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OBSERVATIONS, ANALYSIS AND MITIGATION OF RECURRENT LHC BEAM DUMPS CAUSED BY FAST LOSSES IN ARC HALF-CELL 16L2

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Abstract

Recurrent beam dumps significantly perturbed the operation of the CERN LHC in the summer months of 2017, especially in August. These unexpected beam dumps were triggered by fast beam losses that built up in the cryogenic beam vacuum at the half-cell 16 left of LHC-IP2 and were detected either at that location, but mainly in the collimation insertions. This contribution details the experimental observables (beam losses, coherent instabilities, heat load to cryogenic system, vacuum signals), the extent of the understanding of the beam loss and instability mechanisms and the mitigation steps and new settings that allowed recovering the luminosity performance of the LHC for the rest of the Run.

INTRODUCTION

Following the Extended Year-End Technical Stop (EYETS), the LHC restarted in 2017 for a production year with 25 ns bunch spacing. Very early in the re-commissioning phase of the machine, abnormal background radiation as well as sudden beam losses leading to beam dumps were observed for both proton beams (Beam 1 and Beam 2) near the 16L2 half-cell quadrupole, a standard cryogenic half-cell with 3 dipoles and 1 quadrupole [1, 2]. With increasing beam intensity stored in the machine, these beam dumps (67 in total in 2017) were more systematic and the impact on LHC operation became significant [2] (see Fig. 1).

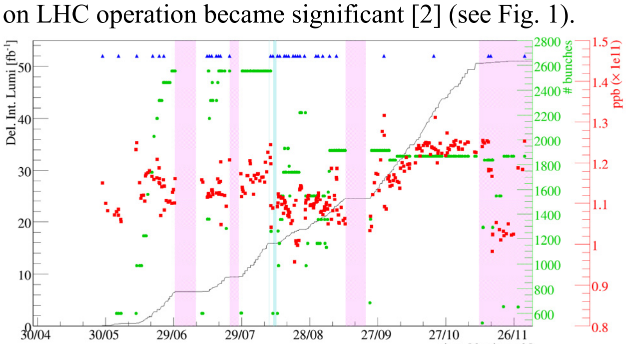

Figure 1: Overview of the 2017 LHC run: integrated luminosity (black line), number of bunches (green circles), intensity per bunch (red squares), days with beam dumps triggered by 16L2 events (blue triangles). Technical stops and special runs appear in pink ribbons and the beam screen regeneration in a light blue ribbon in the timeline.

From mid-June 2017 onwards, this worrying situation triggered many actions and studies in order to understand the origin of the losses and find appropriate mitigations. After a brief account of the current understanding of the origin of the issue, this contribution aims at summarizing the actions taken to avoid these premature beam dumps, which turned out to be the major performance limitation of the 2017 LHC Run. Analysis of available data, dedicated beam tests, elaboration of models and simulations, installation of new instrumentation, and finally proposal and implementation of solutions are briefly described.

ORIGIN OF THE 16L2 BEAM DUMPS

The most probable cause of the abnormal losses that occurred in 16L2 during the 2017 Run is an accidental air inlet into the LHC beam vacuum with beam screen at 20 K at the end of the EYETS [3, 4]. Air entered through a pumping module that was installed for the first time to accelerate the re-pumping down of sector 1-2 following the exchange of a magnet in half-cell 31L2. That pump was left connected during cool-down after beam screen regeneration (i.e. after increasing the beam screen temperature to approximately 80 K with the magnets at operating temperature of 1.9 K) and was connected to both apertures. It lost reading after a power cut and did not restart properly, likely leading to the accidental air in-leak and to the condensation and solidification of gases on the beam screen surface in and around the beam plug-in-module (see Fig. 2) [3].

