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FIELD QUALITY FOR THE HADRON OPTION OF FUTURE CIRCULAR COLLIDER

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Abstract

The updated field quality for the baseline design option of the Nb_3Sn dipoles for Future Circular Collider (FCC-hh) is discussed. The impact on the expected dynamic aperture is shown at injection and collision energy and the consequent non-linear correction schemes together with their integration in the optics are defined.

INTRODUCTION

Following the last European strategy update a future circular collider with the possibility to collide hadrons has been studied and its Conceptual Design Report (CDR) is now available [1]. Using the latest main dipole field quality table computed by magnet designers, this paper presents the Dynamic Aperture (DA) at injection and at collision, the non linear correction schemes are defined and included in the lattice design of the arc sections, as shown in Fig. 1, and in the Experimental Insertions Regions (EIR) [2]. Further considerations of the impact of octupoles for Landau damping and RF bucket size on DA are also presented. Finally, the DA results for the alternative injection energy are also updated with the latest main dipoles errors.

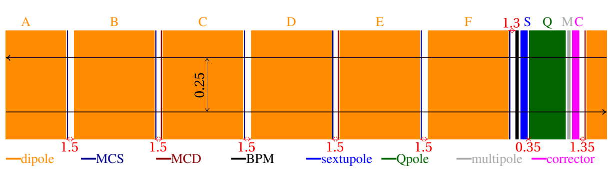

Figure 1: Half cell layout of FCC-hh arcs. MCS and MCD are sextupole and decapole correctors, respectively.

MAIN DIPOLE FIELD QUALITY

The main dipole field quality table is shown in Table 1. The uncertainty and random components at injection and at collision are the same, and greatly reduced with respect to the previous table [3]. The systematic value of b_2 at collision is negligible and below 6 units at injection. This allows to shorten the main quadrupoles in the arc cell and to slightly reduce the main dipoles field [4]. The systematic b_3 and b_5 components due to persistent current at injection are also reduced, considering half artificial pinning and an effective filament diameter of 20 µm [5]. Finally, the systematic values for all the normal harmonics up to 15 are non-zero, contrary to the previous table.

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Table 1: Main Dipole Field Quality Table. The values are in units of 10^{-4} at R_{ref}=17 mm. The injection (inj) and collision (col) values are given for 3.3 and 50 TeV, respectively.

Normal	**systematic inj b_{n_S}**	**systematic col b_{n_S}**	**random inj b_{n_R}**	**random col b_{n_R}**
2	5.634	0.0	0.929	0.929
3	-25.121	0.106	0.668	0.668
4	0.795	0.313	0.467	0.467
5	5.17	0.182	0.283	0.283
6	0.673	0.347	0.187	0.187
7	-1.33	0.184	0.109	0.109
8	0.463	0.375	0.072	0.072
9	2.055	0.568	0.047	0.047
10	0.221	0.13	0.028	0.028
11	1.048	1.05	0.015	0.015
12	0.081	0.088	0.010	0.010
13	-0.227	-0.245	0.005	0.005
14	0.026	0.028	0.003	0.003
15	0.02	0.022	0.002	0.002
Skew	a_{n_S}	a_{n_S}	a_{n_R}	a_{n_R}
2	0	0	1.03	1.03
3	0	0	0.754	0.754
4	0	0	0.473	0.473
5	0	0	0.329	0.329
6	0	0	0.205	0.205
7	0	0	0.114	0.114
8	0	0	0.069	0.069
9	0	0	0.038	0.038
10	0	0	0.023	0.023
11	0	0	0.015	0.015
12	0	0	0.008	0.008
13	0	0	0.005	0.005
14	0	0	0.003	0.003
15	0	0.	0.002	0.002

SEXTUPOLE AND DECAPOLE CORRECTION

Early DA simulations have shown that the local correction of the systematic b_3 error of the main dipole is mandatory at collision for FCC-hh [6]. With the current systematic value of b_3 (about 25 units), its correction is also required at injection energy. One spool-piece corrector (MCS) is placed at each dipole of the arc sections. Its length is 0.11 m (as in LHC) and a maximum strength of 3×10^3 Tm^{-2} seems to be feasible using NbTi technology. Considering the field errors

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model described in [3] and the CDR version of the optics, the maximum MCS gradient, computed over 60 different error configurations of the machine (seeds) at injection, is $1.205 \times 10^3\ \mathrm{Tm}^{-2}$, its gradient distribution is shown in Fig. 2.

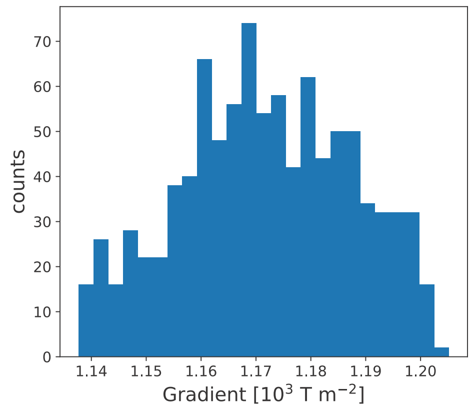

Figure 2: MCS gradients computed for 60 different error configurations of the machine at injection.

