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METHODS TO INCREASE THE DYNAMIC APERTURE OF THE FCC-HH LATTICE *

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Abstract

The Future Circular Collider (FCC) design study aims to develop possible circular colliders in the post LHC era. In particular the FCC-hh will aim to produce proton-proton collisions at a center of mass energy of 100 TeV [1]. Initial tracking studies for the FCC-hh lattice at collision energy including field errors on the final focus triplet showed a very low dynamic aperture, most likely affected by the large beta functions and integrated length of the quadrupoles. Using non-linear correctors, the dynamic aperture was increased to acceptable levels; however, the difficulty to have an accurate magnetic model of the magnets required for this correction motivates the development of alternative methods. This work explores the possibility to increase the dynamic aperture by optimizing the phase advance between the two main interaction regions. The description of this method along with its impact on the dynamic aperture will be given on this paper.

INTRODUCTION

The FCC-hh lattice features two high luminosity insertions and two special purpose experiments. An illustration of the layout of the FCC-hh is given in Fig. 1. The two high luminosity insertions are located in the interaction regions A and G (IRA and IRG).

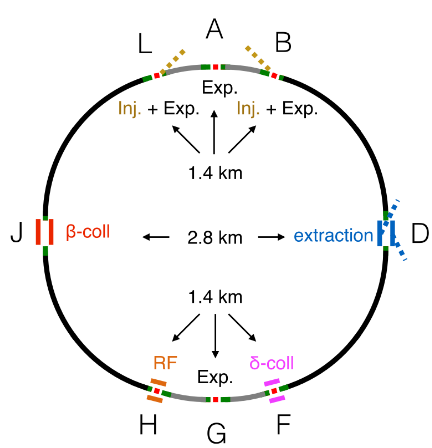

Figure 1: Layout of the FCC-hh ring [2].

Several options have been proposed for the design of the low β interaction regions to achieve values of β^*=0.15, 0.2, 0.3 and 1.1 m [3]. In particular the initial parameters with β^* of 1.1 m are expected to achieve a luminosity of 5×10^{34} cm^{-2}s^{-1}, while the ultimate parameters with β^*=0.3 m aim to increase the luminosity up to $20-30\times10^{34}$ cm^{-2}s^{-1}. An alternative design for the IR has also been developed to achieve the same values of β^* but with the use of a shorter triplet as well as the option to run with flat beams [4, 5].

The two high luminosity insertions require strong magnets to focus the beam into the interaction point. The model of these magnets and its error table have been based on the quadrupole magnet technology of the High Luminosity-LHC (HL-LHC) [6] but the design is adjusted to scale it to the new apertures.

Dynamic aperture (DA) studies were performed for the design with β^* of 0.3 m at collision energy and errors in the triplet. It is expected that a DA of 10-12 σ would be enough to achieve a long term DA of 6 σ, as it was proposed for the LHC [7]; however, initial studies of the FCC-hh lattice with crossing angles proved to be challenging resulting in a very low DA of 2 σ. Following the example of LHC and HL-LHC [8] non-linear correctors were implemented in both main IRs giving encouraging results, increasing the DA up to 10.1 σ when using sextupole, octupole and dodecapole correctors [9].

However, non-linear correctors require the magnetic model of the quadrupoles to give an accurate correction. The objective was then to follow closely the experiments on the LHC combining magnetic measurements during construction and beam-based studies [10], but also to look for alternative methods to avoid relying solely on the correction of non-linearities.

CHANGES TO LATTICE

A series of changes were applied to the lattice. The total length of the complex was reduced to 97.75 km [2], while the distance from the interaction point to the first quadrupole (L^*) decreased to 40 m [11].

As a result of these changes the DA increase to 10 σ, even without non-linear correctors, to compare to the previous results of 2 σ as shown in Fig. 2. The origin of this improvement was investigated not only to understand the problem with the previous lattice but also because it will give an indication of a correction to take into consideration in the future. After a series of tests it was found that the increase in DA was due to the change in phase between the main interaction regions IRA and IRG. A dedicated study was therefore performed to analyse the impact of the phase between the main IRs on the DA.

