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STUDY OF THE CORRECTOR SYSTEMS FOR THE NEW LATTICE OF THE CERN HADRON-HADRON FUTURE CIRCULAR COLLIDER

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Abstract

A new layout for the energy-frontier hadron-hadron future circular collider (FCC-hh) is being studied at CERN, following the constraints imposed by the outcome of recent tunnel placement studies. The new lattice and the need to maximise the dipole filling factor triggered a deep revision of the corrector systems located in the regular arcs, such as orbit, tune, linear coupling, and chromaticity correctors. The octupole system aimed at providing Landau damping has also been reviewed. Furthermore, the corrector package in the experimental insertion aimed at compensating the field quality of the triplet quadrupoles has been reconsidered in view of the experience gained with the design of the corresponding system developed for the CERN HL-LHC. In this paper, we present and discuss this review in detail. These estimates will need confirmation when the magnet design of the various correctors will be studied.

INTRODUCTION

Since the publication of the Conceptual Design Report (CDR) for the Future Circular Collider [1], intense efforts have been devoted to placement studies [2], in view of defining an optimal circumference length of the proposed FCC-ee [3] and FCC-hh rings. As a result, a new layout [4–6], with a circumference of approximately 91 km, eight equal arcs, and a four-fold supersymmetry of the four experimental insertions, has been studied. The primary goal is to increase the dipole filling factor, obtained by stretching the length of the arc FODO cell to comprise 16 dipoles instead of 12 as in the CDR. Furthermore, the nominal field of the main dipoles of the FCC-hh has been set 14 T (for a beam energy E_b of 42.3 TeV) instead of 16 T of the CDR (for $E_\mathrm{b} = 50$ TeV), with the option of envisaging 20 T dipoles (for $E_\mathrm{b} = 60.4$ TeV), possibly based on hybrid technology that includes HTS. The current baseline [6] is compatible with both configurations.

Looking for options to recover space in the arcs to further increase the dipole filling factor has led to a critical review of all corrector magnets. In the arcs, in particular in the regular FODO cells, a number of corrector systems provide control of fundamental properties of the beam dynamics, such as closed-orbit distortion, tunes, chromaticities, linear coupling, and the amplitude detuning that is used to combat beam instabilities. A review of these systems is mandatory at this stage due to their impact on cell length.

Their optimisation can increase the energy reach of the FCC-hh for a given constant field of the main dipoles by making space for more of these dipoles. This is the focus of this paper, which presents recent results and changes in the layout of these corrector systems.

In the experimental insertion regions (IRs), the field quality of the triplet quadrupoles that create the low-beta optics has a strong impact on the beam dynamics, and it is customary to envisage a set of dedicated nonlinear correctors (see, e.g. [7]) for the LHC or [8] for the HL-LHC). In this paper, a discussion of these correctors is also presented, which defines a new baseline for the FCC-hh.

ARC QUADRUPOLES

The revision of the corrector circuits has also triggered a revision of the length of the main quadrupoles. In the CDR [1], the maximum gradient was assumed to be 367 T/m, with an integral strength at 50 TeV of 2260 T and 2240 T for defocusing and focusing quadrupoles, respectively. The magnetic length was set at 6.4 m, leaving a margin of 3.8 % and 4.6 % for the two families, respectively. For the new baseline optics, it was decided to assume 450 T/m as the nominal quadrupole gradient, which gives a peak field of 13 T at the coil aperture of 50 mm, still lower than the nominal field of the main dipoles. The integral quadrupole gradient needed for the 16-dipole cell is 1564 T (considering $E_\mathrm{b} = 45$ TeV to maintain some margin), which requires a magnetic length of 3.6 m, for the same margin of 3.8 %.

ARC CORRECTORS

Figure 1 (top) shows the layout of the cell correctors in the short straight section (SSS) and of the spool piece magnets installed at the extremities of the main dipoles according to the CDR [1]. The corresponding properties of the correction circuits are listed in Table 1. This configuration has been reviewed according to changes made to the periodic cell, and the results are discussed below.

