# BEAM LOSSES AND LIMITING LOCATIONS

A. Nordt, M. Brugger, M. Calviani, M. Dabrowski, B. Dehning, E. Effinger, J. Emery, E. Fadakis, V. Grishin, E. B. Holzer, S. Jackson, C. Kurfuerst, A. Marsili, M. Misiowiec, E. Nebot del Busto, C. Roderick, M. Sapinski, W. Viganò, C. Zamantzas, CERN, Geneva, Switzerland

*Abstract*

About 4000 Beam Loss Monitors (BLMs) are installed along the LHC ring to detect critical beam losses which could quench the superconducting magnets or damage the components of the accelerator. In 2009 and 2010 the LHC BLM system detected all critical beam losses, so that no damage or unscheduled quench occurred. However a further fine-tuning of the beam abort thresholds is needed, especially for the high luminosity and high beam intensity runs planned for 2011. Possible sources of an increased ratio of beam loss to abort threshold will be addressed for the upcoming 2011 run. It will be verified whether the specified beam loss rates can be achieved in 2011, at what locations there are possible limiting thresholds and to what extent an increase of the thresholds at specific elements might be needed. In a second step the locations with the highest beam loss rates will be determined using the integrated dose as a function of integrated luminosity. This is useful in order to define the expected increase in dose for the 2011 operation. A special focus will be given on beam losses at and around collimators.

## POSSIBLE CRITICAL BLM BEAM ABORT THRESHOLDS AT 3.5 TEV

The identification of elements with possible critical beam abort thresholds for the upcoming 2011 run has been performed using the ratios of the maximum measured beam loss to the beam abort threshold for five high luminosity proton physics fills and five high luminosity ion physics fills.

### *Introduction*

The scan was done for all monitors being connected to the Beam Interlock System (BIS) for nine different integration time windows: for the running sums (RS) RS01 up to RS09, i.e. for integration time windows ranging from 40 µs to 1.3 s. The BLM system is using twelve different RS in total; however the loss data from RS10 and RS11 are not logged in the LHC Measurement and LHC Logging databases (DBs). An overview of the different RS and their integration time window is given in table 1.

The monitors not being connected to the BIS are not taken into account in this analysis since they cannot initiate a beam dump. It is not planned to increase or decrease the number of BLMs being connected to BIS for the 2011 run and therefore this analysis should give a reasonable overview of the monitors having a threshold for a specific running sum (or several running sums) that should be re-considered.

In case the ratio of the maximum measured loss to the threshold:

$$r_{l/t} = \frac{Max(Beam\ loss)\ |_{start\ of\ fill}^{end\ of\ fill}}{Applied\ Threshold\ (E = 3.5\ TeV)}$$

is $r_{l/t} \geq 0.1$, the monitor is considered having a threshold possibly too low for the 2011 run, due to the fact that beam losses are increasing with the number of bunches per beam and with luminosity. A margin of a factor of 10 between a maximum beam loss and the applied beam dump threshold is considered to be sufficient for the operation in 2011, since the product of number of bunches per beam and the luminosity will be increased compared to the settings in 2010.

The thresholds are decreasing with beam energy; therefore the thresholds for the beam energy of 3.5 TeV were the lowest being loaded to the BLM system in 2010, since this was the highest beam energy in 2010. The scan concerns only the thresholds at 3.5 TeV since it will most probably be the beam energy chosen for the 2011 run. In case the beam energy will be higher than 3.5 TeV in 2011, even lower thresholds have to be considered.

### *Analysis method*

Two essential beam operation periods were selected during which the beam energy was at 3.5 TeV: the time before the stable beams condition was declared, usually with a duration of around 50 minutes. This period includes the beam modes ‘flattop’, ‘squeeze’ and ‘adjust’. The second operation period being investigated is the period during stable beams, usually with duration of 3 - 12 hours. The start and end times for the two main periods at 3.5 TeV were defined using the following three different timestamps:

- the beam presence flag for both beams (defining the time during which there was beam in the machine or not),
- the loaded BLM threshold settings at the beam energy of 3.5 TeV (defining the 3.5 TeV operational period)
- the stable beam mode flag (defining the stable beam operational period)

The start time for the first period was defined using the BLM threshold settings at 3.5 TeV and the end time was defined using the start time of stable beams. The start time of the second period was defined using the start time of stable beams and the end time was defined using the BLM thresholds settings at 3.5 TeV and the beam presence flag, where the end time taken at 10 -20 s before the BLM thresholds at 3.5 TeV changed or before the beam presence flag changed. The reason is that one has to avoid misleading beam dump losses in this analysis, since the focus is given on thresholds and losses at 3.5 TeV.

The beam presence flag for both beams was used in order to bypass the problem of a not yet automated timing of the stable beams mode flag, that is set manually by the machine operators at the moment (while the switch of the beam presence flag is triggered by hardware, i.e. by beam current transformers). The BLM threshold settings are changed according to the beam energy which is transmitted to the BLM electronics through the Safe Machine Parameters (SMP). The combination of the three flags originating from different sources assures a proper timestamp selection for the two main time periods at 3.5 TeV.

Table 1: An overview of the different integration time windows as used by the BLM system is presented in this table.

| **Running Sum** | **Integration time window** | **Logging of BLM loss data** |
|---|---|---|
| RS01 | 40 µs | Yes |
| RS02 | 80 µs | Yes |
| RS03 | 320 µs | Yes |
| RS04 | 640 µs | Yes |
| RS05 | 2.56 ms | Yes |
| RS06 | 10.24 ms | Yes |
| RS07 | 81.92 ms | Yes |
| RS08 | 655.36 ms | Yes |
| RS09 | 1.31 s | Yes |
| RS10 | 5.24 s | No |
| RS11 | 20.97 s | No |
| RS12 | 83.89 s | Yes |

Several BLM thresholds changes for specific monitors were applied during the operation in 2010, some of them concerning the LSA MASTER Thresholds tables and some of them concerning the monitor factor only. The main changes for the LSA Master Tables are summarized in the next chapter. For each physics fill being analysed the actual applied thresholds for each monitor and each running sum were downloaded from the LHC Logging database specifically, in order to avoid an unrecognized threshold change as it would have been the case when assuming fixed thresholds for all monitors for the fills analysed.

