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Future Accelerators and Experiments

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1. Introduction

At present the fundamental building blocks of nature are divided into generations, of which the following three have revealed themselves.

$$\left.\begin{matrix} u & c & t \\ d & s & b \end{matrix}\right\}\text{Quarks } (\times 3 \text{ colours})$$
$$\left.\begin{matrix} e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{matrix}\right\}$$

In addition, we have the gauge boson for:

Strong interactions	8 gluons
Electroweak interactions	γ, $W^{\pm}$, Z^0
Gravity	?
Masses	Higgs(?)

The above are all predicted by the Standard model$=SU(3)\times SU(2)\times U(1)$. However, there still remain some loose ends which have to be cleared up: Cabibbo angles, CP violation and gravity.

At present we have two main types of high-energy accelerators that play a complementary role in physics (Table 1).

1.1. General Features of Hadron–Hadron Interactions

Collisions are "parton–parton" collisions (Figure 1), and partons tend to have low fractional momentum (x) (Figure 2). Note that the total cross-section for hard collisions is small

$$\sigma(M+X)\propto\frac{1}{M^2}\,f\left(\frac{M^2}{E^2}\right)$$

hence the proton collider will run out of luminosity before it runs out of energy.

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TABLE 1. *High-energy accelerators*

I	II
Electron (and anti-matter twin (positron)) Mainly used to investigate structure e.g. SLAC	*Proton* (and antiproton) Mainly to investigate the fundamental forces e.g. FNAL, SSC

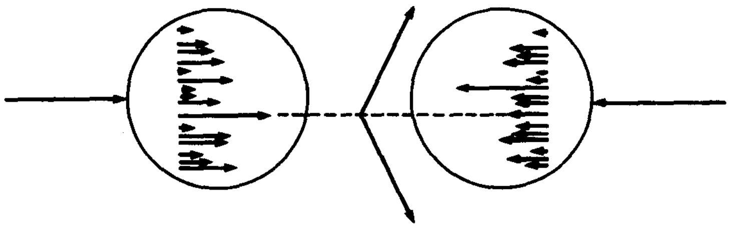


FIGURE 1. Parton–parton collisions as seen in hadron–hadron interactions.

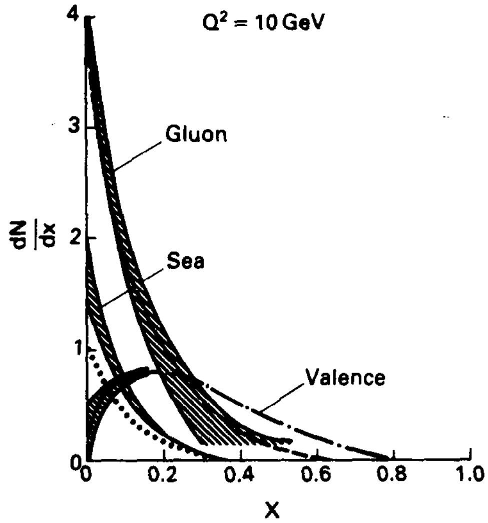


FIGURE 2. Parton distributions within the proton.

1.2. General Features of Electron Positron Interactions

They are elementary in nature (Figure 3). All the energy goes to particle production (most of the time), and hence

$$\sigma \propto \frac{1}{M^2}$$

Final states are relatively simple and easy to analyse (Figure 4).

2. Proton Colliders

The present and the next generation of proton colliding beam machines build on two great pioneering efforts: that of the ISR group at CERN who built and brought into operation the first proton collider, and that of Robert R. Wilson and his colleagues at Fermilab, who made superconducting quality accelerator magnets a practical technology.

We now have two operating proton colliders. These are the Sp$\bar{p}$S at CERN which runs at a centre-of-mass energy of 0.6 TeV, and the Tevatron collider at Fermilab running at a centre-of-mass energy of 2 TeV. Both machines run in the luminosity range of $1–2 \times 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The next generation of machines will be titanic engineering tasks, involving large extrapolation of a basically known technology. The machines will be difficult to use, because of the complexity of the final states, causing a great challenge to the experimenters to design detectors and computer algorithms to extract what we hope is the simplicity hiding in this complexity. We all know the problem. The proton is a composite particle, and what really interests us is the hard collisions of the constituents of the proton. While the cross-section for proton–proton collisions is large, the cross-section for hard proton–proton collisions is small, and there is a great deal of debris in the final state accompanying the particles of interest.

Three new proton colliders are in various stages of the design and approval process. These are the UNK collider at Serpukhov in the USSR, which is an extension to the 3 TeV proton synchrotron now under construction at Serpukhov; the LHC which might be added to the LEP tunnel at CERN; and the SSC, the largest of them all, to be built and at an as yet undetermined site in the US.* We can compare the capabilities of these three possible new facilities and the two existing proton colliders in terms of a somewhat fuzzy and process-dependent concept called "mass reach". This notion combines the given facility's energy and luminosity with theoretical estimates of cross-sections and backgrounds to give the maximum mass one might both be able to produce and detect at a

* The site has meanwhile been finalized. According to this design the SSC will be built at Waxahachie, Texas.

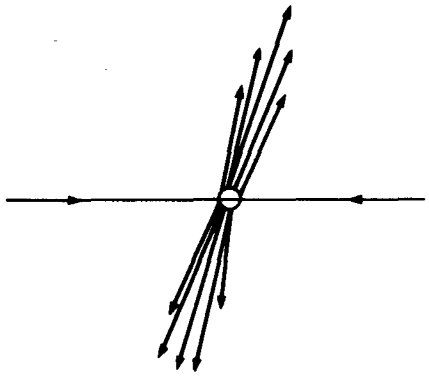
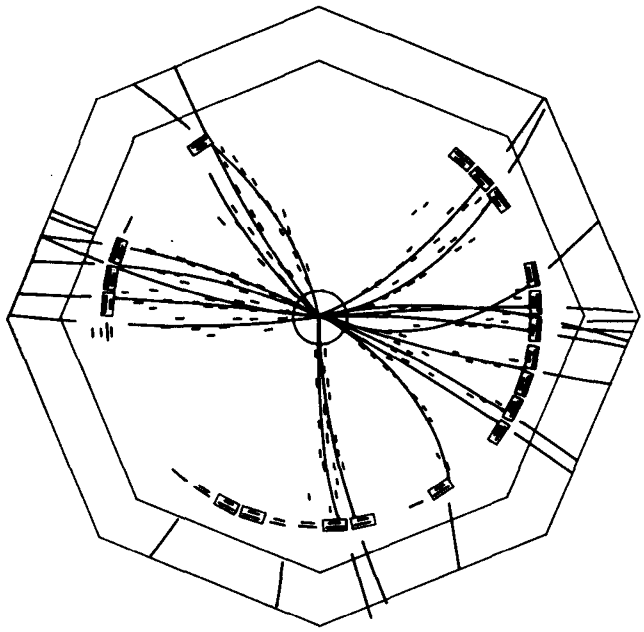


FIGURE 3. "Jets" in electron–positron interactions.



