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THE SLAC LINEAR COLLIDER - A STATUS REPORT*

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1. INTRODUCTION

In this paper we report on the status of the SLAC Linear Collider (SLC), the first of a *new kind of* colliding-beam device. We expect this new technique to allow the extension of electron–positron colliding-beam studies beyond the energies that can be achieved in a cost-effective manner by the use of colliding-beam storage rings. It has been recognised for some time that the extension of the storage ring technique to energies higher than a few hundred GeV is very difficult because of the rapid increase of energy loss from synchrotron radiation in the bending magnets of such machines. The synchrotron radiation losses result in a scaling law where the cost and size of electron storage rings increases as the square of the center-of-mass energy.

In addition to its role as a test vehicle for the linear collider principle, the SLC is designed to do important experiments in high energy physics through operation at an energy equivalent to the Z^0 mass, and thus to be a copious source of these particles. The small size of the SLC collision region and the potential for colliding polarised beams give experimental opportunities that will probably not be available elsewhere.

The project received its first funding in October of 1983, and construction was completed in March of 1987 at a cost of about $115 million. Since the completion of construction we have been engaged in commissioning the machine to bring it to a performance level sufficient to start the high energy physics research program that we wish to carry out in parallel with the accelerator studies required to fully understand the problems associated with this new kind of facility. We have somewhat arbitrarily set the performance level at which we will begin the physics program at a luminosity that yields about 15 Z^0's per day (10^{-3} of full design luminosity).

Table 1 shows a brief summary of progress to date giving some of the critical design parameters, the values of these parameters required to reach the goal for initial physics

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experiments, and present status. In the rest of this paper we will discuss the major subsystems and their performance and problems. We also discuss the initial physics program and some enhancements to the facility which are underway to improve the machine as a high energy physics research tool.

The accomplishments reported on in this paper are the results of the efforts of a large number of individuals. No attempt has been made herein to refer to all of them or cite all of the published documents. Details on most of these systems are reported on fully in the proceedings of the U.S. Accelerator Conference held in Washington, D.C. in April of 1987 (to be published).

Table 1. Basic Parameter Specifications

	Design Goal	Initial Goal	Achieved	Units
Beam Energy at IP	50	46	46	GeV
Beam Energy at End of Linac	51	47	53	GeV
Electrons at Entrance of Arcs	7×10^{10}	10^{10}	2.5×10^{10}	
Positrons at Entrance of Arcs	7×10^{10}	10^{10}	0.3×10^{10}	
Repetition Rate	180	60	5	Hz
Bunch Length σ_z in Linac	1.5	1.5	1.5*	mm
Normalized Transverse Emittance at End of Linac (Electrons)	3×10^{-5}	10×10^{-5}	$3\text{-}20 \times 10^{-5}$	mrad
Spot Radius at IP	1.6	2.6	—	Microns
Luminosity	6×10^{30}	6×10^{27}	—	$cm^{-2}\ sec^{-1}$

*Bunch length increases with current. At 1.2×10^{10}/bunch the bunch length is 1.5 mm in the linac.

2. PROJECT DESCRIPTION

An overall layout of the SLC is shown in Fig. 1. Two 20 cm long bunches of electrons are emitted from a gated thermionic gun and accelerated to 160 keV. The bunches pass through two 178 MHz RF cavities and drift spaces and are compressed in length. Final compression is accomplished in a section of 2.8 GHz cavities. After passing through these cavities the

