

# EXPERIMENTAL INTERACTION REGION OPTICS FOR THE HIGH ENERGY LHC\*

L. van Riesen-Haupt, J. L. Abelleira, E. Cruz-Alaniz, A. Seryi, University of Oxford, Oxford, UK  
 M. Crouch, F. Zimmermann, CERN, Geneva, Switzerland  
 D. Zhou, KEK, Ibaraki, Japan

## Abstract

The High Energy LHC (HE-LHC) is one option for a next generation hadron collider explored in the FCC-hh program. The core concept of the HE-LHC is to install FCC-hh technology magnets in the LHC tunnel. The higher beam rigidity and the increased radiation debris, however, impose severe challenges on the design of the triplet for the low beta insertions. In order to achieve 25 cm  $\beta^*$  optics and survive a lifetime integrated luminosity of  $10 \text{ ab}^{-1}$  a new longer triplet was designed that provides sufficient shielding and enough beam stay clear. This triplet has been designed using complimentary radiation studies to optimise the shielding that will also be presented. The optics for the rest of the interaction region had to be adjusted in order to host this more rigid beam and longer triplet whilst leaving enough room for crab cavities. Moreover, the effects non-linear errors in this triplet have on the dynamic aperture will be outlined.

## INTRODUCTION

### The High Energy LHC

Currently several next generation machines for the post Large Hadron Collider (LHC) era are being explored in the scope of the Future Circular Collider (FCC) program [1]. Besides a 100 km circumference hadron-hadron collider, FCC-hh, that uses state of the art 16 T bending dipoles to reach a 100 TeV centre of mass (CM) energy, the study also looks into a possible energy upgrade of the LHC [2]. This High Energy LHC (HE-LHC) would be built in the existing LHC tunnel but would use FCC-hh technology to reach a 27 TeV CM energy.

The HE-LHC aims to reach a peak luminosity of  $25 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  by using beam parameters similar to the High Luminosity LHC (HL-LHC) [3]. The increased beam intensity creates many challenges for the machine protection and collimation. Moreover, the high beam rigidity demands innovative optics solutions since the HE-LHC has to fit in the existing LHC tunnel. A comparison of the different parameter choices for the FCC-hh, HE-LHC, and LHC is shown in Table 1.

### Experimental Interaction Region

One of the most demanding areas that need to be optimised are the two straight sections containing the experimental interaction regions (EIR), which focus the beams for the high luminosity experiments. In order to reach the luminosity

Table 1: Table Showing Various Machine Parameters for FCC-hh, HE-LHC and HL-LHC

Parameter	FCC-hh	HE-LHC	HL-LHC
C [km]	100	27	27
$E_{beam}$ [TeV]	100	13.5	7
$N$ [ $\times 10^{11}$ ]	1	2.2	2.2
$\bar{\epsilon}$ [ $\mu\text{m}$ ]	2.2	2.5	2.5
$\beta^*$ [m]	0.3	0.25	0.15
$\theta/2$ [ $\mu\text{rad}$ ]	88	131	285
$L$ [ $\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ]	9-20	25	19.5

goals, the EIR has to focus the beam to a  $\beta^*$  of 25 cm at the interaction point (IP). This is achieved by using a quadrupole triplet which squeezes the beams to the required  $\beta^*$  at the collision point. This triplet needs sufficient shielding to withstand the large amounts of collision debris. A new triplet needs to be designed that can achieve this whilst remaining as short as possible. Following the design constraints used for the LHC and HL-LHC design, a beam stay clear of  $12 \sigma$  is chosen as the target physical aperture value in the low  $\beta$  IPs [4]. The collimation system for the HE-LHC is still under investigation and a preliminary design can be found in Ref [5].

The increased beam rigidity is also a challenge for the separation section. The separation section must also be as compact as possible whilst retaining enough shielding from the collision debris to protect the superconducting magnets. Once a triplet and a separation scheme have been designed, the optical functions can be used to calculate the space required for crab cavities which will likely be required in order to obtain the target luminosity [2].

