HOW TO SURVIVE A UFO ATTACK

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Abstract

UFOs in the LHC have proven to be a potential threat to machine availability. While the correlation of peak losses with beam intensity had initially indicated a potential limitation, the fast advance of the conditioning effect appears to have saved the day. In this presentation we present our current understanding of the UFO threat, and the BLM strategy to optimize machine availability and machine protection.

INTRODUCTION

In 2010 and 2011, a phenomenon of short beam losses around the LHC ring was observed [1]. The losses were distributed arbitrarily around the ring, with the exception of the injection kickers, where these losses were frequent and especially intense [2]. Macroparticles, or dust, were identified as the likely cause. These macroparticles enter in contact with the beam, drawn either by gravity or electrostatic forces, and interact with the high-energy protons of the beam [3, 4, 5, 6]. As a result, particle showers, initiated in the dust particles, deposit energy downstream in the superconducting coils. Moreover they are registered in the ionization chambers of the beam-loss monitoring system. Also by interaction with the beam, the dust particle is ionized and, after several 100 microseconds, expelled from the beam by electrostatic repulsion [7, 8, 9]. The phenomenon is called UFO (Unidentified Falling Object).

The injection kickers problem was studied in detail and cleaning as well as refurbishment procedures were devised and implemented. They proved highly effective, so that after the completion of the refurbishment during the first long shutdown in 2013/14, no more large UFOs were noted around the kickers. Operation at 6.5 TeV, however, 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 [10]. In the absence of an effective mitigation of the presence of dust particles distributed all around the 27 km circumference of the LHC, the decisive question became if and how the beam-loss monitoring system can be used to initiate beam dumps early enough to avoid a quench, save valuable hours for cryogenic recovery and pre-cycle, and reduce the risk for electrical faults in the quenching magnet [11]. The distribution of beam-loss monitors (BLMs) was modified during the long shutdown in order to improve the BLM system's overall sensitivity to UFOs.

Since July 2015 we know for certain that UFOs can cause magnet quenches. In this paper we discuss lessons learned with regard to UFOs from operation at 6.5 TeV, as well as strategies to optimize LHC machine availability in the presence of UFOs.

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QUANTIFICATION OF THE UFO THREAT

UFO Rates

UFOs are recorded by the UFO Buster application [12]. The tool records events measured by the beam-loss monitoring (BLM) system that feature losses of short durations and sufficient intensity and which are recorded in more than one monitor. In Run 1, UFO rates started out at ten UFOs per hour in 2010 and decreased to two to three UFOs per hour in 2012 [11]. The reduction was called conditioning.

In 2015 we started operation at a surprising 50 UFOs per hour. Of course, during the initial period of Run-1 operation, the UFO Buster application had not existed, so that we do not know what had been the initial rates. Moreover, the relocation of ionization chambers from the Arc and DS quadrupoles towards the interconnects between main dipoles has increased the sensitivity of the beam-loss monitoring system and, thus, the number of events recorded in the UFO Buster. During August and the first half of September the rates remained around 30 UFOs per hour, before starting to show clear signs of conditioning end of September and early October; see Fig. 1. When related to the beam intensity, the conditioning effect is visible already during the early stages of the intensity ramp.

Figure 2 provides a zoom into the last weeks of 2015 proton operation. It can be seen that conditioning, both, in absolute and relative terms, seems to stagnate. It may be that, for operation at 6.5 TeV with the present BLM locations, rates around ten UFOs per hour are a permanent feature.

Scaling with Intensity

The severity of UFOs can be measured by the maximum signal-to-threshold ratio observed by the BLM system. BLM thresholds in the relevant monitors of Arc and DS sections are set for the UFO scenario, i.e., the BLMs will abort a fill when a UFO event risks to cause a quench; we will discuss this strategy in more detail in the following section. As can be seen from the blue and orange data points in Fig. 3 (50 and 25 ns fills, respectively), fills before 23 September (the date is chosen because of an LHC Machine Committee meeting on that day) showed a clear trend during the intensity increase. Moreover, the trendline shows that a further increase in beam intensity would lead to frequent fills with signal-to-threshold ratios beyond 100%, i.e., most of the fills would be dumped by UFOs.

