RADIATION LOAD OPTIMIZATION IN THE FINAL FOCUS SYSTEM OF FCC-hh

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Abstract

With a center-of-mass energy of up to 100 TeV, FCC-hh will produce highly energetic collision debris at the Interaction Point (IP). Protecting the final focus quadrupoles from this radiation is challenging, since the required amount of shielding placed inside the magnets will reduce the free aperture, thereby limiting the β^* reach and luminosity [1]. Hence, radiation mitigation strategies that make best use of the available aperture are required. In this paper, we study the possibility to split the first quadrupole Q1 into two quadrupoles with individual apertures, in order to distribute the radiation load more evenly and reduce the peak dose.

INTRODUCTION

FLUKA simulations [2] of the FCC-hh interaction region with $L^* = 36$ m have shown that the final focus triplet magnets are exposed to high doses of radiation coming from collision debris. Independent of the shielding thickness, the highest peak dose, limiting the lifetime of the magnets, occurred at the end of Q1 (assuming constant shielding along the triplet). The magnets are expected to withstand a dose of 30 MGy. While the peak doses for an integrated luminosity of 3000 fb^{-1} shown in Fig. 1 look acceptable for 20 mm of continuous shielding, higher luminosities will require an optimization for radiation load mitigation. Various methods have been proposed so far, including more radiation resistant materials in the magnets, optimized running scenarios distributing the radiation over different areas [2], as well as optimizations in the optics of the triplet. Another option is splitting Q1 into two quadrupoles with different gradients and coil apertures in order to distribute the radiation load more evenly over the length of the magnet.

METHOD AND PARAMETERIZATION

The goal of the split Q1 is to reduce the radiation load in the first triplet magnet with minor impact on the optics. The overall effect of Q1 on the optical functions should therefore stay the same. In order to do this, the total integrated quadrupole strength will be kept constant.

$$k_{tot} \cdot L_{tot} = const. \tag{1}$$

Furthermore the length L_{tot} is kept constant. This way, the geometry remains constant and the change of the β functions in the triplet will be kept minimal. The lengths of Q1a and Q1b are defined by the ratio λ:

$$L_{Q1a} = \lambda \cdot L_{Q1b} \tag{2}$$

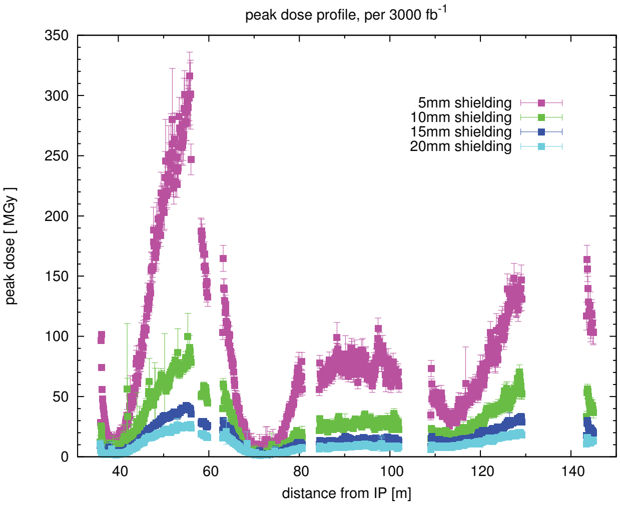

Figure 1: Radiation dose in the triplet magnets from physics debris for different shielding thicknesses. For 20 mm shielding and the indicated integrated luminosity of 3000 fb^{-1}, the dose looks acceptable. Higher integrated luminosities will require optimization.

