PZ side of the TX connecting tunnel it will need to be extended up to the roof of the cavern, leaving both bridge cranes on the detector side available for installation and maintenance. Dividing the existing cavern into two in this way will require an analysis of emergency procedures and access to the detector region will be principally via the PM shaft. An emergency passage and controlled access through the new shielding wall will certainly be necessary, however. The exact thickness of the shielding wall will be determined once the radiation environment simulations using the Monte Carlo program FLUKA, have been completed. These simulations will indicate accurately the equivalent shielding thickness of the detector for both catastrophic LHC beam losses and normal collisions. The thickness to be installed in the different areas of the wall and the form of all passageways will then be agreed with the Radiation Group of TIS. The upper part and sides will be most conveniently built by casting concrete in situ. This will leave a central rectangular volume to be closed with standard blocks. If this central portion is built onto one or more roller

platforms on the existing floor rails, it can be assembled with the existing cranes and pushed into the remaining rectangular space in the cast structure. The approximate dimensions of this mobile part of the wall are 16 m wide by 12 m high, so that a three meter thick wall will weigh around 1500 tons, less than the central barrel of the ALEPH magnet. By pulling out this plug and partially dismantling it a large volume access can be provided to the counting rooms if needed.

The proposal illustrated in Figs. 10.2 and 10.5 shows all of the existing electronics barracks of the ALEPH experiment positioned behind this wall, where they can be used for the accessible electronics and other equipment of FELIX. Additional racks and cryogenics are shown close to the detector mounted on structures around the magnets in such a way that they can be rolled aside with the elements of the magnets, for access to detectors during shut-downs. The close electronics and other equipment will not be accessible during running, but this plan should allow the number of cables and optical fibers which have to go to the shielded counting rooms to be very much reduced. This is important, as a large number of penetrations through the shielding wall for cables, pipes and ducts will greatly increase the amount of concrete to be installed. The presence of

Figure 10.6. FELIX half-open during a shutdown.

the wall cutting the existing cavern into two separate volumes will of course mean some modification to the ventilation scheme. This has been studied in a preliminary manner and looks entirely feasible without any great additional costs. A thorough revision of the LEP ventilation equipment will be necessary in any case, as the current scheme of 100% fresh air is now considered extravagant and better control of the temperature and humidity is expected to be obtained with a recycling system. The fact that FELIX will not operate at high luminosity means that it will not be necessary to make special provisions for dealing with activated air. The revision of the ventilation and cooling system mentioned above is already being planned for point 8 and LHC-B. Similarly, rearrangements of other services such as electrical and fluid distribution and safety systems will also be necessary.

Also shown on Figs. 10.2 and 10.5 are the cold boxes of the machine cryogenic system which will be installed in the end of the UX cavern, a zone which will not be accessible during operation and which will leave 9.5 m to the beam line; more than adequate for all FELIX detectors. The cryolines from these cold boxes into the machine tunnel may have to be re-routed to leave space for access to the FELIX forward detectors.

At this stage it is not possible to make a detailed cost estimate for the rearrangement of the point 4 experimental area for FELIX. A rough indication can be taken from the budget of 6 MCHF foreseen for the adaptation of point 8 for LHC-B where much of the work is similar. This does not include any of the costs of the machine insertion nor any of the detector specific infrastructure such as supports, cabling, cooling and gas distribution. It is of course a very small sum compared to a new experimental area.

The installation of some of the machine cold boxes and cryolines will have to be via the PX, TX and UX and therefore must be carefully planned and interleaved with the installation schedule of FELIX. It will also be necessary to study other possibilities for the installation of the 17m long machine dipole magnets which are at present foreseen to traverse UX45 on a temporary platform. One possibility would be to enlarge the connecting galleries (UJ's) at the far end of the existing klystron galleries as is already foreseen at other points (P2 and P8). The surface hall at point 4 (SX) which also contains the surface control room of ALEPH and the other surface facilities available at P4 are expected to be entirely adequate for FELIX and no important modifications will be needed. A careful plan-

ning of the removal of existing equipment which will not be reused and installation of new equipment for both the LHC machine and experiment at point 4 will be needed. At this stage the sequence of the main events in the UX cavern is expected to be approximately as shown in Table 10.1. The sequence to be followed will be long, but should be entirely feasible within the four years available, without requiring any new facilities beyond the modifications described. After initial installation access to de-

tectors in short machine stops and also during long shutdowns is very important. First ideas on how the different magnets can be opened and displaced in such a way as to give access to the detectors inside is illustrated in Fig. 10.6.

References

- [1] The LHC Study Group, The Large Hadron Collider - Conceptual Design.
CERN/AC/95-05(LHC).

Table 10.1. The installation sequence in UX45 for FELIX and the LHC.

	Main task	Parallel task
1	End of LEP and ALEPH operation	
2	Withdraw the ALEPH solenoid with counting rooms attached to "garage". Uncable the ALEPH detectors and remove.	Prepare the FELIX magnets and detectors elsewhere at CERN.
3	Lift counting rooms D & E to the surface	
4	Dismantle (remove to the surface?) the ALEPH endcaps (500 tons) and coil; modify as necessary	
5	Install a temporary dust wall across the UX in the final position of the shielding wall.	
6	Carry out any civil engineering operations for machine and tunnel modifications which must be performed through the PX and UX.	Remove ALEPH electronics from all mobile counting rooms including D (on the surface) and install FELIX electronics.
7	Install the machine cryogenics in the US end of the UX	Install machine components in the straight section, RF cavities, magnets etc.
8	Install FELIX D0 magnets via the PX, TX & UX	
9	Reinstall the coil and roll the solenoid into the LHC beam position (raised by 300mm).	
10	Reinstall the revised counting rooms D & E.	
11	Construct the final shielding wall.	Start installation of FELIX very forward magnets via the PM and US.
12	Install a temporary crane (1000) tons & lower the modified end caps.	
13	Install the forward calorimeters.	
14	Lower and install the FELIX UA1 magnets equipped with detectors.	Install forward detectors in the machine tunnel via PM45.
15	Test the reopening and equipment access. Install the beam pipe.	
16	Complete installation of FELIX magnets, detectors and close electronics.	
17	Commission the LHC.	Commission FELIX.

11 Detector Performance

11.1. Tracking performance

11.1.1. General tracking considerations

The over-riding design philosophy of the FELIX detector is to attempt to detect and momentum analyze as many as possible, if not all, of the final-state particles produced in LHC pp collisions. In order to accomplish this goal for the case of charged particles, including those produced with high momentum at angles close to zero degrees so that the physics of rapidity gaps is not compromised, the tracking detector is based on the following principles:

- magnets in the machine will be used as spectrometer analysis magnets; hence, forward-going, final-state charged particles will be bent out of the beampipe at different locations depending upon their kinematics;
- tracking detectors will be located in front of each calorimeter; it is expected, therefore, that most tracks would end up in a calorimeter and not in an inactive part of the detector;
- each tracking detector should assist in providing a precise momentum vector for each charged particle. The aim is to achieve a spatial resolution of $50\ \mu\text{m}$ in each plane. The active volumes of the detectors closest to the interaction point (IP) and up to the D0 magnets are placed 25 mm from the center of the beam. In the region after the D0 magnets, all detectors are “Roman pot”-type detectors which, for this study, have been located in the beampipe at a distance of 10 mm from the beam center.
- the amount of material traversed by charged particles should be minimized; this will reduce both the multiple scattering contributions as well as the number of γ conversions;
- each charged particle should be analysed in one magnet and the momentum vector made more precise using the following magnet/detector. To aid in this, the magnetic field is higher in each successive magnetic complex as the particle proceeds downstream, i.e. the field in the D0 magnet is higher than in the UA1 magnet and higher in the D1 magnets

than in the D0 magnet. At the present time, the 5 RHIC-type, D1 magnets with a vertical field are foreseen to be at the same strength.

