Measured Optimum BNS Damping Configuration of the SLC Linac*

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Abstract

Transverse wakefield (or BNS[1]) damping has been successfully used in the linac of the Stanford Linear Collider (SLC) to reduce emittance enlargement from beam trajectory jitter coupled with transverse wakefields[2]. We are presently in the process of raising the bunch intensities from 3×10^{10} particles per bunch to over 4×10^{10}. With these higher currents the RF phasing configuration which produces BNS damping must be improved. Too little "damping" allows excessive emittance growth from jitter but too much damping increases emittance growth from chromatic effects and produces an unacceptable loss of overall energy. Several experiments were performed to find the optimum settings for the present situation. An empirical optimum was found with a combination of 1) somewhat stronger BNS RF phase settings in the upstream section of the linac and 2) a stronger quadrupole lattice in the downstream section.

Transverse (BNS) Wakefield Damping

In the SLC linac high intensity bunches must be accelerated in the 3 km S-Band structure without significant emittance enlargement. Position and angle jitter of the injected beam or beam deflections along the linac can cause significant emittance growth from transverse wakefields. The equation of motion of the particles within a bunch indicates that the head of the bunch will resonantly excite the longitudinal tail of the bunch to ever increasing amplitudes as the bunch makes a betatron oscillation along the linac. A technique to reduce the resonant blowup of the tail by the head is called BNS damping[1] where the energy of the longitudinal tail of the bunch is reduced from that of the head by offsetting the initial RF phases. With this technique, the net "defocusing" transverse wakefield forces on the tail are to a large extent canceled by the increased focusing of the quadrupole lattice for the tail. An analytical model[3] gives the condition for "BNS" damping in the discrete focusing case.

$$[\langle\beta\rangle_{\text{lattice}}\, e^2 N \langle W\rangle_{\text{beam}}] < [2\langle d^2\psi/d\delta\, ds\rangle E \langle\delta^2\rangle^{1/2}{}_{\text{beam}}]$$

where β is the lattice betatron function and e is the electron charge. N is the number of particles, W is the transverse wakefield, ψ is the betatron phase advance per cell, δ is the fractional energy offset, s is the distance along the accelerator, and E is the beam energy,

This condition can be expressed for a multi-particle bunch but cannot be easily produced over the bunch length, so that compromises must be made. Furthermore, several SLC conditions make the matching conditions difficult: the distances between quadrupoles change along the linac, the phase advance per cell changes along the linac, and the energy correlation (spread) is difficult to change rapidly with distance[4].

To show the trajectory enlargement effect from transverse wakefields without BNS damping, a horizontal oscillation in the beam was made at about the 1.8 km location along the linac and the ensuing beam oscillation was recorded. The oscillation is shown in Figure 1. A rapid growth without BNS damping is very evident.

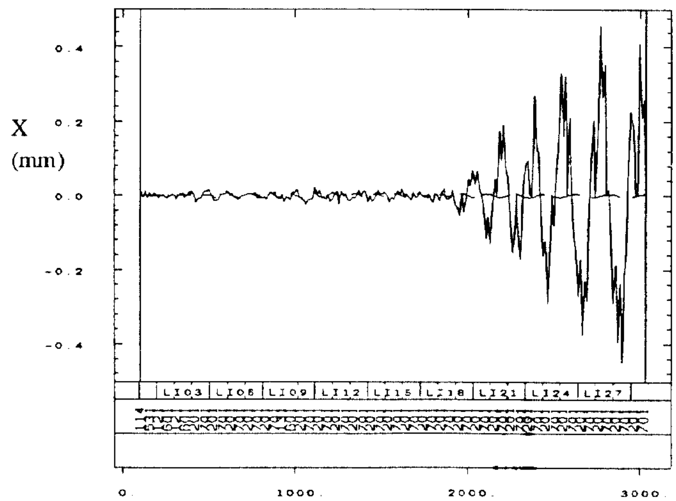

Figure 1 Growth of beam tails and centroid position without BNS damping from a dipole kick starting at about 1800 m.

