BLM THRESHOLD STRATEGY (UFOs AND QUENCHES)

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Abstract

The interaction of the LHC's proton beam with falling macroparticles (dust) in the beam tube causes beam losses with durations ranging from tens of microseconds to several milliseconds. After the long shutdown, the beam energy will be increased from 4 towards 6.5 TeV, as a consequence of which some of these beam-particle interactions, colloquially called "UFOs", are predicted to cause quenches in superconducting magnets. In-depth experimental and numerical studies have been performed to make the most efficient use possible of the LHCs beam-loss monitoring (BLM) system to minimize the number of quenches, while keeping the number of avoidable beam dumps due to the BLM system to a minimum. The results of these studies are presented here, as well as preliminary strategies for the setting of BLM thresholds for the protection of warm magnets and collimators.

ARC UFOS PRE AND POST LS 1

Predictions for UFOs in the Arcs

As the beam energy in the LHC will be increased from 4 to 6.5 TeV, the energy-deposition in superconducting coils due to collisions of the proton-beam with falling macroparticles (UFOs) will increase by a factor 2.4 . At the same time, the minimum quench-energy in the superconducting coils will decrease by a factor 2-3, depending on the duration of the UFO losses [1]. The combination of these two effects means that some UFO losses are expected to be sufficiently important to quench superconducting magnets in the LHC; compare [2]. The most likely functional region around the LHC ring for UFO-induced quenches and/or beam dumps is expected to be the arc region[3]. This assumption is supported by the observation that the UFO hotspots in the injection-kicker regions, which exhibited a high rate of activity prior to the LHC long shutdown (LS 1), have been overhauled with measures that have proven their efficiency in selected locations already during Run 1 [5].

Another relevant observation from Run 1 is the (de)conditioning seen during 2011/12 and illustrated in Fig. 1. After every winter stop, the rate of UFOs in the arcs increased (deconditioning), slowly approaching a lower asymptotic value over the subsequent weeks (conditioning). Another marked increase in UFO rate was observed during opertion with 25-ns bunch spacing. For the early weeks of Run 2 we have to expect an increased UFO activity with a subsequent conditioning, both, during the initial 50-ns operation, and after the switch to 25-ns bunch spacing.

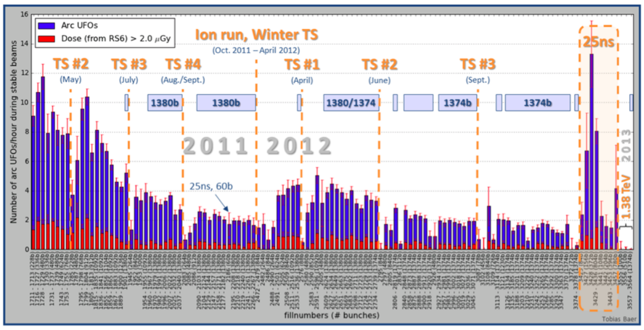

Figure 1: Number of arc UFOs per hour during stable beams in 2011 and 2012. Courtesy T. Baer, [2].

Based on the semi-analytical model of beam-macroparticle interactions of [6, 7], the loss-duration of UFO events decreases linearly with beam size. The reduced beam size at 6.5 TeV will therefore lead to ∼20% shorter losses than at 4 TeV. The significance of this lies in the comparison of the maximum design-response time of the LHC machine protection system (MPS) with the rise time of UFO-induced losses. The maximum MPS response time is 3 turns or ∼270 μs, with typical response times ranging between 80 and 170 μs [8]. UFO-loss rise-times in ∼6000 events recorded during 2011-2012 (3.5 and 4 TeV beam energy, respectively) were found in the range between 50 and 300 μs [9]. Even though the semi-analytical model predicts that UFO events with higher losses also have longer durations, it cannot be excluded that some UFOs can cause a magnet to quench *before* the MPS can dump the beam due to a BLM trigger.

