BLM THRESHOLDS AND UFOS

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Abstract

In 2016, the thresholds of more than half of the LHC Beam Loss Monitors connected to the Beam Interlock System were changed throughout the year. Many of the changes were in one or another way related to losses induced by micron scale dust particles often referred to as Unidentified Falling Objects (UFOs). This paper summarizes the UFO trends, the number of UFO-induced dumps and quenches in 2015 and 2016, and shows how dumps were distributed between arcs and straight sections. The impact of 2016 threshold changes on the number of dumps in the arcs is analyzed and it is estimated how many dumps and quenches would have occurred if other threshold strategies would have been adopted. The paper concludes with a brief summary of non-UFO-related threshold changes and an outlook for 2017.

INTRODUCTION

Presently there are more than 3500 Beam Loss Monitors (BLMs) connected to the LHC Beam Interlock System (BIS). In 2016, the beam abort thresholds of more than 2000 BLMs were adjusted for the proton run (6.5 TeV), and of about 50 BLMs for the heavy ion run (4 ZTeV and 6.5 ZTeV). The thresholds applied in the machine are the product of master thresholds and a monitor factor. The master thresholds are a function of beam energy and BLM integration time, and they are identical for all BLMs in a family (a family groups BLMs at equivalent positions). The monitor factor is constant, but can vary for different family members. The majority of all threshold changes carried out in 2016 ($\sim$83%) involved a concurrent modification of the master thresholds and the monitor factor, while in 6% of the cases only the master thresholds were changed, and in the reminder only the monitor factor was changed. All master threshold changes were empirical corrections based on operational experience gained in 2015 and 2016. The corrections were applied on top of the models which had been established before Run 1 (collimators and Roman Pots) or in Long Shutdown 1 (magnets) [1, 2, 3].

Figure 1 provides an overview of the threshold changes carried out for the 2016 proton run. Multiple threshold changes affecting the same BLM are counted separately if thresholds were active for at least one week of operation. The total number of changes was more than a factor of two less than in the previous year, when about 5700 threshold modifications had been carried out [4]. A large fraction of the changes in 2016 involved a threshold increase, with the main goal to avoid unnecessary UFO-induced dumps while tolerating some quenches. This strategy, which has been proposed in [5, 6], had a positive impact on machine availability, although it had to be partially revoked because of different reasons, for example to reduce the risk of symmetric quenches in independently power quadrupoles (IPQs) in the dispersion suppressors, and to reduce the probability of a fast power abort in Sector 12 (suspected inter-turn short in a dipole). Threshold adjustments were also necessary because of new collimator settings, higher luminosities and longitudinal losses during injections.

This paper summarizes the changes in 2016 and analyses their impact on machine availability. The main focus is given to UFO-induced losses, which were the primary cause of premature BLM dumps, and the only cause of beam-induced quenches at top energy in regular operation. The two next sections are dedicated to UFO losses in the arcs/dispersion suppressors and insertion regions, followed by a brief discussion of non-UFO-related threshold changes, including changes for the proton-Pb ion Run at

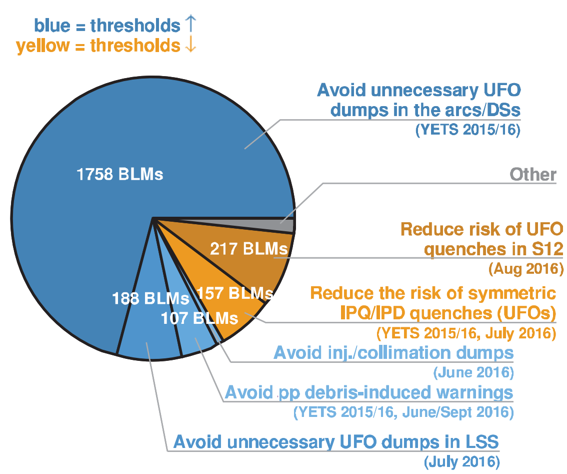

Figure 1: BLM threshold changes for the 2016 proton Run carried out in the Year-End Technical Stop (YETS) 2015/16 and during 2016 operation. Changes involving a threshold increase are indicated in blue, while changes involving a decrease are shown in yellow. Modifications carried out in the YETS 2015/16 are only counted if they resulted in thresholds which were different from the ones active at the end of 2015 proton Run. This excludes for example the reversal of thresholds which had been modified for the 2015 Pb Run.

