Detector Concepts

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1. INTRODUCTION

Over the last 10 years the scientific case for a linear collider has been made. After the decision by the international community, to build the machine in superconducting technologies, the efforts on the machine but also on detector and physics are being reorganised and restructured. While during the past years basic development work of detector technologies has been the focus of the detector oriented work, this is now shifting towards a stronger orientation towards overall detector concepts.

Starting in the summer of 2004, several detector concept groups have formed, encouraged by the world-wide Study [1]. In coordination with the emerging global design effort, GDE, lead by B. Barish, the community has been asked to develop at least two detector concepts, optimized, and priced, which can be used together with the machine proposal to set the stage for eventual negotiations for the realization of the international linear collider.

Throughout the year the efforts have focused on three separate detector concepts, called SiD [2], LDC [3] and GLD [4]. All three are organized internationally, with a leadership made up from people from all three regions involved in the ILC.

2. PHYSICS and DETECTORS

The physics case for the ILC has been worked out in some detail over the years and is documented in a number of papers [5–7]. It has been discussed and accepted by the world-wide particle physics community, and has been endorsed by numerous groups and committees in all three regions of the world. Starting from the physics case, requirements for a detector at the ILC have been worked out. Since precision physics is a major objective of the ILC, precision plays a central role in the list of requirements. At the core of the requirements however is the recognition that a detector at the ILC has to be able to reconstruct the topologies of the events as precisely as possible. The only method known so far which promises to allow the event reconstruction with sufficient accuracy is the so called "particle flow" method. In the particle flow, the contribution of each particle to the event is reconstructed, both for charged and for neutral particles. This puts unprecedented requirements on the ability of the detector to measure individual particles, even in multi-jet final states, and on its ability to reconstruct the energy and the direction of neutral particles. In addition to the capability for particle flow, the detector needs to provide a tracking system of very high precision, primarily for the measurement of isolated leptons, and very good vertexing capability, to help in the separation of heavy flavour final states. These requirements, which were first published in the TESLA TDR in 2001 [5] lead to a vigorous R&D program, both in the area of tracking and vertexing, and in the area of calorimeter developments. More details on this program can be found in [8].

The key performance parameters are summarized in table 2. In addition to the ones listed in the table the detector should be as hermetic as possible, with coverage down to a few mrad around the beam pipe.

Table I: Main detector specifications

Quantity	Value
Charged particle tracking	$\delta(1/p_t) < 5 \times 10^{-5}$ (GeV)$^{-1}$
Impact parameter resolution	$\sigma_{IP} < 5\mu m \oplus 10\mu m/p_t$(GeV)
Jet mass resolution	$30\%/\sqrt{E}$

2.1. Particle Flow

As outlined briefly in the previous section, a detector optimized for particle flow is one of the major requirements for the experimentation at the ILC. The method of particle flow has been first proposed for experiments at the LEP collider, as a way to improve the overall event reconstruction. It was used with some success at LEP and later at the Tevatron, though neither detectors were really optimized for this type of reconstruction paradigm.

The particle flow algorithm has the aim to optimize the reconstruction of the overall event, best measured in the measurement of masses through di-jet systems. The resolution can be improved if for each type of particle the best detector is used for reconstruction. Charged particles are reconstructed in the tracking system, photons in the electromagnetic calorimeter, and neutral hadrons in a combination of electromagnetic and hadronic calorimeter. Separating these components requires a detector with excellent particle separation capabilities, which translates into calorimeters with very fine granularity. One of the main problems of particle flow - apart from technological difficulties - are the by nature very large fluctuations in the hadronic shower development. Event though neutral hadrons make only a small fraction of around 16% of all particles in typical hadronic events at the ILC, nevertheless the HCAL with its limited resolution is a major contributor to the overall performance. The only way to overcome these intrinsic fluctuations is through attempts to topologically reconstruct the hadronic showers, linking the different electromagnetic and hadronic shower components.

