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LHC LUMINOSITY UPGRADE: PROTECTING INSERTION REGION MAGNETS FROM COLLISION DEBRIS

E.Wildner, F. Cerutti, A. Ferrari, M. Mauri, A. Mereghetti

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The Large Hadron Collider built at CERN now enters a starting-up phase where the present design luminosity up to 10^{34} cm^{-2} s^{-1} will be reached after the running in phase. A possible upgrading of the machine to luminosity up to 10^{35} cm^{-2} s^{-1} requires a new insertion region design, and will be implemented in essentially two phases. The energy from collision debris is deposited in the insertion regions and in particular in the superconducting magnet coils with a possible risk of quench. We describe here how to protect the interaction region magnets against this irradiation to keep the energy deposition below critical values estimated for safe operation. The constraint is to keep the absorber size as small as possible to leave most of the magnet aperture available for the beam. This can be done by choosing a suitable material and design minimizing the load on the cryogenic system. Here we will describe design proposals for the phase I upgrade lay-out, i.e. luminosity up to 2.5 10^{34} cm^{-2} s^{-1}.

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Abstract

The Large Hadron Collider built at CERN now enters a starting-up phase where the present design luminosity up to 10^{34} cm^{-2} s^{-1} will be reached after the running in phase. A possible upgrading of the machine to luminosity up to 10^{35} cm^{-2} s^{-1} requires a new insertion region design, and will be implemented in essentially two phases. The energy from collision debris is deposited in the insertion regions and in particular in the superconducting magnet coils with a possible risk of quench. We describe here how to protect the interaction region magnets against this irradiation to keep the energy deposition below critical values estimated for safe operation. The constraint is to keep the absorber size as small as possible to leave most of the magnet aperture available for the beam. This can be done by choosing a suitable material and design minimizing the load on the cryogenic system. Here we will describe design proposals for the phase I upgrade lay-out, i.e. luminosity up to 2.5 10^{34} cm^{-2} s^{-1}.

THE PHASE I UPGRADE SCENARIO

The consolidation of the Large Hadron Collider inner triplets for luminosities up to 2.5 10^{34} cm^{-2} s^{-1} (proton-proton collisions) is presently being prepared [1]. Replacement of the triplet magnets is planned to house larger beams with larger beam separation due to the smaller β* and the resulting larger crossing angle. An important aspect of the design of the magnets is the resistance to the energy released by the collision debris.

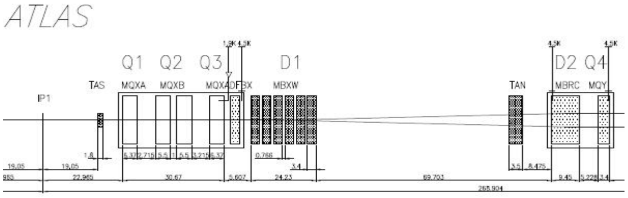

Figure 1: The insertion region 1

An excessive local energy deposition in the superconducting cable may induce magnet quench. One also has to minimize the overall energy transferred to the cryogenic system, i.e. to the helium bath in the magnets and the helium carrying the heat from the beam screen [2], taking into account the limiting constraints on each of them. Good repartition of the absorbed power between the cryogenic systems is granted by choosing a good dimensioning of beam screens and shielding.

Several proposals of triplet optics have been published [3-4]. The initial baseline adopted in the upgrade working group [1] is based on the work described in [3]. The triplet we have used for the evaluation is symmetric, which means the same gradient in all triplet magnets, one length for the Q1 and Q3 magnets and a different length of the two Q2 magnets. Among the different cases discussed in [1] we used the 130 mm aperture as a first baseline. During the study this baseline was modified, see Table 1 where we show both configurations (Case1/Case2). The gradient in the magnets is 122 T/m for Case 1 and 112 T/m for Case 2. Here *D* denotes the front face position of the magnet from the collision point. For Case 2 a 1.2 m long dipolar corrector magnet (QC) of 0.47 Tm (i.e. the MBCX kick for nominal optics) is included between the Q1 and the Q2 magnets counterbalancing the crossing angle for particles coming from the IP.

This study, performed with a vertical crossing angle, reveals important criteria that will be used to set up the shielding design for the final triplet choice.

TABLE 1
DATA FOR THE TRIPLET LAYOUT.

	Case 1 (end at 64.00m)		Case 2 (end at 67.10m)	
Magnet	*D*[m]	Length [m]	*D*[m]	Length [m]
Q1	23.00	9.40	23.00	10.23
QC	-	-	33.24	1.2
Q2a	35.15	7.80	35.98	8.52
Q2b	43.75	7.80	45.30	8.52
Q3	54.60	9.40	56.87	10.23

Three models, a resistive (R), a super-ferric (SF) and a super-conducting (SC), of the D1 separation magnet (see Figure 1), have been investigated. The vertical aperture of the R and the SF models is 120 mm. The SC magnet aperture is 130mm with vertical beam screen.

TABLE 2
DATA FOR THE D1 SEPARATION MAGNET.

