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THE STANFORD LINEAR COLLIDER*

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Abstract

The Stanford Linear Collider (SLC) has been in operation for several years with the initial particle and accelerator physics experiments just completed. A synopsis of these results is included. The second round of experiments is now under preparation to install the new physics detector (SLD) in Fall 1990 and to increase the luminosity significantly by late 1991. Collisions at high intensity and with polarized electrons are planned. Many beam dynamics and technological advances are in progress to meet these goals.

Introduction

The normal collision cycle for the SLC[1,2] is to accelerate a positron and an electron bunch extracted from their respective Damping Rings to 47 GeV in the SLAC Linac. They are then collided after passing through two Arcs and shaped to a small size by the Final Focus (see Fig. 1). The spent beams are discarded in high power dumps after a single collision. On the same acceleration cycle a third (electron) bunch is accelerated to about 30 GeV in the linac (2 km), extracted, and, then, converted to positrons in a high power target. The positrons are accelerated to 200 MeV and transported back to the beginning of the linac. When the positrons arrive, the first 100 m of the linac is pulsed and is used to accelerate the positron bunch and two new electron bunches (made by a gridded gun). These bunches are injected into the two 1.15 GeV Damping Rings where radiation damping reduces the emittances to values required for small beam spots at the final focus. This cycle is repeated at 120 Hz. The inherent instabilities of linacs in general have been compensated by the use of slow (one minute) and fast (every pulse) feedback systems (computer driven). Over seventy variables are now actively controlled.

The SLC came into full operation in 1989 producing its first Z^0 particle on April 11. During that year over 22 nb^{-1} of luminosity were logged (see Fig. 2). Over that period the luminosity was increasing linearly with time ultimately obtaining 0.26 nb^{-1} per day. The Z^0 resonance parameters were measured[3]. The mass is 91.11 (+/- 0.23) GeV, the width 1.61 (+0.60/-0.43) GeV, and the number of neutrino species 2.7 (+/- 0.7). Since these measurements LEP at CERN has had a rapid turn on and presently dominates these measurements. The program of the SLC has now taken on a different direction: to produce polarized Z^0 decays and to study the accelerator physics issues required for the next linear collider. The goal[2] is to make a collision rate comparable to 100 K Z^0 per year with polarization by early 1992. The required parameters for that goal are listed in Table 1. The technological advancements being commissioned now are discussed below.

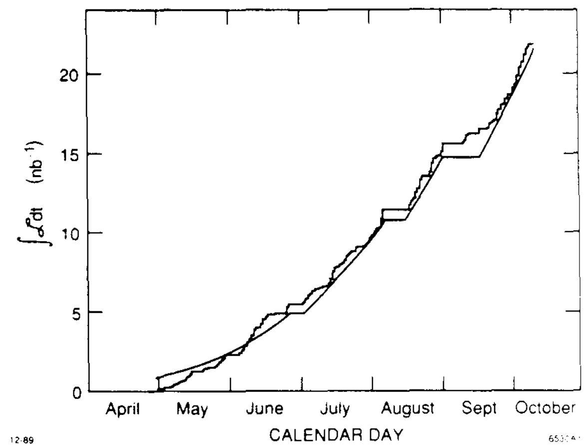

Fig. 2 Integrated luminosity with time in 1989.

Positron Production

The old positron target was fixed in position and could handle only 2 X 10^{10} electrons per bunch at 60 Hz without cracking. This target was sufficient for collision parameters used in 1989. However, for the 1992 goals a significantly higher

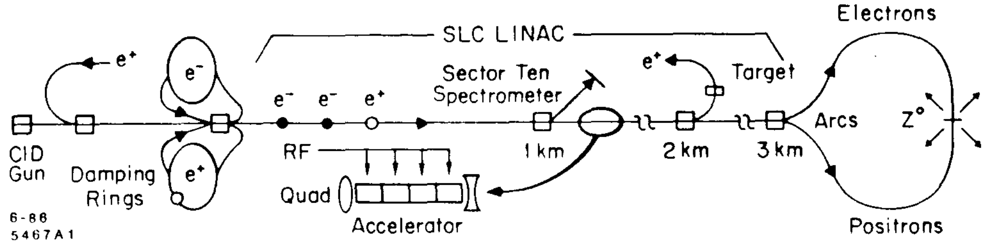

Fig. 1 Schematic view of the Stanford Linear Collider (SLC)

