EMITTANCE DILUTION DUE TO DIPOLE MODE ROTATION AND COUPLING IN THE MAIN LINACS OF THE ILC†

R.M. Jones, and R.H. Miller, SLAC, Stanford, CA 94309, USA

Abstract

The progress of multiple bunches of charged particles down the main L-band linacs of the ILC (International Linear Collider) can be disrupted by wakefields. These wakefields correspond to the electromagnetic fields excited in the accelerating cavities and have both long-range and short-range components. The horizontal and vertical modal components of the wakefield will be excited at slightly different frequencies (the dipole mode frequency degeneracy's are split) due to inevitable manufacturing errors. We simulate the progress of the ILC beam down the collider under the influence of these wakefields. In particular, we investigate the consequences on the final emittance dilution of the beam of coupling of the horizontal to the vertical motion of the beam.

INTRODUCTION

In the successful operation of a linear collider it is important to maximize the luminosity of the colliding beams at the interaction point. It can be shown [1] that the luminosity is inversely proportional to the square root of the product of the vertical and horizontal beam emittances. Furthermore, the emittance is driven by wakefields excited by the charged bunches traversing each of the close to 21,000 superconducting cavities in the ILC [2]. The relatively large iris aperture of each of the cells of the cavities reduces leads to a smaller wakefield compared to its X-band counterpart [3]. For realistic manufacturing frequency tolerances the emittance dilution is well controlled [3]. However, little attention has been paid to the splitting of the degenerate mode frequencies that occurs during the process of manufacturing the cavities and its influence on coupling the horizontal motion of the beam into the vertical motion of the beam. Here we investigate the impact of this transverse mode coupling on the vertical beam emittance.

The paper is organized such that the next main section discusses the wakefields associated with the mode frequency splitting and the penultimate main section deals with simulations of the effect of these wakefields on the final emittance of the beam.

TRANSVERSE WAKEFIELDS

We consider the accelerating mode of the cavity being distorted by rotating it through an angle, ϕ. Thus, as the beam travels down the linac the electromagnetic field rotates and the horizontal kick to the beam is coupled to the vertical motion of the beam. The initial voltage kick along the rotated coordinate frame x'-y' (illustrated in fig. 1) is given by:

† Supported by the U.S. DOE grant number DE-AC02-76SF00515

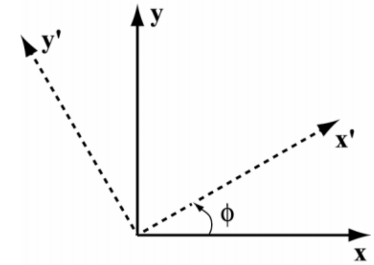

Figure 1: Mode axes for rotational transformation.

$$\left.\begin{aligned} V_{x'}(0) &= V_x(0)\cos\phi \\ V_{y'}(0) &= -V_x(0)\sin\phi \end{aligned}\right\} \qquad (1.1).$$

The resulting voltage kick at any instant in time is then:

$$V_y(t) = V_{x'}(t)\sin\phi + V_{y'}(t)\cos\phi \qquad (1.2).$$

Substituting (1.2) into (1.1) and assuming a time variation of the form $V_{x'}(t) = V_{x'}(0)\exp(j\omega_{x'}t)$, enables the vertical kick that the beam receives to be obtained in terms of the x motion:

$$V_y(t) = jV_x(0)\sin 2\phi \exp\left(j\bar{\omega}t\right)\sin\left(\Delta\omega t/2\right) \quad (1.3)$$

where the average frequency is given by $\bar{\omega}$ and the frequency degeneracy splitting is given by: $\Delta\omega = \omega_{x'} - \omega_{y'}$. The cross-coupled transverse wakefield corresponding to this dipole kick is given by:

$$W_t^{xy}(t)=\sum_p K_p^x\cos(\bar{\omega}_p t)\ \sin(\Delta\omega_p t/2)\ \exp(-\bar{\omega}_p t/2Q_p^x) \ (1.4)$$

where the p[th] modal kick factor and quality factor are given by K_p^x and Q_p^x, respectively. In addition to this cross-coupled term, there is the usual vertical wake [4]:

$$W_t^{yy}(t)=\sum_p K_p^y\sin(\omega_p^y t)\ \exp(-\omega_p^y t/2Q_p^y) \qquad (1.5)$$

where the y superscript indicates a vertical (non-cross-coupled) quantity.