Since $L_{Q1a} + L_{Q1b} = L_{tot}$, we can deduce

$$L_{Q1a} = L_{tot} \cdot \frac{\lambda}{1+\lambda} \tag{3}$$

$$L_{Q1b} = \frac{L_{tot}}{1+\lambda} \,. \tag{4}$$

In order to have different apertures, the gradients must be different. We introduce the ratio of the gradients r with

$$k_{Q1a} = r \cdot k_{Q1b}, \tag{5}$$

so Q1a is r times stronger (gradient wise) than Q1b. For the goal of reducing the radiation load in Q1b, r will be larger than 1. Since the integrated strength should be constant, we can deduce

$$k_{Q1a} \cdot L_{Q1a} + k_{Q1b} \cdot L_{Q1b} \overset{!}{=} k_{tot} \cdot L_{tot} \,. \tag{6}$$

Inserting Eqs. (2) and (5) yields

$$k_{Q1a} = k_{tot} \frac{1+\lambda}{\frac{1}{r}+\lambda} \tag{7}$$

$$k_{Q1b} = k_{tot} \frac{1+\lambda}{1+r\lambda} \,. \tag{8}$$

Thus, with a given lattice (i.e. given k_{tot} and L_{tot}) two degrees of freedom remain for the radiation load minimization: r and λ. For optics adjustments, the parameter k_{tot} is

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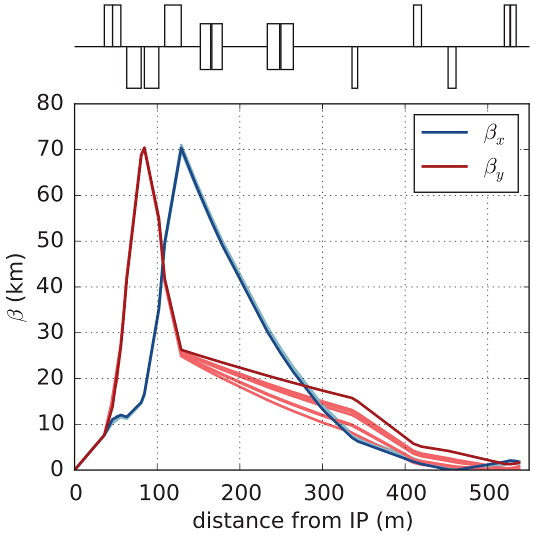

Figure 2: Change of the optics from unsplit (dark) to split (light) Q1 for $r = 1.2$ and 1.5 and $\lambda = 0.3, 1.0, 3.0$. No rematching was performed.

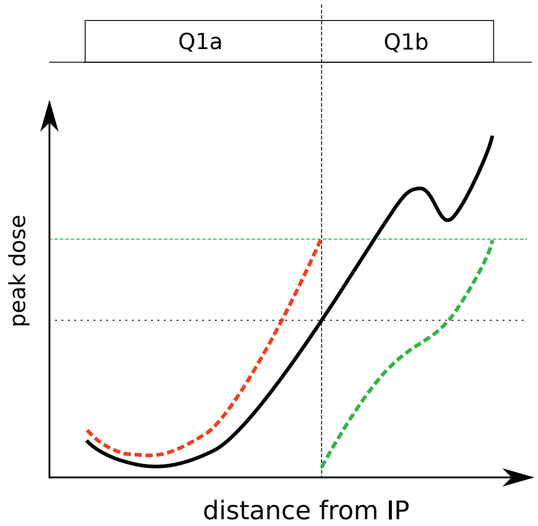

Figure 3: Qualitative sketch of the peak dose in the Q1. The horizontal axis extends over the length of Q1(a/b) shown at the top. The black line describes the peak dose for an unsplit Q1. The expected changes for splitting Q1 are shown by the dashed red and green lines.

used, so the number of optical degrees of freedom remains unchanged.

In Fig. 2, the change of the β functions with r and λ are shown. As intended, they do not change remarkably within the triplet, even without rematching.

In a simple quadrupole model, the apertures of the coils are calculated by

$$x_{ap} = \frac{e}{p}\frac{B_{max}}{k}\,, \tag{9}$$

with e the charge, p the particle momentum, k the quadrupole strength and B_{max} the magnetic field at the coil aperture. For this study, B_{max} was set to 11 T.

