POSSIBLE SOURCES OF PULSE-TO-PULSE ORBIT VARIATION IN THE SLAC LINAC*

R. Assmann and F. Zimmermann
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

Abstract

Pulse-to-pulse variation of the transverse beam orbit, frequently referred to as 'jitter', has long been a major problem in SLC operation. It impairs the SLC luminosity both by reducing the average beam overlap at the IP and by hampering precision tuning of the final focus. The origin of the fast orbit variation is not fully understood. Measurements during the 1994/95 SLC run showed that it is random from pulse to pulse, increases strongly with current and grows steadily along the SLAC linac, with a typical final rms amplitude of about half the beam size. In this paper, we investigate possible sources of the vertical orbit jitter.

Introduction

In the Stanford Linear Collider (SLC), electron and positron beams, which are extracted from two damping rings, are accelerated in the 3 km long SLAC linac to about 50 GeV, then separated and transported through 1.2 km long arc sections, before they are collided at the interaction point (IP). It is a long-standing problem of SLC operation, that the vertical IP orbit position of either beam varies markedly from pulse to pulse, by about 0.4–$0.5\,\sigma_y$. The orbit 'jitter' at the IP is highly correlated to the orbit variation measured at the end of the SLAC linac and of about the same size. The jitter at injection into the linac is much smaller ($\leq\ 0.1\sigma_y$) and only poorly correlated to the IP orbit. The orbit variation has been a main concern and the subject of intense studies during the 1994/95 SLC run [1, 2, 3], in which the orbit jitter was observed to be random from pulse to pulse and to grow steadily along the linac [1]. The jitter also appeared to be strongly current-dependent (see Fig. 2).

The orbit jitter is a concern primarily for three reasons: first, it reduces the overlap of the two colliding beams at the IP and, thus, decreases the luminosity, by about 10%; second and more importantly, it makes measurements of the beam size with beam-beam deflections or wire scans more difficult. Sophisticated techniques using orbit information from strategical sets of upstream beam-position monitors had to be developed [4] to correct for the orbit jitter during a scan; third, as long as its origin has not been uncovered, the jitter adds an uncertainty to the design of future linear colliders.

In this report, we evaluate and compare the importance of several possible jitter sources in the linac, namely: ground motion, uncorrelated quadrupole vibration, accelerator-structure vibration, quadrupole field ripple, bunch length variation and bunch intensity fluctuation. Throughout the text we specify the jitter as a percentage of the beam size, assuming a normalized vertical emittance of 0.5×10^{-5} m-rad at the end of the linac.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515

Ground Motion

The response of the linac to a harmonic vertical displacement of quadrupoles at a certain wavelength can be characterized by a lattice response function G, which is defined as the average squared ratio of the final orbit variation and the perturbation amplitude. For low current, wakefields are not important and G can be written as [5]

$$G(k) = \sum_{j1,j2} \mu_{j1}\mu_{j2}\cos(k(s_{j1} - s_{j2})) \qquad (1)$$

where $k = 2\pi/\lambda$ denotes the wavenumber, s_j is the position of the jth quadrupole, μ_j is equal to $\sqrt{\gamma_j/\gamma_f}k_j R_{34}^{j\to f}$ for $j \neq 1$ and μ_1 equals $-\sqrt{\gamma_e/\gamma_f}R_{33}^{e\to f}$; $R_{34}^{j\to f}$ and $R_{33}^{e\to f}$ are the (3,4) and (3,3) transport-matrix coefficients, respectively, from quadrupole j or from the entrance to the end of the linac; k_j is the integrated strength of quadrupole j; γ_e and γ_f denote the initial and final beam energy, and γ_j the energy at position j, all three in units of the rest mass. We assumed that the vertical betatron-phase advance across the linac is a multiple of π, but this is not essential.

Using the dispersion relation between ground-motion wavelength and frequency that was measured in the SLAC linac tunnel [6], it is possible to convert the response function $G(k)$, Eq. (1), into frequency space. The function $G(f)$ thus obtained is represented by the solid line in Fig. 1, which shows that, at low frequencies, or large wavelengths, the response is strongly suppressed. Also displayed in the figure is the measured ground-motion power spectrum $P(f)$. The spikes of $P(f)$ around 10 Hz and 30 Hz are caused by vibration resonances of the accelerator supports. As a third (dotted) curve, the measured orbit-feedback response for the SLAC linac [7], $F(f)$, is also depicted.

