ALIGNMENT SENSITIVITIES IN THE ILC DAMPING RINGS *

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Abstract

For the International Linear Collider to reach its design luminosity, the damping rings must achieve a vertical emittance that is a factor of two below that achieved in any operating storage ring so far. Magnet alignment, orbit control and coupling correction are therefore critical issues for the ILC damping rings. We present the results of studies of the sensitivity to quadrupole and sextupole alignment errors for a recent lattice design for the damping rings.

ILC LUMINOSITY AND DAMPING RINGS

For the International Linear Collider (ILC) to achieve its luminosity goal of 2×10^{34} cm^{-2} s^{-1}, the equilibrium vertical emittance in the damping rings must be no larger than 2 pm. The lowest achieved vertical emittance achieved in any operating storage ring is 4.5 pm in the KEK-ATF [1]. Demonstrating that the challenging goal of 2 pm emittance can be achieved in the damping rings is a very high priority R&D goal for the ILC. The equilibrium horizontal emittance in a storage ring (in the absence of collective effects such as intrabeam scattering) is generally close to the natural emittance of the lattice, and so is effectively determined at the design stage. However, the vertical emittance is dominated by alignment and steering errors, so the operational value of the vertical emittance is determined by how well the magnets can be aligned, and how well the alignment errors can be characterised and compensated. The impact of any particular magnet alignment error depends on the type and strength of the magnet, the optical functions at the location of the magnet, and global parameters such as the betatron tunes. Therefore, an important consideration at the design stage for the damping rings lattices is the sensitivity of the lattice to realistic alignment errors.

Previous studies [2] of alignment sensitivities in a range of potential damping rings configurations and lattices were a consideration in selecting the present baseline. Recent developments in the lattice design, in particular for the ILC Reference Design Report (RDR) [3], motivate re-evaluation of the alignment sensitivities. Lattice design work is continuing, and it is intended to freeze the design for the Engineering Design Report (EDR) by the end of 2007. Since the EDR lattice will be the basis for a wide range of technical design studies, including specifications of alignment tolerances, mechanical and temperature stability, and diagnostics, tuning and correction systems, it is important that the sensitivity of the lattice to a range of alignment errors is acceptable.

The "OCS6" lattice design used for the studies reported here is described in the RDR [3]. The lattice has a roughly circular footprint with circumference of 6695 m. The arcs are constructed from theoretical minimum emittance cells, detuned from the ideal conditions for minimum emittance to improve the dynamic aperture. Long straight sections accommodate the RF, injection and extraction systems, and 200 m of wiggler to achieve transverse damping times of 25 ms. The beam energy is 5 GeV, and the natural emittance is 0.5 nm.

SENSITIVITY TO ALIGNMENT ERRORS

The vertical emittance must be more than two orders of magnitude smaller than the horizontal emittance, so we are principally concerned with errors that impact the vertical emittance. The tolerances for errors affecting the horizontal emittance will be rather larger. It is not realistic to expect that the initial survey and alignment will result in a machine immediately capable of 2 pm vertical emittance: a systematic and rigorous process of error characterisation and correction using beam-based techniques will be needed, similar to those applied, for example, at the KEK ATF [4]. However, the requirements for initial alignment, the difficulty of tuning for 2 pm vertical emittance, and the frequency with which tuning is required, can all be loosely characterised by a set of sensitivity indicators calculated for the particular lattice design. Comparison of these indicators with corresponding indicators for operating rings provides guidance on whether the lattice design is acceptable from point of view of low emittance tuning, or whether design modifications are needed to relax the sensitivities.

The sensitivity indicators that we report here for the damping rings RDR lattice are as follows:

- the rms vertical closed orbit distortion resulting from random vertical alignment errors on the quadrupoles;

- the vertical emittance resulting from random roll errors (rotation of the magnet around the beam reference trajectory) on the quadrupoles;

- the vertical emittance resulting from random vertical alignment errors on the sextupoles.

In a real lattice, all possible types of error occur simultaneously and are constantly changing; however, our purpose here is to characterise the lattice and identify any potential problems; and for this, it is helpful to consider only static errors, and only one type of error at a time.

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Quadrupole Vertical Alignment Errors

Vertical alignment errors on the quadrupoles distort the vertical closed orbit, and generate vertical emittance by introducing vertical dispersion. The closed orbit distortion also results in vertical offset of the beam with respect to the magnetic centres of the sextupoles; this causes further increase in the vertical emittance, as discussed below. Analysis of the effect on the closed orbit from the quadrupole vertical alignment errors gives the following relationship:

$$\sqrt{\langle y_{co}^2 \rangle} = A\sqrt{\langle y_{quad}^2 \rangle} \tag{1}$$

where y_{co} is the closed orbit distortion at any point in the lattice, y_{quad} is the vertical alignment error on a quadrupole, and the brackets $\langle \cdot \rangle$ indicate an average around the lattice. The "orbit amplification factor" A is given by:

$$A^2 \approx \frac{\langle \beta_y \rangle}{8 \sin^2 \pi \nu_y} \sum_{quads} \beta_y \left(k_1 L \right)^2 \tag{2}$$

where β_y is the vertical beta function, ν_y is the vertical tune, and $k_1 L$ is the integrated strength of a quadrupole. The sum extends over all quadrupoles.

