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Results of the studies on energy deposition in IR6 superconducting magnets from continuous beam loss on the TCDQ system

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Summary

A single sided mobile graphite diluter block TCDQ, in combination with a two-sided secondary collimator TCS and an iron shield TCDQM, will be installed in front of the superconducting quadrupole Q4 magnets in IR6, in order to protect it and other downstream LHC machine elements from destruction in the event of a beam dump that is not synchronised with the abort gap. The TCDQ will be positioned close to the beam, and will intercept the particles from the secondary halo during low beam lifetime. Previous studies [1-4] have shown that the energy deposited in the Q4 magnet coils can be close to or above the quench limit. In this note the results of the latest FLUKA energy deposition simulations for Beam 2 are described, including an upgrade possibility for the TCDQ system with an additional shielding device. The results are discussed in the context of the expected performance levels for the different phases of LHC operation.

1. Introduction

The LHC beam dumping system includes a single sided mobile diluter block TCDQ [5], consisting of two blocks namely TCDQA and TCDQB, in combination with a secondary collimator TCS and an iron shield TCDQM [6], installed in front of the superconducting quadrupole Q4 magnet in IR6, in order to protect it and other LHC machine elements from destruction in the event of a beam dump that is not synchronised with the abort gap [7]. The TCDQ element should protect the LHC from damage from swept bunches under all conditions, in particular the arc aperture at 450 GeV, the low-beta triplet aperture and the tungsten tertiary collimators at 7 TeV. The TCDQ must also prevent quenches of Q4, arising from spurious particles in the abort gap during a normal beam dump, and from particles lost from the beam halo during regular operation.

The two-jawed TCS collimator is located immediately after the TCDQ to precisely define the horizontal beam position and to achieve higher precision collimation of secondary halo particles from both sides. The TCS will receive a potentially high load from the secondary halo in the event of low beam lifetime. The nominal settings of the TCDQ and TCS are assumed to be 8 and 7 σ_x respectively at the injection and 8 and 7.5 σ_x at top energy, where σ_x is the horizontal transverse beam size. The tight settings of the TCDQ imply that the system could intercept a significant continuous beam load from the secondary halo. The TCDQ system must be able to protect the machine at these settings, while not producing a quench in the Q4 due to the power deposited from secondary particles.

2. Performance criteria and load conditions

The continuous power limit for a quench in the superconducting magnet coil is assumed to be 5 mW/cm^3 at 7 TeV and 10 mW/cm^3 at 450 GeV [8].

The details of the number of protons simulated and lost directly in the various IR6 elements are given in Table 1, for the different studied cases [9]. 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 [10] to track an initial distribution of about 5 10^6 p^+ interacting with the primary collimators of IP7 over 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 ß* = 0.55 m in IP1 and IP5 with injection optics for IP2 and IP8. 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.

An operational scenario without secondary collimators in IP7 was also considered. The "TCS retracted" case assumes that the LHC may start up in an early operational phase with only the minimum collimation scheme, consisting of primary and tertiary collimators [11]. The one-sided cleaning case assumes an asymmetric collimator jaw arrangement, which can increase the specific load on the TCDQ system.

Table 1 Protons lost on TCDQ/TCS in the different analysed cases.

450 GeV case	**Protons lost**			
	Total on coll.	TCDQA	TCDQB	TCS.TCDQ
Nominal cleaning	6.4×10^6	1773	20	8425
TCS retracted	6.4×10^6	209227	1390	280480

7 TeV case	**Protons lost**			
	Total on coll.	TCDQA	TCDQB	TCS.TCDQ
Nominal cleaning	5.1×10^6	1146	17	720
TCS retracted	5.8×10^6	83115	502	59730
One sided cleaning	5.1×10^6	1623	29	1005

Normalisation of the results to the absolute loss

The power density in the different elements has been calculated scaling the energy deposition to the absolute loss rate, through an adequate normalisation factor N_f, calculated as follows. The evolution of the beam population as a function of time, $N = N_0 \cdot \exp(-t/\tau)$, is described by the beam intensity lifetime τ, defined as the time needed to reduce the number of protons to a fraction $1/e$ of the nominal intensity N_0. For periods of up to 10 s a minimum allowed beam lifetime of 0.1 h at injection (450 GeV) and 0.2 h at top energy (7 TeV) is assumed [14]. The nominal LHC beam intensity is given by

$$N_0 = 1.15\ 10^{11}\ \text{[protons per bunch]} \times 2808\ \text{[number of bunches]} = 3.2\ 10^{14}\ \text{protons}$$