Inserting Eqs. (7) and (8) into Eq. (9) yields

$$\begin{aligned} x_{Q1a} &= x_{Q1}\frac{\frac{1}{r}+\lambda}{1+\lambda} && (10)\\ x_{Q1b} &= x_{Q1}\frac{1+r\lambda}{1+\lambda}\,, && (11)\end{aligned}$$

where x_{Q1} is the coil aperture of the unsplit Q1. To minimize the radiation load, it is best to put in as much shielding as possible without reducing the minimum beam stay clear. On the assumption that the beam size only changes negligibly, an increase in coil aperture in Q1b allows to increase the shielding thickness by the same amount. Similarly, in Q1a the shielding has to be reduced according to the coil aperture shrinking.

EFFECTS OF SPLITTING Q1

In Fig. 3 the peak dose in Q1 is illustrated by a black line. The dotted red and green lines qualitatively show the expected dose for a split Q1: for a stronger gradient in Q1a, the coil aperture will become smaller, thus increasing the dose. Since the gradient is larger, particles are defocused stronger than before, giving an additional effect on the radiation load that increases with the distance from the IP. Due to the smaller coil aperture, the shielding thickness that can be placed in Q1a will in principle become smaller, resulting in an even larger radiation load in the magnet coils. The shielding could in principle be thicker closer to the IP without compromising the beam-stay-clear. Placing the most possible shielding in Q1a may therefore counteract the increase of radiation at the acceptable price of a beam aperture reduction.

In Q1b the gradient is decreased, giving a larger possible coil aperture. The retracted coils will be exposed to less radiation. The entrance of Q1b should be completely protected by the shielding in Q1a. Due to defocusing, this effect diminishes toward the exit. Since the beam size is intended to be kept roughly the same as in the unsplit Q1, the larger coil aperture also leaves space for thicker shielding, decreasing the dose further.

A counteracting effect comes from the stronger defocusing in Q1a, resulting in debris particles already bent further outwards after exiting Q1a. While the effect of this earlier defocusing on the beam size is kept small, its effect on debris particles with considerably lower momentum will be stronger due to the stronger than linear impact of the defocusing quadrupole.

EFFECTS OF THE FREE PARAMETERS

First, the effect of the gradient ratio r on the radiation load will be studied. For $r = 1$ we have the initial situation of an unsplit Q1. A lower ratio is undesirable since it will reduce the aperture at the point of the already highest radiation load. As discussed before, increasing r will increase the peak dose

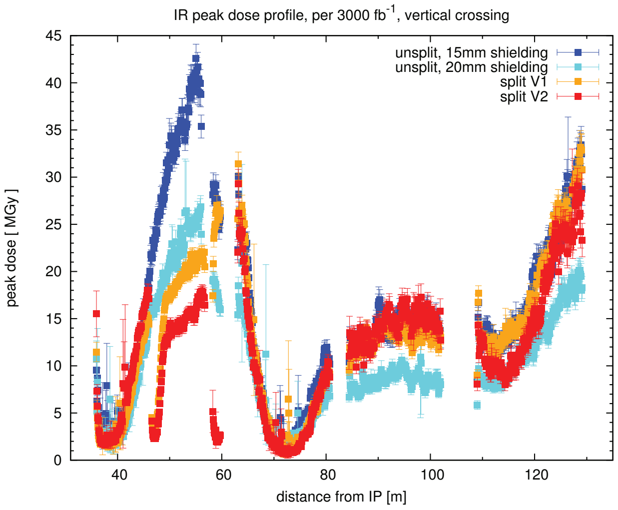

Figure 4: Peak doses of the triplet with unsplit and split Q1. For an optimized Q1 split (V2), the maximum peak dose is reduced by ≈ 33 % with respect to the unsplit 20 mm shielding case.

in Q1a and reduce the one in Q1b. The optimum r is reached at the point where the highest doses in both magnets are the same, meaning both magnets can sustain the same integrated luminosity (green dotted horizontal line in Fig. 3).

