15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC10

DUST-INDUCED BEAM LOSSES IN THE LARGE HADRON COLLIDER

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Abstract

Since the start of the Large Hadron Collider (LHC), dust-induced beam loss events resulted in more than hundred premature beam aborts and more than ten dipole quenches during proton physics operation. The events are presumably caused by micrometer-sized dust grains, which are attracted by the proton beams and consequently give rise to beam losses due to inelastic proton-nucleus collisions. Besides the events which trigger dumps or quenches, a large number of smaller dust events has been detected by the beam loss monitors every year. Although these events are not detrimental for physics operation, they are still carefully scrutinized as they give a better understanding about the correlation with beam parameters, about the long-term evolution of event rates, and about possible correlations with shutdown activities and the installation of new equipment. In this contribution, we present a summary of observations from the first three runs of the LHC.

INTRODUCTION

Dust-induced beam losses had a perceivable impact on the LHC performance since the start of high-intensity proton operation at 3.5 TeV and 4 TeV per beam in Run 1 (2010-2013) [1–8]. The events continued to perturb operation at 6.5 TeV in Run 2 (2015-2018) [9–13] and still persist in Run 3 (from 2022, 6.8 TeV). Dust events occur in all regions of the LHC, including the long straight sections and the cryogenic dispersion suppressors and arcs. The events typically last between 100 µs and 1 ms, i.e., between one and ten beam revolutions. When a dust grain enters the beam, a small fraction of the protons is subject to an inelastic nuclear collision (typically $<10^8$ particles per event) [13]. The resulting collision products give rise to hadronic and electromagnetic showers in nearby accelerator equipment and can trigger beam aborts by Beam Loss Monitors (BLMs). In the worst case, the rapid and localized heat deposition can even provoke a magnet quench. In total, more than hundred beam aborts and more than ten quenches could be attributed to dust particles up to now. The first dust-induced quenches occurred at 6.5 TeV in Run 2, while no quenches were observed in Run 1 due to the lower beam energy and larger quench margin of superconducting magnets. Figure 1 provides an overview of beam-induced aborts and quenches in Run 2 and the first two years of Run 3, illustrating the impact of dust events throughout this period. Besides dust-induced events, the figure also highlights two other types

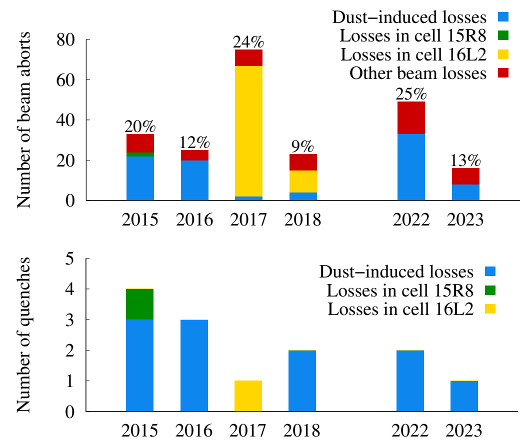

Figure 1: Number of beam aborts (top) and quenches (bottom) due to beam losses in Run 2 (2015-2018) and the first two years of Run 3 (2022-2023). The figure considers only physics fills which reached at least the beam acceleration phase and with a minimum stored intensity of 3×10^{11} protons/beam. The percentage values indicate the fraction of fills aborted by beam losses, considering the different number of physics fills every year.

of loss events, which occurred in two specific arc cells (an obstacle obstructing the aperture in cell 15R8 and aggregates of residual air molecules in cell 16L2, see Refs. [12, 14–17]).

