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RESULTS OF UFO DYNAMICS STUDIES WITH BEAM IN THE LHC

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Abstract

Micrometer sized particles entering the LHC beam (the so called Unidentified Falling Objects or UFOs) are a known cause of localized beam losses since the beginning of high intensity beam operation, however the origin of these particles is not fully known. Their effect limits LHC availability by causing premature dumps due to excessive beam losses and occasionally even magnet quenches. This could become an important limitation for future accelerators such as the High Luminosity upgrade of the LHC (HL-LHC) and the Future Circular Collider (FCC). The dynamics of these UFOs was investigated in two dedicated experiments. In the first experiment, it was shown that the transverse movements of these particles can be studied by observing bunch-by-bunch losses from bunches with different horizontal and vertical emittances. In the second experiment, UFO-like events around the 16L2 interconnect in the LHC, which has seen intense UFO activity in 2017, were studied with the above method. This paper summarizes the results of both experiments.

INTRODUCTION

Unidentified Falling Objects (UFOs), believed to consist of micrometer sized macroparticles, have been known to cause localized beam losses resulting in premature dumps and magnet quenches since the beginning of high intensity beam operation of the LHC [1], however their origin is yet to be understood. UFOs appear sporadically at different positions in the accelerator. As they can only be observed indirectly via the beam losses they produce, it is difficult to study their dynamics. While already present in accelerators with negatively charged beams, where ionized dust is attracted by the beam potential, LHC is the first hadron accelerator to suffer from their impact [2]. The induced beam losses can trigger quenches in superconducting magnets. Extrapolating from the current LHC beam energy, 6.5 TeV, to the nominal energy, 7 TeV, the expected number of UFO induced quenches could increase by up to a factor four [3]. Their origin, the dependence of the UFO rate on beam parameters and the mechanism for how they enter the beam is not well understood. To estimate the criticality of UFOs for the HL-LHC and future hadron accelerators, it is vital to understand their dynamics and the mechanism leading to the conditioning observed in the LHC. This will allow countermeasures to be taken in future machines.

WIRE-SCANNER EXPERIMENT

To study UFOs, a mixture of bunches with different transverse emittances and a fast loss detection system for a bunch-by-bunch resolution, was used. Losses from bunches with a larger emittance should appear earlier if an object is approaching the beam in the plane of the increased emittance. This was verified using the LHC wire-scanners to simulate macroparticles moving in a defined manner through the proton beam. The elastically scattered protons from these interactions were intercepted by the primary collimators of the betatron collimation region (IR7) and the losses observed with a diamond Beam Loss Monitor (dBLM) installed downstream [4].

Procedure

Nominal bunches of 1.15×10^{11} protons per bunch with a normalized emittance of 2.5 µrad were injected in each beam and then accelerated to 6.5 TeV. The emittance was increased by up to a factor four in the horizontal and vertical planes separately with a white noise excitation on selected bunches by the transverse damper [5]. The wire-scanners were then moved in both planes with a constant speed through the beam.

Results

Figure 1 shows the losses induced by two of the ten bunches as measured by the dBLM. The horizontal axis shows the timescale in ns, whereas the vertical axis shows the dBLM signal for consecutive LHC turns. The red line indicates the turn of first detection for each bunch. One can see that the blown-up bunch (right) is detected seven turns earlier than the non blown-up bunch (left). Furthermore, it was possible to reconstruct the beam profiles, which allows determining the position of the wire-scanner in relation to the beam center at each acquisition, based on the known wire movement. The precision of the position measurement was determined to be 10 µm. This method can therefore be used to compare UFO movement models with measurements [6].

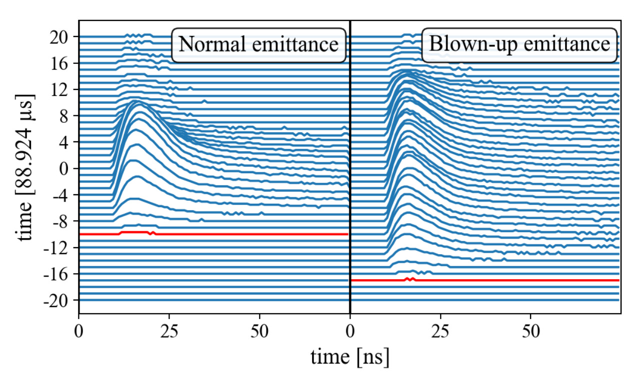

Figure 1: Comparison of two bunches with normal (left) and blown-up (right) transverse emittance. The losses were measured by a dBLM for consecutive turns (vertical axis) over the intervals of signal indicated (horizontal, ns).

