PROGRESS REPORT ON FUTURE ACCELERATORS

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Talking about the future is always difficult but is particularly problematic today when there are so many forces acting on high energy physics in general and SLAC in particular over which the speaker has little control.

SLAC intends to pursue high energy physics work in the future along three lines: (1) continued exploration of electron and photon physics on stationary targets; (2) colliding beam physics using electron-positron storage rings; (3) single-pass collider physics with electrons using first the Stanford Linear Collider (SLC) and eventually a single-pass collider operating near the highest practical upper limit for such devices. Figure 1 gives a time line diagram for such activities.

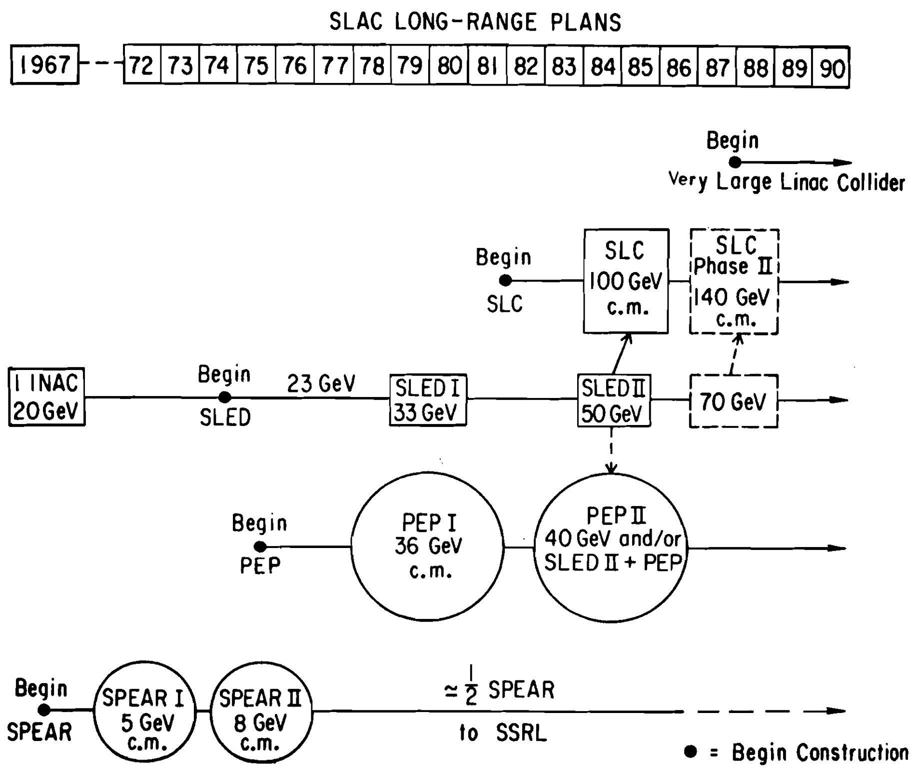

Figure 1 SLAC long-range plans

In contrast to all other high energy electron accelerator laboratories SLAC has not abandoned and does not intend to abandon stationary-target physics using electron and photon beams. The reasons are evident: SLAC operates the highest energy and intensity electron machine in the world, many of our beams are unique in character, and some of the most important physics experiments of the laboratory continue to originate from stationary-target experiments. In addition, the SLED energy-upgrading program has made it possible to increase the electron beam energy to 33 GeV, and SLAC intends to continue this energy growth through lengthening the SLED klystron pulse to 5 microseconds, aiming at a beam energy above 50 GeV. The option also exists to increase the energy of the machine to a level approaching 70 GeV without exceeding the experimentally demonstrated voltage gradients tolerated by the SLAC accelerating structure; this further energy increase can be achieved either by doubling the klystron and modulator stations at current performance, or developing higher unit-power tubes and modulators. We are pursuing the latter approach in a collaborative program with Japanese industry and the KEK high energy laboratory in Tsukuba, Japan.

Despite the foregoing remarks, we would be less than realistic if we were to plan that the total effort dedicated to stationary target physics could remain what it was in the past. We will continue to "tilt" the emphasis of the program towards colliding-beam devices, but at the same time will continue to respond to the singular opportunities in the area of electron-photon physics using stationary targets which can only be successfully attacked at SLAC.

SPEAR will continue to operate in the foreseeable future both for colliding-beam high energy physics and for synchrotron radiation research. No major upgrading programs for SPEAR are planned other than certain consolidation programs of the RF systems and general improvements in instrumentation.

