LOW-EMITTANCE TUNING SIMULATIONS FOR THE ILC DAMPING RINGS [*]

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Abstract

One of the major challenges for the International Linear Collider (ILC) damping rings is the attainment of the 2 pm vertical emittance specification. To achieve such an ultra-low vertical emittance a highly effective diagnostics and correction system is needed. However, since both BPMs and correctors have also negative impacts on the design (cost, complexity, impedance), it is important to understand how the number and locations of both these components affect the correction. In this paper we present the results of simulations for the current Technical Design Phase baseline damping rings lattice (DCO4), aimed at understanding the effectiveness of orbit and dispersion correction for different design and operation scenarios.

INTRODUCTION

The luminosity of a linear collider depends on the vertical emittance of the beam extracted from the damping rings. For the ILC [1] the specified vertical emittance for the beam from the damping rings is 2 pm. Emittances approaching this value have been achieved recently in some operating storage rings [2], but routine operation with this level of emittance in storage rings on the scale of the 6.4 km circumference ILC damping rings remains a challenging goal. Optimisation of the coupling correction system is therefore an important part of the design process. For the ILC damping rings, the situation is made a little more complicated by the fact that the rings are designed to provide a number of different working points for the optics [3].

To understand the issues and optimise the design we perform simulation studies exploring different design scenarios, including variation in the arc cell phase advance. As a first step, we can look at the sensitivity of the vertical emittance to vertical alignment errors on the quadrupoles and sextupoles: these errors are expected to make a significant contribution to the vertical emittance in the operating rings, although other errors, such as quadrupole tilts, are also likely to be important [4]. We can then investigate the effectiveness of a simple combined correction of the orbit and the dispersion in minimising the vertical emittance. We reported the results of such studies for an earlier version of the ILC damping rings lattice in a previous paper [5]. Since then, there have been significant developments in the layout and optics, so we present here an update on these studies, which provide a foundation for more complete investigations.

Table 1: Scenarios studied in orbit and dispersion correction simulations.

Scenario	Arc phase advance	Arc BPM locations
I	72°	every quad
II	90°	every quad
III	100°	every quad
IV	72°	every D-quad
V	90°	every D-quad
VI	100°	every D-quad

The present baseline lattice for the ILC damping rings (DCO4, [3, 6]) has a circumference of 6476 m and a racetrack layout. Two arcs, each consisting of 96 FODO cells, are joined by two long straights containing the damping wiggler, rf cavities and injection/extraction systems. To provide operational flexibility, the momentum compaction factor is tunable between 1.3×10^{-4} and 2.8×10^{-4}; adjustment of the momentum compaction factor is achieved by changing the phase advance in the arc cells. The beam energy is 5 GeV, and the natural emittance varies from 0.40 nm to 0.65 nm, depending on the momentum compaction factor. Achieving the specified vertical emittance of 2 pm will require precise correction of the orbit, dispersion and betatron coupling.

In this paper we present the results of simulations of orbit and dispersion correction in six different scenarios, shown in Table 1. In each case the phase advance across a single arc cell is 72°, 90°, or 100°. BPMs are located at every quadrupole in the straights; in the arcs, BPMs are located either at every quadrupole, or only at every defocusing quadrupole. Note that the number of correctors that we use is always equal to the number of BPMs.

ALIGNMENT SENSITIVITIES

Indications of the sensitivity of the lattice to alignment errors can be obtained by simulating the vertical emittance generated by individual kinds of error. The goal is not to attempt a simulation of a realistic situation, but simply to identify the kinds of errors that are likely to dominate, and to develop an understanding of the parameter regime. Important quantities for low emittance tuning are the response of the vertical closed orbit distortion, vertical dispersion, and vertical emittance to vertical alignment errors on the quadrupoles and sextupoles, and tilt errors on the quadrupoles. As an example, Fig. 1 shows the vertical emittance generated by vertical alignment errors on the sextupoles. While there is a large spread in the results from

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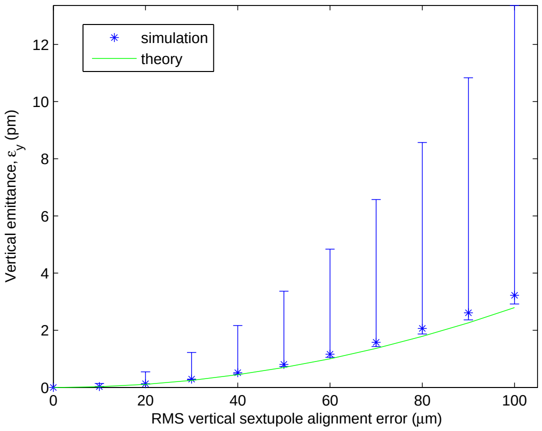

Figure 1: Vertical emittance generated by vertical alignment errors on the sextupoles. The "error bars" show the 5th and 95th percentiles over a distribution from 100 seeds of random error with a given magnitude.

