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OBSERVATIONS OF ACCELERATED HIGH CURRENT LOW EMITTANCE BEAMS IN THE SLC LINAC*

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ABSTRACT

The Linac of the SLAC Linear Collider (SLC) is required to accelerate several intense single electron and positron bunches to high energy while not enlarging their small transverse emittances. The improvements needed by the SLAC Linac to meet these goals have very stringent design criteria. As partial systems have become available, beam tests have been performed to confirm the designs. The results of those beam tests are discussed. Future plans of the improvement program are described.

SLC LINAC DESIGN

From the SLC design[1], the Linac must receive one positron bunch and two electron bunches from their respective damping rings at 1.21 GeV and accelerate them to high energy. The positron bunch and the first electron bunch are accelerated the full length of the three kilometer Linac to about 50 GeV and go on to collide at the interaction point. The second electron bunch is extracted at about two kilometers to make a new positron bunch. A schematic of the SLC Linac is shown in Fig.1. Downstream of the Damping Rings, the Linac consists of 232 12.3 m long accelerator girders, each to be powered by a 50 MW 2856 MHz klystron[2] operating with SLED-II[3]. Each girder contains four 3.05 m long accelerator sections and must provide a maximum unloaded energy gain of 253 MeV so in aggregate 50 GeV is reached. A typical girder is shown in Fig. 2.

In order to provide high charge densities for high luminosity collisions, the very small transverse (invariant)emittances of the beams from the Damping Rings ($\gamma\epsilon_{x,y}=3\times10^{-5}$ m-r) must be maintained during acceleration. Unmatched dispersion from the Ring-to-Linac (RTL) transport lines and transverse wakefields[4] in the Linac accelerator structure can increase the effective emittances. The dispersion must be reduced to below 2 cm at the beginning of the Linac using controls in the transport lines. The transverse wakefields are controlled by shortening the bunch length to 1.0 mm using an RF compressor system in the RTL and by using a strong FODO quadrupole lattice in the Linac (one quadrupole per girder). The beams are required to be centered in each quadrupole to about +/- 100 μm which is accomplished using a pair of X-Y dipole correctors located on each girder and a beam position monitor[5] held in the poles of each quadrupole. The quadrupoles are aligned with respect to the accelerator to about 50 μm. A project to increase the focusing in the early part of the Linac will further reduce the transverse wakefield effects.

The beams must have the correct energy and energy spread at the end of the Linac so that they will transverse the arcs, will have the proper bunch length at the collision point due to compression in the arcs, and will minimize the effects of second-order optics in the final focus region. Longitudinal wakefields from the intense bunches in the Linac cause the tail of a bunch to lose about 2 GeV relative to its head during passage through the Linac and the trailing bunches to be accelerated about 880 MeV less. The intrabunch energy loss is corrected by accelerating the beams ahead of the crest of the RF wave by about 12 S-band degrees to reduce the energy spread to about +/- 0.5%. The interbunch energy loss is corrected by properly adjusting the beam arrival times in the SLED waveform so that both beams have the same final energy. The RF phase and amplitude can be monitored and controlled to +/- 0.5 degrees and +/- 1%, respectively, using a new control system[6]. The SLED pulse can be timed to about 8 nsec.

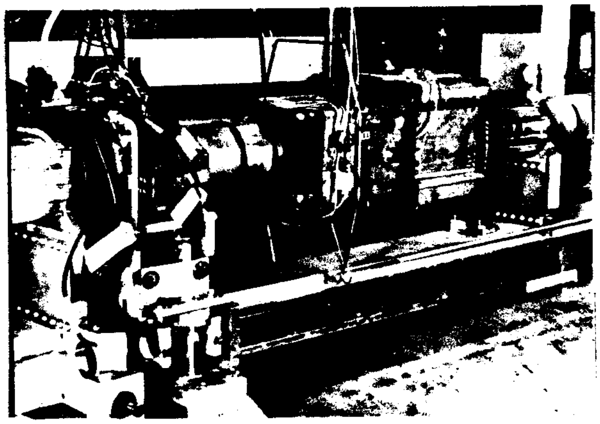

Fig. 2. Linac girder showing the accelerator, quadrupole and dipole correction magnets.

