DETECTION OF UNIDENTIFIED FALLING OBJECTS AT LHC

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Abstract

About 3600 Ionization Chambers are located around the LHC ring to detect beam losses that could damage the equipment or quench superconducting magnets. The Beam Loss Monitors (BLMs) integrate the losses in 12 different time intervals (from $40\mu s$ to $83.8s$) allowing for different abort thresholds depending on the duration of the loss and the beam energy. The signals are also recorded in a database at 1 Hz for offline analysis. Since the 2010 run, a limiting factor in the machine availability occurred due to unforeseen sudden losses appearing around the ring on the ms time scale. Those were detected exclusively by the BLM system and they are the result of the interaction of macro-particles, of sizes estimated to be 1-100 microns, with the proton beams. In this document we describe the techniques employed to identify such events as well as the mitigations implemented in the BLM system to avoid unnecessary LHC downtime.

DETECTION AND OBSERVATIONS

The BLM system [1] is responsible for the protection of the LHC magnets against quenches or damage caused by beam losses. About 3600 Ionization Chambers (IC) are situated at likely-loss locations. The electrical signals of the BLM monitors are integrated via current to frequency converter over a period of $40\mu s$, digitized and sent to the surface installation for further treatment. The system keeps a history and computes 12 running sums, which correspond to signals integrated in 12 different time intervals spanning from $40\mu s$ to $83s$. The BLM system will request a beam dump if any of the 12 Running Sums (RS) exceed a set of predefined thresholds [2], that estimate the quench or damage levels for a given energy and loss duration. Furthermore, the BLM system drives the signals recorded in the 12 RSs and corresponding thresholds of all 3600 detectors to both an on-line display for continuous monitoring and to the LHC logging service, where they are stored for offline analysis. Finally, in case of trigger of a beam dump, post-mortem data with information of the losses around the ring during up to 1000 LHC turns are stored.

On the 7th of July of 2010, the BLM system triggered a beam dump as a consequence of unforeseen beam losses in the time range of $\sim 1ms$. A total of 48 similar events have occurred since then, becoming a limiting factor for the operation of the LHC. The cause of these losses is believed to be the interaction of dust particles of sizes 1-100μm falling into the beam, the so-called Unidentified Falling Objects (UFOs). In order to accumulate statistics and further understand the behaviour of such events, a systematic search for below threshold UFOs was carried out. The detection algorithm requires two BLMs within a distance of 40m to have a signal larger than $1 \cdot 10^{-4} Gy/s$ in RS04 ($0.640ms$ integration window). In addition, constrains are set in the ratio of signals observed in RS02/RS01 ($80\mu s/40\mu s$) and RS03/RS01 ($320\mu s/40\mu s$) to separate low signal UFOs from noise.

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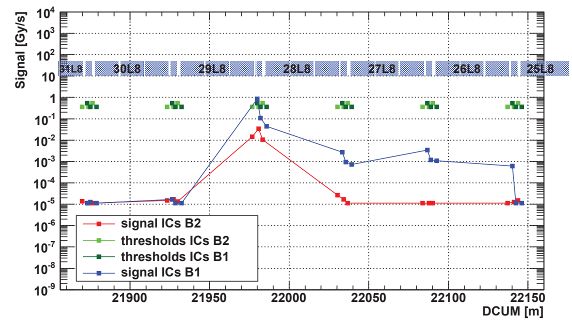

Figure 1: Longitudinal profile of a UFO in the LHC arc.

Figures 1 and 2 present a typical longitudinal and temporal profile of a UFO event as observed by the BLM system. The beam losses may be observed in several cells downstream of where the proton-dust originally interacted as well as aperture limitation (i.e collimation areas). The temporal profile follows a gaussian-like distribution, with $\sigma \sim 100\mu s$.

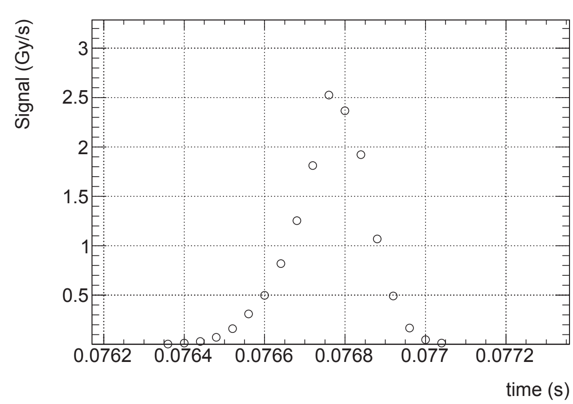

Figure 2: Temporal profile of a UFO in the LHC arc.