TRK	P	ELATOT	ID
1	0.3	0.2	PI−
2	0.5	0.2	PI+
3	0.5	0.1	K−
4	0.3	0.0	PI−
5	1.2	0.2	PI+
6	0.6	...	PI+
7	0.6	0.0	PI−
8	0.6	0.0	PI−
9	1.3	1.4	E+
10	3.5	0.9	PI−
11	1.7	0.0	PI+
12	0.7	0.1	PI−
13	0.6	0.1	PI−
14	0.2	0.0	PI−
15	1.6	0.1	PI−
16	1.9	0.1	PI+
17	0.3	0.1	PI+
18	2.0	0.3	PI+
19	1.0	0.2	P+
20	1.3	0.4	PI+
21		1.0	G
22		0.6	G
23		0.4	G
24		0.3	G
25		1.1	G
26		0.3	G
27		0.8	G
28		1.1	G

FIGURE 4. Example of "jets" detected experimentally in e^+e^- annihilation by the Mark II Group at SLAC.

particular facility. Table 2 gives the mass reach for the two existing and three projected facilities.

Table 2 is an attempt to compare crudely different machines, and should not be taken seriously except in a relative kind of way. "Mass reach" is a well-defined notion for processes such as quark jet production (which is where the numbers in Table 2 come from), and is much more dependent on the experimental assumptions and somewhat questionable background calculations for such things as Higgs production.

I now turn to the three new facilities that are under discussion. I want to take this opportunity to thank Victor Yarba at Serpukhov for the information on UNK, Giorgo Brianti of CERN for the information on LHC, and Chris Quigg of the SSC Central Design Group for the information on SSC.

TABLE 2. *A comparison of proton colliders*

Facility	Mass reach (GeV)
Sp$\bar{p}$S	150
TeV II	300
UNK	600
LHC	1500
SSC	2500

2.1. UNK Collider

The UNK collider is an as yet unapproved addition to the three TeV superconducting proton synchrotron now under construction at Serpukhov in the USSR. The synchrotron is scheduled for completion in 1992 or 1993. It uses the existing 70 GeV Serpukhov machine as an injector into a 400 GeV conventional magnet booster, which in turn serves as the injector into a 3 TeV superconducting final accelerator. Both the 400 GeV booster, and the 5 tesla superconducting main ring are contained in a 20.70 km circumference tunnel which has a 5.1 m bore. The tunnel is about half complete, and the entire project is on schedule for first operation as a fixed target machine in 1993.

The superconducting dipole magnets (5 tesla peak field) are a version of the by now standard HERA modification of the basic Fermilab design. They use a two-layer coil compressed with non-magnetic collars, which in turn are contained in a magnetic iron tube, the magnetic iron being at a sufficient distance from the high field coil to effectively increase the field obtained per ampere in the coil without at the same time distorting the dipole field from saturation of the iron. The entire coil/collar/iron assembly is operated at liquid helium temperature.

The colliding beam phase of UNK will follow on the completion of the 3 TeV fixed-target facility. Its schedule is not yet firm. The Serpukhov group has considered both proton–proton and proton–antiproton colliders. In their minds, considerations of simplicity, reliability, and luminosity lead to the choice of proton–proton instead of proton–antiproton. Because of the large bore of the UNK tunnel (5.1 m) there is no difficulty in putting a second superconducting proton ring in the same tunnel with the first.

Figure 5 shows the proposed layout of the collider facility. The beam crossings are in the horizontal plane and four interaction regions are provided for experiments. The necessary cryogenics and power for the second ring are being provided as part of the first phase of the project, which will simplify the installation of the second ring when that work begins.

The main parameters of the collider are summarized in Table 3. I would characterize this machine as an extremely conservative design. There is a

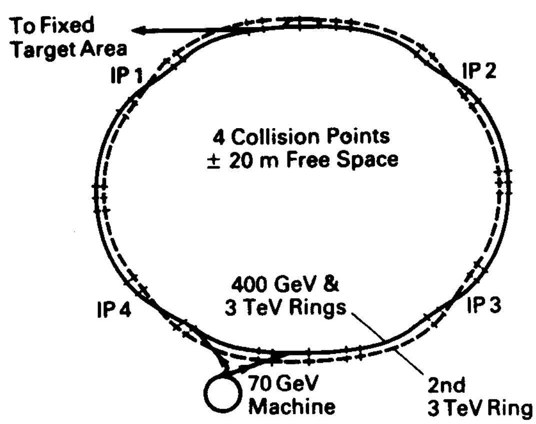


FIGURE 5. Schematic of the UNK 6.0 TeV proton–proton collider.

TABLE 3. *Main parameters of the UNK P–P collider*

Energy (TeV)	3×3
Protons per bunch	3×10^{10}
Number of bunches	8000
β^* (metres)	1
L (cm^{-2} s^{-1})	4×10^{32}
Events per collision	0.35
σ_L (m)	0.10
Crossing angle (rmrad)	1.0
Tune shift	6×10^{-4}

significant potential for lower interaction point β, smaller crossing angle, and higher beam–beam tune shift; all of which could potentially give a large luminosity. Experimenters will also appreciate the relatively low number (compared to the other future colliders) of events per beam–beam collision, which will make detector problems somewhat easier. The project requires no new technical developments and should be able to be completed relatively rapidly, particularly if approval is given by the Soviet government to continue magnet production after the magnets for the fixed-target machine are completed.

2.2. SSC

The largest of the future projects is the superconducting super collider (SSC) designed to reach an energy in the proton–proton centre of mass of 40 TeV with a maximum luminosity of about 10^{33} cm^{-2} s^{-1}. The machine is to be housed in a 84 km circumference tunnel which will incorporate two 20 TeV proton storage rings in an over and under configuration. The proposed facility is shown schematically in Figure 6.