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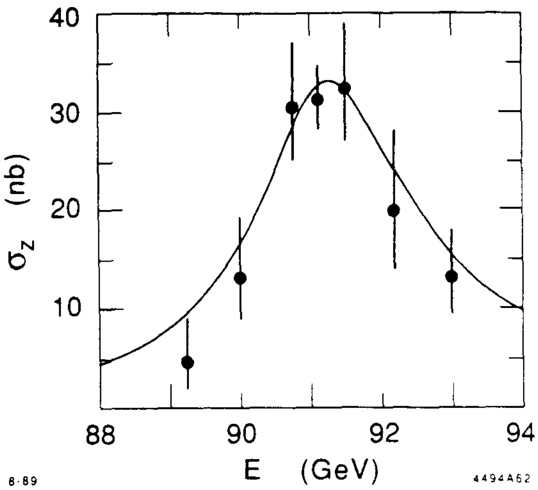

Fig. 3 Measured Z^0 mass in 1989.

incident power is required. A rotating high power target[4] has been installed in January 1990. A 120 Hz pulse rate of over 6 X 10^{10} electrons per bunch can be safely handled. The target does not let two bunches strike the same position over several seconds (see Fig. 4). This new target has been successfully placed in operation. In case of a failure an semi-remote removal system can safely pull the target out of the vault in about 30 minutes with minimal exposure to the crews.

The yield ratio of the number of targeted electrons to the number of positron exiting the positron damping ring needs to be approximately 1.1. The best yield measured is 0.9 with 0.6 as typical. The two problem areas are the momentum collimation region just downstream of the 200 MeV accelerator near the target and the region at the beginning of the two mile accelerator where the positrons are accelerated and injected into the damping ring. Extensive studies are under way to improve the local yields.

Kicker Improvements

The reliability of the damping ring injection and extraction kickers has gone from poor in 1989 to good in 1990. Several improvements including radiation hard magnet insulation, lead shielding, improved pulser design, and magnet heaters have increased the mean time to failure significantly[5]. Furthermore, the two bunch extraction kicker in the electron damping ring must provide equal deflections to the two bunches to about one part in 10^3 to avoid wakefield enlargement of the second bunch in the linac. It was too difficult to make a pulser-magnet combination to do this directly. Consequently, a pulse forming line and a pre-kicker have been added to the primary pulser to make the deflection of the second bunch adjustable (see Fig. 5).

Table 1
SLC Operating Parameters

Parameter	Achieved 1989	Achieved 1990	Desired 1992
N^- (X 10^{10}) (IP)	2.0	3.6	4.0-5.0
N^+ (X 10^{10}) (IP)	1.3	1.9	3.5-5.0
Emittance (10^{-5} r-m)	5.0-6.0	4.5-7.0	3.0-5.0
IP beam size (μm)	2.7-3.3	3.0-4.1*	1.7-2.5
Pinch enhancement	1.0	1.0	1.1-1.2
Repetition rate (Hz)	60	120	120
Efficiency (short term)	0.25	0.3	0.4-0.5
Luminosity (X 10^{29} /cm/s)	0.14	0.30	5.2-9.7

(* Increased with higher Ns.)

