Long-Range Wakefields and Split-Tune Lattice at the SLC

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Abstract

At the SLC, a train consisting of one positron bunch followed by two electron bunches is accelerated in the linac, each separated by about 60 ns. Long-range transverse wakefields from the leading bunch were found to cause up to a factor of three increase in beam jitter for the trailing bunches. Incoming jitter is efficiently damped by BNS damping, but excitations in the middle of the linac from sources such as long-range wakefields can grow in amplitude. To measure the wake function, the time difference between the positron and electron bunches was changed, determining the frequency and strength of the dominant mode contributing to the dipole wakefield. By splitting the horizontal and vertical phase advance, or 'tune', of the magnetic lattice, it was possible to decrease the resonant excitation from these wakefields and thereby reduce the jitter of the electron beam by a factor of two.

1 Introduction

Long-range wakefields cause beam break up in multi-bunch beams [1]. The NLC design has adopted the use of damped and detuned structures to overcome these difficulties [2]. In the SLC the problem is less severe since the e^+ and e^- bunches can be individually steered due to their different beta-functions. However positron jitter translates via transverse wakefield kicks into electron jitter, and a positron orbit change (arising e.g. from orbit oscillations for emittance reduction [3]) will also change the electron orbit. The magnitude of these effects were measured by kicking the positron beam in the ring-to-linac beamline (RTL) and measuring the orbits for both beams in the linac. Observations and experiments are discussed, which led to a cure for the jitter.

2 Operational Observations

Several indirect observations indicated that the dominant beam jitter in the vertical plane for electrons was due to long-range transverse wakefields from the positrons. Large electron y jitter, amplified along the linac about 6 times more than expected from the short-range wakefields[4], e^+/e^- jitter correlation, x/y jitter correlation, and the fact that the electron jitter was reduced by a factor of two if the positrons were not present, all were noted. While beam loading changes with positron intensity was a possible explanation, the long-range transverse wakefield hypothesis was confirmed in the following experiments:

a) kick the positrons in the RTL to induce a large oscillation in the linac, measure the electron orbit shift,

b) change the positron-electron bunch separation and look for changes in the amplitude response.

3 Oscillation Experiments

Figure 1 (a) shows an example in which the positron bunch is kicked in the RTL. A large excitation of the electron bunch in the linac results (b). For a 1 mm oscillation with $3.3\cdot10^{10}$ particles in the positron bunch, the amplitude is 250 μm in electron x, and 500 μm in electron y. The positron oscillation is seen to decohere to 100 μm at the end of the linac.

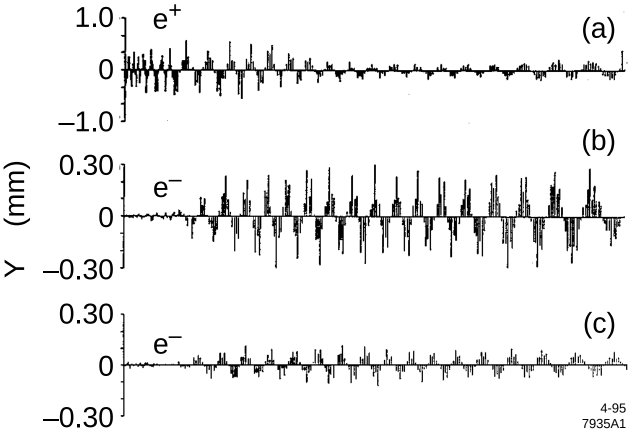

Fig. 1: (a) A positron oscillation in the SLC linac kicks the electrons via long range transverse wakefields, (b) for the design lattice, and (c) the new split-tune lattice (compare Section 6).

Orbits were also measured for different e^+ and e^- bunch spacings, necessarily adjusted in steps corresponding to –2, –1, 0, and +1 S-band buckets, or 0.35 ns intervals. The electron oscillations are locally 90° out of phase with respect to the positron oscillations, as expected if they are driven by the latter. Their amplitude varies in sign and magnitude with the positron bucket. Fig. 2 shows the measured signed amplitude vs. bunch spacing fit to a single mode (see Section 5), which

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is thus determined to have a frequency of 4141.7 MHz and amplitude of 350 μm for a 1 mm oscillation with $3.3 \cdot 10^{10}$ positrons. Shifting the frequency to 4144.5 MHz (dashed curve) would zero the wakefield at the operation separation of 59.0 ns. Early in the history of SLAC [2], cells 3, 4, and 5 following the input couplers in selected accelerator sections were 'dimpled' to raise the modes by either 2 or 4 MHz. Therefore implementing such a frequency shift appears to be feasible.