The configuration of the machine is unusual in that it consists of two long arcs of magnets connecting two clusters of interaction regions, each of which contains four potential crossing points. Since the luminosities in the interaction regions in each cluster are not all the same, the machine actually has a superperiodicity of one. While the machine looks different from existing facilities, there is really not much difference from the beam

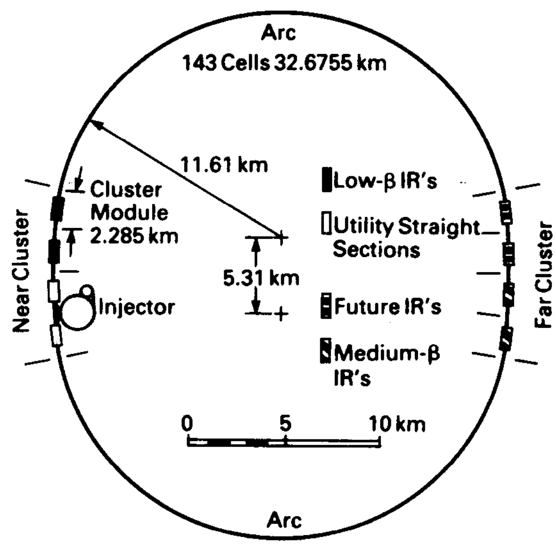


FIGURE 6. Schematic of the SSC 40 TeV proton–proton collider.

dynamics point of view between this facility, and, for example, the Sp$\bar{p}$S or the Tevatron collider. These machines have a high degree of symmetry, but the asymmetric configuration of the interaction regions actually reduces the symmetry to an effective superperiodicity of one.

An intense R & D programme has been under way for more than 3 years. The design of the facility has undergone considerable refinement since the first conceptional design report, and much work has been done on such things as beam dynamics, interaction region configurations, experimental hall design, requirements for experiments, cryogenics, conventional facilities, etc. However, the bulk of the R & D programme has concentrated on the development of the superconducting dipole magnets for this facility. These magnets are also of the collared coil–cold iron design with a peak field of 6.5 Tesla, a bore tube diameter of 4 cm, and a length per dipole of 17 m. The magnet length was chosen on an economic basis. The longer the magnets, the more difficult they are to build and to transport, while the cost per unit length of magnet decreases because of fewer complex magnet ends and fewer interconnections between magnets. While no difficulties were experienced in building short magnet models that met specifications, the first few full-length magnets had considerable trouble with erratic quench behaviour and did not reliably achieve full field. These problems seem to have been solved in the R & D programme, and the most recent full-length magnets reach full field with very few quenches.

The SSC is the first proton machine to be designed at an energy sufficiently high to have to take into account the effects of synchrotron radiation on machine performance. Figure 7 shows the effects of

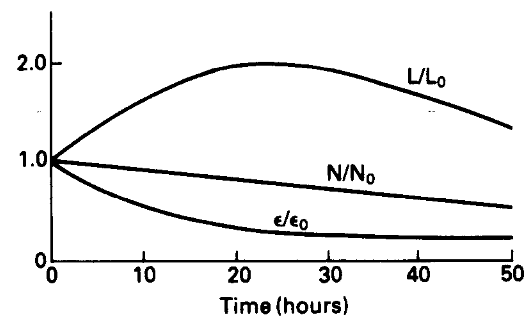


FIGURE 7. Effect of synchrotron radiation on the SSC. The lower curve shows the effect of synchrotron radiation damping on the emittance of the stored beam. The middle curve shows the decrease of the circulating beam intensity from all sources. The upper curve shows the combined effect of radiation damping and beam loss on the luminosity.

synchrotron radiation on the beam size and on the luminosity. The lower curve shows the shrinking of the emittance of the beam from synchrotron radiation. The middle curve shows the decrease in the number of circulating beam particles coming from all the loss mechanisms in the machine. The upper curve shows the luminosity which actually rises during the initial day of the fill, for the decrease in transverse emittance dominates the loss of particles. The synchrotron radiation should also help to stabilize the beam against various slowly growing beam instabilities while at the same time it generates significant amounts of power which will have to be handled by the cryogenic system.

Table 4 shows the main parameters of the SSC at a high luminosity collision point at the beginning of the fill before synchrotron radiation affects the beam size. The mean number of events per bunch collision in the SSC is 1.7. This will pose some increased problems for the experimenters beyond those experienced at the existing proton colliders, though it is claimed that these difficulties are not great for a properly designed detector.

TABLE 4. *Main parameters of the SSC at a high luminosity collision point*

Energy (TeV)	20×20
Protons per bunch	7.3×10^9
Number of bunches	17,100
β^* (metres)	0.5
L ($cm^{-2}\,s^{-1}$)	1×10^{33}
Events per collision	1.7
Tune shift	0.001

2.3. LEP Hadron Collider

Ever since the earliest days of the LEP project there has been some discussion at CERN of the possibility of adding a proton machine to the LEP tunnel. While these discussions were very casual at first, in the past 2–3 years they have become much more serious, and have centred on adding a proton–proton collider to the LEP complex. The facility now under discussion is called the LEP hadron collider (LHC), and the design effort is focusing on a proton–proton collider that will reach 16 TeV in the centre of mass (at a 9.0 tesla bend magnet field) and which includes the possibility of electron–proton collisions at 1.8 TeV in the centre of mass (0.1 TeV electrons on 8.0 TeV protons).

The dipole design is of the "two-in-one" type, wherein two sets of coils are contained in a common collar system, iron yoke, and cryostat, as shown schematically in Figure 8. This design has been chosen both because of space limitations in the LEP tunnel (the proton ring goes

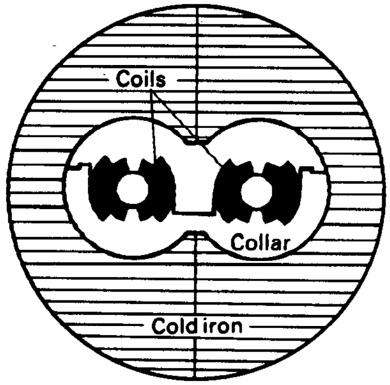


FIGURE 8. Schematic of the LHC two-in-one superconducting dipole magnet.

directly above the LEP magnet ring) and because of the perceived saving in magnet costs and in installation time. However, the two-in-one design does pose some new problems, the principal one being the coupling of the fields in the two beam tubes which may add considerable complexity to the design of the necessary correction magnet system. The aperture of each coil is currently specified as 5.0 cm and the separation of the centres of the two coils is 18 cm.

