LESSONS LEARNT FROM BEAM COMMISSIONING AND EARLY BEAM OPERATION OF THE BEAM LOSS MONITORS (INCLUDING OUTLOOK TO 5 TEV)

E.B. Holzer, B. Dehning, E. Effinger, J. Emery, S. Grishin, C. Jr Hajdu, H. Ikeda, S. Jackson, C. Kurfürst, A. Marsili, A. Nordt, J. Perez Messeri, V. Prieto, M. Sapinski, C. Zamantzas,
CERN, Geneva, Switzerland

Abstract

Results from the 2008 and 2009 operation of the LHC BLM system are presented with respect to the dependability (reliability, availability and safety) of the system. Known limitations and measures taken are discussed. The accuracy of the beam abort thresholds with respect to the magnet quench levels are examined. Threshold levels at different energies are compared to the noise levels and the limits of the readout electronics. An extrapolation from the measured loss profiles (injection losses as well as betatron cleaning and momentum cleaning losses) toward the expected loss profiles at higher intensity is given. It is verified whether they are expected to stay below quench and damage levels (respectively the currently enforced abort thresholds).

INTRODUCTION

The commissioning of the LHC Beam Loss Measurement (BLM) system (2008, 2009 and beginning of 2010 beam operation) is advancing in parallel with the beam commissioning of the LHC. Up to now the performance of the BLM system has been very satisfying. No safety related issues have been discovered.

In order not to compromise the machine availability during commissioning, the machine protection functionalities of the BLM system are being phased in. The input to BIS (Beam Interlock System) from individual monitors (approximately 4000) is being switched from masked to unmasked in stages. Every single unmasked monitor channel is removing the beam permit in case it measures a loss signal above the pre-set threshold values. 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 [1, 2]. A failure of the test on a single channel removes the beam permit. The regular (between beam operations) BLM system tests are to become operational before the 2010 run. These tests are driven by the LHC sequencer. A failure of one of the channels or the non-execution of the tests within 20 hours inhibits the beam injection [2].

In order to allow the injection of beam with damage potential (above SBF, Safe Beam Flag, limit of 1×10^{12} protons at 450 GeV), or to allow the acceleration of fewer protons up to damage level [3], the BLM system has to reach full protection level. The mayor objectives are: The completion of all technological tasks before 2010 start-up [1]; validation of the threshold settings [4] (requiring beam tests for threshold calibration, operational experience and in depth performance analysis); the performance of all defined MPS (machine protection system) tests [5]; the rigorous application of all procedures for system changes as defined in [6]. The above points are mostly not covered in here. The paper will concentrate on the limitations encountered during the run and the proposed solutions. It will be discuss whether possible additional limitations on energy and intensity have to be deduced from the 2009 data (assuming that full protection level had already been achieved).

OPERATIONAL EXPERIENCE

Noise and Offset

Individual channel noise and offset values are important for the availability, as too high values could cause unnecessary beam dumps. Nearly daily checks of all channels allow to detect in time the onset of a problem. The probable cause (cable noise, card non-conformity, etc.) can be identified as well. Long cables (up to 800 m) have been identified as largest noise sources. By changing cables (still multi wire twisted pair cables, but higher quality) a noise reduction by a factor of two could be achieved. It is foreseen to install single pair shielded cables at critical locations (especially around IP3) during the next shut-down. This is expected to yield an additional noise reduction by a factor of five. In parallel, a new radiation tolerant (up to kGy) ASIC (Application Specific Integrated Circuit) readout electronics is being developed within a PhD thesis by Giuseppe Venturini. It is planned to be installed in the long straight sections of the LHC in order to avoid any long cables and reduce the noise levels.

