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OPTIC CORRECTIONS FOR FCC-hh

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Abstract

The FCC-hh (Future Hadron-Hadron Circular Collider) is one of the options considered for the next generation accelerator in high-energy physics as recommended by the European Strategy Group. The evaluation of the various magnets mechanical error and field error tolerances in the arc sections of FCC-hh, as well as an estimation of the required correctors strengths, are important aspects of the collider design.

In this study the mechanical tolerances, dipole and quadrupole field error tolerances for the arc sections of FCC-hh are evaluated. The consolidated correction schemes of the linear coupling (with skew quadrupoles) and of the beam tunes (with normal quadrupoles) are presented. The integration of the different ring insertions (interaction region, collimation, injection, etc) is also discussed.

ERRORS AND CORRECTION SCHEMES

The error tolerances considered for position, rotation, magnetic field, BPM readout of the main arc elements (dipoles, quadrupoles, BPMs) are presented in Table 1, where they are compared to LHC design tolerances. There are no differences between injection and collision energy unless specified. No errors have been applied to the corrector elements themselves. All errors are Gaussian distributed, truncated at 3-σ values. The insertion regions have their own set of tolerance values, presented in Table 2. Tolerances are defined from initial simulations performed with the interaction regions [1] and applied to other insertions. There are some specific cases which differ from the table, for instance quadrupole unit 7 of the interaction regions has a position tolerance of 0.2 mm instead of 0.5 mm due to higher sensitivity to quadrupole errors.

The configuration of the short straight section (SSS) has globally not changed compared to [1], except the length of the quadrupole which is reduced [3]. Since most of the quadrupole correctors available in the short arc sections will be employed for the correction of the spurious dispersion [3], it will be possible to have a correction scheme for the linear coupling and the ring tunes only in the long arc sections.

Orbit Correctors

Orbit correctors have a length of 1.2 m and a maximum field of 4 T, making a maximum integral of 4.8 Tm. They are inserted on each SSS of the arc sections, DIS and insertion regions. Each corrector is coupled with a BPM located at a phase advance of 90°, a corrector located near a focusing (defocusing) quadrupole will correct the horizontal (vertical) residual orbit measured in the BPM located near the following focusing (defocusing) quadrupole. Concerning the insertion regions, the matching sections have a similar correction scheme. In the inner sections (including focusing triplets) there are two correctors next to each quadrupole, one for each plane, with potentially different specifications [4].

Table 1: RMS error tolerances for the main elements of the arc sections. All values are random (r) components except for the dipole a2 for which there is also an uncertainty (u) component. LHC design values are taken from [5] and [6]. LHC value for the dipole b1 includes the roll angle ψ. BPM position errors are given relative to the quadrupole.

Element	Error	Descr.	Units	FCC	LHC
Dipole	ψ	roll ang.	rad	0.50	n/a
	$\delta B/B$	rand. b1	%	0.10	0.08
	$\delta B/B$	rand. b2	%	0.009	0.008
	$\delta B/B$	rand. a2	%	0.011	0.016
	$\delta B/B$	unce. a2	%	0.011	0.005
Quadrupole	x, y	position	mm	0.50	0.36
	ψ	roll ang.	rad	1.00	0.50
	$\delta B/B$	rand. b2	%	0.10	0.10
BPM	x, y	position	mm	0.30	0.24
	read	accuracy	mm	0.20	0.50

Table 2: RMS error tolerances for the main elements of the insertion sections. All values are random (r) components. Field errors are given at injection energy and slightly vary at collision energy. BPM position errors are given relative to the quadrupole.

Element	Error	Descr.	Units	D1	D2
Dipole	ψ	roll ang.	rad	1.00	1.00
	$\delta B/B$	rand. b1	%	0.05	0.05
	$\delta B/B$	rand. b2	%	0.001	0.02
	$\delta B/B$	rand. a2	%	0.002	0.001
				Triplet	Other
Quadrupole	x, y	position	mm	0.20	0.50
	ψ	roll ang.	rad	TBD	0.50
	$\delta B/B$	rand. b2	%	TBD	0.05
BPM	x, y	position	mm	0.30	0.30
	read	accuracy	mm	0.20	0.50

Coupling Correctors

Skew quadrupoles are inserted around the centre of long arc sections, as 2 families of 8 correctors separated by a phase advance of 90°, making a total of 8 families. They have a

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length of 0.5 m and a maximum gradient of 220 T/m. The correction strength is calculated analytically by computing the main driving term contributing to the coupling, e.g. the dipole a_2 error, for each arc section. The overall scheme is inspired by what has been developed for LHC [7, 8].

