BEAM HALO ON THE LHC TCDQ DILUTER SYSTEM AND THERMAL LOAD ON THE DOWNSTREAM SUPERCONDUCTING MAGNETS

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Abstract

The moveable single-jawed graphite TCDQ diluter must be positioned very close to the circulating LHC beam in order to prevent damage to downstream components in the event of an unsynchronised beam abort. A two-jawed graphite TCS.IR6 collimator forms part of the TCDQ system. The requirement to place the jaws close to the beam means that the system can intercept a substantial beam halo load. Initial investigations indicated a worryingly high heat load on the Q4 coils. This paper presents the updated load cases, shielding and simulation geometry, and the results of simulations of the energy deposition in the TCDQ system and in the downstream superconducting Q4 magnet. The implications for the operation of the LHC are discussed.

LHC BEAM DUMP AND TCDQ PROTECTION SYSTEM

To protect the LHC aperture against particles in the abort gap and unsynchronised beam aborts, a single sided mobile diluter TCDQ [1], in combination with a collimator TCS.IR6 and an iron shield TCDQM, will be installed in front of the Q4 superconducting magnet in the IR6 dump insertion. The TCDQ is comprised of two 3.0 m long single-sided graphite absorber blocks, moved horizontally as a unit, and is followed by a 1 m two-sided carbon-composite TCS.IR6 collimator.

At 450 GeV the TCS.IR6 jaws are nominally set at 7 σ, the TCDQ at 8 σ. At 7 TeV the low-β triplets are protected by tertiary collimators TCTs set at 8.5 σ [2]. The tungsten TCT jaws must be in the shadow of the TCDQ, since they could be easily damaged. In collision, therefore, the TCS.IR6 jaws are set at 7.5 σ, the TCDQ at about 8.5 σ.

The tight settings of the TCDQ system mean that the low-Z jaws could intercept a significant load when the LHC beam lifetime is low. This could be an operational limitation, as the TCDQ system must remain close to the beam to protect the aperture, while not inducing a quench in the downstream superconducting magnets MQY (Q4) and MCBY (corrector). The power deposition should not exceed the limits in Table 1.

Table 1: Assumed quench limits for the superconducting MQY and MCBY elements in IR6

Quench limit	450 GeV	7 TeV
Instantaneous	35 mJ/ cm^3	4 mJ / cm^3
Localised power	10 mW / cm^3	5 mW / cm^3
Total power	20 W	20 W

Previous results using a pessimistic halo distribution based on the worst-case cleaning inefficiency gave continuous power depositions in the superconducting coils which were a factor of 5-10 above the acceptable limits, at both 450 GeV and 7 TeV [3]. The simulations were made for LHC Beam 1, which due to the asymmetric layout of the machine is expected to provide a lower beam load on the TCDQ system than for Beam 2.

At 450 GeV there is some operational margin, as the TCDQ jaws can easily be retracted by several σ, reducing the halo load, without compromising the protection of the LHC. However, at 7 TeV there is no such flexibility, and the system has to be positioned at the design settings at all times. In this paper the results from the updated load cases at 7 TeV are presented, including an analysis for both beams for the nominal collimation scheme.

SIMULATED BEAM HALO LOAD

The beam halo load on the TCDQ system elements was simulated in the context of the performance of the overall LHC collimation system using SixTrack [4] to track an initial distribution of about 5×10^6 p+ around the LHC over about 200 turns until almost all particles are lost. Scattering routines are used at collimators, and the LHC aperture model is included. Loss locations are recorded with a resolution of 10 cm. Nominal collimation settings were used for the nominal collisions optics with $\beta^* = 0.55$ m. The simulation assumed a perfect LHC orbit and no geometrical aperture errors. The initial halo distribution was assumed to be either all in the vertical or horizontal direction; the results were found to be similar, so that in the following only the slightly less favourable horizontal halo is presented.

