PROCEEDINGS OF SCIENCE

New baseline layout of the CERN Future Circular hadron-hadron Collider

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The ongoing feasibility study of the Future Circular Collider (FCC) comprises two distinct accelerators: a high-luminosity circular electron-positron collider known as FCC-ee and an energy-frontier hadron collider named FCC-hh. These two facilities are designed to take advantage of a common tunnel infrastructure. We present the new baseline design of FCC-hh, underlining the most recent updates. These include studies of the corrector systems, optimisation of the arc cell, increasing the dipole filling factor, and subsequent updates to the layouts of the different technical and experimental insertions.

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1. Introduction

Since the publication of the Conceptual Design Report (CDR) of the FCC [1], several studies have led to a revised and improved ring layout. Placement studies [2] indicated the need to shorten the FCC rings, primarily by reducing the lengths of the arcs, but also those of the straight sections.

The recent changes in the FCC-ee design introduced a critical constraint: to enable operation with four experimental insertions, the ring must maintain a four-fold super-periodicity, thus impacting the FCC-hh ring geometry. The functions of various technical insertions have been reviewed and merged to exploit synergies and provide the best possible ring layout. A radial shift of the FCC-hh interaction points (IPs) was implemented to align them with those of the FCC-ee ring (see Fig. 1, right). Finally, the final section of the transfer lines will be housed within the ring tunnel, minimising the tunnel length required for the transfer lines from the injector to the FCC(-hh) tunnel.

The updated FCC-hh ring layout [3–5] has a circumference of 90.66 km, with technical insertions that span 2032 m and experimental insertions approximately 961 m. The experimental insertions (IRs) are located at Point A (PA), Point D (PD), Point G (PG) and Point J (PJ). Figure 1 (left) shows the geometric footprint of the FCC-hh ring and the placement of the different insertions.

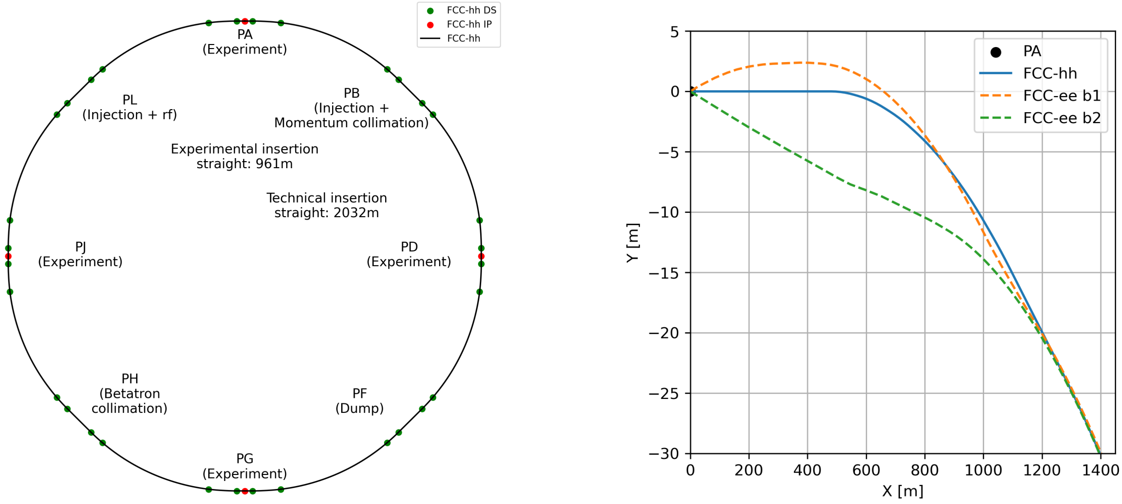

Figure 1: Left: Overall view of the layout of the new baseline FCC-hh ring configuration. The functions of the various insertion regions are mentioned and the boundaries between arcs, dispersion suppressors and straight sections are highlighted. The experimental straight sections are located with respect to a four-fold symmetry of the ring. The length of the straight sections is also mentioned. Right: Comparison of the geometry of the FCC-hh ring and the two FCC-ee rings in the vicinity of PA.

The clockwise beam is injected at PB, where the momentum collimation systems for both beams are also housed, and the counterclockwise beam is injected at PL, where the RF systems of both beams are also housed. Both beams are injected into the external channel of the FCC-hh. PH hosts the betatron collimation systems and the beam dump systems are placed in PF.