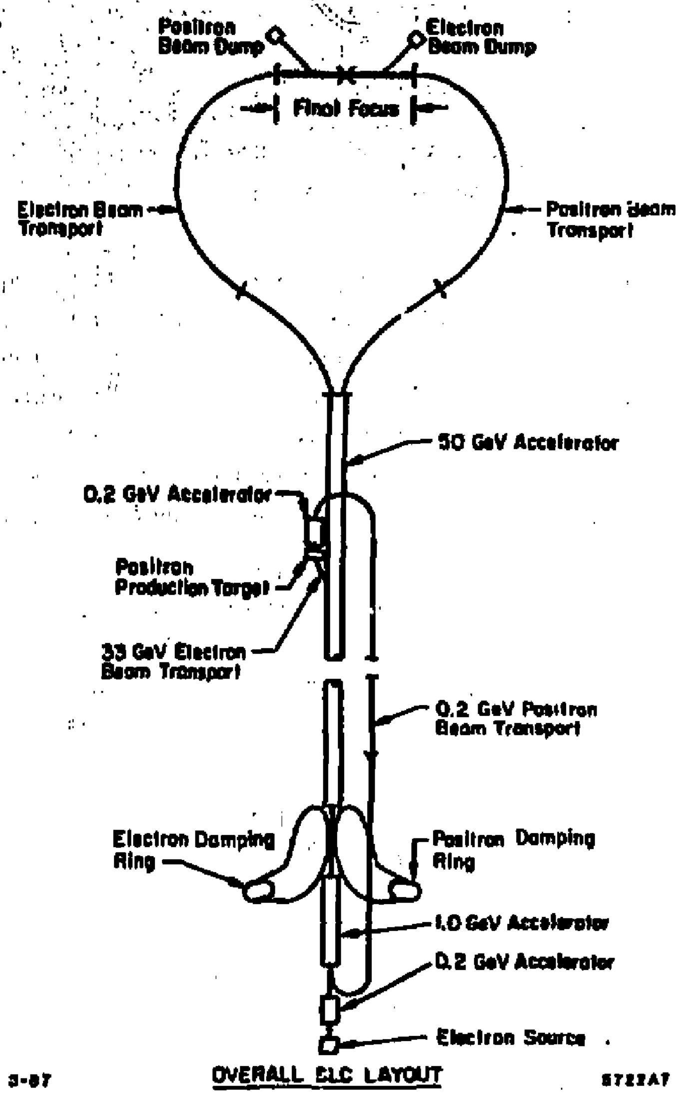

Figure 1

bunches have been compressed to an rms length of about 2 mm each. The short bunches are accelerated in a linear accelerator to 200 MeV. At this point the two electron bunches are joined by a 200 MeV positron bunch and all three bunches are accelerated to 1.2 GeV. A splitter magnet deflects the electron bunches into a storage ring where their transverse emittance is damped by synchrotron radiation. The positron bunch is deflected into a different storage ring where its transverse emittance is also damped. After a time interval of 5.5 ms or longer, depending on the accelerator repetition rate, the positron bunch is extracted from the positron storage ring. Approximately sixty nanoseconds later the first of the two electron bunches in the electron storage ring is extracted. Sixty nanoseconds later the second electron bunch is also extracted.

The beam transport lines between the storage rings and the accelerator are provided with sections of 2.8 GHz accelerator which are used to introduce a correlation between the energy of the particles in the bunches and the positions of the particles along the bunch. This correlation, in combination with the non-isochronous beam transport, causes the length of the bunches to be compressed from the equilibrium value in the storage rings (0.6 cm) to the length needed for acceleration in the linear accelerator (1.5 mm).

The positron bunch and the first electron bunch which follows it in the linac are accelerated to 51 GeV (for 100 GeV at the collision point). The two bunches are separated at the high energy end of the accelerator and travel through beam transports which bring them into collision at the interaction point. After interacting, the bunches are deflected into beam dumps

The second electron bunch accelerated in the linac is extracted at the 2/3 point of the linac, at an energy of 33 GeV, in order to produce positrons. The positrons are accelerated to 200 MeV and are returned to the injector end of the accelerator.

3. STATUS OF COMMISSIONING OF THE MAJOR SLC SYSTEMS

Electron source and 1.2 GeV linear accelerator booster:

The design goal for the electron injector is to provide two bunches of electrons with a population of 7×10^{10} each and a momentum spread of less than $\pm 1\%$ for injection at 1.2 GeV into the electron storage ring. The design goal for the transverse emittance of the bunches from the gun depends on the repetition rate of the linac. A lower repetition rate permits a longer time for synchrotron radiation damping in the storage ring. The specification for 180 Hz operation is a maximum transverse emittance of 30×10^{-6} mrad while the specification for 120 Hz operation is 180×10^{-6} mrad.

In the recent commissioning period bunch populations of 6×10^{10} have been present at 40 MeV and 5×10^{10} at 1.2 GeV at the injection septum of the electron storage ring. The energy spread and transverse emittance specifications have been met without difficulty under this operating condition. Up to now the commissioning has been conducted with the acceleration of a single bunch of electrons. When a faster rise time extraction kicker is installed in the electron storage ring it will be possible to work with two bunches of electrons.

