UFOs in the LHC after LS1

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Abstract

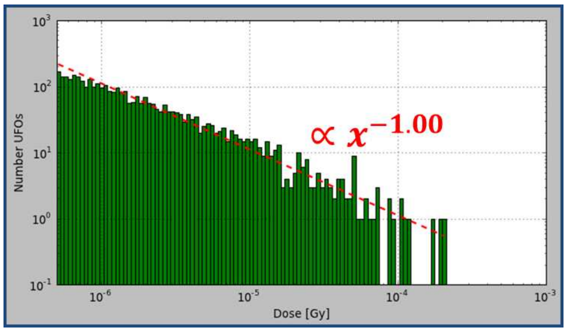
UFOs ("**U**nidentified **F**alling **O**bjects") are potentially a major luminosity limitation for nominal LHC operation. With large-scale increases of the BLM thresholds, their impact on LHC availability was mitigated in the second half of 2011. For higher beam energy and lower magnet quench limits, the problem is expected to be considerably worse, though. Therefore, in 2011, the diagnostics for UFO events were significantly improved, dedicated experiments and measurements in the LHC and in the laboratory were made and complemented by FLUKA simulations and theoretical studies.

In this paper, the state of knowledge is summarized and extrapolations for LHC operation after LS1 are presented. Mitigation strategies are proposed and related tests and measures for 2012 are specified.

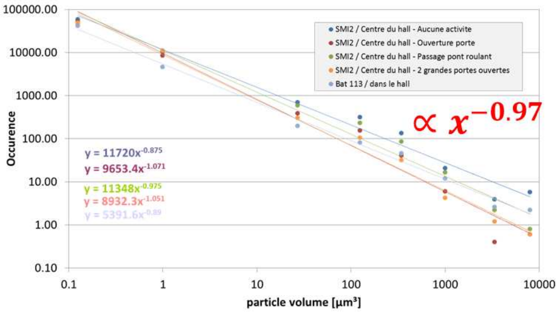
OBSERVATIONS AND CORRELATIONS

Between July 7th 2010 and end of 2011, so called **UFOs led to in total 35 premature protection beam dumps of LHC fills.** UFOs are presumably micrometer sized dust particles that lead to fast, localized beam losses when they interact with the beam. The duration of the beam losses is of the order of 10 turns. Such events were observed in the whole machine and for both beams. With large-scale increases of the BLM thresholds, their impact on LHC availability was mitigated in the second half of 2011. An introduction to the topic is given in [1, 2].

Most of the UFO events lead to beam losses far below the BLM dump thresholds. These events are detected in real time by the *UFO Buster* application from the $1\,\mathrm{Hz}$ BLM concentrator data, which contains the maximum beam loss, integrated over 12 different time intervals between $40\,\mu\mathrm{s}$ and $83.8\,\mathrm{s}$ [1, 3]. In 2011, more than **16'000 candidate UFO events** with a BLM signal below the dump thresholds have been detected. Figure 1a shows the distribution of the integrated beam loss signal (dose) of the UFO events observed in the LHC arcs. The number of events is almost inversely proportional to the dose. A similar dependency was measured for the distribution of the dust particle volume in the magnet test halls (Fig. 1b). Since there is an almost proportional dependency between dust particle volume and resulting beam losses according to the theoretical model [4], **the observed UFO event distribution is well explained by the observed dust particle distribution.**



(a) Distribution of integrated beam loss signal of UFO events.



(b) Distribution of dust particle size (courtesy of J.M. Jimenez).

Figure 1: The histogram of the integrated beam loss signal for 4513 arc UFOs ($\geq$ cell 12) at $3.5\,\mathrm{TeV}$. All proton fills in 2011 since 14th April are taken into account. Only UFO events with a dose $> 5 \cdot 10^{-7}\,\mathrm{Gy}$ are considered (a). The distribution is well explained by the distribution of the dust particle volume measured in the magnet test halls (b).