The remaining space left between the crab cavities and the end of the straight section has to be sufficient in order to house the matching section and dispersion suppressor. These sections have to be optically compatible with the connecting arc with special attention paid to the phase advance. These constraints require an innovative optics design which will be discussed in the following sections.

## TRIPLET OPTIMISATION

The triplet was designed using an optimisation algorithm that had previously been used to design an alternative FCC-hh triplet [6]. This algorithm takes into account the various design constraints including  $\beta^*$ , magnet technological limits, radiation shielding, and the required beam stay clear. The algorithm calculates the shortest possible triplet. Initially it was assumed that 10 mm of shielding would be sufficient to protect the triplet, however various design iterations and

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radiation studies showed that 20 mm of shielding would be needed to protect the triplet sufficiently for a lifetime integrated luminosity of  $10 \text{ ab}^{-1}$  [7]. A detailed overview of this triplet can be found in Table. 2.

Table 2: Properties of Quadrupoles in HE-LHC Triplet

Parameter	Quadrupole		
	Q1	Q2	Q3
Sub-Magnets	1	2	1
Sub Magnet Length [m]	12.9	10.5	12.9
Coil Radius [mm]	70.4	70.4	70.4
Gradient [T/m]	145	146	145
Shielding [mm]	20	20	20

This triplet is relatively compact and provides enough shielding whilst retaining a  $12 \sigma$  beam stay clear with a 25 cm  $\beta^*$  and  $135 \mu\text{rad}$  half crossing angle. Figure 1 shows the beam stay clear for this optics and shows that there is potentially room for extra shielding in Q1, which is the closest quadrupole to the collision point and hence receives the most luminosity debris. The triplet also provides enough aperture for an injection optics with  $\beta^* = 11 \text{ m}$  at an energy of 450 GeV. The triplet and the corresponding beam stay clear is shown in Fig. 2.

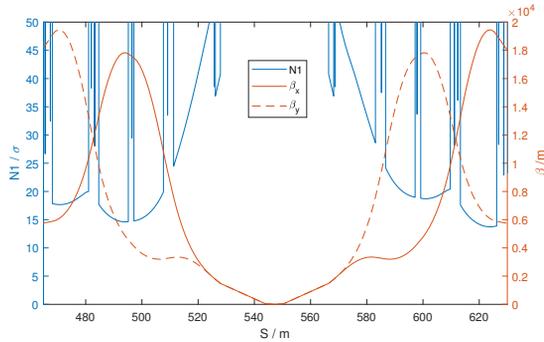


Figure 1: Beam stay clear and  $\beta$  functions in HE-LHC triplet for collision optics.

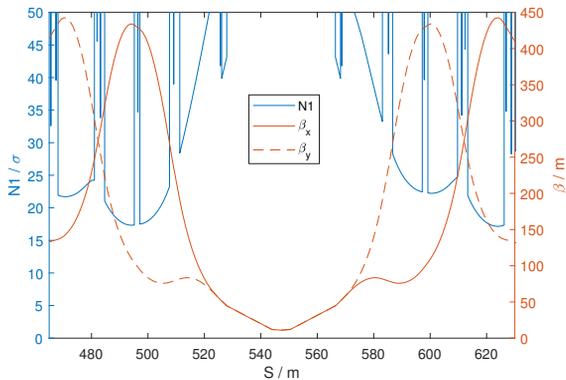


Figure 2: Beam stay clear and  $\beta$  functions in HE-LHC triplet for injection optics.

### SEPARATION DIPOLES

Several dipole options were considered in order to compensate for the higher beam rigidity. After communications

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with the FCC-hh magnet design team, it was established that a superconducting single-aperture dipole with a maximum field of 12 T could be used as the innermost separation dipole (D1) and a double-aperture dipole with up to 10 T could be used for the second, recombination dipole (D2) [4].

