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. Finally, we discuss ways of ameliorating the wake effects in the BDS, such as by changing the metal surface 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 used in this study 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 this study has similarities to Refs. [2],[3].

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

Parameter	Value	Unit
Energy, E	250	GeV
Beamline Length, L	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 two main sources of wakes we consider are the resistance in the walls and the steps of beam pipe transitions. For a metallic beam pipe of conductivity σ and radius a, the dipole resistive wall (RW) wake at position s behind an exciting particle is given by [4]

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

with $Z_0 = 377\ \Omega$ and c the speed of light; $H(s) = 0$ (1) for $s < 0$ (> 0). 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 suffices for our parameter regime. Convolving $W(s)$ with the longitudinal charge distribution, one obtains the bunch wake $\mathcal{W}(s)$. For a Gaussian distribution $\mathcal{W}(s, \sigma_z) = W(\sigma_z)f(s/\sigma_z)$ with

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

and $I_\nu(x)$ the modified Bessel function of order ν. For our parameters the peak $\hat{\mathcal{W}} = 56$ 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 [5],[6]

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

and the wake of the converse, step-in transition is zero. The wake of a (sufficiently separated) matched pair of transitions is the sum of the two. 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 drift error is [4]

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

here L is length of pipe, $\mathcal{W}_{rms}$ the rms of the bunch wake, and β_y the average beta function. The emittance growth for an initial σ_y amplitude oscillation (if υ is not too large) is given by $\delta\epsilon = \sqrt{1 + \upsilon^2} - 1$.

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 $L_a \sim 1$ 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

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$\Delta s = \sigma_z/5$) and the kick experienced by particle i at any time step is

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

with y_a the beam pipe misalignment (discussed later). Note that in the case of the RW wake, the right hand side is multiplied by L_a.

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 [7] 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. By simulation we find that for this configuration with SS an incoming amplitude $y'_0 = \sigma_{y0'}$ yields 85% emittance growth, and that most of the contribution comes from the RW wake (see Fig. 2). To compare with the analytical model (with RW wake only), we note that $\mathcal{W}_{rms} = 0.29W(\sigma_z)$, $\langle\beta_y/a^3\rangle = 6\times10^9$ m^{-2}, $\Rightarrow \upsilon = 1.0$ and $\delta\epsilon = 40\%$, in reasonable agreement.

In a discrete focusing lattice, however, the wake effect of incoming drift (or jitter) depends on the phase of the perturbation. This can be seen in Fig. 3 (the solid curves) where we plot the tolerance for 25% emittance growth as function of incoming phase angle. We see that for this lattice a perturbation in y' is near maximum sensitivity. As a first step to reduce the effect, we considered copper plating the chamber in the 900–1250m region [which we now call the composite (CMP) chamber]. The results are shown in Fig. 3 by dashes. The jitter tolerances are, of course, the tighter of the two and correspond to about half a sigma in the CMP pipe. Note that if the emittance growth tolerance is reduced to a more acceptable 2%, the jitter tolerance becomes 14% of sigma (quadratic dependence of beam emittance on injected beam offset), which is too tight.

MISALIGNMENTS

If the beam pipe is misaligned from the beam axis there will be static emittance growth even without injection error. The strength parameter in a smooth focusing approximation can be written as

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

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 $\delta\epsilon = 12\%$ for the initial beam pipe configuration and SS. To verify the analytical predictions, simulations were performed for an ensemble of 100 machines with different random errors. Results of the simulations are given in Fig. 4 for the SS and CMP chambers. For the latter, we find an average emittance growth $\langle\delta\epsilon\rangle \sim 3\%$,

