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ESTIMATION OF THRESHOLDS FOR THE SIGNALS OF THE BLMs AROUND THE LHC FINAL FOCUS TRIPLET MAGNETS

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INTRODUCTION

The inner triplet is a string of three superconducting quadrupole magnets (Q1-Q3) installed on both sides of every Interaction Point (IP) of the Large Hadron Collider (LHC), aimed at the final squeeze of the beams before collision. Due to its proximity to the IP and its strong magnetic field, the inner triplet is particularly exposed to the proton-proton collision debris and the risk of quench (i.e. a sudden transition from superconducting to normal conducting state) is consequently higher than for other magnets. The impact of the debris has been investigated and suitable protection solutions have been implemented [1]. Nevertheless, abnormal beam losses might occur.

In order to identify possible losses that may lead the magnets to quench, Beam Loss Monitors (BLMs) are installed all along the LHC ring in order to detect an abnormal increase of the radiation field around the accelerator: if the measurements are above the predefined thresholds, a beam dump signal is triggered. The thresholds are set such that the beam is dumped before a quench develops.

BLMs are nitrogen-filled ionization chambers in the form of tubes about 50 cm long and with diameter of almost 10 cm. Eighteen of them are installed on the surface of the vacuum vessels of the inner triplet or in its vicinity.

Thresholds for BLMs are set for twelve signal integration times between $40\ \mu\mathrm{s}$ and 84 s as well as for various beam energies. This study is meant to investigate thresholds for the two extreme cases of fast transient and steady state losses at a beam energy of 7 TeV.

The simulations are performed with the FLUKA Monte Carlo code [2, 3]. The energy deposited in the superconducting coils ($\mathcal{E}$) and in the BLMs active gas ($\mathrm{E_{BLM}}$) is scored: the relation between these two quantities represents an input for setting the BLM thresholds. However, the systematic uncertainties affecting the calculation should not be neglected (in particular, minor geometry details not yet implemented at the stage of this work can appreciably alter $\mathrm{E_{BLM}}$). Nonetheless, our conclusions concerning the possibility of detecting local abnormal losses are expected to hold.

SIMULATION

All main components of the LHC Insertion Region (IR) up to about 280 m on the right side of IP1 (ATLAS experiment) have been implemented with a detailed description of their geometry, materials and magnetic fields. The LHC tunnel and the ATLAS cavern have also been modelled [4]. A zoom on the inner triplet as implemented in FLUKA geometry is shown in Figure 1.

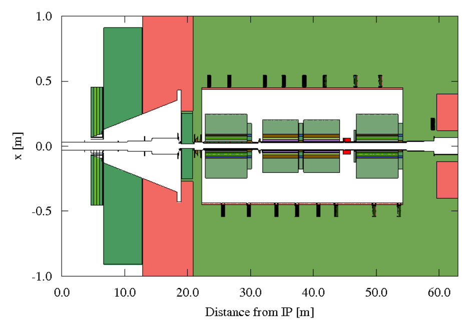

Figure 1: *Horizontal cut at beam height of the FLUKA geometry of IP1, right side; zoom on the inner triplet. The first monitor is not visible since it is at a different height. Note that the scale of the two axes is different.*

The coils are the quench-sensitive parts of the magnets, and they are arranged in layers immediately around the beam pipe. The innermost layer is typically subject to the highest energy deposition.

Collision debris

DPMJET III [5] is the event generator used to simulate proton-proton collisions at 14 TeV center-of-mass energy, directly called from inside Fluka. The results of the simulations are scaled by a collision rate of $8{\cdot}10^8\ \mathrm{s}^{-1}$, obtained by multiplying the nominal peak luminosity $\mathrm{L_0} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ by the proton-proton reaction cross section $\sigma = 80\ \mathrm{mbarn}$. This value of cross section includes inelastic and diffractive events. The plane of crossing of the beams is vertical and the simulated statistics gives about 10^5 primary events.

Beam loss

Simulations performed with tracking codes have demonstrated that the inner triplet is protected against losses if the collimation system is correctly set up. On the other hand, a wrong setting of primary and secondary collimators in the LHC section dedicated to betatron cleaning (IR7) could imply losses peaked almost at the centre of Q2B magnet. A similar tracking simulation result has been obtained in case the tertiary collimators are accidentally retracted [6].

Primary protons for this loss scenario are generated from the loss maps obtained with the tracking code, the longitudinal distribution of which is shown in Figure 2. A total of 10^5 protons have been simulated.

