UFOs: Observations, Studies and Extrapolations*

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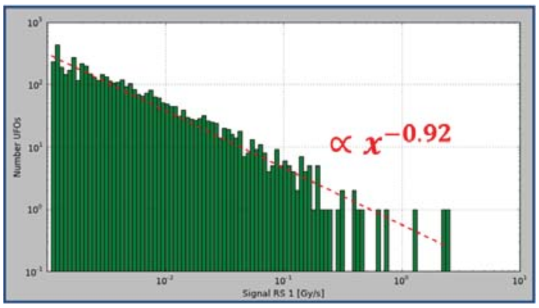
Abstract

UFOs ("**U**nidentified **F**alling **O**bjects") could be one of the major performance limitations for nominal LHC operation. 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. The state of knowledge is summarized and extrapolations for LHC operation in 2012 and beyond are presented. Mitigation strategies are proposed and related tests and measures for 2012 are specified.

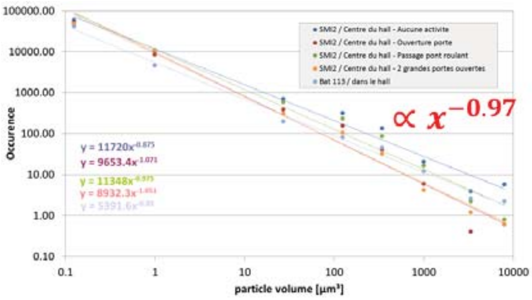
OBSERVATIONS AND CORRELATIONS

Between July 7th 2010 and end of 2011, in total **35 LHC fills where terminated by protection beam dumps due to so called UFOs.** 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 could be mitigated in the second half of 2011. An introduction to the topic is given in [1].

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* 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, 2]. 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 peak signal of the UFO events observed in the LHC arcs. The number of events is almost inversely proportional to the peak signal. 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 [3], **the observed UFO event distribution is well explained by the observed dust particle distribution.**



(a) Distribution of peak signal of UFO events.



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

Figure 1: The histogram of the BLM signal integrated over $40\,\mu\mathrm{s}$ 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 BLM signal $> 10^{-3}\,\mathrm{Gy/s}$ for the $40\,\mu\mathrm{s}$ integration time 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 (Fig. 3).

The spatial distribution of the UFO events (Fig. 4), 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).

Sparking (for example between the RF fingers) is expected to be the most likely production mechanism for arc UFOs, but other mechanisms are imaginable as well [4].

*This document contains colored images. The full color version of this document is available under http://indico.cern.ch/conferenceDisplay.py?confId=155520.

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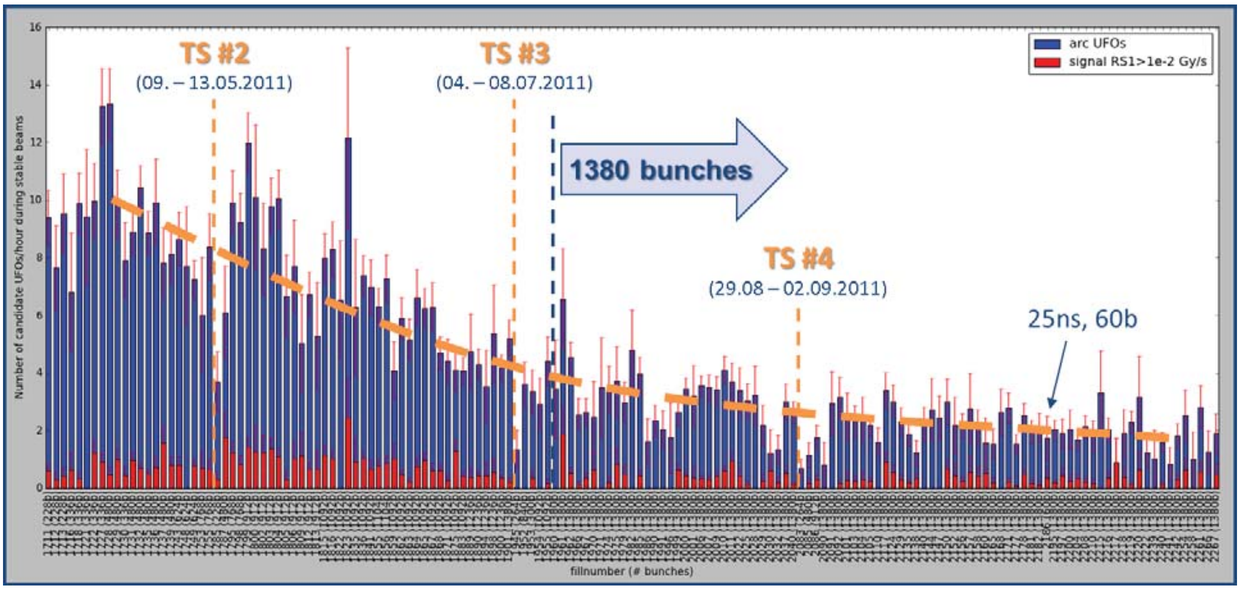


