COMMISSIONING AND OPTIMIZATION OF THE LHC BLM SYSTEM

E.B. Holzer, B. Dehning, E. Effinger, J. Emery, C.F. Hajdu,
S. Jackson, C. Kurfürst, A. Marsili, M. Misiowiec, E. Nebot Del Busto, A. Nordt,
C. Roderick, M. Sapinski, C. Zamantzas, CERN, Geneva, Switzerland
V. Grishin, IHEP, Protvino, Russia and CERN

Abstract

Due to rapid progress with the LHC commissioning in 2010, set-up beam intensities were soon surpassed and damage potential was reached. One of the key systems for machine protection is the beam loss monitoring (BLM) system. Around 4000 monitors are installed at likely or critical loss locations. Each monitor has 384 associated beam abort thresholds (12 integrated loss durations from 40 μs to 84 s for 32 energy intervals). A single integrated loss over threshold on a single monitor aborts the beam. Simulations of deposited energy, critical energy deposition for damage or quench and BLM signal response backed-up by control measurements determined the initial threshold settings. The commissioning and optimization of the BLM system is presented. Test procedures were used to verify the machine protection functionalities. Accidental magnet quenches were used to fine-tune threshold settings. The most significant changes to the BLM system during the 2010 run concern the injection, the collimation and the beam dump region, where hardware changes and threshold increases became necessary to accommodate for increasing beam intensity.

INTRODUCTION TO THE LHC BLM SYSTEM

The main function of the LHC BLM system [1] is damage protection. Additionally, quenches of superconducting magnets have to be avoided. The BLM system's response is critical for short and intense particle losses, while at medium and longer loss durations it is assisted by the quench protection system and the cryogenic system. The system changes its beam abort thresholds automatically, corresponding to the beam energy, and allows to follow the loss duration dependent quench levels of the superconducting magnets (signal integration times from 40 μs to 84 s). The detectors are ionization chambers (IC) and secondary emission monitors (SEM), which are 70000 times less sensitive. In order to give operations a threshold tuning possibility, the 'applied thresholds' are derived from pre-set 'master thresholds' by multiplication with a 'monitor factor' (MF). $\mathrm{MF} \leq 1$ is enforced. Typically, $\mathrm{MF} = 0.1$ on cold magnets. Master thresholds are always set safely below damage level (at least a factor 10 for losses up to 100 ms), typically to three times the quench level. 'Families' of monitors have the same master thresholds. They protect same elements with same monitor locations from similar loss scenarios. Table 1 summarizes the monitors and families. ICs which are not used for beam interlock are installed in the dump lines, for future upgrade elements or redundant monitors with RC signal delay. The BLM system is extensively used for operation verification and machine tuning. The following data sets are available: Logging (one value every second for nearly all integration times); post mortem (online 80 ms and offline 1.72 s of 40 μs integrals); collimation buffer (80 ms of 2.6 ms); capture data (80 ms of 40 μs or 5.2 s of 2.6 ms) and extraction validation or XPOC buffer (80 ms of 40 μs). Logging data is also used for online display.

Table 1: Monitors and Families

Monitors	Purpose	# Monitors	# Families
IC	interlock (97%) observation (3%)	3592	122
SEM	observation	289	22

COMMISSIONING AND SYSTEM VALIDATION TESTS

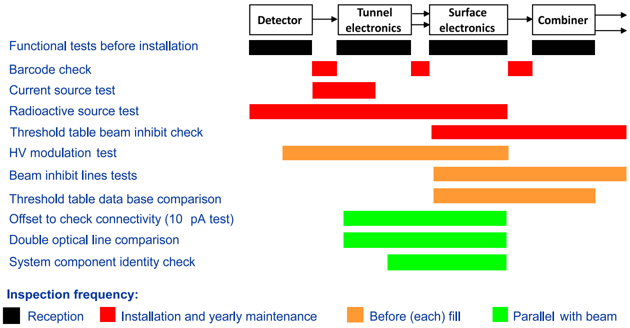

Figure 1: Overview of the most important BLM testing procedures. The colored bars show which part of the system is tested at which frequency.

