UPDATES ON THE OPTICS OF THE FUTURE HADRON-HADRON COLLIDER FCC-hh

A. Chance*, D. Boutin, B. Dalena, CEA, IRFU, SACM, Centre de Saclay, F-91191 Gif-sur-Yvette, France,
B. Holzer, A. S. Langner, D. Schulte, CERN, Geneva, Switzerland

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. 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.

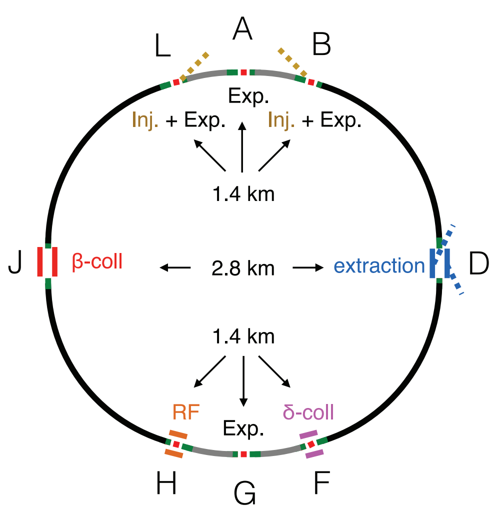


Figure 1: Layout of the FCC-hh ring.

Table 1: Parameters of the FCC-hh Ring

Parameter	Value Baseline	Value Ultimate	Unit
Energy	50		TeV
Circumference	97.75		km
LSS and ESS length	1.4 and 2.8		km
SAR and LAR length	3.4 and 16		km
β^*	1.1	0.3	m
L^*	45		m
Normalized emittance	2.2		μm
γ_{tr}	99.331	99.310	
Q_x/Q_y	111.31/ 109.32		
Q'_x/Q'_y	2/2		
Beam separation	204		mm
Beam separation (RF)	420		mm

The high luminosity interaction points (IPs) are located at the IPA and IPG. The optics of these interaction regions (IRs) is assumed to be antisymmetric and is presented in [2] for the current value of $L^* = 45$ m. In the following, the crossing angles in IPA and IPG are not in the same plane at the collision. The lower luminosity IRs are located at the IPB and IPL. A major change of the new layout is to locate there the injection as well. The beam H1 which runs in the clockwise direction is injected at IPB and the other one H2 at IPL. The RF cavities are located at IPH with a beam separation enlarged from 204 mm to 420 mm thanks to a chicane added at the entrance and at the exit. This section is currently made of FODO cells. Another major change of the current layout is the location of the extraction [3] and collimation sections [4, 5]. The extraction section is located at IPD in one ESS and has been changed to enable the extraction of both beams in the same section. The betatron cleaning section is located in the other ESS at IPJ for both beams. The momentum cleaning section has been shortened to fit in a 1.2-kilometer-long section at IPF.

The dispersion suppressors (DIS) are similar to the ones used in LHC (see Fig. 2). The advantage of this configuration is a good filling factor by keeping a good flexibility [6]. Like in HL-LHC, some space is saved for two 5-meter-long collimators to protect the arc entrances from the debris coming from the collimators in the experimental and cleaning sections [7, 8].

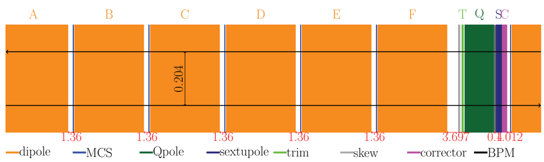
OPTICS OF THE FCC-hh RING

The layout of the arc FODO cells is given in Fig. 2. Each FODO cell has 12 dipoles, 12 b_3 correctors (MCS),

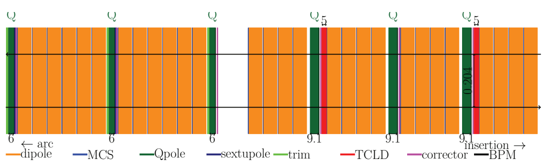
* Corresponding author: antoine.chance@cea.fr

ISBN 978-3-95450-182-3

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.



(a) Arc FODO half-cell



(b) Dispersion suppressor

Figure 2: Layout of the arc FODO half-cell and DIS.

