COUPLING CORRECTION FOR THE ILC DAMPING RINGS*

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Abstract

The damping rings of the International Linear Collider (ILC) are specified to operate with a vertical emittance of 2 pm. To achieve this challenging goal, an effective diagnostics and correction system will be needed; however, BPMs add impedance to the ring, and diagnostics and correctors add complexity and cost. It is therefore desirable to understand how the final achievable vertical emittance depends on the numbers, locations and performance of the BPMs and correctors, and to determine the minimum number of these components required. We present the results of simulations for the damping rings, aimed at indicating the effectiveness of coupling correction for different design scenarios of the diagnostics and correction systems.

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; this is a factor of two lower than the smallest emittance achieved in any existing storage ring. In an electron storage ring, the dominant sources of vertical emittance are the vertical dispersion and the betatron coupling. An important part of the design of the damping rings is the specification of systems capable of correcting the dispersion and the coupling at the necessary level. To understand the issues and optimise the design we perform simulation studies exploring different design scenarios. 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 [2]. We can then investigate the effectiveness of a simple combined correction of the orbit and the dispersion in minimising the vertical emittance. This will provide the foundation for more complete studies, including such effects as BPM noise and rotation.

The present baseline lattice for the ILC damping rings [3] 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

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	72°	every D-quad
IV	90°	every D-quad
V	72°	2/3 D-quads
VI	90°	2/3 D-quads

the phase advance in the arc cells. To achieve the specified damping time of 20 ms with a beam energy of 5 GeV, a damping wiggler of length 200 m is needed. Under ideal conditions the equilibrium emittance is dominated by the lattice functions in the wiggler; however orbit distortion and dispersion in the arcs can make a significant contribution to the vertical emittance if not corrected carefully.

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 either 72° or 90°. 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, or only at two out of every three defocusing quadrupoles. Note that the number of correctors that we use is always equal to the number of BPMs. For each scenario we apply random vertical misalignments to all quadrupoles (50 μm rms) and to all sextupoles (100 μm rms). We then apply a combined orbit and dispersion correction, with the goal of minimising the vertical emittance, as described in the next section.

ORBIT AND DISPERSION CORRECTION

The beam position is measured with a set of N BPMs, which are distributed over the ring depending on the scenario (Table 1). The beam is steered using a set of M dipole magnets (correctors). The BPM readings are represented by a vector $\vec{u}$ of dimension N and the corrector strengths (kicks) by a vector $\vec{\theta}$ of dimension M. Measured dispersion at the BPMs is represented by vector $\vec{D}$ (dimension N). The orbit response matrix (ORM) A describes the change in beam position at each BPM resulting from a change in strength of each corrector. Similarly, the dispersion response matrix (DRM) B describes the change in dispersion at each BPM resulting from a change in strength of each corrector. Both A and B are matrices of dimension $N \times M$.

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For both orbit and dispersion to be corrected simultaneously, a set of corrector kicks $\vec{\theta}$ must be found that solves the following system of linear equations [4]:

$$\begin{pmatrix} (1-\alpha)\vec{u} \\ \alpha\vec{D}_u \end{pmatrix} + \begin{pmatrix} (1-\alpha)A \\ \alpha B \end{pmatrix} \vec{\theta} = 0 \qquad (1)$$

In general, there are $2N$ equations in M unknowns. If, as is the case here, $2N > M$ then it is not possible, in general, to find exact solutions for the kicks $\vec{\theta}$. However, using singular value decomposition, we can find a solution that minimises the residual orbit and dispersion. The factor α appearing in Eq. (1) determines whether more weight is given to correcting the orbit ($\alpha = 0$) or to correcting the dispersion ($\alpha = 1$) in finding the solution. The optimum value of α for minimising the vertical emittance depends on the lattice and the arrangement of BPMs and correctors: one of our goals is to investigate this dependence.

For each scenario in our simulations, we first obtain the ORM and DRM. For a given set of random misalignments we then find the closed orbit and the dispersion at each BPM. The solution for the corrector strengths in Eq. (1) can then be found, for a given weight factor, by singular value decomposition.

