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UPDATES ON THE OPTIC CORRECTIONS OF 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, and the natural evolution of existing LHC. 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 correctors strengths necessary to perform the error corrections, are important aspects of the collider design.

In this study recommended values for the mechanical errors, dipole and quadrupole field errors tolerances are proposed, with the possible consequences on the correctors technological choice and on the beam screen design. Advanced correction schemes of the linear coupling (with skew quadrupoles) and of the beam tunes (with normal quadrupoles) are discussed. Also a combined correction scheme including the interaction regions is tested.

UPDATES ON THE FCC-hh RING LATTICE

The major changes which have occurred since the previous report [1] are presented in [2]. The main magnet specifications have been modified, leading to a change in the FODO cell structure and their arrangement in the arcs. Also the structure of the short straight section (SSS) was changed. The BPM and sextupole were moved in front of each quadrupole, the quadrupole corrector (skew or trim) was moved after the quadrupole with its length increased from 0.36 m to 0.5 m. The orbit corrector length has been increased from 1 m to 1.2 m, and staying around the same position as before.

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. At the moment there are no differences between injection and collision energy. No errors have been applied to the corrector elements themselves. All errors are Gaussian distributed, truncated at 3-σ values. The interaction regions (IR, see [3]) are also included in the analysis, with alignment tolerances of 0.1 mm and 0.5 mm for the inner triplet and for other quadrupoles, respectively. A roll angle tolerance of 2 mrad for all IR dipoles is also implemented.

For each case studied a total of 200 machines have been calculated with the MADX [4] transport code, with a different seed for each machine. It appears that with the 'ultimate' collision optics and very large β functions around the IPs, a significant part of the machines do not converge, but no systematics have been identified so far in these machines.

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. Values used for LHC are taken from [5] and [6]. LHC value for the dipole b1 includes the roll angle ψ. The BPM position errors are given relative to the quadrupole.

Element	Error	Descr.	Units	FCC	LHC
Dipole	x, y	position	mm	0.50	0.50
	ψ	roll ang.	rad	0.50	n/a
	δB/B	rand. b1	%	0.10	0.08
	δB/B	rand. b2	%	0.005	0.008
	δB/B	rand. a2	%	0.010	0.016
	δB/B	unce. a2	%	0.010	0.005
Quadrupole	x, y	position	mm	0.50	0.36
	ψ	roll ang.	rad	1.00	0.50
	δB/B	rand. b2	%	0.10	0.10
BPM	x, y	position	mm	0.30	0.24
	read	accuracy	mm	0.20	0.50

Each short straight section (SSS) has an arc quadrupole and various corrector elements next to it. Attached to a quadrupole there can be either a skew quadrupole or a trim quadrupole depending on the needs. Near each arc quadrupole are also inserted a BPM, a sextupole and an orbit corrector. The layout of a SSS is illustrated in Fig. 1.

Since most of the quadrupole correctors available in the short arc sections will be employed for the correction of the spurious dispersion [2], 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 now a length of 1.2 m and a maximum field of 4 T, making a maximum integral of 4.8 Tm. This is the technological limit for a magnet built with Nb-Ti technology. They are inserted on each short straight section of the arc cells. Each corrector is coupled with a BPM located at a phase advance of 90°, such a way that a corrector located near a focusing (defocusing) quadrupole will correct the horizontal (vertical) residual orbit measured in the BPM

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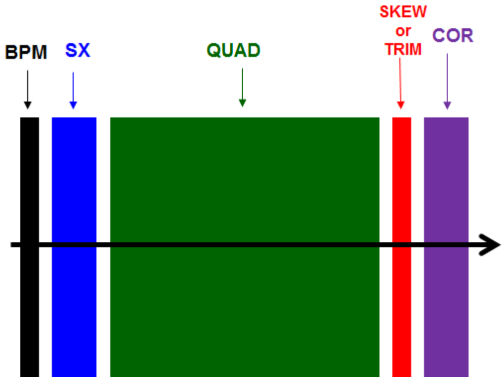

Figure 1: Structure of a short straight section (SSS) with from left to right a BPM, a sextupole, a main quadrupole, a skew or trim quadrupole and an orbit corrector.

located near the following focusing (defocusing) quadrupole. In the interaction region there is also one orbit corrector and one BPM inserted next to each quadrupole, but with different specifications [3].

