# BLM THRESHOLDS. PAST EXPERIENCE AND STRATEGY AFTER LS1.

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### *Abstract*

The history and motivation of dump threshold changes for the Beam Loss Monitoring (BLM) system throughout the 2012 run are described here. Also discussed are several dedicated beam experiments to probe the quench levels at different time scales foreseen for the end of the current run. The implications of these results to the threshold strategy are outlined. Moreover, the noise inherent to the BLM system may become an operational limitation in 2014 if running with the current dump thresholds. The most critical locations are discussed and revised thresholds are proposed that would mitigate the problem. Finally, the installation of new BLMs or the relocation of existing ones will require modifications that are explained in this document.

## RECALL OF THRESHOLD CALCULATION

The main goal of the BLM system is to protect the LHC superconducting magnets against quench and any other equipment against damage induced by beam losses. The beam dump thresholds must be chosen carefully in order to not only protect the LHC equipment but also maximize the machine availability. In the most limiting case, i.e. BLMs protecting superconducting magnets, the dump thresholds may be written as:

$$T(t,E) = 3 \cdot \frac{E_{BLM}(t,E)}{E_{COIL}(t,E)} \cdot Q_L(t,E) \cdot C(t,E) \qquad (1)$$

where $t$ is the beam loss duration and $E$ the beam energy. The values of $E_{BLM}$ and $E_{COIL}$ represent the energy deposited in the BLM and in the magnetic coil respectively. Note that this two quantities are typically extracted from Monte Carlo simulations. The energy dependence in both terms accounts for the fact that the energy density increases with the energy of the primary particle. The quench margin, $Q_L(t,E)$, is an intrinsic property of the protected magnet and it is computed via the algorithms derived from Note 44 [1] or by means of simulation codes such as QP3 [2]. Moreover, several corrections ($C(t,E)$) may be applied in order to account for various effects: electronic saturation, filter delays, margin for injection, etc. By convention, the thresholds are set to a factor three higher than the best estimation of the quench margin. Hence, a multiplicative factor three is present in the equation above. Note that the thresholds are technically implemented as a table of 12x32 (12 running sums and 32 energy levels).

To take into account potential uncertainties on Monte Carlo simulations and for operational flexibility an applied Thresholds Table is defined as:

$$t(t,E) = MF \times T(t,E) \qquad (2)$$

where the monitor factor, $MF$, is enforced to be lower (or equal) than one. The Applied Thresholds are the tables sent to the electronics and they are independent for each BLM. Typically calculated with $MF = 0.1$, the dump thresholds are set to roughly a factor three below the quench limit estimation.

## HISTORY OF CHANGES AND MOTIVATION DURING 2012

A set of 221 modifications for the BLM thresholds of individual detectors have been implemented for the operation of the LHC in 2012 (note that modifications for special running such as Machine Developments, MDs, are not accounted here). The full list of changes is summarized in Table 1. Most of the modifications were driven by Instabilities while Squeezing-Colliding (ISC) the LHC beams. The first set of threshold changes were implemented during the first intensity ramp-up of the year (50 BLMs protecting 2 TCLA collimators and 48 warm quadrupoles in IR3 and IR7) as the thresholds at the time were not able to sustain losses with beams of 824 nominal bunches. The second main modification corresponds to tuning of the dump threshold to allow the collimation system to clean losses of up to 200kW as explained in a subsequent section. After the extensive threshold tuning before the start of the 2011 run to allow UFO losses, only one increase of thresholds was required during 2012. Four BLMs protecting Q4L2 and Q4R8 had their thresholds increased in order to allow losses produced by UFOs generated in the injection kickers. Finally, minor changes in the Roman Pots in IP5, monitor factor increase by a factor 3, were implemented.

Table 1: Summary of BLM threshold changes throughout the 2012 run.

| Date | BLMs | Location | Comment |
|---|---|---|---|
| Mar 12th | 15 | L2,L8 | new BLMs |
| Apr 13th | 50 | IR3,IR7 | ISC |
| Apr 19th | 4 | 4R2,4R8 | MKI UFOs |
| May 4th | 2 | L7 | ISC |
| May 8th | 4 | R6,L6 | ISC |
| Jun 28th | 41 | IR3,IR7 | 200kW IR7 |
| Jul 13th | 72 | IR3,IR7,IR6 | ISC |
| Oct 25th | 1 | 6R5 | correc |
| Nov 8th | 2 | IR5 | Margin RP |
| Nov 30th | 30 | IR3,IR7 | 200 kW IR3 |

Note that despite the large number of BLMs that required modification, there is a reduction of more than a factor 20 with respect to 2011, where about 90% of the roughly 4000 BLMs had their thresholds changed. The number of interventions has also been reduced by a factor 2 with respect to the previous year. Note also that only a 20% (44) of the changes affected the protection of cold elements, while 44% (98) affected warm elements (roman pots and normal conducting quadrupoles) and 36% affected collimators.