The present BNS conditions for the SLC linac are listed in Table 1 and are made by (back) phasing the first 56 klystrons at -20 degrees and (forward) phasing the remaining 176 klystrons at +15 degrees. In this way the desired correlated energy spread is produced along the linac as can be seen in Figure 2. One constraint is that the total energy spread be small (0.26% rms or so) at the end of the linac as needed by the final focus system downstream. Horizontal oscillations for a bunch with 3×10^{10} e^- generated at three locations along the linac using this nominal BNS configuration are shown in Figure 3. Note the significantly reduced growth effects as compared to Figure 1.

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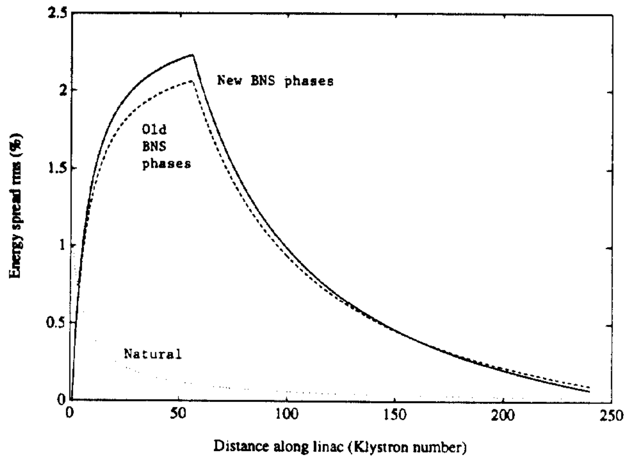

Figure 2 Correlated and uncorrelated energy spreads along the linac for the natural case and for the old and new BNS cases.

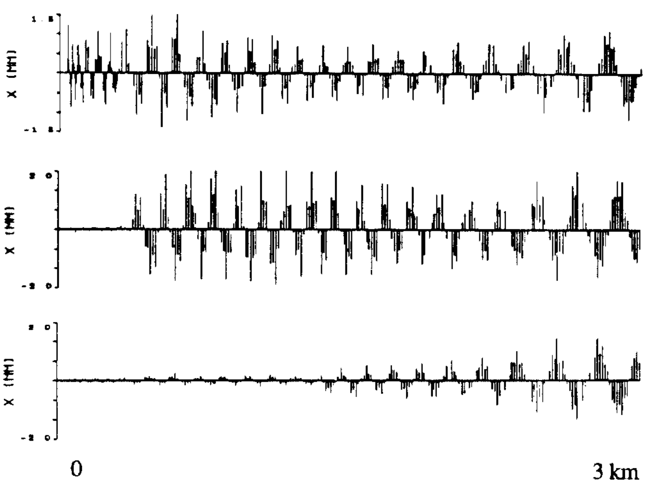

Figure 3 Induced horizontal oscillations at three locations in the linac with the nominal BNS phases: 56 klystrons at -20 degrees and 176 klystrons at +15 degrees.

Optimum BNS Tests

The question we addressed in these tests was: When the beam charge is raised from 3 x 10^{10} to over 4 x 10^{10} will a new RF phase configuration be needed? Simulations[5] indicate that increased energy spreads might help but that issues of energy overhead, stability, and chromatic emittance growth will make the exact optimum choice difficult to predict. Because of these complications, an experimental determination of the best configuration was used.

Several predetermined configurations were studied using the limited accelerator physics time available on the SLC. The measure of comparison was the ratio of the final oscillation amplitude at 47 GeV to the initial amplitude at the source of the dipole change, made at three locations. The studies included four cases: 1) weaker BNS than the present case, 2) the nominal case, 3) a slightly stronger case, and 4) a moderately stronger case. The results of these studies are listed in Table 1. The results indicate that the weaker case is worse than the nominal for jitter enhanced enlargement. The slightly-stronger case is better than the nominal. The moderately-stronger case appears slightly better than the slightly-stronger case but has too large a chromatic emittance enlargement. Thus, the empirically determined best case is the slightly stronger case. The resulting oscillations are shown in Figure 4, allowing a comparison with the nominal case in Figure 3.

