THE FUTURE OF ELECTRON-POSITRON COLLIDERS *

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Abstract

This paper is an abbreviated version of a lecture given at the Snowmass meeting of the Division of Particles and Fields of the APS. Included here are SLAC's plans for the Stanford Linear Collider and my own speculation on the development of the e^+e^- machines beyond the SLC or LEP that will be required to further advance the state of particle physics.

Introduction

Progress in particle physics has always been closely connected with progress in the development of particle accelerators. As accelerators increase in energy, experiments which probe the structure of matter and the forces of nature at a deeper level become possible. The new experiments and the theoretical effort made to understand these new results in turn raise new questions. Eventually these new questions become such that they can be answered only by experiments at higher energy, requiring new accelerators.

As a result of the experimental and theoretical work of the last decade a new synthesis is emerging. In the new view, the weak and electromagnetic interactions are explained by gauge theories and the strong interaction is explained by quantum chromodynamics. Grand unified theories are trying to combine the weak, electromagnetic and strong interactions into a single coherent picture. Many varieties of new models exist, some of which predict quite different phenomena in an energy range not yet accessible. It is now the turn of the accelerator builders to provide the new tools required to test the new models.

The next machine in the electron-positron colliding beam field is the LEP project now under design and soon to be under construction at CERN. This machine uses a traditional technology — the electron-positron colliding beam storage ring. In LEP's first phase it will reach an energy of about 100 GeV in the center-of-mass and in the second phase, if superconducting RF systems can be successfully developed, it will reach 200 GeV.

The construction of the first electron storage ring, the Princeton-Stanford machine, was begun in 1958. The construction of LEP, the newest and largest of the electron storage rings, is beginning now in 1982. In this period of about twenty-five years, the radii of these machines have grown five-thousandfold, from about one meter to about five kilometers. At the same time the energy of the machines has increased a hundredfold, from the 500 MeV of the first machine to the 50 GeV of LEP. I believe many more storage rings will be built in the future, but these machines will not significantly advance the energy frontier for e^+e^- physics beyond that which can be reached in the second phase of LEP.

It is the scaling laws for storage rings which will limit their advance in energy. When electrons are bent in a circle they emit synchrotron radiation and the energy loss per turn required to make up for this sychrotron radiation goes up as the fourth power of energy divided by the first power of the bending radius. Radius-dependent costs, such as magnets, tunnels, etc.; power-dependent costs for the rf system required to make up synchrotron radiation losses; constraints on machine design coming from the beam-beam interaction and the focusing system result in a system of equations that allow the designer to minimize the cost of a machine. For an electron storage ring, the minimum cost solution is one where cost and size are proportional to the square of the center-of-mass energy.[1] The same scaling law is obtained whether a superconducting or conventional rf system is used.

LEP-I costs about $500 million to obtain 100 GeV in the center of mass. I will guess that LEP-II at 200 GeV in the center of mass with superconducting rf will cost about $200 million additional. Using the scaling law implies that a 1-TeV machine, which is a non-unreasonable next step, would cost about $17.5 billion, have a circumference of nearly 700 kilometers, and consume gigawatts of electric power. While the cost of such a device is negligible compared to the arms budget of the world (very roughly $600 billion per year), it is quite large compared to the total high energy physics budget of the world (about $1.4 billion per year). The fiscal feasibility of such a storage ring is in doubt, and, in addition, there is some evidence that there are technical problems in building machines this large.

Prediction is a dangerous thing, but, given the scaling laws, I feel fairly safe in predicting that LEP will be the largest and the last of the big electron-positron storage rings.

If the views that Glashow espoused a few years ago were correct, that there was nothing but a desert between the mass of the Z^0 and the grand unification scale of 10^{15} GeV, we probably would not care if there were no follow-on to LEP. However, since the first flush of enthusiasm for grand unification models, complications have turned up and have led to such hypotheses as technicolor, hypercolor, supersymmetry, composite models, etc., all of which predict new phenomena at an energy of around ten times the LEP energy. Electron-positron machines have been enormously productive in the last decade and are, I believe, the best type of machine to use to investigate the physics of the TeV region. The physics need is clear, but if the cost problem is such that we cannot go on building bigger storage rings, we have to find another way.

