SIMULATION STUDIES ON COUPLER WAKEFIELD AND RF KICKS FOR THE INTERNATIONAL LINEAR COLLIDER WITH MERLIN*

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Abstract

One of the critical issues in the design of the superconducting cavities for the International Linear Collider (ILC) is the influence of the RF and higher order mode (HOM) couplers on the beam dynamics. Both types of couplers break the rotational symmetry of the cavity and introduce non-vanishing transverse wakefields even on the cavity axis. Furthermore, the couplers introduce an asymmetry into the accelerating RF field and thereby additional transverse field components. We have implemented both effects following the calculations presented previously [1] into the MERLIN library [2]. This allows us to study the influence of wakefield and RF kicks on the beam dynamics, the bunch shape and the overall performance of the ILC for the present design and a proposed modification of the coupler orientation.

INTRODUCTION

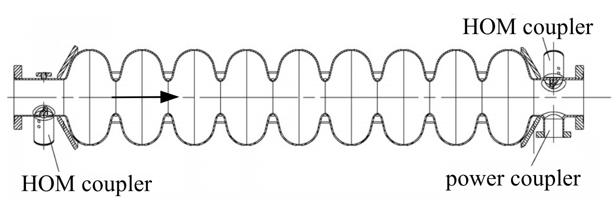

Figure 1: The TESLA cavity with RF power and HOM couplers.

The TESLA 9-cell superconductive cavity (Fig. 1) that has been chosen for the ILC baseline design consists of 9 accelerating cells and 2 end groups. Each end group has a resonant higher order mode (HOM) coupler structure for extracting HOM power. One end group – in the ILC main linac design the downstream end group – carries in addition the RF power input coupler.

Parametrisations of longitudinal and transverse wakefields for the resonator part are available [3] and had been used routinely in MERLIN simulations. Unlike the cavity transverse wakefield, the coupler transverse wakefield does not vanish on the cavity axis since the coupler destroys the rotational symmetry. The couplers also introduce an asymmetry into the accelerating RF field and thereby additional field components. A numerical approximation of these transverse fields in the vicinity of the beam axis has been given recently by I. Zagorodnov and M. Dohlus [1]. In particular (see below) the coupler wakefields have a strong influence on the beam dynamics. As suggested in [1] the HOM couplers could be rotated by 90° relative to the RF coupler (Fig. 2) such that the wakefield kicks partially cancel. In the following we refer to this proposed design change as the *new* compared to the *old* configuration.

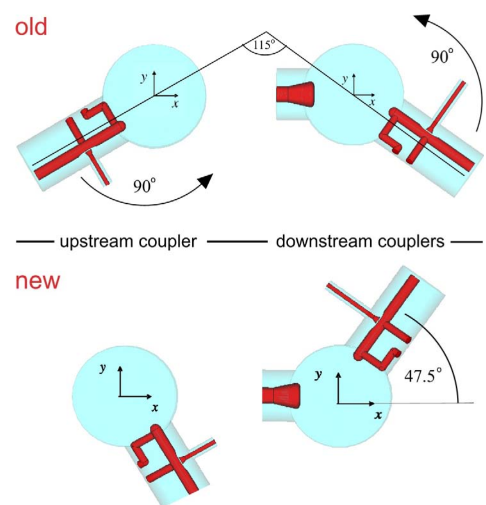

Figure 2: Relative orientation of couplers for the nominal (old) and the modified (new) design.

NUMERICAL APPROXIMATIONS

The different transverse kicks are practically independent over the length of a single cavity and it suffices to add up the transverse components at the cavity exit. The sums of the up- and downstream transverse wakefield kicks are

$$\mathbf{k}(x,y) \overset{old}{=} \begin{bmatrix} -21 \\ -19 \end{bmatrix} + \begin{bmatrix} 4300 & 70 \\ 30 & -900 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (1)$$

$$\mathbf{k}(x,y) \overset{new}{=} \begin{bmatrix} -2.5 \\ -0.2 \end{bmatrix} + \begin{bmatrix} 2330 & 40 \\ -20 & 1100 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (2)$$

where x and y are given in m and the transverse kick $(k_x, k_y) = \mathbf{k} := \langle \mathbf{W} \rangle$ in V/nC. The expectation value is taken over the normalized bunch distribution $\lambda(s)$

$$\langle f \rangle = \int_{-\infty}^{\infty} f(s)\lambda(s)ds. \quad (3)$$

For simulations we assume a purely capacitive wake potential ($w_{x,y} = 2k_{x,y} = const$) i.e. we ignore the slope.

