UFOs: OBSERVATIONS, STATISTICS AND EXTRAPOLATIONS

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Abstract

Unidentified falling objects (UFOs) could be a major limitation for nominal LHC operation. Therefore, in 2011/12, the diagnostics for UFO events were significantly improved, dedicated measurements, MDs and laboratory tests were performed and complemented by simulations (FLUKA & MadX) and theoretical studies.

In this talk the state of knowledge is summarized and extrapolations for LHC operation with $25\,\mathrm{ns}$ bunch spacing and at higher energy are presented. An overview of the mitigation strategies (in particular BLM redistribution and MKI modifications) is given and a first evaluation is shown.

OBSERVATIONS AND STATISTICS

In 2012/13 UFOs led to 22 premature protection beam dumps of LHC fills (in total 58 since 2010). UFOs are presumably micrometer sized dust particles that lead to beam losses with a duration of about 10 turns when they interact with the beam. Such events were observed in the whole machine and for both beams, for proton as well as for lead ion operation. From mid 2011 onwards, their impact on LHC availability was mitigated by increasing and optimizing the BLM thresholds. Figure 1a and 1b show the spatial and temporal loss profile of a typical UFO event. An introduction to the topic is given in [1, 2, 3].

Most of the UFO events lead to beam losses far below the BLM dump thresholds. These events are detected in real time by the *UFO Buster* application [1]. In 2012 more than 17'000 candidate UFO events have been detected (16'000 in 2011).

In 2012 the diagnostics for UFO events were significantly improved: additional BLMs are installed in the arc cell 19R3 [3] and the BLM Study Buffer allows the measurement of the temporal loss profile with $80\,\mu\mathrm{s}$ time resolution also for UFO events below the BLM dump thresholds [3]. Since May 2012, dedicated diamond BLMs in IR7 are used to further improve the temporal resolution for UFO events to ns time-scales [4]. Figure 1c and 1d show the temporal loss profile measured with the beam 2 diamond BLM in IR7. Figure 1d shows that the bunches contribute equally to the beam losses, as expected for a macro particle interaction.

The evolution of the arc UFO rate is shown in Fig. 2. Throughout 2011 and 2012 a clear conditioning effect is observable, which leads to a decrease of the UFO rate by about 80% per year. Over the winter technical stop 2011/12 a deconditioning was observed, resulting in a ≈ 2.5 times

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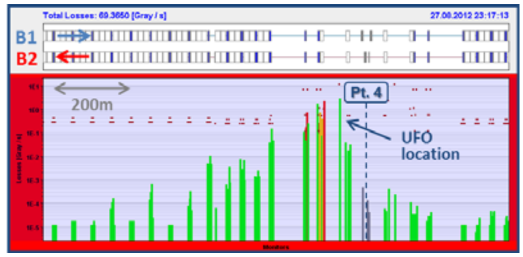
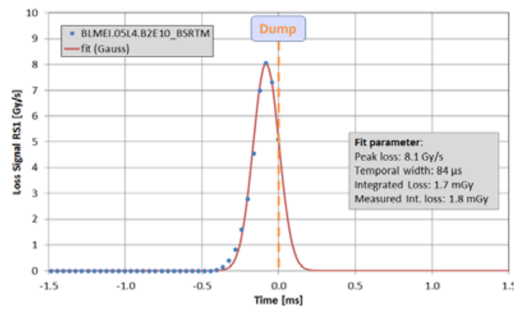
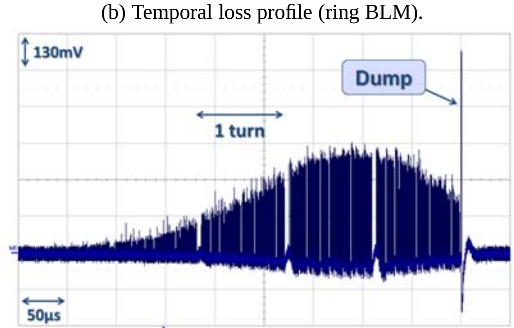


