LOW EMITTANCE TUNING FOR THE CLIC DAMPING RINGS*

J. Alabau-Gonzalvo, F. Antoniou, Y. Papaphilippou, CERN, Geneva, Switzerland

Abstract

A study on the sensitivity of the CLIC Damping Ring lattice to different sources of misalignment is presented. Dipole and quadrupole rolls, quadrupole and sextupole vertical offsets are considered, as well as the impact of a finite BPM resolution. The result of this study defines a low emittance tuning procedure and establishes alignment tolerances to preserve the vertical emittance below the design value (1 pm·rad). Non-linear dynamics studies including dynamic aperture and frequency maps are shown and synchrotron radiation effects are discussed.

INTRODUCTION

The design of the Damping Ring (DR) for a future linear collider foresees unprecedent small emittances. For the CLIC DRs, the zero-current equilibrium vertical emittance is $\gamma\epsilon_y$ = 3.7 nm·rad as compared to the target of 5 nm·rad, providing enough margin for the observed growth due to IBS at the nominal current [1]. This corresponds to an ultralow vertical emittance of around 0.7 pm·rad at the DR energy of 2.86 GeV.

Alignment of the magnetic elements is crucial for reaching this ultra-low vertical emittance. The goal of this study is to define a correction procedure for a realistic machine in order to achieve the design emittance, thus identifying the target misalignment tolerances.

The CLIC DR is a racetrack lattice with Theoretical Minimum Emittance cells in the arcs and superconducting wigglers in the long straight sections. The lattice has BPMs located near the quadrupoles in the straight section FODO cells and in points of alternated high and low dispersion and beta functions in the arcs corresponding to a total of 358 monitors along the machine. Alternated horizontal and vertical orbit correctors are installed close to the straight section quadrupoles, and additional windings in the sextupoles are used for correcting both planes in the arcs, with a total of 320 vertical and 312 horizontal orbit correction knobs. Skew quadrupole correctors are installed as well as additional windings in the sextupoles. The first section of this paper explains the main differences between the previous low emittance tuning and the actual one. The results before and after applying BPM finite resolution are presented in the second section. Lastly, the non-linear behaviour of the lattice is studied with dynamic aperture (DA) and frequency maps.

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LOW EMITTANCE TUNING

As introduced in previous studies [2], four kinds of misalignment are being considered:

- Quadrupole vertical offsets
- Quadrupole transverse rolls
- Dipole transverse rolls
- Sextupole vertical offsets

With respect to the previous low emittance tuning studies the coupling correction procedure has evolved in order to make it more realistic by including BPM finite resolution. Previously, the correcting method cancelled the $\langle xy\rangle$ element from the one turn transfer matrix in each BPM. This parameter was taken directly from MADX [3] and the explicit dependence with the BPM resolution is not straightforward. Now the coupling is corrected along with the dispersion and it is made directly from position measurements taken from the monitors. The response submatrix corresponding to the coupling (C) is built by measuring the change in the beam vertical position at every BPM (Δ_y) when each skew quadrupole is sequentially activated (k_{skew}), while the beam is being horizontally kicked at a fixed point:

$$\begin{pmatrix} \Delta y \\ w \cdot \Delta D_y \end{pmatrix} = \begin{pmatrix} C \\ w \cdot D \end{pmatrix} \cdot (k_{skew}) \qquad (1)$$

The algorithm foresees a weight w between dispersion and coupling correction. The optimization of this weight has been done for each kind of misalignment looking at the value that minimised the vertical emittance. The chosen optimal weight is $w = 2.1$, which corresponds to the optimal correction of the coupling due to vertical quadrupole offset since the lattice is most sensible to it.

SIMULATION RESULTS

Once the correction is applied, the four coupling elements of the one turn transfer matrix are visibly flattened and the maximum error in the dispersion is lowered by a factor 8. The beta beating is also lowered from a maximum value of 5.6% to a 0.13%. The maximum pole tip field after 200 misaligned lattices (using a set of RMS errors equal to the found tolerances, see next section) was 0.03 T for an aperture of 20 mm, which is well within the feasible limits.

Simulations have been done averaging over 200 machines for each of the four misalignment considered, which were distributed according to a 2.5σ truncated Gaussian.

Figure 1 shows the result of applying each error independently. The geometrical vertical emittance as a function of the RMS error is plotted for the uncorrected lattice in solid red line and for the corrected in solid light blue. The colored area represents the 95% and 5% of the lattices. The gray dotted line shows an analytical vertical emittance estimate [4]. In the case of the quadrupole vertical offset and roll, only the values after correction are plotted since the error is applied in seven steps, each one followed by a closed orbit (CO) correction. This is done to avoid MADX not being able to find a CO. Note the 10^3 factor in the quadrupole vertical offset, showing the sensitivity of the lattice to this kind of misalignment. In the right vertical axis, the blue line shows the ratio of lattices for which a solution is found (note that it is less than 100% only for RMS misalignment beyond the found tolerances). The green line shows the ratio of lattices for which the tune has been matched to the nominal value (up to a 10^{-3} level).

