NON-LINEAR DYNAMICS OPTIMIZATION OF THE CLIC DAMPING RINGS

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Abstract

Non-linear dynamics studies are undertaken in order to optimize the dynamic aperture of the CLIC damping rings. In this respect, advanced methods such as frequency map and resonance driving term analysis are used in order to explore the working point space with respect to single particle stability. The impact of magnet errors and misalignments, and in particular, the effect of the super-conducting damping wigglers is evaluated. Additional considerations for the working point choice are presented.

INTRODUCTION

In the CLIC machine, intense bunches are injected into the main linac with unprecedentedly small emittances in order to achieve the design luminosity required for the physics experiments. The positron and electron bunch trains are provided by the injection complex, but with emittances of several orders of magnitude higher. Two predamping rings (PDRs) with large dynamic acceptance and relatively large equilibrium emittance are used to pre-cool the incoming beam. Nevertheless, the beam emittance injected into the damping rings (DR), especially in the horizontal plane is still 100 times higher than the target normalized emittance of 500nm. To achieve this emittance at the design repetition rate of 50 Hz, the DR lattice is filled with Theoretical Minimum Emittance (TME) arc cells producing high chromaticity and super-conducting high-field wigglers in the straight sections. To correct the chromaticity, very strong sextupoles are used which can degrade the dynamic aperture of the DR, thus producing particle losses at injection. The strong sextupoles and the wigglers make the lattice very sensitive to misalignments especially with respect to the vertical emittance and special correction schemes should be implemented in order to restore it. As the misalignments and magnet errors induce an optics symmetry loss, the dynamic aperture may be affected.

This paper focuses on the evaluation of the non-linear dynamics behaviour of the CLIC DR through the construction of frequency and diffusion maps. In particular, the influence of magnet errors and misalignments in the particles' non-linear dynamics using the correction systems to recover the small vertical emittance is evaluated.

PERFECT LATTICE

Frequency maps of the CLIC DR are produced by launching individual particles with different transverse offsets and tracking them with MADX-PTC [1] for 1056 turns or until lost. The synchrotron motion is neglected and 5D tracking is performed with fixed momentum off-sets. The initial conditions are chosen such as to be uniformly spaced with respect to the tune-shift, which is linear with the square of the position, at leading order. If a particle has survived up to the last turn, the tunes are evaluated by analyzing the tracking data with Laskar's NAFF algorithm [2].

The working point of the DR is tuned to $\nu_x = 48.35$ and $\nu_y = 10.40$. To obtain the diffusion rate, the tunes ν_{x1} and ν_{y1} are computed on the first half number of turns and then the tune ν_{x2} and ν_{y2} are computed on the remaining turns. The diffusion indicator D is obtain as :

$$D = \log\left(|\nu_{x1} - \nu_{x2}| + |\nu_{y1} - \nu_{y2}|\right) \quad . \qquad (1)$$

The lattice used in the simulation contains the arc sextupoles tuned for zero chromaticity and hard-edge magnet fringe fields. The wigglers are modelled as a sequence of bends with alternating polarity. Frequency and diffusion maps for the perfect CLIC DR lattice are shown in figures 1 and 2, for both on (center) and off-momentum (left and right) particles of $\pm 5 \times 10^{-3}$.

The large tune shift of 0.3 for around $6\sigma_x$ transverse beam offset in the horizontal plane, is due to the strong sextupoles needed for the chromaticity correction. In this respect, in the horizontal plane, the tune approaches very close to the integer resonance $Q_x = 48$, which seems to be the main limitation of the dynamic aperture, at least for the on-momentum optics. Two more resonances are clearly excited but not seem to be connected with beam loss, at least from the single particle dynamics point of view. The closest to the working point (pink line) is the normal third order resonance $Q_x + 2Q_y = 69$, which can be directly excited at first order by the chromaticity sextupoles and dipole fringe fields. The second one (purple line) is the 4th order normal resonances $2Q_x + 2Q_y = 117$, which can be excited by the quadrupole fringe-fields at leading order or by the sextupoles at higher order. The normal and skew third order resonances $3Q_x = 145$ and $3Q_y = 31$ do not seem to be excited.

