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THE SLAC LINEAR COLLIDER
THE MACHINE, THE PHYSICS, AND THE FUTURE*

by

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I. 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.

It may seem strange to be asking now what can be built beyond LEP, but we must start asking that question now for the scaling laws for electron-positron storage rings are well known and I believe it is very unlikely that there will be a much larger machine of this traditional type.

The scaling laws for any type of accelerator can be derived by taking unit costs for such things as tunnels, magnets, vacuum chambers, power, RF systems, refrigerators, etc., and combining these unit costs in a set of equations constrained by the desired physical parameters of the machine. For an electron storage ring the inputs are the required energy and the required luminosity, and the principal constraints come from the beam-beam interaction, and from the synchrotron radiation losses of the circulating beams. For example, as the radius of the machine of a given energy increases the costs of magnets, tunnels, vacuum chambers, etc., increase, but the cost of the RF power to keep the beams circulating decreases. The cost equations have a minimum and the value of the radius at the minimum defines the machine.

The results of the minimization procedure give a scaling law for storage rings such that the cost and radius of the machine will be proportional to the square of the center-of-mass energy.[1] The constant of proportionality depends on the technology used -- it seems to be slightly smaller for superconducting RF systems than for conventional RF. However, this is not yet clear for no large scale superconducting RF system has been built as yet.

The LEP machine at CERN designed for 70 × 70 GeV using room temperature RF is estimated to cost approximately 500 million dollars and has a circumference of 27 kilometers. The Cornell preliminary study of a 50 × 50 GeV machine using superconducting RF estimates a cost of 200 million dollars and a circumference of about 6 kilometers.

We can use the Cornell estimate to scale to a next generation large machine. Given the growth potential of LEP, a follow-on machine would have an energy of between 400 GeV and a TeV in the center-of-mass. If we take 700 GeV as our design goal and scale from the Cornell cost estimate, we find that the machine will cost 10 billion dollars and have a circumference of 300 kilometers. These enormous numbers would lead most people to question the fiscal feasibility of such a project independent of any technical problems. Prediction is a dangerous thing, but, given the scaling laws, I feel fairly safe in predicting that LEP will be the largest and the <u>last</u> 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.

Finding another way has been the story of particle accelerators for decades. From the Cockroft-Walton generator, to the Van de Graaff, to the cyclotron, to the weak focusing synchrotron, to the linac, to the strong focusing synchrotron, as a particular technique reached its technical or fiscal limitations, a new way was found to go on by using a new technique of particle acceleration.

I believe the same thing will be true with electron-positron colliding beams and I believe that the new technique which will replace these devices is the Linear Collider. Linear Colliders are, in essence, two linear accelerators firing electron and positron bullets at each other with no attempt made to reuse the spent beams after the collision. These devices have different scaling laws from those of storage rings. The luminosity of such a machine, under certain assumptions about the beam-beam interaction, is proportional to the power in the beam and independent of the energy of the machine. Thus, for a fixed luminosity, the cost of a linear collider scales as the first power of the energy rather than quadratically as in a storage ring. Eventually, a machine with a first power scaling law must be less costly than a machine with a second power scaling law.

The SLAC Linear Collider (SLC) will be the first of this new type of colliding beam machine. It has been designed with two goals in mind: to develop a new colliding beam technique, and to produce a facility capable of supporting a strong experimental program in the energy region around 100 GeV where new, weak interaction effects are expected to become manifest.

II. 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.

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

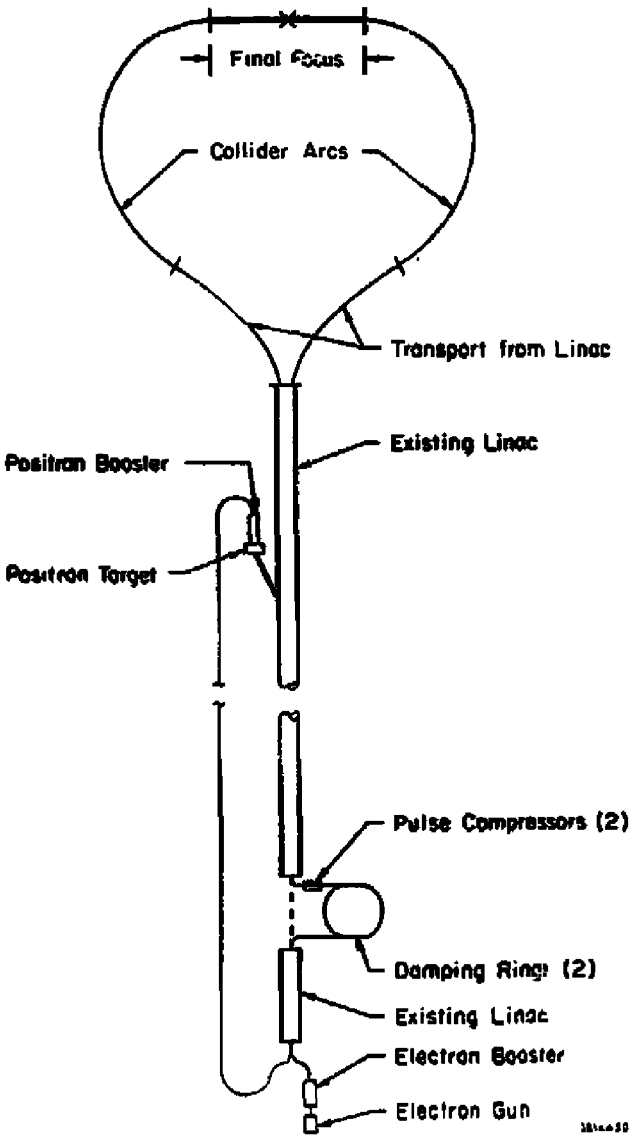

Fig. 1. Schematic layout of the SLC.

Table 1

PARAMETERS OF THE SLC AT 50 GeV

A.	Interaction Point	
	Luminosity	6×10^{30} cm^{-2} sec^{-1}
	Invariant Emittance ($\delta_x \delta'_x \gamma$)	3×10^{-5} rad-m
	Repetition Rate	180 Hz
	Beam Size ($\sigma_x = \sigma_y$)	1.4 microns
	Equivalent Beta Function	5 mm
B.	Collider Arcs	
	Average Radius	290 m
	Focusing Structure	AG
	Cell Length	5.2 m
	Betatron Phase Shift per Cell	108°
	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)	3.059 ms
	Betatron Tune (x;y)	7.23; 2.78
	Circumference	35.27 m
	Bend Field	19.812 kGauss
	Final Emittance $\sigma_x \sigma'_x$	2.1×10^{-5} rad-m

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 in 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 longitudinal 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 precess 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^0 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.

III. NEW ISSUES IN ACCELERATOR PHYSICS

The new problems in accelerator physics which arise in the SLC (and in linear colliders in general) are caused by the interaction of the relatively large charge in the electron and positron bunches with the accelerator structure, and by the very strong (compared to storage rings) beam-beam interaction that occurs at the collision point. Both of these problems have been investigated theoretically and the beam-accelerator interaction is being investigated experimentally in our R&D program. In this section both of these effects are described.

A. Beam-Linac Interactions

The electron and positron bunches in the SLC are expected to contain 5×10^{10} particles in a single S band bunch which is about 1 mm long. The bunches are about 100 times more intense than the bunches that are accelerated in normal operation of the linac. At this very large charge per bunch, space-charge forces that are normally negligible can cause the effective emittance and energy spread of particle bunches to grow as they pass through the linear accelerator. This growth must be limited because the bunches must be focused to a 1.4 micron radius spot at the collision point. The properties of the ion-optics which focus the bunches have been chosen on the assumption that the energy spread of the particle bunches leaving the linear accelerator is ±0.5% and that the effective emittance of the bunches is 3×10^{-10} radian-meters.