Figure 2 shows the evolution of the arc UFO rate in 2011: While the beam intensity was increased from 228 to 1380 bunches, **the arc UFO rate decreased from about 10 UFO events per hour to about 2 events per hour.** Throughout stable beams, the UFO rate is constant [5].

The spatial distribution of the UFO events (Fig. 3), shows that the UFOs occur all around the LHC. Many events occur especially around the injection kicker magnets (MKI). Similarly, there is a significantly increased UFO activity in certain arc cells (144 UFO events in cell 25R3 beam 2, 126 UFO events in cell 19R3 beam 1 and 118 UFO events in cell 28R7 beam 2).

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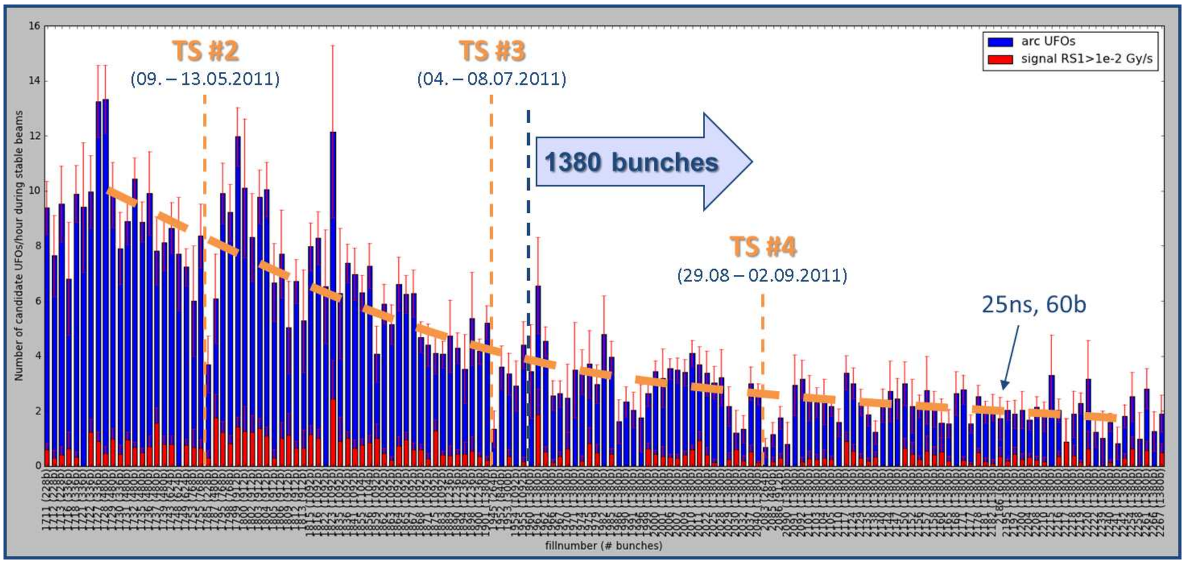


Figure 2: The rate of candidate arc UFO events ($\geq$ cell 12) during stable beams for 5242 candidate UFO events with a BLM signal $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$ for the $640\,\mu\mathrm{s}$ integration time. All proton fills in 2011 since 14th April 2011 with at least one hour of stable beams are taken into account. The average rate decreased from about 10 UFO events per hour to about 2 UFO events per hour throughout 2011. The rate is reduced during the low intensity fills after the technical stops (TS).

