EMITTANCE DILUTION CAUSED BY THE COUPLERS IN THE MAIN LINAC AND IN THE BUNCH COMPRESSORS OF ILC*

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INTRODUCTION

In future linear colliders, such as the International Linear Collider (ILC), axial asymmetries in the accelerating cavities might generate asymmetries in the fields that kick the beam and tend to degrade the beam emittance, and thus the collider performances[1]. In this paper we present the results of calculations of transverse wakefields and RF kicks (from the power- and high order modes- couplers of the acceleration structure) and their impact on the beam dynamics in the main linac as well as the bunch compressors of ILC. Coupler kicks have been implemented in the tracking code PLACET[2] to study and counteract the emittance growth induced by this effect. The results of the simulations are presented in this paper.

RF Kick. Calculations of RF kicks made with numerical codes have been presented in [3]. If ϕ is the cavity's operational phase and V_a is the energy gain per cavity, the intensity $\vec{V}$ of the RF kick can be expressed as $\vec{V} = \vec{V_0}/V_a e^{i\phi}$. Tab. 1 summarizes the results for $\vec{V_0}$, for the upstream and the downstream couplers. As this kick is the same for all acceleration structures, the contributions given by each acceleration structure add coherently along the accelerator.

Table 1: RF kick for the couplers of the ILC acceleration structures[3].

	$10^6\ V_{0_x}/V_a$	$10^6\ V_{0_y}/V_a$
upstream	$-68.8 + \ 3.7i$	$-48.3 - \ 3.4i$
downstream	$-36.5 + 66.1i$	$41.0 + 14.5i$
total	$-105.3 + 69.8i$	$-7.3 - 11.1i$

The fact that $\vec{V}$ is a complex number has a direct implication on the beam dynamics: the real part of $\vec{V}$, in fact, acts on the bunch as a whole and therefore can be compensated -locally- by some alignment technique (a simple 1-to-1 correction for instance is usually sufficient), on the other hand, its imaginary part affects the bunch differently all along its length, causing a dilution that cannot be locally corrected. This happens because the head of the bunch receives a kick of opposite sign with respect to the tail, and this induces an oscillation in the bunch. Analytical calculations show that, in an uniform focusing lattice under the effect of a constant transverse RF kick, the emittance grows as follows:

$$\epsilon \approx \epsilon_0 + \frac{(F')^2\sigma^2\beta^3\gamma_0}{2U_0^2}\left(1 - 2\sqrt{\frac{\gamma_0}{\gamma(z)}}\cos(z/\beta) + \frac{\gamma_0}{\gamma(z)}\right)$$

* Work supported by the US DoE
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where ϵ_0 is the initial emittance, F' is the first derivative of the kick for $z = 0$, σ is the bunch length, β is the betatron amplitude, U_0 is the initial energy and γ_0 the corresponding relativistic factor.

It is convenient to study this formula in two regimes: in presence and in absence of acceleration. In absence of acceleration, $\gamma(z) = \gamma_0$, the growth of the emittance vanishes when the cosine term is 1, that is when $z/\beta = 2\pi n$, with n integer. The simulations reported in this paper show manifestly this effect. See for example Fig. 1. From such a plot we conclude that a careful design of the focusing lattice, taking into account this effect, can be very beneficial for the overall performance of the accelerator.

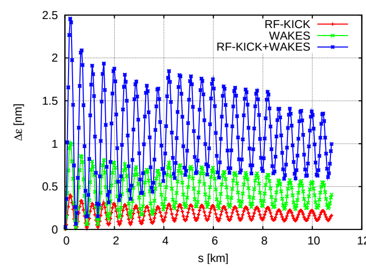

Figure 1: Emittance growth along the ILC main linac under the effects of RF and wakefield kicks induced by the couplers.

In presence of acceleration the oscillatory behavior of the emittance persists, but there is a residual emittance growth that cannot be avoided. This can be understood

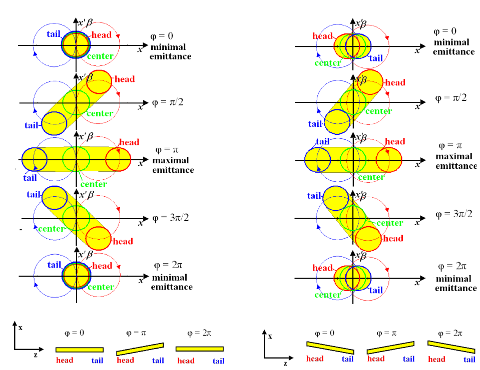

Figure 2: Phase diagrams for different betatron phases for particle belonging to different transverse bunch cross sections: head (red), center (green), and tail (blue). The emittance of the entire bunch is shown in yellow. Left and right hand sides show the cases without- and with- acceleration.

considering that the potential well of the focusing force is shifted by the RF kick and its offset decays faster than the oscillation radius ($1/\gamma \ll \sqrt{1/\gamma}$). A pictorial explanation of this phenomenon is visible in Fig. 2.

