Is the BLM system ready to go to higher intensities?

M. Sapinski, F. Cerutti, B. Dehning, E. Effinger, J. Emery, B. Goddard, A. Guerrero, S. Grishin,
E. B. Holzer, S. Jackson, Ch. Kurfuerst, A. Lechner, A. Marsili, M. Misiowiec, E. Nebot, A. Nordt,
A. Priebe, Ch. Roderick, R. Schmidt, A. Verweij, J. Wenninger, Ch. Zamantzas, F. Zimmermann
CERN, Geneva, Switzerland

Abstract

The higher beam intensities will enhance the effects of the beam losses observed during 2010 run. In particular beam losses due to so called UFO events are discussed, but also other beam loss phenomena like luminosity losses, injection losses and the leakage from the collimation system are considered. The current understanding of the quench limits reflected in the BLM thresholds on the cold magnets is presented. The thresholds for possible increased beam energy are reviewed.

INTRODUCTION

The 2010 LHC beam, despite of its record-breaking stored energy of 30 MJ, has not induced any unintentional quenches of superconducting magnets nor other equipment damage. Nevertheless, a number of unexpected phenomena have been observed, some of them affecting machine operation.

This paper concentrates on understanding of beam losses, with emphasis on UFO phenomena and on accuracy of the present knowledge of the Beam Loss Monitor beam-abort thresholds. It attempts to foresee the problems during LHC run in 2011 and 2012, when intensity, and maybe the energy of the beam, will be significantly increased.

DO WE UNDERSTAND ALL LOSSES?

The loss pattern observed by the BLM monitors around the LHC ring is, in most cases, well understood. Nevertheless, there are special cases of losses which occurred in 2010 run and which need to be further studied in order to understand their mechanism and the BLM signals which they generate.

The important beam losses, generating large signals in the BLMs, have been usually noticed during the operation because they were very visible on fixed displays, they affected the beam lifetime or even initiated the beam dump. Examples of such losses are discussed first. A systematic search of nominal loss level variation has also been performed in order to look for loss variations, which have been unnoticed during operation.

Examples of unexplained losses

One example of unexplained loss has been reported already a year ago [1]. The difference in the loss pattern at overinjection between IR2, where beam 1 is injected, and IR8 where beam 2 injection takes place is illustrated in Figure 1. It has been explained only partly by a presence of a chicane in IP8 which is responsible for significant decrease of the signal in monitors installed on Q1 magnet (first from left) in IP8. Another feature, the signal in the monitor on MBX magnet which is about 3-5 times higher in case of IP8, remains unexplained. Some observations considering the difference in location of the monitors have been done [2], but a simulation has to be performed to evaluate if these differences explain the difference in signal. The beam-abort thresholds for this monitor in IP8 have been temporarily increased in order to allow overinjection without dumping the beam.

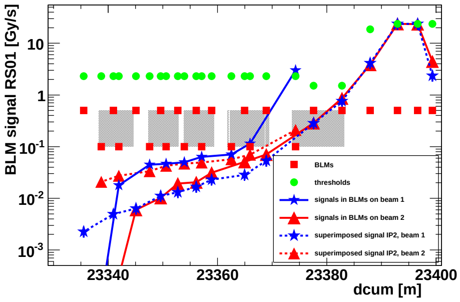

Figure 1: Asymmetry in the BLM signals at injection of beam 1 and beam 2. The MBX magnet is the first dark box from the right. The irregular signal on one of the monitors installed on this magnet is visible.

Another example has a different nature. On the 3rd of October 2010 at 20:28 a sudden increase of BLM signal on the triplet magnets in IP1 led to a beam dump issued by `BLMQI.02R1.B1E23_MQXB` monitor. Signal averaged over long integration times 0.655 - 20.9 s exceeded the beam-abort threshold. Other monitors on the same tunnel card presented behaviour suggesting a very high loss event, but the monitors which are expected to be sensitive to such large loss (BLMs on collimators, ATLAS Beam Condition Monitors) have not confirmed it. The reason of this event, which has been observed only once, remains unclear.