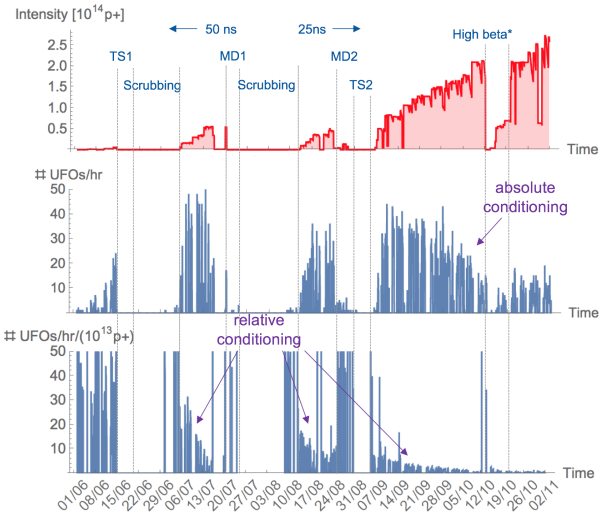

Figure 1: UFO-Buster data, collected during 6.5 TeV proton operation in the ARC and DS sections of the LHC. Top: Beam intensity. Middle: Absolute UFO rate. Bottom: UFO rate per 10^{13} protons.

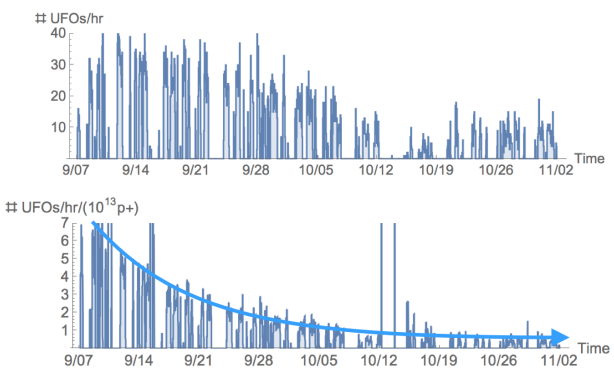

Figure 2: Zoom into Fig. 1 (middle and bottom) to emphasize conditioning during the last weeks of proton operation.

Underscoring this finding, five fills between 25 and 28 September were indeed dumped by UFOs.

It can be seen from Fig. 1 that around that time, the absolute conditioning of UFO rates set in. The trend of green data points is fairly horizontal with large spread around the median. The effect is attributed to the lower UFO rates. We assume that, for a given beam intensity, the probability of a UFO to produce a beam loss of a certain strength is constant, and larger events are much more rare than smaller ones. With lower UFO rates it is, therefore, more likely to see fills of durations well beyond ten hours that do not see a single large UFO event, whereas with higher UFO rates every fill would be dumped prematurely.

In an effort to disentangle UFO rates from the correlation of beam losses with beam intensity, we propose Fig. 4. The plot is used in the following way: assume that we are interested in UFOs during a fill at 50% of nominal (here 3.2×10^{14} protons) beam intensity, and we are interested in

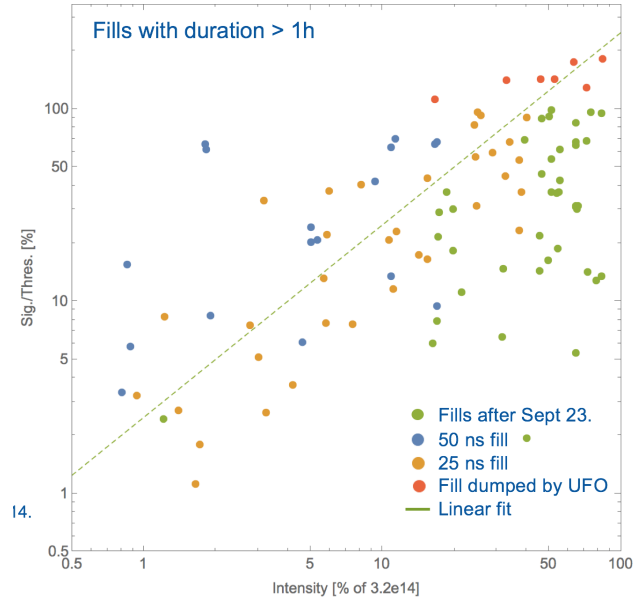

Figure 3: Maximum BLM signal-to-threshold ratio from UFO Buster data during proton operation at 6.5 TeV in Arc/DS sections. Only fills with flat-top times larger than one hour are considered. Blue dots represent fills with 50 ns bunch spacing, orange with 25 ns, red fills that were dumped by UFO beam losses, and green fills occurred on 23 September and later. The linear fit was made on data prior to 23 September.

the probability for a given UFO to exceed 25% of the initial Run-2 BLM thresholds. Then we find from the orange line that this probability is roughly 1%. Every 100th UFO will exceed 25% of thresholds. If the UFO rate is ten per hour, then such an event will occur on average after ten hours at flat-top energy. If the UFO rate, however, is 50, then the event will already occur after only two hours. It should be noted that the plot was done during the intensity ramp, when about 82% of the nominal intensity was reached, i.e., the right-most data point is not representative, and there is too little data overall for data on very large events to be significant. Nonetheless, the plot confirms the general impression that the severity of UFO-induced losses scales with intensity, and that UFO rates must have a strong impact on LHC machine availability.