Measures Taken during LS 1

A mitigation of the origin of UFOs in the arcs, similar to the actions taken in the injection kickers, was not possible during LS 1. Certainly, the risk attached to quenches in the main circuits of the LHC are a lesser after LS 1. This is due to the refurbishment and control of all interconnections, and the qualification by CSCM tests [10] of the current bypass in the RB circuits. Nonetheless, quenches in main magnets at currents equivalent to 6.5 TeV beam energy are expected to lead to more than eight hours of down time – considerably more than a beam dump due to a BLM trigger. The avoidance of quenches, as well as the avoidance of unnecessary beam dumps, are, therefore, decisive factors for the availability of the machine at 6.5 TeV in the

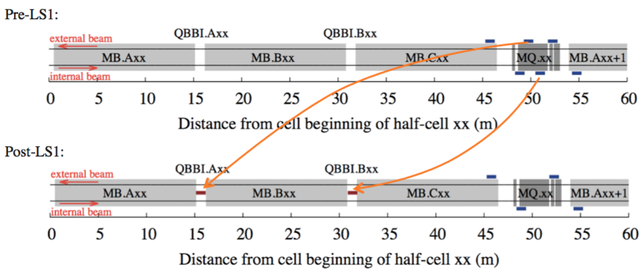

Figure 2: Relocation of BLMs in the arcs and DS from horizontal positions on MQ magnets to vertical positions above the MB-MB interconnects; courtesy A. Lechner [1].

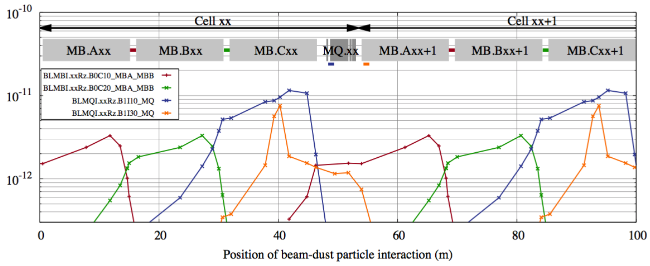

Figure 3: BLM signals in the in the new BLM locations in an arc cell. The signals are plotted as a function of UFO location. Courtesy A. Lechner [1].

presence of UFOs.

Prior to the observation of UFOs, it was assumed that beam-losses in the arcs could occur only in the MQ magnets, where the beta-function is largest. As a consequence, all MQ magnets were equipped with six BLMs each, mounted horizontally, three on either side of the cryostat. For the detection of UFOs in MB magnets, this configuration is not well suited. According to FLUKA simulations [11, 12], the ratio in BLM signal between a macroparticle-proton interaction at the beginning of a half-cell, and the signal of the same type of interaction at the MB-MQ interconnect was 70. The consequence of this bad spatial resolution was that, in order to avoid all UFO-induced quenches, UFOs at the MB-MQ interconnects would have caused dumps already at loss levels 70 times below the actual quench level – with dire consequences for LHC availability.

To mitigate this effect, the central BLMs were relocated from their horizontal MQ positions to vertical positions above the MB-MB interconnects; see Fig. 2. Figure 3 shows FLUKA simulations of BLM signals in the new locations as a function of UFO location. Each signal corresponds to a single interaction between a proton and a macro-particle (carbon). It can be seen that three BLMs (red, green, and blue) together cover the full length of a half-cell. For each detector, the ratio between minimal and maximal signal within its range is down to two or three from the factor of 70 that was mentioned above.

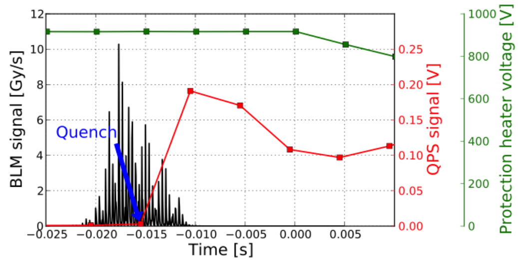

Figure 4: BLM signals and QPS signals recorded during the fast orbit-bump quench test in MQ.12L6.

Lessons Learnt from Quench Tests

After a first beam-induced quenches at injection in 2008 and 2009, dedicated quench tests were performed in 2010, 2011, and 2013. The goal of these experiments was to induce quenches in accelerator magnets by controlled beam losses, the analysis of which would permit to quantify the quench level in the affected magnets at their respective operating points. Losses were induced in the nano-second regime (single-turn losses), over several milliseconds, or over several seconds, thus testing the quench level for different relevant loss mechanisms. The test most relevant for UFOs int he arcs is the fast orbit-bump quench test of 2013 [15, 14, 13], quenching an MQ magnet after roughly ten milliseconds.