The wakefield that the beam experiences as it travels down the linac will be a combination of (1.4) and (1.5) and will not, of course, be identical for each cavity. In practice random errors introduced during the process of fabricating the cavities result in slightly different kicks to the beam from each cavity.

BEAM DYNAMICS

Well-Damped Modes

We track the beam down the linac using the code LIAR [5] under various conditions and the results of these detailed simulations are illustrated in fig 2 and fig 3. In all simulations the beam is subjected to randomly distributed wakefields along the entire linac. Also, in all cases the beam is injected at 5 GeV, offset horizontally by 400 μm vertically by 10 μm, and exits the linac at 250 GeV. The modes which constitute these wakes are all sufficiently well-damped such that little emittance

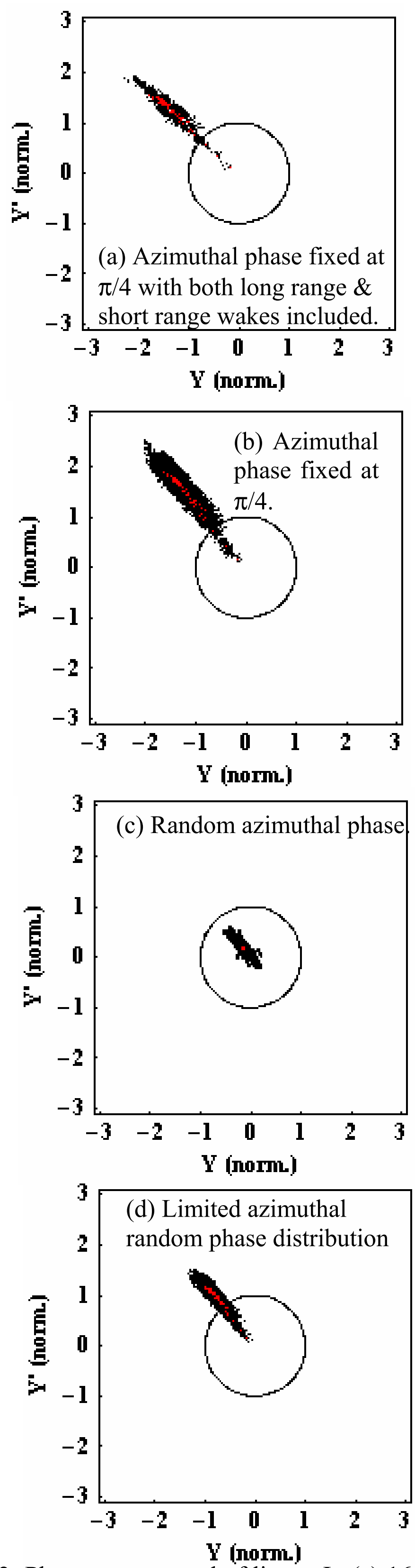

Figure 2: Phase space at end of linac. In (a) 16 machines are simulated. The results of tracking 500 bunches down 200 machines under the influence of *long range wakes* only are illustrated in (b) through (d) for several different azimuthal angle distributions.