A magnet R & D programme is now under way, aimed at producing magnets with a maximum dipole field of 10 tesla, though the numbers that CERN is now using in specifying the energy of the machine correspond to a practical operating field of 9 tesla. It is planned to achieve this high field with the standard niobium–titanium conductor by operating at a temperature of around 1.8–2.0 K. A 1.3 m long model magnet has been built with a modified HERA cable which reached 7.9 tesla after three quenches at 1.8 K. Four two-bore, 10 tesla, short magnets have been ordered from industry. The first long magnet (9.5 m) with twin bores will be built using HERA cable and should reach a field above 7 tesla at a temperature of 2 K.

The LHC layout is shown schematically in Figure 9, the numbering of the interaction points corresponding to that used for the LEP electron–positron collider. There are four potential interaction regions at IP-1, -3, -5 and -7. One of these (the one deepest in the Jura) will be used for the necessary proton machine beam dumps, making three available initially for some combination of proton–proton and electron–proton experiments. Some sort of bypass will be required to carry the proton machine around the LEP experiments installed at IP-2, -4, -6 and -8.

In the proton–proton mode the CERN design study is focusing on

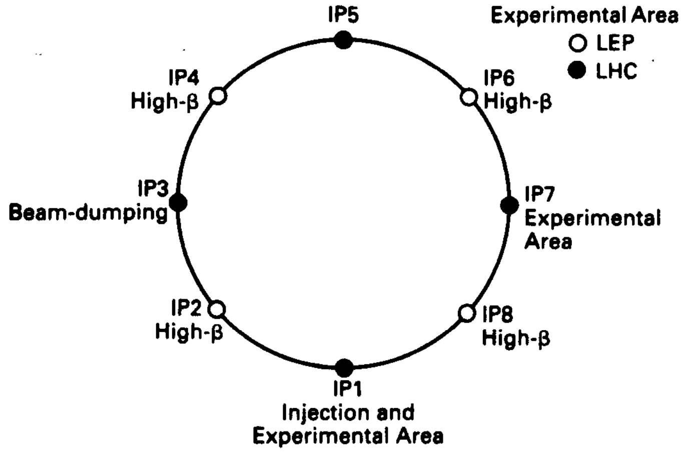


FIGURE 9. Schematic of the LHC indicating the LHC and LEP potential collision points.

providing both a 10^{33} luminosity interaction point for a general-purpose detector, and at least one very high luminosity interaction point which will require some sort of special-purpose detector. Some of the parameters now under study are shown in Table 5, which includes two variants of the high luminosity interaction region. As can be seen, the very large numbers of proton interactions per beam crossing in the high luminosity modes preclude the use of any general-purpose detector both because of the extreme complexity of the analysis of multiple events and because of the extremely high radiation levels around the collision region. The LHC, like the SSC, also has a significant amount of synchrotron radiation emitted by the beams, which will have to be caught on higher temperature radiation catchers because of the very low efficiency of refrigerators which run at the nominal magnet temperature.

The LHC parameters in the electron–proton collider mode are shown in Figure 10. The kinks in the luminosity and electron beam intensity curves are caused by properties of the LEP electron machine. The luminosity

TABLE 5. *Main parameters of the LHC*

P–P Parameters	Nominal	High luminosity	
Luminosity ($cm^{-2}\ s^{-1}$)	1.4×10^{33}	8.2×10^{33}	3.9×10^{34}
Interaction/crossing	2.6	9.2	44
Bunch spacing (N_s)	25	15	15
Protons/bunch (10^{10})	2.6	4.2	12.5
β^* (M)	1	0.25	0.25
Synch. radiation (kW)	4	7	21
$\Delta\nu$	2.5×10^{-3}	2.2×10^{-3}	3.4×10^{-3}

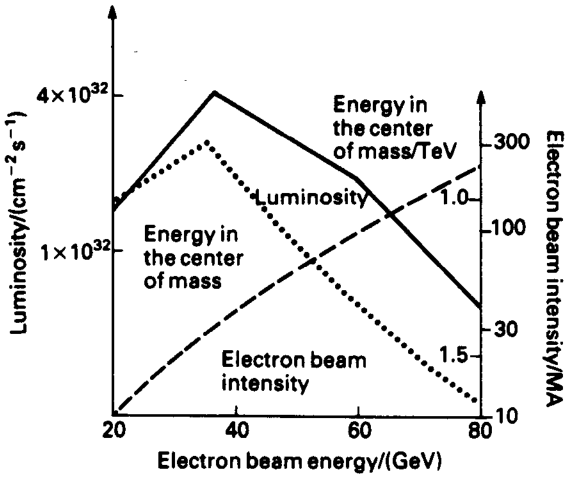


FIGURE 10. Luminosity, electron beam current, and electron–proton centre-mass-energy vs. electron beam energy for the LHC in the electron–proton collider mode. The proton beam energy is 8.0 TeV.

curve assumes that enough RF power is installed on LEP to allow the storage of 5 mA at 100 GeV, and that this full power is used for all electron energies above about 35 GeV. Below 35 GeV the current in the electron beam is limited by the aperture of the LEP machine, and the small kink in the luminosity curve at around 60 GeV is caused by the need to change the focusing structure of the LEP machine at higher energies. In the electron–proton mode there are 540 bunches in each beam, making the peak current in each bunch below that nominally used in the LEP electron–positron collider mode.

If this project is approved, it is planned during the construction and installation phase to operate LEP for around 4000 h per year and use the rest of the year to build and install the hadron collider. The new experimental areas will all be designed in the "garage and beam enclosure" mode like the experimental areas at the $Sp\bar{p}S$. Thus detector fabrication and installation can go on in parallel with normal LEP operation.

In the operational phase, initially both LEP and the LHC are foreseen to be operated each in its own running period, lasting approximately one-half year. In each experimental mode it is planned to have experiments take data when their collider is in operation, or be in their garages when the other collider is in operation. If it is desirable at some time in the future to change some of the LEP areas to LHC areas, this can be done with very little construction.

It is not clear how much downtime will be required of LEP for the construction and installation of the LHC. Present estimates give

24 ± 6 months total downtime, which will be divided into several shorter down-periods so as not to keep the LEP machine off for extended periods of time.

