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PROGRESS ON LOW EMITTANCE TUNING FOR THE CLIC DAMPING RINGS

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Abstract

In the frame of the CLIC main Damping Ring a study on the sensitivity of the lattice to different sources of misalignment is presented. The minimum equilibrium emittance is simulated and analytically estimated under dipole and quadrupole rolls, and quadrupole and sextupole vertical offsets. The result of this study establishes alignment tolerances to preserve the vertical emittance below the design value (1 pm·rad). Non-linear dynamics studies have been done to determine the dynamic aperture in the presence of misalignments.

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 unprecedent low 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. The first section explains the tuning procedure with some stress on the coupling and dispersion correction. After that, the results of the simulations are presented for different scenarios together with the theoretical estimation. Finally a dynamic aperture study including misalignments and correction is shown.

LOW EMITTANCE TUNING

Following previous work [2], four kind of errors have been considered for the vertical emittance increase due to misalignments:

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

Quadrupole vertical offset create a vertical dipole field and, with dipole transverse rolls, are a source of vertical dispersion due to the dipole kick and the non-zero vertical Closed Orbit (CO) through the quadrupoles, and of betatron coupling due to the non-zero vertical CO through the sextupoles. Vertical sextupole offsets generate a skew component, identical to quadrupole transverse rolls and are a source of vertical dispersion and direct betatron coupling. For the time being no field errors are included and the wigglers are modelled as bends with alternating polarity without misalignments, although work is ongoing to have a more realistic magnetic model of the wiggler, based on the prototype built at BINP [3].

The low emittance tuning starts with the CO correction for both planes using all the correctors and BPMs available. The lattice is found to be very sensitive to quadrupole vertical offsets. It is actually impossible to find a solution for a high number of sets of misalignments when the RMS of the error distribution exceeds a certain value. Therefore the amplitude of the RMS errors is divided into steps and introduced iteratively applying, at the same time, an orbit correction.

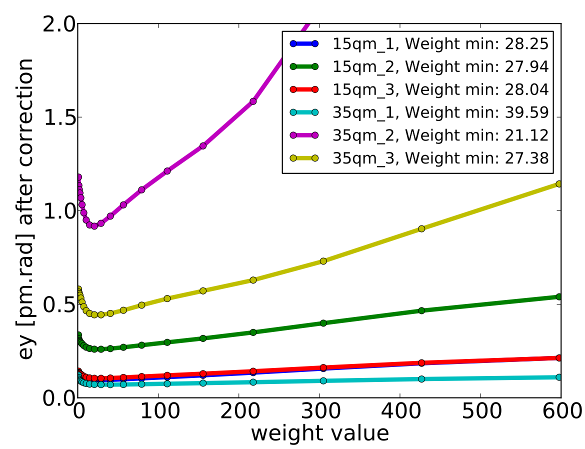

Figure 1: Coupling-dispersion weight scan for a set of errors.

Previous studies showed that a coupling correction scheme was needed in order to allow an achievable sextupole distribution [4]. Skew quadrupoles were installed for this purpose as additional windings in the sextupoles. After the CO, the coupling and dispersion are corrected. A response matrix relating both the transverse coupling term of the one-turn

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beam matrix ($< xy >$) and the vertical dispersion (ΔD_y) with the strength of the skew quadrupoles ($_{skew}$) is built.

$$\begin{pmatrix} < xy > \\ w \cdot \Delta D_y \end{pmatrix} = \begin{pmatrix} C \\ w \cdot D \end{pmatrix} \cdot (k_{skew}) \tag{1}$$

The symbols C and D denote submatrices related to coupling and dispersion. Although ideally the realistic measurement of the coupling term would be done by simulating turn-by-turn BPM data, for the moment finite resolution is not taken into account by the MADX [5] simulations. Once the vertical dispersion and coupling are measured, the skew strengths that minimises them is calculated by pseudo-inverting the response matrix using an SVD. Each skew quadrupole is powered individually. The algorithm implements a weight factor w between coupling and dispersion whose optimal value is found by simulation. Figure 1 shows the scan of the weight (horizontal axis) versus the achieved vertical emittance. Each curve corresponds to a different set of errors for quadrupole vertical offset. The weight leading to the minimum vertical emittance for each case is found and the average of all minima is taken as the optimal w value.