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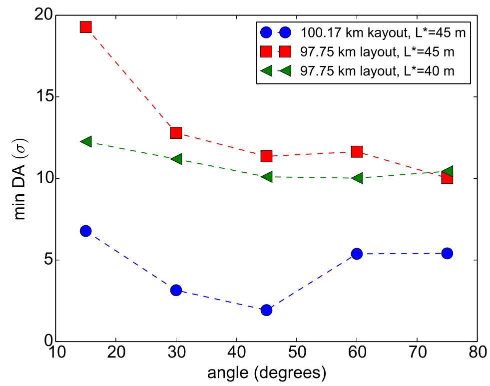

Figure 2: Comparison of DA vs angle between different options of the lattice. The previous lattice with 100.71 km and L^*=45 m is shown in blue, while new lattice with 97.71 km is shown in red with L^*=45 m and green with L^*=40 m.

PHASE OPTIMIZATION

DA studies were performed using SixTrack [12] on a thin-lens version of the FCC-hh lattice with β^*=0.3 m over 10^5 turns with crossing angles on, 30 particles pairs per amplitude step of 2 σ, 5 angles in the transverse plane and a momentum offset of 2.7e-4. The energy was set to 50 TeV and the normalised emittance to ϵ =2.2 μm. A series of corrections were implemented including: tune and chromaticity matching, SSC-like spurious dispersion correction [13] and coupling correction. As mentioned above, in previous studies the use of non-linear correctors was crucial to increase the DA to acceptable levels, in this study however (unless specifically indicated) the non-linear correctors were turned off to investigate the reach of DA without this correction.

For these studies, a further procedure was implemented adjusting the phase between the main IRs using trim quadrupoles in the long arcs between IRA and IRG, while using the trim quadrupoles from IRG to IRA to adjust to the total tune, kept to the default values of 110.31/107.32; this was called the double tuning method. A second method was also investigated using phasors, elements which only change the phase, implemented on the low luminosity interaction regions L and B (IRL ad IRB). The one on IRL change the phase from IRA to IRG, while the one on IRB was used to keep the same tune. Both of the methods showed similar results.

A phase scan with small studies of 10 seeds was performed. Figure 3 shows the change in horizontal and vertical phase with respect to the default values (originally $\mu_{x,y}$ = [55.88, 55.54]) while the colourbar indicates the corresponding DA. These results show the big impact that the phase between main IRs has on the DA, particularly for the vertical phase when a small change can result in an increase from 0-2 σ values to regions with DA of 15-20 σ. Two high DA regions were identified and marked with red squares in the figure. A complete study with 60 seeds was performed in both of these regions. The maximum DA obtained was of 16.5 σ at the location $\Delta\mu_{x,y}$=[0.2,0.05], while a DA of 13.5 σ was obtained at $\Delta\mu_{x,y}$=[-0.2, -0.4]. Even though this last location resulted in a lower DA it was chosen for the following studies given that is closer to the region that reported better results for beam-beam studies [14].

The increase of DA with respect to the already higher result of 10 σ for the default phase shows how this study was useful not only to understand the origin of the DA discrepancy between lattices, but also because this information was then used to implement a new correction and increase the DA even further.

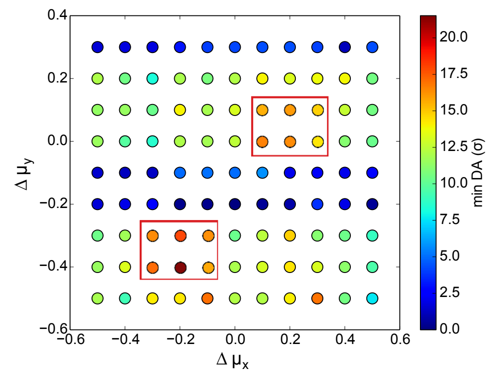

Figure 3: Minimum DA among 10 seeds vs a change in horizontal and vertical phase between main IRs. Two zones with higher DA have been identified and marked with red squares.

Default Case

The increase of DA by changing the phase between main IRs gives some flexibility to allow for a more comprehensive study including also errors on the separation and recombination dipoles, and errors (and sextupole correction) in the arcs [15]. Results presented in Fig. 4 show that the minimum DA among 5 angles resulted in 5.8 σ with the original phase between IRA and IRG of $\mu_{x,y}$ = [55.88, 55.54], an increase is observed along all angles when moving to the more optimal phase with $\Delta\mu_{x,y}$ = [−0.2, −0.4] where the minimum DA is now 10.9 σ. Non-linear correctors were also implemented for the same optimal phase with the combination of both resulting in a minimum DA of 19.3 σ.

The impact of the phase advance between main IRs on DA have also been studied for injection energy [15] and for studies including beam-beam and octupoles compensation [16]. The best phase that works for each is not necessarily the same, so the objective is to find the best phase, or at least the best compromise, for each stage of the operation cycle.

