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Wakefield Effects in the Beam Delivery System of the ILC

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INTRODUCTION

The main linac of the International Linear Collider (ILC) accelerates short, high peak current bunches into the Beam Delivery System (BDS) on the way to the interaction point. In the BDS wakefields, excited by the resistance of the beam pipe walls and by beam pipe transitions, will tend to degrade the emittance of the beam bunches. In this report we calculate the effect on single bunch emittance of incoming jitter or drift, and of misalignments of the beam pipes with respect to the beam axis, both analytically and through multi-particle tracking. As we want to keep emittance growth due to this effect small, we consider also mitigation measures of changing the metallic surface material and/or the beam pipe aperture.

The wake effects are studied in that part of the BDS which includes the collimation and final focus systems. Typical ILC beam parameters are given in Table 1. Initially a stainless steel (SS) beam pipe is considered. Note that the ILC collimator wakes, though very important, are not included in this study; their effects have been studied elsewhere [1]. Note also that similar methods are presented in recent reports Refs. [2],[3].

Table 1: Beamline and bunch properties used in this report.

Parameter	Value	Unit
Energy, E	250	GeV
Beamline Length, L_{tot}	1600	m
Bunch Population, N	2	10^{10}
Rms Bunch Length, σ_z	300	μm
Normalized Vertical Emittance, $\gamma\epsilon$	40	nm
Nominal Typical Pipe Radius, a	1	cm

WAKES

The sources of wakes we consider are the resistive wall (RW) wake and the wake due to the steps of beam pipe transitions (assuming perfect conductivity). As is usually done, although it is an approximation, we treat these two sources independently and then add their contributions.

For a round metallic beam pipe of conductivity σ and radius a, the dipole RW wake at position s behind an exciting particle is given by [4]

$$\frac{W(s)}{L} = \frac{Z_0 c}{2\pi^2 a^3}\sqrt{\frac{c}{\sigma s}}H(s)\ , \tag{1}$$

with $Z_0 = 377\ \Omega$ and c the speed of light; $H(s) = 0$ (1) for $s < 0$ (> 0); the length L is there to remind us that this is a wake per unit length. Eq. 1 is valid provided that the rms bunch length σ_z is large compared to $s_0 = (ca^2/2\pi\sigma)^{1/3}$. Taking $a = 1$ cm as typical aperture and $\sigma = 10^{16}\ s^{-1}$ (SS) we obtain $s_0 = 77\ \mu$m, which is small compared to $\sigma_z = 300\ \mu$m, and thus Eq. 1 is applicable. Convolving the wake with the longitudinal charge distribution, one obtains the bunch wake. For a Gaussian distribution the bunch RW wake $\mathcal{W}(s, \sigma_z)/L = f(s/\sigma_z)W(\sigma_z)/L$ with [5]

$$f(x) = \sqrt{\frac{\pi|x|}{8}}e^{-x^2/4}\left[I_{-\frac{1}{4}}\left(\frac{x^2}{4}\right) + \mathrm{sign}(x)I_{\frac{1}{4}}\left(\frac{x^2}{4}\right)\right] \tag{2}$$

and $I_\nu(x)$ the modified Bessel function of order ν. For our parameters the peak $\hat{\mathcal{W}}/L = 56$ kV/(nC-mm-km).

For $\sigma_z/a \ll 1$ the dipole wake of an abrupt step-out transition in a round beam pipe (one with initial radius a_1 and final radius $a_2 > a_1$) is [6],[7]

$$W(s) = \frac{Z_0 c}{\pi}\left(\frac{1}{a_1^2} - \frac{1}{a_2^2}\right)H(s)\ , \tag{3}$$

and the wake of the converse, step-in transition is zero. The wake of a matched pair of transitions is the sum of the two, provided that the separation is large compared to the catch-up distance $\ell \sim 2(a_2 - a_1)^2/\sigma_z$ (for *e.g.* $a_2 - a_1 = 5$ mm, $\ell \sim 16$ cm). For a Gaussian beam the bunch wake $\mathcal{W}(s) = \frac{1}{2}W(\sigma_z)[1 + \mathrm{erf}(s/\sqrt{2}\sigma_z)]$, with erf the error function. For a pair of steps with $a_1 = 1$ cm and a_2 large, $\hat{\mathcal{W}} = 0.36$ kV/(nC-mm).