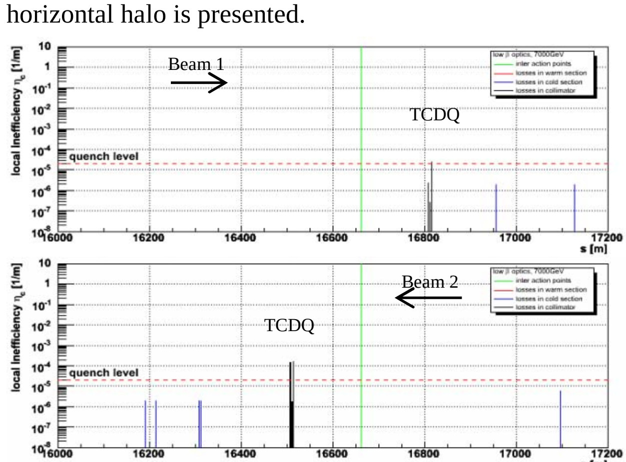

Figure 1: 7 TeV IR6 loss maps for Beams 1 and 2.

Fig. 1 shows the loss pattern around IR6 for the two beams, with the high loss peaks at the TCDQ system clearly visible for both Beam 1 and Beam 2 cases. The loss pattern shows a factor ~15 difference between the TCDQ systems for Beam 1 and Beam 2, due to the layout asymmetry between the collimation and dump insertions in IR7 and IR6. The loss pattern shows that there is no direct beam loss on the superconducting Q4 aperture.

The X-Y distributions for Beam 1 and Beam 2 are shown in Fig. 2 for the nominal collimation case. The shadowing of the left-hand TCS.IR6 jaw by the one-sided TCDQ is visible, together with the much larger impact parameters on the TCDQ for Beam 2. The results gave maps of inelastic scattering locations in the TCDQ and TCS.IR6 jaws, as input for the FLUKA routines.

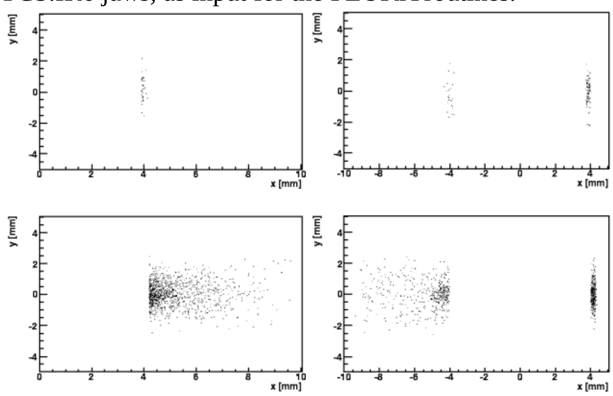

Figure 2: Particle distributions on the TCDQ (left) and TCS.IR6 jaws, for Beam 1 (top) and Beam 2 cases.

The details of the numbers of protons simulated and lost directly in the various IR6 elements are given in Table 2, for the different cases studied. The absolute loss at a particular element is calculated by assuming that the full nominal LHC beam of $I_o = 3.2\times10^{14}$ p+ has an exponential lifetime τ of 720 s (0.2 h) corresponding to a initial loss rate of $I_o/\tau = 4.4\times10^{11}$ p+/s.

Table 2: Details of proton losses for nominal collimation

7 TeV case	Protons lost			
	Total LHC	TCDQ	TCS.IR6	Q4
Beam 1	5.05×10^6	35	117	0
Beam 2	5.11×10^6	1168	756	0

The effects of expected imperfections on the loss maps have also been considered [5], in an effort to determine how representative the results might be. In particular, for the TCDQ system, the effect of a fully one-sided cleaning setup of the primary LHC collimators was checked – preliminary results indicate that this increases the losses at the TCDQ system by only about 5 %. The effect of the orbit at the TCDQ on the losses in this region is not expected to be very important, as the TCDQ and TCS.IR6 jaw positions must always be adjusted to within about 0.5 σ of the beam for protection reasons. Finally, the effect of imperfections (jaw flatness, setup errors, …) will decrease the overall cleaning efficiency and thus increase the load at the TCDQ system in IR6, by a factor estimated to be as large as 2.

