

SPECIAL LOSSES DURING LHC RUN 2

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Abstract

A comprehensive review of special beam loss scenarios during Run 2 is presented, with main focus on studies and actions taken to mitigate their impact on LHC operations. An overview of Beam Loss Monitor (BLM) threshold strategy aimed at reducing the machine downtime caused by the interaction of the beam with Unidentified Falling Object (UFO) is given. The UFO rate evolution during Run 2 is also provided, together with an estimate of UFO rate at the beginning of Run 3. An unexpected aperture restriction was detected in the half-cell 15R8 in 2015: the so called Unidentified Lying Object (ULO). Local aperture measurements, ULO evolution during Run 2, mitigation strategy adopted, and results of the inspections performed during the Long Shutdown 2 (LS2) are described. Sudden increase of losses in the half-cell 16L2 has been the main machine limitation in 2017. The mitigation strategy, lessons learnt, and actions taken to avoid repetition of what was identified as most probable cause are discussed. Several dumps with similar signature of oscillating orbit with 10 Hz frequency were experienced in the last months of the 2018 run. The present understanding of these events, possible actions, and mitigation approach to be taken in future runs are reported.

UNIDENTIFIED FALLING OBJECT

Dust particles falling into the beam, have been one of the main machine limitations in Run 1 and first two years of Run 2: the so called Unidentified Falling Object (UFO). Inelastic interactions between the circulating protons and UFOs generates highly-energetic hadronic showers, leading to an energy deposition in magnet coils that is possibly sufficient to induce a quench. The timescale of these events is of few turns, thus they can be classified as very fast failures that cannot be cured by the collimation system.

UFO detection and BLM threshold

Only passive mitigations can be taken to reduce the machine downtime caused by UFO events, due to their fast timescale. The UFO detection is based on Beam Loss Monitors (BLMs) and several studies have been performed during the years to optimize thresholds of allowed losses before triggering a beam dump [1, 2]. The initial strategy was to set thresholds that prevent quenches. However, spurious dumps can be triggered by UFOs that would not lead to a quench. A comparison between the machine downtime caused by allowing quenches (t_{qc}) and by triggering spurious dumps (t_{sd}) was carried out. This analysis estimated that $t_{qc} < t_{sd}$, thus the thresholds were increased. In particular, in 2016 the

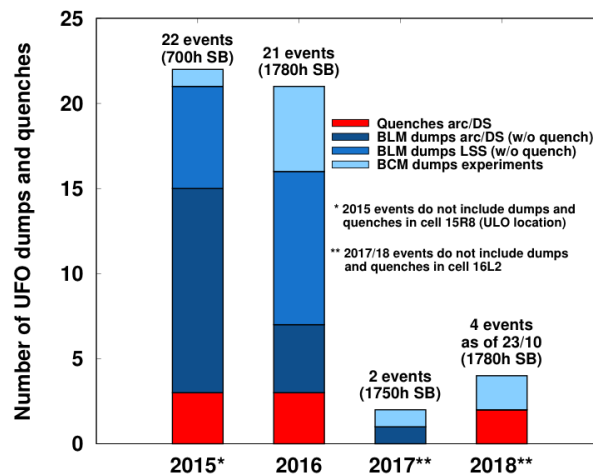


Figure 1: Number of dumps and quenches for each year of Run 2, caused by UFOs [3]. The impacts of change of threshold in 2016 (in arc/DS) and 2017 (in LSS) is clearly visible.

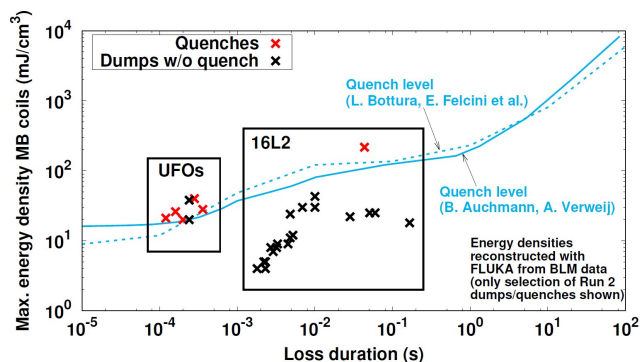


Figure 2: Comparison between quench level models and energy densities deposited in magnet coils reconstructed by simulations. Both regular UFOs around the machine and 16L2 events are reported.