With this technology, the layout used for the HL-LHC can be conserved for the HE-LHC with some minor modifications. The D1 dipole could have the same length as in HL-LHC but would have to be moved back in order to compensate for the longer triplet. D2 could stay in the same position as before but would need to be 25% longer than the HL-LHC. This would allow 205 mm beam separation to be achieved whilst keeping the space available for the matching section, and the dispersion suppressor approximately the same. A survey of both the HL-LHC and HE-LHC triplet and separation section is shown found in Fig. 3.

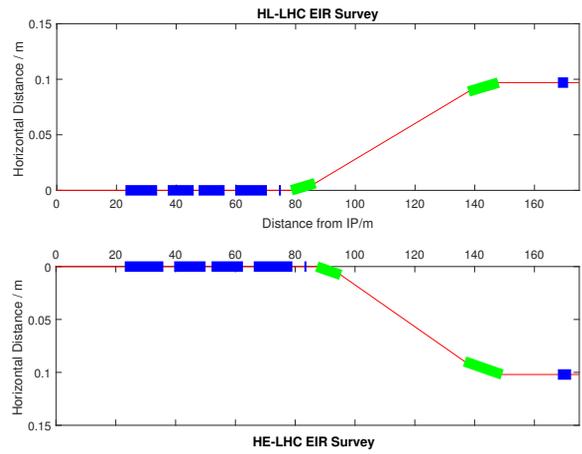


Figure 3: Surveys comparing the HE-LHC layout to that of the HL-LHC. The beam is shown in red, whilst blue and green boxes represent quadrupoles and dipoles respectively.

Once a final layout was established, the position of the crab cavities was set to be after D2. The twiss functions at this location and the properties at the IP could then be used to estimate the required crab cavity voltage using Eq. 1

$$V_c = \frac{2cE_b \tan(\phi_c)}{\omega_{RF} R_{12}}, \quad (1)$$

where  $c$  is the speed of light,  $E_b$  is the beam energy,  $\omega_{RF}$  is the RF frequency, and  $\phi_c$  is the crossing angle.  $R_{12}$  is the 12 matrix element of the transfer matrix from the IP to the crab cavities. Using this formula the required voltage resulted in 6.3 MV, which is just slightly larger than the 6 MV required in HL-LHC [8]. Therefore, the same amount of space reserved for crab cavities in HL-LHC was also taken for HE-LHC.

### MATCHING SECTION AND DISPERSION SUPPRESSOR

The quadrupoles in the matching section and dispersion suppressor have the purpose of matching the twiss functions to be compatible with the arcs. The main challenge in the

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matching section is to reduce the large  $\alpha$  and  $\beta$  functions caused by the strong focusing triplet to values that can be matched more easily using the dispersion suppressor. This requires strong quadrupoles, however, the magnet technology only allows the quadrupoles to have a maximum gradient of 360 T/m. In order to stay within this limit, several matching section quadrupoles had to be increased in length significantly.

The dispersion suppressor is based on the LHC dispersion suppressor which is based on a missing dipole scheme but had to have the same layout as the Large Electron-Positron Collider (LEP). Due to the tight spatial constraints there is not much room to lengthen out quadrupoles in this section. Therefore, the matching of this section is complicated and vulnerable to small changes in the EIR. Moreover, matching the correct phase advance to and between the chromaticity correcting sextupoles is challenging since the length and beta functions in the arc cell are different to those in the HE-LHC. Figure 4 shows a collision optics that was matched using the modified matching section to an  $18 \times 90^\circ$  arc.

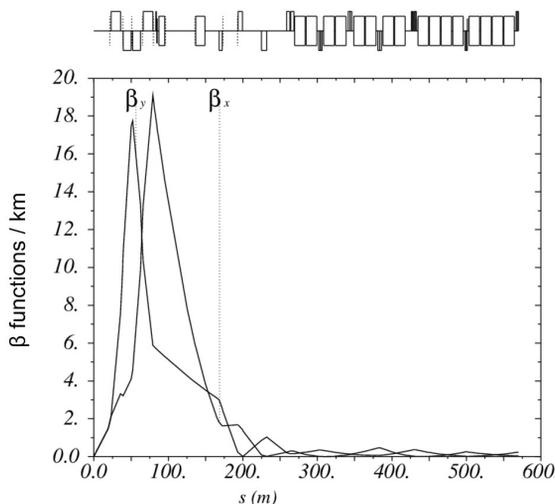


Figure 4: HE-LHC 25 cm  $\beta^*$  Collision Optics designed using modified EIR.

