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THE SLAC LINEAR COLLIDER*

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Abstract: A brief description of the proposed SLAC Linear Collider is given. This machine would investigate the possibilities and limitations of Linear Colliders while at the same time producing thousands of Z^0 particles per day for the study of the weak interactions.

Résumé: Cet article présente une description préliminaire du "SLAC Linear Collider", nouvel instrument proposé au SLAC, qui pourrait étudier les possibilités des "Linear Colliders" tout en produisant des milliers de Z^0 par jour.

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INTRODUCTION

One of the major physics goals of the 80's will be the search for the Z° and $W^\pm$ particles predicted by unified electro-weak theories. If these particles are not found within a fairly narrow range of energies, our present understanding of the weak interaction will have to be substantially modified. If they are found, a measurement of their masses, total widths and branching ratios would give us a great deal of insight into the basic structure of the unified theory. The presence or absence of these particles and a measurement of their properties are the crucial experiments for unified theories.

The advanced accelerator task force (AATF) at SLAC has been looking into the design of a new e^+e^- machine with sufficient energy and luminosity to explore Z° production. The effects of the Z° on the lepton pair and hadron rates are quite spectacular.1) The ratio of the multihadron cross section to the point cross section is expected to be 4300 at the Z° mass, so that with a luminosity of 10^{30} cm^{-2} sec^{-1} one would observe 160 events per hour. The total width and mass of the Z° are thus easily measured and this together with measurements of branching ratios would greatly restrict weak interaction models. Present low energy data from neutrino interactions are consistent with a large class of gauge theories with different symmetries.2,3) Understanding the weak interaction is important in many diverse areas of physics. In the field of cosmology for example, the Z° width measurement is important since the cooling rate for the early stages of the universe and the total width of the Z° are both sensitive to the number of light neutrinos.4) If the Z° is found, its properties should provide many clues to the mechanism of weak electromagnetic unification, and the structure and dynamics of the weak interaction.

The machine which has been studied by the AATF group is not a conventional storage ring. It uses single intense pulses of electrons and positrons accelerated by the SLAC linac. Thus in addition to answering crucial particle physics questions, this machine would begin to explore the new technique of <u>linear</u> colliding beam machines. For some years now it has been recognized that the difficulties in designing an e^+e^- storage ring capable of reaching the Z° are not so much technical as they are financial. The cost of storage rings scales with the square of the energy5) and that of linear devices scales linearly. A storage ring capable of producing the Z° and perhaps $W^\pm$ pairs is feasible and has already been designed[6] but e^+e^- physics beyond the Z^0 and $W^\pm$ will probably require a linac-linac collision device. Until 1979, however, little accelerator research and development had been directed toward questions about the performance of linear colliding beam machines. The proposed machine would be a first step in answering some of the new questions which these machines pose.

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The idea of using linac-linac colliders for e^+e^- physics has been around for some years. Early suggestions by M. Tigner[7] and U. Amaldi[8] attempted to recover the energy supplied to the beams or reuse the particles in the beam. More recently, Augustin *et al.*[9] suggested that if the beams are discarded after each pulse, the small emittance of linac systems could be used to produce very small spot sizes at the final focus thus improving the achievable luminosity. In addition, since the two beams are discarded after each linac pulse, the effective beam-beam force which can be tolerated at the collision point is increased.

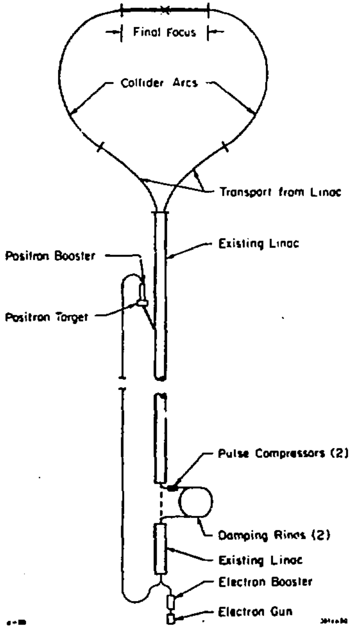

Figure 1—General layout of the Single Pass Collider.