Coupling Correctors

Coupling correctors are so-called skew quadrupoles, e.g. quadrupoles rotated by 45°. They have a length of 0.5 m, and a maximum gradient limit of 220 T/m. They are inserted in the long arc sections only, around the mid-arc as 2 groups of 8 quadrupoles, each quadrupole being separated by a phase advance of 90°. Within each long arc section the strength of all skew quadrupoles are coupled.

This scheme allows to correct the linear coupling without perturbing other quantities like dispersion. The correction strength is calculated analytically by computing the main driving term expected to contribute to the coupling, e.g. the dipole a2 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. The tune correction involves 2 families of 8 quadrupoles inserted on the outer regions of each long arc section. The elements of each family are separated by a 90° phase advance, each family being shifted by one quadrupole unit or 45° phase advance. Each family is coupled within each long arc section.

RESULTS AND DISCUSSION

The simulations have been performed on two configurations of the lattice, at injection (E = 3.3 TeV, $\beta^* = 4.6$ m) and at collision (E = 50 TeV, $\beta^* = 0.3$ m, no crossing scheme). For each configuration the mean value, RMS and maximum value of the correctors strength, residual orbit, residual angle, beta-beating $\Delta\beta/\beta_{ref}$ and dispersion beating $\Delta D/\sqrt{\beta}_{ref}$ are calculated. From the maximum value distribution the 90-percentile value (value for which 90 % of a given distribution is included) is evaluated for each observable. Only the results obtained at injection are displayed, but the results at collision are also discussed.

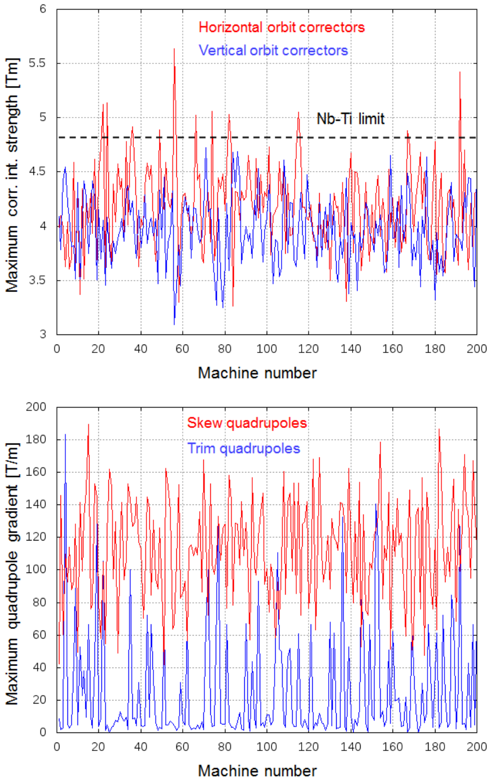

Figure 2: Distribution of the maximum integrated strength of the orbit correctors (top) and gradient of the quadrupole correctors (bottom) for the case at injection and for the 200 machines simulated, normalized to collision rigidity.

Corrector Strengths

The maximum strengths of the different correctors, obtained for the all machines simulated, are shown in Fig. 2. The values are normalized to collision rigidity as strengths at injection are only 7 % of the values at collision. At collision energy the orbit corrector strengths reach the Nb-Ti limit, with a 90-percentile value of 4.8 Tm for horizontal correctors and 4.4 Tm for vertical correctors. About 5 % of the machines simulated have at least one corrector exceeding the Nb-Ti limit, but at most only two correctors on each machine concerned, and never the same corrector(s), which means it is not a systematic effect. A further optimization of the orbit correction procedure should allow to obtain corrector values within the Nb-Ti limit.

The skew quadrupoles have 90-percentile values for the gradient of 157 T/m at collision. The a2(u) dipole error is driving the strength necessary for the coupling correction, its tolerance currently defined in Table 1 should not be increased in order to keep the correctors strengths within the gradient limit. For the trim quadrupoles the 90-percentiles value for the gradient rise to 70 T/m at collision, well below the Nb-Ti limit for this magnet. Nevertheless a large spread in trim quadrupoles strengths between different machines is observed, which means the correction scheme still needs some improvement.