Fig. 11.1 displays an overall view of the FELIX detector and layout, demonstrating the “full acceptance” concept described above.

11.1.2. Acceptance for charged particles

The performance of the detector has been studied using three separate samples of Monte Carlo generated final-state particles:

1. a sample of 2000 minimum-bias (i.e., inelastic, nondiffractive) events have been generated with PYTHIA, using default parameters for the generation of particles at $\sqrt{s} = 14\ \text{TeV}$. In this sample, there are a total of about 80,900 charged particles with $\eta > 2.4$ and a similar number with $\eta < -2.4$.
2. a sample of charged particles which start at the IP but which are generated with a uniform distribution in transverse momentum, pseudorapidity and azimuthal angle; and
3. a sample of single soft diffractive events generated in POMPYT with a p_T cutoff set at 0.9 GeV.

The generated particles are tracked through the experimental layout and hits are generated for each detector plane traversed. Later these hits are smeared with the $50\ \mu\text{m}$ resolution and used for analysis. At this point in time, no reconstruction pattern-recognition program has been employed. All hits are automatically associated with the particle that produced them.

Figs.III(a,b) display the pseudorapidity (η) and momentum (p) distributions of the final-state charged particles. Each forward spectrometer (a system of plane detectors and a magnetic volume) will cover a certain range in η and p . The separate curves on the figures indicate the particles that are detected and momentum analysed in each of the separate detector spectrometers, independent of the precision achieved in the particular station. It should be noted that the meaning of “detected” here is defined as: the particle has been seen in at least

Figure 11.1. The top view of the FELIX detector, showing the different magnets and planar detectors.

2 stations, and the location of the vertex at the IP has been assumed.

One can see that the full acceptance of the FELIX detector is displayed in Fig.III(a) in that ~ 12 units of rapidity are covered (at this value of η , the statistics consist of only a few tracks per 2000 PYTHIA events). The spectrometers have been designed so that the acceptances of each detector are overlapping to a large extent, so that successive stations will provide a higher precision measurement. It is also clear that the likelihood of having two very forward particles is suppressed by the kinematics. Hence the occupancies in the more forward planes are expected to be small. The efficiency is determined by summing the curves in this figure, after correctly accounting for particles detected in more than one system.

Fig.III(b) indicates that the range of momenta produced (in 2000 minimum-bias PYTHIA events) extends up to about 7 TeV. The leading, forward-going, diffractively produced particles will be discussed later, using the POMPYT sample of events.

The acceptances are shown in Fig.III(a,b) illustrating that the FELIX detector generally has very high acceptance (above about 95%) over the full LHC kinematic range. The lower acceptance at $\eta \approx 7-9$ and momenta ~ 350 GeV is under study and it is expected that an additional Roman pot station (which will also provide an active detector volume

closer to the beam) at the exit of the D0 magnet would increase the acceptance. Similar results have been obtained using the sample of uniformly distributed particles. It should be noted that neutral particle decays are still under study. It is expected that the acceptance for detecting the decay products is high.

11.1.3. Detector station occupancy

To demonstrate the magnetic function of the various sub-spectrometers in the FELIX design and to determine the required spatial granularity and the optimum locations for the stations, Figs. 11.3(a-f) display scatter plots of the $(x-y)$ position of the particles at each of the following positions:

- (a) at the detector in front of the UA1 calorimeter (station 6);
- (b) at the detector in front of the D0 calorimeter (station 13);
- (c) at the detector at the exit of the $D1^1$ magnet (station 15);
- (d) at the detector in front of the D1 calorimeter (station 17);
- (e) at the detector in front of the $D1^4$ magnet (station 19); and

Figure III: The distribution of charged particles produced at $\sqrt{s}=14$ TeV as a function of a) pseudorapidity, and b) momentum. The different coloured regions represent particles measured in the different parts of the FELIX detector. The color key along the top axis identifies the specific spectrometer elements. These distributions are based on 2000 inelastic, nondiffractive events generated by PYTHIA. The overlapping acceptances from the various spectrometer elements can be clearly observed

Figure 11.2. The acceptance in FELIX for charged particle momentum measurements as a function of (a) the pseudorapidity; and (b) the momentum of the particles.

- (f) at the detector at the end of the D1⁵ magnet (station 22),

respectively. These distributions are based on the 2000 minimum-bias PYTHIA events. Fig. 11.3a shows a rather symmetric distribution, since the p_T -kick imparted to the particles at that point is about equal to the p_T at its production. As one proceeds further away from the IP, Fig. 11.3b shows the effect of the p_T -kick from D0 and that there is now a distinct separation based on the charge of the particle. Figures 11.3c and 11.3d show the effect of the vertical magnetic field in D1. There are fewer particles here since some have hit the D0 calorimeter and there are fewer high-momentum, negatively charged particles. The particles are now constrained to occupy specific regions in the azimuthal angle (ϕ). Similarly, Figs. 11.3e and 11.3f show the profiles at the front of the D1⁴ and the end of the D1⁵ magnets, respectively. The number of particles is now greatly reduced with even fewer negatively charged particles. It should be noted that the noninteracting proton beams are located at $(x = \pm 1.9, y = \mp 0.5)$ cm and $(x = \pm 4.7, y = \mp 0.44)$ cm at these two points in z .

Figure 11.4 shows the radial density distribution about the beam center ($r = \sqrt{(x - x_B)^2 + (y - y_B)^2}$, where x_B, y_B are the coordinates of the nominal center of the beam)

at each of the above locations. One sees that the density of particles decreases from about 2×10^{-3} particles/event/mm², at a distance of 25 mm in a non-Roman pot detector located at the exit of the UA1 magnet, to less than 7×10^{-6} particles/event/mm² at the exit of the D1⁵ magnet. These figures illustrate that the proposed granularity will accomplish the stated goal.

Fig. 11.5 displays the location along the beam direction (z -position) where each particle leaves the FELIX detector, illustrating the tracking station in which the particle is last detected. The shaded areas represent particles detected, but in fewer than two stations. In the region $z < 6$ m, these are particles with $p < 1$ GeV. The insertion of additional planes in this region is under study. The shaded area in the region around 20 m corresponds to the loss of ~ 350 GeV particles discussed earlier. Similarly, Table 11.1 shows the fraction of particles which are analyzed for the final time in each magnet. This table also provides the mean momentum of the particles so analysed.

Table 11.1. Track distributions from 2000 minimum-bias PYTHIA events in the FELIX detector.

Magnet/field	No. of tracks	Mean momentum
	%	GeV
ALEPH/solenoid	37.3	1.12
UA1/horiz. dipole	41.1	12.8
D0/horiz. dipole	18.4	128.9
D1-1/vert. dipole	1.1	1012
D1-2/vert. dipole	0.76	1276
D1-3/vert. dipole	0.28	2574
D1-4/vert. dipole	0.18	3395
D1-5/vert. dipole	0.05	4531

Figure 11.5 illustrates the degree to which the original goals of the FELIX detector have been achieved at the present time. Improvement could yet come from further optimization of the components. One sees that the largest populations occur immediately in front of the calorimeters located at $z = 7.9$ m, 16.9 m and 31.3 m (the UA1, D0 and D1 calorimeters), thus ensuring that these particles impinge on a calorimeter rather than, for example, on a magnet pole-face, as happens at 25 m and for $z > 35$ m. In addition, one observes that each of the more forward detectors (with $z > 18$ m) is effective in terms of detecting the charged particles.

Figure 11.3. (a-f) The $x - y$ position scatter plots of charged particles at various positions in z . The various locations are described in the text. These plots are based on 2000 minimum-bias PYTHIA events.

