NON LINEAR FIELD CORRECTION EFFECTS ON THE DYNAMIC APERTURE OF THE FCC-hh*

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Abstract

The Future Circular Collider (FCC) design study aims to develop the designs of 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]. Given the large beta functions and integrated length of the quadrupoles of the final focus triplet the effect of systematic and random non linear errors in the magnets are expected to have a severe impact on the stability of the beam. Following the experience on the HL-LHC this work explores the implementation of non-linear correctors to minimize the resonance driving terms arising from the errors of the triplet. Dynamic aperture studies are then performed to study the impact of this correction.

INTRODUCTION

The FCC-hh lattice features two high luminosity insertions and two special purpose experiments, just like the LHC. 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).
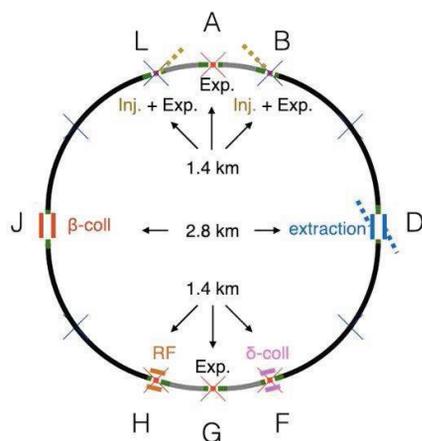

Figure 1: Layout of the FCC-hh ring [2].

Several options have been proposed for the design of the low β interaction regions [3]. This study will present in the case with the distance between the interaction point and the first quadrupole (L^*) of 45 m and a β^* of 30 cm [3]. 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 has been based on the quadrupole magnet technology of the High Luminosity-LHC

(HL-LHC) [4] but the design is adjusted to scale it to the new energies.

Previous studies have been performed to study the dynamic aperture (DA) at injection with errors on the arcs [5], as well as studies performed at collision energy with no errors on the arc dipoles (minimum DA= 30-85 σ) and with errors on the inner triplet but crossing angles off (minimum DA= 20 σ) [6]. However, studies with errors on the inner triplet and crossing angles on proved to be challenging [6] due to the fact that the resulting orbit made it more sensitive to errors. This works aims to address this issue by the use of different orbit correction techniques and the implementation of non linear correctors to compensate for non linear triplet errors.

DYNAMIC APERTURE STUDIES

DA studies were performed using SixTrack [7] on a thin-lens version of the FCC-hh lattice with $\beta^* = 30$ cm over 10^5 turns with crossing angles on, 30 particles pairs per amplitude step of 2 σ, 5 angles and a momentum offset of 2.7e-4. The energy is 50 TeV and the normalised emittance is $\epsilon = 2.2\mu$m.

Concerning the magnetic imperfections of the triplet 60 different realisations (seeds) have been used. These errors are given in the following form [8]:

$$b_n = b_{nS} + \frac{\xi_U}{1.5} b_{nU} + \xi_R b_{nR}, \qquad (1)$$

with b_{nS}, b_{nU} and b_{nR} referring to the main, uncertainty and random components, and both ξ_U and ξ_R are Gaussian distribution random variables cut at 1.5 a 3 σ respectively; ξ_U changes from seed to seed but remains the same for all magnets of the same class while ξ_R changes also from magnet to magnet. The magnetic field in the magnets is then given as:

$$B_y + iB_x = B_{\text{ref}} \sum_{n=1}^{N} (b_n + ia_n) \left(\frac{x + iy}{R_{\text{ref}}} \right)^{(n-1)}. \qquad (2)$$

The errors for the triplet of the FCC have been based on the error table for the HL-LHC triplet [9] but adapted to the corresponding aperture of the FCC magnets. The nonlinear terms affecting the beam stability derived from these magnets will change with respect to the HL-LHC depending on the new aperture and β function at their location [10].

Several corrections are also used for the tracking studies: a chromatic and tune correction with the sextupoles and trim quadrupoles in the arc respectively, correction of the dispersion generated from the crossing angle (spurious dispersion)

and finally a coupling correction. In order to correct the spurious dispersion two different methods have been proposed: the HL-LHC like [11] and the SSC-like correction [12]. The first method has been adapted to the FCC [13] and corrects the dispersion by creating an orbit excursion using kickers while the second method performs the correction with a pair of normal and skew quadrupoles at both sides of the IR.