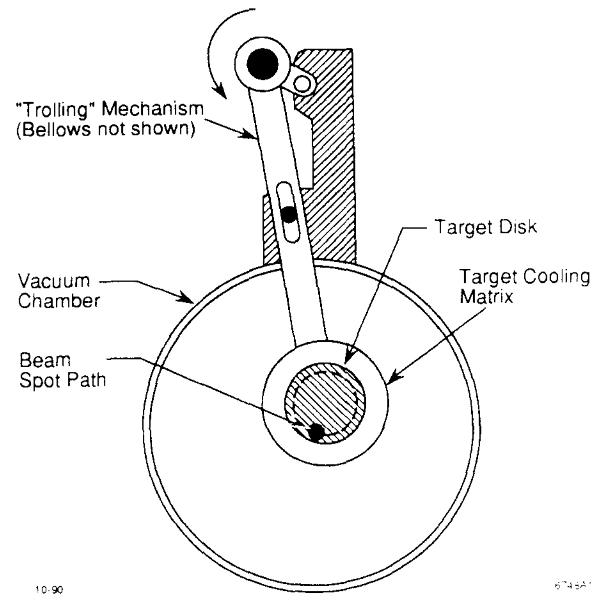

Fig. 4 New high power rotating positron target.

Wire Scanners

The measurement of beam transverse dimensions is crucial for maintaining the beam emittances generated in the Damping Rings and transported through the Linac to the Arcs and Final Focus. At beam currents above 2 X 10^{10} particles and spot sizes below 200 microns, the old SLC profile monitors (phosphor screens) become radiation damaged in tens of minutes. After that these monitors are no longer satisfactory for detailed emittance measurements. (However, they remain good for observing beam transverse tails.) Furthermore, these profile monitors are thick enough so that they generate sufficient beam spray that the machine protection systems start to trip. Systems of wire scanners were installed in the Linac and Final Focus to avoid these problems.

A schematic view of a wire scanner is shown in Fig. 6. The scanner has three wires (x,y,and u) which can be moved through the beam. A photomultiplier tube at 90 degrees and an ion chamber downstream are used to sense the number of particles striking the wire. A histogram of a measured beam shape is shown in Fig. 7. A wakefield tail on the beam can be clearly seen. The signal fall times were arranged so that bunches 60 nsec apart could be cleanly resolved. Initial problems with signal saturation and wire vibration were alleviated by reducing the number of photons reaching the photocathode and by

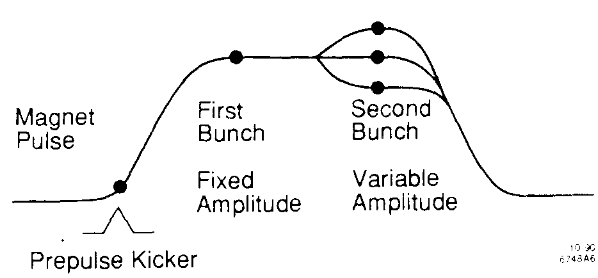

Fig. 5 Improvements to the Damping Ring extraction kicker to allow independent control of both electron bunches.

choosing the optimum scan speed, respectively. Nearby klystrons sometimes produce dark current from the accelerating structure which give a long time background signal. Reducing the accelerating gradient by about 10 % usually eliminates this noise source.

Systems of four scanners were placed over a distance of 10 m at the beginning of the linac and 50 m at the end so that different betatron phases can be sampled (for both positron and electrons). Using these four scanners complete emittance measurements including the Twiss parameters can be obtained. A complete measurement takes about one minute. An automatic computer program systematically measures the emittances every 30 minutes and makes a long term history plot. During collisions when the linac collimators are inserted, the wire scans in the linac

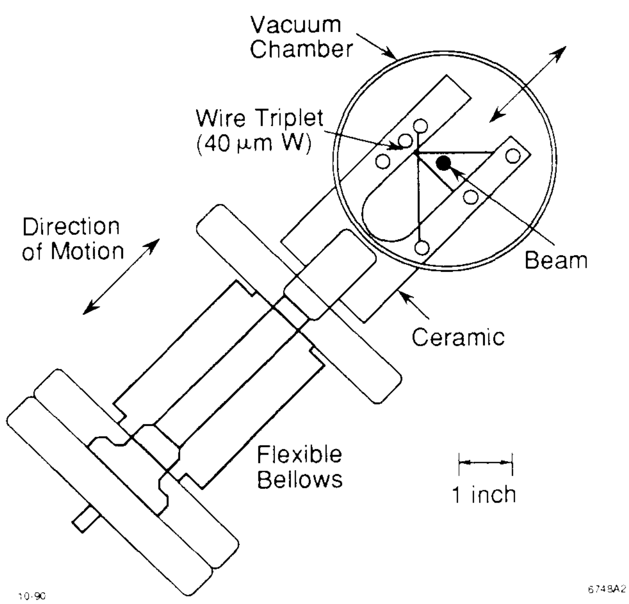

Fig. 6 New wire scanner for the SLC. The wire is made to move through a beam fixed in position.