The resolution which can be obtained for the jet-mass resolution can be written as

$$\sigma(JET) = \sqrt{\sum \epsilon_T^2 E_i^4 + \sum \epsilon_{ECAL}^2 E_i + \sum \epsilon_{HCAL}^2 E_i}$$

. Here the ϵ are the respective weights of tracker, ECAL and HCAL (charged, photon, neutral hadron) contributions to the total energy of the event. The above formula describes the ideal case. In addition, imperfect reconstruction and confusion further deteriorates the resolution. The relative importance of the different terms contributing to the overall resolution is illustrated in Fig. 1. From this it is clearly visible that assuming the confusion term can be controlled the energy resolution of the HCAL is actually the most important contribution, assuming that all particles have been separated correctly. Therefore in a particle flow calorimeter the main thrust of the optimization has to be on the particle separation, not on the energy resolution. Moderate energy resolutions are acceptable.

2.2. Optimising a particle flow detector

The optimization of a detector has to be done within a number of very different boundary conditions. The main driving force of course has to be the performance of the detector. Requirements are given by the physics groups, have been iterated and have resulted in a widely accepted table of required performances. On the other hand technological feasibility and cost have to be taken into account, and might severely restrict the available phase space.

As particle flow heavily relies on the separation of particles, particular attention is given to paving the way for this. The separation between particles in a jet increases if the distance between the interaction point and the entry into the calorimeter system is as large as possible, and if a magnetic field, ideally applied perpendicular to the direction of motion of the particles, is present. Reconstructing the topology of showers requires that there be no large dead area in the middle of the calorimeter, thus forcing the coil to the outside of the calorimeter system.

In the barrel region of a typical detector equipped with a solenoidal field, the separation between particles in a jet scales like BR^2, where R is the radius of the electromagnetic calorimeter. In the forward region, where the field is

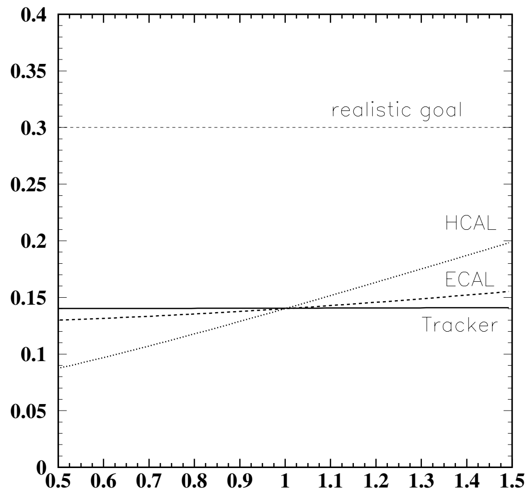

Figure 1: Influence of the energy resolution of Tracker, ECAL and HCAL on the overall particle flow performance, under the assumption, that all particle have been correctly separated. The overall jet energy resolution is shown as a function of a scaling factor, applied individually to each of the resolutions. A scaling factor of one corresponds to a tracker resolution of $\delta(e/p) = 7 \times 10^{-5} GeV^{-1}$, an ECAL resolution of $\delta E/\sqrt{E} = 11\%/\sqrt{GeV}$, and an HCAL resolution of $\delta E/\sqrt{E} = 40\%/\sqrt{GeV}$.

no longer perpendicular to the particle direction, the separation scales more like L, where L is the distance between the interaction point the start of the endcap-electromagnetic calorimeter.

The size of the shower in the electromagnetic calorimeter is primarily given by the Moliére radius in the calorimeter. Therefore a very dense absorber like Tungsten is preferable, at least for the first part of the calorimeter. The required small cells, which are of order of a cm, can be realised with SI detectors. At the same time the interaction length Λ in the electromagnetic calorimeter should be large, to maintain the hadronic showers in the ECAL as pencil-like as possible.

The hadronic calorimeter has to cope with two very different types of showers. A hadron shower has a number of contributions from hadronic interactions of the shower particles in the matter of the calorimeter, but also small, localized electromagnetic showers. The job of the HCAL is to confine the showers to the smallest size possible, and at the same time attempt to link all the different parts which belong to one hadron.

