OVERVIEW OF DESIGN DEVELOPMENT OF FCC-hh EXPERIMENTAL INTERACTION REGIONS*

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Abstract

The experimental interaction region (EIR) is one of the key areas that define the performance of the Future Circular Collider. In this overview we will describe the status and the evolution of the design of EIR of FCC-hh, focusing on design of the optics, energy deposition in EIR elements, beam-beam effects and machine detector interface issues.

INTRODUCTION

FCC-hh 100 TeV CM collider is one of the options for future large scale particle physics experiments [1]. Design studies enabled by EuroCirCol [2], as well as wider FCC design studies [3], highlighted the EIR [4] as one of the key areas that defines the performance of this future machine.
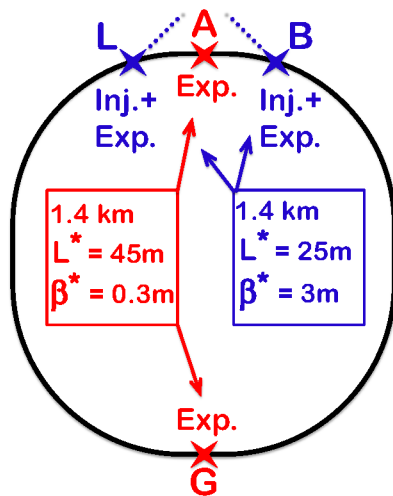

Figure 1: FCC-hh layout and key parameters of the main and low-luminosity Experimental Interaction Regions.

The FCC-hh, housed in a 97.75 km perimeter racetrack tunnel [5] filled with 16 T SC magnets, includes four EIRs – two for nominal/high luminosity and two for low-luminosity experiments. Each of the EIR straight sections is 1400 m

long, while in low-luminosity EIR sections the experiments are combined with injection sections, as shown in Fig. 1.

FINAL FOCUS OPTICS

The final focus (FF) optics of main EIR is designed to provide the target luminosity of 20×10^{34} cm^{-2}s^{-1}, and therefore aims to reach β^* of 0.3 m. With L^* of 45 m there is sufficient space for the baseline detector [6] (unshielded solenoid with balanced conical solenoid) as well as for the alternative longer detector considered earlier (twin shielded solenoid with dipole spectrometers).
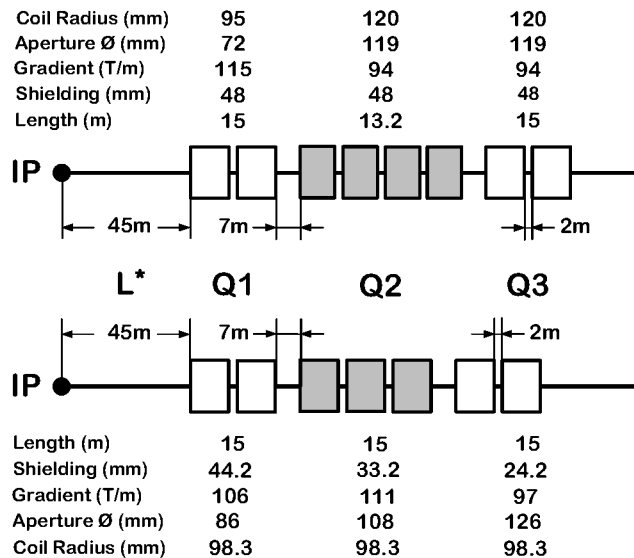

Figure 2: Main EIR inner triplet layouts and key parameters – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole. Above – long triplet optics version, below – short triplet optics version.

Two versions of the FF EIR optics are presently under detailed investigation – the optics with longer triplet and the so-called flat optics with somewhat shorter triplet. The key parameters of the triplets of these FFs are shown in Fig. 2. The maximum lengths of the quadrupoles and their spacings are set by the manufacturing and installation constraints.

The present design of the longer triplet FF provides the most flexibility in terms of β^* reach and the best performance in terms of energy deposition protection. Large apertures of the quadrupoles allow reaching β^* below 0.1 m (with 15 mm shielding) or significantly increasing shielding (corresponds to Fig. 2) still with good β^* reach of 0.2 m [7]. However, this optics is about 1500 m in total. The possibility of reducing its length to the allocated 1400 m is currently under study. If it cannot be shortened, the additional length will have to be compensated by shorter arcs, increasing the required dipole field strength.