The conceptual design of the LHC is still evolving. It is clear that the highest luminosity numbers will be challenging for the machine builders and very challenging for the experimenters. In particular, much more work needs to be done on detectors that can operate at luminosities of 4×10^{34}, including studies of radiation problems, the effect of the necessary shielding on mass resolution, and on the probability of more than 40 events per beam crossing generating some odd background which might mimic or mask the effects that one is looking for. It will probably take another 6–12 months to firm up the LHC design.

3. Electron Colliders

Although I have discussed future proton colliders first in this paper, historically, electron colliders preceded proton colliders. The first electron colliding beam storage ring was begun in 1958 as a joint project between physicists of Princeton and Stanford Universities. The pioneering studies carried out at the end of the 1950s and in the first part of the 1960s formed the basis both for the development of proton colliders and for a large number of electron–positron colliding beam facilities of ever higher energy. Many of the earlier machines have already been shut down, and Figure 11 shows the machines which will, I believe, be running in the decade of the 1990s. The vertical scale gives the centre-of-mass energy and the lines indicated for each machine show the range of centre-of-mass energies over which they can reasonably operate.

All but two of the machines are storage rings. The highest energy of the pure electron–positron storage rings is that of the LEP machine at CERN, with an initial centre-of-mass energy of 100 GeV and the potential to be improved to reach 200 GeV. This machine is 27 km in circumference and is sure the last and the greatest of the electron–positron storage rings, because of a scaling law drawn by the necessity to make up for the emission of synchrotron radiation in storage rings that makes the size and cost of these machines scale as the square of the centre-of-mass energy.

The SLC is the first of a new type of colliding beam device for electrons and positrons – a linear collider. There is no synchrotron radiation emitted in a pure version of this kind of machine and so the scaling law in size and cost is much more favourable than for storage rings.

In this section, I will briefly discuss one new low-energy storage ring project, a B Factory, where studies are being pursued at many laboratories in the world. However, most of this section will be devoted to the new technique of linear colliders and what will have to be done to make these machines practical in the near future.

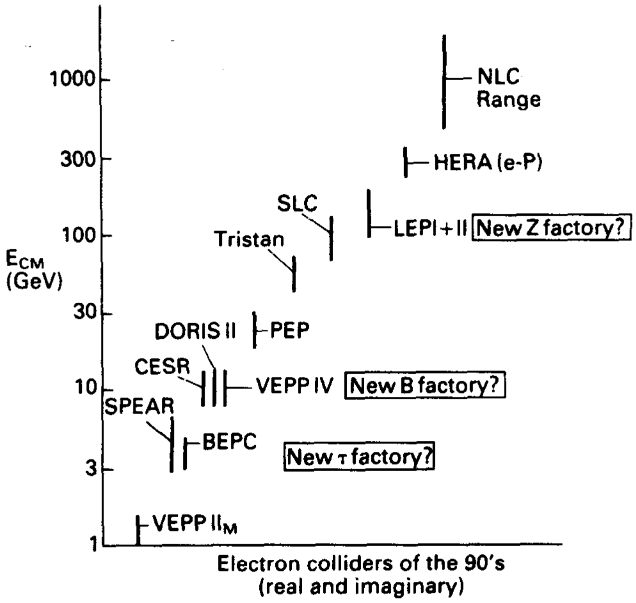


FIGURE 11. Electron colliders of the 1990s (real and imaginary).

3.1. B Meson Factories

The results of the Argus group on $B\bar{B}$ mixing,[5] first reported at the Lepton Conference in Hamburg in 1987, have stimulated an enormous amount of interest in facilities that can produce a large number of *B* mesons. The reason for the interest is that there appears to be a chance to study CP violation in non-kaon systems as well as the intrinsic interest in the meson system. The interest is great enough, I believe, to lead to the construction of one or more new colliders specifically aimed at experiments on the *B* meson system in the next few years. In this section I will summarize what is going on in the study of *B* meson factories, and try to compare the large number of different approaches from the perspective of the possibility of studying CP violation. Almost all of these studies are aimed at new kinds of electron–positron colliders or improvements of existing ones.

Before going on to describe the variety of approaches in electron colliders I should mention that proton machines are also copious sources of *B* mesons. For example:

1. The Tevatron and UNK operating in the fixed-target mode are capable of producing 10^8 to 10^9 *B* mesons per year, the partial *B* cross-section being a few times 10^{-6} of the total cross-section.
2. The Tevatron collider can produce 10^8 *B* mesons per year, the partial cross-section being a few times 10^{-4} of the total cross-section.

3. SSC or the LHC can produce 10^{12} to 10^{13} *B* mesons per year, the partial cross-section being a few times 10^{-3} of the total cross-section.

While the number of *B* mesons produced in these proton machines is enormous, certainly enough to study CP violation if a good detection system could be devised, I have as yet seen no credible experiment with sufficient efficiency and resolution to separate out the interesting final states, and to do the required physics experiments. However, many groups are studying the problem, and perhaps a good experiment can be devised.

Electron–positron colliders seem much more promising as *B* meson factories. Three machines are running now at the upsilon 4S region. They are CESR at Cornell with a luminosity of 10^{32} cm^{-2} s^{-1}, DORIS II at DESY with a luminosity of 4×10^{31}, and VEPP IV at Novosibirsk with a luminosity of 4×10^{30}. For reference, a machine running with a luminosity of 10^{32} for 10^7 s per year at a reconstruction efficiency of 1.0 in the 10 GeV centre-of-mass region will produce:

9×10^5 tau pairs
2.8×10^6 non-*B* hadrons
1.8×10^6 $B\bar{B}$ (4S)
2.9×10^5 $B\bar{B}$ (continuum).

Most studies indicate that roughly 10^8 *B* mesons are needed for the study of CP violation.

Many different approaches are being pursued. Conventional storage rings at around 10 GeV in the centre of mass are being studied at Cornell, KEK, Novosibirsk and the Paul Shearer Institute (SIN). Asymmetric storage rings with a centre-of-mass energy of around 10 GeV are being studied at DESY, KEK and SLAC/LBL. The possibilities of *Z* factories as *B* meson factories are being reviewed at CERN and at SLAC. Linear colliders in the 10 GeV region are being studied at Frascati and UCLA. Hybrid systems involving linacs colliding with the circulating beam in the storage ring are beginning to be looked at as well. All studies are aimed at high luminosities, and some of them may have advantages over others in the detectability of CP violation given the same number of *B* mesons.