PEP has not yet completed its first full year of physics operation; you have heard some of the initial results at previous sessions. All six interaction regions are operative, but the two largest and hopefully most powerful detectors (the High Resolution Spectrometer and the Time Projection Chamber) are not as yet installed; they will become operational in the fall of 1981 and some time in 1982, respectively. The productivity of PEP in the longer run is difficult to predict. The laws of physics are the same on both sides of the ocean, and with the mini-Beta installed this summer, the general performance of PEP and PETRA as far as luminosity is concerned should be comparable, although SLAC continues to enjoy the advantage of the higher energy injector which makes it unnecessary to ramp the storage ring from injection energy to operating energy. Thus the physics output of the two laboratories should remain complementary as defined by the diverse character of the detection instruments and the differences in chosen programs and techniques. Currently, SLAC is not planning to upgrade the energy of PEP to any significant extent, since competition for resources with the single-pass collider program makes this infeasible, and since the electric power costs are already a very serious operating consideration at SLAC.

This brings me to the main subject of this discussion, which is the project for design and construction of a single-pass collider at SLAC. This audience is fully familiar with the arguments that define the cost scaling of electron-positron storage rings of conventional design, and the current likelihood that such machines will not be built at energies exceeding that of LEP. Moreover, the fundamental limitations engendered by the beam/beam interaction make much higher energies technically infeasible. In contrast, the single-pass collider, with its linear cost-scaling law, will reach a fundamental economic boundary at much higher energies, and the technical limit caused by beam/beam interactions is not set by the basic feasibility of attaining stable beams, but rather by excessive broadening of the energy spectrum and various backgrounds due to synchrotron radiation in the beam/beam interaction itself. This again is expected to become a serious limit only at hundreds of GeV per beam. You all know that the feasibility of all single-pass colliders rests on the expectation that the much lower interaction repetition rate of such devices can be offset by the use of beams of very small diameter and thus of high density.

SLAC has been pursuing this idea for several years under the leadership of Burt Richter; related efforts have been pursued by our colleagues at the Nuclear Physics Institute at Novosibirsk. Our plans have become concrete with the inception of the SLAC Linear Collider (SLC). This installation will serve the dual purpose of becoming the first operating demonstration of the feasibility of the single-pass collider principle while at the same time providing an important tool for physics experimentation by reaching an electron-positron collision energy of 100 GeV in the center-of-mass. Since this energy is presumably above the mass of the Z^o boson, the SLC should be a copious source of these particles thus permitting detailed investigation of the multitude of Z^o decay channels. It is, however, inherent in the design of this machine that only a single interaction region can be available for experimentation at any one time. It is planned that either two experimental detectors can be staged simultaneously for introduction into a single interaction region, or, alternatively, that two different foci for beam/beam interactions will be provided at two detector positions.

Figure 2 shows the main parameters of the SLAC Linear Collider as currently planned. As essential feature of the design is a final focus producing a beam radius of less than two microns standard deviation. Note that the requirement of 100 GeV center-of-mass energy dictates an unloaded linear accelerator energy of around 54 GeV.

Figure 3 shows the general layout of the SLC in schematic form. The basic idea is to accelerate electrons and positron in successive buckets of the RF wave in the linear accelerator. Electrons are injected into a subharmonic buncher from a high-current gun consisting of a gallium arsenide cathode illuminated by a laser beam. Positrons are produced by accelerating an auxiliary electron beam pulse which is deflected and then strikes a positron conversion target. The resulting positrons, in turn, are piped back to the injector end and introduced into the accelerator.