For off-momentum particles with momentum spread of $\pm 5 \times 10^{-3}$, there is a 25% reduction of the dynamic aperture. The same major resonance lines are visible, but the loss is observed earlier, probably due to the overlapping of a large amount of resonances near the horizontal integer line, which indeed is also a systematic one. It should be noted that, for the vertical plane, where the beam is entering the DR with an emittance which is 50 times lower than the horizontal one, the dynamic aperture is still comfortable. This is visible in the right and top axes labels of the diffusion marks, where the number beam sizes are quoted instead of the real size in mm (bottom and left axes labels).

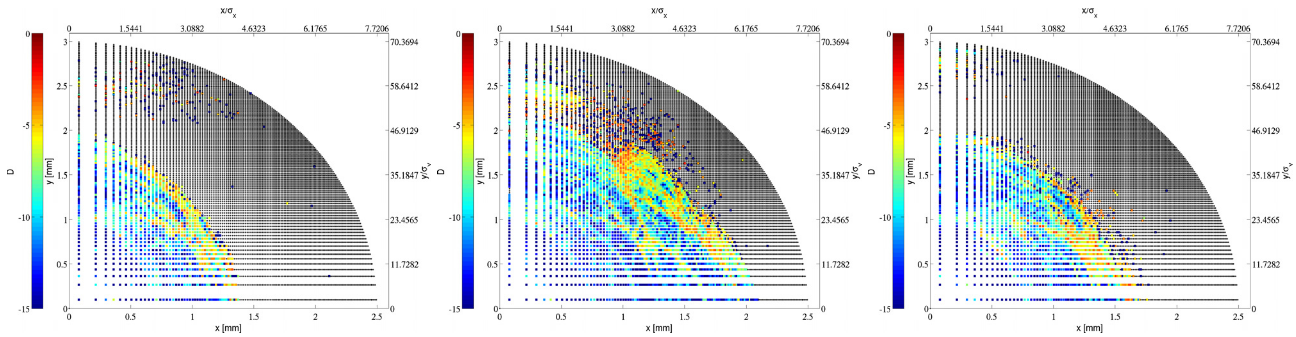

Figure 1: Dynamic aperture of the ideal CLIC DR with, from left to right, a momentum deviation of respectively -5×10^{-3}, 0 and 5×10^{-3}. Black markers are for lost particles.

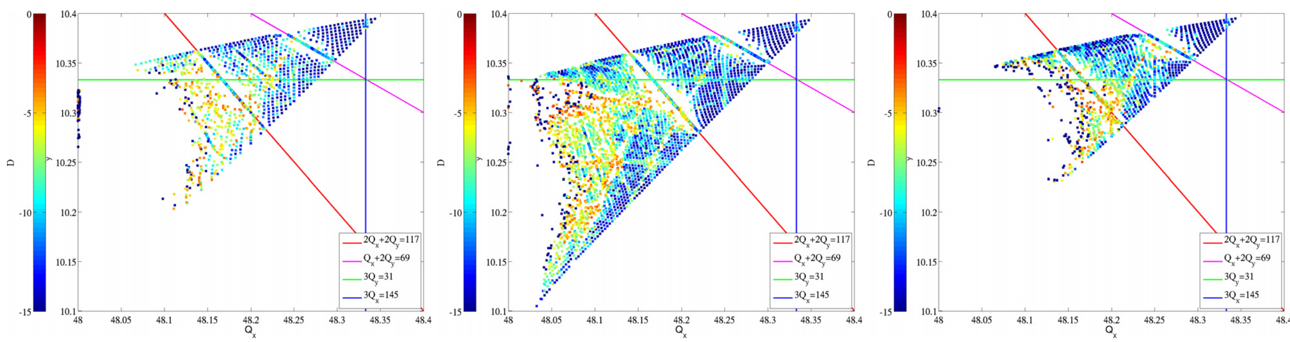

Figure 2: Frequency map of the ideal CLIC DR with, from left to right, a momentum deviation of respectively -5×10^{-3}, 0 and 5×10^{-3}. Some relevant resonance lines are shown.