Derivation of the expression (2) requires the assumption that the quadrupole alignment errors are uncorrelated. In practice, some correlation always occurs, with the result that for any given value for the rms quadrupole alignment error, the rms closed orbit distortion may be much greater than, or much less than, that expected from the amplification factor calculated from equation (2).
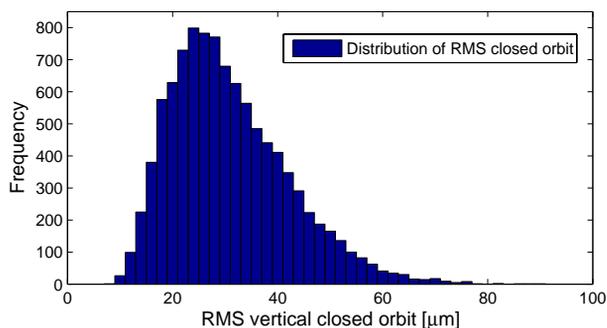

Figure 1: Statistical distribution of rms closed orbit distortion for 1 μm rms quadrupole alignment.

Figure 1 shows the statistical distribution of rms vertical closed orbit distortion resulting from different sets of quadrupole vertical misalignments, all with 1 μm rms, applied to a model of the lattice using the simulation code Merlin [5]. Plotting the mean of the distribution for a range of rms alignment errors between 0.2 μm and 5 μm shows the linear relationship between closed orbit distortion and quadrupole alignment error - see figure 2. The "error bars" indicate the range of the distribution by showing the 5th and 95th percentiles. The slope of the line is close to the value of the amplification factor calculated from equation (2).
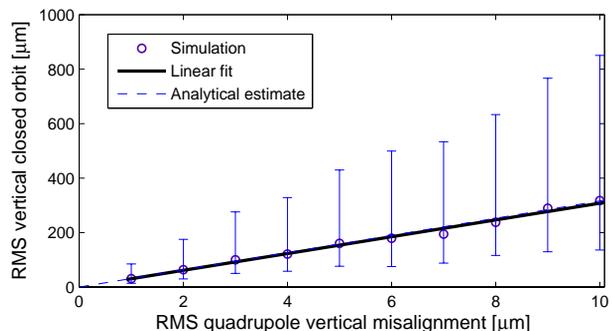

Figure 2: Variation of rms vertical closed orbit distortion with rms quadrupole vertical alignment error.

Quadrupole Roll Errors

Quadrupole roll errors generate vertical emittance by coupling horizontal betatron oscillations and horizontal dispersion into the vertical plane. The relationship between the vertical emittance and the rms roll error is:

$$\frac{\epsilon_y}{\langle \theta_{quad}^2 \rangle} \approx$$
$$\frac{J_x \left(1 - \cos 2\pi\nu_x \cos 2\pi\nu_y \right) \epsilon_x}{J_y \left(\cos 2\pi\nu_x - \cos 2\pi\nu_y \right)^2} \sum_{quads} \beta_x \beta_y (k_1 L)^2$$
$$+ \frac{J_z \sigma_\delta^2}{\sin^2 \pi \nu_y} \sum_{quads} \beta_y \eta_x^2 (k_1 L)^2 \tag{3}$$

where $\langle \theta_{quad}^2 \rangle$ is the mean square quadrupole roll error, ϵ_y and ϵ_x are the vertical and horizontal emittances, J_y and J_x are the vertical and horizontal damping partition numbers, ν_y and ν_x are the vertical and horizontal tunes, η_x is the horizontal dispersion function, and σ_δ is the rms energy spread. As in the case of the closed orbit distortion, this expression assumes no correlation between errors around the ring, and there is a wide statistical distribution resulting from correlations that occur in practice. Figure 3 shows the variation of vertical emittance with size of the rms quadrupole roll error; the points show the mean of the distribution in each case, with the "error bars" indicating the 5th and 95th percentiles. The relationship has the expected quadratic form, with good agreement between the theory and simulation results.