thresholds of BLMs in the arc and Dispersion Suppressor (DS) were set at values 3 times larger than the quench level, leading to a significant reduction of spurious dumps with respect to 2015, as shown in Fig. 1. Thus, similar strategy was adopted for the BLMs in the Long Straight Section (LSS), where thresholds were set exactly at the quench level in 2017, together with further optimizations at collimators and Roman Pots. Only few spurious dumps were triggered in 2017 without any quench. Nevertheless, two quenches were experienced again in 2018 together with few dumps triggered by the experiments, on which there is no control from the machine side.

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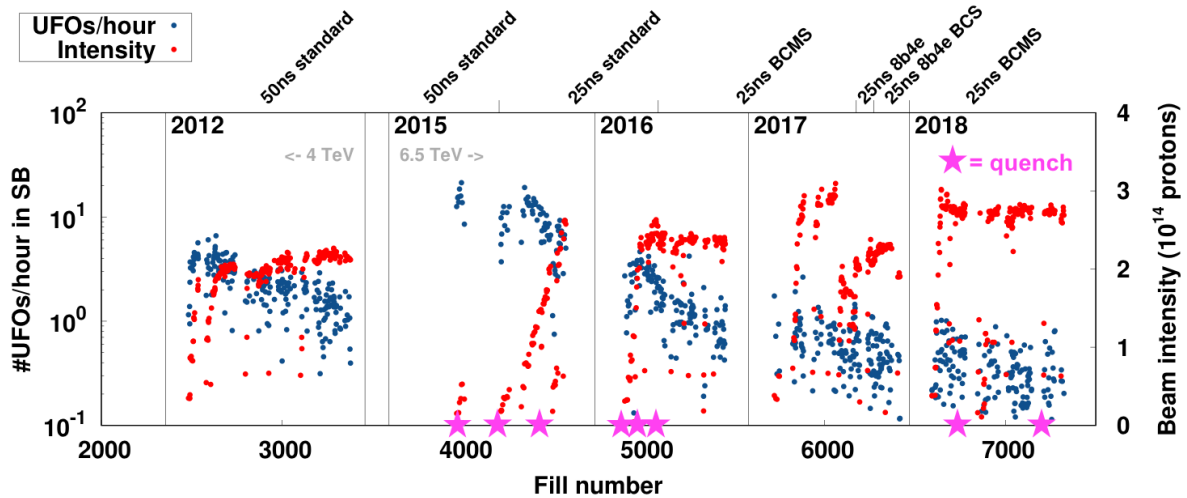


Figure 3: UFO rate in stable beams (blue dots) as a function of fill number, from the last year of Run 1 to the end of Run 2. The total stored beam intensity at the beginning of stable beams is also reported (red dots), together with quench occurrences (pink stars) [3].

Of course, a tight correlation between quench levels, BLM thresholds, and energy deposition simulations is present. An example of comparison between quench level models and energy densities reconstructed by simulations is shown in Fig. 2. A magnet quench is expected if the deposited energy in the coils is above the quench level model [4, 5]. A good agreement is visible in Fig. 2, providing a valuable experimental validation of these models. The main lessons learnt are:

- Similar losses in all quenches (within a factor of 2).
- Inelastic collision in the range of $6 \times 10^7 - 1.2 \times 10^8$.
- UFO radius in the range of $40 - 100 \mu\text{m}$.

UFO rate evolution and expectations after LS2

The rate of UFOs in the arc (i.e. half-cell ≥ 12) during stable beams from the last year of Run 1 to the end of Run 2 is shown in Fig. 3. A clear conditioning as a function of time is visible when beams are circulating in the machine. However, a significant de-conditioning was experienced during the Long Shutdown 1 (LS1). A similar UFO rate as at the end of Run 1 was recovered after about 1.5-2 years of operations in Run 2. Unfortunately, the causes of the de-conditioning during LS1 are not yet fully clear. Assuming the same de-conditioning during LS2, a few UFOs/hour in stable beams are expected at the beginning of Run 3.

