Updates on the optics of the future hadron-hadron collider FCC-hh

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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. The layout of FCC-hh has been optimized to a more compact design following recommendations from civil engineering aspects. The updates on the first order and second order optics of the ring will be shown for collisions at the required centre-of-mass energy of 100 TeV. Special emphasis is put on the dispersion suppressors and general beam cleaning sections as well as first considerations of injection and extraction sections.

### UPDATES ON THE LAYOUT OF THE FCC-hh RING

The layout of the FCC-hh ring (see Fig. 1) has dramatically changed since the one shown in Ref. [1]. The total circumference of the FCC-hh ring has been shortened from 3.75 times the one of LHC, i.e. 99.97 km, to 11/3, i.e. 97.75 km. The choice of this new circumference is a compromise between civil engineering constraints (a longer ring will be much more costly because of the ground state) and dipole feasibility (shorter arcs imply a higher dipole field). The FCC-hh ring is made of 4 short arcs (SAR), 4 long arcs (LAR), 6 long straight sections (LSS) and 2 extended straight sections (ESS). To fit with the new circumference, the ESS has been shortened from 4.2 km to 2.8 km. The parameters of the ring are given in Table 1.

![Layout of the FCC-hh ring.](image)

### OPTICS OF THE FCC-hh RING

The layout of the arc FODO cells is given in Fig. 2. Each FODO cell has 12 dipoles, 12 $b_3$ correctors (MCS),
2 quadrupoles, 2 sextupoles, 2 BPMs, 2 dipole correctors. The correction of the misalignment is explained in Ref. [9] and will not be developed here. Currently, a skew and a trim quadrupole are inserted at each quadrupole in the aim of tune, coupling, or spurious dispersion corrections. When the correction schemes are refined, removing the trim or/and the skew quadrupole will be then decided.

Table 2: Parameters of the Arc FODO Cell

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell length</td>
<td>211.986</td>
<td>m</td>
</tr>
<tr>
<td>Cell phase advance H/V</td>
<td>90</td>
<td>deg</td>
</tr>
<tr>
<td>Number of dipoles per cell</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>dipole magnetic length</td>
<td>14.3</td>
<td>m</td>
</tr>
<tr>
<td>dipole maximum field</td>
<td>15.7</td>
<td>T</td>
</tr>
<tr>
<td>quadrupole magnetic length</td>
<td>6.0</td>
<td>m</td>
</tr>
<tr>
<td>quadrupole maximum gradient</td>
<td>380</td>
<td>T/m</td>
</tr>
<tr>
<td>sextupole magnetic length</td>
<td>1.2</td>
<td>m</td>
</tr>
<tr>
<td>sextupole maximum gradient</td>
<td>4545</td>
<td>8539</td>
</tr>
</tbody>
</table>

The optics of the different main insertions are given in Fig. 3 for the ultimate parameters given in Table 1. The arc FODO cells are optimized to have the largest filling ratio [6, 10]. The current parameters of the FODO cell are summed up in Table 2. The phase advance in the FODO cells is exactly 90° in the SAR whereas it is 90 + ϵx,y° in the LAR. The value of ϵx,y is adjusted to tune the whole ring. The large number of FODO cells in the LAR enables to keep the value of ϵx,y small.

A dipole is removed at the middle of the LAR to save some space for the technical straight sections (TSS). To cancel the dispersion wave generated by this missing dipole, another dipole is removed downstream at the phase advance of about 180 degrees (two FODO cells far away). Since the phase advance is not exactly 90°, there is a residual dispersion beating which is canceled in the DIS downstream. The phase advance between IPA (IPG) and the first focusing/defocusing sextupole of the SAR is respectively adjusted to 90 + ϵ° modulo 180° in the horizontal/vertical plane as explained in [11]. Currently, the chromaticity is corrected by two sextupole families distributed in the SAR and LAR. More advanced schemes will be studied in the next future.

**CORRECTION SCHEMES**

While colliding, both beams cross with an angle which can reach values up to P_lXing = (2πXing) / 2π, where Xing is the half-crossing angle in sigmas [2]. The crossing angle can then reach values up to 89 μrad for the ultimate configuration. The orbit excursions in the triplet generates a residual dispersion, which must then be corrected. In the case of a similar scheme to HL-LHC [11], a dispersion wave is generated by switching on the entrance correctors and exit correctors of the SAR: the closed orbit in the SAR quadrupoles generates a dispersion wave which cancels the spurious dispersion. Unfortunately, the studies have shown that the maximum closed orbit in the arcs reaches values up to 8.6 mm/10.9 mm in the horizontal/vertical plane, which cannot be accepted [1]. The main reason of a so large value compared to HL-LHC is a much shorter arc and a much higher dispersion wave generated in the IR triplet. Even if the ATS scheme is used with a reduction by a factor 2, these values stay too large. That is why another scheme has been studied: the scheme proposed for SSC [12]. The idea is to use trim quadrupoles to generate a dispersion beating. If we assume that the perturbation induced by the quadrupoles stays small, the betatron and dispersion waves and the tune change generated by a normal quadrupole of length l_q and normalized strength δk is given by:

\[ Δβ_x(s) = -l_qδK_qβ_xqβ_x(s) \sin 2(μ_x(s) - μ_xq) \]  
\[ Δη_x(s) = -η_ql_qδK_qβ_xqβ_x(s) \sin (μ_x(s) - μ_xq) \]  
\[ ΔQ_x = l_qδK_q / 2π \]

The vertical spurious dispersion can be corrected the same way by using skew quadrupoles instead of normal ones. Equations (1) and (2) show that the betatron wave and tune change are nullified at the end of a couple of quadrupoles with opposite strength and a phase of 180° in between (two FODO cells in our case), contrary to the dispersion wave. If we use another couple of quadrupoles with a phase advance difference of 90° with the first family, it is then possible to cancel the spurious dispersion and its derivative. In theory, only one quadrupole couple is sufficient if the phase advance with the IP is the right one. In practice, this condition cannot be perfectly fulfilled and the second family enables to cancel the residual dispersion. For FCC-hh, with 0.32-meter-long correctors, the studies have shown that the needed maximum gradient is 220 T/m (660 T/m) for the normal (skew) quadrupoles by using two sets of only 2 correctors. Since these values are too large, it was decided to use more trim quadrupoles to reduce the needed maximum gradient. Currently, two sets of 6+2 (first and second family) are used in each SAR. The maximum gradient has then been reduced to 100 T/m (220 T/m), which is affordable. The obtained
Like in LHC, if we use a set of 4 normal quadrupoles with a phase advance of 90° in between and the same polarity, the betatron and dispersion waves are canceled whereas the global tune is changed (see Eq. (1), (2), (3)). We use then 2 sets of 4 trim quadrupoles at the entrance of the LAR to correct the tune in each plane. By the same way, we use 2 sets of 4 skew quadrupoles in the LAR to correct the coupling driving terms. More details on the coupling and tune correction are given in Ref. [9].

CONCLUSION

An updated status of the layout and optics of the FCC-hh ring has been given. The correction of the spurious dispersion has been investigated by using a SSC-like scheme. The proposed scheme is to use trim and skew quadrupoles in the arcs to generate a dispersion wave and then to mitigate the residual dispersion. In the current state, realistic gradients were reached for ultimate parameters. The correction of the chromaticity is made by two sextupole families. In the future, a tune scan of the machine with an optimization of the phase advances between IPs will be performed.

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REFERENCES