Storage Rings:

Two identical small storage rings are used in the SLC design to damp the transverse emittance of positrons or electrons to meet the SLC invariant emittance specification of 3.0×10^{-5} mrad. The commissioning of rings has been completed. Figure 2 shows a measurement of the transverse emittance of the extracted electron beam as a function of storage time. At the present time the SLC cannot operate at a repetition rate greater than 120 Hz (8.3 ms storage time) because of power limitations on the linac modulators. The storage rings easily meet the SLC specification for emittance at 120 Hz. To meet the SLC specification at 180 Hz it will be necessary to couple vertical and horizontal betatron motion to decrease the horizontal emittance.

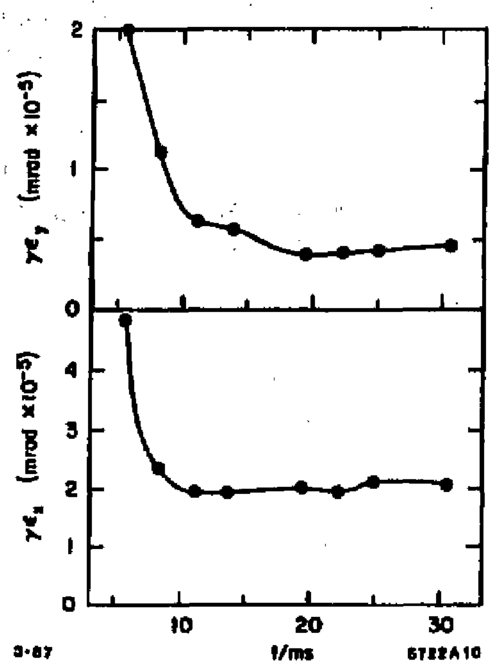

Fig. 2. Invariant beam emittance vs. time after injection into the SLC damping rings. The design value is 3×10^{-5} mrad.

The specification on the equilibrium rms bunch length in the storage rings is 6 mm. The bunch compression system between the rings and the linac was designed to allow the compression of a 6 mm bunch to as little as 0.5 mm. Figure 3 shows a measurement of the bunch length of the beam extracted from the electron ring *vs.* the charge per bunch. The increase with current of the bunch length was not anticipated in the design of the compression system. Because the storage ring bending magnets operate at a field of 2 Tesla an objective of the initial design was to make the size of the vacuum chamber as small as possible. Recent calculations have indicated that the longitudinal impedance of the vacuum chamber is too large. There are many transitions where the shape of the vacuum chamber changes. Although an attempt was made in the original design to smooth these transitions, recent calculations show that the impedance reduction that was achieved was insufficient. Until the rings and compression system are modified it will not be possible to reach the SLC design luminosity. Modifications to the compression system will be made in the fall of 1987 which should allow $\geq 3 \times 10^{10}$ particles per bunch to be compressed. Full current operation may require further modifications.

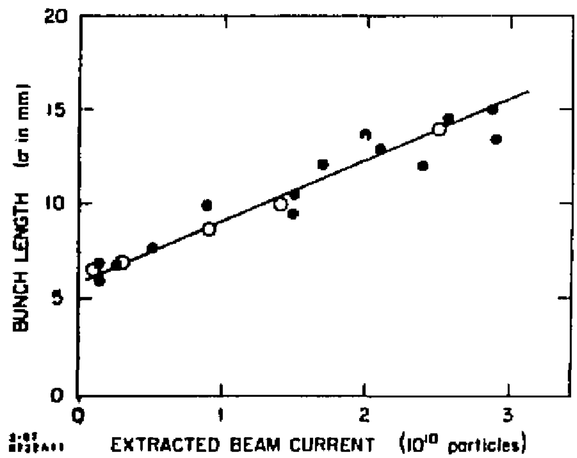

Fig. 3. Bunch length vs. charge per bunch in the damping ring.

The SLC specification calls for the simultaneous injection and extraction of two electron bunches separated by about half a ring circumference. The difficulty of constructing sufficiently fast injection and extraction kickers was not appreciated at the time the rings were designed. The space allowed for the kicker magnets turned out to be too small for magnets that could be constructed easily and the first kicker design did not meet the required specifications. A new kicker system has been designed and the first example constructed has been installed as the injection kicker. Two bunches with a population greater than 1×10^{10} electrons each have been injected into the ring. A kicker suitable for extraction is being constructed now. Until this kicker is installed and successfully commissioned, the SLC will have to operate in a mode in which only one bunch of electrons is present in the storage ring at any time. In this mode, collisions at the interaction point will occur on every other linac pulse.