However, for the horizontal plane, the dynamic aperture becomes really tight and equal to around $4.5\ \sigma_x$. This shows how critical is the performance of the PDRs in order to produce the lowest possible horizontal emittance without compromising their performance with respect to their proper dynamic aperture. In addition, it is important to find sextupole settings that reduce the tune-shift with amplitude, without exciting other resonances, as with this large tune-shift there is no hope in finding a working point, with a much larger dynamic aperture.

MAGNET IMPERFECTIONS AND CORRECTION

Magnet errors and misalignments can drastically change the optics properties of the DR, breaking symmetries of the lattice. To obtain more realistic frequency and diffusion maps, errors on magnetic fields and misalignments have been introduced (see table 1). The high quality fields for quadrupoles can be obtained as the beam is pre-damped and so the beam pipe can be small (around 2cm diameter). No higher order multi-poles above sextupoles are considered for the time being. In addition, there are no multi-pole errors included in the dipoles. The values for the integral of the magnetic field errors in the wigglers are obtained as the third of the maximal values given by the specifications[3].

Once these errors are introduced, the orbit and Twiss functions are greatly perturbed, resulting in well above

Table 1: Magnetic errors included in simulation.

Error type	Elements	RMS
Misalignment (Hor. & Vert.)	Quadrupoles	5 μm
Normalized multipole	Quadrupoles	
Quadrupolar		10^{-4}
Skew quadrupolar		10^{-5}
Sextupolar		10^{-4}
Skew sextupolar		10^{-5}
Integral field error	Wigglers	
1st vertical		10^{-5} Tm
1st horizontal		10^{-6} Tm
2nd vertical		10^{-4} Tm^2
2nd horizontal		3×10^{-6} Tm^2

specification emittances, tune shift and a large reduction of the dynamic aperture. To restore the optics of the DR, a series of corrections are performed [4]: First the orbit is corrected with the available steerers and then the tune is matched to the nominal one, by varying the straight section quadrupoles. The dispersion is then rematched to the nominal values and suppressed from the straight section, with the steerers and quadrupoles in the dispersion suppressor. A final chromaticity correction is performed using the arc sextupoles.

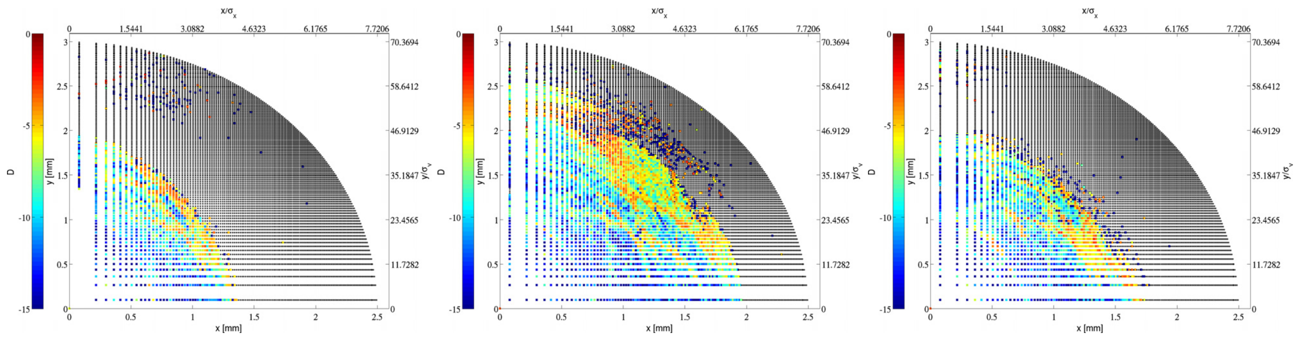

Figure 3: Diffusion map of the CLIC DR after corrections with, from left to right, a momentum deviation of respectively -5×10^{-3}, 0 and 5×10^{-3}. Black markers are for lost particles.

