EVALUATION OF THE COMPONENT TOLERANCES FOR THE ILC MAIN LINAC ASSUMING GLOBAL LINEAR CORRECTIONS*

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Abstract

The small energy-spread, weak wakefields and relatively weak focusing in the International Linear Collider (ILC) superconducting Main Linac result in little or no filamentation beam mismatch errors: linear correlations such as dispersion or cross-plane coupling from transverse misalignment or rotation errors of the quadrupoles respectively do not decohere as the beam is transported (accelerated) along the linac. Using corrections available in the Beam Delivery System (BDS), the increase in projected emittance due to this linear correlations can to a large degree be corrected. In this paper we present component tolerances based on the assumption of a global correction at the end of the Main Linac. Some discussion on the impact of ground motion is also given.

INTRODUCTION

At the ILC, the luminosity will depend on maintaining the emittance growth delivered to the BDS. The emittance growth, particularly in the vertical plane, in the Main Linac (ML) arises primarily from misalignment and rotation errors of the various elements such as cryomodule, Beam Position Monitor (BPM), quadrupole, and RF cavities. This increase can be mitigated within the ML using Beam Based Alignment (BBA) techniques such as Dispersion Free Steering (DFS). Slow component drifts due to ground motion and other effects can be substantially mitigated by applying one-to-one steering on a short-term basis; longer-term correction will require a re-application of BBA.

The achievable performance with respect to emittance preservation (growth) is determined by the sensitivity of the emittance to the various component errors, which ultimately define the allowed component installation tolerance in the tunnel. The same sensitivities – together with the ground motion characteristics – also define the average time over which the emittance degrades to the point that a full application of BBA is required.

The alignment sensitivity can be significantly reduced by assuming a global correction of the primary linear correlations introduced by the errors, namely dispersion and cross-plane coupling. This is possible due to the weak-focusing lattice used in the ILC ML and the small beam energy-spread, resulting in little or no filamentation in the beam.

In the following report, we re-evaluate the primary alignment sensitivities for the ILC main linac, assuming a perfect global correction of the linear correlations at the exit.

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GLOBAL CORRECTIONS

Two types of global correction are studied: energy correlation correction (dispersion) and cross-plane coupling correction. For simplicity, the corrections are applied numerically to the resulting simulated beam phase space; this represents a perfect correction at the exit of the linac. Realistic corrections using magnet systems ("knobs") and beam diagnostics would result in some degradation in performance (residual emittance growth). With this in mind, the simplistic numerical correction applied here represents the best that can be achieved.

Energy Correlation Correction

To remove the linear energy correlation a bump [1] can be used at the end of the linac. The corrected emittance is the normalised emittance with the linear energy correlations numerically removed *i.e.*

$$\gamma\varepsilon_{yc} = \gamma\sqrt{\left\langle y^2\right\rangle_c \left\langle y'^2\right\rangle_c - \left\langle y\ y\ '\right\rangle_c^{\ 2}}\ ,$$

where

$$\left\langle y^2\right\rangle_c = \left\langle y^2\right\rangle - \left\langle y\delta\right\rangle^2/\left\langle\delta^2\right\rangle$$
$$\left\langle y'^2\right\rangle_c = \left\langle y'^2\right\rangle - \left\langle y'\delta\right\rangle^2/\left\langle\delta^2\right\rangle$$
$$\left\langle yy'\right\rangle_c = \left\langle yy'\right\rangle - \left\langle y\delta\right\rangle\left\langle y'\delta\right\rangle/\left\langle\delta^2\right\rangle$$

and y and y' represent the vertical phase space coordinates of the particles in the beam*. In practise, the correction of the energy correlations can be performed with a closed trajectory dispersive bump.

Cross-plane Coupling Correction

Correction of the cross-plane coupling can be made with a method based on a system of skew-quadrupoles combined with laser-wire beam profile measurements. In the present study, it is assume that the correction is perfect. The beam sigma covariance matrix σ^2 is parametrized as follows:

$$\sigma^2 = B.C.E.C^T.B^T \quad (1)$$

Where E is the 4×4 matrix of the intrinsic beam emittance, C is the coupling matrix and B is the beta matrix [2]. The matrix C has four independent parameters, which are determined numerically using an iterative procedure to diagonalize the beam matrix. The resulting diagonal terms of E yield the so-called *intrinsic* or non-projected emittances.