It is a simple matter to produce a low-intensity beam exceeding this specification. As the current is increased, however, the emittance and energy spread of the beam will grow. The maximum current which can be accelerated subject to the conditions on maximum usable emittance and energy spread is determined by the space-charge-control measures which are adopted.

The space-charge effects which are important here are the head-to-tail type which are common in particle accelerators. The leading particles at the head of the bunch leave behind fields (wake fields) in the linac RF structure that act on particles which follow in the tail of the bunch. Once the distribution of fields which a single particle leaves behind is known, it is a straightforward matter to compute the space-charge disruption of the ensemble of particles which constitute a bunch.

Two types of wake field trail behind a particle passing through the linac RF structure. There is a longitudinal wake which decelerates and a transverse wake which deflects particles that follow. The longitudinal wake field depends only on the distance between the particle generating the wake field and the particle upon which the wake field acts. The transverse wake field is more complicated. Like the longitudinal wake this wake depends on the distance between the particle which generates it and the particle on which it acts. It is also proportional to the distance between the path of the generating particle and the geometrical center line of the linac RF cavities, but is independent of the transverse position of the particle on which it acts. There are other higher order wake fields which depend on higher powers of the distance between the path of the generating and following particles and the axis of the RF cavities, but these fields are unimportant in the present application.

The transverse wake field that causes growth in the effective transverse emittance of the bunches and the longitudinal wake field that causes growth in energy spread differ in their dependence on the distance between the leading particle that generates the wake and the following particle that is acted on by the fields. For the range of bunch lengths appropriate to the Collider, the transverse wake increases with increasing separation between the particles, while the longitudinal wake decreases. For this reason, the energy spread increases when the bunch is made shorter, while the transverse emittance growth decreases. The bunch length, which is a controllable parameter, must be chosen to best balance these two space-charge effects. For the present Collider parameters, a Gaussian bunch with a rms length of 1.0 millimeter is consistent with the acceleration of 5×10^{10} particles/bunch with the required limits on energy spread and transverse emittance.

The effect of the longitudinal wake field is illustrated in Fig. 2. The upper part of the figure shows the distribution of charge in the bunch, and the lower part shows the decelerating wake integrated over the length of the linac. The large energy loss of the particles near the tail of the bunch can be partly compensated by accelerating the bunch ahead of the crest of the RF wave in the linac. Particles in the tail of the bunch will receive more energy than those at the head from the main RF field and the sum of the main field and the wake field gives an energy spread of ±0.1% at the end of the linac.

The effects of the transverse wake field can be controlled by steering the beam so that it is close to the center line of the accelerator thus minimizing the strength of the field; and by using a tightly focused quadrupole lattice on the linac, thus minimizing the emittance growth from a given wake field. It is also necessary to inject the beam into the linac with a very small component of free betatron motion. This can be accomplished by empirical tuning of injection conditions using emittance detectors at the end of the linac as monitors. This procedure has been tried successfully with short trains of bunches during accelerator physics experiments.

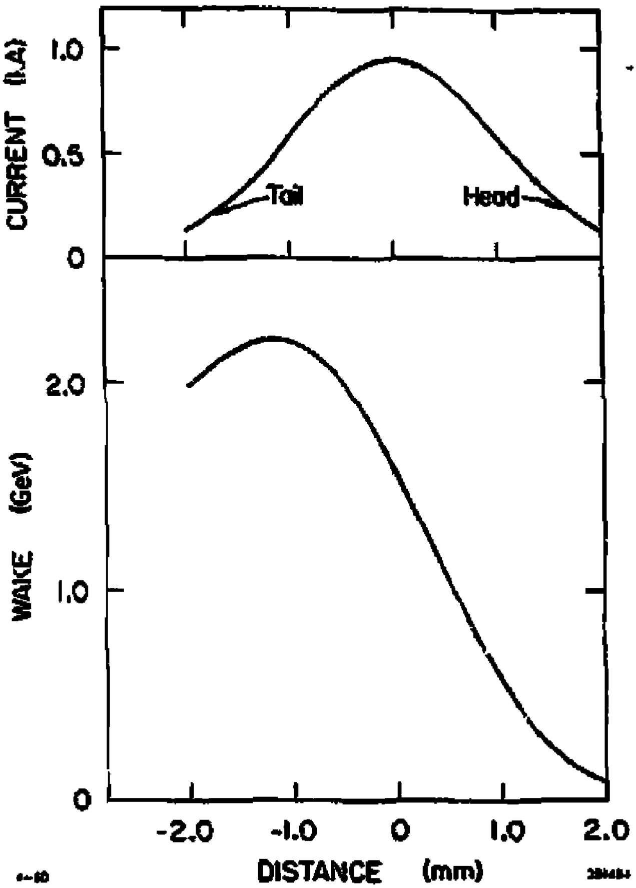

Fig. 2. The longitudinal wake for the design intensity of 5×10^{10} particles/bunch and the design bunch shape, a Gaussian with $\sigma = 1.0$ mm. The peak current in the bunch is 950 a.pares.

With proper steering and injection, the emittance growth is determined by the random misalignments of the sections of the accelerator. Figure 3 shows the reduction in luminosity at the SLC collison point arising from transverse emittance growth in the linac, versus the rms misalignment of the linac sections. The luminosity calculated for the SLC assumes a 100 micron rms misalignment.

Figure 4 shows the results of a computer simulation of the effects of the transverse wake in a misaligned machine. The position of the centers of various slices through the bunch are shown in x - x' phase plane.

B. Beam-Beam Interaction

Linear colliders achieve a high luminosity by focusing the beams down to a very small size at the collision point. In the SLC the very large charge and current densities at the collision point give rise to an effective field in the beam of the order of a megagauss. For the parameters of the SLC, one beam looks to the other beam like a magnetic lens with a focal length of about 1 mm! This strong focusing action results in a mutual pinch effect that can significantly increase the charge density in the collision region, increasing the luminosity over what it would be in the absence of the beam-beam effect.

Hollebeek has done a 3-dimensional computer simulation of the pinch effect.[9] The strength of the interaction is measured by a disruption parameter defined for round Gaussian beams as

$$D = \frac{\sigma_z}{f} = \frac{N\, r_e\, \sigma_z}{\gamma\, \sigma_t^2} \qquad (1)$$

where σ_z and σ_t are the longitudinal and transverse standard deviations of the bunch, f is the focal length of the magnetic lens formed by one unperturbed beam as seen by a single particle at small displacement in the other beam, N is the number of particles in the bunch, r_e is the classical electron radius, and γ is the energy in electron rest mass units.

Figure 5 shows an x,z projection of the particles in the e^+ and e^- bunches during the collision. As the bunches approach each other they are

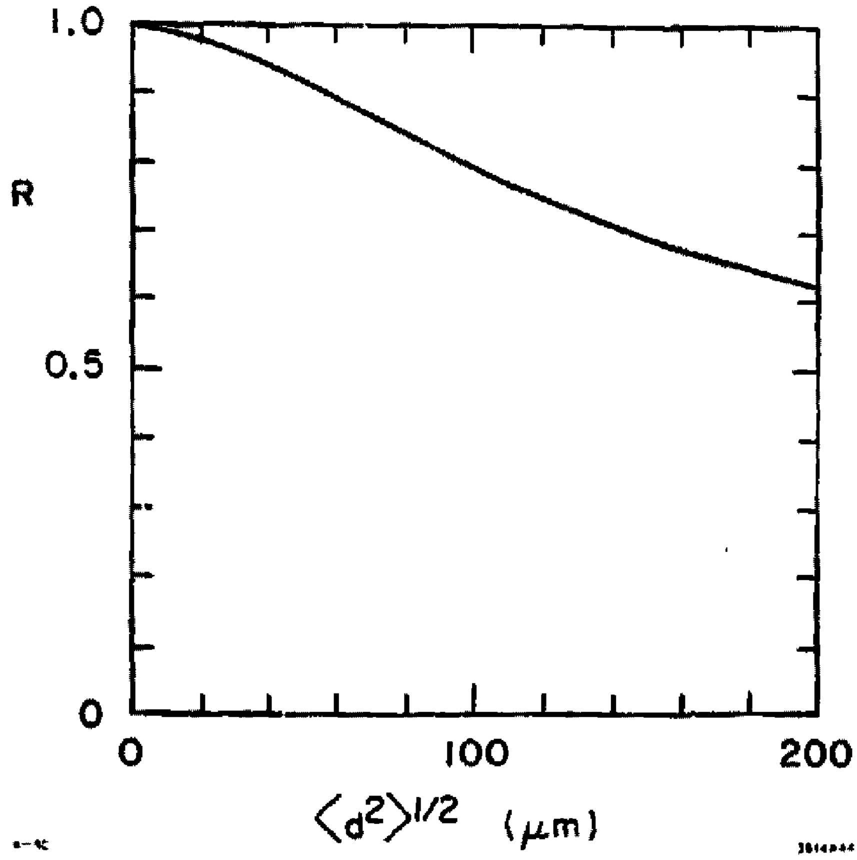

Fig. 3. The luminosity reduction factor R versus the misalignment tolerance of the accelerator pipe $\langle d^2\rangle^{1/2}$.

