SLAC–PUB–5784
March 1992
(A/I)

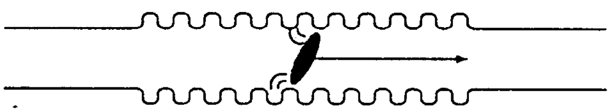
Transverse Wakefields at High Dispersion*

Franz-Josef Decker

Stanford Linear Accelerator Center, Stanford University, Stanford CA. 94309

Abstract

In high energy linear colliders the transverse beam emittance has to be preserved in order to achieve small interaction spots. If the beam is off-center in an accelerating cavity, it excites transverse wakefields, mainly the dipole mode, which deflects the tail of the beam leading to an emittance growth. In a high dispersive region, even a well centered beam can excite wakefields of higher order modes since the energy spread of the beam causes a transverse beam size which is comparable with the beam pipe. During the bunch length compression in the ring-to-linac (RTL) section of the Stanford Linear Collider (SLC), the beam pipe of 75 mm diameter is practically filled in the horizontal plane. Especially, if beam losses start to be involved, the very outer parts of the beam excite wakefields at any pipe irregularities like bellows, diameter steps, etc. Measured evidences, theoretical estimates and comparisons to other effects, like higher order magnet optics, are presented.



1 Introduction

At the SLC, the 10 mm long bunch of the damping ring (DR) is compressed in the RTL section down to the necessary 1 mm length for the main linac. The compression is achieved by introducing an longitudinal energy correlation with a compressor cavity followed by a high dispersive region (η), where particles of different energy travel along different trajectories. Particles at $\pm 2\sigma_l$ (bunch length $\sigma_l \approx 10$ mm) get an energy difference of $\Delta E/E = \pm 2.4\,\%$ and therefore are with $\Delta x = \pm 39$ mm at $\eta = 1.4$ m near the aperture of the pipe,

$$\Delta x = \eta \cdot \frac{\Delta E}{E} \quad \text{and} \quad \Delta E = E_{rf} \sin(2\pi\sigma_l/\lambda), \qquad (1)$$

with an energy $E = 1150$ MeV, rf-amplitude of $E_{rf} = 30$ MeV and $\lambda = 105$ mm. Additionally to the intended path length difference, the off axis particles also experience any nonlinear kicks coming from wakefields or higher order magnetic fields. This causes an emittance blow up at the beginning of the linac, where the 39 mm size of the RTL should be reduced to the nominal beam size of about $\sigma_x = 300\,\mu$m. Besides the direct emittance blow up, there is another even more disturbing mechanism: A small jitter of the DR phase and/or the bunch length σ_l will cause a different off axis beam population (or even losses at the aperture) and therefore different amounts of particles away from the axis at the beginning of the linac. A few particles (say 5 %) at an offset of 2 mm (measured, see below) are worse than an unacceptable offset of the whole beam by 100 μm (=0.05·2 mm), if they are in the head of the bunch, since these particles are not fully compressed and therefore ahead of the main bunch distribution creating stronger transverse wakefields along the linac. The experimental observations are presented first. Then some theoretical investigations show the size and the effect of the transverse wakefields compared to magnetic errors and finally other effects especially of the longitudinal wakefield are estimated.

2 Experimental Observations

A limitation in going to higher beam currents ($> 3 \cdot 10^{10}$ particles/bunch) resulted in unstable beam positions and emittance blow up at the end of the linac. At lower currents, this so called "linac instability" was tracked down to some occasions where particles were further away from the normal distribution ("fliers", see Fig. 1).