50 GeV Linear Accelerator:

In order to achieve the energy gradient required for SLC operation it was necessary to design and produce a new higher power klystron. This klystron is known as the 5045 and it replaces the previously installed XK5 klystrons. This new klystron operates with a peak power output of about 67 MW and a pulse length of 3.5 μs. The original specification of the new klystron was 50 MW and 5.0 μs. Midway along in the installation of new klystrons it was found that the new klystron had a better energy efficiency when operated at a higher peak power and a shorter pulse length. All of the klystrons that were not yet installed were provided with pulse transformers with a higher step-up ratio in order to accommodate the new operating condition.

The principal difficulties which were encountered in the production of the new klystron were window breakage, cathode gas emission, and microwave instability. Despite a considerable effort, no single window solution was found. The output power from the klystron is now split in half and directed through two windows and then is recombined. Window breakage is now a very infrequent event. The emission of gas from the cathodes has been eliminated by altering the cathode manufacturing procedures. Finally, a beam breakup instability has been improved by small changes in the klystron cavities. The present yield for producing a satisfactory klystron from parts in the SLAC factory is greater than 75%.

The linac is now equipped with 200 of the new klystrons and 44 of the old klystrons. The average energy gain provided by 40 feet of accelerating structure powered by one of the new klystrons is 240 MeV. Over one million operating hours have been accumulated, mostly at a repetition rate of 10 Hz. The cathode lifetime is now projected to be greater than 40,000 hours and the mean time between failures is now about 18,000 hours and is rising.

Space charge forces within the accelerating structure are very large. In order to keep transverse wake fields from displacing the phase space of the trailing part of the bunch from the phase space of the head of the bunch, strong focusing and accurate beam centering within the linac irises is necessary. The SLC design calls for an rms beam centering error of 100 microns or less at full current. Typical recent operation is with an rms error of 200 microns.

Figure 4 is the profile of the electron beam at 47 GeV. The profile has a small tail caused by wake fields and a residual shape from mismatch from compression in the transfer line between the storage ring and the linac. Figure 5 shows a profile when the beam in the linac is not carefully centered in the irises. The tails contain a larger proportion of the charge than when the beam is centered in the irises.

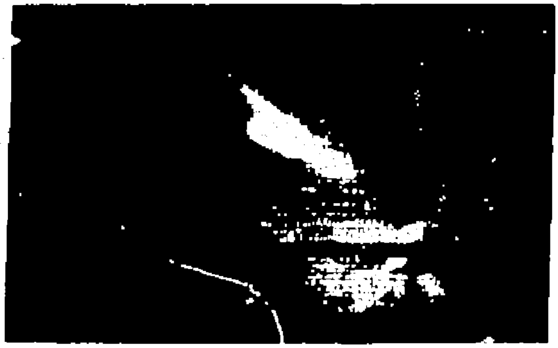

Fig. 4. Beam profile at the end of the linac for a well steered bunch. The horizontal beam size is about 250 microns (FWHM).

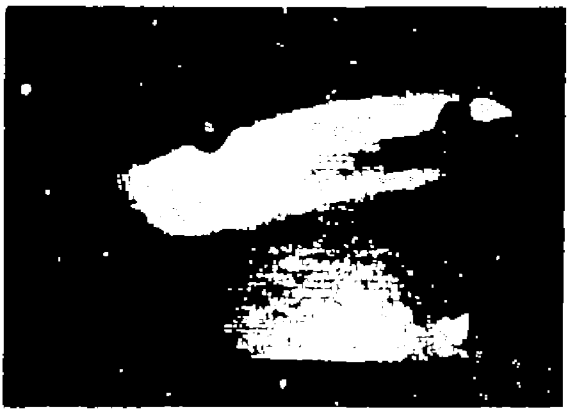

Fig. 5. Beam profile for a poorly steered bunched. The long tails are produced by the transverse wake field.