To give the most reasonable indication of possibly low thresholds at specific elements for the 2011 operation, the proton (and ion) fills with the highest number of bunches per beam in 2010, i.e. 368b/beam (121b/beam for ions) and the highest integrated luminosity during the stable beam condition have been selected for this analysis, i.e. proton fill numbers 1440, 1443, 1444, 1450 and 1453 (1520, 1521, 1522, 1525 and 1526 for ions). The same bunch spacing of 150 ns (500 ns for ions) and the same filling scheme was applied for these fills.

## *Results: possibly critical dump thresholds*

The ratio of maximum loss to beam dump threshold $r_{l/t}$ for each monitor connected to BIS as measured during the proton fills 1440, 1443, 1444, 1450, 1453 for RS01 - RS09 for the beam energy of 3.5 TeV during the stable beams period is shown in fig.1. Note that there are in total ~ 3 x $10^5$ values given in fig. 1 which were calculated out of a dataset of ~ 3 x $10^8$ values. The same data are presented in fig. 2 but as a scatter plot, i.e. the maximum losses are plotted versus the corresponding applied thresholds for each monitor. In such a plot it is possible to recognize whether a high ratio $r_{l/t}$ is originating from high beam losses or from low thresholds (or from the combination of the two).

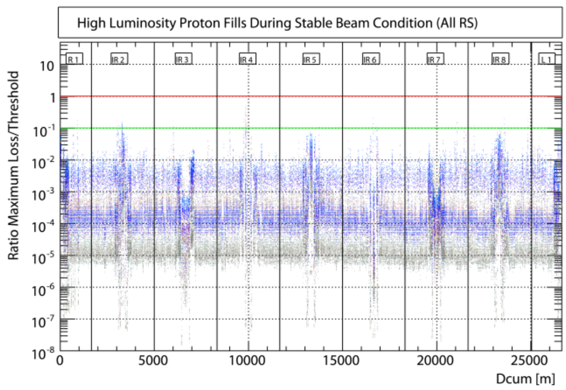


Figure 1: Shown is the ratio of the maximum measured loss to threshold $r_{l/t}$ for RS01 - RS09 for each monitor as measured during the fills 1440, 1443, 1444, 1450 and 1453 for the beam energy of 3.5 TeV during the stable beams period. The monitors are sorted by their dcum [m] and the different IR's 1 - 8 are indicated with a black line. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red.

Fig. 3 and 4 show the results of this scan for the period where the beam energy was 3.5 TeV, but before the stable beam condition was declared. A summary of the statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the analyzed proton and ion fills is given in tables 2 - 5. Statistically significant means that the ratio $r_{l/t} \geq 0.1$ for a specific monitor was observed at least during two fills out of the five protons and ion physics fills.

Statistically significant monitors were exceeding $r_{l/t} \geq$ 0.1 only in the LSS for both, proton and ion fills. The following monitors fulfil $r_{l/t} \geq 0.1$ during the five selected proton fills: five triplet monitors in 01L2, 02L2 and 03L2, one monitor in 04L6 (TCDSA) and one monitor in 04R6 (TCDQA) (during the stable beam period). During the period before stable beam was declared the following

monitors were observed having a ratio $r_{l/t} \geq 0.1$: one monitor in 04R8 (MQY), one monitor in 07R8 (MQM) and one monitor in 04R8 being installed next to the TCTH collimator.
Note that the triplet monitors are exceeding $r_{l/t} \geq 0.1$ only for RS01.

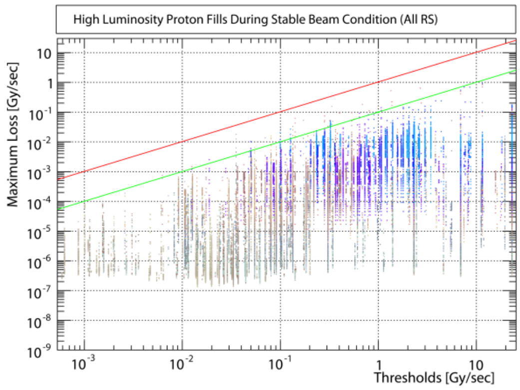


Figure 2: Shown is the maximum measured loss versus applied threshold in Gy/s for RS01- RS09 for each monitor as measured during the fills 1440, 1443, 1444, 1450 and 1453 for the beam energy of 3.5 TeV during the stable beams period. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red.

In total three out of the ten monitors mentioned have a RC signal reduction filter installed (so called filter monitors). For more details on RC signal reduction filters see next chapter where a summary about the "Modification of monitors in the injection and dump lines" is given. The TCDSA and TCDQA monitors have a filter installed with R = 150 kΩ, C = 47 nF and the MQM monitor with R = 150 kΩ, C = 2.2 nF. As it can be seen in fig.5 the applied thresholds for the TCDSA monitor are not dependent on the different integration time windows. The signal is reduced by a factor of 180 (for RS01) due to the installed filter, i.e. the measured loss without a filter would have been 180 times higher than shown in fig.5.

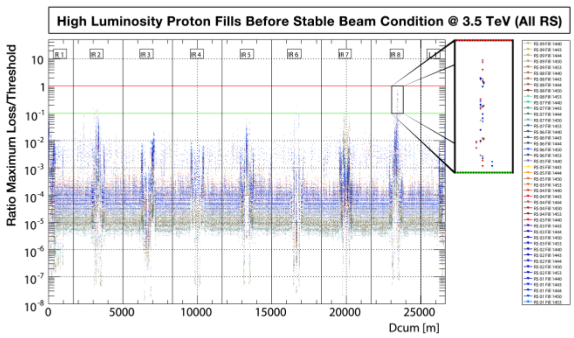


Figure 3: Shown is the ratio of the maximum measured loss to threshold $r_{l/t}$ for each monitor as measured during the proton fills 1440, 1443, 1444, 1450 and 1453 for RS01 - RS09 for the beam energy of 3.5 TeV before the stable beams period. The monitors are sorted by their dcum [m] and the different IR's 1 - 8 are indicated with a black line. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red. Higher ratios, i.e. $r_{l/t} \geq 0.1$ for IR 8 are shown as a zoomed plot on the right side.