Systematic studies

A method of systematic studies leading to a detection of abnormal losses has been proposed. The method uses the integrated dose measurement by the BLMs during stable beams periods, normalized to integrated luminosity. As the beam conditions during these fills were identical, small variations are awaited. Large fill-to-fill variations indicate the unexpected loss rate change and their should be investigated in order to understand loss rate variations.

Figure 2 presents such a variation analysis for high-intensity proton fills. Monitors with the largest variations are located in the Long Straight Sections. Understanding of these variations need further investigation, but they will probably not affect the running of the machine in 2011 and 2012. Details of this study can be found in [3].

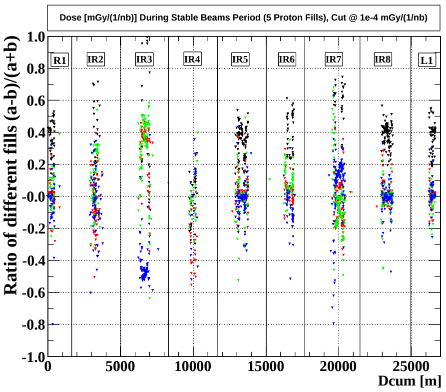

Figure 2: Study of fill-to-fill variation of beam losses: **a** and **b** are the total doses normalized to the luminosity integrated during the fill. Every point depicts ratio $(\mathbf{a}-\mathbf{b})/(\mathbf{a}+\mathbf{b})$ for one monitor (and for two fills).

WHAT DO WE KNOW ABOUT UFO?

The term "UFO" has been adopted from the plasma physics community, where a phenomena of dust particles falling into plasma has been observed. In LHC, this name is used for the sudden losses with a millisecond-scale duration appearing in any part of the accelerator ring. The properties of these events suggest that they are generated by small objects (dust) falling into the beam or being attracted by the beam electromagnetic fields.

The first UFO event has been observed on July 7th, 2010 as it triggered a beam dump, because of losses observed by the BLM system. The post-mortem data [4] of this event, presented in Figure 3, show a complex time structure with 6 peaks separated by 70 or 100 μs . For a detailed analysis see [5].

Sub-thresholds analysis

A systematic search for sub-threshold UFO events (i.e. events which have not initiated beam dump) has been launched after July 7th. A collection of 111 such events has been gathered in 2010 data during the periods when beams were declared stable [6]. The data have been extracted from the Logging Database using the following criteria:

- Signal is observed on primary collimators (TCP).

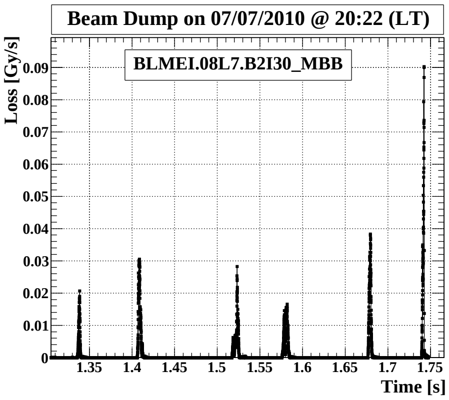

Figure 3: The post-mortem data of the first UFO event which caused a beam dump.

- Signal is observed in at least three neighbouring BLM monitors.
- Loss duration is in the millisecond scale.

Additional analyses with loosen conditions are ongoing.

The analysis of this sample revealed the following properties of the UFO events:

- The UFO event rate increases linearly with the beam intensity, as shown in Figure 4; the rate expected at beam of 1000 bunches, extrapolated from the linear tendency, is about 1 event every half hour.