Figure 11.5. The location along the beam (z -position) where each particle leaves the FELIX detector. These plots are based on 2000 minimum-bias PYTHIA events. The shaded areas represent particles detected, but in fewer than two stations.

11.1.4. Momentum and angular resolution

An important property of the FELIX detector is its ability to detect and momentum analyze essentially all of the charged particles produced in pp collisions at the LHC. However, the performance of the detector should also reflect the precision achieved in determining the momentum vectors. Figs. 11.6(a-c) present the status of the present determination of the momentum resolution for particles whose final momentum measurement occurs in (a) the UA1, (b) the D0, and (c) the D1 dipoles. Figs. 11.6(a and b) are based on the PYTHIA events while 11.6(c) is based on the single charged particles generated with uniform distributions. The $50\ \mu\text{m}$ spatial resolution per detector plane and the multiple scattering contribution from the 2% radiation length for each plane traversed have also been taken into consideration in determining the precision in the measurement. These figures show the momentum resolution ($\sigma(p)/p$ in %) as a function of the momentum, p , for the different detectors. Here, $\sigma(p)$ is the estimated uncertainty in the momentum for a particular particle. For a given spectrometer volume, different combinations and different numbers of planar detectors will be traversed by different particles. Thus the curves represent the averages over many particles for each of the different configurations possible. The resulting performance for each configuration may be

Figure 11.4. (a-f) The radial distribution of charged particles about the beam center. The different curves correspond to different z locations, see text. These plots are based on 2000 minimum-bias PYTHIA events.

Figure 11.6. The momentum resolution for charged particles analysed in (a) UA1; (b) in D0; and (c) D1.

characterized by the expression

$$\frac{\sigma(p)}{p} = a + b \cdot p. \quad (11.1)$$

The results of fitting the data of Fig. 11.6 to this expression are presented in Table 11.2. It should be noted that the values of a are dominated by the multiple scattering contribution.

Figure 11.7. The polar-angle resolution ($\sigma(\theta)/\theta$) as a function of θ for particles measured with UA1, D0 and D1.

In Fig. 11.7 we show the expected resolution in the polar angle measurement as a function of polar angle, θ . The resolution is displayed in terms of $\sigma(\theta)/\theta$, where $\sigma(\theta)$ is the estimated uncertainty in θ for each detected particle.

Note that this figure extends up to $\theta = 0.022$ rad; between this angle and 0.20 rad, the resolution from UA1 is constant at about 4×10^{-3} . Again, the different curves correspond to different configurations, e.g., the higher set of D0 points (light grey crosses) represent tracks detected in 9 or more stations, while the black crosses are from tracks detected in 3-8 stations. The difference at the larger angles ($\theta > 0.01$ rad), arises from the extra material and the subsequent increased multiple scattering contribution.

The resolution in p_T , the transverse momentum of the particle, is shown in Fig. 11.8 as a function of p_T . In general, the resolution is better than 2%, except for particles with $p_T < 0.1$ GeV where the resolution rises to $\sim 30\%$.

Table 11.2. Momentum resolution determined from events detected in FELIX. The results of the fits to Eq. (11.1) are shown.

Mag. detector	a	b
UA1	3.6×10^{-3}	1.1×10^{-4}
UA1	3.3×10^{-3}	0.96×10^{-4}
D0	1.5×10^{-4}	2.5×10^{-5}
D0	3.2×10^{-4}	1.3×10^{-5}
D0	4.2×10^{-4}	9.3×10^{-6}
D0	1.0×10^{-3}	5.3×10^{-6}
D1	3.0×10^{-4}	5.4×10^{-6}
D1	2.0×10^{-4}	1.7×10^{-6}
D1	2.0×10^{-4}	5.0×10^{-7}
D1	1.0×10^{-4}	3.6×10^{-7}
D1	1.0×10^{-4}	1.0×10^{-7}

Table 11.3. The coefficients of the energy resolution for the UA1 electromagnetic calorimeter.

θ value	A in %	B in %
$\theta = 0.01$	0.66	6.4
$\theta = 0.05$	0.62	6.2
$\theta = 0.1$	0.67	5.4

both the shower reconstruction algorithm and from the tracking chambers it is possible to improve the energy resolution. Special studies using the combined tracking chambers and the ECAL coordinate reconstruction will be performed to study the reduction of the constant term.

Figure 11.9. The energy resolution of the UA1 ECAL for two different incident angles.

The selected cell size for the inner part of the electromagnetic calorimeter is fixed at 2.6 cm. This ensures that the main energy deposition from a single particle occurs in one cell. A typical energy deposition from a 100 GeV e^- is presented in Fig. 11.10. The separation of two particles with a relative distance of about 5 cm at the entrance to the calorimeter looks quite easy to distinguish. The standard technique of shower-profile fitting can be applied to separate closer showers.

The chambers positioned inside the UA1 magnet are placed near the electromagnetic calorimeter and can be affected by the albedo radiated from the calorimeter. During the Monte Carlo simulation, all particles which escape from the calorimeter in the

Figure 11.10. A typical energy deposition for a 100 GeV e^- .

backward direction were counted in order to estimate the albedo level. Fig. 11.11 shows the energy spectrum of these particles for an incident 300 GeV e^- . A separation of about 15 cm between the last

Figure 11.11. Albedo particle energy spectrum for an incident 100 GeV e^- .

chamber and the front of the calorimeter is sufficient so that, due to the magnetic field, these charged particles will not enter the tracking chamber. The neutral component (γ 's) of the albedo can be seen from Table 11.4.

Table 11.4. Mean number of albedo γ 's per incoming charged particle of energy E_{part} .

E_{part} [GeV]	10	30	100
$\bar{N}_\gamma/\text{particle}$	0.1	0.2	0.7

11.2.3.1. UA1 hadronic calorimeter

The UA1 hadronic calorimeter has been simulated in different modes with different ways of splitting the calorimeter body into two parts. For the mode of an unsplit calorimeter, the sampling parameters have been optimized. The current version of the calorimeter is based on a sampling ratio of Cu/Scint of 5/1. This gives an energy resolution of the form of Eq.(11.2) with the values of A and B as given in the first column of Table 11.5. The constant term is due to the transverse sampling structure and is a subject of optimization for the combined ECAL and HCAL simulation.

The split of the hadronic calorimeter was chosen to be 40 cm inside the UA1 magnet and 120 cm after the UA1 magnet coil. The resulting resolution function for this combination was obtained by the proper weighting of the energy depositions from the two parts.

Table 11.5. UA1 HCAL energy resolution coefficients. (H refers to the unsplit mode with no UA1 coil; C + H refers to the mode in which the entire HCAL lies behind the UA1 coil; and E+H+C+H refers to the mode in which the ECAL and 40 cm of HCAL lie inside the coil and 120 cm of HCAL lie outside the coil)

Coef. %	H	C+H	E+H+C+H
A	5.3	4.5	3.9
B	48.6	52.1	48.6

The combined simulation of the electromagnetic and hadronic calorimeters is a key point for the estimation of the Forward Calorimeter performance with respect to hadrons. The weights for the parts of HCAL were taken to be the same as for the stand-alone simulation. The only parameter for the optimization was the relative weight of the ECAL energy deposition. Finally, we get the values for the energy resolution function given in Table 11.5 where it can be seen that a small reduction of the constant term and an increase in the stochastic term was observed

compared to HCAL alone.

It can be seen that the reduction of the constant term is quite small. The final value of 4% is a factor of two higher than in our list of calorimeter requirements. Nevertheless, we believe that this can be reduced by further optimization of the design.

