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AN OPTIMISED TRIPLET FOR THE FINAL FOCUS OF THE FCC-HH WITH A 40M FINAL DRIFT *

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Abstract

The sizes of the β functions in the final focus triplet of a synchrotron collider have a great impact on the chromaticity and dynamic aperture of the machine. These β functions are proportional to the square of the length of the final drift so it is desirable to keep it as short as possible whilst leaving enough room for the experiment. In the latest design of the FCC-hh this drift was reduced from 45 m to 40 m. In the following an alternative final focus for this new design will be presented. The effects this change has on the interaction region will examined and discussed.

INTRODUCTION

FCC-hh

The Future Circular Collider (FCC) collaboration explores the possibility of building a various next generation collider in a 100 km tunnel around the CERN site [1]. One of the machines that could be housed in this tunnel is a hadron-hadron collider (FCC-hh) that would reach a centre of mass energy of 100 TeV using novel Nb_3Sn superconducting magnets that can produce dipole fields of up to 16 T [2].

Nb_3Sn can also be used to produce magnetic quadrupoles with gradients up to 360 T/m at the nominal magnetic aperture of 50 mm [3]. These 50 mm aperture magnets are used for the machine optics in the arcs and all eight straight sections, however, special purpose quadrupoles with larger apertures and lower gradients are used in certain places.

Experimental Interaction Region

The FCC-hh plans to have two high luminosity experiments located in interaction regions (IR) A and G. The target luminosity for these experiments is $20\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which it plans to achieve by focusing the beam to have an interaction point (IP) β^* of 0.3 m in both planes. In order to compensate for the large crossing angle, the FCC-hh plans to use the novel crab cavity technology [4].

The beam is focused to such a small β^* using a specially designed triplet. In this triplet both beams will pass through a single aperture. The small β^* results in large β functions in the triplet, requiring it to have a large aperture to allow both beams a 15.5σ beam stay clear (BSC). Moreover, the aperture also has to have enough space to install shielding to protect the magnets from the collision debris.

A larger aperture forces the quadrupole magnets to have a lower field than usual so magnets have to be relatively long in order to have enough integrated focusing strength. Longer magnets however, take up more space, cost more and can generally cause a larger chromaticity and reduce the dynamic aperture (DA). Therefore, a major optimisation goal was to create a triplet that is as short possible but has enough BSC and shielding.

Two separate design efforts were made in parallel – the baseline design used scaling laws to derive a triplet based on that of the LHC [5]. An alternative approach used a dedicated triplet optimisation algorithm to find an optimal solution [6], a first solution is shown in Fig. 1 [7]. The progress of this alternative approach will be outlined in this publication. The alternative triplet is also capable of matching a flat optics that could be used in case the crab cavity performance is not sufficient.

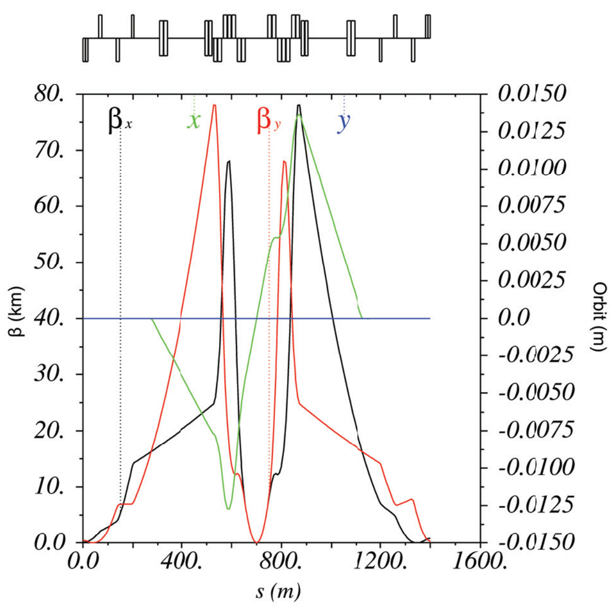

Figure 1: β functions and orbit for 0.3 m β^* collision optics with alternative triplet and 45 m L^*.

Apart from being shorter, another benefit of the alternative triplet is that it is made with seven identical quadrupole magnets that are all 15 m long and with a 98.3 mm coil radius, whilst the baseline would require several different quadrupoles.

Reduction in L^*

The length of the final drift between the triplet and the IP, L^*, is dependent on the space required for the detector and experimental cavern. From the accelerator point of view, it is desirable to have an L^* that is as short as possible since the β at the exit of the triplet varies as

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$$\beta = \beta^* + \frac{L^{*2}}{\beta^*}. \tag{1}$$

In general, a smaller L^* would result in smaller β functions in the triplet and would require less strength to focus. This should result in a larger aperture, optics that can be matched more easily and a reduction in chromaticity.

Initially, the L^* was set to 45 m and the alternative triplet for this case is shown in Fig. 1. However, changes in the detector and cavern design now allow for a $L^* = 40$ m. This would reduce the exit β function from 6750 m to 5333 m. The effect of this change will be highlighted in the following.