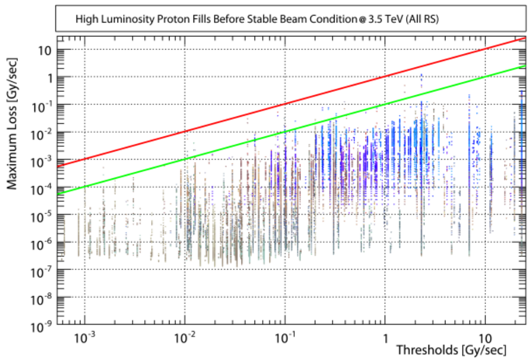


Figure 4: Shown is the maximum measured loss versus applied threshold in Gy/s for each monitor as measured during the fills 1440, 1443, 1444, 1450 and 1453 for RS0 1- RS09 for the beam energy of 3.5 TeV during the stable beams period. The ratio $r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red.

The same holds for the TCDQA monitor. Both monitors are in the same 'LSA threshold family', i.e. they are protecting the same elements. The 'LSA family name' is THRI_TCD_RC.

Monitors being affected during the five ion fills are: nine triplet monitors in 01L2, 02L2, 03L2 and 01R2 (stable beam condition) and three triplet monitors in 03L2 and 01R2 (before stable beam). The main difference compared to the proton fills is that for the triplet monitors the ratio $r_{l/t} \geq 0.1$ has been observed during the longer running sums as well and not only during RS01 (see tables 4, 5).

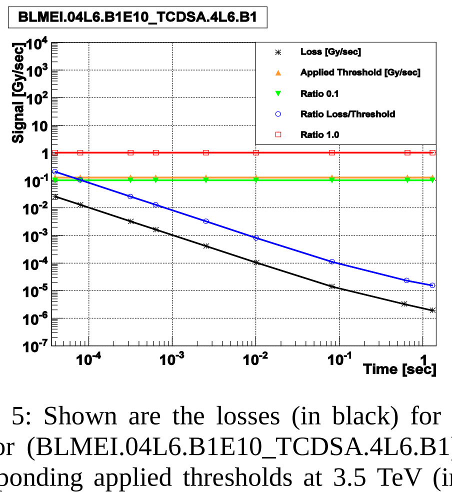


Figure 5: Shown are the losses (in black) for one filter monitor (BLMEI.04L6.B1E10_TCDSA.4L6.B1) and the corresponding applied thresholds at 3.5 TeV (in orange) for the proton fill 1444 (during the period of stable beams) for RS01 – 09. The maximum loss was found for RS01. The ratio of loss to threshold is shown in blue and it is greater than 0.1 for RS01 and RS02 ($r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red).

Note that the LSA MASTER Table thresholds were not changed for the ion run compared to the proton run, even though the loss scenarios are different for proton physics and ion physics.

In fig. 6 the losses for all running sums (RS01 - RS09) are shown for one of the mentioned triplet monitors for the ion fill 1522 (during the period where the stable beam condition was fulfilled). The ratio of loss to threshold was higher than 0.1 for RS01 - 05.

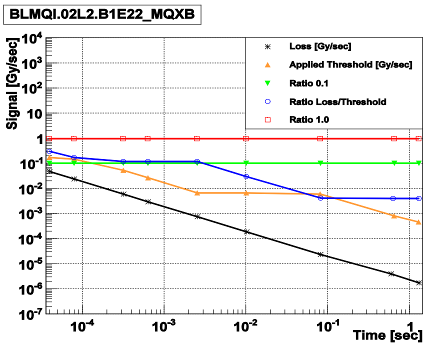


Figure 6: Shown are the losses (in black) for one monitor (BLMQI.02L2.B1E22_MQXB) and the corresponding applied thresholds at 3.5 TeV (in orange) for the ion fill 1522 (stable beam) for RS01 - 09, where the maximum loss was found for RS01. The ratio of loss to threshold is shown in blue and it is greater than 0.1 for RS01 - RS05 ($r_{l/t}$ = 0.1 is indicated in green and $r_{l/t}$ =1.0 in red).

Table 2: Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the proton fills 1440, 1443, 1444, 1450 and 1450 for RS01 - 09 at 3.5 TeV during the stable beam condition.

| **Monitor Expertname** | **Running Sum** | **Highest Ratio** |
|---|---|---|
| BLMQI.01L2.B2I30_MQXA | 01 | 0.14 |
| BLMQI.02L2.B2I21_MQXB | 01 | 0.14 |
| BLMQI.02L2.B1E22_MQXB | 01 | 0.12 |
| BLMQI.02L2.B1E23_MQXB | 01 | 0.16 |
| BLMQI.03L2.B1E30_MQXA | 01 | 0.14 |
| BLMEI.04L6.B1E10_TCDSA.4L6.B1 | 01-02 | 0.21 |
| BLMEI.04R6.B1E10_TCDQA.B4R6.B1 | 01 | 0.10 |

Table 3**:** Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the proton fills 1440, 1443, 1444, 1450 and 1450 for RS01 - 09 at 3.5 TeV before the stable beam condition was declared.

| **Monitor Expertname** | **Running Sum** | **Highest Ratio** |
|---|---|---|
| BLMQI.04R8.B2E20_MQY | 01-06 | 0.71 |
| BLMEI.04R8.B2E10_TCTH.4R8.B2 | 01 - 09 | 0.52 |
| BLMQI.07R8.B2E20_MQM | 01-02 | 0.12 |

Table 4**:** Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the ion fills 1520, 1521, 1522, 1525 and 1526 for RS01 - 09 at 3.5 TeV during the stable beam condition.

| **Monitor Expertname** | **Running Sum** | **Highest Ratio** |
|---|---|---|
| BLMQI.01L2.B2I30_MQXA | 01-02 | 0.23 |
| BLMQI.02L2.B1E22_MQXB | 01 - 05 | 0.29 |
| BLMQI.02L2.B1E23_MQXB | 01 - 05 | 0.30 |
| BLMQI.02L2.B2I21_MQXB | 01 - 05 | 0.30 |
| BLMQI.02L2.B2I22_MQXB | 01 - 02 | 0.20 |
| BLMQI.02L2.B2I23_MQXB | 01 - 05 | 0.27 |
| BLMQI.03L2.B1E30_MQXA | 01 - 02 | 0.16 |
| BLMQI.01R2.B2E20_MQXA | 01 | 0.13 |
| BLMQI.01R2.B1I20_MQXA | 01 | 0.13 |