This situation, wherein cost or technical limitations closes the energy frontier for a given type of accelerator is not new. We have faced this problem often in the past. For many years the energy frontier for accelerators has moved up by a factor of ten every six years. We have maintained the pace by switching to new types of accelerators when one type has reached technical or fiscal limitations.

Is there an alternative to the storage ring? I think there is, and I think it is the linear collider system whose scaling laws were worked out at the first ICFA workshop by Tigner (Cornell), Skrinskii (Novosibirsk), myself, and others. The luminosity of these machines is proportional to the power in the beam and independent of the energy. The scaling law is such that the cost and length of a facility, where two linacs fire intense electron and positron bullets at each other, are proportional to the first power of the energy rather than to the square. Linear colliders tolerate a much stronger beam-beam interaction than do storage rings, and the beam-beam interaction seems to enhance the luminosity rather than to decrease it, as is the case in storage rings. There are new issues in the accelerator physics involved in linear colliders, among which are the production and control of micron-size beams at the

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collision point, and the handling of peak currents in linacs that are a hundred times more intense than we are used to.

At SLAC we hope to start building a variant of the linear collider schems — the SLC — in late 1983, if the U.S. Government follows the recommendations of its Department of Energy Advisory Committees and supplies the funds. The SLC, when completed (at the end of 1986 at the earliest) will allow us to investigate such things as the beam accelerator interaction, the beam-beam effect, control problems, etc., as well as to carry out an exciting high energy physics experimental program at 100 GeV in the center of mass.

A Brief Description of the SLC

The SLC is designed to operate at energies up to 100 GeV in the center-of-mass system with a luminosity at 100 GeV of 6.5×10^{30} cm^{-2} s^{-1}. The main components of the project are an energy upgrade of the SLAC linac; a transport system from the end of the linac to a small-aperture magnet ring; the magnet ring itself; a special focusing system near the interaction point; the necessary housing; an experimental hall and staging area; a high-power positron-production target; a positron booster; a transport system from the positron target at the two-thirds point of the linac back to the injection end of the linac; a new high-peak-current electron gun; two small storage rings to reduce the emittances of the electron and positron beams by radiation damping; pulse compressors to reduce the length of the bunches in the storage ring before injection into the linac; and the necessary instrumentation and control systems for both the linac and the collider system. A schematic of the complete system is shown in Fig. 1, and Table 1 summarizes the important parameters.[2] Since the collider is a new kind of machine, a typical operation cycle is described below.

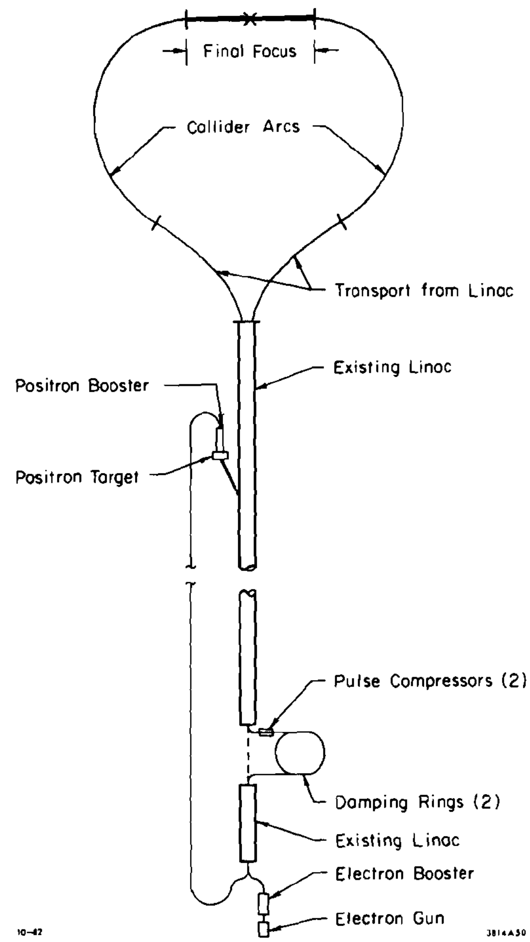

Fig. 1. Schematic layout of the SLC.

