IMPACT OF COLLISION DEBRIS IN THE HL-LHC ATLAS AND CMS INSERTIONS*

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Abstract

The High Luminosity upgrade of the LHC (HL-LHC) foresees the baseline operation of the accelerator at a 5 times higher peak luminosity (5.0×10^{34}cm^{-2}s^{-1}). The impact of collision debris on the magnets and other equipment in the triplet region and matching section of the ATLAS and CMS insertion regions (IRs) has been evaluated by means of detailed FLUKA models implementing the latest optics and layout version. Qualitative and quantitative differences between the vertical and horizontal beam crossing schemes are highlighted. The role of dedicated measures to mitigate the effects of the beam-screen interruption in the triplet interconnections and the Q4 aperture reduction is investigated. Total heat loads in magnets and protection elements were also estimated, along with dose and particle fluence maps relevant for Radiation to Electronics (R2E) aspects. The effect of a displacement of the interaction point is also addressed.

INTRODUCTION

In view of the High Luminosity upgrade of the LHC (HL-LHC) [1], a careful study of the radiation impact on machine elements and surrounding areas from physics debris is essential in order to identify potential weaknesses in the machine protection scheme and to estimate quantities relevant for cryogenics, electronics equipment etc. Indeed, the higher rate of proton-proton collisions in HL-LHC (5 times the nominal peak LHC luminosity, after levelling) and the target integrated luminosity of 3000 fb^{-1} (one order of magnitude higher than the LHC before the upgrade), pose new challenges for machine protection. The degradation of the coil insulation in the super-conducting magnets due to accumulated dose is the most challenging aspect; different solutions, such as beam-screens with Inermet (95% tungsten) absorbers and shielded interconnections in the triplet and collimators and masks in the matching section (MS) have been adopted in order to keep peak dose values in the coils below the operational limit of 30 MGy, while providing a sufficient margin with respect to the adopted design limits (12 mW/cm^3 in the Nb_3Sn and 4 mW/cm^3 in the Nb-Ti coils), embedding a safety factor of 3 with respect to expected quench levels. The goal of the present study is to provide an updated estimate of relevant quantities for the latest layout and optics baseline scenario in the IR1 (ATLAS) and IR5 (CMS) insertion regions.

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SIMULATION SETUP

Detailed geometries of the ATLAS and CMS Insertion Regions have been built with the FLUKA code [2, 3], including a 3D description of the tunnels and using the latest hardware designs of the various objects. The exact positioning of all elements, as well as the magnetic settings, are generated automatically based on the optics files [4] and checked against the ideal beam trajectory. In particular, version 1.3 of the HL-LHC ATS round optics, with β^*=20 cm and a half crossing angle of 255 μrad, was used as a basis for these calculations. The crossing scheme is vertical and horizontal for IR1 and IR5 respectively. Results are normalised assuming an inelastic proton-proton cross-section of 85 mb at 7 TeV beam energy, an instantaneous luminosity L=5.0×10^{34}cm^{-2}s^{-1} and an integrated luminosity L_{int}=3000 fb^{-1} for the entire HL-LHC lifetime.

ENERGY DEPOSITION IN THE INSERTION ELEMENTS

Triplet-D1

The peak dose profile in the triplet-D1 coils is shown in Fig. 1. Despite qualitative differences between horizontal and vertical crossing, values remain mostly below 20 MGy for an integrated luminosity of 3000 fb^{-1} with local peaks not exceeding 30 MGy in both cases. Peak power density values remain below 3 mW/cm^3, comfortably lower than design limits. The steady-state heat power that needs to be evacuated by the cryogenics system has been estimated and the results are summarised in Table 1. The adequate protection of the triplet and D1 is achieved by a combination of hardware solutions, two among which have a prominent contribution: the beam-screen absorbers and the refined design of the interconnects between consecutive cryostats.

Beam Screen Absorbers The octagonal 1 mm thick beam screen in the HL-LHC triplet is fitted with Inermet absorbers in order to mitigate the radiation impact to the coils. The shielding in Q1 has a maximum thickness of 16 mm at the mid-planes. From Q2 to D1, the maximum thickness is 6 mm and the shielding is extended towards the poles along about 20% of its length, as explicitly modelled in the FLUKA geometry. It has been shown [5] that the absence of these absorbers can lead to an increase of peak dose values by several times. It is also worth noting that the addition of the absorbers re-balances the heat load share between the 1.9 K cold mass circuit and the higher temperature one extracting heat from the beam-screen, as can be seen in Table 1.

Triplet Interconnects The harmful role of the interruption of the beam-screen shielding in the interconnects has

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Table 1: Total Power (W) Deposited in Triplet-D1 Region and Matching Section for a Luminosity of $5.0\times10^{34}cm^{-2}s^{-1}$.