For an exercise, a much stronger BNS condition was tried in the early linac, as is shown in Figure 5. Here, chromatic effects are quite strong and the two nodes in the downstream oscillations show complicated head-tail offset changes.

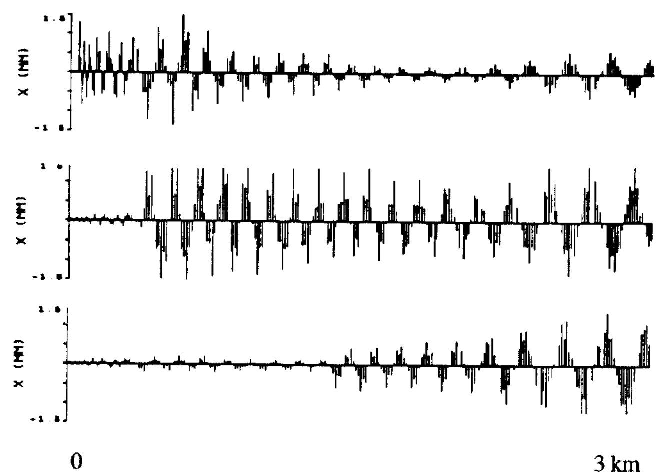

Figure 4 Induced horizontal oscillations at three locations in the linac with the new stronger BNS phases: 56 klystrons at -22 degrees and 176 klystrons at +16 degrees.

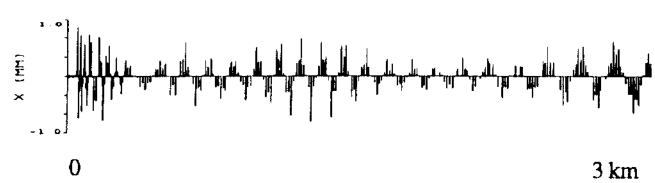

Figure 5 Induced oscillation with a much stronger BNS.

Stronger Quadrupole Lattice

In the downstream half of the linac, BNS damping is no longer very effective against jitter starting midway along the linac. This is because the BNS optimized head-tail energy correlation can no longer be maintained, as can be seen in Table 1 and Fig. 2. Thus, a study of potential improvements suggested stronger quadrupole strengths in that region. By increasing the quadrupole lattice strengths from the present 45 to 60 degrees per cell, the betatron function could be reduced and the phase advance per cell increased. Historically, the quadrupole lattice in this region has been operated somewhat below its maximum so that the lattice could be rescaled to an RF configuration without BNS damping. Since BNS damping is now used continuously, a lattice with an increased strength is feasible. Reducing the betatron functions helps in two ways: 1) The oscillation amplitude given a source deflection is smaller for the reduced βs and 2) the effects of wakefields from the head of the bunch on the tail are also reduced.

To implement the improved lattice, 1) the quadrupole strengths were increased, 2) the betatron functions were matched at the sector boundaries (every 100 m) with small adjustments, and 3) the chromatic effects on the betatron functions were studied, showing only small sensitivites. A comparison of the vertical betatron functions before and after the change is shown in Figure 6. The horizontal functions are similar. Beam tests of the old and new lattices are shown in Figure 7. The amplitudes of oscillations starting in the middle of the linac (Sector 15) show that the new lattice reduces the resulting oscillation by about 30%, a significant gain.