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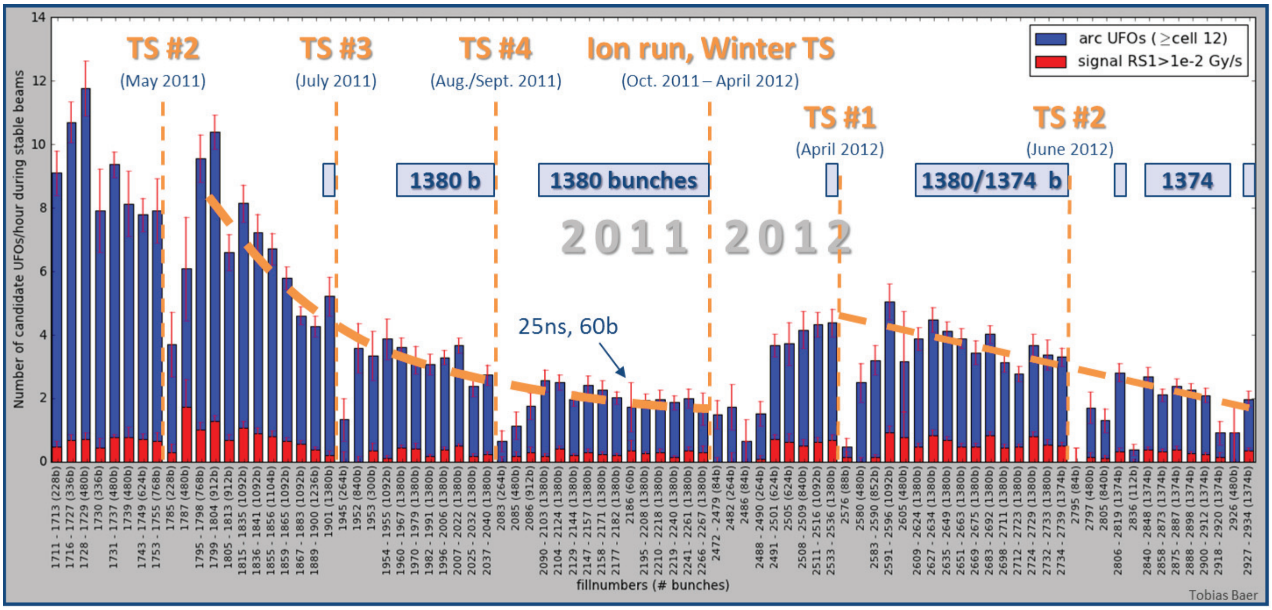

Figure 3: UFO rate evolution throughout the 2011 and 2012 runs. Only UFOs detected in the arc during fills of a duration larger that one hour are considered.

The UFO events [3] occur all around the LHC ring with a few locations, such as the injection kicker magnets in IP2 and IP8 and several cells in the arcs, observing a significant excess. The frequency of observation has been found to increase linearly with intensity [4, 5, 6] up to a few hundred of nominal bunches (typical bunch intensity $1.5 \cdot 10^{11} p$). A saturation effect is observed for larger intensities, where the UFO rate remains roughly constant. Figure 3, presents the UFO rate in the LHC arcs throughout the 2011 and 2012 runs. A clear conditioning effect is observed with the number of observed UFOs decaying from $10 evts/h$ to $2 evts/h$ at the end of the 2011. The UFO rate increased to $5 evts/h$ in the 2012 run and it had decreased back to $2 evts/h$. A drop in the UFO rate is observed every Technical Stop (TS) due to the LHC intensity ramp up and it recovers to the normal trend after the intensity reaches the current maximum of 1380 bunches.

Figure 4 presents the UFO rate versus normalized emittance as calculated from luminosity at the beginning of the LHC fill. The green points represent the UFO rate observed in each individual fill, whereas the blue circles represent the average of all fills within an emittance bin. A linear fit performed over the binned data is compatible with an increasing tendency of the UFO rate with emittance. For the calculation, gaussian round beams with identical size in the horizontal and vertical plane are assumed. Moreover, the emittance values are overestimated by 20% due to the fact that no crossing angle is considered.