The integral over the product of $P(f)$, $G(f)$ and $F(f)$ yields the rms orbit jitter caused by the ground motion [5],

$$\Delta y_{f,\mathrm{rms}}^2 = \int_0^\infty df\ G(f)P(f)F(f), \qquad (2)$$

assuming that all quadrupoles move exactly as the ground beneath them. Integration over the frequency range from 0.008 to 64 Hz predicts an rms orbit variation of about 40 nm with feedback on, and 32 nm without feedback. (The main contribution to the integral (2) comes from the resonance-spikes at frequencies where the feedback amplifies.) The nominal beam size for our reference point at the end of the linac is $52\ \mu$m ($\beta_{y,\mathrm{f}} \approx 50$ m, $\epsilon_y \approx 54\ \mu$m μrad); hence, the expected jitter arising from ground motion is less than 0.001 σ_y.

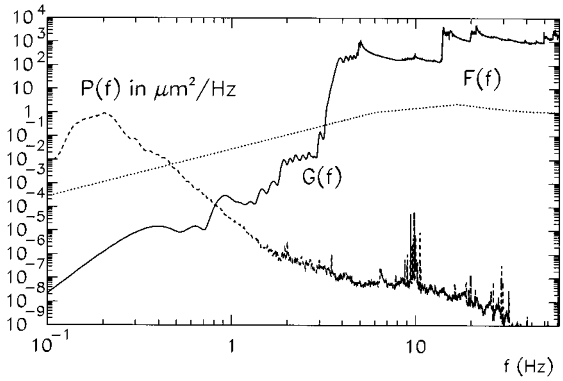

Figure 1: Low-current lattice response function $G(f)$, feedback response curve $F(f)$ [7] and ground-motion spectrum $P(f)$ measured on the tunnel floor of the SLAC linac [6].

At high current, dipole wakefields increase the effective R_{34} matrix elements by up to a factor of 3 [8]. Even with this additional factor of 3, the expected jitter is still negligible.

Quadrupole Vibration

Quadrupole vibration in the SLAC linac [9, 10] was measured to be of the order of 250 nm rms. Mechanical resonances in the quadrupole support structures, at 8–14 Hz and 28–30 Hz, as well as excitation by the accelerator-structure cooling water, at frequencies around 59 Hz, have been identified as its main sources [9].

If we assume that the quadrupole vibration is random and uncorrelated, we can use the high-frequency limit of the response function $G(f)$ in Fig. 1 to estimate the resulting orbit jitter. Thus, we expect the orbit variation due to 250 nm rms quadrupole vibration to be amplified by a factor $\sqrt{G(\infty)} \sim \sqrt{10^3}$ to a value of about 8 μm or $0.16\ \sigma_y$. Again, at high current, the beam response is further increased by wakefield effects.

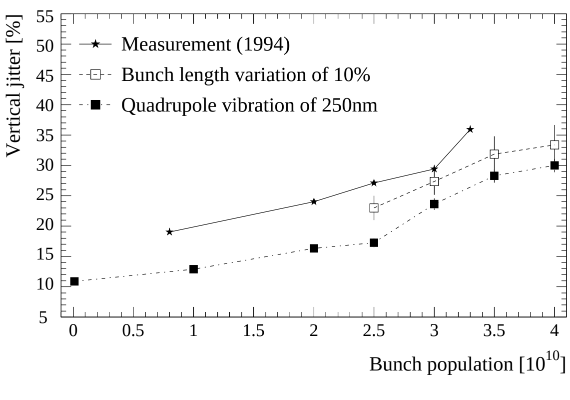

Figure 2: Vertical beam jitter in percentage of the beam size as a function of the bunch population. The solid curve shows the measured rms positron-orbit variation at high-beta points in the SLC final focus, averaged over data from 1994. The dashed-dotted curve presents simulation results for an uncorrelated rms quadrupole vibration of 250 nm. Finally the dashed curve shows simulation results for an emittance-optimized linac with an rms bunch length variation of 10%. All simulation results refer to the end of the linac.

To confirm these rough estimates, we have performed a computer simulation using the program LIAR [11]. The simulation includes the transverse and longitudinal wakefields in the accelerator structures as well as the energy profile due to BNS damping, *i.e.*, the correlated energy spread introduced for wakefield compensation. Specifically, the rf phase with respect to the rf crest in the first third (last two thirds) of the linac is chosen as 22° (-16.5°) for bunch populations larger than 2.0×10^{10}, and as 12° (-3°) for 1.0×10^{10}. There is no BNS phase change for the zero-current case. Simulation results are shown in Fig. 2. The simulated beam jitter grows from zero at the beginning of the linac to the final value shown. It increases linearly with the rms vibration amplitude.

