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PROOF-OF-PRINCIPLE EXPERIMENT TO RECONSTRUCT THE TRAJECTORY OF DUST GRAINS INTERACTING WITH THE LHC BEAMS

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Abstract

Interactions of dust grains with the LHC beams cause beam losses that can trigger premature beam aborts or even quenches of superconducting dipoles. While the simulated motion and ionisation of dust grains inside the proton beam are in good agreement with measured beam-loss data, a direct measurement of the dust movement is not available.

A novel method was developed that reconstructs the trajectory of a dust grain based on the different beam loss profiles of transversely displaced bunches. A proof-of-principle experiment to validate the method using a thin wire to simulate the dust grain was performed in June 2024 at the LHC. This paper describes the beam experiment, compares the achieved displacements with simulations, and shows the reconstructed trajectories. Finally, it is discussed how the method can be applied for real dust events occurring during LHC operation.

INTRODUCTION

Since the LHC start-up, dust grains interacting with the proton beams have induced beam losses and impacted operation [1, 2]. In the first three years of Run 3 (2022-2024), 45 premature beam dumps and five magnet quenches were caused by these losses.

The simulation of the motion and ionisation of dust grains inside the proton beam agrees well with the measured beam-loss data [1, 3–5]. However, as dust events can occur at random locations in the ring, a direct imaging of the dust movement is currently not available. Therefore, a novel method is proposed for reconstructing their motion based on loss asymmetries of transversely displaced bunches.

EXPERIMENTAL SETUP

A proof-of-principle experiment took place on June 7/8, 2024 at the LHC. The proton bunches were transversely displaced by the beam-beam force [6] or by electrostatic excitation from the transverse feedback system (ADT) [7]. The 30 µm thick beam wire scanner (BWS) was then used as artificial dust grain, which moves either horizontally or vertically through the beam with a constant speed [8]. The maximum allowed intensity for using the BWS was 168 and 10 bunches at 450 GeV and 6.8 TeV [9, p. 5], respectively.

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The bunch-by-bunch displacements were measured with different beam-instrumentation devices: BWS, Beam Synchrotron Radiation Monitor [10], ADTObsBox [11], and Beam Position Monitors [12], as well as the LHCb VELO detector [13]. About 10 km downstream the BWS, beam losses at the primary betatron collimators were recorded by diamond Beam Loss Monitors (dBLMs) [14] with 1.5 ns sampling, providing bunch-by-bunch resolution.

BUNCH DISPLACEMENTS

Two main parts of the beam experiment are reported in this paper. The first part was performed at LHC injection energy of 450 GeV. A *weak–strong* filling scheme was used. The high-intensity *strong* Beam 2 was used to provide the beam-beam (BB) kick [6] to the bunches in the low-intensity *weak* Beam 1, on which the wire scans were performed.

The filling scheme was optimised such that bunches in Beam 1 experienced different combinations of Long Range (LR) BB effects [7, 15]. After each injection step of either one train of 12 or of 48 bunches into the *strong* Beam 2, wire scans were performed for Beam 1. The effect of increasing LR BB effect after each injection step can be seen in Fig. 1. The bunch positions as measured by the wire scanner are shown in blue, while the bunch positions that were simulated with the pyTRAIN code [17] are depicted in orange. Overall, measurement and simulation agree well, even though a systematic shift for some bunch trains can be observed, which is still under investigation.

The maximum displacement along the diagonal, obtained through a linear fit of all measured bunch positions, is shown in purple (Fig. 1, bottom plot). The maximum off-diagonal displacement along the orthogonal axis is displayed in red. The final configuration with 335 bunches in Beam 2 leads to a displacement of 340 µm along the diagonal and 270 µm along the off-diagonal.

The second part of the experiment was performed at the LHC top energy of 6.8 TeV. A filling scheme with 10 bunches in Beam 1 and 135 bunches in Beam 2 was used. With this filling scheme, four bunches collided in Interaction Point (IP) 1 and 5, three in IP 2 and 8, while three bunches received no BB kick. Figure 2 depicts the resulting bunch positions. Measurements from the wire scanner (blue) as well as simulations with pyTRAIN (orange) and MADX [18] (green) are shown.