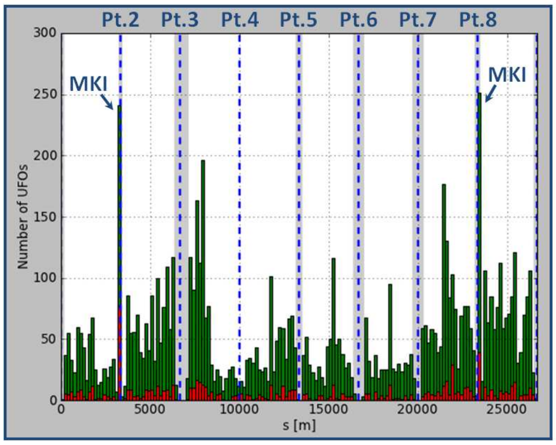


Figure 3: The spatial distribution of 7784 candidate UFO events at $3.5\,\mathrm{TeV}$ with a BLM signal $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$ for the $640\,\mu\mathrm{s}$ integration time (green) and with an additional cut which discards events with a BLM signal below $10^{-2}\,\mathrm{Gy/s}$ for the $40\,\mu\mathrm{s}$ integration time (red). The vertical dashed blue lines indicate the locations of the interaction regions. The gray areas are excluded from UFO detection.

MKI UFO STUDIES

Four injection kicker magnets (MKIs) are installed both in Pt. 2 for the injection of beam 1 and in Pt. 8 for the injection of beam 2. The MKIs in Pt. 2 and Pt. 8 are labeled *MKI.A - MKI.D* with MKI.D being the magnet seen first by the injected beam [6].

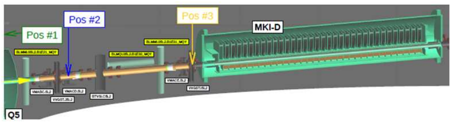
With 11 beam dumps in 2011, the UFOs at the MKIs had the largest impact on LHC operation. Eight of these events occurred at $3.5\,\mathrm{TeV}$, but only 2 during stable beams. Ten events occurred at the MKI.D in Pt. 2. In total, 847 UFO events with a BLM signal below dump threshold were observed around the MKIs in Pt. 2 and 1493 events around the MKIs in Pt. 8. As presented in [1], **most of the UFO events around the MKIs occur within about 30 minutes after the last injection.** Additionally, as shown by two MDs in 2011, **many events occur within a few hundred milliseconds after pulsing the MKIs** [6, 7]. Assuming that a dust particle is released from the aperture at the moment of the kicker pulse and accelerated only by gravitational force towards the beam, the expected delay until the particle reaches the beam center is $62.3\,\mathrm{ms}$ [6]. Many events with a shorter delay have been observed (the shortest observed delay is $3.3\,\mathrm{ms}$ [1]). A possible explanation for the short delays could be initially charged dust particles which are accelerated also by the electric fields of the MKIs and the proton beam [8].

Dedicated vibration studies of the MKIs showed that pulsing the MKIs leads to mechanical vibrations [9]. Although the measured displacements are only about $10\,\mathrm{nm}$, such vibrations could also have a substantial influence on the production and release of macro particles in the MKIs.

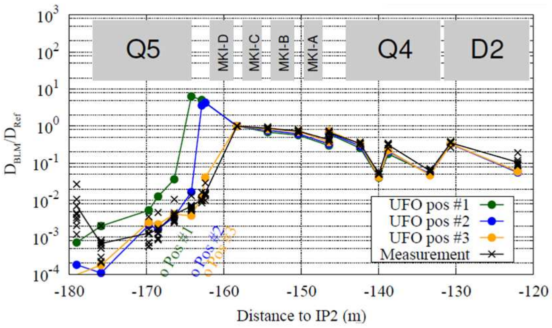
FLUKA Studies and Dust Particle Size

Dedicated FLUKA simulations of UFOs at the MKIs in Pt. 2 were made [10]. These simulations reveal that **the UFO location must be in (or nearby upstream) of the MKIs** in order to explain the observed loss patterns (Fig. 4).

Furthermore, based on the FLUKA simulations, it is estimated that a minimal radius of $\approx$ **40 μm** for spherical macro particles is needed in order to explain the loss signal in the BLMs of large UFO events [5] (assuming an Al_2O_3 particle).



(a) Layout for FLUKA simulations.



(b) Simulated beam losses.

