MACROPARTICLE-INDUCED LOSSES DURING 6.5 TEV LHC OPERATION

G. Papotti, M. Albert, B. Auchmann, E. B. Holzer, M. Kalliokoski, A. Lechner,
CERN, Geneva, Switzerland

Abstract

One of the major performance limitations for operating the LHC at high energy was feared to be the so called UFOs (Unidentified Falling Objects, presumably micrometer sized dust particles which lead to fast beam losses when they interact with the beam). Indeed much higher rates were observed in 2015 compared to Run 1, and 20 fills were prematurely terminated by too high losses caused by such events. Additionally they triggered a few beam induced quenches at high energy, the first in the history of the LHC. In this paper we review the latest update on the analysis of these events, e.g. the conditioning observed during the year and possible correlations with beam and machine parameters. At the same time we also review the optimization of beam loss monitor thresholds in terms of machine protection and availability.

INTRODUCTION

Since early operation with beam, the LHC has had detection of fast, localized loss events, which at times exceeded the thresholds of the Beam Loss Monitors (BLMs), leading to beam dumps [1]. These events have been nicknamed "UFOs", or Unidentified Falling Objects, as the likely cause for the losses are micrometer-sized dust particles that interact with the beam either by falling due to gravity or by electrostatic forces. The resulting particles showers deposit energy downstream in the superconducting coils, and are registered in the ionization chambers of the BLM system. The deposited energy and BLM signal depend on the size and composition of the dust particle, as well as on the path inside the beam [2]. These events are observed in the whole machine and for both rings, and have a typical duration of a few turns (where one LHC turn is ≈89 μs). About 20 dumps/year were triggered by UFOs in 2010, 2011, 2012, and 2015, i.e. 2 – 5% of the total number of dumps in a year.

Luckily, most of the UFO events lead to beam losses that are well below the BLM dump thresholds. Thousands of small UFOs are detected in real time by the "UFO Buster" application [3]. The UFO buster is based on the analysis of the BLM concentrator data. The BLM concentrator provides the maximum beam loss, integrated over 12 different time intervals between 40 μs and 83.8 s, at a 1 Hz rate. When losses are of short duration and sufficient intensity, and recorded by more than one monitor, the BLM concentrator data set is recorded as a candidate UFO event. Additionally, but only for a subset of events, "capture data" is available, i.e. a 300 ms-long buffer of 80 μs data. The capture data allows looking at the temporal shape of the candidate event. An example is shown in Fig. 1.

UFOs can have an important impact on LHC availability: a premature dump of a physics fill provokes a loss of at least 2 – 3 hours to refill, and in case of a magnet quench this time is extended by several hours due to the need to re-establish the cryogenic conditions and precycle the machine. Consequently, while the underlying origin of the events is not yet fully understood, quite a bit of effort was so far successfully invested in mitigating the effects on the machine availability by limiting the number of unnecessary dumps and allowing few UFO-induced quenches. This was achieved by subsequently increasing the BLM dump thresholds, from rather conservative values to values closer, and partly above, the quench limits.

Operation at 6.5 TeV reduced thermal margins in the superconducting magnet systems, and increased the energy deposition due to UFO-related particle showers with respect to 3.5 and 4 TeV [4]. As a consequence, UFOs were feared to be one of the major threats to machine availability at high energy. This paper first focuses on the update on UFO rates observed in 2015, then it recalls the actions taken during the year to limit their impact on machine availability.

UFO RATES

The rates of UFO events recorded in 2015 is shown in Fig. 2. We count here the number of UFOs in the LHC arcs that were generated during the periods of luminosity production ("fills"). Luminosity production is the phase in which the machine is the most stable and during which manipulations are minimized, which simplifies the identification of UFOs. Other phenomena, e.g. beam instabilities or fast losses for machine protection validation, could complicate or impair the analysis in the other phases of the cycle.

The rates for arc UFOs were non-negligible already at the start of the year, for only few tens of bunches per ring. For

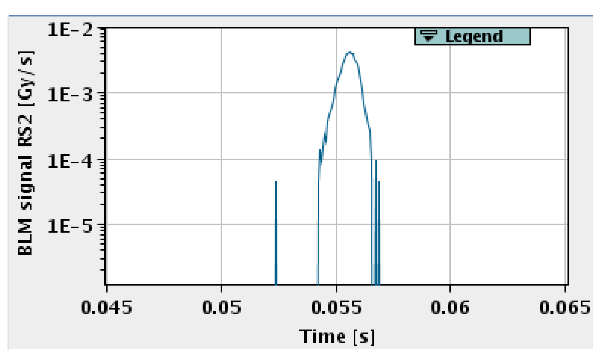

Figure 1: Typical signal shape of a UFO recorded by the capture buffer of the BLM system. RS2 stands for Running Sum 2, i.e. loss signals integrated over 80 μs.

