ENERGY DEPOSITION IN THE LHC HIGH LUMINOSITY INSERTIONS

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Abstract

The Large Hadron Collider (LHC) built at CERN now enters a starting-up phase in order to reach the present design luminosity (L_0) of 10^{34} cm^{-2} s^{-1}. A possible upgrade of the machine to a luminosity value of 10 L_0 requires a new design of some insertion region magnets, and will be implemented in essentially two phases. The energy from collision debris is deposited in the insertion region elements and in particular in the superconducting magnet coils with a possible risk of quench. The role of the key parameters (such as the magnet aperture, the crossing scheme, the thickness of a possible shielding liner...) is pointed out, with particular regard to the Nb-Ti superconducting (SC) magnets to be used for the phase-I upgrade, aiming to reach 2–3 L_0 [1]. The problem of the damage to the equipment is briefly addressed, characterizing the dose to the coil insulator and giving the expected high energy hadron fluences in the tunnel, relevant to single event errors of sensitive electronics.

INTRODUCTION

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 [2].

The interface boundary between the two LHC high luminosity experiments, ATLAS and CMS, and the LHC machine is located at about 19 m on either side of the interaction point (IP) and is represented by the TAS absorber, the function of which is to shield the triplet and reduce backscattering to the experiments. 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 going 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, as shown in Figure 1. The magnetic field of the low-beta quadrupoles turns out to capture a significant amount of the charged component

of the debris, leading it to shower outside the aperture limit represented by the beam screen.
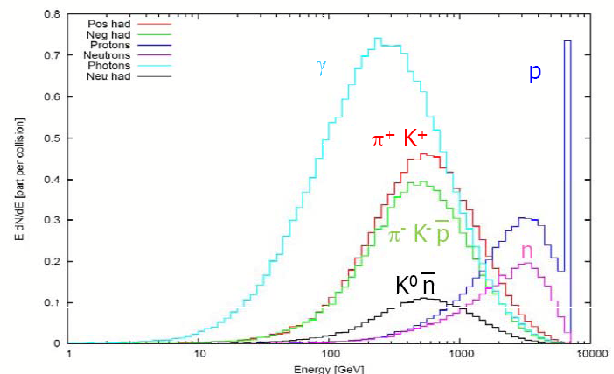

Figure 1: Spectra of the 14 TeV center-of-mass energy proton-proton collision products going through a 50mm diameter aperture at 21 m from the IP. The areas give the number of secondaries per collision which escape the TAS. Positive pions, negative pions and neutral kaons contribute to the integral of their curve by roughly 90%, 85% and 80%, respectively.

All the results here presented were obtained with the Monte Carlo code FLUKA [3, 4], relying on DPMJET3 as proton-proton event generator [5]. It has to be understood that although they 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 interaction/transport models, extrapolation of cross sections to the 14 TeV center-of-mass energy, 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.

POWER DEPOSITION IN THE MAGNETS

The energy deposition in the triplet depends on several parameters, notably on the distance from the IP, the triplet aperture, gradient and length. The last one can be treated as the free variable constraining the quadrupole strength, aperture and length. A parametric study, based on the "symmetric" layout [6] and $L^\star$ of 23 m, has been carried out considering the FDDF configurations indicated in Table 1 [7]. The aperture of the TAS was assumed 55 mm and the half crossing angle at the IP was 225 μrad in the vertical plane. Also the longitudinal separation between the

Table 1: The layout configurations in the parametric study of energy deposition in the new inner triplet.