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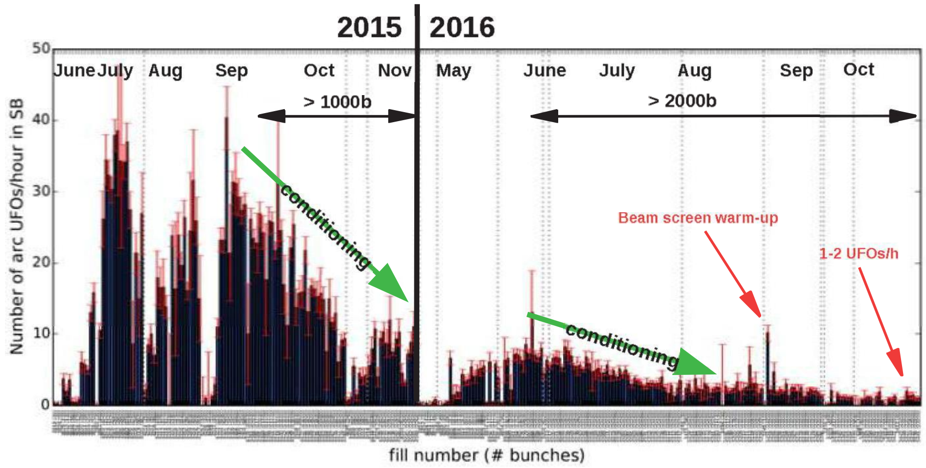

Figure 2: Number of arc UFO events (cells ≥12) per hour of stable beams in 2015 and 2016. The events were recorded with the UFO Buster application [8]. Each bar represents a different proton fill. The algorithm for counting UFO events was the same in both years. The green arrows indicate periods when the UFO rate exhibited a decreasing trend over many weeks of operation. The periods when the number of bunches exceeded 1000 (2015) and 2000 (2016) are indicated in the upper part of the figure.

end of 2016. The paper concludes with a brief outlook for 2017.

UFO-INDUCED LOSSES IN THE ARCS AND DISPERSION SUPPRESSORS

In Long Shutdown 1 (LS1, 2013–2014), more than 700 BLMs were relocated from MQs to MB-MB interconnects to improve the detection of UFO-induced losses in MBs [1, 2, 3]. The relocation significantly reduced the variation of the BLM response versus loss position, which is fundamental for setting BLM thresholds without limiting availability. Despite the much better spatial BLM coverage in Run 2, unnecessary dumps can still not be fully avoided if a quench-preventing BLM threshold strategy is deployed. This can mainly be attributed to the remaining variation of the BLM response depending on the UFO position inside MBs. If losses occur at the upstream end of a MB, the signal per proton lost in the closest downstream BLM is a factor of 3-4 lower than if losses occur towards the end of the MB, whereas the shower-induced energy density in coils remains approximately the same [3]. If the BLM thresholds are set to prevent UFO-induced quenches for less sensitive loss locations, one can therefore not avoid unnecessary dumps by UFOs which are closer to BLMs.

Change of threshold strategy from 2015 to 2016

In 2015, UFOs gave rise to 3 quenches and 12 BLM dumps without quench in the arcs and dispersion suppressors (all at 6.5 TeV, not counting the dumps and quenches caused by the obstacle in cell 15R8). An analysis of the dumps showed that only in one case a quench was possibly prevented [5, 6]. In most of the other cases the losses were not even cut short since it takes 1-3 turns until beams are extracted once the thresholds have been exceeded [5, 6]. At the same time, thresholds would have needed to be a factor of 2-3 lower in order to avoid the quenches, which would have meant many more unnecessary dumps [5, 6]. The overall impact on availability would have been much worse than the gain due to the prevented quenches. Based on the experience in 2015, a different threshold strategy was adopted in 2016, with the goal to avoid unnecessary dumps while tolerating some quenches [5, 6]. For this purpose, the thresholds at MBs and MQs were increased in the Year-End Technical Stop (YETS) 2015/2016 to be three times higher than in 2015 [7].