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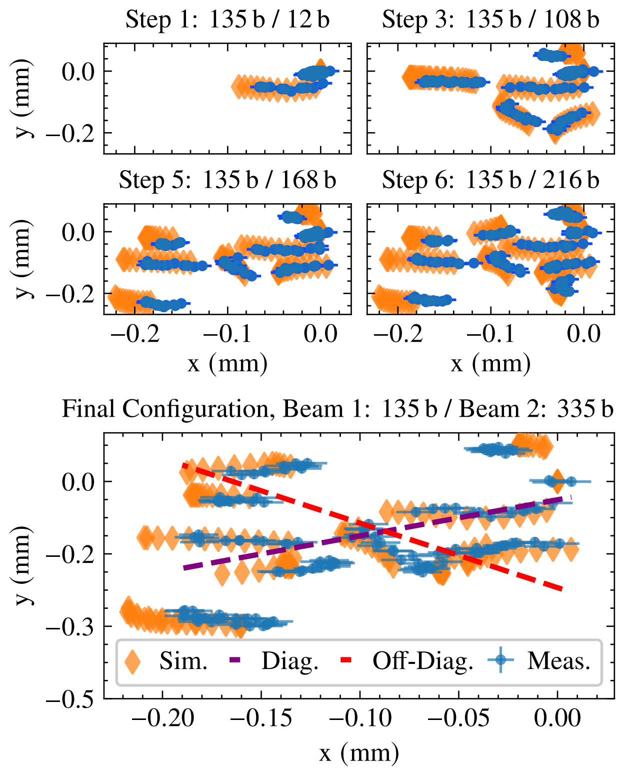

Figure 1: Increasing displacements in Beam 1 due to Long Range Beam-Beam effects at 450 GeV after each injection step into Beam 2. Measurements (Meas.) with the wire scanner with uncertainty of 10 µm [16] are shown in blue and pyTRAIN simulations (Sim.) in orange.

Due to LHC's symmetric layout, bunches receive equal vertical and horizontal kicks in IP 1 and 5, respectively. Therefore, the bunches are displaced along a diagonal with less off-diagonal contributions from IP 2 and 8 than at 450 GeV. This results in a total diagonal displacement of 220 µm (purple line in Fig. 2) and 10 µm off-diagonal displacements due to BB.

To increase the off-diagonal spread, bunches without Head-On [6] collisions in IP 1 and 5 (green in Fig. 2) were additionally displaced by the ADT. This resulted in an off-diagonal displacement of 60 µm (red line in Fig. 2).

BEAM LOSSES OF DISPLACED BUNCHES

Figure 3 shows the raw dBLM signal at 6.8 TeV recorded during a wire scan of the ten displaced bunches from Fig. 2. The beam-wire interaction lasts approximately 1.5 ms.

The dBLM signals were normalised by the individual bunch intensities. For further processing, the signal height was calculated by taking the difference of the maximum and minimum value for each bunch.

An example of the resulting signal is shown in Fig. 4 for two LHC turns of 89 µs each. Bunches undergoing Head-On collisions, i. e. those shown in the lower-left corner of Fig. 2, are marked in orange in Fig. 4. These bunches show higher signal, as they cause higher beam losses during the incoming

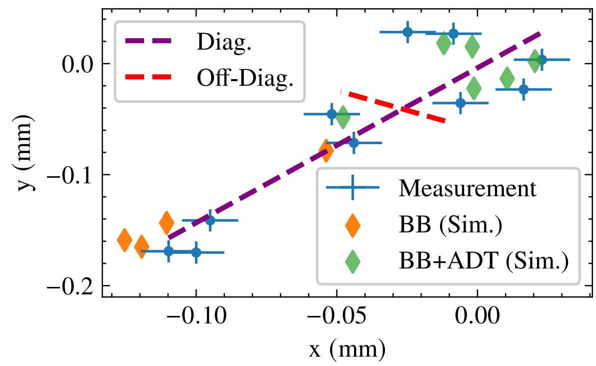

Figure 2: Bunch positions at 6.8 TeV measured with wire scanner (blue) with uncertainty of 10 µm [16] and simulated (Sim.) with MADX and pyTRAIN. The bunches were displaced by beam-beam (BB) effect (orange) or additionally kicked by the ADT (green).