Orbit Correction Dipoles

Orbit correction dipoles have a length of 1.1 m (instead of 1.2 m in the CDR), which has been made possible by increasing the field. They are located in the SSS of the arcs and dispersion suppressors. A dipole magnet near a focusing or defocusing quadrupole corrects the horizontal or vertical orbit, respectively. The study is carried out using MAD-X [9] considering one of the arcs with alignment and field errors in all main dipoles and main quadrupoles [10]. The distribution of the corrector strengths for several realisations of the errors is shown in Fig. 2. The resulting residual orbit remains below 1 mm in both planes and the residual angle does not exceed 8 µrad.

Trim Quadrupoles

Trim quadrupoles are 0.45 m long (instead of 0.5 m in the CDR), which slightly reduces the available integral field.

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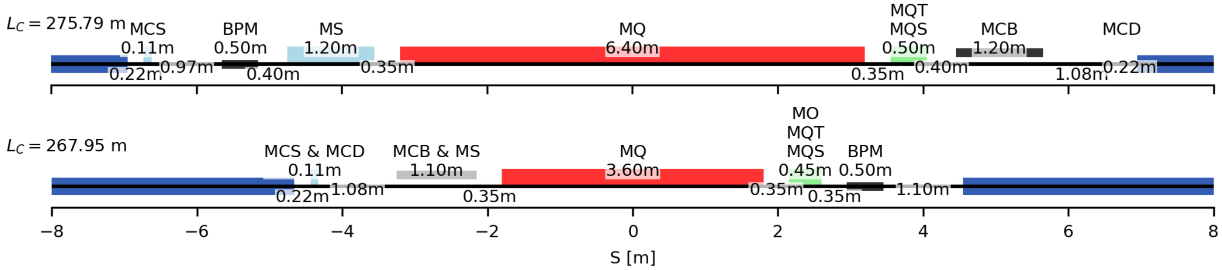

Figure 1: Top: layout of the CDR periodic arc cell (left to right: sextupole spool piece, beam position monitor, chromatic sextupole, main quadrupole, trim quadrupole, skew quadrupole, and orbit corrector). Bottom: layout of the new baseline arc cell (left to right: combined sextupole and decapole spool pieces, combined chromatic sextupole and orbit corrector, main quadrupole, trim quadrupole, skew quadrupole, Landau octupole, and beam position monitor).

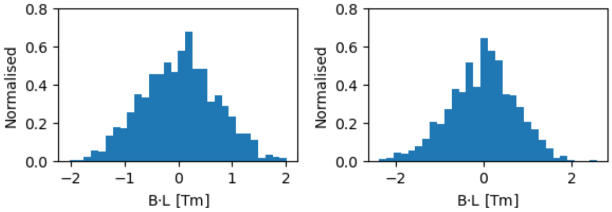

Figure 2: Distribution of horizontal (left) and vertical (right) integral orbit corrector strengths over several machines minimising residual orbit in an arc.

The trim quadrupoles share a slot in the SSS that can instead be taken by skew quadrupoles or Landau octupoles, depending on the position in the arcs. Trim quadrupoles are used to correct the tune. They are located in the outermost cells of every arc, totalling two families of four trim quadrupoles. The resulting β- and dispersion-beating for a few values of the tune shifts is shown in Fig. 3. The shorter trim quadrupoles can still provide suitable tunability.

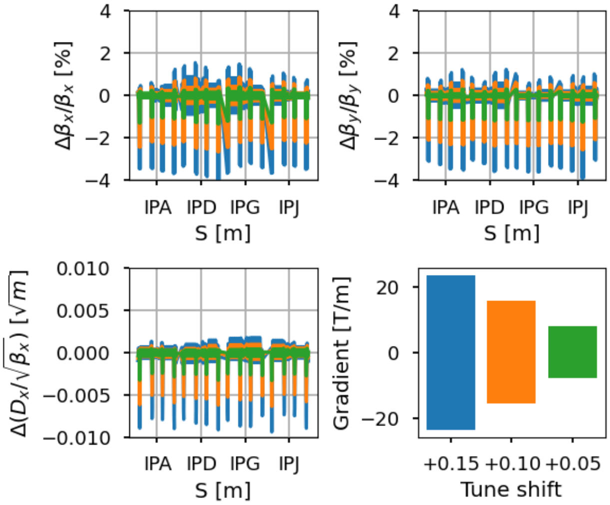

Figure 3: Top: Horizontal (left) and vertical (right) β-beating. Bottom: Dispersion-beating (left) and MQT field gradients (right) for different tune shifts. In the arcs, the β-beating remains below 1 % in all cases.