While the physics requirements tend to favor the largest detector possible, cost consideration of course go in the opposite direction. In particular the cost of the coil, which should be able to maintain a magnetic field of at least 3, better 4-5 T, over the full calorimeter plus tracking region, is a major cost driver. Its costs scales approximately with the volume it contains, so that a smaller coil means major cost savings.

3. DETECTOR CONCEPTS

Over the last year three different detector concepts have emerged. They all start from the same bottom line - particle flow, precision tracking and vertexing. The main difference is in the size of the coil, and in the realization of the tracking system. The SiD detector [2] opts for a comparatively compact coil, tries to compensate by raising the magnetic field, and by reducing the size of the cells in the ECAL to $0.5 \times 0.5 cm^2$. Tracking is done in a pure silicon based tracking detector. In the large detector concept (LDC)[3] a somewhat larger ECAL radius is proposed, but still small enough that the cost of a Si-W calorimeter are not yet excessive. Tracking is based on a combination of a large volume TPC, and SI-based detectors. The GLD concept [4] really uses size to optimize the particle separation, but can do this only by compromising on the materials and technologies of the calorimeters. The tracking concept

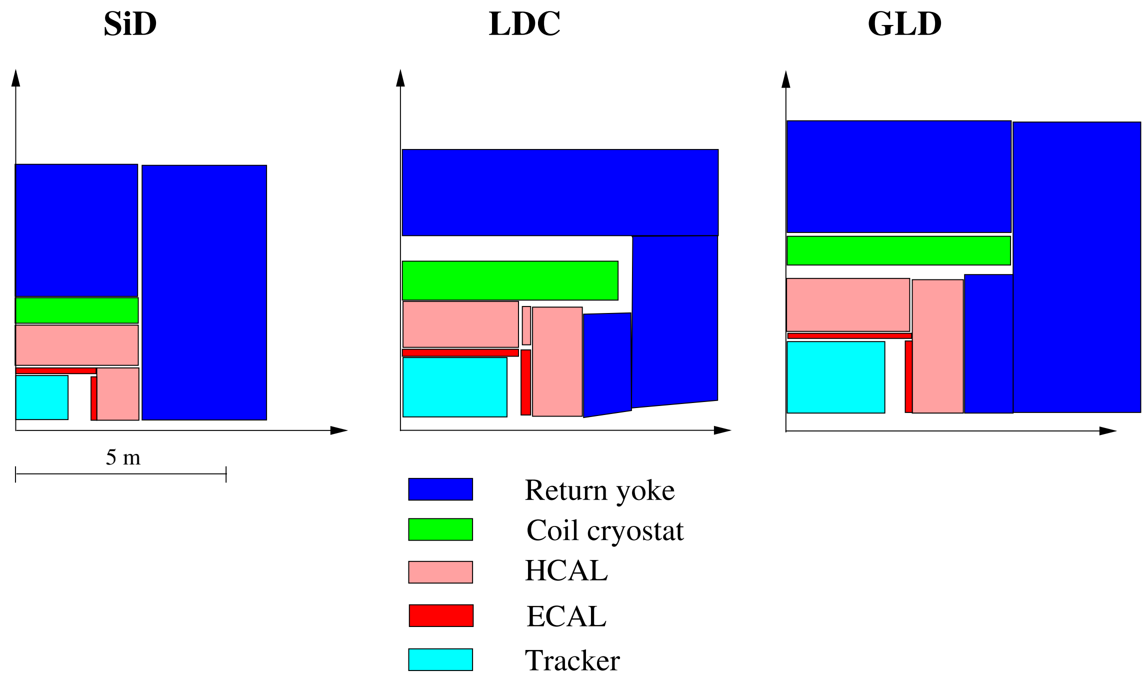

Figure 2: Comparison of the three currently discussed concepts SiD, LDC and GLD.

is rather similar to the one of the LDC group. A comparison of the different sizes of the detector concepts is given in 2.

