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OBSERVATION AND CONTROL OF EMITTANCE GROWTH IN THE SLC LINAC*

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Abstract To produce high luminosity at a linear collider, the impinging beams must be focused to extremely small spots, thus requiring low beam emittances. At the SLAC Linear Collider (SLC), low emittance beams are provided by the damping rings, then accelerated in the linac. The linac cannot be allowed to cause significant emittance growth. We describe here the observed emittance of the beam at its launch and at various locations along the linac. Emittance growth has been observed, and steps have been taken, to reduce this growth. The growth effects resulting from high beam intensities have been reduced by trajectory correction, quadrupole alignment, and transverse wakefield damping.

EMITTANCE MEASUREMENTS

The horizontal (x) and vertical (y) emittances of the positron and electron beams were measured at the exit of the damping rings, at the entrance to the linac (just after bunch length compression), and at the end of the linac at full energy. The measurements were made using a fixed profile monitor and an adjustable upstream quadrupole[1] at each location. The nominal betatron phase advance between the quadrupole and the profile monitor was about 90 degrees. The region between the quadrupole and profile monitor contained additional quadrupoles and drifts with known properties. The profile monitors consisted of insertable targets coated with Gd_2O_2S:Tb phosphor and were viewed by silicon diode TV cameras with unity optical magnification. The video signals were digitized using triggered frame

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grabbers. The digitized signals after background subtraction were fit to a Gaussian. The widths were recorded as a function of the quadrupole strength and the β, α, and emittance of the beam extracted. The beam sizes ranged from 100 to 300 μm. The measurement resolution was about 60 μm. This resolution was subtracted in quadrature from the width data before further analysis.

RECENT EMITTANCE AND BEAM INTENSITY HISTORY

The measured horizontal and vertical emittances of the SLC electron beam along the linac are plotted versus time (since February 1988), as shown in Fig. 1. The emittance values from the Final Focus were measured using beam–beam deflections.[2] Significant improvement over time of the emittance growth in both planes has been made. Furthermore, the beam intensities have been increased a factor of 3 over that period. The positron emittances are not plotted, but have been equal to or somewhat smaller than the electron emittances at all locations and have been within error bars the same as electrons since September 1988. All emittances are now within 50 percent of the design values.

Over the past year, several beam dynamics issues were resolved in the linac which allowed the emittances to be reduced. These issues include dispersion correction, betatron phase–space matching, horizontal–vertical coupling, and transverse wakefield control.

LAUNCH DISPERSION

The Ring-To-Linac transport line (RTL) between the damping ring and the linac is used to shorten the bunch length of the beam in the damping ring (6 mm) to about the 0.75 mm needed in the linac. This task is accomplished by adding a head–tail energy spectrum in the bunch and passing it through a nonisochronous bend (RTL). The required horizontal dispersion, η, in RTL is about 1.2 m and must be removed at the entrance to the linac to below one percent (less than 1 cm). If the dispersion is above that value, the emittance of the beam will increase as soon as the incoming energy spectrum is made negligible by acceleration. Early attempts at reducing anomalous dispersion were made by changing the beam energy; this was accomplished by changing the compressor RF phase and observing the transverse position shifts in the linac. Then, quadrupoles in the RTL were adjusted to reduce