Skew Quadrupoles

Skew quadrupoles are 0.45 m (instead of 0.5 m in the CDR), which slightly reduces the available integral field, and are used to correct the linear coupling between the horizontal and vertical planes, mainly introduced by skew quadrupole errors in the dipoles, as well as roll angle misalignment of the lattice quadrupoles, and the residual vertical orbit in the lattice sextupoles. These correctors are placed near the centre of the arcs and are divided into two families, separated by a phase advance of 90°, which are used to correct the real and imaginary part of the difference resonance driving term C^-, following the analytical approach in [11] with $C^- = \frac{1}{2\pi}\int\sqrt{\beta_x\beta_y}\,k_s e^{i(\mu_x-\mu_y)}\mathrm{d}s$, where $\beta_{x,y}$, k_s and $\mu_{x,y}$ are the beta functions, skew quadrupole gradient, and phase advances, respectively. The distribution of the corrector strengths for 400 realisations of the errors is shown in Fig. 4. Note that in ~1 % of the seeds studied, a complete cancellation of the linear coupling requires a higher-than-nominal gradient. However, a reduction of C^- by more than a factor of 10 can be achieved with the available strength.

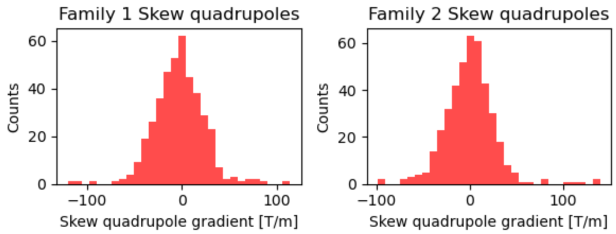

Figure 4: Distribution of skew quadrupole gradients of the two corrector families for 400 realisations of the errors. Complete error cancellation is usually achievable, with an order-of-magnitude reduction in linear coupling possible in edge scenarios that remain compatible with the available strength.

Chromatic Sextupoles

Every SSS contains a 1.1 m-long sextupole (instead of 1.2 m in the CDR) to correct for linear chromaticity. The change is made possible by the longer FODO cell, which corresponds to an increase in the beta- and dispersion-function.

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[1] In the CDR design, these correctors are only present in the long arcs [1].
[2] The two figures refer to the case of short and long arcs [1].

Table 1: Corrector Circuit Properties for the FCC-hh Ring from the CDR and the New Layout

	CDR configuration					**New baseline configuration**				
	Length [m]	Strength [$\mathrm{Tm^{-n}}$]	Integral strength [$\mathrm{Tm^{1-n}}$]	N_c	N_m	Length [m]	Strength [$\mathrm{Tm^{-n}}$]	Integral strength [$\mathrm{Tm^{1-n}}$]	N_c	N_m
Orbit dipoles	1.2	4	4.8	41/159	1	1.1	4.5	4.95	61	1
Trim quadrupoles	0.5	220	110	2[1]	8	0.45	220	99	2	8
Skew quadrupoles	0.5	220	110	2[1]	8	0.45	220	99	2	2
Chromatic sextupoles	1.2	7000	8400	2	41/159[2]	1.1	7000	7700	2	28
Landau octupoles	0.5	2×10^5	1×10^5	2	30	0.45	2.2×10^5	1×10^5	2	18

All this, makes the chromatic sextupoles more efficient. To increase the dipole filling factor of the regular FODO cell, we combined lattice sextupoles with orbit correctors. The chromatic sextupoles are arranged in two families depending on whether they are placed next to a focusing or defocusing quadrupole. In the most challenging scenario for this correction, namely at top energy and with the beam squeezed in all experimental insertions down to 30 cm, the integral strength required to obtain a chromaticity $Q' = 20$ is 2291 T/m and 4273 T/m for focusing and defocusing sextupoles, respectively.