4. THE DETECTOR COMPONENTS

All different concepts share a similar structure of the detector. The interaction point is surrounded by a high precision vertex detector, followed by a central tracking detector. This is surrounded by a dense and granular calorimeter, which is always contained inside the coil. Outside the coil the return iron is instrumented as a muon system and tail catcher. The differences between the three concepts are in the realization of the different components, with the largest differences found in the tracking system.

4.1. The Vertex Detectors

The designs of the vertex detector are quite well developed, and very similar between the different concepts. They are driven by the requirements for excellent detection of secondary vertices. Apart from the obvious tagging of bottom flavored mesons, charmed mesons play an important role in the ILC physics. Recently a number of studies have shown the in addition the reconstruction of the charge of the secondary or tertiary meson through the reconstruction of the vertex charge is a very powerful tool, which however puts very stringent requirements on the performance of the vertex detectors.

The typical ILC vertex detector has five layers of pixelated silicon. One of the main external constraints is the survival of the rather intense background from beam beam effects. In particular the innermost layers, which typically sits at something like $1.5cm$ radius, sees a large number of hits from beamstrahlung. To keep the occupancies at manageable levels a pixel detector is the only option. A number of different technologies are currently under study, and are reviewed e.g. in [8].

One of the most challenging tasks of the vertex detector is the reconstruction of heavy flavour events. Extensive simulations have been performed to evaluate the performance of the proposed devices. In Fig. 3 the performance for

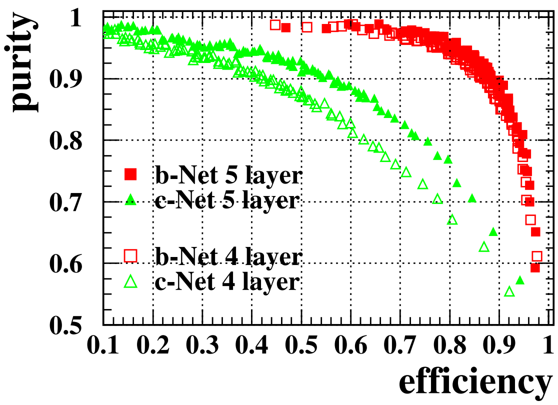

Figure 3: Efficiency vs purity relation for the detection of ZH events with subsequent heavy flavour decays. The open triangles correspond to the performance of the charm tag with a vertex detector with the innermost layer at 2.5cm, the closed one to a vertex detector with the innermost layer at 1.5 cm.

bottom and charm tagging is shown. It is compared for a 4 and 5 layer detector, and also for two different values of the radius of the innermost layer, $1.5cm$ and $2.5cm$. While there is little difference between these options for bottom tagging, the efficiency / purity relation clearly deteriorates significantly for charm tagging.

4.2. Tracking Detectors

The tracking detectors have to serve a dual purpose in the ILC detector. On the one hand side they need to measure the charged particles with excellent accuracy. This is particularly important for the reconstruction of the Higgs boson in the model independent channel $e^+e^- \rightarrow ZH$, where only the recoiling Z is reconstructed. On the other hand particle flow requires an extremely efficient track reconstruction, including low energetic tracks, curling tracks, and decay in flight. While the first requirement stresses the intrinsic resolution, the second one relies more on an efficient, robust track reconstruction, while best possible resolution is less important. Two of the three concept groups rely on a gas filled TPC to provide redundant and efficient pattern recognition, backed up by a number of SI based tracking devices. The third concept, the SiD group, has proposed a fully Silicon based tracking system. Pattern recognition in this case is done primarily by the Vertex detector, while the tracker per se is responsible for the measurement of the momentum of charged particles [9]. A schematic overview of both fundamental options is shown in Fig. 4.

At the moment a final decision on which proposal is better suited for a particle flow based detector are not yet possible. First results from both concepts do look promising, both in terms of the reachable resolution as well as in terms of the track reconstruction efficiency. However a number of important questions remain, among the most important one being the robustness of the overall tracker, particularly against backgrounds, and the possibility to calibrate the detector to the required precision.