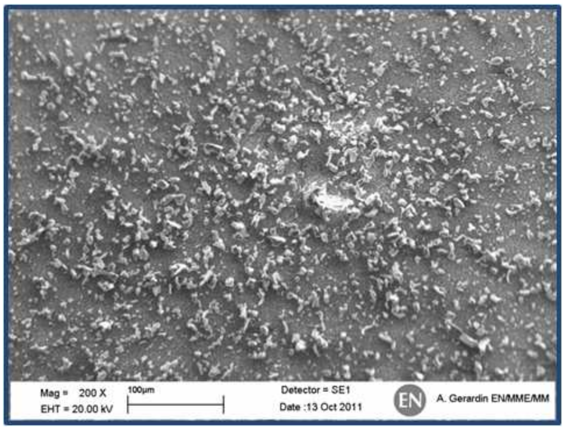
Figure 4: The interaction of macro particles with the proton beam was simulated for different locations (*Pos #1 - Pos #3*) around the MKI.D in Pt. 2 using FLUKA (a). The comparison of the expected loss patterns and some typical measured UFO loss patterns shows discrepancies for UFOs occurring too much upstream of the MKI (b) (courtesy of A. Lechner and the FLUKA team [10]).

MKI Inspection for Macro Particles

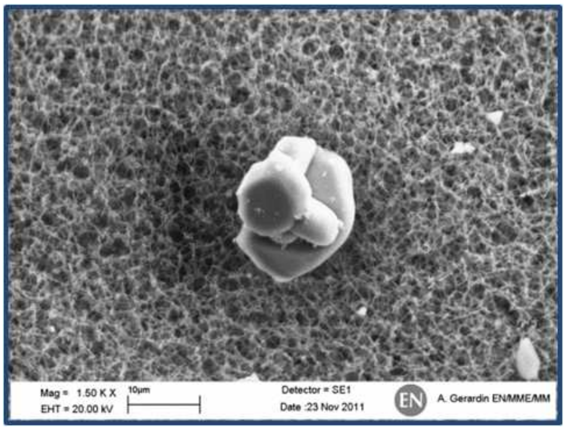
In the winter technical stop 2010/11 the MKI.B was removed from Pt. 2 and replaced. This tank was opened in October 2011 and inspected for macro particles. In a standardized procedure, the tank was flushed with N_2 through a filter to sample macro particles [11]. In reference measurements with clean room air and a new ceramic tube, 100 and 10'000 macro particles, respectively, were found on the filter. **In the inspection of the MKI tank 5'000'000 particles were found on the filter** (Fig. 5a). Most of the macro particles are of micrometer size, but a few range up to about 100 μm. An energy-dispersive X-ray spectroscopy of the particles showed that they mainly consist of Al and O, leading to the conclusion that **the macro particles originate from the Al_2O_3 ceramic tube.**

THEORETICAL MODEL

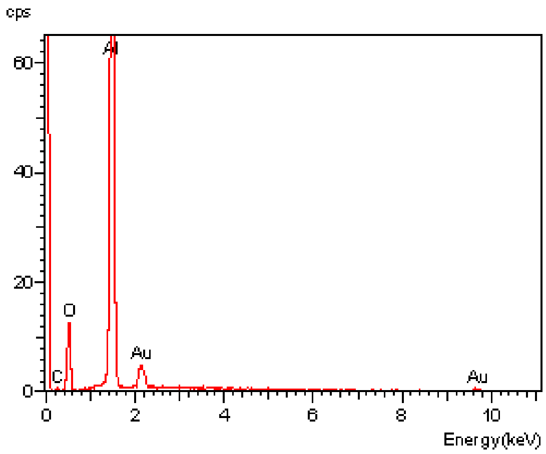
Dedicated simulations of the dynamics and interactions of macro particles falling from the top into the circulating proton beam were made [4]. A general conclusion is that macro particles are charged up positively by the proton beam and are deflected or even repelled by the beam. Many predictions are described in [4], among which are (in agreement with the observations [1, 12]) that the typical loss duration is of the order of 1 ms and that the loss duration becomes shorter for larger beam intensities. Figure 6 shows the predicted normalized beam loss rates for different macro particle masses. In 2012, the diagnostics are improved [6], which will allow to observe the predicted asymmetry in the loss profile.