3.2. Linear Colliders

It is now generally agreed that the linear collider technique is the only way to reach centre-of-mass energies in the electron–positron system much higher than the centre-of-mass energy of LEP II. In an electron storage ring intense synchrotron radiation is emitted as the beam circulates with an energy loss to synchrotron radiation proportional to the fourth power of the energy divided by the bending radius. A scaling law for an electron storage ring can be written down which minimizes the cost of a machine for a fixed energy, and this scaling law yields a size and cost for such a machine proportional to the square of the beam energy.[1] Thus to achieve an energy ten times that of LEP II one would have to increase the circumference by a factor of 100–2700 km with a concomitant cost of $1\text{–}2 \times 10^{11}$ Swiss francs. While there are technical problems in building an electron storage capability of this size, it is clear that the fiscal problems are such that such machines are not really feasible.

In a linear collider, on the other hand, no synchrotron radiation is emitted in the acceleration process, resulting in a more benign scaling law making the cost of high-energy linear colliders considerably less than an electron storage ring. Beams in linear colliders can be extremely small, and so high luminosities can be obtained even at the relatively low repetition rate of room temperature linear accelerators.

The first machine of this type, the SLC at the Stanford Linear Accelerator Center, is just now coming into operation. Beams of 3 or 4 μm radius can be routinely produced at the collision point, and the stability of these beams is such that they can easily be held in collision by simple feedback systems that hold the beams centred to a small fraction of their size. While the SLC has not yet achieved sufficient operating reliability to begin producing data for physics experiments, it is already clear that the goal of the proof-of-principle has been met. This in turn has led to a great expansion in the R & D devoted to high-energy linear collider systems.

This interest in high-energy electron–positron colliders comes about because it is possible to do physics with these machines not easily accessible to proton colliders.[2] There is a kind of democracy in the final states produced in electron–positron collisions in that all partial cross-sections are comparable as long as the particles in the final state have either electromagnetic or weak charge. In addition, peripheral processes at large transverse momentum are small, and are easy to distinguish from the interesting events with relatively simple cuts. The cleanliness of the final state of electron–positron processes makes the life of the experimenter very much easier than it is at proton colliders. The absence of "debris" like that present in hard proton–proton collisions makes detectors much easier to design and build, and analysis much simpler to carry out.

The luminosity required in a high-energy electron–positron collider is roughly given by

$$L = 10^{33} E_{\mathrm{cm}}^{2}\ (\mathrm{TeV})\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

With this luminosity, roughly 1000 events per 10^7 operating seconds are produced for each R unit of cross-section (one unit of R is the cross-section for electromagnetic production of mu pairs). Many of the new kinds of particles which are thought to possibly exist at high mass have cross-sections on the order of one unit of R.

Laboratories in the US, Europe, the Soviet Union and Japan are engaged in R & D aimed towards what I will call the next linear collider (NLC), which will be a machine somewhere in the energy region 0.5–2.0 TeV in the centre-of-mass.

A very qualitative picture of the state of linear collider technology is shown in Figure 12, which illustrates in the energy/luminosity plane what might be done with small extensions of present technology and the region that will certainly require some kind of new approach. The energy and luminosity requirements of the NLC, which are determined by its physics goals, push us toward the new approaches region.

A numerical example is shown in Table 6. Here the parameters of the SLC are compared to two variants of an NLC, one using the well-tested

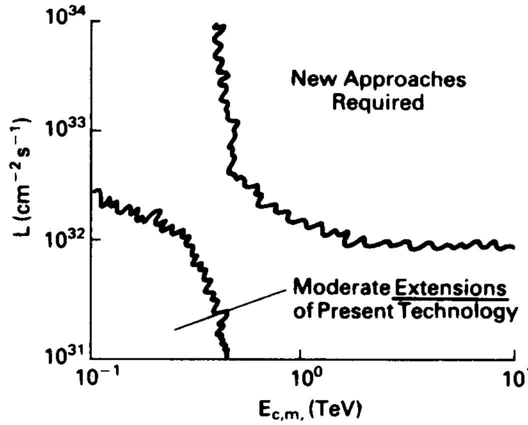


FIGURE 12. Technology requirements of a next-generation linear collider in the luminosity–energy plane.

TABLE 6. *Some critical parameters of SLC, "old" and "new" technology NLC*

		NLC	
	SLC	SLC technology	New technology
Energy (TeV)	0.1	1	1
Rep rate (Hz)	180	360	90
Luminosity ($cm^{-2}\,s^{-1}$)	6×10^{30}	10^{33}	10^{33}
Accelerating grad. (MV/M)	20	20	200
Length (km)	3	50	5
RF frequency (GHz)	2.9	2.9	11.4
Total "wallplug power" (MW)	50	500	100
$\sigma_x \times \sigma_y (\mu)^2$	$(1.6)\times(1.6)$	$(0.4)\times(0.4)$	$(1)\times(5\times10^{-3})$

linac technology of the SLC, and another using what seems to be plausible parameters which require the development of new technology. The NLC has 10 times the energy of the SLC but requires a luminosity more than 100 times as great. Using the technology of the SLAC linac, which has an accelerating gradient of 20 MeV/m and runs at an RF frequency of 2.9 GHz, results in a machine that is approximately 50 km long and uses a wall plug power of about 500 MW. This is to be compared with what might be done with an accelerating gradient of 200 MeV/m, which has been demonstrated in single cavities, at an RF frequency of 11.4 GHz, which is four times that of SLAC. The resulting accelerator is 5 km long and uses a total wall power plug of about 100 MW. The new technology machine uses a flat beam at the collision point compared to the round beam of the SLC, and results in one of the beam dimensions being very small indeed – around 5 nm. Perhaps we cannot push quite as far as this new technology example, but it is clear that increased accelerating gradient and higher RF frequency will result in a considerably less costly accelerator facility.

Before going on to discuss the state of linear collider R & D, I want to give a brief introduction to what goes on in the collision region of a linear collider.[3] There are problems here that will affect the experimenter's ability to do experiments, and questions which require answers that cannot be determined solely by the accelerator physicists.

The beam–beam interaction in linear colliders can be very much stronger than would be allowed in a storage ring. The reason for this is that, since the beam is to be used only once, one can allow the electromagnetic fields of the two beams to disrupt their phase spaces to a much larger extent than is allowable in a storage ring, where the beams must continue to circulate in a magnet ring for a very long time. In an electron–positron collider the collective fields of one beam will focus a single particle in the other beam, as illustrated in Figure 13.