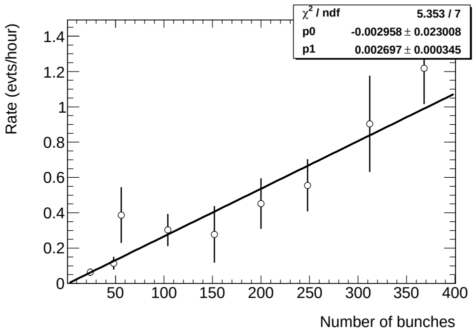

Figure 4: Dependence of the UFO event rate on the beam intensity.

- The observed signal length becomes shorter with increasing beam intensity, as shown in Figure 5.
- The BLM signal amplitude, measured as a signal accumulated in 40 μs integration time, is independent on the beam intensity, as shown in Figure 6.

Model of dust particle

A model describing a dust particle falling into a beam has been developed [7]. The model includes the effect of change of the particle charge due to interaction with the beam. The movement of the particle is guided by forces

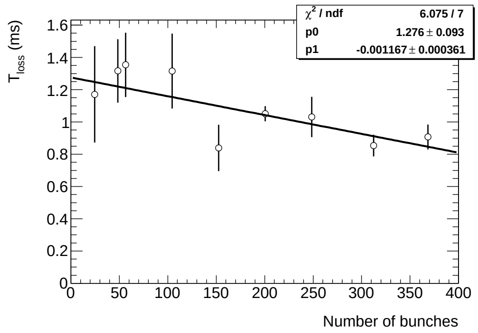

Figure 5: Dependence of duration of the UFO event signal on the beam intensity.

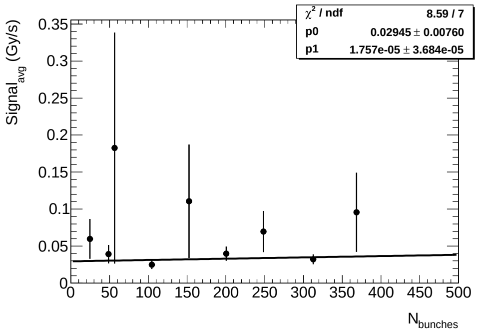

Figure 6: Dependence of the amplitude of the UFO event signal on the beam intensity.

due to the electric fields of the beam charge and of the image charge at the chamber wall and by gravity. Interestingly the model predicts the signal shortening with increasing beam intensity and lack of dependence of the signal amplitude on the beam intensity (see Figure 7). It also predicts the existence of UFO events with a precursor loss. Such type of events has been observed (see Figure 3 for event with multiple precursors), however in most cases the losses have only one peak.

FLUKA simulations

The effect of the LHC beam interactions with the obstacles has been also investigated using particle shower simulations in [8]. This study does not take into account the additional forces acting on an object due to electromagnetic interactions with the beam, which modifies the object trajectory. The outcome of the study is a relation between the beam intensity needed to quench the LHC magnets and the size of the object itself. For beam energy of 3.5 TeV, a nominal bunch intensity and assuming a metallic object of size x (expressed in μm), the quench should occur if the beam intensity exceeds $220/\mathrm{x}$ bunches. For a plastic object the size must be almost 10 times larger to generate a quench. According to this results, the lack of UFO-generated quenches during the 2010 run suggests that the size of the falling objects is smaller than $0.3\ \mu$m if the object is metallic or $3\ \mu$m in case of plastic one.

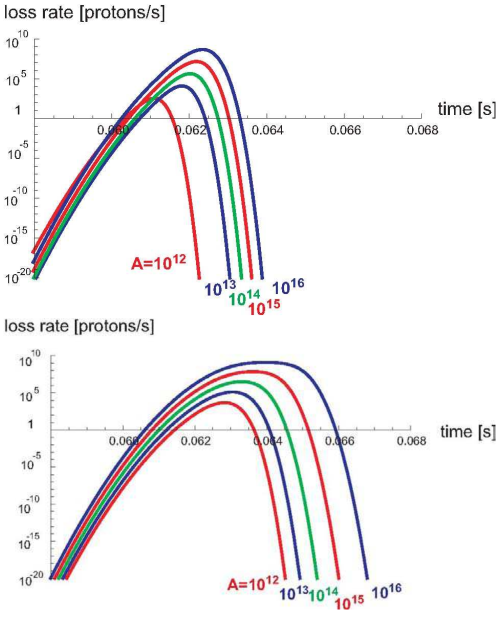

Figure 7: Model predictions of UFO loss rate for nominal (upper plot, $3.2 \cdot 10^{14}$ protons) and low (bottom plot, $2.3 \cdot 10^{12}$ protons) intensities.