However, the beam emittance grows throughout an LHC fill [8, 9]. The UFO rate for a beam with emittances within two limits ($\epsilon_L < \epsilon < \epsilon_H$) is calculated as:

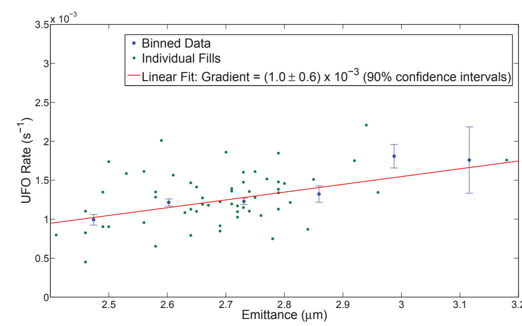

Figure 4: UFO rate vs normalized emittance calculated from luminosity at the beginning of the LHC fill. Only fills from April until July 2012, with duration larger than 1 hour and 1374 or 1380 nominal bunches are considered.

$$Rate(\epsilon) = \frac{N_{UFOs}(\epsilon_L < \epsilon < \epsilon_H)}{\Delta t(\epsilon_L < \epsilon < \epsilon_H)} \quad (1)$$

where N_{UFOs} and Δt are the number of observed UFOs and the integrated time for beams with emittances in the given interval. The UFO rate is presented in Fig. 5 (6) versus horizontal (vertical) emittance as computed from Beam Synchrotron Radiation Telescope (BSRT) beam size measurements at the moment of occurrence of the UFO[1]. Due to technical issues with the absolute calibration of the BSRT in Beam 2 (B2), the results presented reffer exclusivelly to B1. A different tendency is observed for UFO rates versus horizontal and vertical emittance. The rate is fitted to a straight line obtaining a slope significantly larger for

[1] The BSRT provides measurements of horizontal and vertical beam size for both beams with a relative (absolute) precision of 10 % (30 %)

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the horizontal case. This asymmetry suggest that the UFO may be caused by the interaction of dust particles falling into the beam under the influence of mainly gravity and the due to electromagnetic attraction.

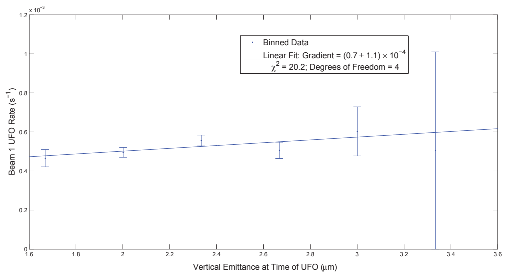

Figure 5: UFO rate vs normalized vertical emittance calculated from BSRT beam size measurements at the moment of UFO occurrence. Only LHC fills from April until July 2012, with duration larger than 1 hour and 1374 or 1380 nominal bunches are considered.

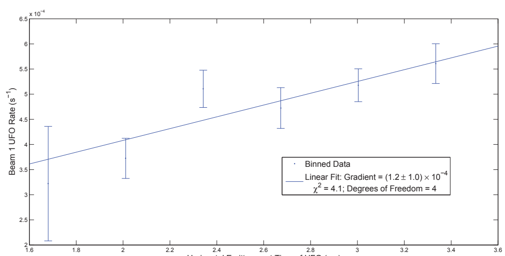

Figure 6: UFO rate vs normalized horizontal emittance calculated from BSRT beam size measurements at the moment of UFO occurrence. Only LHC fills from April until July 2012, with duration larger than 1 hour and 1374 or 1380 nominal bunches are considered.

Note that a correlation between bunch charge and emittance has been observed during the LHC fills under investigation. However, previous studies [7] had shown that the UFO rate remains independent on the bunch intensity. Moreover, an increase on the UFO rate due to bunch charge variation would not explain the horizontal/vertical asymmetry observed.