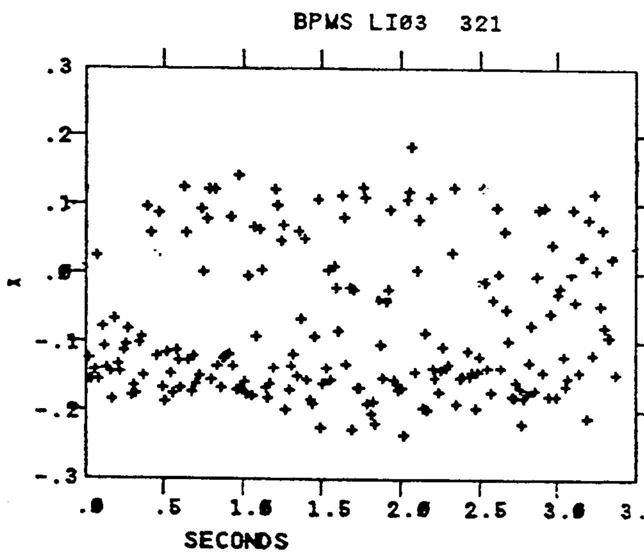


Figure 1: Fliers in the Linac.

Above $3 \cdot 10^{10}$ particles per bunch some pulses are far off axis in the linac. The measurement was taken in Sector 3 (Li03) with BPM 321 over 3.5 sec.

The behavior was nearly invisible at the beginning of the linac, so the source was unclear, until a special BPM (beam

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

Contributed to the 3rd European Particle Accelerator Conference, Berlin, Germany, March 24–28, 1992

position monitor, number 544) in the RTL showed something like a 90° correlation ("donut") with BPMs in the linac (see Fig. 2). The BPM 544 was in at least two ways special: First, it was just downstream of some beam loss and might have been irritated by the spray of secondary particles. And second, the BPM is at a high dispersion and has therefore a bigger diameter than other BPMS, which enables that BPM to recognize particles near the aperture in x-direction. All BPMs are less sensitive for particles further off axis, since the BPM electrodes are arranged at 45° to the x and y plane (see effect Fig. 3). So the attention was moved to the DR area and since BPMs in the RTL measure mainly the position of the beam, which corresponds to the DR phase and energy, these quantities were (unsuccessfully) investigated for any kind of jitter source.

Then the DR bunch length (σ_l), was measured in the RTL with a screen showing some increases of the jitter from 0.5 % to 3.5-5 % of σ_l if the number of particles per bunch was above $4 \cdot 10^{10}$.

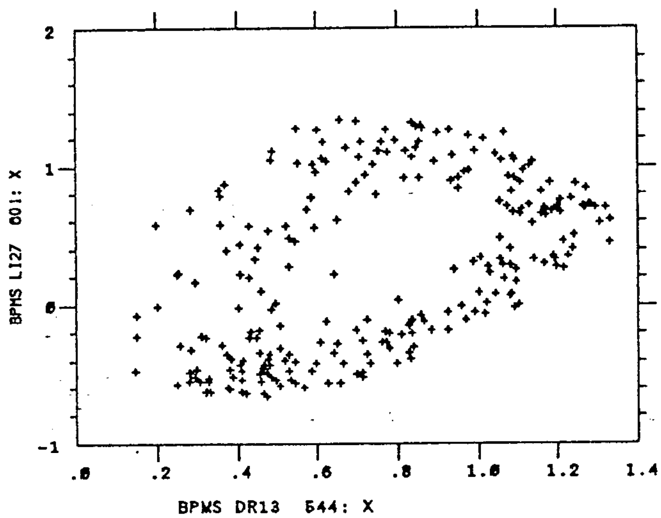


Figure 2: Donut Correlation.

At about $4 \cdot 10^{10}$ particles per bunch a correlation of a linac BPM versus an RTL BPM indicates, that the problem source is upstream of the RTL (scales in mm).

2.1 DR-Jitter

Just recently, in the ongoing running cycle, an even more complicated mechanism of bunch length blow up was recognized [1]: Instead of slowly damping down to a somewhat larger bunch length (at high current), the bunch length decreases further to a too small size. Then it blow up very quickly (0.1 ms) to a too big value afterwards it decreases again slowly by radiation damping (1.5 ms). So a "saw tooth" pattern is visible in a bunch length (or phase) versus time plot (see Fig. 4).