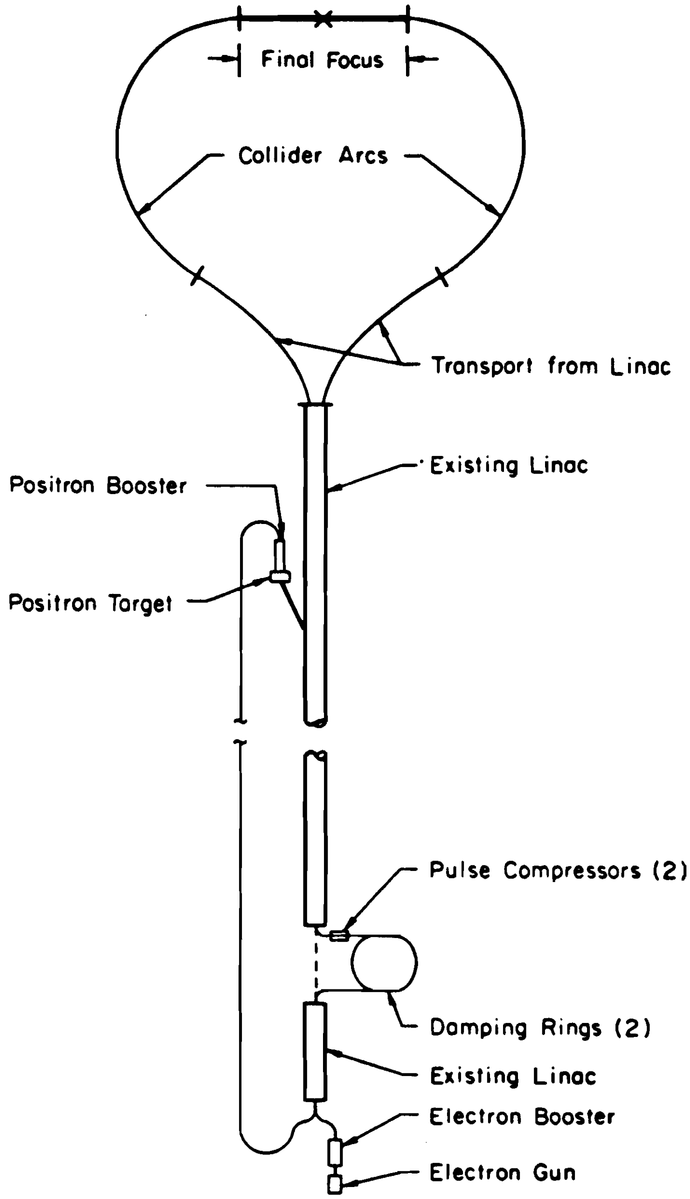

Figure 2 General layout of the SLAC Linear Collider (SLC)

The requirement for the small final focus of course translates into the need for a very small invariant emittance, in fact a figure of 3×10^{-5} radian-meters. This is somewhat below the number expected from the electron gun and is greatly below the number pertaining to the positrons generated in the conversion process.

A.	Interaction Point	
	Luminosity	6×10^{30} cm^{-2} sec^{-1}
	Invariant Emittance ($\sigma_x \sigma_x' \gamma$)	3×10^{-5} rad-m
	Repetition Rate	180 Hz
	Beam Size ($\sigma_x = \sigma_y$)	1.3 microns
	Equivalent Beta Function	0.5 cm
B.	Collider Arcs	
	Average Radius	290m
	Focusing Structure	AG
	Cell Length	4.4m
	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	± ½%
	Bunch Length (σ_z)	1 mm
D.	Damping Rings	
	Energy	1.21 GeV
	Number of Bunches	2
	Damping Time (Transverse)	3.0 msec
	Betatron Tune (x;y)	7.23; 2.75
	Circumference	35.27m
	Aperture (x;y)	± 6; ± 7 mm
	Bend Field	19.8kG

Figure 3 Design parameters of the SLC at 50 GeV

Accordingly, the SLC system provides for damping rings, shown in Figure 4, which store electrons for one interpulse period and positrons for two interpulse periods during which radiation damping of the betatron oscillations reduces the emittance below the required amount.

The electron and positron beams emerging from the accelerator are split and then guided by extremely strong-focusing beam-transport systems into the final straight sections, where a special focusing system leads to the desired electron-positron collisions.

The critical requirements to make this system work as specified are, of course, to prevent undue emittance growth on the one hand, and undesired energy spreading on the other. The need for confining the emittance growth is obvious; the need for limiting the energy spread originates partially from the desire for large interaction rates at potentially narrow resonances, but primarily in order to reduce the required chromaticity corrections of the final-focus system to a feasible value.

