FIRST EVALUATION OF DYNAMIC APERTURE AT INJECTION FOR FCC-HH*

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Abstract

In the Hadron machine option, proposed in the context of the Future Circular Colliders (FCC) study, the dipole field quality is expected to play an important role, as in the LHC. A preliminary evaluation of the field quality of dipoles, based on the Nb_3Sn technology, has been provided by the magnet group. The effect of these field imperfections on the dynamic aperture, using the present lattice design, is presented and first tolerances on the main multipole components are evaluated.

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. The behavior of the particles in presence of magnet imperfections cannot be cured by dedicated feedback, therefore, it is important to know them in advance and be able to correct for them if they reduce, below the safety limit, the dynamic aperture (DA) of the machine, defined as the region in phase space where stable motion occurs. As in the LHC also in the FCC-hh different magnets are expected to play a role in the definition of the DA at injection and at collision energy. At injection the main dipole field quality is the major contributor to the reduction of DA in LHC [1], while in collision the triplet field quality and the beam-beam effects are the major sources of the DA reduction [2]. The baseline injection energy for FCC-hh has been fixed at 3.3 TeV, which gives more or less the same ratio between injection and collision energy as in the LHC. In the following we discuss first the status of the arc cell design for FCC-hh [3] and then the first evaluation of DA at injection and collision energy, in presence of main dipole field errors. We have considered different insertion optics, in particular for the Interaction Region [4] [5] and momentum collimation [3], as far as they became available, always keeping the same arc layout. The numerical computation of DA consists in tracking simulations performed with the SixTrack code [6], which had to be adapted to handle the size of the FCC ring.

ARC CELL, MAIN DIPOLE FIELD QUALITY AND CORRECTORS

Currently the total cell length is ~214 m with 12 dipoles and 12 spool piece correctors for the chromaticity correction, one attached to each dipole of the cell. Both the dipole and the spool piece correctors have the same length as LHC magnets, respectively. The same interconnection lengths between two dipoles, and between the main dipole and the main quadrupoles have been estimated to be feasible by the magnet group [7]. Octupoles for Landau damping and octupole or decapole correctors are not included in the current version of the lattice layout, neither are skew sextupoles. The dipoles are set at almost their maximum strength (16 T). At this field and at a reference radius of 17 mm a first estimate of the expected field quality for the injection and the collision energy has been provided by the magnets group [7], as shown in Table 1.

Table 1: Multipoles used for the main dipole field quality. The values are in units of 10^{-4} at R_{ref}=17 mm.

Normal	Systematic inj b_{n_S}	Systematic col b_{n_S}	Uncertainty b_{n_U}	Random b_{n_R}
3	-5	20	0.781	0.781
4	0	0	0.065	0.065
5	-1	-1.5	0.074	0.074
6	0	0	0.009	0.009
7	-0.5	1.3	0.016	0.016
8	0	0	0.001	0.001
9	-0.1	0.05	0.002	0.002
Skew	a_{n_S}	a_{n_S}	a_{n_U}	a_{n_R}
3	0	0	0.256	0.256
4	0	0	0.252	0.252
5	0	0	0.05	0.05
6	0	0	0.04	0.04
7	0	0	0.007	0.007
8	0	0	0.007	0.007
9	0	0	0.002	0.002
10	0	0	0.001	0.001

As in the LHC case [8], each multipole harmonics entering in the dipole field expansion (a_n and b_n) is modeled as the sum of three contributions:

$$b_n = b_{n_S} + \frac{\xi_U}{1.5} b_{n_U} + \xi_R b_{n_R} \quad (1)$$

where ξ_U and ξ_R denote the random numbers with Gaussian distribution truncated at 1.5 and 3σ, respectively. The spool pieces are meant to correct the b_3 harmonics of the dipole field. The maximum strength of the spool pieces correctors has been fixed at 2 times the LHC strength value. This ensures to have the same specification for the b_{3_S} error

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(≤ 3 units) as calculated for LHC in Ref. [9]. It is worth noticing that the value reported in the Table 1 is far above this specification. The maximum strength used for the main quadrupole of the arcs is equivalent to a field gradient of 360 T/m over a 6.3 *m* long magnet. The main specifications of all the magnets included so far in the arc cell are summarized in Table 2.