11.2.3.2. The very forward calorimeters (VFC)

The Very Forward Calorimeters (D0, D1 and Zero-Degree) have the same structure and consist of electromagnetic and hadronic parts, with preshower converters (PC) placed just in front of the electromagnetic part of the calorimeter. As they will work in the very forward region, the calorimeters should be quite dense so as to absorb hadrons with an energy in the range of $E_h > 1$ TeV. The main material considered for these calorimeters is tungsten but, as an option, we also consider the possibility of using lead as an absorber for the electromagnetic part of the calorimeters.

The Monte Carlo simulation has been done for both options for the electromagnetic part of the VFC – tungsten and lead. It was also assumed that the electromagnetic part is rotated about the x -axis by a small angle (~ 0.01 rad) to prevent particles from passing through parallel to the capillaries. The calorimeter was simulated in a stand-alone mode as well as with the PC so as to estimate its influence on the energy resolution.

The ECAL part of the VFC exhibits a good energy resolution in the stand-alone tests, although a dependence of the resolution on the particle coordinate at the entry into the calorimeter was observed that leads to the constant term in the energy resolution function. By adding the PC and combining the energy depositions in the PC with those from the main ECAL, in terms of MIPs, we obtain the same stochastic term but the constant term is reduced by almost a factor of two. The resulting energy resolution for both options of the ECAL are given in Table 11.6 and displayed in Figs. 11.12 and 11.13.

Table 11.6. Energy resolution function coefficients for the ECAL of the VFC.

Material	ECAL		ECAL+Preshower	
	A%	B%	A%	B%
Tungsten	0.92	10.76	0.64	10.99
Lead	0.91	8.35	0.57	8.87

Figure 11.12. Energy resolution for the ECAL of the VFC, without any preshower converter.

Figure 11.13. Energy resolution for the ECAL of the VFC with a preshower converter.

The combined simulation of the VFC for incoming neutrons was also performed. During energy reconstruction we neglect the energy deposition from the preshower converter and the following energy resolution has been obtained:

$$\frac{\sigma}{E} = 1.4\% \oplus \frac{55.5\%}{\sqrt{E}}.$$

11.2.3.3. Preshower converters (PC) for the VFC

Special studies have been undertaken to estimate the preshower converter performance due to its primary importance for the general reconstruction efficiency of FELIX in the very forward region. The PC coordinate reconstruction precision will greatly affect the mass resolution as well as particle separation in the VFC.

The current version of the PC consists of four layers, with 3 mm tungsten plates and two orthogonal coordinate planes in each layer. Each coordinate capillary plane is doubled but the second one is shifted by a distance equal to the capillary radius so as to overlap the dead zones in the capillary walls of the first plane.

Different versions of the PC have been considered. On the one hand, we need many capillaries to be hit by the developing shower so as to perform a consistent coordinate fitting procedure. On the other hand, the transverse shower size should be sufficiently small to ensure good spatial resolution between two incoming particles.

1. We have studied different tungsten plate thicknesses varying from 2 to 4 mm. It was observed that for small values of the thickness, the electromagnetic shower does not develop enough to ensure that the number of capillaries hit is suitable for the fitting procedure. For large values of tungsten thickness, a plane is affected by albedo particles from the following plane so that the precision of the coordinate reconstruction is reduced.
2. It is important to obtain not only the value of the coordinate but also the direction of the incoming particle in order to estimate the z -position of a possible secondary vertex coming from long-lived particles (Λ , Σ , Ξ). To estimate the entrance angle of the incoming particle we can use "sparse" preshower planes, i.e. spacing the planes with large distances between them. Spacings of 10 and 20 cm between planes have been studied. It was found that by spreading the planes we degrade the precision of the coordinate reconstruction dramatically.

The angular resolution, on the other hand, is not improved too much and cannot reach the desired value of better than 10^{-3} radians.

In the current version of the PC the planes are placed close to each other and the secondary vertex reconstruction is performed by means of constrained fitting for a particular final state.

A typical shower profile is given in Fig. 11.14, where the x -coordinate plane in the third layer is shown. The width of the shower is 0.6 mm and two showers separated by a distance of 2 mm can be easily distinguished. It should be noted that the transverse size of the shower profile does not depend on the energy of the incoming particle.

Figure 11.14. A profile of a typical shower. Each bin corresponds to a separate capillary.

The coordinate is reconstructed by fitting the shower profile in each plane to a Gaussian distribution with one iterative step to suppress albedo signals. After the first iteration, all hits with amplitudes less than 20% of the Gaussian maximum were removed and the fitting procedure was repeated.

The coordinate resolutions were determined for all planes and the resolution function was assumed to be of the form:

$$\sigma = A + \frac{B}{\sqrt{E}} \mu\text{m}.$$

The resulting resolution coefficients are given in Table 11.7 and shown in Figs. 11.15 and 11.16. The errors in the parameters shown in Table 11.7 will be reduced after additional Monte Carlo simulation.

Table 11.7. Coordinate resolution coefficients.

Coeff.	Plane	Iter.1	Iter.2
A	2	$64. \pm 6.$	$69. \pm 5.$
	3	$44. \pm 3.$	$43. \pm 3.$
	4	$41. \pm 6.$	$45. \pm 3.$
B	2	$377. \pm 40.$	$246. \pm 43.$
	3	$320. \pm 28.$	$276. \pm 25.$
	4	$447. \pm 37.$	$336. \pm 28.$

The efficiency of the coordinate reconstruction varies from 50% for 10 GeV γ 's to about 85% for 100 GeV γ 's. For low energy γ 's, the efficiency increases from the first plane to the fourth, while for high energy γ 's it remains practically constant from plane to plane.

Figure 11.15. Coordinate reconstruction from the PC after iteration 1.

11.3. Leading particles

The Zero-Degree calorimeter with PC has been tested in the mode of neutral-particle mass reconstruction. As a first test, π^0 and η 's coming from the primary vertex have been considered. The "minimum-bias" events were generated by PYTHIA.5.7 and γ 's entering the acceptance of the Zero-Degree Calorimeter have been considered. As no GEANT simulations have been done for this test, only γ 's with momenta $p > 30$ GeV have been considered. This cut removes secondary γ 's arising

Figure 11.16. Coordinate reconstruction from the PC after iteration 2, when low energy albedo particles have been removed.

from electromagnetic showers from the beam-pipe, magnets, chambers and the Very Forward Calorimeters.

All γ 's separated by a distance of less than 2 mm have been considered as a single cluster in the electromagnetic part of the Zero-Degree Calorimeter and the PC. The energy of the clusters and the reconstructed entry point have been smeared about their true values according to the energy and coordinate resolution functions discussed above.

All possible pair combinations have been calculated assuming the decay point to be at the primary vertex position. The resulting mass spectra in the regions of the π^0 and η are given in Figs. 11.17 and 11.18. The mass spectra presented show a very good mass resolution in the π^0 region that gives us the possibility to explore this in cascade decay reconstruction. As an example, the decays $\Lambda \rightarrow n\pi^0(\rightarrow \gamma\gamma)$ and $\Sigma^0 \rightarrow \Lambda(\rightarrow n\pi^0)\gamma$ have been considered. As have been generated with a fixed momentum (2 TeV along the z -axis), they have been propagated to the decay point generated in the standard way, and then they were allowed to decay into n and π^0 with a constant matrix element in its rest frame and the neutron and two γ 's from the π^0 decay were propagated to the z -position of the Zero-Degree Calorimeter. The same cuts as for the π^0 reconstruction have been applied to the electromagnetic clusters. Two electromagnetic clusters (if they are well separated) have been used to construct the π^0 mass using the z -position of the π^0 decay as a parameter to be determined by the fit. The quality of

Figure 11.17. $\gamma\gamma$ mass spectrum in the π^0 region.

the secondary vertex reconstruction can be seen in Fig. 11.19, where no backgrounds from any source have been included. The value of σ for the vertex position is 47 cm.