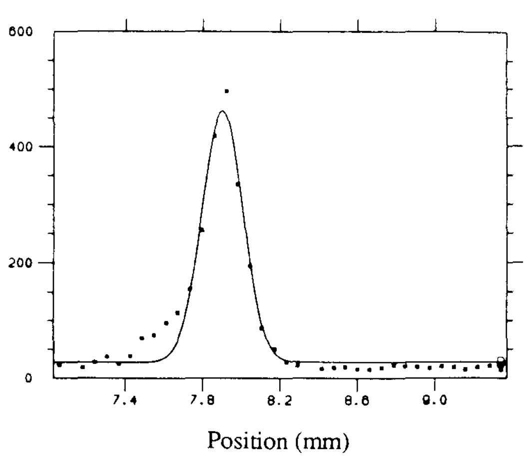

Fig. 7 Measured beam shape showing a wakefield tail. The measured beam size is 105 +/- 5 μm. The invariant emittance is measured using four separated scanners to be 5. (+/- 0.3) X 10^{-5} r-m at 3 X 10^{10} e- / bunch.

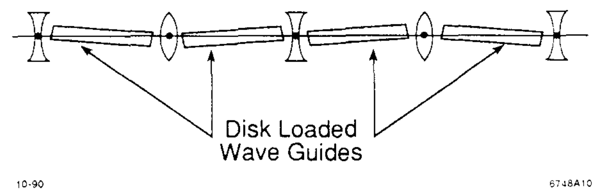

Fig. 8 Schematic view of misaligned accelerating structures.

can be performed without interruption to the physics data taking at the IP. There are twelve scanners installed at present[6]. Twelve more are due for installation in early 1991.

Emittance Control

The emittance of a beam accelerated in the linac can be enlarged by misalignments of the quadrupoles, position monitors (BPM), and accelerating structures. A beam based alignment technique using two beam trajectory information combined with different lattice strengths has reduced the quadrupole rms offsets from about 250 microns in 1988 to 100 microns in 1990. The BPM rms errors have been reduced from 150 to 75 microns. So far no successful technique has been developed to identify particular accelerator offsets (see Fig. 8) using beam data. The difficulty lies in the long distance integral of the beam over the locally generated wakefields to make a transverse tail. In addition, the energy spread introduced via transverse wakefield (BNS) damping makes filamentation more rapid and reduces the growth of a wakefield signal. From mechanical alignment data the accelerator offset errors are approximately 300 microns rms. Tracking simulations[7] with these errors have been made (see Fig. 9). The calculated emittance enlargement ranges from 20 to 150 % dominated by the structure errors. The component of the error at the betatron frequency likely dominates the emittance enlargement. The betatron component is strongly seed dependent.

Injection jitter makes the emittance change pulse by pulse. Several photographs of observed wakefield induced tails are shown in Fig. 10. Many sources of launch jitter have been found and cured. The resulting jitter is now about 35 % of the injection beam transverse sigma (= 350 microns) (mostly horizontal). The extraction kicker contributes one third; unknown sources the rest.