Originally, a 16 T dipole field was assumed in the CDR, providing the 100 TeV centre-of-mass energy for the nominal 97.75 km ring circumference. However, after the FCC-hh layout review resulted in a reduction of the arc length, the value of the dipole field was also reviewed, and the current nominal value is of 14 T (based on Nb_3Sn magnets), with a high-field option considering a 20 T main dipole (based on high-temperature superconductors). These variants correspond to the centre-of-mass energies of 84.6 TeV and 120.8 TeV, respectively. These results were achieved because a meticulous revision of the arc cell has been performed to maximise its filling factor, which has a direct impact on the energy reach of the collider. In fact, the current baseline layout is built using 16-dipole FODO cells, while the CDR design consisted of 12-dipole arc cells, with an optimised short straight section that allows the cell filling factor to increase from 0.80 to 0.85.

A comparison of the various versions of the FCC-hh layout is shown in Table 1.

Table 1: Layout parameters of FCC-hh at the CDR stage and current design

	CDR design	Intermediate design [1]	Current baseline [5]
Circumference [km]	97.749	90.657	90.657
Total arc length [km]	83.749	78.685	78.685
Bending radius [m]	10540	9682	10079
Short insertion length [m]	1400 (×6)	961 (×4)	961 (×4)
Long insertion length [m]	2800 (×2)	2032 (×4)	2032 (×4)
Dipoles per cell	12	12	16
Regular cell filling factor	0.80	0.80	0.82
Total number of dipoles	4668	4288	4464

2. Changes in straight sections

In the CDR, the injection of both beams was performed in conjunction with two of the experimental insertions, similar to the current design of the CERN LHC [6]. In the current baseline, the four interaction regions are not shared with other technical systems and therefore are identical in terms of the magnetic layout except for the polarity of the separation dipoles due to the exchange of beam aperture. At injection, the β function at the collision points is 10 m and is squeezed to 30 cm in physics. Some of the planned upgrades for HL-LHC [7] inspired further changes in the experimental insertion design. The separation dipoles are superconducting with the D1, closest to the IP, consisting of a single-aperture 10 m-long magnet with a nominal field of 13 T. The D2 in turn consists of a pair of twin-aperture 13 m-long magnets with a nominal field of 5 T. There is reserved space for a scaled version of the non-linear corrector package aimed at compensating the field imperfections in the low-beta triplet quadrupole. Finally, as a result of the radial displacement of the IPs to match those of FCC-ee, the dispersion suppressors of the experimental insertions have an irregular distribution of dipoles; this enables reuse of civil engineering work for both stages of the FCC project. However, this dispersion suppressor design, which now includes two more quadrupoles that used to be part of the straight section, is one of the most challenging areas for finding suitable optical solutions given the additional constraints.

Moving on to the technical insertions, Points F and H have a single role each, namely to house the beam dump and betatron collimation systems, respectively. These two technical systems have been significantly reduced in length from the CDR layout, going from 2800 m to 2032 m.

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[1] This version of the FCC-hh layout has been presented in the Mid-term Review process.

Points B and L house two technical systems each, beam injection and momentum cleaning or RF, respectively. Efforts have been made to shorten the required space for the injection line, which takes the beams from the transfer lines into the collider ring. The momentum collimation and RF systems were already placed in shorter technical insertions in the CDR design, so it was natural to assign them to a technical insertion shared with the injection system.

Two different optical solutions have been envisaged for the betatron collimation, low-beta and high-beta. The first configuration is to be used at injection, transitioning to the second either at flat-top or during the energy ramp. Primary collimators are placed in doglegs to avoid showers of secondary neutral particles on the downstream superconducting elements. The design employs warm quadrupoles in the areas that will be subject to increased losses due to the halo cleaning. In addition, a constant inter-beam distance allows the implementation of exactly the same optics for both beams, simplifying the design of the insertion and the overall ring configuration.

Efforts have been made to harmonise the hardware requirements of the injection and extraction elements. As such, a single type of kicker will be needed for all insertions. In the RF section, about 900 m are available for RF systems where the inter-beam distance is increased to 420 mm with respect to the nominal value of 250 mm. To allow the cohabitation of the momentum collimation and injection elements, a matching section between both systems is foreseen as a buffer zone with shielding protecting electronics from radiation damage.

3. Changes in the arcs

To maximise the energy reach of the collider and its physics potential, a review of the arc cell was performed to increase the dipole filling factor. The limiting factor was found to be the beam aperture at injection (13.4σ at injection energy). Solutions were found allowing for longer cells, from 12 to 16 dipoles per cell, after a small change of the beam screen geometry. This redesign resulted in an increase in the total number of dipoles in the ring from 4288 to 4464, a ~4 % increase.