Wakefield Kick. Calculations of wake-potentials in the acceleration structures of ILC, including RF cavities and input/high order modes (HOM) couplers, have been presented in [4]. Calculations of the associate transverse wakefields $W_{x,y}(z)$ are also presented in the same paper, where the wakefield functions are calculated for Gaussian bunches.

It must be noted that, similarly to the imaginary part of the RF kick, also the wakefield kick does not depend on the transverse coordinates of the particles but only on their longitudinal position within the bunch. This dependence causes an emittance dilution that cannot be locally compensated by elementary techniques. For a bunch length of 0.3 mm (main linac) the horizontal an vertical kick-factors are -1.8 V/nC and -1.7 V/nC, respectively. As the kick-factor depends linearly on the bunch length, the emittance dilution for the bunch compressor may constitute a more serious problem than for the main linac.

IMPLEMENTATION IN PLACET

All beam dynamics simulations have been carried out using the tracking code PLACET, that has been accordingly modified in order to take into account the couplers' effects.

RF kick. The RF kick has been implemented using a crab cavity. The original element present in the code has been modified to accept a complex number as a voltage. When the voltage is just a number the crab kick reduces to its usual form, when it is a complex number, $\vec{V}$, the kick is

$$\Delta y' = \frac{e}{E_0}\left(V_{\mathrm{real}}\cos(ks) \;-\; V_{\mathrm{imag}}\sin(ks)\right),$$

which corresponds to the RF kick definition as given in [3].

Wakefields. Wakefield functions caused by the couplers in the acceleration structures of ILC, have been calculated by numerical electromagnetic solvers and implemented in PLACET using tables of function profiles. The PLACET implementation consists of a Octave-like[5] script that is available upon request. This implementation has been successfully benchmarked against its equivalent in LUCRETIA[7].

EMITTANCE GROWTH IN THE MAIN LINAC

Simulations of the couplers' kicks in the main linac of the ILC have been carried out. We used the positron line of the "ILC2007b" version of the lattice[6], because this line does not include the undulator section. All simulations presented in this paper show the emittance growth along the lattice for a perfect machine, i.e. without any element misalignment and with ideal beam position monitors (BPM). A step of 1-to-1 correction is necessary in order to steer the beam back to the center of the BPMs. The final vertical emittance growth is 0.6 nm after a dispersion correction. "Dispersion-corrected" emittance is the emittance calculated after removing the dispersion from the bunch in both transverse planes. This is a better estimate of the actual, physical, beam emittance.

Fig. 1 shows the emittance growth along the lattice and Tab. 2 reports the emittance growth due to the individual contributions of both kicks, as well as the emittance growth after each step of correction. Note that the RF kick is dominant, when not corrected, because the average kick is two orders greater than the kick spread, for a bunch 300 μm long.

Table 2: Final vertical emittance growth, in nm, in the main linac.

Method	RF	Wakes	RF+Wakes
no correction	46.6	0.3	50.2
1-to-1	0.2	0.24(9)	0.7
1-to-1 disp. corrected	0.1	0.24(8)	0.6

EMITTANCE GROWTH IN THE BUNCH COMPRESSOR

Two-Stage Bunch Compressor. The effects of the coupler kicks have been studied also in the ILC bunch compressors. We used the baseline configuration, which is part of the ILC2007b archive, consisting of a double stage bunch compressor designed to compress the bunch length from 6 mm to 300 μm, passing by an intermediate length of $\approx$ 1 mm.

Similarly to the main linac, the simulations presented in this section show the emittance growth for a perfect machine with ideal beam position monitors. Also in this case, a step of 1-to-1 correction is applied in order to steer the beam back to the center of the BPMs. The final vertical emittance is calculated removing the dispersion from the bunch, as described in the previous section. Result of the simulation shows a final vertical emittance growth as big as 5.6 nm. This value is clearly not acceptable, as it exceeds the required bunch compressor budget of 5 nm emittance growth, foreseen for the bunch compressor including element misalignment. Results for RF and wake kicks separately are given in Tab. 3.