Tune Correctors

Tune correctors or trim quadrupoles have also a length of 0.5 m and a maximum gradient of 220 T/m. They are inserted near the entrance and exit of each long arc section. As for the skew quadrupoles they are not inserted into the short arc sections. They are arranged in 2 families of 8 quadrupoles per arc section, making a total of 8 families.

RESULTS AND DISCUSSION

The study is performed for two settings of the collider, at 3.3 TeV injection energy with a β^* of 4.6 m ('baseline injection'), and at 50 TeV collision energy with a β^* of 0.3 m ('ultimate') and crossing scheme. For each setting studied a total of 200 machines have been simulated with the MAD-X [2] transport code, with a different seed for each machine. It appears that a significant part of the machines do not converge for the tune correction (5 % at collision and 25 % at collision), but no systematic deviation has been identified in those machines.

For each observable the mean value, standard deviation and maximum value are computed over the 200 machines. The maximum value distribution is used to obtain the 90-percentile value, the value for which 90 % of the data points of a given distribution are included, e.g. it gives a number for which 90 % of the machines do not exceed this number. The dependance on the percentile value is shown for corrector strengths in Fig. 1, for residual orbit and angle in Fig. 2, and for beta and dispersion beating in Fig. 3. The 90-percentile values obtained are summarized in Table 3.

Corrector Strengths

Orbit corrector strengths are below the NbTi limit at the 90 % level, vertical correctors exceed the limit only for a few machines. The values are obtained with orbit correctors in the arc sections and in arc-like quadrupoles of the DIS regions. If the analysis is extended to elements of the DIS and insertion regions (except interaction regions with specific orbit corrector designs) the 90-percentile values would increase to 5 Tm and 4.9 Tm in the horizontal and vertical plane, respectively. This will require further optimization of the correctors design or of the correction scheme in the corresponding regions. Skew quadrupoles values are all below 200 T/m. Trim quadrupoles are also within the NbTi limit at the 90 % level, and it appears that with 220 T/m quadrupoles one can correct up to 0.03 tune fractions.

Residual Orbit and Angle

The results indicate that the residual orbit stays below 1 mm in both planes and for almost all machines. The residual angle does not exceed 35 μrad at injection. At collision the residual angles are very similar. Considering a drift of 11 m for an emitted synchrotron radiation before it hits the chamber walls, and an ejection cone of 19 μrad, a total vertical shift of 1.2 mm can be expected, far from the 7.5 mm half-aperture of the beam screen.

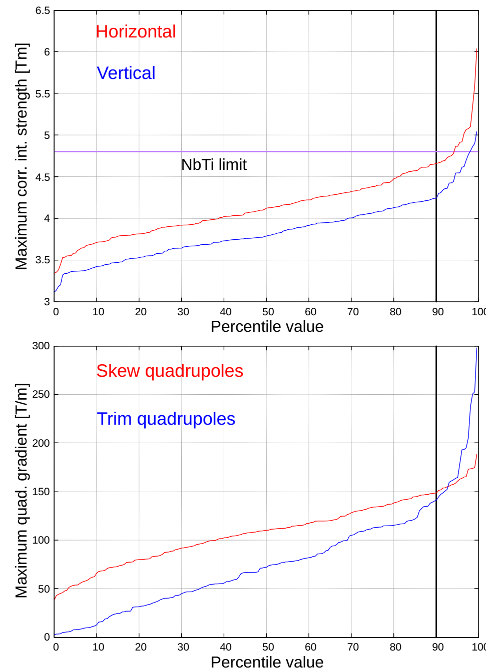

Figure 1: Evolution of the corrector strengths with percentile value for the collision settting. The 90 % value is indicated with a vertical solid line.