The reconstructed π^0 was required to have a z -coordinate of its origin, as obtained from the fit, which is a distance > 1 m from the primary vertex. The Λ -mass was then reconstructed assuming the Λ decay position coincides with the reconstructed π^0 vertex. The resulting spectrum for the $n\pi^0$ invariant mass in the Λ region is shown in Fig. 11.20.

Figure 11.18. $\gamma\gamma$ mass spectrum in the η region.

Figure 11.19. Secondary vertex reconstruction (without any background). The σ is 47 cm.

Figure 11.20. $\Lambda (\rightarrow n\pi^0)$ mass spectrum (without any background).

Figure 11.21. $\Sigma^0 (\rightarrow n\pi^0\gamma)$ mass spectrum (without any background).

A sample of Σ^0 with an initial momentum of 3 TeV is allowed to decay into a Λ and a γ at the primary vertex, and the decay particles are propagated to the Zero-Degree Calorimeter. A decay is generated in just the same way as described above. All combinations of γ 's have been considered as π^0 candidates and their decay positions are calculated. Any pair that gives a z -coordinate of the π^0 decay position with $z > 1$ m (for a Σ^0 that moves in the positive z -direction) is used to calculate the Λ mass. Combinations with a calculated M_Λ within ± 5 MeV of its Particle Data Group value are considered as good Λ candidates and all the particles determined in this way are used for the Σ^0 mass calculation. The resulting mass spectrum is given in Fig. 11.21. The efficiency of the Σ^0 reconstruction is around 30%.

As was mentioned above, all of these calculations have been performed with a pure sample of Λ and Σ^0 . In the Σ^0 mass spectrum only combinatorial background occurs. In the real situation we will deal with the physics backgrounds coming from the primary vertex and with particles from secondary vertices arising from particle interactions with material inside FELIX. The former source of the background can be estimated to be small because the mean number of primary particles coming into the Zero-Degree acceptance is around 2.5 particles/event.

The latter source of background can be strongly suppressed by applying a cut on the energy of the electromagnetic clusters.

Studies of leading particle decay modes involving charged particles have also been made. Preliminary results of, for example, Δ^+ decay modes, using

parametrized calorimetry and tracking resolutions as outlined above, confirm that the tracking is well-matched to the calorimetry, and that the mass resolution is small compared to the intrinsic width of the resonances. More detailed studies are in progress.

11.4. Elastic scattering and diffraction

11.4.1. Concept of the measurement

Forward protons with momenta close to the beam momentum arise either from elastic scattering or from single or double diffraction. These protons are very close to the beamline and can only be measured upstream using detectors housed in Roman pots, which allow one to approach the beams to small transverse distances. In the following considerations, the kinematics is expressed by the relative momentum loss ξ , and by the momentum transfer squared t . Useful variables are the production angles Θ_x in the horizontal machine bending plane (x) and Θ_y in the plane perpendicular to it (y). The case $\xi = 0$ corresponds to the elastic scattering while for the diffractive protons ξ is in the range of 10^{-7} to 0.1. The beam momentum spread of 10^{-4} does not allow the momentum measurement at the lowest ξ values. In order to detect protons over the largest possible range of ξ - and t - values and to measure them with good precision, the optics has to be optimized carefully and the geometrical restrictions imposed by the beam line, e.g. the exact shape of the vacuum chamber, including screens and other features need to be taken into account. Optimization implies that the displacement of the protons at the locations where detectors can be placed should be maximal, while at the same time, keeping the beam profile as small as possible. To follow a particle at nominal momentum through the machine lattice, it is convenient to use the optical transfer functions, which are expressed by the magnification v and the effective length L^{eff} (Eq. 11.3). $\Delta\mu_{x,y}$ is the betatron phase advance along the beamline at the point s for the betatron oscillations in the two projections.

$$\begin{aligned} L_{x,y}^{eff} &= \sqrt{\beta_{x,y}\beta^*} \sin \Delta\mu(s) \\ v_{x,y} &= \sqrt{\frac{\beta_{x,y}}{\beta^*}} \cos \Delta\mu(s) \\ \Delta\mu(s) &= \int \frac{1}{\beta(s)} ds \end{aligned} \quad (11.3)$$

The used variables are:

p_0	: beam momentum (7 TeV)
$\xi = \frac{\Delta p}{p}$	: relative momentum loss of the proton
$\xi_0 = 1.1 \cdot 10^{-4}$	: momentum spread of the beam
Θ^*	: production angle at the IP
$\Theta_{x,y}^*$	: projections in (x,z) and (y,z) plane
$\beta_{x,y}(s)$	: betatron amplitude at position s
$\beta^* = \beta(0)$	: betatron amplitude at IP
$\epsilon = 3.75 \mu\text{m} \cdot \text{rad}$	: normalized emittance
$t \sim p^2 \cdot \Theta^2$	: momentum transfer
D	: dispersion
$\gamma=7461$	: relativistic factor

Applying the above optical transfer functions, the transverse position of a proton along the beam line can be derived exclusively from the initial coordinate and angle at the IP $((x^*, \Theta_x^*), (y^*, \Theta_y^*))$

$$\begin{aligned} y(s) &= v_y(s) \cdot y^* + L_y^{eff} \cdot \Theta_y^* \\ x(s) &= v_x(s) \cdot x^* + L_x^{eff} \cdot \Theta_x^* + \xi D(s) \end{aligned} \quad (11.4)$$

As an example, the r.m.s. beam width can be calculated directly by adding the components in quadrature

$$\begin{aligned} \sigma_y^{beam} &= v_y \cdot \sigma_y^* \oplus L_y^{eff} \cdot \sigma_{\Theta_y}^* \\ &= \sqrt{\frac{\epsilon}{\gamma} \beta_y(s)} \\ \sigma_x^{beam} &= v_x \cdot \sigma_x^* \oplus L_x^{eff} \cdot \sigma_{\Theta_x}^* + \xi_0 D \\ &= \sqrt{\frac{\epsilon}{\gamma} \beta_x(s)} \oplus \xi_0 D \end{aligned} \quad (11.5)$$

with:

$$\sigma_x^* = \sigma_y^* = \sqrt{\frac{\epsilon}{\gamma} \beta^*} \quad (11.6)$$

and:

$$\sigma_{\Theta_x}^* = \sigma_{\Theta_y}^* = \sqrt{\frac{\epsilon}{\gamma \beta_{x,y}^*}} \quad (11.7)$$

The optics has to be optimized at the locations where detectors can be installed. Besides the free region of ± 120 m around the IP, there seems to be only one more location available without serious disturbance to the LHC design. This is 420 m away from IP, close to Q11 where a free space of 14 m exists. There is some hope of finding some limited free

Figure 11.22. The optical functions for $\beta^*=900$ m for the horizontal and vertical plane vs. the distance to the IP. At the top the phase advance is indicated; chamber positions are marked by an arrow.

space around Q9, but this location has not been considered in the following analysis. Thus the lay-out of the optics has to be designed so that L^{eff} is maximized and v is close to zero at the chosen detector position, which in our case is 420 m away from the IP. With such an optic, called parallel-to-point focussing, the position of a scattered proton does not depend on its position at the IP and therefore not on the beam size. From Eq. 11.3 it becomes obvious that parallel-to-point focussing occurs at phase advances $\Delta\mu = (n + 1/2)\pi$. For the elastic scattering with a proton on each side only one parameter, the scattering angle Θ , has to be determined. The coplanarity of the two protons helps to improve the measurements and to reduce the background. In contrast to this, in diffractive events, each side is independent and furthermore the diffractive proton is described by two parameters (ξ and Θ). The measurement of both parameters requires two stations with sufficient space between them.