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 $90 + \epsilon_{x,y}{}^\circ$ in the LAR. The value of $\epsilon_{x,y,}$ is adjusted to tune the whole ring. The large number of FODO cells in the LAR enables to keep the value of $\epsilon_{x,y}$ 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 $90 + \epsilon^\circ$ 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 $P_{\text{Xing}} = \sqrt{\frac{\epsilon_N}{\gamma\beta^*}} \times n_{\text{Xing}}$ where n_{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 excursion 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

Table 2: Parameters of the Arc FODO Cell

Parameter	Value	Unit
Cell length	211.986	m
Cell phase advance H/V	90	deg
Number of dipoles per cell	12	
dipole magnetic length	14.3	m
dipole maximum field	15.7	T
quadrupole magnetic length	6.0	m
quadrupole maximum gradient	380	T/m
sextupole magnetic length	1.2	m
sextupole maximum gradient Baseline/Ultimate	4545/8539	T/m^2

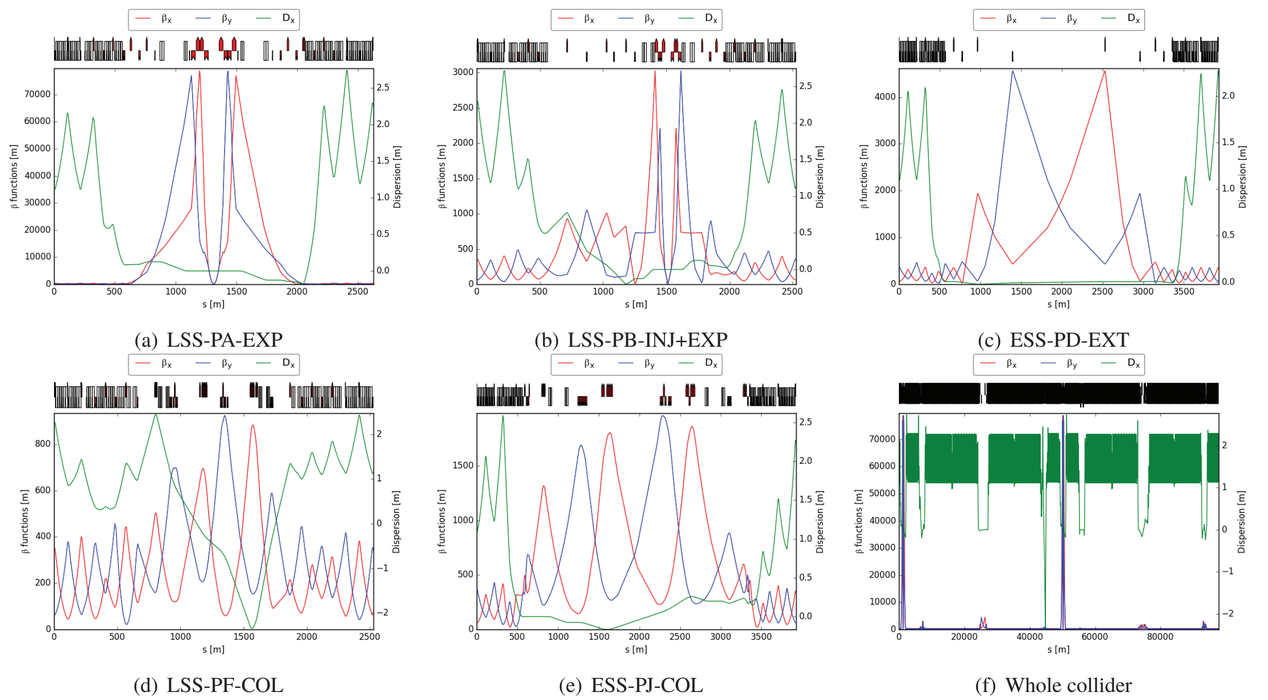
quadrupoles generates a dispersion wave which cancels the spurious dispersion. Unfortunately, the studies have shown that the maximum closed orbit in the arcs reaches values up to 8.6 mm/10.9 mm in the horizontal/vertical plane, which cannot be accepted [1]. The main reason of a so large value compared 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:

$$\Delta\beta_x(s) = -l_q\delta K_q\beta_{xq}\beta_x(s)\sin 2\left(\mu_x(s) - \mu_{xq}\right) \quad (1)$$

$$\Delta\eta_x(s) = -\eta_q l_q\delta K_q\sqrt{\beta_{xq}\beta_x(s)}\sin\left(\mu_x(s) - \mu_{xq}\right) \quad (2)$$

$$\Delta Q_x = \frac{l_q\delta K_q}{2\pi} \quad (3)$$

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



(a) LSS-PA-EXP (b) LSS-PB-INJ+EXP (c) ESS-PD-EXT

(d) LSS-PF-COL (e) ESS-PJ-COL (f) Whole collider

Figure 3: Optical functions of the insertion regions at collision: high-luminosity IR, low-luminosity IR with injection, extraction section, betatron and momentum collimation section.

dispersion in the machine after correcting the spurious dispersion is given in Fig. 4.

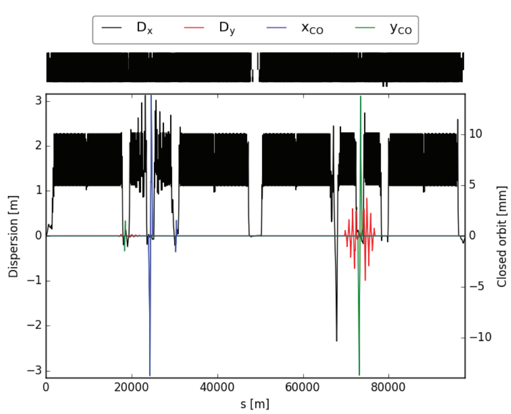


Figure 4: Closed orbit and dispersion in the ring after correction of the spurious dispersion in presence of the crossing scheme.

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.

ACKNOWLEDGEMENT

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

REFERENCES

[1] A. Chance *et al.*, "Status of the Beam Optics of the Future Hadron-Hadron Collider FCC-hh," in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 1470–1472.

[2] A. Seryi *et al.*, "Overview of Design Development of FCC-hh Experimental Interaction Regions," presented at IPAC'17, Copenhagen, Denmark, May 2017, paper TUPVA040, this conference.

ISBN 978-3-95450-182-3

[3] F. Burkart, *et al.*, “Conceptual Design Considerations for the 50 TeV FCC Beam Dump Insertion.” in *Proc. IPAC’16*, Busan, Korea, May 2016, pp. 1356–1358.

[4] J. Molson, P. Bambade, S. Chance, and A. Faus-Golfe, “Simulation of the FCC-hh Collimation System.” in *Proc. IPAC’16*, Busan, Korea, May 2016, pp. 1381–1383.

[5] J. Molson, and A. Faus-Golfe, ”Status of the FCC-hh Collimation System,” presented at IPAC’17, Copenhagen, Denmark, May 2017, paper MOPAB001, this conference.

[6] A. Chance *et al.*, “First results for a FCC-hh ring optics design,” Tech. Rep. CERN-ACC-2015-0035, CERN, Geneva, Apr 2015.

[7] R. Bruce, A. Marsili and S. Redaelli, ”Cleaning performance with 11 T dipoles and local dispersion suppressor collimation at the LHC,” in *Proc. IPAC’14*, Dresden, Germany, pp 170–172.

[8] H. Rafique *et al.*, ”Proton Cross-Talk and Losses in the Dispersion Suppressor Regions at the FCC-hh,” presented at IPAC’17, Copenhagen, Denmark, May 2017, TUPIK037, this conference.

[9] D. Boutin *et al.*, “Progress on the Optics Corrections of FCC-hh,” presented at IPAC’17, Copenhagen, Denmark, May 2017, paper TUPVA001, this conference.

[10] B. Dalena *et al.*, “First Considerations on Beam Optics and Lattice Design for the Future Hadron-Hadron Collider FCC-hh,” in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 2466–2468.

[11] S. Fartoukh, “Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade,” *Phys. Rev. ST Accel. Beams*, vol. 16, p. 111002, Nov 2013.

[12] Y. Nosochkov, and D. M. Ritson, ”The provision of IP crossing angles for the SSC,” in *Proc. PAC’93*, Washington, DC, USA, 1993, pp. 125–127.