The history of emittance and beam current measurements

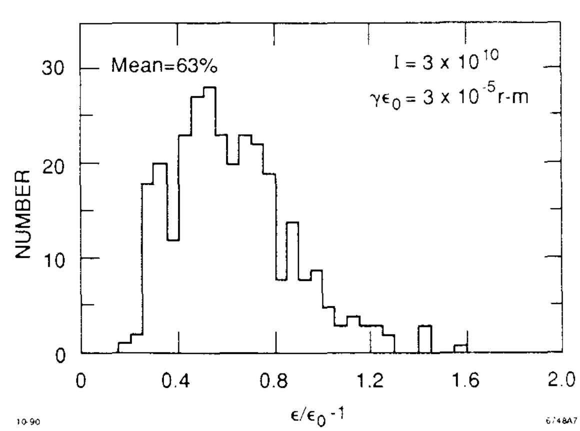

Fig. 9 Emittance growth from accelerator errors for 300 simulated linacs using 100 μm quadrupole and BPM random offsets, 300 μm accelerator errors, 2 % energy scale errors, and 2 degrees input RF phase errors.

is shown in Fig. 11 indicating that many studies[8] were completed to reduce the emittance to within a factor of two of the design. The June 1990 increase in the emittances is due to a mechanical alignment procedure error of the accelerating structure (subsequently fixed). The structure temperature was held constant during alignment but the housing doors were open allowing cold air to distort the mechanical support vertically on the order of 0.5 mm. The alignment procedure and conditions are under review.

A new method for controlling wakefield effects produced by offset accelerators has been suggested[9] where structure distortions at the betatron frequency are actively added to the linac (without damage) to counterbalance the random offsets. This technique has the hope of significantly increasing the alignment tolerance of the structure, providing on line wakefield control, and reducing the need for manual alignment in the tunnel.

SLC Arc Correction

The correction of the Arc optics is now nearly complete with the use of a new closed magnet bump. This closed trajectory distortion is used to compensate for random and systematic errors which have caused coupling of horizontal and vertical betatron motion. These errors generate increased projected emittances and betatron function mismatches. This new bump is shown in Fig. 12. With these corrections the electron and positron Arcs now have projected emittance enlargements less than 10 % and 30 %, respectively. In addition, there are optical adjustments in the Final Focus which can remove most of these projected growths.

Backgrounds and Collimation

The MKII physics detector is sensitive to several kinds of backgrounds. (1) Beam particles displaced more than four transverse sigma produce synchrotron radiation in the final quadrupole triplet. This radiation scatters from the internal masking and is mostly absorbed. However, a small fraction enters the vertex and central chambers, causing multiple hits in the sense wires. (2) Off energy particles strike the collimators in the final focus and produce muons. Finally, (3) only a few errant particles need strike the vacuum chamber in the quadrupole triplet to generate 50 GeV electromagnetic showers too near the detector to shield. A system of eight adjustable collimators was installed at the end of the linac to make a rectangular square cut in betatron space to eliminate many of these errant particles. This system (see Fig. 13) then allowed the other collimator in the Arcs and Final Focus to become secondary phase space cuts. They have been very successful. The four upstream collimators are the primary cuts placed at three sigma. The downstream jaws are set to four sigma as secondary cuts. The jaws themselves are titanium blocks with water cooling through a copper-stainless steel arm. The blocks are 1.8 radiation lengths long. Stepping motors control their positions to about 50 microns. Each jaw can withstand 7 KW of incident beam power in a 150 micron square beam.

Operation at 120 Hz

Running the SLC at 120 Hz collision rate requires full three bunch operation in which two electron bunches are