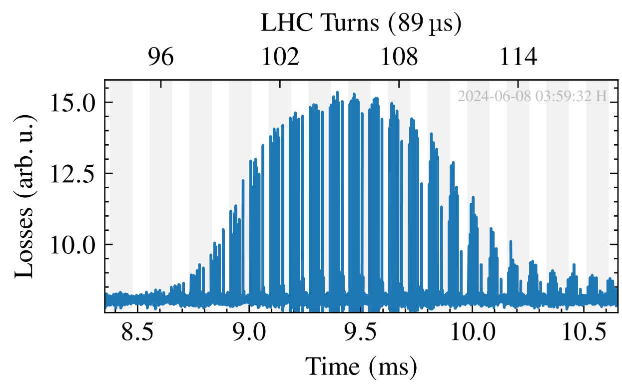

Figure 3: Raw dBLM signal during horizontal wire scan.

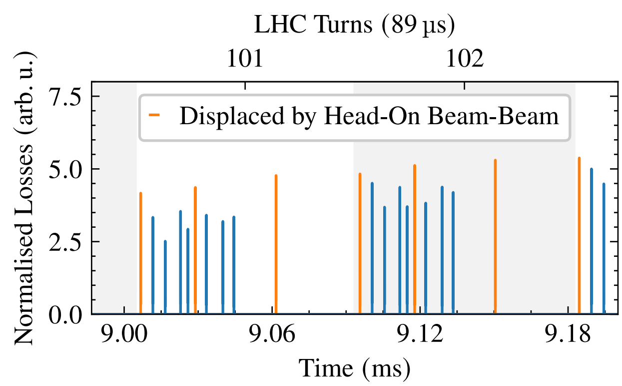

Figure 4: Zoom into normalised beam losses caused by 10 bunches within two turns from Fig. 3. Bunches that are displaced by Head-On Beam-Beam effect as shown in Fig. 2 are displayed in orange.

motion of the BWS. Compared to non-colliding bunches (upper-right corner in Fig. 2), they exhibit a relative delay in reaching their maximum beam losses of ≈ 60 µs during horizontal scans. From the measured bunch positions and the time when single bunches reach their maximum signal, the correct wire speed of $(1.10 \pm 0.14)\,\mathrm{m\,s^{-1}}$ was found [8].

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METHOD OF DISPLACED BUNCHES

To reconstruct the dust position, the algorithm initially proposed in [19, 20] for displaced bunches with the same beam size is extended to the variation of both bunch positions and bunch sizes. Specifically, the loss m_i of a bunch at slot i with bunch spacing $t_b = 25$ ns is modelled as the spatial overlap between the bunch and a dust grain. The density of protons within the bunch is represented by a Gaussian with centre (x_b, y_b) and standard deviations (σ_x, σ_y), while the dust grain moving with velocities (v_{Dust_x}, v_{Dust_y}) is located at (x_{Dust}, y_{Dust}).

$$m_i \propto \frac{1}{\sigma_{x_i}\sigma_{y_i}} \exp\left(-\frac{(x_{Dust} + v_{Dust_x} \times t_b \times i - x_{b_i})^2}{2\sigma_{x_i}^2} - \frac{(y_{Dust} + v_{Dust_y} \times t_b \times i - y_{b_i})^2}{2\sigma_{y_i}^2}\right) \quad (1)$$

Considering the ratio of two loss signals yields a set of equations of beam loss signals with corresponding dust positions. The turn-by-turn position is obtained by solving the quadratic set of $\binom{N}{2}$ equations [20, p. 8]: $\log(m_i/m_j)$ for N displaced bunches.

