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ENERGY DEPOSITION STUDIES AND LUMINOSITY EVOLUTION FOR THE ALTERNATIVE FCC-hh TRIPLET*

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Abstract

The international Future Circular Collider (FCC) study comprises the development of a new scientific structure in a tunnel of 100 km. This will allow the installation of a proton collider with a centre of mass energy of 100 TeV, called FCC-hh. An alternative design of the final focus triplet for the FCC-hh has been developed in parallel to the alternative one, and adapted to the constraint of a free length (L^*) of 40 m. We discuss in this paper the energy deposition issues as well as the luminosity evolution for two different optics choices: round and flat beams.

FCC-hh FINAL FOCUS SYSTEM

The design of the FCC-hh has been largely studied in the context of the EuroCircol Collaboration [1, 2]. Two high luminosity EIR (Experimental Interaction Regions) are foreseen in opposite sides of the collider. An identical final-focus system for each high luminosity EIR focalizes the beams at collision to meet the luminosity requirements. For this final-focus system, two triplet designs have been studied in parallel, the nominal final-focus [3] and the so-called alternative [4].

THE ALTERNATIVE TRIPLET DESIGN

The latest design of the alternative triplet is explained in [5]. This triplet is compatible with a free length of 40 m, and has been matched to the full ring to deliver both a round and a flat optics. To ensure the stability of this triplet, dynamic aperture studies have been performed with the full lattice [6]. The main parameters of the quadrupoles for the alternative triplet are shown in Table 1.

Table 1: Quadrupole Parameters of the Alternative Final-Focus Triplet: Gradient, Inner Radius. Absorber Thickness and Inner Coil Radius

Quadrupole	Q1(x2)	Q2(x3)	Q3(x2)
|g| [T/m]	108	112	98.5
r_i [mm]	45.1	56.1	65.1
Δ_{abs} [mm]	44	33	24
r_c [mm]	96.6	96.6	96.6

The comparison in length with the nominal final-focus is shown in Fig. 1. The main advantage is that there is one element less for each EIR side and all quadrupoles have the same length.

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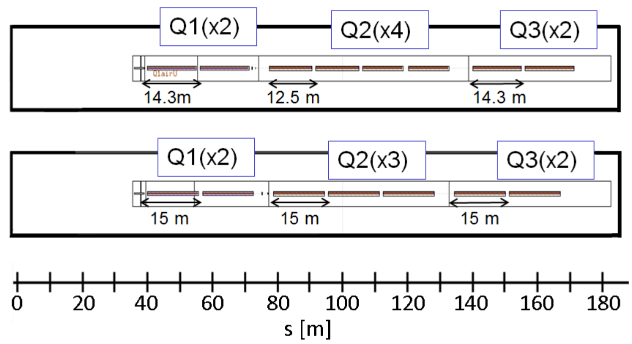

Figure 1: Comparison between the nominal (top) and the alternative triplet (bottom).

FLAT BEAM OPTION

The main purpose of a flat-beam optics is its use as a back-up option in case crab-cavity operation is not possible. Flat beams can minimize the effect that crossing angle has on luminosity. This is due to several effects, as β_x^* is enlarged and β_y^* is reduced (assuming here a crossing in the horizontal plane):

- Crossing angle (θ) reduction from the enlargement on the horizontal β^*, as $\theta = \Delta_{in}\sqrt{\epsilon/\beta_x^*}$, with Δ_{in} being the beam separation in units of σ_x.
- Piwinski angle reduction from an enlargement on the horizontal beam size and a reduction on the crossing angle, $\phi = (\theta\sigma_s)/(2\sigma_x^*)$.
- Emittance reduction with respect to nominal. This is due to the fact that noise injection is not needed, as the beam-beam parameter is reduced [4].

On the other hand, we need to consider that the beam separation (Δ_{in}) must be increased for flat beams [7], so that the θ reduction is cut down. However, the crossing angle is still smaller for flat beams, and this has the advantage of a reduction on the peak dose, as discussed at the end of this section.

Luminosity Comparison

Figure 2 shows the luminosity evolution for round and flat beams, until their respective optimum run times. Both optics designs are explained in [5]. We have assumed $\beta^* = 0.3$ m and $\theta = 176$ mrad (with crab cavities) for round; $\beta_x^* = 1.2$ m, $\beta_y^* = 0.15$ m and $\theta = 114$ mrad for the flat beam case. For the round optics, we have assumed that noise injection is applied, to keep the total beam-beam parameter below

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0.03. The corresponding beam separation has been increased from 15σ to 19.5σ for the flat optics. This is the minimum increase required from beam-beam studies for a flat-beam ratio of 4 [4].

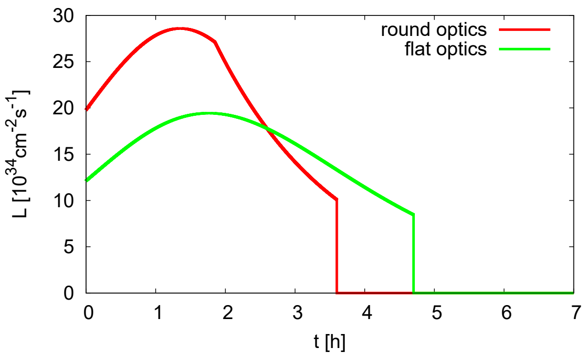

Figure 2: Luminosity evolution for round and flat beams, indicating the optimum run time for t_p = 4 h.

