ENERGY DEPOSITION STUDIES FOR THE LHC INSERTION REGION UPGRADE PHASE-I

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Abstract

While the Large Hadron Collider (LHC) at CERN is starting operation with beam, aiming to achieve nominal performance in the shortest term, the upgrade of the LHC interaction regions is actively pursued in order to enhance the physics reach of the machine. Its first phase, with the target of increasing the LHC luminosity to 2-3 10^{34}cm^{-2}s^{-1}, relies on the mature Nb-Ti superconducting magnet technology and is intended to maximize the use of the existing infrastructure. The impact of the increased power of the collision debris has been investigated through detailed energy deposition studies, considering the new aperture requirements for the low-β quadrupoles and a number of other elements in the insertions. Effective solutions in terms of shielding options and design/layout optimization have been envisaged and the crucial factors have been pointed out.

INTRODUCTION

The present goal of the Phase-I Upgrade is to enable focusing of the beams to β* of 0.3 m and reliable operation at a luminosity of 2 to 3 L_0 (being L_0=10^{34}cm^{-2} s^{-1}). The upgrade concerns in the first place the low-β triplets in the two high-luminosity experiments, ATLAS and CMS, and assumes the same interface boundaries with the experiments as at now, located at 19 m on either side of the Interaction Point (IP). The low-β quadrupoles will feature a wider aperture than the present ones and will use the technology of Nb-Ti Rutherford-type cables cooled at 1.9 K developed for the LHC dipoles. The D1 separation dipoles, as well as a number of other elements in the insertions, will also be modified so as to comply with a larger beam envelope associated with a smaller β*. However, the present cooling capacity of the cryogenic system and the other main infrastructure will remain unchanged, and will ultimately limit the luminosity reach of the upgrade.

With high luminosities the protection of magnets and other equipment from particles generated in the collisions is of crucial importance. The starting point is to ensure that the magnets can sustain steady-state heat loads generated by the particle debris with adequate margin with respect to the quench limit. This issue has been studied in considerable detail for the present LHC triplets and the coil protection was steadily improved until a factor of three safety margin with respect to estimated quench limits was achieved for nominal luminosity L_0 [1].

As the power density from the debris scales with luminosity, it is clear that the protection efficiency of the magnets in the Phase-I Upgrade must be higher than in the present triplet. It is assumed for the purposes of the conceptual design that the heat transfer properties of the new low-β quadrupoles will be the same as in the present magnets, although work has started on improvements [2]. The same design limit for power density (4.3 mW/cm^3) is therefore assumed.

All the results presented in this paper were obtained with the Monte Carlo code FLUKA [3,4], relying on DPMJET3 as proton-proton event generator [5]. They refer to a half crossing angle of 225 μrad. It has to be understood that although the results are given with good statistical errors (about 10% for peak power values and less than 1% for integral values), they carry significant systematic uncertainties related to the extrapolation of cross sections to 14 TeV centre-of-mass energy, interaction/transport models, geometry and material implementation, crucial dependence on a very small angular range of the reaction products, etc. Thus, a safety margin of a factor of three in peak power density is a necessary assumption for this kind of calculations.

CHARACTERIZATION OF THE COLLISION DEBRIS

In the Insertion Regions (IR) 1 (ATLAS) and 5 (CMS), the interface boundary between the experiment and the LHC machine is represented by the TAS absorber, the function of which is to shield the triplet and reduce backscattering to the detector. In fact, only the first element (Q1) of the triplet profits from the protection of the TAS, which collects in its copper core a power ranging from 325 to 385 W with aperture decreasing from 55 to 45 mm for L=2.5L_0.

The fraction of the collision debris going through the TAS aperture is less than 10% in terms of particle number (counting the neutral pion decay products instead of the parent particle generated at the IP and immediately decaying), but corresponds to almost 80% as for energy, carried mainly by high energy protons, neutrons, charged pions, and photons.

Figure 1 shows the spectra of the particles inside the vacuum chamber at the exit of the TAS and of each of the four triplet magnets (Q1, Q2a, Q2b, and Q3). The magnetic field turns out to capture a significant amount of the charged component of the debris (mainly pions), leading it to shower outside the aperture limit represented by the beam screen. This capturing effect can be clearly appreciated from the difference between the black curve and the red one in the two right frames, displaying what is impacting the Q1, where the beam screen aperture, for the reasons discussed later, is reduced with respect to the rest of the triplet. The fractions of charged hadrons but protons hitting the following quadrupoles are also visible in the same frames. The purples curves give the debris component travelling beyond the triplet.