Recent simulations and measurements showed that the dust particles are attracted by the beam, indicating that the dust grains are negatively pre-charged [13, 18, 19]. Theoretical studies [19] suggest that the negative charge of dust grains can possibly be explained by the presence of synchrotron radiation and electron clouds in the vacuum chamber. Once a dust grain enters the beam, it gets rapidly ionized by the traversing protons and is repelled from the beam, likely before reaching the beam center [18, 20–23]. While beam-dust interactions and the resulting beam losses are well understood and can be reproduced by simulations [13, 18, 19, 23], the mechanism governing the release of dust particles into the beams still lacks a theoretical explanation [24]. A large number of smaller dust events are detected by the BLMs every physics run, which are recorded by a dedicated software application [7]. Although these events do not perturb operation, they still provide an empirical understanding about the correlation with beam parameters, about the long-term evolution of event rates, and about possible correlations with the installation of new equipment. In this paper, we summarize some of the key observations from the first three LHC runs, with focus on dust events in the cold LHC arcs.

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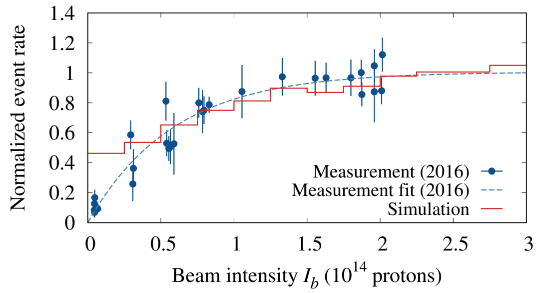

Figure 2: Dust event rate measured in different physics fills at 6.5 TeV in early 2016 as a function of the average beam intensity in the fills (blue dots). See text for details.

DUST EVENT RATE IN THE ARCS

The measured dust event rate is a key observable for gaining a deeper understanding about the root cause of these events. For a given physics fill, the event rate is calculated as $N/\Delta t_{sb}$, where N is the number of events during stable proton-proton collisions at top energy and Δt_{sb} is the duration of stable collisions. Other beam modes like the energy ramp or the β^*-squeeze are excluded due to the dynamically changing conditions, which could possibly bias the results. Figure 2 shows the measured dust event rate in the arcs as a function of the time-averaged stored beam intensity per fill. The measurements, which were recorded during the 2016 intensity ramp-up period, illustrate that the rate of detected events increases with intensity. Similar observations were already made in Run 1 [3, 4, 7]. This increase can at least partially be explained by the dynamics of dust particles; simulations predict that the number of events exceeding the detection threshold increases with intensity due to the higher beam losses generated by dust grains [13]. This is illustrated by the red histogram in the figure, which shows the relative increase predicted by the simulation model if one assumes a constant event rate. At intensities above 5×10^{13} protons, the simulation matches well the measurements. This suggests that the total number of dust particles released into the beam might only weakly depend on the stored intensity, but the number of detected events increases.

Figure 3 shows the fill-by-fill evolution of the dust event rate in the arcs from 2011 (middle of Run 1) to 2022 (first year of Run 3). The graph combines measurements from all eight arc sectors. The x-axis indicates the fill number, which is an unique identifier for LHC fills. The figure also shows the average circulating intensity per fill, I_{av}, which increased throughout the years. To allow for a fair comparison, the event rate has been multiplied with a weight function, $f(I_{av})$, which removes the dependence on the beam intensity and gives the projected rate at $I_{av} = 3\times10^{14}$ protons ($f(I_{av})$ is the inverse of the exponential fit shown in Fig. 2). The labels on the top of the figure indicate the bunch spacing and the main beam type in the different running periods [25]. As can be seen in the figure, the dust event rate exhibits a continuous decline during runs, whereas a significant deterioration can be observed in Run 2 after Long Shutdown 1, and in Run 3 after Long Shutdown 2. During both shutdowns, the arc sectors were warmed up to room temperature and were vented. Different maintenance activities were carried out, including the exchange of some superconducting magnets in different arc sectors (17 magnets in the first shutdown and 23 magnets in the second shutdown). In Run 2, it took almost two years of operation to reach again similar event rates as at the end of Run 1, whereas the conditioning of the event rate was much faster in Run 3. As discussed in the next section, new dust contamination is likely not the main cause of the strong increase of the rate after long shutdowns.