Table 1. Parameters of the SLC at 50 GeV

A. Interaction Point	
Luminosity	6.5×10^{30} cm^{-2} sec^{-1}
Invariant Emittance ($\delta_s \delta_s' \gamma$)	3×10^{-5} rad-m
Repetition Rate	180 Hz
Beam Size ($\sigma_x = \sigma_y$)	1.4 microns
Equivalent Beta Function	5 mm
B. Linac	
Accelerating Gradient	17 MeV/m
Focusing System Phase Shift	360° per 100 m
Number of Particles/Bunch	5×10^{10}
Final Energy Spread	±1/2%
Bunch Length (σ_z)	1 mm

The cycle begins just before the pulsing of the linac. The electron and positron damping rings each contain two bunches of 5×10^{10} particles at an energy of 1.2 GeV. One of the positron bunches is extracted from the damping ring, passes through a pulse compressor which reduces the bunch length from the centimeter typical of the storage ring to the millimeter required for the linac, and is then injected into the linac. Both electron bunches are extracted from the electron damping ring, pass through an independent pulse compressor, and are injected into the linac behind the positron bunch. The typical spacing between bunches is about 15 meters in the linac.

The three bunches are then accelerated down the linac. At the two-thirds point, the trailing electron bunch is extracted from the linac with a pulsed magnet and is directed onto a positron-production target. The positron bunch and the leading electron bunch continue to the end of the linac, where they reach an energy of about 51 GeV. At the end of the linac, the two opposite-charge bunches are separated by a DC magnet, pass through a transport system which matches the focusing of the linac to that of the main collider ring, and then begin to travel around the ring in opposite directions, losing about 1 GeV each synchrotron radiation. The collider ring is composed of small-aperture magnets with very strong alternating-gradient focusing, which is required to hold down emittance growth in the collider arcs. After emerging from the arcs, the bunches pass through an achromatic matching and focusing section which focuses the beams to a very small size at the collision point.

The positrons produced by the electron bunch that was extracted at the two-thirds point of the linac pass through a focusing system at the positron source, a 200 MeV linear accelerator booster, a 180° bend, and an evacuated transport pipe located in the existing linac tunnel. This brings the positron bunches back to the beginning of the linac. At this point, the positron bunch passes through another 180° bend and is boosted to an energy of 1.2 GeV in the first sector of the existing linac and is then injected into the damping ring.

Because the emittance of the positron beam is very much larger than that required for Collider operation, a positron bunch must remain in the damping ring for approximately four radiation damping times, which corresponds to twice the time interval between linac pulses. Thus the positron bunch to be used in the next linac cycle is the one that is still stored in the damping ring from the previous cycle.

Electrons for collider operation are produced from a special gun equipped with a subharmonic buncher located at the beginning of the linac. Two bunches of electrons are produced, are boosted to 200 MeV in a dedicated section of linac, and are then injected into the same section of linac used to boost the positron bunch to 1.2 GeV. At the end of this section the 1.2 GeV electrons are injected into their own damping ring. The electron bunches at the time of injection into their damping ring have an emittance somewhat larger than required for collider operation but considerably smaller than the emittance of the positron bunch and thus need only be damped for two damping times or one interpulse period. The entire cycle repeats 180 times per second.

The beam from the electron source may be polarized by using a suitable laser-illuminated semiconductor photocathode. Whereas the linac preserves the longitudindal polarization of the electron beam, special transport systems are required at the damping ring to avoid depolarization of the beam. This is accomplished by spin rotating solenoids in the transport to and from the ring. In the ring, the spin is made vertical so it is aligned along the magnetic field direction of the ring dipoles. Two solenoids in the transport back to the linac provide the control to process the spin to any desired direction, thereby leading to control of the polarization axis at the interaction point.