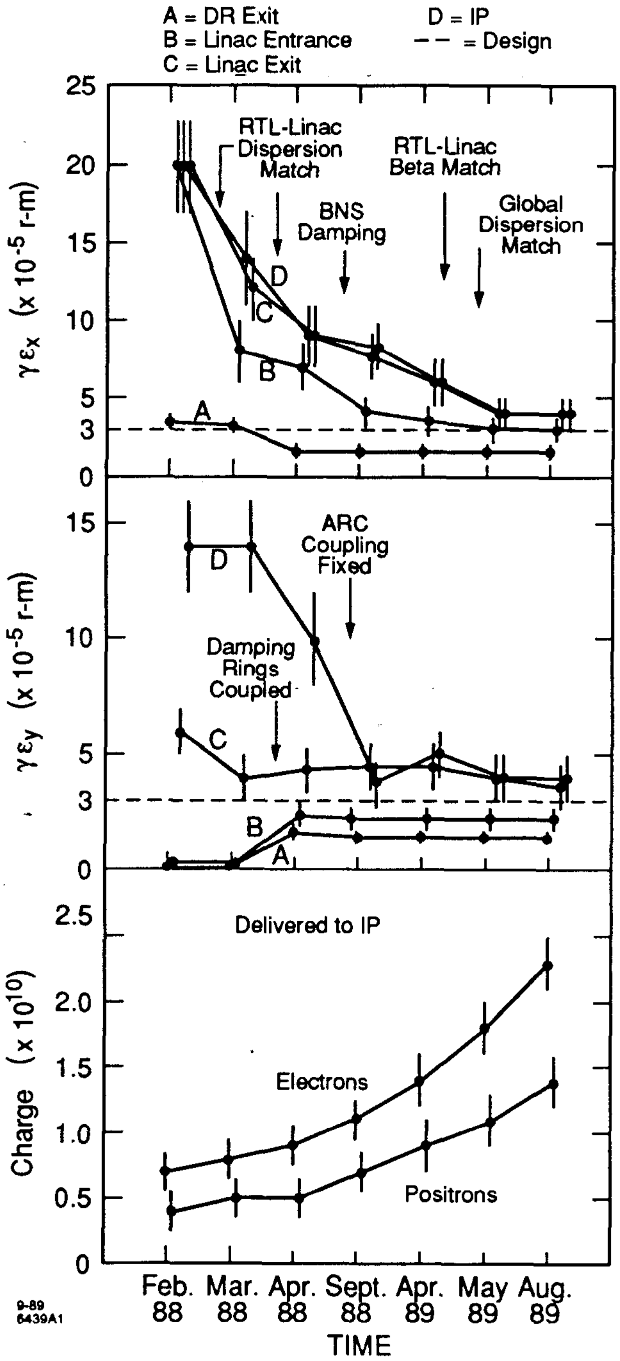

FIGURE 1 Time evolution of the SLC linac beam emittances and intensities.

the apparent η and angular dispersion η'. However, RF deflections in the compressor were found to mimic dispersion through the measurements,[3] and another reduction method had to be found. In the end, the direct method of minimizing the dispersion by measuring the emittance at the entrance to the linac as a function of η and η' controls proved most effective. Examples of this method are shown in Fig. 2. Once fixed, these corrections remain stable for months.

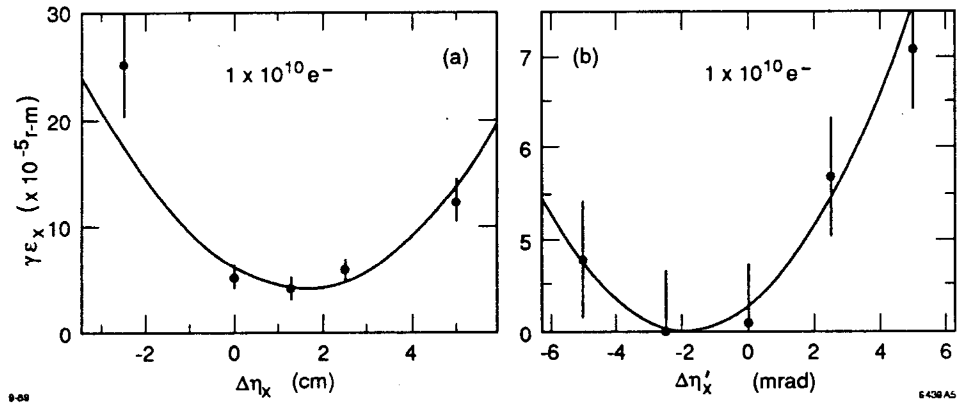

FIGURE 2 Optimization of the electron beam emittance using RTL η controls.

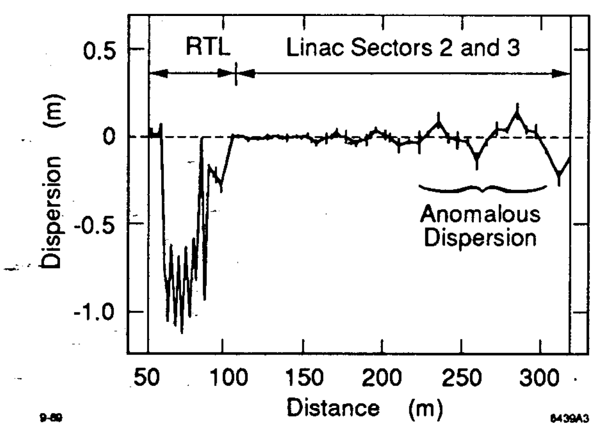

FIGURE 3 Growth of anomalous dispersion in the first 200 m of the linac.