Table 5: Summary of statistically significant monitors with a ratio of $r_{l/t} \geq 0.1$ for the ion fills 1520, 1521, 1522, 1525 and 1526 for RS01 - 09 at 3.5 TeV before the stable beam condition was declared.

| **Monitor Expertname** | **Running Sum** | **Highest Ratio** |
|---|---|---|
| BLMQI.03L2.B1E30_MQXA | 01 - 05 | 0.26 |
| BLMQI.01R2.B2E20_MQXA | 01 | 0.12 |
| BLMQI.01R2.B1I20_MQXA | 01 | 0.11 |

### *Attempt to establish a scaling factor for the maximum beam losses as function of luminosity*

In a second step of the analysis an effort has been made to establish the increase in maximum beam loss per second with luminosity in order to scale the expected maximum loss rates for the 2011 run. A complication comes from the fact that this analysis was performed using the BLM loss data from the LHC Logging DB, which are ‘filtered’ compared to BLM loss data from the LHC Measurement DB. Note that the beam loss data are stored on the LHC Measurement DB for only 7 days with a frequency of 1 Hz and during the transfer for long term storage in the LHC Logging DB are reduced using a fixed interval filter of 1 minute values (e.g. 5.43 x $10^{-3}$ Gy/s for RS01, see table 6). The fixed interval filter values are different for each RS and have been introduced in order to reduce the amount of stored data. It is important to mention that only the last value within a minute is stored, not the maximum or average measured value. Therefore it is not possible to define the maximum loss within a minute for losses being below the filter value. To be able to define the increase in maximum beam losses for all monitors as a function of luminosity it is needed to use the loss data from LHC Measurement DB and the author strongly suggests to repeat the analysis in 2011 using the higher frequency data from the LHC Measurement DB. However it is partially possible to determine the increase in loss using data from LHC Logging DB for cases when the losses were logged with a 1 Hz frequency, i.e. high losses. In such cases it turns out that the maximum measured beam losses increase on average (for all monitors available) with a factor of about 0.3 - 0.6 with luminosity, depending on the integration time window (see table 6). Such conclusion was made assuming a linear increase:

$$f = \langle a * x \rangle, \qquad \text{with } x = \frac{Max.loss\ (high\ lumi\ fill)}{Max.loss\ (low\ lumi\ fill)}$$

The slope *a* was defined for all available monitors during the highest and the lowest luminosity fill and the losses had to be higher than the filter interval values for both fills. But it has to be underlined that the factor of 0.3 - 0.6 is certainly biased and varies in addition with the IR and the element. Maximum losses on triplet and collimator monitors are increasing much more with luminosity than on monitors in ARC regions and on cold magnets (where the slope was almost not measurable, i.e. *a*=0). A better way for defining the increase in beam loss as a function of luminosity is by using longer integrated dose values as described later in the section "Definition of the most critical BLM locations".

Table 6: A summary of factors for the increase in maximum beam loss with luminosity per RS is given in this table as well as the number of monitors that were taken into account for this calculation.

| RS | Slope | # monitors | DB Filter [Gy/s] |
|---|---|---|---|
| 01 | 0.27 | 414 | $5.43 \times 10^{-3}$ |
| 02 | 0.29 | 367 | $2.96 \times 10^{-3}$ |
| 03 | 0.36 | 302 | $8.8 \times 10^{-4}$ |
| 04 | 0.41 | 265 | $4.8 \times 10^{-4}$ |
| 05 | 0.44 | 241 | $1.43 \times 10^{-4}$ |
| 06 | 0.43 | 314 | $4.24 \times 10^{-5}$ |
| 07 | 0.51 | 300 | $6.88 \times 10^{-6}$ |
| 08 | 0.55 | 130 | $3.75 \times 10^{-6}$ |
| 09 | 0.50 | 154 | $2.23 \times 10^{-6}$ |

### *Conclusions*

The need of a threshold change at 3.5 TeV for the monitor findings of this report (see tables 2 – 5) probably requires additional measurements in 2011 for a final confirmation of the criticality. Also the respective quench limits for the elements concerned need to be checked before changes can be applied. A final decision will be taken by the responsible machine protection representatives.

## BLM LSA MASTER TABLE THRESHOLD CHANGES IN 2010 IN IR2, 3, 6, 7 AND 8

Following a brief description on the 'applied BLM beam abort threshold settings', the LSA Master Table threshold changes for monitors in IR2, 3, 6, 7 and 8 as well as the major hardware changes being applied in 2010 will be summarized in this section.

The beam abort threshold settings for each running sum (RS01 - RS12) and 32 different beam energy levels for each BLM are managed and controlled by using the LHC Software Architecture (LSA) [1]. LSA depends on an on-line database and its software is based on Oracle. BLM LSA Master Table threshold changes can be performed only by a restricted group of people who have been assigned the necessary privileges in the Role Based Access Control (RBAC) system. Any changes are confirmed by a before-after comparison that must be equal to the pre-defined settings as described in an approved Engineering Change Request (ECR). The values on the LSA MASTER Tables are the maximum allowed values and they are set generally above the quench level (for cold elements) and below the damage level (for all elements). The LSA MASTER Table thresholds are multiplied with the so called monitor factor, ranging from $1 \times 10^{-3}$ to 1.0. Both, the LSA Master Table settings and the corresponding monitor factor are (can be) set separately for each monitor and are sent to the BLM electronics. The product of the two values defines the so called 'applied threshold' for each monitor, initiating a beam dump in case a loss is measured being equal or higher than the applied threshold. The monitor factor can be changed without changing the LSA Master Table settings but such changes are as well restricted to a small group of people who have been assigned another RBAC role. The LSA Master Table thresholds changes generally need a longer time than a monitor factor change, due to the fact that such changes must be verified within an ECR, the need of a longer calculation time and because the LSA tables have to be updated.

LSA MASTER Table threshold changes were applied in 2010 for the following monitors and monitor families (BLM monitor families are groups of monitors that share the same values since they are protecting the same type of element from identical topology).

