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EXPERIMENTAL CHARACTERISATION OF A FAST INSTABILITY LINKED TO LOSSES IN THE 16L2 CRYOGENIC HALF-CELL IN THE CERN LHC

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Abstract

The operation during the summer months of the 2017 Run of the CERN LHC was plagued with fast beam losses that repeatedly occurred in the 16th arc half-cell at the left of IP2 as well as in the collimation insertion, leading to unwanted beam dumps. Transverse coherent oscillations were observed during this fast process. We detail here the experimental observations of coherent motion that allowed shedding light upon parts of the mechanism and identify the potential mitigations that were successfully implemented in the second half of the Run.

INTRODUCTION

Very early in the recommissioning of the LHC machine in 2017, abnormal background radiation as well as sudden untimely beam losses leading to beam dumps were observed near the quadrupole of the 16L2 cryogenic half-cell [1, 2]. The situation got worse with increasing beam intensity stored in the machine and led to 67 beam dumps in total (including one dump that led to a quench).

Analysis of post-mortem signals of the LHC tune measurement (BBQ) and transverse damper (ADT) bunch-by-bunch turn-by-turn position monitoring revealed that fast transverse coherent motion was occurring just before the beam dump [3].

The summary of the actions and studies performed in order to understand and mitigate the operational issues linked to these events are summarized in another contribution [4].

This contribution reports the steps to analyse this fast instability with the available beam instrumentation as well as the improvements that allowed giving a more detailed characterization of the transverse instability. It starts from the initial observation that coherent motion was involved and continues with increasingly detailed analysis to capture the instability pattern: coupled bunch motion, azimuthal and radial mode numbers. This characterization provided timely, important indications that electron cloud was likely to be a crucial player in the complex process of these 16L2 events [5, 6], and allowed focusing on efficient mitigations [7].

DETECTION OF COHERENT MOTION

Transverse coherent motion was observed a few turns before every 16L2 related beam dump thanks to the BBQ system [8]. The example of LHC fill 5848 dumped after 16 h of stable beams on June 20th 2017 is given in Fig. 1. One can see that a vertical instability (defined as an exponential growth of the amplitude of coherent motion) takes place on beam 1 with a rise time of the order of 20 turns. Fourier analysis of the loss signal revealed that the initial losses only contains the revolution frequency while the last rise also contains a significant contribution at the betatron tune. The loss at the revolution frequency indicates that something is touching the beam every turn, while the additional contribution at the betatron tune is a signature of transverse coherent motion leading the bunches to hit the collimators in IR7 [9].

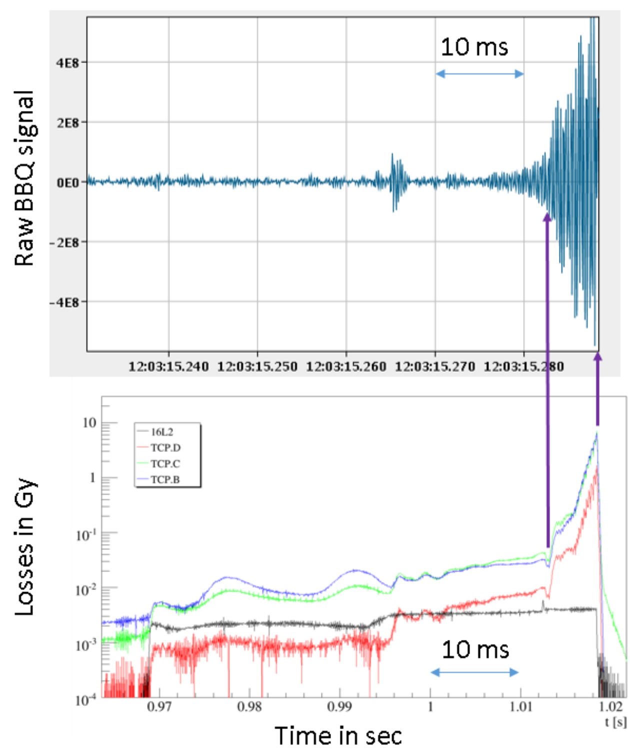

Figure 1: Superposition of raw post-mortem BBQ signal for the vertical plane of B1, which is representative of transverse coherent motion of the whole beam (top in blue) [9] with losses observed at the 16L2 quadrupole (black) and at the 3 primary collimators (TCP, red black and blue) [10, 11]. Both plots were vertically aligned in time (see purple arrows) to show the synchronization of the final loss increase in TCPs to the instability observed on the BBQ.