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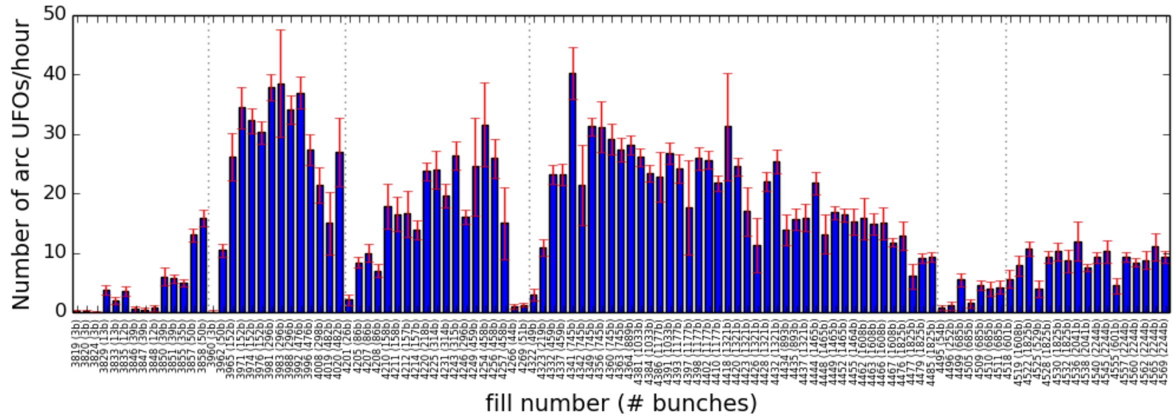

Figure 2: Rates of UFO events during physics production. The horizontal axis indicates the fill number and the number of bunches circulating per ring. The vertical dotted lines separate different operational periods: operation with less than 50 bunches/ring, with 50 ns beams, with 25 ns beams with up to 500 bunches, with 25 ns beams up to 1800 bunches, high-beta run with 100 ns spaced beams, with 25 ns beams up to 2244 bunches.

comparison, the first UFO beam dump in 2010 happened with 8 bunches per ring. The rates quickly increased during the intensity ramp-up, with peaks of 30 – 40 UFOs per hour reached for a few hundred 50 ns spaced bunches per ring.

A direct comparison to the 2010 initial rates is not possible, as the UFO Buster application had not existed back then. The comparison to the Run 1 rates is moreover complicated by the BLM relocation campaign that took place during the Long Shutdown [4]. Some ionization chambers from the arc and dispersion suppressor quadrupoles were moved on top of the interconnects between the main dipoles, and this increased the sensitivity of the BLM system to UFO losses and, thus, the number of events recorded in the UFO Buster.

Despite an exact comparison not being possible, we recall that UFO rates started out at ten UFOs per hour in 2011 and decreased to 2 – 3 UFOs per hour in 2012 [5]. The reduction of the rates observed with beam time was called conditioning. The expectation for conditioning to happen also in 2015 was the main source of hope after the observation of the very high rates at the start of the year. Indeed conditioning was observed over the course of the year, and it's most clearly visible in the second period of intensity ramp-up with 25 ns beams, where rates started out at ≈30 UFOs per hour and lowered to ≈10 UFOs per hour.

The other main feature of the rate evolution over the course of 2015 is the dependence on beam intensity. That is most evident at the start of every different period of operation in Fig. 2: there the intensity is increased rapidly, often one fill to the next one, and the UFO rate increases sharply.

Rates seem to have settled at ≈10 UFO per hour in the last period of proton running, with ≈2000 bunches of 25 ns beams per ring. It may be that rates ≈10 UFOs per hour are a permanent feature at 6.5 TeV with the present BLM locations. Looking back at the Run 1 data, rates had also settled to a plateau (≈2 UFO per hour for ≈1400 50 ns bunches per ring, at a beam energy of 3.5 – 4 TeV).

Another feature observed in Run 1, between the end of 2011 and the restart in 2012, is the increase of about a factor 2 of the UFO rates after the extended technical stop, when no beam was in the machine for an extended period of time. Similarly it is expected that UFO rates at restart in 2016 will be higher than at the end of 2015. Then the rates will most likely decrease again with beam time, and the 10 UFO per hour plateau will be possibly confirmed.

Correlation with Other Parameters

Possible correlations with other beam or machine parameters were much sought after, and a thorough review is presented in [6].

In October 2015 the high-β^* run was carried out with 100 ns spaced bunches (fills 4495 – 4511 in Fig. 2), and no significant reduction of UFO rates was observed in this period. As in these conditions the electron-cloud effect is vanishingly small compared to 25 ns beams [7], this observation ruled out a possible correlation between electron-cloud and UFO rates.