DRIFT/JITTER TOLERANCES

In the BDS incoming drift/jitter will, through the wakefields, result in emittance growth. By a drift we mean a relatively slow change so that the emittance growth can be partially compensated with a corrector at the end of the beamline. Thus a drift emittance growth is calculated with respect to the bunch centroid. In the case of incoming jitter, however, correction cannot be done, and emittance is obtained with respect to the beam pipe axis.

For a periodic wake (like the RW wake) the wake strength in a transport line can be quantified, in the smooth focusing approximation, by the parameter υ, which in the case of injection drift error is [4]

$$\upsilon = \frac{e^2 N L \beta_y (\mathcal{W}_{rms}/L)}{2E}\ ; \tag{4}$$

here L is length of pipe, β_y the average beta function, and the subscript *rms* indicates the rms of a function. The vertical emittance growth for an initial σ_y amplitude oscillation (if υ is not too large) is given by $\delta\epsilon = \sqrt{1 + \upsilon^2} - 1$. Note that for a highly irregular β-function as is found in a BDS, this analytical model gives only a rough approximation.

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We have written a Mathematica program to simulate to first order the wakefield effects in the BDS. The input is Twiss parameters, bunch properties, and the aperture along the beamline. We cut the beamline into $\Delta z \sim 1$ m-long pieces. At each time step the beam properties are advanced through matrix multiplication and a wakefield kick is administered. The beam is cut into slices (typically of length $\Delta s = \sigma_z/5$) and the kick on particle i at any z location is

$$\Delta y'(s_i) = \frac{eN\Delta s}{E}\sum_{j=1}^{i-1} W(s_i-s_j)\lambda(s_j)[y(s_j)-y_a]\,, \tag{5}$$

with y_a the beam pipe misalignment (discussed later). In the case of the RW wake, W on the right hand side is replaced by $\Delta z(W/L)$. Note that in the program the step wake kick is applied at the location of the step-out transitions. This is an approximation: in reality the kick is distributed over the distance $\sim \ell$ from the transitions.

The beta function and initial configuration of the BDS vacuum chamber aperture are shown as functions of beamline position z in Fig. 1(a-b). This aperture configuration has long drifts with a 7 mm aperture where tail folding octupoles [8] are placed. In Fig. 1(c) the quantity β_y/a^3 is plotted, showing that, for the RW wake, the area near $z = 1000$ m can be expected to contribute most to emittance growth. To evaluate the analytical model (with RW wake only) we take $a = 1$ cm, $\beta_y = 6$ km (the average weighted by $1/a^3$), and note that $\mathcal{W}_{rms}/L = 0.29W(\sigma_z)/L \Rightarrow \upsilon = 1.0$ and $\delta\epsilon = 40\%$.

By simulation we find that for this configuration with SS an incoming amplitude $y'_0 = \sigma_{y0'}$ yields 85% emittance growth. We find that most of the contribution comes from the RW wake (see Fig. 2) and that the result is in rough agreement with the analytical model. Note, however, that in a discrete focusing lattice the wake effect of incoming drift (or jitter) depends on the phase (in y_0-y'_0 space) of the perturbation. This can be seen in Fig. 3 where we plot the tolerance for 25% emittance growth as function of incoming phase angle. We see that for this lattice an initial perturbation in y' is near maximum sensitivity.

MISALIGNMENTS

If the beam pipe is misaligned with respect to the nominal beam orbit there will be static emittance growth even without injection error. The strength parameter (for a periodic wake) in a smooth focusing approximation is

$$\upsilon = \frac{e^2 N L_a (y_a)_{rms} \mathcal{W}_{rms}/L}{E}\,\frac{1}{\sqrt{2N_a}}\sqrt{\frac{\beta_y}{\epsilon}}\,. \tag{6}$$

Let us assume that the beam pipe consists of $N_a = 160$, $L_a = 10$ m-pieces that are misaligned randomly with rms $(y_a)_{rms} = 100$ μm. In this case, the smooth focusing approximation predicts $\delta\epsilon = 12\%$. Simulations were also performed for an ensemble of 100 machines with different random errors (see Fig. 4). We find an average emittance growth $\langle\delta\epsilon\rangle \sim 18\%$, a median of 11%, and an rms of 21%.