Magnet	No	D[m]	Field [T]	Length [m]
R	6	72.6	1.4	3.4
SF	6	72.6	1.4	3.4
SC	1	72.6	4.5	6.0

PROTECTING THE MAGNETS

The TAS protects the first magnet from the collision debris. The TAS aperture should be as small as possible to protect the magnet, but large enough to give sufficient beam clearance. The aperture of the TAS for the upgrade has been increased from 34 mm to 55 mm to comply with upgrade beam conditions.

The cold bore tube (CBT) and the beam screen (BS) are also shielding the magnets. The thicknesses of the CBT and the BS are derived from the aperture and set by mechanical constraints. For 130 mm aperture we get a CBT thickness of 3.44 mm and the BS thickness is 2 mm.

The energy deposition in the triplet has first been studied without extra shielding i.e. only with the TAS, having the same length and outer dimension as the present TAS, and the CBT and BS of the quoted minimum thickness. Since we assume β*=0.25 m, the half crossing angle is 220 μrad. The peak power density in the inner cable, resulting from calculations using FLUKA [5-6] is shown in Fig. 2 The outer cable has considerably lower power deposition, and therefore not shown for clarity.

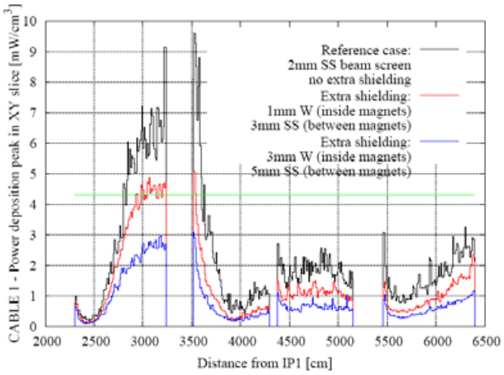

Figure 2: Peak power density in the inner cable for the reference case and for different shielding thicknesses [Case 1]. The shielding is continuous over the triplet.

Fig. 2 shows that the two first magnets need extra shielding: the recommended limit for the power deposition in the cable is 4.3 mW/cm^3 [7]. The first approach is to insert continuous liners of different thickness inside the magnets over the whole triplet to estimate the shielding effects, a second approach is to use the available aperture in the Q1 magnet to insert a very thick liner to protect and to “shadow” the cable at the entrance of Q2.

Continuous liners inside apertures

To keep the aperture as large as possible we used an efficient non magnetic shielding material (tungsten) inside the magnets, between the BS and the CBT. We know that the energy is mainly deposited in the horizontal and vertical directions, so we propose a liner as in Figure 2.

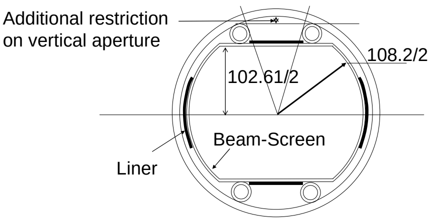

Figure 3**:** One possible proposed layout for protection inside the magnet, this example is for 3 mm W layers between the BS and the CBT.

Between the magnets we used stainless steel since we have more space. We show the efficiency of the different liner thicknesses in Figure 3. An additional 1 mm thick tungsten liner inside the magnets with a 3 mm thick stainless steel liner in the interconnections reduces the peak power density in the second quadrupole (Q2a) by a factor 2, bringing Q1 and Q2a close to the target 4.3 mW/cm^3.

A shielding close to the aperture between the magnets is important for protecting the cable at the beginning of the downstream magnet from the collision debris in the solid angle corresponding to the magnet interdistance. The shield of 3 mm tungsten if usable at low temperature or 5 mm stainless steel is a safe choice.

Thick shadowing liner in Q1

An alternative way to shield the Q1 and to limit the peak in the first Q2 magnet [7] is to use the available aperture in Q1 to insert a thick liner to “shadow” also the entrance of Q2. In fact the beam size in Q1 is smaller than in the other triplet magnets and since in this layout all magnets have the same aperture, a large clearance between the beam size and the magnet is found in the Q1. We have chosen the largest liner thickness permitted by the 130 mm aperture in Q1, i.e. 13 mm, and 8 mm for comparison (see Fig. 4). The liner extends also in the corrector magnet, which is powered (the effect of its dipole magnetic field is not crucial). There is no effect of the thick shield after the first half of the Q2a magnet. The total heat deposited in the triplet for the case of the thicker liner is shown in Table 3. The total power deposited in the triplet is 428 W (QC included), the 27% of which is absorbed by the BS and the extra-shielding, cooled at a higher temperature than the rest. A study of the dependence of energy deposition on the triplet length for the Nb-Ti case can be found in [8].

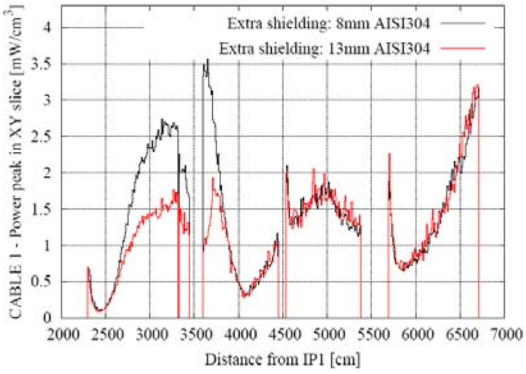

Figure 4: Thick liner in Q1 and in QC [Case 2].

