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INTERACTION REGION FOR A 100 TeV PROTON-PROTON COLLIDER

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Abstract

As part of its post-LHC high energy physics program, CERN is conducting a study for a new proton-proton collider, FCC-hh, running at center-of-mass energies of up to 100 TeV, pushing the energy frontier of fundamental physics to a new limit. At a circumference of 80-100 km, this machine is planned to use the same tunnel as FCC-ee, a proposed 90-350 GeV high luminosity electron-positron collider. This paper presents the design progress and technical challenges for the interaction region of FCC-hh.

INTRODUCTION

FCC-hh aims to provide proton collisions almost one order of magnitude higher than the Large Hadron Collider (LHC), posing a great challenge for the interaction region optics.

The current lattice for the interaction region is shown in Fig. 1. Each side of the Interaction Point (IP) consists of a final triplet, a beam separation section and a matching section, followed by the dispersion suppressor (not pictured here). For the dispersion suppressor (DS), two options are currently considered: a half bend DS and an LHC-like DS. The decision for one DS design will be based on optics considerations as well as a cost optimum in terms of dipole filling factor and number of independently powered quadrupoles.

Table 1: Parameters for the FCC-hh Interaction Region (IR) [1]

	Baseline	Ultimate
Beam energy [TeV]	50	
IR length [m]	1400	
Number of IPs	2 + 2	
Luminosity [10^{34}cm^{-2}s^{-1}]	5	20
IP β function β^* [m]	1.1	0.3
Normalized emittance [μm]	2.2	

Final Triplet

In a first approach, the LHC interaction region design was scaled up by a factor of $(50/7)^{1/3} \approx 2$, resulting in an L^* of 46 m. This early design showed a large radiation load from the debris at the IP. As a solution, the longer triplet design of HL-LHC [2] was adapted. To mitigate the radiation dose further, the quadrupoles were lengthened by an additional ≈ 30 %, giving a length of 20 m for Q1 and Q3 and 17.5 m for Q2a/b . At the same time, L^* was reduced to 36 m in order to keep the maximum β function at the same level [3]. With a coil aperture of 100 mm and a shielding thickness of 15 mm, the radiation dose for this triplet is acceptable (Fig. 2).

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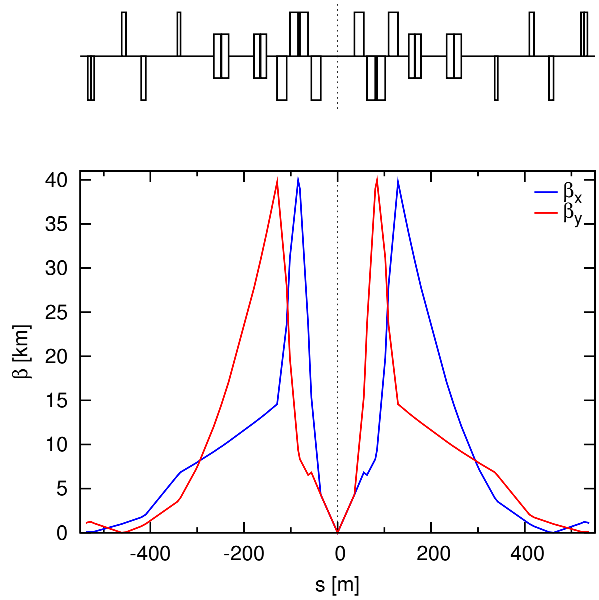

Figure 1: FCC-hh interaction region design with $\beta^* = 0.3$ m and $L^* = 36$ m.

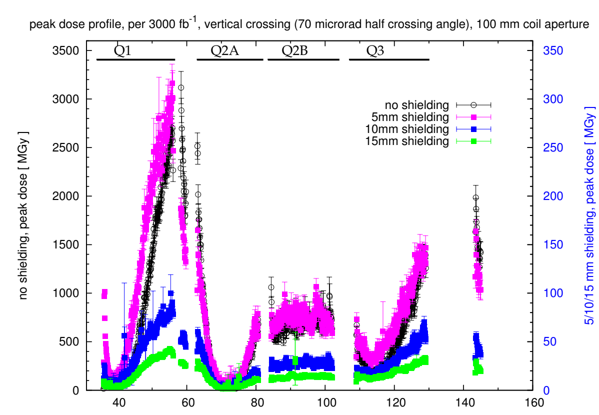

Figure 2: Radiation dose in the triplet magnets from physics debris with (right scale) and without (left scale) shielding. For 15 mm shielding and the shown integrated luminosity of 3000 fb^{-1}, the dose looks acceptable [4].

