OBSERVATION OF FAST LOSSES IN THE LHC OPERATION IN 2017

A. A. Gorzawski, Univ. of Manchester; CERN, Geneva, Switzerland

S. Redaelli, H. Garcia-Morales, N. Fuster-Martinez, C. Zamantzas,
C. Xu, CERN, Geneva, Switzerland,

R. B. Appleby, Univ. of Manchester; Cockcroft Institute

Abstract

Four diamond detectors that provide beam loss measurements with time resolution in the nanosecond range were added in the vicinity of the primary collimators of the Large Hadron Collider (LHC). This is a powerful diagnostic tool that provides the unique chance to measure bunch-by-bunch losses. The operation of the LHC in 2017 presented several unusual events of fast, high intensity beam losses, many of them captured by the diamond detectors in the betatron cleaning region. In this paper we review some of the relevant loss cases that were analyzed in the wider scope of determining the source of the instability generating these losses. We show few of the possible applications of this detectors in daily operations.

INTRODUCTION

The primary collimators of the Large Hadron Collider (LHC) at CERN have tight gaps throughout the operational cycle in order to ensure adequate machine protection and cleaning against beam losses. The total stored energy in the LHC beams at 6.5 TeV exceeds 300 MJ and in 2017, the primary collimator gaps at top energy were as small as 2 mm. Monitoring losses at these collimators can provide an early detection of various accelerator physics mechanisms that lead to beam losses. The standard beam loss monitoring system that provides loss data at 40 µs has been recently extended with a new setup based on diamond detectors that enable recording losses at a sampling time of 1.6 ns. Four monitors installed in the betatron cleaning insertion (IR7) of the LHC were used extensively in 2017 in standard operation and in dedicated collimator measurements. In this paper we present a summary of applications for this system and its performance in monitoring collimation losses.

SYSTEM LAYOUT AND DATA ACQUISITION

Diamond beam loss monitors (dBLM) are installed in various locations in the LHC tunnel [1]. For this paper we only focus on the installation in IR7. Figure 1 shows the actual diamond detector installed next to a primary collimator (TCP). Two sets of measurement devices (detectors and acquisition boxes) were set up in IR7. For each beam, one sensor sits immediately downstream of the primary collimators (we call these dBLM-B1-1 and dBLM-B2-1, for Beam1 and Beam2 respectively) and a second one downstream of a secondary collimator close to the central part of IR7 (called dBLM-B1-2 and dBLM-B2-2). The former ones were found
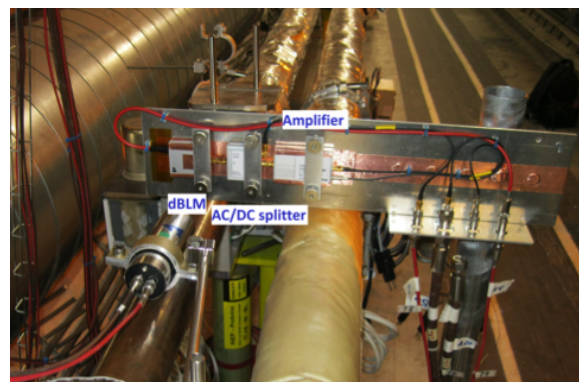

Figure 1: The diamond detector installed in IR7, down stream of secondary collimators.

to be more sensitive to losses and are those that are primarily used for this work.

dBLMs are polycrystalline diamonds with a size of 10 mm times 10 mm × 0.5 mm with a set of signal amplifiers and high voltage cables. The measurement channel is connected to the data acquisition system [2], that can be operated simultaneously in two modes: time histogram and waveform measurements.

In the histogram mode, the system is simultaneously able to produce a high sampling rate waveform and provide a real-time beam loss time histogram. The source signal is looped (by synchronization to the LHC turn time of ≈89 µs) and divided in time bins, with an individual counter set. The bin width is 1.6 ns. This mode was continuously recording at an update rate of 1 Hz.

In the waveform mode, the system has 4 analogue input channels for the waveform measurement. This is a direct oscilloscope–like measurement that records the signal with a defined sampling rate, length and voltage range. Each channel has a maximum sampling rate of 5 GS/s. A maximum buffer size of 10^9 samples is available to store the data from all 4 channels. Typically, 10^6-10^8 data points (i.e., ≈100 ms at the lowest sampling time of 1.6 ns) per channel was used, as any larger value significantly reduced the availability of the device.