	Vertical crossing		Horizontal crossing	
Magnets	**Magnet cold mass**	**Beam screen**	**Magnet cold mass**	**Beam screen**
Q1A + Q1B	114	170	113	168
Q2A + corr.	101	68	96	62
Q2B + corr.	126	87	137	98
Q3A + Q3B	134	80	118	68
CP	54	62	45	49
D1	79	56	67	46
Beam pipe extensions	21	72	19	64
TOTAL Triplet-D1	**629**	**595**	**595**	**554**
D2 + corr.	17	1.1	33	1.9
Q4 + corr.	6.8	0.2	8.2	0.4

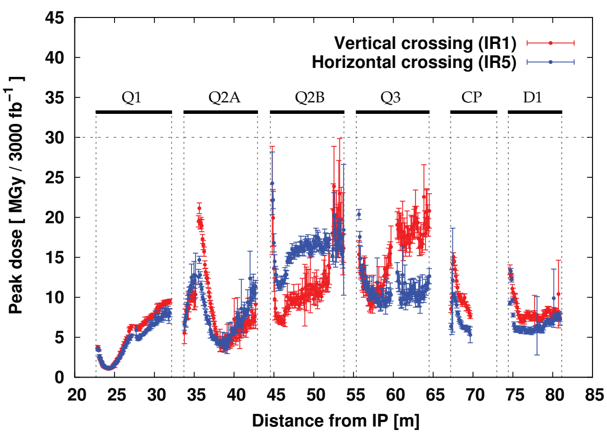

Figure 1: Peak dose profile in the triplet-D1 inner coils for horizontal (blue) and vertical (red) crossing in IR1 and IR5 respectively. The 30 MGy operational limit is also shown. (CP stands for 'Corrector Package'.)

already been identified [6] and can locally lead to peak dose values in the coils in excess of the 30 MGy limit even for gaps of 50 cm. This gap was over 70 cm long in the original interconnect design for the HL-LHC triplet, leading to peak dose values of 36 MGy on the IP-face of Q2B. The addition of a 7 cm Inermet insert acting as an extension of the beam-screen shielding on the non-IP side of the interconnect, as well as the replacement of the cylindrical BPM (Beam Position Monitor) with an 'octagonal' variant featuring 18 cm long Inermet inserts on the mid-planes lead to a reduction to 26 MGy. At present, this improved design was only assumed for the interconnect preceding Q2B, where the highest dose peak was observed.

Matching Section

The maximum peak dose values in the matching section are found on the IP-face of D2 and reach 6 MGy and 12 MGy for vertical and horizontal crossing respectively, while peak power density values remain below 1 mW/cm^3.

With the decision to postpone the use of a new 90 mm aperture design (MQYY) for Q4, remaining instead with the current 70 mm aperture MQY, the presence of an Inermet mask (TCLMB), 1 m in length and 14 cm in external diameter, on the outgoing beam bore became essential for the protection of the magnet. Indeed, even a 2 mm increase in its aperture (now fixed to the dimensions of the Q4 beam-screen) can lead to worrying peak dose values of about 35 MGy in the IP-face of the first Q4 corrector, highlighting also the need for its accurate alignment. Similar masks are foreseen in front of Q5 and Q6, between the respective TCL collimator and the magnet. A smaller variant (TCLMC) with a 10 cm external diameter is to be used for Q6.

The expected heat loads on D2 and Q4 are given in Table 1. As far as the protection elements are concerned, the 85 mm twin aperture TAXN absorber receives about 740 W for horizontal crossing and about 1 kW in the vertical case, where the peak of the debris distribution impacts the centre of the absorber, rather than nearer the outgoing beampipe. Consequently, this entails a larger leakage towards the MS in the horizontal case. Indeed, TCL4 receives a total of 280 W in horizontal crossing (only 80 W in vertical), while the TCL5 and TCL6 receive 95 W (50 W) and 40 W respectively. The tertiary collimators on the incoming beam receive up to 25 W in the worst case (TCTH4). The difference is quite marked also in the case of D2. Among the masks in the MS, only the one on the outgoing beam in front of Q4 is expected to take around 20 W, with values up to a few W in all other cases. Up to a few hundreds of mW will be deposited in the crab cavities, located after D2, where a maximum dose of 2 MGy is estimated for 3000 fb^{-1}.

Dispersion Suppressor

Beam losses in the dispersion suppressor (DS) are composed mainly of off-momentum protons with a $\delta p/p_0$ of 2-20% up to cell 9, 1-2% up to cell 11 and below 1% in cell 13 (up to 550 m from the IP). The peak power density profile in the DS of IR5 is shown in Fig. 2 for a scenario with TCL6 in garage position (25 mm halfgap) and TCLs 4 & 5

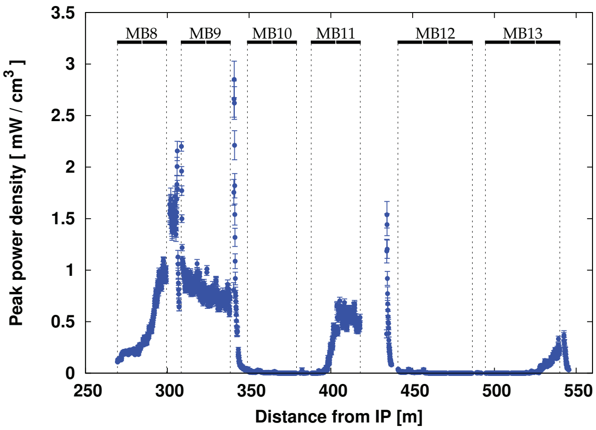

Figure 2: Peak power density profile in the dispersion suppressor coils for horizontal crossing assuming the TCL6 in garage position. Its closing has an impact only up to cell 8.