Fig. 1 top row shows the noise single channel frequency distribution for 40 μs integration time over 9 hours for two channels. On the left a low noise channel with a short cable and on the right a high noise channel with a long cable. Fig. 1 bottom row shows the maximum noise frequency distribution (for 40 μs integration time) of the Ionization Chambers (IC) on the left and the Secondary Emission Monitors (SEM) on the right. There are approximately 3600 ICs and 300 SEMs in the LHC. A SEM is always installed next to an IC. It is less sensitive by factor of 70000. Channels which have a maximum noise reading above the

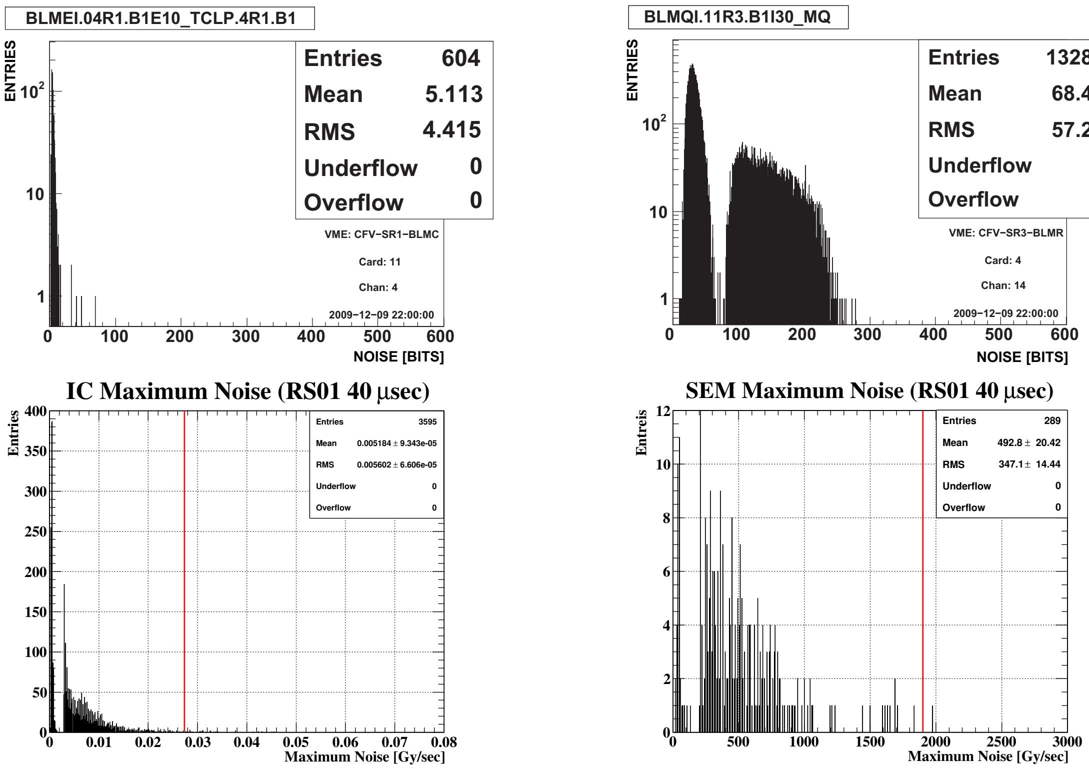

Figure 1: Noise single channel frequency distribution on the top and maximum noise frequency distribution on the bottom (see text).

vertical line (300 bits) will be repaired. 300 Bits correspond to 0.027 Gy/s and 1898 Gy/s on the IC and SEM 40 μs integration time respectively.

SEMs have a higher percentage of high noise channels. Whether this effect is (only) caused by the typically much longer cables on the SEMs is under investigation.

Dependability (Reliability, Availability and Safety)

No safety related issues have been detected on any of the system components (hardware, firmware, software or system parameters). Concerning the availability, it is too early to define hardware failure and intervention rates. All hardware items which had given problems during the run, had already been detected beforehand. During approximately one month of beam operation no issue had newly developed. False dumps were caused by three different hardware problems: two of them were not considered urgent before the run (optical fiber, tunnel card); one had only been detected intermittently during the 2009 shutdown (mezzanine surface card).