## UFO RELOCATION

The BLM system in the LHC arcs equips the Main Quadrupoles (MQ) with three Ionization Chambers (IC) per beam separated by 3 and 4 m respectively. This provides both redundancy and spacial resolution to distinguish between beam losses originated at different points within an MQ, but it prevents from determining the original location of the beam loss if it happens anywhere within the three Main Bending (MB) dipoles located in between. During the beginning of the 2011 LHC run, four ICs were situated at the MB magnets of cell 19R3[1] as shown in Figure 1. Comparison of data collected during the 2012 run with FLUKA simulations [3] demonstrated that UFO losses can originate anywhere within the LHC FODO cell. Therefore, the BLM system in its current configuration does not protect MB magnets against potential quenches generated by UFO losses.

Several new configurations of the BLMs have been discussed, all of them based on the relocation of the second BLM at the MQ to a certain position along the arc cell. The first proposal consists of moving the IC to either immediately after the interconnection MB.A-MB.B (BLM N2) or immediately after the interconnection MB.B-MB.C (BLM N3). Table 2 summarizes simulation results [4] for three different UFO locations and the two proposed BLM positions. The numbers indicate the threshold reduction that would be required at the BLMs in their current position in order to protect against the various UFO losses. Note that, even though the signal gain is quite significant in all cases, some of the configurations do not protect for all the UFO scenarios. The possibility of locating the BLMs at the interconnect between MB.A and MB.B (and MB.B and MB.C) has been found as a better solution. This proposal presents the advantages (with the proper choice of transverse position) of covering UFO losses originated anywhere along the arc cell. Note that dedicated simulations will be required in order to estimate the BLM signals necessary to calculate specific BLM threshold.

## QUENCH TESTS

A period of 48 hours has been allocated at the end of the 2013 run in order to perform dedicated exercises to probe the quench limits in different time scales. In this section are described the expectations of those test as well as the impact on the threshold strategy for LS1.

Table 2: Signal gain factor for several BLM relocation and UFO scenarios.

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

Possibly the test that could have a biggest impact will be the test trying to probe the Quench level in the ms scale, where the current calculation (based on Note 44) seems to underestimate the quench margin. In previous MDs, it has been demonstrated that the tranverse damper (ADT) and kicker for tune and aperture measurements (MKQ) can be used to generate losses in the ms scale. The QP3 code predicts a quench margin which at 3.5 TeV is on the order of $30\,\mathrm{mJ}\cdot\mathrm{cm}^3$. However, extrapolations from data collected during 2012 [5] indicate that the maximum energy deposited in the coils is at the level of 10% of the estimated quench margin. Geant 4 simulations with geometries equivalent to that in cell 12L6, are used to estimate the energy depositions in the magnetic coils within the conditions of the proposed experiment. Comparing those energy depositions with the estimated quench levels with the QP3 code [2], a quench is expected to occur for total beam losses in the order of $10^8$ protons. This, if confirmed, will have a severe impact on the BLM thresholds as corrections would be required in all BLMs protecting cold elements.

Two independent exercises are foreseen to test if magnets MQ8R7 or MQR9R7 could be quenched due to collimation cleaning losses. In previous tests [6], losses of $500\,\mathrm{kW}$ at the primary collimator were achieved while reaching 70% of the assumed quench level in Q8. In this case the beam was excited by tune resonance crossing, generating beam losses of about one second. The proposed test will apply an ADT excitation to generate losses of a longer scale. The BLM threshold for Q8 and Q9 are calculated based on a different (direct impact of protons in the beam screen) loss scenario. Therefore, a quench may occur for signals that exceed the current estimated quench level. If this is confirmed, it may have an impact on the BLM thresholds for the cold elements in the Dispersion Suppressor (DS). The same exercise is scheduled with an ion beam. The previous attempt [7] achieved BLM signals at the estimated quench level for losses in a shorter time scale. The expected impact on BLM thresholds is a potential increase for cold elements in the DS as well as possible specific loss locations for the ion operation.