ENERGY DEPOSITION SIMULATIONS

The FLUKA-2003 Monte-Carlo code [6] was used to simulate primary and secondary particle cascades. Interactions, transport and energy deposition were followed down to the kinetic energy threshold of 100 keV for charged particles, 10 keV for photons and 19.6 MeV for neutrons. Particles reaching or produced below these thresholds were assumed to deposit their energy locally. Multiple Coulomb scattering was included.

For the FLUKA simulations, 20,000 p+ were followed in 4 separate runs, with magnetic fields switched on in the MCBY and MQY magnets. A sensitivity study to the MCBY magnetic field was also made. Cartesian binning was chosen for each element, with D_x=D_y=1 mm and D_z = 2 cm. The worst-case lifetime of 0.2 h was assumed.

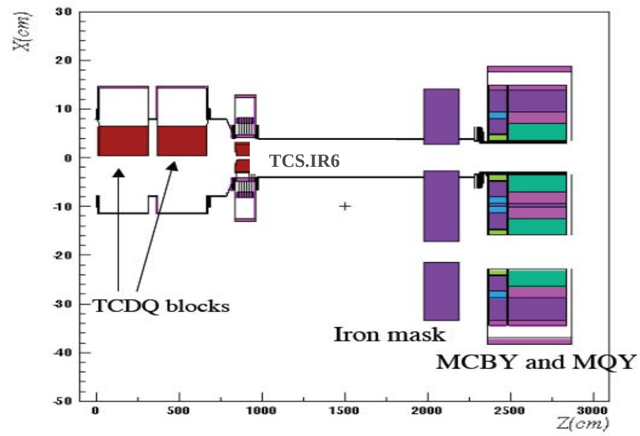

Figure 3: Horizontal section of the FLUKA geometry.

Fig. 3 shows a horizontal section of the FLUKA geometry for the system. About 30 m of the LHC was simulated, including vacuum chambers and flanges, together with the beam screen, cold bore and coils and yokes of the superconducting magnets.

The power deposited in the Q4 coil for the nominal Beam 2 case is shown in Fig. 4, in a transverse cut taken at the maximum of the longitudinal profile.

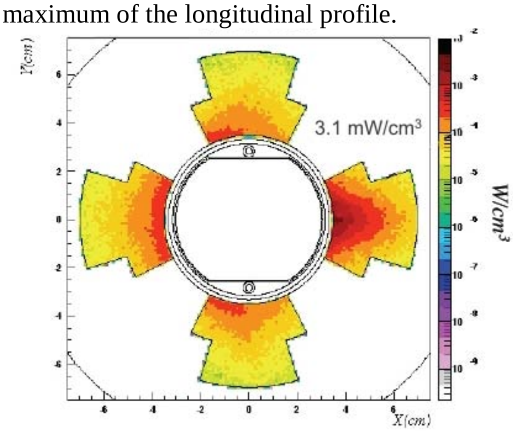

Figure 4: Power deposited in the MQY coil, for nominal 7 TeV Beam 2 halo, with 100% MCBY corrector strength.

The dipole field of the MCBY corrector magnet has a noticeable influence on the energy deposition results for the Q4 coil for Beam 2, since on this side of the IP the corrector magnet is between the TCDQ system and the Q4 magnet. The effect of this field was studied in a series of simulations with varying MCBY field, from 0 to 100% of the maximum 2 T dipole field. A summary of the results is shown in Fig. 5. – the error bars are estimated from the longitudinal profile by the observed statistical variation in the energy deposition near the maximum.