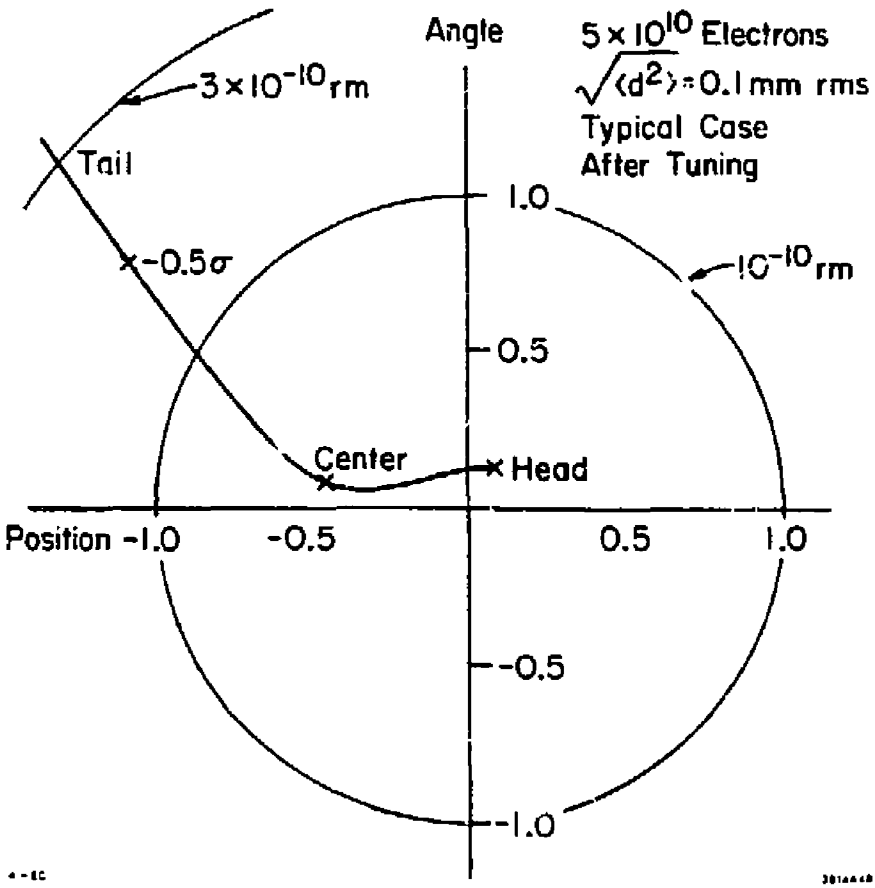

Fig. 4. The transverse phase space position of the center of various slices along the bunch at 50 GeV after empirical tuning of the injection conditions.

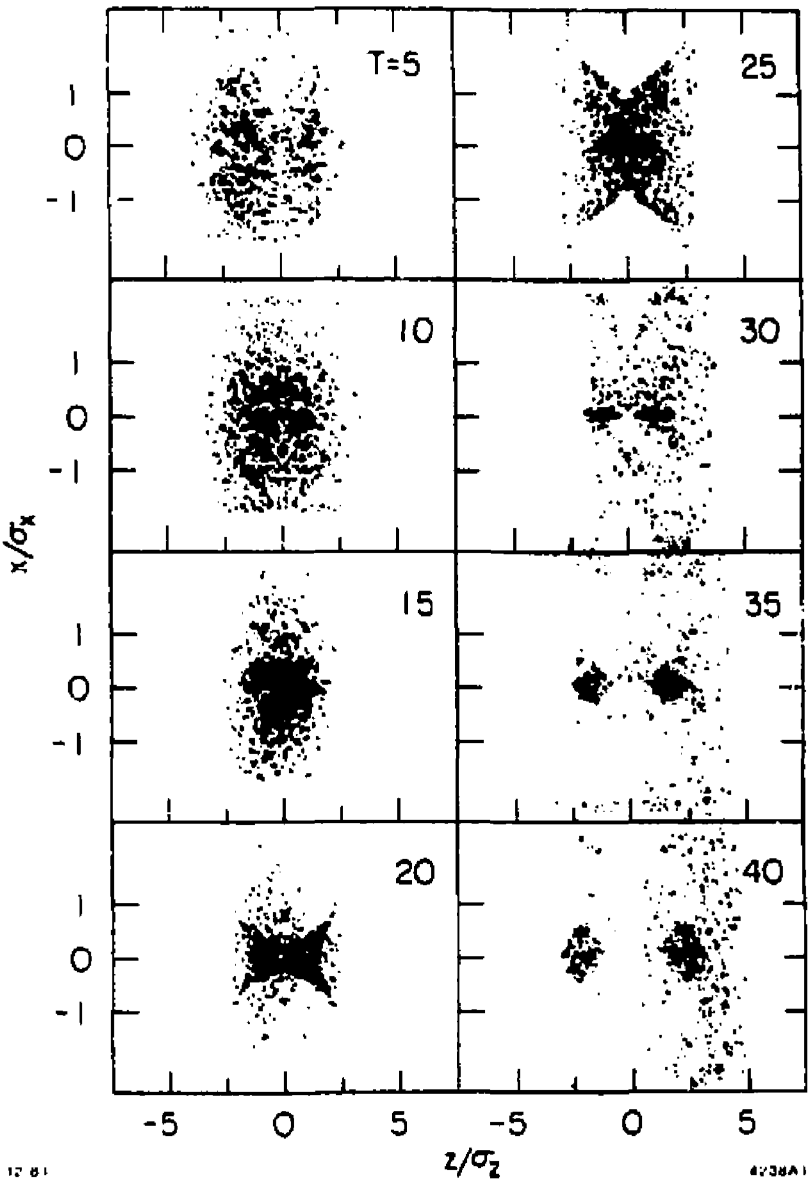

Fig. 5. Longitudinal and transverse distribution of particles at various times during the collision for a disruption parameter of three.

Gaussian in both dimensions. As they begin to overlap, the strong focusing effect of the beam-beam interaction begins to increase the charge density along the axis. At the point of maximum overlap, the central charge density is greatly increased. The beams finally separate, having been strongly disrupted by the collision. In this example the divergence angle is more than an order of magnitude larger than before the collision.

The pinch effect increases the luminosity, and this is shown quantitatively in Fig. 6. Here the luminosity enhancement factor (the ratio of the actual luminosity including the pinch to the luminosity which would have been obtained with no pinch) is plotted against the disruption parameter. The enhancement factor saturates at about six for a disruption parameter of two. For larger values of D, the beam cross section oscillates during the collision and no further increase in the mean charge density occurs. The SLC operates at D ≈ 0.8.

The length to diameter ratio of a bunch at the collision point is about 1000/1. For this large ratio, one must worry about plasma instabilities. Fawley and Lee[b] at Lawrence Livermore Laboratories have modified one of their plasma codes to handle the extreme relativistic case and find no instability problems up to a value of D ≈ 40 (two betatron oscillations of a particle in the field of the other beam).