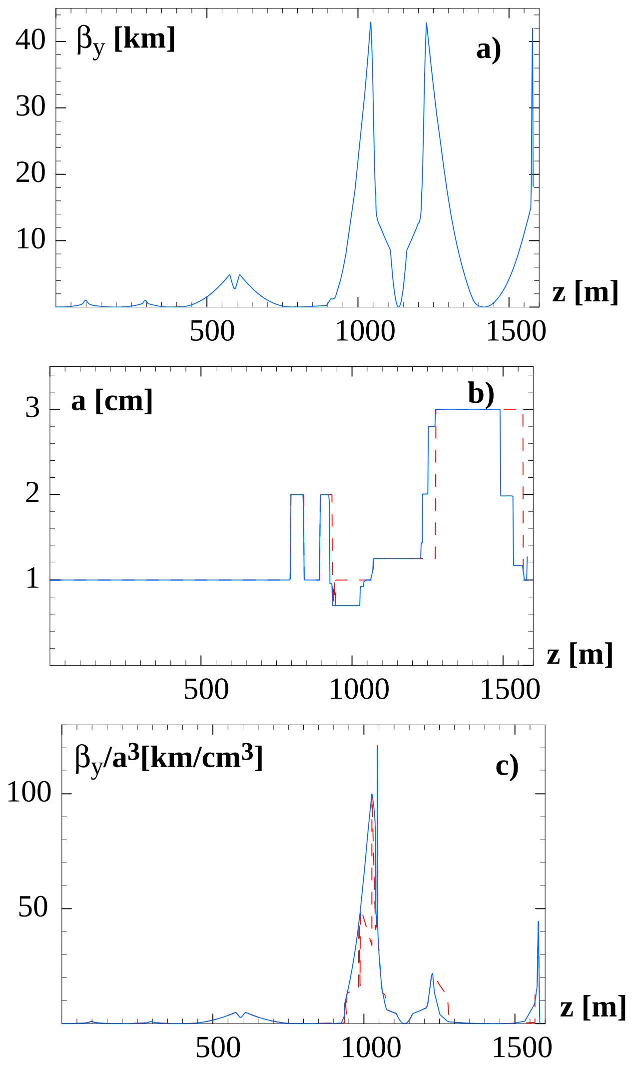

Figure 1: For the initial BDS configuration: β_y, beam pipe radius a, and the quantity β_y/a^3 *vs.* z. In the final ("1 cm") configuration the 7 mm beampipe aperture near 950 m was opened to 1 cm (the dashes, discussed below).

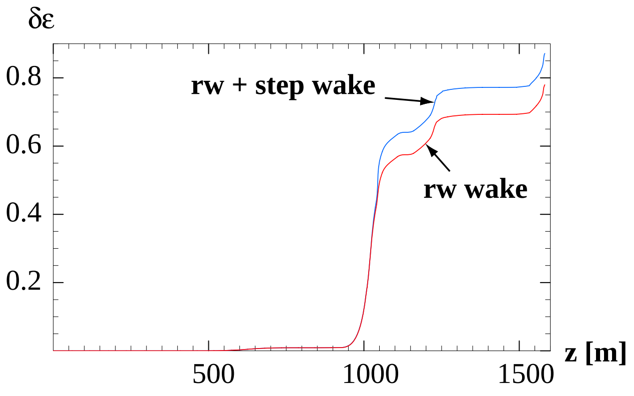

Figure 2: Effect of injection drift: growth in relative emittance caused by initial angle $y'_0 = \sigma_{y0'}$, showing the effect of the RW wake only and the total effect. Corresponds to initial configuration of BDS chamber with SS walls.