Since the length of the inner triplet translates into the total length of EIR FF with a large multiplication factor of about seven, the shorter by ten meters triplet of the other FF option fits comfortably to the allocated 1400 m space. Dedicated code [8] has been used to optimize [9] this optics to be compatible with round beam collisions as well as for flat beam collisions with $\beta^*_{x/y} = 1.0/0.2$ m which can be suitable for the option of operation without crab cavities.

The main EIRs are planned to be operating with a half-crossing angle of about 90 μrad. The local crabbing scheme is foreseen. While the leakage of the deflection into the arcs is being studied, it is estimated that the total crab cavity voltage of 10.4 MV is necessary to accomplish full crabbing in one plane at $\beta^* = 0.3$ m. The ultimately desired full crabbing at $\beta^* = 0.1$ m would require around 18 MV, for which 20 m of space is allocated for crab cavities in the optics between the recombination dipole D2 and the first quadrupole of the matching section.

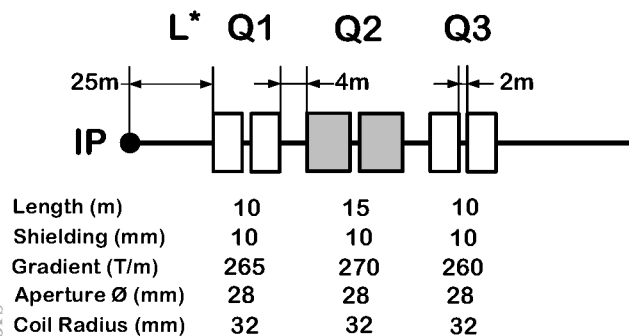|	L*	Q1	Q2	Q3
Length (m)		10	15	10
Shielding (mm)		10	10	10
Gradient (T/m)		265	270	260
Aperture Ø (mm)		28	28	28
Coil Radius (mm)		32	32	32

Figure 3: Low-luminosity EIR inner triplet layout and key parameters of the quadrupoles.

The optics of low-luminosity EIRs, where FF is co-located with injection, has to take into account requirements arising in particular from the need to protect cold elements from mis-kicked injected beams, which impose additional constraints on phase advance and reduce optics flexibility. The optics design [10] that accommodates all known requirements features L^* of 25 m, which was suggested by the detector design group, and β^* of 3 m. The half-crossing angle at these EIRs is about 19 μrad and with the triplet parameters shown in Fig. 3 the achieved beam stay clear is about 15 σ.

Optimization of dynamic aperture (DA) of FCC-hh are ongoing, taking into account errors in the main dipoles of the arcs [11] as well as nonlinear errors in the EIR inner triplets and possible nonlinear corrections in EIR [12, 13].

The DA was found to depend, in particular, on the procedures for correction of spurious dispersion arising from the crossing angle bumps. The results obtained so far indicate that 10 σ DA is possible in case of collisions with all errors and crossing angle when the full set of EIR correctors (a3, b3, a4, b4 and b6 components) installed on either side of IR outside of the inner triplet are used. Further optimizations of the dynamic aperture are ongoing.

MACHINE-DETECTOR INTERFACE

The Machine-Detector Interface (MDI) topics impregnate through all the aspects of design of the EIRs. Survivability of the inner triplets, subjected to the flux of collision debris, is of utmost importance. With the required minimum beam stay clear of 15 σ defined by collimation requirements, the inner triplets need to include sufficient shielding to protect the SC coils. The longer triplet version, with 15 mm shielding, can observe around 30-40 MGy dose in the coils after an integrated luminosity of 5 ab^{-1} (one high-luminosity run)[1]. Since the location of the peak depends on the crossing plane orientation, switching between horizontal and vertical crossing can smear out the peak dose. In particular, assuming to run 50% of the time in vertical crossing (25% with an upward angle and 25% with a downward angle) and 50% in horizontal crossing (this would imply hardware changes for the crab-cavities), the maximum peak dose is reduced to 25 MGy for both high luminosity insertions. Considering the present limit of 30 MGy, the triplet could survive a long luminosity run [14]. The long triplet, having large apertures, allows increasing shielding to 48 mm while still maintaining β^* reach of 0.2 mm. Peak dose in this case would reduce another factor of ten, indicating expected survivability towards integrated luminosity of 20-30 ab^{-1}, i.e. several full high-luminosity runs. The shorter triplet optics is showing comparable performance [15], exceeding requirements for one full high-luminosity run. Preliminary studies for the low luminosity EIR have shown that the radiation dose for 0.5 ab^{-1} is about 20 MGy, consistent with the triplet survivability requirements.