Hollebeek has also studied the effect of misalignments and finds no significant reduction of the luminosity for transverse offsets of up to 1/2 σ_t.

IV. 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. 7) is determined by the interplay of adiabatic damping and transverse wake field effect in the linac, quantum fluctuations in the synchrotron radiation

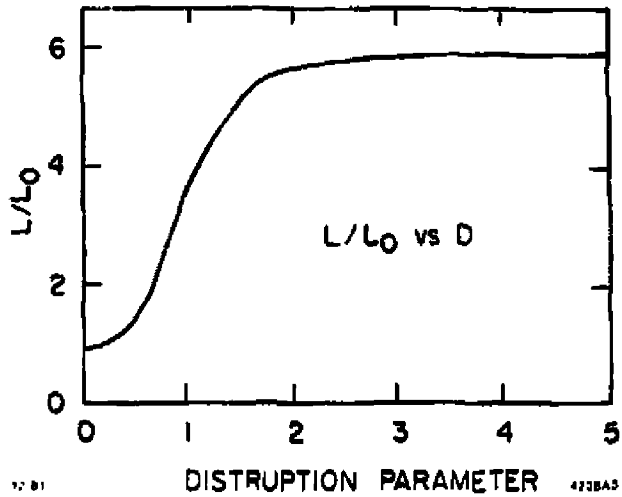

Fig. 6. The luminosity enhancement factor as a function of the disruption parameter.

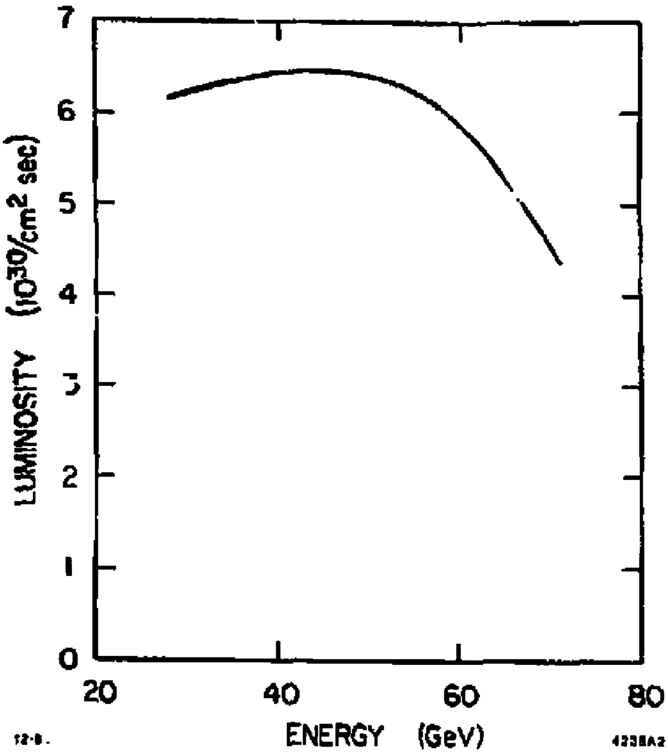

Fig. 7. Luminosity versus single beam energy of the SLC.

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 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 <u>additional derating factor</u> 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^0 peak to be

$$\int \mathcal{L}\, dt = 6 \times 10^{37}\ \mathrm{cm}^{2} \qquad (2)$$

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^0 peak would be

$$Y(Z^0) = 3.3 \times 10^6 \text{ per year} \qquad (3)$$

where we assumed the standard model value of R = 4500, which includes radiative corrections. If there were no Z^0, 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 be

$$Y\left(M_{Z^0} = \infty\right) \approx 7000 \text{ per year} \qquad (4)$$

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

$$\frac{\sigma_{E^*}}{E^*} = \frac{[(0.5)^2 + (0.2)^2]^{1/2}}{\sqrt{2}} \simeq 0.4\% \quad . \tag{5}$$

For special experiments, such as a precision measurement of the Z^0 width, the energy spread can be reduced to about ±0.1% with a loss of a factor of three to five in luminosity.

V. PHYSICS POTENTIAL

A large literature exists on the physics potential of 100-GeV e^+e^- colliding beams.[5] In this section we shall not attempt an exhaustive review of all the physics that one could study; rather, we select a few topics that show what the SLC can do in some standard, and not-so-standard, experiments.

A. Testing the Standard Model

Once the Z^0 mass can be reached in electron-positron collisions, a series of very precise tests of the standard SU(2) × U(1) theory can be made, and the one free parameter, $\sin^2\theta_W$, can be measured to an accuracy of a few percent or better. Simply finding the Z^0 peak already gives information on $\sin^2\theta_W$, for M_Z and θ_W are related by

$$M_Z = 37.3\ \mathrm{GeV}/\sin\theta_W \cos\theta_W \quad . \tag{6}$$

With $\sin^2\theta_W = 0.23$ (present errors are ±10%) extracted from polarized electron and neutrino experiments, and using lowest-order formulas, $M_Z \sim 90$ GeV. Higher-order corrections shift the mass upward to ~94 GeV. A measurement of M_Z to ±0.3 GeV from the radiatively-skewed event yield versus energy curve gives $\sin^2\theta_W$ to ±0.0015.

An independent and very sensitive method for determining $\sin^2\theta_W$ comes from measuring the vector coupling of the Z^0 to charged leptons such as the muon, since the vector coupling, with the assignment of fermions to left-handed doublets and right-handed singlets, is $g_V = \left(1 - 4\sin^2\theta_W\right)$. As $\sin^2\theta_W$ is close to 1/4, g_V is small; its deviation from zero thus yields the deviation of $\sin^2\theta_W$ from 1/4.

More specifically the front-back angular asymmetry in $e^+e^- \to \mu^+\mu^-$ is proportional to

$$\frac{g_V^e\, g_A^e}{\left(g_V^e\right)^2 + \left(g_A^e\right)^2} \cdot \frac{g_V^\mu\, g_A^\mu}{\left(g_V^\mu\right)^2 + \left(g_A^\mu\right)^2} \quad .$$

This asymmetry, being effectively quadratic in the small quantity $g_V = g_V^e = g_V^\mu$, is only a few percent at the Z^0 pole. It also has a rapid energy variation, so that while it is possible to determine g_V and hence $\sin^2\theta_W$ accurately this way, it is difficult and probably entails running at energies off the Z^0 peak where asymmetries are large but counting rates low.

With the longitudinally-polarized electron beam available in the SLC, the same measurement becomes much easier. An electron of definite helicity produces a Z^0 of definite helicity, in which case the front-back angular asymmetry become proportional to

$$\frac{g_V^\mu\, g_A^\mu}{\left(g_V^\mu\right)^2 + \left(g_A^\mu\right)^2} \quad .$$

This is effectively linear rather than quadratic in $g_V = g_V^\mu$ and leads to an asymmetry of 10% to 20% at the Z^0 by reversing the longitudinal polarization of the electron beam. The cross section difference is proportional to $g_V^e\, g_A^e$. This is true not only for the total cross section but also for any partial hadronic or leptonic cross section; thus, a measurement can be made using any kind of detector (calorimeter, special-purpose, etc.). The expected asymmetry is 10% to 20%, and this type of measurement is unique to polarized beams.

Looked at the other way, the muon asymmetry and the electron cross section asymmetry with polarized beams are elegant ways of determining g_V^e/g_A^e and g_V^μ/g_A^μ, which can then be checked against the formulas of the standard model. Similarly, we can determine the couplings of the Z^0 to the tau. Here we also have the additional handle of tau decay as a polarization analyzer. For quarks we are in a much more difficult situation, since quantities like the front-back asymmetry require determining the parent quark in a jet. This determination may be possible with vertex tagging, which is described in Section V.C below.