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UFO TYPE 2 EXPERIMENT

During 2017, considerable UFO activity was observed at a specific magnet interconnect in the LHC, following an air influx into the beam pipe during cool-down [7], having a significant impact on machine availability. Besides beam losses these so-called UFO type 2 events led to a fast beam instability, not observed in the previously known so-called UFO type 1 events. The frequency of their appearance could be correlated to bunch and total beam intensities. An experiment to trigger such events with blown-up bunches in addition to the normal ones was performed. Local beam losses were detected by dedicated dBLMs installed close to the interconnect. This allowed studying UFO dynamics using real macroparticles interacting with the beam and further validating the measurement procedure.

UFO type 1 particles, as well as the wire-scanners, intercepting the beam lead to enough scattered protons to be detected by particle showers created in the collimators of IR7 [1]. UFO type 2 events are believed to have been caused by frozen gas flakes (e.g. nitrogen) [7] and losses from the solid macroparticle interaction were only detectable locally by the dBLMs, although the standard Ionization Chamber Beam Loss Monitors (ICBLMs) [8] could detect them both locally and in IR7.

Procedure

High-intensity beams of 1868 bunches with 1.25×10^{11} protons per bunch were injected. 224 bunches distributed in four evenly-spaced groups had their emittance increased by the transverse damper by a factor two, for each plane separately. Due to coupling between the transverse planes, horizontally blown-up bunches were also slightly blown-up vertically and vice versa. The beams were then accelerated toward 6.5 TeV.

Results

A beam dump due to a UFO type 2 was triggered during the ramp at 5.5 TeV. Figure 2 shows a comparison of signals of the dBLM and an adjacent ICBLM. The dBLM signal has been integrated in intervals of 40 µs and scaled to the ICBLM signal. Despite the statistical fluctuations of the dBLM signal, there is a good linear correlation. The losses coming from interaction with the solid macroparticle at the start of the event are indicated by a small spike, extending over more than two LHC turns. This is followed by increasing losses supposedly due to the beam interacting with the gas cloud created after the macroparticle evaporates. Taking the ICBLM signal as the calibrated measurement allowed estimating the statistical error in the dBLM signal under the assumption of normally distributed errors.

In Fig. 3, the losses from the three different groups of bunches - non blown-up, horizontally blown-up and vertically blown-up - are compared around the initial loss spike. The dBLM signal is integrated in half LHC turns, 44.5 µs, and normalized to the number of bunches in each group. Losses from the vertically blown-up bunches were detected about 1.5 turns earlier than the other bunches, implying that the macroparticle was moving in the vertical plane. Furthermore, the vertically blown-up bunches gave rise to more losses throughout the whole initial loss spike, implying that the macroparticle did not enter the beam core but remained in the tails of the bunch distribution, before either being repelled or vaporized.

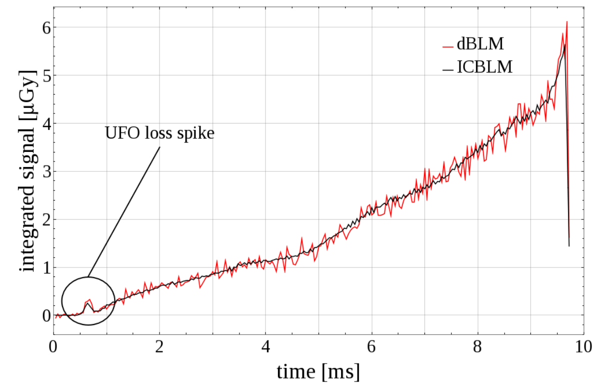

Figure 2: Comparison between the dBLM and ICBLM signals. The dBLM signal is integrated in 40 µs and scaled to the ICBLM signal.

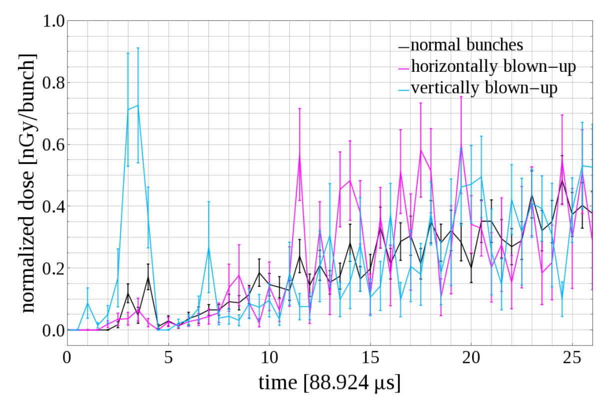

Figure 3: Comparison of the losses from the three different groups of bunches: non blown-up (black), horizontally blown-up (magenta) and vertically blown-up (cyan) during the initial loss spike. The dBLM signal is integrated in half LHC turns (44.5 µs) and normalized to the number of bunches in each group.

The transverse position of the macroparticle in relation to the beam center can be calculated by dividing the losses detected from bunches of different emittances. These losses are proportional to the proton density at the interaction point, following the Gaussian bunch profiles, and correspond to the ratio of the bunch profiles. By averaging the peak of the loss spike, the vertical position was determined to be between 2.9 and 3.4 σ.