4.3. The Calorimeter

In a detector optimized for particle flow the calorimeter naturally plays a very central role. It is the main device which is needed to translate the vision of particle flow, spelled out in the previous parts of this paper, into reality.

A main difference between a conventional detector and a particle flow detector is the much stronger emphasis given to the reconstruction of the topology of the events in a particle flow detector. The intrinsic single particle energy

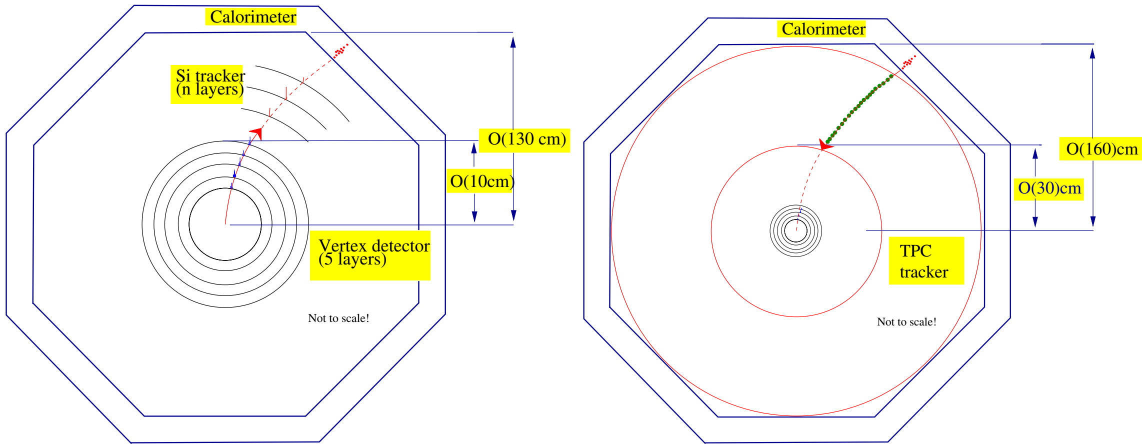

Figure 4: Schematic side view of the two fundamental tracker options: SI-based (left figure) and TPC based (right figure). Numbers shown are indicative and are only meant to set the scale.

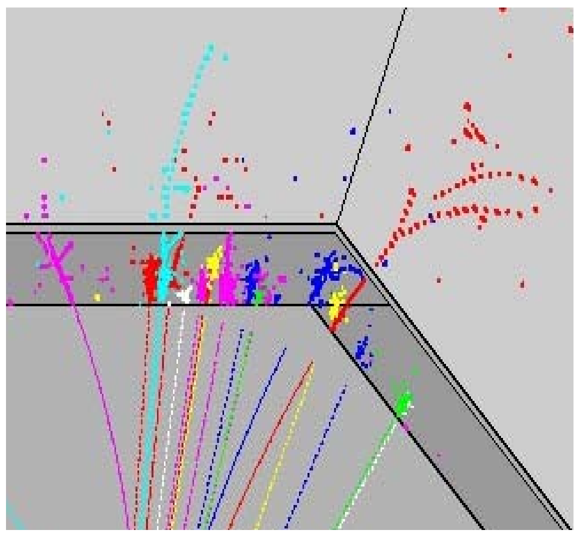

Figure 5: Closeup view of an event in the very finely granular calorimeter proposed for the ILC

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resolution, usually the most relevant performance parameter, is no longer the central variable for an optimization. Instead the capability to separate close-by tracks is becoming much more important [10]. A closeup view of a simulated part of an event is shown in Fig 5.

The typical particle-flow inspired calorimeter therefore is extremely granular, both in the transverse and in the longitudinal direction. At the same time it should be dense, to minimize the size of the showers, and thus the possible overlap between neighboring ones.

A very promising candidate for the electromagnetic part of the calorimeter is a Silicon - Tungsten sampling calorimeter, as proposed e.g. in the TESLA TDR. Tungsten is a very attractive absorber material, as it has a very small Moliére radius of around $9mm$, Silicon diodes as detectors are attractive because they allow the construction of small cells, which can cover large surfaces.