TABLE 3

TOTAL POWER DEPOSITED IN TRIPLET MAGNETS [W] [CASE2]

Magnet	Q1	Q2a	Q2b	Q3	QC
Beam Screen	14	5	10	14	4
Shielding	56	/	/	/	12
Beam Pipe	7	6	12	16	1
1st cable	17	11	23	25	4
2nd cable	10	5	10	12	/
S-Steel Collar	21	10	18	25	/
Iron Yoke	24	10	15	22	8
TOTAL	150	46	88	115	29

The horizontal crossing changes the shape of the peak power deposition profile, increasing values in Q2b (by

~75%) and in particular at the entrance of Q3 (3.6 mW/cm^3). A liner in the interconnection before Q3 could be envisaged, however the distance between the magnets will probably be reduced to 1.3 m, thus reducing the build-up of the peak on the Q3 front face.

Influence of the crossing angle

The effect of the crossing angle on the peak power density is shown in Fig. 5 for three cases: no crossing angle, 142.5 µrad (nominal LHC) and 220 µrad (upgrade with β^*=0.25 m). Q1, Q2a and Q3 are affected. When the crossing angle is increased, a larger fraction of the central part of the debris cone (where particles are more energetic [9]) are intercepted, thus implying an increase in the peak values.

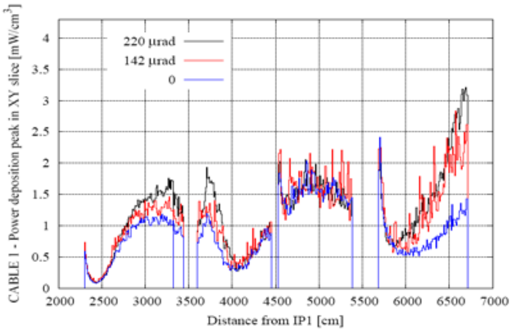

Figure 5: Power deposition in the triplet for different values of the vertical crossing angle [Case 2 with 13mm stainless steel extra-shielding in Q1 and QC].

The effect of a dipole field of 1.8 Tm in the TAS, i.e., between the IP and the triplet, has also been investigated. The overall results indicate that a magnetic TAS can reduce the deposited power in the triplet, see Figure 6.

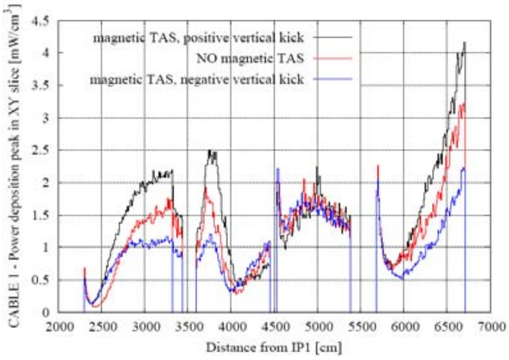

Figure 6: Power deposition in the triplet for different dipolar magnetic fields in the TAS [Case 2 with 13mm stainless steel extra-shielding in Q1 and QC].

The D1 magnet

We also considered the energy deposition in the first separation dipole D1. The peak power density in the cables of SC and SF models is below the recommended limits without any extra shielding; indeed, preliminary results with horizontal crossing angle indicate that for the SC model, due to its coil design, the 4.3 mW/cm^3 limit is approached. Both in the SF and in the R magnets an important issue is the energy deposition in the return coils, in particular for the modules closest to the IP. An important constraint for the R magnets is to keep a low dose to prevent ageing of the resin in the coils: the limit design values for the R magnets in the LHC are 10 to 50 MGy. The estimated dose of 2.5 MGy/y (Table 4, for a total luminosity of 2.5 120 10^{15} b^{-1} y^{-1}) would imply reaching the lowest limit in 4 years. Shielding of the front face of the R magnet or a different return coil design (keeping them farther from the beam) should be envisaged.

TABLE 4
SUMMARY D1(NO SHIELDING)

Magnet	Power Peak in cable [mW/cm^3]	Total [W]	Dose Peak in cable [MGy/y]
R	-	196 (all 6)	2..5
SF	2.8	185 (all 6)	-
SC	1.5	82	-

CONCLUSIONS

The 130 mm aperture magnets for the triplet can be shielded from the collision debris by a liner of 3 mm tungsten inside every magnet plus a liner of 5 mm stainless steel between the magnets. Another possibility is to insert a thick liner of at least 8mm stainless steel covering the Q1 and the corrector to shadow the entrance of Q2a. A liner (a thicker beam screen) over the complete triplet can redistribute the deposited power to different cryogenic systems. The SC solution for the D1 (130 mm aperture) comes out to be feasible. The return coils of the R model should be either re-designed or protected.

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