The analysis of this test revealed that the magnet quenched after a deposition of four times more energy than expected. This result gives grounds for hope as far as the electrothermal stability of arc magnets vis-a-vis UFOs is concerned. The interpretation of the result is, however, not straight forward. Figure 4 shows BLM and QPS signals recorded during the event. Not only is the precise moment of quench difficult to determine (given the five-millisecond resolution of QPS data), but the BLM signals reveal a substructure of short pulses. This substructure may well have been responsible for the elevated quench levels that were observed.

We conclude that the real quench level in case of UFO events may be up to a factor four higher than the model; an overview of quench test results and quench-level estimates is shown in Fig. 5. For this reason, we propose to implement a correction factor four in the BLM thresholds of all integration times below 80 milliseconds for arc BLMs. Experience will show whether this optimistic assumption is justified.

New BLM Thresholds for the Arcs

BLM thresholds for the protection from quenches in superconducting magnets are formulated by the three below

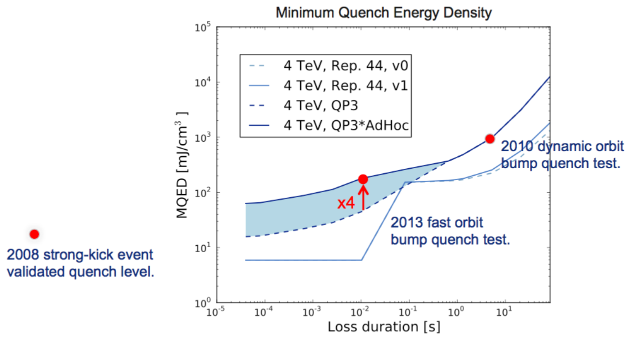

Figure 5: Electro-thermal estimate of quench levels as a function of loss duration in MB mid-plane inner-layer turn at 6.5-TeV equivalent current. The horizontal axis of the graph spans the range of BLM signals, i.e., the relevant range of integration-times for the setting of BLM thresholds.

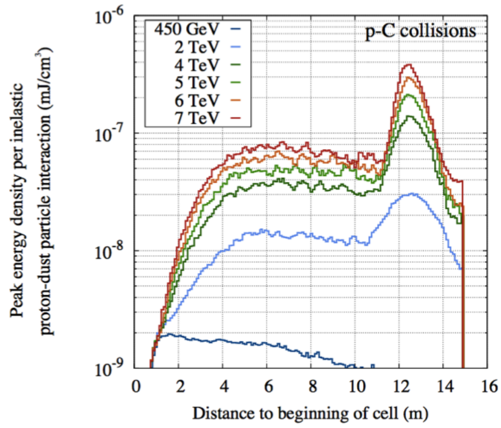

Figure 6: Peak energy deposition in MB coil per proton-dust-particle interaction for different beam energies. The dust particle is assumed to be made of carbon. The characteristic peak is due to neutral particles hitting the downstream beam pipe due to the slight curvature of the MB magnets. Courtesy A. Lechner [1].

formulas:

$$\text{BLMSignal@Quench} = \frac{\text{BLMSignal}(E) * \text{QuenchLevel}(E,t)}{\text{EnergyDeposit}(E)} \quad (1)$$

$$\text{MasterThreshold}(E,t) = N * \text{BLMSignal@Quench} * \text{AdHoc}(E,t) \quad (2)$$

$$\text{AppliedThreshold}(E,t) = \text{MonitorFactor} * \text{MasterThreshold}(E,t). \quad (3)$$

The QuenchLevel factor, given in mJ/cm^3, is the electro-thermal estimate given by the QP3 software [16]. The BLMSignal, given in Gy/proton, and the EnergyDeposit, given in mJ/(cm^3 proton), are the results of FLUKA simulations. The FLUKA simulation represents the type of loss scenario to which the BLMs are set to react. Results for the UFO scenario are shown in Figs. 3 and 6 [17]. Note that, even if the FLUKA and QP3 simulations are highly accurate w.r.t. the given beam-loss scenario, any deviation of a real event from that scenario means that thresholds will not be set in the optimum way to protect from quenches and avoid unnecessary dumps. The ratio of QuenchLevel and EnergyDeposit gives the number of protons lost to provoke a quench in the given scenario. This number is multiplied by the BLMSignal to give the BLMSignal@Quench.