Finally the two sextupole families are used to correct chromaticity.

SIMULATION RESULTS

Simulations of the tuning have been done for the aforementioned errors, averaging over 200 machines for each of the RMS misalignments, which were distributed according to a 2.5 σ truncated Gaussian.

Figure2 shows the results of applying each kind of misalignment 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 blue (completely flat in all plots). The coloured area represents the standard deviation of the distribution. The gray dotted line shows an analytical vertical emittance estimate for each error [2]. In the case of the quadrupole vertical offset (bottom left plot), only the values after correction are plotted, due to the iterative correction procedure in every step of the applied error, as mentioned in the previous section. Note the 10^3 factor in the vertical axis, proving the sensitivity of the lattice to this kind of misalignment.

For every case, the misalignments leading to a 1 pm·rad vertical emittance were over the range studied and therefore what Table 1 presents is a lower limit for the tolerances.

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

Misalignment	**Tolerance**
Dipole transverse roll	$>$ 300 μrad
Sextupole vertical offset	$>$ 100 μm
Quadrupole vertical offset	$>$ 100 μm
Quadrupole transverse roll	$>$ 300 μrad

A case combining all errors has been simulated using 100 μm for the RMS vertical offsets and 100 μrad for the

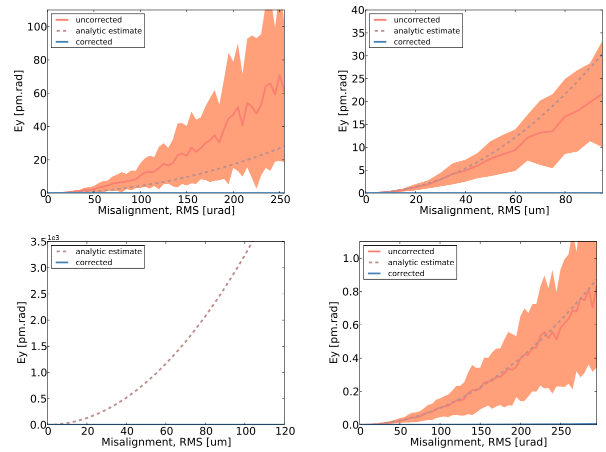

Figure 2: Vertical emittance before and after tuning under: dipole rolls (upper left), sextupole vertical offsets (upper right), quadrupole vertical offsets (lower left) and quadrupole rolls (lower right).

RMS transverse rolls. The theory predicts the contribution from the quadrupole vertical offset to be 3 nm·rad, two orders of magnitude higher than the one from the sextupole vertical offset, and even higher for the other two misalignments. The relative contribution of the different sources of emittance increase is shown in Fig. 3 for every applied misalignment. It is evidenced the large contribution of sextupole vertical offset to coupling and the necessity to correct it with the skew quadrupole windings. The quadrupole vertical offset and dipole roll are mainly sources of emittance growth through closed orbit distortion in quadrupoles and therefore it was well corrected with the orbit correctors.

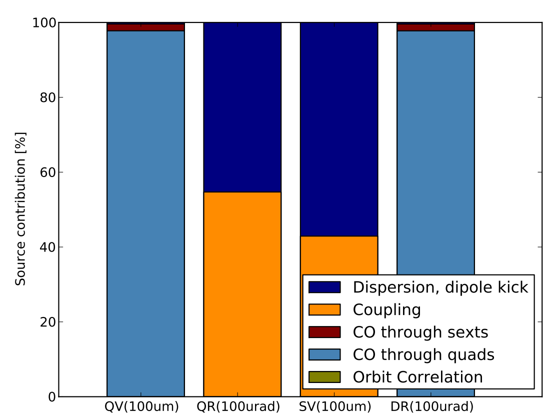

Figure 3: Theoretical relative contribution of different sources to the emittance growth (the four columns being Quadrupole Vertical, Quadrupole Roll, Sextupole Vertical, Dipole Roll misalignments).