The b_5 component due to persistent current at injection given in Table 1 also requires correction in order to ensure enough DA at injection and to limit momentum detuning with respect to amplitude detuning. An analytic estimate of the required strength can be obtained using the following formula [7]:

$$\frac{2\pi}{N_{\mathrm{dip}}}\frac{(n-1)!b_{n_S}N_{\mathrm{dip}}}{R_{\mathrm{ref}}^{n-1}} = N_{\mathrm{cor}}\frac{0.3}{p[\mathrm{GeV}]}(n-1)!GL \qquad (1)$$

where, the l.h.s. of the equation is the sum over the N_{dip} ring dipoles of the considered error component and the r.h.s. is the equivalent strength required by the N_{cor} correctors. In particular, G is the gradient of the corrector and L is its length. Using L=0.066 m, one corrector (MCD) in each other dipole and Eq.(1) the correction of the systematic b_5 error in the dipoles requires a MCD gradient of $2.77 \times 10^6\ \mathrm{Tm}^{-4}$. Considering NbTi technology, a maximum gradient of $4.3 \times 10^6\ \mathrm{Tm}^{-4}$ or $2.8 \times 10^6\ \mathrm{Tm}^{-4}$ is respectively reached for an aperture diameter of 58 mm or 63 mm [8]. For comparison, at collision the same corrector field would allow to correct up to 0.53 units of b_5. Using the field errors model described in [3,7] and the CDR version of the optics, the maximum MCD gradient, computed over 60 different seeds at injection, is $2.94 \times 10^6\ \mathrm{Tm}^{-4}$, and its distribution is shown in Fig. 3. This value is compatible with or equal to (within few ‰) the maximum value reachable by NbTi technology, therefore the LHC scheme and corrector length are kept for FCC-hh, as seen in Fig. 1.

DYNAMIC APERTURE

The DA is computed using SixTrack [9], for the same initial conditions and parameters described in [6,10]. Contrary to Ref. [6,10], DA is defined as losses at 10^5 turns which is found to be a more stable indicator with respect to the

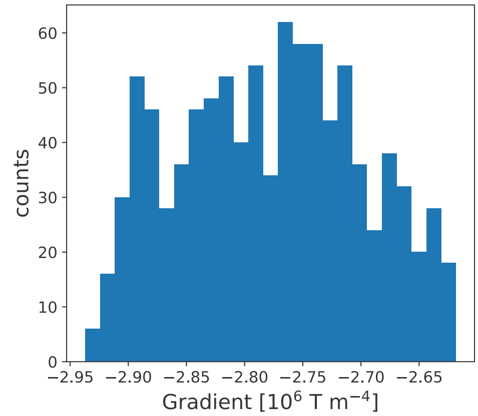

Figure 3: MCD gradients computed for 60 different error configurations of the machine at injection.

value containing the onset of chaos. Also the initial relative momentum offset of the particles in these simulations is set to 3.2×10^{-4} , which correspond to 2/3 of the maximum momentum offset allowed in FCC as discussed in the next subsection. We have verified that the triplet and separation dipoles field errors of the two EIR do not impact DA at injection, as expected. Therefore these errors are included in the following results without non-linear corrections, and the phase advance between both EIRs is not optimised, contrary to the collision case.

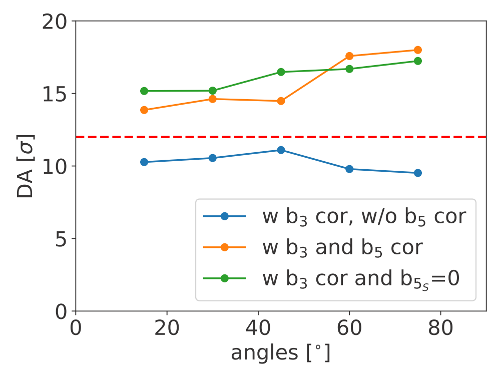

Figure 4: Minimum DA over 10^5 turns for 5 directions $\phi = \arctan(\sqrt{\epsilon_y/\epsilon_x})$ of the space, 60 seeds and 109.28/107.31 tunes.

With the old error tables, DA was dominated by the combination of random dipole errors at injection; with the present table the impact of the systematic part of the b_5 dipole field errors on DA is clearly visible and correction is required, as discussed in previous section. The decapole correction scheme proposed is able to increase the minimum DA value above the 12 σ target, leaving a small residual reduction of DA towards the horizontal plane, as shown in Fig. 4.