The energy of the SLC can be increased, should that be desired, above the initial design value of 100 GeV by adding RF power to the linac. This possibility is an important safety factor for the experimental physics program, for the Z^o mass, which sets the energy scale of the machine, has not yet been determined and the theoretical estimates of this mass have been increasing over the years. The simplest and most "brute force" technique to increase the energy is to increase the number of klystrons feeding the linac — doubling the number of klystrons increases the energy by a factor of 1.4.

Luminosity, Yields and Energy Spread

The luminosity of the SLC at 100 GeV in the center-of-mass is expected to be 6.5×10^{30} cm^{-2} s^{-1}. This luminosity is larger than indicated in our design report of June 1980, for we have now succeeded in the design of a final focus system with $\beta^* = 0.5$ cm and have also taken proper account of the beam-beam interaction.

The shape of the luminosity curve versus energy (Fig. 2) is determined by the interplay of adiabatic damping and transverse wake field effect in the linac, quantum fluctuations in the synchrotron radiation emitted in the magnets that bring the beams from the linac to the collision point, and the beam-beam interaction. As the energy decreases from 50 GeV/beam, the quantum fluctuation effects decrease and the transverse

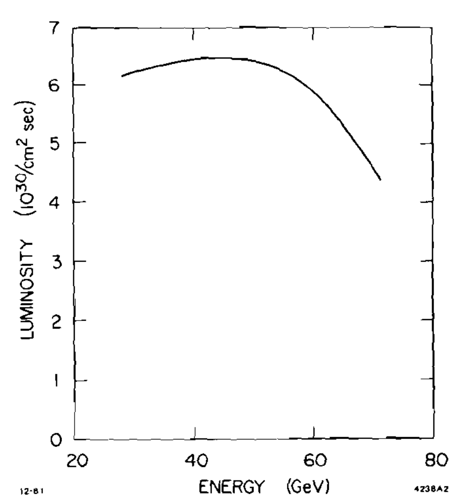

Fig. 2. Luminosity versus single beam energy of the SLC.

wake effects increase, resulting in a fairly flat luminosity curve. Above 50 GeV/beam the quantum effects begin to dominate and the luminosity begins to drop, reaching about 70% of its 50 GeV/beam value at 70 Gev/beam.

The integrated luminosity expected per year is obtained simply by multiplying the peak luminosity by the time ON of the linear accelerator, including an allowance for the fraction of the time that can reasonably be expected to be efficiently used for data taking. The situation in the SLC is quite different from that in a storage ring, where an additional derating factor must be added to take account of the decrease in luminosity caused by the decay of the stored beam current, and of the time spent filling the ring. In practice (SPEAR, PETRA, PEP), the effective luminosity of a storage ring must be decreased by about a factor of three from its peak value.

We estimate the yearly integrated luminosity of the SLC at the expected Z^o peak to be

$$\int \mathscr{L}\, dt = 8 \times 10^{37} \text{ cm}^2 \tag{1}$$

This value is based on the assumption of 40 weeks per year of linac running time and 50% effective data-taking time (the 50% derating factor is to account for time spent on machine physics, on other uses of the linac such as storage-ring fills, on breakdowns in the experiments, etc.). The yearly accumulated number of events at the Z^o peak would be

$$Y(Z^o) = 3.5 \times 10^6 \text{ per year} \tag{2}$$

where we assumed the standard model value of R = 4500, which includes radiative corrections. If there were no Z^o, using the known strength of the neutral-current weak interactions we would expect R to be about 10, and the yearly accumulated number of events would

$$Y\left(M_{Z^o} = \infty\right) \simeq 7000 \text{ per year} \quad . \tag{3}$$

The energy spread in the SLC is dominated by longitudinal wake-field effects in the linac. At full luminosity the energy spread in the linac beams is about ±0.5% (each beam), quantum effects in synchrotron radiation from the bending magnets contribute negligibly, and the synchrotron radiation emitted in the beam-beam collision contributes about ±0.2% (including the effect of the luminosity enhancement from the beam-beam pinch). The center-of-mass energy spread is

$$\frac{\sigma_{E^*}}{E^*} = \frac{\left[(0.5)^2 + (0.2)^2\right]^{1/2}}{\sqrt{2}} \simeq 0.4\% \tag{4}$$

For special experiments, such as a precision measurement of the Z^o width, the energy spread can be reduced to about ±0.1% with a loss of a factor of three to five in luminosity.