SIMULATION RESULTS

First we look at how the orbit and the dispersion behave as we apply the correction. Fig. 1 shows the results for scenario I averaged over 100 seeds of random errors. As expected the orbit is almost perfectly corrected for $\alpha = 0$, and the dispersion is almost perfectly corrected for $\alpha = 1$.
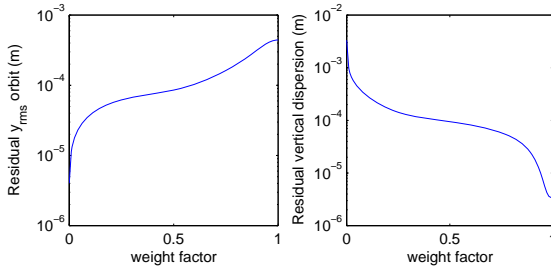

Figure 1: Orbit and dispersion correction in scenario I.

Given the orbit and dispersion, it is possible to make an analytical estimate of the vertical emittance using the following equation [5]:

$$\begin{aligned} \epsilon_y &= \frac{J_x}{4J_y} \frac{1 - \cos(2\pi\nu_x)\cos(2\pi\nu_y)}{[\cos(2\pi\nu_y) - \cos(2\pi\nu_x)]^2} \epsilon_x \times \\ &\quad \sum_{sexts} \beta_y\beta_x(k_2L)^2 \left[\langle y_{sext}^2\rangle + \langle y_{orbit}^2\rangle\right] \\ &\quad + J_z\sigma_\delta^2 \left\langle \frac{\eta_y^2}{\beta_y} \right\rangle \end{aligned} \qquad (2)$$

where J_x, J_y and J_z are the horizontal, vertical and longitudinal damping partition numbers; ν_x and ν_y are the betatron tunes; ϵ_x is the horizontal emittance; β_x and β_y are

the horizontal and vertical beta functions; k_2L is the integrated normalised sextupole strength; σ_δ is the rms energy spread; η_y is the vertical dispersion; y_{sext} is the vertical displacement of a sextupole magnet with respect to the design reference trajectory; and y_{orbit} is the vertical closed orbit distortion with respect to the design reference trajectory. The estimate of the vertical emittance using this formula may be compared to that obtained from the simulation code. The result, for scenario I, is shown in Fig. 2. While
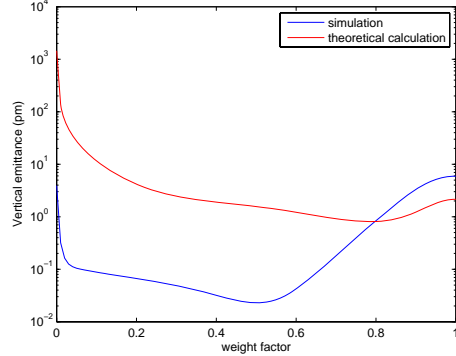

Figure 2: Emittance following orbit and dispersion correction, as a function of weight factor in scenario I. The red line shows the theoretical expected emittance from the corrected orbit and dispersion; the blue line shows the actual calculated emittance

the theoretical emittance shows broadly similar behaviour to the simulated emittance there are also considerable discrepancies, particularly at low values of α. It appears that the theoretical relationship can not be used for a quantitive prediction of the vertical emittance; this is beccause the derivation of Eq. (2) makes a number of assumptions that are not expected to be completely valid in the present model.

Now we compare the final vertical emittance as a function of the weight factor for the different scenarios given in Table 1. For each scenario, we vary the weight factor in steps of 0.01, between 0 and 1. For each weight factor, we apply the correction to each of 100 seeds of random misalignments. The final vertical emittance averaged over 100 seeds is shown in Fig. 3. We see that in several scenarios the final vertical emittance is less than 1 pm; this is not realistic, and occurs because of the limited set of errors we have applied. On the other hand, in scenarios V and VI the vertical emittance does not come down below 10 pm. We therefore focus our attention on scenarios I to IV. As well as a distribution in the final emittance there is a distribution in the weight factor that gives the minimum vertical emittance. For tuning the machine in practice, i.e. without explicit knowledge of the magnet misalignments, it is important to know the optimum weight factor, i.e. the weight factor that is (in a statistical sense) most likely to lead minimum emittance. One way to define the optimum weight factor is as follows. For a given scenario and set of random errors, we can determine the weight factor that leads