Commissioning of the BLM system (2008, 2009 and beginning of 2010) was advancing in parallel with the beam commissioning of the LHC [2]. The machine protection functionalities of the BLM system had been phased in. This way, they provided the required protection level for each stage of the commissioning, without compromising the machine availability. The input to BIS (Beam Interlock System) from individual monitors was switched from 'masked' to 'unmasked' in stages. At the end of the 2009 run the LHC was operating with most of the channels unmasked. The continuous (during beam operation) acquisition system self tests became operational during the 2009 run.The regular (between beam operations) BLM system tests became operational before the 2010 run.

The system validation test procedures are described in [3] and [4]. They have been defined to achieve the required reliability and availability of the system. The functionality of all components was tested before installation. Thereafter, there are three different inspection frequencies: tests after installation and during yearly maintenance, tests before (each) fill and tests which take place continuously (also during beam operation). Figure 1 lists the most important tests and their frequency. Additional machine protection tests [5] (mostly verification tests of the above system tests) have been executed during the commissioning phase. Before start-up and before a new release the firmware is tested extensively for all operational (protection relevant and other) aspects. A dedicated test is included for each issue found in the past on a previous firmware version. The 'vertical slice' test is executed on a test system located at the LHC point IP2. The complete hardware chain from the ionization chamber to the beam interlock output is verified. A specific part of the test uses a front-end emulator of the analogue part of the electronics. It allows for exhaustive threshold triggering tests, optical link reception and status tests and verification of the response to predefined input signal patterns (linearity tests, etc.). Performance tests with beam include beam aborts with defined injection losses (on a closed collimator) and measurements of the reaction time of the BLM (from injection to breaking of beam permit loop by BLM). The validation tests between fills are enforced by the BLM system to be executed at least once in 24 hours (else the next injection into the LHC is inhibited). The tests are executed and analyzed in BLM surface electronics FPGAs (combiner cards) and take about 7 minutes to execute. Three tests are executed on each monitor: A comparison of system parameters (including thresholds) between data base and surface electronics; an internal (VME crate) beam permit line test and a connectivity check (by modulation of chamber high voltage). A similar approach (rigorous testing of protection relevant functions) will have to be applied to the software for generating and changing abort thresholds including regular and/or automated threshold tests.

OPERATIONAL EXPERIENCE

Table 2 summarizes the beam aborts requested by the BLM system February to August 2010 for energies above 450 GeV. Out of a total of 220 beam aborts, 24 were requested by the BLM system due to losses above threshold. Three were due to BLM system hardware failures (system unavailability). No safety related issues have been detected on any of the system components (hardware, firmware, software or system parameters). BLM system failure rate and availability have been evaluated [3] using the Safety Integrity Level (SIL) approach with downtime cost evaluation as input. The required probability of not detecting a dangerous beam loss, with the consequence of damaging a magnet, is below 10^{-3} per year (SIL3). The system design was adapted to satisfy the SIL3 requirement, assuming 100 dangerous losses per year, which can only be detected with one BLM. Experience has shown a redundancy in the BLMs to measure losses and request beam aborts. This has the potential to decrease the damage risk considerably. False beam aborts decrease the availability of the LHC. The required probability was calculated to below 20 false dumps per year (corresponding to SIL2). From the experience of February to August 2010, 7 to 14 false dumps can be extrapolated for one year of standard LHC operation (Table 3). This is consistent with the predictions and satisfies the requirements.

Table 2: Statistics of beam aborts requested by BLM system for energies above 450 GeV (after the start of the ramp) from February to August 2010 [6].