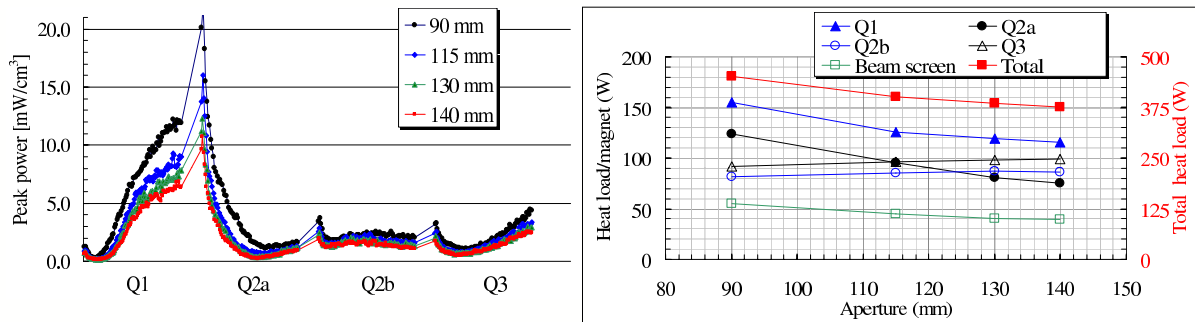| Aperture (mm)	Gradient (T/m)	L(Q1,Q3) (m)	L(Q2a,b) (m)	Total length (m)
90	156	8.69	7.46	36.2
115	125	9.98	8.42	40.7
130	112	10.81	9.04	43.6
140	104	11.41	9.49	45.7

Figure 2: Left: Longitudinal profile of peak power deposition in the SC coils for different apertures. Each magnet length has been rescaled so that the same length is obtained for different layout cases. Right: Integrated powers in the four triplet elements and in the beam screen as a function of the coil aperture. The total heat load in the triplet is also shown on the red scale on the right. Peak and integrated values refer to $L = 2.5L_0$.

magnets is an important parameter, as it defines the energy deposition at the entrance of the downstream magnet. The 1.3 m separation was taken, corresponding to the estimated minimum distance needed for interconnecting the magnets in the tunnel. The cold bore thickness was calculated to satisfy the pressure code requirements. The beam screen was 2 mm thick in all cases. The binning of the coil was chosen to correspond to a minimum volume of thermal equilibrium (radial and azimuthal widths of the bin equal to the cable transverse dimensions, length equal to the twist pitch of the cable). The heat transfer properties of the present magnets imply a design limit of 4.3 mW/cm^3 for power density, although work has started on improvements.

The results in Figure 2 show that the peak power density values in the SC coils decrease with increasing triplet length and quadrupole aperture. Also the total heat load in the triplet, including the beam screen, decreases with length, contrary to the load in the last two elements, Q2b and Q3. Other calculations pointed out that increasing the aperture has a less pronounced effect if the gradient and the layout remain identical.

One can note that the hot spot extends over the second half of Q1 and the IP-side of Q2a, where the peak power density reaches for $L = 2.5L_0$ unacceptable levels in any configuration. A continuous liner inside the aperture all along the triplet, covering the interconnections too, provides the SC cables with a substantial shield [8]. The alternative envisaged for the phase-I upgrade consists of a thick beam screen in Q1 fully exploiting the reduced aperture requirement in the first triplet magnet in order to cast a

shadow over the downstream quadrupole, effectively lowering the peak at the beginning of Q2a, as can be seen in Figure 3. The effect of this shadow is limited to the first half of Q2a. On the other hand, the role of special masks protecting the magnet front face outside the cold bore tube, has been found to be minor, indicating that the relevant part of the particle shower comes from the inside.

