EMITTANCE PRESERVATION IN THE INTERNATIONAL LINEAR COLLIDER RING TO MAIN LINAC TRANSFER LINE*

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Abstract

The very small vertical beam emittance in the International Linear Collider (ILC) can be degraded by dispersion, xy coupling, transverse wakefields, and time-varying transverse fields introduced by elements with misalignments, strength errors, xy rotation errors, or yz rotation errors in the Ring to Main Linac (RTML) transfer line. We present a plan for emittance preservation in this beamline which uses local, quasi-local, and global correction schemes. Results of simulations of the emittance preservation algorithm are also presented and discussed.

INTRODUCTION

The Ring to Main Linac (RTML) transfer lines connect the 5 GeV damping rings of the International Linear Collider (ILC) to the main linacs which accelerate the electron and positron beams to 250 GeV each. There are 2 RTML beamlines in the ILC, one for electrons and one for positrons, and the two are identical. The main functions of the RTML beamlines are bunch compression, acceleration from 5 GeV to 15 GeV, spin rotation, collimation of any beam halo particles generated in the damping ring, and feed-forward correction of damping ring extraction jitter. The layout of the RTML is shown in Figure 1, and the Twiss parameters are shown in Figure 2. The RTML is typically divided into an "upstream RTML" region, prior to the bunch compressor, in which the energy spread is low but bunches are long; and a "downstream RTML," which includes the compressor, in which the energy spread is large and the bunches are shorter.

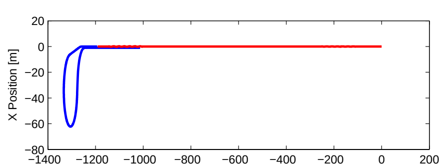

Figure 1: Layout of the RTML, showing the "Upstream" (blue) and the "Downstream" (red) areas.

A key requirement of the RTML is preservation of the very small normalized vertical emittance (20 nm) produced

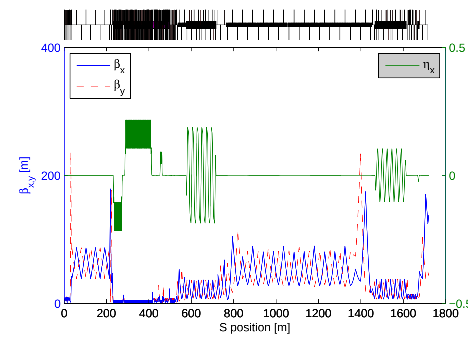

Figure 2: Twiss functions of the RTML.

by the damping rings: the nominal emittance growth budget for the RTML is 4 nm. The main sources of emittance dilution are: dispersion, from misaligned quadrupoles or rolled bend magnets; betatron coupling, from rolled quadrupoles or errors in the spin rotator section (where strong coupling from the spin rotator solenoids is corrected by an optical transformer system [1]); and time-varying vertical kicks from RF cavities which are pitched relative to the nominal beam trajectory. We present the result of a series of simulation studies on the effectiveness of emittance preservation techniques in the RTML.

The studies described were performed using an early version of the RTML optics. In the intervening period, the RTML has been redesigned to accommodate relocation of the damping rings to a central injector campus, and the parameters of the beam extracted from the damping ring have changed as well [2]. The performance of the latest optics has not yet been studied.

UPSTREAM RTML

Upstream of the RF cavities used in the first-stage bunch compressor (BC1), the sources of emittance growth are: dispersion from misaligned quads and rolled bends; and betatron coupling from rolled quads and errors in the spin rotator. Table 1 shows the RMS misalignments and errors used in studies of the Upstream RTML. In the absence of all correction, the errors in Table 1 would result in hundreds of nm of emittance growth. In these studies, it is assumed that the tight tolerance on the alignment of the BPM to the quad is achieved through a beam-based alignment process using quad shunting [3]. This process is not simulated. The

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Table 1: Misalignments and Errors used in Upstream RTML simulations.

Error type	RMS Error	With Respect To
Quad misalign	150 μm	Survey Line
BPM misalign	7 μm	Quad Axes
Quad rotation	300 μrad	Survey Line
Quad strength	0.25%	Nominal
Bend rotation	300 μrad	Survey Line
Bend strength	0.5%	Nominal

remaining residual misalignment is an estimate of the systematic limits of the procedure [4].