Losses above threshold	**24**
Fast (ms) loss events	7
Collimator adjustment	7
Losses on resonance, during scraping, octupole studies and wire scans	7
Changes of beam parameters and feedback problems	3
BLM system failure	**3**
Optical link	2
VME64x crate CPU	1

Table 3: Damage risk and false dumps for one year required and predicted by simulation and extrapolated from 2010 experience.

per year	Requirement	Simulation	Estimate based on 2010 Feb. - Aug.
Damage risk	$< 10^{-3}$	$5 \cdot 10^{-4}$	–
False dumps	< 20	10 - 17	7 - 14

Hardware

Each individual of the 3600 BLM channels connected to the beam interlock system (BIS) requests a beam abort if one of the 12 integration windows gives a loss above threshold. It equally requests a beam abort (or inhibits beam injection) if one of its internal system checks fails. In order to allow operation of the LHC in the presence of noisy or broken channels, a procedure to disable single monitors was established [7]. On the database and on the application levels it is enforced that no critical monitor (and only one monitor out of a group of redundant monitors) can be disabled. Until September 2010, not a single monitor needed to be disabled, showing a remarkable availability of the system. Table 4 summarizes the hardware interventions of February to August 2010. Most of the interventions were prompted by the onset of system degradation detected by regular offline checks. Hence, the component was replaced before malfunctioning. Some interventions became necessary because a failure was detected by one of the automatic internal system tests, preventing beam injection. Interventions mostly took place during scheduled technical stops or in the shadow of other interventions. The availability of the LHC was not seriously compromised by BLM system failures and repairs. Figure 2 shows the noise levels and the applied threshold values for all monitors for 40 μs integration time and 3.5 TeV. A safety margin of 10 is aimed for between the threshold and the noise. Abort thresholds decrease with increasing beam energy. Hence, solutions to decrease the noise levels will have to be implemented for 7 TeV operation, in order to ensure this safety margin.

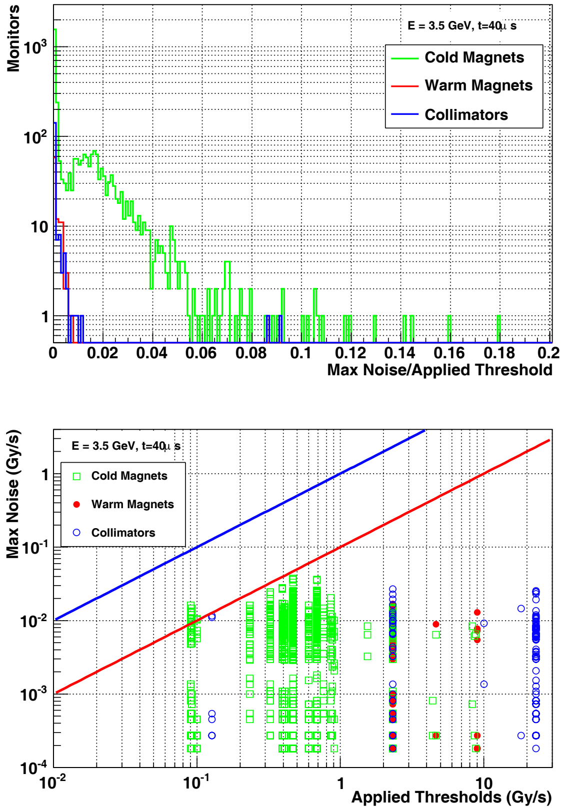

Figure 2: Noise levels and the applied threshold values for all monitors for 40 μs integration time and 3.5 TeV.

Thresholds

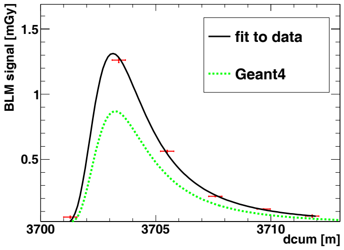

Figure 3: Second quench GEANT4 simulations compared to measurements.