Studies have been carried out regarding any possible re-distribution of UFO during LS1. No significant changes have been observed, as shown in Fig. 4.

The influence of magnet exchange has been also taken into account, looking at the correlation between UFOs and location of magnets exchanged during LS1 and Extended Year Technical Stop (EYETS) 2016-2017. The exchange of some magnets created local spots with larger UFO rate, in particular in sector 12 during the EYETS, as clearly visible in Fig. 5. However, no correlation between quench and

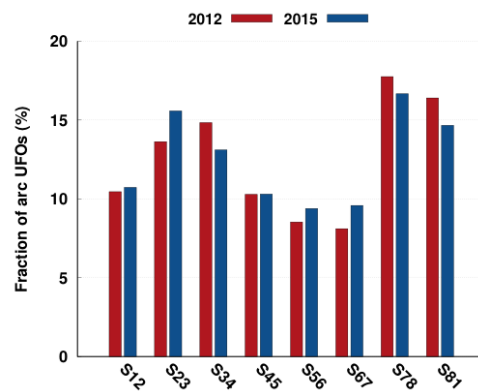


Figure 4: Comparison between distribution of UFOs in the 8 sectors before and after LS1 [3].

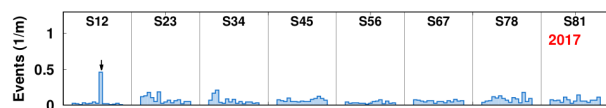


Figure 5: UFO events in the 8 sectors after the EYETS 2016-2017. The black arrow shows location where magnets were exchanged [3].

these spots has been observed. A total of 18 magnets were exchanged during LS1, while 22 magnets will be exchanged during LS2.

A difference between the restart after LS1 and LS2 can come from the beam energy. In particular, the higher the energy, the smaller the UFO that can lead to a quench. In particular, going from 6.5 TeV to 7 TeV beams it is expected that:

- The quench levels in the range of $100 \mu\text{s} - 1 \text{ms}$ losses decreases by about 30%.
- The energy deposition density in the coils increases by about 14%.