Dispersion Correction

The first step in dispersion correction is orbit correction. The orbit correction technique used for the upstream RTML is Kick Minimization (KM) [5]. In KM, the BPM vertical reading ($Y_{\rm BPM}$) and the normalized corrector-BPM difference ($K_{\rm Q}L_{\rm Q}Y_{\rm BPM} - \theta_{\rm corr}$) are simultaneously minimized, with a χ^2 defined as follows:

$$\chi^2 = \sum_{\rm BPMs} \frac{Y_{\rm BPM}^2}{(150\mu{\rm m})^2} + \sum_{\rm BPMs} \frac{(K_{\rm Q}L_{\rm Q}Y_{\rm BPM} - \theta_{\rm corr})^2}{(7\mu{\rm m})^2}. \tag{1}$$

Eq. 1 assumes that there is a quadrupole and a vertical orbit corrector at each BPM location, which is the case in the RTML, and the weights in the minimization are based on the estimated relative scales of the misalignments.

A simulation study was performed which applied the errors described above to 100 seeds of the upstream RTML, and applied the kick minimization steering correction procedure in both planes. The mean emittance growth after 2 iterations of KM orbit correction was reduced to 23.3 nm.

The second step in dispersion correction is to use global dispersion knobs to directly minimize the emittance. For this purpose, skew quadrupoles were inserted in the dispersive region of the turnaround. The skew quads were placed in pairs with 180 degrees of phase advance in x and y between the skew quads of each pair. By exciting the skew quads with equal and opposite strengths, it is possible to generate dispersion without generating any unwanted betatron coupling. Two pairs of skew quads, with a phase offset of 90 degrees between pairs, permits both phases of dispersion to be corrected.

The dispersion correction was implemented by varying the strength of a knob and observing the resulting change in the beam size on the wire scanners located downstream of the spin rotator. When the steering plus knobs algorithm was applied to a 100 seed simulation, the mean resulting emittance growth was reduced to 7.6 nm.

Upon further investigation, it was found that the 7.6 nm of emittance growth was dominated by betatron coupling (6.1 nm); the second most significant contribution to the emittance growth was found to be chromatic effects from the matching regions between the weak-focusing collimation lattice and the strong-focusing lattices which precede and follow it (1.5 nm); the actual emittance growth due to dispersion was almost completely eliminated.

Coupling Correction

Four skew quadrupoles in non-dispersive regions are used to correct betatron coupling globally. The phase advances of the coupling correction skew quads are set such that all 4 phases of betatron coupling can be independently corrected. The coupling is applied by varying the strengths of the skew quads and measuring the beam size on the wire scanners downstream of the spin rotator, in particular minimizing the beam rotation (or $< xy >$ value) at an appropriate wire or set of wires. This emittance station contains sufficient wire scanners, at appropriate phases, for full reconstruction of the normal-mode emittances and coupling parameters of the beam.

The original placement of the coupling correction skew quads was far upstream of the wire scanners, near the damping ring extraction point. Attempts to correct the coupling using these skew quads and the emittance wires downstream of the spin rotator did not converge. It was discovered that the misaligned skew quads were introducing betatron oscillations when excited to produce global coupling correction; the oscillation of the beam through the strong focusing of the turnaround introduced large amounts of vertical dispersion, leading to a very complicated and non-orthogonal tuning space.

Subsequently, a modified lattice was developed in which the coupling correction section was immediately upstream of the emittance wire scanner section. With this modification, the global coupling minimization was extremely successful, with correction of betatron coupling down to a mean level of about 0.2 nm over a 100 seed simulation study.

An additional study of coupling correction examined the possibility of performing the correction without the use of $< xy >$ as a tuning signal, but utilizing only the measured vertical spot size on an appropriate wire scanner. This was found to be much less effective, leaving approximately 4 nm of emittance when averaging over 100 seeds.