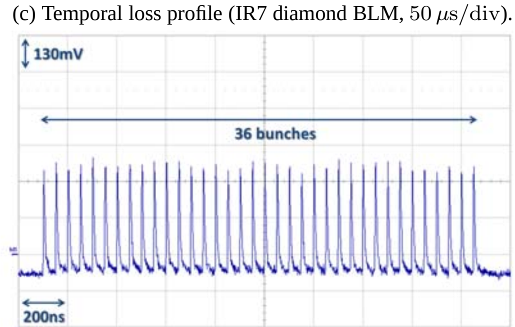
(a) Spatial loss profile (ring BLMs).



(b) Temporal loss profile (ring BLM).



(c) Temporal loss profile (IR7 diamond BLM, $50\,\mu\mathrm{s/div}$).



(d) Temporal loss profile (IR7 diamond BLM, $200\,\mathrm{ns/div}$).

Figure 1: Spatial (a) and temporal (b, c, d) loss profile of an UFO event around the beam 2 synchrotron light monitor during stable beams, measured with the ring BLMs (a, b) and the beam 2 diamond BLM in IR7 (c, d). The beam losses reach up to 219% of the BLM dump thresholds. The losses start $\approx 5\,\mathrm{turns}$ before the beam dump (b, c). All bunches contribute equally to the beam losses (d).