The average luminosity is 8.9 fb^{-1}/day for round and 7.2 fb^{-1}/day for the flat optics. This represents a 20 % reduction, but this is still a good number compared to the result of using the round optics without crab-cavities, which is 6.3 fb^{-1}/day. For these estimations, a preparation time between physics runs of 4 h is assumed. The optimum run time is longer for flat beams, and the luminosity evolution is smoother, with a reduced peak luminosity (from 28 to 20$\times$10^{34} cm^{-2}s^{-1}).

Energy Deposition Simulations

The debris coming from the *pp* collisions at 100 TeV has a considerable impact on the magnet lifetime. The tungsten shielding protects the superconducting coils, and its thickness has been optimized to minimize the peak dose. In order to study the effect of the collision debris on the magnet coil, FLUKA [8, 9] simulations have been performed.

Figure 3 shows the peak dose in the triplet magnets along the longitudinal axis. Two cases have been simulated, with crossing in the horizontal and vertical plane. This profile is symmetric on both sides of the interaction point, as from the reference system of the debris particles, the quadrupole arrangement is symmetric too. The differences between the two crossing planes are caused by the quadrupolar field of the triplet magnets, which changes from focalizing to defocalizing for the horizontal and for the vertical plane. The vertical crossing presents higher peak doses, which can be explained as Q1 and Q3 are defocalizing for this plane while Q2 is focalizing.

The maximum dose is found at Q3, with a maximum of 30 MGy/10 ab^{-1} (excluding the peak at the beginning, that can be reduced by reducing the missing gap for the interconnects). This means 65 MGy for the entire life of the magnet, assumed to resist, at least, an integrated luminosity of 18.5 ab^{-1}. This is twice the present limit for the magnet survival. However, it is expected that by the time of magnet manufacturing, some improvements may have been done

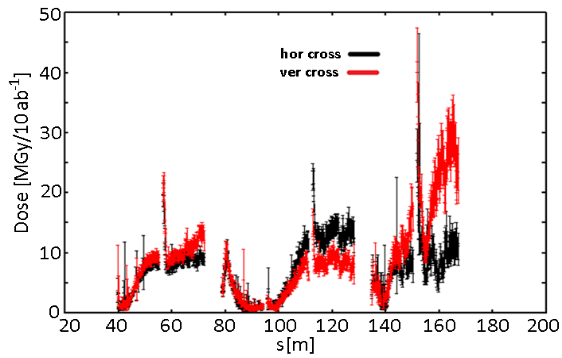

Figure 3: Peak dose profile for the round optics (θ = 176 mrad).

to extend considerably this limit. In addition, the dose can be reduced if alternate crossing is applied, as for each longitudinal position, the peak is found in a different location of the coil. This has been presented both for the nominal triplet [3, 10] and for the alternative one [4].

On the other hand, the peak dose profile for the alternative flat beam option is shown in Fig. 4. The peak dose is reduced to 46 MGy for 18.5 ab^{-1}, as expected from the crossing angle reduction.

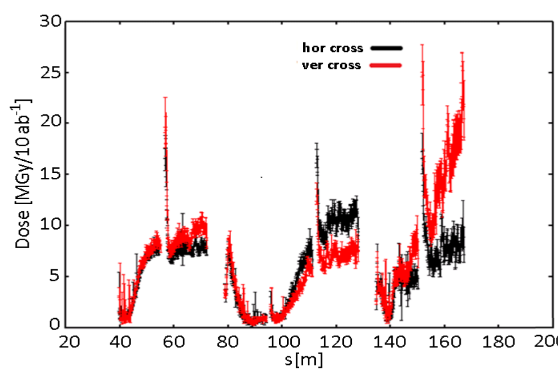

Figure 4: Peak dose profile for the flat optics (θ = 114 mrad).

CROSSING ANGLE VARIATION

For the peak dose calculations shown in Fig 3, it was implicitly assumed that the entire luminosity run is done at the nominal crossing angle. However, if we just want the beam separation at 15σ by controlling the crossing angle, this can be reduced as $\theta = 15\sigma\sqrt{\epsilon/\beta_x^*}$. The emittance shrinks due to the large synchrotron radiation, and we have considered that noise injection is needed, as for the round beam optics at a constant angle, to keep the total beam-beam parameter below 0.03.

This is particularly interesting from the point of view of radiation protection, as the radiation dose can be reduced. Figure 5 shows the dose profile for different crossing angles. The total effect, taking into account the luminosity weight of each crossing angle is also shown. The reduction on the maximum dose with respect to the case of running with the

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nominal angle is evident, especially for the magnet with the highest dose, which is the downstream Q3 unit.

