# ACCELERATION OF HIGH CHARGE DENSITY ELECTRON BEAMS IN THE SLAC LINAC*

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## Summary

The SLAC Linear Collider (SLC) will require both electron and positron beams of very high charge density and low emittance to be accelerated to about 50 GeV in the SLAC 3-km linac. The linac is in the process of being improved to meet this requirement. The program to accelerate an electron beam of high charge density through the first third of the SLC linac is described and the experimental results are discussed.

## Introduction

The SLAC 3-kilometer linac[1] consists of approximately 960 3.05-meter long, constant-gradient, traveling-wave accelerator sections. Power is delivered to these structures from 240 klystrons operating at a frequency of 2856 MHz. In SLED I[2] mode operation, the no-load energy gain of the linac is about 31 GeV. At present a combination of DC and pulsed quadrupoles allow operation of multiple interlaced beams at energies between 1.5 GeV to 30 GeV. The extant focusing has been designed to control multibunch beam breakup of current pulses up to 80 mA in amplitude and 1.6 $\mu$s in duration.

SLC operation requires that single s-band bunches of electrons and positrons containing $5 \times 10^{10}$ particles/bunch be accelerated to an energy of 50 GeV with a transverse emittance of less than $\gamma\epsilon = 3 \times 10^{-5}$ m-rad. These specifications are to be accomplished through an upgrade of the RF-system and through control of the emittance spoiling wakefields which are a consequence of the high charge density bunches and the linac structure. Changes to the RF-system include the development of higher average power klystrons[3] required for SLED II operation and the development of accurate RF phase and amplitude diagnostic and control apparatus. Wakefield effects will be controlled with a stronger focusing lattice, augmented beam position monitoring and handling system, extensive beam injection diagnostics, emittance monitoring devices, and the development of automated feedback loops to control beam injection. Reliability and ease of operation will be afforded through the development of computer control for the entire SLC.[4] At present, the first third of the SLAC linac has been equipped with the required SLC magnets and diagnostics. A major program was conducted in January 1984 to test the operation of the electron injector, the electron damping ring, and the first 900 meters of linac, albeit without the SLED II klystrons. Those systems pertinent to the linac will be described below along with the performance observed during the tests.

## Linac Lattice

The main consideration that has influenced our choice for the linac lattice has been the need to minimize the beta function in order to reduce beam emittance growth caused by transverse wakefields. A DC FODO array with a quadrupole placed at the end of each 12.3 m linac girder has been adopted. A nominal phase advance of 90 degrees per cell will be maintained through sector 13 to a beam energy of 22.4 GeV by scaling the quadrupole strengths appropriately with beam energy. A power limitation of the magnets requires that the maximum focusing fields are kept below 9.7 Tesla in the remainder of the linac. The phase advance per cell will be reduced between sectors 13 and 30 from 90 degrees down to 43 degrees at a beam energy of 50 GeV.

SLC FODO array DC quadrupoles have been installed in the first 10 sectors (100 meter/sector) of the linac. The magnets in the upstream 4 sectors and injector region are powered from individual, unipolar drivers. Quadrupoles in sectors 5 through 10 are powered in series from one power supply per sector; shunts on each magnet allow the requisite variability in the individual magnet currents. Magnet currents are set and monitored by the SLC control computer. For non-SLC running, the linac lattice is typically set for 76 degree phase shift per cell for the lowest energy beams. Online modeling and configuration management permit a simple and quick change between different magnetic configurations. There have been few surprises associated with commissioning the first third of the SLC quadrupole lattice.

## Linac Beam Position : Monitors and Steering

Because of the severity of the effects of single bunch transverse wakefields on emittance growth, it is necessary to keep beams in the linac to within 100 $\mu$m of the iris center line. To accomplish this feat, a collection of beam position measuring devices and steering magnets have been incorporated into the linac design.