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The instabilities were so fast (10 to 100 turns for 16L2 events, one or two orders of magnitude smaller than that observed for electron cloud and impedance related instabilities so far [12]) that at first, it was not realized that transverse coherent motion was involved in the 16L2 events. Once the instability was detected by the BBQ, its characterization required deeper analysis, in order to assess which bunches are unstable, their possible correlation, with what unstable frequency with respect to the betatron frequency (tune shift) they oscillate and whether there is intra-bunch motion. In other words, one needs to identify the instability mode numbers: coupled bunch, azimuthal and radial.

MULTIBUNCH ANALYSIS

The ADT pickups allow measuring and storing the transverse coherent motion of the centroids of each bunch within the beam. The existing post-mortem buffer was recording the last 72 turns for all bunches and confirmed the transverse coherent motion observed by the BBQ system. Even though the loss pattern turned out to be very similar from one dumped fill to the next, the pattern of unstable bunches changed dramatically from fill to fill [13]: in some fills, Single Value Decomposition (SVD) analysis of the ADT data revealed that only a few bunches at the head of the trains were oscillating (see Fig. 2), while in other fills clear coupled-bunch motion could be observed (see Fig. 3), and in some other fills not much coherent motion could be seen at all.

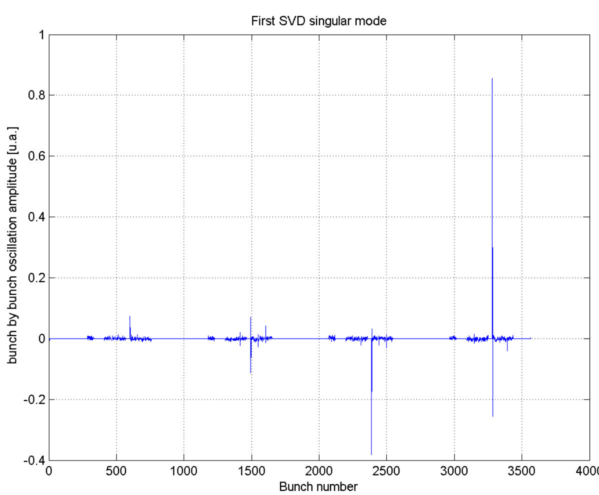

Figure 2: Beam 2 ADT horizontal oscillation amplitude for the first SVD singular mode for fill 5946: only few bunches are clearly oscillating more than the others (the first one or two bunches of the second injected train).

Significant effort and hardware were invested in the instability trigger network linked to ADTObsbox [14] and Headtail Monitor in order to record large amount of data in case of instabilities [15]. Once it was realised that 16L2 instabilities were much faster than the usual impedance or electron cloud driven instabilities and was systematically leading to beam dumps, the instability monitoring system had to be modified to also record data before beam dumps. This allowed catching all remaining 16L2 events for 2017. In total, out of the 67 dumps, 30 fills showed coupled motion, while 10 showed single bunch motion at the head of the train, the rest not revealing clear transverse motion.