Initial beam abort thresholds have been established by simulations and test measurements. Faced with uncertainties, a conservative approach has been taken. Hence, a certain number of threshold increases were necessary (see below) at BLM locations with significant non-local losses. Mostly, the initial thresholds appeared appropriate for the 2010 run. Neither damage nor a single avoidable quench occurred (the BLM system cannot protect against quenches by injected beam). Most of the monitors were not causing undesired beam aborts, none triggered on noise. In case of exceptionally high losses (see Table 2) beam aborts were requested. No event was detected where the system failed to trigger. Five beam induced magnet quenches occurred, two in 2008, two in 2009 (see Fig. 4) and one in 2010. In all of them injected beam was lost at cold aperture and MB (main bending) magnets quenched. The 2008 quenches were analyzed in detail, as enough information about the proton impact distribution and the BLM response was available. The BLM signal could be reproduced by GEANT4 simulations to within a factor of 1.5 (see Fig. 3). Consequently, in 2009 the thresholds on all cold magnets were raised by approximately 50% [8]. The most likely loss locations with circulating beams are the quadrupole magnets. Most of the monitors are installed there. The proton impact distribution on the aperture influences significantly (up to a factor of 6 in [8]) the quench levels as measured by the BLM. As it varies between the losses, it is an inherent uncertainty. First measurements (wire scanner losses, fast losses, first magnet quench tests) indicate that the quadrupole thresholds could be too conservative. Beam tests are planned using injection losses (transient), creating orbit bumps with circulating beam (steady state) and creating losses with the wire scanner (ms time range). A dedicated QPS (quench protection system) diagnostics allows to measure the onset of a quench and to avoid an actual magnet quench during the test. A more elaborate magnet model will be used to establish new quench levels by the end of 2010. A certain number of human threshold manipulation errors have occurred. Database and software checks have been introduced (or will be introduced) to avoid (or reduce) manipulation errors in the future.

Unexplained Fast Losses

Seven beam dumps due to fast (ms scale) beam losses ($<$ 1% of beam intensity) of yet unidentified origin have been observed. The losses are always detected by more than six local monitors, at least three of them getting close to (or above) the abort threshold (in the 2.5 ms integration window), confirming the redundancy in the system. Furthermore, the losses from these events are seen at all aperture limits (collimation regions). Figure 5 shows the local longitudinal pattern of one of these events and the signal in the different integration times for the monitor with the highest loss compared to the applied thresholds. Additional BLMs at aperture limits with a bunch-to-bunch resolution are planned. At the moment three test set-ups are installed

Table 4: Hardware Interventions Due to Channel Degradation or Failure Since February 2010

Element	Details	Number	Out of total installed
IC	bad soldering	9	3600
tunnel electronics	noisy analogue component (CFC)	7	359
tunnel electronics	bad soldering	2	720
tunnel electronics	low power optical transmitter (GOH)	9	1500
surface electronics	weak optical receiver	7	1500
surface electronics	failed SRAM	2	350
VME64x Crate	failed CPU RIO3	2	25
VME64x Crate	failed power supply	1	25

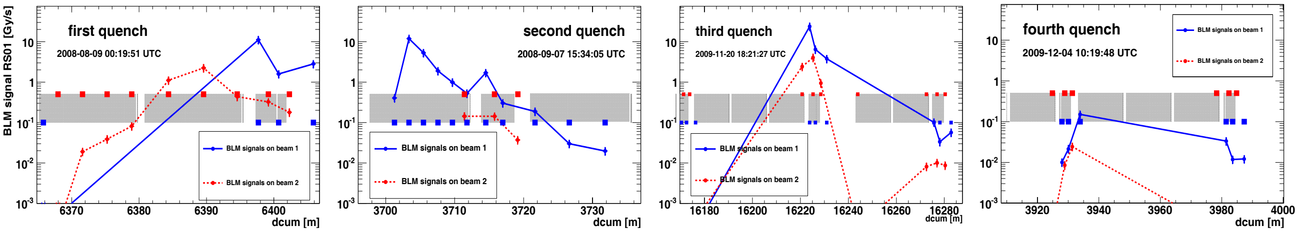

Figure 4: Beam induced quenches 2008 and 2009. The first and second quench occurred at an MB which was equipped with BLMs (for the first quench only the opposite beam side was equipped). During the third quench the IC with the highest signal saturated. The fourth quench happened at an MB after the MQ, which is not equipped with monitors.

at the betatron collimators in IP7 using diamond detectors and ACEMs (Aluminum Cathode Electron Multiplier). They are expected to help identifying the origin of the fast loss events. A recent search (using BLM logging data) for similar events which did not trigger a beam abort (spanning 230 hours of stable beam for physics), found 0.06 of such events per hour for fills with 24 bunches per beam, while for fills with 48 bunches per beam the frequency increased to 0.13 events/hour. The magnitude of the loss signals increased as well with the number of bunches in the machine.