Individual particles in the electromagnetic calorimeter are reconstructed through the reconstruction and analysis of the shape and size of their energy deposits in the sensitive layers. Cell sizes which are of the same order than the Moliére radius make sure that the maximum available information on the transverse shower shape is available. The number of samplings is large enough to allow for a detailed measurement of the longitudinal shower development.

Typical cell sizes are between $5 \times 5mm^2$ and $10 \times 10mm^2$, typical thicknesses of the absorber are around $5mm$. Several groups around the world are currently working on significant prototypes for these types of devices [11, 12].

The main advantage of this approach is the very dense absorber, combined with a very stable, and easily read out, sensitive medium. The main disadvantage is the cost, which is comparatively large for both the absorber and the sensitive detector.

Alternatives to a Si-W electromagnetic calorimeter are studied by a few groups with the ILC community. The latest approach is followed by groups in Asian, as part of the GLD effort. Here the SI detectors are replaced by thin, long scintillator strips, arranged in a cross-like fashion between the absorbers. In this way much similar to a double sided SI-strip detector, coordinate information for a hit in the calorimeter is obtained through the combination of two layers, to get an effective $10 \times 10mm^2$ granularity. The main questions for this technology is whether the occupancies in the proposed detector are small enough to keep the confusion through multi-hits at a minimum. Studies are ongoing, but no final results were available at the time of this writing.

While showers from electro-magnetically interacting particles are well confined, and are reasonably well understood, the situation is very different for hadronic showers. Neutral hadrons will start interaction with the calorimeter well into the absorbers. With the current choice of geometries, the ECAL typically has a thickness of one interaction length, so that on average the neutral hadrons do not interact significantly in the ECAL. In the HCAL they produce a combination of nuclear interactions, which sometimes are the starting points for small electromagnetic showers inside the hadronic shower. The hadronic calorimeter then has to provide enough information that all the different components can be re-attached to each other, and thus the energy and the direction of the neutral hadron can be precisely measured.

At the moment two quite different approaches are being studied. In the more conventional one the readout planes of the HCAL are subdivided into cells. For each cell the energy deposited in this cell is read out. Through topological reconstruction algorithms, cells are combined into showers, and the parameters of the showers and thus of the originating particles are reconstructed.

In an alternative scheme, only the fact whether or not a cell was hit is recorded. The number of cells hit is in some approximation proportional to the total energy of the particle which produced the hits. This so called digital scheme works well if the average occupancy per cell within a shower is smaller than one. For the expected rates at the ILC this indicates that the typical cell size has to be of the order of the one for the ECAL, $10 \times 10mm^2$. For these cells a proportional response has been observed over a wide energy range.

The analogue HCAL option investigated relies of scintillator tiles to read out the energy. Novel semi-conductor based photo detectors (SiPM's, [13]) are used to record the light produced in the tiles. These SiPM are mounted right on the tile, thus minimizing the amount of optical elements needed to collect and readout the light. The smallest cell size currently possible with this scheme is around $30 \times 30mm^2$. One plane of a prototype calorimeter currently under construction by the CALICE collaboration is shown in Fig. 6.

The digital option needs cells with an area about an order of magnitude smaller. At the moment, SI detectors or gaseous detectors are the only alternatives. For cost reasons the main investigations are done for resistive plate chambers (RPC's).

While the analogue calorimeter is in principle a well proven option, the digital one is a novel concept, which has never been operated in a large scale detector. Significant development work therefore is needed before this can be used in a detector at the ILC. This work and other R&D for the ILC calorimeters is carried out e.g. in the CALICE collaboration.