* Since the vertical emittance is by far the most critical, we restrict ourselves here to a discussion of the vertical plane.

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IMPACT OF QUADRUPOLE ROTATION ERRORS ON BBA

As a first example, the impact (tolerance) of the quadrupole rotation errors on the achievable performance of Dispersion Matched Steering (DMS)† was studied. The Merlin based [3] C++ ILCDFS package [4] was used for the present simulation. The initial energy of the test beam and a constant gradient adjustment of -20% are used. This strategy was shown to be the most effective in reducing the emittance growth along the linac [5]. Throughout the study, a simplified lattice with a split phase advance 75/60 degrees was used. The initial beam energy was 15 GeV (accelerating up to 250 GeV), with an initial RMS energy spread of 1.07%.

Table 1 shows the now standard component alignment tolerances used in the simulations. For the following study, all the RMS errors were kept constant except for the quadrupole rotation. The results (averaged over 100 random seeds) are shown in Fig. 1.

Table 1: Alignment random gaussian errors of the various components used throughout the simulations.

Components	Type of Error	Reference axis	Errors Values (RMS)
Quadrupole	Transverse	cryomodule	300 µm
	Rotation	cryomodule	300 µrad
BPM	Transverse	cryomodule	200 µm
RF structure	Transverse	cryomodule	300 µm
	Rotation	cryomodule	300 µrad
Cryomodule	Transverse	nominal beamline	200 µm

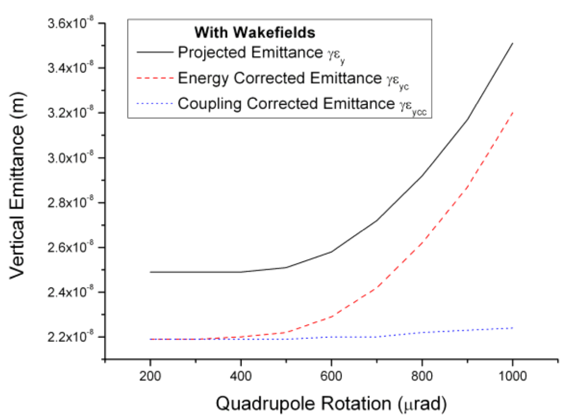

Figure 1: Vertical emittance in m after DMS as a function of the quadrupole rotation (averaged over 100 seeds). The injection emittance is $\gamma\varepsilon_{yi}$ = 20 nm.

The solid line indicates the as simulated RMS vertical emittance (*projected emittance*). Both the red-dashed line and the blue-dotted lines indicate the resulting emittance after simulating the application of perfect global corrections, by numerically removing dispersive and coupled correlations. Comparing first the dispersion corrected result (red-dashed) with the uncorrected result (solid-black), we observe the same basic quadratic behaviour as a function of the quadrupole rotation, but with the latter being offset by about 3 nm; this represents the average contribution to the project emittance from the uncorrected (residual) linear dispersion due to the DMS procedure; it can be almost entirely corrected by the global dispersion correction. Extrapolating to zero rotation errors, the remaining 2 nm of dispersion growth can be directly attributed to the wakefield effects arising from the cavity misalignments, for which no global correction has been applied (see Table 2).

Looking at the dispersion corrected result (red-dashed), we see that the nominal 300 µrad RMS errors have virtually no impact on the emittance growth. At 600 µrad RMS the projected emittance increases by ~1 nm. The blue-dotted line indicates that a global coupling correction at the exit of the linac can substantially mitigate the coupling introduced, with 1 mrad RMS now adding less than ~1 nm of emittance growth.

	Projected Emittance	Energy Corrected Emittance
No wakefield	23.6 nm	20.8 nm
With wakefield	24.9 nm	21.9 nm

Table 2: Mean vertical emittance with / without wakefield for 100 seeds including all random errors in Table 1.

ALIGNMENT SENSITIVITY

Historically component tolerances are generally specified by first estimating the *sensitivity* to each family (type) of error. The total emittance growth is generally the addition of the specific contributions (scaled to the appropriate error magnitude). To again indicate the lack of filamentation and the possible gains of a global dispersion and coupling correction, we estimate the sensitivities with and without such corrections when one-to-one steering is applied. The results are shown in Table 3.

