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ANALYSIS OF LOSS SIGNATURES OF UNIDENTIFIED FALLING OBJECTS IN THE LHC

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Abstract

Macroparticles in the LHC beam pipes can interact with the proton beams and cause significant beam losses. The "UFO" (Unidentified Falling Objects) hypothesis describes a macroparticle falling into the beam, creating particle showers, being ionized and repelled. Though the signals of the beam loss monitors support this, many aspects remain unknown. Neither the source of the dust nor the release mechanism from the beam pipe are understood. The same holds for the forces involved in the interaction and the observed UFO rate reduction over the years. These open questions are approached from different angles. Firstly, a new data analysis tool was established which allowed advanced studies of the post-mortem data. Secondly, dust samples were extracted from LHC components and are being analyzed to gain insight into the size distribution and material composition of the contamination. The results from direct LHC observations lead to a better modeling of the UFO events and question the initial UFO model. Updated and validated UFO models will be crucial in view of the high luminosity project of the LHC and the Future Circular Collider.

INTRODUCTION TO MACROPARTICLE-BEAM-INTERACTIONS

Accelerators operating with negatively charged beams are known to suffer from the interaction between the particle beam and particulate contaminations [1]. Ionized dust gets attracted by the beam potential and stays trapped inside the beam causing a reduction in beam lifetime. During the design and construction phase of the LHC, impact from such contamination on a positively charged beam was not expected. Hence it was a surprise, when a prior unknown type of beam loss mechanism could only be explained by the interaction of macroparticles with the proton beam [3–6]. The size distribution of these macroparticles was assumed to be in the range of 1 – 100 µm [7]. On-going experimental studies aim to validate this assumption and to explain the origin of the particulate contamination, which is responsible for the UFO phenomenon.

In 2017 a new type of UFO events was observed, in which the interaction between macroparticles and the rigid LHC beam led to a very fast developing beam instability. The loss signatures suggested another physical mechanism behind the macroparticle-beam-interaction and the hypothesis of the so-called UFO type 2 involves the evaporation of the initially solid macroparticle.

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UFO TYPE 1

Protection of the LHC from the large energy stored in the beams requires a sophisticated system to detect failures and dump the beams. The key part are 3600 beam loss monitors (BLMs) installed along the LHC that record any type of beam loss with a time resolution of µm [2]. In case of beam losses measured by one of the BLMs that exceed a predefined threshold, the beams are dumped. Since June 2010 frequently recurring localized beam losses at different locations all along the ring were observed. The vast majority of these events have a duration of less than a millisecond. Many of these events triggered a beam dump, some of them led to particle showers that deposited enough energy in the superconducting magnet to cause a quench [7–10].

The Gaussian-like loss signal can be explained by a macroparticle interacting with the proton beam. Inelastic interactions between protons and nuclei lead to particle showers observed in BLMs in the vicinity of the UFO location. Elastic interactions create a halo around the beam and protons with large betatron oscillation are captured by collimators. While the macroparticle penetrates deeper into the beam, the scattering losses increase. Due to ionization the macroparticle becomes positively charged and is repelled from the beam. It was assumed that the macroparticles fall from the top of the beam screen into the beam due to gravity.

Figure 1 shows the typical signature of a UFO type 1. The respective UFO event was one of the rare occasions when the beam dump was not triggered by the local UFO losses but by

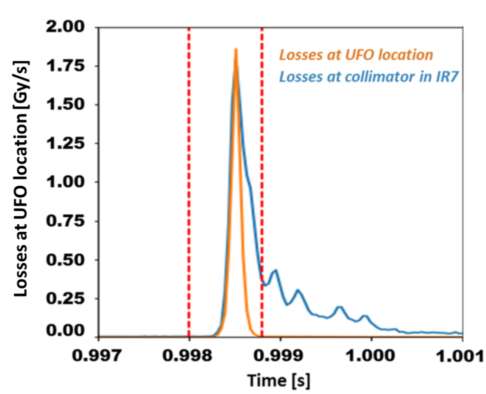

Figure 1: Loss signature for UFO type 1, measured close to the location of the UFO and at the position of the IR7 collimators. The IR7 losses were divided by a scaling factor of around 3. The vertical lines mark the duration of this UFO event.

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a subsequent quench. The quench in a downstream magnet was detected about 20 ms after the UFO event. Inelastic collisions and the related particle showers cause the localized UFO losses and the losses due to elastically scattered protons (registered at the collimators) are about proportional. Figure 2 illustrates the layout of the LHC and the order of interaction regions (IR). Due to the phase advance between the location of the macroparticle and the collimators, some of the protons make several turns. This explains the oscillating losses in IR7 (see Fig. 1).

Initially, significantly higher UFO rates were observed at the kicker magnets in the injection region. During an intervention in 2011, millions of ceramic particulates with a size in the order of several microns were extracted from the inside of the vacuum chamber. A careful cleaning mitigated the UFO problem locally and therefore confirmed that macroparticles are involved in the UFO events [12].