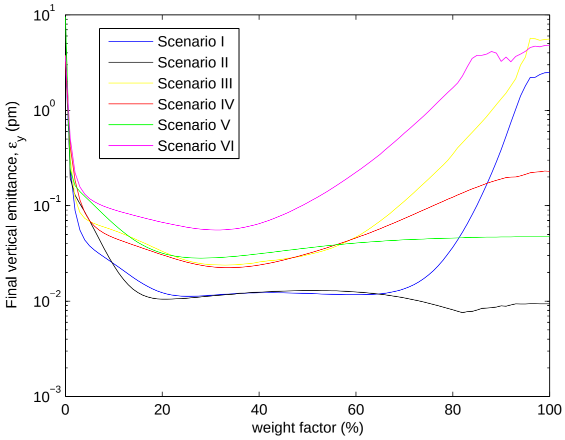

Figure 2: Emittance following orbit and dispersion correction, as a function of weight factor in different scenarios (averaged over 100 seeds).

different seeds, the trend agrees well with a theoretical estimate, based on the formula:

$$\varepsilon_y \approx 2\frac{j_z}{j_y}\left\langle\frac{\eta_y^2}{\beta_y}\right\rangle\sigma_\delta^2 + \left(1 - \frac{1}{\sqrt{1+\kappa^2/\Delta\omega^2}}\right)\frac{\varepsilon_0}{2}. \quad (1)$$

The first term represents the dispersion contribution, and the second term represents the coupling contribution. The dispersion contribution can be related to the sextupole alignment errors ΔY_S by:

$$\left\langle\frac{\eta_y^2}{\beta_y}\right\rangle \approx \frac{\langle\Delta Y_S^2\rangle}{8\sin^2\pi\nu_y}\sum_{\text{sexts}}\eta_x^2\beta_y(k_2L)^2. \quad (2)$$

The coupling can be related to the sextupole alignment errors by:

$$\left(\frac{\kappa}{\Delta\omega}\right)^2 \approx \frac{\langle\Delta Y_S^2\rangle}{4\pi^2\Delta\nu_y^2}\sum_{\text{sexts}}\beta_x\beta_y(k_2L)^2. \quad (3)$$

We find that the dispersion contribution dominates the vertical emittance; and that an rms sextupole alignment error of 100 μm generates a vertical emittance of 3 pm (on average: the emittance in particular cases can be four or five times larger). This suggests that to achieve 2 pm vertical emittance, the sextupole alignment with respect to the beam needs to be better than 100 μm rms, and that correction should focus on the dispersion rather than the betatron coupling. Of course, in a realistic situation, quadrupole alignment errors also need to be taken into account.

ORBIT AND DISPERSION CORRECTION

A good survey could achieve vertical alignment errors on the quadrupoles of less than 50 μm rms, and on the sextupoles of less than 100 μm rms. Sensitivity studies show that an alignment error of 50 μm rms on the quadrupoles in DCO4 will lead to a closed orbit distortion of order 1 mm rms. If the vertical orbit can be corrected to between 50 μm and 100 μm rms (assuming effective beam based alignment of the BPMs to the adjacent quadrupoles), then the remaining sextupole alignment errors will generate a vertical emittance of order 10 pm. Correction of the vertical dispersion could then lead to a significant further reduction in the vertical emittance. To test the effectiveness of this strategy, we simulate a combined orbit and dispersion correction on a lattice in which the only errors are vertical alignment errors on the quadrupoles and sextupoles. Since the number of correctors is equal to the number of BPMs, it is not possible, in general, to correct exactly both the orbit and dispersion at the same time. Therefore, as described previously [5], we use an algorithm based on SVD inversion of a combined orbit and dispersion response matrix, with a relative weight factor α on the dispersion ($\alpha = 0$ gives a "pure" orbit correction; $\alpha = 1$ gives a "pure" dispersion correction).

For each of the scenarios in Table 1, we vary the weight factor α from 0 to 1. For each value of the weight factor, we apply 100 seeds of random alignment errors to the quadrupoles (50 μm rms) and sextupoles (100 μm rms), then apply a combined orbit and dispersion correction. The average final emittance for each scenario, as a function of the weight factor, is shown in Fig. 2.