11.4.2. Elastic scattering

In principle, the measurement of the scattering angle is best performed in the vertical ($y-z$) plane so as to be independent of the machine dispersion acting in the horizontal bending plane. The optics is designed [1] to maximise the vertical amplitude at Q11 of a trajectory starting with an angle at the IP.

The betatron value at the IP should be the largest possible. Its present limit of $\beta^*=900$ m, imposed by the RF, corresponds to a r.m.s. beam size of 0.6 mm, yet has the advantage of a small beam divergence of $0.7 \mu\text{rad}$ at the IP. To be independent of the large beam size, the phase advance at the detector position has to fulfill the parallel-to-point focussing conditions, i.e. $v=0$. Thus the vertical phase between the IP and Q11 should be close to $3/2\pi$. With the present dispersion suppressor it is possible to obtain a phase of 1.42π which is satisfactory. The associated beta functions around the IP were discussed in Chapter 4. The optical functions are determined using the tracking programme MAD [2] and are optimized for the detectors positions at 420 m in the vertical ($y-z$) plane. They are shown for both projections in Fig 11.22, where the phase advance is also indicated. The optimization has led to an effective length L_{eff} of more than 300 m in the ($y-z$) plane at the Q11 position, three times larger than in the other detector position which is at 120 m. As a result of optimizing the particle trajectory in the ($y-z$) plane, the optics is less favourable in the ($x-z$) plane, where the effective length varies between 20 and 60 m over the 14 m space close to Q11.

In order to demonstrate the possibility of detecting elastically scattered protons down to the small-

Figure 11.23. The 10σ beamprofile in the vertical and horizontal plane for $\beta^*=900$ m vs. the distance to the IP. The proton trajectories starting at the IP with $14.3 \mu\text{rad}$ ($t=0.01 \text{ GeV}^2$) are also shown.

est angles, the trajectories of two protons (opposite in ϕ), emitted with the nominal beam energy and an angle of $14.3 \mu\text{rad}$ ($t=0.01 \text{ GeV}^2$) have been traced and are presented in Fig. 11.23 for both projections. The 10σ beam profile, also shown, is the closest transverse distance to which detectors can be placed. Detectors positions are indicated by arrows. In the horizontal plane the contribution from the beam momentum spread ($1.1 \cdot 10^{-4}$) was added. It is obvious that the measurement at $t \sim 10^{-2} \text{ GeV}^2$ can only be done in the vertical plane. The upper t -value is limited by the vertical beam tube dimension of 18 mm (including the screen). As the largest displacement occurs at around 430 m, the scattered protons are not lost in the beam pipe between the IR and the detector. If the detectors approach the beam as close as 10σ , corresponding to a distance of 2.2 mm from the beam centre, the measurable range in momentum transfer squared is:

$$2.5 \cdot 10^{-3} \text{ GeV}^2 < t < 0.18 \text{ GeV}^2 \quad (11.8)$$

This range just overlaps with the acceptance of the station behind the D2 magnet measuring the large t -region (see Table 11.8). Increasing the overlap would involve the removal of the screen between 410 m and 430 m or else the installation of an additional station, e.g. at the Q9 position.

It is likely that special runs for low- t elastic scat-

tering will take place, each lasting a few hours, so as to accumulate the needed statistics. Only a tenth of the nominal beam current would yield the required luminosity. In these special runs, one could envisage changing the bunch structure, squeezing the emittances by a factor 5, and approaching the beams more closely with the detectors. The larger overlap in the t -range of the measurements at 120 m and 420 m would enable us to calibrate the measurements against each other with the aim to reduce uncertainties arising from the position and the field of the machine magnets. The smallest measurable t value could then be well below 10^{-3} GeV^2 . It is an advantage of the large effective length (300 m) that these small t -values can still be reached at a reasonable transverse distance of about 1 mm. In summary, the complete t -range is covered with detectors placed behind D2 and before Q11, where the free space of 14 m allows the installation of a spectrometer with a lever arm of 10 m.

We will now consider the t -resolution for elastically scattered protons. The optical functions, the dispersion and the beam profile at the above detector stations are summarized together with the t -acceptance in Table 11.8. Using Eq. 11.4, the particle displacement in x and y at the various stations can be calculated from the position and the emission angle at the vertex. ξ is then the beam momentum

Table 11.8.

The values of the optical function parameters for the FELIX experiment					
$\beta^* = 900\text{m}$	$L_{EFF} \text{ (m)}$	v	$D \text{ (m)}$	$10 \sigma \text{ (mm)}$	$t \text{ range, (GeV}^2\text{)}$
$s=120\text{m } x$	120.	1.	0.2	6.8	> 0.13
y	120.	1.		6.8	
$s=420\text{m } x$	-16.	-0.26	1.3	2.3	$0.0025 \div 0.18$
y	-293.	-0.083		2.2	
$s=430\text{m } x$	-51.	-0.18.	1.2	2.0	$0.0022 \div 0.1225$
y	-360.	-0.062		2.4	
$\beta^* = 110\text{m}$	$L_{EFF} \text{ (m)}$	v	$D \text{ (m)}$	$10 \sigma \text{ (mm)}$	$t \text{ range (GeV}^2\text{)}$
$s=120\text{m } x$	120.	1.	0.2	3.5	> 0.03
y	120.	1.		3.5	
$s=420\text{m } x$	-76.	0.19	1.3	2.2	$0.021 \div 2.0$
y	-87.	-0.66		2.4	
$s=430\text{m } x$	-60.	0.3	1.2	2.0	$0.025 \div 1.4$
y	-106.	-0.69		2.8	

spread ξ_0 . As an example, the hit distribution in the transverse plane at 420 m is plotted in Fig. 11.24 for protons with $t=0.01 \text{ GeV}^2$.

Figure 11.24. Hit distribution at $s=420 \text{ m}$ for protons with $t=0.01 \text{ GeV}^2$. The vertical cuts correspond to the 10σ beam profile.

Note that the horizontal and vertical scales are different. They are scaled with the ratio of the effective lengths in the two planes so that the points are uniformly distributed on a circle which is then smeared by the effect of the vertex position, the beam divergence and the momentum spread. As the

magnification v is three times larger in x than in y , the smearing amount is $160 \mu\text{m}$ (x) and $60 \mu\text{m}$ (y) due to the vertex uncertainty whereas the smearing is $14 \mu\text{m}$ (x) and $200 \mu\text{m}$ (y) due to the beam divergence of $0.7 \mu\text{rad}$ and $130 \mu\text{m}$ in x due to the momentum spread. 65 % of the protons with $t=0.01 \text{ GeV}^2$ exceed the vertical cut of 2.2 mm (horizontal line), representing the closest approach to the beam, and hence fall into the detector acceptance. With this cut we accept mainly protons which scatter in the vertical plane. Monitoring the acceptance in the analysis, we will additionally select protons with $\Theta_y \gg \Theta_x$. The effect of the vertex position can be completely excluded once the coplanarity of the two scattered protons is used. By taking an average of the two sides the scatter angle is given by:

$$\Theta = \frac{y_r - y_l}{L_{eff}^l + L_{eff}^r}. \quad (11.9)$$

With an adequate chamber resolution the final error of the scattering angle is given almost exclusively by the beam divergence. Taking an average of the two protons reduces this error by $\sqrt{2}$ to $0.5 \mu\text{rad}$ or 4 % at a scattering angle $\Theta = 14.3 \mu\text{rad}$. The error in t is then given by:

$$\frac{\sigma(t)}{t} = a \sqrt{\frac{10^{-2}}{t}} \quad t \text{ in } \text{GeV}^2 \quad (11.10)$$

where:

$$\begin{aligned} a &= 8 \% \text{ for } \beta^*=900 \text{ m} \\ &= 23\% \text{ for } \beta^*=110 \text{ m} \\ &= 50\% \text{ for } \beta^*=23 \text{ m} \end{aligned}$$

Figure 11.25. As Fig. 11.22 but for $\beta^*=110$ m.