SYSTEMATIC FILL BY FILL LOSSES

LHC Beam Types and Fill Selection

In this section we present a selection of results from the loss analysis of physics fills in 2017 in different phases of the LHC operational cycle. We consider only the standard,

physics production fills that produced at least one hour of Stable Beam (SB) with total intensity larger than 2^{14}p per beam. In the middle of the year, due to instabilities coming from an vacuum nonconformity [3], the standard LHC filling scheme consisting of batches of 48 bunches spaced by 25 ns (48b) was replaced by a scheme featuring eight bunches separated by four empty 25 ns slots (8b4e). This gaps limits effects from electron cloud. This scheme also benefited from smaller emittances, from $\overline{\varepsilon}$ =2.5 μrad down to $\overline{\varepsilon}$ =2.0 μrad, thanks to the batch compression scheme (BCS) [4].

In this analysis we consider data from 20 fills from each of the three periods of the operational year listed in Table 1. Within each case we focus on one colliding train at the end of the beam (*last colliding*) and the abort gap (AG) region in the filling scheme. The former case is selected so that the same collision pattern of trains is considered when comparing different schemes. The following analysis shows the loss normalized to the first 8 bunches of each train; we choose that number for the convenience of the analysis. For the AG we consider instead the total integrated loss. For all the following subsections, we observe a noticeable reduction of losses while changing the filling scheme from the 48b to 8b4e scheme.

Ramp Losses

An example of bunch losses from the histogram mode, which illustrates how data are recorded, is given for dBLM-B1-1 in Fig. 2. In the following, we show plots of losses as a function of time for different phases of the cycle. These are produced by integrating the signal over a certain number of bucket slots (e.g., those that longitudinally correspond to the abort gap, AG).

Figure 3 shows the average train losses (solid lines) plotted as a function of time during the LHC energy ramp as measured by the monitor dBLM-B1-1. The light areas around solid lines give the spread over the considered fills. Note that a partial betatron squeeze takes place in the ramp, with IP1

Table 1: Selected 2017 Operational Parameters for LHC [5]

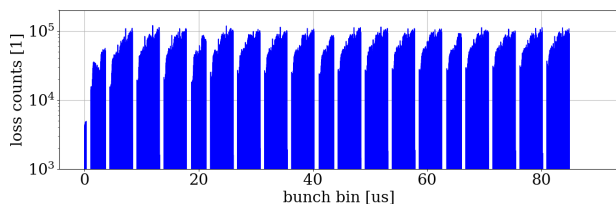| Id	Month in 2017	β^* [cm]	Initial $\frac{\phi}{2}$ [μrad]	Beam/Train, Type
1	Apr – Aug	40	150	standard 25 ns, 48b
2	Aug – Sep	40	150	BCS 25 ns, 8b4e
3	Sep – Dec	30	150	BCS 25 ns, 8b4e

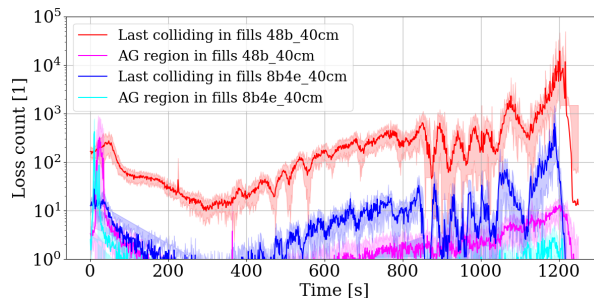Figure 2: Bunch-by-bunch losses integrated over 1h of collisions.