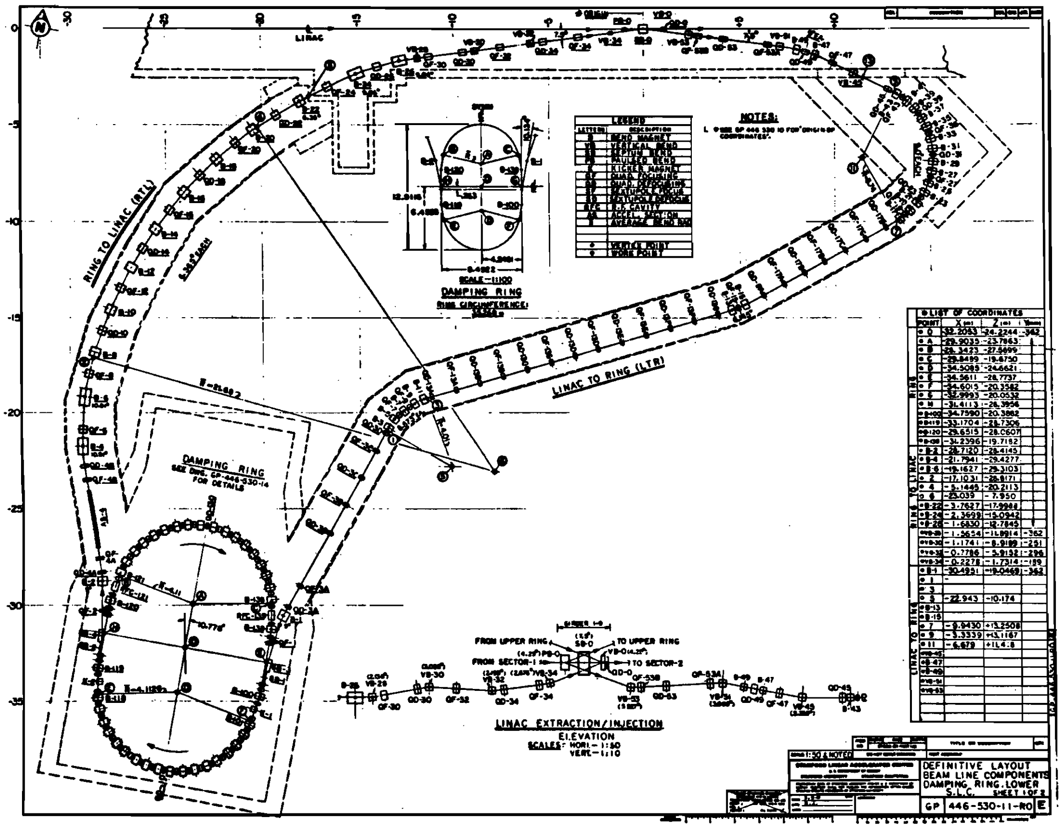

Figure 4 Layout of the damping rings and the transport lines to and from the SLAC linac

Emittance growth in the SLC beam can be produced by a number of causes, all of which, hopefully, are understood, even through the remedial actions needed to cope with all of them are not as yet fully developed. The potentially most serious source to emittance growth originates if the centroid of the beam does not travel precisely along the electromagnetic axis of the linac accelerating structure. If the beam travels off-axis, then wall currents are induced in the disk-loaded structure by the leading edge of the beam pulse, which causes fields, which in turn act on the tail of the pulse. Notwithstanding the fact that the beam pulse is only about 2 millimeters in length, this effect could for even small misalignment distort the beam from its initial simple cylindrical structure into a banana-shaped object; if misalignment is more severe, this effect can lead to actual radial beam blowup. Analysis of this phenomenon indicated that the root-mean-square misalignment should be held to about 100 microns (.1 millimeter) if the degeneration of final luminosity due to this cause is to be held below 25 %. Happily, failure beyond this point is fairly graceful; for instance, if the misalignment is twice the specified amount, then the loss in final luminosity is only 37 %. In addition to misalignment tolerances on the accelerator itself there are similar tolerances which must be met when the beams pass through other enclosures with conducting walls, such as the vacuum pipe in the bending magnets.

In addition to these electrical tolerances, unusual care must also be given to the mechanical stability of components. Vibrations of the accelerating structure and of the magnetic elements must be limited to the micron level. We have investigated the seismic conditions on the site and find that ground vibrations are within the required limits, although vigilance is necessary to prevent nearby installation at the laboratory of unbalanced rotating machinery, poorly shock-insulated compressors, etc., etc. In addition, care has to be taken in water cooling systems to avoid induced vibrations from turbulent flow.

At the design intensity of 5×10^{10} particles per pulse, the energy spread of the beam would be enhanced to an unacceptable degree by the longitudinal electromagnetic forces within the bunch; again the induced currents in the disk-loaded structure are the main source of this effect. This can be counteracted by placing the bunch on the rising part of the accelerating RF voltage; under that condition the later electrons in the pulse receive more acceleration, thus compensating for the space-charge retardation. The consequence of this offpeak placement of the bunch is, of course, a small decrease in the energy attained. This is one of the reasons why the final practical energy attained is below the peak unloaded beam energy; a further reason is the mean synchrotron radiation energy loss in the magnetic bending arcs.

The magnetic guide fields are simple in principle. The fundamental design requirement is set by the fact that the emittance growth due to quantum fluctuations of the synchrotron radiation must not broaden the beam emittance by a substantial fraction. This, in turn, limits the magnitude of the bending radius and requires that the focusing action must be extremely strong, in fact requiring a ν value of about 100. It can be shown that the phase space growth due to quantum fluctuations varies as the fifth power of the energy, and inversely as the cube of the bending radius. Accordingly the feasibility of constructing a single-pass collider by using only a single linac to accelerate the electron and positron beams faces a severe energy limit. The planned SLC could operate productively up to 70 GeV per beam, providing the linac is appropriately upgraded, but there would be significant deterioration in luminosity at higher energy values. There is little question that extension of the single-pass collider principle beyond attainable LEP energies would require two separate linacs.

The final focus is produced beyond the bending arcs by a complex system of lenses. A design for this of length about 100 meters has been completed, and the site is being planned to accomodate this system. There are good expectations that considerably shorter designs may also be feasible. Moreover, we expect to have the last lens element be a pair of samarium cobalt quadrupoles directly installed in the detectors at a quadrupole-to-quadrupole distance of one meter. This magnetic material has the desirable property of having incremental permeability of unity; thus the final beam focus is independent of the detector magnetic field. After beam/beam interaction the "used" beams reenter the beam-transport system but are removed by pulsed deflectors into two beam dumps.