(a) Macro particles on filter.



(b) Zoom of a macro particle.



(c) Energy-dispersive X-ray spectrum of particle in b.

Figure 5: The MKI tank which was removed from the LHC was flushed in a standardized procedure with N_2 through a filter. By this, about 5'000'000 particles were sampled on the filter (a). An energy-dispersive X-ray spectroscopy (EDS) of the samples reveals that most particles consist of Al and O (c). Traces of gold in the EDS spectra are because gold is sputtered on the filters after sampling the dust particles in order to ensure electrical conductivity (courtesy of A. Gérardin et al. [11]).

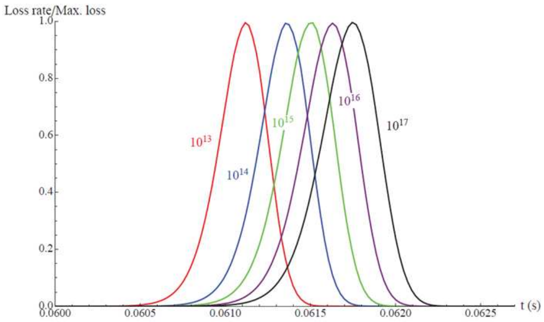


Figure 6: Normalized beam loss rate for macro particles with different masses (in atomic mass units) and a beam intensity of $1.6 \cdot 10^{14}$ protons as predicted by the theoretical model (courtesy of N. Fuster Martinez et al. [4]).

MID-TERM EXTRAPOLATION

As implicated by Fig. 2 there is no increase of UFO activity with the beam intensity observed for intensities above several hundred bunches. This is in accordance with the expectation from the theoretical model [4].

25 ns Operation

During the MD with a bunch spacing of 25 ns on 24th/25th October at 450 GeV, a rather high UFO activity was observed. In 9.1 hours (beam 1) and 13.3 hours (beam 2), with a beam intensity of more than 10^{13} protons, in total 159 MKI UFOs and 22 arc UFOs were observed. The normal arc UFO rate at injection energy is below 0.5 UFOs per hour [12].

Also the 25 ns fill 2186 with only 60 bunches had about 2 arc UFO events per hour during stable beams - a rate comparable to the 1380 bunch fills at the same time (Fig. 2). Normally, the UFO rate is significantly decreased for the fills with reduced beam intensities after technical stops.

Energy Dependence

As shown in [12], the beam loss due to UFOs is expected to increase with beam energy. Based on wire scanner measurements at different energies, it is expected that the BLM signal of an UFO at 7 TeV is about three times higher than at 3.5 TeV. The same scaling was found for the peak energy deposition in the D2 separation dipole magnet from the MKI FLUKA simulations [10]. Moreover, due to higher currents, the magnet quench limit is lower for higher beam energy (about a factor 5 for operation at 7 TeV compared to 3.5 TeV). Figure 7 shows the expected scaling of BLM signal/BLM threshold with energy normalized to 3.5 TeV. When applying the expected scaling to the BLM signals and thresholds of all arc UFOs that were recorded in 2011, they would have caused **81 beam dumps**, if the LHC would have been operated at 7 TeV instead of 3.5 TeV (Fig. 7). An additional **27 beam dumps** would have been caused by MKI UFOs. These numbers have to be compared to two actual dumps by arc UFOs and 11 dumps by MKI UFOs in 2011. Concerning the MKI UFOs, 4 out of the 11 dumps would have been avoided with the increased BLM thresholds that were in use during the second half of the year. It has to be noted that this extrapolation assumes (apart from the beam energy) identical running conditions as in 2011. Excluded are potential increases of the BLM thresholds, the conditioning effect (Fig. 2), a possibly increased UFO rate at 25 ns operation and changes in beam intensity and beam size. Concerning the MKI UFOs, only the BLM thresholds at the superconducting elements are assumed to be limiting.

