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OPTICS FOR RF ACCELERATION SECTION FOR THE HIGH ENERGY LARGE HADRON COLLIDER *

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Abstract

As part of the FCC study, the design of the High Energy LHC (HE-LHC) is addressed. A proposed layout for the interaction region for the containing the radio frequency (RF) cavities and various beam instrumentation will be discussed. The higher energy requires more RF cavities, which strongly restricts the space available for optics and instrumentation. Another challenge arises because the beam rigidity increases whilst the LHC geometry has to be conserved. To this end, next generation dipoles have to be used in order to achieve sufficient beam to beam separation. A design that provides enough beam stay clear (BSC) in all the magnets will be presented. The design introduces an additional quadrupole on either side of the RF region to be used for phase advance adjustments that can increase the dynamic aperture.

INTRODUCTION

HE-LHC

The Large Hadron Collider (LHC) has played a crucial role in completing the standard model. By using NbTi superconducting magnets in the 27 km Large Electron–Positron Collider (LEP) tunnel, protons can be accelerated to 13 TeV centre of mass energy. The data from collisions at this energy led to the discovery of the Higgs boson and the confirmation of the standard model [1].

The Future Circular Collider (FCC) collaboration explores several options for next generation machines for the post LHC era. One of these options is an energy upgrade of the LHC that plans on using novel Nb_3Sn technology to reach a centre of mass energy of 27 TeV [2]. The collisions in this High Energy LHC (HE-LHC) would allow the exploration of a whole new realm of energies and potentially lead to the discovery of new physics.

One of the largest challenges faced when designing the optics for the HE-LHC are the geometrical constraints of the existing tunnel that can only partially be solved by using FCC technology Nb_3Sn magnets. Especially the length of the straight sections that contain various insertions make this a challenging task that requires new optics solutions. This paper is focused on the optics in Insertion Region four (IR4) which contains the accelerating cavities as well as the beam instrumentation and electron lens.

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RF Insertion

The main function of IR4 is to host the accelerating cavities and beam instrumentation devices. Radio frequency (RF) cavities are located in the middle of the insertion, which is around 538 m long. The rest of the elements are placed on both sides of them.

A larger than nominal inter-beam separation is required for the cavities. To this purpose, dipoles are installed either side of the cavities. It is also of great importance to ensure that the dispersion is zero along the acceleration region.

A compromise between the strength of the magnetic field and the separation between the dipoles has to be reached in order to meet the inter-beam separation requirement using technologically achievable magnetic fields and gradients.

As a consequence of the new layout of the interaction region and the beam stay clear being higher than in current LHC, the study of the mechanical aperture arises as a critical point for the optics design.

Finally, placing the beam instrumentation required becomes a challenging task due the strong restriction in the space available in the IR .

METHOD

Increasing Space for RF

Although the final length of the accelerating cavities remains unknown, different scenarios have been studied assuming reasonable sizes. Even in the most pessimistic case, where the space needed for acceleration would be around 85 % bigger than in current LHC, there would be no insurmountable obstacle to the optics design.

In order to optimise the space available in IR4 after having increased the space devoted to RF, different layouts have been studied, searching for a balance between what is technologically achievable and the beam requirements, keeping in mind space requirements for instrumentation too.

Dipoles

As a first approach and in the attempt to use dipoles with similar characteristics to the ones in current LHC, a layout doubling the number of dipole magnets was sketched. Placing four dipoles on each side of the cavities instead of two allows to change the inter-beam separation from 204 mm to 420 mm with fields lower than 3.5 T, this layout is shown in Figure 1 a). They were originally conceived as a module that could be moved depending on the final length of the RF cavities. However, this layout presents several prob-

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lems regarding aperture and limits the space available for instrumentation.

The situation mentioned above can be overcome with FCC technology. Two superconducting dipoles separated 55.4 m are enough to bend the beam in a similar layout as found in the current LHC IR4, this is shown in Figure 1 b).

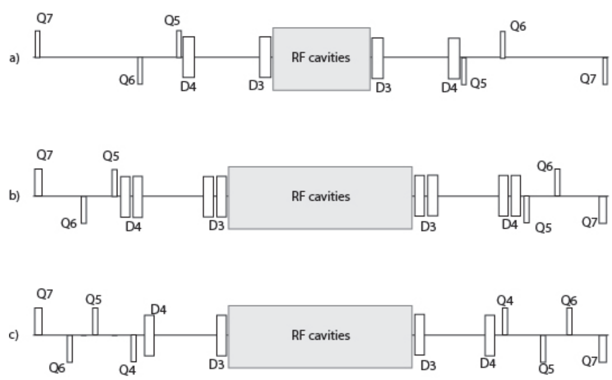

Figure 1: Diagrams of the different designs of IR4 for beam 1. a) IR4 in current LHC, b) IR4 design doubling the number of dipoles, c) IR4 final design using FCC technology and additional quadrupoles for tuning.