The above is a broad outline of the functioning of this system. SLAC is intensely pursuing research and development toward this new installation, hoping for official authorization for the U.S. Fiscal Year 1983 or 1984. This R&D program encompasses many elements including the following:

(1) Both a laser-pumped gallium arsenide gun and an additional conventional thermionic gun have been constructed, and tests have been carried out. A maximum of 2×10^{10} electrons per RF bucket have been accelerated through the SLAC linac, but considering the present inadequacy of linac alignment, the crude focusing system and component jitter, a bunch of 5×10^{9} electrons is used for experiments. At these lower intensities the correctness of the theory relating emittance growth to misalignment is being verified.

(2) Excavation and construction of the damping ring vault is in progress, and one of the two damping rings is in the process of fabrication.

(3) The magnetic guide system has been designed, and prototypes have been built.

(4) Vibration surveys have been made.

(5) An architect-engineering firm is in the process of carrying out site analyses in order to determine the optimum location of the SLC elements on site.

(6) The design of the positron source involves unusually high power densities in order ot achieve the required positron flux. Suitable targets have been built, and the design power density has been achieved, albeit with only a small additional factor of safety.

(7) Most important is the development of a totally revised instrumentation and control system for the linac and the SLC. SLAC's instrumentation and control system was designed starting in 1961, when it was still uncertain whether computer control was "here to stay". Since that time the machine has been in continuous operation so that drastic revision of the instrumentation and control system was neither fiscally nor operationally feasible. The SLC requires a complete new set of beam-position indicators and control elements associated with a modern computer net. This has been largely designed, and the first 100 meters of the machine have been retrofitted to test the new system. It is planned to convert the first one kilometer of the SLAC linac to the control system as part of the research and development effort, and this work will be completed in less than two years. Naturally all these activities have to be carried out with minimum interference to the research program.

(8) Attainment of a final interaction energy of 100 GeV is, of course, critically dependent on the success of the SLED energy upgrading program. Theoretically an increase in the pulse length of the klystron to 5 microseconds would be adequate to store sufficient electromagnetic energy in the SLED cavities to produce the required beam energy if all klystrons operated at a peak energy output of 42MW. However, in practice performance might well be marginal under these conditions for a number of reasons:

1. Not all 245 stations are apt to be available for acceleration.
2. Not all klystrons and accelerator stations would be expected to

operate at peak performance.

3. Current indications are that klystron life is substantially shortened at 5 microsecond operation, and klystron fault rates are substantially increased.

This general picture is currently being investigated as part of the R&D program. A decision has been made to replace the SLED cavities with their present Q value of 100,000 with larger spherical cavities operating in a higher mode at a Q of 250,000. This gives an expected energy increase of 3 %. In addition, the causes of the life shortening and high fault rate at long klystron pulse lengths are being investigated and the difficulty has tentatively been identified. We expect that improvements will remedy most if not all of the long-pulse difficulties.

(9) A number of backup programs are in process whose main objective is not so much to assure the 50 GeV beam energy goal as it is to open the door towards higher energies. The first is a collaborative program between SLAC, the Japanese laboratory at KEK, and the Mitsubishi and Toshiba companies aimed at developing a 150 MW klystron. This is a 3-year program and is expected to lead to an increased injection energy in Japan for the TRISTAN storage ring as well as giving an alternative approach to SLAC higher energies in place of the long-pulse-length SLED arrangement.

A further avenue toward our energy increase, although a fairly costly one, is of course a simple increase in the number of modulator/klystron stations at SLAC. Such an increase, be it as a remedy or for purposes of beam energy augmentation, could be invoked on relatively short notice once funding for that purpose is available. Figure 5 summarizes the available avenues for a linac beam energy increase program.

SLC Energy at Interaction Point for 5×10^{10} $e^{\pm}$/Bunch

RF Pulse Length (μs)	Klystron Peak Power (MW)	Additional Stations Needed	SLED Cavity Q_o	Maximum SLED Gain	One-Half Collision Energy (GeV)
2.5	36	0	10^5	1.4	32.3
5	36	0	10^5	1.78	42.7
5	36	0	2.5×10^5	1.91	45.9
5	42	0	$2.5\ 10^5$	1.91	50
5	36	230	$2.5\ 10^5$	1.91	64.8
1	150	0	No SLED	1	51.4
1	150	230	No SLED	1	71

Assumptions

1. Sector 1 (with damping ring) contributes 1.21 GeV.
2. Sectors 2-30 contain 230 stations; 226 are assumed to be on at all times. Maximum contribution per station is $20\sqrt{P_{MW}}$. Because of nonstandard girders, total contribution is 99 % of maximum.
3. SLED gain is reduced to 96 % of maximum because of SLED slope curve. This reduction has been applied equally to all cases.
4. Beam loading compensation is assumed to lead to 3.57 GeV reduction at 50 GeV (this number is 35 % higher than P. Wilson's calculated value).
5. Phasing of individual stations is assumed perfect.
6. Synchrotron radiation loss in arcs is assumed to be 1 GeV at 50 GeV.