EVENT DISTRIBUTION IN THE ARCS

In many cases, an elevated number of dust events is observed in cells where new magnets were installed in preceding shutdowns. This is illustrated in Fig. 4, which shows the cell-by-cell distribution of dust events in two out of the eight arc sectors, including the sector with most magnet exchanges in both shutdowns (Sector 12). The upper and lower plots correspond to the first ~1000 hours of stable beam operation

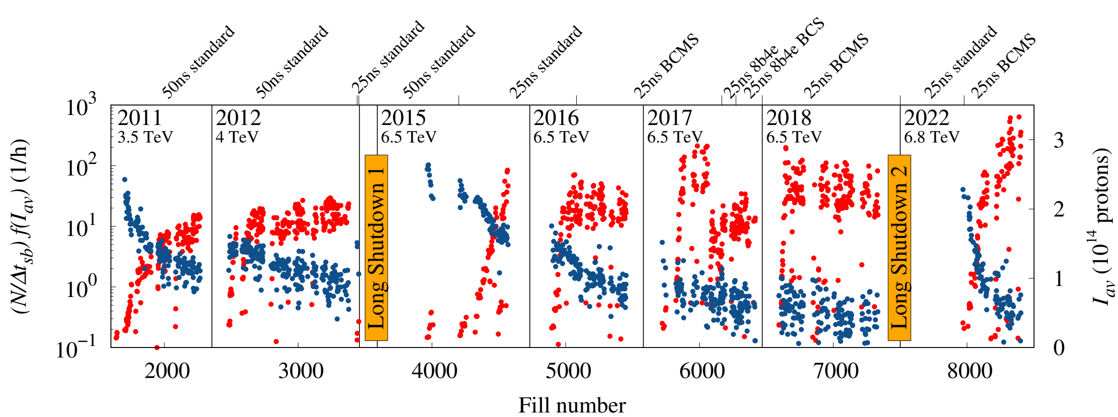

Figure 3: Fill-by-fill evolution of the dust event rate in the LHC arcs during stable beam operation in the last two years of Run 1 (2011-2012), in Run 2 (2015-2018), and in the first year of Run 3 (2022-2023) (blue dots - left axis). Only fills with more than one hour of stable collisions and with more than 100 bunches per beam are shown. The average beam intensity per fill, I_{av}, is displayed in red (right axis). The beam energy increased from 3.5 TeV in 2011 to 6.8 TeV in 2022.

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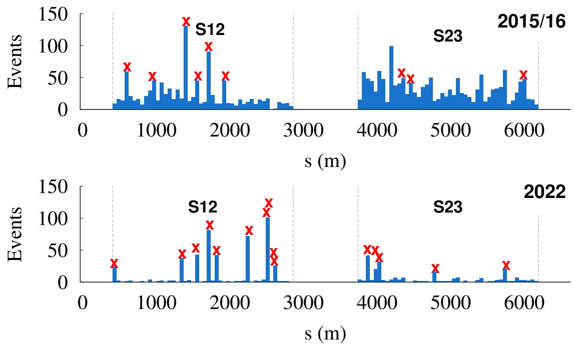

Figure 4: Number of dust events per arc half-cell in Sector 12 and 23. The upper plot shows the first 1.5 years of Run 2 (2015/16, 6.5 TeV), whereas the bottom plot shows the first year of Run 3 (2022, 6.8 TeV). The red crosses indicate the locations of new magnets installed before Run 2 and Run 3.

in Run 2 and Run 3, respectively. In both runs, a distinct correlation between new magnets and event hot spots can be seen. It remains unclear if the events are due to dust present in the vacuum chambers of new magnets, or if they are due to new dust contamination during the installation process. A distinct difference between the two runs is the number of events in cells where no shutdown activities were carried out. While these events were significant in Run 2, they became less frequent in Run 3. Integrated over all arc sectors, events in cells without shutdown activities accounted for almost 90% of all dust events in the first year of Run 2, while they represented about half of all events in the first year of Run 3. It is assumed that the events in these cells are due to dust present since the early days of the LHC. This hypothesis is supported by the relative distribution of events in different sectors and beam apertures, which was found to be similar in Run 1 and Run 2 (see Fig. 5).

