BEAM LOSSES AND THRESHOLDS

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Abstract

The motivation for the original BLM locations and the arguments for their rearrangement during LS1 in order to protect against UFO losses are explained here. The results of several quench tests, their extrapolation to 7 TeV and the implications on the BLM thresholds are discussed. Special emphasis is put in the UFO timescale test, where a quench of an MQ magnet was achieved in 10 ms, reaching BLM signals over five times larger than the estimated quench level. During the quench test with the collimation system, a power loss of 1MW was achieved at the primary collimator in IR7 without the generation of a magnet quench in the dispersion suppressor. Signals five times higher than the estimated quench level were reached in the BLMs. Finally, the procedures for BLM threshold management as well as a more reliable and maintainable approach for the threshold calculation and deployment are described here.

BLM DETECTOR LOCATION AND UFO INDUCED RE-LOCATION

The BLM system in the LHC arcs is equipped with three Ionization Chambers (IC) located 1 m, 3.5m and 5m downstream of the interconnection between the Main Bending magnet (MB) and Main Quadrupole (MQ). In the following, we will refer to this detectors as BLM1, BLM2 and BLM3 respectively. The MQs were selected as the most likely loss location due to the larger beam size at this point and in agreement with the result of tracking simulations with dedicated aperture models [1]. The installation of three BLMs per beam was established in order to maximize the detection of beam losses originated at different positions within the MQ. Moreover, the presence of multiple BLM minimizes the uncertainties on the estimation of energy deposition in the magnetic coils based on BLM signals. Finally, the location of ICs on both left and right sides outside of the vacuum chambers allows for a determination of the beam causing the observed losses.

Before the start of the 2011 run, several extra ICs were installed within the LHC arc cell 19R3. This cell was chosen as it observed larger occurrence of UFO-like beam losses. Comparing the BLM data with dedicated simulations [2] it was possible to show that UFO-like losses are generated in MB magnets as well as MQs. Therefore, the BLM system in its current configuration does not protect against potential quenches generated by UFO losses in MB magnets. Various re-distributions of the monitors have been discussed, all of them based on the relocation of BLM2 to another position within the arc cell. Two proposals consisted of moving BLM2 to either a few centimeters downstream of the MB.A-MB.B (configuration BLM N2) or the MB.B-MB.C (configuration BLM N3) interconnection.

A summary of the simulated BLM signals [3] in configurations BLM N2 and BLM N3 for various UFO location can be found in Table 1. In particular, the numbers show the expected BLM signal normalized to the estimated signal at BLM1. In the final BLM relocation proposal, it is foreseen to move BLM2 to the MB.A-MB.B interconnection (configuration BLM N1). A schematic view of the current BLM configuration in the ARCs as well as the three poposed BLM relocations is presented in Figure 1. The detector will be centered with respect to the two beams. By doing the same with BLM2 of the opposite beam, this option ensures the protection against beam losses originated anywhere along the arc cell. Dedicated simulations to estimate the expected BLM signals and energy deposition in the coil are necessary to determine of the dump thresholds. Note that with this approach, the displaced BLMs will get dedicated thresholds while all other thresholds will remain identical.

Table 1: Signal gain factor for two BLM relocations and three UFO scenarios..

UFO location	BLM N2	BLM N3
MB.A end	80	13
MB.B beginning	–	50
MB B end	–	7

QUENCH TEST RESULTS AND CONSEQUENCES ON BLM THRESHOLDS

At the end of the 2013 run, dedicated beam time was allocated for experiments that probe the quench level of different magnets at various time scales. This section focuses on the preliminary results of these tests as well as on the consequences for the beam dump thresholds.

Millisecond scale quench test

A three corrector orbit bump combined with a MKQ kick and a sign flip (i.e anti damping mode) transverse damper (ADT) excitation was used to generate losses in the horizontal plane at the main quadrupole Q12L6. In this experiment, using a proton energy of 4 TeV, the beam losses reached a total duration of the order of 10 milliseconds before the magnet quenched.

A summary of the experiment is given in Figure 2. The signal observed at the BLM protecting Q12L6 (green line) rises up to values of 10 Gy/s and it has fully decayed within