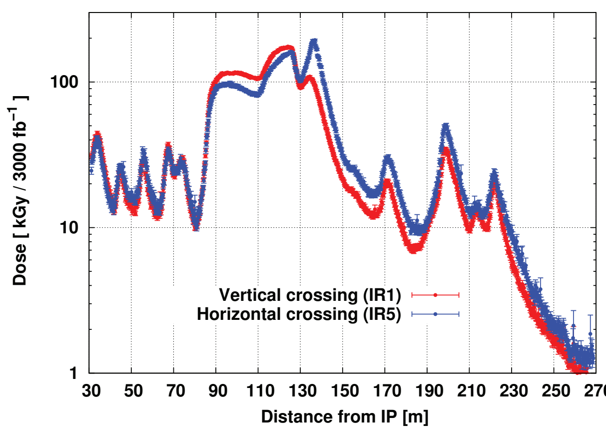

Figure 3: Dose profile in the tunnel at beam elevation and at x=-1.6 m, for horizontal (blue) and vertical (red) crossing. From left to right, the peaks correspond to the triplet-D1 interconnects, the TAXN and TCL4 around 130 m, the Q4 mask, TCL5 and TCL6.

at 12σ. Compared with the present LHC, losses in the DS scale with luminosity with the exception of cell 8, where the cleaning from the TCLs is less effective. Peak power density values in the coils are nevertheless found to remain below 3 mW/cm^3, still within operational limits. Peak dose values, on the other hand, may locally challenge the insulator limit, in particular on the MQMC magnet in cell 9.

RADIATION IN THE TUNNEL

Electronic components and other equipment present in the tunnel and adjacent areas are exposed to a mixed radiation field which varies significantly in intensity and composition depending on the exact location with respect to the loss points. This exposure induces both cumulative and stochastic effects that can lead to permanent or temporary failures. Long-term effects are related to Total Ionising Dose and displacement damage (generally associated to 1-MeV neutron equivalent fluence), while the frequency of Single Event Effects is dependent on the accumulated high energy hadron fluence. Figure 3 shows the dose profile in air at beam elevation and at a distance of 1.6 m from the beamline inside the ring for vertical and horizontal crossing. As before, higher dose levels are observed in the matching section in the horizontal case. Yearly (per 250 fb^{-1}) high energy hadron fluence and 1-MeV neutron equivalent fluence values of 3×10^9 cm^{-2} and 3×10^{10} cm^{-2} respectively are expected in the RR alcoves (except near their entrance), where the radiation impact is strongly dependent on the TCL6 settings (here closed at 12σ, representing the most severe scenario). Values are 5×10^9 cm^{-2} and 5×10^{10} cm^{-2} in the UJ and 10^8 cm^{-2} and 10^9 cm^{-2} in the UL, while in more exposed sections of the tunnel they can exceed 10^{13} cm^{-2} and 10^{14} cm^{-2} respectively.

INTERACTION POINT DISPLACEMENT

The displacement of the IP by up to 2 mm downwards through an orbit bump may be implemented in order to compensate for the incorrect centring of the experiments (e.g. due to ground motion). This can have an important effect on the impact to the IR magnets: in a vertical crossing scenario with the outgoing beam moving towards negative y at the IP, a downwards vertical displacement of the IP will lead to the peak of the debris distribution entering the triplet further off-centre in a region of higher magnetic field, resulting in a larger deflection and impact on the triplet elements which can increase peak power density values in the coils by up to few tens of percentage points. An upwards crossing will instead move the debris closer to the beam-line axis where it will encounter lower magnetic field values, reducing the impact.

CONCLUSION

With the appropriate protection measures in place, peak dose values in the triplet-D1 coils remain below the adopted limit of 30 MGy, with peak power density values well below the quench limit all the way to the dispersion suppressor. In the matching section this is achieved thanks to the presence of collimators and masks on the outgoing beam (especially before Q4). A further mitigation of peak dose values could be achieved by regularly switching crossing planes between IR1 and IR5, a possibility that is under consideration but is not included in the present baseline. Quantities relevant for R2E generally scale with luminosity compared to the present LHC, but depend locally (e.g. in the RR alcoves) on the operational collimator settings.

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