Table 3: Component alignment sensitivities. Sensitivity is here defined as the RMS error which results in an average 10% emittance increase (2 nm) after the application of perfect one-to-one steering correction.

Elements	Type of error	sensitivity after global correction		
		none	disp.	coupling
BPM	Transv.	11.5 µm	26 µm	26 µm
Quad.	Transv.	350 µm	550 µm	550 µm
Quad.	Roll	540 µrad	540 µrad	1850 µrad
RF cavities	Transv.	760 µm	800µm	800 µm
RF cavities	Tilt	960 µrad	1480 µrad	1480 µrad
Cryomodule	Transv.	17 µm	47 µm	47 µm

† Due to non-zero design dispersion which must be matched, the more general algorithm applied here is the DMS rather than the DFS.

The change in error sensitivity differs for each of the global corrections studied, which is indicative of the type of aberration each error generates (dispersive or coupling). The dispersion correction has a substantial impact on the sensitivity of the transverse errors; e.g. the sensitivity to the BPM error increase from 11.5 µm for the projected emittance to 26 µm for the dispersion corrected emittance. The emittance sensitivity to the quadrupole roll is relaxed by more than a factor of 3 by the cross-plane coupling correction (from 540 µrad to 1850 µrad).

DYNAMIC IMPACT OF GLOBAL CORRECTIONS

In order to evaluate the dynamic impact of the global corrections, a simulation was performed including a diffusive ground motion model (*ATL*) [7]. The ground motion produces vertical displacements of the cryomodules[6]. The parameter A was chosen to be 4×10^{-18} $m.s^{-1}$ (so-called quiet site). A continuous one-to-one correction was applied to the model and no noise was assumed for the BPMs. In this case, the linac was modelled laser-straight.

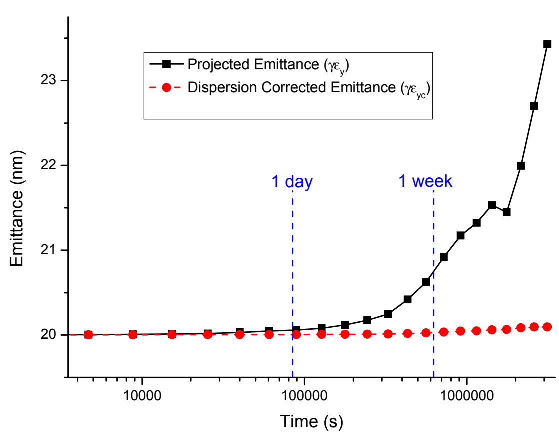

Fig.2 : Average over 50 seeds of projected and dispersion corrected emittance at the end of the linac as a function of the time, assuming a perfect one-to-one steering.

The results of the projected emittance and energy correlation corrected emittance as a function of time for the ML are shown in Fig. 2.

After 25 days, the projected emittance degrades from the initial 20 nm to 22 nm, while the energy correlation corrected emittance ($\gamma\varepsilon_{yc}$) is still at 20.1 nm. The growth in the dispersion-corrected emittance ($\gamma\varepsilon_{yc}$) only reaches 10% after more than 1 running year (3×10^7 s). The results indicate that a dispersion correction performed on average once a day is sufficient to maintain the beam quality (emittance). The average time between re-applications of invasive BBA is now defined by the available correction range of the dispersion tuning in the BDS. It has to be noted that the ATL model affects only the transverse misalignment errors and so there is no effect of the cross-plane coupling correction. In addition, this simplified lattice does not contain the 1.2 km positron source insertion, which is known to have a significant effect on the stability of the emittance [6]; however, the current study is applicable to the positron Main Linac, where there is no such insertion.

CONCLUSION

We have shown that the use of energy correlation (dispersion) and cross-plane coupling corrections can help to reduce the emittance growth after BBA and, to a large degree, relax the tolerances on the various elements of the main linac. Potential gain of each global correction is given for static misalignment and rotation errors. As a consequence, global corrections at the exit of the linac can significantly increase the long-term stability of the beam emittance in the presence of diffusive ground motion, thus extending the average time between re-alignment of the quadrupoles using invasive BBA.

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