A possible cross-talk between EIRs, via elastic and inelastic protons, and via muons, may be an issue and has been studied. In particular, the proton cross-talk [16], while manageable, has implications on the collimation system design. The muon cross-talk, with the present separation between the nearest EIRs, was found negligible [17].

Background from synchrotron radiation (SR) photons emitted by protons in and on the way to the EIRs have been studied. It was found that while the SR power emitted in the last four bending magnets upstream the IP is of the order of 100 W, the fraction of this power that enters the experiment area, defined as the space between the TAS absorbers, is only around 10 W, out of which only about 1 W is expected

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[1] These results have been obtained considering unsplit longer triplet magnets, characterized by lower gradients and larger coil apertures. In the layout shown in Figure 2 we expect slightly worse results, because of the gaps and of the reduced coil aperture.

to hit the ±8 m long inner Beryllium pipe. Most of the photons will be absorbed in this pipe, while just less than 1 photon per bunch with an energy of the order of 1 KeV will traverse the Be pipe towards the experiments, making this background source not a concern [18].

The key parameter both for the experimental detector and for the EIR final focus is the value of L^* which was chosen to be 45 m in early 2016 to accommodate the detector design featuring dual shielded solenoid and a dipole spectrometer. After the forward spectrometer dipole was dropped from the baseline detector design [6], the remaining space was used to mitigate the back-scattering from the TAS in the detector and for space for opening the detector. For the alternative detector design, the forward spectrometer is still present but significantly shorter. The potential impact on L^*, especially in the light of the thicker shielding wall, has not yet been evaluated in detail. A shorter L^* would reduce the peak beta functions in the triplet, reducing chromaticity, and potentially making integration of EIR optics easier. A reduced chromaticity would also require less or shorter sextupoles in the arcs, leaving more space for dipoles and hence potentially increasing the maximum beam energy. Overall, some beneficial reduction of L^* is thus remain to be studied and potentially implemented.

BEAM-BEAM EFFECTS

Dynamic aperture has been studied for the full FCC optics together with beam-beam effects. For these studies only two main EIRs have been taken into account. Assuming an alternating horizontal and vertical crossing scheme to profit from the passive compensation of the long-range tune and chromaticity shifts, it was found that the DA of $6\,\sigma$ is ensured for a half crossing angle of 85 μrad resulting in a separation of 14.5 σ at the first long-range encounter. These results confirm the baseline scenario choices but highlight the fact that no margins are left for the negative effects of multipolar errors, Landau octupoles spread, high chromaticity operation and for the two low luminosity EIRs [19]. Detailed studies of the beam-beam effects, including the most recent flat optics that lacks the passive compensation and thus would require a slightly larger crossing angle, low luminosity EIRs, as well as long-range beam-beam compensation with octupoles [20], are ongoing.

CONCLUSIONS AND OUTLOOK

Our studies performed so far have confirmed, in general, that the current tentative design is consistent with the overall FCC-hh design and its performance goals. Below we reiterate on the issues that have been studied, solved, and also indicate the directions of future studies and optimizations.

The separation of the points with experiments A, B and L appears large enough to avoid significant background from one experiment into the other.

The power deposited by SR in the experimental beam pipe is in the order of 1 W, which is considered negligible.

Preliminary designs of the low luminosity insertions have been made matching the newly proposed collider layouts. Their luminosity is limited by β^* and the envisaged triplet shielding is adequate for providing the triplet survivability for luminosity ten times below that of the main experiments.

The main EIR length can be made to be 1400 m significantly decreasing the operational margins and flexibility. In particular the final quadrupoles might only survive one 5-year run, while with 1500 m three runs are at reach. This has an effect on the eventual choice of L^* and also motivates R&D to develop materials more resilient to radiation.

The inner triplet design respects the manufacturing and installation requirements of the maximum length of quadrupoles 15 m and minimum separation of 2 m. These constraints significantly affect the operational margins and triplet lifetime. It is therefore important to explore further the margins on these values.