Table 2: Arc Magnets Specifications

Magnet	Magnetic Length [m]	Max Strength	Unit
Dipole	14.3	16	T
Spool pieces	0.11	0.43	10^{-2}m
Quadrupole	6.29	360	T/m
Sextupole	0.5	16059.	T/m^2
Orbit corrector	0.647	3.6	Tm

Concerning the spool piece correctors, with present technology, is possible to obtain a gradient of 4430 T/m^2 for a magnet with the same length as the LHC one (0.11 m) [7]. A first study of the main quadrupole design shows that a 400 T/m gradient is possible over a 6 m long magnet [7, 10]. For what concerns the orbit corrector, current technology is able to provide up to 4 T for a 1 m long magnet, see ref. [11] for details. The only concern, so far, is the required strength of the sextupoles for the ultimate β^* of 0.3 m that is feasible with present technology (5560 T/m^2) and considering a magnet length ≥ 1.2 m [7]. Thus leaving no margin for reducing β^*, unless special chromaticity correction schemes are considered.

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 all the tracking simulations the fractional part of the tunes have been fixed to (.28,.31) at injection and (.31, .32) at collision, established for LHC upgrade in luminosity. Misalignment errors are not included in order to evaluate the effect of the multipole errors alone, as also been done in [1]. As far as the dipole field imperfections are concerned, sixty different machines (also called seeds) have been generated, using Eq. (1). The ξ_U random number is kept constant for all the dipoles of the same arc, while ξ_R changes for each dipole. The momentum offset is set to 7.5×10^{-4} and 2.7×10^{-4} at the injection and at collision energy, respectively. This is a safe assumption considering that they are the same as the LHC at injection and collision energy, respectively. The normalized rms beam emittance is kept to ε_n =2.2μm for both the injection and collision energy (3.3 TeV and 50 TeV). In the following, we discuss first the results of DA computation at injection and then at collision.

Injection

At injection, without dipole imperfections the DA is above 80σ for each angle explored. As far as the main dipole field imperfections are considered in the tracking simulations the minimum DA reduces to 14σ, as shown by the Blue dots in Fig. 1.

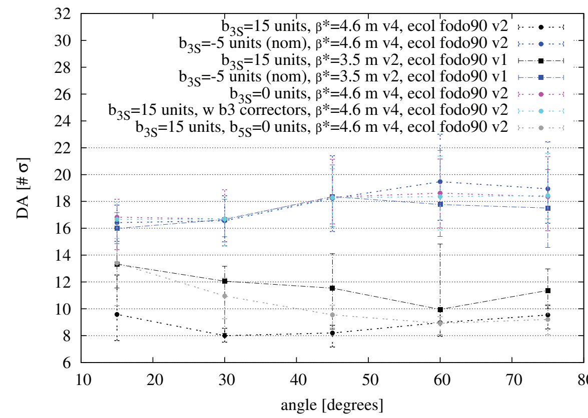

Figure 1: Dynamic Aperture (DA) in number of σ of the beam as a function of the phase space angles explored for the baseline injection energy of 3.3 TeV, see text for details.

In these simulations, the geometric aberrations induced by the sextupole component of the dipole field are not corrected, while the chromatic aberrations, induced by the b_3 harmonics of the dipoles, are corrected using the main sextupoles of the arcs. The minimum DA is above the target value of 12σ (safety margin adopted for the LHC design). Moreover, by comparing the Blue dots in Fig. 1 with the Pink dots, where the systematic b_3 harmonics is set to 0 on purpose, the geometric aberrations generated by the 5 units of b_{3_S} are well compensated by the 90° phase advance of the arc cell. Therefore, the chosen working point and the first dipole field quality estimates are not critical in terms of DA at the injection energy of 3.3 TeV. Considering that the ratio of DA at two different energies is equal to the ratio of the corresponding $\sqrt{\gamma}$, the lower limit for injection energy, as far as DA is concerned and with the present field quality table, is set to ∼2.6 TeV. In order to reach the 1.5 TeV proposed in [12] tighter tolerances on the random and uncertainty components of the main dipoles imperfections will be required to ensure the DA is above the 12σ target value.

The Black dots and squares in Fig. 1 represent DA computed with two different optics configurations (the two high luminosity interaction regions and the momentum collimation insertion slightly differ) and with b_{3_S} set to 15 units on purpose. In both cases the minimum DA is below the target value of 12σ (i.e. $\sim 8\sigma$). Not only the geometric aberrations generated by the b_{3_S} are no more perfectly compensated by the arc cell phase advance, but the main sextupole integrated strengths, required to correct the chromatic aberrations, run at values well above the reach of present technology. Therefore, if the dipole field quality degrades due to persistent

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current at injection energy (up to 15 units of b_{3_S}), a local correction scheme is needed, namely spool pieces correctors attached to the main dipole, like in the LHC. The light Blue dots in Fig. 1 show that the 15 units b_{3_S} are fully corrected using spool pieces correctors placed at each dipole of the arcs, correcting each the average b_3 of the 8 arcs. Furthermore, the correctors strength effectively used for the correction is $\sim 15\%$ of the maximum integrated strength that could be reached by present technology [7], leaving a lot of margin for correction. It is worth reminding that in these simulations the mis-alignment of the magnets is not included, therefore the feed-down on b_2 due to mis-alignment is not taken into account in this DA evaluation.