The simulation confirms that quadrupole vibration can explain a substantial part of the observed SLC beam jitter.

Structure Vibration

The 12-m long girders which support the accelerator structures vibrate at rms amplitudes Y_s of about 1 μm [9, 10]. Because an off-center beam induces a transverse wakefield, also structure vibration can cause an orbit variation. For a driving point charge transversely offset by y, the linear slope of the dipole wakefield is given by [12] $W_\perp = 0.33\ \mathrm{V/(ps\ pC)}\ y/a/cell$, where a denotes the disk iris radius (a =1.16 cm). A Gaussian bunch of rms length σ_z experiences a centroid kick of $\Delta(cp_\perp) = W_\perp \sigma_z e^2 N/(c\sqrt{\pi})$. Here, N is the number of particles in the bunch. A kick $\Delta y'$ received at position s causes an orbit change $\Delta y_f \approx \bar{\beta}_y(\Delta y')/\sqrt{2}/\sqrt{\gamma(s)\ \gamma_f}$ at the end of the linac, where we have averaged over the betatron phase, $\gamma(s)$ is the beam energy at position s and γ_f the final beam energy, both in units of the rest mass, and $\bar{\beta}_y \approx 30$ m denotes the average beta function.

The SLAC linac consists of about 200 girders. Each girder carries four 80-cell structures. Let us assume that the 4 structures on each girder and all cells which compound these structures vibrate at about the same amplitude and in phase, and ignore possible correlations between different girders. Abbreviating the number of cells per girder by n_{cell}, the number of girders by n_g, the final beam energy by E_f, and averaging over the linac, one finds

$$\Delta y_{f,\mathrm{rms}} \approx \bar{\beta}_y\ \frac{W_\perp e^2 n_c \sqrt{n_g}}{2cE_f\sqrt{2\pi}}\ Y_s\ \sigma_z\ N \qquad (3)$$

or $\Delta y_{f,\mathrm{rms}} \approx 10\ \mathrm{nm}\,\sigma_z[\mathrm{m}]\ N\,Y_s$. For a vibration amplitude Y_s of 1 μm, a bunch length of 1 mm and $N \approx 4\times10^{10}$, we obtain $\Delta y_{f,\mathrm{rms}} \approx 400$ nm (0.008 σ_y), which is insignificant. In order to contribute sensibly to the observed orbit jitter, the vibration amplitudes must be a factor of 5 larger (5 μm rms); this seems rather unlikely.

Quadrupole Field Ripple

Quadrupole field ripple induces an orbit jitter of about

$$\Delta y_{f,\mathrm{rms}} \approx \left(\sqrt{\gamma_e/\gamma_f}R_{33}^{e\to f} - 1\right)\left(\frac{\Delta k}{k}\right)_{\mathrm{rms}} y_{\mathrm{rms}} \qquad (4)$$

where y_{rms} and $(\Delta k/k)_{\mathrm{rms}}$) denote the rms beam offset and ripple, respectively. We have used the relation [5] $\sqrt{\gamma_e/\gamma_f}R_{33}^{e\to f}$ −

$1 \;=\; \sum_i R_{34}^{i\to f} k_i \sqrt{\gamma_i/\gamma_f}$ (k_i is the strength of the ith quadrupole), which can be derived by considering a constant vertical displacement of the entire beam line. Assuming an rms orbit offset $y_{\rm rms}$ of 0.5 mm and using $(\sqrt{\gamma_e/\gamma_f} R_{33}^{e\to f} - 1) \approx 0.5$, we find that an unrealistically large field ripple $(\Delta k/k)_{\rm rms}$ of 10% is required to explain an orbit jitter of 0.5 σ_y.

Bunch Length and Charge

There is some evidence that the longitudinal 'sawtooth' instability which occurs at high current in the two SLC damping rings [13] contributes a sizable part of the jitter [14, 15]. Streak-camera and rf-monitor measurements show a pulse-to-pulse bunch-length variation of about 10%, both in the damping rings and in the linac [15, 14].

To study how a bunch-length change affects the orbit in the presence of wakefields and with proper klystron phasing for BNS damping, we have again performed simulations with LIAR [11]. We assumed realistic misalignments and correction methods, and included orbit bumps for emittance control. A number of different random seeds were considered for the misalignments. The simulation results, depicted in Fig. 2, suggest that a bunch-length variation of 10% causes a beam jitter of 0.35 σ_y. Figure 3 displays the simulated vertical beam jitter as a function of position.