Many diagnostic monitors have been installed in the Linac. Seven phosphorescent profile monitors[7] are located in appropriate positions to allow beam emittances to be measured and transverse wakefields minimized. Four resonant toroidal current monitors allow measurement of the beam intensities. A seven degree

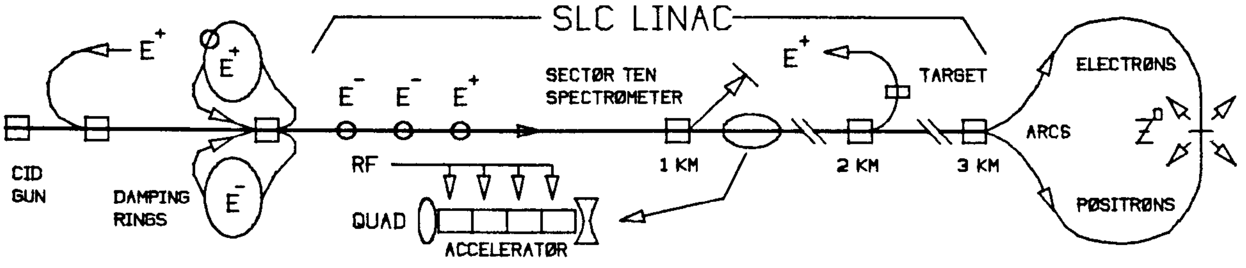

Fig. 1. Schematic of the SLC

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spectrometer has been installed 900 meters downstream of the Damping Rings to allow measurements of the energy and energy spread.

OBSERVATIONS

RF Acceleration

Seven 50 MW klystrons[2] operating in the SLED-II mode were beam tested using the spectrometer to determine their energy contributions. By varying the timing of the beam with respect to the RF pulse, the SLED gain profile was measured and was found to be in good agreement with the predictions. The observed peak energy gains produced by the klystrons operating at various output powers are shown in Fig.3. A klystron's power can be adjusted by changing the pulsed voltage applied to the cathode. The power is determined by measuring a klystron's output directly or the pulsed voltage. The curve in Fig. 3 is the design goal of 51 MW and 253 MeV scaled with power.

Small asymmetries in the RF fields in the accelerating structures of the Linac deflect the beams, require special trajectory corrections and dictate tight RF stability tolerances. Observations of RF deflections are reviewed in Ref. 8.

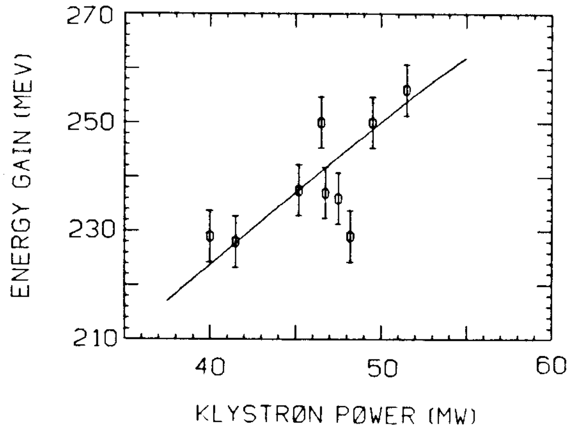

Fig. 3. Measured energy gain v.s. klystron power.

Transverse Effects

In the first 1000 meters of the Linac the quadrupole lattice and dipole correction magnets were installed in the fall of 1982. The beam position and RF klystron monitors for the same region were implemented in the following year. Studies of reinjection of damped electron bunches into the Linac and their acceleration to the spectrometer were conducted in late 1983 and early 1984 in the so-called Ten Sector Tests[9]. These tests were performed using 35 MW klystrons without SLED resulting in a beam energy at the spectrometer of 6.5 GeV. Although the beam only experienced one third the Linac transverse impedance, the wakefield effects were expected to be as great as those for the whole Linac when the accelerating gradient is three times larger. In all the tests of wakefields the beams were steered to the center of the quadrupoles to about 200 μm, then the launching position and slope in each plane were adjusted in the RTL to minimize the transverse beam wings or tails.

The horizontal and vertical emittances of a low intensity bunch ($\sim 4\text{x}10^9$ electrons) were measured at various locations along the linac and are plotted as a function of beam energy in Fig.4. As the measured invariant emittances are independent of energy, the emittances drop inversely with energy as required for the SLC.