However, the UFO phenomenon remained in the other parts of the accelerator. The residual contamination is likely to be from a non-ceramic material. Dust extraction from LHC components and subsequent analysis is currently ongoing to shed more light on the origin of the UFO macroparticles. First wipe tests were performed on the open beam pipes, when a dipole magnet had to be exchanged between IR1 and IR2. The preliminary analysis results indicate that apart from a large quantity of micron-sized particulates, bigger grains of several 10s of microns are present. They are considered relevant for the UFO phenomenon. Moreover, the contamination contains material which is used in the plug-in modules (e.g. Au and In) and the vacuum system (e.g. Fe, Mn, Ni, Co, Cu). These preliminary results originate from a very small surface area close to the interconnect and it requires more studies before drawing a conclusion. Additional dust analyses are planned for the next months to compare the materials from different parts of the vacuum system, as there might be different contributors to the dusty contamination.

A simulation program could reproduce the signature of Gaussian UFO losses based on the hypothesis of a macroparticle interacting with the LHC proton beam [1, 11]. A novel extension of this program shows that negatively charged dust particles can be dragged into the beam. There are some indications that macroparticles might enter the beam from the bottom of the vacuum pipe as well. At a specific location (cell 15R8), a lying obstacle acts as an aperture restriction. Whenever the beam gets sufficiently close to the bottom, losses occur which sometimes have the signature of UFO losses. A local adjustment of the beam position away from the aperture limitation resolved the problem [13]. Recent experiments are in agreement with the assumption that macroparticles can enter the beam from the bottom [14]. Negative charging and levitation of particles can, for example, be seen in electron microscopy, where an electron beam scans the surface of a sample. The problem of light dust grains charging up and leaving the surface is the reason to apply a conductive coating to the sample [15]. There have been different observations on the contribution of the electron

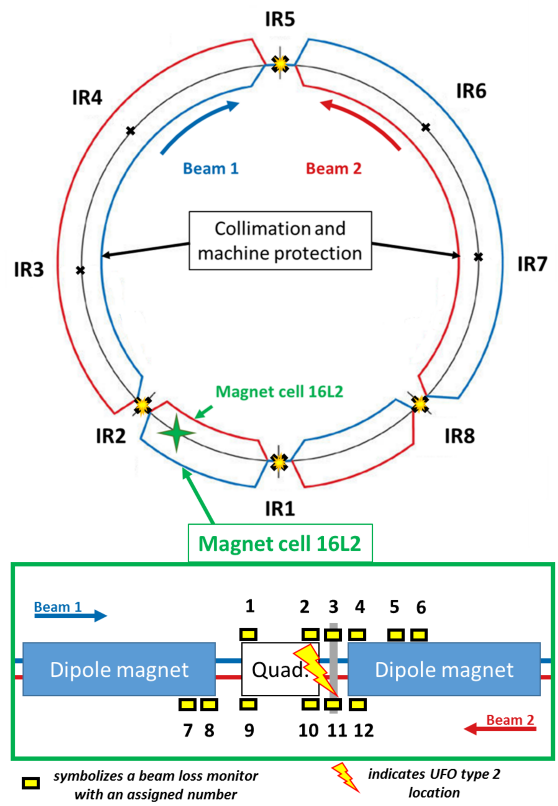

Figure 2: Schematic layout of the LHC and the related interaction regions (IR). The accelerator ring contains 1232 dipole 392 quadrupole magnets, which are arranged in numbered FODO cells. The green box zooms into cell 16L2, location of a new UFO type.

cloud to the charging and the dynamics of a macroparticle and further investigation is needed.

UFO TYPE 2

A new worrisome phenomenon manifested in 2017 after the magnet exchange, during which the vacuum system between IR1 and IR2 was warmed up and vented. Already during the re-commissioning phase of LHC, small localized losses in the interconnection between two magnets in cell 16L2 triggered a beam instability (for the loss location check Fig. 2). This instability was responsible for growing beam losses in the cleaning insertion in IR7 and a subsequent beam dump. In total, 68 beam dumps were caused by this effect. To gain more statistics and a better understanding of these events, additional BLMs were installed (see Fig. 2).

The comparison of the local losses and the observed losses in IR7 explains the differences between the two UFO types. Figure 3 reveals that (compared to Fig. 1) the loss signals from 16L2 and IR7 are in the beginning about proportional. After a short time the beam losses in IR7 increase drastically (see red circle in Fig. 3). At this point in time the instability begins to develop. The careful analysis of the other 16L2 UFO events suggests that the instability is driven by the rising tail seen in the 16L2 losses after the first millisecond.