Beam Separation

As in the LHC layout, the two beams are colliding under a small crossing angle introduced by orbit correctors. Both beams pass the same final triplet and are separated and re-

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combined by the dipole pairs D1 and D2. Compared to LHC, a more challenging magnet design was chosen with D1 having a magnetic field of 12 T and D2 10 T [5]. The integrated strength for each is 150 Tm, giving a beam separation of 0.4 m at a total separation section length of 112.55 m. D1 is a single aperture dipole, therefore aperture requirements will be a minor issue. D2 on the other hand is a double aperture dipole and unlike the arc dipoles, the magnetic field has the same direction in both apertures, so the cross talk between the two coils will produce unwanted multipoles. This makes the magnet design very challenging and will limit the available aperture. If aperture requirements become too large, the magnetic field in D2 will have to be reduced, increasing the overall length of the separation section.

Matching Section

The matching section is a scaled up version of the LHC matching section. It features four independent quadrupoles. Keeping in mind that the dispersion of the beam separation dipoles has to be matched to the arcs, the four quadrupoles offer not enough degrees of freedom, thus quadrupoles from dispersion suppressor need to be used for matching as well, adding further independently powered magnets to the interaction region.

MAGNET APERTURES AND β^* REACH

The aperture of the triplet quadrupoles will determine the minimum β^*. The thick shielding that is required to reduce the radiation load limits the aperture, increasing the minimum β^*. It is therefore important to get an estimate on the minimum β^* that can be reached with a certain design. This estimate will allow to optimize the beam optics with respect to luminosity performance.

For an initial β^*, the final triplet was rematched so that $\beta_{x,\text{max}} = \beta_{y,\text{max}}$ (Fig. 3 top). For the actual aperture requirements of the beam, the shape of the orbit bump producing the crossing angle will play a role, as well as the gradients in the magnets. However, forcing the maximum beam sizes to be equal is a good approximation to the optimum solution, especially when considering that the triplet optics are anti-symmetric (i.e. β_x and β_y switching shape from one side of the IP to the other) and the orbit bump behaves similar to β_x. After rematching the orbit bump, the coil aperture diameter of the triplet quadrupoles were calculated as

$$d_{\text{coil}} = 2 \cdot \frac{e}{p} \frac{B_{\text{max}}}{k_1} \tag{1}$$

with e being the elementary charge, p the proton momentum, B_{max} the maximum field strength at the coil aperture and k_1 the quadrupole coefficient. To get the free aperture of the magnet, the coil aperture is then reduced by the shielding thickness and several other layers as indicated in Table 2.

This calculation does not take into account that the manufacturing of the magnets may require different thicknesses of the superconducting strands for different apertures, nor e.g. the scaling of the cold bore thickness with coil aperture. However, the rather conservative guesses for B_{max} and beam screen insulation thickness should provide realistic apertures. In further work, the estimation of the free aperture will be refined. With the lattice rematched and the apertures set, the beam stay clear is checked using the APERTURE module of MAD-X [6]. If the beam stay clear is below the target value, the procedure is repeated with a larger β^* until the requirements are met (Fig. 3 bottom).

Table 2: Parameters for the free aperture calculation.

B_{max}	11 T
crossing angle θ	$12\,\sigma_{\text{p}}$
Layer thickness [mm]	
- Shielding	15
- Liquid helium	1.5
- Kapton insulator	0.5
- Cold bore	2
- Beam screen	2.05
- Beam screen insulation	2

The APERTURE module was originally designed to calculate the n_1 value, the maximum primary collimator opening for which the secondary collimators still provide protection of the local aperture from the secondary beam halo. However, using the halo input parameters indicated in [7], the module calculated the beam stay clear in units of nominal beam σ.

In the HL-LHC, the dispersion produced by the crossing angle orbit correctors is not matched via matching quadrupoles. Instead, the dispersion is compensated by orbit correctors in the arcs. This way, the orbit bump - and thereby the crossing angle - remains a degree of freedom that can easily be changed during operation. The dispersion compensation has not yet been implemented in FCC-hh. In order to avoid using an unreasonable dispersion in the triplet, all aperture calculations were performed for on-momentum particles. Thus, dispersive effects are not yet included, neither are magnet misalignments and tolerances of the mechanical parts (e.g. beam screen). Therefore, the resulting values should be regarded as lower limits for the β^* reach for the given input (Table 3).