As discussed earlier, the radiation load in Q1a can only increase (assuming perfectly shaped shielding). Thus, the load at the end of Q1a for $r = 1$ (black dotted horizontal line in Fig. 3) is a lower limit for the achievable maximum peak dose. From this point of view, it is clear that Q1a should be rather short, i.e. λ should be rather small. This, however, limits the gain achievable in Q1b.

For the optimization of the peak dose, it will be best to optimize r for a set of given values of λ, rather than vice versa. The expected strong and monotonous effect of changes in r on the peak dose, as well as a known lower limit will likely lead to a faster convergence to a reasonable result.

SIMULATION AND RESULTS

To explore the effect of splitting Q1, the FCC-hh interaction region lattice with $L^* = 36$ m was used. For the first simulations of the radiation load, λ was set to 1. In order to get a realistic design, a gap of 0.64 m between Q1a and Q1b was introduced. To compensate the slight change in focussing, the triplet was rematched for maximum beam stay clear. As a result, k_{tot} of Q1 changed by a factor of less than 10^{-4}, while the strengths of Q2a/b and Q3 stayed constant. Thus, the radiation optimization has a negligible impact on the beam optics, the minimum beam-stay-clear was unchanged as it was intended by the parameterization.

In Fig. 4, the simulation results for the split Q1 with $r = 1.1$ (V1) and $r = 1.2$ (V2) are plotted together with the distribution of the unsplit Q1 (from 36 m to 57 m). There is a good agreement of the resulting doses with the qualitative predictions (Fig. 3). The dose in Q1a did not increase much, because the shielding in this region actually increased as discussed earlier. For V2, the maximum peak doses in Q1a and Q1b are the same, thus the optimum was found. The optimization in r only took two iterations, proving the optimization strategy efficient. As the maximum peak dose is now at the beginning of Q2a and the end of Q3, further optimization in λ was omitted. For the $L^* = 36$ m lattice studied here, the Q1 split decreased the maximum peak dose from ≈ 27 MGy to ≈ 18 MGy, which is a reduction of ≈ 33 %. This was achieved with a shielding thickness of 21 mm / 24 mm and a coil aperture of 92 mm / 110 mm in Q1a and Q1b respectively. In the rest of the triplet the assumed shielding thickness and coil aperture are 15 mm and 115 mm. In the unsplit case, the shielding was 20 mm thick at a coil aperture diameter of 100 mm.

With an acceptable dose of 30 MGy, Q1 now could survive an integrated luminosity of 5000 fb^{-1}. This corresponds to the goal for a five-year operation cycle at ultimate parameters [3] allowing to run the full period without replacing Q1. In order to take full advantage of this, the radiation load in the rest of the triplet needs to be decreased to similar levels. Optimized running scenarios with alternating crossing planes that distribute the radiation azimuthally [2] have shown to be able to reduce the peak doses in the whole triplet to ≈ 30 MGy per 4500 fb^{-1}, coming close to the targeted values.

CONCLUSION

We introduced a method of radiation mitigation for the FCC-hh final focus system, by splitting the first quadrupole into two quadrupoles with individual apertures. By using the available aperture more effectively and distributing the radiation doses more evenly, the maximum local dose was reduced by ≈ 33 %. Due to the parameterization presented in this paper, the feedback of this method on the beam optics is minimized. Unlike a simple increase of the shielding thickness, the beam-stay-clear is not reduced by the Q1 split. The basic principle of this method makes it applicable even though parameters like L^* and triplet length are still evolving (the efficiency may vary though). In combination with optimized running scenarios, this method increases the withstandable integrated luminosity to the order of magnitude of a high luminosity run, i.e. three years of operation at "ultimate" parameters [3] without the need to replace the magnets.

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