Quadrupoles and Optics

Following the layout used in LHC IR4, an optics design consisting on 6 quadrupoles was suggested. The role of these magnets is to match the beam parameters on both sides of the IR as well as to ensure that dispersion is kept as close to zero as possible in the cavities.

Including FCC dipoles in the design leaves more free space in the insertion and it is possible to include two extra quadrupole magnets, one on each side as shown in Figure 1 c). These allow one to have two extra variables when matching the optics. It is important to point out that quadrupoles in the DS region are also included in the matching procedure.

Tuning Quadrupole

One additional function of IR4 in the LHC is to help regulate the tune of the machine for different optics. Studies in the FCC hadron-hadron collider have shown that the phase advance between the experimental interaction points has a dramatic impact on the dynamic aperture [3]. An additional quadrupole, Q4, was added to either side of the RF cavities in order give this IR to provide more flexibility.

This quadrupole would enable changes in the β functions slightly in the matching section but match the twiss to be constant in the cavities and at the start of the arcs.This additional degree of freedom allows one to change the tune of the machine significantly whilst having minimal impact on the rest of the accelerator.

RESULTS

Optics

The values of the β-functions in the matching section were initially around 40% bigger than in LHC and consequently, the 12.5 σ BSC couldn't be achieved. Nevertheless, the use of the extra quadrupole helps to make the β-functions comparable to the ones in LHC, as it can be seen in Figure 2.

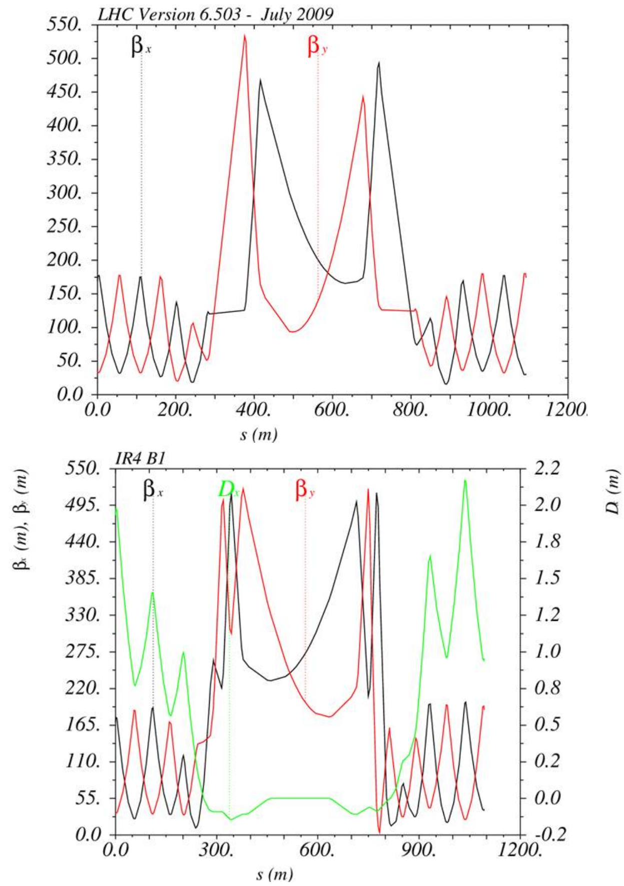

Figure 2: Comparision between the β functions in LHC (above) and HE-LHC IR4

Dispersion is kept constant and equal to zero along the region were the RF cavities are located.

Aperture

The optics of IR4 stays unchanged during the acceleration process, so it is very important that the IR has enough BSC at the injection energy, when the emittance is the largest. The β functions in the DS are of the same magnitude as in the arcs, ensuring that there is enough BSC in this region.

The β functions in the matching section are significantly larger due to the large drift. However, because there are no bends in this region, a larger beam screen with less or no protection could be feasible in this case. Moreover, the lack of dipoles means that quadrupoles with weaker fields and larger apertures can be used.