When the step occurs at ejection a flier might be seen in the linac. The donut is a little bit more complicated: Positive values at BPM 544 were also correlated with beam loss. So a larger bunch and therefore losses might indicate an extraction near the peak of the saw tooth. Damping down the bunch length leads to the nearly straight line in

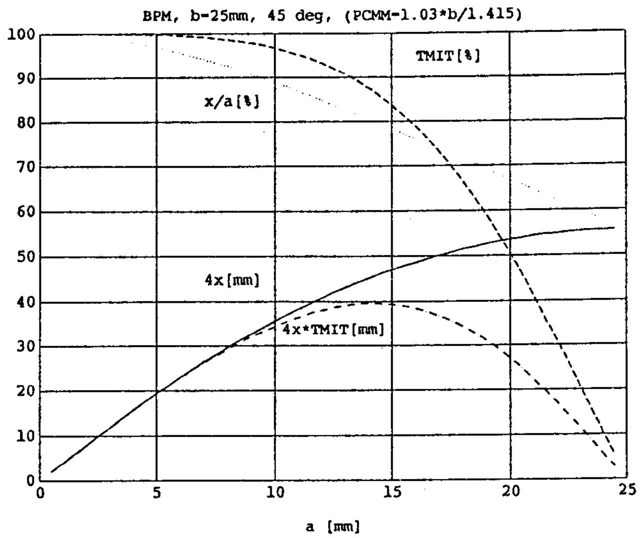


Figure 3: BPM response.

*The calculated response of a perfect BPM with 45° wide electrodes at 45° is shown. If the beam moves from a = 0 to 25 mm (=b=radius of BPM) between the electrodes, a smaller variation in x is detected (solid line). Compared to the expected value x/a (dotted) drops from 100 % to 55 %. The current measurement (TMIT dashed) would show a strong dependence. Therefore in a wider beam distribution, particles near the aperture a≈25 mm have much less influence on the mean position measurement, instead of 55 % it is more like 0 % for x*TMIT (dash-dotted).*

Fig. 2. Point d on the other side of the donut is the difficult part: Why should a beam which is located at the same position in the RTL get an offset of up to 1.5 mm at the end of the linac. During the blow up not only a quadrupole mode (bunch length) with nearly twice the synchrotron frequency (ν_s) occurred, but also a frequency less than three times ν_s showed some indication of a sextupole mode (bunch form). Different bunch forms and lengths might be responsible for the wider scatter of the other half of the donut. This model indicates that the saw tooth should get more symmetric at higher currents (not yet tested). The timing jitter of the saw tooth is currently stabilized by starting the instability externally by switching the rf off and on ("bunch munching" [2]) during the store time.

2.2 RTL-Sensitivity

Any longitudinal jitter or distribution change of the DR bunch should be decreased to 10 % by the RTL since the compression is not totally. A total compression should leave the RTL in first order unsensitive to changes. The nonlinearity of the rf-slope brings some particles in front and the back of the short linac bunch. An even more important aspect are the transverse kicks along different trajectories (see Fig. 5). The cause might be magnetic multipoles and/or transverse wakefields, the later one will be discussed in more detail.

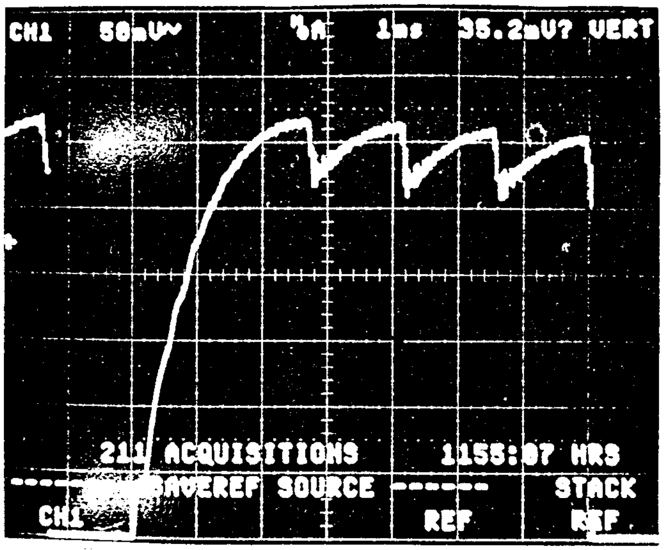


Figure 4: Saw tooth pattern of the DR bunch length.