The minimum DA is shown in Fig. 2 as a function of the angle over the 60 seeds for both spurious dispersion corrections. For the case of HL-LHC like correction a chromatic correction was used such that the sextupoles located in the orbit offset around IRG are excluded, resulting in a minimum DA for all seeds of 1.9 σ. On the other side the SSC-like correction used a chromatic correction using all sextupoles obtaining a slightly better minimum DA of 2.3 σ. The low DA values show that the FCC-hh is more challenging than the HL-LHC, where the DA without non linear correctors was of 5 σ [8].
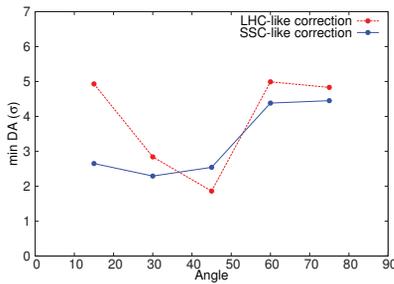

Figure 2: Minimum DA as a function of the angle over 60 seeds for the HL-LHC like and SSC-like spurious dispersion corrections.

NON-LINEAR CORRECTORS

In order to increase the minimum DA non-linear correctors have been added to the lattice to compensate for the errors in the triplet. These correctors were installed on the side of the triplet opposite to the IP, after the third quadrupole (Q3) and the skew quadrupole used for coupling correction. These correctors are installed on either side of the IR and with similar lengths as the ones considered for HL-LHC correctors. The location of the non-linear correctors with respect to other elements in the interaction region is illustrated in Fig. 3.
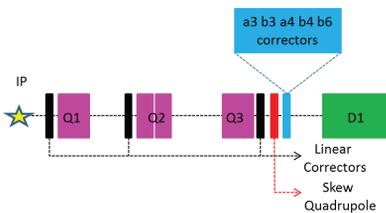

Figure 3: Location of the non-linear correctors with respect to other elements in the interaction region, mainly the triplet quadrupoles (Q1, Q2 and Q3) and the interaction point.

The resonance driving terms (RDTs) arising from the imperfections in the triplet can be given as [14]:

$$c(b_n; p, q, l, m) \equiv \int_{IR} ds K_{n-1}(s)\beta_x^{p/2}\beta_y^{q/2} e^{\pm i[(p-2l)\mu_x \pm (q-2m)\mu_y]},$$
(3)

$$c(a_n; p, q, l, m) \equiv \int_{IR} ds K_{n-1}^s(s)\beta_x^{p/2}\beta_y^{q/2} e^{\pm i[(p-2l)\mu_x \pm (q-2m)\mu_y]},$$
(4)

where K_{n-1} and K_{n-1}^s corresponds to the normal and skew fields respectively, and p, q (even for b_n and odd for a_n), l and m denote integers such that $|p| + |q| = n$, $0 \leq 2l \leq p$ and $0 \leq 2m \leq q$. Given that at low β^* there is a π phase advance between the left and right part of the insertion the previous expressions reduce to [14]:

$$c(b_n; p, q) = \int_{IR_{left}} ds K_{n-1}(s)\beta_x^{p/2}\beta_y^{q/2} +$$
$$(-1)^n \int_{IR_{right}} ds K_{n-1}(s)\beta_x^{p/2}\beta_y^{q/2},$$
(5)

$$c(a_n; p, q) = \int_{IR_{left}} ds K_{n-1}^s(s)\beta_x^{p/2}\beta_y^{q/2} +$$
$$(-1)^n \int_{IR_{right}} ds K_{n-1}^s(s)\beta_x^{p/2}\beta_y^{q/2},$$
(6)

with q even for the normal fields (b_n) and odd for the skew fields (a_n).

The strategy now consists in including the non linear correctors into the previous integrals, weighted with the corresponding β functions, and adjusting the strengths such that the RDTs are set to zero. With one corrector located at each side of the two low β^* interaction points each pair of correctors has the possibility to correct the RDTs arising from two different resonance lines.

The RDTs to be corrected had been chosen with the proximity of their associate resonance lines to the working point. With the fractional part of the horizontal and vertical tunes in the FCC being 0.31 and 0.32 respectively the RDTs to be corrected are: c(b_3;1,2), c(b_3;3,0), c(a_3;0,3) and c(a_3;2,1) for order n=3, c(b_4;0,4), c(b_4;4,0), c(a_4;3,1) and c(a_4;1,3) for order n=4, and finally c(b_6;0,6) and c(b_6;6,0) for order n=6.