A dependence of the rates on beam size could be expected: if the beam size is not uniform across the bunches and a few bunches are larger, a particle interacting with the beam would interact first with the tails of the larger bunches, and might never get to interacting with the smaller bunches. This would result in smaller losses generated by these UFO events, which is equivalent to smaller UFO rates given the cut-off of the detection at a certain event size. A clear correlation between rates and beam size could not be found in 2015. Even if there, it would probably be small compared to the dependence on beam intensity and the effect of conditioning. This dependence might need a follow up later in Run 2, when conditioning might have settled.

Lastly, it was studied whether there was any correlation between the number of UFOs counted in a sector, and the number of high-current quenches in the sector. This is relevant since it has been found by simulation and measurement that a quench at high currents induces strong vibrations in the beam screen [8, 9], which were suspected to shake loose dust particles. Assuming that dust particles fall from the top of the beam screen, a sector that quenched a lot during the training campaign of 2015 would, in this line of reasoning, see lower UFO counts. No such correlation was found.

BLM THRESHOLDS

In the absence of an effective mitigation measure for the loss events, the decisive question became if and how the BLM system could be used to initiate beam dumps early enough to avoid quenches. This would save hours for cryogenic recovery and machine precycle, and reduce the risk for electrical faults in the quenching magnet. The initial Run-2 strategy on quenches had then been to set BLM thresholds at the highest possible threshold that would allow to avoid all of beam-induced quenches due to UFOs. Details on the thresholds setting can be found in [4]. Note that, at that time, considerable uncertainties remained on the actual quench level, i.e. the deposited energy density in the coil that would induce a quench [10].

In July 2015 the first UFO-induced quench occurred at a BLM signal strength of 91% of threshold. At the same time though, several events at about 70% of the BLM threshold did not result in magnet quenches. For the analysis we use only UFO events in the positions of highest BLM sensitivity, i.e. the position for which the threshold was determined. This allowed reducing considerably the uncertainty on the quench level, and proved that the quench-level estimate was just about correct.

Unnecessary Dumps

Figure 3 shows two examples. The upper figure shows an event that did not lead to a magnet quench. The UFO event is essentially over roughly 160 μs before the signals at the beam dump appear, i.e. before the beam is extracted. This beam dump was unnecessary as the event on its own would not have caused a dump nor a quench. Note that the BLM signals strongly depend on the UFO position with respect to the BLM location. Hence, if we want to protect against UFOs which are further away, we cannot avoid unnecessary dumps for UFOs which are closer.

In the lower part of Fig. 3, the beam dump did shorten the UFO event. However, since the beam loss continued to grow between the passing of the threshold and the absence of beam in the UFO location, the quench could not be avoided.

Threshold Modifications for 2016

In order to avoid the first event, thresholds should be increased, while to avoid the second event, the thresholds should be reduced. Since the vast majority of dump events were of the first kind, the BLM Thresholds Working Group [11] proposed to increase BLM thresholds in the UFO time scale (40-640 μs) by a factor 1.5 for the last two weeks of running in 2015. This aims at allowing few UFO-induced quenches to limit the number of unnecessary dumps. This is in favour of machine availability and a change with respect to the initial thresholds strategy that had strived to avoid beam-induced quenches. Another increase is in place for 2016 (factor 2).

Figure 3: Screenshots of the BLM post-mortem analysis tool for a UFO event that dumped the beam without quench (top), and for a UFO event that caused a beam-induced quench (bottom).

Only 3 UFO-induced quenches took place in 2015, as opposed to 17 unnecessary dumps. All of them occurred at very different UFO rates and beam intensities than those expected for 2016, making it difficult to extrapolate to a number of expected quenches in 2016 with the proposed setting. However, the fact that only a single UFO-induced quench was observed during the last two months of proton operation in 2015 augurs well for a limited number also in 2016. In order not to jeopardize the protection of the superconducting magnets, the new strategy foresees to be reassessed in case many UFO-induced quenches are observed.

CONCLUSIONS

Experience with UFOs in 2015 has shown that, for operation at 6.5 TeV, UFOs have the potential to cause beam-induced quenches (3) and disrupt operation (17 unnecessary beam dumps). UFO events were as frequent as 30 events per hour in the initial phases, but luckily the rates then conditioned and stabilized at a plateau of 10 events per hour at the end of the year. An increase of the rates is expected at restart in 2016 due to the long stop without beam around Xmas time.

The strategy with respect to quenches was revised taking into account operational experience. A further increase of the BLM thresholds in the UFO range is in place for 2016 to allow few UFO-induced quenches and avoid unnecessary dumps.

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