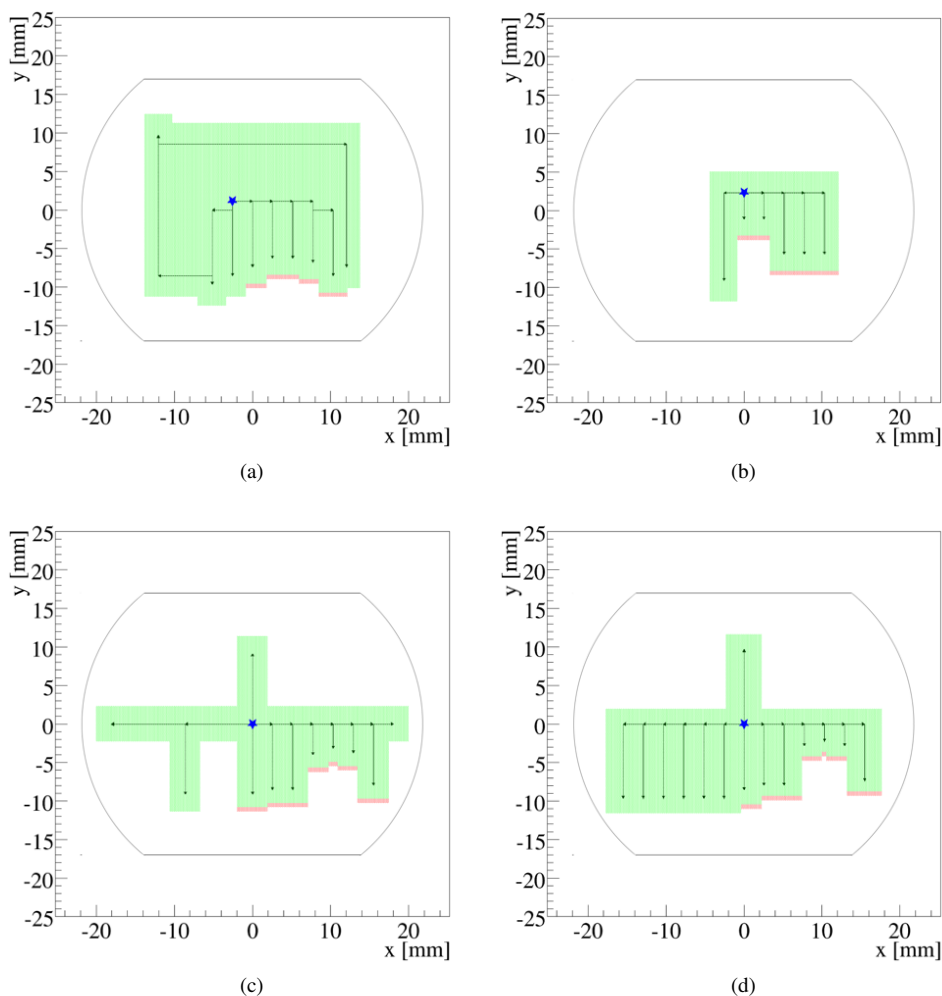


Figure 6: ULO evolution during Run 2, as measured in 2015 (a), 2016 (b), 2017 (c), 2018 (d). The beam screen is shown by the black line, black arrows are the path performed by the beam centre using local orbit bumps, the reference orbit at the moment of the measurement is shown by the blue star, clear aperture is reported in green while the measured edge of the ULO is shown by red boxes with dimensions defined by the measurement resolution. The machine reference frame is used, with the Beam 2 entering in the plane of the plots.

- Smaller UFOs can lead to an increase of $\times 2 - 4$ number of quenches.

However, it is difficult to make absolute predictions about the number of quenches per year, since the number of quenches so far was too small to reach a statistically meaningful conclusion. Nevertheless, it might be not excluded to have of the order of 10 quenches in 2021 with 7 TeV beams, if the UFO rate is similar to 2015.

UNIDENTIFIED LYING OBJECT

A significant UFO activity in the half-cell 15R8 was observed during the machine commissioning in 2015. Fast losses at this location led to 14 beam dumps, 3 of which caused a magnet quench. Energy deposition studies showed that the vertex of the hadronic showers is likely situated within 1 m from the center of the dipole MB.C15R8 (Beam 2 beam screen) [6]. Thus, several local aperture measurements

were performed in that area, which revealed the presence of the Unidentified Lying Object (ULO). Different investigations were performed in 2015, which were based on three main observables: dedicated local aperture measurements, analysis of UFOs at the ULO location, and parasitic monitoring of beam losses during standard cycles. An extensive summary can be found in [7].

ULO evolution and mitigation

A constant monitoring of the ULO during Run 2 was carried out by means of local aperture measurements, which were performed at every beam commissioning of each year of run. The detailed description of the procedure used to perform these measurements is described in [7]. The measured aperture restriction at the ULO location along Run 2 is shown in Fig. 6.

Table 1: Bump amplitude at the ULO during Run 2.

Year	Plane	
	Horizontal [mm]	Vertical [mm]
2015	-3	+1
2016	-3	+2
2017	-2	0
2018	-2	0

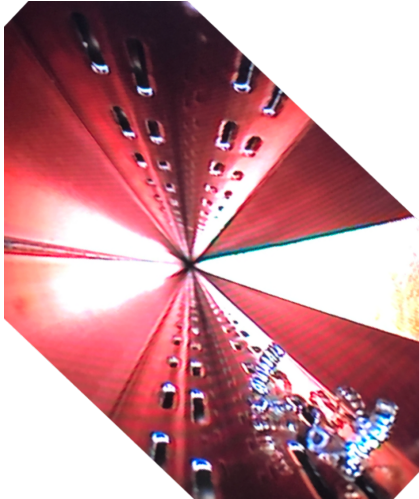


Figure 7: Picture of the ULO, as found during the first endoscopy in April 2019.

The mitigation strategy adopted was the deployment of a local orbit bump to bypass the ULO, while ensuring at least 10σ of available aperture at injection energy. The bump amplitude at the ULO in the horizontal and vertical planes is reported in Table 1, which was optimized following the results of local aperture measurements. This mitigation strategy allowed this limitation to be successfully removed.