RESULTS

Optics

The triplet designed for the 45-m and all other magnets up to and including the first separation dipole were moved 5 m closer to the IP. Next the quadrupoles in the triplet had to be rematched in order to compensate for the change in the focal point. This rematching only changed the gradients of the quadrupoles by about 2%. In order to compensate for slightly higher fields the coil radius of the quadrupoles reduced from 98.3 mm to 96.5 mm. The optics was then matched with a 0.3 m β^* and is shown in Fig. 2.

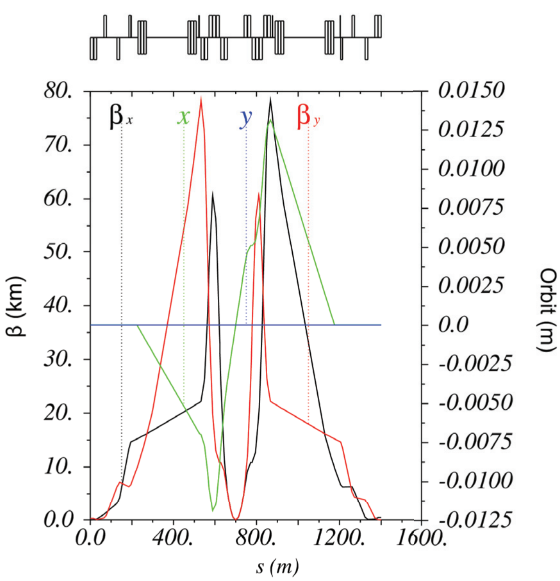

Figure 2: β functions and orbit for 0.3 m β^* collision optics with alternative triplet and 40 m L^*.

From Fig. 2 one can see that the maximum β function is roughly the same, however, on average the β functions are noticeably smaller. In order to examine the effect this has on the chromaticity, one can calculate the integral of $k \times \beta(s)$ across both triplets. Due to symmetry, it is sufficient to do this in one plane only. For the 45-m, this integral is equal to 1790 m^{-1}, whilst in the 40 m case this reduces to 1718 m^{-1}, showing that the new triplet reduces the chromaticity.

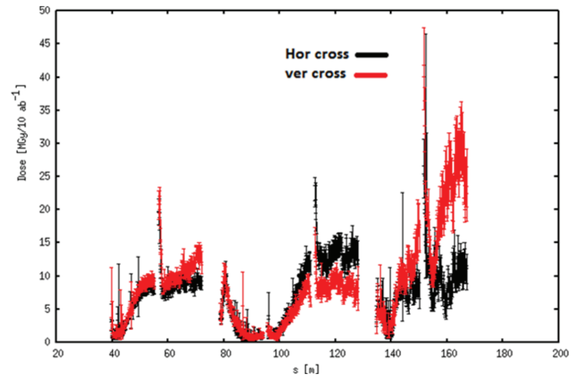

Figure 3: Triplet radiation studies for round collision optics with 40 m L^*.

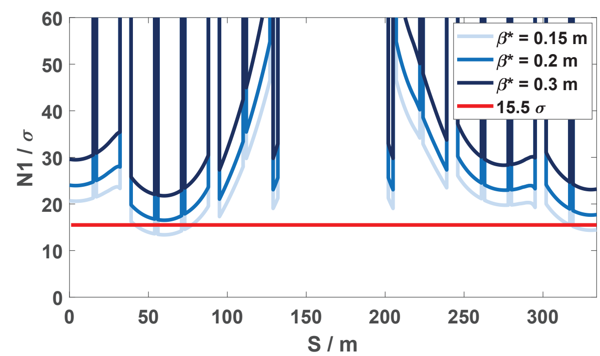

Figure 4: BSC in triplet for various β^* optics options.

Shielding and Aperture

Previously, radiation studies have been done for the triplet at 45 m L^* and it was shown that it would survive a lifetime integrated luminosity of 17 ab^{-1} by having a dose less than 30 MGy when spreading the peak across the vertical and horizontal planes [8]. The same studies were done for the triplet at 40 m and it was shown that the changes are not very significant. The results from this study are shown in Fig. 3 [9].

One of the most important aspects of the triplet is whether it has enough aperture for the when all the shielding is installed. Whilst the ultimate optics uses a 0.3 m β^*, it is common to design the machine such that there is some margin for further reducing the β^* to provide a handle to increase the luminosity. To this end, two further optics with 0.2 m and 0.15 m β^* were matched. The BSC for all three cases was computed using the MADX aperture model and is show in Fig. 4.

As one can see from Fig. 4, a 0.2 m β^* would be possible whilst maintaining a BSC larger than 15.5σ. The 0.15 m β^* goes below this limit, however, this case goes far beyond the luminosity goal required. Moreover, one major cause of needing a 0.15 m optics could be to compensate for a lower beam current - in this case the collimation system could perhaps be tightened to allow a this lower BSC. The results are very similar to the case with the 45-m layout.