Within each quadrupole of the SLC lattice is a beam position monitor (a set of four striplines)[5] which is electrically gated so that the transverse position of the electron and positron beams can be measured separately with a relative accuracy of 25 $\mu$m. The position monitors are self-jigging to their host quadrupoles to insure proper alignment. Alignment of the centers of the position monitors to the centerline of the quadrupoles should be better than 50 $\mu$m. Quadrupoles are placed on the linac axis with an absolute tolerance of 50 $\mu$m.

Beam position monitors were installed in the first 10 linac sectors during the summer of 1982. Electronics for these monitors were installed in the summer and fall of 1983. A number of tests have been performed to characterize the performance of the position monitoring system. These tests include the response of the BPMs to known beam deflections, the sensitivity of position to beam current, the pulse to pulse jitter in the apparent beam position due to the BPM electronics rather than to actual motion of the beam, and the relative electrical center of the monitors with respect to their encompassing quadrupoles. To lowest order, the installed BPMs are in working condition. Figure 1(a) shows the beam position as read from a monitor as a function of the strength of an upstream dipole magnet. Figure 1(b) indicates the deviation of the data from the expected straight line. This error is due to the granularity of the BPM processing ADC, indicating a differential system performance of better than 10 $\mu$m. Measured beam position is essentially independent of beam current and the pulse to pulse jitter seen

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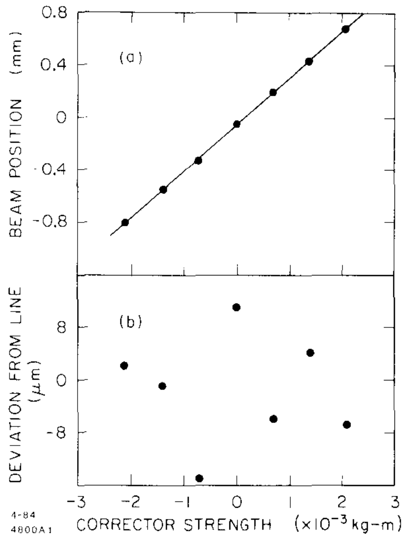


Fig. 1. (a) Beam position monitor readings as a function of the strength of an upstream dipole. (b) Deviation of observed position in (a) from a straight line.

for stable beams is at the level of 1 to 2 counts on the ADC used to process the signals. Beam position monitor centers as observed using quadrupole shunting techniques are at present somewhat larger than the expected 50 $\mu$m rms. This discrepancy may be due in part to the large-sized, multibunch, low current beams used to make the measurements. This work is continuing using a more suitable single bunch beam.

Associated with each quadrupole is a pair of horizontally and vertically bending dipole magnets for use in correcting the beam trajectory. Typically, these dipoles are placed around the RF accelerating sections, less than a meter downstream of each quadrupole. Five types of dipoles are being used, increasing in bending strength down the length of the linac. The dipoles are individually controlled from bipolar current supplies. These corrector magnets are required for compensation of quadrupole alignment errors, misalignment of the BPM with respect to the magnetic center of the quadrupoles, RF steering effects, and for stray fields in the accelerator housing.

Once the beam position monitoring system became functional it was possible to minimize orbit distortions using the corrector magnets. The dominating cause of trajectory errors was discovered to be the misalignment of the quadrupole centers with respect to one another. While initially aligned to better than 50 $\mu$m with respect to the linac irises, it was noted from the array of corrector strengths necessary to center the beam on the BPMs that the quadrupole fields caused a substantial deflection of the beam. Corrector strength data was used to detect quadrupole alignment errors which were subsequently corrected during dedicated linac shutdown periods. At present, the known offsets have been corrected and a beam accelerated to 10 GeV may now be steered to the center of all BPMs in the first 10 sectors of the SLC.