The general layout of the SLAC Linear Collider (SLC) is shown in figure 1. It is a variation of the true linear collider because it uses only a single linear accelerator. In this machine, a positron bunch and an electron bunch are accelerated simultaneously by the existing SLAC linac and are brought into collision by a special transport system. The transport at the end of the linac is specially designed to minimize the emittance growth of the beams in the arcs by using a large phase advance per cell. The final focus at the collision point must be optimized to third order in the chromatic corrections and have a small β (~1 cm) to produce the minimum possible beam size. The beam size is approximately 90μ at the exit of the linac, 30μ in the arcs, and 2μ at the final focus.

The low emittance required for this small final spot size is achieved by pre-damping the electron and positron bunches in small damping rings near the linac injector. An electron gun (see Fig. 1) feeds the electron damping ring via a small booster and a 1.2 GeV section of linear accelerator. This gun also produces a pulse which is used to produce positrons from a standard positron target system. The bunch of electrons used for positron production follows the predamped electron and positron bunches for two thirds of the length of the linac. It is then extracted and directed onto a target. Positrons from the target are boosted to 200 MeV, transported back to the injection area, boosted to 1.2 GeV by the same linac section used for the electrons, and finally injected into the positron damping ring. The timing of the operations is such that the bunch to bunch separation in the linac is about 15 meters. The entire process is repeated at a frequency of 180 Hz. Further details of the design can be found in Table 1.

The luminosity in this device is

$$\mathcal{L} = \frac{N^2}{A} \cdot f$$

where f is the repetition rate of the linac, N is the number of particles per bunch, and A is the effective area at the collision point. Compared to a storage ring, the lower repetition rate ($f_{SLC} \sim 4 \times 10^{-4}\ f_{PEP}$) and the smaller number of particles per bunch ($N^2_{SLC} \sim 10^{-3}\ N^2_{PEP}$) are almost compensated for by the much smaller spot size at the final focus ($A_{SLC} \sim 10^{-6}\ A_{PEP}$). The average luminosity for the SLC is 10^{30} cm^{-2} sec^{-1}. The same average luminosity would of course require a somewhat higher design luminosity for a storage ring since experience at SPEAR has shown that the average luminosity is typically a factor of two to five smaller than the luminosity at the beginning of a fill.10)

Table I

Parameters of the Single Pass Collider at 50 GeV

A. Interaction Point	
Luminosity	10^{30} cm^{-2} sec^{-1}
Invariant Emittance ($\sigma_x \sigma'_x \gamma$)	3×10^{-5} rad-m
Repetition Rate	180 Hz
Beam Size ($\sigma_x = \sigma_y$)	2 microns
Equivalent Beta Function	1 cm
B. Collider Arcs	
Average Radius	300 m
Focusing Structure	AG
Cell Length	5 m
Betatron Phase Shift per Cell	110°
Full Magnet Aperture (x;y)	10; 8 mm
Vacuum Requirement	$<10^{-2}$ Torr
C. 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
D. Damping Rings	
Energy	1.21 GeV
Number of Bunches	2
Damping Time (Transverse)	2.9 ms
Betatron Tune (x;y)	7.1; 3.1
Circumference	34 m
Aperture (x;y)	±5; ±6 mm
Bend Field	19.7 kg

FUTURE LINEAR MACHINES

The beam energy and diameter of some of the storage rings built or proposed in the past decade are shown in Table II. The rapid growth of the size and cost of these rings is primarily a result of the energy loss per turn of the stored particles which is given by

$$\Delta E = \frac{4}{3} \pi \frac{r_e}{(mc^2)^3} \frac{E^4}{\rho} = 8.8 \times 10^{-5} \mathrm{m}\ \mathrm{GeV}^{-3} \frac{E^4}{\rho}$$

Modest increases in beam energy are accompanied by large increases in either the power required to run the machine, the size of the machine or both. Simply extrapolating the last step in Table II indicates that the next entry in the table would have 280 GeV per beam with a 70 km diameter!