UFO trends, dumps and quenches in 2016

The new threshold strategy had a positive impact on availability in 2016. While the number of quenches remained small (3, like in 2015), the number of dumps in the arcs and dispersion suppressors could be kept to a minimum (4 dumps, three of them being in Sector 12 where thresholds had been decreased by a factor of 10 in August 2016 as a temporary measure to reduce the risk of quenches in view of a suspected inter-turn short in MB.A31L2, see next section). An important factor contributing to the improved availability in 2016 was a strong decline of the UFO event rate in the arcs at the end of 2015, which also continued throughout the first months in 2016. Figure 2 illustrates the evolution of the cumulative event rate for all arc cells ≥12 recorded by the UFO Buster application [8]. Unlike in Run 1, the UFO rate did not increase after the YETS and eventually levelled off at 1–2 events/hour at the end of the 2016 proton run. A declining trend has also been observed in 2011 and 2012, however an absolute comparison with Run 1 event rates (see Fig. 1 in Ref. [2]) is not possible because of the BLM relocation in LS1.

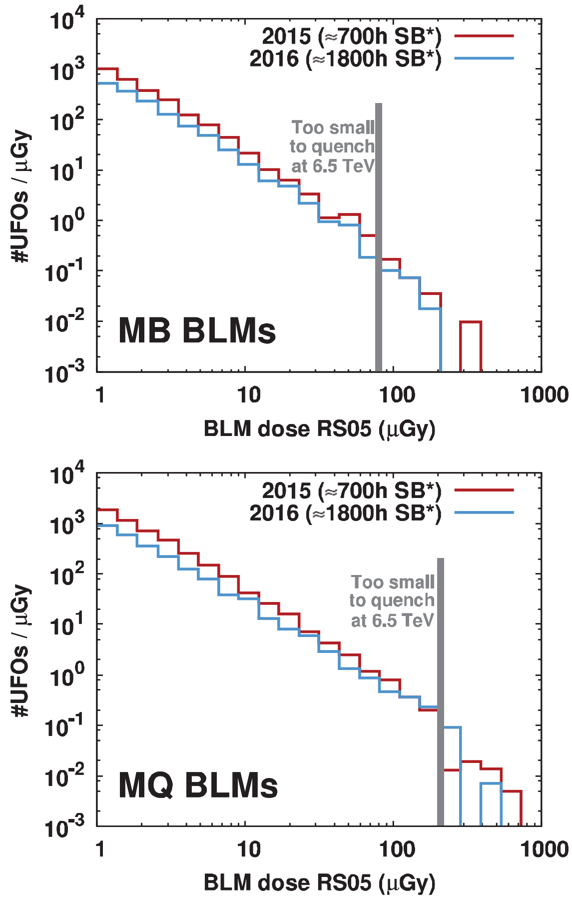

Figure 3: Number of arc UFO events (cells ≥12) at 6.5 TeV in 2015 (red) and 2016 (blue), as a function of the BLM dose (top: BLMs on top of MB-MB interconnects, bottom: BLMs located at the upstream end of MQs). The events were recorded with the UFO Buster application [8]. For each event, only the BLM with the maximum signal was considered, i.e. either a MB or a MQ BLM. All dose values are integrated over the whole loss duration. The events left of the solid vertical line are too small to induce a quench at 6.5 TeV, as inferred from events in 2015 and 2016.