Occurrence vs. Flat-top Duration

For the above reasoning to hold, it should be that the probability for the occurrence of UFOs, in particular of large ones, does not depend on the duration spent at flat-top energy. To study this, we look at Fig. 5. For every fill we determine the time of occurrence of the maximum signal-to-threshold ratio, and relate it to the overall time spent at flat-top. Low percentages mean that the largest event occurred upon arrival at flat-top, possibly during squeeze or adjust beam modes. 100% means that the fill was most likely dumped by a UFO. We note that, if all fills are con-

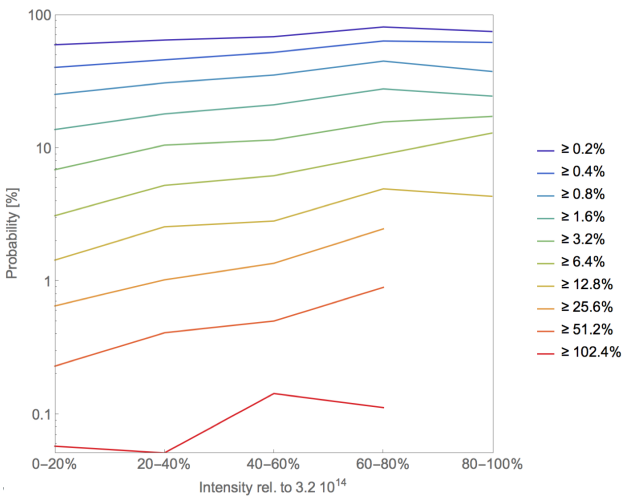

Figure 4: Probability for a given UFO event in the Arc or DS sections at 6.5 TeV during proton operation to produce beam losses that exceed a given percentage of the BLM thresholds (initial Run-2 setting).

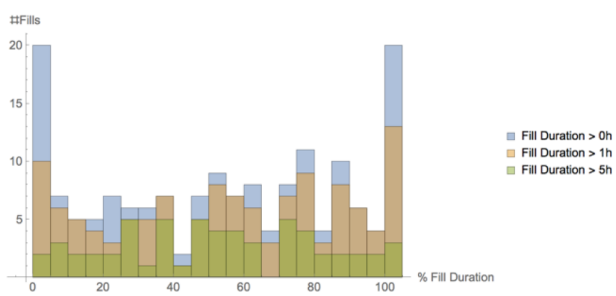

Figure 5: Histogram of the moment of maximum signal-to-threshold ratios during the time at flat-top. Blue, orange, and green histogram take into account fills of a minimum duration of 0, 1, or 5 hours, respectively.

sidered, there is a preponderance for maximal events at either the very beginning or the very end of the fill. Note that for very short fills this could be one and the same effect, depending whether the event was large enough to dump the fill or not. As we exclude shorter fills from the analysis, the histogram gets more evenly distributed. For fills with five hours at flat-top or more, the histogram is basically flat.

We interpret this plot in the following way: there is a propensity for UFOs to occur upon arrival at flat-top. This effect has been observed by the LHC operators, and is confirmed here by data. However, as the fill goes on, we are more and more likely to see a UFO event that is even larger than those initial ones. Hence, if the fill survives the initial time span at flat-top, the probability to see a large event is evenly distributed over the fill duration, as was assumed in the example above. We have no explanation ready for the increased number of UFOs at the early moments at flat-top energy.

Special Fills and Other Correlations

In October 2015 the high-β^* run was carried out with a filling scheme that featured 100 ns bunch spacing. With this filling scheme, the electron-cloud effect is vanishingly small, relative to 25 ns bunch spacing [13]. Since it had been observed that scrubbing runs tend to attenuate both, the electron-cloud effect and the UFO rates, it was of interest to observe how the UFO rates would fare in the absence of the electron cloud. No significant reduction in UFO rates was observed. Similarly, no significant change of the UFO rate was observed during a fill with BCMS beam. Due to the short duration of the fill, the data is, however, hardly significant.

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 major vibrations in the beam screen [14, 15], 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. However, no such correlation was found.

BLM THRESHOLD SETTINGS

Initial Threshold Settings

We recall that the initial Run-2 strategy vis-à-vis quenches had been to set BLM thresholds at the highest possible threshold that would allow to avoid 100% of beam-induced quenches due to UFOs. The strategy was presented and approved at the Chamonix LHC Performance Meeting in 2014 [16]. Considerable uncertainties remained on the actual quench level, i.e., the deposited energy density in the coil that would induce a quench [17]. Details on the thresholds setting can be found in the Proceedings of the 2014 Workshop on Beam-Induced Quenches [18].