A consequence of the change in the cell length is a reduction in the number of cells and therefore a decrease in the number of short straight sections (SSS) around the arc quadrupoles hosting different corrector systems. However, longer cells also have larger beta functions and dispersion, making correctors more efficient, according to studies recently performed [8]. A diagram of the SSS as designed for the CDR is shown in Fig. 3 (top). The bulk of the footprint is taken up by the main quadrupole. The combined effect of reducing the integrated gradient required due to longer cells and pushing the nominal gradient can translate into significant length gains i.e. increasing from 367 T/m to 450 T/m could mean shortening the MQ from 6.4 m to 3.6 m.

Looking specifically at the correctors, the greatest reduction in length would come from combining the orbit corrector and main sextupole by using nested magnets. After reducing their length to 1.1 m, the sextupoles are still capable of compensating for the chromaticity in the most challenging setting (all 4 IPs squeezed to $\beta^* = 30\,\mathrm{cm}$) and the same integrated field can be achieved in the orbit correctors by modestly increasing their nominal field. Trim quadrupoles, skew quadrupoles, and main octupoles are used to correct the tune, linear coupling, and provide amplitude detuning, respectively. Which one is present in the SSS depends on its position along the arc, with trim quadrupoles placed at the extremities of the arcs, skew quadrupoles symmetrically around the middle of the arc, and octupoles present in the remaining slots. After reviewing the

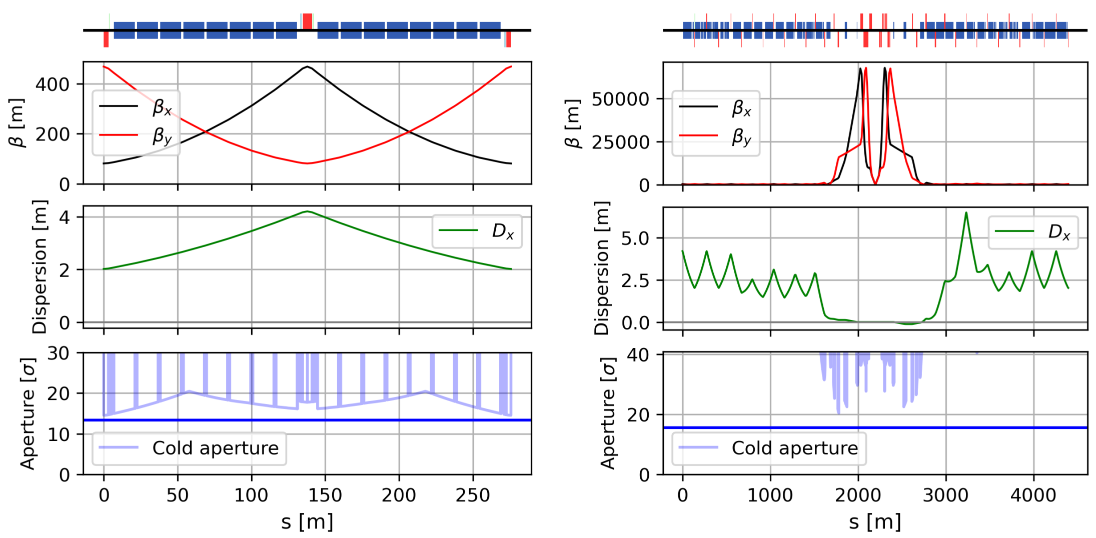

Figure 2: 16-dipole cell layout (left) and experimental insertion with collision settings (right) including optical functions (top), dispersion (middle) and beam aperture (bottom). Dipoles are shown in blue and quadrupoles in red. The horizontal blue line represents the value of the aperture target.