Table 2 shows a summary of apparent invariant emittance measurements made at various distances along the linac. The vertical emittance meets the SLC design specification

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of 3×10^{-5} mrad at bunch populations up to 1×10^{10}. The horizontal emittance is somewhat larger. It is believed that this difference results from residual dispersion present at the injection point in the linac where the horizontally-bending beam transport between the storage ring and the linac are joined.

Table 2. Summary of Transverse Emittance Measurements
Invariant emittance in units of 1×10^{-5} mrad.
I is in units of 1×10^{10} and E in GeV.

Location in Linac	I	E	$\gamma\epsilon_x$	$\gamma\epsilon_y$
Ring Exit	2	1.2	2.2 ± 0.3	0.4 ± 0.1
0 Km	2	1.2	13 ± 3	1.3 ± 0.3
1 Km	0.7	6.5	8 ± 1	
1 Km	1.6	6.5	11 ± 2	2.5 ± 0.3
3 Km	0.4	43	7 ± 1	
3 Km	0.8	47	12 ± 4	1.1 ± 0.3
3 Km	1.0	34	25 ± 5	2.1 ± 1.0
3 Km	1.5	43	20 ± 5	4 ± 1

At bunch populations below 1×10^{10} it is routinely possible to maintain a total energy spread in the beam of less than 0.4%. When larger populations are accelerated, the energy spread increases because of the bunch lengthening in the storage ring. It is intended to maintain the energy and energy spread of the linac beams constant by the use of feedback systems. The rms energy jitter is typically less than 0.13% with the feedback system operating.

Positron Source:

A schematic diagram of the SLC positron production system is shown in Fig. 6. About 2.4 positrons are present in the momentum-analyzed 200 MeV return line beam for every electron incident on the positron production target. About one positron per electron is present at the damping ring injection septum which should give about 0.8 reinjected into the linac.

The presently installed positron source hardware is not operating at the design specification. In particular, the solenoidal focusing throughout the system is operating at from 0.6 to 0.75 of the design values. Furthermore, the accelerating gradient in the section where the positrons are captured into RF buckets is operating at 0.5 of the design value. Finally, the channel in the septum where the electrons are extracted from the linac contains a partially collapsed vacuum chamber. All of the components that are not operating

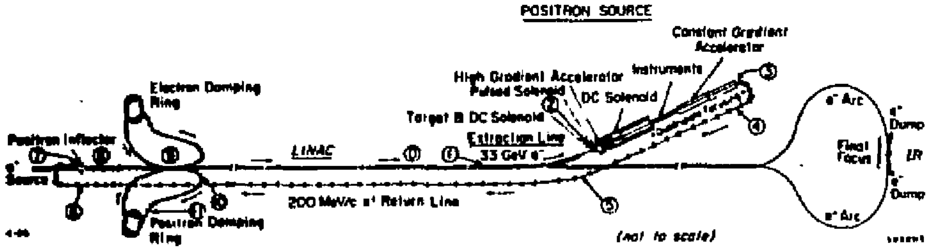

Fig. 6. The positron production system of the SLC (not to scale).

according to specification will be replaced in the fall. When these changes are made, it is expected that the positron yield will double.

4. BEAM TRANSPORT BETWEEN THE LINAC AND THE FINAL FOCUS

A very high gradient beam transport system (n = 32824) is used between the linac and the final focus. Strong gradients are used to suppress the emittance growth caused by quantum fluctuations in the emission of synchrotron radiation. Figure 7 shows a schematic cross section of the beam transport magnets. Because the gradients are high, it was necessary to survey the magnets into place with 100 micron accuracy. The survey task was complicated by the fact that the high gradient transport is not all in one plane. It is steeply contoured to follow the slope of the site on which the SLC is constructed.

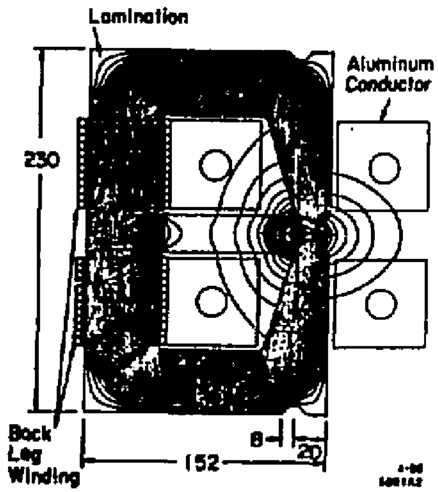

Fig. 7. Cross section of the high gradient bending magnets of the SLC arc showing physical size and magnetic flux distribution.

