Flat Beam Studies in the SLC Linac

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Abstract

The Stanford Linear Collider (SLC) was recently converted to flat beam operation ($\gamma \varepsilon_x = 10 \, \gamma \varepsilon_y$), producing a factor of two increase in luminosity[1]. In this paper we review the results of flat beam studies in the SLC Linac. In summary, the injected beams from the damping rings had invariant horizontal emittances as low as 30 mm-mrad and invariant vertical emittances as low as 2 mm-mrad. The emittances measured at the end of the linac after tuning for 3×10^{10} particles are about 5 to 8 mm-mrad vertically and 40 to 50 mm-mrad horizontally. Flat beam operation began 3/17/93.

Introduction

Two bunches (e^- and e^+) are accelerated in the linac from 1.19 to 47 GeV in 3 km of S-band RF structure. Special measurements, component tolerances, and controls are needed to maintain the initial 10 to 1 emittance ratios. Transverse wakefield damping (BNS) is used in the first two-thirds of the linac to control wakefield growth from beam injection jitter[2]. A small energy spread (0.26 %) at 47 GeV is made by careful overall klystron phasing (+/- 0.5 degrees). Along the linac, eight feedback loops (x,x',y,y' for two beams) updating at 30 Hz maintain the trajectory to about 25 μm. Emittance measurements are made at three locations along the linac (at 1.2, 15, and 47 GeV) using three sets of four wires scanners, each with an emittance resolution of 0.5-0.75 mm-mrad. Typical vertical beam sizes (σ_y) at 47 GeV are 35 to 60 μm. The emittance and TWISS parameters are measured automatically by the control computer in all parts of the SLC about every 30 minutes and recorded in long term history buffers for analysis. The linac emittance histories showing the start of flat beam running on 3/17/93 can be seen in Figure 1.

Emittance Optimization

The study of flat and round beam cases allows the comparison of various types of linac emittance enlargements. Betatron mismatches with filamentation cause multiplicative enlargements: $B_{mag} = \varepsilon/\varepsilon_0$. Dispersion, wakefields, and coupling, followed by filamentation, generates additive growth: $\varepsilon = \varepsilon_0 + f/2$. Sqrt(f) is the normalized 'kick' amplitude.

Prior to the conversion to flat beams, the emittance enlargement effects along the linac were feared to be mostly additive. Thus, changing to flat emittances would lead to minimal overall luminosity gain. However, as it turned out, the multiplicative effects dominated the residual emittance increases with round beams and significant emittance reductions were made with the new smaller initial emittances.

The dispersion and beta-functions are carefully tuned in the ring-to-linac transport line to provide the best injected beam emittances[3]. The linac klystron phases and accelerating gradient must be accurately maintained (a few degrees and 5%, respectively) in the first few hundred meters to avoid chromatic emittance enlargement. Furthermore, the strengths of three quadrupoles in the early linac were empirically adjusted by up to 10% to minimize the emittances at the 15 GeV location. The linac support girders were mechanically clamped to reduce component vibration[4] below 100 nm. These clamps were set at full tunnel temperature to avoid systematic transverse component offsets leading to dispersion and wakefield errors.

The emittance growth from residual dispersion and wakefield effects is reduced by cancellation using "trajectory bumps" located along the linac[5]. In the tuning process, the SLC operators try to minimize the beam emittance at two downstream wire scanner locations (15 GeV and 47 GeV). The setpoints of the linac feedback loops are adjusted for this purpose. For each loop, there is a position and angle setpoint, which when varied, generates a betatron oscillation that extends downstream until the next feedback loop removes it. First, the setpoints of the loop at 8 GeV are tuned looking at emittance and beam tail changes at the 15 GeV point. Second, the setpoints at 16 GeV are used to reduce the emittance at 47 GeV. Occasionally, other loops are tried. Typically, 8 to 12 distinct "trajectory bumps" are in use at any given time with amplitudes of order 100-200 μm with lengths of 200 to 800 m. Most of these bumps are stable to 90% in amplitude over several weeks; however, fine tuning (10%) is often done to track hour-by-hour and diurnal changes. For vertical emittances of order 6 mm-mrad, bump control at the 25 μm level is needed. The tuning procedure typically requires 15-30 minutes per beam. Measured data from tuning two representative feedback setpoints at the 16 GeV location to reduce $\gamma \varepsilon$ at 47 GeV are shown in Figure 2. Note that the increase in the vertical emittance with bump amplitude is about the same as that of the horizontal because the wakefield and dispersion induced growth is nearly additive for small induced errors.