BEAM DUMP STATISTICS, MITIGATIONS AND DIAGNOSIS IMPROVEMENT

The 48 beam dumps requested by the BLM system due to UFO losses observed around the ring are classified according to their location and beam energy in tables 1 and 2 respectively. The lack of UFOs observed during injection and ramp are attributed to two factors, namely: lower energy density of the secondary shower produced by lower energy protons and a significantly shorter integrated beam time at energies lower than top energy[2]. The reduction in the number of observed UFOs in the LHC arcs, Dispersion Suppressor (DS) and Straight Section (SS) and injection kickers (MKI) for later runs is a consequence of the mitigation strategies applied. At the beginning of the 2011 run, the BLM thresholds were increased by a factor 5 in the $2.5ms$ running sums in order to avoid unnecessary downtime. Note that the numbers of dumps requested by the experiment Beam Condition Monitors (BCM) remain constant.

[2] 3.5 TeV during the 2010 and 2011 run and 4TeV during the 2012 run

Table 1: Summary table of UFOs producing beam dumps at different locations during the 2010, 2011 and 2012 runs.

Run	ARC	DS and SS	MKI	BCM
2010	3	11	2	2
2011	2	1	11	3
2012	0	3	7	3

Table 2: Summary table of UFOs producing beam dumps at different beam energies during the 2010, 2011 and 2012 runs.

Run	Injection	Ramp	Top Energy
2010	0	1	17
2011	1	2	14
2012	2	1	10

The BLM system in the LHC arcs equips the Main Quadrupoles (MQ) with three ICs (per beam) separated by ∼3 and ∼4 m respectively. This provides both redundancy and spacial resolution to distinguish between beam losses originated at different points within a MQ. However, the absence of BLM monitors between two MQs (separated by $\sim 50m$) prevents from determining the original location of the beam loss if it happens anywhere within the three Main Bending (MB) dipoles located in between. During the beginning of the 2011 LHC run, four BLM detectors were situated at the MBs magnets of cell 19R3[3] as shown in Fig. 7(a). Data collected during the 2012 run have shown that UFO losses may originate anywhere within the LHC FODO cell. Two extra BLM monitors located in the surroundings of the MKI magnets and two extra BLMs downstream of the Q5 magnet have also provided information to determine the location of the UFOs in those areas. Moreover, diamond detectors located in the momentum cleaning and betatron cleaning areas are being investigated as extra diagnosis for UFO detection [10]. The fast response of these detectors allows to investigate the interaction of dust particles with individual LHC bunches.

Finally, a specific data capture buffer has been developed in order to allow a further understanding of the UFO temporal evolution. When a UFO event is identified the BLM data during a window of $\sim 350ms$ is frozen and saved, in integration widows of $80\mu s$, for offline analysis.

[3] Cell 19R3 is one of the LHC locations where a larger fraction of UFOs has been systematically observed

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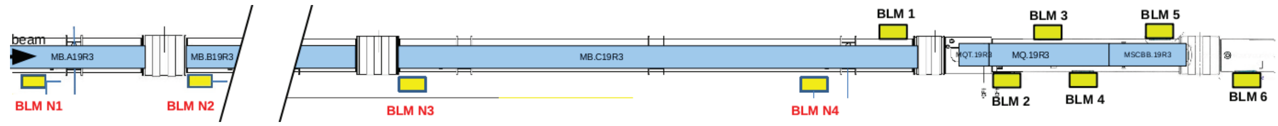
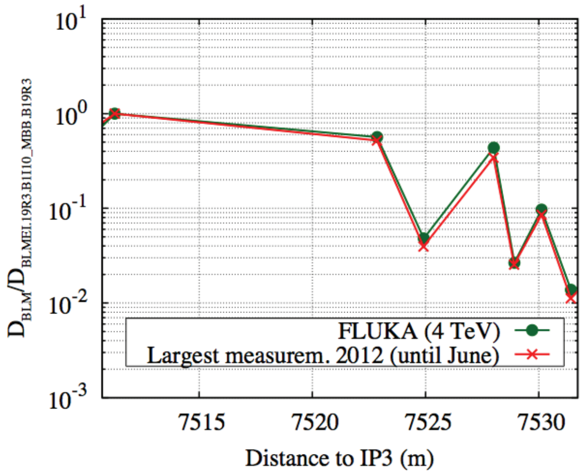
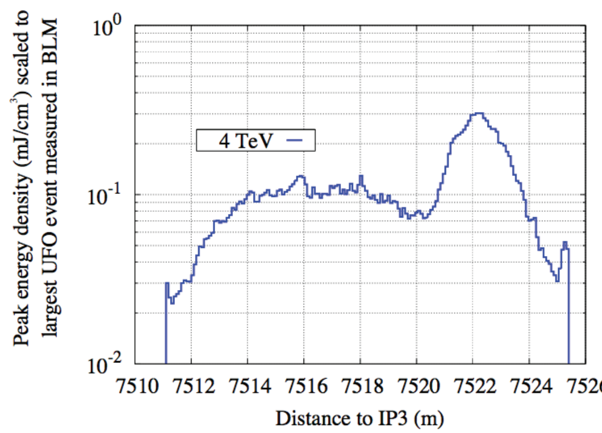