The proton loss rates at different energies are

$$R_{loss}\left[\text{protons}/\text{s}\right] = \left.\frac{dN}{dt}\right|_{t=0} = \frac{3 \cdot 10^{14}\ \text{[protons]}}{\tau\,\text{[s]}}$$

$$R_{loss}^{inj} = 8.6\ 10^{11}\ \text{p/s}$$
$$R_{loss}^{top} = 4.3\ 10^{11}\ \text{p/s}$$

Thus the normalisation factor is calculated as

$$N_f = \frac{\text{Losses (TCDQ + TCS)}}{\text{Protons absorbed into collimators}} \times R_{loss}$$

3. Energy deposition simulations

The FLUKA-2006 Monte-Carlo code [12] was used to simulate particle cascades induced in the TCDQ/TCS/Q4 system in case of constant load from secondary halo at 450 GeV and 7 TeV.

Particle transport

Primary and secondary cascades induced by beam protons have been simulated. The interaction transport and energy deposition processes were followed down to the kinetic energy threshold of 100 keV for electrons and positrons, 10 keV for photons, thermal energies for neutrons[1] and 3 MeV for all the other types of particle. Particles reaching or produced below these thresholds were assumed to deposit their energy locally.

Geometry model

The TCDQ/TCS/Q4 geometry described in [4] has been used in simulations. In one of the analysed cases, the addition of a further absorber TCLA was studied as a possible upgrade, to reduce the heat load on the Q4. The prototype of the TCLA has been exported from the IR7 prototypes [13] and placed between the TCDM and the MCBY.

Source description

The simulated showers were initiated in FLUKA by the interaction of protons with the coordinates and direction provided by the SixTrack code. The transformation of coordinates into the FLUKA IR6 reference system has been made with MATLAB scripts.

4. Energy deposition results

Case 1: Beam 2, nominal cleaning, nominal geometry

Table 2 and Table 3 show the peak energy deposited in the various elements of the TCDQ-TCSG-Q4 line. The maximum peak deposited energy in the coil of the superconducting magnets at top energy is 3.1 mW/cm^3 for the MQY (Q4) and 2.3 mW/cm^3 for the dipole corrector (MCBY).

Table 2 Summary of local peak energy density due to the protons lost on TCDQ/TCS in case of nominal cleaning at **7 TeV**. The energy deposited per incoming proton has been converted to power densities using the normalisation factor N_f= 1.65 10^8 p/s.

	TCDQA	TCDQB	TCSL	TCSR	MASK	COIL MCBY	IRON MCBY	COIL MQY	STEEL MQY
J/cm^3/p	3.7 10^{-10}	2.6 10^{-10}	1.3 10^{-10}	1.2 10^{-10}	7.9 10^{-11}	1.4 10^{-11}	2.7 10^{-12}	1.9 10^{-11}	4.9 10^{-12}
mW/cm^3	60.4	42.2	21.4	19.3	13.1	2.3	0.445	3.1	0.81

Table 3 Summary of local peak energy density due to the protons lost on TCDQ/TCS in case of nominal cleaning at **450 GeV**. The energy deposited per incoming proton has been converted to power densities using the normalisation factor N_f= 1.43 10^9 p/s.

	TCDQA	TCDQB	TCSL	TCSR	MASK	COIL MCBY	IRON MCBY	COIL MQY	STEEL MQY
J/cm^3/p	1.2 10^{-11}	1.6 10^{-12}	6.0 10^{-12}	1.4 10^{-12}	2.9 10^{-12}	2.9 10^{-13}	7.5 10^{-14}	2.5 10^{-13}	1.44 10^{-13}
mW/cm^3	17.0	2.3	8.6	2.0	4.1	0.42	0.11	0.36	0.2

[1] Transport of neutrons with energies lower than 19.6 MeV is performed by a multigroup treatment.

