SLAC-PUB-5705
August 1992
(A)

# THE INTRODUCTION OF TRAJECTORY OSCILLATIONS TO REDUCE EMITTANCE GROWTH IN THE SLC LINAC*


J. T. Seeman, F.-J. Decker
Stanford Linear Accelerator Center, Stanford, California 94309 USA

and

I. Hsu
Institute of Nuclear Science, National Tsing Hua University, Hsinchu, 30043, Taiwan



## ABSTRACT

Emittance growth of accelerated beams in the 50 GeV linear accelerator of the Stanford Linear Collider (SLC) arises from the effects of transverse wakefields and momentum dispersion. These effects are caused by small misalignments of the beam position monitors, lattice quadrupoles, and accelerating structure and by the energy spectrum of the beam which changes along the accelerator. The introduction of strategically placed trajectory oscillations over finite lengths of the linac has been used to generate beam errors which cancel the emittance accumulation from these small unknown, random alignment errors. Induced oscillations early in the linac cancel effects which filament along the accelerator affecting mostly the beam core. Induced oscillations located at the center of the accelerator or beyond cancel wakefield and dispersion errors which do not completely filament but cause the beams to have, in addition, an apparent betatron mismatch and transverse tails. The required induced oscillations of a few hundred microns are reasonably stable over a period of several weeks. Of course, the optimum induced oscillations depend upon the beam charge. Emittance reductions of 30 to 50% have been obtained.


## 1 EMITTANCE CHANGES WITH OSCILLATIONS

The emittance parameters of the beams at injection into the linac are optimized using upstream controls. Then, the trajectories are nominally corrected along the linac to about 100 μm rms. However, after these corrections the beam experiences emittance growth during acceleration because of alignment errors of the accelerator components. This results from the trajectory being steered through misaligned quadrupoles and accelerator structures onto beam position monitors with finite residual offset errors. Consequently, transverse wakefields and dispersive effects enlarge the emittances. Methods to reduce these effects have been theoretically studied [1,2]. It has been shown that the addition of appropriate injection launch errors (Δx, Δx', Δy, and Δy') can cancel most of the emittance enlargement. Since the advent of BNS damping [3], a more global scheme of distributing short range oscillations along the accelerator has been shown to be satisfactory [4]. These oscillations are routinely optimized in the SLC linac to control emittances. Examples of these oscillations are shown in Figure 1.

The emittance at full energy was measured as a function of the amplitude of these oscillations. The results are shown in Figures 2 and 3. The consequence of these observations is that the proper choice of the amplitude of short range oscillations at the appropriate linac locations can significantly reduce the observed emittance enlargement. Furthermore, the betatron match of the beam can be properly maintained or corrected. Betatron mismatches [6] occur when the beam has a phase-space orientation (β,α) that does not match the linac lattice. Given beam Twiss parameters $\beta_b$ and $\alpha_b$ that are mismatched from the lattice design values $\beta_l$ and $\alpha_l$, the emittance enlargement after filamentation is given by a parameter Bmag.

$$(\gamma\varepsilon)_{final} = \text{Bmag} \cdot (\gamma\varepsilon)_{initial} \qquad (1)$$

with

$$\text{Bmag} = \frac{1}{2}\left[\frac{\beta_l}{\beta_b} + \frac{\beta_b}{\beta_l} + \beta_b\,\beta_l\left(\frac{\alpha_b}{\beta_b} - \frac{\alpha_l}{\beta_l}\right)^2\right] \qquad (2)$$

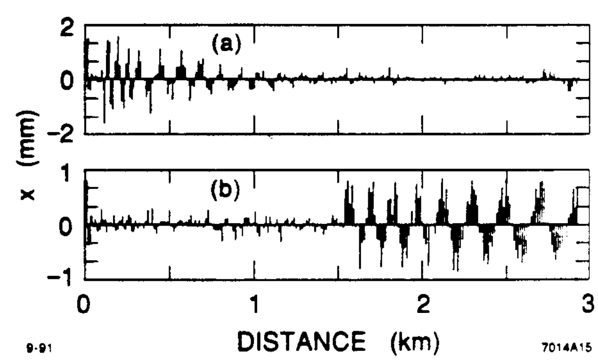


Figure 1 Two induced oscillations in the SLC accelerator used to test potential cancellation of accumulated wakefields and dispersion errors in the linac, see Figures 2 and 3.