Imperfections in the SLAC 3-m sections cause the RF to deflect the beam transversely. Rf steering is primarily a problem in the early portions of the linac where the beam energy is low. Whereas coupler asymmetries may be responsible for some of the observed deflections, not all of the observations are consistent with coupler problems.[6] The magnitudes and phases of this steering have been recently measured by observing the transverse motion of the beam on downstream position monitors while the phase of the accelerating RF is rotated through 360 degrees. Figure 2 illustrates a typical measurement. The new data agree qualitatively with similar measurements performed when the SLAC linac was first turned on. Several of the klystron kicks are intolerably large. Currently under way is a program to alleviate these problem areas through bends and realignments of the culpable waveguides.

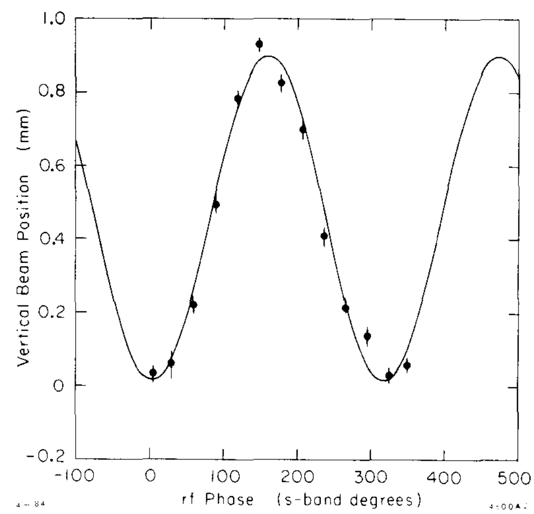


Fig. 2. Beam position on a downstream monitor as a function of the phase of a klystron.

## Linac Emittance

The transverse emittance of the SLC beams which are reinjected into the linac from the damping rings is required to be less than $\gamma\epsilon = 3 \times 10^{-5}$ m-rad. Beam emittances and the corresponding beam phase space orientations are to be measured at several locations within the linac. Such knowledge will permit proper beam injection through optical matching to the linac lattice. Transverse emittance is being measured by observing the beam size on a fluorescent screen while the strength of an upstream quadrupole is varied.[7]

Because of the small emittance of the SLC beam, it has been necessary to develop a high resolution profile monitor. This monitor consists of a fine grained, $Gd_2O_2S$:Tb phosphor screen with an ultracon camera in close proximity. Single line scans across both dimensions of the camera image are digitized and sent to the control computer for processing. An array of fiducial holes, 320 $\mu$m in diameter separated by 1.5 mm, on the screens permit in situ scale calibrations. Resolution of the screen-camera system is found to be better than 50 $\mu$m whereas the system resolution for signals arriving at the computer is about 100 $\mu$m. Improvement of the system resolution and extension to a full 2 dimensional digitization will be completed in the fall of 1984.

Profile monitors for emittance measurements have been installed in the damping ring to linac return transport line, and in the linac 100 m , 300 m, and 920 m downstream of reinjection. In addition, a high resolution profile monitor was installed in the sector 10 beam analyzing station.

A Cerenkov radiation port has been installed 100 m downstream of the reinjection point. This installation consists of a thin quartz radiator, mirrors and imaging optics. Visible radiation is transported from the accelerator housing to the klystron gallery where it can be analyzed with a streak camera. This arrangement permits destructive monitoring of the bunch length of beams in the linac with better than 3 ps of resolution. SLC bunches will have a $\sigma = 3$ ps. The port has been used to look for satellite bunches containing less than $5 \times 10^8$ $e^-$/bunch.

## Sector 10 Diagnostics

A beam analyzing station has been installed at the 1 kilometer point in the linac. This station consists of a 14 degree achromat which bends the beam out of the linac and down a transport line to a beam dump. The achromat consists of two 7 degree bends with four quadrupoles between bends to image the first bend onto the second. Second order corrections are made using a single sextupole. A screen located at the high dispersion point gives an energy resolution of 1% per cm. If the achromat quadrupoles and sextupole are turned off, the energy resolution is enhanced by 20%. Besides spectral measurements, the analyzing station is equipped with two high resolution profile monitors. Remoteness from the linac vacuum makes the beamline an ideal location for installing diagnostic devices for beam tests.