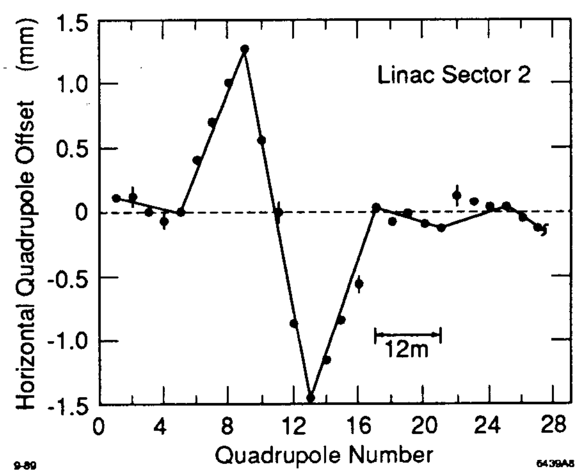

FIGURE 4 Quadrupole-girder misalignments in the early linac.

Finally, the source of an observed anomalous vertical dispersion was traced to coupling from the horizontal in the RTL and was corrected by adjusting a weak skew quadrupole in that region. The remaining anomalous dispersion is now below 5 mm in both planes.

LATTICE DISPERSION

The reduction of the anomalous dispersion exiting the RTL did not eliminate all dispersion effects in the linac. When the RTL compressor RF phase was changed and a difference trajectory recorded, a growing dispersion was observed in the linac (see Fig. 3). This phenomena was traced to two causes.

The first cause was a chromatic mismatch in the linac quadrupole lattice near the 200 m position, where the quadrupole spacing changes from 3 m to 6 m. The dipole corrections here which compensate for off-axis quadrupoles produce energy-dependent trajectories. This effect was fixed by adjusting the quadrupole strengths near the transition to minimize the chromatic mismatch.

The second cause was a systematic quadrupole transverse misalignment which allowed a local dispersion to accumulate. Transverse surveys of the quadruples from the 120 m to the 160 m position in the linac were performed using optical and beam-based techniques. The data are shown in Fig. 4. The quadrupoles in this region are mounted on 12-m-long girders (four quadrupoles on each) and are internally aligned in a straight line. The ends of the girders are tied together but can be moved transversely; they were originally aligned using the linac laser alignment system. The girders are shown as straight lines in Fig. 4. From the data, the quadrupoles on the girders are aligned in a straight line, but the girders themselves are misaligned. These errors are remnants from alignment work done 25 years ago when the tolerances were not as tight as for the SLC. These offsets were quickly fixed. The consequence of these offsets was to produce a systematic increase in the anomalous dispersion since the dipole corrections needed to center the beams in the beam position monitors added in phase in this particular case. The phase advance per cell is 90 degrees. The beam position monitors throughout this exercise indicated no obvious systematic displacement for both beams. Only a study of the magnet strengths and tunnel survey gave the correct picture.

BETATRON MISMATCH

A mismatch of the beam shape to the transport lattice causes filamentation of phase–space because of the finite energy spectrum within the bunch. Two possible sources for betatron mismatches are the linac quadrupole lattice extending over two miles and the entrance match between the RTL and linac. The linac lattice was checked by exciting oscillations in a low intensity beam at the beginning of the linac and comparing the measured and predicted trajectories. Several errors were found resulting from misphased klystrons. These errors have been corrected.

The beam exiting the RTL and entering the linac was found to be quite mismatched in phase–space, producing betatron function beats of a factor of ≈ 4. This magnitude of error doubled the emittance at the end of the linac. This error was traced to a modeling error of quadrupole placements at the entrance to the linac, to lattice errors in the RTL from the η/η' controls discussed previously, to an RTL quadrupole miscalibration, and to a betatron mismatch at the entrance to the RTL. The modeling problem is fixed. The RTL errors have largely been fixed by adjusting several matching quadrupoles to make the phase–space look proper throughout the RTL. The present mismatch is at the 50 percent level leading to an emittance enlargement of about 10 percent.