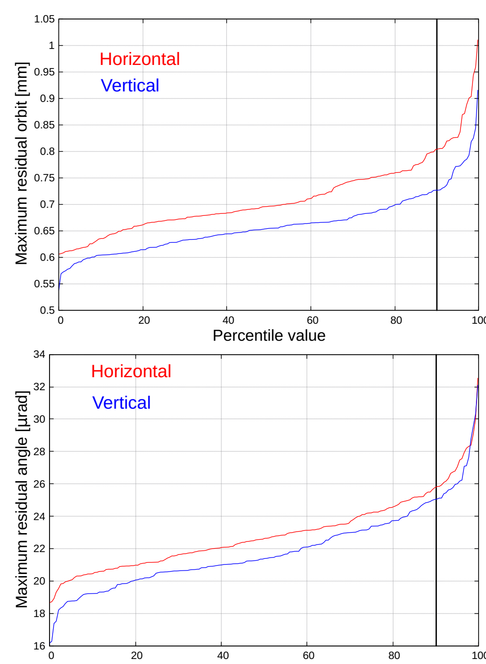

Figure 2: Evolution of the residual orbit (top) and residual angle (bottom) with percentile value for the injection setting. The 90 % value is indicated with a vertical solid line.

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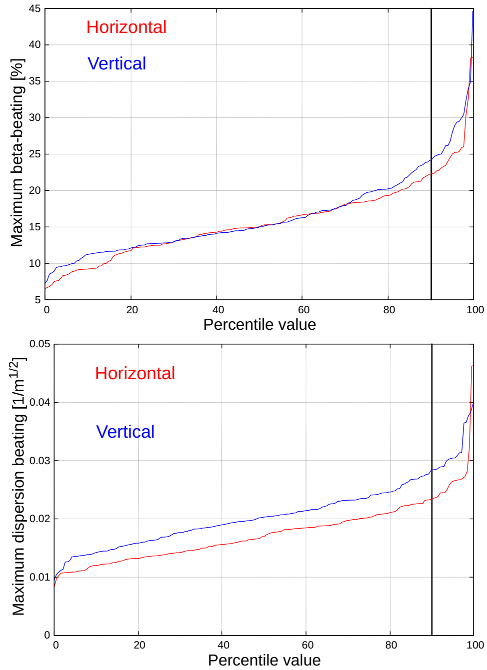

Figure 3: Evolution of the beta- (top) and dispersion beating (bottom) with percentile value for the injection setting. The 90 % value is indicated with a vertical solid line.

Beta-beating and Dispersion Beating

The beta-beating is relatively high at injection, with a 90-percentile value close to 25 % in both planes, and well above the target of 10 % considered by beam stay clear calculations [9]. At collision it goes significantly higher, up to 34 % in horizontal plane and 42 % in vertical plane. Currently there is no dedicated correction of the beta-beating, and the coupling and tunes correction do not cancel it very efficiently. The results for dispersion beating seem satisfactory at injection, with 90-percentile values below the LHC design values. With the collision setting, the horizontal dispersion beating is slightly higher than the LHC design constraints, while the vertical dispersion beating is similar to the injection case. As for the beta-beating, a dedicated correction to improve the results is not implemented yet but envisaged.

CONCLUSION

An updated error correction scheme for the orbit, linear coupling and tune has been applied to the FCC-hh ring, both at injection and collision regimes. All insertion regions are now included in the simulations. The results show that the residual orbit and angle are in accordance to the synchrotron radiation evacuation. The beta-beating has values well above the limit of 10 % set for FCC-hh. Dispersion beating is within the LHC design limits. Both beta and dispersion beating can be improved by implementing a dedicated correction scheme as in LHC. As for the corrector strengths, maximum values currently needed for orbit correctors of the arcs sections, for skew quadrupoles and for trim quadrupoles are within the specifications considered for magnets built with NbTi technology. Some of the orbit correctors inside the dispersion suppression regions and insertion regions exceed those specifications and require further optimization.

Table 3: 90-percentile results obtained for the injection and collision settings.

Observable	Injection	Collision
Hori. orbit	0.80 mm	0.79 mm
Vert. orbit	0.73 mm	0.73 mm
Hori. angle	26 μrad	26 μrad
Vert. angle	25 μrad	27 μrad
Hori. beta-beating	22 %	34 %
Vert. beta-beating	24 %	42 %
Hori. disp. beating	0.023 $\frac{1}{\sqrt{m}}$	0.036 $\frac{1}{\sqrt{m}}$
Vert. disp. beating	0.028 $\frac{1}{\sqrt{m}}$	0.027 $\frac{1}{\sqrt{m}}$
Hori. orbit corr. str.	0.31 Tm	4.7 Tm
Vert. orbit corr. str.	0.28 Tm	4.2 Tm
Skew quad. str.	8.57 T/m	148 T/m
Trim quad. str.	3.68 T/m	140 T/m

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