## RF Monitoring

An RF phase and amplitude detector was installed in the summer of 1983 for each of the sub-booster and high power klystrons in the first kilometer of the accelerator. Each of the nearly 100 detectors measure the characteristics of the RF delivered to the linac using the signal on a high quality, temperature stabilized, coaxial line for reference. The detectors can be read remotely with the SLC control system. These phase and amplitude detectors allow long term, accurate monitoring of linac RF. Such monitoring has helped to identify sources of beam jitter and drift.

## Sector 10 Test Results

In January 1984 a series of tests were initiated to measure the performance of the 10 sectors of SLC installation. These tests were sucessfully concluded on February 4, 1984. The plan was to transport a single s-band bunch of electrons from the SLC source through the first 100 meters of linac. At this point the beam was injected into the south damping ring wherein the transverse emittance was reduced. After damping, this beam was longitudinally compressed and reinjected into the linac, again at the 100 m location. Reinjected beam was then accelerated through the linac and its properties analyzed using the sector 10 diagnostics.

The goal of the tests was to extract a single bunch beam of $10^{10}$ electrons from the south damping ring with SLC specified transverse emittance and accelerate it through the first third of the linac. Such a beam demonstrates the feasibility of producing a colliding beam machine with a luminosity of $10^{29}$ $cm^{-2}$-$sec^{-1}$.

A single bunch of about $3 \times 10^{10}$ electrons was delivered from the SLC source to sector 1. Approximately $1.75 \times 10^{10}$ electrons arrived at the beginning of the linac to damping ring transport line with a FWHM energy spread of about 1%. From this beam, $1 \times 10^{10}$ electrons were captured and damped in the ring. Extraction, compression, and linac reinjection efficiencies of 100% could be routinely achieved. The current of $1 \times 10^{10}$ $e^-$ per bunch is just at the threshold where transverse deflecting wakefields are expected to become important. A rms orbit distortion of less than 500 $\mu$m at this current is sufficient to prevent wakefield induced emittance growth. Longitudinal wakefields are not important at these currents. All of the reinjected beam which was observed at the beginning of the linac could be transported through the first kilometer of linac.

In order to transport the beam from the 100 m point to the sector 10 spectrometer, a 90 degree phase shift per cell lattice was set for the operative complement of klystrons. After setting the quadrupoles, an undamped beam of about $3 \times 10^9$ $e^-$/bunch was used to check the lattice and phase the klystrons. Automated and manual steering techniques were used to reduce the low current beam trajectory to less than 200 $\mu$m rms distortion. The steered lattice was then fixed; only beam launching parameters and the phase of the RF in the linac were varied to optimize the reinjected beam at the 1 kilometer analyzing stations. Care was taken to insure that residual dispersion from the ring to linac transport line was minimized. This was accomplished through a combination of empirical and model based iterations on eta measurements taken in the linac. Longitudinal bunch length as well as linac phasing were tuned by observing the beam spectrum in the sector 10 spectrometer. Tuning takes the form of minimizing the energy spread and maximizing the peak energy. For reinjected beams, the nonSLEDded mean energy observed at sector 10 was 6.5 GeV with a half width of about $\pm 0.3\%$. Extensive studies of the spectral shapes were not conducted.

Beam launching into the linac became a two step process. First, the orbit through the linac was minimized by observing the readings of the position monitors. While observing the beam shape on the sector 10 linac screen, dipoles at the point of injection were varied to minimize the wakefield induced tails. Figure 3 illustrates the beam trajectory which reduced the observed transverse tail for a current of $1 \times 10^{10}$ $e^-$/bunch. The betatron oscillations seen in this figure were required for compensation of transverse emittance spoiling effects which had been initiated upstream of linac reinjection. On other occasions, flat linac orbits optimized the beam quality, as viewed on the sector 10 screen. The emittance of the optimized beams was measured at sector 10 for a variety of beam currents. These results are shown in Fig. 4. In Fig. 4, profile monitor resolution of 100 $\mu$m has been removed in quadrature from the beam size data before emittance fitting. Errors on the data are due to scatter in the individual beam size measurements and due to the deviation of the fit to the beam size data. The average