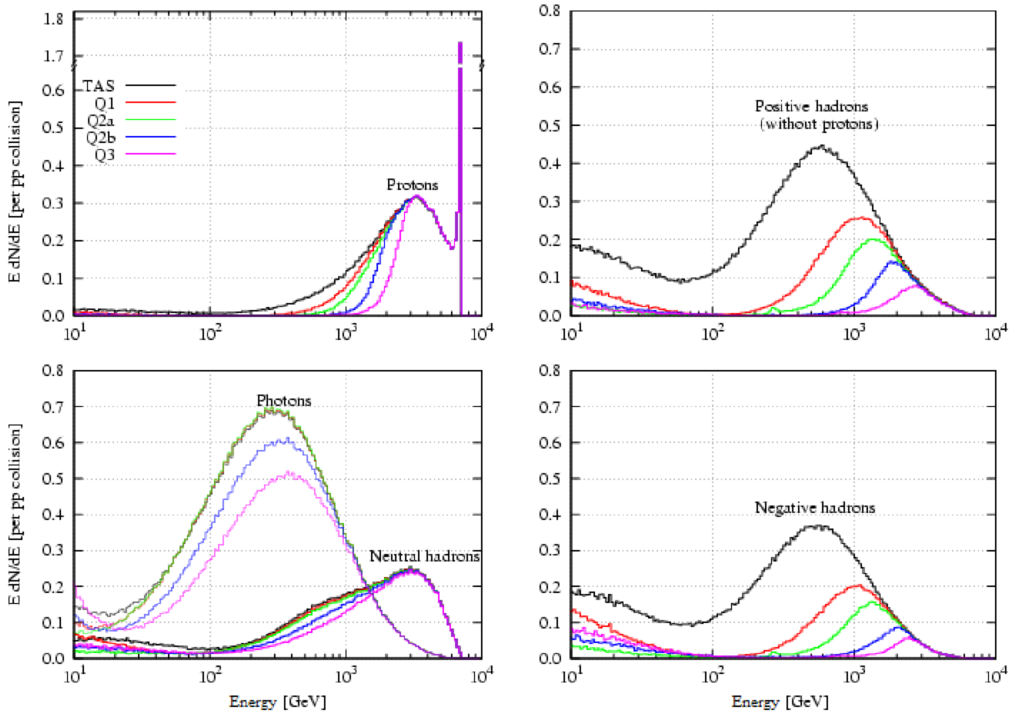

Figure 1: Spectra of particles in the vacuum chamber at the non-IP end of the TAS (black curve) and of each of the triplet quadrupoles (color curves). The four frames refer to different particle families as indicated.

High energy protons (top left frame) are captured in a smaller amount, mainly in the Q3, whereas the diffractive peak is expected to penetrate much deeper along the machine. On the other hand, for neutral particles (bottom left frame), not affected by the magnetic field, the shadow provided by the TAS covers the first half of the triplet (almost no primary photon and neutral hadron losses appear in the Q1 and Q2a), according to purely geometrical reasons. One has to take into account that secondary particles, generated by interactions of p+p primary products in the upstream elements (starting from the TAS), significantly contribute to the spectrum tails below 100 GeV.

POWER DEPOSITION IN THE MAGNETS

Previous studies [6] indicate that the peak power density for the luminosity of 2.5 L_0 is expected to be within the design limit along most of the triplet length. It has been evaluated by averaging over a minimum thermal equilibrium volume, taking the width/height of the scoring bin equal to the superconducting cable transverse dimensions and the length equal to the cable twist pitch. The peak in the coils exceeds the limit of 4.3 mW/cm^3 only in the second half of the Q1 and in the first part of the Q2a. A continuous liner (e.g. 3 mm tungsten) inside the vacuum chamber, extending in the interconnections too – since a larger aperture prolonged over a long longitudinal separation between the quadrupoles implies an abrupt increase in the energy deposition at the front face of the downstream magnet –, could effectively bring the expected values below the limit, significantly lowering the peak profile in the coils all along the triplet. As an alternative, thanks to the less strict aperture requirement for the Q1, a thick shielding can be included as part of the beam screen assembly of the first quadrupole, protecting the most exposed Q1 cables and dropping the maximum at the beginning (i.e. IP side) of the Q2a by the shadowing effect. For this purpose, it has to be noted that local shielding outside the cold bore tube (such as thick end plates) is of quite limited help.

Figure 2 shows the longitudinal profile of peak power density in the quadrupole cables for the preferred 120 mm coil aperture triplet (top frame). This layout includes, in addition to a 2 mm thick beam screen along the magnets and a 3.2 mm thick cold bore tube all along the triplet, a 10 mm thick stainless steel liner in the Q1. A two cable layer design is implemented. The cable composition and density are calculated taking into account the superconductor to copper ratio, kapton insulation and free void volume (filled by liquid helium). Both vertical and horizontal beam crossing schemes have been considered. The examination of the power density transverse maps at different longitudinal positions (bottom frames) points out that the peaks lie in the crossing plane and change position in the middle of the Q2a. E.g., in case of horizontal crossing, they move from the right (at positive x, according to the crossing angle sign) to the left (at negative x), as indicated by the two central maps, referring to the Q2a and Q3 maximum, respectively. The two longitudinal patterns reflect the different focusing-defocusing action in the crossing plane. In particular, the Q3 field is defocusing positively charged particles in the vertical plane and this implies, for vertical crossing, an increasing impact of the collision debris towards the end of the triplet and on the following beam line elements.