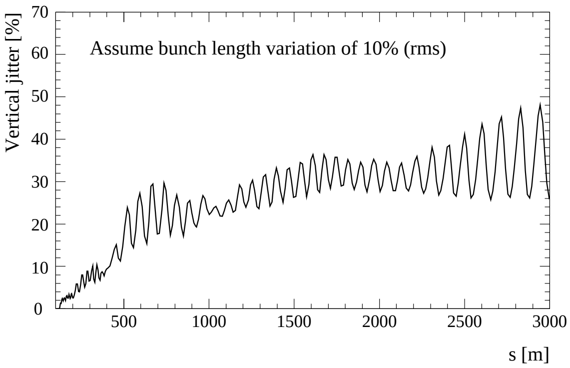

Figure 3: Vertical beam jitter in percentage of the expected beam size along the linac. The simulation assumes a random bunch length jitter of 10% and a bunch population of 3.5×10^{10}. The oscillations reflect a beta mismatch between the simulation and the design lattice.

Figure 4 demonstrates that the orbit changes observed when varying the bunch length are mainly effected by the transverse wakefields. These introduce a dependence of the betatron phase advance on the bunch length, $d\psi_\beta/ds \;\approx\; \bar\beta W_\perp \sigma_z e^2 N n_{cell}/(2\sqrt{\pi} mc^3 \gamma(s) L_g)$, where L_g denotes the girder length, and, thereby, convert bunch-length changes into orbit jitter. In the SLAC linac, the effect of a betatron phase shift is aggravated by the large orbit bumps over a few hundred meters, which are introduced for emittance reduction. Phase advance variations result in an imperfect termination of these bumps, so that part of the induced oscillation leaks out and manifests itself as jitter downstream.

Finally, we have investigated the beam jitter due to current variation. According to our simulations, even for an intensity variation as large as 5% the beam jitter is smaller than 0.04 σ_y, and, thus, intensity changes do not appear to be important.

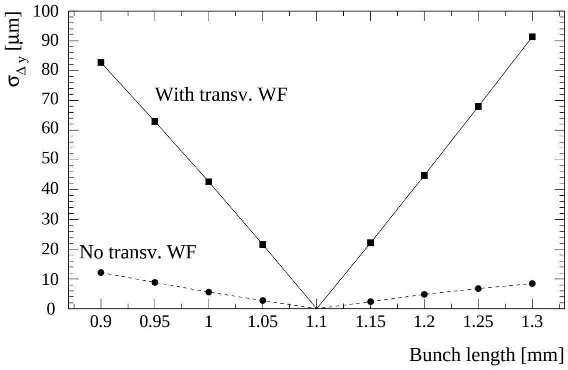

Figure 4: The rms trajectory change as a function of bunch length. A nominal bunch length of 1.1 mm is used as a reference for the other points. For this study we excited a 200 μm rms trajectory oscillation in the SLAC linac. The solid line presents the full simulation, while transverse wakefields were switched off for the dashed curve.

Conclusion and Thanks

We have studied several possible sources of the vertical-orbit jitter in the SLAC linac. The most prominent source that we identified is the bunch-length variation of about 10%. Quadrupole vibration, with measured rms amplitudes of 250 nm, may account for much of the rest. Both these sources would lead to a monotonic jitter growth along the linac, consistent with observation. The effects of field-ripple, ground motion, structure vibration and intensity jitter all appear to be insignificant. We thank C. Adolphsen, F.J. Decker and T. Raubenheimer for helpful discussions.

References

[1] C. Adolphsen, T. Slaton, PAC 95 Dallas, p. 3034 (1995).

[2] C. Adolphsen et al., PAC 95 Dallas, p. 646 (1995).

[3] F. Zimmermann et al., PAC 95 Dallas, p. 656 (1995).

[4] P. Raimondi, private communication (1996).

[5] J. Irwin and F. Zimmermann, EPAC 96 (1996).

[6] C. Adolphsen, private communication (1996).

[7] L. Hendrickson, private communication (1996).

[8] T. Raubenheimer, private communication (1996).

[9] J.L. Turner et al., PAC 95 Dallas, p. 665 (1995).

[10] J.T. Seeman et al., PAC 93 Washington, p. 3564 (1993).

[11] R. Assmann et al., LIAR, SLAC AP-103 (1996).

[12] SLC Design Handbook (1984).

[13] K. Bane et al., PAC 95 Dallas, p. 3109 (1995).

[14] F.J. Decker et al., this conference, SLAC-PUB-7260 (1996).

[15] B. Podobedov, private communication (1996).