Accuracy of Thresholds

Fig. 2 shows the four beam induced quenches. All quenches occurred with injected beam on a dipole magnet (MB), while the most likely loss locations with circulating beam are the quadrupole magnets. The two quenches

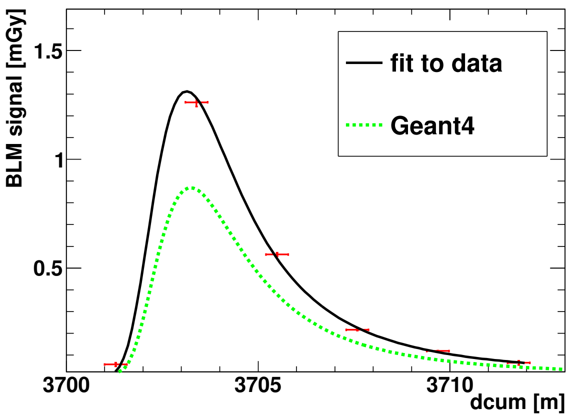

Figure 3: Second quench GEANT4 simulations compared to measurements.

in 2008 have been analysed. The BLM signals could be reproduced by GEANT4 simulations to within a factor of 1.5 (see Fig. 3). Consequently, the thresholds on the cold magnets had been raised by approximately 50% [7]. It is proposed to proceed with the beam induced ‘recovering quench’ (or quench) tests on the different magnet types, as defined in [5] at the very beginning of the 2010 run. For fast transient losses (tested with injected beam) the recovering quenches can be detected with a special version of the nQPS (new Quench Protection System). The nQPS voltage

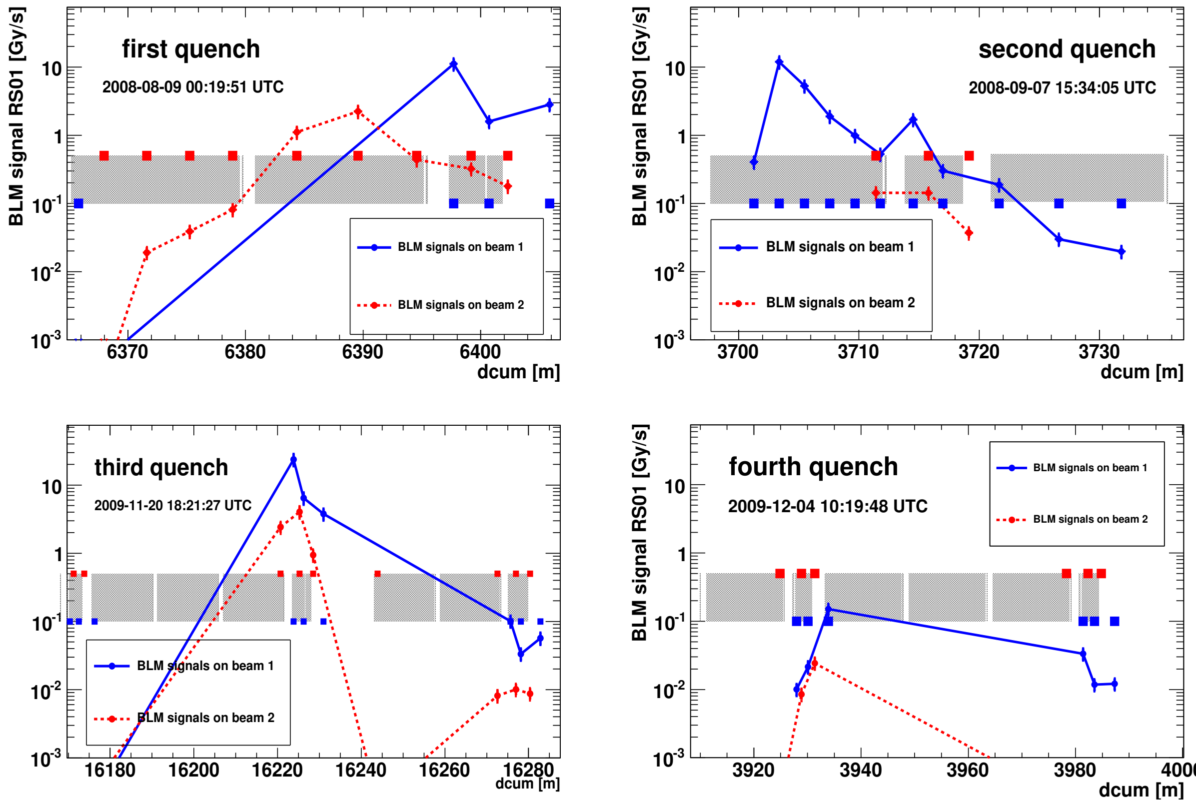

Figure 2: The four beam induced quenches. The first and second quench occurred at an MB which was equipped with BLMs (for the first quench only the opposite beam side was equipped). During the third quench the IC with the highest signal saturated. The fourth quench happened at an MB after the MQ, which is not equipped with monitors.