Emittance versus Beam Charge

In the fall of 1992 the SLC was operated at 10 Hz to study the emittance increase along the linac versus beam charge. At 10 Hz a ring store time longer than the nominal (1/120 sec) is possible, decoupling the exit emittances from the entrance emittances, so smaller values are achieved. The electron results with a mixture of short and long store data are shown in Figure 3. (Positron data is similar.) The increase in the emittances at the entrance to the linac with current is due to bunch lengthening in the damping ring (which doubles σ_z and makes σ_E/E 50% higher) and chromatic effects in the bunch compressors. An increase in emittance along the linac was observed, although there was not sufficient beam time to perform all the tuning techniques described above. Thus, these curves may over estimate the possible emittances. One example is from Figure 1 where an incoming vertical invariant emittance of order 3.5 mm-mrad can be maintained over long
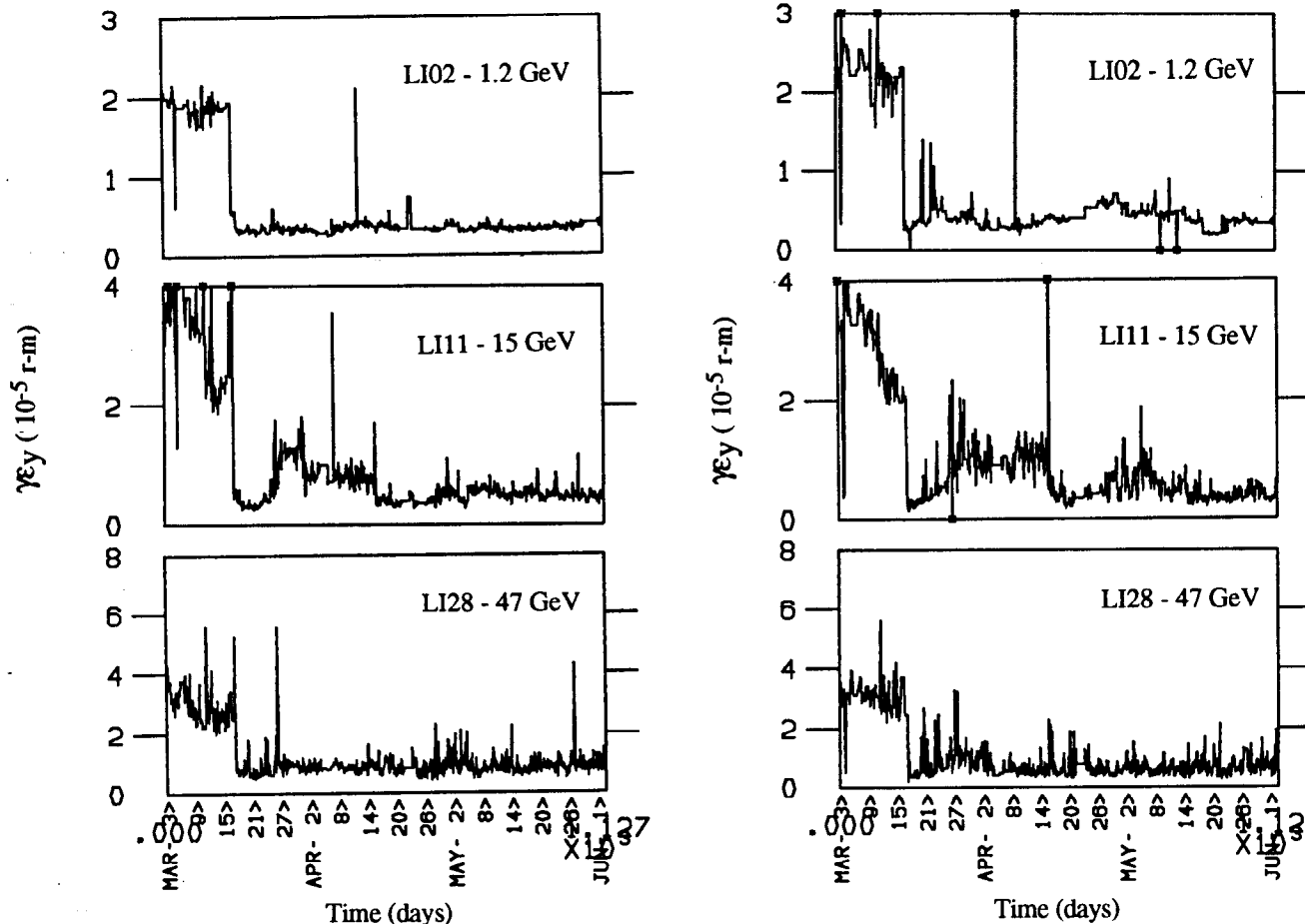
Figure 1   Histories of SLC invariant vertical emittances for e⁻ (left) and e⁺ (right) at 3 x 10^10 at linac locations: entrance (1.2 GeV, top), 1 km (15 GeV, center), and exit at 3 km (47 GeV, bottom). The period is March 3 - June 2, 1993.
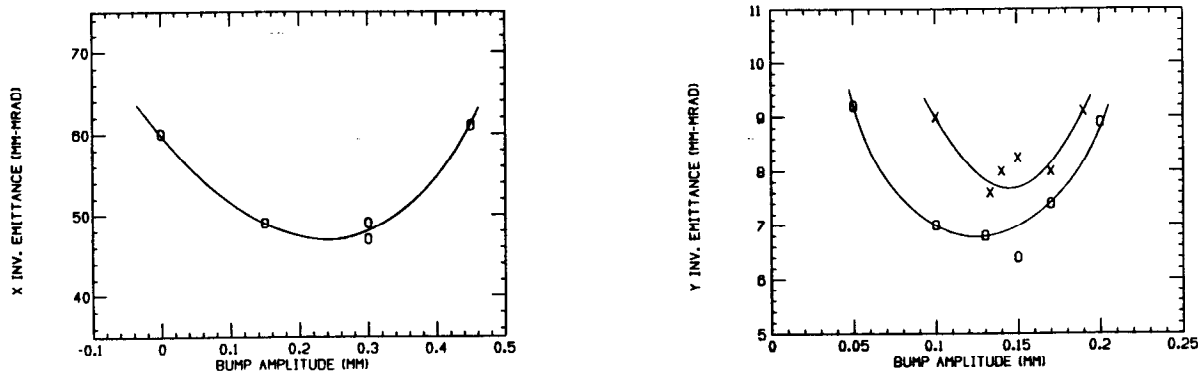