UFO speed

In case of UFO events which dumped the beam, the high-time-resolution post-mortem data [4] are saved. In 2010 there were 18 beam dumps due to UFO events. Out of these 10 events had a signal shape which can be well fitted with gaussian, reminding a signal shape obtained during the wire scan. An example of such data is shown in Figure 8.

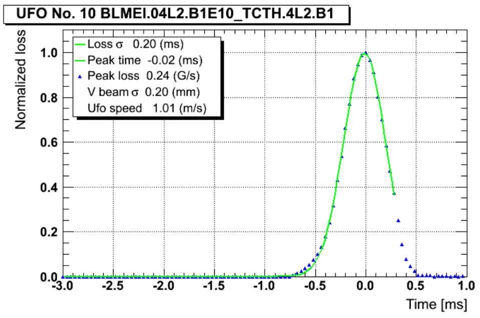

Figure 8: BLM Post-Mortem data generated by a UFO event which dumped the beam.

Assuming that the size of the UFO particle is much smaller than the beam size one can calculate the speed of the particle passing through the beam. The speeds found in this analysis vary from 0.4 to 4.5 m/s, what supports the idea that the electromagnetic forces have dominant contribution to the movement of the UFO objects.

Remedy to UFOs

The study of UFO events will continue during the 2011 run. As the frequency of these events is expected to increase, a strategy to avoid spurious beam dumps must be developed.

One possibility is so called scrubbing run foreseen during the first weeks of 2011 operation. During the scrubbing a high intensity beam at injection energy is circulating in the machine in order to enhance outgassing from the internal surfaces of the beam chamber. It is possible that the scrubbing will also enhance the release rate of the dust particles therefore suppressing the rate of UFO events in the following physics runs. The UFO activity before, during and after scrubbing run will be carefully monitored.

The second possibility relies on the lack of UFO-induced quenches during 2010 run. The BLM thresholds at the end of the run have been already increased to about 60% above the originally estimated quench level. This modification allowed to avoid spurious beam dumps which would have been generated by the BLM system if lower thresholds had still been applied.

The signals observed during the UFO events have exceeded the expected BLM signal at quench. The reason can be two-fold:

- The BLM thresholds have been set assuming the beam loss due to orbit deviation and therefore the beam hitting directly the beam screen; UFO events correspond to different loss scenario.
- For the losses in the millisecond-scale the cooling contribution of helium it is not well established.

In order to investigate the impact of these two unknowns, a simulation study has started and a special quench test has been performed.

It must be stressed that, in case of the beam energy increase, the amplitude of the loss generated by UFO will increase (as in case of BLM signal during the wire scan, see Figure 9). Together with the reduced quench level, this might lead to a significant increase of the quench probability when running the LHC with energies above 3.5 TeV.

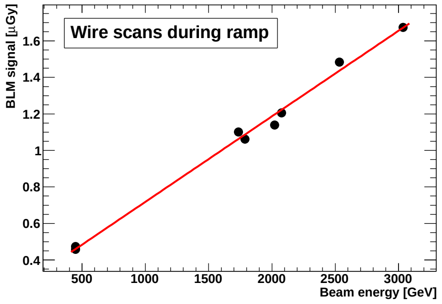

Figure 9: BLM signals registered during the wire scans when beam energy has been ramped.

Quench test at millisecond timescale

In order to investigate the quench margin at the millisecond timescale a loss of this duration must be generated. Such a loss is generated by the wire scanner during its normal operation. Therefore a quench test using this device has been performed.

