RESIDUAL ORBIT CORRECTION STUDIES FOR THE 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 [1]. Preliminary studies have started to estimate the design parameters of FCC-hh. One of these studies is the calculation of the residual orbit in the arcs of the collider. This is very important for the evaluation of the alignment tolerances of the quadrupoles used in the arcs, the dimensioning of the correctors and of the beam screen. Moreover it has an impact on the dynamic aperture of the ring and the field tolerances of the arc multipoles. To perform the simulations, the beam transport code MADX has been used. Systematic studies of the residual orbit and of the correctors' strength dependence on the magnets misalignment or field errors are presented and discussed.

THE FCC-HH RING

FCC-hh is the hadron-hadron option considered for the Future Circular Collider accelerator facility that will come after the LHC. The circumference of the ring will be around 100 km and the proton beam energy at collision 50 TeV. The general layout of FCC-hh and its optics are described in [2]. The ring has several long and short arc sections amounting to about 80% of the total ring circumference. One of the studies concerning the arc sections is the correction of the beam residual orbit created by magnet errors. The goal of this study is to find a good correction scheme and to estimate which tolerances on the magnets errors can lead to acceptable results for the corrector strengths, residual orbit and related variables.

ERRORS AND CORRECTION SCHEME

Error Description

There are several error contributions that can affect the closed orbit of the particles in the arcs of the FCC-hh ring:

- Quadrupole alignment errors
- Dipole field errors (random *b1*)
- Quadrupole roll angle errors
- Dipole roll angle errors
- BPM readout errors

For the present study only the first two contributions are studied. The errors are considered as static. Also the incoming beam errors are currently not taken into account.

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Correction scheme

Next to each of the quadrupoles of the arcs ('MQ' type) and of the neighbouring dispersion suppression regions (DIS, 'MQ' and 'MQB' type), there are a BPM (Beam Profile Monitor) and an orbit corrector (0.647-meter-long) made with Nb-Ti technology (as well as a sextupole), both located after the quadrupole. Figure 1 shows the structure of an arc cell around a 'MQ' quadrupole unit.

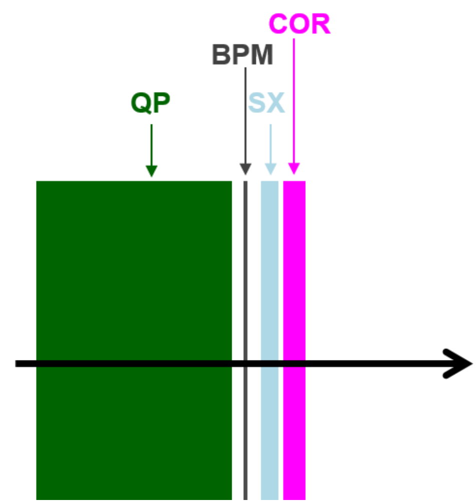

Figure 1: Structure of a quadrupole unit in the arc sections, with from left to right, the quadrupole itself (QP), a BPM, a sextupole (SX), and an orbit corrector (COR).

The following correction scheme has been defined: all BPMs and all correctors are used, the polarity of each corrector and the plane in which each BPM is measuring the beam position, corresponds to the plane in which the neighbouring quadrupole is focusing (a BPM next to a quadrupole focusing in the horizontal plane will only measure the horizontal orbit). This scheme means that a residual orbit measured by a BPM will be compensated by an orbit corrector placed in the second next quadrupole (located at a phase advance of 90° downstream). With this scheme the horizontal and vertical orbit corrections are made with a separate set of BPMs and correctors.

The orbit correction optimization was performed with the MADX [3] code. The complete FCC lattice has been used for the simulations with a tuning at collision energy. The alignment error was defined only for the 'MQ' type quadrupoles. The field error was defined for the all the dipoles present in arcs and in DIS sections. A systematic study on each of the error contributions was investigated, within the following ranges of RMS values:

- $0 < \sigma_{\delta x,y} < 0.5$ mm for quadrupole alignment errors
- $0 < \sigma_{\delta B/B} < 0.5$ % for relative dipole field errors

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For a given set of error contributions, a total of 500 runs has been simulated. In each run, the errors were randomly generated with a different seed, and within a Gaussian distribution truncated at 3-σ values. Only one error contribution was varied once, the other error contribution being fixed to 0.35 mm and to 0.1 % for the quadrupole alignment error and the dipole field error, respectively. Those values are currently considered as reference tolerance values. In the study the horizontal and vertical alignment error distributions were always kept identical.

After the correction was performed for each run, the integrated strength of all correctors was obtained, the RMS and maximum values of the residual orbit, the residual angle, the beta-beating parameter $\Delta\beta/\beta_{ref}$ and the dispersion beating parameter $\Delta D/\sqrt{\beta_{ref}}$ were computed for all elements of the arc sections in both transverse planes. For more details on the definition of those variables see [4]. In this paper only the corrector strengths, residual orbit and angle are discussed.