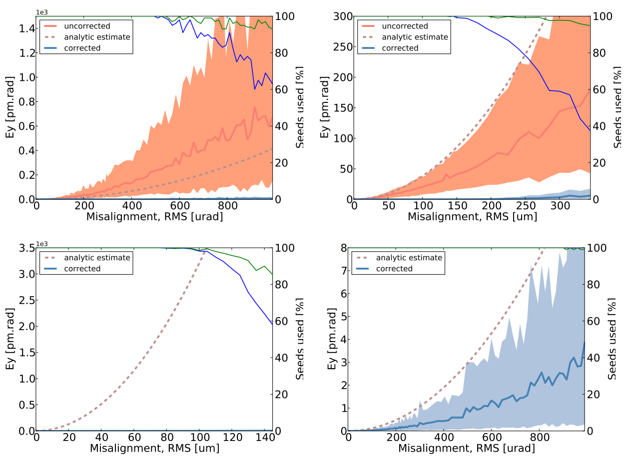

Figure 1: Vertical emittance before and after tuning under: dipole rolls (upper left), sextupole vertical offsets (upper right), quadrupole vertical offsets (lower left) and quadrupole rolls (lower right).

Theoretical estimations of the emittance growth before correction at the chosen tolerances show that the quadrupole vertical offset is the most contributing misalignment, followed by sextupole vertical offset and dipole roll, both about a factor four lower, as shown in Fig. 2 left. Quadrupole roll contribution is two orders of magnitude less. Figure 2 left shows that for the quadrupole vertical offset and dipole roll more than 95% of the contribution comes from CO passing through quadrupoles and the rest comes from CO passing through sextupoles. For the sextupole vertical offset and quadrupole roll betatron coupling and dispersion contribute equally to the emittance growth.

Adding BPM Resolution

So far the tolerance for each source to the vertical emittance budget has been calculated considering no BPM resolution. After that, a parametric study has been done scanning the BPM resolution and a factor (between 0 and 1) to be multiplied to the found tolerances, as in the left plot of Fig. 3. The vertical emittance for the 95% of 200 lattices is shown as a function of the BPM resolution, the horizontal dashed line

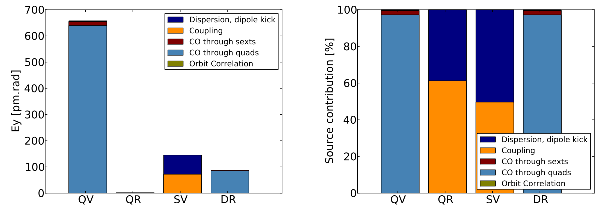

Figure 2: Absolute and relative contribution to the emittance growth for the four misalignment and their main sources in colour code.

showing the target emittance and the different colours representing different multiplication factors. If now we look at the points where the emittance coincides with the target value we have the right plot in Fig. 3 where the vertical axis now is the RMS quadrupole vertical offset, being this the limiting misalignment. At this point it is necessary to make a compromise between vertical misalignment and BPM resolution, which has been decided at 18 μm and 200 nm respectively.

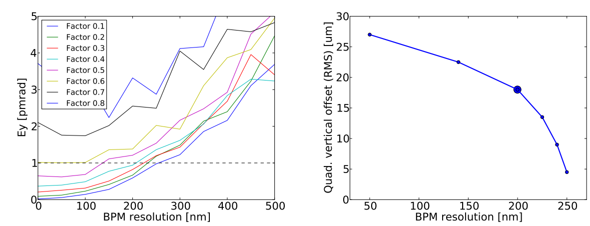

Figure 3: Left: BPM resolution impact on the vertical emittance for different multiplication factors of the found misalignment tolerances. The lines represent the 95% of the lattices. Right: Vertical quadrupole offset versus BPM resolution for solutions giving the target vertical emittance.

Table 1 shows the final alignment and resolution tolerances considered. Although tight, they are still within the state-of-the-art technology.

Table 1: RMS Errors Leading to a 1 pm·rad Vertical Emittance

Error source	**Tolerance**
Dipole transverse roll	180 μrad
Sextupole vertical offset	78 μm
Quadrupole vertical offset	18 μm
Quadrupole transverse roll	138 μrad
BPM resolution	200nm

NON-LINEAR STUDIES

The DA for the ideal lattice comes out to be $9.3\sigma_x$ in the horizontal plane and $77\sigma_y$ in the vertical one (where the beam sizes are expressed at injection). When the found set of tolerances is introduced, including BPM resolution, one

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obtains a DA as in Fig. 4. In this plot the on-momentum and off-momentum DA are the black and coloured lines respectively. For the on-momentum case there is also shown the apertures corresponding to the 95% and 5% of the lattices. 1056 turns are considered. The red line shows the 5σ ellipse as a reference, and the points correspond to the tracked initial positions. For the on-momentum case the 95% of lattices (inner dashed line) can be accommodated in about $5\sigma_x$ in horizontal and about $22\sigma_y$ in vertical.