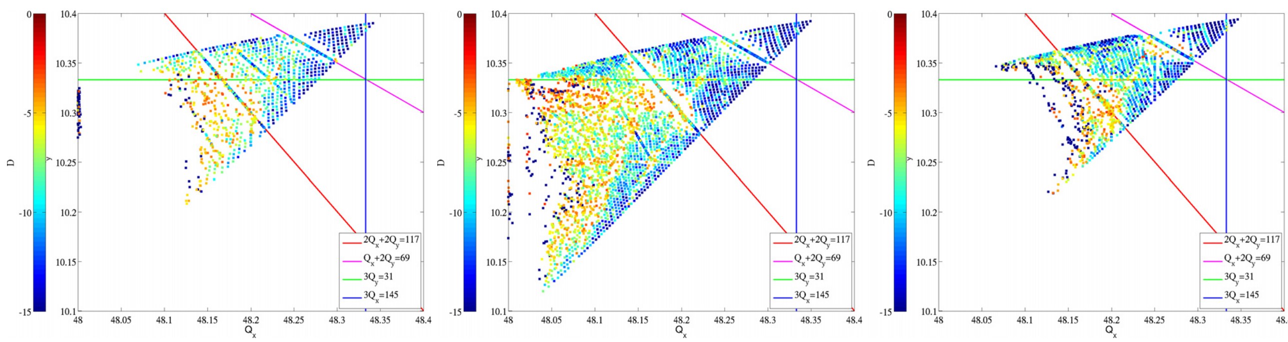

Figure 4: Diffusion (top) and frequency map (bottom) of the CLIC DR after corrections with, from left to right, a momentum deviation of respectively -5×10^{-3}, 0 and 5×10^{-3}. Some relevant resonance lines are shown.

The diffusion and frequency map with errors and after corrections are shown in figures 3 and 4, for on (center) and off-momentum (left and right) particles. The frequency maps are very similar as compared to the lattice without magnet errors for all three momentum deviations. The same type of resonances are observed as in the perfect lattice. The diffusion seems to be slightly increased in the area were the beam survives the short term tracking, probably because resonances are more excited due to the breaking of the symmetry of the lattice by the errors, as compared to the perfect lattice. On the other hand, it seems that the correction has completely restored the dynamics as the dynamic aperture is almost identical, thereby proving the efficiency of the correction.

DISCUSSION

Non-linear dynamics studies have been initiated to determine the dynamic aperture of the CLIC damping rings. Frequency and diffusion maps have been employed in order to explore its non-linear dynamics limitations. For the perfect lattice, the main problem is associated to the large horizontal tune-shift with amplitude which drives particles with around $6\sigma_x$ horizontal transverse amplitude right to the integer resonance. A choice of a different working point seems impossible, and thus further studies should focus in the elimination of this large tune-shift, other with other sextupole families or with octupoles, but without exciting additional resonances. Although the vertical dynamic aperture is very large due to the very small emittance coming from the PDRs, it may become critical in the future: actually, modern electron sources and linacs are within the reach of the horizontal emittance performance of the PDRs (around 60μm). In this respect, the electron PDR becomes obsolete, with a very important cost saving impact, provided that the vertical dynamic aperture is also large.

Errors on quadrupoles and wiggler magnetic fields has been introduced as well as quadrupole misalignments and the optics restored with a series of corrections. The dynamic aperture after correction is almost identical as for the perfect lattice showing greatly the efficiency of correction systems. This is indeed only a first indication, as other magnetic field errors and misalignments should be included in simulations in order to have a more realistic model.

Finally, it should be stressed that the dynamics at injection is still dominated by strong damping but also collective effects. In particular, space charge moves vertically the tune to around 0.1 and this should be taken into account in the simulations as a further step.

REFERENCES

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