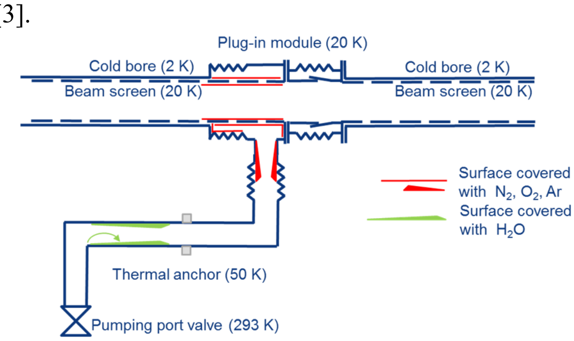

Figure 2: Schematic of the pumping system at the interconnect between the 16L2 quadrupole and neighbouring dipole, with the surfaces believed to be affected following the accidental inlet of air at the pumping port. For a detailed description of the LHC vacuum system, see [5].

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The interaction of the LHC proton beam with flakes of these frozen gases detaching from the beam screen surface is assumed to be at the origin of the beam losses in 16L2 during the 2017 Run [6-8].

ANALYSIS OF BEAM DATA

The analysis of data from existing monitoring instruments allowed identifying correlations of several signals with the beam dumps: Beam Loss Monitor (BLM) data in the collimation insertion (IR7) and 16L2, which triggered the beam dumps, radiation monitors (RadMON), cold mass dynamic heat loads for neighbouring cooling loops, and transverse beam position monitor signals. A typical "16L2 dump" event is preceded with steady losses of the order of 10^{-6} Gy/s at the 16L2 location, which are observed during the energy ramp and along the entire fill. A 16L2 event starts with a sharp sudden rise of losses by 3 to 4 orders of magnitude. This rise is sometimes typical of Unidentified Falling Objects (UFOs) in other locations of the LHC [9, 10]. Contrary to other UFO events in the ring, this loss event in 16L2 is systematically followed by a fast loss rise at the IR7 primary collimators (TCP), which most of the time triggers a beam dump [2, 8, 11] (see in Fig. 3).

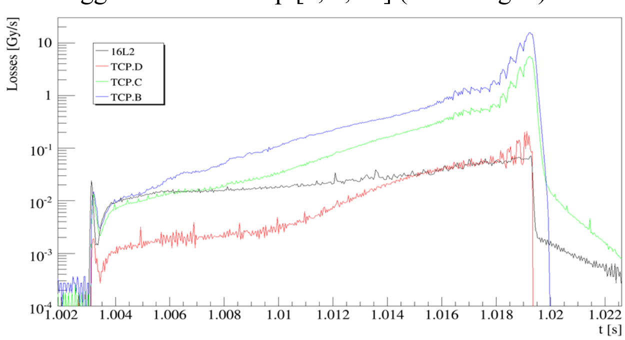

Figure 3: A typical 16L2 loss event monitored by BLMs: the UFO-like loss spike in 16L2 (in black) is followed by a loss rise at the three IR7 TCPs (in red, blue and green).

Fourier analysis of BLM signals at 16L2 during the events revealed that the initial loss spike contains the revolution frequency primarily, while the later rise in IR7 also contains a significant contribution at the betatron tune, which can be seen in Fig. 3. In fact, the available post-mortem buffers of the transverse damper (ADT) and base-band tune pick-up (BBQ) were also showing evidence of very fast increase of the transverse coherent motion [12]. Diamond BLMs, which allow for bunch-by-bunch loss monitoring, revealed that the first UFO-like loss spike was affecting all bunches [13, 14]. It was therefore concluded that the initial spike is due to all bunches hitting nuclei, while the later loss rise in IR7 is caused by a transverse instability, whose growth rate was 1 to 2 orders of magnitude larger than instabilities that had previously been observed in the LHC and could be predicted from models including electrons or ions effects separately [15].

ADDITIONAL MONITORING

Several additional diagnostics were improved or put in place in order to understand further the mechanisms behind the available observations. First, x-ray tomographies of the 16L2 and nearby interconnects were performed during a machine stop, but did not reveal anything abnormal at the hardware level.