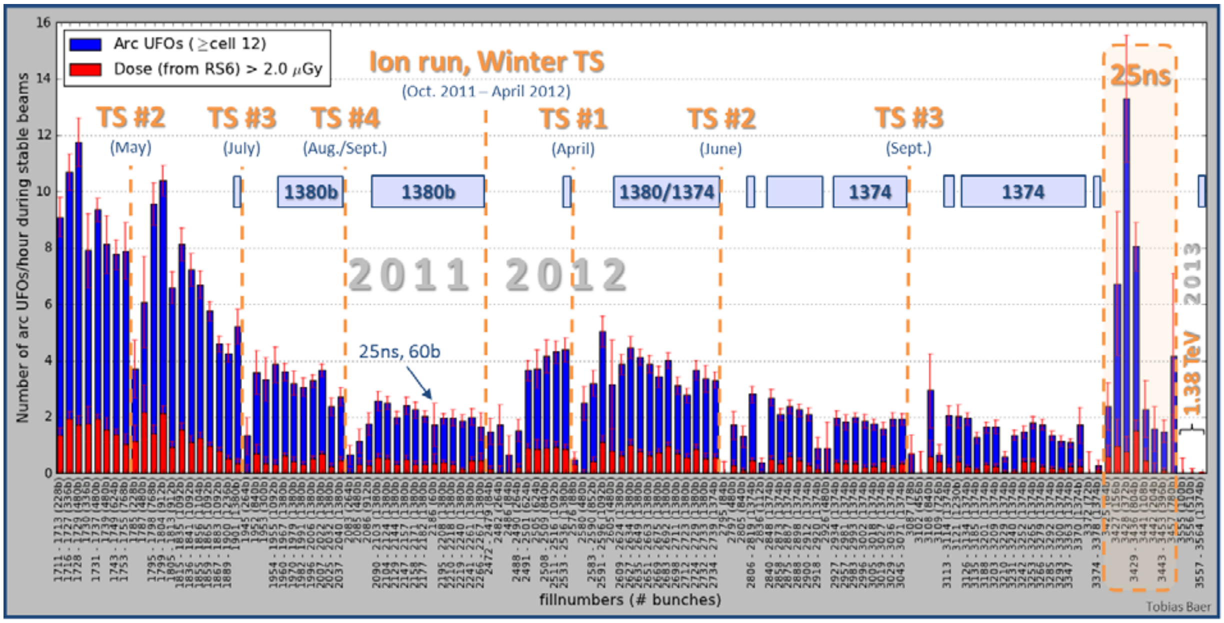


Figure 2: The arc UFO ($\geq$ cell 12) rate during stable beams. The rate is decreased in the intermediate intensity fills after the technical stops (TS). 9406 UFOs in all proton-proton fills with at least one hour of stable beams since 14.04.2011 until the end of the 2012/13 run are taken into account. Up to 5 consecutive fills with the same number of bunches are grouped. Only UFOs with a signal in $640\,\mu\mathrm{s}$ running-sum $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$ and with a signal in $320\,\mu\mathrm{s}$ running-sum / signal in $80\,\mu\mathrm{s}$ running-sum ≥ 0.45 are considered.

increased arc UFO rate in the beginning of 2012. In the fills with $25\,\mathrm{ns}$ bunch spacing, the UFO activity is significantly increased (initially by over a factor 10 [5]). During the intermediate energy run in February 2013, not a single UFO was observed in about 17.5 hours at $1.38\,\mathrm{TeV}$ with 1374 bunches.

The dependence of the UFO rate on the beam intensity could be observed during the fast intensity ramp up in 2012 without being biased by the conditioning effect (Fig. 3). In agreement with previous studies [6] the rate of detectable UFO events increases proportionally to the beam intensity for small intensities. Above a few hundred bunches the effect saturates.

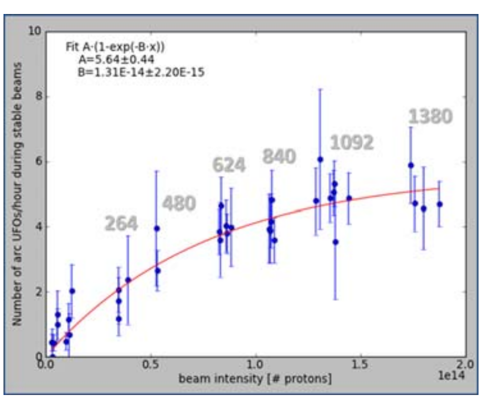


Figure 3: The arc UFO ($\geq$ cell 12) rate as a function of the beam intensity. The gray numbers indicate the number of bunches. 667 UFOs in 37 fills with at least 1 hour of stable beams during the intensity ramp up between 05.04.2012 and 10.05.2012 are taken into account. Signal in $640\,\mu\mathrm{s}$ running-sum $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$.

Based on the different running-sums of the BLM data, the temporal structure of the UFO events can be determined. Figure 4 shows the distribution of the temporal width of UFO events assuming a Gaussian loss profile. For many UFOs the temporal width is in the order of the LHC revolution period ($89\,\mu\mathrm{s}$), or even faster. It is expected that the temporal loss profile becomes even faster for operation at higher energies due to the smaller transverse emittance. This implies that some UFOs may be too fast for active quench protection by a beam dump[1].

To identify potential UFO locations, FLUKA [7, 8] simulations of (inelastic) proton-UFO interactions and the in-

[1] Up to three turns are needed until the full beam is extracted after the detection of an abnormal beam loss.