SYSTEM CHANGES

System changes became necessary for two reasons (see [9] for documentation of all system changes and [7] for the procedures): increasing of the upper end of the dynamic range and adaptation for particle showers from non-local losses. Very high losses (above 23 Gy/s) measured with an IC surpass the operational range of the electronics, while they are still below the noise level on short integration times for most of the SEMs. Therefore, a few (redundant or additional) ICs in the injection, extraction and cleaning regions were equipped with RC readout delay filters (reducing the peak signal by approximately a factor of 180). They are only used for measurements. The BLM system currently employs a local protection strategy. Each machine element deemed to require protection, is protected by locally installed monitor(s). Large particle showers reaching a monitor from a distant loss location compromise this approach. Losses from the injection line collimators and from over-injection (pilot bunch dumped on the ring element TDI) are visible on injection region ring monitors. There, smaller RC readout delay filters (reducing the peak signal by approximately a factor of 10) were installed. Short integration time thresholds at injection energy had to be increased. Thresholds at all other energies were reduced to counteract the effect of the RC filter. See Fig. 6 for an example of threshold change. At the same time a lower limit for thresholds of 0.1 Gy/s was introduced, in order to safely stay above the noise. As a consequence, quench

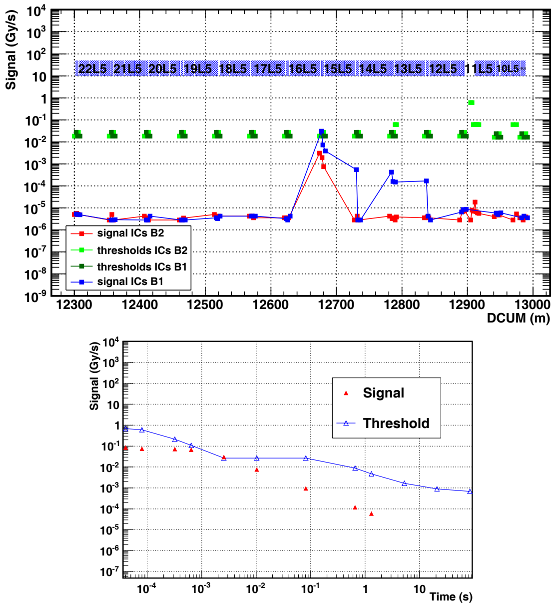

Figure 5: Longitudinal pattern of a fast loss event and signal in the different integration times for the monitor with the highest loss. The beam abort was triggered on the 2.5 ms integration time.

of eight cold magnets (24 BLMs) at injection energy cannot be excluded by local BLM, while damage protection rests ensured. Shielding blocks were installed recently and the installation of more shielding is planned. The possibility to 'blind' the BLM system at injection is investigated. Similarly, in the collimation regions losses from upstream collimators can be larger than signals from local proton impact. In a deviation from the local protection scheme, damage to four TCLSs in IP7 and possibly eight TCLAs in IP3 cannot be excluded by local BLMs. There, protection is based on collimator hierarchy, position interlocks, temperature interlocks and on BLMs further downstream. Table 5 summarizes the requested system changes since Feb. 2010.