ULO inspection and removal

An endoscopy was performed in April 2019 [8], which revealed the object shown in Fig. 7. It is located at about 9 m from upstream interconnection of the MB.C15R8, bottom right part of the beam screen, in the Beam 2 direction. Transverse area and location are consistent with aperture measurements performed with beam. The longitudinal position is also in agreement with respect to what expected. This



Figure 8: Picture of the ULO after its removal in May 2019.

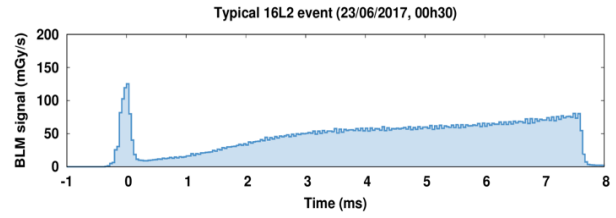


Figure 9: Characteristic loss profile detected in the half-cell 16L2 during a dump event.

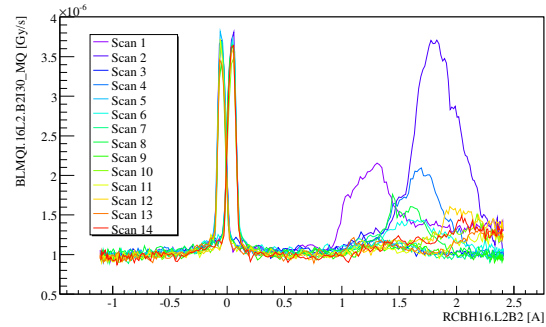


Figure 10: Local losses in 16L2 as a function of the current in the local MCB [16].

first inspection revealed that the ULO is a twisted string, which was stuck between the pumping slots of the beam screen and the cold bore.

A second intervention was carried out in May 2019 [9], in which the ULO was successfully removed. The main hypothesis is that it is a strip of the plastic that was ripped from the wrapping of the beam screen during the installation. A picture is shown in Fig. 8, from where it is clearly visible that the part that was lying between the beam screen and the cold bore is still transparent (bottom left part of the picture), while what was sticking out became much darker due to the interaction with the beam. Detailed analysis of its composition are also foreseen.

No interventions were carried out at this location during LS1 [10]. Thus, it is plausible that this object was present since the beginning of Run 1. A possible explanation of the missed observation of local losses during Run 1, it is the reduced granularity and different locations of BLMs with respect to Run 2 [7]. The inspection and removal showed that this object is very flexible, which can explain why the RF ball did not reveal its presence and the varying vertical shape along the years (see Fig. 6 and [7]).

16L2

The sudden increase of losses in the half-cell 16L2 represented the main machine limitation in 2017, causing 67 dumps (2 at injection and 65 at top energy or during the energy ramp, one of which induced a quench) [11]. These events were characterized by three stages of loss rate:

1. Steady loss in 16L2 along the entire fill ($\sim 10^{-6}$ Gy/s), arising during the energy ramp.

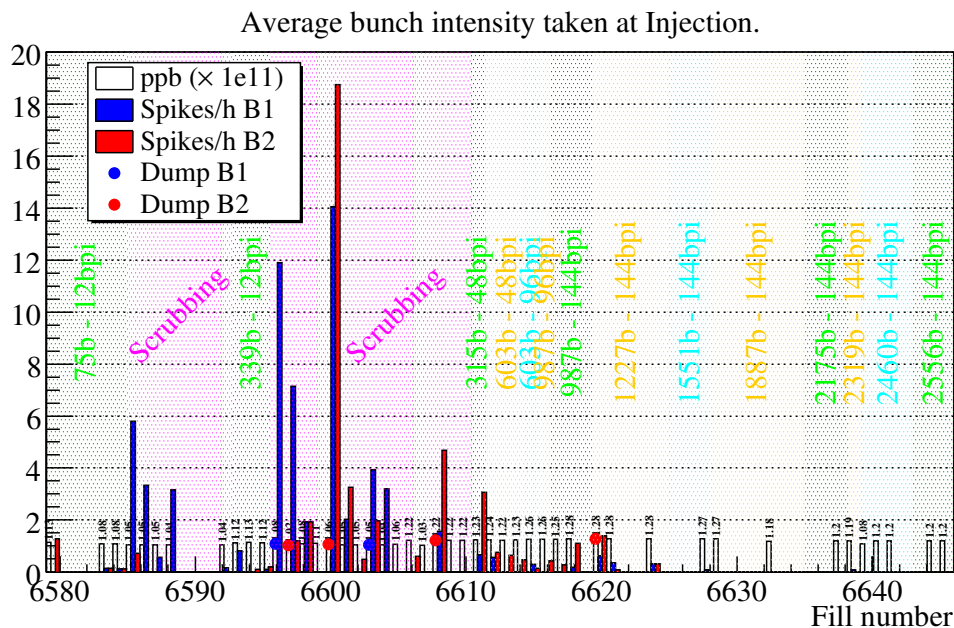


Figure 11: Rate of loss spikes in 16L2 during the 2018 intensity ramp up as a function of the fill number. Each fill is composed by three bins: white, blue and red that show the average bunch population, spike rate in Beam 1 and in Beam 2, respectively. Fills that were dumped by a 16L2 event have a dot on top of the bunch population, with color associated to the beam in which the event took place.

2. Sharp rise of losses in 16L2 “UFO-like” ($10^{-3} - 10^{-2}$ Gy/s).
3. Very fast rise of losses at collimators in IR7 triggering a dump (few ms)

A characteristic 16L2 event is reported in Fig. 9. The spectrum of the BLM signal in 16L2 shows a peak at the revolution frequency during the “UFO-like” event, while diamond BLMs indicate vertical losses coming from all the bunches. Thus, the beam is touching something in 16L2 at every turn. On the other hand, spectrum of the BLM signal at primary collimators (TCPs) in IR7 shows a peak at the tune value during the fast rise of losses triggering the dump. It was also observed that the loss plane at TCPs in IR7 is in agreement with the polarity of the main quadrupole in 16L2. Thus, beams become unstable and undergo betatron oscillations causing most these losses, while scattered protons in 16L2 reach TCPs in IR7. The long loss tail after the “UFO-like” rise could possibly be explained by a phase transition of a macroparticle to the gas phase. A wider overview of the present physics understanding and main actions taken in 2017 can be found in [12–14] and [15], respectively.

Source, correlations and mitigations

The source of the hadronic showers has been identified by means of energy deposition simulations and located close to the orbit corrector (MCB) in 16L2 [17]. A clear correlation between local steady state losses and MCB current (i.e. dipolar field) was identified [18], indicating that the process leading to such losses was sensitive to the variation of the

local fields at the level of a few mT (i.e. low energy particles were involved), as shown in Fig. 10. Moreover, a correlation between local electron cloud and losses could be inferred from tests with 50 ns beams [18], together with a positive tune shift along the train observable in the post-mortem of the dump occurring as a result of the instability [19]. Thus, the main mitigation strategy in 2017 was the use of the MCB dipolar field and 8b4e filling pattern, in order to suppress multipacting and prevent “UFO-like” events; the installation of a solenoid in the field-free region of the interconnection [20], which allowed the bunch population to be increased by about 10% (and mitigate loss spikes at injection in 2018); the BCM production scheme was adopted in order to increase the beam brightness. The bunch population beyond which 16L2 events occurred in 2017 was of about 1.3×10^{11} ppb [15], using the mitigations described above.

The most probable scenario causing this machine limitation has been identified as an accidental air venting during the removal of the mobile group for the final pinch-off in the EYETS 2016-2017. Actions have been taken to avoid repetitions, such as an upgraded design of pumping ports, new pumping scheme, and procedure integrated into a dedicated QA and checklist [15].

It was planned to bring the sector 12 to room temperature during the YETS 2017-2018, in order to induce the evaporation of the contaminant. However, the warm up was stopped at 80-90 K after the analysis of the gas released [21], as a compromise between risks associated to bringing a sector to room temperature and vacuum quality reached.