After injection (left) the bunch length decreases (or here the measured peak current increases) till it starts a rapid blow up. The start time jitter of the saw tooth is about 20-30 % of one tooth length (≈ 1.5 ms).

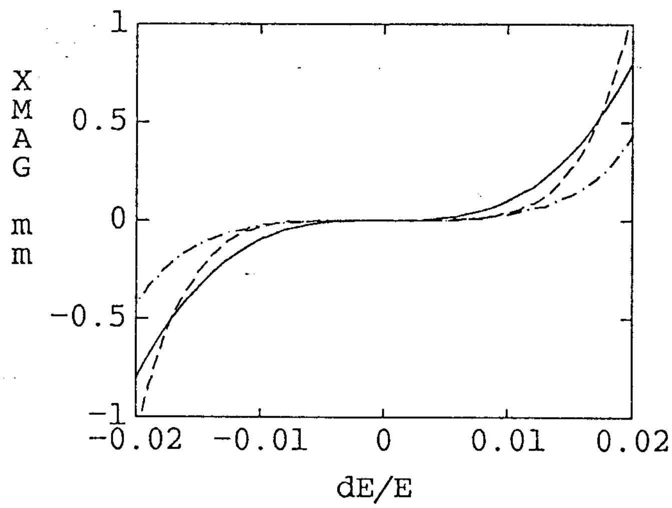


Figure 5: Third order dispersion.

The dependence of the linac position (at maximal excursion) versus the energy in the RTL show a strong third order term (fit to measurements solid). The measured 12-pole field of 2 % at the pole tip of the quadrupole at the highest dispersion gives a 5th order contribution (dashed) of about the right magnitude. The calculated effect of the wakefield contribution at $5 \cdot 10^{10}$ is about half that effect (dashed-dotted, see below).

3 Wakefields of Bellows

Besides the necessary compressor cavity in the north RTL, the smooth vacuum pipe is interrupted by about 40 bellows (30 in the south) and about ten other devices with bigger holes: profile monitors (screens) and T-connections to vacuum pumps. Since each bellow consists of 20 cells (some are different) let's concentrate on them.

3.1 Wakefield Size

If the longitudinal wake is purely inductive, the transverse wakefield $W_\perp$ is proportional to the current. This assumption is o.k. for bunches longer than the geometric variations of the bellow. An analytic formula [3] for the peak of the dipole kick

$$W_{\perp peak}[\text{Volt/cell}] = \frac{Z_o g \Delta}{\pi a^3} \cdot \frac{crQ}{\sigma_l} \tag{2}$$

gives about a peak $W_\perp = 5.9\,\text{kV}$ for one bellow with 20 cells and a bunch length $\sigma_l = r(\text{offset}) = 6\,\text{mm}$, ($Z_o = 377\,\Omega$, gap width $g = 2.5\,\text{mm}$, bellow height $\Delta = 6\,\text{mm}$, bellow inner radius $a = 24.5\,\text{mm}$ (see Fig. 6), c = velocity of light and $Q = 8\,\text{nC}$ ($5 \cdot 10^{10}$ particles).