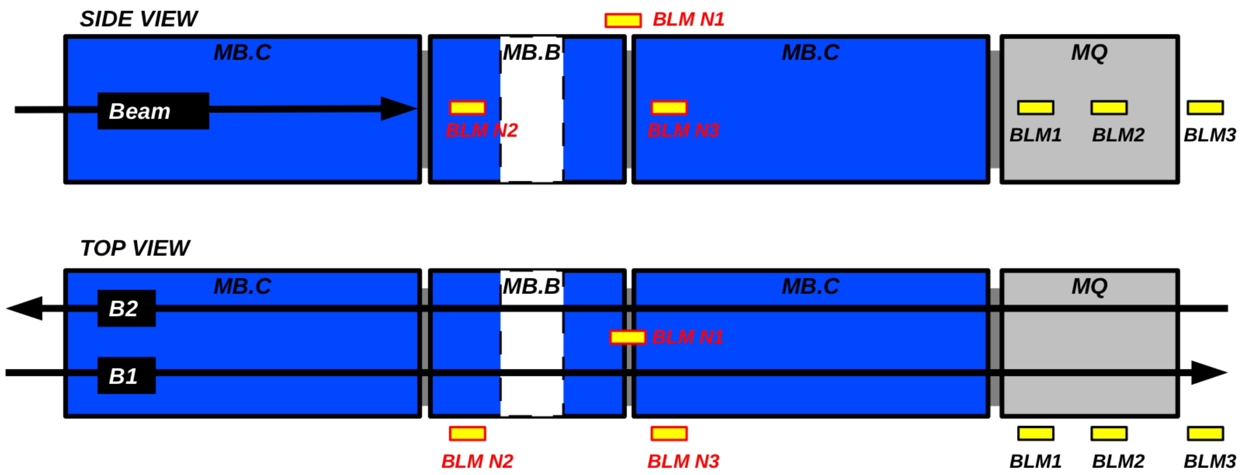

Figure 1: Side and top view of the current and various proposed BLM layouts in the ARC.

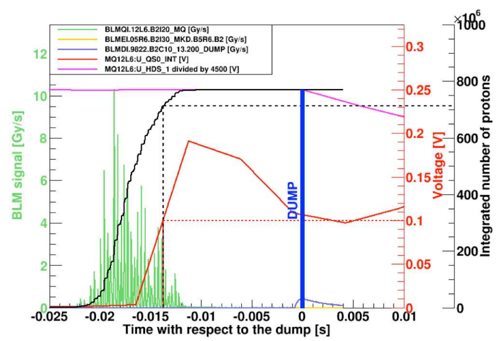

Figure 2: Measurements of BLM signals, voltage drops and number of lost protons during the quench test.

15 ms. The quench, as defined by a 100 mV change in the coil voltage, occurred after 10 milliseconds equivalent to $7.1 \cdot 10^8$ lost protons. The total integrated number of lost protons reached $7.7 \cdot 10^8$. The signals observed in the IC compared to the signals expected at the quench (from simulation at different loss scenarios) are shown in Table 2. The largest difference was observed in the 10 ms integration window, where the signal exceeded the estimated quench level by a factor 12. However, the quench onset threshold for which no return from starting quench is expected, was reached before. For shorter time scales, the quench estimation were exceeded from a factor ranging from 1.2 to 6.1. With this results, it is clear that the BLM thresholds in the millisecond scale are largely overestimated and they can be safely increased. This modification will affect all the BLMs protecting cryogenic magnets around the machine.

Collimation Quench test. Performance reach

This test was performed by using relaxed collimation settings and an ADT excitation to produce beam losses at a primary collimator with a duration of 10 s [4]. The goal was

Table 2: BLM signals and ratio to estimated signal at quench in six integration windows.

Δt	S_{BLM} **(Gy/s)**	S/Q
40μs	10.28	2.8
80μs	7.61	2.3
320μs	2.31	1.2
640μs	1.99	2.1
2.56ms	1.46	6.1
10.2ms	0.73	12.0

to determine if losses leaking to the cold elements Q8/Q9 could produce a magnet quench. For beam losses of the order of 1 MW, the signals in the most limiting BLMs (Q8) exceeded the estimated quench level by a factor 5.2 (in the 5.2 s integration window) without the observation of a magnet quench. This is attributed to the different loss scenario considered for the estimation of the current quench level. In the scenario probed during this collimation quench test, the ICs are expected to receive a larger contribution from showers produced in upstream elements. Moreover, the energy deposition in the coils, as well as the relation between BLM signals and energy in the coil, are expected to be considerably different. Hence, dedicated simulations are required in order to study the possibility of increasing the dump thresholds at these specific locations in the dispersion suppressor.

Other tests

One experiment to probe the quench level with transient losses was performed. The test consisted on directing a single bunch with intensities on the order of $6 \cdot 10^{10}$ p onto a closed injection protection collimator (TCLIB) and observing the BLM signals in the ICs downstream. The electric current in magnet Q6 was increased in steps to study the dependency of the quench level as a function of the magnet current. A quench was achieved for a current of 2000 A, corresponding to a proton energy of 4.5 TeV. The signals at the BLMs protecting Q6 were in saturation; the readings from monitors in elements further downstream are still under investigations. Once again, the probed loss scenario is very different from the one used to set the BLM thresholds. Therefore, dedicated simulations are being conducted [5] to estimate the expected energy depositions in the coil and BLM signal for this type of beam losses. The outcome of this test may lead to an increase of the BLM thresholds in the shortest integration windows for monitors protecting specific cold elements in the injection region.

Finally, a second experiment explored the quench levels under continuous irradiation at 4 TeV. A rather constant loss rate over 20 s was achieved via an ADT excitation, which allowed to study the quench margin in a quasi-steady state. The observed signal at the quench was in agreement with observations performed in 2010. Hence, no threshold changes are indicated by this measurement.