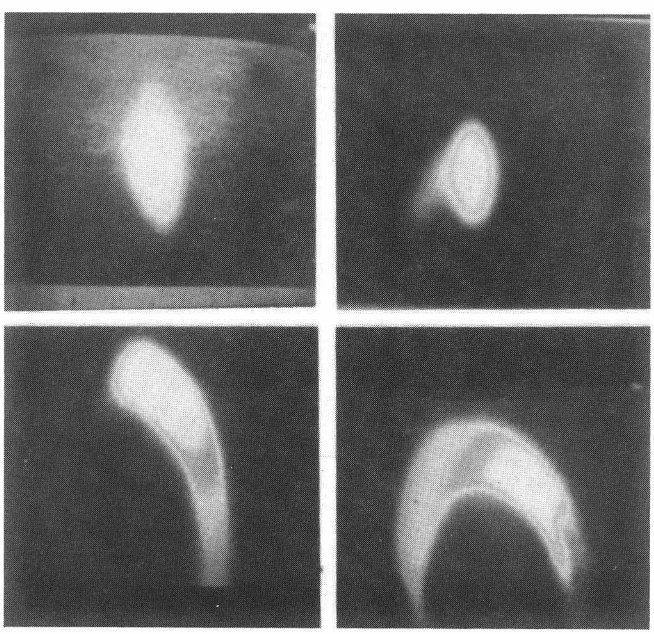

Fig. 10 Observed wakefield beam tails at 47 GeV. The upper left photo shows a well steered beam. The lower right shows a 3×10^{10} e- bunch with a 1 mm betatron oscillation.

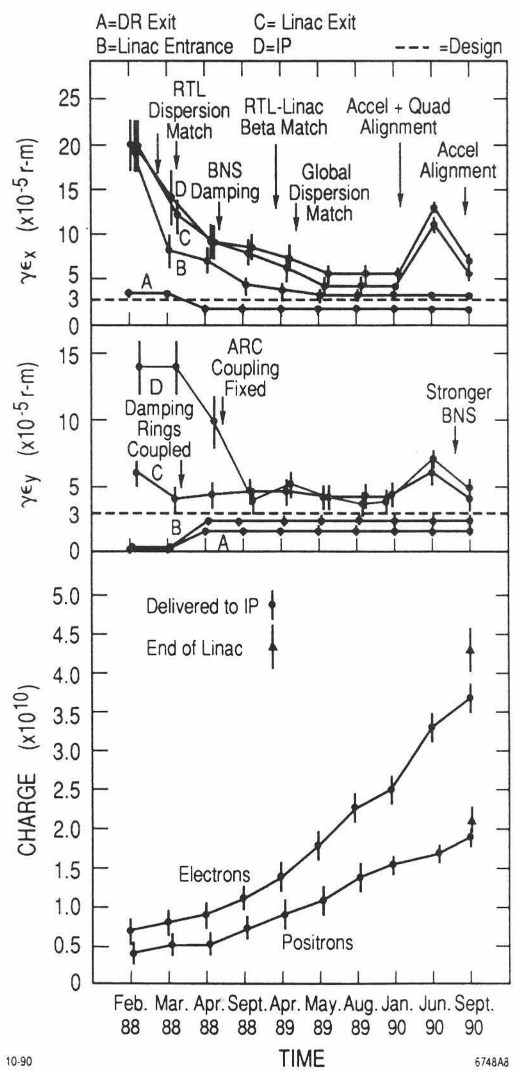

Fig. 11 History of the beam emittances and currents versus time. As the intensities have increased the emittances have been maintained through better control and alignment.

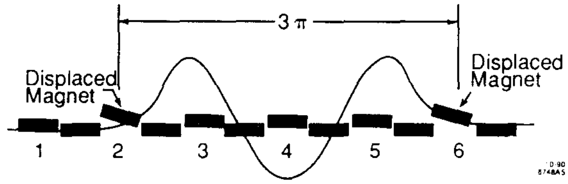

Fig. 12 Magnet 'bumps' in the SLC Arcs which have provided the final needed correction for cross plane coupling.

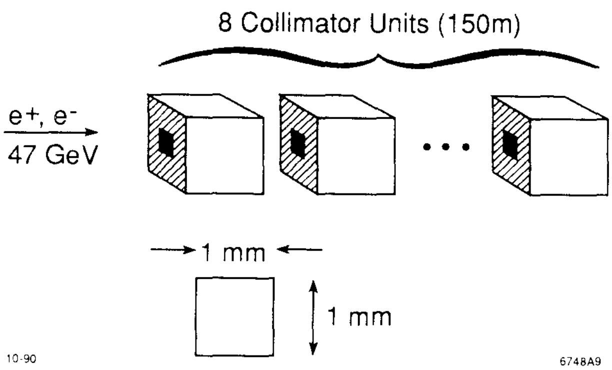

Fig. 13 Adjustable collimators at the end of the linac provide 3 σ transverse cuts on the beam tails. The eight collimators make a 1 mm square hole over 150 m through which both beams pass. Only 10 to 30 % loss of beam is typical.