Since the error is dominated by the beam divergence at the IP, it will not depend on the station location. However, the possible systematic uncertainties which may arise from beam- and vertex- displacement or due to the field- and position- changes of the magnetic elements, have not been taken into account.

The large beta value of 900 m will be used mainly for special runs so as to study elastic scattering at the lowest t -values, but most of the runs will take place with $\beta^*=110$ m, where the optical functions are not optimized anymore (Fig. 11.25).

In fact, the effective lengths at the close and the far stations are now of a similar value (approximately 100 m), which implies that the elastic scattering measurement will be performed almost exclusively with the close stations. The beta value of 110 m has been chosen to minimise the beam envelope around the D2 position. With a 10σ beam size of about 3mm the t - acceptance starts at $3 \cdot 10^{-2} \text{ GeV}^2$ as can be deduced from the beam profile (Fig. 11.26), which is almost independent of the azimuthal angle. The tracking stations in the D1 and the D2 regions will cover the complete accessible large t -range in both projections as demonstrated in Fig 11.27, where the efficiencies for the different region of the near stations are plotted versus t .

We intend to measure elastic scattering over the largest possible t -range from less than 10^{-2} GeV^2 to

Figure 11.26. As Fig. 11.23 but for $\beta^*=110$ m.

Figure 11.27. Acceptance vs t for the region behind D2 (a), between D1 and D2 (b), and D1 (c).

above 30 GeV^2 (see Fig. 2.20, page 36). Below 0.4 GeV^2 , the t -distribution follows an exponential law:

$$\frac{d\sigma}{dt} = 600 \text{ mb} \cdot e^{Bt}, \quad B = 20 \quad (11.11)$$

In order to obtain the total cross-section via the optical theorem, the intercept at $t=0$ has to be determined with great precision. Since statistics are large we will run at $\beta^* = 900 \text{ m}$, where the precision is best and the lowest t -value of about $2.5 \cdot 10^{-3}$ can be reached. Extrapolating to $t=0$ is then a 5% effect. Avoiding the threshold effect at the lowest t , the ratio of the measured-to-original distributions deviates from unity by less than 10^{-4} , enabling a precise extrapolation. To illustrate the statistics, Fig. 11.28 shows the cross-section per bin, where the binsize is variable and amounts to 10% of the t -value. Also given on the right hand scale is the corresponding number of events for an integrated luminosity of 10^{32} cm^{-2} . In a run of a few hours at a luminosity of $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ we obtain 10^4 to 10^6 events per bin in the exponential t -range ($t < 0.4 \text{ GeV}^2$). Above the diffractive pattern a power law with t^{-8} to t^{-10} , depending on the theory, is expected. It is of great interest to measure this tail of the t -distribution to the highest possible values. Fig. 11.29 presents the large t -range. With an integrated luminosity of 10^{39} cm^{-2} , i.e. continuous running over 3 years at a luminosity of $3 \cdot 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$, we obtain a few events per bin at 20 to 30 GeV^2 , depending on the t -behaviour. It is worth mentioning that these

rare events may also arise from double diffraction (Pomeron-Pomeron interaction) with both protons close to the beam momentum. The distinction of elastic scattering and diffraction is therefore essential. There are two features of FELIX which are of benefit to us. On the one hand, the hermetic acceptance of our detector allows us to measure even the smallest activities distributed somewhere over the phase space, thus helping us to identify double diffraction. On the other hand, the spectrometers at the near and far stations determine the proton angle with a precision of the order of $1 \mu\text{rad}$, assuming a position resolution $\sigma_{pos} = 10 \mu\text{m}$, independent of the relative momentum loss ξ of the proton.

$$\Delta\Theta = \frac{\sigma_{pos}\sqrt{2}}{\Delta L_{eff}} \quad (11.12)$$

Since the scatter angles of the diffractive protons are independent of each other, the coplanarity constraint will reduce the background from diffraction.

11.4.2.1. Total cross-section

The total cross-section σ_{tot} is the sum of the elastic and inelastic rates divided by the machine luminosity:

$$\sigma_{tot} = \frac{1}{L} (N_{el} + N_{inel}) \quad (11.13)$$

The optical theorem connects the total cross-section with the elastic scattering rate at $t=0$.

$$\sigma_{tot}^2 = \frac{1}{L} \frac{16\pi}{1 + \rho^2} \left. \frac{dN_{el}}{dt} \right|_{t=0} \quad (11.14)$$

By combining the two equations, we can determine the total cross-section in a luminosity independent way, provided the rate of elastically scattered protons is simultaneously measured together with the total inelastic rate.

$$\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \left. \frac{dN_{el}}{dt} \right|_{t=0} \frac{1}{(N_{el} + N_{inel})} \quad (11.15)$$

The ratio of the real to imaginary part of the forward elastic scattering amplitude ρ is not known at LHC energies, but its influence on σ_{tot} is probably small since its value is predicted to be between 0.1 to 0.2.

Above we have demonstrated the capability of measuring low- t elastic scattering with a high precision. It is a further great advantage that the full acceptance FELIX detector measures the total inelastic rate precisely, including low mass diffraction and forward particle production which are not accessible to any of the other LHC detectors. Most

Figure 11.28. Cross section per bin for low- t elastic scattering. The bin size is variable and equal to 10% of the t -value.

of these rates are unknown and Monte Carlo simulations may not describe the truth in the very forward cones. As an example, the low ξ behaviour of single and double diffraction is unknown at LHC energies and substantially adds to the error in σ_{tot} , if not measured. We therefore believe that FELIX is the only experiment that is capable of measuring the total cross-section with a precision of the order of 1% without any assumptions on the forward particle production. Likewise, partial cross-sections for given topologies, either in the central part or forward, will be determined. The other experiments and the machine can use them to their advantage to monitor their luminosities on an absolute scale.

11.4.3. Diffractive processes

A large fraction of the total inelastic cross-section is due to diffractive processes. Our principal interest in this section is the detection of quasi-elastic protons associated with processes such as single diffraction and double Pomeron exchange. In a simplified model, single diffraction is mediated by a Pomeron which interacts with the partons of the other proton giving rise to an excited mass M_X recoiling against the intact proton. The momentum transfer squared t and the mass M_X are determined by the recoil proton momentum :

$$t \sim -p_0 p_{rec} \cdot \Theta^2$$

Figure 11.29. As Fig. 11.28 but for the large t -region.

$$\xi \sim \frac{M_X^2}{4p_0^2} \quad (11.16)$$

where p_0 and p_{rec} are the beam and recoil proton momenta and Θ the scattering angle. The mass M_X of the diffractively produced hadronic system, as measured by the forward spectrometers and calorimeters, can be compared with the mass calculated from the momentum loss ξ of the recoil proton. The FELIX set-up enables the investigation of diffractive processes over a wide range of excited masses not accessible to the other experiments. In most of the cases, the intact proton can be detected down to the lowest ξ values. The measurement of diffractive protons is complicated by the fact that two variables, the momentum loss ξ and the scattering angle Θ , have to be extracted from the data. However, there is also an inherent advantage in this, namely that the protons can be pushed out of the beam halo either by their momentum loss or by their scattering angle. The momentum measurement of diffractive protons is performed in the horizontal ($x-z$) bending plane, where the dispersion is between 1.2 m and 1.3 m at the far station and reaches a maximum of 0.2 m at the near station. The transverse position of a proton along the beam line depends on the momentum loss ξ , the emission angle Θ and the transverse vertex positions (x^*, y^*), as described by Eq. 11.4. Figs. 11.22 and 11.25 show the optical functions for a β^* of 900 m and 110 m

respectively; Table 11.8 gives the values at the three stations. Since both the horizontal scattering angle Θ_x and ξ lead to an excursion of the proton in x , a spectrometer with a large lever arm has to be used for their individual determination. The excursions in the two detector planes are given by:

