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Dalena, Barbara () *et al.*

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ADVANCE ON DYNAMIC APERTURE AT INJECTION FOR FCC-hh *

B. Dalena†, D. Boutin, A. Chancé
CEA/SACLAY, DRF/Irfu/SACM F-91191, Gif-sur-Yvette, France
B. Holzer, D. Schulte, CERN, Geneva, Switzerland

Abstract

In the Hadron machine option, proposed in the context of the Future Circular Colliders (FCC) study, the first evaluation of dipole field quality, based on the Nb_3Sn technology, has shown a Dynamic Aperture at injection above the LHC target value. In this paper the effect of field imperfections on the dynamic aperture, using the updated lattice design, is presented. Tolerances on the main multipole components are evaluated including feed-down effect.

INTRODUCTION

The main dipole magnets are critical elements for the machine performance for LHC and FCC-hh. In particular their field quality impacts the long term stability of the particles in the machine. Considering the first estimate of the main dipole field quality the dynamic aperture of the current optics design of the future Hadron-Hadron Collider is above the target value of 12σ at injection energy (3.3 TeV), as reported in [1]. The current main dipole imperfections would allow to reduce injection energy to a minimum value of ~2.6 TeV, as far as dynamic aperture is considered as criterion. The possibility to correct up to 15 unit of the systematic b_3 harmonics of the main dipoles has been shown, leaving a lot of margin in the correctors strength at the injection energy of 3.3 TeV. The impact of the b_5 harmonics is small and having the DA above the target of 12σ after correcting the b_3 harmonics of the main dipoles, decapole correctors are not required at this stage of the design.

At collision energy the first estimate of the main dipole field quality strongly reduces DA (below 10σ). In particular, a new systematic value of the b_3 harmonics (3 unit) has been specified as the target. The sextupole correctors strength and length have been specified to the magnet group [1]. In the following we examine a new layout configuration of the FCC-hh that was designed to solve geological problems. First tolerances on the b_4 and b_5 harmonics are given and the impact of linear imperfections and their corrections on DA is shown.

OPTICS CONFIGURATIONS

The preliminary layout of the FCC-hh ring is made of 4 short arcs of about 3.6km (called SAR), 4 long arcs of about 15 km (called LAR), 6 long straight sections of about 1.4 km (called LSS) and 2 extended straight sections of about 4.2 km (called ESS). The target circumference is 3.75 times the one of LHC, i.e. 99.97 km. The main ring parameters and the main functionality of each of the insertions are reported in [2]. An updated version of the FCC-hh ring, which takes into account geological and beam transfer considerations is now under study [3]. The extended straight sections and the overall circumference are reduced as described in [3]. Here we describe the different versions of the insertion optics, used in the tracking simulations. We have considered different insertion optics design for the Interaction Region (IR) and the momentum collimation, and as far as they become available, injection, extraction and betatron collimation optics. The concept of the injection and extraction insertions can be found in [4], [5], the betatron and momentum collimation design are described in [6] and [7]. The FODO cells of the arcs are optimized to have the largest filling ratio. The phase advance in the FODO cells is 90° [3].

A first injection optics (in the following called **optics I**) is put together using an IR insertion designed with a L^* of 36 meters, a β^* of 4.6 meters and a momentum collimation optics made of simple FODO cells with a maximum dispersion of 4 meters. The IR phase advance between the IPs A/G and the first focusing/defocusing sextupole of the short arcs is respectively adjusted to 90° modulo 180° in the horizontal/vertical plane.

A second injection optics (in the following called **optics II**) is made by integrating an IR insertion designed with a L^* of 36 meters, a β^* of 3.5 meters and a momentum collimation optics made of simple FODO cells with a maximum dispersion of 5 meters. The β^* of 3.5 meters, initially considered for the injection optics, has been increased to 4.6 meters to ensure that the mechanical aperture bottleneck, and as a consequence the collimation settings, are dominated by the arcs and not by the IRs at injection.

Finally, the third injection optics (in the following called **optics III**) corresponds to the design described in [3].

It is worth noting that the details of the insertions design are not directly relevant for the present study, since no multipole or linear errors are considered in any of the insertion magnets. This is done on purpose to study only the impact of the main dipole field quality. The main interest of using different insertions optics is to compare the impact of different arcs cell phase advances and of different phase advances between the long arcs on the DA study.

DYNAMIC APERTURE

The DA has been computed simulating the particles motion over 10^5 turns, using a set of initial conditions distributed on a polar grid, in such a way to have 30 particles (different initial conditions) for each interval of 2σ. Five different phase space angles have been used. Moreover, in

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† barbara.dalena@cea.fr

all the tracking simulations the fractional parts of the tunes have been fixed to (.28,.31) at injection. As far as the dipole field imperfections are concerned, sixty different machines (also called seeds) have been generated, using Eq. (1) in Ref. [1] and Table 1 in the same reference. The ξ_U random number is kept constant for all dipoles of the same arc, while ξ_R changes for each dipole. The initial momentum offset is set to 7.5×10^{-4} at the injection.This is a safe assumption considering that is the same as the LHC and it is expected to be smaller in FCC. The normalized rms beam emittance is kept to ε_n =2.2μm.