Studies were also performed at collision energy, same initial parameters and errors in both the arcs and EIR magnets, although only b_3 correction in the arcs is considered for this case. For these studies the phase advance between EIRs is optimised to increase the DA. The use of normal and skew

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sextupole (b_3 and a_3), and octupole (b_4 and a_4) correctors is also explored; the strength of these correctors is calculated to compensate for the non-linearity in the triplet magnets of the EIRs. The minimum DA for different cases of β^* with and without non-linear correctors is shown in Fig. 5. Results show that the use of non-linear correctors provides a considerable increase in DA but are particularly important for the cases with β^* below 30 cm, for which the target at collision energy of 10 σ is only achieved (or nearly achieved for the case with β^*=15 cm) with the use of these correctors. It is worth noticing, that the main sextupoles strengths are running out of their maximum allowed by NbTi technology, for these cases.

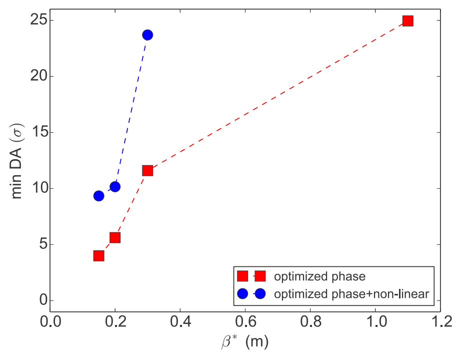

Figure 5: Minimum DA over 60 seeds versus β^* with and without non-linear correctors.

Octupoles and RF Bucket

As for LHC, octupoles used for Landau damping reduce DA below the target value of 12 σ. In particular, when an octupole current of -15/720 A is used for all the Landau damping octupoles of the ring, the minimum DA at injection reduces to 9.4 σ for an initial momentum offset of the particles of 3.2×10^{-4}

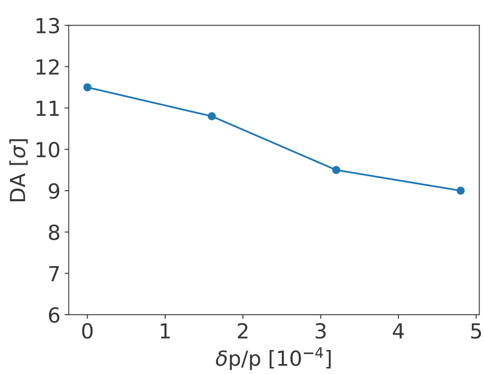

Figure 6: Minimum DA over 10^5 turns, 5 directions $\phi = \arctan(\sqrt{\epsilon_y/\epsilon_x})$ of the space and 60 seeds as a function of initial momentum offset of the particles. The maximum RF bucket size is at 4.8×10^{-4} δp/p. The Landau damping octupoles current is set to -15/720 A.

Figure 6 shows the minimum DA at injection considering a Landau octupole current of -15/720 A as a function of initial energy offset of the particles. The maximum RF bucket is at about 4.8×10^{-4} , as given in [11]:

$$\left(\frac{\Delta p}{p}\right)_{max} = \sqrt{\frac{2V_{RF}}{\pi h|\eta|cp_0}} \tag{2}$$

where V_{RF} is the total RF voltage and $\eta = \frac{1}{\gamma_{rel}^2} - \alpha_c$. The minimum DA decreases by about 2.5 σ moving from zero initial energy offset to the maximum allowed. This has to be taken into account when reading the DA results commonly given for an initial energy offset corresponding to the 2/3 of the maximum allowed by the RF bucket size.

Alternative 1.3 TeV Injection Energy

In the FCC-hh study, two possible injection energies are considered: the baseline value at 3.3 TeV, using LHC or an High Energy Booster as an injector (to which all previous results refer) and an alternative energy at 1.3 TeV, using a superconducting SPS as an injector [12]. The dipole field quality table has also been evaluated for the injection energy of 1.3 TeV. The systematic values of the allowed harmonics of the dipole ($b_3, b_5, b_7, \ldots$) increase further (up to doubling) at lower energy due to the persistent current. Therefore, the minimum DA due to main dipole and the EIR errors is already at 8.3 σ without taking into account Landau damping octupoles.

CONCLUSION AND PERSPECTIVES

The updated version of the main dipole field quality for the hadrons option of the future circular collider ensures a minimum DA at injection above the target of 12 σ, if the systematic part of the sextupole and decapole errors are corrected. The proposed correction schemes are the same as the LHC machine and are compatible with NbTi technology. Landau octupoles reduce DA below the target, giving a minimum DA similar to the measurements at LHC [13]. The RF bucket size gives a 2.5 σ decrease in DA going from 0 initial momentum offset to the maximum allowed. Finally, the minimum DA at the alternative injection energy of 1.3 TeV is below the target of 12 σ with the current table. At collision, the use of non-linear correctors of the final triplet quadrupoles field errors increases DA considerably and is particularly crucial for the cases with β^* below 30 cm. The study should be extended to include main quadrupole field quality as well as linear imperfections [14] that can affect the final DA results. Also a tune scan can be useful to further optimise DA at injection. Finally, the possibility to use artificial intelligence is planned in order to speed up the calculation of DA and detect the chaotic regime [15].

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