Figure 2: The rate of candidate arc UFO events ($\geq$ cell 12) during stable beams for 5242 candidate UFO events with a BLM signal $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$ for the $640\,\mu\mathrm{s}$ integration time. All proton fills in 2011 since 14$^{\mathrm{th}}$ April 2011 with at least one hour of 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).

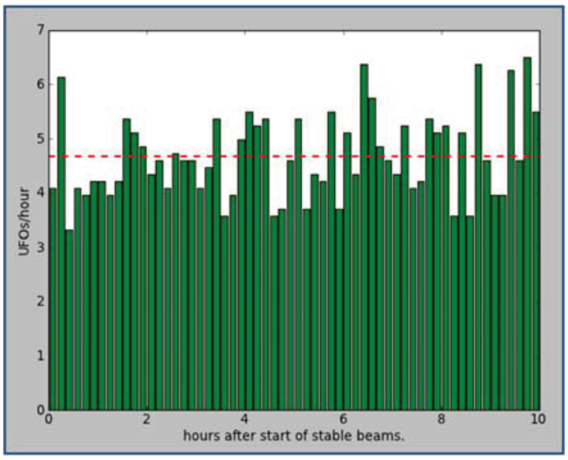


Figure 3: The rate of candidate arc UFO events ($\geq$ cell 12) throughout stable beams. All proton fills in 2011 since 14$^{\mathrm{th}}$ April with at least $10\,\mathrm{hours}$ of stable beams are taken into account. 3185 candidate UFO events with a BLM signal $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$ for the $640\,\mu\mathrm{s}$ integration time are considered.

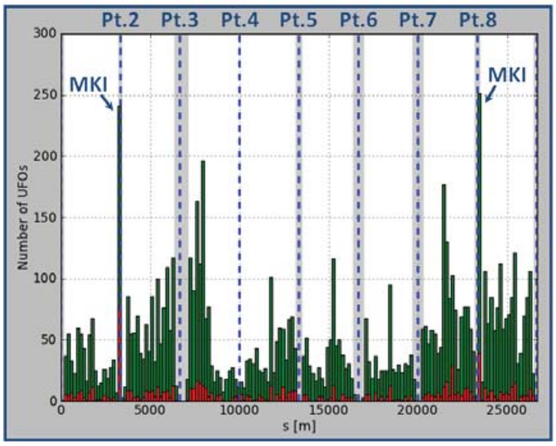


Figure 4: The spatial distribution of 7784 candidate UFO events at $3.5\,\mathrm{TeV}$ with a BLM signal $> 2 \cdot 10^{-4}\,\mathrm{Gy/s}$ (green) for the $640\,\mu\mathrm{s}$ integration time and with an additional cut that discards events with a BLM signal below $1 \cdot 10^{-2}\,\mathrm{Gy/s}$ (red) for the $40\,\mu\mathrm{s}$ integration time. The vertical dashed blue lines indicate the locations of the interaction regions. The gray areas are excluded from UFO detection.