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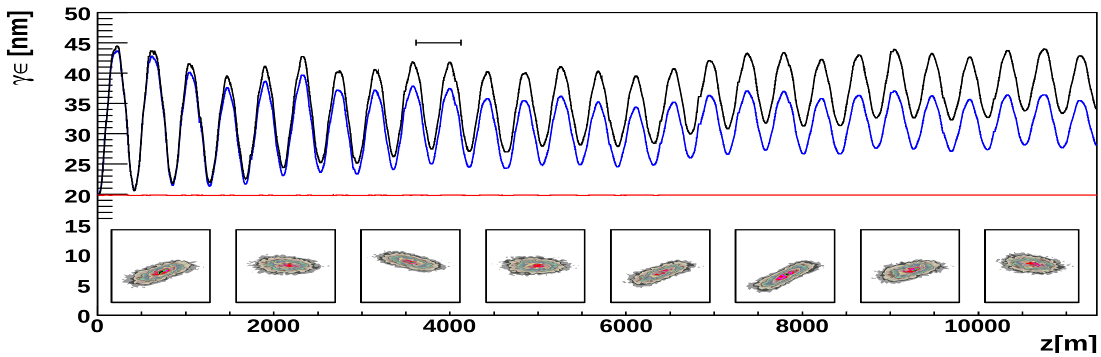

Figure 3: Coupler wakefield kicks: The projected emittance $\gamma\epsilon_y$ along the main linac. The old coupler design is shown in black, the influence of the 1-2-1 steering in blue. The flat red line shows $\gamma\epsilon_y$ for the new configuration. The additional small plots show the bunch in the y-ct-plane ($-1mm \leq ct \leq 1mm$, $-20\mu m \leq y \leq 20\mu m$) in the middle (marked by a short black line) of the linac. The head of the bunch points to the right.

This is valid for short bunches and is to be considered as an upper limit in the general case. The transverse bunch wakefield for a particle at distance s from the bunch head is then given by

$$\mathbf{W}(s) = 2\mathbf{k}\int_{-\infty}^{s}\lambda(s)ds. \tag{4}$$

The second effect, the transverse components of the accelerating field, can be described by the complex ratios $\mathbf{v} = (v_x, v_y) := 10^6 \cdot \mathbf{V}/V_{||}$, where $V_{||}$ is the accelerating potential.

$$\mathbf{v}(x,y) \overset{old}{=} \begin{bmatrix} -82+58i \\ -9.2+1.8i \end{bmatrix} + \begin{bmatrix} -29-27i & 63+5.1i \\ 63+7.0i & 28+24i \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} \tag{5}$$

$$\mathbf{v}(x,y) \overset{new}{=} \begin{bmatrix} -82+58i \\ -74-8.7i \end{bmatrix} + \begin{bmatrix} -29-27i & 63+5.1i \\ 4.9+2.9i & -48-12i \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} \tag{6}$$

Numerical RF field calculations for the new coupler configuration are not given in [1]. As an approximation we use the mirror image $\mathrm{v_y} \rightarrow -\mathrm{v_y}$. The angle between the x-axis and the HOM coupler is in this case only $42.5°$ instead of $47.5°$. The transverse kick is proportional to the real part $\Re\{\mathbf{v}(x,y)\} = \Delta\mathbf{p}_T/\Delta p_{||}$, with $\Delta p_{||} = \Delta E = gl$, $g = 31.5$ GeV/m, $l = 1.036$ m (gradient and cavity length). For example

$$p_y = \Delta E|v_y|\Re\left\{e^{i(\phi_c-\varphi-k\Delta z)}\right\}. \tag{7}$$

Here ϕ_c is the coupler phase, φ the RF phase, $\Delta z = -\Delta ct$ the longitudinal position of a particle at φ and $k = 2\pi f/c$ (ILC: $\varphi = 5.3°$, $f = 1.3$ GHz).