produced every pulse and the positron Damping Ring contains two bunches, which alternately damp through two collision cycles. At 120 Hz rate the alternate acceleration cycles occur 180 degrees apart on the AC power cycle and have measurable differences (see Fig. 14) which affect beam tuning and detector backgrounds. Most of the differences appear as beam energy differences. Some of the sources have been identified and cured. The remaining problems are reduced by accelerating slightly (10 %) different beam currents on the alternate pulses.

Electron Polarization

A polarized electron source[10] with a 3-electrode photocathode is being prepared for use in Fall 1991 to provide longitudinally polarized electrons at the interaction point for a

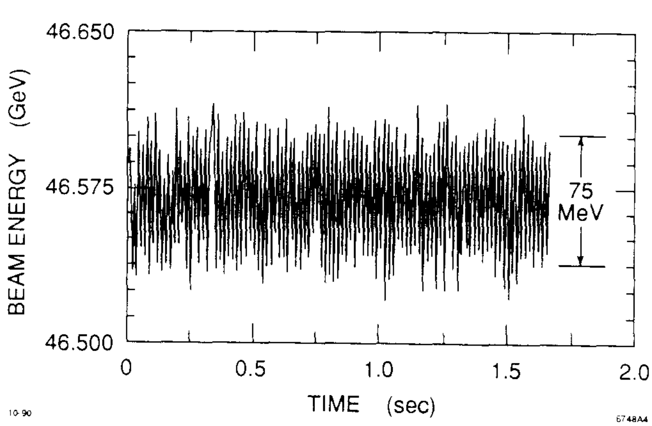

Fig. 14 Observed 'time-slot separation' of the beam energy in the final focus during operation at 120 Hz.

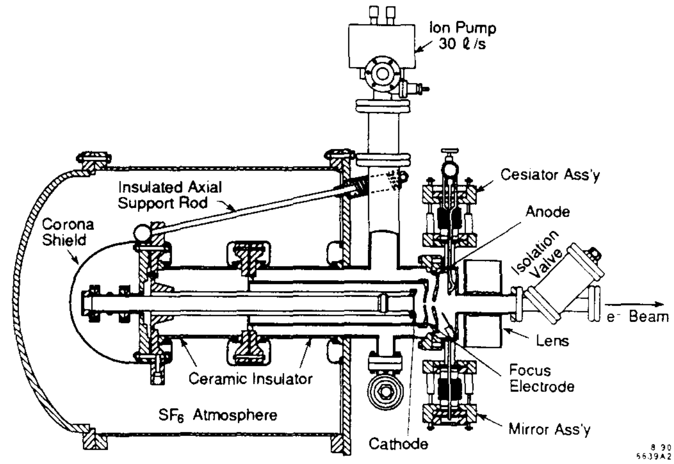

Fig. 15 New polarized electron gun using a GaAs photocathode.

precision measurement of $\sin^2 \theta_W$. A second gun with an improved design is under construction (see Fig. 15). Tests to improve the lifetime, peak beam current, and vacuum properties of the first gun are underway. The three spin manipulation solenoids (superconducting) used to get the beam in and out of the Damping Ring are build. Two are installed and operational; the third is to be installed in Summer 1991. The Compton and Moller polarimeters at the end of the linac and in the final focus are installed and being tested. The source polarization is expected to be 39 % and, due to some depolarization effects in the Damping Ring and e^- Arc, the IP polarization should be 34 %.

Acknowledgments

The construction, commissioning, and operation of the SLC required the dedication, insight, hard work, and perseverance of many people at SLAC and from associated universities and laboratories. It is to their credit that significant progress in understanding the accelerator physics of linear colliders and the first observations of hadronic decays of the Z^0 have been made.

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