Figure 5 SLC energy at interaction point for $5\times10^{10}e^{\pm}$ per bunch

Let me close this brief summary of SLC work with some reference to the conditions at the final beam/beam collision point. First, a few remarks about the beam/beam interaction itself.

The mutual electromagnetic effects between the electron and positron beams are attractive, and the equivalent combined electric and magnetic fields are of the order of a megagauss. Accordingly, one expects actual focusing oscillations of significant magnitude as a result of the beam/beam interaction. To a first approximation this mutual focusing is beneficial in that it is actually expected to enhance the luminosity.

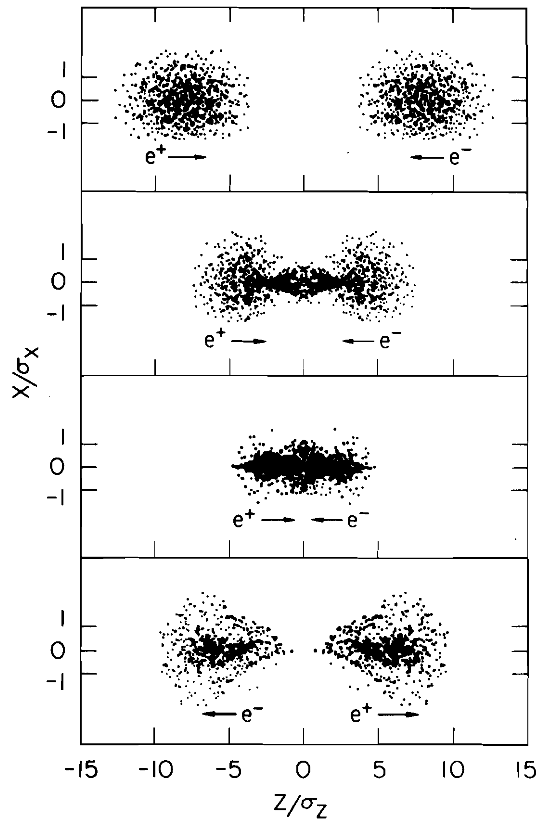

Figure 6 Side view of the collision of oppositely charged beams, showing the pinch effect for Gaussian profiles and a disruption factor D = 14.4

Figure 6 shows a series of computational results indicating the behavior of the beams as they pass through one another. It is seen that for reasonable values of parameters a mutual pinch effect does indeed occur. This, in turn, results in the curve of expected luminosity against energy that is shown in Figure 7.This curve encompasses all of the expected effects on the luminosity, including the emittance growth produced by the bending magnets and the effect of the beam/beam interaction. The decline of luminosity beyond 120 GeV is caused by the emittance growth in the bending magnets.

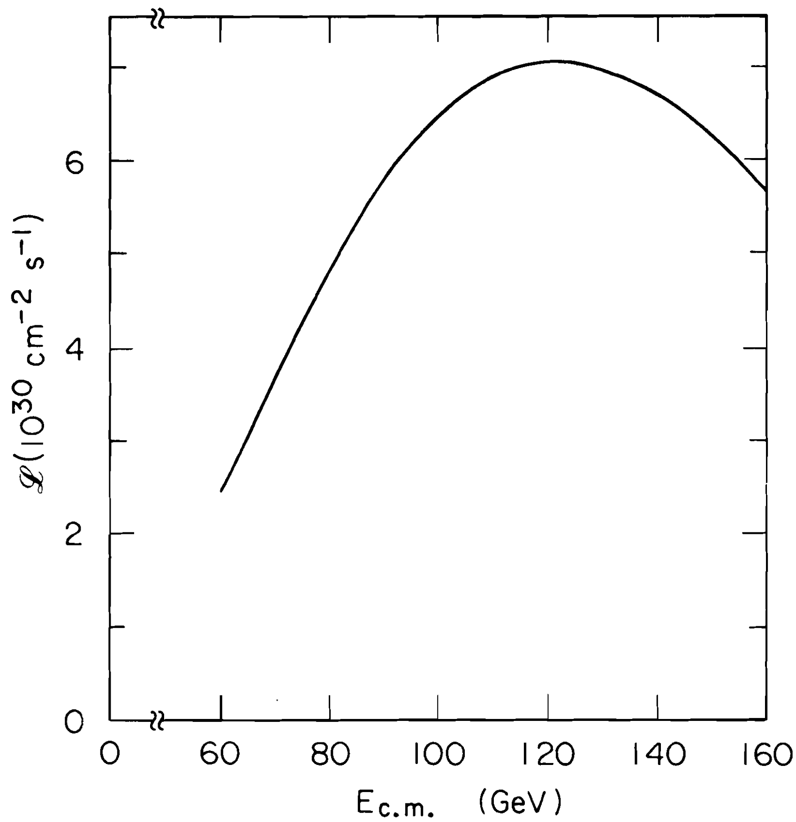

Figure 7 Luminosity vs. center-of-mass energy in the SLC for $\beta^* = 0.5$ cm and for a beam-beam pinch-effect enhancement factor of 3