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} L_1 & D_1 \\ L_2 & D_2 \end{pmatrix} \begin{pmatrix} \Theta \\ \xi \end{pmatrix} + \begin{pmatrix} x^* v_{1x} \\ x^* v_{2x} \end{pmatrix} \quad (11.17)$$

$$\begin{aligned} y_1 &= L_{1y} \Theta_y + y^* v_{1y} \\ y_2 &= L_{2y} \Theta_y + y^* v_{2y} \end{aligned} \quad (11.18)$$

The two components of the emission angle Θ and the relative momentum loss ξ can be calculated from the above equations:

$$\begin{pmatrix} \Theta \\ \xi \end{pmatrix} = \frac{1}{\Delta} \begin{pmatrix} D_2 & -D_1 \\ -L_2 & L_1 \end{pmatrix} \begin{pmatrix} x_1 - x^* v_{1x} \\ x_2 - x^* v_{2x} \end{pmatrix} \quad (11.19)$$

with $\Delta = L_1 D_2 - L_2 D_1$

Propagating the errors and assuming a detector resolution of $10\mu\text{m}$, the uncertainties in ξ and Θ are determined mostly by the transverse vertex distribution and are similar in the far and the near stations:

$$\begin{aligned} \sigma(\Theta) &\sim 1 \mu\text{rad} \\ \sigma(\xi) &\sim 3 \cdot 10^{-4} \end{aligned} \quad (11.20)$$

These values are close to the beam divergence of $0.7 \mu\text{rad}$ ($2.1 \mu\text{rad}$) for $\beta^* = 900\text{m}$ (110m) respectively and the beam momentum spread of 10^{-4} . The dispersions at the near and the far stations differ by a factor 5 and consequently acceptances are different. How the acceptances of the near and the far stations tend to overlap can be seen from Fig. 11.30. The trajectory of a proton with a scattering angle of $\pm 50 \mu\text{rad}$ and a momentum loss of $\xi = 2 \cdot 10^{-3}$ is given in the horizontal plane together with the 10σ beam envelope. We have chosen the optimal beta value of 110m which minimizes the beam size at the near station and corresponds to our normal running condition. At the far station the particle is seen due to its momentum loss at the near station dominantly due to its scatter angle. A 1% momentum change is at the detection limit of the far station since the particle will hit the vacuum chamber before reaching the station (Fig. 11.31). In the near station such a particle cannot be observed for all t -values. The acceptance overlap of the two stations is marginal and an additional station around Q9 would definitely improve the situation. The situation is rather similar for $\beta^* = 23\text{m}$, except that the beamsizes are larger at the near station.

Figure 11.30. The 10σ beam profile in the horizontal plane for $\beta^* = 110\text{m}$ vs. the distance to the IP. Also shown is the trajectory of a diffractive proton with a scattering angle of $50 \mu\text{rad}$ and $\Delta p/p = 0.002$.

Figure 11.31. As Fig. 11.30 but for $\Delta p/p = 0.01$.

To obtain a better understanding of the proton acceptance we have generated diffractive events in a simplified way:

$$\frac{d\sigma}{dt d\xi} = C \cdot \frac{1}{\xi} \cdot e^{10t} \quad (11.21)$$

Fig. 11.32 shows the proton acceptance of the near station vs. t and ξ for the three beta values 110 m (a), 23 m (b), and 900 m (c). For the best case ($\beta^*=110$ m), almost all protons with $t > 0.03$ GeV² are observed even at the lowest ξ -values. The acceptance is on average 79% increasing towards 100% at the highest ξ -values. Fig. 11.33 shows the acceptance of the near station alone (a), of the far station alone (b), and the total acceptance of both stations (c). The two stations are complementary in their ξ -acceptance. It is of great importance that diffractive protons can be detected even if their parameters cannot always be well measured.

Figure 11.32. Acceptance of the near station for diffractive protons as a function of t and ξ for $\beta^*=110$ m (a), 23 m (b) and 900 m (c).

Figure 11.33. Acceptances as a function of t and ξ for the near stations alone (a), the far station alone (b), and both stations (c).

References

- [1] A. Verdier, *A tunable insertion in point 4 for the LHC*, LHC Project Note 93, June 26, 1997.
- [2] H. Grote, F.C. Iselin, CERN/SL/90-13(1995)

12 Costs, Schedules, and Organization

The FELIX LoI has been prepared with careful attention to the affordability of the detector, beamline and infrastructure. Working guidelines have been that the cost of the detector should be no more than about 50 MCHF, and that the cost of the beamline and infrastructure should be held to about 20-30 MCHF. These figures are approximately 10% of the costs associated with either ATLAS or CMS.

While these funds are not sufficient for everything that FELIX ought to have, the most notable absence being central calorimetry, this LoI demonstrates that FELIX will be a superb detector, with genuine full acceptance in charged particles, and complete calorimetric coverage for $|\eta| > 2.3$. The physics this buys, otherwise largely inaccessible at the LHC, is extraordinary.

Table 12.1 summarizes the cost of the detector presented in this LoI, while Table 12.2 shows the cost of bringing the beams into collision and of modifying the infrastructure at I4 for the experiment. The details of each estimate can be found in the appropriate chapter of the LoI. Wherever possible, these cost estimates have made use of similar estimates for other LHC experiments. Note that if the calorimeters are built in Russia, the total estimated cost for the detector is 48.9 MCHF.

It is important for FELIX to be commissioned concurrently with the LHC. FELIX thus seeks expeditious approval from the LHC committee to proceed to the preparation of the technical proposal in 1998. In the meantime, we will seek additional collaborators and work to identify funding sources.

Since FELIX is stageable, the decision to proceed to the technical proposal should not be postponed even if we have not yet identified sources for complete funding.

FELIX welcomes additional collaborators. The organizational structure of the collaboration has been kept as simple as possible during the period of preparation of this Letter of Intent. The organizational structure for the technical design phase of the FELIX collaboration has not yet been defined. It is expected that it will maintain the present open spirit of collaboration while providing a more formal definition of responsibilities.

System		Cost (both arms)
UA1 - magnets		2.8 MCHF
D0 - magnets		1.4 MCHF
D1 - magnets ^{a,b}	cryostats	2100 k\$
	cold mass	4930 k\$
D2 - magnets ^b	cryostats	420 k\$
	cold mass	1200 k\$
	other	440 k\$
Total magnets		17.8 MCHF
Infrastructure		6.0 MCHF
TOTAL		23.8 MCHF

^a Includes 2,150 k\$ for overhead, contingency and labor.

^b \$1.00 $\approx$ 1.5 CHF has been used.

Table 12.2. Cost of the FELIX beamline and infrastructure.

System		Cost (both arms)
Tracking	Silicon pixel tracking stations	10.9 MCHF
	GEM tracking stations	4.5 MCHF
	Roman Pots (mechanics)	1.2 MCHF
	Microvertex (Si pixels + GEM barrels)	1.4 MCHF
Calorimeters ^a	UA1	11.3 MCHF
	D0-D1-ZD	14.5 MCHF
	preshower	2.3 MCHF
Muon chambers		4.0 MCHF
Trigger / DAQ		5.0 MCHF
TOTAL^a		55.1 MCHF

^a Calorimeter cost is 6.2 MCHF less if built in Russia.

Table 12.1. The cost of the FELIX detector.