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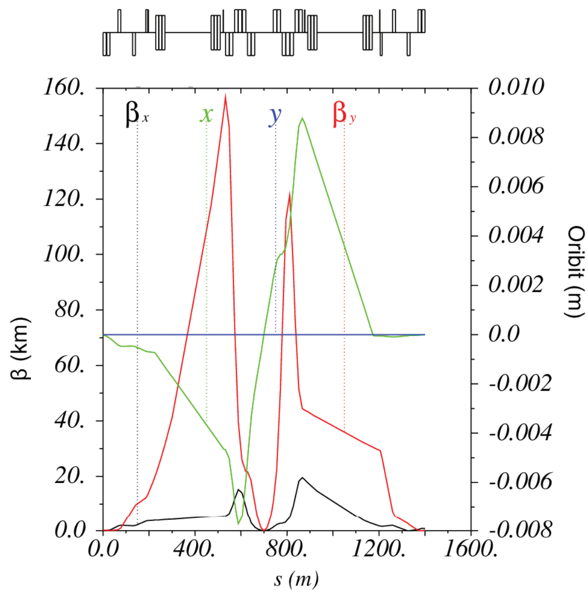

Figure 5: β functions and orbit for 1.2×0.15m flat collision optics with alternative triplet and 40 m L^*.

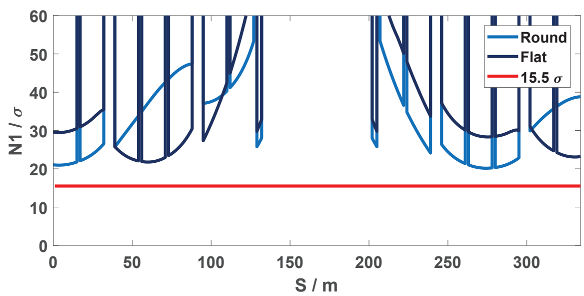

Figure 6: BSC in triplet for flat and round collision optics.

Flat Optics

Since the crab cavity technology is very new and has not yet been applied to hadron colliders with energies close to that of the FCC-hh, more conventional solutions to maximise the luminosity should also be considered. One such solution could be using a flat beam optics. After considering the outcomes of investigation in the luminosity evolution for various options and the results from beam-beam studies, it was decided that a β_x^* 1.2 m $\times$ β_y^* 0.15 m flat optics would be the optimum case.

This kind of optics can be achieved using the same triplet as used for the round optics when changing the strength of the matching section quadrupoles, Fig. 5 shows an optics matched in such a way. Moreover, from Fig. 6 the flat optics would have a very similar BSC to the round optics so the triplet and shielding could stay unaltered. This would mean that if the crab cavity technology fails to deliver, the optics can be adjusted and a large portion of the luminosity goal can be achieved without major interventions.

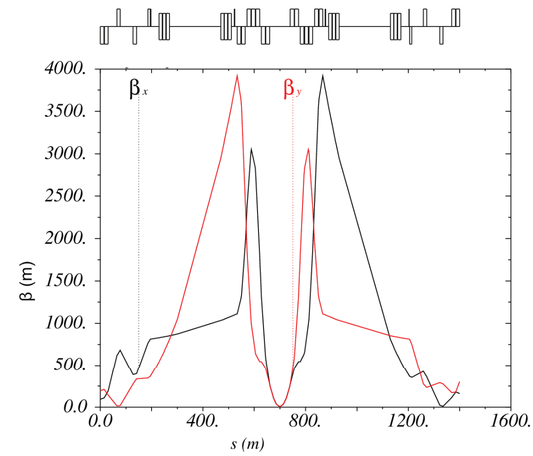

Figure 7: Optics for 6 m β^* injection optics with 40 m L^*.

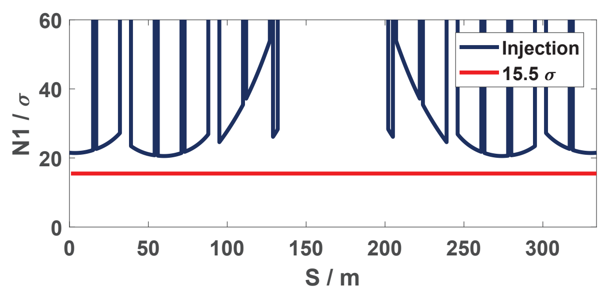

Figure 8: BSC in triplet for 6 m β^* at an injection energy of 1.3 TeV.

Injection Optics

For completeness, an injection optics was also designed for this triplet. A β^* of 6 m is more than sufficient to provide enough BSC at injection energies. This optics can be matched without changing the triplet strength and is shown in Fig. 7. This optics provides more than 20σ BSC for the planned injection energy of 1.3 TeV and a 15.5 σ separation, this is shown in Fig. 8.

CONCLUSION AND DISCUSSION

The move from a 45 m to 40 m L^* has not had a significant impact on the key properties of the interaction region. The triplet had to be modified slightly but still has enough protection and BSC. On the other hand the β functions in the triplet are slightly lower and the chromaticity is also reduced.

The impact these improved features have on the overall machine design will only fully be seen once triplet errors and beam-beam effects have been studied. These studies will also be important when comparing this triplet to the baseline design. Moreover, studies of the flat beam optics will show how adequate this solution would be should crab cavities not be available.

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