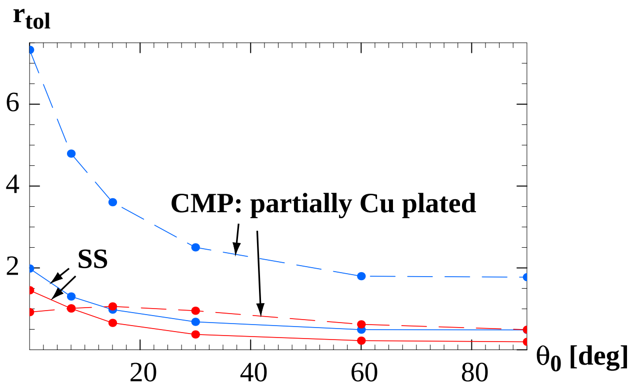

Figure 3: Injection error tolerance r_{tol}, *i.e.* initial offset, normalized to beam size, that gives 25% emittance growth *vs.* angle in $\beta_{y0}y_0'$ by y_0 space, θ_0. Shown are jitter (red) and drift (blue) tolerances; for SS (solid) and the CMP pipe (dashes). Corresponds to initial configuration of BDS vacuum chamber.

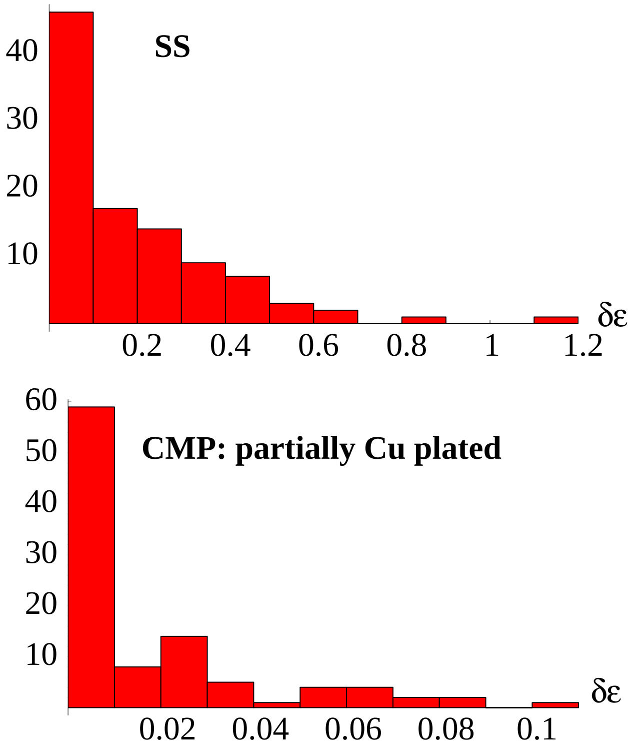

Figure 4: Results of 100 seeds: emittance growth due to misalignments in SS and in the CMP pipe. The misalignment rms size $(y_a)_{rms} = 100\ \mu$m and length $L_a = 10$ m. These correspond to the initial BDS chamber.

a median of 1.7%, and 80% of the cases have $\delta\epsilon < 5\%$. Note that for small growth, the emittance growth scales as $(y_a)^2_{rms}/N_a$. We see that the beam pipes in the delivery system need to be well aligned to the beam axis.

APERTURE VARIATION

As a way to further mitigate the wake effects, we considered 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 case; see Fig. 1, the dashes]. We have studied also increasing the vacuum chamber aperture in all drifts, while keeping it unchanged in magnets (“2 cm” and “3 cm” cases). This, however, resulted in increased geometric wakes and was discarded as a non-optimal approach (see Table 2). We take the “1 cm” case with full Cu plating as being optimal. Note that a more systematic optimization of the apertures to best balance the RW and the geometric wakes locally has not been performed.

Table 2: Emittance growth in [%] due to injection drift $y_{0'} = \sigma_{y0'}$ for varius beam pipe configurations. “Cmp” designates SS, but with Cu at $z = 900$–1250 m. The number of step-pairs N_s is also given.

Case	**SS** $\delta\epsilon_{rw}$	**SS** $\delta\epsilon_{tot}$	**Cu** $\delta\epsilon_{tot}$	**CMP** $\delta\epsilon_{tot}$	N_s
initial	78	87	4.9	13	61
1 cm	46	59	5.1	15	18
2 cm	5.6	39	21	25	97
3 cm	2.8	40			110

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%.

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 of 100 μm 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 this source of emittance growth will be kept to 1-2%.

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