SLAC has recently held a major workshop on the SLC that attracted a large segment of the user community, and has subsequently set up a parallel set of working groups dedicated to investigating various aspects of the prospective physics program. In addition, many members of the user community are participating with us in the solution of machine-related problems. A key element of this work is, of course, to determine the configuration of the interaction hall and of the ancillary facilities. We are currently pursuing this question in conjunction with the geological site investigation of the area. Two principal approaches are incorporated in these studies. One is a single hall which provides staging space for two experiments, each of which can be introduced into the collision point. This arrangement is, of course, relatively inefficient assuming that only brief testing periods for the detectors are necessary. An alternative is to replicate the final focusing system so that beam/beam interaction points can be alternately illuminated in two interaction halls. Unfortunately the beam optics require that not only the final focusing system be replicated but that a fair fraction of the entire bending arc must be constructed in "double track" also. As a result, the second system, although clearly more efficient from the point of view of particle physics, is significantly more expensive.

The design of suitable detectors themselves is also under extensive investigation. We have purposefully refrained from soliciting specific proposals at this stage of conceptual design; rather, we have strongly encouraged examination of basic principles of detector design, and we have been greatly encouraged by the very extensive cooperation we have received in this respect from the user community. Early next year we will also take a look at the possible adaptability of existing detectors for SLC use.

This talk omits a great deal of essential detail and can of course only reflect the general flavor of this undertaking. The work is being pursued enthusiastically by many members of what are usually three distinct technical communities: linear accelerator experts, accelerator physicists experienced in electron-positron storage rings, and elementary particle physicists. All three groups have been collaborating to such an extent that it is frequently difficult to distinguish which is which. It is the restoration of unity between the "ends" and the "means" for elementary particle physics which has been one of the most satisfying byproducts of developing the SLC.

Although the SLC has the dual objective of providing a tool for physics in the expected Z^o region and of being a pilot project leading to higher collision energies through the new realm of single-pass colliders, it is only too easy to postpone serious consideration of the second goal. The detailed attention the SLAC accelerator physicists have given to examining the problem of a truly large linear collider has thus far been small. We do not even know whether it is conceivable that a very large collider, say a machine of 300 GeV electrons against 300 GeV positrons, might be accomodated on the Stanford site, or whether such a device would imply utilization of a new location. Somehow it appears easier for our friends from Novosibirsk in their VEPP studies to draw long lines on a map of Siberia without hitting too many populated areas than it is to do so on a map of the San Francisco peninsula! The critical question is, of course, the attainable field gradient. Here the Novosibirsk group has demonstrated the feasibility of gradients in the 100 MeV per meter range, at least for short cavities. SLAC has carried out numerous parametric studies for various types of accelerating structures in order to examine the economic feasibility of large single-pass colliders. A machine in the 300 GeV by 300 GeV range attaining luminosities of $10^{32}cm^{-2}sec^{-1}$ or higher appears feasible with average electric power consumption below 100 megawatts. However, this involves extensive component development, including high-gradient accelerating structures of novel design, fast switching of ultrahigh-power microwave devices, and development of new microwave power sources. We are initiating efforts in all these areas, but under pressure of our attention being given to PEP, the SLC, and the energy upgrading of the linac, together with our ongoing particle physics research program, we anticipate only slow progress along these lines. Yet I am persuaded that the long-range future of electron-positron colliding-beam physics lies in this direction. I conclude with a chart, Figure 8, showing the growth of electron-positron collision energy with time. This chart shows that if some approximation to the exponential growth of the past is to be continued in the future, then indeed linear colliders are the only avenue which now appears open.