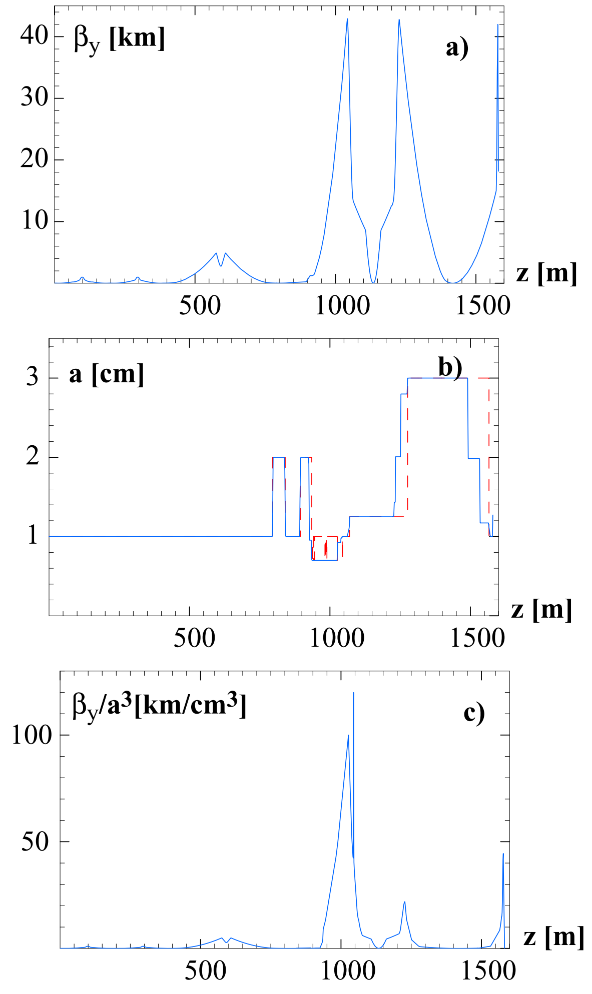

Figure 1: For the initial BDS configuration: β_y, beam pipe radius a, and the quantity β_y/a^3 *vs.* z. In the “1 cm” configuration the 7 mm beam pipe aperture near 950 m was opened to 1 cm (the dashes, discussed below).

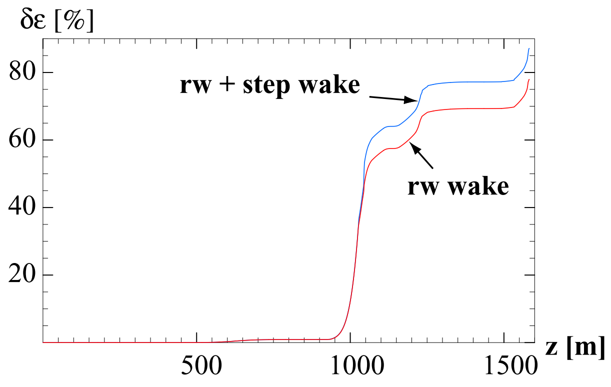

Figure 2: Effect of injection drift: growth in relative emittance caused by initial angle $y'_0 = \sigma_{y0'}$, showing the effect of the RW wake only and the total effect.

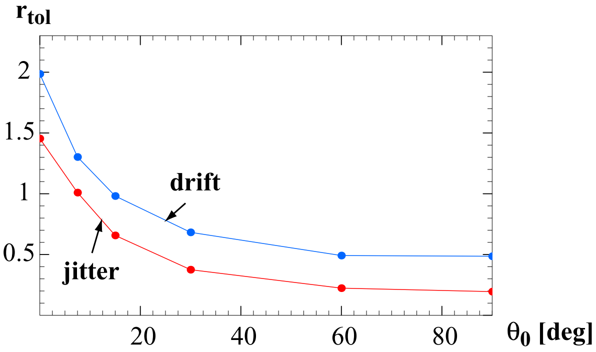

Figure 3: Injection error tolerance r_{tol}, *i.e.* initial offset, normalized to beam size, that gives 25% emittance growth *vs.* angle in $\beta_{y0}y_0'$ by y_0 space, θ_0. Shown are jitter (red) and drift (blue) tolerances.

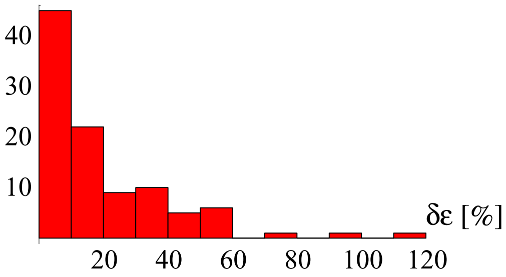

Figure 4: Results of 100 seeds: emittance growth due to misalignments.

For one of the seeds, the development of emittance growth along the beamline is shown in Fig. 5. We again note that the region around $z = 1000$ m dominates in effect.