Sextupole Vertical Alignment Errors

A vertical alignment error on a sextupole introduces a skew quadrupole field at the location of the sextupole, and has a similar effect on the beam as a quadrupole roll error. The relationship between the vertical emittance and the mean square sextupole vertical alignment error $\langle y_{sext}^2 \rangle$ can be obtained from equation (3) by replacing $\langle \theta_{quad}^2 \rangle$ with $\langle y_{sext}^2 \rangle$, and the integrated quadrupole strength $k_1 L$ with half the integrated sextupole strength, $k_2 L/2$. Of course, the summations now extend over all sextupoles, rather than over all quadrupoles. Figure 4 shows the ex-
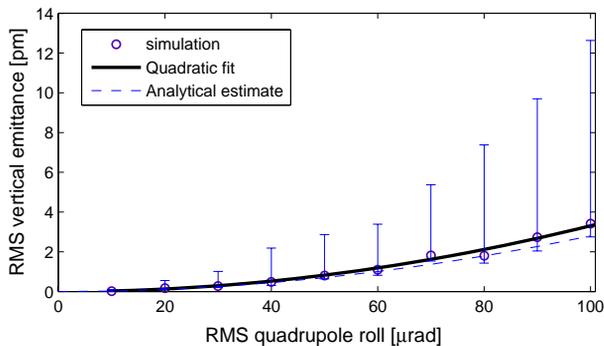
Figure 3: Variation of rms vertical emittance with rms quadrupole roll error.

pected quadratic relationship between rms sextupole alignment, and the vertical emittance generated by these errors. There is again good agreement between the theory and the simulations.
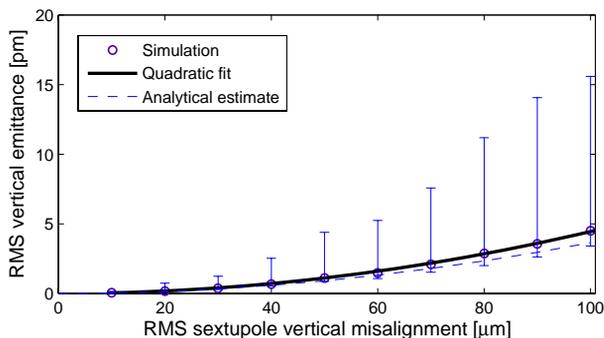

Figure 4: Variation of rms vertical emittance with rms sextupole vertical alignment error.

The sensitivity of the lattice to quadrupole and sextupole alignment errors depends on the tune of the lattice. This is illustrated in figure 5, which shows the dependence of the vertical emittance on the mean square sextupole alignment error for a range of vertical tunes. The effects of coupling resonances are clearly evident. The nominal tunes for the OCS6 lattice are 52.397 horizontal, and 49.305 vertical. The working point in tune space is generally determined by the need to achieve a dynamic aperture sufficient to ensure good injection efficiency; however, the impact of the tunes on alignment sensitivities should not be ignored.

SUMMARY AND DISCUSSION

Table 1 compares the alignment sensitivities in the OCS6 damping rings lattice with the sensitivities in the KEK-ATF. The quadrupole roll sensitivity and sextupole alignment sensitvity are defined as the rms errors that will generate, in an otherwise perfect lattice, 4.5 pm vertical emittance in the ATF, or 2 pm vertical emittance in the OCS6 lattice.

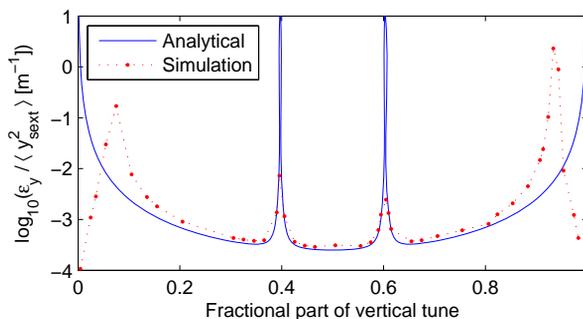The OCS6 lattice appears to have sensitivities to align-

Figure 5: Dependence of vertical emittance on sextupole alignment for a range of vertical tunes in the OCS6 damping ring lattice.

Table 1: Comparison of alignment sensitivities.

	ATF	OCS6
Orbit amplification factor	20.6	31.6
Quadrupole roll (μrad)	582	78.3
Sextupole alignment (μm)	34.8	67.1

ment errors that are comparable to, or worse than, the sensitivities of the ATF lattice. We should mention that the sensitivities we find in the OCS6 lattice are typical for the kind of low-emittance lattice needed for the damping rings, and are looser than those observed in some alternative lattice designs. The vertical emittance of 4.5 pm in the ATF was achieved only after considerable effort, and this emphasises the need for careful consideration of alignment sensitivities in the lattice design. Also needed are further studies of methods for coupling correction, and continued development of the high-performance diagnostics required to implement beam-based alignment and coupling correction with the necessary precision.

ACKNOWLEDGEMENT

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