The much lower rates in 2016 were a key factor that the number of quenches did not increase compared to 2015 despite many more hours accumulated in stable beams (about 700h in 2015 and 1800h in 2016, including intensity ramp-up and high-β^* run). The total number of arc UFO events in cells ≥12, which produced a time-integrated BLM dose of at least 1 μGy, was about a factor two lower in 2016 than in 2015. Figure 3 shows the differential distribution of UFOs as a function of the dose measured in MB and MQ BLMs. BLMs on MBs and MQs exhibit a different response to UFO-induced losses because of their different position. The BLM dose does not unambiguously reflect the number of inelastic proton-UFO collisions because of the aforementioned variation of the BLM response with the UFO position, however it still provides a rough idea of the severity of events. Based on different events in 2015 and 2016, one can establish the critical BLM dose below which a UFO does not have the potential to induce a quench at 6.5 TeV even if it were at the least sensitive location with respect to the BLM. The critical dose is indicated as a vertical line in Fig. 3 (strictly speaking, the ability of a UFO to cause a quench depends also on the duration of the event; here we consider the most limiting cases). As can be seen in the plots, the occurrence of events with high signals follows the general trend, i.e. large events become less frequent if the overall UFO rate decreases. Considering that only a relatively small number of events had the potential to induce a quench and that the occurrence of such events was subject to large statistical fluctuations, it was a coincidence that the number of quenches was exactly the same in 2015 and 2016.

BLM threshold reduction in Sector 12

Following the observation of a sudden voltage change in a dipole (MB.A31L2 in Sector 12) during two QPS trips in June and August 2016, it was suspected that an inter-turn short might be present in the magnet [9]. In presence of such a short, it cannot be excluded that the magnet suffers damage if it quenches or if there is a fast power abort in the sector at high current [9]. In order to reduce the probability of UFO-induced quenches and hence the risk of a fast power abort, the BLM thresholds were decreased by a factor of 10 in the entire sector in August 2016 (i.e. the thresholds were a factor of 3.33 lower than in 2015) [10]. The effectiveness of such a reduction in preventing quenches is discussed in the following, at the example of previous quenches at 6.5 TeV.

Figure 4 shows the time profiles of BLM signals measured during UFO events which lead to a magnet quench in 2015 and 2016. In all cases, the BLM with the highest signal amplitude is displayed. Most of the time profiles are asymmetric, with loss durations between 80 and 440 μsec (full width at half maximum). In two of the three events in 2015, BLMs triggered a beam dump and likely shortened the loss duration. The point in time when the signals exceeded the thresholds are indicated as vertical red lines. The losses were still increasing for 1.5-2 turns once thresholds had been surpassed and hence the quenches could still develop, as already pointed out in a previous analysis [5].

The factor by which thresholds would have needed to be lower in order to prevent the quenches differs slightly from event to event. The black vertical lines in Fig. 4 illustrate the point in time when BLMs would have triggered the dump if thresholds would have been the same as in Sector 12 after the reduction in August 2016. These settings would have likely prevented the quenches in four out of the six cases. In one case (first quench in 2016) it is doubtful if the quench would have been avoided since the trigger would have come only 1.5 turns before the loss peak. In the last case (third quench in 2016) the loss event was very fast and it cannot be established with certainty if the quench