difference detection level will be set to 50 mV (a factor four below QPS and factor two below nQPS limits). These tests are similar to a 2009 MPS test, where a (slowly increased) local bump was used together with reduced threshold levels to induce beam dumps. The analysis of these tests show, that the conditions of the bump are well understood and reproducible (see Fig. 4). The transverse beam position reproducibility is estimated to 150 µm peak to peak. The nQPS tests will most likely not cause a real magnet quench and they should be perfectly safe for the machine. For steady state losses (tested with circulating beams) it might be possible to detect the recovering quenches with the magnet temperature monitors.

Known Limitations

Over-injection: Over-injection is an operational procedure by which the already circulating pilot beam bunch is sent on the TDI when injecting the first higher intensity bunch(es). Two problems have occurred during over-injection in 2009. The signal for short integration times in the two ICs at the TDIs is above the electronic measurement limit. For the 2010 run one of the ICs (per TDI) has been equipped with a R-C (resistor-capacitor) filter. The peak signal of fast transient losses is reduced by a factor of 175 and the signal length is increased by the same amount. The upper end of the dynamic range for shortest integration time (40 µs) is increased from 23 Gy/s to 4 kGy/s. The threshold values for the TDI monitors will be set according to beam measurements. The additional signal delay will be taken into account. The second IC on the TDI is not equipped and serves as a reference measurement for low losses. It will not be connected to BIS (Beam Interlock System), as no thresholds can be set.

The second problem occurred only when over-injecting beam 2 in IP8. An IC protecting the triplet magnet from losses of beam 1 (BLMQI.03R8.B1I30_MQXA) went above threshold (see Fig. 5). Measurements and beam tests confirm that radiation from the TDI reaches the monitors at the triplet magnets from the outside (through the tunnel). This IC had been installed with a non-standard vertical position (due to space conflict with a RAMSES - Radiation Monitoring System for the Environment and Safety - monitor). For the 2010 run, the monitor in IP8 was moved up by about 30 cm (conform with the equivalent monitor in IP2). Simulation studies would be needed to clarify whether the difference in position (and some differences in the tunnel) can explain the factor of 10 difference in signal between IP2 and IP8, and how to best shield this IC from the over-injection showers as a possible long term solution. Should the problem persist in 2010, the applied thresholds of this

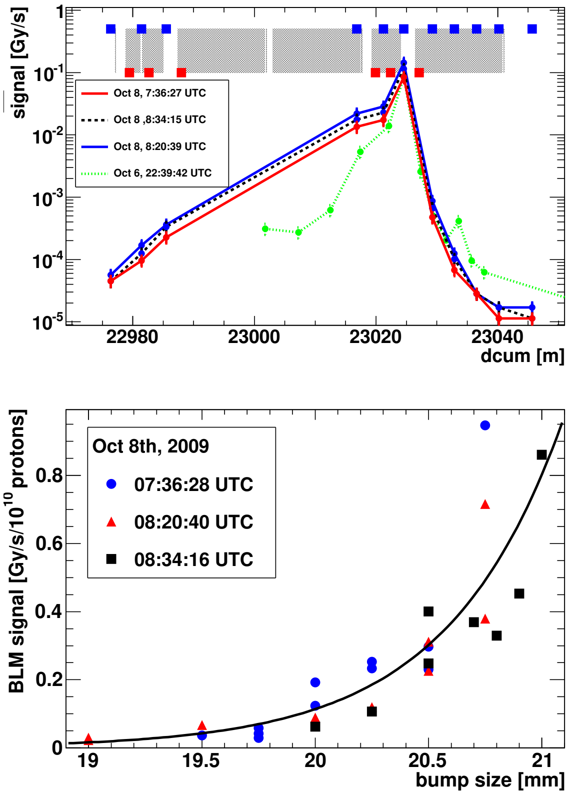

Figure 4: Position and detection reproducibility of four beam tests. Three test (October 8) were done on the same magnet with beam 2. The fourth one (October 6) on the top plot is a superimposed mirror image of a beam 1 test on a different magnet. The plot shows the last position measured, which corresponds to beam permit inhibit by the BLM system.

