GENERATION OF 1.5 MILLION BEAM LOSS THRESHOLD VALUES

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Abstract

CERN's Large Hadron Collider will store an unprecedented amount of energy in its circulating beams. Beam-loss monitoring (BLM) is, therefore, critical for machine protection. It must protect against the consequences (equipment damage, quenches of superconducting magnets) of excessive beam loss. About 4000 monitors will be installed at critical loss locations. Each monitor has 384 beam abort thresholds associated; for 12 integrated loss durations (40 μs to 83 s) and 32 energies (450 GeV to 7 TeV). Depending on monitor location, the thresholds vary by orders of magnitude. For simplification, the monitors are grouped in "families". Monitors of one family protect similar magnets against equivalent loss scenarios. Therefore, they are given the same thresholds. The start-up calibration of the BLM system is required to be within a factor of five in accuracy; and the final accuracy should be a factor of two. Simulations (backed-up by control measurements) determine the relation between the BLM signal, the deposited energy and the critical energy deposition for damage or quench (temperature of the coil). The paper presents the strategy of determining 1.5 million threshold values.

INTRODUCTION TO THE LHC BLM SYSTEM

The BLM system detects and quantifies the amount of lost beam particles. It generates a beam abort trigger when the losses exceed predetermined threshold values. The main detector type is an ionization chamber (IC). About 4000 will be installed, mostly around the quadrupole magnets, where they probe the transverse tails of the particle showers through the magnets. The dynamic range of these monitors is 10^8. At certain locations, higher loss rates could occur due to machine component failures. The highest continuous loss rates will be in the collimation sections. Secondary emission monitors (SEMs) are added at these locations. Their sensitivity is approximately $7 \cdot 10^4$ times less than the one of an IC.

BEAM ABORT THRESHOLDS

The BLM interlock limits can be set for each monitor individually. In the arcs they will be set to 30% of the magnet quench levels. They vary with integration time (12 integration time intervals between 40 μs to 83 s) and the energy of the beam (32 energy ranges). The BLMs are grouped into families of monitors which, because of their location and loss maps, are expected to have the same thresholds. The largest families belong to the arcs where the same configuration is repeated. The 6 arc families contain more then half of all the monitors, but the remaining configurations on the Long Straight Sections, injection and dump lines represent a large variety corresponding to an additional number of 300 families. A factor of 5 and a factor of 2 are the specified initial and final absolute precisions on the prediction of the quench levels respectively. The relative precision for quench prevention is requested to stay below 25%. The dynamic range of the system is given by the calculated damage and quench levels (and the expected usage from pilot beam intensity to ultimate beam intensity. The observation time range is defined by the fastest possible use of the trigger signal by the beam dump (on the side of short integration intervals), and the response time of the helium temperature measurement system (on the long side). Damage and quench limits of sensitive LHC components, i.e., collimators and cold magnets, are given for transient losses by a maximal energy density and for steady-state losses by a total energy deposited in the sensitive equipment in a time interval.

Technical Implementation

The threshold settings [1] of the BLM system are stored in the LHC Software Architecture (LSA) database, which is a standard way to manage operational settings. The information about assignment of the monitors to families and family thresholds is send to LSA tables by a set of SQL scripts. The threshold tables, in the form corresponding to their image in the front-end electronics, are created. The tables are created in Master and Applied version. The Master threshold levels are well below damage levels of the LHC elements, although they exceed the quench level of cold magnets. The Applied thresholds are scaled down to the values which prevent from quench. Every monitor can be scaled separately by applying a monitor factor. To provide safety of the system, the Master thresholds are protected from any change not agreed by Machine Protection Working Group and BLM Experts. The tables in LSA are doubled in a stage/final mechanism. Loading the threshold values to staging tables allows to compare them with the original values present in the final tables. If the comparison is satisfactory the decision can be made to load the stage tables to final ones. The history of changes made to the tables in LSA is stored and old settings can always be re-loaded. Thresholds plausibility checks are foreseen.