A large literature exists on the physics potential of 100 GeV e^+e^- colliding beams.[3] Rather than repeating what most of you know about testing the standard model, determining the number of low mass neutrino species, finding the Top, etc., I will only mention three special opportunities that exist with the SLC.

Polarization

Longitudinally polarized electron beams are already available at SLAC, and we expect that we can produce longitudinal electron polarizations of 40% to 80% at the SLC collision point. With a polarized beam some unique weak interaction experiments become possible and other experiments become more sensitive. In electron storage rings at 50 GeV it is not clear that polarization is possible and, if possible, the systems required to turn the transverse polarization naturally produced in storage rings into the longitudinal polarization desired for weak interaction physics, are very complex.

Vertex Detection

The beam radius at the SLC collision point is only ~1.3 μ, and the angular divergence of the beam is small. The present design of the SLC final focus system uses a close-in quadrupole of about 1-cm bore diameter, and thus the vacuum pipe through the interaction region can also be about 1 cm in diameter without creating background problems.

The small beam pipe allowed in the SLC presents new opportunities for lifetime measurements and particle identification. For example, the best lifetime measurement of the D^+ meson puts τ_D between 6×10^{-13} and 10×10^{-13} sec. For a 25-GeV/c $D^\pm$, between 29% and 45% of the D's decay outside of the beam pipe. Appropriate detectors (holographic bubble chambers, high-resolution solid-state detectors, or precision drift chambers, for example) can be used to find the decay vertex, and this information can be used to measure short lifetimes (to about 10^{-14}s) or as an aid in the identification of the parent particle. A great deal of physics becomes possible with this technique. For example, leading D mesons can be identified, allowing a determination of their weak coupling.

Since the beam pipe is small, the detectors need only have a small depth of field to cover a large fraction of the solid angle. In contrast to the SLC, storage rings typically have beam pipes an order of magnitude larger, making the measurements more difficult and the detectors larger.

e^+e^- Physics

Although the main focus of the SLAC linear collider is e^+e^- annihilation, the SLC has the unique capability of providing high-energy e^-e^- collisions with fully-controllable electron polarization. This opens up a number of new physics opportunities; one example of which is the basic process $e^-e^- \to e^-e^-$ that can be studied at s ≈ 10,000 GeV^2. In addition to checking standard features of the electroweak models, this process provides a probe of lepton substructure at distances down to about 0.5 (TeV)$^{-1}$. Single and double polarization measurements are even more sensitive to possible deviations of the $e^-e^- \to e^-e^-$ amplitudes from conventional theory.

The luminosity of the SLC in the e^-e^- mode must be reduced from that given for the e^+e^- mode. The reason for this reduction is that the beam-beam interaction, which pulls electrons and positrons together, pushes electrons and electrons apart. We expect the maximum luminosity in the e^-e^- mode to be about 10^{30} cm^{-2} sec^{-1}.

Very High Energy Colliders

Setting the Stage

Part of the motivation for the SLC project is to develop the technology of linear colliders so that a very high energy machine can be built when much higher energy in the e^+e^- system is needed for physics. The physics requirements set the parameters of the machine, and the parameters required for the machine point to the critical technological developments that are needed to make such a machine possible.

There is as yet no guidance from e^+e^- experiments at 100 GeV or from high-energy $\bar{p}p$ experiments to set an energy scale for new phenomena that one might want to investigate with a very high energy collider. We must guess at an appropriate energy scale and will choose 1 TeV in the center-of-mass system for this discussion. This energy is ten times that of the SLC and LEP phase I, and five times that of the full LEP project with superconducting RF, and thus seems a large enough step.

We also have no guidance as to the required luminosity for such a 1-TeV collider. We need a cross section to set a scale for the counting rate at a given luminosity, and we simply do not know enough to do more than guess at a value. We shall assume the worst case, that the Weinberg-Salam model describes most of the physics of the weak-electromagnetic interaction. If we further demand 1000 μ-pair evenys (and many times more Z^oZ^o, W^+W^-, Z^oH^o, etc.)[4] per running year (again using 40 weeks and 50% efficiency) under this assumption, the required luminosity is 10^{33} cm^{-2} sec^{-1}.