Figure 3: Average loss evolutions along the ramp for Beam 1, for first two analyzed periods (from Table 1).
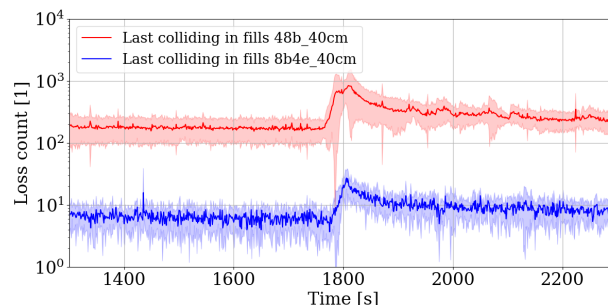

Figure 4: Overview of few minutes before and after crossing angle change for two periods (1 and 2 from Table 1)

and IP5 reaching 1 m at 6.5 TeV. A first increase of losses just after the start can be attributed to losses of uncaptured particles and the later peaks (as of 400 s) are related to the squeeze process incorporated in the ramp [6]. Losses are synchronized to changes of optics as expected.

We can see losses coming from the AG region (magenta and cyan) that vanish after the first 20 s of the ramp. Their level remains orders of magnitude lower than that of the regular bunch losses of either scheme.

Stable Beams and Crossing Reduction Losses

The "crossing angle anti-leveling" [7] is a luminosity leveling technique deployed at the LHC in 2017 that consists of reducing the angle in steps during the collision process, to increase the peak luminosity. Figure 4 illustrates the evolution of losses before and after one step of crossing angle change is executed. Although the loss levels are different for the two schemes, with the standard 48b being about one order of magnitude above, one can notice similar transient changes when the crossing angle is reduced. Figure 5 shows the losses of individual bunches along the 48b train at the moment of the angle change (color coding: more – blue – or less – red – than 32 long-range encounters).

SINGLE BUNCH INSTABILITY DETECTION

The bunch by bunch resolution allows us to determine which bunches are responsible for losses in case of instabilities. See an example in Fig. 6. By identifying them and providing their time evolutions (see Fig. 7) one can detect the
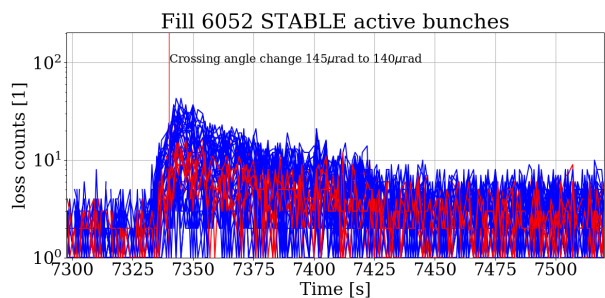
Figure 5: Single bunch losses recorded by dBLM-B1-1 versus time around a crossing angle change, for bunches with more (blue) or less (red) than 32 long-range encounters.
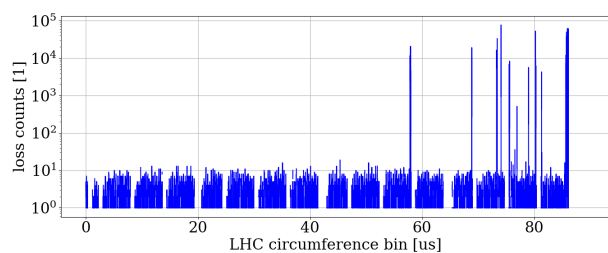

Figure 6: Profile of the beam indicating the integrated loss over the squeeze mode. In the right hand side the unstable bunches visible with losses higher than 10^3.
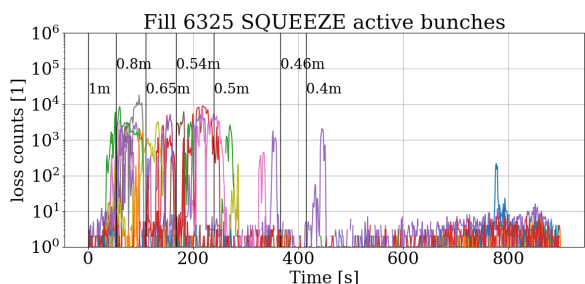

Figure 7: Time evolution of the losses of the bunches of Fig. 6 with largest loss contribution.

moment in the cycle when a particular bunch became unstable. The example shown here is one of the very few, almost unnoticed in operation that however triggered interesting analysis of instabilities [8].

In 2017 the LHC was heavily disturbed by the vacuum nonconformity in cell 16 left of point two (16L2). While the details of the origin and the mitigations are described in [3, 9], we focus only on usage of selected waveform data sets. Figure 8 illustrates the integrated loss over 100 turns with a strong indication of loss decrease and build up along the trains after longer gaps in the filling scheme.