Both vertical and horizontal beam crossing schemes were considered and the power deposition maps show that the peaks, which are increasing with the crossing angle, lie in the crossing plane and change position in the middle of Q2a. The two patterns reflect the different focusing-defocusing action in the crossing plane. The vertical crossing features the maxima at the entrance of Q2a and at the end of Q3, and appears more disadvantageous for the elements downstream of the triplet, e.g. the two dipole correctors with the same coil aperture as the triplet of the case reported in Figure 3. The high peak power deposition on the front face of the first element downstream, very sharply localized on the vertical axis, can be significantly decreased by enlarging the downstream aperture with respect to the triplet one, this way obtaining once more the shadowing effect mentioned above and in addition making room for a shielding liner if needed to protect from the debris capture along the element length. Conversely, it has to be kept in mind that any abrupt reduction of the actual aperture is obviously implying a strong rise of the deposited energy.
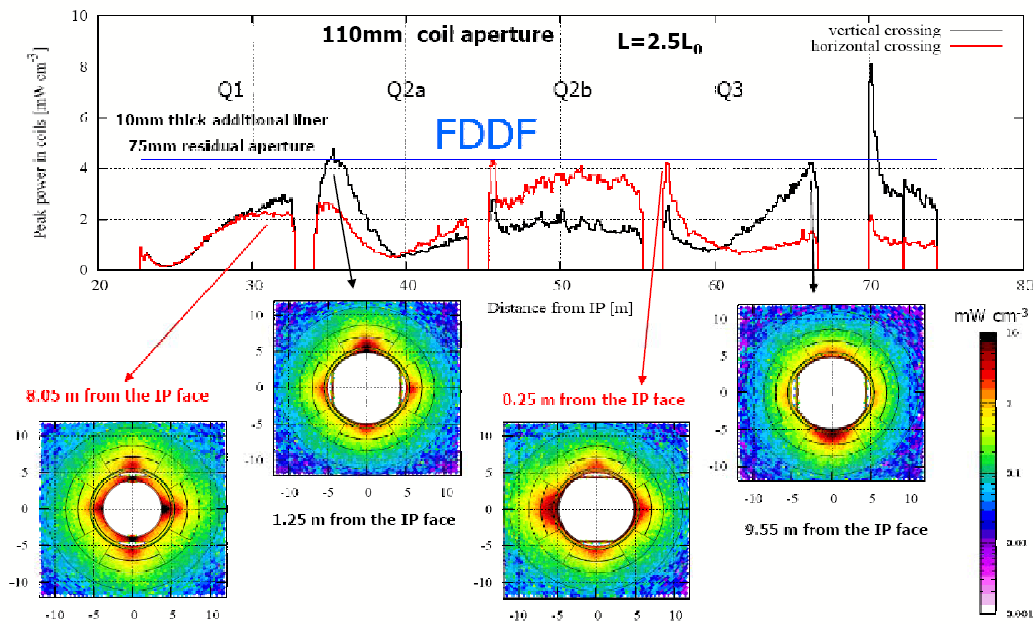
Figure 3: Top: Longitudinal profiles of peak power deposition in the SC coils for vertical and horizontal beam crossing. The layout includes a corrector package downstream of the triplet. Bottom: Power density transverse distributions at the indicated longitudinal maxima. In the left frame, referring to Q1, the thick stainless steel beam screen can be seen.

DAMAGE TO THE EQUIPMENT

In the present LHC triplets, a peak dose of 3.5 MGy is expected in the coil for a standard annual run during which 75 fb^{-1} of luminosity are accumulated. In the new phase-I upgrade triplets the dose in the coil inner layer is estimated at about 2 MGy/100 fb^{-1} but can reach about 5 MGy/100 fb^{-1} in the innermost strands of the cable. In fact, the dose has a strong azimuthal and radial dependence. The particle fluence over the coils is dominated by photons (about 85%), then neutrons (7%), electrons (3.5%) and positrons (2.5%) contribute. Peak neutron fluences are of the order of 0.5–1 10^{16} cm^{-2}/100 fb^{-1} depending on the coil aperture.

A further consequence of high luminosities is the significant level of hadron fluence on the electronics equipment. The CNGS run in 2007 has revealed that high energy (>20 MeV) hadron fluence above 10^8 cm^{-2} may provoke many failures in sensitive electronics due to single event upsets. The alcoves close to the experiment caverns where the electronics of the installed triplets is now housed (UJ56 for CMS and UJ14 and UJ16 for ATLAS), are exposed - for the present machine layout – to a fluence of high energy hadrons above 10^9 cm^{-2}/100 fb^{-1}, whereas values above 10^{12} cm^{-2}/100 fb^{-1} are reached around the beam line elements. Therefore, radiation tolerance of electronics in the tunnel and shielded areas nearby must be assured.

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