MKI UFO STUDIES

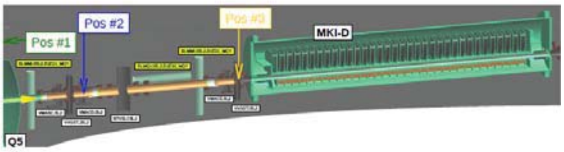
Four injection kicker magnets (MKIs) are installed both in Pt. 2 for the injection of beam 1 and in Pt. 8 for the injection of beam 2. The MKIs in Pt. 2 and Pt. 8 are labeled *MKI.A - MKI.D* with MKI.D being the magnet seen first by the injected beam [5].

With 11 beam dumps in 2011, the UFOs at the MKIs had the largest impact on LHC operation. Eight of these events occured 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** [5, 6]. 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 centre is $62.3\,\mathrm{ms}$ [5]. 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 [7].

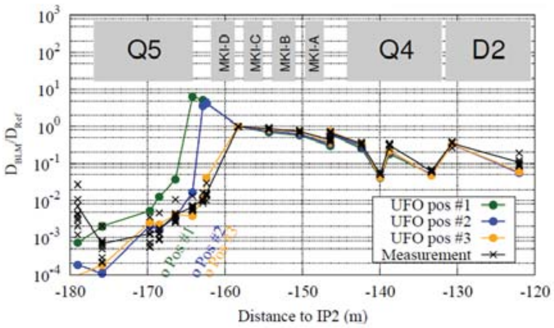
Dedicated vibration studies of the MKIs showed that pulsing the MKIs leads to mechanical vibrations [12]. Although the measured displacements are only about $10\,\mathrm{nm}$ such vibrations could also have a substantial influence on the production and release of macro particles in the MKIs.

FLUKA Studies and Dust Particle Size

Dedicated FLUKA simulations of UFOs at the MKIs in Pt. 2 were made [8]. 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. 5).



(a) Layout for FLUKA simulations.



(b) Simulated beam losses.

Figure 5: The interaction of macro particles with the proton beam were simulated at 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 [8]).

According to the FLUKA simulations, at $3.5\,\mathrm{TeV}$ a signal of $1\,\mathrm{Gy}$ at the BLM after MKI.D in Pt. 2 corresponds to about $4 \cdot 10^{11}$ inelastic nuclear interactions [9]. Thus, taking the large MKI UFO on 16th July 2011 at 14:09:18 for example [9], the peak loss of $8.45\,\mathrm{Gy/s}$ corresponds to $\dot{N}_{p,max} = 3.5 \cdot 10^{12}$ inelastic nuclear interactions per second. Assuming a macro particle in the beam centre with a radius r, which is small compared to the horizontal and vertical beam size σ_x and σ_y, $\dot{N}_{p,max}$ is (in accordance with [3]) given by

$$\dot{N}_{p,max} = \frac{N_p \cdot f_{rev}}{2\pi\sigma_x\sigma_y} \cdot \frac{A \cdot u}{l \cdot \rho}, \tag{1}$$

with N_p being the number of protons in the beam, $f_{rev} = 11,245\,\mathrm{Hz}$ the revolution frequency, A the macro particle mass in atomic mass units u, l the inelastic nuclear interaction length of the macro particle's material and ρ the mass density of the macro particle. For an Al_2O_3 macro particle ($l = 24.8\,\mathrm{cm}$, $\rho = 3970\,\mathrm{kg/m^3}$) and $N_p = 1.02 \cdot 10^{14}$, $\sigma_x = 325\,\mu\mathrm{m}$ and $\sigma_y = 140\,\mu\mathrm{m}$ for the example case, a macro particle mass $A = 5.2 \cdot 10^{17}$ would explain the observed $\dot{N}_{p,max}$. This corresponds to a **radius of 37 μm for a spherical particle.** This result has to be understood as the minimum particle radius needed in order to explain the loss signal of the large example MKI UFO event.