Case 2: Beam 2, no secondary collimator cleaning, nominal geometry

In this configuration the secondary collimators of IP7 have been retracted, whereas TCP's and TCLA's have been kept to their nominal settings. The total number of protons lost on TCDQA, TCDQB and TCSG is 76 times higher than in the nominal cleaning case. Separate FLUKA simulations showed that the energy per proton lost deposited on these elements does not change with respect to the nominal case: the difference in terms of power density, see Table 4 and 5, is given by the normalisation factor determined by the huge number of protons per second lost in the two cases.

Table 4 Summary of local peak energy density due to the protons lost on TCDQ/TCS in case of cleaning without secondary collimators at **7 TeV**. The energy deposited per incoming proton has been converted to power densities using the normalisation factor $N_f = 1.12\ 10^{10}$ p/s.

	TCDQA	**TCDQB**	**TCSL**	**TCSR**	**MASK**	**COIL MCBY**	**IRON MCBY**	**COIL MQY**	**STEEL MQY**
J/cm³/p	$2.7\ 10^{-10}$	$1.7\ 10^{-10}$	$1.0\ 10^{-10}$	$1.5\ 10^{-10}$	$7.7\ 10^{-11}$	$1.3\ 10^{-11}$	$2.6\ 10^{-12}$	$1.9\ 10^{-11}$	$5.2\ 10^{-12}$
mW/cm³	$3.07\ 10^{+3}$	$1.86\ 10^{+3}$	$1.13\ 10^{+3}$	$1.69\ 10^{+3}$	$0.86\ 10^{+3}$	$0.15\ 10^{+3}$	29.2	$0.22\ 10^{+3}$	58.0

Table 5 Summary of local peak energy density due to the protons lost on TCDQ/TCSG in case of cleaning without secondary collimators at **450 GeV**. The energy deposited per incoming proton has been converted to power density using the normalization factor $N_f = 6.88\ 10^{10}$ p/s.

	TCDQA	**TCDQB**	**TCSL**	**TCSR**	**MASK**	**COIL MCBY**	**IRON MCBY**	**COIL MQY**	**STEEL MQY**
J/cm³/p	$4.7\ 10^{-12}$	$1.5\ 10^{-12}$	$3.3\ 10^{-12}$	$2.3\ 10^{-12}$	$2.4\ 10^{-12}$	$2.6\ 10^{-13}$	$6.8\ 10^{-14}$	$2.0\ 10^{-13}$	$1.2\ 10^{-13}$
mW/cm³	$0.32\ 10^{+3}$	$0.1\ 10^{+3}$	$0.22\ 10^{+3}$	$0.16\ 10^{+3}$	$0.17\ 10^{+3}$	18.3	4.7	14.0	8.6

Case 3: Beam 2, nominal cleaning, additional TCLA

A tungsten absorber with the same design of the TCLA's of IP7 was implemented in the geometry to study the reduction in terms of power deposited on the magnets. This is a possible upgrade of the IP6 layout to improve the performance of the TCDQ system, based on an existing LHC collimator design. In the simulation it was placed downstream of the mask (passive absorber, TCDQM), Figure 1. The jaws are set at ±6 mm for the 7 TeV configuration and at ±25 mm for the 450 GeV configuration, corresponding to 10 σ_x opening in both cases.

The proton distribution in the *nominal cleaning* case (1) was used as a source. The peak energy deposited on the coil of the MQY is $9.6\ 10^{-12}$ J/cm^3/p$^+$; this value has been normalized by $N_f = 1.65\ 10^8$ p$^+$/s to give the power density, 1.6 mW/cm^3.

The power density has to be compared with the one obtained for the nominal geometry without TCLA, which is 3.1 mW/cm^3, almost a factor of 2 higher. The energy distribution on the TCDM (mask) placed upstream of the Q4 is the same for both cases, with and without TCLA, Figs. 2 and 3.

The TCLA intercepts the shower coming from the mask and part of the shower coming from the TCS, Figure 4, since the opening for the beam in the TCDM mask is set at ±21.5 mm while the TCLA jaws sit at ±6 mm.