AdHoc corrections are foreseen to implement operational experience, and to implement missing features in the FLUKA and QP3 models. For example, the factor four mentioned above is implemented as an AdHoc correction. The factor N, where $N > 1$ deliberately sets the master threshold higher than the presumed BLMSignal@Quench. It works in conjunction with the MonitorFactor, where $0 < \text{MonitorFactor} \leq 1$, which allows to tune thresholds efficiently during operations on a per-monitor basis. The factor N, which allows to set thresholds above quench levels, has to ensure that any beam-loss event is intercepted safely below damage levels. Note, howver, that quench levels are expressed in mJ/cm^3, whereas damage-levels are expected to be many J/cm^3, leaving some latitude for threshold tuning. In 2009, $N = 3$ and $\text{MonitorFactor} = 0.1$ was the standard setting. For after LS1, we propose for the arcs $N = 3$ and $\text{MonitorFactor} = 0.33$, i.e., to set the AppliedThreshold to the BLMSignal@Quench, adjusted by AdHoc corrections. This is done to find, in the most efficient way possible, the optimal BLM thresholds in terms of protection and availability. Figure 7 compares pre-LS1 settings (BLMSignal@Quench∗AdHoc) with the proposal for post-LS1 settings. It can be seen that, despite a large discrepancy in the quench-level data (see Fig. 5), the thresholds are very similar. This is due to the fact that the increase in QuenchLevel is more than counterbalanced by the worse BLMSignal/EnergyDeposit ratio of the UFO scenario w.r.t. the scenario used during Run 1 (losses on the MB-MQ interconnects).

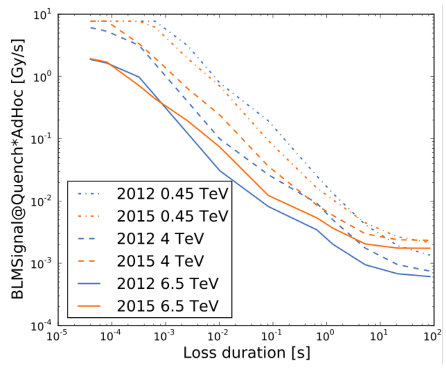

Figure 7: Comparison of BLMSignal@Quench∗AdHoc between pre- and post-LS1 settings in a BLM mounted in position 1 of an MQ magnet in the arc for different energies and loss durations.

It is interesting to note that BLMs in the arcs are set to prevent quenches in MB magnets only. MQ magnets are then implicitly covered as well. UFO locations that produce the highest losses in the MQ magnet are found in Fig. 3 at the location of the the narrow orange peak. Quench levels in MQ magnets, however, are higher than MB inner layer quench levels, and neutral particles in quadrupoles are much smaller and, hence, the energy deposition in quadrupoles is lower than in dipoles.

Since UFO losses are relevant only in time intervals below 10 ms and for energies above 4 TeV, another beam-loss scenario should be adopted to set thresholds for losses longer than 10 ms and lower energies. The scenario of an inadvertently set orbit bump was studied, based on the analysis of several orbit-bump type quench tests. The orbit-bump scenario would lead to lower thresholds than the UFO scenario at very low energies (where the peak of neutral particles fades away; see Fig. 6), and to higher thresholds at longer time intervals and higher energies. In order to cover both scenarios, UFOs and orbit-bumps, we are currently studying whether the orbit-bump scenario could be applied for the settings of the downstream BLM at the MQ (orange in Fig. 3), and the UFO scenario for the upstream BLM at the MQ (blue in Fig. 3).

