A COMPARISON OF TUNING STRATEGIES FOR A LINEAR COLLIDER DAMPING RING*

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Abstract

Emittance preservation is an important aspect in the design and running of any new Linear Collider, with a direct consequence on the luminosity of the machine. Damping rings provide the lower limit on achievable emittance, and so are designed to produce as small a vertical emittance as possible, not only for luminosity considerations, but also to relax tolerances in downstream, emittance diluting systems. Maintaining such small emittances requires that the damping ring emittance is regularly "tuned". Several methods of damping ring tuning are investigated, and analysed both in terms of their relative effectiveness, under a variety of conditions. The effects of reducing the number of dipolar correctors and skew quadrupoles are also investigated.

INTRODUCTION

The damping rings are the primary emittance damping mechanism for any linear collider, and thus provide the achievable lower limits for the luminosity of the system. In recent years, designs for a linear collider damping ring have been investigated and optimised to fit the needs of the International Linear Collider. This design has been whittled down from over 7 original designs to one, the so called OCS6 lattice, which has recently been modified again, and replaced with the DCO lattice. The new DCO lattice is very different to the previous OCS6 design, and the effects of this change on the emittance tuning are still to be investigated. The design of this new lattice is detailed in [1].

There are many methods that have been developed for tuning damping ring lattices, and all have positive and negative points related to the ability to tune, speed of tuning, computational efficiency and complexity, as well as cost. Some methods also scale better with the number of correctors and/or inputs.

Emittance diluting effects can be characterised by their origins. Broadly speaking, we can divide these into Alignment tolerances, Ground Motion and Cultural Noise [2]. These effects lead to disturbances in the positions of elements relative to each other. These disturbances in themselves cause three main effects: a change in the closed orbit; an increase in the vertical dispersion; an increase in the linear-coupling. Only the vertical dispersion and the coupling lead to a direct increase in the extracted emittance from the damping ring, but they can be driven by the change in the closed orbit of the machine.

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VERTICAL EMITTANCE TUNING

There are various methods for tuning the vertical emittance of the damping rings. In general there are several steps to performing a tuning of the extracted emittance.

Closed Orbit Correction

Closed orbit correction is required both to minimise the emittance diluting effects arising from a non-zero closed orbit, and also to maximise the benefits of other correction methods. Most further tuning methods require that the closed orbit is as close to zero as possible in the correcting elements. Deviations away from this will directly limit the achievable extracted emittance from the damping ring.

The closed orbit is assumed to be corrected by combined horizontal and vertical corrector magnets placed near to the quadrupole magnets throughout the lattice, with dual plane beam position monitors nearby. The closed orbit is corrected by use of an inverted response matrix. The matrix is created as the beam position at each BPM in response to a change in strength of each corrector magnet. The matrix is then inverted using the Singular Value Decomposition (S.V.D.) method. The efficiency of the correction can be changed by varying the number of singular values retained during the inversion.

Dispersion Correction by Dipoles

The vertical dispersion in the ring can be corrected by the use of dipolar correctors in the vertical plane. These correctors are combined with those used for vertical closed orbit correction, with the two contributions to the correction being adequately weighted. The dispersion correction is performed via the use of a modified response matrix containing both the closed orbit response and the dispersion response at each BPM. The matrix inversion is again performed via SVD, and the number of retained singular values is variable. The weighting between the closed orbit correction and the dispersion correction is given as:

$$R_{C.O.} \rightarrow (1 - \text{Dispersion Weighting})\, R_{C.O.}$$
$$R_{\eta y} \rightarrow (\text{Dispersion Weighting})\, R_{\eta y}$$

Dispersion Correction by Skew Quadrupoles

The vertical dispersion can also be corrected by skew quadrupoles in the ring. Skew quadrupoles are assumed to exist near every sextupole. Again, the correction is determined from the inverse of the SVD of a response matrix of dispersions at each BPM for each skew quadrupole. The dispersion correction is performed in parallel to the correction of the cross-plane coupling, and so the two corrections must be weighted adequately to ensure good correction of both quantities.

Coupling Correction

Coupling correction, in this case, is through the correction of the vertical response to several horizontal kicks. Any coupling in the ring should cause linear horizontal betatron motion to be transferred to the vertical plane. Assuming that both the induced horizontal closed orbit and the coupling are large enough, the resulting motion in the vertical plane should be detectable by the vertical beam position monitors. In all, 4 horizontal correctors are used, 2 correctors are $\mu_x+\mu_y=\pm 90°$, with 2 other correctors at $\mu_x-\mu_y=\pm 90°$. The correction is performed by the inversion of a vertical response matrix at each BPM from a horizontal kick for each corrector.