The strength of the interaction is measured by a dimensionless

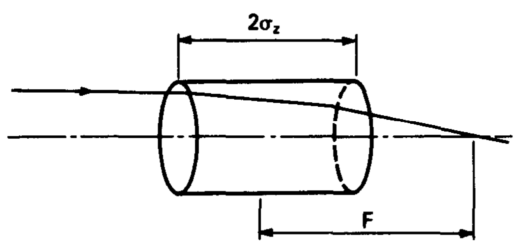


FIGURE 13. Effect of the intense fields in one bunch of a linear collider on a particle in the other colliding bunch.

parameter (D), the disruption parameter, which is the ratio of the bunch length to the focal length of an equivalent lens. For round trigaussian beams, D is given by

$$D = \frac{\sigma_z}{F} = \frac{r_e \sigma_z N}{\gamma \sigma_r^2}$$

where the bunch has a longitudinal standard deviation σ_z, a radial standard deviation σ_r, a number of particles N, and an energy γ in rest-mass units; r_e is the classic electron radius, and F is the small amplitude focal length of an equivalent thin lens.

The effective fields in a linear collider tend to be very large, and the focal lengths can be very small. Even in the SLC the fields are of the order of megagauss, F is in the order of millimetres, and D is about one. In the higher-energy machines being discussed now, the fields are tens of megagauss, F is tens of microns, and D is 5–10.

Large values of D imply that the beam cross-section is strongly perturbed during the collision. For values as high as 5–10 the interaction is sufficiently strong so that a kind of mutual pinch occurs, reducing the radius of both beams during the collision period and hence enhancing the luminosity.[4]

While synchrotron radiation is no problem in the acceleration process in a linear collider, the very large effective fields in the collision region can generate extremely intense synchrotron radiation. At high luminosities the synchrotron radiation, called "beamstrahlung", dominates the energy spread in the beam. What is important to the experiments, and hence to the machine designers, is the spread in centre-of-mass energy generated by this beamstrahlung phenomenon. Particles in one beam lose energy to synchrotron radiation as they pass through the other beam, and so even for the case of zero energy spread in the incident beams there can be long tails in the energy distribution of the colliding beams if the synchrotron radiation is sufficiently intense. Naturally, it turns out to be easier for the machine designers to make machines with very large values of the centre-of-mass energy spread, while it turns out to be difficult for the experimenters to do experiments if this energy spread is too big.

Qualitatively, for small values of δ, a parameter approximately equal to the mean loss in energy of a particle in one beam in travelling through the other beam, the centre-of-mass energy distribution is sharply peaked around the initial centre-of-mass energy, while for large values of δ the distribution has long tails stretching out towards low centre-of-mass energy. Figure 14 shows the integral distribution of the square of the centre-of-mass energy (S). I have plotted three cases which show the fraction of the time that S/S_0 is greater than a given value vs. that value. For $\delta = 0.4$, only around 20% of the time is S within 2.0% of its maximum value, while for $\delta = 0.1$, it is within 2.0% for 60% of the time. Studies at

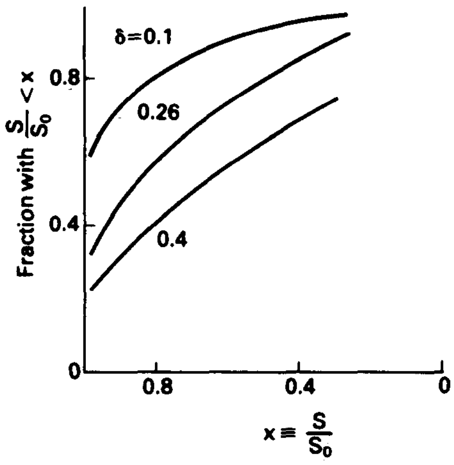


FIGURE 14. Integral distribution of the energy spread in a 1.0 TeV linear collider for various values of the beamstrahlung energy loss parameter, δ.

SLAC and CERN indicate that a reasonable compromise would be a value of δ of around 0.25.

Let me now turn to a discussion of the state of accelerator technology. There are four main areas that need considerable research and development before we are ready to build a machine. These are the electron and positron sources where the beams are born, the accelerators that boost them to the required high energy, the final focus system that squeezes them to an exquisitely small size, and the beam dynamic studies that will tell us how all of these systems interact with each other. The largest and most expensive part of the NLC will be the accelerators, and so I will spend most of my time on that topic. It is, however, worthwhile to say a few words about the other three.

It is easier to make a small beam at the collision point if the beam has been born small at its source. The term "small" in this context means that we require a source of low emittance (the invariant emittance of the beam is proportional to the energy times the transverse size times the transverse angular spread). The NLC will require sources with an invariant emittance no more than about 10% of that used in the SLC. I think we understand how to do that job – we can use existing storage ring technology, but must pay a great deal of attention to the details to make sure that the emittance does come out as small as it can, in principle, be. The damping storage rings will be somewhat different in design from that used now, but it looks like the energy of these damping rings will be in the GeV region.

The final focus system will be difficult. The beam sizes are much smaller than they are in the SLC, while the energies are much higher so that the focusing system requires much stronger elements. The final focusing magnets will surely be superconducting, though some work is going on using plasma lenses which can be made even stronger than superconducting magnets for final focus elements. This focusing system becomes more difficult the larger the energy spread in the incoming beam will be, and regrettably, the smaller the required energy spread at the end of the accelerator the harder the accelerator is to build. This area needs a great deal of work, which can be theoretical for a while, but eventually we are going to have to build some prototypes.

More detailed beam dynamic studies are required everywhere. The interaction of the beam with the accelerating structure (Wakefields) must be better understood, and much work is required on tolerances, stability requirements, etc. There is more than enough to do to keep the theoreticians in the accelerator community busy for some time.

As mentioned earlier, the accelerators and their power sources will be the most expensive part of the new machine, and it is here that most of the R & D work is now concentrated. The accelerators must be energy-efficient, stable, and able to preserve the small emittance of the beam from the sources through the full acceleration cycle. If one doesn't care about a few billion dollars here or there, one could probably use the SLAC linac technology for the NLC. The machine would be long, expensive and a terrible power hog. New developments in this area will strongly affect not only the construction costs of the machine, but its operating costs as well.

Four main approaches have been under discussion. These are:

1. laser accelerators
2. plasma accelerators
3. Wakefield accelerators
4. conventional RF structures with either conventional or exotic power sources.