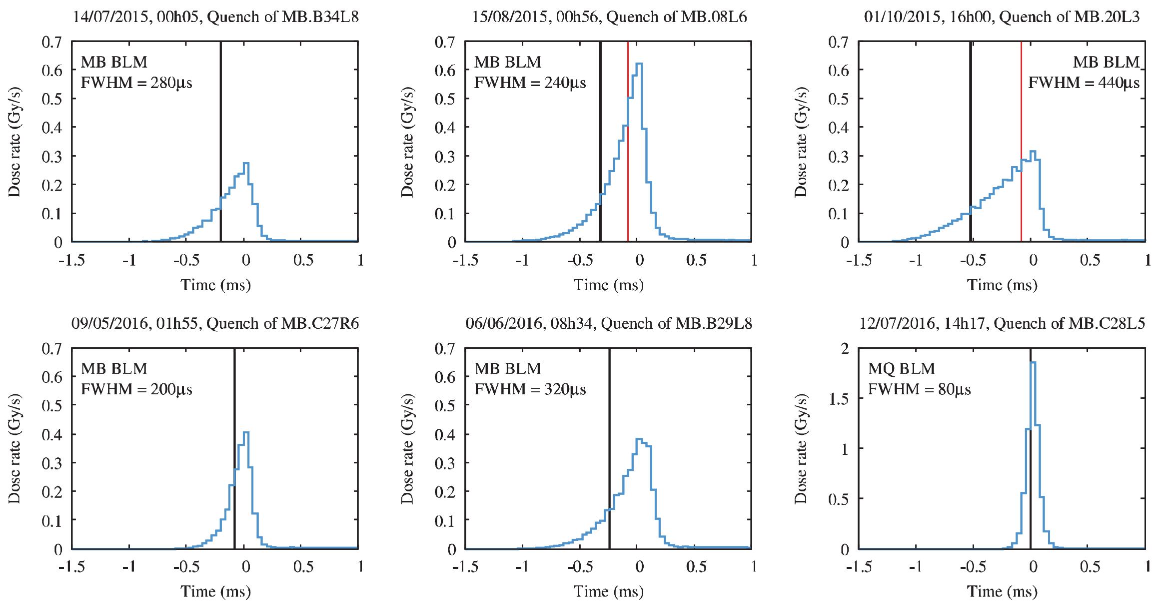

Figure 4: Time profile of BLM signals measured during UFO events which lead to a magnet quench at 6.5 TeV in 2015 (top) and 2016 (bottom). In each case, the BLM with the highest signal is shown, which was in five cases a BLM above the MB-MB interconnect and in one case a MQ BLM. The red vertical lines indicate the points in time when BLM thresholds were exceeded (in two cases only), whereas the black line indicates the time when thresholds would have been exceeded if they would have been the same as in Sector 12 from August 2016.

could have been avoided at all with the BLM system. This shows that, even with strongly reduced thresholds, a risk remains that UFOs induce a quench.

The impact of the reduced thresholds in Sector 12 on availability was small since only one sector was affected. If a quench-preventing strategy like in Sector 12 would have been employed in all sectors for the full operational year, UFOs would have been a dominating factor for machine availability. An analysis of the events at 6.5 TeV in 2016 indicates that a dump would have occurred on average every 17 h of stable beams. In total, more than 40% of the physics fills in 2016 (71 out of 173) would have been affected if multiple occurrences per fill are only counted once. At the same time, the analysis in the previous paragraph showed that 1-2 of the quenches would have likely not been avoided with these threshold settings. This clearly confirms previous assessments [5, 6] that it is by far more beneficial for availability to avoid unnecessary dumps than to prevent quenches. It is therefore foreseen to retain the present threshold strategy (factor 3 above quench level) also in the following years if there is no necessity to reduce the risk of quenches like in Sector 12.

BLM threshold reduction at Q10 magnets

In addition to Sector 12, an adjustment of thresholds was also necessary for Q10 magnets of MQM-type. Like for other IPQs, the detection of quenches in Q10s relies on the differential voltage between two coils in the same cold mass and aperture, i.e. a quench can only be detected if there is an asymmetry in the particle shower-induced energy deposition in the coils [11]. In order to enhance the quench detection level, it was recommended to decrease the QPS thresholds at MQM magnets operated at 1.9 K [11]. Because of relatively high noise levels on the Q10 quench detection cabling, a reduction of Q10 QPS thresholds was however not favourable as this could have lead to a significantly increased number of false trips [11]. As an alternative mitigation measure, the BLM threshold increase introduced in the YETS 2015/2016 was revoked at Q10s (and monitor factors were decreased) to reduce the probability of UFO-induced quenches [12]. The lower thresholds did not give rise to any premature dumps in 2016.