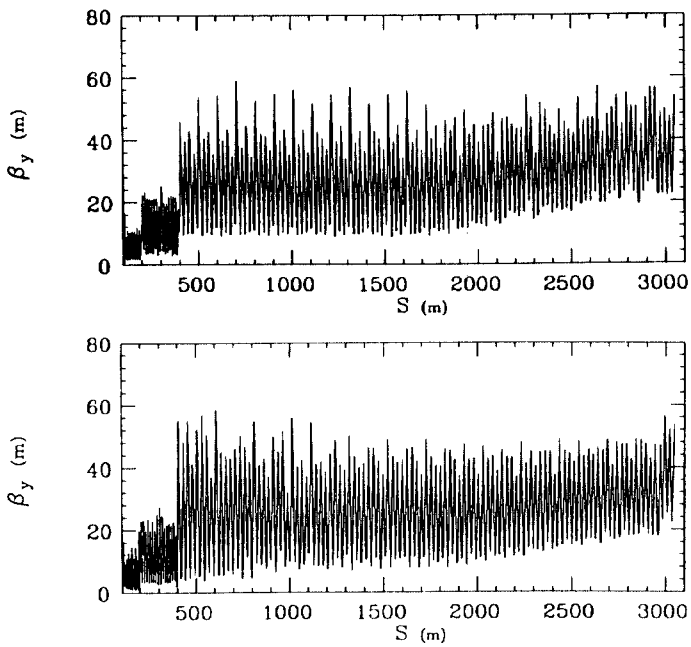

Figure 6 Vertical betatron functions for the old (upper) and new (lower) linac quadrupole lattices. Note that $<\beta_y>$ is lower at the end of the linac for the new lattice.

Conclusions

Transverse wakefield (BNS) damping works very well and must be used during high charge per bunch running of the SLC linac. At higher currents (4 x 10^{10}), the BNS RF phase offsets must be increased slightly to maintain optimum suppression of injection jitter enlargement of the emittances. In the SLC BNS damping is ineffective in the downstream half of the linac. Here a stronger quadrupole lattice has been generated to reduce the effects of jitter.

Further empirical tests will be made in the next running cycle to determine the fine details of the new BNS configuration including effects of bunch length, luminosity, and detector backgrounds. Tests aiming at higher currents (5 x 10^{10} or so) are also being considered.

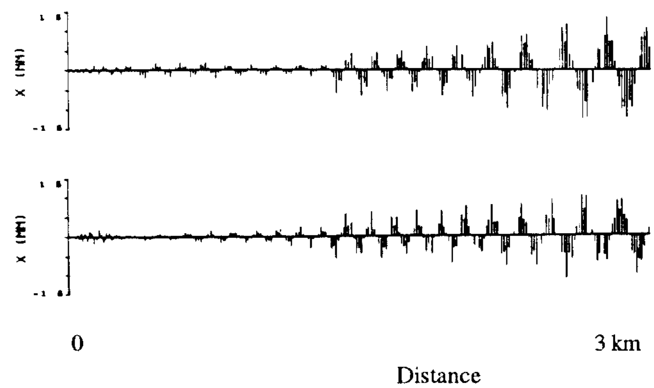

Figure 7 Induced horizontal oscillations at the 1500 m location in the linac with the old (upper) and new (lower) lattices with the new stronger BNS phases: 56 klystrons at -22 degrees and 176 klystrons at +16 degrees.

References

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Table 1 Accelerator conditions for several BNS damping measurements at the end of the linac. The last three columns show the ratio of the oscillation amplitudes starting at 10 m, 500 m, and 1500 m and measured at the end of the linac (47 GeV).

Linac Test Condition	# klys A	ϕ (A)	# klys B	ϕ (B)	x(3km)/x(10m)	x(3km)/x(0.5km)	x(3km)/x(1.5km)
Nominal BNS	56	-20 deg	176	+15 deg	1.0	1.6	5.0
Weaker BNS	56	-15 deg	176	+13 deg	1.3	2.5	5.5
Slightly Stronger BNS*	56	-22 deg	176	+16 deg	0.5	1.1	4.7
Moderately Stronger BNS	64	-23 deg	168	+18 deg	0.25	0.8	4.4
New Lattice + BNS of (*)	56	-22 deg	176	+16 deg	0.46	1.0	3.3