DOWNSTREAM RTML

The downstream RTML includes the two-stage bunch compressor, an additional emittance diagnostic section with multiple laser wire scanners, and a section which performs the beta match from the emittance diagnostic section into the main linac. Although the upstream RTML has many more betatron oscillations than the downstream RTML, the typical energy spread in the downstream RTML is much larger, typically between 1% and 2% compared to 0.15% in the upstream RTML. This makes the downstream RTML quite sensitive to dispersion errors. In addition, the long initial bunch (6 mm RMS) introduces sensitivity to the time-varying kicks from pitched RF cavities.

Since the first-stage compressor (BC1) operates near the zero-crossing of the RF, the effect is extremely important in this area.

Errors and Misalignments

The errors and misalignments used in the tuning simulations of the downstream RTML are shown in Table 2. Since the quadrupoles in the downstream RTML are in many cases superconducting magnets placed in RF cryomodules, the tolerances implied by Table 2 are somewhat more optimistic in some cases than what is actually expected, and some errors such as the cavity misalignments are not represented in this study.

Table 2: Misalignments and Errors used in Downstream RTML simulations.

Error type	RMS Error	With Respect To
Quad misalign	150 μm	Survey Line
BPM misalign	7 μm	Quad Axes
Bend misalign	150 μm	Survey Line
Cavity pitch	300 μrad	Survey Line

Orbit Correction

The first step in the downstream emittance correction, as in the upstream emittance correction, is the use of KM to correct the orbit. The correction is applied in the same manner, and with the same weights, as in the upstream RTML case. Averaged over 100 seeds, the mean emittance growth after this procedure is 36 nm.

Global Correction

Global correction of emittance in the downstream RTML is provided by a set of dispersion knobs in the bunch compressor wigglers, which are identical in concept to the dispersion knobs in the upstream RTML described previously. The dispersion knobs are effective against both dispersion and cavity pitch errors: in the latter, the projection of the fundamental mode into the transverse plane introduces a nonzero $< p_y z >$, while the longitudinal component of the fundamental mode introduces a nonzero $< Pz >$; taking both correlations into account, the pitched RF cavities are to lowest order introducing a nonzero $< p_y P >$.

In a simulation study of 100 seeds, in which first KM and then tuning of the dispersion knobs was applied, the mean emittance growth was reduced to 3.9 nm, with a 90% confidence level of emittance growth of 7.5 nm.

In another set of studies, all errors except for cavity misalignment were included. In this case, mean emittance growth was 6.3 nm with KM alone, and KM plus knobs yielded a mean emittance of 1.3 nm and a 90% C.L. of 2.5 nm. Considering both simulations with cavity pitches and simulations without, it is clear that the cavity pitch errors are a major issue for the downstream RTML, that dispersion knobs are an effective remedy, but that the method described here is not quite sufficient.

Dispersion-Free Steering

Dispersion free steering (DFS) [6] of the bunch compressors has also been used as an initial semi-local steering-based correction, as an alternative to KM. In this study, a somewhat larger and more complete set of errors, shown in Table 3, was used. The beam energy was varied by changing the phase of all RF cavities in BC1 and BC2 by a common offset. After iterating DFS to convergence, the skew quad based global correction was applied in the manner described above.

Table 3: Misalignments and Errors used in DFS studies.

Error type	RMS Error	With Respect To
Quad misalign	300 μm	Survey Line
Quad roll	300 μrad	Survey Line
BPM resolution	1 μm	
BPM misalign	300 μm	Survey Line
Bend roll	300 μm	Survey Line
Cavity misalign	300 μm	Survey Line
Cavity pitch	300 μrad	Survey Line

When a phase offset of $\pm 5^\circ$ was used in both bunch compressor stages, a simulation of 50 seeds resulted in an average emittance growth of 2.8 nm. Increasing the phase offset to $\pm 10^\circ$ resulted in a small additional improvement.

CONCLUSIONS

The Budget for growth in the normalized vertical emittance in the ILC RTML is 4 nm, or 20% of the emittance which is extracted from the damping ring. We have considered a number of techniques for obtaining such a small growth in normalized emittance, and addressing the challenges which present themselves in the RTML. The results indicate that emittance growths comparable to the budget are achievable, though more effort is needed to fully quantify the expected emittance growth in the RTML.

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