(a) View of cell 19R3



(b) Normalized signal for data and fluka simulation



(c) Peak energy density along the third MB

Figure 7: Layout of the BLMs in 19R3 LHC cell (Top) as implemented in FLUKA, results of the simulation compared with data (bottom right) and estimation of the peak energy density deposited in the MB coil.

FLUKA SIMULATIONS

The FLUKA [11, 12] geometry of a LHC arc cell[4] (MB-MB-MB-MQ) has been implemented and the (inelastic) interaction of Fe particles with the beam at different positions within the cell have been simulated [14]. It was demonstrated that the six BLMs installed around the MQ magnet, do not provide enough information to distinguish between different UFO locations. The obtained longitudinal profiles were considered for the installation of more monitors as described above.

A comparison of the predicted loss profile with data observed during the 2012 run [15] is presented in Fig. 7(b). The UFO is simulated to occur 1.3 meters upstream of the interconnection between the second and third MB. A very good agreement between data and simulation is observed. Figure 7(c) shows the peak energy density along the third MB as obtained by the FLUKA simulation. The peak observed towards the end of the magnet is due to neutral particles hitting the MB aperture. The peak energy density estimated by Fluka at 7TeV increases by a factor ~ 4 with respect to 4TeV. Since the quench limit at high energy is reduced by a factor ~ 5, UFO events may become a potential limitation for the operation of the LHC at nominal top energy.

A different distribution of BLMs in the arc cells, which would provide extra flexibility in local increases of dump thresholds, is under investigation. In the new configuration, one of the redundant BLMs located at the MQ would be moved to one of the bending magnets.

[4]FLUKA simulations of Al particles interacting with the proton beam around the MKI magnets in IP2 have been also performed [13]

THE THEORETICAL MODEL

A model that describes the interaction of particles with the beam has been developed [16]. It is assumed that the micron-size particle is influenced by electric beam force, electric image force, gravity and magnetic force. Under certain assumptions, the model derives equations for the trajectory and charge rate of the particle as well as for the proton loss rate.

Several of the model predictions have been confirmed by observation, namely:

- A decreasing tendency of the loss duration with beam current was presented in [5].
- The model predicts, assuming spherical macro-particles, a gaussian-like distribution with asymmetric tails for the proton loss rate. This is observed in the BLMs as shown in Fig. 2
- A proton loss rate proportional to the particle mass is predicted. This agrees with the observation, since the UFO peak signals distribution [3] shows the same $1/x$ behaviour as the measured distributions of particle sizes in test [17].
- The model predicts events in which a UFO falls into the beam, it gets positively charged and it is repulsed by the electromagnetic force with the possibility to fall back into the beam. Such UFO events with precursors have been observed [4].

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CONCLUSIONS

Unforeseen beam losses in the ms time range have been systematically observed during the LHC operation. The observed losses are attributed to the interaction of micron-sized particles with the beam. A total of 48 beam dumps have been requested due to UFO losses, requiring to tune the BLM dump thresholds in order to reduce the number of unnecessary dumps without compromising the protection of the LHC equipment. Moreover, several improvements on the diagnosis (location of extra BLMs, diamond detectors and UFO capture buffer) have been implemented or they are under investigation in order to better understand the behaviour of such events. FLUKA simulations of the interaction of Fe (Al) particles with the beam in the arc (and MKI magnets) have been studied. A good agreement between the simulated and observed BLM signals has been found and predictions of the peak energy density deposited in the magnetic coils are given. Taking this results into consideration, a re-arrangement of the BLM detectors in the LHC arcs (to be implemented during the long shut down in 2013) is under investigation. Finally, a theoretical model of the interaction of micron-size particles with the proton beam has been developed. Several of its predictions have been confirmed by the observation of UFO events in the LHC.

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