The test conditions were the following: beam with energy 3.5 TeV and intensity of $1.53 \cdot 10^{13}$ protons. The MBRB magnet is situated 32 meters downstream the wire scanner. The magnet quenched when the wire speed reached $5\ \mathrm{cm/s}$. The overlapped post-mortem data from the BLM monitor and QPS system are shown in Figure 10. The irregular BLM signal (blue points) shows that the carbon fiber was vibrating during this scan. The electron microscope picture of the fiber made after the test has shown that about 50% of the wire diameter sublimated due to heating from the beam.

The raise of the QPS signal started about 10 ms after the start of the beam scan seen by the BLM system. Therefore the probed time scale was longer than the one characteristic for UFO events (about 1 ms).

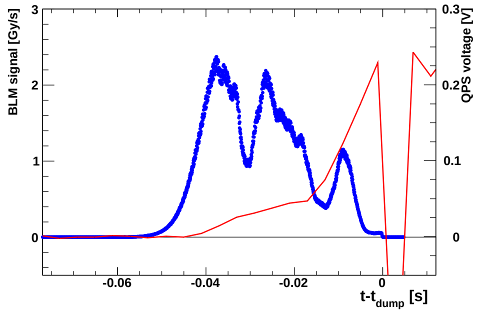

Figure 10: BLM post-mortem signals (blue) overlapped with QPS voltage readout (red) during the wire scan which led to quench of MBRB magnet.

The preliminary results of the quench analysis using the QPS and BLM post-mortem data [9] and QP3 code [10] suggest that the quench limit for the 10-ms perturbation is in the range $35 - 42\ \mathrm{mJ/cm^3}$. The preliminary results of FLUKA simulations have been presented [11], and the final conclusions from this experiment are expected soon.

A repetition of this test during 2011 run is strongly suggested. The conditions should be modified, especially the beam intensity should be increased by about factor of 4.

HOW CORRECT ARE THRESHOLDS?

The BLMs are protecting various machine elements against beam losses. The beam-abort thresholds have been computed differently depending on type of protected element. For cold magnets the methods of thresholds computation are described in [12, 13, 14]. In case of collimators the relevant document is [15] and in case of warm magnets the present strategy is documented in [16, 19].

Two aspects of threshold correctness are discussed here:

- The locations where the observed losses were close to beam-abort thresholds.
- The accuracy of the threshold values.

The major modification to cold magnet thresholds, which has been done before 2011 run, is presented.

Low margin locations

The threshold setting is based on two threshold tables called master and applied [17]. The master table is the one which assures protection of the accelerator components against damage. The thresholds which are actually used in the electronics (applied thresholds) must be below the master table. The following convention is used: in the normal situation the applied thresholds are 10 times below or equal the master thresholds. This allows the operators to raise, fast and safely, the thresholds up to factor 10, when needed. This method has been found very useful in 2010 run, when UFO events became an important thread to the beam availability.

The weakness of this approach is seen for the short signal integration times. The upper bound of the dynamic range of the BLM channels (with standard ionisation chamber) is about 23 $\mathrm{Gy/s}$. According to the convention the applied threshold values must be set to maximum 2.3 $\mathrm{Gy/s}$. In case of short signal integration times this value is often much lower than the estimation of the physical threshold. Therefore the BLM system is often overprotective for short losses.

The above arguments should be kept in mind when looking at the results of the systematic search for channels where signals are close to the thresholds. Figure 11 illustrates the results of such search. Every point depicts a maximum registered ratio of signal to applied threshold for every monitor. The red line represents the dump level, and the green line 10% of the dump level. Higher beam intensities and higher luminosity expected in 2011 run will increase the losses, while higher beam energy will decrease the thresholds, so factor 10 between loss and threshold as observed last year might not be enough during 2011 run. More details on this analysis can be found in [3], where also a lists of monitors with low margin to thresholds (above green line) are published.