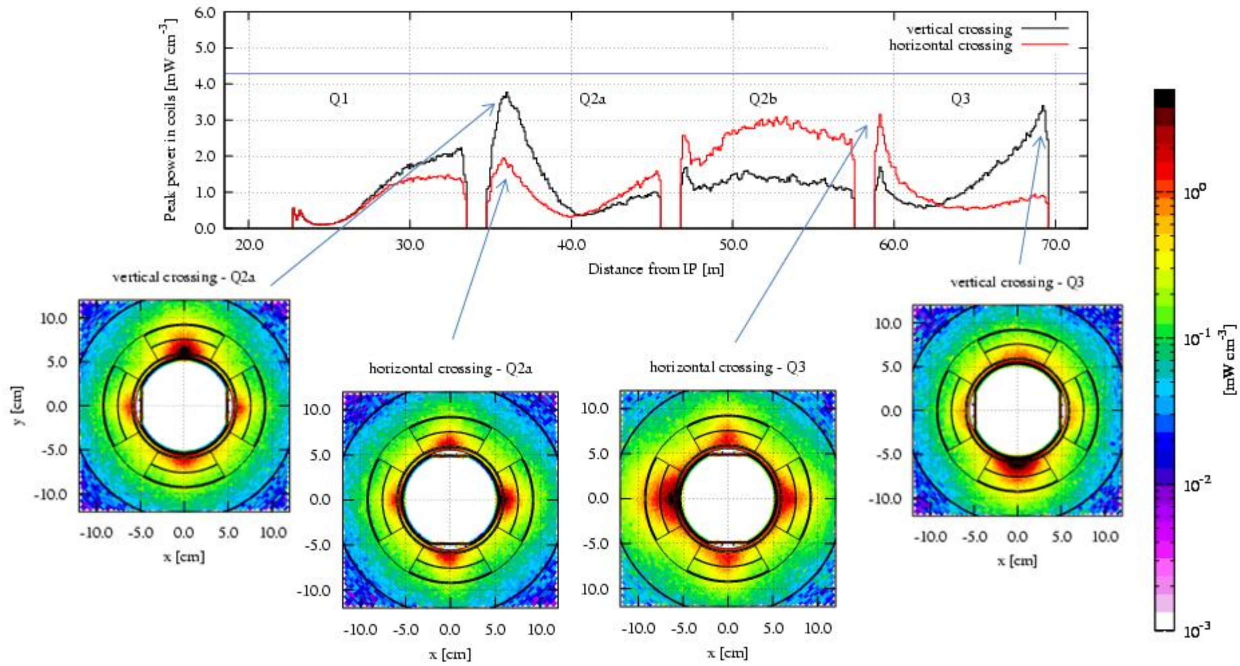

Figure 2: Top frame: Longitudinal profile of peak power density in the quadrupole cables for vertical (black line) and horizontal (red line) beam crossing. Bottom frames: Power density transverse maps at the longitudinal positions corresponding to the maxima indicated by the arrows. The coil aperture is 120mm. Power density values refer to 2.5 L_0.

Figure 3 refers to a possible corrector package downstream of the triplet, consisting of a short sextupole, a skew quadrupole, and two dipoles (horizontal and vertical). In case of vertical crossing, the remarkable peak close to the IP side of the first corrector magnet (red line), which is found on the vertical axis in the bottom half plane, is significantly reduced if adopting a larger aperture (black line), so profiting from the triplet shadow. That is the reason why the proposed 180mm D1 is predicted to stay quite far from quench levels (<1mW/cm^3). Moreover, the protection provided by a long liner exploiting the increased aperture margin, turns out to be beneficial for the last dipole (blue line).

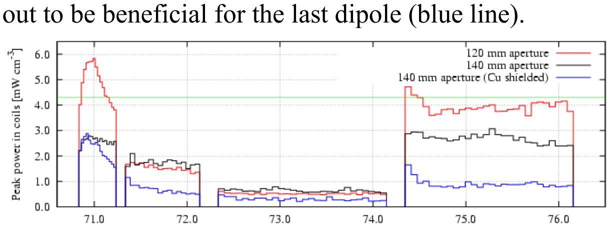

Figure 3: Longitudinal profile of peak power density – for L=2.5L_0 – in the corrector package cables for vertical beam crossing. The red and black curves refer to 120mm (as in the triplet) and 140mm coil aperture, respectively. In the case of the blue curve, a 10mm thick copper liner has been added inside the 140mm coil aperture.

The lower values displayed by the skew quadrupole and the horizontal dipole are due to the position of their coils, not lying on the vertical axis where the debris is mostly impacting for the considered crossing scheme.

The total heat load on the triplet and the corrector package for L=2.5L_0 is about 400 W at 1.9 K, which is still compatible with the existing maximum cooling capacity. In addition, 100 W have to be evacuated at higher temperature by the beam screen, half of which is intercepted by the thick liner in the Q1.

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