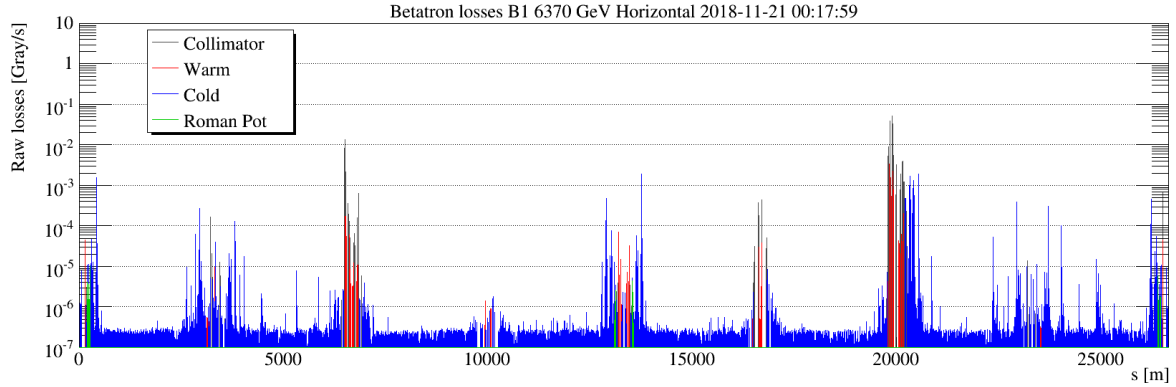


Figure 12: Beam loss pattern at the moment of a dump caused by 10 Hz horizontal orbit oscillations (Fill 7459).

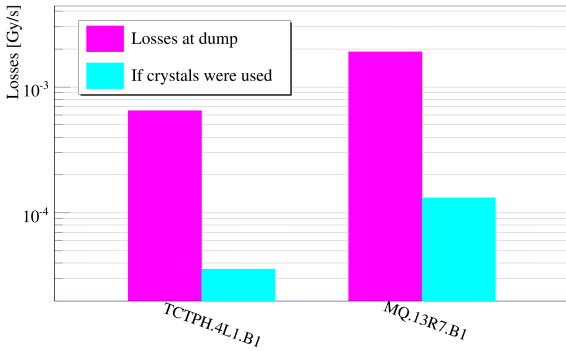


Figure 13: Measured losses at the two limiting locations during a 10 Hz dump event (magenta) and expected losses with crystal collimation (cyan) using scaling factors measured during operational tests [25].

Nevertheless, few dumps were experienced also in 2018 with a gradual conditioning along the year, as shown in Fig. 11. Anyhow, a fast recovery procedure was established to avoid subsequent dumps, consisting on a short fill with reduced intensity (i.e. 2-3 hours in stable beams with 900 bunches) after a 16L2 event. The bunch population beyond which 16L2 events occurred in 2018 with 25 ns filling pattern was of about 1.15×10^{11} ppb [22].

10 Hz OSCILLATIONS

Several dumps with similar signature were experienced toward the end of 2018. In particular, 2 during the proton run and 7 during the lead ions run (out of 48 physics fill). These dumps were characterized by fast horizontal orbit oscillations with a frequency in the range of 8-12 Hz, leading to increasing losses at TCPs in IR7 (same plane and frequency). Outscattered particles from primary collimators were causing losses above BLM threshold at the TCSG.A5L7.B1, MQ.13R7.B1 and TCTPH.4L1.B1. Unfortunately, BLM thresholds were already set at the quench level and it was not possible to further increase them. The characteristic beam loss pattern of the entire ring during these events is shown in Fig. 12.

Present understanding

The location where these oscillations are originated can be inferred by looking at the normalized beam position as a function of phase advance. In particular, the observed kink in the closed orbit and its displacements are compatible with the horizontal movement of the main quadrupole in the half-cell 21L4 during the proton run, while in a region between the inner triplet (ITR2) and half-cell 5R2 with lead ion beams. It is difficult to distinguish between ITR2 and Q5R2 because of the small phase advance between them. The horizontal orbit displacement is detected in both beams and it is consistent with the $\sqrt{\beta_{x1}/\beta_{x2}}$, where β_{x1} and β_{x2} are the horizontal beta function at those locations in Beam 1 and Beam 2, respectively [23].