Landau Octupoles

Octupoles are placed in every SSS that does not contain a trim quadrupole or a skew quadrupole. With the arrangement of correctors described above, there are currently 296 slots available for octupoles. This is reduced from 480 in the CDR studies, as lengthening the arc cell results in fewer SSS. To maintain the same amount of amplitude detuning considered in previous studies [12] and assuming that the only change with respect to the CDR is the cell length (from 213.04 m to 267.95 m), we obtain the scaling of amplitude detuning vs. action J_x, J_y between two lattices

$$\frac{\Delta\nu^{\mathrm{F,D}}_{x,y}(J_x, J_y)}{\Delta\tilde{\nu}^{\mathrm{F,D}}_{x,y}(J_x, J_y)} = \frac{N^{\mathrm{F,D}}_{\mathrm{oct}}}{\tilde{N}^{\mathrm{F,D}}_{\mathrm{oct}}}\frac{K^{\mathrm{F,D}}_4}{\tilde{K}^{\mathrm{F,D}}_4}\left(\frac{L_\mathrm{c}}{\tilde{L}_\mathrm{c}}\right)^2, \qquad (1)$$

where $N^{\mathrm{F,D}}_{\mathrm{oct}}, K^{\mathrm{F,D}}_4, L_\mathrm{c}$ stand for the number of lattice octupoles, their integral strength, and the cell length, respectively, and the tilde indicates the CDR lattice case. Equation (1) indicates that an increase by 5 % of the integral octupole strength would be needed to generate the same amplitude detuning as in the CDR lattice. However, this is almost balanced by the reduction in beam energy and, after rounding, the values reported in Table 1 are confirmed.

NEW CORRECTORS LAYOUT

The layout of the cell correctors proposed for the new baseline periodic cell is shown in Fig. 1 (bottom), which incorporates the results of the studies presented before. The main changes with respect to the CDR configurations are: The length of the main quadrupole has been reduced; the orbit-corrector dipoles and the chromatic sextupoles are combined in a shorter nested-magnet configuration; the octupolar spool pieces have been suppressed; the arrangement of the correctors around the main quadrupole has been revised. As a result of these changes, the length of the 16-dipole cell is reduced from 275.79 m to 267.95 m with a dipole filling factor of 0.847 (compared to 0.823 before these studies).

In Table 1, a summary of the main properties of the corrector circuits is provided, where N_c represents the number of circuits per arc, while N_m stands for the number of magnets per circuit. The symbol n in the units represents the order of the magnetic multipole, which is 0 for a dipole. In general, the same peak field assumed in the CDR has been retained in our proposal, although a large margin of integral strength is available according to the results of our simulations. In the case of the orbit corrector, given the indications of previous studies [10], it has been decided to push the peak field with respect to the CDR configuration.

EXPERIMENTAL IRS CORRECTORS

The four experimental insertions host a special set of corrector magnets to compensate for the nonlinear field imperfections of the triplet quadrupoles close to the interaction point. The design of the nonlinear correctors follows that of the corresponding set for HL-LHC [8] but uses superconducting magnets instead of superferric ones, doubling the peak field. Together with the energy scaling of a factor of ~ 7 between HL-LHC and FCC-hh, the total length required is $7/2$ that of the corresponding system in HL-LHC.

CONCLUSIONS AND OUTLOOK

In this paper, all arc corrector systems have been reviewed. Two main changes have been considered and will be part of future FCC-hh lattices: the orbit correctors and the chromatic sextupoles will be nested; the octupolar spool pieces will be removed, and the Landau octupoles will provide full control of the amplitude detuning that is needed to combat beam instabilities. The gain in cell length, combined with a shortening of the main arc quadrupoles, will be used to probe future cell configurations with 18 instead of 16 dipoles. The corrector package in the experimental insertion to compensate for the field errors of the triplet quadrupoles has also been reviewed assuming a layout based on the HL-LHC design extrapolated to the FCC-hh energy.

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