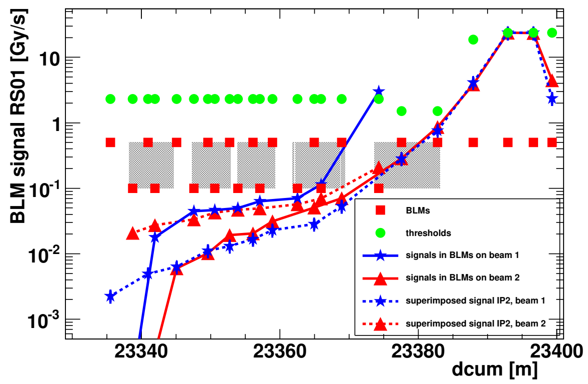

Figure 5: Over-injection in IP2 and IP8.

IC will be increased for the short integration times to allow for over-injection (but still kept below the calculated quench levels for the triplet magnets).

Triplet magnets at collision: Simulation studies [8] show that debris from the interactions yield a BLM signal of similar magnitude as the one of a critical beam loss. The proposed long term solution is to develop new monitors for these locations which are integrated with the new triplet magnets and placed close to the coil. No problem with the current set-up is expected up to a luminosity of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Dynamic range: Ionization in air on a 1 cm long piece of non-insulated signal wire caused a spurious signal on certain SEM channels. It has already been corrected by adding a new insulation. The remaining high noise levels on some of the SEMs (up to approximately 2000 Gy/s for short integration time) leads to an ambiguity for short losses in the gap between the IC (up to 23 Gy/s) and the SEM dynamic range. Also due to this noise, thresholds cannot be set in SEM. The installation of the new radiation hard analogue electronics should solve the noise problem.

A partial activation of the beam abort functionality is not possible. The design of the electronics does not foresee to set thresholds partially in SEM and partially in IC.

Two options exist, depending on requirements, to bridge the gap between the IC and the SEM on a short time scale: the installation of additional R-C filters to spread the signal over a longer time; or the installation of a new monitor type, LIC (Little IC), which is 30 times less sensitive than an IC (approximately 56 monitors could be installed in 2010). The first LIC prototype has been installed in the LHC for test measurement. It has the same design as a SEM, but instead of being under vacuum, it is filled with nitrogen gas at 1.1 bar.

THRESHOLD LEVELS COMPARED TO DYNAMIC RANGE

At the lower end of the dynamic range it has to be ensured, that the lowest threshold levels are still safely above the channel noise, not to cause unwanted beam aborts. Threshold values (expressed in dose rate) decrease with the beam energy and with the length of the integration time window. The analysis per channel for 40 µs and 1.3 s integration times (the longest one which was logged in 2009) for energies up to 3.5 TeV shows that there is at least a factor of 10 between the lowest threshold and the highest noise value measured over 10 days (see Fig. 6). For 5 TeV, due to a change in threshold calculations for the second monitor on MQM, MQY and MQML in 2010, at the moment there are approximately 12 monitors with a factor between 5 and 10 between threshold and noise. This remains to be investigated.