* Work supported by US Department of Energy contract DE-AC03-76SF00515.



*Presented at the XV International Conference on High Energy Accelerators, Hamburg, Germany, July 20-24, 1992.*

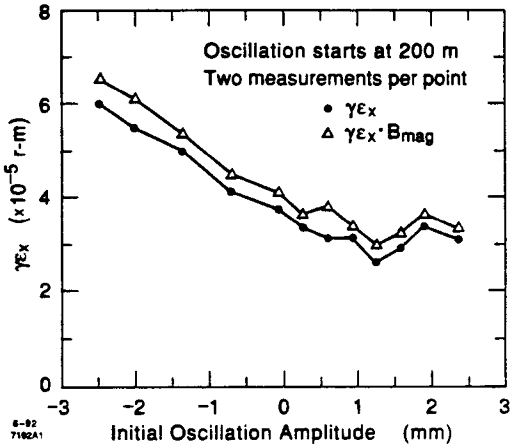


Figure 2 Invariant emittance changes at the end of the linac (47 GeV) as a function of the amplitude of an oscillation starting early in the linac (upper plot in Figure 1). The emittance measurements and the emittance times Bmag measurements track each other very well. Since Bmag is a measure of the expected filamentation from betatron mismatches, the beam at the end of the linac has nearly filamented. A decrease in the transverse emittance (25%) is observed with a finite oscillation added to the beam. The error which caused the original emittance enlargement is thus near the beginning of the linac.

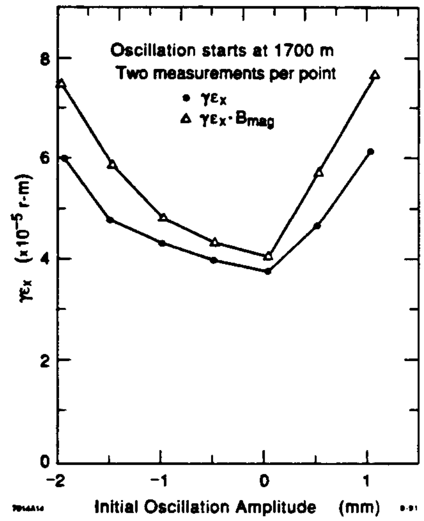


Figure 3 Invariant emittance changes at the end of the linac (47 GeV) as a function of the amplitude of an oscillation starting in the center of the linac (lower plot in Figure 1). There is no reduction of the emittance from this oscillation and, furthermore, a large betatron mismatch (tails) has developed signaled by the separation of the curves for $\gamma\varepsilon$ and $\gamma\varepsilon \cdot$ Bmag.

## 2 COLLIDING BEAM OPERATION

During colliding beam operation, combinations of short range (200 - 800 m) oscillations in the SLC are applied to the two beams to reduce the emittances. The position and angle fast feedback systems [5] (eight parameters each) placed along the linac (100, 300, 400, 600, 1100, 1800, 2300, and 2700 m) are used to generate the oscillations. A set point of one feedback loop is changed to a finite value. The resulting oscillation is then removed naturally in the next feedback system downstream. Many oscillations are tried; the best are kept. The resulting $e^-$ and $e^+$ trajectories for reducing the emittances to near the design values during the August 1991 physics run are shown in Figure 4. Note that significant trajectory offsets were needed. In practice, the set points of the feedback systems at the 600 and 1100 m locations are used most often. At any given time for two beam operation, 1 to 10 set points have non-zero values, with a mean of 7.

## 3 PRACTICAL OPERATION AND STABILITY

The oscillations in Figure 4 used to reduce the emittances are not the same for the two beams. The dispersion and wakefield errors accumulate differently because of the differences in the betatron functions. The random offset errors for the linac components have been determined from other measurements to be about 70 μm for the position monitors, 100 μm for the quadrupoles, and 200 to 300 μm for the accelerating structure. Furthermore, the two beams often have different bunch lengths in the range 0.9 to 1.2 mm which produce energy and energy spread profile differences along the linac.