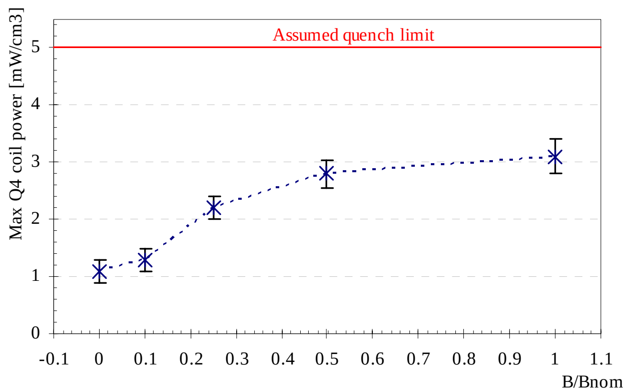

Figure 5: Sensitivity of max. power density in Q4 coil to corrector MCBY field. A factor of ~3 difference is seen.

DISCUSSION OF RESULTS

The secondary halo load on the TCDQ system is about 15 times higher for Beam 2, due to the fact that the halo generated at the collimation insertion in IR7 only passes through the arc 7-6 before reaching the TCDQ, while for Beam 1 the particles transit nearly all the LHC, including many aperture restrictions (tertiary collimators and triplets at the experimental IPs, momentum collimation insertion). The distribution of the halo particles on the jaws appears reasonable, with larger impact parameters for Beam 2, up to 5 mm from the jaw edges.

The FLUKA analysis shows that, for Beam 1, the expected thermal load in the Q4 coil should be about 2 orders of magnitude below the quench level, for the full beam intensity and 0.2 h lifetime, Table 3. For Beam 2 the peak thermal load is about 60 % of the quench level, still a cause for concern given the uncertainties in the loss map simulations, the FLUKA simulations and also the knowledge of the quench limits. The factor 3 increase with full strength of the MCBY corrector illustrates that all fields must be taken into account.

Table 3: Summary of FLUKA energy deposition results in superconducting elements for nominal collimation

7 TeV case	Q4		MCBY	
	mW/cm^3	Total W	mW/cm^3	Total W
Beam 1	0.03	0.11	0.02	0.07
Beam 2	3.1	9.5	2.3	2.5

Previous studies have shown that, for a halo distribution generated with all primary and secondary collimators retracted, the peak power load on the Q4 coil for the Beam 1 case at 7 TeV is about 15 mW/cm^3 (the figure for Beam 2 will probably be somewhat higher). This is relevant for early operation of the LHC, since there is a proposal to commission the machine with a reduced collimation system [2]. The actual situation will depend on the β* value used, as this will determine the TCDQ setting; realistic simulations of the halo at the TCDQ for commissioning schemes are under way [7].

If further refinement or early experience shows that operation is limited, which is more likely for Beam 2, some actions are possible. The layout of the TCDQ system has space between the TCS.IR6 and the TCDQM mask, for an eventual upgrade; one possibility is to install in this space a horizontal TCLA device, which is essentially a two-jaw movable 1 m long copper/tungsten mask. This could be closed to something like 15 σ (±8 mm) to the beam at 7 TeV, which is already much tighter than the fixed aperture 55 mm full aperture of the TCDQM – however, this option needs to be studied in detail, since this device would have to withstand the asynchronous dump case, and the control and interlocking would also need to be carefully integrated into the collimator and machine protection systems.

CONCLUSION

The TCDQ system remains an area for concern for secondary halo losses. The requirement that the system be closed to about 7.5 σ at 7 TeV to protect the fragile tertiary collimators and triplet aperture, means that the system intercepts a significant secondary halo load, which risks quenches in downstream superconducting elements. Detailed simulations made for Beam 1 and Beam 2 cases reveal that the Beam 2 case is worse and may be an operational limit, with the nominal collimation case giving peak power densities at about 60 % of the assumed 5mW/cm^3 quench limit. Work on refining the studies and on possible improvements is in progress.

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