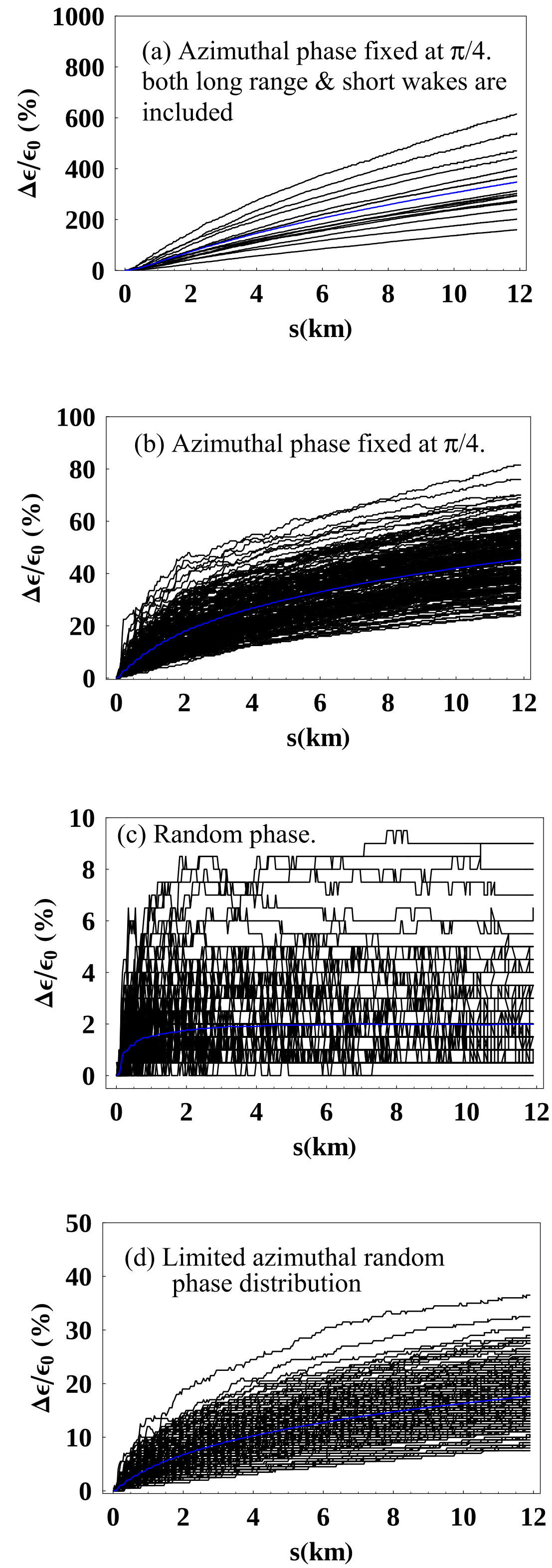

Figure 3: Emittance dilution down linac for the corresponding 200 machines in fig 2. The mean emittance dilution for all machines is indicated by the solid blue line.

dilution occurs when there is no mode coupling [1]. Fig 2(a) and fig 3(a) illustrates the effect of both long and short range wakefield on the beam when the couplers are randomly distributed azimuthally along the linac (with a mean of $\pi/4$). In this case the emittance is diluted by more than 600 % at the end of the linac in the worst case machine. The mean emittance dilution over 16 possible machines is more than 347 %. A substantial fraction of the dilution in the emittance comes from the long-range wakes alone, as readily seen in fig 3(b) in which a similar tracking simulation is made but only long-range wakes are allowed to kick the beam. Allowing the azimuthal angle at which the couplers are positioned along the linac to be randomized (over 0 to 2π) with a mean angle of $\pi/4$ is illustrated in fig 3(c) and here it is clear that the emittance is well preserved down the linac (the worst case machine dilutes the emittance by less than 10 %). However, if we limit the allowable spread in the randomization of the angle to 10 % of the $\pi/4$ then the emittance is not preserved so well and this simulation is shown in fig. 3(d). In practice the couplers will indeed be randomly distributed azimuthally along the linac but at this stage the expected angular spread is not known.

Single-badly Damped Mode

We consider the same dipole mode spectrum as utilized in the previous section except that a high frequency mode is poorly damped. The kick factors and Q values are illustrated in fig 4. On including random frequency errors, we calculate 50 different wakefields and these are illustrated in fig. 5, together with the sum wakefield. The sum wakefield at a particular bunch is defined as the sum of the wakes at all previous bunches [6]. There are resonances in the sum wakefield in which it is significantly larger than unity. From past experience [3] with the simulation of the beam dynamics of X-band accelerating structures we expect BBU [7] to occur when the wake is appreciably larger than unity. Monitoring the emittance dilution as the beam is tracked down the complete linac with the code LIAR is illustrated in fig 6. In the simulation the 50 wakefields have been distributed randomly throughout the entire linac and the azimuthal phases of the couplers have been randomly distributed