The field quality of the final focusing triplets strongly affects the achievable DA and requires accurate corrections with dedicated coils, challenging machine operational phases before corrections are applied. It should be explored if better field quality can be achieved. Reducing L^* even by 10% will have great benefits in terms of field quality tolerances, operational margins and triplet lifetime.

Beams are separated in the common beam-pipe with a half crossing angle of about 90 μrad. This is assessed sufficient but without considering the impact from the triplet non-linearities and the low luminosity experiments.

Crab cavities are foreseen, which require 20 m of space.

Alternative operational scenarios without crab cavities, using flat beams, have been explored yielding integrated luminosity very close to the design goal.

The presently chosen L^* of 45 m is affecting the length of the EIR straight section (presently 1500 m for one of the EIR optics options, i.e. longer than 1400 m allocated). A longer insertion could be allocated, but would either require significant modifications of the civil engineering, or would decrease the arc length, which requires to increase the field in magnets in the arcs – this increases their cost or eat up the margins. The value of L^* is kept at 45 m to preserve the option of the dipole spectrometer in the detector, while the baseline detector is smaller and may live with shorter L^*. Therefore, keeping the option of the dipole spectrometer in detector increases the cost of magnets in arcs. Dropping the option of dipole spectrometer, and better planning for the EIR space in the detector hall (where each extra meter translates into the total EIR length with a multiplication factor of around fifteen), may allow some reduction of L^*, reduction of length of FF and reducing the risks for arcs and arc magnets. This global dependency will need to be addressed so that the overall performance/cost of the FCC-hh design will be further optimized.

ACKNOWLEDGEMENT

REFERENCES

[1] M. Kramer, "The update of the European strategy for particle physics," Phys. Scr. 2013 014019 (2013).

[2] EuroCirCol – EU Horizon 2020 design study project, http://www.eurocircol.eu/

[3] FCC design studies, https://fcc.web.cern.ch/

[4] A. Seryi, et al., "Requirements and constraints of EIR design option on WP2, WP4, WP5: Milestone M3.3," FCC publication CERN-ACC-2017-0022, 28 April 2017, https://cds.cern.ch/record/2261545/

[5] A. Chance et al., "Updates on the Optics of the Future Hadron-Hadron Collider FCC-hh," this conference, TUPVA002.

[6] W. Riegler, "Baseline Geometry, 2018 report," FCC hadron detector meeting, 3 August 2016, https://indico.cern.ch/event/557684/

[7] R. Martin, "IR/FF optics," EIR WP3 meeting, 4 April 2017, https://indico.cern.ch/event/627884/

[8] L. van Riesen-Haupt, "A Code for Optimising Triplet Layout," this conference, TUPVA043.

[9] L. van Riesen-Haupt, A. Seryi, R. Tomas, "Exploring the Triplet Parameter Space to Optimise the Final Focus of the FCC," this conference, TUPVA041.

[10] M. Hofer, "Updates on the Magnets for the Low Luminosity IRs," EIR WP3 meeting, 28 April 2017, https://indico.cern.ch/event/629956/

[11] B. Dalena, et al., "Advance on Dynamic Aperture at Injection for FCC-hh," this conference, TUPVA003.

[12] E. Cruz-Alaniz, et al., "Non Linear Field Correction Effects on the Dynamic Aperture of the FCC-hh," this conference, TUPVA038.

[13] E. Cruz-Alaniz, et al., "Effect of Orbit Errors on the Interaction Region of the FCC-hh," this conference, TUPVA039.

[14] R. Martin, M. I. Besana, F. Cerutti, et al., "Interaction Region Design driven by Energy Deposition," submitted for publication, 2017.

[15] J. L. Abelleira, et al., "FCC-hh Final-Focus for flat-beams: parameters and energy deposition studies," this conference, TUPVA037.

[16] H. Rafique, et al., "Proton Cross-Talk and Losses in the Dispersion Suppressor Regions at the FCC-hh," this conference, TUPIK037.

[17] J. Abelleira, R. Appleby, H. Rafique, "Cross-Talk Studies Between FCC-hh Experimental Interaction Regions," this conference, TUPVA036.

[18] F. Collamati, et al., "Synchrotron Radiation Backgrounds for the FCC-hh Experiments," this conference, TUPVA004.

[19] J. Barranco, et al., "Beam-Beam Studies for FCC-hh," this conference, TUPVA026.

[20] J. Barranco, et al., "Study of Beam-Beam Long Range Compensation With Octupoles," this conference, TUPVA027.