3. New Particles

At the same time as one "finds" . Z^0, one can also measure its width. This measurement permits the "count. " of the number of low-mass neutrinos, for in the standard model each additional neutrino adds about 160 MeV to the total Z^0 width. With the full-luminosity SLC energy spread of $\sigma_{E*}/E* \approx \pm 0.4\%$, the apparent Z^0 width is increased by 4% from the energy spread in the beam, while each additional neutrino increases the width by 6%. If it was desirable, the SLC could be run at reduced luminosity with a $\sigma_{E*}/E* = \pm 0.1\%$. While unfolding the radiative tail of the Z^0 will be difficult, "counting" to ±1 neutrino seems quite possible.

An alternative method of neutrino counting is to run the machine above M_Z, detecting the radiative transition to the Z^0 and the absence of any other Z^0 decay products.[6,7] This tagging method appears to be more precise than the width method.

Searching for either charged or neutral heavy leptons at the SLC would follow the path laid down by the discovery of the tau at SPEAR and the searches at PETRA and PEP: look at low-multiplicity events with e and/or μ. With a neutral lepton produced in ~6% of Z^0 decays and a charged lepton in ~3%, detection seems straightforward with only a small integrated luminosity.

Searching for new quarks is nearly as easy: if allowed by phase space at all, $Z \to t\bar{t}$ should have a branching ratio of ~10%. The event class searched is almost the opposite to that for leptons: high multiplicity, high sphericity, possibly with multileptons. This is the sort of search that could be successfully conducted with the first few thousand Z^0 decays.

Finding toponium and the bare top threshold is a good example of the physics the SLC can do below the Z^0 peak. Suppose $m_t = 30$ GeV and $m_{t\bar{t}} = 60$ GeV. The area under the lowest $(t\bar{t})$ resonance can be scaled from the area of the ϕ and is

$$\int \sigma(t\bar{t})\ dE = 10^4 \left(\frac{m_\phi}{m_{t\bar{t}}}\right)^2 = 27\ \text{nb-MeV} \quad . \tag{7}$$

With an energy spread in the SLC of about ±1/2%, this corresponds to a cross section of 4.5×10^{-2} nb, which is a change of 1.8 units in R. Given the luminosity of 6×10^{30}, it takes 1.5 days to establish a 4-standard-deviation effect. A few months would suffice to search the entire energy range above the energies accessible to PEP and PETRA.

Better mass resolution can be obtained by decreasing the energy spread in the beam. Although this decreases the luminosity, in first approximation the rate from a narrow resonance does not change while the background rate decreases.

The threshold for the production of T mesons can be determined from a sphericity analysis. Using the Mark II Monte Carlo including u, d, s, c, b quarks, radiative corrections, and gluons, the mean sphericity at 60 GeV is $\bar{s} = 0.123$. For T mesons $\bar{s} = 0.413$. If a test is defined which counts the number of events with $s > 0.5$, about 5% of "old" quark events and 33% of T meson events are counted. About 10 days is required to establish a 4σ effect.

At the opposite extreme are searches for the Higgs boson. The process of preference is $Z \to H^0 e^+ e^-$ or $H^0 \mu^+ \mu^-$. With branching ratios of several times 10^{-5} for $M_H < 30$ GeV, it will take about a one year run at maximum luminosity to do something definitive. The situation is better according to recent calculations for Z decay into a pair of pseudo-Goldstone bosons expected in technicolor models which contain no elementary Higgs fields. Some of these bosons are expected with masses O(10 GeV) and the Z^0 would decay into pairs of them with branching ratios of order one percent.

C. Special Opportunities

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.

Measurement of the lifetime of a lepton such as the τ is a simple matter for they are not accompanied by a flood of other particles produced at the primary vertex. Working with D, B and T mesons will be more difficult for they will be accompanied by other particles. Detectors need good transverse resolution to pick out the appropriate tracks. Bubble chambers have been operated with 8μ bubbles (holographic) to 30μ bubbles (conventional). Solid-state-diode chambers are being developed with ~100μ resolution. With resolutions of this order, a detector should be able to separate tracks at 5000μ from the collision point.

D. 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:

1. The basic process $e^-e^- \to e^-e^-$ can be studied at $s = 10{,}000\ \mathrm{GeV}^2$. In addition to checking standard features of the electroweak models, this process provides a probe of lepton substructure at distances down to about $0.5\ (\mathrm{TeV})^{-1}$. Single and double polarization measurements are even more sensitive to possible deviations of the $e^-e^- \to e^-e^-$ amplitudes from conventional theory.

2. Searches for processes such as $e^-e^- \to \mu^-e^-$, $\mu^-\mu^-$, τ^-e^-, and $\tau^-\tau^-$ will place further constraints on lepton conservation. It is expected in many grand unified models that lepton-number conservation is a broken symmetry. In Harari's Rishon model the electron is a composite of subfermions, and the muon and tau correspond to different internal excitations of this system. If the internal "hypercolor" mass scale is in the TeV region or below, lepton number nonconservation subprocesses could become manifest in the SLC energy range.

3. The processes $e^-e^- \to e^-e^-X$ at SLC provide the opportunity to study the two-photon processes $\gamma\gamma \to X$ up to very high energies in isolation from annihilation processes. Photon-photon collisions allow the study of hadron dynamics and fundamental QCD processes in reactions where the initial state is simple and controllable. Exclusive and inclusive cross sections can be studied as a function of photon polarization and, in the case of lepton tagging, as a

function of photon mass. Among the processes that can be studied with polarized photons are:

a. the total photon-photon cross section $\sigma_{\gamma\gamma}(s)$;

b. specific exclusive channels such as $\gamma\gamma \rightarrow M\bar{M}$ and searches for new C = + mesons, e.g., the large threshold enhancement observed at PETRA and SPEAR in $\gamma\gamma \rightarrow \rho^0\rho^0$ which may indicate new $qq\bar{q}\bar{q}$ or gg resonances;

c. the photon structure functions (including F_4^{γ}, which requires longitudinally polarized photons). Measurement of the scaling behavior of the photon structure functions can provide one of the most critical checks of QCD.

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}.

With this luminosity the e^-e^- elastic scattering yield in the angular range 60° to 90° is ~10/day. A fit to the angular distribution obtained in a 100-day run gives a cutoff parameter limit of 200-500 GeV.

The signature of lepton nonconserving events is unique, and with no observed events, the nonconserving amplitude can be limited to ≤1%.

The $\gamma\gamma$ rate for double-tagged events ($10 < \theta < 300$ mrad) with 10 GeV and above in the $\gamma\gamma$ center-of-mass is about 30/day.

VI. ACCELERATOR RESEARCH AND DEVELOPMENT

A. Introduction

We are conducting a broad research and development program at SLAC on linear colliders in general, and the SLC in particular. There are four main lines to this program. The first is the "Sector One" program where we are developing the high current electron source necessary for a linear collider, and equipping the first 100 m of the linac with the necessary focusing, controls, and beam monitoring equipment to measure quantitatively the effects of the transverse wake field.

The second item is the construction of a damping ring which can take a beam from the first section of the linac, shrink the beam's emittance to that typical of a linear collider, and reinject the beam into the linac for further acceleration. This is the most costly element of the R&D program and when completed near the end of 1982 will allow us to do a combination of fundamental work on colliders and development work on SLC components such as controls, beam monitoring, etc.

The third part of the program is concerned with development of components for the SLC itself. The areas that are being studied are the positron source where the required energy density in the positron target is very large, and the positron collection is difficult; the Collider arc magnets which are small and have very high field gradients; and the final focus system which requires careful correction of chromatic and geometric aberrations to produce the value of $\beta^* = 1/2$ cm that we plan to use.

The fourth part of the program consists of engineering studies of soil conditions, tunnel construction methods and experimental hall designs. This work is being done for us by Tudor Engineering Company of San Francisco.

In addition to this work, we are doing some mostly theoretical studies of big colliders. Some of our thinking about big machines is described in the next section.

In the remainder of this section, more details are given on the main parts of our R&D program.