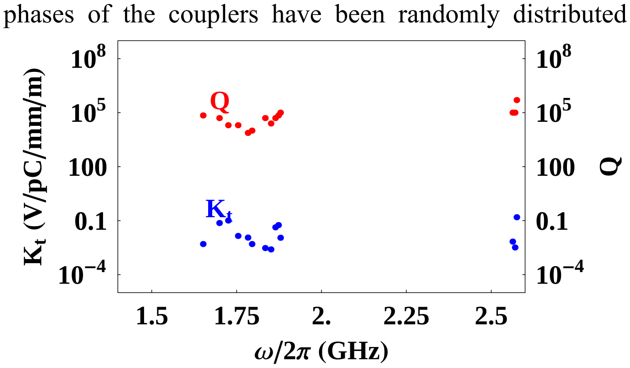

Figure 4: Kick factors and Q values for ILC cavities. The Q at 2.575 GHz has been increased by a factor of 10 to 5 x 10^5.

from 0 to 2π with a mean phase of $\pi/4$. In this situation the final emittance dilution, averaged over 200 machines is 46 %. The maximum dilution of one particular machine in the simulation is almost 150 %. Thus, randomizing the phase distribution of the coupler, together with randomizing the wakefields is insufficient in this situation to produce manageable emittance dilution.

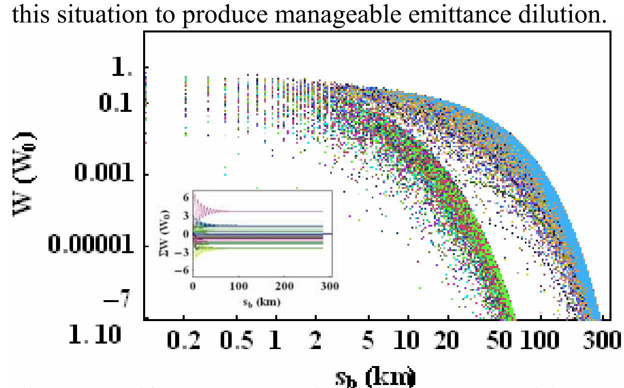

Figure 5: Fifty separate wakefields (represented by each separate color) at the location of each bunch (2820 are shown). The wake is normalized with respect to W_0 = 0.11 V/pC/mm/m. Also shown inset, is the sum wakefield for each of the 50 wakefields.

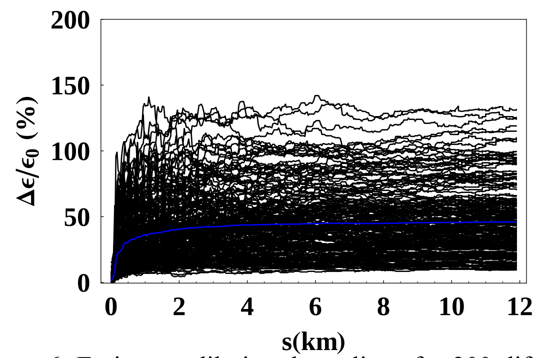

Figure 6: Emittance dilution down linac for 200 different machines under the influence of randomly distributed wakefields. All wakes have one mode which is poorly damped. The blue line corresponds to the average emittance dilution.

CONCLUSIONS

Further detailed simulations into the effect of mode rotation on the beam emittance are required. However, these initial simulations suggest that mode coupling may lead to a significantly degraded beam emittance.

ACKNOWLEDGEMENTS

This work has benefited from stimulating discussions in the weekly ILC structures meetings at SLAC. I am grateful to Peter Tenenbaum for modifying LIAR.

REFERENCES

[1] N. Baboi *et al.*, LINAC04, SLAC-PUB-10684
[2] http://www.interactions.org/linearcollider/
[3] R.M. Jones *et al.*, EPAC04, SLAC-PUB-10556
[4] P.B. Wilson, SLAC-PUB-4547
[5] R. Assman *et al.*, LIAR, SLAC-PUB-AP-103
[6] R.M. Jones *et al.*, LINAC04, SLAC-PUB-10683
[7] K. Yokoya, DESY Report 86-084, 1986