Finally, the impact on DA of 1 unit of b_{5_S} can be seen by comparing the black dots with the Grey dots in Fig. 1, where its value is artificially set to 0. This unit of b_5 reduces the average DA of $\sim 3\sigma$ at 15°, a similar impact is given by a difference of 1° in the horizontal phase advance in the long arc cell, required by re-tuning the whole ring to the injection fractional tunes while having different insertion phase advances (Black dots and squares in Fig. 1). Moreover, with the correction of up to 15 units of b_{3_S} the minimum DA is already above the target of 12σ. Therefore, decapole correctors do not seem to be required at this stage of the design study. As for the b_3 case, note that the effect of b_5 feed-down on b_4 is not included in these simulations.

Collision

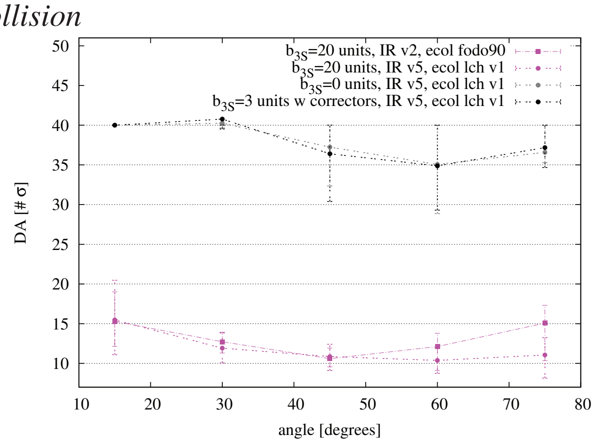

Figure 2: Dynamic Aperture (DA) in number of σ of the beam as a function of the phase space angles explored for the collision energy of 50 TeV, see text for details.

At collision energy, for the ultimate β^* value of 0.3 m the minimum DA without any magnet imperfections is above 54σ, with minimum values at $30 - 45°$. When the dipole field imperfections of Table 1 are included in the simulations, the DA drastically drops with a minimum DA value of less than 10σ, as shown in Fig. 2. This is mainly due to the geometric aberrations induced by the 20 units of b_{3_S} as shown by the Grey dots in Fig. 2, where the b_{3_S} value is set to 0. Moreover, the main sextupole strengths required to correct the chromatic aberrations induced by this b_{3_S} are a factor 4 out of the reach of present technology. In order to ensure that the arcs have a small impact on the DA at collision (which is already greatly reduced by triplet imperfections [13] and beam-beam) it is important to fully correct the b_{3_S}. Given the maximum integrated strength reachable by the spool piece correctors, the maximum amount of b_3 we can correct for is ~6 units. The Black dots in Fig. 2 show the perfect compensation of the chromatic and geometric aberrations due to 3 units of b_{3_S} at collision. As for the injection case the average b_3 of each of the 8 arcs is corrected by the 12 spool pieces attached to each of the main dipoles. About 54% of the maximum strength of the spool pieces is used to correct for 3 units of b_{3_S}. Therefore, a maximum value of 3 units is assigned as target value for b_{3_S}, which seems to be feasible if up to 7 units of b_{3_S} are allowed at injection [7].

CONCLUSION

The arc magnet specifications are reported and discussed in connection with the magnet group feedback.
As far as the first estimate of the main dipole field quality is considered, 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). 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 criterium. The possibility to correct up to 15 units of the systematic b_3 harmonics of the main dipoles is 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 comparable to the impact of reducing by one degree the horizontal phase advance in the long arc cell and having the DA above the target of 12σ after correcting for the b_3 harmonics of the main dipoles, no specification for the decapole correctors are given 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 units) has been specified as target. Moreover, a minimum spool pieces integrated strength of a factor 2 higher with respect to LHC is required. Further studies are needed to fully specify the main dipole field quality, in particular evaluate the impact on dynamic aperture of the random b_2 harmonics present in the main dipoles, of different arc cell phase advances and of feed-down due to mis-alignment errors.

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