ESTIMATES

A first insight into the coupler related disturbances can be gained by comparing with cavity misalignments that produce effects of similar order. The increase in bunch size is related to the RMS defined as $\mathbf{k}^{RMS} = \sqrt{\langle(\mathbf{W}-\langle\mathbf{W}\rangle)^2\rangle}$. With the assumption of a constant $w_{x,y}$ it holds that $\mathbf{k}^{RMS} = \mathbf{k}/\sqrt{3}$ and from (1) we get $Q\,k_y^{RMS} = 34$ V for a typical ILC bunch ($Q = 3.2$ nC) on cavity axis. For the cavity transverse wakefields given in [3] we get $Q\,k^{RMS} = 20$ V/mm and conclude that the old coupler wakefield is comparable to a 2 mm transverse displacement of a cavity. Equation (2), the new design, gives the much smaller result of $Q\,k_y^{RMS} = 0.37$ V.

Equation (7) can be approximated for a short bunch as $p_y = \Delta E|\mathbf{v}_y|(\cos(\phi_c-\varphi)+k\Delta z\sin(\phi_c-\varphi))$ and we have $\langle p_y\rangle = \Delta E\Re\{v_y e^{-i\varphi}\}$ and $p_y^{RMS} = \Delta E\sigma_z k\Im\{v_y e^{-i\varphi}\}$. On the other hand a cavity tilt α produces a similar effect given by [4] $p_{tilt} = \frac{1}{2}\alpha\Delta E\Re\{e^{-i(k\Delta z+\varphi)}\}$. If we compare this numerically with (5) and (6) for a gaussian bunch with $\sigma_z = 300\,\mu$m the additional spread p_y^{RMS} is negligible on crest and even at zero-crossing smaller than for a 100 μrad cavity tilt. The kick on the bunch centroid is about 284 V in the old configuration and becomes even larger with new coupler orientation: 2350 V.

SIMULATION RESULTS

In this section, simulation results for a model of the ILC electron linac without the undulator section are given. For simplicity we neglect all component errors and consider a perfect machine with longitudinal and transverse cavity wakefields included. The linac contains 312 quads, each instrumented with a corrector and a BPM for x and y separately. The bunch is kept on the nominal orbit at the BPMs by a 1-2-1 steering algorithm. We assume a vertical emittance of 20 nm at the start of the linac. The bunch is accelerated from 15 GeV to 250 GeV

First we add the transverse coupler wakefields to this model. The emittance along the linac is shown in Fig. 3. Snapshots of the bunch profile in the y-ct-plane in the middle of the linac (quads $100, 102, \ldots, 114$) are added to illustrate the effect. The bunch tail immediately starts to oscillate strongly driven by the coupler wakefield. The kick is stronger at low energy i.e. at the begin of the linac. The 1-2-1 steering can only compensate the offset of the centroid but not the oscillation within the bunch. The vertical