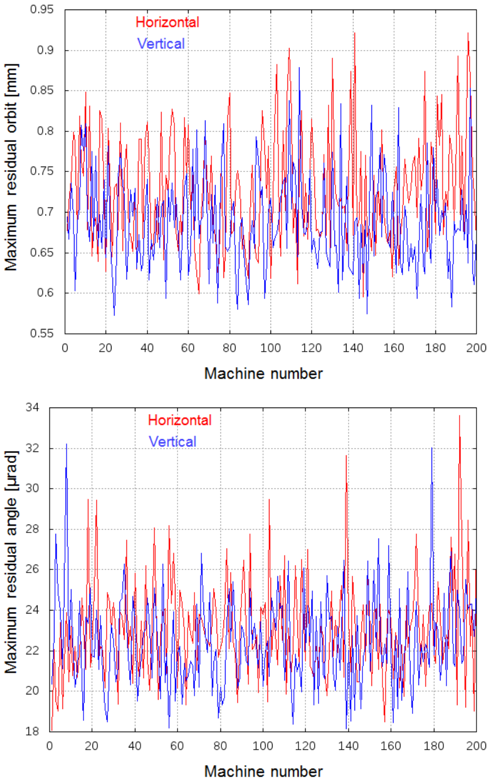

Figure 3: Distribution of the maximum residual orbit (top) and residual angle (bottom) after correction, for the case at injection and for the 200 machines simulated.

Residual Orbit and Angle

The maximum values of the residual orbit and angle after correction obtained for the case at injection can be seen in Fig. 3. The 90-percentile values are 0.82 mm for the horizontal orbit, 0.77 mm for the vertical orbit, 26 μrad for the horizontal angle and 25 μrad for the vertical angle. Values are not different at collision except in the interaction regions (IR) where the orbit reaches 1.6 mm near the IPs, which means the IR orbit correction scheme needs further optimizations. The combined contributions of the vertical residual orbit, vertical residual angle and emission cone (19 μrad at collision) to a radiation emitted in the arc sections and drifting around 11 m before hitting the chamber walls leads to a total vertical offset of ±1.3 mm and is compatible with the current design of the beam screen [9]. On the other hand, the residual orbit obtained may be not sufficient for the proton beam circulation and the orbit correction still needs further investigations.

Beta-beating and Dispersion Beating

Figure 4 displays the maximum values of the residual beta-beating and dispersion beating for the case at injection.

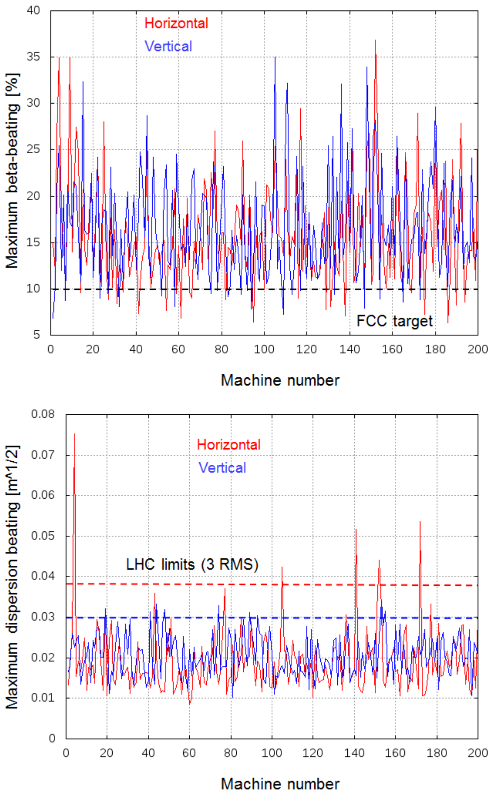

Figure 4: Distribution of the maximum residual beta-beating (top) and residual dispersion beating (bottom) for the case at injection and for the 200 machines simulated.

It appears that the beta-beating is not satisfying the 10 % limit defined for FCC-hh. 90-percentile values are 24 % for both horizontal and vertical beta-beating. The relatively large values may have an influence on the dynamic aperture [10] and it is important to correct beta-beating with a more advanced correction scheme. Dispersion beating is just within the LHC design limits at 3 RMS, with 90-percentile values being 2.8×10^{-2} $\mathrm{m}^{1/2}$ for both horizontal and vertical dispersion beating.

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. The results show that the residual orbit and angle are in accordance to the synchrotron radiation evacuation. The beta-beating is problematic with values well above the limit of 10 % set for FCC-hh. Dispersion beating is within the LHC design limits. As for the corrector strengths, maximum values currently needed for orbit correctors, for skew quadrupoles and for trim quadrupoles are compatible with Nb-Ti technology. The interaction region does not influence the results at injection, whereas at collision the specific optics with very large β require further optimizations of its correction scheme.

In the future the correction of the other insertions will be added to the integrated scheme, starting with the collima-

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tion section, systematic errors will be added, and a global correction scheme for the beta-beating, dispersion beating and coupling will be tested.

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