We notice that for all scenarios, the emittance with a weight factor $\alpha = 0$ (pure orbit correction) is around 10 pm, which is consistent with the value expected with 100 μm rms vertical alignment error on the sextupoles, and no orbit distortion (i.e. no alignment errors on the quadrupoles). As the weight on the dispersion correction is increased, there is a significant reduction in the vertical emittance. This may be because the algorithm achieves the correction by steering the beam through the centres of

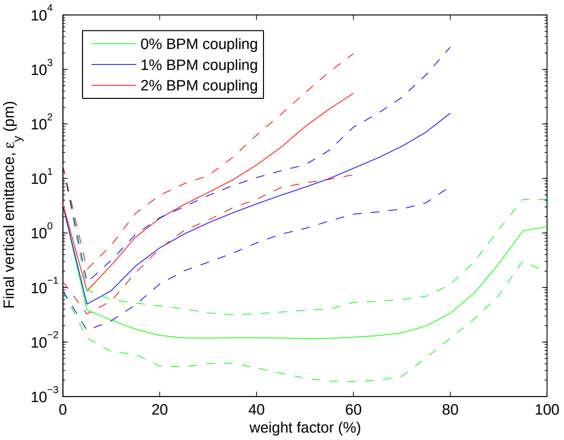

Figure 3: Effect of BPM coupling errors on orbit and dispersion correction in scenario I. Solid lines show the average, and the dashed lines the full range, over 100 seeds of random errors.

the sextupoles: although the orbit distortion itself generates some vertical dispersion, this is small compared to the dispersion generated by coupling from the horizontal dispersion when the beam is off-centre in the sextupoles. The fact that emittances of less than a picometre are achieved is a result of the idealised system (neglecting, for example, BPM errors), and would not be achieved in practice. Finally, if the weight on the dispersion is very high, then in attempting to correct even the dispersion generated by the orbit distortion, the correction results in significant residual beam offset in the sextupoles, which leads to generation of vertical emittance from betatron coupling.

EFFECT OF BPM ERRORS

BPM errors could have a significant impact on the correction in a number of ways. For example, limits on BPM resolution could limit the precision with which the dispersion can be measured. BPM coupling errors would mean that the measurement of the vertical dispersion is affected by the presence of horizontal dispersion. While the random errors (e.g. from limited resolution) can be addressed, for example, by averaging over many measurements, systematic errors (e.g. from BPM coupling) can be more difficult to deal with.

To investigate the effect of BPM couplings, we repeat the correction simulation, but applying coupling errors to the BPM readings, so that the measured changes in horizontal and vertical orbit are obtained by multiplying the actual changes by a 2×2 gain matrix, g. BPM coupling errors are represented by non-zero off-diagonal components in g. The impact of BPM coupling errors on the combined orbit and dispersion correction in scenario I is shown in Fig. 3.

For low dispersion weights ($\alpha = 0$, pure orbit correction) the behaviour of the correction is little affected: this is not surprising, since the simulation includes no horizontal orbit distortion, so the BPM coupling makes no real difference. Even if horizontal orbit distortion were introduced, since it is likely to be on the same scale as the vertical orbit distortion, BPM coupling at a reasonably low level would mean that there would still be little impact on the correction.

However, where there is a greater weight on the dispersion correction (α close to 1), the effectiveness of the combined orbit-dispersion correction is significantly impaired. This is because the design horizontal dispersion is large (of order 0.5 m) compared with the vertical dispersion (a few mm) that would generate a few pm vertical emittance. Even a small amount of BPM coupling can have a large impact on the measurement of the vertical dispersion.

Significantly, the weight factor that is most likely to lead to a minimum vertical emittance is much lower (about 0.05) in the cases with BPM coupling errors, than in the case without BPM coupling errors (between approximately 0.2 and 0.6). This shows the importance of including BPM coupling errors in simulations aimed at the development of low-emittance tuning strategies.

CONCLUSIONS

Combined orbit and dispersion correction will be an important first step in tuning the ILC damping rings for the goal of 2 pm vertical emittance. In the presence of only quadrupole and sextupole vertical alignment errors, it is possible to optimise the correction process so that in simulations, a vertical emittance significantly below 1 pm can be achieved, even where the number of BPMs and correctors is reduced by half in the arcs. However, other kinds of errors are likely to play a significant role, and will need careful investigation. As an example, we have found that BPM coupling errors can have a large impact on the behaviour of the orbit-dispersion correction.

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