PROGRESS ON THE OPTICS CORRECTIONS OF FCC-hh*

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Abstract

The FCC-hh (Future Hadron-Hadron Circular Collider) is one of the three 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. Studies are ongoing about the evaluation of the various magnets mechanical errors and field errors tolerances in the arc sections of FCC-hh, as well as an estimation of the correctors strengths necessary to perform the corrections of the errors.

In this study advanced correction schemes for the residual orbit, the linear coupling and the ring tune are described. The impact of magnet tolerances on the residual errors, on the correctors technological choice and on the beam screen design are discussed. In particular the effect of the dipole a2 error is emphasized.

UPDATES ON THE FCC-hh RING LATTICE

Many changes have occurred since the previous report [1]. The overall ring length has been reduced from around 100 km to 97.75 km, mainly due to civil engineering constraints. The structure of the arcs has been changed, short arcs sections having now a length of 3.4 km and long arc sections a length of 16 km. This leads to a change in the number of FODO cells available on each arc section. More details on the FCC-hh lattice updates are given in [2].

ERRORS AND CORRECTION SCHEMES

The errors definition has been greatly expanded. All most important sources of errors (position, rotation, magnetic field, BPM readout) have been now included for the main arc elements (dipoles, quadrupoles, BPMs). No errors have been applied to the corrector elements themselves. The error tolerances considered for this study are presented in Table 1, and compared to LHC tolerances. All errors are Gaussian distributed, truncated at 3-σ values. Only random errors are considered for the study, except for the dipole a2 error which has an uncertainty component when included.

For each studied case a total of 100 runs have been calculated with the MADX [7] transport code, with a different seed for each run. It appears there is a significant number of runs where the ring tunes do not converge, especially when the dipole a2 error is included, but no systematics have been identified so far in these runs.

Table 1: RMS error tolerances studied, 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 (taken from [3] and [4]) are also put for comparison. LHC value for the dipole b1 includes the roll angle ψ. The BPM position errors for LHC 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
	$\delta B/B$	rand. b1	%	0.10	0.08
	$\delta B/B$	rand. b2	%	0.005	0.008
	$\delta B/B$	rand. a2	%	0.011	0.016
	$\delta B/B$	unce. a2	%	0.011	0.005
Quadru-pole	x, y	position	mm	0.20	0.36
	ψ	roll ang.	rad	1.00	0.50
	$\delta B/B$	rand. b2	%	0.10	0.30
BPM	x, y	position	mm	0.35	0.24
	read	accuracy	mm	0.20	0.50

Each arc quadrupole unit has various corrector elements attached to it. Before the quadrupole there can be a skew quadrupole (correcting the linear coupling) or a trim quadrupole (correcting the ring tunes). Only one of the two will be inserted for a given quadrupole unit, unless they can be combined. After the quadrupole is inserted, by order of appearance, a BPM, a sextupole and an orbit corrector. The layout of a quadrupole unit is illustrated in Fig. 1.

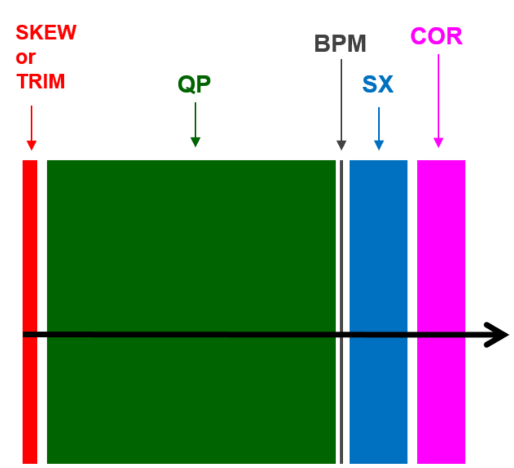

Figure 1: Structure of a quadrupole unit, with from left to right a skew or trim quadrupole, the quadrupole itself, a BPM, a sextupole and an orbit corrector.

Since most of the quadrupole correctors available in the short arc sections will be employed for the correction of

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the spurious dispersion [2], it will not be possible to have a correction scheme for the linear coupling or the ring tunes on these sections. Only the long arcs will have such correction schemes.

Orbit Correctors

Orbit correctors have a length of 1 m and a maximum field of 4 T, making a maximum integral of 4 Tm. This corresponds to the technological limit for such a magnet built with Nb-Ti technology. They are inserted on each quadrupole unit of the arc sections. Each corrector is coupled with a BPM located at a phase advance of 90 degrees, such a way that a corrector located in a focusing (defocusing) quadrupole unit will correct the horizontal (vertical) residual orbit measured in the BPM located in the following focusing (defocusing) quadrupole unit.