The ability to analyse losses near the 16L2 quadrupole during dump events was significantly improved during the run. First, additional mobile BLMs were installed to increase the longitudinal granularity of loss monitoring. This allowed narrowing down the loss origin for both beams within 1.3 m in between the quadrupole MQ.16L2 and the dipole MB.C16L2, thanks to fitting simulation results of energy deposition from hadronic showers [16] (see Fig. 4).

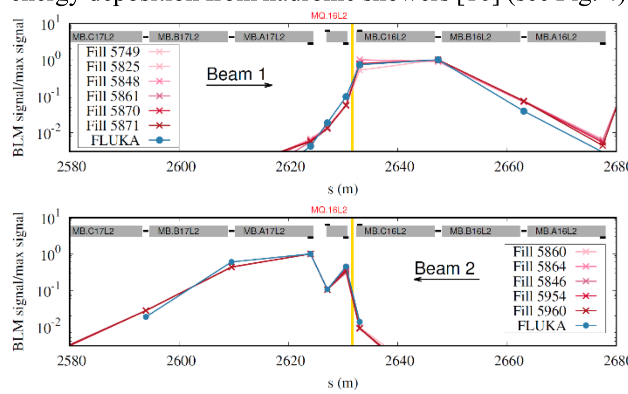

Figure 4: Loss pattern as a function of position along the machine for 16L2 dumps due to losses for Beam 1 (top), and Beam 2 (bottom). Measured data are displayed with red crosses and FLUKA [17] simulation best fit results with blue dots. The expected loss location providing the best fit to the measured data is indicated by a yellow line.

Increased sensitivity on the beam losses could be gained by installing 2 bundles of 15 standard BLMs in 16L2 allowing to identify lower levels of steady state losses.

Additional vacuum gauges were connected to the 16L2 pumping port, but they did not allow measuring the pressure near the cold beam screen during dumps due to the large pumping speed of the cryogenic surfaces of the pipe connecting the cold beam screen with the warm temperature gauge.

The instability-monitoring network (ADTObsbox and instability detection trigger network linking several instruments) – that was operational in 2017 [18] – was reconfigured and managed to resolve and store turn-by-turn and bunch-by-bunch positions during the transverse instability process: large positive tune shift of the unstable mode and the travelling-wave intra-bunch motion caught by a wideband monitor were observed. These provided an indication that the instabilities were driven by electrons, that they could not be due to, for instance, a simple malfunction of the ADT [12, 19], and that the corresponding expected electron densities could not be achieved without the presence of significant ion densities.

TESTS AND MITIGATION MEASURES

Many tests with and without beam were performed to improve the understanding of the mechanisms behind the instability and possibly find mitigation measures.

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Several sessions of dedicated aperture measurements did not reveal any evident local aperture restrictions [1].

The strict asymmetry between the plane of loss for both beams (vertical for Beam 1 and horizontal for Beam 2) led to suspect that the orbit corrector MCB.16L2 could play a role [20]. Tests to run with that corrector switched off led to systematic beam dumps of all subsequent LHC fills. Dedicated tests allowed identifying clear correlations between the current in MCB.16L2 and 16L2 steady-state losses as well as 16L2 events [8], while it was checked that local orbit changes had no impact. A first mitigation to 16L2 events therefore consisted in setting an operational bump throughout the fill so to keep a small but non-zero current in the orbit corrector. That same week, a test using a beam with 50 ns bunch spacing showed that the normalised background losses were lower than for the 25 ns bunch spacing for the same number of bunches. Both these observations (sensitivity to bunch spacing and corrector current) were early signs that electrons could play a role in this mechanism [21].