Table 3: APERTURE Input Parameters. The halo parameters were all set to the same value, this way APERTURE calculates the beam stay clear in normalized beam σ

Normalized emittance ϵ_n	2.2 μm
Closed orbit uncertainty	2.0 mm
momentum offset δ_p	0.0
β beating coefficient	1.1

The results of the β^* reach calculation are shown in Fig. 4. There are two lines: the red one for individual magnet apertures, meaning the aperture was calculated according to equa-

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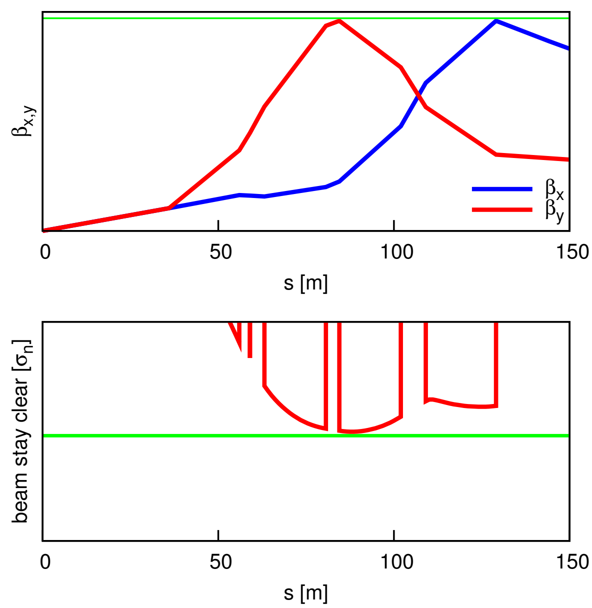

Figure 3: Principle of the β^* reach calculation: the triplet was rematched to have the same maximum β function in the vertical and horizontal plane (top). After rematching the crossing angle orbit correctors and setting the apertures, the beam stay clear was evaluated. Repeating this procedure, β^* was varied until the required beam stay clear was achieved (bottom).

tion 1 for each magnet separately. The uniform apertures of the green line mean, that the aperture was calculated for the magnet with the largest k_1. This way, all magnets are identically manufactured, potentially saving costs. Since the first quadrupole from the IP, Q1 has a gradient of 220 T/m while Q2a/b and Q3 only have 190 T/m, it also mean, the aperture in those magnets is reduced without a physical reason. As can be seen in Fig. 4, the β^* reach is significantly larger for uniform apertures, it is therefore advisable to manufacture the triplet magnets according to the individual gradient.

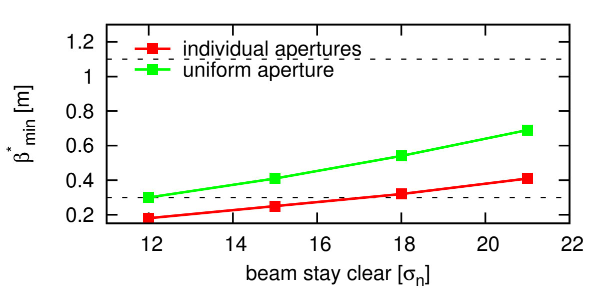

Figure 4: β^* reach with a coil aperture field of 11 T. The dotted lines indicate baseline and "ultimate" value. Note that the shown values present a lower limit for the given input since dispersive effects, magnet misalignments and manufacturing tolerances are not yet taken into account. There is a comfortable margin to the baseline goal so reaching it should not become a problem.

It should be highlighted that the baseline goal of $\beta^* = 1.1$ m does not seem to be a problem in either case, the "ultimate" goal of $\beta^* = 0.3$ m will barely be possible with uniform apertures in this design.

The required beam stay clear will be determined by the collimation system. The first conceptual collimation section for FCC-hh was scaled up from the LHC. For the secondary and tertiary collimator to protect the magnets, the magnet apertures (in normalized beam σ) needs to be larger than the collimator apertures. For HL-LHC the protected aperture needs to be larger than 12.3 σ. Due to impedance issues, the collimator gaps cannot be scaled down with the emittance. With the same absolute collimator gaps as in HL-LHC, the required beam stay clear will be 18.5 σ, using the same relative gaps 15.5 σ. The required beam stay clear has a considerable impact on the β^* reach in Fig. 4, so the luminosity performance of FCC-hh strongly depends on the collimation system.

OUTLOOK

Currently an interaction region with an L^* of 61.5 m is studied. It is a result of a scaling of the HL-LHC interaction region with the energy. Applying the scaling factor $\sqrt{50/7}$ allows to use the same magnets as in HL-LHC. With the rather large aperture of 150 mm [8] a smaller impact of the shielding is expected, possibly allowing an even better β^* reach. In order to mitigate the radiation load in the first triplet magnet, possibilities of splitting Q1 in two magnets with different gradients will be studied. Compared to HL-LHC, where all triplet magnets have the same gradient, Q1 in the current FCC design is considerably stronger than Q2 and Q3. The impact of different matchings of the triplet on β^* reach and radiation load will be investigated.

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