Simplex Tuning

An alternative method of tuning the emittance is to use an optimisation algorithm that takes as its measure of fitness the extracted emittance from the ring. This method does not necessarily rely on any a-priori knowledge of the accelerator, and so can be more effective when the limiting factor in the emittance tuning is due to the sensors in the system. In this paper, a Nelder-Mead simplex algorithm is used to tune the values of the skew quadrupoles in the lattice. Closed orbit correction is performed before the optimisation to ensure greater linearity of the skew quadrupoles, and thus achieve a faster optimisation. This method effectively removes limitations due to the limited accuracy of the BPMs in the lattice, but does so at the expense of a longer tuning time.

OPTIMISING RESPONSE MATRICES

As noted in the previous section, the emittance tuning algorithms are sensitive to the specifics of the matrix inversion via SVD. The number of eigenvalues and the weights between closed orbit/dispersion correction and/or dispersion/coupling correction must be optimised to achieve the smallest extracted emittance from the ring. This tuning is performed both empirically, and by the use of optimising strategies, such as a Nelder-Mead simplex algorithm.

In the case of the closed-orbit correction, the efficiency of the correction is determined by the minimising the R.M.S. closed orbit after correction, over several random seeds of realistic errors.

For the closed orbit/dispersion correction algorithm and the dispersion/coupling algorithm, the figure of merit is the extracted vertical emittance of the machine. Both systems are optimised post-orbit-correction, and again over several random error seeds.

ANALYSIS OF THE DCO LATTICE

Previous work on damping ring emittance tuning has been performed on the OCS6 lattice [2], the lattice design referenced in the RDR. Recently, the nominal lattice design for the ILC has been changed to the, so-called, DCO lattice. The effectiveness of the DCO lattice, a FODO structured lattice, in terms of its emittance tuning, has been analysed. Comparisons to the previous OCS6 lattice are given where applicable.

In the DCO lattice the number of C.O. correctors and BPMs is reduced compared to OCS6, and they are situated at just over half of the total number of quadrupoles (690 in total). Skew quadrupole correctors occur next to every sextupole in the lattice.

The DCO lattice comes in 3 standard operating modes, related to the extracted bunch length of the machine. These tunings are characterised by the vertical phase advance per arc cell, and are 72°, 90°, and 100°. Analysis of the new lattice has so far concentrated on the 72° and 90° tunings.

Analysis of the two lattice designs is performed with a standard set of errors, given in Table 1, with Ψ being the rotation around the S-axis . Errors are applied to the lattice in fractions of these errors, and the emittance tuning algorithms applied.

Table 1: Standard Alignment Errors

	Δx (μm)	**Δy (μm)**	**ΔΨ (mrad)**
Quadrupole	30	30	0.3
Sextupole	30	30	0.3
BPM	100	100	20

The results of the analysis are given in Table 2. The numbers represent fractions of the standard errors at which the R.M.S. emittance reaches 20nm-rad. Comparison is made with previous results from the OCS6 lattice. The lattice “DCO 72° Thin” is a theoretical lattice, and has been created in a manner analogous to OCS6 – that is, with thin correction elements placed at every quadrupole and sextupole, as required.

Table 2: Fraction of the standard errors at which the R.M.S. emittance reaches 20nm for several lattices.

	C.O.	**C.O. + Disp.**	**C.O. + Skew Disp.+Coupling**
OCS6	*0.27*	*0.28*	*1.16*
DCO 72°	0.49	0.63	1.95
DCO 72° Thin	0.45	0.49	1.58
DCO 90°	0.43	0.51	1.94

It is clear from Table 2 that the change in lattice design has dramatically improved the error tolerance of the damping ring. The differences between the “thin” lattice and the thick model are also pronounced. The reason for this is not clear, although the emittance correction routines are less over-constrained in the thick model, as the total number of BPMs is reduced. This difference highlights that there may be scope to reduce the number of BPMs in the lattice, although this requires further study.

Analysis of the effectiveness of dipolar dispersion correction compared to skew dispersion correction shows that the latter case produces lower vertical emittances in nearly all cases. The increased vertical closed orbit in the dipolar dispersion correction case can be shown to reduce the effectiveness of the coupling correction, and so lead to the increased vertical emittance.

Table 3 summarises error tolerances for the DCO lattice for various errors. Standard alignment errors are applied with varying amplitudes of the specified error. The tolerance is the value at which the R.M.S. emittance reaches 20nm. Full emittance tuning with skew quadrupole dispersion correction is performed in all cases. The results are presented for the 90° lattice, although results are similar for the 72° lattice.