MITIGATION MEASURES

To reduce the wake effect we consider plating the inner surface of the beam chamber with copper (since the conductivity $\sigma_{\rm Cu} \sim 50\sigma_{\rm SS}$) either everywhere (the Cu chamber) or only in the region $z = 900$–1250 m [the composite (CMP) chamber]. We also consider replacing long drifts of $a = 7$ mm by ones with $a = 1$ cm leaving only a few, short segments at $a = 7$ mm where tail folding octupoles are located; minimizing the number of beam pipe transitions to reduce the geometric wake effect was also performed (the "1 cm" aperture chamber, where transition pairs were reduced from $N_s = 61$ to 18). "2 cm" ($N_s = 97$) and "3 cm" ($N_s = 110$) versions were also considered.

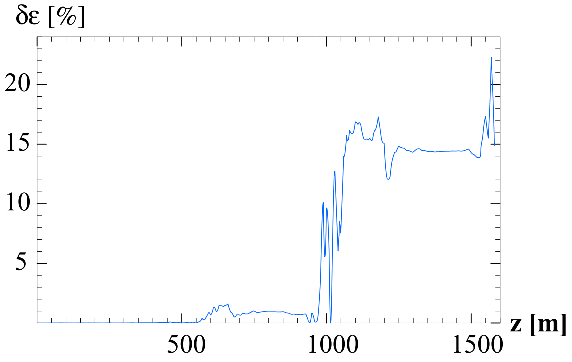

Figure 5: For one example of the misalignment cases of Fig. 4: emittance growth *vs.* z.

The simulated emittance growth due to injection drift for all these cases is given in Table 2. For SS we see that opening up the chamber helps; for CMP and Cu it doesn't. In these cases the four transition pairs around the octupoles generate a step wake that is comparable in size to or larger than the RW wake. The best results are for Cu for the initial or "1 cm" aperture ("1 cm" is slightly worse due to the extra steps at the octupoles), but we choose the "1 cm" variant since the beam pipe chamber is simpler.

Table 2: Emittance growth in [%] due to injection drift of $y_{0'} = \sigma_{y0'}$ for various beam pipe chambers. The RW contribution alone and the total (RW + steps) are given.

Case	RW Contribution			Total		
	SS	CMP	Cu	SS	CMP	Cu
Initial	78	8.7	2.1	87	13	4.9
"1 cm"	46	7.5	1.1	59	15	5.1
"2 cm"	5.6	0.8	0.1	39	25	21
"3 cm"	2.8	0.4	0.1	40	29	26

In the case of bunch-to-bunch jitter, where the offset of the beam centroid at the IP cannot be corrected, with the fully copper-coated "1 cm" chamber an initial jitter amplitude of $y_0' = \sigma_{y'}$ results in 37% emittance growth; this requires the intra-train bunch jitter to be below a quarter sigma, in order to reduce the emittance growth to 1-2%. As to the misalignment effect we find that with $(y_a)_{rms} = 100\ \mu$m, $L_a = 10$ m, for 100 seeds $\delta\epsilon$ has a mean 1.5%, median 0.9%, and rms 1.8%.

CONCLUSION

In the BDS of the ILC the RW wakefield of the beam pipe and the geometric wakefield of the transitions, coupled with incoming (transverse) drift/jitter and/or beam pipe misalignment, will generate emittance growth. To keep the growth to an acceptable level, the BDS vacuum chamber needs to be coated in copper and aligned to an accuracy $\sim 100\ \mu$m rms, and the incoming beam jitter needs to be limited to $\frac{1}{2}\sigma_y$ train-to-train and $\frac{1}{4}\sigma_y$ within a train. Then emittance growth due do this source will be kept to 1-2%.

REFERENCES

[1] ZDR for the NLC, SLAC Report 474 (1996); P. Tenenbaum, SLAC-LCC-0101, Aug. 2002.

[2] G. Rumolo et al, EPAC06, p. 780, 2006.

[3] A. Bungau and R. Barlow, EPAC06, p. 2209, 2006.

[4] A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators (J. Wiley, New York, 1993).

[5] A.W. Chao ed., Handbook of Accelerator Physics, 3rd printing (World Scientific, New Jersey, 2006) p. 237.

[6] E. Gianfelice and L. Palumbo, IEEE Trans. Nucl. Sci. **37**, 1081 (1990).

[7] G. Stupakov et al, PRST-AB **10**, 054401 (2007).

[8] B. Parker et al, "The Superconducting Magnets of the ILC Beam Delivery System," in these Proceedings.