RECONSTRUCTION RESULTS

Numerically solving the system of equations derived from Eq. (1) with bunch positions and sizes measured by the BWS and the processed dBLM signal yields a turn-by-turn position of the wire. Equations of loss-ratios from bunches with relative displacements lower than the assumed resolution limit of 10 µm of the BWS [16] are discarded to improve the reconstruction accuracy.

Figure 5 shows the reconstructed paths of the wire during a horizontal (left) and vertical (right) scan with 10 bunches at 6.8 TeV. The corresponding bunch displacements are shown in Fig. 2 and the measured dBLM signal during the horizontal scan in Fig. 3. The colour of the dots illustrates the corresponding turn at which the beam losses were measured. Hence, for a horizontal scan, we find that the wire moves left to right, while it moves from bottom to top during vertical scans. The wire motion could be reproduced for all scans with off-diagonal displacements larger than 60 µm at 6.8 TeV or larger than 260 µm at 450 GeV.

CONCLUSIONS AND OUTLOOK

A proof-of-principle experiment at the LHC successfully demonstrated a novel method for reconstructing the trajectory of dust grains that interact with the particle beam. Using bunch displacements through beam-beam effects and electrostatic kicks, the experiment validated a trajectory reconstruction algorithm based on bunch-by-bunch loss asymmetries.

The direction of motion of a 30 µm thick wire traversing the beam could be reconstructed when bunches at the wire location had transverse off-diagonal displacements ≥ 60 µm at 6.8 TeV and ≥ 260 µm at 450 GeV. With smaller off-diagonal bunch displacements, the motion could not be reliably reconstructed. However, comparing the timing of losses per bunch with measured bunch positions still allowed to conclude whether the wire approached from top or bottom.

As next step, the method will be applied to real dust events occurring during LHC operation in order to reconstruct their incoming direction. During a physics fill, the bunches are naturally displaced by the BB effect due to the collisions in the IPs. The displacements at the event location depend on the phase difference to the IPs. Simulations with pyTrain for the location of the BWS show a displacement of 110 µm along the diagonal and 15 µm along the off-diagonal for a typical physics fill in 2024. Although the off-diagonal displacement is smaller, the presence of more than 2000 bunches during regular fills provides higher statistics for the reconstruction.

Comparing the reconstructed paths with simulated trajectories and local beam losses will provide further insights of initial conditions of dust grains and its release mechanism.

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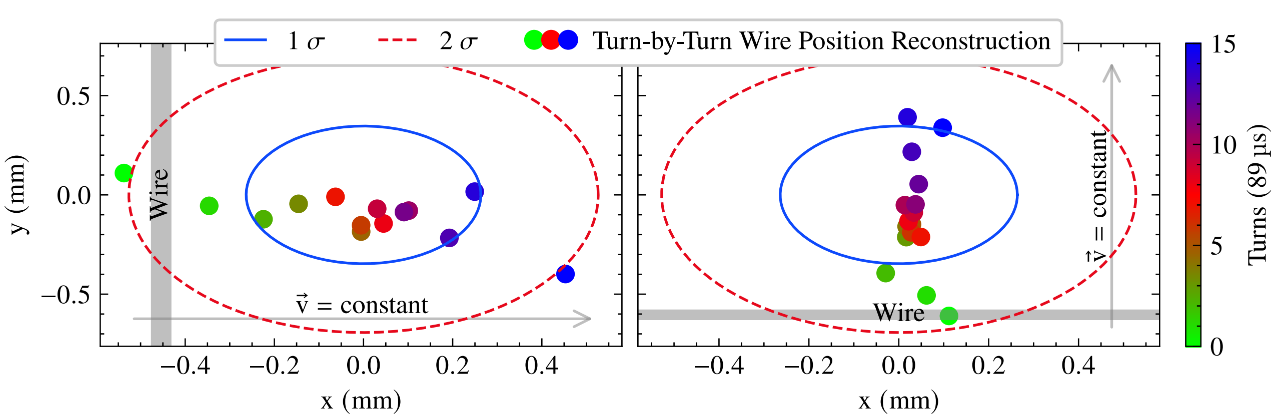

Figure 5: Reconstruction of constant horizontal (left) and vertical (right) wire motion.

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