FREQUENCY ANALYSIS OF LOSSES

From the dBLM's waveform mode, extracting the turn by turn loss data one can reconstruct the frequency content of losses, e.g. to reconstruct the betatron tunes. Figure 9 shows the FFT of this fast loss signal for one bunch. The present
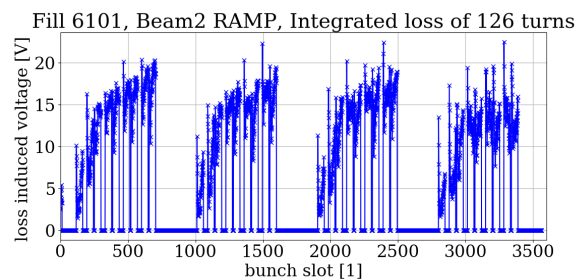

Figure 8: The maximum loss per bunch recorded over 100 turns in a "16L2" loss event [9].
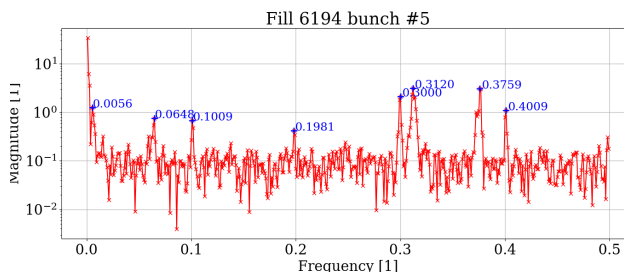

Figure 9: FFT amplitude of beam losses versus frequency for a dBLM-B1-1 measured during a collimator step.

setup does not allow us to distinguish horizontal and vertical losses, so it is not straightforward to conclude on the plane of losses. But several peaks are noticeable in the frequency region of the nominal betatron tunes ($Q_x = 0.31$ and $Q_y = 0.32$).

OUTLOOK AND CONCLUSIONS

We presented some applications of the diamond BLM system installed in the LHC betatron collimation insertion. A selection of results illustrates the potential of this measurement system to understand better the losses at the LHC. Measurements range from the bunch-by-bunch analysis in different phases of the operational cycle, to the frequency analysis of fast losses. This work will continue in 2018, in collaboration with the various teams at CERN.

New hardware is planned to improve the system. The addition of one monitor per beam will allow distinguishing the horizontal and vertical contents of losses at primary collimators, thus opening the possibility for a better understanding of loss mechanisms and for further study of correlation with other bunch-by-bunch measurements.

ACKNOWLEDGMENTS

REFERENCES

[1] C. Xu and A. Gorzawski, "Using diamond BLMs in the LHC", BI-Day 2017, 29th June 2017, `https://indico.cern.ch/event/641870/`

[2] A. Gorzawski *et al.*, "Fast loss analysis with LHC diamond detectors in 2017", CERN Technical Report, Geneva, April 2018, to be published.

[3] B. Salvant *et al.*, "Observations, analysis and mitigation of recurrent LHC beam dumps caused by fast losses in arc half-cell 16L2", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, this conference.

[4] A. Lasheen *et al.*, "Overview of the beams from the injectors", contribution at the LHC Operations Workshop in 2017, Evian, France, December 2017.

[5] R. Steerenberg *et al.*, "Summary of 8th LHC operations Evian workshop", Evian, December 2017, `https://indico.cern.ch/event/641870/`

[6] M. Solfaroli Camillocci *et al.*, "Combined ramp and squeeze to 6.5 TeV in the LHC", in *Proc. of IPAC 16*, Busan, Korea, 8-13 May 2016, paper TUPMW031.

[7] N. Karastathis *et al.*, "Crossing angle anti-leveling at the LHC in 2017", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, this conference.

[8] L.R. Carver *et al.*, "Instabilities and beam induced heating in 2016", contribution at the LHC Operations Workshop in 2017, Evian, France, p. 141, December 2017.

[9] B. Salvant *et al.*, "Experimental characterisation of a fast instability linked to losses in the 16L2 cryogenic half-cell in the CERN LHC", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, this conference.