Table 5: Changes Requested Since February 2010

	# Monitors	**# Families**
HW changes	**67**	
RC delay filter installation	64	19
New monitors	3	2
Threshold changes	**97**	
New Families	**73**	**25**
RC signal delay filters	64	19
Over-injection losses	7	4
Injection losses (no RC filter)	2	2

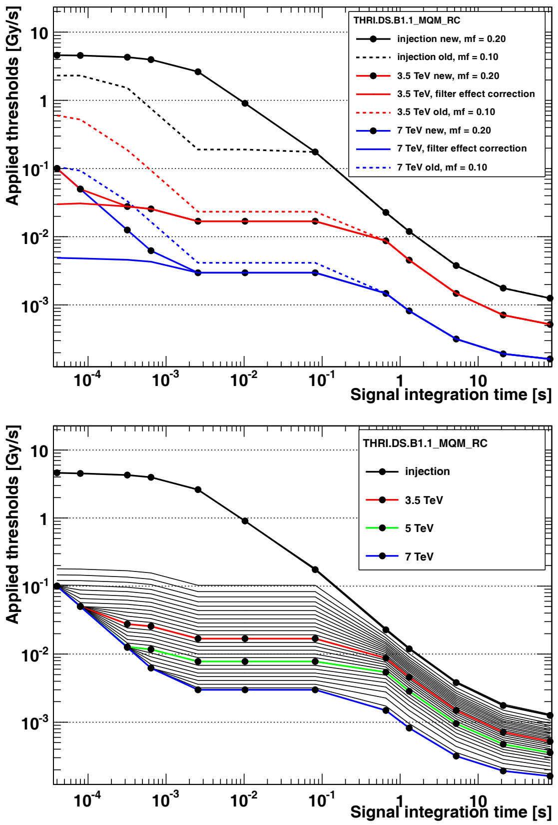

Figure 6: Threshold changes on a cold magnet in the injection region after installation of a RC delay filter. The injection energy threshold was increase to allow for injection losses. All other energies were decrease to counteract the effect of the filter. Finally, a minimum threshold of 0.1 Gy/s was enforced to avoid dumping on noise.

SUMMARY

Until today the machine protection by the BLM system has been fully reliable. No avoidable quench occurred. There is no evidence of a single beam loss event having been missed. Hardware issues never caused a degradation of the reliability. The number of false beam aborts due to hardware failures are as expected and within requirements. Noise events never caused beam aborts. Not a single monitor needed to be disabled. The initial thresholds (even though set conservatively) proved mostly adequate 2010 operation. No big deviation has been detected between the protection thresholds and the magnet quench levels. Further beam test will help to establish new threshold values. Losses were always seen by several local monitors and at the aperture limits, showing a certain protection redundancy. Open issues and future upgrades include shielding of injection losses and a redefinition of the injection region and collimation region protection approach. The dynamic range will have to be increased on the lower end by noise reduction (reduced cable length due to new radiation hard electronics, better cables). On the upper end it will be increased by a new monitor type, bridging the gap between the IC and the SEM.

REFERENCES

[1] B. Dehning et al., "The LHC Beam Loss Measurement System", PAC 07, Albuquerque, New Mexico, USA.

[2] E.B. Holzer et al., "Lessons learnt from Beam Commissioning and Early Beam Operation of the Beam Loss Monitors (Including Outlook to 5 TEV)", Chamonix 2010 Workshop, Chamonix, France.
B. Dehning et al., "First Experience with the LHC Beam Loss Monitoring System", PAC 09, Vancouver, Canada.

[3] G. Guaglio, "Reliability of the Beam Loss Monitor System for the Large Hadron Collider at CERN," PhD Thesis, Université Clermont Ferrand II - Blaise Pascal, CERN-THESIS-2006-012.

[4] B. Dehning et al., "Individual system tests of the LHC beam loss [BLM] monitors", EDMS 877031.

[5] E.B. Holzer et al., "MPS aspects of the beam loss monitor system commissioning", EDMS 896394.

[6] R. Schmidt, J. Wenninger and M. Zerlauth, Post Mortem Analysis, private communication.

[7] E.B. Holzer et al., "Management procedures of the BLM system settings (including description of software configuration and database structure)", EDMS 1027851.

[8] B. Dehning et al., "Energy deposition in LHC MB magnet and quench threshold test with beam", LHC Project Note 422.

[9] E.B. Holzer, documents LHC-BLM-ECR-0001 to LHC-BLM-ECR-0014, `https://edms.cern.ch/project/CERN-0000083600/0`.