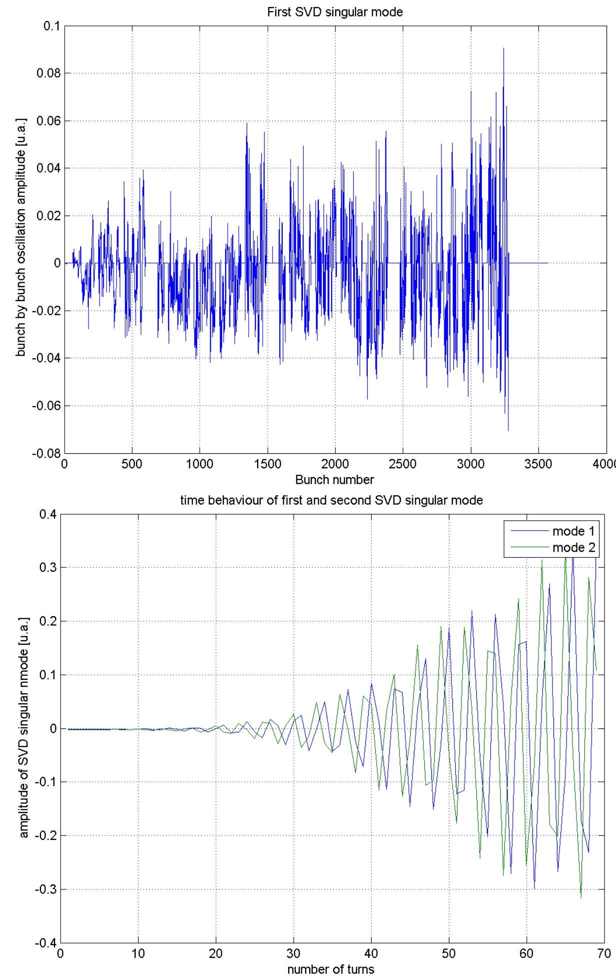

Figure 3: Beam 1 ADT vertical oscillation amplitude for the first SVD singular mode (top) and amplitude of the two first SVD singular modes as a function of the number of turns (bottom) for fill 5951: fast widespread growth of coupled-bunch motion is observed.

UNSTABLE TUNE SHIFT ANALYSIS

Most fills became unstable within few tens of turns, which does not allow for acceptable frequency analysis of the unstable motion, even with interpolated Fourier Transform techniques.

Nevertheless, a few beam dumps occurred a lower energy, which allowed longer instability time until the dump was triggered due to losses. In these cases, the amplitude of the coherent motion measured at the ADT pickup data was large enough to allow for clear analysis, even with a 20-turn window. The analysis of such fills revealed a large positive single bunch tune shift (~ +0.02) between before the instability and during the instability (see Fig. 4) [5], indicating that the azimuthal mode(s) getting unstable has(ve) a large positive index (at least 5 times the synchrotron tune). This large positive shift is very surprising since LHC instabilities so far have presented a negative mode

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number (mode -2 due to chromaticity). This important observation in mid-July 2017 was an early sign that negatively-charged particles may be involved in the instability process.

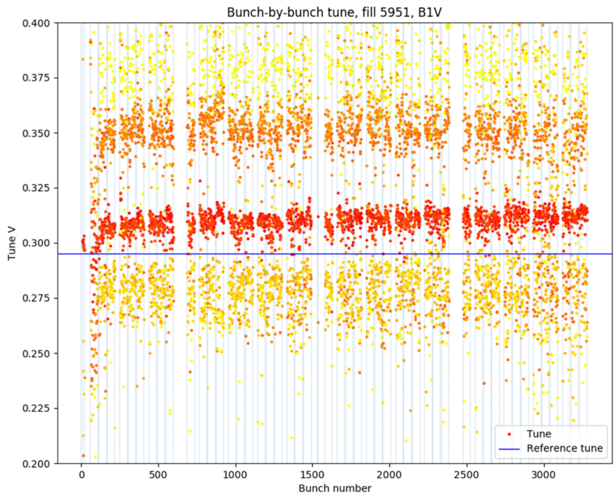

Figure 4: Bunch-by-bunch spectrum for LHC fill 5951 computed from the last 20 turns of ADT data before the beam dump (red dots). The blue line indicates the reference tune computed for the first 20 turns of the 71-turn acquisition before the instability took off. The instability therefore led to a single-bunch tune shift of ~ +0.02.