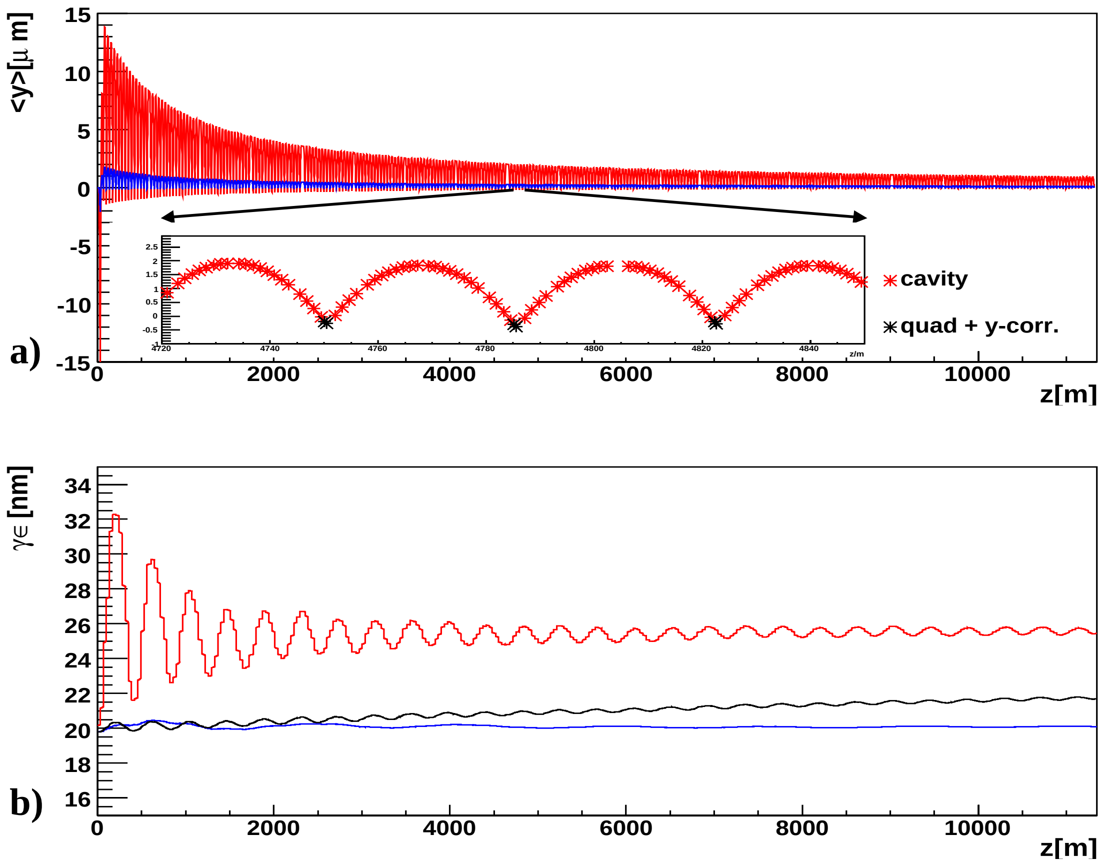

Figure 4: Coupler RF kicks: The new coupler design is shown in red, the old configuration in blue. The upper plot shows the trajectory $\langle y \rangle$ along the main linac. The lower plot shows projected emittance $\gamma\epsilon_y$ and the dispersion corrected emittance for the new coupler orientation in black.

emittance increases to 28 nm at the end of the linac. In the new configuration the coupler wakefield kicks are suppressed by about a factor of 10 in x and about 100 in y according to (1) and (2). The strong cancellation is visible in Fig. 3. The emittance stays constant over the full length of the linac (red line).

In Fig. 4a the RF kicks are included and the coupler wakefields are set to zero. There are 26 cavities between 2 correctors. At each cavity the bunch receives a negative y-kick which is compensated by a positive corrector kick. The y-trajectory is forced thereby into a kind of jumping ball orbit. This results in an increase of the emittance along the linac (Fig. 4b). If one corrects for dispersive effects the emittance increases to 21.8 nm at the end of the linac.

CONCLUSION

The additional contribution to the emittance budget by the coupler wakefields would not endanger the operation of the linac. Nevertheless, the large size of the effect makes an intrinsic compensation desirable as given by the modified design. The large improvement depends on the exact cancellation of the wakefield kicks. It needs further studies in as much this cancellation stays valid if fabrication tolerances are considered. A disadvantage of the modified design is the stronger RF kick. Even though the effect still appears to be acceptable, one should keep in mind that the wakefield calculations in [1] are meant as an upper limit and it had been argued [5] that for a periodic structure the wakes may be reduced approximately by factor of 3.

Acknowledgement

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REFERENCES

[1] I. Zagorodnov and M. Dohlus, LCWS/ILC, Hamburg 2007.

[2] `http://www.desy.de/~merlin`.

[3] T. Weiland, I. Zagorodnov, TESLA Report 2003-19.

[4] Note that the kick is only proportional to $\alpha/2$,e.g. G.V. Stupakov, LCC-0018, LCC Tech Note, SLAC.

[5] V. Yakolev et al., Wake Fest 07, SLAC 2007, K. Bane and I. Zagorodnov ibid.