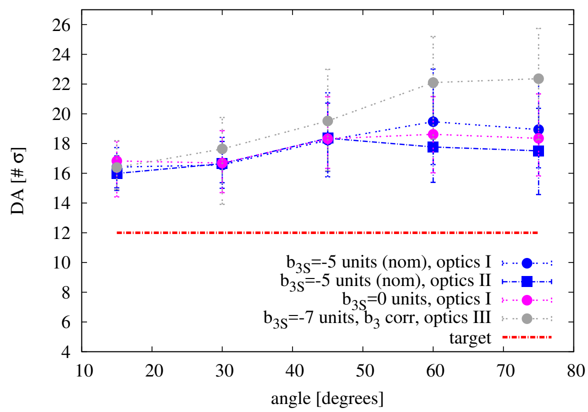

Figure 1: Dynamic Aperture (DA) in number of σ of the beam as a function of the phase space angles explored for the baseline injection energy of 3.3 TeV, see text for details.

As shown in [1] and reported in Fig. 1, the dynamic aperture at injection is dominated by the random component of main dipole field quality. Despite the larger DA for big angles the minimum dynamic aperture remains substantially unchanged for the new layout of the machine: namely 13.9 σ against 14.6 σ of the previous layout configuration.

b_4 AND b_5 TOLERANCES

In order to establish the need of octupole and decapole correctors we have evaluated detuning with momentum and with amplitude which are driven by the b_4 and b_5 field components.

They are shown in Fig. 2 and Fig. 3, respectively. The maximum tune spread with momentum is $6 \cdot 10^{-3}$ and with amplitude (up to 7σ) is $5 \cdot 10^{-3}$, using all the errors reported in Table 1 of Ref. [1]. They are mainly due to the b_5 component and they are considered acceptable for machine stability. Thus, we define the tolerances on b_4 and b_5 using DA as figure of merit, and including feed-down effect.

Table 1: Alignment Specification of Main Dipoles

type of magnet	$\Delta_{x/y_{sys}}$ [mm]	$\sigma_{x/y_{ran}}$ [mm]
main dipole	± 0.1	± 0.5

Following Ref. [8] the expected feed-down of b_5 on b_4 due to position errors of main dipoles can be calculated

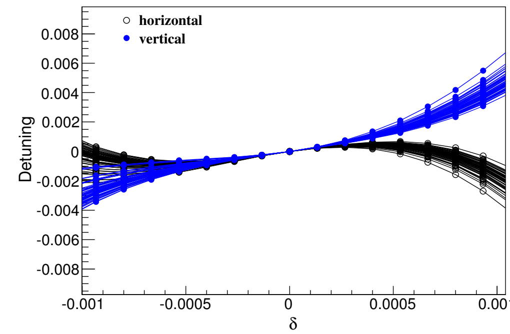

Figure 2: Detuning with momentum driven by the multipole errors Table 1 of Ref. [1], where b_{3_S} has been set to 7 unit and corrected with spool pieces (for the 60 seeds used in DA simulations). The lines show resonances up to the 9^{th} order.

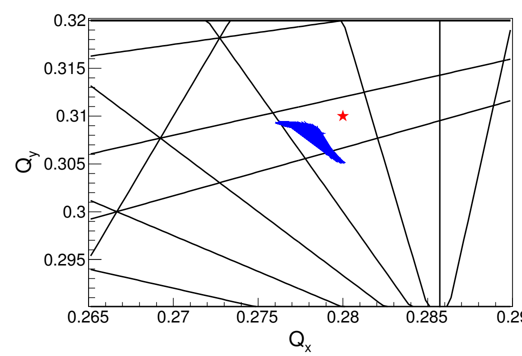

Figure 3: Detuning with amplitude up to 7 beam σ driven by the multipole errors Table 1 of Ref. [1], where b_{3_S} has been set to 7 unit and corrected with spool pieces (for the 60 seeds used in DA simulations). The lines show resonances up to the 9^{th} order.

analytically. Considering the same alignment position errors reported in Table 1 (as of Ref. [8]) the systematic component and random b_5 feed-down on b_4 is calculated as:

$$b_{4_S}^{feed-down} = \pm 4 \cdot 0.0071 \cdot b_{5_S} \quad (1)$$

$$\sigma_{b_{4_R}}^{feed-down} = 4. \cdot \sqrt{0.0033 b_{5_S}^2 + 0.0015 \sigma_{b_{5_R}}^2} \quad (2)$$

which are equal to 0.028 unit and 0.239 for the b_5 component reported in Table 1. Nevertheless these values are bigger than the components reported in Table 1 of Ref. [1] for b_4, their impact on the minimum dynamic aperture is equal to a reduction of 0.5σ. The minimum value of the systematic component of b_4 that brings the computed DA below the target of 12σ is -0.142 unit. Therefore, a first tolerance on the systematic component of b_4 is set to < -0.142 unit at injection.