The theoretical thresholds of certain elements at short integration times are above the dynamic range of the (electronics of the) ICs. In the functional specification it was already foreseen that the shortest running sums on cold magnets at injection energy are limited by the dynamic range of the BLM system. The shortest integration times for the highest thresholds on cold magnets is a maximum of a factor of three above the dynamic range. Table 1 [9] gives the

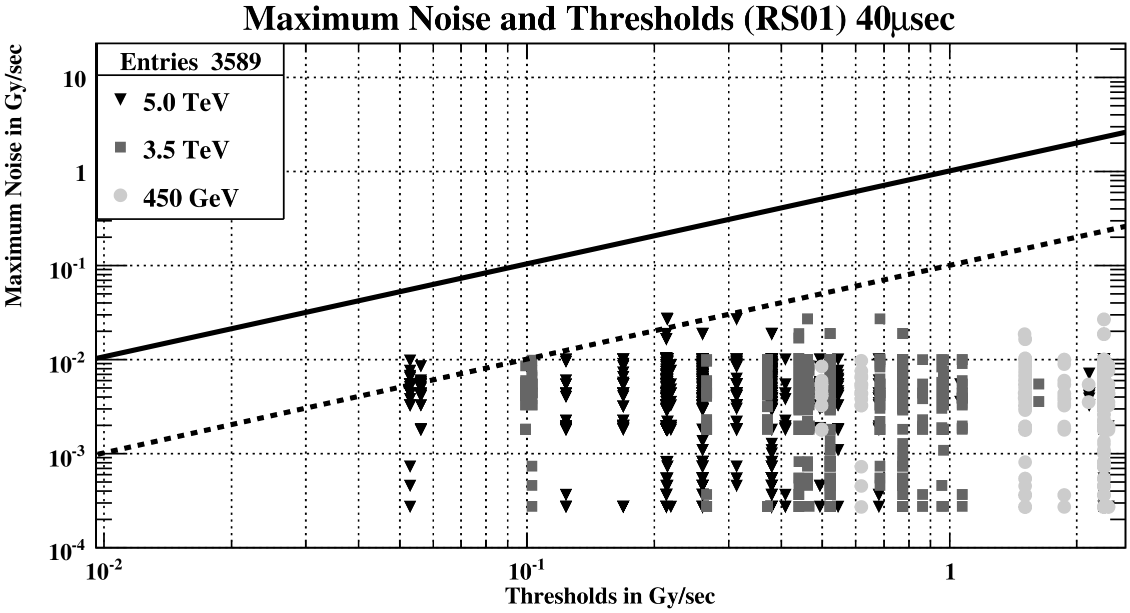

Figure 6: Maximum noise versus threshold value for 40 µs integration time; one entry per channel and energy.

factor missing between the upper end of the IC dynamic range and the theoretical threshold value at 450 GeV and 40 µs integration time (worst case). The problem reduces with higher energies and integration times. On tungsten collimators (TCT, TCLA) the theoretical threshold values are all within the dynamic range of the ICs.

Table 1: Factor missing between the upper end of the IC dynamic range and the theoretical threshold value at 450 GeV and 40 µs integration time (worst case).

TCP IP3	TCP IP7	TCSG IP3 TCLI	TCSG IP7 TCLP
1'611	97	161	8

For warm magnets as well, the theoretical threshold values for short integration times and low energies are above the dynamic range of the ICs. With the exception of the TDI no limitation had stemmed from this lack of dynamic range. Higher beam energies will not cause a limitation either. In the next section it will be examined whether the existing dynamic range will allow to increase the beam intensity to nominal.

EXTRAPOLATION TO HIGHER INTENSITIES

This section discusses the preliminary analysis of six data sets. The data sets had previously been presented and discussed ([10] for collimation losses and [11] for injection losses). The analysis assumes that only the beam intensity increases, and all other conditions remain unchanged. The purpose of this analysis is to estimate whether additional limitations on intensity have to be deduced from the 2009 data. In each case the most-critical elements - i.e. the elements whose beam loss monitors are closest to thresholds (will first take away the beam permit) - are identified.

Beam Cleaning

For the collimation cleaning, data at 450 GeV 1.3 s integration time (the longest integration time logged in 2009) are compared to 84 s threshold values (the lowest threshold values). The elements with the longest minimum lifetime (at which the BLM thresholds are reached) are identified (most-critical elements). Beam 1 and beam 2 longitudinal cleaning (RF detuning), beam 1 vertical cleaning and beam 2 horizontal cleaning (crossing of vertical/horizontal third integer resonance) was analysed. The results are scaled to nominal beam intensity (3×10^{14}), and the minimum beam lifetime at which the losses reach the threshold values are calculated. Table 2 shows the beam lifetime at threshold for the three most-critical elements for horizontal and longitudinal cleaning, and the two most-critical collimators, the most-critical warm magnet and the most-critical cold magnet for the vertical cleaning of beam 1.