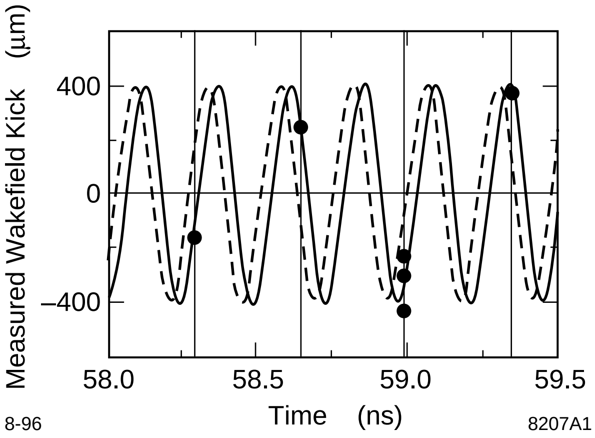

Fig. 2: The average kick in amplitude and sign is plotted versus the time for the different positron buckets. The solid curve has a frequency f = 4142 MHz while f = 4144.5 MHz for the dashed curve.

4 Static Bucket Changes

In addition to communicating jitter from the leading positron bunch to the following electron bunch, the long-range wakefield will be excited to the extent that the average steered positron trajectory is offset in the accelerator structures. This 'static' long-range wakefield effect is manifested when the distance between the positron and electron bunches is changed.

Fig. 3 shows the measured trajectory shift due to a shift in the positron-electron separation by one S-band bucket. The positron orbit shift reflects beam jitter and position monitor noise, while the electron shift is clearly an oscillation driven by the static positron wakefield. Its 150 μm peak amplitude is large compared to the 20 μm expected from a single 12 m long structure offset by 1 mm.

Static long-range wakefield effects are not very important for the SLC operation, since they can be steered out. The measurements of the static e^- deflections due to bucket changes however, contain information about the offsets between the positron trajectory and the accelerating structure, including structure misalignments. Preliminary studies aimed at isolating structure misalignments from bucket shift data have demonstrated the need for further work before the technique can be applied to practical alignment problems.

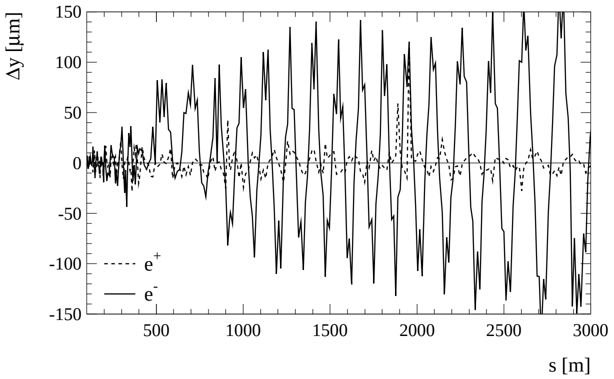

Fig. 3: Difference orbit in the electron beam by moving the leading positron bunch by one bucket.

5 Theoretical Estimates

Fig. 4 shows the dipole wakefield for the SLAC linac structure, calculated using a two-band circuit model [5]. Although the lowest dipole mode has the strongest kick factor of the structure by at least a factor of two, there are about 50 modes of similar strength that span 4140 MHz to 4320 MHz. These modes rapidly decohere for increasing bunch separation up to 10 ns, after which they partially recohere, exhibiting various beating patterns.

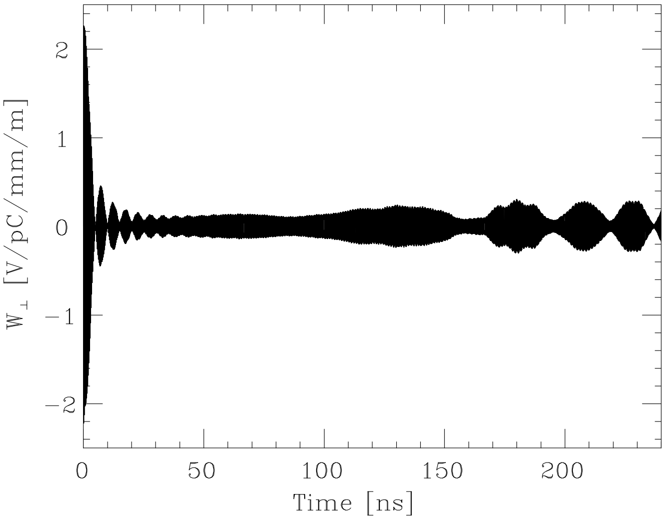

Fig. 4: Theoretical calculation of the transverse wakefield vs time for the lowest dipole modes of the SLAC structure.