If vector bosons that mediate the weak interaction do not in fact exist, and if the weak cross section continues to increase as it does at low energy, then the μ-pair cross section will be near the unitary limit (about 10^5 times the Weinberg-Salam value), and luminosities of 10^{33} will give many more events than anyone knows what to do with.

The Machine

Given an energy and a luminosity, the machine is almost completely specified. If no exotic methods of controlling beam-beam synchrotron radiation at the collision point are postualted (co-moving e^+e^- beams colliding with another co-moving pair, for example), this "beamstrahlung" determines the energy spread in the collision. We shall guess that no narrow resonances exist, and that $\sigma_{E*}/E^* = 5\%$ is tolerable. The parameters of the machine are given below.

$\mathscr{L}$	10^{33} cm^{-2} sec^{-1}
E*	1 TeV
Invariant Emittance ($\gamma\sigma_x\sigma_x'$)	3×10^{-5} rad-m
β*	0.5 cm
Beam Radius at 500 GeV (σ_r)	0.4 micron
Pulses per Second	2000
Bunch Length (σ_z)	2 mm
Disruption Parameter	1.5
Enchancement from Pinch Effect	6
Particles per Bunch	4×10^{10}
Power in Each Beam	6.4 MW

Many of the beam parameters listed above are near to the parameters of the SLC. The two that are very different are the energy and the beam power. It is certainly not feasible to simple extend standard linacs like SLAC, for if we did, we could have a total length of machine of about 60 km, a power consumption of gigawatts, and a cost on the order of $\$2 \times 10^9$. However, if we can make energy efficient, low cost per unit length accelerators, the world high energy physics community can afford such a machine at its present budget level. We don't know the best way to build such a machine and an intense R&D program will be required to determine the best road.

The first decision which one might make I would call the "warm or cold" decision, i.e., normal or superconducting rf structures. Table 2 shows what one might expect for a superconducting system based on presently achievable Q. The table assumes a Q of 5×10^9 at S-band, a shunt impedance of 2.4×10^{13} Ω/m, a refrigerator efficiency of 0.1% at 2.3° K, a heat leak to room temperature of 2 watts per meter; and then displays as a function of accelerator gradient the length of the system, the refrigerator required to handle the load coming from finite Q and the refrigerator power required to handle the load from the heat leak. At present we can probably obtain a gradient of 5 MV per meter reasonably reliably. This gradient is at the power consumption minimum, but using some cost per unit length figures for superconducting structures from Tigner, it is not at the cost minimum.

Table 2. Some parameters of superconducting linear colliders. For various values of accelerating gradient (G), I give the total length of the two linacs (2L), the refrigerator power required because of finite $Q(P_Q)$, the refrigerator power required because of heat leaks (P_L calculated for a heat leak of 2W/m) and the total refrigerator power (P_T).

G (MV/m)	2L (km)	P_Q (MW)	P_L (mW)	P_T (MW)
0	∞	0	∞	∞
1	1000	42	2000	2040
2	500	84	1000	1080
5	200	210	400	610
10	100	420	200	620
20	50	840	100	940
50	20	2100	40	2140
100	10	4200	20	4220

Taking a cost per unit length of $\$5 \times 10^7$/km, a power cost of \$0.05/kw=hr, and assuming 5000 hrs/yr of operating time for ten years, the cost minimum would be at a gradient of 21 MV/m and the cost of the linac alone would be about $\$2.7 \times 10^9$. I would conclude that superconducting systems need considerable work on improving the attainable gradient and cavity Q's to reduce costs significantly.

There is much activity in the study of warm systems, all of which emphasizes high accelerating gradients which are required to reduce the effect of the beam accelerator structure interaction and to reduce capital costs. Below is a brief description of four systems that I know about — there may be more.