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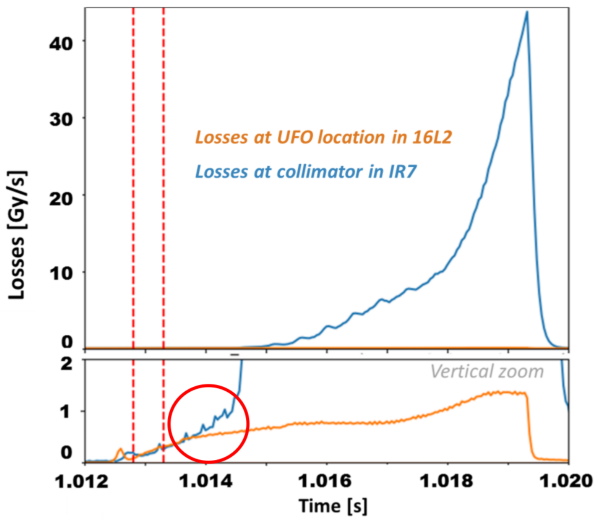

Figure 3: Comparative plot of the local 16L2 loss signature caused by inelastic scattering and the losses in the collimation region. The bottom is a vertical zoom into the same plot. The IR7 losses are about 1 order of magnitude higher than those at 16L2. The red lines indicate the scaling window. The peak losses in IR7 correspond to 25 Gy/s.

The individual time span between the local UFO losses and the dump in IR 7 ranges from a few hundred microseconds to hundreds of milliseconds. A change in the field strength of a nearby corrector magnet suggested that the magnetic field had an impact on the phenomenon. The installation of an additional solenoid field around the interconnect and the 8b4e filling scheme significantly reduced the frequency of 16L2 dumps [16]. This suggests that free negative charges inside the proton beam play a role in the instability mechanism.

A detailed analysis of the loss signals showed that in multiple cases these "16L2 events" started with a UFO-like peak. But adversely to the regular UFO signals (see Fig. 1), the local losses did not stop after one ms. Such a signature can be explained by a particulate, which is not repelled as in the case of a UFO type 1. The rising tail after the first millisecond indicates that some matter remains in the beam.

A closer look into the loss signals registered by the BLMs installed in 16L2 (see Fig. 2) helped to gain further insight. For better visualization all the losses were multiplied by a scaling factor (derived from the losses between the red lines). BLM 5 is the monitor with the highest registered loss signal and acts as a reference.

The comparison of the losses (see Fig. 4) shows a clear divergence of the scaled signals at the point of the instability development (highlighted by the red circle). This means that some of the local BLMs see a different loss pattern over time than BLM 5. This can be explained if the macroparticle changes its properties such as size or location. The comparison for several events strongly suggests a longitudinal expansion of the scattering source. This expansion could be the result of a macroparticle with a sufficiently low melting point (e.g. a N_2 flake) getting into the beam. Instead of being

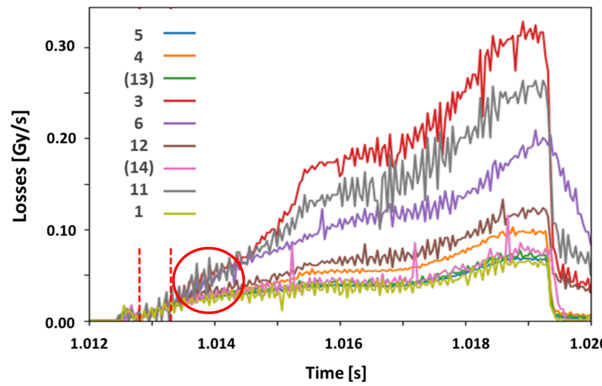

Figure 4: Loss signatures for a UFO type 2 as detected by BLMs in 16L2. The event occurred in beam 1 at 6.5 TeV. The losses between the red lines are scaled to the reference BLM 5, which showed the highest losses with about 0.3 Gy/s. The sorted scaling factors are: 1.00, 4.14, 3.24, 42.62, 30.78, 25.77, 23.57, 69.25, 30.78.

ionized and repelled (as for UFO type 1) it gets vaporized by the proton beam and creates an atom cloud. A small fraction of the atoms remain inside the high-energy proton beam and due to the ionization cross section the neutral gas atoms quickly become a plasma with free electrons.

This hypothesis was firstly described in [17] and further developed and explained in [18]. Plasmas can have very strong electromagnetic fields which could dramatically affect the proton beam. The exact mechanism of the instability development is being studied [19], but it seems likely that this can explain the drastic effect on the beam. This explanation is in good agreement with the findings that an accidental air in-leak during the maintenance work between IR1 and IR2 had led to a condensation and hence a solidification of gases on the beam screen surface [16, 20]. This could have been the source for the 16L2 UFOs.

CONCLUSION

The appearance of unexpected interactions between macroparticles and proton beam is a continuous hazard for the LHC and affects also other accelerators with positively charged beams [21]. UFO events of type 1 can be explained by solid macroparticles interacting with the proton beams and on-going investigations will narrow down potential sources. The post-mortem analysis of the 16L2 events underlined the UFO type 2 hypothesis of a macroparticle that gets vaporized by the proton beam and the resulting gas cloud contributing to the rapidly developing instability [17]. This needs to be taken into account for future machine protection systems.

At LHC the protection system can react to excessive beam losses and dump the beam within about three turns. In case of an accelerator with larger circumference (e.g. Future Circular Collider), an extended reaction time after very fast beam losses could be a threat to the machine. However, neither UFO type 1 nor UFO type 2 are fully understood.

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Continued studies are needed, especially on their origin, the release mechanism as well as the reduction in UFO rates for type 1 (conditioning effect) which has been observed over the years.

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