Figure 2   Measured horizontal and vertical emittances for electrons at 47 GeV as a function of amplitude of respective oscillations induced from 1000 m to 1800 m. Two independent vertical data sets are shown.

times during collisions at 3 x 10^10 particles per bunch with only 50 to 100% enlargement along the linac. The incoming horizontal emittance can be maintained at about 35. mm-mrad with just 5-15 mm-mrad increase along the linac. Finally it should be noted that vertical emittances of about 2.0 mm-mrad have been produced at 47 GeV at 1 x 10^10 / bunch.

Simulations

From previous measurements and simulations, we believe that the wakefields generated from misaligned accelerator structures to be the dominate growth mechanism at high currents. In the simulation model, we assume that the accelerator sections are misaligned independently at each end with 300 μm rms offsets. The position monitors and quadrupoles are assumed to have 100 μm rms errors.

With these misalignments, simulations of the beam transport were done to compute their effect on the beam emittance[6]. In addition, beam steering and tuning effects were included. As in the SLC, a one-to-one steering procedure was used, where a dipole near each focusing quadrupole is adjusted to zero the BPM reading at the next focusing quadrupole.
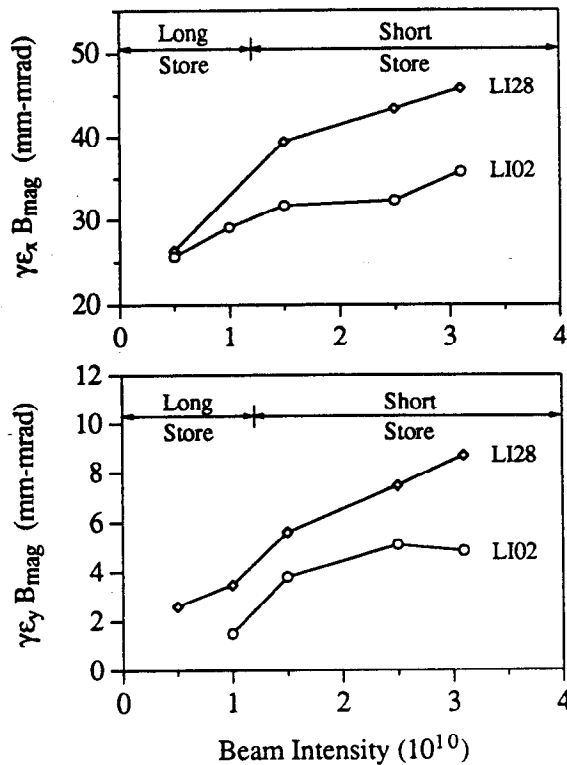
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Figure 3 Measured horizontal (upper) and vertical (lower) emittances as a function of beam charge at 47 GeV.