CHROMATIC ENLARGEMENT

A coherent betatron oscillation of a bunch in the linac causes both chromatic enlargement of phase–space and transverse wakefield blowup. Wakefields are discussed in the next section. The chromatic enlargement occurs because the finite energy spectrum in the beam forces particles of different energies to follow different trajectories after an initial deflection and ensuing oscillation. For a free betatron oscillation, the chromatic effects add coherently and produce larger beam sizes. An example of this effect in the SLC linac is shown in Fig. 5, where an induced oscillation of 2-mm amplitude started at the linac entrance increased the measured vertical emittance of a low intensity beam by up to a factor of 3. Thus a limit on oscillation amplitudes of about 300 μm is established. This is not hard to remove with trajectory correction. A correction is done once or twice each shift.

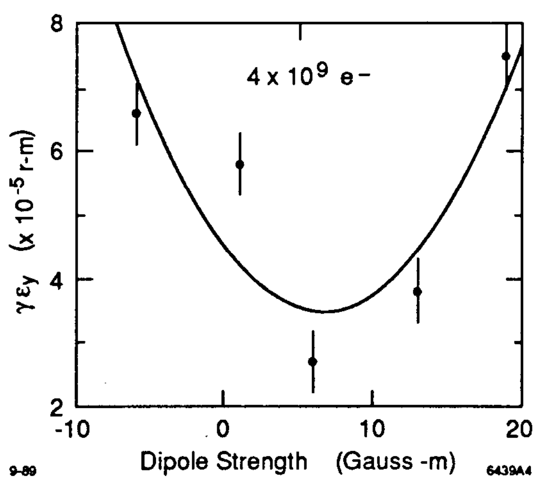

FIGURE 5 Observed chromatic emittance enlargement from induced oscillations.

TRANSVERSE WAKEFIELDS

At high beam intensities more severe limits on trajectory correction are required due to transverse wakefield-induced emittance enlargement. Effects of wakefields are clearly seen, as indicated in Fig. 6 where oscillations of 1 mm cause severe beam blowup at 2×10^{10} electrons per bunch.

FIGURE 6 Images of an e^- beam on a profile monitor showing wakefield growth with increasing oscillation amplitude. The left image is for a well-steered beam and the right one for an oscillation amplitude of 1 mm. The beam intensity is 2×10^{10} electrons. The core sizes σ_x and σ_y are about 120 μm.

Three programs have been adopted to reduce wakefield effects: First, trajectory corrections are made approximately hourly when the beam intensities are above 2×10^{10} per bunch in order to reduce both beam size growth and detector backgrounds. The rms trajectory is reduced to about 200 μm after steering. During the next hour, the rms error grows to about 300 μm. The drift in the trajectory is believed to come from slow magnet changes in the damping ring/RTL/linac complex, RTL–linac feedback drifts, and energy profile changes. Fast position jitter is also observed and has a magnitude of about 25 percent of the beam σ; this jitter level is not harmful at present. Trajectory correction in the downstream half of the linac is especially important, as transverse wakefield damping is ineffective there.

Second, the transverse alignment offsets of the quadrupoles in the linac have been reduced over the past year using beam-based alignment techniques.[4] The alignment of these quadrupoles is important in order to reduce beam enlargement from chromatic orbit errors and wakefields. Initially, the rms offset was about 300 μm with peak quadrupole offsets up to 1.5 mm. After about 150 small quadrupole moves, the rms offset is now less than 200 μm with maximum peak offsets of 400 μm. This alignment process is ongoing.

Finally, transverse wakefields have been ameliorated by using transverse wakefield (BNS) damping.[5,6] An energy spread is introduced into the beam early in the linac (up to two percent) and removed at the linac exit such that the tail of the bunch is low in energy relative to the head. This technique allows the radially outward wakefield force on the tail to be largely cancelled by the increased focusing of the quadrupole lattice, thus reducing the sensitivity of the beam to an incoming position and angle errors by about a factor of 5 at these beam intensities. BNS damping is now used continuously. It, however, reduces the maximum beam energy by 1.5 GeV in the present configuration and makes chromatic growth worse. At higher currents, the klystron phase profile will be changed to optimize the machine performance.

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