## DYNAMIC APERTURE

Understanding the effects the new EIR has on the Dynamic Aperture (DA) of the machine is also an important factor when designing the EIR. To this end, the magnet error table used in the HL-LHC was applied on the HE-LHC for DA studies [4]. SIXTRACK was used to compute the DA using random and systematic errors calculated for 60 different seeds.

The DA was computed at 7 different angles with only  $a_3/b_3$  errors,  $a_3/b_3$  and  $a_4/b_4$  errors and all errors switched on in order to see the effects the individual errors have on the DA. Initially the tracking was done without any correction scheme and without any crossing, resulting in a zero  $\sigma$  DA when all errors were activated.

Next the studies were repeated but with a half crossing angle of  $135 \mu\text{rad}$  and a corrector package next to the triplets on either side of the IP. These corrector packages are based

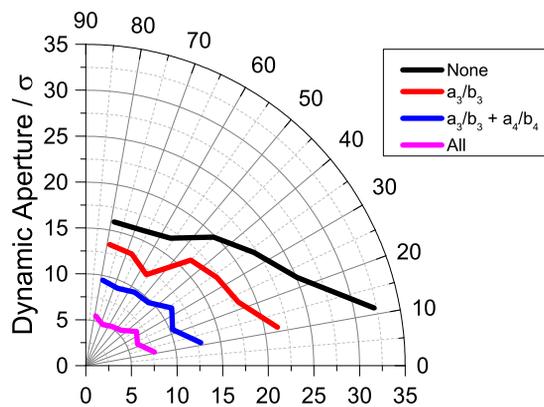


Figure 5: Dynamic aperture with crossing angle for various degrees of triplet errors added.

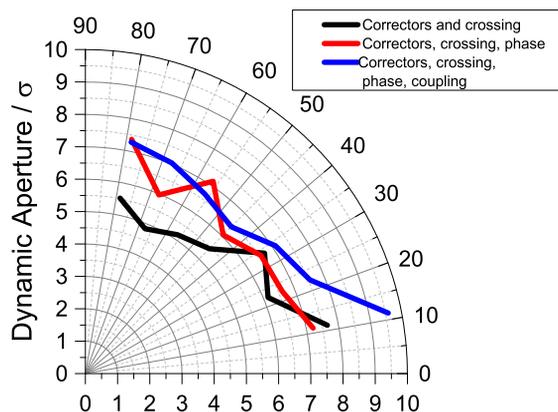


Figure 6: Dynamic aperture with crossing angle with various corrections applied.

on the ones used in the LHC and correct the  $a_3$  and  $b_3$  errors by activating the  $c(a_3; 0, 3)$  and  $c(a_3; 3, 0)$  as well as the  $c(b_3; 1, 2)$  and  $c(b_3; 2, 1)$  corrections respectively [9], the resulting DA is shown in Fig. 5.

This DA can be further increased by applying other optimisation techniques. One technique that was successful in the FCC-hh is the optimisation of the phase advances between the two EIR [10]. The results of a study where this has been added is shown in Fig. 6. Figure 6 also shows the results of a DA study that corrects the coupling using a skew quadrupole behind the triplet on top of the other corrections. Whilst there was an improvement in the DA to  $6.4 \sigma$  using these methods, further work will be implemented to achieve the LHC target DA of  $6 \sigma$  with all imperfections, including separation and arc dipole errors [11].

## CONCLUSION AND OUTLOOK

This research has provided a first baseline for the HE-LHC EIRs that overcomes the challenges one would expect to face in this machine. The DA is relatively low, however, these studies are still in an early stage and more corrections can be applied. Undoubtedly, the EIR will continue to change as the arc optics are optimised further but the current optics presents a positive outlook.

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