Strength Requirements

The strengths needed for the non linear correctors for all 60 seeds were calculated and are shown in Fig. 4. To make sure the strengths needed are within the limits of the available technology the maximum strength needed along all 60 seeds is shown in the first column in Table 1 and compared with the agreed specification of each corrector for the HL-LHC [8], shown in the second column. As can be seen from this comparison the values required for the correctors strengths
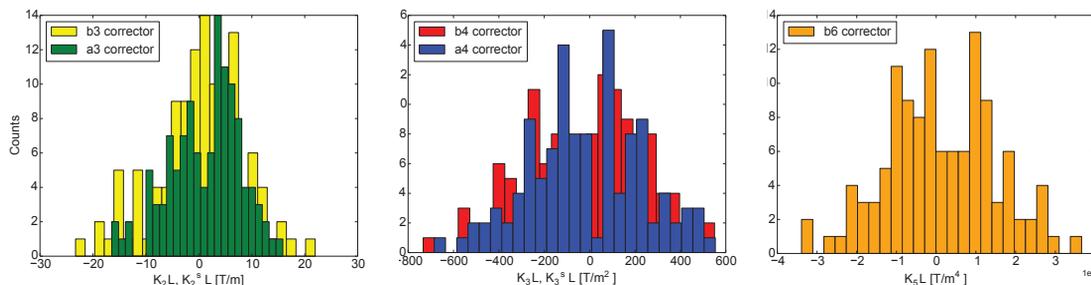
Figure 4: Histogram of the strengths required by the non-linear correctors left and right of the low β^* interaction regions for all 60 seeds of order n=3 (left), order n=4 (middle) and order n=6 (right).

are within the margin of the specification by a factor of 3 or more.

Table 1: Maximum strength of the non-linear correctors compared to the specification.

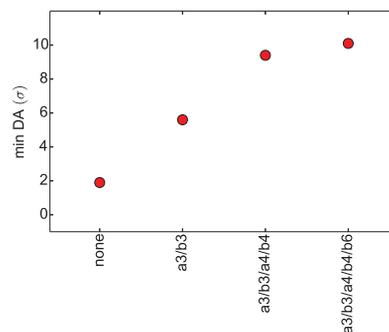| Corrector	Strength K_{n-1} $[T/m^{n-1}]$	Specification K_{n-1}^{max} $[T/m^{n-1}]$
b3	46.6	454
a3	164.5	454
b4	5353	25739
a4	4961	25739
b6	5.95e6	7.68e7

Figure 5: Minimum DA with respect to the non-linear correctors used in the lattice explored for the collision energy of 50 TeV and errors in the triplet

Impact on Dynamic Aperture

To asses the performance of these correctors, DA studies have been made using the same conditions and corrections presented in the DA studies section but with the corresponding calculations of Eqs. 5 and 6. For these results the HL-LHC like spurious dispersion was used. Figure 5 illustrates the minimum DA over all seeds and angles versus the non linear correctors used. The benefits of including non-linear correctors show a clear increase of the minimum DA from 1.9 σ (shown in Fig. 2) to 5.6 σ when including a3 and b3 correctors, to 9.4 σ when including also b4 and a4 correctors, and finally to 10.1 σ including as well b6 correctors.

Thus, this work shows that the stability of the FCC-hh lattice relies on the accurate correction of the non-linear errors in the IR. Another method has been considered for the HL-LHC based on the direct compensation of the transverse map coefficients [15], and could also be considered for the FCC. Both strategies however require a magnetic model of the magnets. Based on the experience on the LHC, magnetic measurements during construction do not always provide a good description of the real machine, and therefore must be complemented by beam-based studies [16]; this task by itself can be very challenging and new methods are currently being studied [17].

CONCLUSIONS

The stability of the FCC-hh lattice with crossing angles on and errors in the inner triplet was studied via DA studies, resulting in a minimum DA of about 2 σ. The FCC-hh presents then a more challenging case than for the HL-LHC where the corresponding DA was of 5 σ. This work presented a solution to this problem by the implementation of non-linear correctors, resulting in an increase of the DA up to 10.1 σ.

Therefore, the FCC-hh feasibility relies upon the accurate correction of high order multipolar errors in the interaction region area. The magnetic model needed for this procedure however, presents by itself a series of challenges; the work on the LHC combining magnetic measurements during construction and beam-based studies should then be followed closely to check on its reliability.

ACKNOWLEDGEMENTS

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