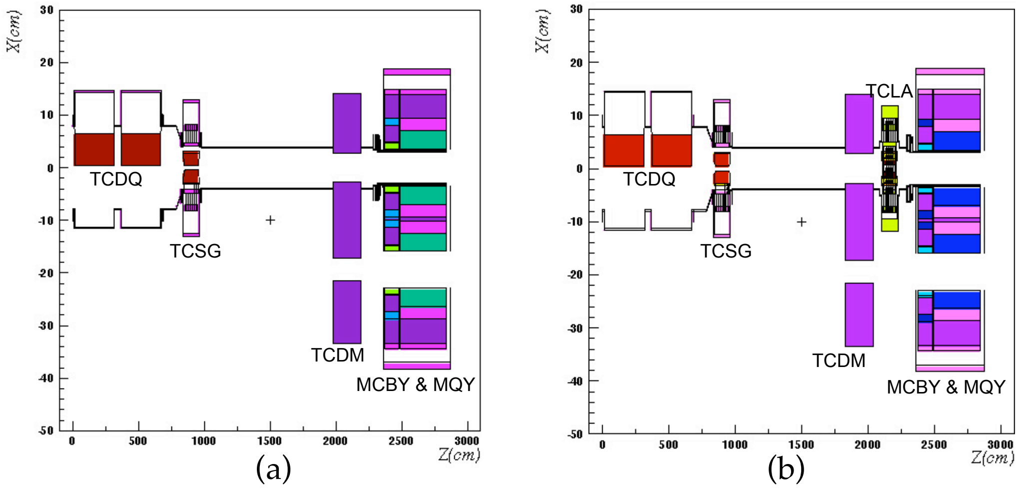


Figure 1 2 D plot of the geometry: (a) standard geometry used in Case 1 and 2; (b) Case 3 geometry with an additional absorber, the TCLA.

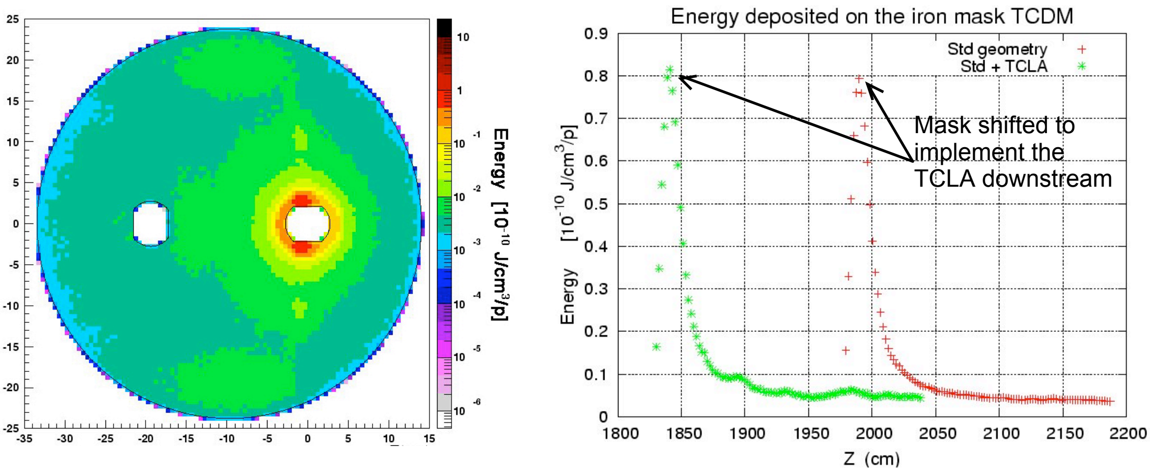


Figure 2 Iron mask TCDM: energy density [10^{-10} J/cm^3/p] on a plane perpendicular to the beam direction (on the left) and longitudinal energy distribution (right). Note that the shift is due to the introduction of the TCLA absorber.