I think all of us who are active in this field (SLAC, Novosibirsk, KEK, CERN) have come to the conclusion that the NLC can only be built via the fourth method. It is the only one where we can see how, at least in principle, to get the required stability and energy conversion efficiency.

The stability requirement is very severe, for we want to make a colliding-beam device, and not a fixed-target device. Beams from two independent accelerators must meet each other reliably and reproducibly within tolerances of a tiny fraction of a micron. The first three methods all have severe problems – intensity fluctuation and mode structure (lasers), laser drivers and plasma uniformity (plasmas), and azimuthal asymmetry of drive beams (Wakefield). All of them seem to suffer from serious inefficiency problems as well. I believe they are not for the next generation of linear colliders, though it may well be that new approaches and new technology may make these kinds of systems viable in 15–20 years.

The most promising system appears to be the conventional linear accelerator with some kind of high-power driver, which itself will have to be some new technology. The machines will probably use much higher accelerating gradients than are used now, and will almost surely be considerably shorter RF wavelengths than are used in the SLAC machine. The push toward high accelerating gradients is driven by the costs of the accelerator structure itself. The higher the accelerating gradient, the shorter the machine and its civil construction can be. At SLAC we have shown that for about 1 μs pulses, copper structures can stand accelerating gradients of more than 100 MV/m at 3 kMHz, and more than 300 MV/m at 10 kMHz. Thus, high accelerating gradients also seem to benefit from higher RF frequency.

The electrical efficiency of the accelerating system also benefits from higher RF frequencies. For a given accelerating gradient the stored energy per unit length in an accelerator is proportional to the square of the RF wavelength. Thus, for a given charge per bunch, the fraction of the energy stored in the accelerating structure that can be extracted by the bunch increases as the wavelength decreases. Of course, if one had a superconducting accelerator structure, one would not have to worry about the fraction of stored energy extracted, for the leftover energy could be used to accelerate the next bunch. However, superconducting systems cannot attain very high accelerating gradients, and so the cost of a main accelerator done with superconductivity will be very high, as will be the power required to run the compressors of the refrigerator unless the Q of these systems can be significantly increased. Everyone now seems to be talking about systems with frequencies from 10 to 30 GHz.

The power sources for these machines will require something new. Very high accelerating gradients go with high peak power in the accelerating structure. The machines under discussion at various laboratories in the world use peak powers on the order of $\frac{1}{2}$–1 GW/m of accelerating structure. Generating these high peak powers will be quite a challenge. Fortunately, the average power is not much higher than we deal with today. These high peak powers are associated with short pulse lengths (typically 50 ns or so) and so the average power required is not much different from that which comes from conventional klystrons.

One method that has been investigated at SLAC to generate high peak power from almost conventional klystrons is pulse compression. By combining multiple power sources through low-loss delay lines, with proper phase manipulation at the power sources, it is possible to get pulse compression ratios of ten or twenty to one. These systems are complicated, delicate, and require an enormous amount of plumbing for the delay lines, but they do seem workable.

Of more interest are the variants of what might be called two-beam accelerator systems. One beam with low energy and high current in one accelerator structure is used to generate RF power which drives a second accelerator structure. Two variants of this are currently under investigation. One being pursued by a Berkeley/Livermore/SLAC collaboration uses induction linacs to produce beams of several kA current at energies of several MeV, with klystron-like bunching and energy extraction cavities. We hope to demonstrate a 500 MW, 50 ns pulse length RF source some time next year.

A different approach is being pursued at CERN. The "CLIC" group is investigating the use of superconducting cavities like those already designed and tested to increase the Tristan or LEP energy for the high-current, low-energy accelerator. A train of short, high-current bunches rides in this low-frequency accelerator and interacts with a high-frequency cavity structure to produce RF power which is used to charge the high-energy accelerator. The CLIC group are interested in frequencies of around 30 GHz for the high-energy machine, and are modelling the energy extraction cavities for tests at a lower RF frequency.

This field is moving very fast, and I think in a few years' time there is a very good chance that a practical power source/accelerator combination will be available.

Major R & D programmes are either in place or are developing in Japan, Europe, the USSR and the US. In Japan a group centred at KEK, with contributions from other Japanese universities, is aiming towards a machine with about 1.0 TeV in the centre-of-mass. This programme is growing as people and resources are freed from work on the Tristan colliding beam storage rings. The main emphasis is now on studies of high gradients and appropriate structures for large linear colliders.

In Europe there is the "CLIC" programme at CERN, which aims towards a 2.0 TeV machine. The R & D work here is concentrating on a superconducting RF generator running at 35 GHz in combination with a room-temperature high-gradient accelerator. Intense work is under way on the beam dynamics of the driver and on the problem of transferring energy from the superconducting RF generator to the high-gradient accelerator.

In addition in Europe there is the Frascati "ARES" project, which is aiming towards a recirculating superconducting linac to produce the beams and SLC-like collision geometry. The final phase of the project might be a *B* factory, while the first phase under study is a nuclear physics facility. Fifty-four million dollars have been assigned to INFN over a 5-year period for R & D.

At Orsay there is a smaller programme aimed at high brightness electron guns and on the use of field emission and lasers to produce high-power RF generators.

In the USSR there is a programme centred at Novosibirsk which aims at building a 2.0 TeV facility at Serpukhov in stages. This project has conditional approval from the Soviet authorities. If certain milestones are met, conventional construction might start in 1992 or 1993 on the tunnel to house this facility. The main milestone is the development of a 10-m long accelerating section with RF drivers to run at a gradient of 100 MeV/m.

In the US the SLAC programme is aimed at a 0.5–1.0 TeV machine, and is concentrating on the development of new power sources, structures for high-frequency accelerators, and on theory. In addition, a final focus test facility is in design which could allow all the groups in the world interested in this kind of machine to try out new ideas in this very difficult area. There are also programmes at LBL, Lawrence Livermore National Laboratory, and UCLA.

No-one is ready to proceed as yet with a machine. There is much R & D to do in all areas before a believable design study can be produced with a reasonably reliable cost estimate. The four regions now heavily involved in this kind of work are going to try to carry out the R & D programme internationally with a mixture of coordinated and collaborative work. No single group can investigate all the promising alternatives, and all groups will move faster by cooperating. The first international workshop on linear collider R & D will be held at SLAC in November 1988. If things go well, I think we can expect serious proposals in 3–4 years.

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