At a profile monitor just upstream of the spectrometer the emittances were measured as a function of bunch intensity. At high charges the launching conditions into the Linac had to be tuned every few minutes using RTL magnets to minimize the transverse wakefield effects. The largest bunch reinjected was $1.3\text{x}10^{10}$ electrons.

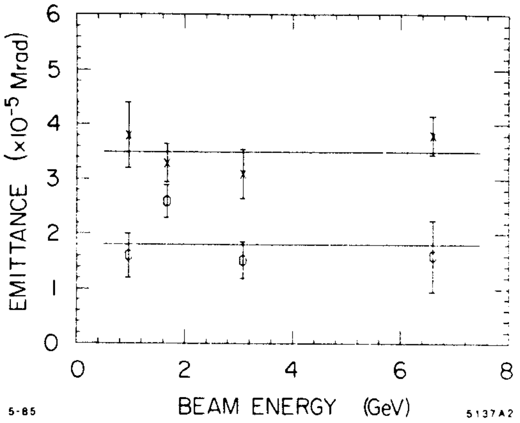

Fig. 4. Measured invariant emittances v.s. beam energy. An X represents horizontal data and an O vertical data.

Subsequent to these tests, several components in the RTL were identified as contributing to the trajectory drifts in the Linac and have been fixed. The measured emittances as a function of beam intensity are shown in Fig. 5. The emittances at 1 x 10^{10} electrons per bunch are consistent with the SLC design goal of 3 x 10^{-5} m-r (invariant).

A picture of a beam profile at 6.5 GeV is shown in Fig. 6. The beam halo illuminates a 340 μm fiducial hole in the monitor screen. The RMS width of this beam is about 120 μm. A translation of this spot to the collision point using the beam energy and the betatron functions predicts a spot size less than 2 μm and a luminosity of 10^{29} $\text{cm}^{-2}\text{sec}^{-1}$ for 1 x 10^{10} particles in both bunches. This is the SLC design for these bunch intensities. Of course, much effort is being expended to extend these results to full SLC currents of $5\text{x}10^{10}$ particles per bunch.

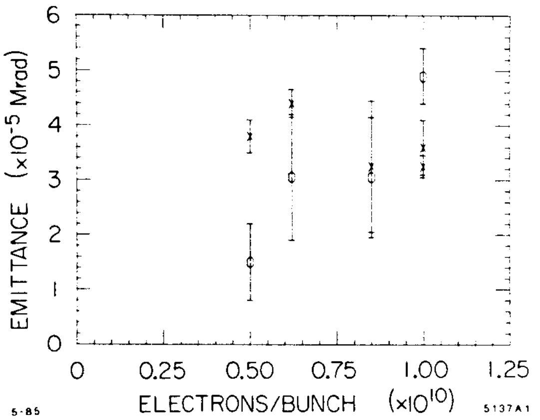

Fig. 5. Measured invariant emittances v.s. beam intensity at 6.5 GeV. An X represents horizontal data and an O vertical data.

Bunch Length Compression

The bunch length of a beam from a damping ring must be compressed from the equilibrium length of 6 mm to 1 mm needed for transverse wakefield control in the Linac. The RTL contains an RF accelerating section designed for this compression[10]. The concept was tested using a Cerenkov radiator and streak camera[11] located 100 meters downstream of the RTL in the Linac. The measured bunch length as a function of compressor peak field is shown in Fig. 7. The results are in agreement with the required compression, although some beam loss occurred at large voltages.

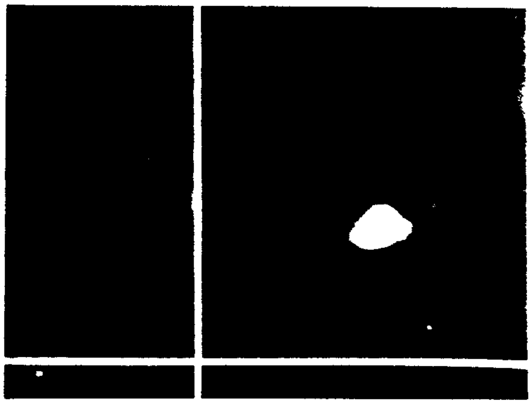

Fig. 6. Beam spot on a profile monitor at 6.5 GeV near a 340 μm fiducial hole. The crossed lines indicate the digitized scan lines.