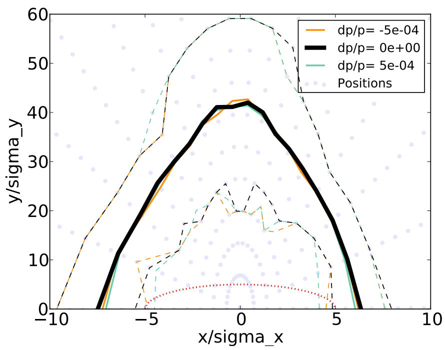

Figure 4: On and off-momentum DA for the lattice fed with errors at the obtained tolerances.

In order to have a better non-linear performance, especially in the horizontal plane, the sextupole vertical offset has been scanned to calculate the DA and the result is that, aligning the sextupoles at the same level as the quadrupoles (i.e. 20 μm RMS), 8.5 σ_x could be horizontally accommodated and about 70 σ_y vertically, for the 95% of the lattices.

Having in account the fact that the effects of SR are slow compared to the revolution frequency (one damping time corresponds to about 1400 turns), in order to estimate how it affects the DA, the particles are tracked for one single turn and the exit position and angle are used as an input for the next one-turn tracking, repeating for 1056 turns. Between two consecutive turns, the coordinates are multiplied by a damping factor which comes from the exponential decrease of the emittance. The results of this simulation show that the differences between DA with and without SR are not perceptible at least to the level of the simulation step, which is $0.6\sigma_x$ horizontally and $6.5\sigma_y$ vertically.

The wiggler is modelled as a hard-edge sequence of sector bends, with parallel faces so that there is a vertical focusing component. In order to have a more realistic model, the octupolar component predicted from theory [5] has been added as a thin octupole after each wiggler period. This lowers the ideal lattice DA to $8.1\sigma_x$ in the horizontal plane and $64\sigma_y$ in the vertical one. Figure 5 compares the on-momentum frequency maps for the ideal lattice with and without the wiggler octupolar component. The color code represents the diffusion parameter, red being chaotic and blue stable particles. Resonances up to fourth order are shown.

At the moment the work is focused on a scheme to correct the octupolar component, visible in the frequency maps and on the analysis of higher order dynamics via resonance driving terms elimination.

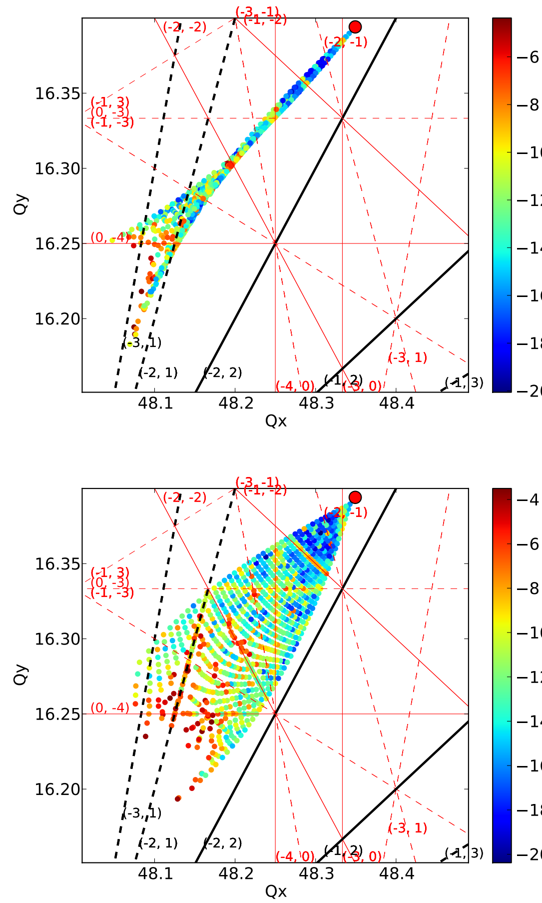

Figure 5: Top: Frequency map for the perfect aligned lattice with a linear hard-edge wiggler. Bottom: Frequency map including a thin octupole per wiggler period.

CONCLUSIONS

A corrector scheme has been elaborated in the CLIC DR, including kickers, skew quadrupoles and BPMs and, along with them, a tuning method to correct CO, dispersion and coupling has been developed. Using this procedure, studies have been done in order to reproduce the vertical nominal emittance under a realistic lattice and the alignment tolerances for vertical offset and rolls of the main magnetic elements have been identified. This study includes finite BPM resolution. The set of tolerances found is within the state-of-the-art technology, being 20 μm the tighter RMS alignment and 200 nm the BPM resolution. Moreover DA has been calculated, studying the effect of SR and the wiggler model. Those simulations show that the horizontal aperture is about 8 σ_x for the 95% of the lattices. Frequency maps have also been generated in order to study in detail the resonance structure.

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