B. Sector One

The first 100 meter section of the SLAC linac (Sector One) is the site for three tests:

1. the development of a new high-intensity, single-bunch injector for the SLC;
2. the conversion of the present control system of the linac to a prototype of that planned for the SLC; and
3. a demonstration that the beam produced by the new injector can be accelerated in the linac and injected into the damping ring.

A new injector has been built which produces more than 10^{11} electrons in a single S-band bunch. This injector appears to be adequate for the SLC. The injector control system is presently being modified to allow remote operation of the new injector through the SLC control programs.

The magnet focusing system throughout the injector and Sector One has been upgraded and extended to allow the SLC control program to set the magnet lattice for minimization of the beta function and for energy compensation, thus allowing matching to the injector emittance ellipse. The injector line consists of a series of solenoids and quadrupole triplets, and Sector One is a FODO array of four cells with 90° phase advance per cell.

It is important that the beam remain close to the axis of the linac in order to prevent emittance growth associated with transverse wake fields. New, highly accurate beam position monitors have been installed inside each quadrupole. The SLC control system monitors the beam position, calculates the appropriate orbit corrections, and then adjusts the steering dipoles located at each quadrupole. This new control system has been successfully tested during the past year.

The high-intensity, single-bunch beam is being extensively tested in Sector One. Additional instrumentation installed for measuring beam parameters includes energy analyzers at the beginning and end of Sector One, and several profile monitors. The initial beam tests were conducted in the last few weeks of the Spring 1981 running cycle. These first tests achieved a beam transported through Sector One of 2×10^{10} electrons per pulse, a factor of 3 below the desired intensity.

In order to measure the magnitude of the wake field phenomena, a lower intensity bunch of 5×10^{9} electrons was allowed to drift in the final part of Sector One where it was given various transverse offsets up to 12 mm using the orbit correctors. The observed deflections in the tail of the bunch relative to the head of the bunch agreed within errors of 50% with the predictions of wake field theory.

Changes in the injector, which are expected to reduce emittance growth and simultaneously to improve transmission, are nearly completed.

These changes include new focusing elements in the injector region, new beam diagnostic equipment, and extension of the SLC control system to include the injector steering.

These tests have been made with a high-performance thermionic electron gun. In parallel with this, a laser-activated, gallium-arsenide cathode gun has been built which is compatible with the existing injector. This gun, which uses a mode-locked, Q-switched laser will ultimately be used to provide polarized electrons for the SLC.

C. Damping Ring

The damping rings reduce the transverse phase space of the e^+ and e^- beams coming from Sector One of the linac by several orders of magnitude, thus providing the small emittance required for subsequent acceleration down the linac to the final high-density collisions at the interaction point. The design of the transport lines to and from the ring must allow for control of the longitudinal bunch length of both beams, as well as for preserving and manipulating the spin polarization of the electron beam. The purpose of the R&D program in this area is both to develop the accelerator technology required by the damping rings and to provide an apparatus with which to test the linac wake field calculations. To accomplish this, a single high-field, high-gradient, high-tune ring for electrons is being built. The project was initiated in October 1980, and present plans call for low repetition rate injection tests into the ring during the SLAC running cycle of Fall 1982, with tests of reinjection into the linac in the Spring of 1983. The design parameters of the ring system are now fixed and the optics design completed. The overall design is shown in the engineering drawing in Fig. 8.

The complexity of the system results from the future requirement of dealing with electron spin polarization. The longitudinally oriented spin of the electrons must first be rotated perpendicular to the beam in the plane of bending, and then rotated again perpendicular to the plane of the ring so that the polarization is not lost in the 50,000 turns of the damping cycle.

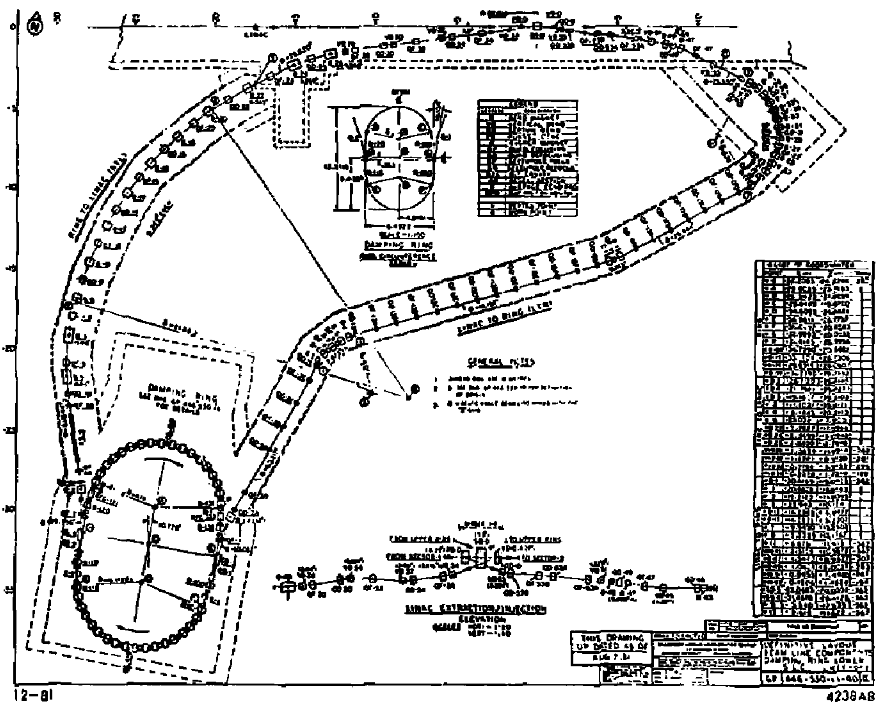

Fig. 8. Layout of the damping ring and its transport lines.

Longitudinal phase compression of the beams leaving the ring is accomplished by exchanging phase spread for energy spread through acceleration in an RF field at zero equilibrium phase and then passing the beams through an achromatic but non-isochronous transport system. The transport lines must also match the eight beam parameters β_x, α_x, β_y, α_y, η_x, η_x', η_y, η_y' at the four injection-extraction points as well as maintain overall length constraints consistent with the beams' longitudinal phase. All RF components will operate in a phase-locked mode at submultiples of the linac frequency, and all components except the ring injection and extraction kickers will run DC.

The contract for the vault to house the damping ring was let in May 1981. Break-in to the linac housing for the two transport lines was completed on schedule on September 11, thus permitting the linac to start up for the Fall running cycle. The main project, construction of the vault itself, is scheduled to be finished by the end of December. Electrical facilities, such as major transformers, are ready and the mechanical services will be prepared in the Spring of 1982.

There are 212 magnets in the damping ring system. The ring bend magnet model, with its positive and negative sextupoles at the ends, is finished and measured. All steel is on hand, and coil production has begun using several coil-winding machines in two-shift operation. The 17,000 'fine-blanked' laminations required for the quadrupoles are in hand and eighty cores have been fabricated. A trimming sextupole design exists. The specifications for the eight major power supplies and about 40 quadrupole trimming supplies, which provide DC power for the full system, have been written.

Calculations of synchrotron radiation power into the vacuum pipe walls have shown that distributed pumping is required to reach a pressure of 5×10^{-8} torr. Clearing electrodes must also be provided to remove ions from the beam. The questions of beam-electrode interaction are being studied in detail but are not thought to present serious problems.

A surplus RF transmitter from CEA has been restored and provided with a new klystron. Power tests into a water load are scheduled for October.

Parts are being ordered for the low-level driver which is similar to the successful PEP design. Considerable theoretical work on dynamic beam loading has been completed, and cavity design is nearly completed with construction scheduled to begin in November.

D. SLC Components

1. Positron Source. Two components of the positron source require feasibility studies: the target which is bombarded by the primary electron beam to produce positrons and the downstream high-field pulsed solenoid which is part of the system to capture the positron spray and return it to the injector end of the linac. A program of testing various target materials was carried out during the last year in the electron beam at SLAC. The tests of seven different styles of solid target showed that severe damage occurs for high energy electron pulses (~25 GeV) of $>10^{11}$ e/mm^2 while no damage occurs for prolonged exposure of $<7 \times 10^{10}$ e/mm^2.