Apart from the questions of cell size, stability and other technical issues, the choice of active medium also has a significant influence on the response of the calorimeter. While the scintillator based solution allows the efficient recording of the pulse height, the sensitive layer also includes hydrogen, which has a large cross section for reacting with neutrons, which are produced quite copiously in the hadronic showers. These neutrons travel significant distances in the HCAL, before they interact or are absorbed. In a scintillator based calorimeter spurious hits far removed from the main shower are attributed to such neutrons. In a gas filled RPC the hydrogen content is much lower, and thus the probability of such spurious hits is much reduced. This shows up in a visually much clearer structure of

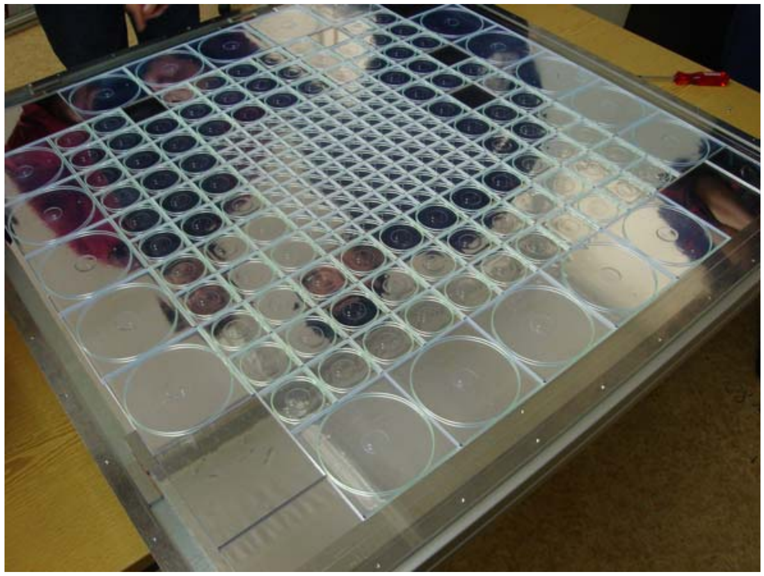

Figure 6: Photograph of a plane of scintillator tiles arranged for a HCAL prototype.

the hadronic showers in the simulation. However care has to be taken in the interpretation of these results, as the additional amplitude information available in the scintillator based calorimeter allows one to efficiently eliminate most of the spurious neutron hits.

4.4. Machine Detector Interface

The success of the detector program at the ILC depends to a large extend on a close cooperation between machine and detector groups in the design and instrumentation of the interaction region. The physics requirements of the ILC demand that the detector is as hermetic as possible, providing coverage down to very small angles. On the other hand the intense beam beam interactions produce large backgrounds, which primarily go into the very forward region. All concept groups have studied in detail the sources, the distribution and the influence of these backgrounds. A careful design of the instrumentation of the very forward region is essential, to shield the detector from the backgrounds, and at the same time to maximize the coverage for physics [14].

An important issue in the discussions is whether or not the accelerator is built with or without an crossing angle. Introducing a small crossing angle (around 20 mrad is the most probable value) does make the job if extracting the outgoing beam much easier, but at the same time distributes the backgrounds over a larger area in the forward direction, and thus reduces the coverage. Recently a small angle option with a crossing angle of 2 mrad has been proposed and is being studied. While not all technical problems have been solved yet it appears that this might be promising candidate for a compromise solution, allowing an extraction of the beams and at the same time minimizing the loss of physics potential. Careful studies of these questions have started.

5. CONCLUSION

Over the last year three detector concept groups have formed: SiD, LDC, and GLD. The concept groups supplement the already existing detector R&D groups, and focus on overall system optimization, rather than detailed technical studies. While these concepts are seen as pre-runners of collaborations, they are not yet as the same level of organization as a real collaboration. Membership in a concept is not exclusive, and in fact, membership in more than one concept is encouraged.

The goal of the concept groups is to work out and document a cohesive design of a detector for the international linear collider. While all concepts agree on the basic principles driving this - that is, the paradigm of particle flow, supplemented with precision tracking - still the ways to achieve this goal are different. In this way a healthy number of different and complementary options are being developed. Through these concepts the experimental community at the ILC is preparing to meet the challenge of this machine, and will be ready to come forward with concrete proposal in time for the technical design report of this machine, expected for the year 2007.

Acknowledgments

I like to thank numerous colleagues in the ILC experimental community who assisted me in the preparation of this review through providing material and advice.

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