Threshold changes

The changes of thresholds which took place in 2010 were due to hardware modifications (for instance filter installations) as well as due to debugging of the threshold generation code. These changes are described in [3, 18, 19].

The most important change, affecting almost all monitors on superconducting magnets, follows the better understanding of the quench limits due to lack of quench induced by UFO event (millisecond scale, described before) and as a conclusion of quench test for long losses (1-5 second scale).

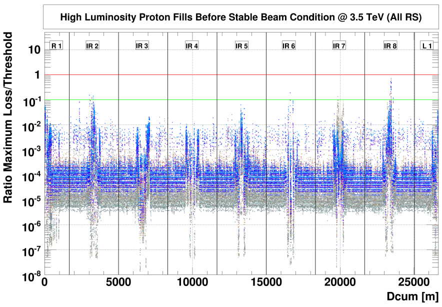

Figure 11: Ratio of maximum signal to the applied threshold registered during the stable beam period, as a function of monitor location, for 5 high luminosity proton fills.

The quench tests performed before Autumn 2010 were testing only MB magnets at injection energy and for very short losses, where the quench limit can be easily calculated as an enthalpy limit of a dry superconducting cable [13]. A series of tests performed in September and October 2010 used orbital bump technique to provoke slow losses on arc MQ magnet for injection energy and at 3.5 TeV. An example of the loss signals observed during the quench test at 3.5 TeV are shown in Figure 12. The small blue and red squares mark the positions of the BLM monitors observing beam 1 and beam 2 respectively. The beam direction was from right to left (beam 2). The green line shows the signals expected in the second and the third monitor in the moment of quench. The red line connects the signal actually registered by the BLMs during the quench. The existing threshold was overestimated by factor 2 to 3 [20].

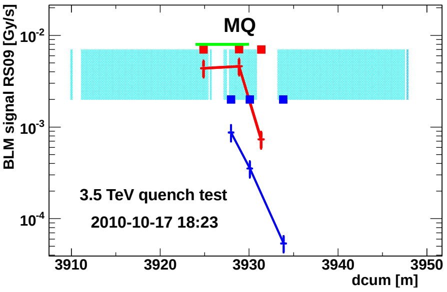

Figure 12: Signals registered in the BLM system during the quench test of MQ magnet at 3.5 TeV.

Corrections to BLM thresholds on cold magnets have been applied before the start of 2011 run. They are depicted in Figure 13, where the solid line is an example of old 3.5 TeV quench thresholds, and dashed line shows the new thresholds.

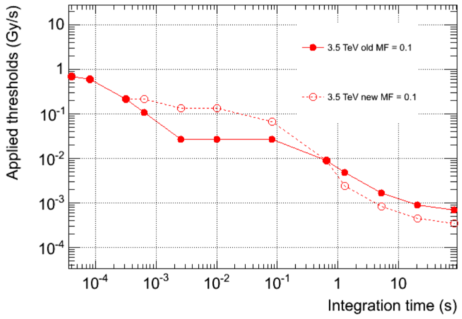

Figure 13: Example of BLM thresholds for beam energy 3.5 TeV.

CONCLUSIONS

The beam losses as observed by the Beam Loss Monitoring system, are generally understood, but a few specific cases need more study or a follow-up. A systematic study of the fill-to-fill variations of the total dose registered by the BLMs gives a hint about variation of small losses, which will probably not affect the operation of the machine, but which are not understood yet.

The UFO events, which are millisecond-scale losses provoked probably by small objects falling into the beam, are feared to affect the operation in 2011 and 2012. The analysis of sub-threshold UFOs reveal lack of dependence of UFO amplitude from beam intensity, what should allow to keep the dump rate due to UFOs under control.

The analysis of the UFO events and the results of quench tests with circulating beam lead to massive upgrade of BLM thresholds on cold magnets. A list of monitors where the observed signals were close to the beam-abort thresholds has been extracted from 2010 data.

The BLM system is well prepared to high intensities expected during 2011 run but a careful follow up on UFO events and signals close to the thresholds is necessary.

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