With appropriate scaling to SLC conditions, the tests indicate that a solid, high-Z target of tungsten alloyed with 25% rhenium is feasible, with a safety factor of two to three — provided the incident beam area is kept larger than 2 mm^2, corresponding to a σ of 0.8 mm.

Two low-field, full-scale models of the pulsed solenoid have been built and tested. The second unit gave the desired field profile, agreeing with calculations. It has been modified for testing in a vacuum at a high field, using radiation-hard insulators. Tests of this model will begin this Fall.

2. Collider Arc Magnets. A full-scale, 2.5-meter-long collider arc magnet core has been constructed using 'fine-blanked' laminations. The mechanical rigidity of this core meets specifications; however, gap size variations in the laminations need improvement. The main coil is hard-anodized to provide 1000-volt insulation.

Magnetic measurements are scheduled for early in 1982, using a precision measuring machine with a resolution of a few microns. Conceptual design of a magnet support girder has begun.

High-field, rare-earth permanent magnet quadrupoles can be used to good advantage in the final focus of the SLC. Field Effects Inc., of Carlisle, Massachusetts, has been engaged to advise SLAC regarding the design, procurement of materials, fabrication procedures and measurement of samarium-cobalt quadrupoles. Their report has been completed and, as a result of this work, a 25-cm-long by 1.8-cm-diameter quadrupole is being constructed. Parts are on order and assembly should begin in October, while measuring equipment is being prepared.

3. Final Focus. The final focus system occupies roughly the last 100 m of the collider arc before the collision point. In this region, provision must be made for β matching, dispersion correction at the collision point, and aberration control. The system which has been developed has been checked by a second order ray tracing program and achieves the desired β^* of 1/2 cm.

The last quadrupole of the final focus section will be within a meter of the collision point. The samarium-cobalt permanent magnet quads that we have been studying have an incremental permeability very close to one, and high coercive force. These properties allow these magnets to be immersed in a solenoidal detector field of 10 to 15 kG without affecting their focusing properties.

4. Linac Energy Upgrading. There are three components to the program of increasing the energy of the beams available from the linac to the level needed by the SLC: one involving the SLED mode of linac operation with current klystrons, and two involving klystron development projects.

In tests of the SLED-II 5 μsec mode, the current 36 MW klystrons present two types of problems. The first is an increase in missing pulses, due to either high-voltage breakdown in the gun region or RF breakdown in the klystron output region, mainly in the output window. The second problem is that window fractures occur more often in this extended pulse operation of the tubes at 265 kV.

Several steps have been taken to correct these problems. A tube has been built with a lower gradient gun to avoid the high-voltage breakdowns.

Another tube is being built with two output cavities in order to reduce the output voltage across the gap. Window design and technology are being reviewed carefully, with special emphasis on the use of higher purity ceramics and better controlled coating techniques. Results from recent tests with such tubes are very encouraging and data on full design improvement should be available during the next year.

A design study for 42-49 MW klystrons with the necessary focusing magnets and high power modulators has recently begun. A 42 MW tube, operating at 300 kV in the 5 μsec mode with improved SLED-II cavities, would give the required SLC beams with the present complement of 245 stations. At 49 MW, the existing SLED cavities would be sufficient for SLC operation.

Another approach is through a new generation of 150 MW klystrons, operating at 450 kV with 1 μsec pulses. A program to develop such tubes has been underway for about one year in collaboration with the Japanese. With 245 of these klystrons, the SLC conditions could be met without using the SLED cavities.

E. Site Engineering

SLAC has retained the services of Tudor Engineering as an architect and engineering firm to perform the Title I and Title II designs of the collider housing, the experimental hall and the site work. The main geotechnical field work has been to determine an optimum tunnel alignment having a minimal environmental impact. The results have forced the tunnel and interaction region locations deeper under the surface, such that the interaction hall will be a deep pit instead of a surface structure.

Rough cost estimates are being made and preparations are under way for further geotechnical studies along the tunnel site. Another arrangement involving two interaction points, one 14 meters east of the first, is also under study.

Title I design of the tunnels is scheduled for completion in March 1982. An aerial photograph of the SLAC site indicating SLC tunnel locations is shown in Fig. 9.

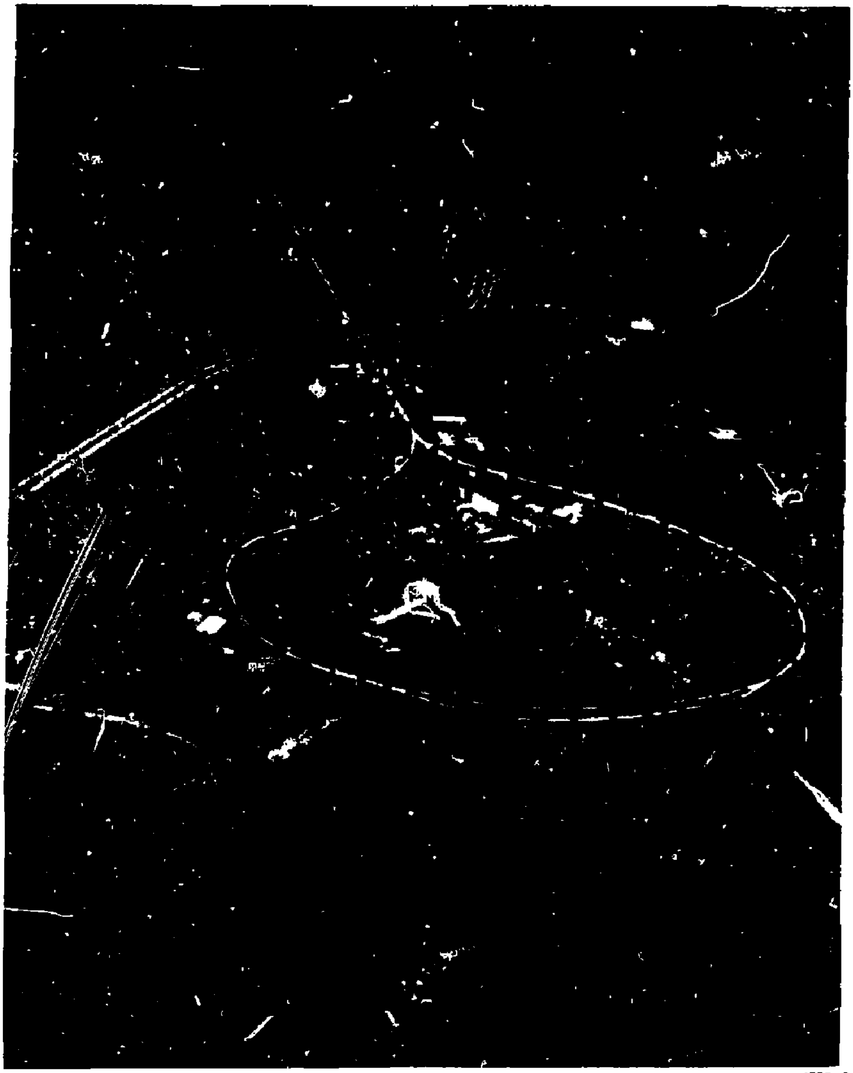

Fig. 9. Aerial view of SLAC showing the location of the SLC.

VII. VERY HIGH ENERGY COLLIDERS

A. 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 events 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 10^3 times the Weinberg-Salam value), and luminosities of 10^{33} will give many more events than anyone knows what to do with.

8. 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 postulated (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 $\sigma_{E^*}/E^* \approx 5\%$ 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
Enhancement from Pinch Effect	6
Particles per Bunch	4×10^{10}
Accelerating Gradient	100-200 MeV/m
Power in Each Beam	6.4 MW

The invariant emittance of the beam is the same as that of the SLC, as is the value of β^*. The beam radius is reduced from that of the SLC by the additional adiabatic damping which occurs during acceleration from 50 to 500 GeV. The number of pulses per second is about 5 times the maximum repetition rate of the SLAC linac, and one would expect to accelerate several bursts per pulse of a linac.