A regeneration of the 16L2 beam screen was discussed and decided, in order to see if it would have an impact and could yield more understanding of the origin of the problem (in particular, detecting species other than hydrogen and helium) [22]. That beam screen regeneration (represented as a blue ribbon in Fig. 1) indeed detected significant outgassing at the newly installed vacuum gauges in 16L2, which shed light on the origin of the problem. Unfortunately - and unexpectedly – it also modified the configuration of the frozen species inside the beam vacuum in such a way that the situation after the regeneration was much worse than before. Keeping the corrector current high did not mitigate the beam dumps anymore, and the beam intensity had to be lowered to avoid systematic beam dumps. It was also observed that steady-state losses decreased and the additional heat load to the 16L2 cryogenic loop had disappeared.

A task force was then set up to co-ordinate CERN efforts and gather all relevant information and, in this context, a test to probe whether beam intensity had an impact on 16L2 events was proposed [3] and indeed indicated the existence of a threshold effect at about 1700 bunches [23].

At that point, it was considered to warm up the cold mass to 70 K [3], but this would have costed several weeks of operation. Since there had been several converging signs that electrons were part of the mechanism of 16L2 events, it was proposed to try using the anti-electron cloud filling scheme 8b4e [24], which reduces significantly electron multipacting while keeping a 25 ns bunch spacing [25]. Loss spikes reduced significantly and stable operation could be restored with 1830 bunches provided the number of protons per bunch remained below 1.17 10^{11}: above that threshold, beams were systematically dumped due to 16L2 events [8].

The smoother operation with 8b4e confirmed that electron multipacting plays a role in 16L2 events. Simulations showed that a solenoidal field could significantly decrease multipacting, provided the secondary electron yield is much larger than 1.0 and the installation of a solenoid was proposed around the 16L2 interconnect [26]. The design, production and implementation of the solenoid was performed in a record time, and operation with the 16L2 solenoid current at 55 A (~ 6 mT) after the technical stop was possible at higher bunch intensity: 16L2 events were only observed when the number of protons per bunch was above 1.3 10^{11} [8]. A test with solenoid off at the end of the run with 1868 bunches each of 1.25 10^{11} p led to a beam dump linked to a 16L2 event, thereby confirming the beneficial effect of the solenoid on the intensity threshold [27].

Besides, 16L2 events came back on Beam 2 during the 2.51 TeV run towards the end of 2017, as the bump to keep the MCB current away from zero was not used. As soon as the operational bump was restored and the MCB current moved away from zero, stable operation could resume [8]. This confirmed, once more, the impact of the orbit corrector current on 16L2 events, even with low electron cloud filling schemes.

PROPOSED SOLUTIONS

As described above, all mitigation measures to the 16L2 events were contributing to the reduction of the electron cloud multipacting in the region of the 16L2 interconnect: increasing the magnetic field in the involved zone (through the MCB.16L2 corrector current and the solenoid) and using special filling schemes such as 50 ns and 8b4e. Thanks to these solutions, steady luminosity production could be recovered for the end of the year as seen in Fig. 1. As a final step to remove the air from the beam pipe, it was decided to warm up the sector 1-2 to room temperature during the winter shutdown 2017-18 [28]. In view of the amount of air that was pumped out, the expected amount of gas species that could still be trapped was expected to be small enough and it was decided to stop the warm-up at 90 K to avoid the need to requalify electrically the sector [29].

OUTLOOK

Consistent models appeared when gathering all available information, in particular the missing pieces of the puzzle that (1) there was a potential air inlet in 16L2, (2) very high local pressure could go unnoticed with the current gauges and (3) electron cloud had a significant role in both the trigger and the instability mechanism.

Several features of the mechanism of the 16L2 events were anticipated early in the run [6, 30] and the current understanding is [6, 7, 30]: (1) Desorption of frozen nitrogen/oxygen flakes could be stimulated by electron multipacting. (2) The proton beam interacts with the flakes, generating a UFO loss spike. (3) The flake undergoes phase transition to a gas and is ionized, generating a plasma of high density of electrons and ions in the beam path, both generating a very fast instability.

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