Studies have been performed to understand at which point of the cycle these oscillation starts. The spectrum of both ADT and 100 Hz BLM at TCPs in IR7 show that they are always present [23].

Measurements of possible ITR2 cryostat vibrations were carried out, which did not reveal any clear signature [24]. Nevertheless, it is not possible to exclude internal vibrations. Moreover, measurements at Q4R2 and Q5R2 were not performed.

A possible explanation of why these events were particularly severe during the 2018 heavy ions run could be the fact that IP2 was squeezed down to 50 cm for the first time. Thus, the induced orbit displacement was amplified due to the larger beta in the region ITR2-Q5R2 with respect to previous years, where the minimum $\beta_{IP2}^* = 80$ cm was reached. However, a possible mechanism that could explain the oscillations originated in 21L4 during the proton run has been not yet identified. Moreover, similar signature were recently identified also in 2 dumps occurred during the p-Pb run in 2016, but with orbit oscillations originating in 13L8. Detailed studies are on-going.

Possible actions for future mitigations

Of course, a better understanding of these events is crucial to deploy the best mitigation strategy. In particular, the main pending questions are:

- What is the trigger of sudden amplitude increase of these orbit oscillations?
- Will the amplitude keep increasing indefinitely?

Unfortunately, present studies are based on Post Mortem (PM) data that are available only in the event of a beam dump. More observations are needed, in particular to study events not leading to a dump. Thus, a “PM-like” logging is needed (mainly turn-by-turn Beam Position Monitor acquisition), which is triggered if certain conditions are reached (e.g. orbit oscillations above a threshold are detected). Moreover, the installation of accelerometer on cryostats of suspected MQs originating these oscillations is desirable.

The best mitigation would be the identification of vibrating MQs to understand if it is possible to remove such oscillations. Nevertheless, a passive mitigation strategy could be improving the cleaning performance of the collimation system for ion beams. Two beam loss mitigations can be envisaged for Run 3:

- Crystal collimation that showed a reduction of losses on limiting locations of a factor larger than 10 (Fig. 13).
- Use of TCLDs, which are planned to be installed during LS2.

Looking further in the future, the presence of hollow electron lens can contribute to mitigate such losses. This because the estimated orbit displacement at the primary collimators in IR7 is of about 0.5σ [23] and this portion of beam halo would be efficiently depleted by electron lens. Thus, leading to reduced loss spikes in case of orbit oscillations.

CONCLUSIONS

Different special beam loss scenarios were experienced during Run 2, which were successfully addressed and their impact on LHC operations mitigated, contributing to the excellent machine performance achieved in these years. Nevertheless, some observations are not yet fully understood and detailed studies are on-going.

The operational experience gained with UFOs led to a valuable experimental validation of quench level models and improved BLM threshold strategy, allowing to reduce significantly the machine downtime due to these events. However, it is still hard to predict the UFO rate expected after LS2, which should be in the range of rates in 2012-2015 if equivalent de-conditioning as in LS1 is assumed.

The limitations induced by the presence of the ULO were successfully mitigated throughout Run 2 by means of local orbit bumps, based on a constant monitoring of the ULO shape. An endoscopy was carried out in April 2019, which allowed to identify a plastic twisted string that was stuck between the pumping slots of the beam screen and the cold bore. A second intervention was performed in May 2019, in which the ULO was removed.

Although the significant limitation of machine performance induced by the presence of vacuum contamination in

the half-cell 16L2 during 2017, it was successfully mitigated by reducing the multipacting and increasing the beam brightness. The most probable cause has been identified and actions have been taken to avoid repetition. This limitation is expected to literally evaporate during LS2 with the warm up to room temperature.

A possible explanation has been found for the dump triggered by the 10 Hz orbit oscillations during the 2018 lead ions run. However, a possible mechanism that could explain the sudden oscillation amplitude increase and the dump event during the proton run has not been identified yet. Possible improved diagnostics has been proposed to better understand these events. Nevertheless, passive loss mitigations have been discussed and can significantly help in Run 3.

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