Conventional rf structures with high-power sources. At SLAC in the mid 1960's it was shown that copper can stand surface fields of at least 150 MV per meter. These fields imply, in properly designed structures, accelerating gradients of more than 100 MV per meter. Such structures need gigawatt peak power sources to drive them. The Novosibirsk group will soon be testing a structure designed for these kinds of accelerating gradients, and preliminary design studies on structures and power sources are going on at SLAC.

RF transformer systems. These transfer the energy from a low energy, high current beam to accelerate a lower current beam. An example of this type of system is the "Wake Field" accelerator of Voss and Weiland which will be discussed later at this meeting.

Laser accelerators. One of the early suggestions for a laser accelerator was that of Palmer which proposed the use of the longitudinal field near a grating for accelerating particles. A system which promises a larger phase acceptance is what might be called a laser "beat wave" accelerator recently described by Tajima and Dawson. In this system two laser beams are fired into a plasma. The difference in frequency of the lasers is equal to the plasma frequency. This generates a traveling plasma wave with a large electron density that does the acceleration.

The ionization front accelerator. The advance of a high current, low energy electron beam entering a neutral plasma is controlled by the ionization of the plasma with an auxiliary laser. The ionization front is made to travel in synchronism with the velocity of the particles to be accelerated. Olsen et al., Sandia, have demonstrated proton acceleration of about 5 MeV in 10 cm with this system.

One can see there are many new ideas for accelerating systems. Not all of them will be applicable to the acceleration of the very small, very intense beams required for linear colliders, but in the next few years we will have to see which of these (or other) systems shows the most promise and to begin prototype accelerator system studies to evaluate costs and technical feasibility. I would hope to see a 1 GeV accelerator, less than 10 m long, in the late 1980's. Once we have reached this stage we can then begin a large-scale physics machine aimed at reaching greater than 1 TeV in the center of mass. Since many of these promising ideas are new, there are no "experts" and any of the physics community can contribute. I look forward to an exciting decade of development.

Further Speculation on the Use of Big Colliders

Electron-proton collisions. Protons as well as electrons can be accelerated in electron linacs. For a machine fed every 3 m (like SLAC) a proton injector of about 10 GeV is required. Using the transverse emittance of the FNAL linac, an e-p luminosity of 10^{31} cm^{-2} sec^{-1} would be obtained at 1 TeV. Use of proton cooling techniques would raise this luminosity.

Proton-proton collisions. Proton injectors for both linacs would give 10^{31} luminosity in the pp system without cooling. However, the low duty cycle may make all but specialized experiments difficult.

Use of the technology for fixed target machines. A gradient of 160 MeV/meter gives the same energy per unit length of machine as is obtained in proton machines with 40 kg superconducting magnet technology. For example, the FNAL Tevatron is designed to reach 1 TeV with a machine of 6 km circumference.

The big linac is also a low power consumer compared to the proton machine. For 10^{14} protons per 100 seconds (Tevatron design intensity), 2500 linac proton pulses must be delivered in 100 seconds. The average beam power for a 1 TeV linac is only 190 kw. Even a 1% efficient linac would use considerably less power than the Tevatron (30-40 MW).

In the 1940's, before the invention of the strong focusing synchrotron, many felt that proton linacs were the best way to achieve high energy. After the passage of 40 years, they may be proved right.

Conclusion

The 1980's will be an exciting time for electron-positron colliders. The standard model will be given a thorough workout by both LEP and the SLC. At the same time an accelerator R&D program will be developing the techniques required to increase radically the energy of e^+e^- machines. These new techniques may well be cost effective for proton acceleration as well. In the late 1980's, I think a serious proposal, with accurate cost figures, can be presented to the high energy community for consideration.

I do not know if this next step can fit on the sites of any of our existing laboratories. If the next machine can fit at a developed site, it will certainly be less costly than if a new lab would have to be built with the accelerator.

There has been much discussion at this meeting of a new laboratory for very large machines. I think it is obvious that we will eventually need a new site as machines continue to grow larger. The only questions are when, and will it be on international or a national facility? It is not worth losing much sleep over these questions — time, the needs of the field, and the resources available to us will answer them. More gatherings like this one, involving the accelerator, experimental, and theoretical physics communities will be an important part of reaching a consensus on the proper next steps.

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