- <u>Modification of monitors in the injection and dump lines</u>: in total 68 BLMs were modified in 2010 and RC signal reduction filters (called filter for simplification) were added to the signal readout chain since injection and dump line losses at specific monitors were above and/or equal the applied beam dump threshold, being already set to the maximum possible value of a measurable loss of 23 Gy/s at which the BLM electronics saturates. In order to overcome the electronics saturation issue two different types of RC signal reduction filters have been installed: a) R = 150 kΩ, C = 47 nF and b) R = 150 kΩ, C = 2.2 nF, depending on the losses being expected at these locations. A filter of type a) (b)) reduces the amplitude in RS01 by a factor of 180 (8) for an instantaneous loss and stretches the length of the signal by the same factor. For longer integration times the reduction in maximum measured amplitude of the signal is decreasing with integration time. The rise time of such modified monitors is higher than for the non-modified ionization chambers, i.e. the time needed to collect 95% of all charges is longer by a factor of ~ 1.5 – 2.5, depending on the type of filter [2]. The charge collection time for a non-modified monitor for injection losses, i.e. instantaneous losses, is 80 - 120 µs. Also BLMs around collimators (close to the injection lines) were modified by adding a filter. The thresholds for these filter monitors were adapted according to the different signal shape by applying the formula:

$$T = \mathrm{T}' \left(1 - \mathrm{e}^{(-\mathrm{RS}/\tau)}\right) \;,$$

where T is the corrected threshold per RS and beam energy, T' the initial threshold per RS and beam energy, RS describes the length of the integration time window and τ is the RC time constant. The RC time constant τ describes the time required to charge a capacitor to 63 % of full charge and is given in theory via the product of capacitance and resistance. Taking into account the additional resistance from the signal cables in the tunnel and the signal cable length, the time constant for filter monitors is increased in reality and strongly dependent on the cable length [2]. The monitor families with filter monitors are MSD, TCD, TDI, TCTVB, MSI, MQM and MQML with monitors in IR 2, 6, 7 and 8. In addition BLM threshold changes were applied for monitors that see injection losses but no RC signal reduction filters have been installed. These changes affected basically the injection energies and were done mostly according to the measured loss distributions. Since injection losses are ultra-fast or instantaneous losses, basically the thresholds for RS01 - RS03 had to be adapted only.

- Other regions: The LSA Master Table thresholds for MQW families were corrected since the initial thresholds (from 2009) did not have an energy dependency, i.e. they were equal for the energies between 450GeV and 5.0 TeV. The energy dependency between 450GeV and 5.0 TeV has been introduced in 2010.
- TCLA: In IP7 the thresholds were changed for cell 6 in position A and B. These monitors sit in the shower of the TCP losses and thresholds were changed in a way that the TCLA's in cell 6 in position C and D protect them now. Thresholds in cell 7 in position A and B were changed and increased. The thresholds for TCLA's in IR 3 were increased as well.

For a more detailed description of the applied changes in 2010 see [3].

## DEFINITION OF THE MOST CRITICAL BLM LOSS LOCATIONS

For the determination of the most critical locations along the LHC ring in terms of beam losses, the integrated BLM dose has been calculated for the stable beams condition for 23 different proton fills and 17 different ions fills. The dose is determined as the sum of the RS12 BLM signal.

Since a permanent offset current is applied to each BLM in order to check continuously the availability of the electronic channel and in order to avoid lockups due to noise and radiation deposited in the electronics, this offset must be subtracted in order to calculate the integrated dose being deposited in a monitor due to beam losses.

In the following subsection the offset level will be described in more detail in order to show the importance of a properly calculated offset level for the dose determination. Afterwards a description of the calculation of the BLM integrated dose as well as the results of this analysis will be presented.

### *The offset level*

The offset current is varying for each of the monitors around the ring between 5 – 30 pA in an optimum case, leading to an apparent dose of 1.5 - 5 x $10^{-7}$ Gy/s (RS09 with an integration time of 1.3 s).

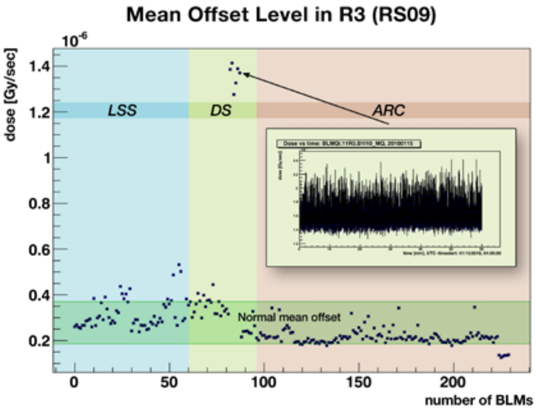


Figure 7: Example for the variation of the mean offset level in units of Gy/s for the Long Straight Section (LSS), the Dispersion Suppressor (DS) and the ARC region for all monitors in R3, being calculated by using the RS09 data (with an integration time of 1.3 s). No beam was in the machine at this time. The mean offset level is higher

and fluctuating more in the LSS and DS than in the ARC (see text).

A mean offset level of 5 – 40 pA for all monitors in the LHC ring being connected to BIS has been assured during the LHC operational periods in 2010. In fig.7 the mean offset level is presented in Gy/s as measured by the RS09 for all monitors in R3. The average offset level is taken from an one hour dataset and the smaller plot indicated in fig. 7 is showing the RS09 data per second over this period of one hour, for one specific monitor having a high offset level, i.e. higher than 30 pA, here 80 pA (~ 1.3 x $10^{-6}$ Gy/s).

The plot indicates also 6 monitors, which are connected to one tunnel card, where the mean offset level exceeds the operational allowed level of 30 pA and a tunnel card reset was needed in order to set the offset level back to the operational level. The reset was done before the LHC started operating.

The offset level is increasing over time by about 2 - 5% during a time period of 2 weeks without beam in the machine. In fig. 8 such time variation is indicated using again the example of all monitors in R3. In this example the mean offset level was determined four times a day over a period of one hour using the RS09 data from LHC Measurement DB during 14 days when there was no beam in the machine.