MKI Inspection for Macro Particles

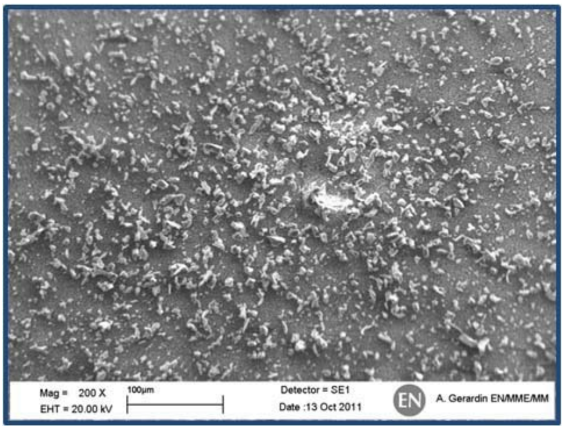
In the winter technical stop 2010/11 the MKI.C was removed from Pt. 2 and replaced. This tank was opened in October 2011 and inspected for macro particles. In a standardized procedure, the tank was flushed with N_2 through a filter in order to sample macro particles [10]. In reference measurements with clean room air and a new ceramic tube, 100 respectively 10'000 macro particles were found on the filter. **In the inspection of the MKI tank 5'000'000 particles were found on the filter** (Fig. 6a). Most of the macro particles are of micrometer size, but a few range up to about $100\,\mu\mathrm{m}$. 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

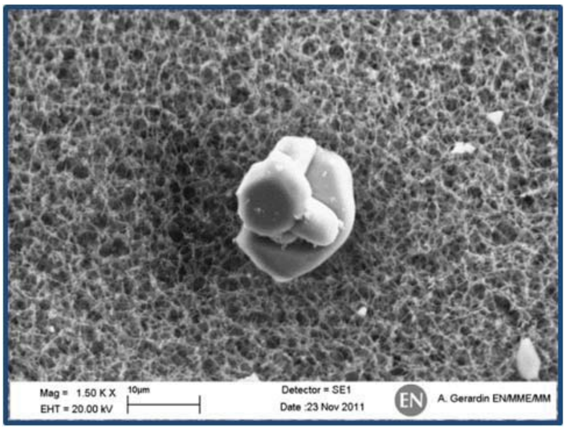
Dedicated simulations on the dynamics and interactions of macro particles falling from the top into the circulating proton beam were made [3]. A general conclusion is that macro particles are charged up positively by the proton beam and are likely to be deflected or even repelled by the beam. Many predictions are described in [3], among which are (in agreement with the observations [1, 11]) that the typical loss duration is of the order of $1\,\mathrm{ms}$ and that the loss duration becomes shorter for larger beam intensities. Figure 7 shows the predicted normalized beam loss rates for different macro particle masses. In 2012 the diagnostics will be improved [5], which will allow to observe the predicted asymmetry in the loss profile.

MID-TERM EXTRAPOLATION

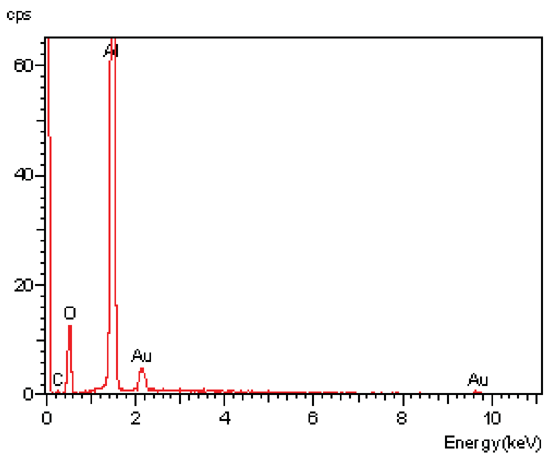
As shown in Fig. 2 there is no increase of UFO activity with the beam intensity observed for intensities above several hundred bunches. This is in accordance with the expectation from the theoretical model [3].



(a) Macro particles on filter.



(b) Zoom of a macro particle.



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

Figure 6: 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). Most particles are of μm size, but particles up to about $100\,\mu\mathrm{m}$ were found. An energy-dispersive X-ray spectroscopy (EDS) of the samples reveals that most particles consist of Al and O and most likely originate from the Al_2O_3 ceramic tube (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. Gerardin et al. [10]).