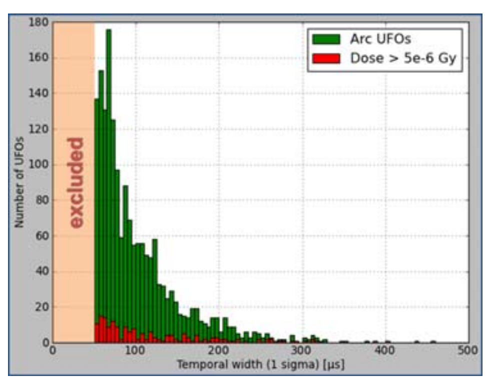


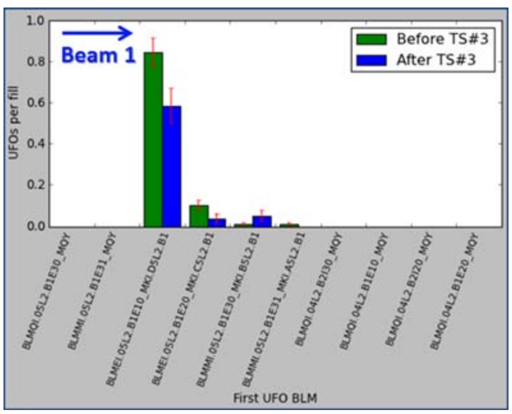
Figure 4: Distribution of temporal width from Gaussian fit of UFO events. 1753 arc UFOs ($\geq$ cell 12) at $4\,\mathrm{TeV}$ operation with 1374/1380 bunches are taken into account. UFO events with a temporal width $< 50\,\mu\mathrm{s}$ or a peak loss rate of the fit $< 1 \cdot 10^{-3}\,\mathrm{Gy/s}$ are excluded from the analysis.

duced particle showers were performed [9]. The simulations reveal that with standard quadrupole BLMs a precise loss location cannot be identified. To improve the spatial resolution, additional BLMs were installed at the three dipole magnets in cell 19R3 in early 2012. UFO events observed in cell 19R3 in 2012 indeed exhibit different loss patterns, suggesting that UFOs originate from various positions across the arc cell [10]. In particular, loss patterns suggesting UFO locations close to the magnet interconnections have been observed as well as loss patterns suggesting UFO locations inside dipole magnets [11].

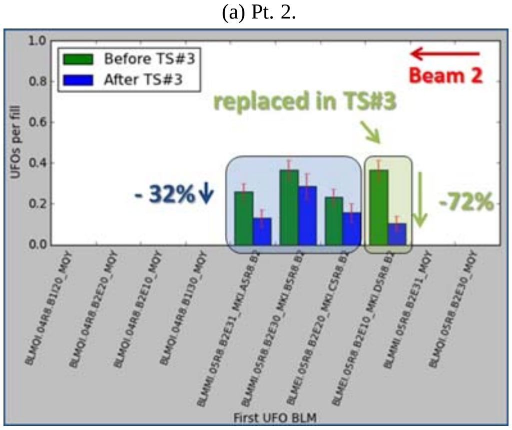
MKI UFOS

Four injection kicker magnets (MKIs) are installed in each injection region (Pt. 2 for injection of beam 1, Pt. 8 for injection of beam 2). The MKIs in Pt. 2 and Pt. 8 are labeled MKI.A - MKI.D with MKI.D being the magnet seen first by the injected beam.

With 21 beam dumps since 2010 (8 in 2012), the UFOs at the MKIs had the largest impact on LHC operation. 16 of these events occurred at top energy, but only 5 during stable beams. 17 events occurred at the MKI.D in Pt. 2.



(a) Pt. 2.



(b) Pt. 8.

Figure 5: Distribution of UFOs among the individual MKI magnets in Pt. 2 (a) and Pt. 8 (b) before and after TS#3 in 2012. The BLMs at the MKIs indicate in which magnet an UFO occurs. 145/52 UFOs (a) and 194/52 UFOs (b) in 159/77 fills with stable beams and at least 1000 bunches before/after TS#3 are taken into account. Signal in $640\,\mu\mathrm{s}$ running-sum $> 5 \cdot 10^{-4}\,\mathrm{Gy/s}$.

After a comprehensive study program in 2011 the MKI UFOs have been identified as macro particles originating from the ceramic tube inside the MKI magnets [12]. In the technical stop in September 2012 (TS#3), the MKI.D in Pt. 8 was replaced by an improved version, which includes UFO-mitigation measures[2].

Figure 5 shows the distribution of UFOs among the different MKIs in Pt. 2 and Pt. 8 before and after TS#3. Whereas in Pt. 2, the UFO activity in MKI.D is dominant, the distribution is more equal among the four MKIs in Pt. 8. Notably, before TS#3, MKI.D had the highest UFO activity of the MKIs in Pt. 8; after the replacement MKI.D has the lowest UFO activity. The number of UFOs per fill at MKI.D is reduced by $(72 \pm 11)\%$ compared to an average reduction (due to the general conditioning effect) of $(32 \pm 12)\%$ at the other MKIs. This shows that the modifications of MKI.D in Pt. 8 indeed significantly mitigated the UFO activity.