COLD MAGNETS

Amongst others, the proton loss in LHC Short Straight Section (SSS) made of Main Quadrupole (MQ), Octupole

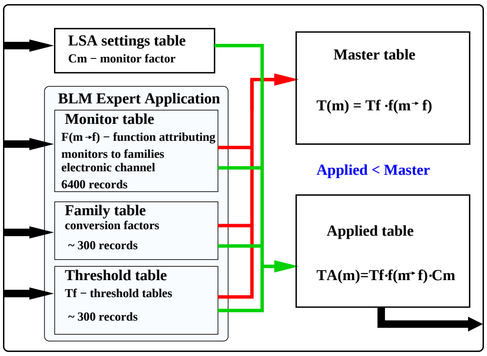

Figure 1: Schematic view of data organization in LSA database. The master table is created from expert input.

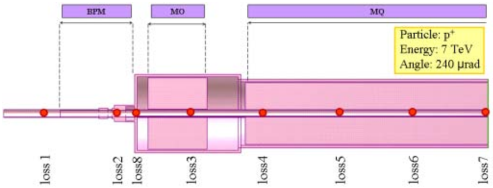

Figure 2: The longitudinal cross-section of SSS and beam loss locations.

Corrector (MO) and Beam Position Monitor (BPM) has been simulated with the Geant4 package [2]. The energy deposition (ED) in MQ coils was scored in cells with dimensions smaller than the shower scale. Several beam loss locations, as presented in Fig. 2, have been simulated. The secondary particles were registered outside the cryostat in volumes corresponding to the monitor placement (Fig. 3). The peak of the secondary particle multiplicity is found to be about one meter after the loss location. As the BPM is one of the most probable loss locations, it can be concluded that the first BLM is placed in the peak of the cascade, which means that it is placed optimally to detect losses in BPM. Taking into account the fast loss quench level of 1.41 mJ/cm^3 the critical number of protons to quench the magnet has been found to be between approximately $0.3 \cdot 10^6$ and $2 \cdot 10^6$, depending on the loss location. The fluence of particles hitting the monitor is folded with the BLM response function to find the generated charge (Fig. 4). This is converted to radiation dose seen by the BLM. The quench preventing threshold for fast losses in MQ magnet is found to be about 0.1 mGy and about 5 mGy/s for steady-state losses.

COLLIMATORS

The LHC has a multi-stage cleaning system consisting of several types of collimators, see Tab. 1. Most LHC collimators are located in the momentum and the betatron cleaning insertion (IR3 and IR7) [5, 6]. Inherent damage thresholds for collimators are provided by the LHC collimation working group [7]. Simulations for the assessment of the BLM thresholds focus on the cleaning insertions. Each collimator is protected by an IC and a SEM detector. Fig. 5 depicts the typical schematic setup of the BLM detector positions w.r.t. a collimator. Simulations done with FLUKA [3, 4] address the relation of BLM detector signal to total and maximal ED in the collimator jaws dependent on different parameters. ED in the detectors is scored and transformed with a conversion factor to the corresponding detector signal.

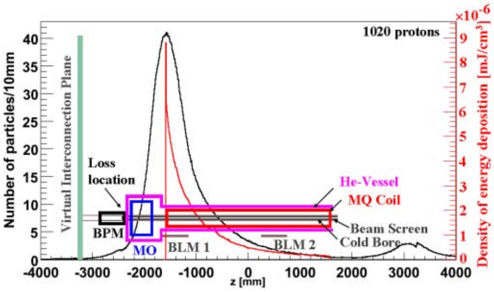

Figure 3: Correlation between energy deposition inside the coils (red curve) and the number of secondary particles outside of the cryostat (black curve).

Table 1: Collimator types in cleaning regions. Similar collimators are placed along the LHC ring.

Collimator	Jaw Length & Material	
Primary (TCP)	60 cm	C reinforced graphite
Secondary (TCSG)	100 cm	C reinforced graphite
Absorber (TCLA)	100 cm	W embedded in Cu

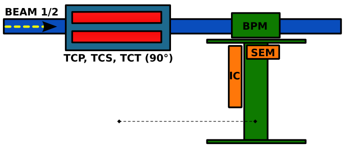

Figure 5: Structural view of a collimator (tilted at 90°) and its dedicated BLM detectors, an IC and a SEM, as mounted in the LHC cleaning insertions IR3 and IR7.