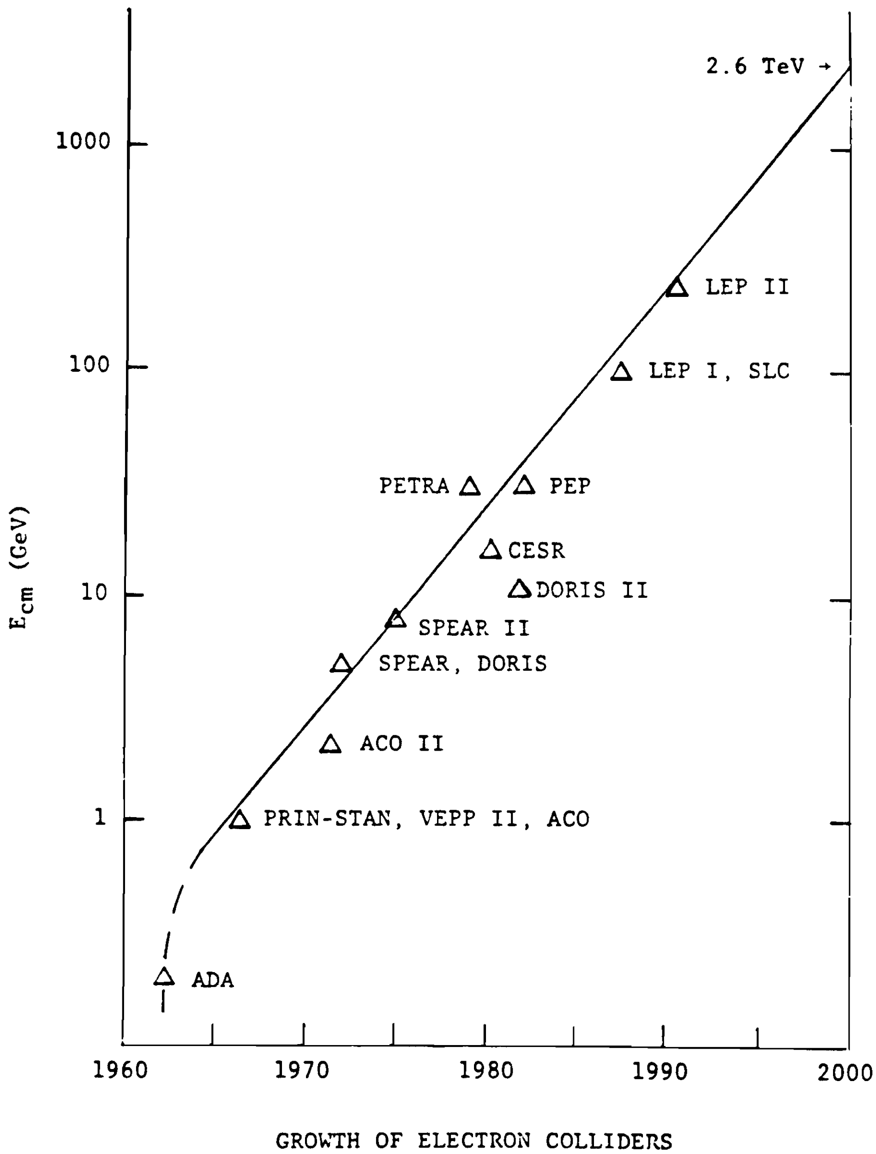

Figure 8 Growth of electron colliders: center-of-mass energy vs. time

Discussion

R. Hofstadter, Stanford: Could you comment on dynamic effects of beam-beam interactions such as instabilities that might be present at the SLC?

W.K.H. Panofsky: We have looked at that in considerable detail. It is possible to analyse the beam-beam interaction by something which one calls the disruption parameter. Consider a particle in one bunch at a distance d to the beam axis. Due to the beam-beam interaction it is focussed by the other bunch with a focal length f. If the ratio $D = \frac{d}{f}$ is a small number, let's say 3 to 4, nothing much happens. You just get an enhanced luminosity. On the other hand the luminosity as a function of D saturates because if the particle oscillates several times you don't gain anymore. The mean radial displacement then stays the same. If D starts going up to 15 or 20, or something of that magnitude, you may run into instabilities. But there is no motivation to go that far.

M.T. Ronan, LBL: What additional equipment is necessary and what is the cost in order to add another intersection region?

W.K.H. Panofsky: There is of course a fundamental problem with this machine. It is a dual-purpose machine both for doing particle physics and for being a technological great leap forward. Therefore, it is not ideally suited for either alone. The experimentalists would like to have more interaction regions and the machine builders would like to avoid all the complications needed to build more interaction regions to make the thing useful. Since in the interaction the beams undergo angular deflections of the order of several milliradians you cannot have a useful second intersection with the same pulse ever. So there is only one interaction point at one time and in order to permit multiple access to the interaction point you either have to move the different detectors into the beam or you have to move the beam to different detectors. We are studying as a matter of architectural engineering both alternatives. It is obviously a great deal cheaper, that is what your question relates to, to move the different detectors into the beam. The reason is in order to have multiple interaction regions you have to duplicate not only the final focussing system but also a fair fraction of the bending arc. Not only that you have different site problems and access problems and so forth. The work to determine the incremental pricing for that has not been completed but it looks offhand as if it is in the 10 to 20 million dollar range.

J. Adams, CERN: So your idea is to put the experiments on a sort of a moving belt?

W.K.H. Panofsky: We have not made the decision. Apart from that the total integrated luminosity is whatever it is and therefore quite apart from the cost and all that the incentive to share among too many people may not be all that great. In addition to that in respect to any luminosity which you have seen in the entire session the question is always the fundamental one as to which liar to believe.