MID-TERM EXTRAPOLATION

As shown in Fig. 3 there is no significant increase of the UFO activity expected for operation with design intensity.

As shown in Fig. 2 the UFO rate is significantly increased with $25\,\mathrm{ns}$ operation (initially over a factor 10 [5]). Nevertheless, with higher UFO activity, also a faster conditioning effect is expected [5].

The beam losses due to UFOs are expected to increase with beam energy. Figure 6 shows the peak energy density per inelastic proton-UFO interaction (at the interconnection between two arc dipole magnets) in the downstream dipole magnets. The highest energy density is caused by the neutral collision products of the proton-UFO interac-

[2]In particular, an improved cleaning procedure was applied and the electrical field during most of the MKI pulse is reduced by four additional screen conductors.

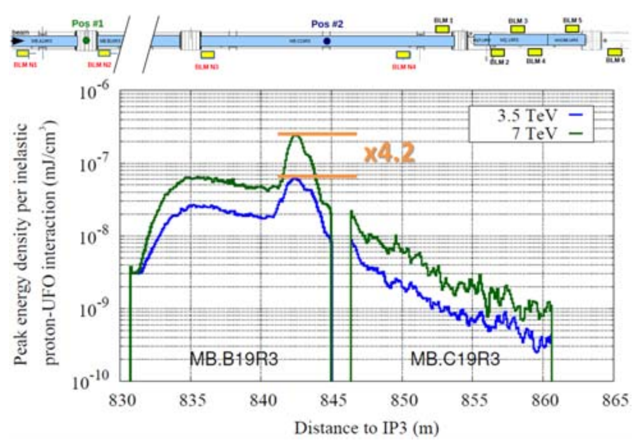


Figure 6: Peak energy density per (inelastic) proton-UFO interaction at *Pos #1* (dipole-dipole interconnect) in the downstream dipole magnets simulated with FLUKA (courtesy of A. Lechner and the FLUKA team [9]).

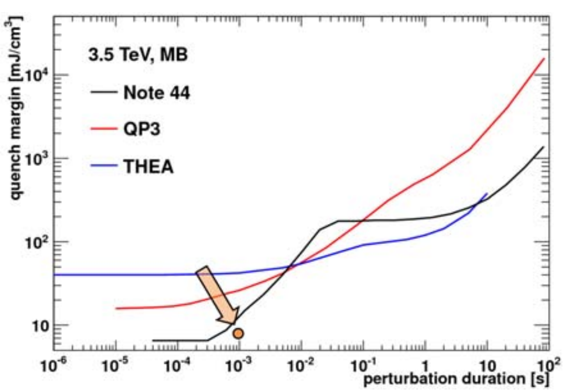
tions, which impact the magnet $\approx 11\,\mathrm{m}$ downstream of the UFO location due to the geometrical bending of the magnet [9]. Fig. 6 shows that the peak energy density per inelastic proton-UFO interaction is about a factor 4.2 higher for $7\,\mathrm{TeV}$ operation compared to $3.5\,\mathrm{TeV}$ operation[3].

Based on the FLUKA simulations [9], about $1.3 \cdot 10^8$ inelastic proton-UFO interactions are needed to explain the observed beam losses for the largest arc UFO which was observed in 2012[4]. An UFO event at *Pos #1* with the same number of inelastic proton-UFO interactions would according to Fig. 6 imply a peak energy density in the dipole magnet of $\approx 7.8\,\frac{\mathrm{mJ}}{\mathrm{cm}^3}$ for $3.5\,\mathrm{TeV}$ operation and $\approx 32.5\,\frac{\mathrm{mJ}}{\mathrm{cm}^3}$ for $7\,\mathrm{TeV}$ operation.