RESULTS AND DISCUSSION

Results Analysis

For each variable, the distribution of the maximum values over the 500 runs and its 90-percentile value (value for which 90% of a given distribution is included) were calculated. It gives a good estimate of the risk of having a corrector strength larger than this value. The distributions of the maximum values of the integrated corrector strengths having reference errors are shown in Fig. 2.

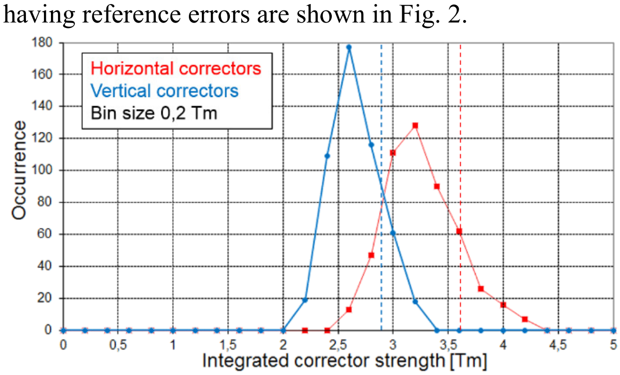

Figure 2: Distribution of the maximum values of the integrated corrector strengths over the 500 runs calculated in the case with quadrupole field errors of 0.35 mm and dipole field errors of 0.1 %. The corresponding 90-percentile values are indicated with dashed lines.

Corrector Strengths

The sensitivity of the 90-percentile value of the horizontal and vertical integrated corrector strengths to the different error contributions is displayed in Fig. 3. The integrated strength limit for a corrector made with the Nb-Ti technology, defined as 4 Tm [5], is reached for an alignment error of around 0.4 mm. For the vertical correctors the 4 Tm limit is reached for a 0.5 mm error.

The integrated strength of the horizontal corrector increases strongly with dipole field error, and a relative field error of 0.15 % already leads to strengths above the Nb-Ti technological limit. As expected there is no evolution of the vertical corrector strengths (no roll angle error included so far) with dipole field error and the value is always below the Nb-Ti limit.

For the reference case with quadrupole alignment error of 0.35 mm and dipole field error of 0.1 %, the integrated strength of the horizontal and vertical correctors are respectively 3.6 Tm and 2.9 Tm, both below the Nb-Ti technology limit of 4 Tm.

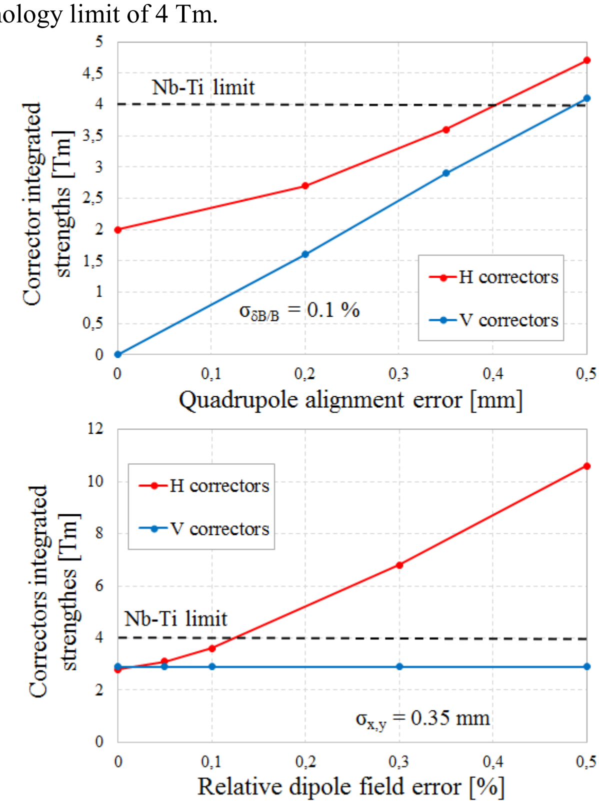

Figure 3: Sensitivity of the integrated corrector strengths to the quadrupole alignment error (top) and the dipole field error (bottom).

Residual Orbit

The sensitivity of the 90-percentile value of the residual orbits to the different error contributions is displayed in Fig. 4. There is currently no well-defined specification for the residual orbit. As a reference, the LHC has a peak radial closed orbit limit of 3 mm at collision [4]. The residual orbit increases almost linearly with quadrupole alignment errors. The LHC limit is not reached for all input errors.

As with the correctors, the horizontal residual orbit increases strongly with relative dipole field errors. The residual orbit is below the LHC limit even with a dipole field error of 0.5 %. The vertical residual orbit does not evolve with dipole field error and is well below the LHC limit.

For the reference case with quadrupole alignment error of 0.35 mm and dipole field error of 0.1 %, the horizontal and vertical residual orbits are 0.57 mm and 0.44 mm, respectively. The impact of these results to the calculations of the dynamic aperture of the ring has still to be investigated [6].