Simulations

A model for the dynamic interaction between macroparticles and the beam is described in [9, 10]. The model allows

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simulating the energy deposition in the macroparticle, its state of ionization and the dynamics of its movement. It was extended to enable simulation of initially charged macroparticles, as well as determining the conditions necessary for vaporization [11]. Figure 4 shows the vertical offset of solid nitrogen particles with different radii being attracted by the beam from the beam screen below, as suggested by an aperture measurement [12]. The estimated particle position at the initial loss spike during the beam experiment is also indicated. The simulated particles are spherical with a density of 1.029 g/cm^3 [13].

Initially, the N_2 particles are assumed to have a slight negative charge such that the net force is ten percent of their gravity. This negative charge might be due to electron cloud activity. As the N_2 particles approach the beam, they become positively ionized and start being repelled by the beam potential. The loss signal is expected to reach its maximum at the closest vertical position, or the point where the N_2 particle is vaporized. The penetration depth depends on the total mass of the particle. A range of appropriate masses was determined from the number of inelastic collisions, comparing the ICBLM data with FLUKA models [14], which gives a range of $2.5 - 5.0 \times 10^5$ total collisions or $1.5 - 3.0 \times 10^9$ collisions/second. The best match from the simulation is the particle with a radius of 20 µm, which would experience a total of 5.3×10^5 collisions and a peak rate of 1.8×10^9 collisions/second.

The operational temperature of the beam screen lies between 5 and 20 K. The saturation vapor pressure of nitrogen at 20 K is approximately equal to the nominal pressure in the beam pipe [15]. The plot markers indicate different temperature increases during the simulation. Squares correspond to an average temperature increase of 15 K, which would be a particle heated from 5 K to 20 K. The points and the triangles are temperature changes of 43 and 58 K, corresponding to heating from the beam screen temperature range to the nitrogen triple point at approximately 63 K. The results show that there is a good qualitative agreement between the estimated position and the temperature increase.

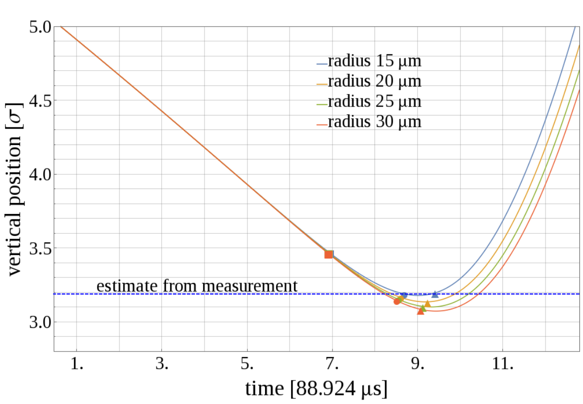

Figure 4: Simulated vertical offset of solid nitrogen particles with different radii being attracted by the beam from below in comparison to the estimated particle position at the initial loss spike during the beam experiment (dashed blue line).

DISCUSSION

One of the limitations of the experiment was the low local loss signal, leading to only a small fraction of bunches being detected per turn. Furthermore, there are uncertainties in the shape of the actual bunch profile. In the above estimates, single Gaussian profiles with RMS size as fitted to the emittance measurements were assumed, although the blow-up likely leads to non-Gaussian profiles. More measurements are required to further validate the simulation models. In general, for UFO type 1 events, the loss levels are significantly higher during the initial loss spike giving a clear signal in the IR7 dBLMs and allowing for better statistics.

The UFO type 2 experiment showed that the macroparticle enters the beam in the vertical plane, but whether from the top or the bottom can not be distinguished by the chosen method. The estimated position of the macroparticle during the initial loss spike, lasting about three LHC turns, is qualitatively in good agreement with the results of the simulation model. In a second phase of the event, the local beam losses rise over a period of about 9 ms (~100 turns), where losses from all bunches are observed equally. This could be explained by the vaporization of the particle and the beam interacting with a gas cloud. Due to a malfunction of a vacuum pump [7] it is believed that air entered the LHC beam pipe. Therefore, frozen nitrogen with its low sublimation point was present at the UFO type 2 location. Flakes of frozen nitrogen entering the beam could explain these observations, as well as the observed beam instability [16].

CONCLUSIONS

The LHC performance already suffered from UFO type 1 and type 2 events. Therefore, it is important to improve the understanding of the origin of the UFOs as well as potential countermeasures, particularly in view of future upgrades of the LHC as well as future accelerators. The dynamics of macroparticles intercepting the beam can be studied using bunches of different transverse emittances in conjunction with fast loss detectors, to resolve bunch-by-bunch losses. This principle was successfully demonstrated in an experiment with wire-scanners. It was also used in a UFO type 2 experiment and confirmed that the particle moved in the vertical plane. With the help of simulations the size of the particle was estimated to a radius of 20 µm. From the measurements a maximum penetration depth of 3.2 σ was derived.

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