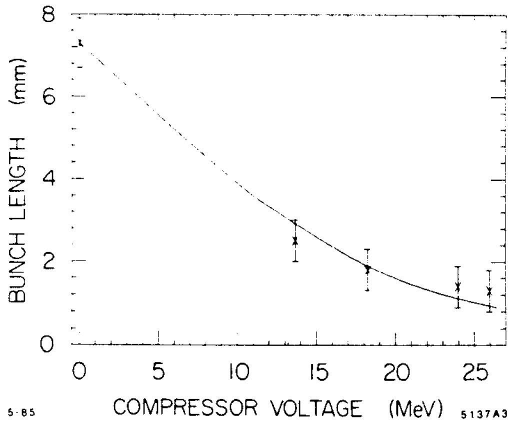

Fig. 7. Measured bunch length v.s. compressor voltage.

Longitudinal Effects

The longitudinal wakefields in the Linac affect the energy spectrum of the particles within an intense bunch and the energy gain of bunches which follow behind. The intrabunch effect was tested during the Ten Sector Tests where the energy spectrum of a bunch of 1 x 10^{10} electrons was measured in the spectrometer at the one-third point in the Linac. The half width of the spectrum was about +/- 0.3% after the RF phases were adjusted for minimum energy distribution. This value agrees with that expected given the accelerating gradient[4]. The long range wake was studied using a straight ahead Linac beam with several adjacent bunches filled with equal but low intensities. The displaced centroids of the bunches on the spectrometer monitor allowed the relative energies of the bunches to be determined. With about 2 x 10^9 electrons per bunch, adjacent bunches had centroid displacements of about 12 MeV. This is in agreement with expectations.

Fluctuation Spectra

The stability of beam energies and trajectories is very important for the SLC. Much work has been devoted to the minimization of possible sources of fluctuations: RF phase and amplitude, mechanical vibration, power supply regulation, extraction kicker timing and amplitude, etc. A first look at the stability of the energy of a reinjected damped beam was taken using a specially constructed beam position monitor located in the spectrometer where the dispersion dominates the horizontal beta function. The resulting spectrum is shown in Fig. 8. Due to the 10 hertz damping ring repetition rate for these tests, only a limited spectrum was obtained. The structure at low frequencies has been identified with unstable water temperature regulation of the Linac accelerator. The temperature regulation system will be upgraded in the next year. The transverse position fluctuations of the reinjected beam were measured using a beam position monitor in the Linac just upstream of the spectrometer. A plot of the spectrum is included in Fig. 8. In addition to the low frequency structure, there are two resonances at 1.25 and 2.5 Hz. These lines may represent aliasing of higher frequencies. It is likely that these lines correspond with observed fluctuations in the extraction kicker amplitude in addition to equilibrium orbit fluctuations in the damping ring. Plans are being made to extend the frequency range of observations and to build monitors with enhanced sensitivities. A moderate feedback system can suppress all the observed coherent signals in Fig. 8.

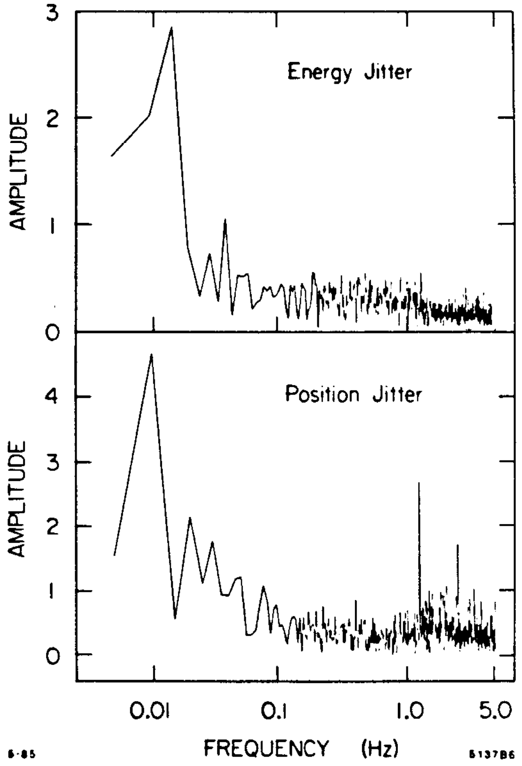

Fig. 8. Spectra of position and energy fluctuations.