For the simulations including all errors, 200 seeds were launched using 100 μm for the RMS vertical offsets and 100 μrad for the RMS transverse rolls (for 3 of them no CO

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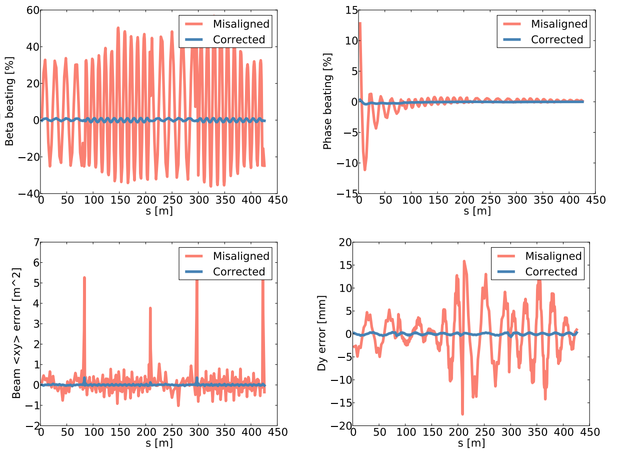

Figure 4: Beta beating (top left), phase beating (top right), error in the coupling term of the beam one-turn matrix (bottom left) and error in vertical dispersion (bottom right).

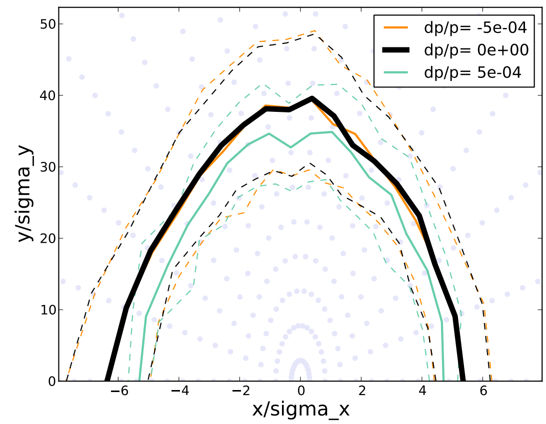

Figure 5: Dynamic aperture for on-momentum and off-momentum particles.

was found). The extracted emittance after the tuning was 0.2 ± 0.4 pm·rad, well within the limits. The maximum kick needed for the correction was 0.332 mrad (which means about 0.021 T for a 15 cm corrector) and the maximum skew quadrupole pole tip field for a 20 mm aperture (same aperture as in sextupoles) was 0.1 T. Orbit correctors and skew quadrupoles are then feasible. The two plots on the top of Fig. 4 show for one of the random seeds, the performance of the correction in terms of beta and phase beating (the relative error of the measured value with respect to the nominal one), the error in the transverse coupling term of the one-turn beam matrix and the error in the vertical dispersion. The values before (red) and after (blue) the correction are compared along the line. The performance of the correction is satisfactory, in particular beta beating shrinks down to a few percent and the error in vertical dispersion after correction is no more than 2 mm.

DYNAMICS APERTURE

In order to correct the high chromaticity generated in the arcs strong sextupoles are installed. This can degrade sensibly the dynamic aperture, leading to a loss of particles and bad injection efficiency. In this respect, studies have been carried out using 50 machines after the tuning procedure, where 100 μm for the RMS vertical offsets and 100 μrad for the RMS transverse rolls where introduced. The particles were tracked 1056 turns. Figure 5 shows the result of this study. Grey dots correspond to the points scanned. Thick lines and dotted lines show the mean and standard deviation for 50 machines for on-momentum and $\Delta p/p = \pm 5 \cdot 10^{-4}$ off-momentum particles. The result is similar to previous studies [6] for a perfect machine, showing the efficiency of the correction schemes.

CONCLUSIONS

A skew quadrupole scheme has been installed in the DR model and is used to correct dispersion and coupling by means of a response matrix algorithm. The performance of the whole tuning procedure is satisfactory and relaxes the tolerances to misalignment with respect to previous studies.

The tuning has been simulated for 200 lattices and the tolerances to misalignment in order to extract the nominal vertical emittance have been found well within the feasible limits, as well as the correctors and skew quadrupole settings. The main contribution to emittance growth comes from the high sensibility of the lattice to quadrupole vertical offsets.

Dynamic aperture studies were done, frequency maps calculations are ongoing to complement the information and study the main limitations.

The model will be complemented with a more accurate wiggler model and including BPM resolution and the effect of IBS.

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