Beam trajectory correction is accomplished with a system of beam position monitors and mechanical magnet movers. An electron beam has been transported from the end of the linac to the final focus. It is relatively simple to correct the trajectory in the arc to an rms error of about 300 microns.

Tests have shown a high sensitivity to systematic phase shift errors in the arc. The problem occurs because of the "terrain following" nature of the transport line which is broken into 24 achromatic sections, each composed of 10 F-D cells and designed to have a total phase shift of $3 \times 2\pi$ per achromat. The beam is made to follow the terrain by rolling an achromat with respect to the preceding one. To illustrate the problem, consider the example of a simple change in level of the beam. To accomplish this an achromat is rolled by an angle θ with respect to the preceding (level) one, and the next is rolled by an angle $-\theta$. The first roll introduces a horizontal – vertical coupling and the second roll cancels this coupling *if* the phase shift between rolls is an integer times 2π. If the phase shift is not correct a coupling remains and a mismatch in the β function occurs. The cumulative phase error in the SLC arc was, initially, beyond tolerance. It has been corrected by a combination of magnet position shifts and correction coils.

5. FINAL FOCUS

The final focus optical system is designed to produce a chromatically corrected 1.7 mrad beam spot at the interaction point. When the momentum of the incident beam is within ±0.5% of the design value, the optical system produces a beta value at the interaction point of 0.75 cm. The final focus system basically consists of four main subsystems — first, a matching section to adjust the optical properties at the ends of the arcs to those required for the final sections; second, a demagnifying section; third, a chromatic correction section; and fourth, a final demagnifier.

A 7 micron diameter movable wire has been installed at the interaction point to measure the beam profile. When beam profiles that are smaller than the wire diameter have been achieved the 7 micron wire will be replaced with a 4 micron wire. After the optical elements have been adjusted to produce a small beam spot, the beams will be brought into collision through the use of a precision beam position monitor at the interaction point. This monitor has sufficient accuracy to bring the beams to within 10 microns of each other. When the beams are separated by less than 40 microns the steering effect of one beam on the other can be detected with other beam position monitors. The steering effect, which vanishes when the beams collide head on can be used to center the beams with an accuracy of better than one quarter of their transverse dimension. Finally, detectors have been constructed to observe synchrotron radiation emitted during the collisions. The synchrotron radiation strength will be used to reduce the spot size below that which can be resolved with the 4 micron wire.

Electron and positron beams were simultaneously sent to the collision point for the first time near the end of March 1987, and the first beam-beam collisions occurred on March 27th. Since that time we have returned to working with a single beam to properly tune up the system. The minimum beam size measured at the collision point is 4.6×7.5 microns. Figure 8 shows a horizontal scan of the beam with the 7 micron wire. Unfolding the measure size of the scan and the wire size yields a 4.6 micron rms horizontal size. A reduction in size to the design value requires the completion of the arc correction program and the proper tune up of the final focus system.

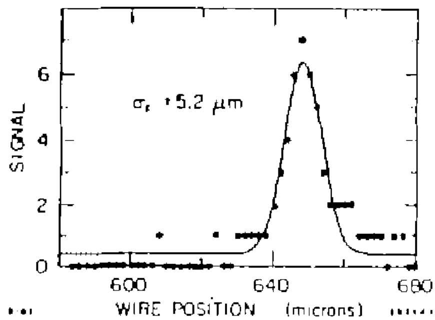

Fig. 8. A scan of the beam at the SLC collision point with the 7 micron diameter wire. An unfold of the wire size contribution give an rms beam size of 4.6 microns.