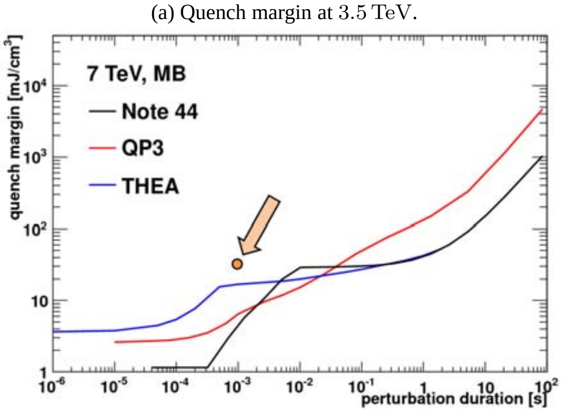
These values are compared in Fig. 7 to the expected quench margin for the LHC arc dipole magnets. For $3.5\,\mathrm{TeV}$ operation, the beam losses are at about 30% of the QP3 quench margin, for $7\,\mathrm{TeV}$ about a factor 5 above the QP3 quench margin.

[3]The scaling is geometry dependent. A scaling of a factor 3 was found from wire scanner measurements at different energies [6] and FLUKA simulations for MKI UFOs [13].

[4]The event occurred on 05.10.2012 at 06:19:41. Beam losses of $0.67\,\mathrm{mGy}$ were measured at *BLM 2* (cp. Fig. 6). It is assumed that the UFO occurred at *Pos #2*, i.e. close to the quadrupole magnet. The FLUKA simulations for $3.5\,\mathrm{TeV}$ are used for the analysis.



(a) Quench margin at $3.5\,\mathrm{TeV}$.



(b) Quench margin at $7\,\mathrm{TeV}$.

Figure 7: The estimated quench margin of the LHC main dipole magnets as function of the beam loss duration from LHC Project Note 44 [14], the QP3 model and the THEA model [15] for operation at $3.5\,\mathrm{TeV}$ (a) and $7\,\mathrm{TeV}$ (b). The orange point indicates the estimated peak energy density in the magnet for $1.3 \cdot 10^8$ inelastic nuclear proton-UFO interactions at *Pos #1* (cp. Fig. 6).

The expected scaling of BLM signal/BLM threshold for UFO events is shown in Figure 8. Applying the scaling to the BLM signals and thresholds of all 2012 arc UFOs, they would have caused 91 beam dumps, if the LHC would have been operated at $7\,\mathrm{TeV}$ instead of $4\,\mathrm{TeV}$ (112 beam dumps from 2011 arc UFOs). An additional 21 beam dumps would have been caused by MKI UFOs (27 beam dumps from 2011 MKI UFOs)[5]. These numbers have to be compared to one actual dumps by arc UFOs and 8 dumps by MKI UFOs in 2012 (2011: 2 dumps by arc UFOs, 11 dumps by MKI UFOs).

In February 2013, a dedicated magnet quench test with beam losses on UFO-timescales was performed. The initial analysis indicates that the quench level is significantly above the expected level, which would allow for large-scale increases of the arc BLM thresholds and significantly mitigate the extrapolation shown in Fig. 8 [5]. A detailed analysis of the quench test is ongoing.

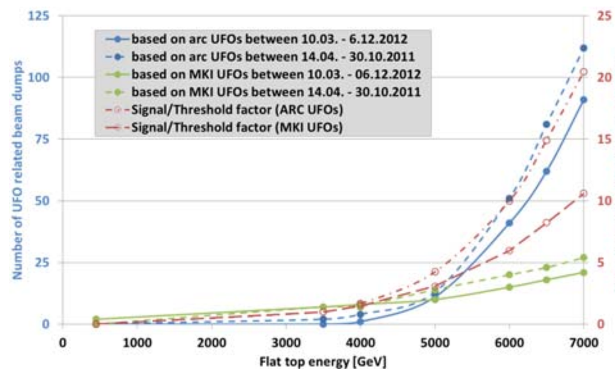


Figure 8: The expected number of beam dumps by arc and MKI UFOs and the expected scaling of BLM signal/BLM threshold as function of the beam energy (based on [6, 9, 13]).