Trajectory bump tuning, as described above, was also done first at 15 GeV and then at 47 GeV, but a least-squares procedure is used to fit for the effective feedback setpoint changes corresponding to the minimum emittances. A beam with a vertical invariant emittance of 3.5 mm-mrad and an intensity of 3.0×10^{10} was assumed to be injected on-axis into the linac.

The simulation program was used to compute the fractional vertical emittance enlargements at 47 GeV for many misalignment configurations. Figure 4 shows the resulting distributions for three linac conditions: 1) no BNS damping and no bumps, 2) BNS damping with no bumps, and 3) BNS with bumps. Thus, BNS damping helps emittance enlargement by a factor of about two and the further addition of trajectory bumps helps by an additional factor of six, a large gain! The mean of the final distribution corresponds to a 52% growth, comparable to the vertical results of the SLC as in Figure 1. [There is slightly poorer agreement when comparing the horizontal data and simulation where a measured growth of 20% or more at 15 GeV was measured when less than 10% was expected. The source of this growth is under investigation but may simply be insufficient tuning.] A final note: if the linac were operated without the large energy spread from the BNS phase configuration, the tuning would further reduce the emittance growth (on average, about 25% at 15 GeV and 60% at 47 GeV). This is the opposite to what happens with one-to-one steering only, where zeroing the BNS phases leads to a 30% (200%) larger growth at 15 GeV (47 GeV). This difference may be related to the nearly 'auto-phased' beam in the upstream end of the linac where the tail growth generated from betatron oscillations is nearly suppressed, making the tuning less efficient.
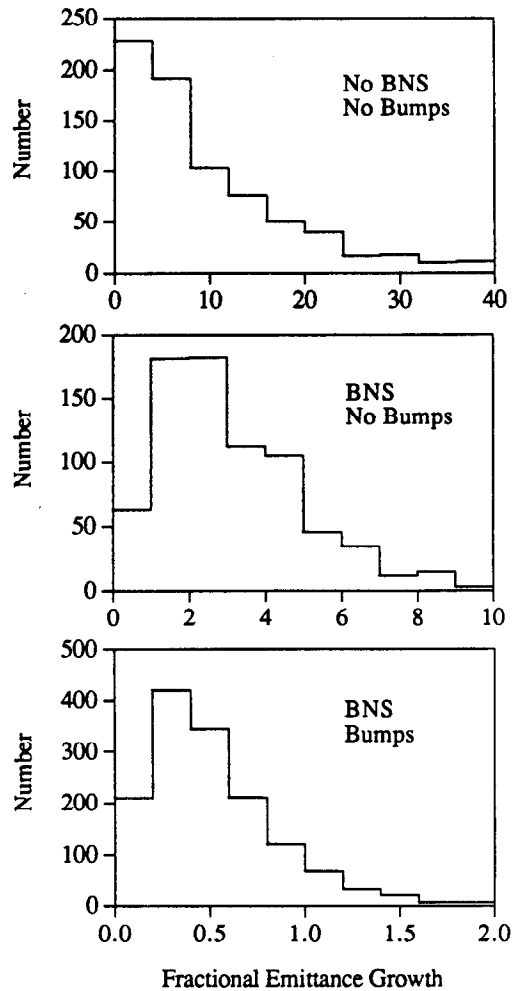

Figure 4 Distributions of final enlargement factors for vertical emittance for simulated linacs with errors without BNS damping (top), with BNS damping (center), and with BNS damping and linac bumps at two locations (bottom).

References

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