In the neighborhood of 59 ns, where the SLC normally runs, a single frequency with an amplitude $W_\perp$ = 0.13 V/pC/mm/m dominates. This is relatively weak compared to the short-range wakefield which peaks at

$W_\perp$ = 5 V/pC/mm/m, and averages $W_\perp$ = 0.9 V/pC/mm/m over a 1 mm (rms) bunch. In addition, non-cylindrically symmetric external loading gives a damping factor w, different in x and y. For our regime w_y = 0.85 and w_x = 0.45, since the input couplers are oriented horizontally. A 1 mm oscillation extending over 500 m of a bunch with $3.5 \cdot 10^{10}$ particles induces an oscillation with a peak transverse momentum eV_y = 1/2 W_y (500 mm-m)(5.6 nC) $w_y \cong$ 155 keV/c. For a 8 GeV beam this corresponds to an angle of 20 µrad, and for β = 20 m a peak position offset Δy = 400 µm, in agreement with measurements (Fig. 2).

6 Split-Tune Lattice

In a *simple* FODO lattice, the long-range wakefield produced by coherent betatron oscillations in a leading positron bunch will *resonantly* drive betatron oscillations in a trailing bunch. Despite their opposite electric charges, both bunches see the same magnetic lattice (offset by one quadrupole), and hence have identical free betatron frequencies. The resonance is easily alleviated, however, by using a less symmetrical 'split-tune' lattice in which 'focusing' and de-focusing' magnets are given different absolute strengths. The betatron phase advance in the x and y planes for a particular charge differ, and are interchanged for the opposite charge.

A phase advance difference $\Delta(\Delta\psi)$ between the two bunches accumulated over some length of the linac will inhibit the growth in the trailing bunch's oscillation amplitude by $\sqrt{2(1-\cos[\Delta(\Delta\psi)]}\big/|\Delta(\Delta\psi)|$ relative to perfect resonance. Thus $\Delta(\Delta\psi)$ = 218° is required for a factor of 2 reduction, 262° for a factor of 3, and 885° for a factor of 7.8. The corresponding F-D magnet fractional strength difference to produce a unit (small) phase advance split, $1/2 \cos[(\Delta\psi + \Delta\psi)_{\text{cell}}/4]$ for thin quadrupoles, is typically 0.617%/°/cell (for an average 90°/cell lattice).

A split-tune lattice was implemented in the first half of the SLC linac—more precisely in Sectors 2 through 16, comprising 79 FODO cells. 31 cells (sector 2, 3, and 4) had had nominal 90°/cell phase advance in both planes, and the remaining 48 had had 76°/cell. The new lattice has 31 cells with average $\Delta\psi_x \cong 95°$, and $\Delta\psi_y \cong 91°$, and 48 cells with $\Delta\psi_x \cong 81°$, and $\Delta\psi_y \cong 69°$, all as seen by electrons. Thus the absolute accumulated phase advance difference between electrons and positrons, in both planes, is 680°.

The choice of 'sign' for the split, i.e., the fact that the positron y plane phase advance is the larger, was made on the basis of its implications for intra-bunch (short-range) wakefield effects. An essential component in the control of the latter in the SLC is BNS damping [6], in which a systematic energy variation along the bunch, in conjunction with phase advance chromaticity, inhibits the resonant excitation of oscillations in the tail of the bunch, and partially compensates the short-range wakefield phase shift. Since the vertical jitter sensitivity is the greater, the positron jitter has tended to be worse than the electron, and a reduction in the former leverages a reduction in the latter, the chosen split direction favors positron vertical phase advance chromaticity. The beam envelope (beta-function) is little affected by the asymmetry in 'focusing'.

Figure 1 (c) shows about a factor of 3 less e^+ to e^- coupling. This reduced the rms jitter by about 30% in y from 75% to 50% of σ_y, and 15% in x from 40% to 35% of σ_x. (see Fig. 5).

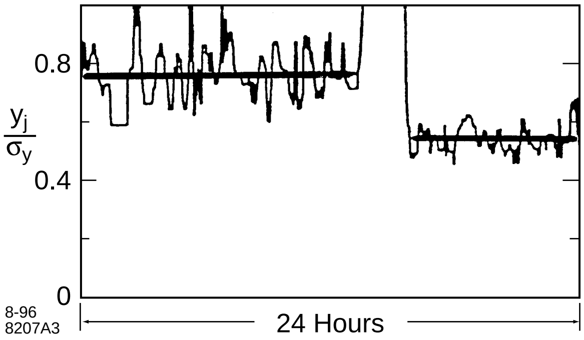

Fig. 5: Jitter reduction after the introduction of the split-tune lattice.

7 Conclusion

The static effect of long-range transverse wakefield kicks from positrons to electrons were measured, but they can be generally tuned out. However a jittery positron beam has caused an even higher electron jitter. The split-tune lattice has helped to reduce that effect below the natural jitter of the electron beam.

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