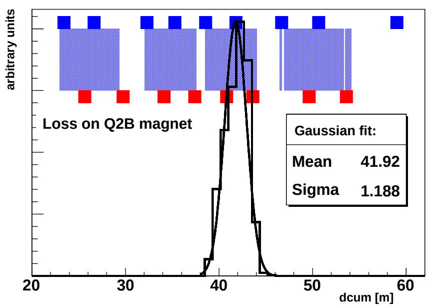

Figure 2: *Longitudinal distribution of protons in case of wrong collimators settings. The beam comes from the right.*

ENERGY DEPOSITION IN THE COILS

The energy density distribution in the superconducting coils has been estimated with a scoring mesh in cylindrical coordinates (r, ϕ and z). Its binning has been set according to the different mechanisms ruling the quench limit:

- energy deposition due to steady state losses, $\mathcal{E}_{cable}$: since the heat has time to locally spread, the binning is sized on the volume of cable that can be considered in thermal equilibrium. This volume was assumed to be defined by the cable transverse dimensions and a longitudinal length equal to the cable transposition pitch. The quench limit is defined as the maximum heat transfer rate from the coil to the cryogenic system (P_{QL});
- energy deposition due to fast transient losses, $\mathcal{E}$: the energy density is scored with a finer binning on the radial dimension; the quench limit is defined as enthalpy margin of a dry cable (ΔH);

The highest (hereafter, "maximum") energy density value in the coils, usually corresponding to the innermost layer, determine the quench location and the number of lost protons or the loss rate needed to quench.

The patterns of $\mathcal{E}_{cable}$ produced by the debris have been described in detail in [4]. Figure 3 shows the longitudinal distribution of peak($\mathcal{E}$) and peak($\mathcal{E}_{cable}$) (both over r and ϕ) along the coils of the inner triplet quadrupoles in case of debris. The maximum values are reached at the end of the Q1 magnet.

The number of protons needed to quench a magnet in case of fast loss can be estimated as:

$$N_{QL} = \frac{\Delta H}{max(\mathcal{E})} \tag{1}$$

and the loss rate needed to quench in case of steady-state loss can be computed as:

$$R_{QL} = \frac{P_{QL}}{max(\mathcal{E}_{cable})} \tag{2}$$

The values of $max(\mathcal{E})$, $max(\mathcal{E}_{cable})$, N_{QL} and R_{QL} are shown in Table 1.

SIGNALS IN BLMS

The energy deposition in the active gas of the BLM obtained with simulations is between 1 and 20 keV per proton-proton collision or 0.3 and 60 keV per lost proton. Those values must be multiplied by N_{QL} or R_{QL} and divided by the mass of the active gas (about 2 g) in order to calculate dose or dose rate at quench (D_{BLM}). For relevant monitors, signals from debris and the ones expected at quench for fast and steady state scenarios are presented in Table 1 ($D_{BLM10} - D_{BLM12}$).

QUENCH-PREVENTING THRESHOLDS

Thresholds on BLMs signals should allow the safe and reliable operation of the machine, i.e. they should prevent magnet quench as well as avoid unnecessary beam dumps. Currently thresholds are set at about 30% of the signal expected at quench.

Fast losses

During the $40\ \mu$s shortest integration time of the BLMs electronics the maximum energy density released by the debris in the coil is about $0.2\ \mu\mathrm{J/cm^3}$, some 6000 times smaller than the enthalpy limit of the dry cable (ΔH). Therefore, for losses on this timescale the contribution from the debris can be neglected. Typical values of signal at quench are between 1 mGy/s and 0.61 Gy/s. About $5 \cdot 10^6$ protons must be lost to provoke the quench.

Steady-state losses

The deposited heat is constantly evacuated through the cooling system of the magnet: the equilibrium between heat deposition and removal is achieved on a timescale of the order of seconds.

The power deposited in the coil by the debris is about $3.2\mathrm{mW/cm^3}$ at maximum, only about 3-4 times lower than the quench limit (P_{max}).

The BLM signal at quench is compared to the debris signal in Figure 4. In the most sensitive region the loss signal at quench is only 3 times higher than the signal from the debris making the determination of thresholds impractical.