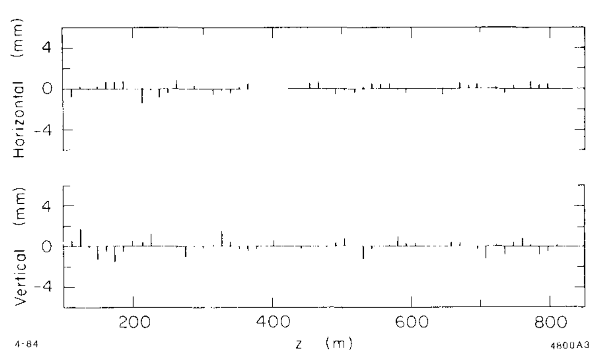


Fig. 3. Beam trajectory which produced the best quality beam spot on the sector 10 screen for a particular measurement.

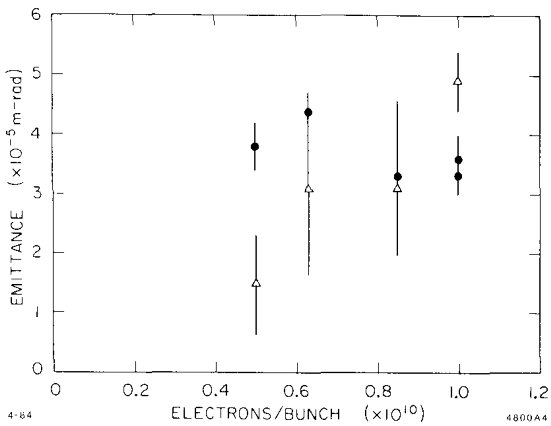


Fig. 4. Emittance of a damped electron beam as measured after 1 kilometer of acceleration. Dots refer to the horizontal plane; triangles indicate vertical plane measurements.

of horizontal and vertical emittances for beam currents in the range of $5 \times 10^9$ to $10^{10}$ $e^-$/bunch is $\gamma(\epsilon_x\epsilon_y)^{1/2} = 3.3 \pm 0.6 \times 10^{-5}$ m-rad. Measurements performed at beam currents of less than $7 \times 10^9$ $e^-$/bunch show that the emittances seen at the end of the linac are identical to those seen 3 meters downstream of the damping ring.

Figure 5 shows the projected luminosity, based on the measured beam emittances and currents and on expected SLC repetition rates and final focus $\beta$'s. A normalization has been made such that the luminosity of $10^{29}$ cm$^{-2}$-sec$^{-1}$ occurs for beam currents of $10^{10}$ particles/bunch at $\gamma\epsilon_x = \gamma\epsilon_y = 3 \times 10^{-5}$ m-rad. The line in the figure illustrates this normalization.

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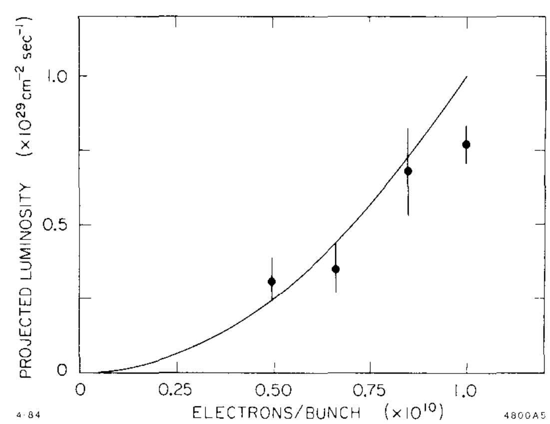


Fig. 5. Projected luminosity based on beam measurements taken during the January 1984 tests.

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