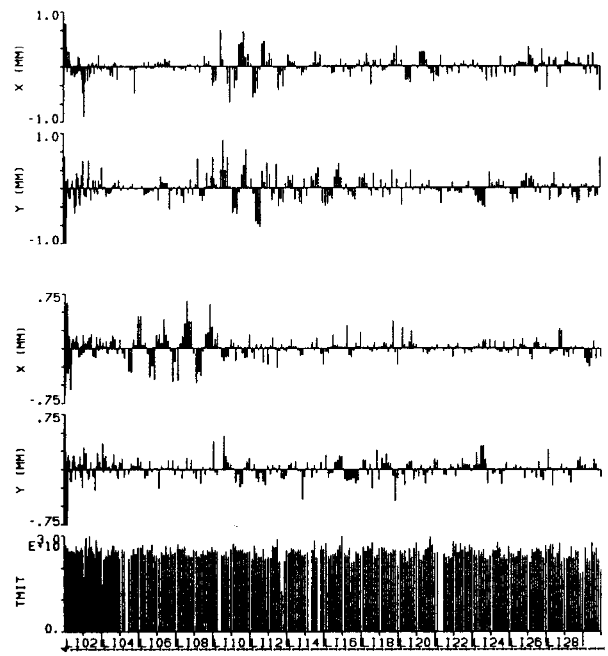


Figure 4 Empirically determined linac trajectories ($e^+$ upper, $e^-$ lower) which cancels the errors from the accumulation of dispersion and transverse wakefields errors at $3 \times 10^{10}$ particles per bunch. All invariant emittances are below $3.5 \times 10^{-5}$ r-m at 47 GeV.

The optimized trajectories are not unique as other similar oscillations can produce comparable reductions. This effect can be seen in Figure 5 where multiple trajectories produce similar results. The short range oscillations used to cancel accumulated errors in these examples are obviously not all near the actual positions of the errors. If emittance measurements could be made at more places along the linac, then better local corrections could be made. For example, the trajectory in Figure 5c has emittances optimized not only at the end of the linac but also at the 1100 m (Sector 11) location. Bunch intensities in Figure 5 are about 2.8 x $10^{10}$ $e^-$.

The minimization procedure is to reduce the transverse tails first and then reduce the core size using induced oscillations for both. The addition of oscillations to eliminate wakefield tails is a very rapid process with satisfactory solutions often found in 15 minutes or so. These oscillations are generally located in the last two thirds of the linac where the energy spread from BNS damping is small. After the tails are removed, a more subtle set of oscillations are added upstream to reduce the size of the beam core which has been enlarged by both wakefield and dispersive effects. During this tuning phase the bunch profile always remains Gaussian. This adjustment period is much larger (on the order of several hours) requiring many small oscillations to be added, often in combinations at different locations. Transverse beam jitter and slow drifts (for example with temperature) have strong effects at this stage. An average solution must be found. During collisions over a period of months, the required trajectories change slowly. Histories of the set point changes of the feedback system at the 600-m location (Sector 6) are shown in Figure 6. As seen in these histories, non-zero trajectories remain optimized for days to weeks at a time. In other observations, the induced oscillation with the largest amplitude changes most rapidly. The likely reason is that the local energy profile along the linac changes with time leading to betatron phase changes between the location of the unknown errors and the location of the oscillation, altering the carefully arranged cancellation. In addition, the larger the required oscillation is, the larger is the emittance change with a betatron phase change. Thus, minimum emittance solutions having smaller oscillation amplitudes are preferentially selected.