Another experiment will be conducted to explore the quench level in the steady-state limit. In this case, an orbital bump and an ADT excitation will be produced to generate losses at the center of Q12L6. In previous tests the estimation of the quench level for losses of 5 seconds was found to be a factor 3 too high and the BLM thresholds

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[1] Cell 19R3 is one of the LHC locations where a larger fraction of UFOs has been systematically observed.

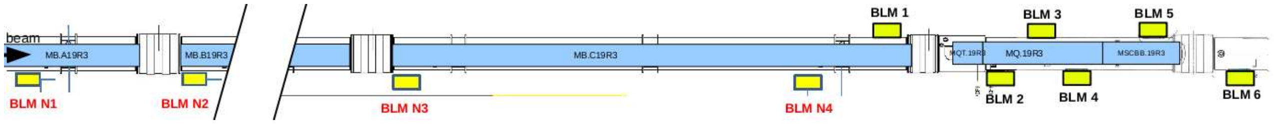

Figure 1: Schematic view of the BLM location in cell 19R3.

were accordingly corrected. The goal of the exercise is to achieve longer losses that approximate better to the steady-state case. The results of this test may impact the dump threshold for all the BLMs protecting cold elements.

The last proposed test consists of injecting probe bunches onto a closed TCLIB in order to produce showers that may quench Q6. The current of Q6 will be increased to study the energy behaviour of the quench level. No quench was achieved in previous attempts [8].

## NOISE

In order to study the performance of the BLM system in terms of noise, the signals observed in the detectors are analyzed during periods without beam. The noise of a BLM is defined as the maximum signal (integrated over $40\ \mu$s) recorded in a period of 9 h. As an example, Figure 2 shows the noise versus threshold for 7 TeV operation with data collected on December 11th starting at 17:00 local time. The aim of this analysis is to identify potential locations where the BLM system could trigger a beam dump as a consequence of its intrinsic noise. The red line corresponds to the case in which the noise would reach the dump thresholds while the blue line represents a noise level at 10% of the dump threshold. The later is choosen as level for comfortable operation. The analysis showed no signals higher than 50% of the threhold but about 40 BLMs were found above the operational limit. The list includes BLMs protecting MQM and MQML magnets in the long straight section and Dispersion Suppressor (DS), MB magnets in the DS, several quadrupoles in the arc and injection septa magnets MSI.

Several mitigation strategies have been applied in the past. During the previous shut down period, about 3 km of standard BNC read-out cable (affecting 90 monitors) were replaced by a new NES-18 cable with a double copper shielding in order to minimize the effect of noise. Further cable replacements (6 km affecting 22 BLMs) are foreseen during LS1.

Typically, a correction that allows at least 10 times the noise level (i.e operational margin) has been applied, by imposing a minimum threshold of 0.15 Gy/s in the $40\ \mu$s integration window and decaying exponentially to simulate the signal collection time. This value, as shown in Figure 2, is above the dump threshold for several monitors. However, note that there is some margin in the dump thresholds as they are typically set well below (factor 3.3) the estimated quench limit. In case of this level being above the estimated quench levels, redundancy of the BLM system would need to be considered.

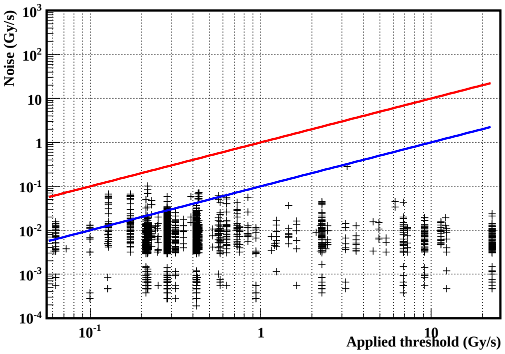

Figure 2: Noise vs thresholds for all ionization chambers. Data collected during December 11th 2012.