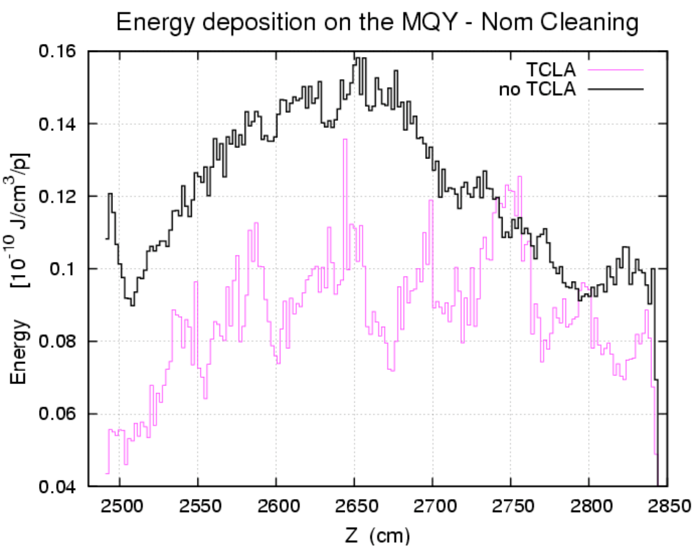
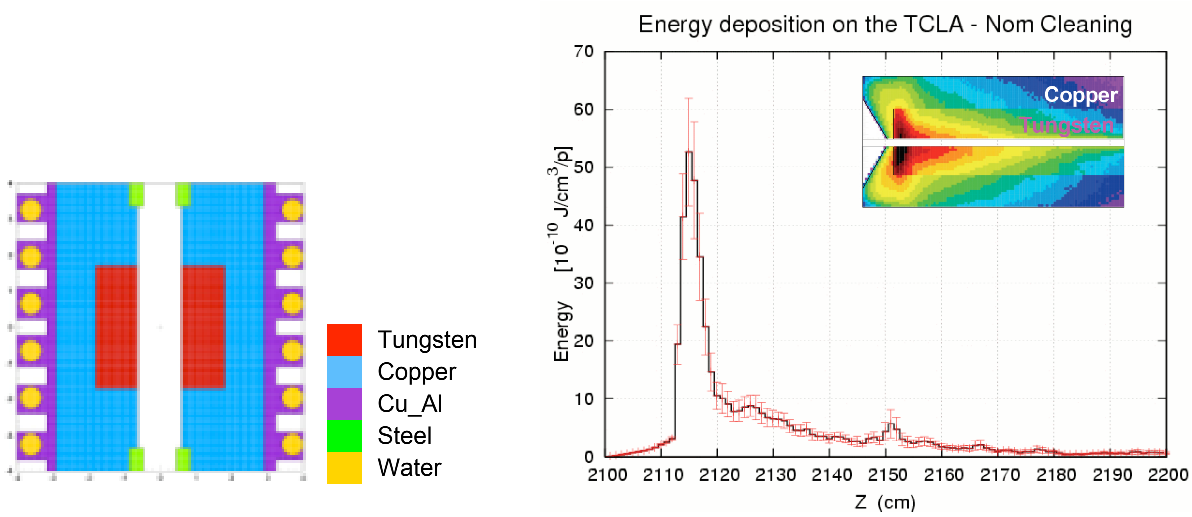


Figure 3 Maximum energy deposited on the MQY along the longitudinal coordinate: the black line is for the nominal geometry; the pink line includes the additional shielding TCLA.



(a) (b)

Figure 4 TCLA absorber, transversal cut: (a) the materials used in the FLUKA geometry implementation are specified; (b) energy deposited in the absorber [10^{-10} J/cm^3/p].

Case 4: beam 2, one sided losses, nominal geometry

For this case (ideal machine) the only difference was the number of protons impacting the TCDQ system elements. Given the results from case 2 the heat load estimate on the magnet is made by simply rescaling the energy deposited in the nominal cleaning case by a normalisation factor N_f= 2.3 10^8 p/s. The local peak energy deposited on the MQY coil is 1.9 10^{-11} J/cm^3/p, the resulting power density is 4.4 mW/cm^3.

5. Comparison with Beam 1 results

The beam losses at the TCDQ system are much lower for Beam 1, Table 6, due to the asymmetry in the LHC collimation betatron cleaning system in Point 7 with respect to the Beam Dumping System in Point 6. The expected power loads in the MQY magnet were previously obtained with FLUKA simulations using a simplified geometry (no magnet cold-bore, no beam screen, one 6 m long TCDQ block rather than the two 3 m long TCDQA and TCDQB blocks). The results obtained are shown for comparison in Table 7.

Table 6 Protons lost on TCDQ/TCS for the Beam 1 and Beam 2 cases, at 450 GeV and 7 TeV.

Nominal cleaning	**Protons lost**			
	Total on coll.	TCDQA	TCDQB	TCS.TCDQ
Beam 1, 7 TeV	5.1×10^6	117		35
Beam 2, 450 GeV	6.4×10^6	1773	20	8425
Beam 2, 7 TeV	5.1×10^6	1146	17	720

Table 7 Summary of peak loads due to secondary beam halo at 450 GeV and 7 TeV for Beams 1 and 2, for the case of nominal cleaning and nominal geometry (slightly simplified in the Beam 1 case).