Simulations with TBCI [4] showed that $W_\perp$ is about 2.6 keV at $\sigma = 6\,\text{mm}$. Fig. 6 shows the shape of the input bellow with 4 cells and the longitudinal (W_z) and transverse (W_ϕ) wakefields for the transverse mode $m = 3$, $\sigma = 2\,\text{mm}$ and $r = a$. The peak longitudinal wake for $m \geq 1$ is about twice that for $m = 0$ and the transverse wakefield scales with m like expected [3]:

$$W_{zm} = \left(\frac{r'}{a}\right)^m \left(\frac{r}{a}\right)^m \cos m\theta \sum_n^\infty 2k_{mn} \cos\frac{\omega_{mn} s}{c} \qquad s > 0 \tag{3}$$

$$W_{\perp m} = m \left(\frac{r'}{a}\right)^m \left(\frac{r}{a}\right)^{m-1} (\hat{r}\cos m\theta - \hat{\theta}\sin m\theta) \cdot \sum_n^\infty \frac{2k_{mn}}{(\omega_{mn} a/c)} \sin\frac{\omega_{mn} s}{c} \tag{4}$$

following the Panofsky-Wenzel Theorem

$$\frac{\partial}{\partial s} W_{\perp m} = \nabla_\perp W_{zm}. \tag{5}$$

A test particle has a radius r and a distance s behind the exciting particle (r'), $\hat{r}$, $\hat{\theta}$ are unit vectors and ω_{mn} is the frequency of the mode with the loss parameter k_{mn}. Since the scaling with m, particles near the aperture have an enormous effect and even orders of $m_{max} \approx \pi a/\sigma \approx 30$ have to be taken into account. At 70 % of the aperture the contribution of the higher order transverse modes decreases slowly with $m/2^{m-1}$, $m = 6$ has still about 20 % of the dipole value.

3.2 Effects of Wakefield Kicks

A bunch with $5 \cdot 10^{10}$ particles and an offset of 17.4 mm (corresponds to $\Delta E = +20\,\text{MeV}$ at $\eta = 1\,\text{m}$) will get a dipole wakefield kick of about $6.6\,\mu\text{rad}$ from one bellow.

This has to be compared with the angular divergence $\sigma'_x = \sqrt{\varepsilon/\beta}$ of the beam. With a range in the beta function $3 < \beta < 50\,\mathrm{m}$ and a normalized emittance of $\gamma \cdot \varepsilon = 1.6 \cdot 10^{-5}\,\mathrm{m\,rad}$ (γ = relativistic energy factor) the range of σ'_x is from $12 - 50\,\mu\mathrm{rad}$. Since the effects of the 30 bellows cancel partly each other due to different phase advances, about $\sqrt{30} \cdot 6.6\,\mu\mathrm{rad} = 36\,\mu\mathrm{rad}$ is expected which is of the same order of σ'_x. The detailed effects with m up to 6 for each bellow at its specific RTL lattice place was simulated and their summed up maximal influence at the beginning of the linac e is shown in Fig. 5.

The beam is normally more in the center of the pipe, therefore only the higher modes contribute which are excited by a broad centered beam. Since both, this effect and the magnet errors can be cancelled up to third order by octupoles, two of 8-pole magnets were installed last down time and they improved the emittance by 5–10 %.