Multibunch Operation

Calculations[4] have shown that the long range transverse wakefields from the positron bunch should not affect the following electron bunch. The effects on the second electron bunch can be ignored because its tolerances are more relaxed. Although two bunches have not been reinjected from the damping ring, two intense single bunches with the correct longitudinal spacing have been launched straight down the Linac using the SLC injector. Each bunch contained about 2 x 10^{10} electrons and were easily contained within the Linac over the one kilometer distance of the strong quadrupole lattice. Tests with two reinjected beams will soon commence when the new extraction kicker is installed.

LANDAU DAMPING

Landau damping can be used in linear colliders to reduce the effects of transverse wakefields. It is implemented by introducing an energy spread into the beam in the early part of the Linac by back phasing the klystrons from their nominal values and removing the energy spread at the end of the Linac by forward phasing the downstream klystrons.

Two effects are produced by the beam's energy spread: 1) the tail of the bunch is resonantly detuned from the head, and 2) there is a partial compensation of the wakefields from the head on the tail by the slightly increased oppositely-directed focusing force of the quadrupoles on the tail due to its lower energy. The penalty for Landau damping is a loss of beam energy. However, a sizable reduction in the wakefield effects is expected[12]. Landau damping in the SLC Linac has only been tested with low intensity beams where the expected effects are not large. Nevertheless, a small improvement of the wakefield induced enlargement from trajectory errors was seen, and no ill effects from the induced and removed energy spread were observed. A computer program has been written[13] to allow many variables (here klystron phases) to be controlled with different proportionality constants with a single knob. A test of this program on Landau damping proved successful.

BETA REDUCTION PROGRAM IN THE EARLY LINAC

The effects of transverse wakefields can be reduced by increasing the focusing of the quadrupole lattice in the Linac. The increased focusing reduces the oscillation amplitude of the head of a bunch executing a betatron oscillation and, thus, reduces its generated wakefields. Also, the sensitivity of the tail of the beam to the deflecting fields is reduced. The deflections become a smaller part of the angular divergence of the beam. A program to increase the number of quadrupoles a factor of four in the first 100 meters of the Linac downstream of the Damping Ring and a factor of two in the next 200 meters over that of the old design has been approved, and fabrication of components has started. The space for the new quadrupoles in the Linac will be made by shortening existing 3.05 m long accelerator sections by four cells near the output coupler creating a 17 cm drift length. Each of the 67 new quadrupoles will have a beam position monitor and dipole correction magnets. The calculated vertical beta function for the first 400 meters of Linac is displayed in Fig. 9. The horizontal beta function is very similar except for having the opposite phase. The tolerance for trajectory errors is expected to increase a factor of two because of this program.

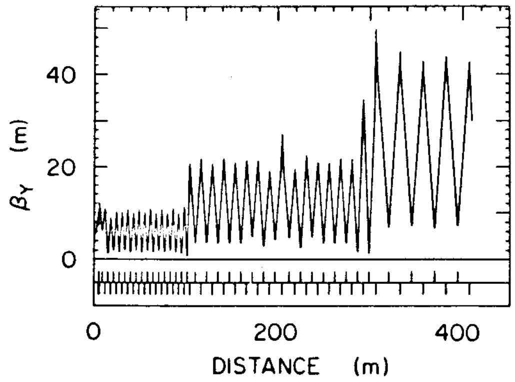

Fig. 9. Reduced beta function in the early Linac.

SLC LINAC STATUS AND FUTURE PLANS

The present schedule for the SLC calls for the completion of installation of all hardware upstream of the arcs by late spring 1986. Thus, commissioning will begin shortly thereafter so that full SLC beams can be delivered to the arcs and final focus in October 1986. A brief history of the Linac improvement program and a list of required installation dates to meet this SLC goal are shown in Table 1.

Table 1: Milestones for the Linac Improvement Program

Magnetic lattice (1 km) installed	Fall 1982
RF monitors (1 km) installed	Fall 1983
Ten Sector Tests	Fall 1983-Feb.1984
Completion of RF monitors and Controls	Fall 1985
Magnetic lattice completed (3 km)	May 1986
Beta reduction program installed	May 1986
Beam diagnostics and feedback systems	Summer 1986

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