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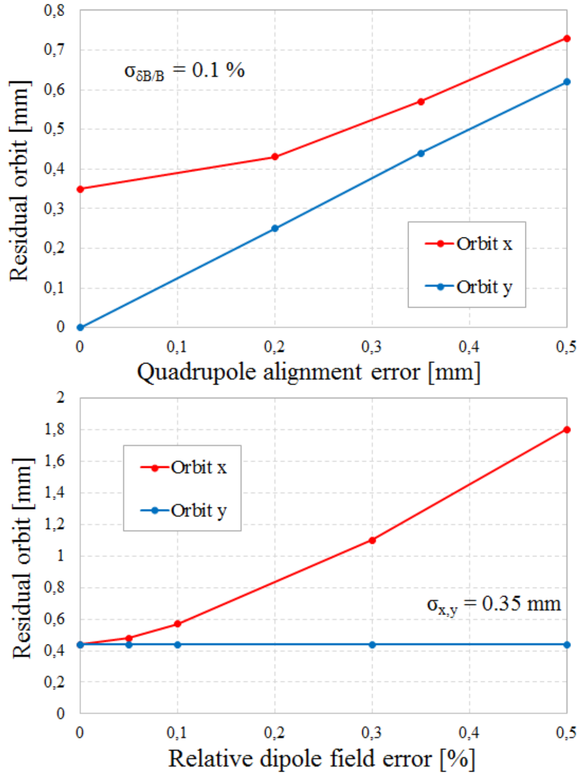

Figure 4: Sensitivity of the residual orbit to the quadrupole alignment error (top) and the dipole field error (bottom).

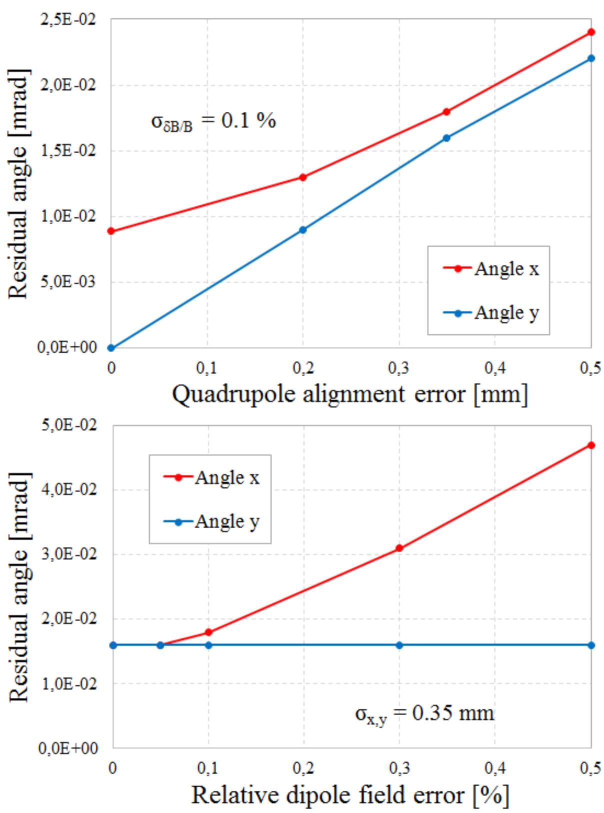

Figure 5: Sensitivity of the residual angle to the quadrupole alignment error (top) and the dipole field error (bottom).

Residual Angle

The sensitivity of the 90-percentile value of the residual angles to the different error contributions can be seen in Fig. 5. The vertical residual angle is important to study, as photons that are emitted by the protons circulating in the arcs are supposed to be caught and evacuated by the slit in the beam screen designed in the arc quadrupoles [7]. If the photons would hit the area outside the slit aperture, it would lead to desorption and vacuum problems in this area.

Again, the residual angle increases linearly with quadrupole alignment error. All values are rather small with a maximum of 24 μrad for a 0.5 mm error. The horizontal residual angle evolves strongly with dipole field error, but does not exceed 50 μrad with an error of 0.5 %. Taking a vertical residual angle of 16 μrad obtained for the case with the reference errors, for a photon emitted in the last dipole before an arc quadrupole, the contribution to the vertical offset of the photon hitting the quadrupole is about 0.4 mm, which becomes not negligible compared to the 1.6 mm half-aperture of the beam screen.

CONCLUSION

The first orbit corrections for the arcs of the FCC-hh ring have been performed. A correction scheme using all available BPMs and orbit correctors has been described. With this scheme, an input error of 0.35 mm for the quadrupole alignment error and 0.1 % for the relative field error leads to integrated strengths for the orbit correctors below 4 Tm, which is compatible with the Nb-Ti technology for these magnets. The residual orbits are below reasonable limits based on LHC specifications. Residual angle may have an impact on the beam screen design but it needs further investigations. Additional error contributions like quadrupole roll angle, BPM readout error will be added in the near future.

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