EXPLORING THE TRIPLET PARAMETER SPACE TO OPTIMISE THE FINAL FOCUS OF THE FCC-hh*

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Abstract

One of the main challenges when designing final focus systems of particle accelerators is maximising the beam stay clear in the strong quadrupole magnets of the inner triplet. Moreover it is desirable to keep the quadrupoles in the triplet as short as possible for space and costs reasons but also to reduce chromaticity and simplify corrections schemes. An algorithm that explores the triplet parameter space to optimise both these aspects was written. It uses thin lenses as a first approximation and MADX for more precise calculations. In cooperation with radiation studies, this algorithm was then applied to design an alternative triplet for the final focus of the Future Circular Collider (FCC-hh).

INTRODUCTION

FCC-hh Experimental Interaction Regions

The FCC-hh aims to accelerate protons to up to 50 TeV and plans to collide them in two high luminosity experimental interaction regions (EIR) [1]. The detector design team impose several design constraints such as the target luminosity of $20 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the final drift, L^*, of 45 m that would give the detector enough space.

The baseline optics designed to fulfill these requirements use crab cavities and a round beam with $\beta^* = 0.3 - 1.1$ m. The main parameters are shown in Table 1. Table 1 also shows parameters for a proposed alternative flat beam that would also fulfill these requirements without the use of crab cavities.

Table 1: Table Showing Machine Parameters for Initial and Ultimate Round Optics as well as the Proposed Flat Optics

Parameter	Optics		
	Initial	Ultimate	Flat
$N\ [\times 10^{11}]$	1	1	1
$\epsilon\ [\mu\mathrm{m}]$	2.2	2.2	2.2
β_x^* [m]	1.1	0.3	1.0
β_y^* [m]	1.1	0.3	0.2
$\theta/2\ [\mu\mathrm{rad}]$	92	176	96
$L\ [\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	5	9-20	12

Other constraints such as the coil aperture, length or radiation hardness of the magnets are set by technological limitation. It is also desirable to keep the triplet as short as possible in order to keep the chromaticity low and to make sure the EIR fits into the space reserved in the short straight section.

Optimisation

The starting point for this optimisation are initial optics presented during FCC week 2016 and are shown in Fig. 1. The total length of the triplet was 186 m and it had a beam stay clear (BSC) of 40σ at the ultimate $\beta^* = 0.3$ m [2]. However, a BSC of 15.5σ would already be acceptable so there was potential to shorten the triplet at the expense of BSC. Moreover, the total length of the EIR was 1.5 km – a shorter triplet would also help shortening it to the required 1.4 km.

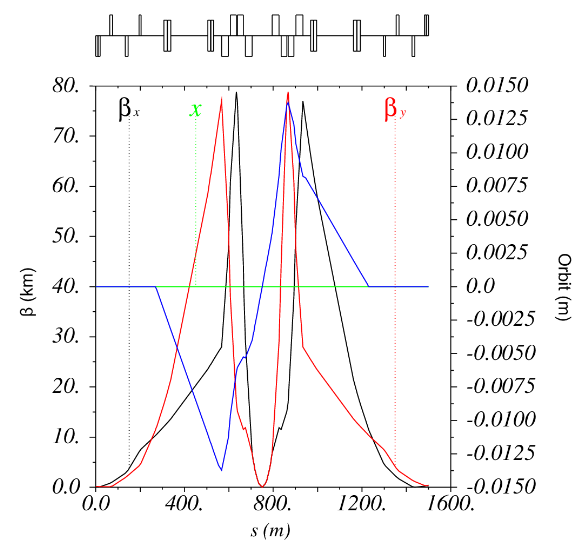

Figure 1: Twis Functions and Orbit of the Initial Optics

The magnets of this initial design were not yet split to the target maximum length of 15 m. The apertures of the magnets were designed to be compatible with the field strength and shielding required from them; quadrupole 1 (Q1) had a radius of 76 mm and quadrupoles 2 and 3 (Q2 and Q3) a radius of 96 mm. The magnets had a shielding of 15 mm to protect them from radiation. Initial estimates suggest that the magnets could survive a radiation dose of 30 MGy from collision debris, by varying the crossing planes, this limit would be reached at about 6000 fb^{-1} [3]. The FCC-hh aims to have a lifetime integrated luminosity of several ab^{-1}, so the goal was to match or surpass this performance.

ALTERNATIVE INTERACTION REGION

Whilst the EIR from the previous section was further developed [4], the aim of this study was to produce an al-

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ternative design in parallel. In this approach the triplet was completely redesigned from scratch and then integrated in the previous optics by adjusting the strength of the magnets in the matching section.