Coupling Correctors

Coupling correctors are so-called skew quadrupoles, i.e. quadrupoles rotated by 45°. They have a length of 0.32 m, the maximum gradient limit is still under discussion. They are inserted in the long arc sections, around the mid-arc as 4 groups of 4 quadrupoles separated by a phase advance of 180°, each quadrupole being separated also by a phase advance of 180°. Within each arc section the strength of all quadrupoles is identical.

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 terms expected to contribute to the coupling (quadrupole roll angle, vertical orbit in sextupoles, dipole a2 error) for each arc section. The overall scheme is very similar to what has been developed for LHC [5], [6].

Tune Correctors

Tune correctors or so-called trim quadrupoles have also a length of 0.32 m and a maximum field gradient under discussion. The tune correction scheme involves 2 families of 8 quadrupoles inserted on all long arc sections, in the parts of each arc section next to the neighboring dispersion suppressor. The quadrupoles of each family are separated by a phase advance of 90°, the families being shifted by one quadrupole unit or 45° phase advance. The strength of each family of quadrupoles is the same for all arc sections.

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 simulations were performed either with or without the a2 error components for the arc dipoles. This makes a total of four different cases. For each of the 100 runs simulated on each case, the mean value, RMS and maximum value of the correctors strength, residual orbit, residual angle, beta-beating $\Delta\beta/\beta\text{ref}$ and dispersion beating parameter $\Delta D/\sqrt{\beta}$ 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 variable.

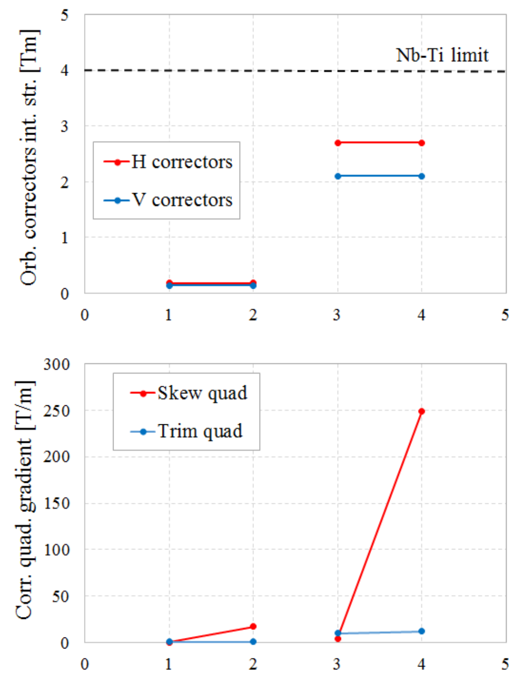

Figure 2: 90-percentile of the integrated strength of the orbit correctors (top) and gradient of the quadrupole correctors (bottom) for the cases at injection with no dipole a2 error (1), at injection with dipole a2 error (2), at collision with no dipole a2 error (3), at collision with dipole a2 error (4).

Corrector Strength

The 90-percentile of the strengths for the different correctors, obtained for the different configurations studied, are shown in Fig. 2. At injection all corrector strengths are very low, as expected with the lower magnetic rigidity (7 % of the value at collision). At collision the orbit corrector strengths are still well below the 4 Tm limit for Nb-Ti, with values up to 2.7 Tm for the horizontal correctors. Such margin was not observed in the previous studies. The reduction may come from the new correction scheme of the linear coupling. The same study was performed on the 100 km lattice and similar results were obtained.

The skew quadrupoles have gradients up to 17 T/m at injection, 249 T/m at collision when the dipole a2 error is included. Such gradient should be still possible using the Nb-Ti technology. Similarly for the trim quadrupoles the gradient rises to 12 T/m at collision, which is still well below the value needed for the spurious dispersion correction. The a2 dipole error is driving the strength necessary for the skew quadrupole correctors.

Residual Orbit and Angle

The 90-percentile of the residual orbit and angle obtained for the different configurations studied can be seen in Fig. 3.