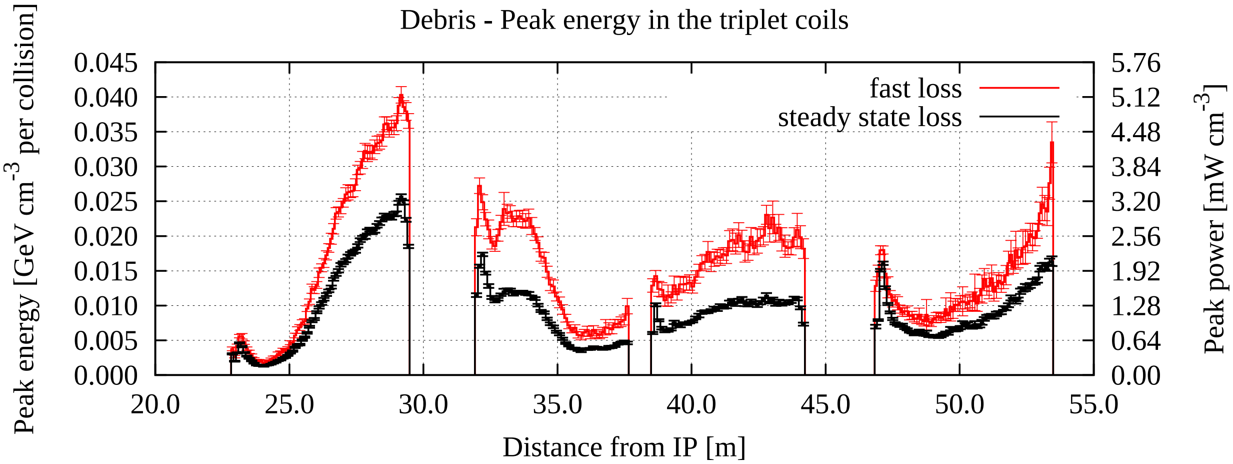

Figure 3: Longitudinal profile of peak($\mathcal{E}$) and peak($\mathcal{E}_{cable}$) along the coils of the magnets of the inner triplet, induced by the proton-proton collision debris. The red curve shows the energy density calculated for fast losses (fine mesh) and the black one for steady state losses at nominal luminosity (mesh corresponding to the cable size). The scale on the right axis applies only to the curve for steady-state.

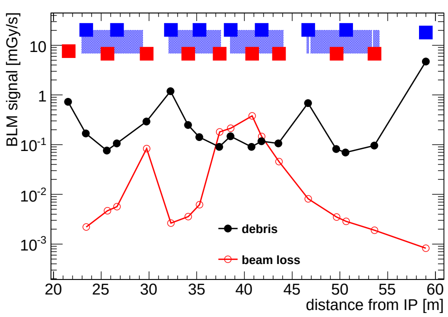

Figure 4: *BLM signals at quench in case of steady state beam loss (red curve) and due to collision debris (black curve).*

Table 1: Maximum of energy deposition in the coils, numbers of protons to quench and BLM signals for debris and for beam losses.

	debris	**fast loss**	**slow loss**
max($\mathcal{E}$) [$\mathrm{GeV/cm^3}$]	0.04	1.48	-
$\mathrm{N_{QL}}$	-	$5.1 \cdot 10^6$	-
max($\mathcal{E}_{cable}$) [$\mathrm{GeV/cm^3}$]	0.026	-	0.948
$\mathrm{R_{QL}}$ [$\mathrm{s^{-1}}$]	-	-	$7.9 \cdot 10^7$
D_{BLM10} [Gy/s]	$1.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-1}$	$2.5 \cdot 10^{-4}$
D_{BLM11} [Gy/s]	$8.7 \cdot 10^{-5}$	$6.1 \cdot 10^{-1}$	$3.8 \cdot 10^{-4}$
D_{BLM12} [Gy/s]	$1.1 \cdot 10^{-4}$	$2.3 \cdot 10^{-1}$	$1.5 \cdot 10^{-4}$

CONCLUSIONS

For **fast transient losses** the BLMs placed close to the loss location on the triplet magnets would be able to prevent quenching. A conservative threshold value is at maximum $0.2\ \mathrm{Gy/s}$.

In the case of **steady-state losses** the situation is more complicated as the signals from quench inducing losses do not clearly stand out from those produced by the collision debris. A long-term solution to this problem should be studied.

One such solution is the installation of detectors closer to the coils, so that the measured dose better reflects the dose actually received by the coils [7]. This development might be particularly important for the upgrade of the LHC towards higher values of luminosity.

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