Table II

Storage Ring Beam Energies and Diameters

Ring	E_{BEAM} (GeV)	Diameter (m)
ACO	0.5	6.8
SPEAR	3.0	63
PEP	18.0	700
LEP	70.0	7069

Linear accelerator sizes are determined by the gradient which can be achieved in the accelerating structure. Present gradients of 10-15 MeV/m are sufficient for linacs in the 50 GeV range, but a two linac system with 280 GeV per beam would still be rather large. Fortunately there is room for improvement since this gradient is well below the limit set by the surface properties of typical accelerating cavities. The present SLAC structure, for example, can produce up to 45 MV/m even though it is not optimized for high gradients.11) At this accelerating gradient, the surface gradients are 160 MV/m, so that a cavity with a higher ratio of accelerating gradient to surface gradient could perhaps produce 100 MV/m. At 100 MV/m, a two linac system with 280 GeV per beam would have a total length of only 5.6 km. Collective acceleration schemes may eventually provide gradients of several GeV per meter which would reduce this length by another order of magnitude.

Assuming that the gradient problem can be solved, the problem which remains is that of finding an efficient high peak power system to drive the cavities. Two beams of 280 GeV, 5×10^{10} particles each, and a repetition rate of 10^4 Hz represent a beam power of 44 MW! Losses in the drive system and in the cavities must be minimized in order to transmit as much power as possible to the beams.

Since the power used by a linac is proportional to $f \cdot N$ and the luminosity is N^2f/A, the power required for a given luminosity can only be decreased by decreasing the area A as much as possible. Linacs for linear colliders must be optimized to give the lowest possible emittance per unit current. By decreasing the emittance and focusing the beam more tightly, the density at the collision point and hence the luminosity can be increased.

The real object however is to maintain the luminosity at some usable level and reduce the current and power requirements.

The density at the collision point cannot be increased indefinitely however. At some density, the interaction of the two beams as they collide will generate plasma instabilities which could reduce the luminosity. This "disruption limit" is quite different from the beam-beam limit in a storage ring since the disrupted beam is discarded after a single collision. Figure 2 shows a computer simulation of the collision of two beams where the density is approximately two orders of magnitude larger than the storage ring limit.

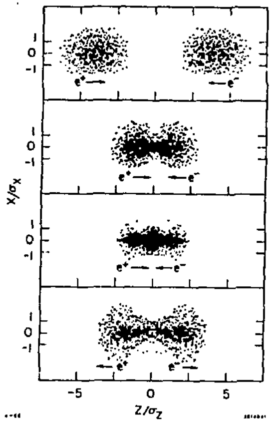

Figure 2--Computer Simulated Collision of Intense Beams Illustrating the Pinch Effect.

Even for this density, the beam dynamics can be reliably calculated since the number of plasma oscillations during the collision is only of order one and stability is not a problem.$^{12)}$ For oppositely charged beams, the disruption causes the beams to pinch, and the reduced average area of the beams as they collide can enhance the luminosity by as much as a factor of six.$^{12)}$ As in the case of reduced emittance, this enhancement is a means of reducing the amount of power required to produce a given "design" luminosity. An optimized design would adjust the beam profile and focusing to produce the greatest possible enhancement. Some experience is needed with real beams before one can estimate what the eventual "disruption limit" will be and what the optimum beam profiles are for linear colliders.

The existence of the SLAC linac and the properties of the proposed SLAC linear collider give us a unique opportunity to begin to explore the performance and limitations of the class of machines which we know must be built in the future. At the same time, the energy range of the SLC would provide the answers to many of our questions about the weak interactions. Both studies would have a profound effect on the future of high energy e^+e^- physics.

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4) $\Gamma \sim 0.075$ GeV $\left[N_{L^-} + 2N_\nu + \frac{10}{3} N_u + \frac{13}{3} N_d\right]$ for $\sin^2\theta_W \sim 1/4$ and N_{L^-}, N_ν, N_u, N_d the number of charge -1 leptons, neutrinos, charge 2/3 quarks and charge -1/3 quarks into which the Z decays.

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10) The average luminosity at SPEAR differs from the luminosity at the beginning of a fill by a factor of two when running in the "top-up" mode where current can be added directly to the colliding beam configuration. If configuration changes or energy ramping are required, the average luminosity is typically one fifth of the initial value.

11) G. Lowe, private communication.

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