UFO-INDUCED LOSSES IN THE LONG STRAIGHT SECTIONS

In contrast to the arcs and dispersion suppressors, the number of UFO-induced dumps in the Long Straight Sections (LSS) doubled from 7 in 2015 to 14 in 2016. The UFOs typically occurred several tens of meters upstream of the monitors which triggered the dump. UFO events are often visible at collimators (TCLs and TCTs) and Roman Pots as these devices represent a local aperture bottleneck and therefore intercept secondary particles from inelastic proton-UFO collisions. About one third of the dumps in 2016 (5 out of 14) were due to UFOs in a single cell (5L1). Another third (5 dumps) was triggered by the Beam Condition Monitors (BCMs) of the experiments, compared to only one BCM dump in 2015. More details about these dumps are presented in the following sections. It is not trivial to establish a trend chart of UFO event rates as in Fig. 3 for the Long Straight Sections. Contrary to the arcs, one cannot rely on the periodicity of cells (and BLMs) to collect sufficient statistics. In addition, UFO-induced losses need to be detected on top of a steady-state background (collimation losses, collision debris), which can lead to ambiguous or false triggers in the UFO Buster application. It can therefore not be determined if a similar decline of the event rates took place as in the arcs.

Dumps due to UFOs in cell 5L1

The spatial BLM patterns measured during five UFO-induced dumps in IR1 showed similar (although not fully identical) features, indicating that the UFOs must have been located in similar locations in cell 5L1 (losses were on Beam 2). The dumps were triggered by BLMs at the Q5.L1/Q6.L1 magnets and/or the TCL.6L1, and happened during different beam modes (adjust, squeeze and stable beams). In two cases, the dumps occurred during the movement of the TCL.5L1 jaws. It seems likely that in these two events the loss location was in or around the collimator (high BLM signal at the TCL.5L1), while in the other cases the UFOs appeared to be somewhat more downstream (in or around the Q5). Several of the events exhibited multiple loss spikes separated by tens or hundreds of msec. Each spike had a typical UFO-like time structure and duration. Some of the dumps were only triggered by thresholds in longer BLM integration times because of the dose accumulated over several spikes.

The number of dumps in cells 5L1/6L1 could be successfully mitigated in the second half of the year by increasing the BLM thresholds at insertion region quadrupoles to the quench level, and by applying threshold corrections for the TCLs [13]. The thresholds at quadrupoles up to the Q6 had originally been kept at more conservative settings to enable further investigations about the protection level in case of symmetric quenches. In July it was concluded that BLM thresholds could be raised [11]. After the threshold increase at quadrupoles and TCLs, only one dump occurred in cell 5L1 over a period of 3 months. As an additional measure, thresholds were also increased at TCTs and TOTEM Roman Pots since a few UFO dumps had previously been triggered at these devices [13].

UFO-induced dumps by BCMs

In 2016, UFOs gave rise to dumps in all four experiments, once in ATLAS, ALICE and CMS, and twice in LHCb. The spatial BLM patterns suggest that in all cases the UFOs were either in the triplet or in the D1, i.e. several tens of meters upstream of the Interaction Points (IPs). In two of the events (ALICE and CMS), the signal-to-threshold ratio at triplet BLMs reached more than 60%, while it remained below 10% in the three other cases. Although the latter UFOs were rather small, they were still well visible up to the matching section on the other side of the IP. A more detailed assessment is needed to determine if premature dumps by the BCMs can be avoided in the future.

BLM THRESHOLD CHANGES NOT RELATED TO UFOS

Adjustments for luminosity, collimation and injection losses in 2016

Because of the new record luminosities achieved in ATLAS and CMS, thresholds at triplet quadrupoles, TCLs and TCTs had to be increased to avoid premature dumps due to the hadronic collision debris [7, 14]. The thresholds were adjusted such that debris-induced signals remained below warning level (i.e. below 30% of the thresholds). This policy was adopted to avoid too many messages in the BLM application which could hide other warnings.

The BLM thresholds had been tuned in 2015 to trigger a dump if the power loss in the collimation system exceeds 40 kW in steady-state conditions, and or if it exceeds 200 kW for shorter durations up to 10 sec. Because of tighter collimator gaps in 2016, the BLM response per proton lost increased at different collimators (up to a factor of 6 at the TCTs) and thresholds had to be adjusted to re-establish the same policy as in 2015 [14].