Energy extrapolations

The results of the various test need to be extrapolated in order to determine the dump thresholds over the full energy range. Different approaches will be followed for different integration times, namely:

- The steady state quench level determined with direct impact of protons follows the prediction of the model of Note 44 [6]. A good agreement was found between measurements performed at 4 TeV and previous measurements at 450 GeV and 3.5 TeV. Hence, it is assumed that the current extrapolations will also apply to 7 TeV.

- A quench at the millisecond scale was exclusively performed for 4 TeV proton beam, hence energy extrapolation will be based on simulations. From the experience collected today, it is clear that the model of Note 44 fails to describe the quench levels at this time scale. Therefore, the QP3 code [7], which shows a better agreement, is expected to be used for estimation of quench levels at different energies.

- For the transient losses, two inputs will be taken into account in the extrapolation of the measured quench levels: The results obtained in the test at Q6 will be further studied, considering the differences in the probed loss scenario with respect to failure induced loss scenario. The experiment to study UFO-like losses, which showed large spikes signals in the 40 μs integration window of up to 10 Gy/s without the observation of a quench.

In all cases, comparisons of the quench levels as estimated by the QP3 code and the Note 44 model will be performed.

PAST, PRESENT AND FUTURE OF THRESHOLD HANDLING

The dump thresholds of the BLM system can be independently set, for each one of the 4000 detectors, in the form of a 12x32 master table that accounts for the 12 BLM integration windows and the 32 LHC energy levels. To allow correction of possible uncertainties, some extra flexibility in tuning the dump thresholds is provided through a table multiplier. This so-called Monitor Factor (MF) is an extra independent parameter for each BLM and is enforced to be lower than 1. Therefore, over 1.5 million critical parameters need to be calculated, stored and sent to the appropriate processing modules for the system to function. To minimize the risk of introducing errors during manipulations, the BLM team has defined specific procedures to be followed when a threshold modification is required [8]. Several test are executed both during the processing of BLM thresholds and after the thresholds have been sent to the electronics. But some of the potential errors are intrinsic to the calculation process.

The original threshold calculation code was based on a set of C++ classes using ROOT functions [9] to evaluate the dump thresholds based on several inputs. One script, producing a threshold table, was created for each BLM family, defined as a group of BLMs with the same master table. In the script, the C++ classes were configured with information from the required inputs: energy deposition in the coil, quench levels, BLM signal estimation, etc, and their functionality allowed to compute the threshold table with simple operations. Additional consistency checks were applied to ensure the expected behaviour of the quench levels as a function of energy and loss duration. Furthermore, multiple corrections were applied in order to account for several observations: no quench on UFO losses, margin for injection losses, margin for luminosity losses, effect of RC filters in the readout electronics, etc. The script/family approach provided flexibility but required the editing of source code for every threshold modification with the corresponding risk of human error. Moreover, the book-keeping of the scripts and tables (as well as the inputs necessary in the calculation) for each of the near 200 families had become difficult to manually handle. The tests and verifications requested by the threshold procedure during the modification process were performed by running standalone software that compares two tables of 12x32 numbers.

The current threshold calculation program tries to minimize the amount of source code editing and restricts the number of operations that can be executed on the threshold table. It includes two new classes: One implements all the corrections that had been used in the calculation of the BLM thresholds. The second handles the configuration of the original threshold calculation and the additional corrections that may be requested via CARD files (configuration files with a very simple syntax). In this case the full code is compiled and the executable program takes as input a CARD file. With this approach, no source code editing was required for the computation of new thresholds during the 2012-13 run. However, this still requires the book-keeping of one CARD/table per BLM family to be manually handled. The various test and verifications are still executed in stand alone programs.

The latest proposal for threshold calculation [10] aims to keep the flexibility and reliability of the current calculation and includes the functionality to perform the required test during the calculation process. Moreover, functionality will be provided for a safe and automatic book-keeping in order to maintain the different thresholds, as well as the inputs for their calculation. With this approach an appreciable performance improvement of the threshold deployment procedure can be expected, as some of the verification steps will be integrated into the designed tool. The proposed system is based on the migration from C++ standalone threshold generation to an implementation of the algorithms in Procedural Language/Structured Query Language (PL/SQL) to be executed in the LSA database. In order to execute specific algorithms, visualize parameters, generate thresholds and execute tests and comparisons, a Graphical User Interface (GUI) is foreseen.

CONCLUSIONS

The ionization chambers in the LHC arcs will be redistributed during LS1. The optimal new configuration will move one of the chambers on the side of the MQ to the MB-MB interconnection. Monte Carlo simulation are required to evaluate the new BLM thresholds at this detector locations. Several quenches produced under controlled conditions, will have important implications for the BLM dump threshold. An increase of thresholds for the millisecond integration widows is expected for all monitors protecting cold elements. The data obtained for the estimation of the quench level for transient losses may also be applied to all the BLMs around the ring. For the steady state case, the dump thresholds may be adjusted at several specific locations (dispersion suppressor). In all cases, dedicated Monte Carlo simulations and comparison of the different models for the quench level are required. Finally, a new approach for the calculation of BLM thresholds is proposed. It will include the flexibility of the current tools but it will also add features that improve the reliability, safety and long term maintainability.

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