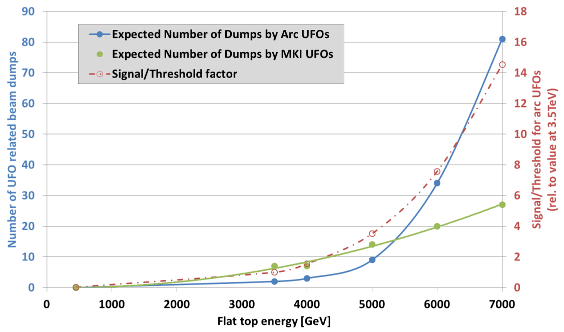


Figure 7: The expected number of beam dumps by arc UFOs and MKI UFOs and the expected scaling of BLM signal/BLM threshold for different energies. All 2011 UFO events since 14th April are considered (based on [10, 12]).

OUTLOOK

For 2012, an additional focus is put on the study of arc UFOs. For this purpose, the arc cell 19R3, in which exceptionally many UFOs were observed in 2011, was equipped with additional BLMs to allow a better spatial localization of the UFO events. Corresponding FLUKA simulations are ongoing, which will also improve the accuracy of the energy extrapolation. First results are presented in [13].

Complementary to the FLUKA simulations (which are based on inelastic proton-UFO interactions), MAD-X simulations are launched to address beam losses due to elastic proton-UFO interactions.

An additional improvement of diagnostics concerns the BLM study buffer, which will provide data from all BLMs with 80 μs temporal resolution also for UFO events below the BLM dump threshold.

Further tests focusing on 25 ns operation and on the influence of electron-cloud on the UFO activity are foreseen. In particular, a 25 ns fill with at least several hundred bunches which is kept for a few hours at top energy is needed to be able to make educated predictions. Moreover, a MKI UFO MD is planned, in which, apart from the influence of 25 ns operation, the production mechanism of UFOs and potential mitigation strategies are studied.

As long as the production mechanism of the arc UFOs is not understood, the main mitigation strategy is to increase the BLM thresholds towards the quench limit of the superconducting magnets. Thus, a better understanding of the quench limit for UFO type beam losses is crucial for the extrapolations and mitigations for the time after LS1. Two complementary quench tests are proposed:

- **Wire-scanner quench test:** The wire-scanner can produce a loss pattern with a temporal and spatial distribution which is very similar to an UFO event. Simulations can account for the specific characteristics of the geometry and the magnets studied (cf. [14]).

- **ADT quench test:** The transverse damper (ADT) can produce fast losses with a duration which is similar to UFO events. In combination with an orbit bump, localized losses at a dedicated arc dipole magnet can be generated. Particularities of the spatial beam loss patterns can be generalized based on simulations.

Furthermore, it is proposed to increase the arc BLM thresholds of selected sectors, in which the dipole busbar splices were measured to be of good quality, which would allow for operation at even higher energies[1], by a factor 3.3. Apart from a possible gain in availability by avoiding beam dumps due to large UFOs, such events would carefully probe the magnet quench limit at controlled locations.

Another possible mitigation is based on a different distribution of the BLMs within an LHC arc cell, which could also allow for increased BLM thresholds. The arc FLUKA simulations and the additional instrumentation in cell 19R3 will provide the necessary input.

For the MKIs, the main mitigation is an improved cleaning. In addition, two internal modifications, presently being actively considered for other reasons, should be benifical for reducing UFO's in the MKIs: namely, the use of 24 screen conductors instead of the usual 15 screen conductors and closed slots for the screen conductors. For 2012, it is planned to replace during the August technical stop the MKI.D in Pt. 8 by a MKI tank with 24 screen conductors. This will substantially reduce the electric field in the ceramic chamber during the flattop of the field pulse [15]. In the long term, closed slots would prevent Al_2O_3 particles falling from the screen conductor slots into the beam.