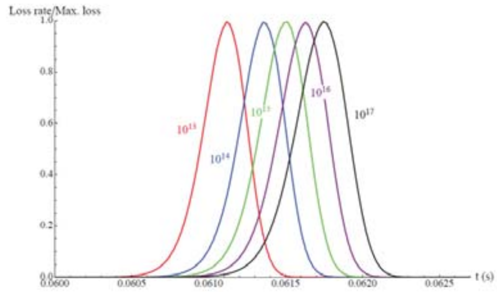


Figure 7: Normalized beam loss rate for macro particles with different masses (in atomic mass units) and a beam intensity of $1.6 \cdot 10^{14}$ protons as predicted by the theoretical model, (courtesy of N. Fuster Martinez et al. [3]).

25 ns Operation

During the MD with a bunch spacing of $25\,\mathrm{ns}$ on 24th/25th October at $450\,\mathrm{GeV}$ a rather high UFO activity was observed. In 9.1 hours (beam 1) respectively 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 [11].

Also the $25\,\mathrm{ns}$ 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. Further dedicated studies are foreseen for 2012.

Energy Dependence

As shown in [11], 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 $7\,\mathrm{TeV}$ is about three times higher than at $3.5\,\mathrm{TeV}$. Moreover, due to higher currents, the magnet quench limit is lower for higher beam energy (about a factor 5 for operation at $7\,\mathrm{TeV}$ compared to $3.5\,\mathrm{TeV}$). Figure 8 shows the expected scaling of BLM signal/BLM threshold with energy normalized to $3.5\,\mathrm{TeV}$. 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 $7\,\mathrm{TeV}$ instead of $3.5\,\mathrm{TeV}$ (Fig. 8). This number has to be compared to two actual dumps by arc UFOs in 2011. It has to be noted that this extrapolation assumes (apart from the beam energy) identical running conditions as in 2011. Excluded are MKI UFOs, potential margins to increase the BLM thresholds, the conditioning effect (Fig. 2), a possibly increased UFO rate at $25\,\mathrm{ns}$ operation and changes in beam intensity and beam size.

Similarly, according to the FLUKA simulations, for the MKI UFOs, the peak energy deposition in the D2 separation dipole magnet is expected to be more than three times higher at $7\,\mathrm{TeV}$ compared to $3.5\,\mathrm{TeV}$ [8].

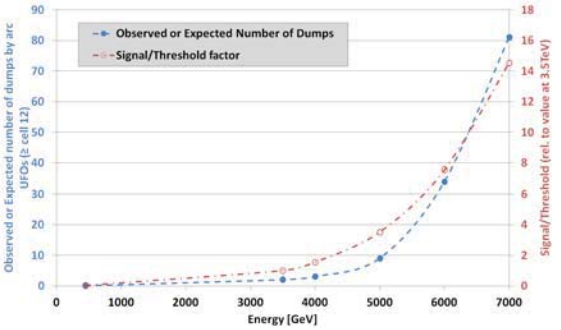


Figure 8: The expected number of beam dumps by arc UFOs and the expected scaling of BLM signal/BLM threshold for different energies. All 2011 arc UFO events since 14th April are considered, (based on [11]).

CONCLUSION AND OUTLOOK

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, 5], dedicated experiments in the LHC [5, 6] and in the laboratory [10, 12], FLUKA simulations [8] and theoretical studies [3]. 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.

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, an additional focus will be put on the study of arc UFOs. Besides a continuous improvement of the diagnostics, the installation of additional mobile monitors in a LHC arc cell in combination with dedicated FLUKA simulations is ongoing. This will allow a better localization of the UFO events and improve the accuracy of the energy extrapolation. Further tests focusing on $25\ \mathrm{ns}$ operation and on the influence of electron-cloud on the UFO activity are foreseen. In order to gain a better understanding of the magnet quench limits, an increase of BLM thresholds for UFO type beam losses to probe the magnet quench limits is planned. 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.

For the MKIs, the long term mitigation could imply a modification of the inner structure. 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 instead of the usual 15 screen conductors. This will substantially reduce the electric field in the ceramic chamber during the flattop of the field pulse [13]. Furtermore, a new cleaning method will be applied before the installation of this MKI tank.

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