Triplet Optimisation Code

The primary aim was to design a triplet that was as short as possible but still had enough aperture for sufficient BSC and shielding. To this end a triplet optimisation code was developed that would scan through the triplet parameter space to find the shortest possible triplet for a given BSC and shielding thickness [5].

The exact BSC can only be obtained using precise MADX aperture computation, which are relatively slow. In order to decrease the parameter space over which these precise scans are performed, a simpler fast scan is performed to identify the approximate region where one would expect the optimum solution. This scan approximates the quadrupoles as thin lenses and analytically works out the strengths required for a given layout. It then tracks a particle originating from the interaction point (IP) using matrix multiplication and works out a figure of merit (FOM) in each quadrupole equal to $\frac{L_Q}{gx}$, where L_Q is the quadrupole length, x is the orbit of the tracked particle and g is the thin lens strength.

The code then does a precise scan in the region identified by the fast FOM and find the configuration with the highest BSC. If this BSC is higher than the minimum required BSC the details of the configuration are printed and the code stops. If the BSC is not sufficient the algorithm increases the total length of the triplet and redoes the scan. In order to produce a configuration that is easier to manufacture further constraints were introduced – the length of Q1 and Q3 was set to be equal and all magnets were to have the same aperture.

Energy Deposition

In order to ensure that the configuration produced by the optimisation code would be sufficiently protected against the collision debris, energy deposition studies were performed on the final triplets [6].

Since the triplets designed using the optimisation are much shorter than the original triplet, the debris would be spread over a shorter distance. This would potentially increase the radiation dose and hence require more shielding. If it was found that the shielding was not sufficient the shielding in the individual quadrupoles was increased, whilst still maintaining the enough BSC. If this was still not good enough the shielding thickness in the optimisation code was adjusted and the process was repeated.

Integration and Splitting of Magnets

Once a short triplet with sufficient BSC and radiation protection was found it would be integrated into the FCC-hh lattice. In order to make it more realistic, the long quadrupole magnets would be split into shorter submagnets with a maximum length of 15 m. The submagnets were separated by 2 m drifts, leaving enough space for cryogenic, vacuum and different interconnect systems. The spacing between the main quadrupoles was set to 7 m, to also allow space for kickers and beam instrumentation.

The optics of the EIR was then rematched to the arcs for the different β^* using the MADX matching module to adjust the strength of the matching section quadrupoles. The optics would then be ready to be integrated into the rest of the lattice for further studies.

RESULTS

This section illustrates the alternative optics these studies have converged to by May 2017.

Magnets

Table 2: Properties of Quadrupole Groups in Alternative Triplet

Parameter	Quadrupole		
	Q1	Q2	Q3
Sub-Magnets	2	3	2
Sub Magnet Length [m]	15	15	15
Coil Radius [mm]	98.3	98.3	98.3
k $\left[\times 10^{-4}\text{m}^{-2}\right]$	- 6.37	6.64	- 5.81
Shielding [mm]	44.2	33.2	24.2

The alternative triplet consists of seven identical quadrupole submagnets in a 2-3-2 triplet configuration. The magnets are powered slightly differently to give different k-values. Whilst the coil apertures of the different magnets are identical Q1 has the most shielding and Q3 has the least. The overall length of this new triplet is now only 129 m. A detailed overview of three quadrupoles and their submagnets can be found in Table 2.

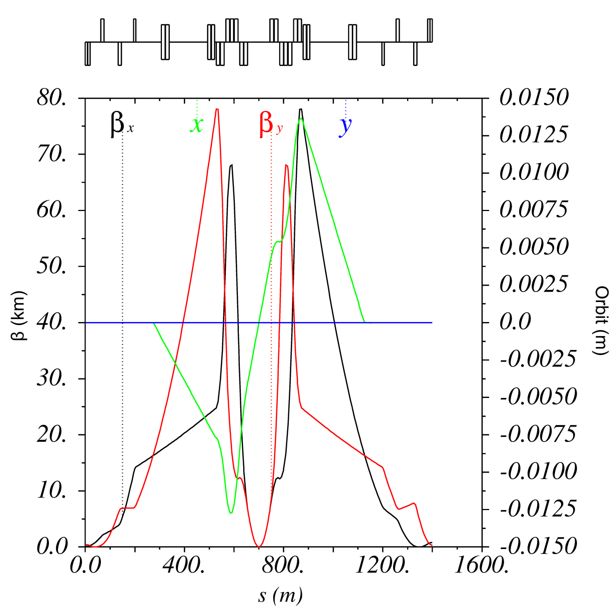

Figure 2: Twis Functions and Obit for 0.3 m β^* Round Optics

Optics

Figures 2 and 3 show the Twiss functions of the EIR for $\beta^* = 0.3$ m round optics and $\beta^* = 0.2$ m $\times$ 1 m flat optics matched to the arcs. Since the alternative triplet is significantly shorter than the original one it was possible to achieve this with the total length of the EIR being the target 1.4 km instead of the 1.5 km from before.