CONCLUSION

In 2010 and 2011, in total 35 LHC fills were dumped due to UFOs. In the second half of 2011, the impact of UFOs was mitigated by large-scale increases and optimizations of the BLM thresholds and a conditioning effect for arc UFOs. Nevertheless, 16'000 candidate UFO events below the BLM dump thresholds were recorded and analyzed.

Throughout 2011, intensive studies especially concerning the MKI UFOs were made, which include improvements of the diagnostics [1, 6], dedicated experiments in the LHC [6, 7] and in the laboratory [11, 9], FLUKA simulations [10] and theoretical studies [4]. As a result, the MKI UFOs have been identified as being most likely macro particles originating from the ceramic tube. Their production mechanism, dynamics, the response of the BLM system and fundamental correlations are characterized, which allows for mid-term extrapolations and mitigation strategies.

The energy dependence underlines that UFOs could be a major performance limitation for LHC operation after LS1. With the present operational scenarios, the situation is not expected to be worse for 2012 compared to 2011, though.

For 2012, the specific instrumentation will be further improved. Complementary FLUKA and MAD-X simulations are ongoing. Additional experimental studies, including MDs and quench tests are foreseen and will be essential for the development and testing of adequate mitigation strategies for the time after LS1.

[1] This would apply to the sectors 12, 34, 56 and 67.

REFERENCES

[1] T. Baer et al., "UFOs in the LHC", IPAC'11, TUPC137, Sept. 2011.

[2] M. Sapinski et al., "Is the BLM system ready to go to higher intensities?", Chamonix 2011 Workshop, Jan. 2011.

[3] C. Zamantzas et al., "The LHC Beam Loss Monitoring Systems Data Contribution to Other Systems", Nuclear Science Symposium Conference Record NSS '07, vol.3, pp.2331-2335, Nov. 2007.

[4] N. Fuster Martinez et al., "Simulation Studies of Macroparticles Falling into the LHC Proton Beam", IPAC'11, MOPS017, Sept. 2011.

[5] T. Baer et al., "UFOs: Observations, Studies and Extrapolations", Evian 2011 Workshop, Dec. 2011.

[6] T. Baer et al., "MD on UFOs at MKIs and MKQs", CERN-ATS-Note-2012-018 MD, Aug. 2011.

[7] T. Baer et al., "MKI UFOs at Injection", CERN-ATS-Note-2011-065 MD, Aug. 2011.

[8] F. Zimmermann, "Update on Dynamics Modeling - Effect of Kicker Field", 66th LHC Injection and Beam Dump Meeting, Nov. 2011.

[9] R. Morón Ballester et al., "Vibration analysis on an LHC kicker prototype for UFOs investigation", CERN EDMS Document No. 1153686, Aug. 2011.

[10] A. Lechner, "FLUKA Studies of UFO-induced Beam Losses in the LHC", CERN Accelerator School Poster Session, Sept. 2011.

[11] A. Gérardin et al., "EDS analyses of filters used for UFO sampling", CERN EDMS Document No. 1162034, Sept. 2011.

[12] E. Nebot del Busto et al., "Analysis of fast Losses in the LHC with the BLM System", IPAC'11, TUPC136, Sept. 2011.

[13] A. Lechner et al., "FLUKA Simulations of UFO-induced Losses in the LHC arc", 4th LHC UFO Study Group Meeting, April 2012.

[14] M. Sapinski et al., "LHC Magnet Quench Test with Beam Loss Generated by Wire Scan", IPAC'11, WEPC173, Sept. 2011.

[15] M.J. Barnes, "MKI UFO LIBD Meeting", 64th LHC Injection and Beam Dump Meeting, Nov. 2011.