For transverse cleaning, the first limiting elements are collimators of the opposite beam. The signals seem to be caused by 'crosstalk' particle showers: Fig. 7 shows horizontal cleaning of beam 2. Systematically, the first beam 1 monitor downstream of a beam 2 collimator loss location shows a high signal. For horizontal cleaning of beam 2, the most-critical cold element is in IP6, it is only a factor 3.4 further away from threshold than the 'crosstalk' collimators. For vertical cleaning of beam 1, the first cold element is only on position 17, 6×10^{-3} times further away from threshold than the first collimator.

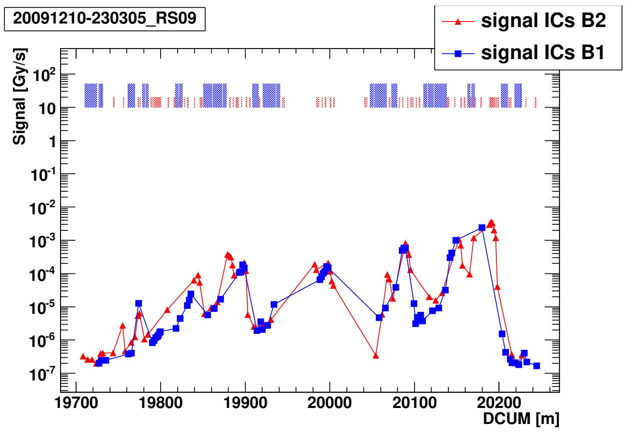

Figure 7: Horizontal cleaning of beam2, losses in IP7.

For longitudinal cleaning of beam 2, the most-critical element is a cold dipole. For beam 1, the cold dipole is within a factor of two to the collimators. The longitudinal losses are localized in IP3, the first element in IP7 is a factor 10 lower than IP3. Cleaning for beam 1 is mirror-symmetric to beam 2: The corresponding collimators get the signals closest to threshold; the MBs with the highest signals are next to each other.

The cleaning performance is not limited by the BLM dynamic range, as all long integration time thresholds are within the dynamic range of the BLM system. The philosophy for setting thresholds in the LHC is local damage protection. But a monitor cannot distinguish between a local loss on the collimator it is protecting (danger of damage above a certain limit) and a broad particle shower coming along the tunnel (which, at the same signal height, will certainly not cause damage to the collimator it is protecting). With the exception of beam 1 vertical cleaning (by far the less critical one) the 'crosstalk' issue does not seem to significantly limit the cleaning performance. It should be investigated, whether the thresholds for the collimators could still be increased while staying safely below damage limit at the same time.

The required minimum beam lifetime at injection and ramp is 0.1 h (during 10 s) and 0.006 h (during 1 s) respectively [12]. The beam intensities foreseen for 2010 are up to $3 - 6 \times 10^{13}$. For the 2010 intensities a cleaning performance as the one analysed would already be sufficient for injection. The vertical cleaning of beam 1 even fulfills the requirements for the ramp. A factor of 17-50 of improvement would be required to reach the requirements for the ramp for the worst case (beam 2 horizontal cleaning).

Injection Losses

For injection losses, 40 µs loss data are compared to 40 µs thresholds. Beam 1 and beam 2 cleanest injections in 2009 were analysed. Scraping in the SPS was used and the TCDI were set to $6\,\sigma$ horizontal and $4.5\,\sigma$ vertical. The injected beam intensity at which the threshold level would be reached is calculated and the most-critical elements are identified. The nominal beam intensity for injection in 3×10^{13} and the injection intensity foreseen for 2010 is 4×10^{12}.

Table 2: Elements whose beam loss monitors will first take away the beam permit at nominal beam intensity 3×10^{14}. The uncertainty is estimated from the uncertainty in the measurement of the beam lifetime by the one second logging data.