A setup of collimator and BLM detectors as shown in Fig. 5 was implemented with interchangeable collimators (TCP, TCSG, TCLA). Focus in geometrical implementation was put on the collimator, the IC and the BLM support. Simulations were run at LHC injection and top energy, 450 GeV and 7 TeV, respectively. Changes in response of the IC by omitting an implementation of a collimator support were assessed by the insertion of a steel block of 5 cm thickness and resulted in deviation of the IC signal of 7%. Transversal misalignment of the BLM detectors of ±5 cm (vertical) and ±2 cm (horizontal) provoked a deviation of the IC signal of maximal 34.1%. Fig. 6 shows the ratio of signal seen by the IC to ED in the jaw for selected settings as function of proton impact depth in the jaw. One can observe that the signal to ED ratio is virtually constant for impact parameters of up to 1 mm. The signal to ED ratio for a secondary shower is about 50% lower than the ratio for beam protons on the collimator. For critical failures, the ratio of IC signal to maximal energy density within a TCP

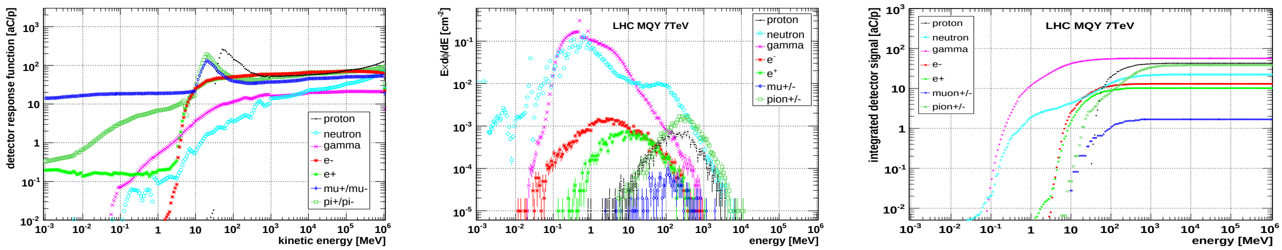

Figure 4: Left: GEANT4 simulated LHC BLM detector response functions for particle impact direction of 60°. Center: Secondary particle fluence spectrum on the outside recorded in a 3.4 m long stripe, lethargy representation, MQY magnet, protons with 7 TeV impacting on the beam screen. Right: Integrated detector signal.

jaw is of the order of 10^{-14} Gy/(GeV/cm^3). This relation is still subject to more detailed studies.

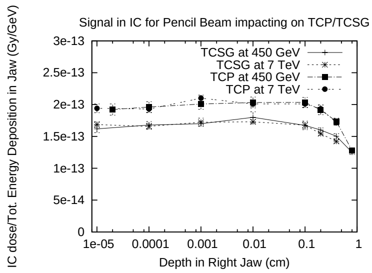

Figure 6: Ratio of dose deposition in the IC to total energy deposition (ED) in the right collimator jaw vs. the impact depth of a pencil proton beam for the TCP and the TCSG collimator.

An experimental setup consisting of a prototype TCSG collimator and a set of BLM detectors is mounted in the SPS, see Fig. 7. Responses of the BLM detectors were taken at 26 GeV with up to $1.3 \cdot 10^{13}$ protons impacting on the collimator. This setup was implemented in FLUKA using a similar approach as above. Systematic deviations of the detector signals due to misalignment and simplification in geometry were assessed and found to be smaller than 5% each. A preliminary comparison of dose per proton on collimator between experiment and simulation shows an agreement within 18% for the IC and an agreement within 25% for the SEM signal. More measurements for detailed comparison are planed.

SUMMARY

The start-up of the LHC being now imminent, the 1.5 million beam abort threshold values are being currently finalized. Presented are the two most copious cases, the arc (and dispersion suppressor) cold magnets and the BLMs at the collimators (and absorbers). The simulations involved in determining the thresholds as well as the technical implementation of their deployment are described.

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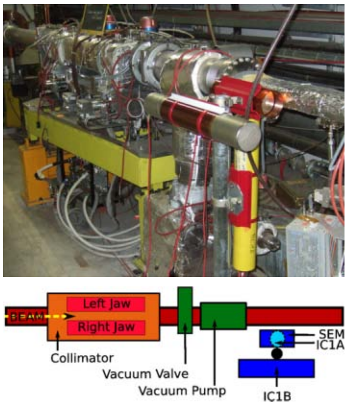

Figure 7: The upper figure shows the prototype TCSG collimator as mounted for test purposes in the SPS. The schematic drawing shows a top view of the arrangement. The collimator is equipped with two ICs (IC1A and IC1B) and a SEM.

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