In order to further reduce the emittance, another step of optimization is necessary. We examined three possibilities: (1) use of dispersion bumps, (2) optimization of the girder pitches and (3) compensation using crab cavities. The first method consists in adding two dispersion bumps to the lattice, one at the entrance and another at the exit of the bunch compressor, then tuning the dispersion at both ends until the final vertical emittance is minimal. The second method,

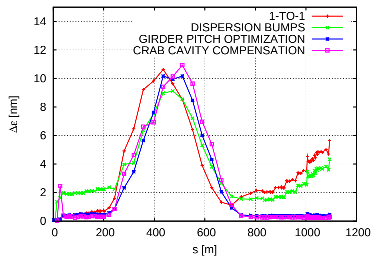

Figure 3: Emittance growth along the two-stage bunch compressor after the three correction schemes proposed.

Table 3: Final vertical emittance growth, in nm, in the two-stage bunch compressor.

Method	RF	Wakes	RF+Wakes
no correction	28.0	6.9	23.4
1-to-1	2.1	3.4	7.8
1-to-1 disp. corrected	1.6	2.8	5.6
dispersion bumps	1.4	2.4	4.3
girder optimization	0.3	0.5	0.5
crab cavity compensation	0.2	0.3	0.3

called girder pitch optimization, consists in vertically tilting three cryomodules in BC1 and four in BC2 in order to generate a transverse kick spread that compensates the coupler kick (this is possible as cavities operate out of crest). The third method consists in adding a crab cavity kick at end of three cryomodules in BC1 and four in BC2, at the same purpose. All these methods proved to be very effective: dispersion bumps reduced the emittance growth to 4.3 nm, girder pitch optimization to 0.6 nm and the crab cavity option to 0.3 nm. Compensation using crab cavity kicks seems to be the most effective, but the insertion of a real crab cavity would require the design of a new deflecting cavity, operating at TM_{110} mode, that fits into the cryomodule, and the redesign of the power distribution system for the sections containing the crab cavity.

Single-Stage Bunch Compressor. The option for a single-stage bunch compressor is under study as an alternative to the baseline two-stage compression. Single-stage bunch compressor features a RF section to introduce the energy chirp in the bunch, a wiggler to compress the bunch length and an accelerating linac to boost the particles from 5 to 15 GeV.

Simulations showed that the final emittance growth after 1-to-1 correction is 4.2 nm. Although this value is already below the threshold which is acceptable for the RTML, the three alignment techniques described in the previous paragraph have been tested to further reduce it. A total of six cryomodules has been used for the girder pitch optimization: three in the first RF section and three in the pre-linac section. Resulting angles after girder optimization are of the order of $\approx 100\ \mu$ rad, misplacements of 10 μm at the two ends of the girders cause 0.5 nm emittance growth. For the crab cavity compensation, a total of six crab cavity kicks has been inserted in the lattice: three in the RF section and three in the pre-linac section. The results are summarized in Tab. 4 and shown in Fig. 4.

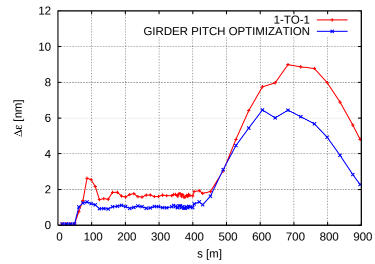

Figure 4: Emittance growth along the single-stage bunch compressor.

Table 4: Final vertical emittance growth, in nm, in the single-stage bunch compressor.

Method	RF	Wakes	RF+Wakes
no correction	72.2	4.6	57.6
1-to-1	2.4	2.4	4.8
1-to-1 disp. corrected	2.0	2.0	4.2
dispersion bumps	1.3	2.0	3.4
girder optimization	0.7	1.1	2.5
crab cavity compensation	0.3	1.6	1.4

CONCLUSIONS

Coupler kicks have been implemented in the tracking code PLACET to study the emittance growth induced in the main linac and in the bunch compressors of the ILC. Beam-based alignment techniques have been tested to counteract it. Simulations showed that in the main linac this effect does not seem to be critical, whereas in the bunch compressors it may constitute a problem. Emittance growth in the two-stage bunch compressor is beyond the budget, even after the standard alignment routines. To eliminate this growth further alignment procedures have been envisaged and tested, with very good results. Nevertheless, as their practical implementation would require additional efforts and costs, a modification of the coupler unit may eventually be necessary, instead, to preserve the cavity axial symmetry. Single-stage bunch compressor shows acceptable performances even after standard alignment techniques.

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