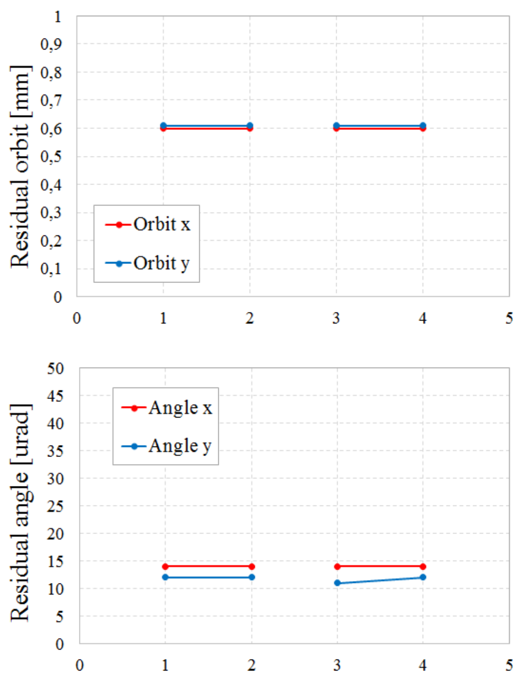

Figure 3: 90-percentile of the residual orbit (top) and angle (bottom), see Fig. 2 for the description of each case studied.

Residual orbit is around 0.60 mm and residual angle around 12 μrad in both planes and for all cases. The values are not different at injection or collision, and are not affected by the dipole a2 error. The combination of the contributions from the vertical residual orbit, vertical residual angle and emission cone (19 μrad) 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 0.94 mm and is totally compatible with the current design of the beam screen [8].

Beta-Beating and Dispersion Beating

Figure 4 displays the 90-percentile of the residual beta-beating and dispersion beating for the different configurations studied. At injection and collision, for cases without the dipole a2 error, the beat-beating is within the LHC limits. If the dipole a2 error is present, beta-beating increases drastically, up to 40 % at injection and 54 % at collision. It may be due to the fact that trim correctors are present only in the outer part of the arc sections, so the beta-beating is not well canceled in the inner part of the arc sections. The increased beat-beating may have an influence on the dynamic aperture studies [9] so it is important to correct it, for example by using the main quadrupoles.

The dispersion beating is below the LHC limits at injection, and going well above at collision. In both configurations there is a strong effect on the vertical beating with dipole a2 error. Values can be up to 7.8×10^{-2} m$^{1/2}$.

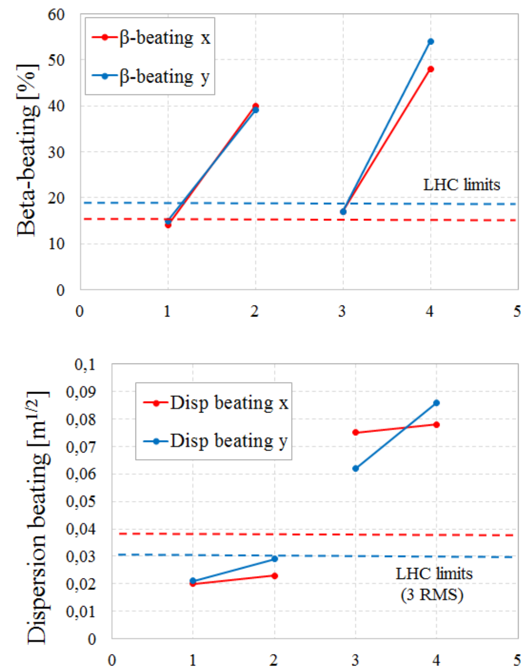

Figure 4: 90-percentile of the residual beta-beating (top) and dispersion beating (bottom), see Fig. 2 for the description of each case studied.

CONCLUSION

A different error correction scheme for the orbit, linear coupling and tune has been applied to the FCC-hh ring, both at injection and collision regimes. Compared to the previous studies made with the 100 km lattice, results are similar except for orbit correctors which are 30 % weaker and the dispersion beating which has strongly increased. The results show that the beta-beating becomes problematic at injection (40 %) when dipole a2 error is included. At collision, without dipole a2 error, dispersion beating is already well above the LHC limits (6.5×10^{-2} m$^{1/2}$). With dipole a2 error, dispersion beating increases further (7.8×10^{-2} m$^{1/2}$), and beta-beating is even higher than for injection (54 %). As for the corrector strengths, maximum values currently needed are 2.7 Tm for orbit correctors, 249 T/m for skew quadrupoles and 12 T/m for trim quadrupoles, all compatible with Nb-Ti technology. The dipole a2 error is a sensitive parameter of the accelerator, as it has a strong impact on several observables of the ring optics. It should be optimized as much as possible.

In the future the correction scheme of the spurious dispersion, the interaction regions and their crossing scheme will be inserted, systematic errors will be added, the error correlations for runs that do not converge properly will be studied more in detail.

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