6. EXPERIMENTAL PHYSICS PROGRAM

The Mark II detector stands completed and is running on cosmic rays outside of the SLC collision region. The detector was upgraded from the configuration in which it was used at PEP by the replacement of the old main drift chamber with a new drift chamber with many more layers of wires to improve tracking and with de/dx capability to allow π/e separation; the replacement of the old time-of-flight scintillators with new thicker scintillators; the addition of new end cap electron calorimeters with a measured resolution $(\sigma_E/\sqrt{E}) = 17\%$; the replacement of the damaged aluminum coil with a new room temperature coil bringing the field back to its design value of 5 kilogauss; the addition of a new high resolution vertex chamber designed to take advantage of the small SLC beam pipe; and the addition of new small angle tagging and monitoring systems. All of these new components, with the exception of the vertex chamber and small angle devices, have been fully tested during a run on the PEP storage ring prior to the shift of the detector to the SLC collision region (the vertex detector and small angle components could not be fit around the PEP storage ring beam pipe). This test allowed the new components to be checked and allowed the new tracking and analysis programs to be tuned up. The new components all met or exceeded their design specifications. Because of the test run, we expect the time between the installation of the Mark II detector at the SLC and the production of good quality data for analysis to be considerably reduced over that which would be required for a completely new and untested facility.

A new and potentially much more capable detector, the SLD, is under construction by a broad collaboration consisting of many U.S. groups and groups from Canada, Great Britain, and Italy. The new detector includes full solid angle electromagnetic and hadron calorimetry, as well as particle identification through the use of Cherenkov Ring Imaging. A very high resolution vertex detector fabricated from an array of CCD chips is also under construction. The pace of this detector is being determined by the rate of funding made available to the laboratory by the DOE. It could in principle all be ready to use in 1989, but it is doubtful that the funds available in the next two U.S. fiscal years will be sufficient to complete the detector on that schedule.

Two improvements to the physics capabilities of the SLC machine are now under construction. The first of these is the so-called energy spectrometer. This is a pair of devices which are set in the transport systems which carry the SLC beams after collision to the beam dumps and measure their energy to very high precision through the use of the most classic technique — a precision measurement of the bending angle in a precisely determined magnetic field. We expect these devices to be installed sometime in FY88, and they should allow the determination of the energy of each beam to about 20 MeV on each pulse of the SLC. With this system we can determine the mass of the Z^0 to about 40 MeV, allowing a high-precision determination of $\sin^2\theta_W$.

The second improvement project is the development of a longitudinally polarized electron beam for the SLC. We know from previous experiments at SLAC that polarized electrons are not depolarized by transit through the linear accelerator. Thus, if we can get the polarization right on injection into the linac we can preserve it during the acceleration process. The production of polarized beams is complicated by the necessity to take the electrons through the SLC damping ring complex. We have already produced longitudinally polarized electron beams at the gun, and to preserve their polarization through the damping ring it is necessary to rotate the spin of the electrons from longitudinal to transverse and parallel to the damping ring magnetic field before injection into the damping ring. This is done by taking advantage of the $g-2$ precession that occurs in the first part of the linac-to-damping ring transport system which rotates the spin from longitudinal to transverse and in the plane of the damping ring, and following this by a superconducting solenoid which turns the spin parallel to the field in the damping ring. After extraction, a combination of two solenoids plus the $g-2$ bending in the transport line back to the linac allows the spin vector to be pointed in an arbitrary direction. This is necessary because the $g-2$ precession in the horizontal and vertical planes in the transport system from the end of the linac to the collision point requires an initial spin direction which depends on energy if the spin is to end up longitudinal at the collision region. We aim to have the polarized beam capability available late in 1989.

7. CONCLUSION

The construction of the SLC in a period of three and one-half years has been a great challenge to the laboratory. We have learned a lot and it will be much easier to build the next linear collider than to build this one. I summarise the status of the machine as follows:

- The linac has been somewhat easier to bring to SLC specifications than we expected. There are no problems making the necessary energy or with the stability of the machine. We do need to make some improvements in the positron source and in the damping ring to handle the bunch lengthening problem. We expect to tackle both of these in the fall, and hope to have a positron per electron ratio of > 1 and to be able to handle the damping ring bunch lengthening at least up to charges per bunch of 3 to 4×10^{10}.
- The arcs have been somewhat harder than we expected. The coupling problem that comes from the terrain-following nature of the SLC is understood, and the first pass at correcting it has been made. We may have to go through the system again to tighten the tolerances still further. Beam transmission through the arcs is now 100% and it is simple to get rms orbit errors of 200 to 300 microns.
- Tune-up of the machine is continuing, and we hope to begin the move of the Mark II detector on to the beam line sometime in the fall of this year. Given good luck we may start taking data at the Z^0 around the first of the year and hope to have several thousands Z^0s for analysis by the physicists by the time the summer of 1988 comes around.