## TRIPLET MAGNETS

Initial thresholds settings for triplet magnets were calculated according to the Note 44 quench level estimations [1] and dedicated FLUKA simulations [9] of three different failure scenarios (at 7 TeV), namely:

- Beam loss at TAS. The obtained energy depositions in the coil were on the order of $2-3\cdot 10^{-9}\mathrm{mJ}\cdot\mathrm{cm}^{-3}$ per lost proton.
- Proton direct impact at the center of a triplet magnet as a consequence of misalignment of primary and secondary collimators (or accidental retraction of tertiaries). For the so-call Q2B loss scenario, the estimated maximum energy depositions in the coil were in the order of $159\cdot 10^{-9}\mathrm{mJ}\cdot\mathrm{cm}^{-3}$ per lost proton.
- Particle debris originated in the interaction point due to p-p collisions. In this case, $5\cdot 10^{-9}\mathrm{mJ}/\mathrm{cm}^3$ per proton-proton interaction was computed.

As the most limiting case (by two orders of magnitude), the Q2B loss scenario was the selected case for the calculation of the original thresholds. However, several changes were introduced to the original settings during the 2011 run. Moreover, the dump thresholds in the long integration windows (5.3 seconds and above) were increased in order to allow for extra luminosity induced losses [10].

During high luminosity fills at 4 TeV, the signals observed in BLMs protecting triplet magnets systematically reached 50-80% of the dump threshold due to signals induced by particle debris. The current thresholds decrease by a factor 4.5 when going from 4 TeV to 7 TeV operation. Moreover, the signals observed in the BLMs are expected to increase by a factor 1-3.3 depending on the considered magnet and the BLM position. Hence, it is expected that the BLMs would get signals a factor 2.25-7.42 over the dump threshold, making operation not possible with the current settings. However, it is believed that the current quench levels are very conservative and the situation will be revised. As an example, when comparing the estimated quench levels for MQ magnets ($24\ \mathrm{mW}\cdot\mathrm{cm}^{-3}$ at 450 GeV and $5\ \mathrm{mW}\cdot\mathrm{cm}^{-3}$ at 7 TeV) and triplet magnets ($50\ \mathrm{mW}\cdot\mathrm{cm}^{-3}$ at 450 GeV and $12\ \mathrm{mW}\cdot\mathrm{cm}^{-3}$ at 7 TeV) only a factor 2-2.5 difference is found. This is in contradiction with the fact that the triplet magnets were designed to sustain significantly more radiation than the standard quadrupoles. Moreover, the loss scenario used to set thresholds in the steady-state case (currently Q2B in the full time range) may be revisited. Finally, note that the long term plan (foreseen for LS2) is to provide a more direct measurement of the energy depositions in the magnetic coil by locating diamond detectors in the cold mass [11].

## OPTIMIZATION OF COLLIMATION THRESHOLDS

Several changes were introduced to the original threshold settings [12] for the BLMs protecting LHC collimators during the 2012 run. The dump thresholds for BLMs at TCP, TCSG and TCLA collimators in IR7 [13] were increased to allow (collimation design) 500 kW[2] power loss at primary collimators by scaling the beam losses observed during betatron loss maps. This was possible as such beam losses have been measured during MDs [6] without the observation of any magnet quench. In a subsequent step, a similar change was introduced for IP3 collimators in order to avoid limiting losses due to off-momentum particles [14]. Further threshold increases at collimators are foreseen at the beginning of the 2014 run. In particular, tertiary collimators in IP1/5 have been observed to exceed the warning level (30% of threshold) during high luminosity fills.

## SUMMARY AND CONCLUSIONS

A large campaign of threshold changes is expected during LS1. Potentially all the BLMs protecting cryogenic magnets and several monitors protecting collimators will require a modification. Two ionization chambers per quadrupole will be moved to a different location for better protection of MB magnets against UFO losses, and this monitors will require specific thresholds. The result of several dedicated experiments to probe the quench level in different time scales will be taken as input for the BLM thresholds. An intensive effort will be necessary for understanding the different measurements. The signals observed in the BLMs will be taken as input and Monte Carlo simulations will provide the energy depositions in the magnetic coil. Furthermore, the energy deposition in the coils needs to be compared with the quench levels predicted by the Note 44 model as well as the QP3 program. The BLMs at locations affected by Noise may need to be increased in the short running sums in order to overcome false dumps. Finally, monitors protecting triplet magnets will also have their thresholds revisited. The loss scenarios as well as the quench level predictions that determine the original BLM threshold calculation need to be investigated.

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[2] Note that the thresholds are reduced to sustain a power loss of 200 kW, as mentioned in previous sections, via the monitor factor.