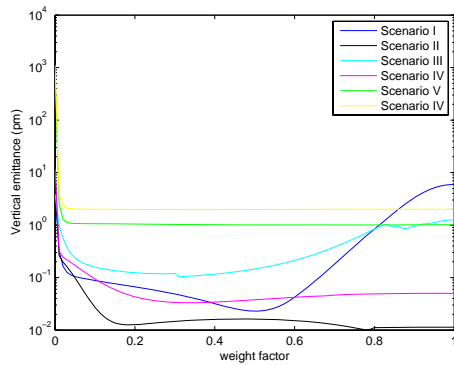03 Linear Colliders, Lepton Accelerators and New Acceleration Techniques

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Figure 3: Corrected vertical emittance, averaged over 100 seeds of random errors, as a function of weight factor.

to the minimum emittance. We can repeat for a number of sets of random errors, recording the "best" weight factor for each set. The weight factors thus recorded have some distribution–see Fig. 4 for the cases of scenarios I through IV. The optimum weight factor is the point at which the distribution peaks. The width of the distribution is also important: a lattice that has a very wide distribution for the optimum weight factor may be harder to tune than a lattice with a very narrow distribution, since the statistical optimum weight factor is less likely to be close to the "best" weight factor in any given case. On the other hand, if the final vertical emittance has a very broad minimum, then tuning the lattice may not be very sensitive to the weight factor.
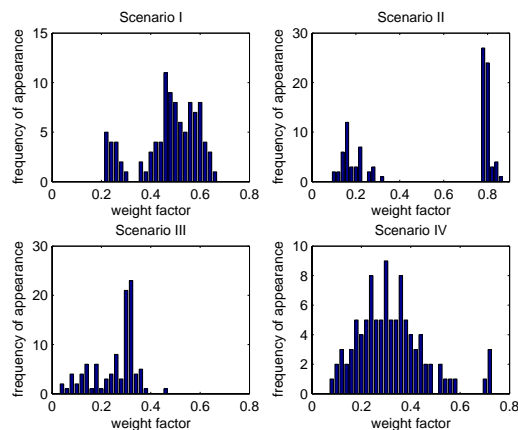

Figure 4: Distribution of weight factors leading to the lowest emittance for each of 100 seeds of random errors.

Finally, we can apply the correction to each of a number of sets of random errors, using a single optimised weight factor for each scenario. The average final vertical emittances obtained in this way are shown in Fig. 5. Note that, as already mentioned, the absolute values obtained are not very meaningful, because of the idealised nature of the simulations. However, the relative values obtained (and their spread) give some indication of how the different scenarios behave in comparison with each other.
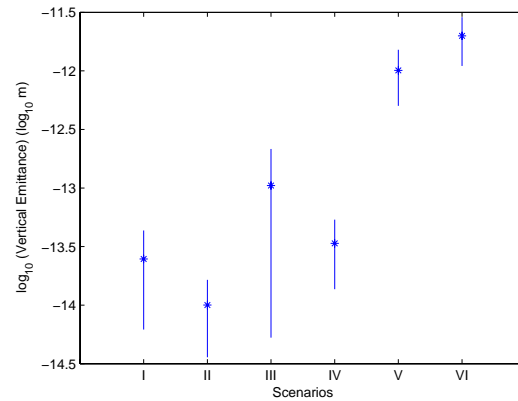

Figure 5: Final vertical emittances. The error bars show the 5th and 95th percentiles, over 100 seeds of random errors.

CONCLUSIONS

A combined orbit and dispersion correction is most effective when a BPM is located at every quadrupole (scenarios I and II). However, the correction is almost as effective if, in the arc cells, the number of BPMs is reduced by half (scenarios III and IV), so that the BPMs are located only at horizontally defocusing quadrupoles. If the number of BPMs is further reduced, then we begin to see a more significant degradation in the performance of the correction algorithm. There is some indication that a lower final emittance is achieved in the lattices with phase advance of $90°$ per arc cell, though the differences to the lattices with phase advance of $72°$ is not large.

Focusing on scenarios I through IV, we observed some variation in the optimum weight factor to use in each case. However, even when the distribution of weight factors had a relatively large width, it was possible to obtain an effective correction using a single optimised weight factor for a given scenario. The results of our simulations provide a useful basis for more detailed and detailed studies of the coupling correction scheme in the ILC damping rings.

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