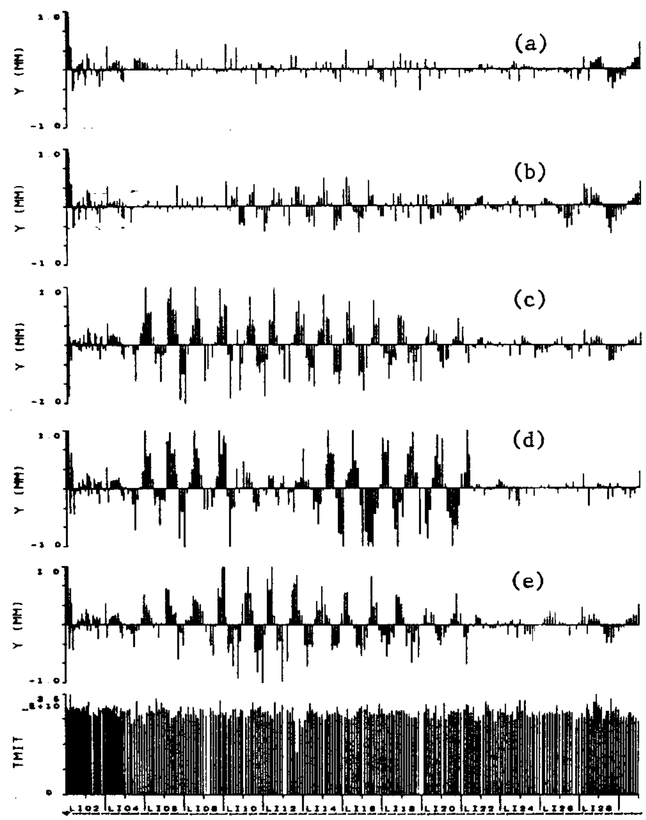


Figure 5 Several vertical trajectories for the electron beam with approximately equal emittances at the end of the linac. Trajectory (a) is for the beam steered to the position monitor centers, producing about a 25% enlarged emittance. Trajectories (b) through (e) produce essentially the same small vertical emittance at the end of the linac. Different feedback set points were used in each example to provide the desired trajectory. Trajectory (c) also has the emittance small at the 1100 m position along the linac (Sector 11).

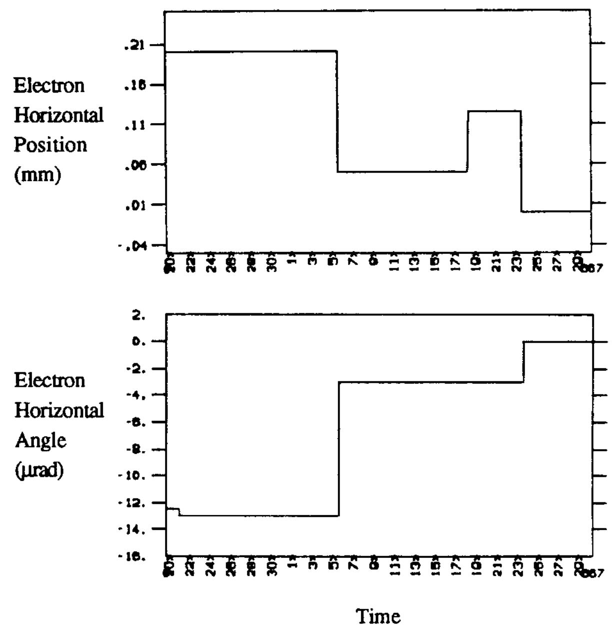


Figure 6 Examples of the stability of the feedback set points used to generate the required beam oscillations over 43 days of colliding beam operation. The changes represent emittance tuning episodes. Tuning is not done often.

## 4 REFERENCES


[1] A. Chao, B. Richter, and C. Yao, *Nucl. Inst. Meth.* 178, p. 1(1980).

[2] K. Bane, *IEEE Trans. Nucl. Sci.* NS-32, No. 5, p. 2389 (1985).

[3] J. Seeman, Advanced Beam Dynamics Workshop, Corpus Christi, *AIP Conf. Proceedings* No. 255, p. 339 (1991).

[4] J. Seeman, Advanced Beam Dynamics Workshop, Corpus Christi, *AIP Conf. Proceedings* No. 255, p. 19 (1991).

[5] T. Himel, et al, SLAC-PUB-5470, Stanford (1991).

[6] C. Adolphsen, et al, *IEEE USPAC*, 91CH3038-7, p. 503 (1991).