	Power deposited in the Q4 coil at 0.2 h beam lifetime [W/cm^3]				
	TCDQ	TCS	TCDQM	MCBY	MQY
Beam 1, 7 TeV				2×10^{-5}	3×10^{-5}
Beam 2, 450 GeV	0.13	2.4	0.33	0.12	0.12
Beam 2, 7 TeV	0.73	0.59	0.029	0.017	0.024

6. FLUKA simulation accuracy

The presented simulation results have a statistical uncertainty, calculated as the relative error on the number of run cycles. The value of the maximum heat load has a 20 % uncertainty, while the error for the total energy deposited in the coils is less than 10 %.

When simulating the cascade of 7 TeV beams, additional sources of error have to be taken into account. Some of them are explained below, with a rough estimate of the error margin that they could contribute:

- Error due to the physics modelling, *a)* in the uncertainty in the inelastic p-A extrapolation at 7 TeV lab (cross section, $p_{\perp}$ distribution, and multiplicities); *b)* uncertainty in the modelling used from the simulation code. One would expect a factor of 1.8 at 7 TeV and 1.5 at 450 GeV on the integral quantities scored like energy deposition (peak included) on the quadrupoles.

- Errors due to the assumptions used in the description of the geometry and of the materials under study. Experience has shown that a factor of 2 can be taken as a safe limit.

- Errors when having particles running parallel to the collimators' surfaces, where the roughness is not taken into account. A factor of 2 can be taken as a reasonable assumption, [15].

7. Discussion of implications for LHC commissioning and operation

The asymmetry between Beam 1 and Beam 2 is due to the layout of the LHC, and means that the TCDQ system to the left of Point 6, which is used for Beam 2, will be the critical location with highest power loads on the Q4 and corrector coils. The simulations have been refined to include the realistic geometry, including cold bore, beam screen, split TCDQ block and as-built element locations. The result show that, with the nominal LHC cleaning collimation case at a beam lifetime of 0.2 h at 7 TeV, the power load expected in the Q4.L6 coil is about 3.1 mW/cm^3, which is less than a factor of 2 below the quoted quench limit. The power load for the one-sided cleaning case increases to about 4.4 mW/cm^3: this value is "on the edge" of the quench limit, taking into account a statistical uncertainty of about 20% for the maximum energy deposited. Additional uncertainties in the simulations for the loss maps will make the situation worse.

These numbers show that the TCDQ system for Beam 2 risks to be an operational limit once the LHC intensities are above about half nominal. As a possible upgrade, the addition of a TCLA mask was studied. It was shown that this reduces the power in the Q4 coils by a factor of about 2. This appears a fairly simple way of improving the system performance, should this effect prove limiting at higher LHC intensities.

Concerning the commissioning of the LHC and early collimation schemes, and in particular the proposal to operate with all secondary collimators retracted, the huge increase in the number of secondary halo protons impacting the TCDQ system limits this scheme to low intensities, as was anyway foreseen. The increase in the number of protons is a factor of 76, which means that, to respect the 5 mW/cm^3 limit in the Q4 coil, the total beam intensity must be limited to a factor of around 50 below nominal, or to something like 6×10^{12} p^+, corresponding to a possible operation with 156 bunches of 4×10^{10} p^+ [11].

8. Conclusion

The TCDQ system for Beam 2 presents a potential limitation for operation, since the TCS/TCDQ jaws must never be closer to the circulating beam than the secondary collimator of IP7 for intensities above about 2% of the nominal. Even with the full multi stage betatron cleaning in place, the energy deposited in the Q4 coil is uncomfortably high, at about half of the quench limit for an ideal two-sided cleaning, and at about 90% of the limit for a one sided cleaning. An additional TCLA mask reduces these figures by about a factor of 2 – in view of the uncertainties associated with the loss map and energy deposition simulations, it seems essential to foresee at least the manufacture of one additional TCLA collimator for installation in the Beam 2 TCDQ system. Further studies on ways to reduce the halo load at the beam 2 TCDQ would also appear justified.

9. Acknowledgement

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