INTRA-BUNCH MOTION ANALYSIS

While the ADT pickups record one measurement point per bunch, the Headtail monitor is able to record the transverse position of several slices inside the bunch, and can therefore indicate whether the bunch is oscillating as a whole or if there is an oscillation pattern along the bunch. Depending on the instability type, this pattern can be very different: travelling-wave for mode coupling and electron-cloud instabilities, standing-wave for Headtail instability [16].

Due to its larger acquisition bandwidth, the signal to noise ratio for the Headtail monitor is much worse than for the ADT pickups and the BBQ. Due to the large number of acquisition points per turn, the Headtail monitor acquisition was limited to 11 turns in 2017. The chance of catching a 16L2 instability with the Headtail instability was therefore slim. In spite of this, the Headtail monitor was set up to catch the last 11 turns before a dump. Most of the time, the signal was too small to be detected, but there was a couple of notable exceptions, for which the amplitude was large enough to be observed (see one example for one bunch at the end of the 16L2 event at 2 TeV during LHC fill 6164 on Fig. 5). All unstable bunches presented a similar pattern. In addition to being compatible with electron cloud instabilities, that type of intra-bunch motion cannot be explained by other origins (issue with transverse damper, linear coupling or chromaticity).

CONTRIBUTION TO UNDERSTANDING OF INSTABILITY MECHANISM

From the previous observations, classical impedance-driven instabilities could be excluded. Early in the year, the loss showers indicated that hadrons had to be involved in 16L2 events [17]. Preliminary models of proton beam interacting with ions showed that atomic densities around 10^{24} m^{-3} could lead to fast instabilities with coupled bunch motion [18].

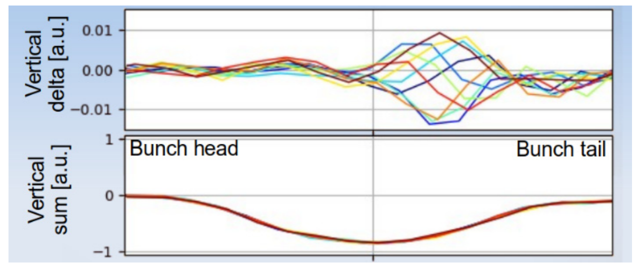

Figure 5: Intra-bunch motion in the last turns of a 16L2 event (overlaid coloured lines): vertical delta signal (top) and sum signal (bottom). A travelling wave motion is visible at the tail of the bunch.

Nevertheless, producing a large amount of ions through beam-induced ionization would also produce an equal amount of electrons. In addition, ions cannot readily explain the positive tune shift and the intra-bunch motion mentioned in the previous paragraphs. This is why models with electrons were also considered. A simple model using an equivalent impedance resonator to represent the interaction of the proton beam with an electron could reproduce the observed instability growth rate (20 turns) and the intra-bunch pattern, starting from the positive tune shift (+0.02) as input [19]. More involved electron cloud simulations confirmed that very high densities (10^{17} m^{-3} over 10 cm) may lead to positive tune shift of 10^{-2}, instability rise times below 100 turns, and intra-bunch travelling wave motion at the tail of the bunch [20].

However, simulations with electron cloud alone predict that such a large electron density cannot be accumulated along the train because of the space charge effect of the electrons surrounding the beam and can only be explained by the presence of significant positive ion densities. Simulations of electron dynamics accounting also for the presence of a large density of ions are ongoing and indicate that these ions could allow accumulation of electron density along the train [21].

CONCLUSION

The full characterization of the instabilities that constituted the last part of the 16L2 events required changes in the usual instability acquisition process in all transverse position monitoring devices (BBQ, ADT and Headtail monitor). These instabilities could be defined as transverse instabilities with 10- to 20-turn growth rate, sometimes coupling many bunches and characterized by a +0.02 tune shift and a travelling wave intra-bunch motion.

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Put together with other observables and models anticipated early in the run [11], this characterization provided timely important indications that electron cloud was likely to be a crucial player in the complex process of these 16L2 events. It allowed focusing on efficient mitigations, such as filling schemes that reduce electron cloud and the solenoid that was installed for the last part of the run [7].

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