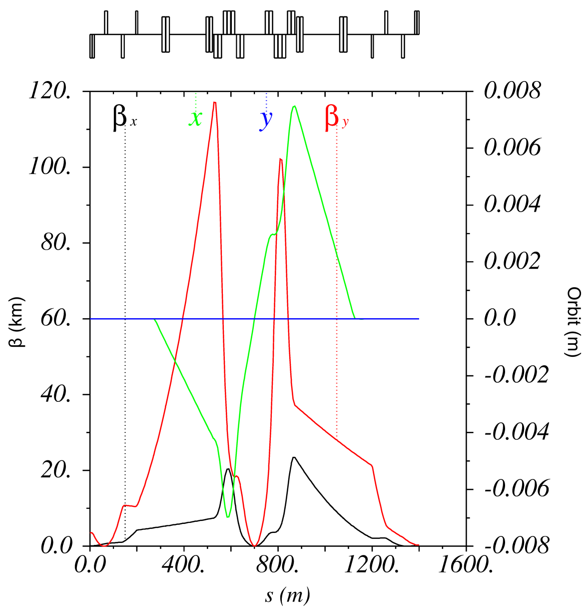

Figure 3: Twis Functions and Orbit for 0.2 $\times$ 1 m β^* Flat Optics

Beam Stay Clear and β^* Reach

After matching the EIR the MADX aperture module was used to calculate the minimum BSC of the two optics. Without mechanical tolerances the BSC was found to be 21σ and 22.7σ for the round and flat optics respectively. Once mechanical tolerances are included the BSC is expected to decrease by about one or two σ – still remaining above the target 15.5σ. A plot of the BSC for the two optics is shown in Fig. 4

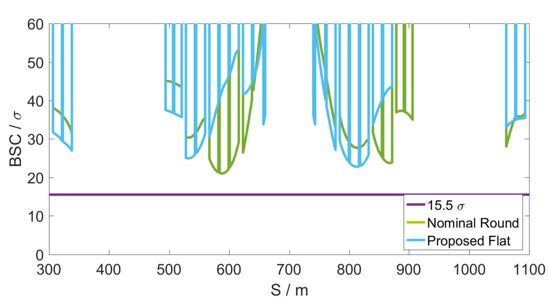

Figure 4: Plot Showing BSC for Ultimate Round and Proposed Flat Optics

The fact that the BSC is slightly higher than necessary allows the design to have some flexibility. This could be valuable if new limitations such as maximum magnet length or limitations in field strength occur. This margin could also be used to reach a β^* beyond the target 0.3 m, this could be used as a handle if the luminosity is lower than expected. To this end the EIR was also matched to a round $\beta^* = 0.2$ m and 0.15 m optics and the aperture was calculated and is shown in Fig. 5.

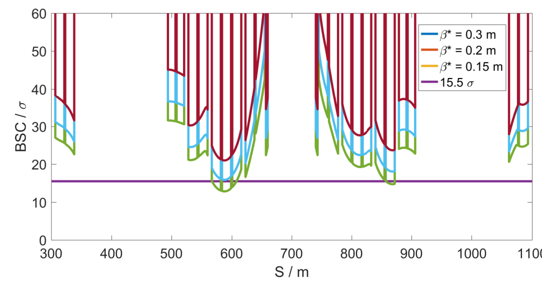

Figure 5: Plot Showing BSC for $\beta^* = 0.15$, 0.2 and 0.3 Round Optics

Figure 5 shows that without tolerances the 0.2 m optics still has a BSC of 15.9σ whilst the 0.15 m optics has a BSC of 12.8σ. This shows that there is enough flexibility to go to 0.2 m and even though the BSC is too low at 0.15 m, it would not be unrealistic to achieve this with some compromises.

CONCLUSION AND OUTLOOK

This study has produced a process that can systematically and efficiently design the optimum triplet that fulfills user defined machine constraints. It does this by scanning through the parameter space of the the triplet initially using thin lenses and then the MADX aperture module.

This process was accompanied by detailed energy deposition studies to produce an alternative triplet for the FCC-hh. This triplet fulfills all the requirements and even has some margin for changes when integrated into the EIR. Whilst this not may be the final design for the FCC-hh EIR the nature of the process allows new triplets to be designed quickly should requirements change.

ACKNOWLEDGEMENTS

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