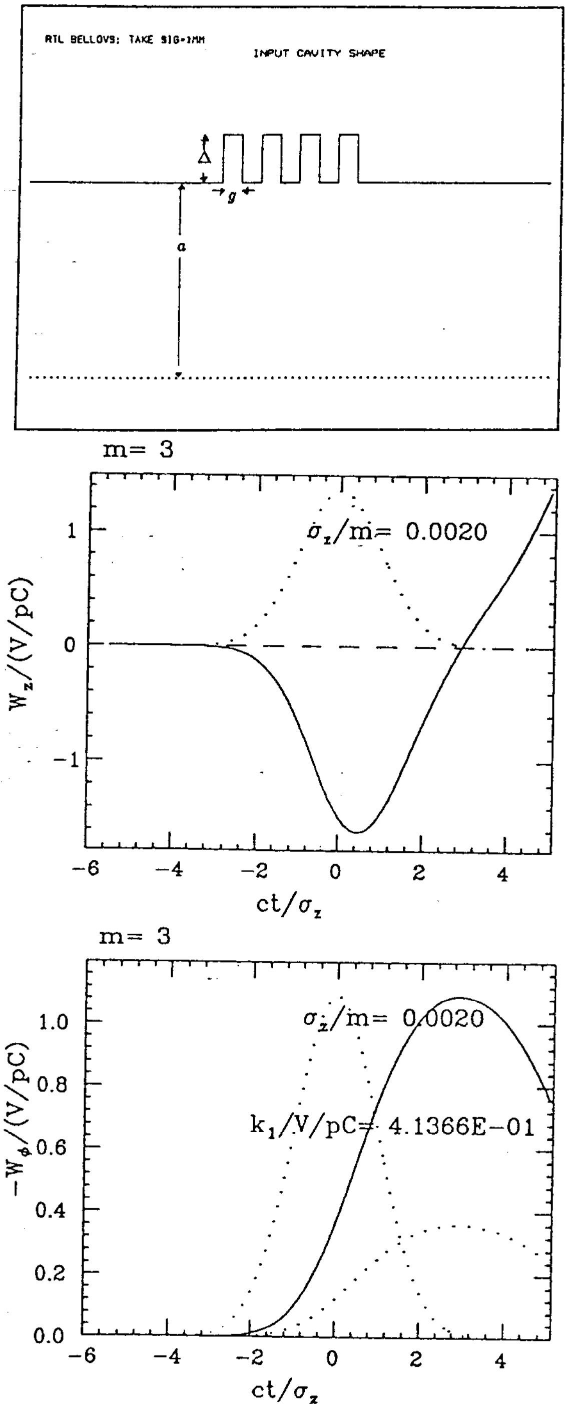


Figure 6: Wakefield calculation.

The input shape for TBCI and the calculated longitudinal and transverse wake potentials for m=3 and $\sigma = 2\,mm$ is shown.

3.3 Longitudinal Wakefield

The longitudinal wakefield scales with $1/2^m$ ($m \geq 1$) for 70 % of the aperture and is about 1 MeV for $m = 0$ or 1. With 3 MeV which is about $3\sigma_E$ (DR energy spread) the bunch compression might be disturbed. Since the bunch shortens in the RTL, there are less wakefields at the beginning causing a factor of about 1/2 and also the higher orders cancel or decrease with a centered beam, so the maximal real effect is more like $\sigma_E/2$. The effect of a longer bunch can be adjusted by a stronger compression.

Besides effects on the 10-to-1 longitudinal compression, the induced energy spread in the RTL might indirectly effect also the 100-to-1 transverse beam size reduction!

4 Conclusion

The transverse wakefields of a beam at high dispersion lead to dispersive abberations of higher order, which can be mainly compensated by magnetic elements, like for higher order magnetic errors. The longitudinal wakefield has a small effect on the compression process, but seem to have an indirect effect on the transverse beam size reduction. This chromatic like effect should be avoided be reducing the amount of wakefields, e.g. with sleeves in the bellows.

Acknowledgement

I would like to thank the members of the Linac, Damping Ring and RF Group for all their support and helpful discussion. Special thanks to M.C. Ross and to P. Krejcik for bringing the attention to the bunch length variation and saw tooth pattern, respectively.

References

[1] DR-Group, *Microwave Instability Oscillations*, to be published.

[2] F.-J. Decker, T. Limberg, J. Turner, *Pre-Compression of Bunch Length in the SLC Damping Rings* , HEACC'92 Hamburg, July 1992 (to be published).

[3] K.L.F. Bane, private communication and *Wakefield Effects in a Linear Collider* , SLAC-PUB-4169, December 1983.

[4] T. Weiland, *Transverse Beam Cavity Interaction, Part I: Short Range Forces* , NIM 212 (1983), 329-348.