In July 2015 the first and above-mentioned UFO-induced quench occurred at a BLM signal strength of 91% of threshold. The resistive-voltage rise seen by the quench-protection system was relatively slow, comparable to a training quench. We interpret this as indicating that the beam loss was just strong enough to induce a quench in a small coil volume, i.e., the event produced an energy deposition in the coil very close to the quench level. 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. Given the large uncertainties in the initial setting of thresholds, this finding is very positive: the quench level that was assumed for the threshold setting hinged upon a very optimistic interpretation of a quench test in 2013 [19]; for as much as we knew at the beginning of Run 2, the quench level could have been as much as four times lower.

Figure 6: Screenshots of the BLM post-mortem analysis tool for (Up) a UFO event that dumped the beam without quench, and (Down) the third UFO-induced quench.

Unnecessary Beam Dumps

After the multitude of UFO-induced beam dumps at the end of September and in early October 2015, a detailed analysis of the post mortem data of the individual events was carried out. It was established that the relative timing between data from different ionization chambers is accurate to within 40-80 μs [20]. Plotting the registered BLM signals of the monitors that recorded the strongest signal during the UFO side-by-side with the monitor at the beam dump allows to establish whether the beam dump occurred sufficiently early to shorten the UFO event significantly.

Figure 6 shows two samples of this analysis. The upper plot shows an event that did not lead to a magnet quench. The UFO signal is essentially over roughly 160 μs before the signals at the beam dump appear. We see that the UFO event was already over by the time the beam dump had started. In the lower event, which shows the third UFO-induced magnet quench, the beam dump did cut the event short. 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.

Further analysis showed that out of eleven beam dumps in Arc and DS sections which caused beam dumps without quenching, nine events were of the type shown in Fig. 6 (Up), i.e., the beam dump did not shorten the UFO; one event may have been shortened, but, given the BLM sensitivity in the UFO location, the beam dump did not avoid a quench; the last remaining beam dump in this category may have actually avoided a quench. At the same time, analysis of the three UFO-induced quenches showed that in order to avoid all three quenches, thresholds would have had to be reduced by 50%. Comparison with UFO-buster data reveals that such a reduction would have added another 20 unnecessary beam dumps to the above ten.

Availability studies have revealed that in the 2015 proton run a premature beam dump reduced the time in stable-beams mode on average by three hours. In case of a quench we have to add to this time the cryogenic recovery and the precycle, resulting in a total of twelve hours lost for physics [21]. Combined with the findings of the precedent paragraph we see that raising thresholds in order to avoid dumping on UFOs, on the one hand, would have resulted in at most 48 hours of down time due to quenches and no unnecessary dumps. Lowering thresholds by 50%, on the other hand, would have caused 90 hours of down time for unnecessary dumps, and no quenches. The actual setting resulted in 33 hours lost due to unnecessary dumps and 36 hours due to quenches. We conclude that the optimum setting in terms of sensitivity is a threshold that is high enough to avoid dumping on UFO events.

As an intermediate step in this direction, thresholds in Arc and DS sections were increased by 50% in mid October, with two weeks of proton operation remaining. One unnecessary beam dump and no UFO-induced quenches were recorded in that period. One unnecessary beam dump could be avoided. Coincidentally, the fill that was not dumped after 16 hours due to the increased thresholds turned out to be the record fill of 24 hours duration of 27 October.

Threshold Modifications during YETS

As a consequence of the above, the BLM Thresholds Working Group proposes to increase BLM thresholds for loss durations in the UFO time scale (40-640 μs) by another factor of two. It is acknowledged that this setting is a departure from the initial thresholds strategy that had strived to avoid beam-induced quenches. Given the very low number of UFO-induced quenches in 2015, all of which occurred at very different UFO rates and beam intensities than those expected for 2016, it is not possible 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.

We note that it is to be expected that initial UFO-rates in 2016 will be higher than at the end of 2015. We are, however, confident, that the initial scrubbing and the conditioning during the intensity ramp will be effective enough to make the above-proposed strategy viable also in the initial phases. Moreover, in order not to jeopardize the protection of the superconducting magnets, we propose to reassess the strategy in case an overall number of 15 UFO-induced quenches per year is exceeded.

SUMMARY

Experience with UFOs in 2015 has shown that, for operation at 6.5 TeV, UFOs have the potential to cause beam-induced quenches and disrupt operation. Such events, however, appear to be sufficiently rare that they are not expected to cause a major limitation to operation in 2016, provided

BLM Thresholds are not set too tightly. We note that UFOs, while known in principle [3, 4, 22, 5, 6], had not been expected to pose any kind of threat for LHC operation before the machine had started operation. However, as of today we look at data that suggests that we narrowly escaped a crisis. A change by several tens of percent in any of the parameters of the mathematical model of UFO dynamics [7, 8, 9] could have held back the potential of the machine. Recall in this context that before Run 2 the quench levels in the range of UFO-loss durations had been uncertain to within a factor of four. Referring, therefore, to the title of this contribution, we state that luck appears to be an important factor when it comes to surviving a UFO attack.

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