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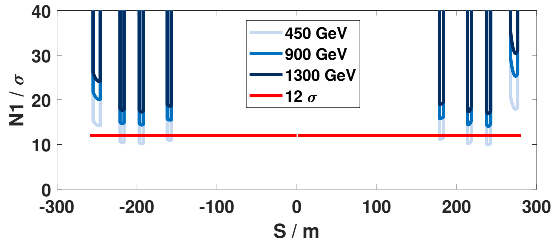

Figure 3: Beam stay clear in IR4 matching quadrupoles for various injection energies

To encompass these properties, the beam-pipe in this region can be approximated as 44 mm diameter circle. This would correspond to a 3 mm beam screen in normal aperture quadrupoles. The resulting BSC in this beam-pipe for various injection energy options is shown in Fig. 3. For the 450 GeV option, the BSC is slightly lower than the target 12σ, however, this is even more of a problem in the arcs and other solutions would have to be found [4].

Tuning

In order to study the phase flexibility the extra quadrupole in IR4 provides, the IR was rematched to achieve the maximum possible deviation from the nominal phase advances that are found in the optics presented in the previous sections. This was done by using the MADX matching function to increase or decrease the phase advances in both planes as much as possible whilst ensuring that no magnet exceeded the limit of 360 T/m and the β-beating was below 10% at every point. Examples of optics matched using this procedure are shown in Fig. 4.

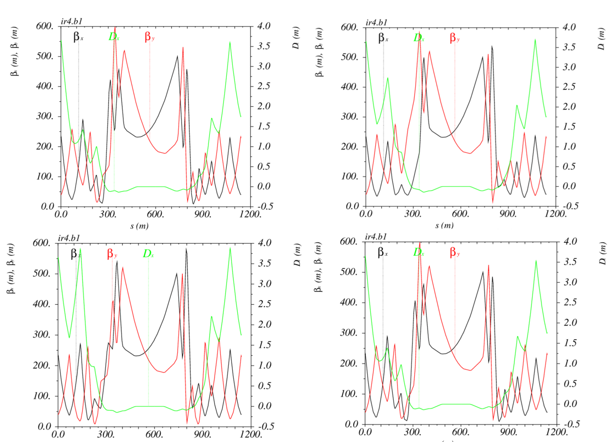

Figure 4: Optics of IR4 matched to change the phase advance in the IR as much as possible

The tune range found using this procedure is shown in Fig. 5. This procedure gives a range of about π in each plane. If a similar procedure was applied in IR6, one could tune the machine to any fractional tune just using these IRs and also control the phase advances between the main experiments without using the tuning quadrupoles in the arcs in order to optimise the dynamic aperture.

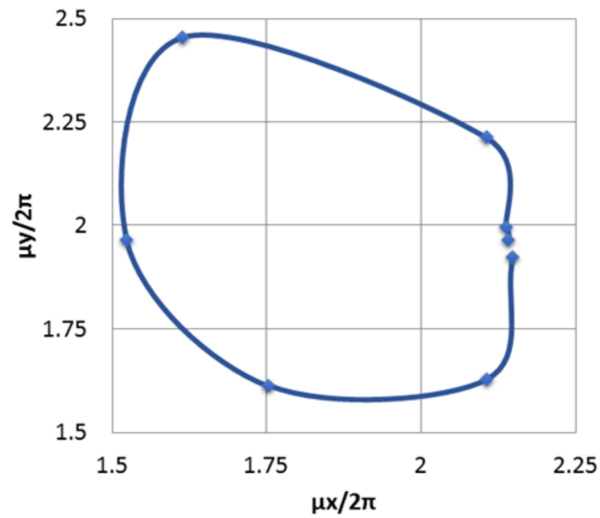

Figure 5: Diagram showing tune range achievable by using Q4 in RF insertion

CONCLUSION AND OUTLOOK

The RF insertion has been sufficiently modified to meet the new demands set out by the high energy upgrade of the LHC. The magnets have been moved and the optics rematched to provide enough space for the addition RF cavities whilst ensuring there is sufficient aperture. An extra quadrupole was added either side of the cavities to allow extra tuning - this flexibility can be used in the future to optimise the machine tune and dynamic aperture.

Next, this design has to be passed on to the machine instrumentation group that can give feedback on whether modifications are needed in order to accommodate all the required devices. The design will undoubtedly need modifications once further RF cavity and dispersion suppressor design iterations demand the geometry and optics to be changed, however, it sets a baseline and demonstrates that the demands can be met in principle.

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