Other Optics Cases

It has been shown in the previous sections that the use of phase optimization and non-linear correctors were both very useful techniques to increase the DA to acceptable levels for the case with β^*=0.3 m. In this section this study was also expanded to include the other β^* options mentioned in the introduction section, with the main purpose of finding

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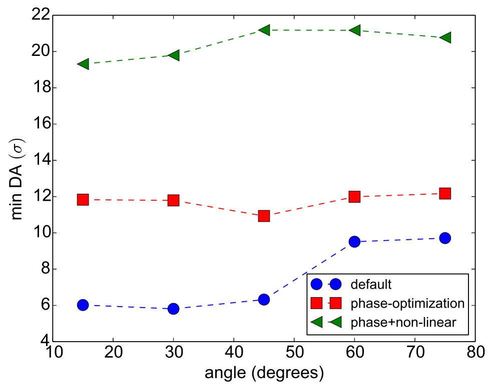

Figure 4: Minimum DA among 60 seeds vs angle with errors on the triplet, separation and recombination dipoles, and errors (and b3 correction) in the arcs. Cases with the default and optimized phase are shown (blue and red respectively) as well as the case with optimized phase and non-linear correctors (green).

whether the phase optimization was equally important for these options and to evaluate at what point the use of non-linear correctors becomes more crucial.

The DA for the default cases and including the phase optimization and non-linear corrections is illustrated on Fig. 5. The case for β^*=1.1 m shows a large DA (>20 σ) even without non-linear correctors or phase optimization. However, for the more challenging cases of β^*=0.15 m and 0.2 m the phase optimization helped increase the initial values of 0 sigma to more acceptable, although still low values, of 4-6 σ. With the use of non-linear correctors, the case for β^*=0.2 m was increased to acceptable values of 13 σ, while for the case β^*=0.15 m only an increase of 0.5 σ was obtained; however, it is expected that a dedicated search for an optimized phase advance, including non-linear correctors, can increase this value.

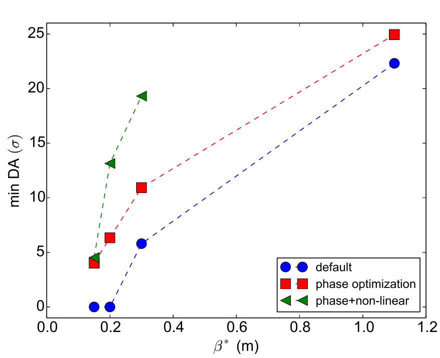

Figure 5: Minimum DA among 60 seeds and 5 angles for different cases of β^*. Results are shown for the default phase (blue), the optimized phase (red) and including non-linear correctors (green).

Alternative Triplet

The introduction section also mentions an alternative design for the IR for both round and flat beams. The advantages of this design is that it uses identical magnets and the overall length of the triplet is shorter, which could result in a minimization of costs [4]. Furthermore, the flat option is also considered to provide an alternative in the case crab cavity technology is found not be feasible in the timeline of the FCC-hh [5]. DA studies were done for these designs, not only to analyze their stability, but also to study whether the phase optimization and non-linear correctors are equally useful in these cases.

The DA results obtained for this case were also largely depending on the phase between main IRs, although the optimal phase varies from that observed for the baseline design. The largest DA found for 60 seeds for the case of round beams with β^*=0.3 m was of 13.6 σ, while the best result for flat beams with β^*=1.2/0.15 was of 10.3 σ. When implementing non-linear correctors these values increased to 22.6 σ for the case of round beams while a DA of 17.3 σ was obtained for flat beams.

CONCLUSIONS

This work explores the different techniques that have been applied to increase the DA at collision energy including crossing angles. In particular, it was found that both non-linear correctors and finding the optimal phase between main IRs helped increase the DA to acceptable levels, even for a more comprehensive study including arc and IR errors. The study was expanded to include other β^* options and alternative designs for the IR, for both round and flat beams.

In conclusion with the phase scan optimization almost all studies (except for the beyond ultimate cases of β^*=0.15 and 0.2 m) showed good results with a minimum DA above 10 σ, even without non-linear correctors. The non-linear correctors increased the DA to 17-22 σ for both triplet design options of round beams with β^*=0.3 m and for the case of flat beams, giving a safety margin in case further errors affect the DA; but are particularly important for the case with β^*=0.2 m were only with non-linear correctors the DA target is reached. Further work remains to be done for the more challenging case of β^*=0.15 m and to check the compatibility with beam-beam studies.

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