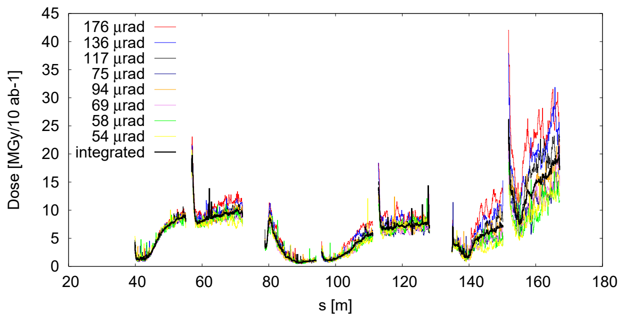

Figure 5: Peak dose profile for different crossing angles, and the total dose for varying angle runs.

DIPOLE SEPARATOR MAGNETS

Figure 6 shows the FLUKA model of the dipole separator magnets D1 and D2. Their design is based on the MBXW and MBW LHC warm magnets, respectively. A similar study has been presented for the nominal triplet [10]. Both D1 and D2 are made of three units. Each unit has a nominal field of 1.91 T and a length of 12.5 m [11].

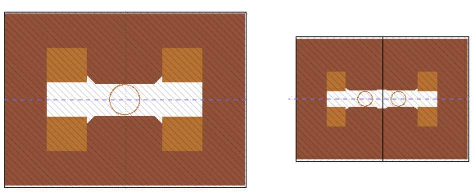

Figure 6: Transverse cross section of the FLUKA model for the dipole separator magnets: D1 (left) and D2 (right).

Energy Deposition for D1 and D2

For the energy deposition simulations with FLUKA, the TAN (Target Absorber Neutrals) model before D2 model has been included [12]. For this study, no shielding has been considered. Figure 7 shows, for the D1 magnets, the peak dose profile on the copper coils for the round optics.

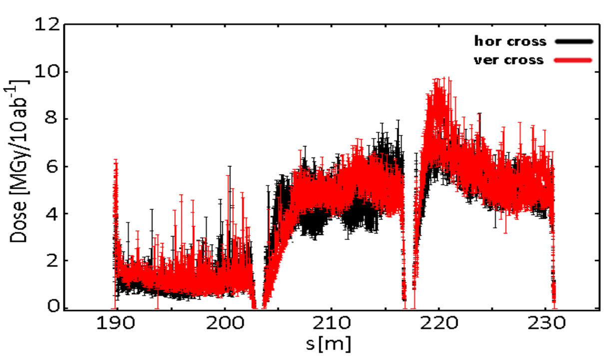

Figure 7: Peak dose profile for D1.

The doses are considerably lower than those on the quadrupoles. This is explained by the fact that the coils are not all around the beam, but located at angular positions of $n\pi/4$, with n being odd. On the contrary, most of the radiation is distributed in the respective crossing plane, with maxima at $m\pi/2$. The differences on the dose received by the EIR quadrupoles and dipoles are explicit by looking at the transverse peak dose in Fig. 8.

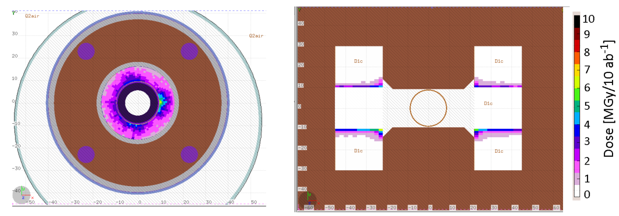

Figure 8: Transverse cross section of the magnets Q2 (left) and D1 (right), including the dose (in MGy/10 ab^{-1}) on the magnet coils.

Figure 9 shows the peak dose for D2. The dose for the vertical crossing is much lower than the horizontal one. This is because the TAN absorbs the collision debris distributed in the vertical plane, while letting some radiation in the horizontal plane through the pair of apertures for the particle beams [10]. In any case, the dose in the dipoles can be reduced by adding some shielding upstream each magnet [10].

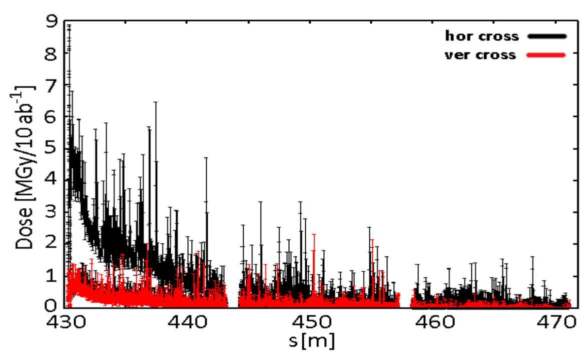

Figure 9: Peak dose profile for D2.

CONCLUSIONS

We have presented an alternative triplet for the FCC-hh, which has been optimized to minimize the energy deposition in the coils. Besides the round optics, this triplet can deliver a flat optics, as a solution in the absence of crab cavities. The flat optics does not only recover some of the luminosity lost without crab cavities, but it reduces the peak dose on the magnets too. In addition, we have shown the reduction on the peak dose if a scheme with a varying crossing angle is applied. Finally, we have performed radiation studies on the dipole separator magnets.

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