The bunch length postulated here is a factor of two longer than planned for the SLC and gives a higher disruption parameter and a larger luminosity enhancement than the SLC, while the number of particles per bunch is slightly lower than in the SLC.

The accelerating gradient is much larger than anything now in routine use, but experiments done on the SLAC accelerating structure show that copper can stand a surface electric field >160 MV/meter. The low field gradients attainable in the superconducting system make it likely that room temperature, high gradient RF will be the most cost effective acceleration method, but this is by no means sure.

The beam power is moderate, but an energy-efficient machine will be required (10% to 20%) to keep operating costs reasonable. For comparison the SLAC linac is 4% efficient in its long-pulse mode and 1/2% efficient in its SLC mode. Electron induction accelerators have been built that are 20% efficient.

Much technological development must be done before a very high energy machine can be built. The most important requirement is for an energy efficient, cost effective accelerating system. The prospects for success given five to ten years of R&D seem reasonable.

In the spirit of this section, we wave our hands and say "DONE."

C. Physics

The best systematic speculation on physics with very high energy colliders is in an article by J. Ellis[8] in the Proceedings of the Second ICFA Workshop. Ellis' compilation of cross sections is given in Table 2. The Ellis menu covers the usual items; W pairs, point bosons, conventional quarks and leptons, new quarks, technicolor and supersymmetric particles.

Since his article was written, theoretical interest in physics in the 1-TeV region has increased considerably. Among the developments since 1979 have been the following:

Technicolor and its extensions. These theories predict a complete new set of strong interactions in the TeV region, with a spectroscopy much more complicated than that of QCD. For example, there are many more vector mesons that can be produced directly in e^+e^- annihilation.

Quark and lepton substructure. Many physicists believe that substructure must underlie the present proliferation of quark and lepton flavors. It arises naturally in the context of new strong interactions with a scale of order 1 TeV. High energy e^+e^- machines with their clean event structure have unique capabilities for studying such possible substructure.

Table 2

COMPILATION OF CROSS SECTIONS

Taken from J. Ellis, "e^+e^- physics beyond LEP," Proceedings of the Second ICFA Workshop, CERN (1979)

	$e^+e^- \rightarrow$	Cross-section in units of σ_{pt}	Remarks
Weak vector bosons	W^+W^-	~ 20	Background reactions.
	Z^0Z^0	~ 20	
	$Z^0\gamma$	~ 20	
Higgs bosons	Z^0H^0	0.16	Best ways to look for heavy Higgs?
	$W^\pm H^\mp$	0.10	
	H^+H^-	$0.25\ \beta^3$	Useful for $H^\pm$ which are not superheavy.
Fermions	$\mu^+\mu^-$	1.19	Includes Z^0 contribution as well as γ.
	$Q(\frac{2}{3})\bar{Q}(-\frac{2}{3})$	2.04	
	$Q(-\frac{1}{3})\bar{Q}(+\frac{1}{3})$	1.17	
	3 generations of $q\bar{q}$	9.6	
Resonances	New Z^0	~ 5000?	Assuming couplings similar to first Z^0.
	New onium	1 or 2	Broadened by weak decays.
	Technicolour ρ	~ 7?	Assuming couplings similar to ordinary ρ^0.
Super-symmetric continuum	$\tilde{W}^+\tilde{W}^-$	1.99	Partners of $W^\pm$.
	$\tilde{W}^0\tilde{W}^0$	0	Partners of $I = 1$ part of Z^0.
	$\tilde{Q}(\frac{2}{3})\bar{\tilde{Q}}(-\frac{2}{3})$	0.37	Partners of charge $+\frac{2}{3}$ quarks.
	$\tilde{Q}(-\frac{1}{3})\bar{\tilde{Q}}(\frac{1}{3})$	0.11	Partners of charge $-\frac{1}{3}$ quarks.
	$\tilde{L}^0\bar{\tilde{L}}^0$	0.60	Partners of neutral leptons.

Supersymmetry. The motivations for supersymmetry theories have grown greatly in the last few months, with the realization that they can alleviate many problems with Higgses and their technicolored alternatives. Many more detailed predictions can now be made for the masses of the hitherto unobserved supersymmetric partners of known particles, which put them squarely in the center-of-mass energy range accessible to the very-high-energy collider discussed here.

For recent updates on speculations about the physics to be encountered in the 1-TeV region, see M.A.B. Beg, Lisbon International Conference Talk, Rockefeller University preprint RU/81/B/9 (1981); and J. Ellis, SLAC Topical Conference Talk, CERN preprint TH-3139 (1981), and references therein

The luminosity we have chosen, 10^{33}, gives 1000 events per running year for the point cross section. Rates per year for interesting processes vary from 20 K for W pairs to 1/4K for Higgs pairs. The luminosity, and thus the number of events, can be divided arbitrarily between several interaction regions (say four), and for some processes each will have plenty of events, and for others rates may be marginal. In any event, the programming of the machine pulses to the various interaction regions is arbitrary. The Proceedings of the Second ECFA Workshop include a discussion on appropriate experimental techniques for the energy range, and we shall not discuss them here. We give below a few examples of what could be done in a running year with the full luminosity.

Suppose that another weak neutral boson exists at high mass (the Z_R of left-right symmetric theories, for example), and that this boson has exactly the couplings of the Weinberg-Salam Z^0. If its mass were 2 TeV, the μ-meson front-back asymmetry would be 18%, and 1000 events would give a 6-standard-deviation result. If no asymmetry were observed, the lower bound (90% confidence) on the Z_R mass would be 3 TeV. For a 2 TeV mass the μ cross section would allow a measurement of the "new Weinberg angle" or $\sin^2\theta_R = 0.25 \pm 0.025$ with the same 1000 events.

Bhabha scattering can measure the "size" of the electron. A fit to the angular distribution will determine if the rms radius of the electron is $<(7\ \mathrm{TeV})^{-1}$, a range of interest to composite models of the fermions.

The final states generated in e^+e^- reactions are very clean compared to those produced in proton reactions. It is likely that new phenomena that occur in the region between 100 GeV and a few TeV can best be investigated with a very large e^+e^- collider.

D. Further Speculation on the Use of Big Colliders

1. 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.

2. 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.

3. 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.

IX. CONCLUSION

The cost of the SLC is 87 millions in FY 82 dollars. The construction schedule is such that the machine could turn on 2-1/2 to 3 years after construction authorization. The physics capabilities of the SLC are clear, and its role as a tool for the development of linear colliders seems at least as important as the physics which will be done with it.

If a large collider is ever to be built, some experience with this kind of machine will be needed before anyone will be willing to commit the large funding which will be required. We at SLAC believe that the SLC offers a unique opportunity to combine an essential machine development program with a physics program that addresses some of the most important questions of the day. We hope that the High Energy Physics community will agree and support our request to begin this project.

REFERENCES

1. B. Richter, Nucl. Instrum. Methods 136, p 47 (1976).
2. SLAC Linear Collider Conceptual Design Report, SLAC-Report-229, June 1980.
3. R. Hollebeek, Nucl. Instrum. Methods 184, p 333 (1981).
4. W. M. Fawley and E. P. Lee, Lawrence Livermore Laboratories Report UCID-18584.
5. See for example, CERN 76-16, Physics with 100 GeV Colliding Beams, CERN 1976; CERN 79-01, Proceedings of the LEP Summer Study, CERN 1979.
6. G. Barbiellini, et al., Phys. Lett. B (to be published)(1981).
7. R. J. Cence, Proceedings of the Cornell Workshop on Experiments at 100 GeV, CLNS 81-490 (1981).
8. J. Ellis, Proceedings of the Second ICFA Workshop, p 261, CERN (1979).