BLM THRESHOLDS IN OTHER LOCATIONS

Cold Magnets

The UFO scenario is relevant for all cold magnets around the ring. Only very specific regions need to be studied for other scenarios. Note that it is proposed to use a less aggressive setting for magnets in the matching section, separation dipoles, and inner-triplet quadrupoles. If in the arcs and dispersion suppressors we use a MonitorFactor of 0.33 to set the AppliedThreshold to the BLMSignal@Quench, in those other regions, we propose a MonitorFactor of 0.1, as in LS 1. The reason for this decision is that fewer spare magnets are available, and the likelihood for quenches due to UFOs in the affected magnets is much smaller due to geometrical considerations and larger margins.

Dispersion Suppressor Most of the dispersion-suppressor region is handled analogously to the arcs. Only few monitors in IRs 3 and 7 may see their thresholds raised in the long integration times to accommodate non-quench-provoking losses from the collimation regions, which have a very large BLMResponse/EnergyDeposit ratio. A number of dipole magnets close to the IPs and collimation regions are equipped with horizontally mounted BLMs. These have been installed for ion operation, to monitor specific loss locations due to secondary ion beams. These monitors will be set for the specific ion-loss scenario, and raised if necessary to prevent them from interfering with proton operation.

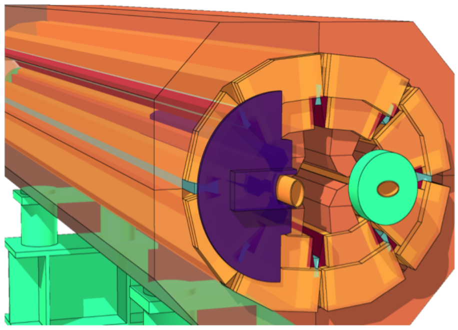

Figure 8: Detail of the FLUKA model of MQW magnets. Courtesy of E. Skordis.

Matching Section Quadrupoles The UFO scenario for BLM thresholds in the matching-section quadrupoles has been studied, based on similar FLUKA models as the ones presented above. Since the resulting thresholds would be very high (close to the electronic maximum), we are studying an orbit-bump scenario, taking into account the different cable properties of individual magnet types in the quench-level model.

Separation Dipoles Similarly, separation dipoles will be protected against quenches from UFO losses. They require a different FLUKA model from arc dipoles as they are not bent and, therefore, are not exposed to the neutral particles emanating from the proton-macro-particle collisions.

Inner Triplets Three differente loss scenarios are considered for the triplet. The UFO scenario is used in Q1 and Q3. For Q2, due to the very large beta function, an orbit-bump-like scenario is used, documented in [21]. In addition, it must be made sure that collision debris, with its much larger BLMSignal/EnergyDeposit ratio, cannot trigger beam dumps in the longer integration times at top energy [18]. This is ensured by means of AdHoc corrections.

Warm Magnets

Detailed FLUKA models of MQW magnets, including the shielding elements installed during LS 1 (see Fig. 8), are used to set thresholds in warm magnets. The protection goal here is to stay safely away from damage to the beam pipe (for short integration times) [19], and from overheating the water-cooled coils (for long integration times).

Collimators

The goals for the setting of BLM thresholds for collimators are to ensure their protection from damage, and to ensure the hierarchy of collimators. The proposed strategy is to set the thresholds as tight as possible, based on loss-maps to be carried out at the beginning of Run 2. A combination of updated damage levels in terms of the allowable number of protons lost for the respective scenario [22], and FLUKA models will provide a cross-check to ensure that the thresholds thus obtained protect the collimators from damage under all circumstances.

SUMMARY

We have presented the rationale for the setting of BLM thresholds in the LHC after LS 1. The most important topic is the determination of optimal BLM settings in the arcs vis-a-vis UFO-induced losses. A body of knowledge in terms of FLUKA models and quench-test analyses are at our disposal to make a first setting. For the arcs thresholds are chosen rather optimistically. Some UFO-induced quenches in the arcs are to be expected. This will serve to find the final and optimal settings in the most efficient way possible. With the new BLM locations we will be able to localize UFOs all around the arcs and prevent UFO-induced quenches while causing a minimal amount of unnecessary beam dumps. BLM thresholds are under preparation for all BLM families around the ring, to be ready for first beams in spring 2015.

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