When changing to BCMS beams in July 2016, high injection losses close or above the BLM dump thresholds were observed at the TDIs because of satellites kicked on the TDI jaws. The BLM thresholds at the TDI were already at the electronic maximum and could therefore not be raised further. The issue could be mitigated by extending the injection cleaning to the rising MKI pulse edge and, in addition, by exchanging the filter at the most limiting BLM at the TDI in IR2 with a larger one [15], which attenuated the signal in short integration times.

Adjustments for the heavy ion run 2016

In 2015, a machine development study with 6.37 ZTeV Pb ions was carried out to assess the performance limitation of the collimation system due to fragments leaking to the neighouring dispersion suppressor [16]. The losses in IR7 were deliberately increased until a dipole quench was provoked in cell 9 [16]. The BLM measurements in the test showed that the signals at cold magnets at the onset of the quench were higher than the BLM thresholds used in regular heavy ion operation (during the test, the thresholds had been increased) [17]. Based on this observation, the thresholds in cell 9 and 11 were modified for the heavy ion run in 2016 to avoid premature dumps well below the quench level [17]. The corrections were only adopted at 6.5 ZTeV (increase of up to a factor of 5.4), while scaling to 4 ZTeV indicated only minor bottlenecks and hence no adjustments were made for the 4 ZTeV run [17].

Complementing the increase in the dispersion suppressors, thresholds were decreased at selected collimators in IR7. The cleaning inefficiency is about a factor of hundred worse for Pb ions than for protons and therefore the signal-to-threshold ratio would be more than ten times lower at IR7 collimators than at dispersion suppressor magnets if proton thresholds are kept for Pb ions [17]. In order to avoid that, in case of beam instabilities, dumps would be triggered first at cold magnets, the thresholds at two secondary collimators were decreased by a factor of 20 and 29, respectively, such that the signal-to-threshold ratio was higher than in the dispersion suppressor [17]. The modified dumping hierarchy worked as intended. In several cases of transverse instabilities, dumps were triggered at secondary collimators, which would have otherwise been triggered at dispersion suppressor magnets.

SUMMARY AND OUTLOOK FOR 2017

In 2016, UFOs were as expected the main cause of premature BLM dumps, and the only cause of beam-induced quenches at top energy. While the number of dumps in the arcs and dispersion suppressors was significantly less than in 2015 thanks to a new threshold strategy, more dumps were observed in the long straight sections. By applying several threshold adjustments at TCLs, TCTs, Roman Pots and IPQs, the impact of UFOs in the straight sections could however be mitigated in the second half of the year. It is to be determined if similar adjustments are possible for the BCMs of the experiments, which accounted for one fourth of all UFO dumps in 2016. In general, the impact of UFOs on availability improved with respect to 2015, considering that the number of quenches did not increase (3 in both years) and the total number of dumps decreased from 19 to 18, despite many more hours accumulated in stable beams.

The main reason that only 3 quenches occurred in 2016 was a significant decline in the UFO event rate in the arcs at the end of 2015 and throughout 2016. In particular, the activities carried out in the YETS 2015/16 had no detrimental effect on the UFO rate. It can however not be excluded that some degradation takes place in the EYETS 2016/2017 as the event rate at the end of 2016 was considerably lower than at the end of 2015. In addition, some deconditioning can be expected for Sector 12 because of the warm-up needed for the dipole exchange in cell 31L2. However, even with a higher UFO rate in Sector 12, UFOs are not expected to be a major limitation for availability in 2017, although some quenches might be unavoidable since thresholds in Sector 12 will be reverted to their initial 2016 settings.

Only minor threshold changes are foreseen to be carried out for the start-up in 2017. They include a revision of old threshold models for dipole monitors in the dispersion suppressors, and a modification of master tables for redundant monitors at IPQs which are presently set to the electronic limit. As in the previous years, several adjustments are expected to be carried out throughout operation.

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