The origin of the different levels in offset fluctuations over region and over time are summarized in the following:

- One of the main contributors in the change of the offset level of one monitor is the noise that is introduced into the acquisition input.
- A charge balance integrator is used in order to construct the Current to Frequency Converter (CFC) and it can end up in a locked-up state in case the current flows in the opposite direction. In such a situation a protection circuit is adding a constant current of 1 pA every 20 - 25 s until the CFC exits the locked-up state. The different noise levels depend on the monitor’s position within LSS, DS and ARC due to the different length of signal cables and the quality of the cabling [4].
- A slightly increased offset level of around 30 - 40 pA on all channels of several cards has been observed and can be explained with a difference in the temperature at which the CFC cards have been calibrated. The CFC tunnel cards (with a maximum of 8 connected monitors) are calibrated in the laboratory at a temperature of 20 - 30 °C before they are installed in the LHC tunnel. The average temperature in the tunnel is slightly lower with 15 - 20 °C [5].
- On a regular basis the so called BLM sanity checks for all BLM monitors are performed. The checks are systematically executed (at least once every 24 hours) by the machine operators, testing the electrical part of all monitors, their cable connections to the front-end electronics, further connections to the back-end electronics and their ability to request a beam abort [6]. Due to the connectivity check, being one part of the sanity checks, the offset level can be slightly increased, but with a maximum increase of 1 % (compared to the level before the check).
- In total there are three VME crates (right, centre, left) installed within one rack for IR1 - 6 and IR8; in IR7 four crates are installed. The right VME crate controls the HV supplies for the full rack. In case the right VME crate has a breakdown, the HV supply will trip to zero Volt what will induce a negative current into the CFC cards. Therefore the charge balance integrator is entering a locked up state and a constant current of 1 pA is added every 20 - 25 s until the CFC exits the locked-up state. In such a failure case, a CFC card reset is needed.

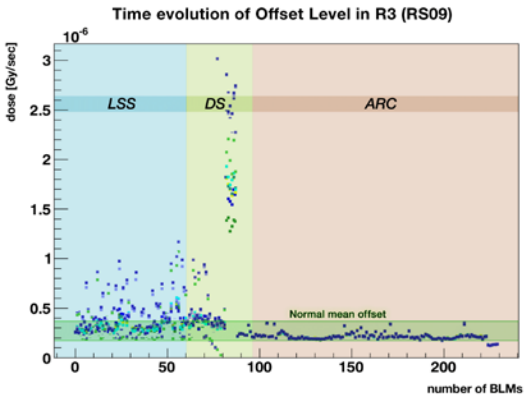


Figure 8: Example for the variation of the mean offset level with time for each monitor in R3, calculated using the RS09 in Gy/s. A time period of 2 weeks was taken into account during which the mean offset level has been defined four times a day using a time interval of one hour. Deviations are higher in the LSS and DS than in the ARC, where the mean offset level is constant (see text).

It has to be mentioned that the increase of the mean offset level seems to be higher than 2 - 5% during operational periods due to additional beam induced losses. A more detailed analysis on the effect of beam induced losses on the increase in offset level over time is ongoing and the final conclusions cannot be presented in this paper.

On a regular basis a CFC card reset of the system is performed in order to avoid an increase of the offset level over time (at least once per technical stop) and in order to assure the operational offset level for all monitors along the ring.

### *Calculation of the offset level and integrated dose per monitor*

Because of the variations mentioned it is important to define the offset level for each monitor and each fill that has been analyzed, separately. The offset for the integrated dose analysis presented here is defined as an average value (using RS09) over a time interval of at least 10 min, several times during the day when the fill took place, but only when there was no beam in the machine. This has been done in order to achieve a statistically relevant data set for the mean offset level per monitor. Also the standard deviation of the mean offset has been calculated for each monitor and each fill separately. The times of having no beam in the machine were defined using the beam presence flag and the timestamps from the sanity checks since the beam presence flag can be at zero even though beam injections are ongoing or while injection tests are performed. The BLM sanity checks however can only be performed if there is no beam at all in the machine.

The criteria for the physics fill selection and for the quality of the data will be summarized in the following:

- Only fills with 2 beams in the machine, fill duration of at least 1 hour and only fills where both beams were dumped within a minute were selected. This has been done using the beam presence flags for beam 1 and 2. In case beam 1 was injected first, this timestamp is chosen as the start time and vice versa.
- The stable beam mode flag was used for the definition of the start time for each fill's stable beam period.
- In order to define the mean offset level (to be subtracted from the integrated dose values) for each monitor separately, a very precise check was made concerning the condition whether there was any beam in the machine or not, using the beam presence flag, the BLM threshold settings and the BLM HV modulation timestamps.

Several data quality checks have been implemented in the analysis:

- The offset fluctuations (i.e. the standard deviation of the mean offset level) should not exceed 10 %. In case offset instabilities over time with more than a 10 % deviation (comparing 2 - 3 sets of 10 minutes per day) were observed, the data quality of the integrated dose cannot be ensured and such results are excluded from this analysis.
- The quality of the logging of the RS12 was investigated and in case an entry was not recorded every 84 s in the LHC Logging DB, the correctness of the integrated dose value cannot be ensured for the monitor concerned, but only in case data are missing by more than 1 % out of the total. The reason of such data loss is still under investigation.
- A check concerning the monitor's noise (RS01 with an integration time window of 40µs) has been implemented, since in case of an increased noise level the signal in RS09 and RS12 are higher as well (see reasons for offset level fluctuations). Therefore a subtraction of the mean offset level from RS12 can lead to a negative integrated dose, because the offset level is overestimated. Higher fluctuations in RS01 introduce higher fluctuations in RS12 and in this case the 'spikes' originating from noise would be interpreted as beam induced losses.
- Furthermore it has been investigated whether the HV modulation (i.e. the BLM connectivity check as part of the BLM sanity checks), being performed at least once a day, has any influence on the offset level (a maximum increase of the mean offset level of 1 % can be introduced). In such cases, the offset level was not calculated for this time period and another time for the offset level determination was selected.

The integrated dose was calculated for physics fills with a different integrated luminosities and a different number of bunches following the formula:

$$D = \sum_{start\ of\ fill}^{end\ of\ fill} (\mathrm{RS12} - \langle 4 * \langle \mathrm{RS09}\ |_0^{600\ \mathrm{s}} \rangle\rangle) * 83.89\ \mathrm{s}$$

RS12 and RS09 are given in Gy/s.

In a first approach it has been tried to define the increase in integrated dose per monitor depending on the number of bunches per beam. The dose was not normalized to integrated luminosity in a first step but defined in mGy per hour.