Table 3: Tolerances for several important error sources

	Tolerance
Quadrupole ΔΨ	0.78 mrad
Sextupole Y	420micron
BPM Y	370micron
BPM ΔΨ	108mrad

SIMPLEX EMITTANCE TUNING

Analysis of the limits of achievable emittance tuning of the lattice is performed by optimising the skew quadrupoles in the lattice through a Nelder-Mead Simplex algorithm. The algorithm is applied to a varying number of skew quadrupoles in the lattice and over a number of random seeds. The algorithm is allowed to run until either the normalised extracted emittance from the lattice is less than 20nm-rad, or the simplex algorithm converges. The algorithm is allowed to run only once per seed, which provides a worst case scenario.

Figure 1 shows the extracted vertical emittance, and number of iterations for a variety of scenarios with differing number of skew correctors.

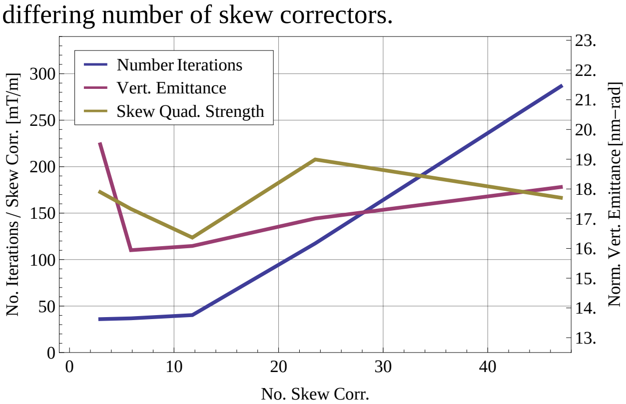

Figure 1: Results of Simplex optimisation versus number of skew correctors.

Although figure 1 shows that it is possible with the standard errors to achieve less than 20nm-rad with 2 skew quadrupoles in the lattice, this is only true in an R.M.S. sense. With at least 6 skew quadrupoles, less than 20nm-rad was achieved over all random seeds investigated.

The limits of the simplex optimisation were investigated by analysing the sensitivity to the magnitude of the alignment tolerances in the lattice. This was performed for only one seed, which gave a post-orbit-correction emittance of 123nm-rad. The results are shown in Figure 2.

Figure 2 clearly shows that the reasonable limit to the alignment tolerances with Simplex optimisation is around a factor 3 higher than the values given in Table 1. It should be noted that the Simplex algorithm is not affected by BPM errors, as are the other methods, and that limits on the skew quadrupoles was not included in this analysis. Still, it is clear that a Simplex optimisation of the skew quadrupoles can achieve the required emittances for the ILC damping rings with a drastically reduced number of skew quadrupoles, but at the expense of dramatically increased tuning time.

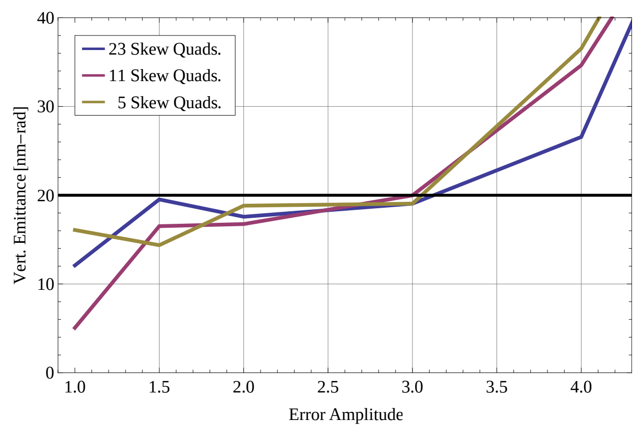

Figure 2: Residual vertical emittance versus magnitude of alignment tolerances, for varying number of skew quadrupoles.

CONCLUSIONS

Analysis has been performed of the effectiveness of emittance tuning on the latest ILC damping ring lattice, DCO. The analysis shows that the new lattice has a marked increase in emittance tuneability as compared to the previous OCS6 lattice.

Error tolerances for a variety of error sources have also been calculated, and show that the emittance tuning of the DCO damping ring is relatively resistant to a variety of errors. The analysis has also shown that there is virtually no difference in the lattice tuneability with varying arc-cell phase advance.

Analysis of the limits of emittance tuning with a reduced number of skew quadrupoles has also been investigated. Using a general simplex algorithm, which negates the effects of BPM errors, has shown that the realistically achievable error tolerances for the new lattice are roughly a factor of 3 higher than the expected tolerances.

REFERENCES

[1] A. Wolski, et al, See https://wiki.lepp.cornell.edu/ilc/bin/view/Public/DampingRings/
[2] J. K. Jones, "Tuning Algorithms for the ILC Damping Rings", proceedings of EPAC 2006.