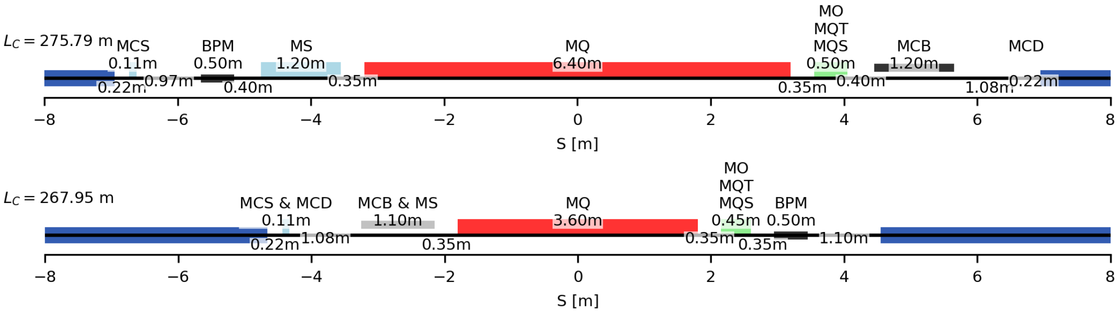

Figure 3: Layout of the arc cell short straight section (left to right: sextupole spool piece, beam position monitor, chromatic sextupole, main quadrupole, trim quadrupole, skew quadrupole, and orbit corrector) as presented in the CDR (top) and following the recent optimisations (bottom).

corrections provided by these correctors in the new longer cells, we concluded that it is viable to shorten the common slot to 45 cm. The quadrupole corrector scheme is changed from that in the CDR where trim and skew quadrupoles were also used to correct spurious dispersion, which is now corrected by chromatic bumps in the arcs. The effect of the octupoles scales quadratically with the optical functions, and thus with the cell length, whereas the number of corrector slots available for the octupoles is inversely proportional to the cell length. If all these changes are implemented, the new SSS configuration would be as shown in Fig. 3 (bottom). Overall, the expected reduction of the SSS amounts to almost 8 m per cell, which frees space for more cells per arc and/or more dipoles in the dispersion suppressors, further increasing the energy reach of FCC-hh.

4. Outlook and conclusions

A new baseline layout has been designed for the CERN Future Circular hadron-hadron Collider following the outcome of placement studies and recent developments for the electron-positron collider. To maximise the physics potential of the collider, different studies have been carried out, increasing the dipole filling factor as a result. Firstly, the arc cell has been reworked from 12 dipoles per cell to 16 dipoles per cell, reducing the number of short straight sections in the arcs. Secondly, the performance of the corrector systems in the short straight sections has been evaluated and it has been concluded that it is viable to shorten the SSS by almost 8 m per cell. This reduction will be used to probe future cell configurations with 18 dipoles instead of 16 dipoles. This series of studies is part of the efforts towards the FCC integrated feasibility study to be submitted for review by the scientific community during the spring of 2025.

References

[1] A. Abada, M. Abbrescia, S. AbdusSalam, I. Abdyukhanov, J. Abelleira Fernandez, A. Abramov et al., *FCC–hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3. Future Circular Collider*, *Eur. Phys. J. Spec. Top.* **228** (2019) 755.

[2] J. Gutleber, P. Laidouni, V. Mertens et al., *Synthèse des contraintes et opportunités d'implantation du Futur Collisionneur Circulaire (FCC)*, Dec., 2023. 10.5281/zenodo.10369593.

[3] M. Benedikt, A. Chance, B. Dalena, D. Denisov, M. Giovannozzi, J. Gutleber et al., "Future Circular Hadron Collider FCC-hh: Overview and Status." arXiv:2203.07804 [physics.acc-ph], 2022.

[4] M. Giovannozzi et al., *Recent updates of the layout of the lattice of the CERN hadron-hadron Future Circular Collider*, in *Proc. IPAC'23*, International Particle Accelerator Conference, pp. 598–601, JACoW Publishing, Geneva, Switzerland, 9, 2023.

[5] G. Perez-Segurana et al., *A new baseline layout for the FCC-hh ring*, in *Proc. IPAC'24*, no. 15 in IPAC'24 - 15th International Particle Accelerator Conference, pp. 75–78, JACoW Publishing, Geneva, Switzerland, 05, 2024, DOI.

[6] O.S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole et al., *LHC Design Report*, CERN Yellow Rep. Monogr., CERN, Geneva (2004), 10.5170/CERN-2004-003-V-1.

[7] O. Aberle, I. Béjar Alonso, O. Brüning, P. Fessia, L. Rossi, L. Tavian et al., *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, CERN Yellow Reports: Monographs, CERN, Geneva (2020), 10.23731/CYRM-2020-0010.

[8] G. Perez-Segurana, M. Giovannozzi and E. Todesco, *Study of the corrector systems for the new lattice of the CERN hadron-hadron Future Circular Collider*, in *Proc. IPAC'24*, no. 15 in IPAC'24 - 15th International Particle Accelerator Conference, pp. 79–82, JACoW Publishing, Geneva, Switzerland, 05, 2024, DOI.