If new dust contamination accounted only for a small fraction of events in the beginning of Run 2, then the large increase of the event rate after Long Shutdown 1 (see Fig. 3) must have another root cause. A similar conclusion applies to Run 3, since old dust still accounted for at least half of the events. The release of dust from the cold beam screens

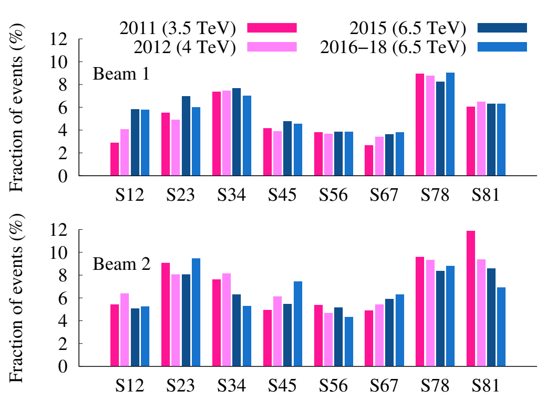

Figure 5: Fraction of dust events per arc sector and per beam aperture in the last two years of Run 1 (2011-2012) and in Run 2 (2015-2018).

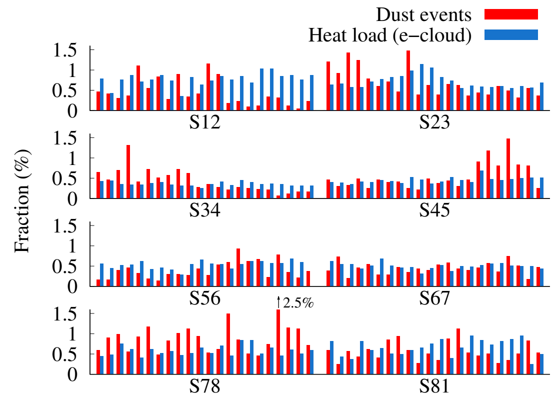

Figure 6: Relative fraction of dust events in cryo cells in Run 2 (6.5 TeV) versus relative heat load distribution due to e-clouds. Each histogram bin represents two neighbouring cryo cells in the eight arc sectors.

might be influenced by environmental conditions such as the dynamic heat load. One of the main sources of heat deposition in the arcs is the build-up of electron clouds due to multipacting [26]. Like for the dust event rate, a deterioration of the electron cloud-induced heat load was observed after the first two long shutdowns [27], possibly due to the venting of the machine and the resulting formation of CuO on the beam screen surfaces [28]. Measurements showed that the heat load can vary strongly between arc cells and even between neighboring magnets, likely due to a different oxidation of the beam screens. If the release of dust from the surface is favored by the heat load, a correlation between the number of events and the heat deposition would be expected. Figure 6 compares the spatial distribution of dust events at 6.5 TeV in Run 2 with the relative heat load distribution in cryo cells. The heat loads were measured during a representative physics fill in October 2015. The total heat load declined throughout Run 2, but the relative heat load distribution between cells remained similar. The comparison does not show a clear correlation between heat load and event counts in different cells. It is hence unlikely that heat load is the main factor for dust release into the beam, but electron clouds might nevertheless play an important role in the charging process of dust grains [19].

CONCLUSION

This paper summarized some of the key observations related to dust-induced beam loss events in the cold LHC arcs. The number of detected events increases with beam intensity, likely because of a stronger attraction of negatively pre-charged dust grains by the beam, which leads to higher beam losses and hence to more events above detection threshold. A strong increase of the event rate is observed after long shutdowns, which cannot be explained solely by new dust contamination, although event hot spots are typically observed at the location of new superconducting magnets. The increase can also not be attributed to the heat load due to electron clouds. The mechanism driving the release of dust into the beam hence remains one of the main open points.

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