MITIGATION AND OUTLOOK

The energy dependence indicates that UFOs could be a major performance limitation for LHC operation after the long shutdown in 2013/14 (LS1).

Concerning the MKIs, the source of the UFOs is identified and many mitigation measures are in preparation for after LS1:

- All MKI magnets will be equipped with 24 screen conductors. This reduces the electric field during the majority of the MKI pulse. The electric field is thought to be responsible for causing the detachment of macro particles from the ceramic tube [12].

[5]The extrapolation assumes (apart from the beam energy) identical running conditions as in 2011/12. Excluded are potential increases of the BLM thresholds, the conditioning effect, the increased UFO rate at $25\,\mathrm{ns}$ operation and changes in beam intensity and beam size. Concerning the MKI UFOs, only the BLM thresholds at the superconducting elements are assumed to be limiting.

- An improved cleaning procedure will be applied to all MKIs. This is expected to reduce the initial macro particle contamination by a factor 5-7 [12].
- The MKI interconnect, bypass-tubes and close-by equipment will be NEG coated. This mitigates electron-cloud and improves the vacuum in the MKIs. Electron-cloud and high vacuum pressure were observed to enhance the UFO activity.
- A coating of the ceramic tube, possibly with carbon or Cr_2O_3, is under investigation. This would reduce electron-cloud activity and the risk of surface flash-overs in the MKIs and could seal the surface of the ceramic tube.

In particular the successful reduction of the UFO activity with the replacement of the MKI.D in Pt. 8 demonstrates the effectiveness of the mitigation measures.

The main mitigation strategy for arc UFOs is to increase the BLM thresholds towards the magnet quench limit and to profit from the conditioning effect.

Nevertheless, the arc FLUKA simulations and the additional instrumentation in cell 19R3 show that the current BLM distribution (six BLMs per half-cell, all at the quadrupole) is highly inefficient for protection against beam losses due to UFOs at the dipole magnets [16]. Furthermore, the current BLM distribution implies an over-redundancy for protection against beam losses at the quadrupole magnet. Thus, a systematic relocation of the arc BLMs is proposed: Two BLMs of each half-cell will be moved from the quadrupole and be positioned vertically above the dipole-dipole interconnects as illustrated in Fig. 9.

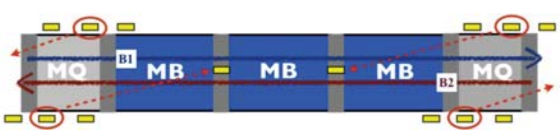


Figure 9: Proposed relocation of BLMs during LS1, seen from the top (courtesy of E. Nebot del Busto [16]).

Moreover, during LS1, several magnets will be replaced, which allows an endoscopic inspection of three locations with particularly high UFO activity (16L3.B2, 25R3.B2, 28R7.B2).

CONCLUSION

Since 2010 in total 54 LHC fills were terminated above injection energy due to UFOs. Thus, between 2011 and 2013 intensive studies were made, which include improvements of the diagnostics, dedicated experiments in the LHC (including a magnet quench test) and in the laboratory, FLUKA and MadX simulations and theoretical studies. As a result, fundamental correlations were found, the macro particle dynamics are characterized, the response of the BLM system is understood and the source of the UFO events at the MKIs has been identified. This allows for mid-term extrapolations.

In particular the energy and bunch-spacing dependence imply that UFOs could be a major performance limitation for LHC operation after LS1. Thus, various mitigation measures for MKI UFOs are ongoing and a large-scale relocation of the arc BLMs during LS1 is proposed to allow a better protection against arc UFO events.

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