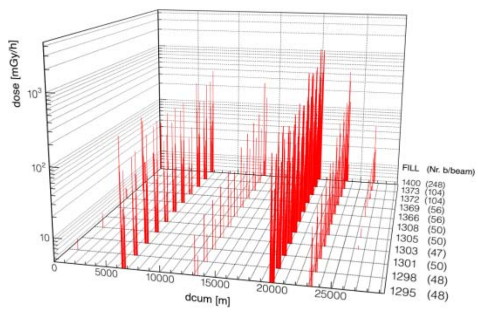


Figure 9: Shown is the integrated dose in mGy/h per monitor versus their position within the ring in metres. Only monitors are shown at which the integrated dose was higher than 5.0 mGy/h. The integrated dose was calculated for several physics proton fills with a different number of bunches per beam in the machine. Note: the dose is not given per integrated luminosity unit in this example, but per hour.

As an example fig. 9 shows the dose in mGy/h for physics proton fills with a different number of bunches per beam.

In a second step it has been tried to decouple the effect of number of bunches from integrated luminosity in order to see the contribution from the number of bunches only. The dose was normalized to integrated luminosity and the increase in dose was determined assuming a linear increase with the number of bunches. The physics proton fill 1400 with 248b/beam was compared to the physics proton fill 1295 with 48b/beam.

$$f = \langle a * x \rangle, \qquad \text{with } x = \frac{Dose/h\ (248b/beam)}{Dose/h\ (48b/beam)}$$

As a general result it turned out that the slope *a* is ranging between 0.3 and 0.6, strongly depending on the IR and on the specific element. Triplet monitors and collimation regions are affected much more by the number of bunches than ARC regions and cold magnets (where the slope was almost not measurable, i.e. zero).

Table 7: Summary of the integrated luminosity per fill.

| Fill Nr. | Int. Luminosity [$nb^{-1}$] |
|---|---|
| 1440 | 6015 |
| 1443 | 1493 |
| 1444 | 4025 |
| 1450 | 6375 |
| 1453 | 2658 |
| 1520 | 337 |
| 1521 | 240 |
| 1522 | 487 |
| 1525 | 545 |
| 1526 | 329 |

In a second approach the effect of luminosity on beam losses at different locations/elements has been investigated more detailed using the increase of integrated dose per integrated luminosity. Only high luminosity fills being equal in number of bunches (368b/beam) were investigated. The ratio in dose ($mGy/nb^{-1}$) for high luminosity fills compared to lower luminosity fills was defined for several combinations of the fills summarized in table 7 (proton and ion fills were treated seperately).

$$Ratio = \frac{D_{high\ \mathcal{L}} / \int \mathcal{L}_{high}}{D_{low\ \mathcal{L}} / \int \mathcal{L}_{low}}$$

However fluctuations were observed from fill to fill, so that the only reasonable solution involves the use of the ratio between highest and lowest luminosity from fills 1450/1443 for protons and 1525/1521 for ions respectively. In an ideal case the ratio should be 1.0, i.e. the integrated dose should increase linearly with integrated luminosity. In case the ratio is greater than 1.0, it means that the losses increase more with luminosity than expected.

### *Results*

Table 8 summarizes the average increase in integrated dose per integrated luminosity unit in $nb^{-1}$ per left and right side of an IR and it's LSS, DS and ARC excluding the TCP's, TCSG's, tertiary collimators, TDI's, MSI's, MKI's and triplet monitors for the fills 1450/1443 with a bunch spacing of 150 ns and 368 bunches per beam.

The tables 9, 10 and 11 give an overview of the increase for the collimator regions, the injection regions and on triplet monitors. It should be mentioned that only 3 TCP collimators are installed in L7 and R7, but 4 monitors on each side and all monitors have been taken into account here.

Table 8: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for proton fills 1450/1443 for LSS, DS and ARC monitors of each IR.

| IR | LSS (#monitors) | DS (#monitors) | ARC (#monitors) |
|---|---|---|---|
| L1 | 0.82 (27) | 1.05 (36) | 1.95 (103) |
| R1 | 0.77 (27) | 0.58 (22) | 1.09 (109) |
| L2 | 0.92 (27) | 3.54 (41) | 0.64 (103) |
| R2 | 1.56 (20) | 4.37 (25) | 4.69 (118) |
| L3 | 4.81 (24) | 2.51 (32) | 0.75 (100) |
| R3 | 4.58 (22) | 1.48 (26) | 1.90 (122) |
| L4 | 0.79 (23) | 1.31 (12) | 6.40 (111) |
| R4 | 0.95 (23) | 0.59 (16) | 1.21 (112) |
| L5 | 1.65 (28) | 1.13 (32) | 0.96 (100) |
| R5 | 1.18 (28) | 1.08 (34) | 1.48 (111) |
| L6 | 0.75 (28) | 1.81 (24) | 0.78 (97) |
| R6 | 1.28 (27) | 2.60 (12) | 1.43 (111) |
| L7 | 0.69 (28) | 5.29 (35) | 1.05 (107) |
| R7 | 0.83 (28) | 0.72 (40) | 0.67 (102) |
| L8 | 1.03 (24) | 1.14 (34) | 1.56 (97) |
| R8 | 1.06 (25) | 1.64 (31) | 1.42 (111) |

The results for the ion fills 1525/1521 with 121b/beam are summarized in table 12, 13, 14 and 15 respectively. The highest ratios have been observed in the LSS of R1, DS of L2, R2, L7 and R8 and in the DS of L7 and ARC of L8.