In Table 2 the minimum DA due to increased systematic component of b_5 are reported. In these simulations the uncertainty and random components of the b_5 harmonics and of all the other dipole field errors are equal to the estimated value of Table 1 of Ref. [1]. Therefore, a tolerance on the maximum b_5 component of the field can be fixed to strictly

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Table 2: Minimum DA as a function of different systematic values of b_5. The other multipoles are set to the values reported in Table 1, except for the systematic value of b_3 which is set to 7 unit and corrected with spool pieces.

$\mathbf{b}_{5_S}$	**min. DA [σ]**
-1	14.6
-2	11
-3	9

< 2 unit. This value takes also into account a negligible effect on b_4 due to feed-down.

IMPACT OF LINEAR IMPERFECTIONS AND THEIR CORRECTIONS

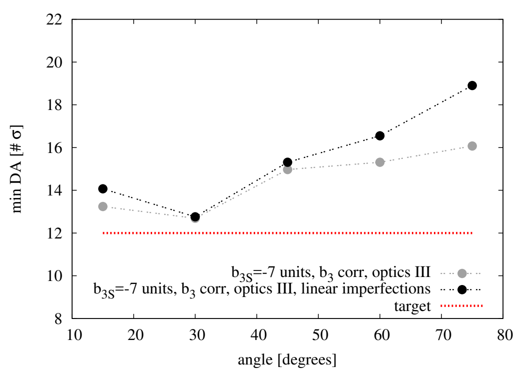

Figure 4: Minimum Dynamic Aperture (min DA) in number of σ of the beam as a function of the phase space angles explored for the baseline injection energy of 3.3 TeV, see text for details.

In Fig. 4 the minimum DA in presence of linear imperfections is compared to the minimum DA due to non-linear imperfections only. In these simulations the misalignment errors and correction procedure described in [9] together with dipole field errors are applied to 100 machines. About 50% of them converge to a stable machine after the correction of the linear imperfections, the minimum DA of these 50 machines corresponds to the black dots in Fig. 4. In these simulations the dimension of the polar grid is increased up to 50σ, and 10^6 turns are used to compute DA. Although there is no visible effect on the minimum DA, this result describes half of the initially studied machines, only, where errors could be combined resulting in an almost perfect machine. It is worth noticing that there is about one σ difference using 10^5 or 10^6 turns in DA computation.

IMPACT OF DIPOLE TYPE

In all the simulations presented curved dipoles (SBEND type) have been considered, and the multipole field expansion is done around the magnetic center of the dipole, which coincides with the reference particle trajectory. Due to the properties of the Nb_3Sn material, it has been proposed to build them straight (RBEND type). This implies that the reference particle does not travel always on the magnetic center of the element. The maximum beam excursion (the Sagitta x_S) due to the dipole field is about 2.5 mm. Assuming the multipole field expansion is always done with respect to the magnetic axis of the dipole, the maximum error on the b_3 component of the field can be calculated using the same formula given for the feed-down harmonics (see Eq. (15) of Ref. [8]):

$$\begin{aligned} b_{3err} &= b_5 \cdot 6 \cdot \left(\frac{x_s}{R_{ref}}\right)^2 \quad (3) \\ &= (b_{5S} + b_{5U} + b_{5R}) \cdot 6 \cdot \left(\frac{x_s}{R_{ref}}\right)^2 \\ &\sim b_{5S} \cdot 0.13 = -0.13 \end{aligned}$$

This value is less than the random component of b_3 reported in Table 1 of Ref. [1], which dominates the DA results at injection, as discussed in the third section of this proceeding. Moreover, considering that the multipole errors in the magnet are dominant at the magnet ends and almost zero at the longitudinal center of the magnet, the error on b_3 is even less than the previous calculated value, if the beam is off-axis in the longitudinal center of the magnets. On the other hand the useful mechanical aperture of the beam will be reduced, therefore a balance should be found on the beam excursion along z in the magnet. Whatever the choice, as far as DA is concerned, the additional error would be systematic for each of the dipole, thus the additional b_3 error would be corrected by the spool pieces, and correctors for the additional b_4 and b_5 components could be foreseen.

CONCLUSION

We have evaluated the dynamic aperture at injection for the new layout optics, using the 2015 dipole field quality table. The minimum DA stays above the target of 12σ. Moreover, first tolerances on the systematic value of b_4 and b_5 at injection have been estimated, within these values octupole and decapole correctors are not required. The impact of linear imperfections and their corrections on DA at injection seem to be negligible but further studies are needed before quantifying it. Finally, an analytic estimate of the impact of the dipole type on DA computation is reported. In perspective we plan to study: the impact of main quadrupole field quality; the tolerances on the random components of the arcs magnets; the impact of Landau Damping octupoles on DA; the impact of the overall tuning strategy and consequently a tune scan to validate the current choice; the impact of the inner triplet field quality; the impact of the residual linear imperfections coming from the IRs.

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