Element	**Beam lifetime at threshold [minutes]**
Beam 1 vertical cleaning	
BLMEI.05R7.B2I10_TCSG.B5R7.B2	1 - 1.5
BLMEI.06L7.B2I10_TCLA.B6L7.B2	0.06 - 0.09
...	...
BLMEI.06L7.B1E10_MBW.B6L7	0.03 - 0.05
...	...
BLMQI.01R2.B1I20_MQXA	0.006 - 0.009
Beam 2 horizontal cleaning	
BLMEI.06R7.B1E10_TCLA.B6R7.B1	62 - 86
BLMEI.06R7.B1E10_TCLA.A6R7.B1	26 - 37
BLMQI.04L6.B2I10_MQY	18 - 24
Beam 1 longitudinal cleaning	
BLMEI.05L3.B1I10_TCSG.5L3.B1	13 - 18
BLMEI.05R3.B1I10_TCLA.A5R3.B1	7 - 10
BLMEI.08R3.B1I23_MBB	7 - 10
Beam 2 longitudinal cleaning	
BLMEI.08R3.B2I30_MBA	22 - 31
BLMEI.05R3.B2E10_TCSG.5R3.B2	7 - 10
BLMEI.05L3.B2E10_TCLA.A5L3.B2	5 - 7

Table 3 shows the number of injected protons at threshold for the most-critical element of each category (collimator, warm magnet and cold magnet) for beam 1 and beam 2. Numerous elements (collimators, cold and warm magnets) yield similar limits. For beam 1, 16% of the 38 most-critical elements are cold magnets. For beam 2 injection (which was 4.4 times further away from threshold than the one of beam 1), 55% of the 27 most-critical elements are cold magnets. The critical elements spread over several IPs, the losses are not loccalised to the insertion region.

IC thresholds (40 µs) in warm elements (collimators and warm magnets) are limited by the BLM dynamic range. But losses at cold magnets are about equally close to threshold. Hence, injection losses need to be reduced further, and scraping in the SPS seems crucial. It is possible to increase thresholds on primary and secondary collimators and on warm magnets (by additional R-C filter or installing small ICs). But most likely the limit for the injection are the losses in the cold magnets and not the dynamic range of the BLM system.

Table 3: First element of each category (collimator, warm and cold magnet) whose beam loss monitor will first take away the beam permit.

	Element	Injected prot. at threshold
Beam 1		
Coll.	BLMEI.06L7.B1E10_TCP.A6L7.B1	$1.5 \cdot 10^{11}$
Warm mag.	BLMEI.06L7.B1E10_MBW.B6L7	$5.5 \cdot 10^{11}$
Cold mag.	BLMQI.08L2.B1E30_MQML	$6.7 \cdot 10^{11}$
Beam 2		
Coll.	BLMEI.06R7.B2I10_TCP.C6R7.B2	$3.4 \cdot 10^{12}$
Warm mag.	BLMEI.06R8.B2E10_MSIB	$9.8 \cdot 10^{12}$
Cold mag.	BLMEI.04R8.B2E10_MBXB	$3.9 \cdot 10^{12}$

SUMMARY

The crucial task for the BLM system in the beginning of the 2010 run is to reach full protection level. Beam tests are needed to determine the safe threshold settings. Full application of the BLM system tests and system change procedures will be enforced. The known BLM system limitations and the foreseen upgrades seem compatible with the LHC schedule. Typically, warm elements should have higher thresholds for short integration times. The locations which *need* higher thresholds in order not to limit the performance of the LHC can be equipped with an R-C filter or with new LICs. Alternatively, a different monitor location could be chosen or shielding installed. No additional limitation had been identified for energies up to 5 TeV. The first (preliminary) analysis of collimation cleaning data shows that the 2010 requirements for 450 GeV where already fulfilled by the 2009 set-up. (Cleaning losses during ramp will have to be investigated.) The (preliminary) analysis of injection losses shows that they will have to be reduced for the 2010 intensities, especially for beam 1. Various cold magnets are affected by injection losses, and the BLM system does not seem to be the limiting factor.

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