Table 9: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for proton fills 1450/1443 for collimator monitors.

| IR | TCP (#monitors) | TCSG (#monitors) | TCL & TCT (#monitors) |
|---|---|---|---|
| L1 | - | - | 0.93 (2) |
| R1 | - | - | 1.33 (2) |
| L2 | - | - | 0.80 (2) |
| R2 | - | - | 3.07 (2) |
| L3 | 6.64 (1) | 5.21 (4) | - |

| | | | |
|---|---|---|---|
| R3 | 3.82 (1) | 4.36 (4) | - |
| L5 | - | - | 1.30 (2) |
| R5 | - | - | 1.02 (2) |
| L6 | - | 0.04 (1) | - |
| R6 | - | 1.20 (2) | - |
| L7 | 0.58 (4) | 0.71 (11) | - |
| R7 | 1.47 (4) | 0.95 (13) | - |
| L8 | - | - | 1.00 (2) |
| R8 | - | - | 0.99 (1) |

Table 10: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for proton fills 1450/1443 for TDI, MSI and MKI monitors in L2 and R8.

| IR | TDI (#monitors) | MKI (#monitors) | MSI (#monitors) |
|---|---|---|---|
| L2 | 0.79 (3) | 0.72 (2) | 1.12 (6) |
| R8 | 0.92 (3) | 0.47 (2) | 1.21 (6) |

Table 11: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for proton fills 1450/1443 for triplet monitors.

| IR | Triplets (#monitors) |
|---|---|
| L1 | 0.74 (18) |
| R1 | 0.78 (8) |
| L2 | 0.73 (18) |
| R2 | 0.77 (12) |
| L5 | 0.69 (18) |
| R5 | 0.89 (18) |
| L8 | 0.89 (18) |
| R8 | 0.95 (18) |

During the ion fills the monitors on triplets show an asymmetry between the left and right side in IR2 and 5, what was not observed during the proton fills. The beam intensity was 1e11p/bunch and the filling scheme was 150ns_368_348_15_344. In most of the regions around the ring the dose scales linearly with luminosity (i.e. the ratio is close to 1.0), except in the DS of L2 and R2, the ARC of R2, the LSS of L3 and R3, the ARC of L4 and the DS of R6 and L7.

Table 12: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for ion fills 1525/1521 for for LSS, DS and ARC monitors of each IR.

| IR | LSS (#monitors) | DS (#monitors) | ARC (#monitors) |
|---|---|---|---|
| L1 | 0.61 (17) | 0.86 (34) | 1.65 (109) |
| R1 | 3.94 (19) | 1.68 (21) | 1.85 (101) |
| L2 | 27.87 (13) | 0.76 (36) | 0.73 (100) |
| R2 | 3.34 (9) | 0.79 (33) | 0.71 (101) |
| L3 | 1.66 (24) | 1.26 (29) | 2.72 (97) |
| R3 | 1.33 (24) | 1.25 (30) | 1.84 (105) |
| L4 | 0.40 (9) | 0.74 (10) | 1.85 (93) |
| R4 | 1.24 (15) | 0.93 (13) | 0.44 (103) |
| L5 | 0.90 (22) | 1.26 (30) | 1.21 (96) |
| R5 | 0.98 (13) | 0.94 (31) | 0.63 (108) |
| L6 | 0.52 (27) | 1.06 (23) | 1.22 (84) |
| R6 | 0.70 (23) | 0.75 (18) | 0.67 (104) |
| L7 | 10.24 (25) | 3.14 (36) | 0.71 (95) |
| R7 | 1.51 (21) | 1.10 (31) | 0.62 (115) |
| L8 | 1.36 (10) | 0.92 (26) | 4.64 (94) |
| R8 | 60.50 (20) | 1.68 (28) | 0.88 (99) |

Table 13: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for ion fills 1525/1521 for collimator monitors.

| IR | TCP (#monitors) | TCSG (#monitors) | TCL & TCT (#monitors) |
|---|---|---|---|
| L1 | - | - | 0.72 (2) |
| R1 | - | - | 1.79 (2) |
| L2 | - | - | 0.68 (2) |
| R2 | - | - | 1.01 (1) |
| L3 | 1.35 (1) | 1.79 (4) | - |
| R3 | 1.26 (1) | 1.70 (3) | - |
| L5 | - | - | 1.61 (2) |
| R6 | - | 1.13 (2) | - |
| L7 | 0.73 (4) | 1.14 (11) | - |
| R7 | 0.56 (4) | 0.74 (13) | - |

Table 14: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for ion fills 1525/1521 for TDI, MSI and MKI monitors in L2 and R8.

| IR | TDI (#monitors) | MKI (#monitors) | MSI (#monitors) |
|---|---|---|---|
| L2 | 0.93 (2) | - | 0.55 (6) |
| R8 | 2.01 (3) | - | 3.45 (3) |

Table 15: Summary of the average ratios in dose in mGy per luminosity in $nb^{-1}$ for ion fills 1525/1521 for triplet monitors.

| IR | Triplets (#monitors) |
|---|---|
| L1 | 0.79 (11) |
| R1 | 0.93 (8) |
| L2 | 0.41 (8) |
| R2 | 2.25 (5) |
| L5 | 0.44 (11) |
| R5 | 2.10 (10) |
| L8 | 0.77 (4) |
| R8 | 1.69 (8) |

## ACKNOWLEDGEMENTS

The authors would like to thank for the support given by the Controls and Operations groups (especially thanks to Fabio Follin, Grzegorz Kruk, Pascal Le Roux and Sonia Mallon Amerigo), to Brennan Goddard and Jörg Wenninger as well as to the Protvino and FSU teams.

## REFERENCES

[1] G. Kruk et al, "LHC Software Architecture (LSA) - Evolution Toward LHC Beam Commissioning", ICALEPCS'07, Knoxville, Tennessee, USA, WOPA03C

[2] A. Nordt, "Filter Monitors and Noise in IR3", 21.05.2010, Machine Protection Panel meeting, http://lhc-mpwg.web.cern.ch/lhc-mpwg

[3] E.B. Holzer et al, "LHC-BLM-ECR-0003", "LHC-BLM-ECR-0004", "LHC-BLM-ECR-0005", "LHC-BLM-ECR-0006", "LHC-BLM-ECR-0007", "LHC-BLM-ECR-0008", "LHC-BLM-ECR-0010", "LHC-BLM-ECR-0011", "LHC-BLM-ECR-0012", "LHC-BLM-ECR-0013", "LHC-BLM-ECR-0014", https://edms.cern.ch/document

[4] C. Zamantzas et al, "Beam loss monitor system", Proceedings of the 2010 Evian workshop on LHC commissioning 19th-20th January 2010, https://espace.cern.ch/acc-tec-sector/Evian/2010-Proceedings/default.aspx

[5] Priv. Communication with E. Effinger

[6] J. Emery et al "First experiences with the LHC BLM sanity checks", 2010 JINST 5 C12044 http://iopscience.iop.org/1748-0221/5/12/C12044