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BEAM LOSS SIGNAL CALIBRATION FOR THE LHC DIAMOND DETECTORS DURING RUN 2

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Abstract

Chemical Vapour Deposition (CVD) diamond detectors can be used as fast beam loss monitors in particle accelerators. In the Large Hadron Collider (LHC) at CERN, they are installed in the betatron collimation region, a high-radiation environment. In addition to their high-radiation tolerance, their main advantage is a time resolution of 1 ns which makes possible not only turn-by-turn, but also bunch-by-bunch loss measurements. An analysis of the LHC diamond beam loss monitor signals recorded during the last months of Run 2 (September 2018-November 2018) is presented with the aim of obtaining a signal-to-beam-loss calibration.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is the largest and most powerful accelerator ever built. It has a 27-kilometre long circumference and it is located 100 m underground. The LHC accelerates protons and ions up to a design energy of 7 TeV, with up to 2 556 particle bunches per beam and, on average, 1.15×10^{11} particles per bunch, achieved during Run 2 (2015-2018) [1].

Dipole electromagnets create a field of up to 8.33 T that is used to bend the trajectory of the beam particles along the accelerator. In order to reach and maintain the current of around 11 850 A required to produce this magnetic field, superconducting coils are employed in the LHC magnets [2]. Under these conditions, losses on the level of 30 mJ/cm^3 induced by a local transient beam loss of 4×10^7 protons could provoke a transition from superconducting to normal conducting state (quench) in the magnets and generate an accelerator downtime in the order of hours or even months [3]. Additionally, beam losses could damage the accelerator or detector equipment.

Driven by these concerns, a Beam Loss Monitoring (BLM) system is installed in the LHC. The system includes around 4 000 beam loss detectors placed all around the accelerator ring downstream the most probable loss locations. They measure continuously the beam losses and trigger a beam dump signal when the losses reach certain predetermined thresholds [4]. Even though it is seen mainly as a machine protection system, the signals from the beam loss detectors can also be used to provide a precise number of the lost beam particles and to identify the different loss mechanisms, making it a powerful diagnostics tool to improve the performance of the accelerator. This type of analysis has already been carried out in the past, but only considering the signals from the Ionization Chamber (IC) BLM detectors [5–7]. This work aims at reproducing the same results using the signals from the Diamond BLM (dBLM) detectors that were under test in certain locations in the LHC during Run 2, which offer a bunch-by-bunch loss signal resolution and therefore could provide a more detailed information about the LHC beam loss patterns.

LHC BLM SYSTEM DETECTORS

The LHC BLM system includes four different types of beam loss detectors. The most relevant ones for this analysis are the IC BLMs and the dBLMs.

Ionization Chambers

The IC is the most common beam loss detector type in the LHC BLM system, with around 3 600 installed downstream the most probable loss locations. The IC is made of a stainless steel cylindrical tube which is 50 cm long, with a diameter of 9 cm and filled with nitrogen gas. It contains aluminium plates that are alternatively used as high voltage and signal electrodes. A voltage of 1.5 kV is applied between the electrodes, which generates an electric field of 3 kV/cm inside the chamber. The internal part of an IC BLM detector is shown in Fig. 1. The analog beam loss signal is induced when the lost beam particles or their products traverse the chamber and ionize the gas inside [8]. The signal is then continuously integrated and digitized in the front-end analog electronics using a Current-to-Frequency-Converter card that provides measurements every 40 µs [9]. The read-out electronics then converts the signal bits to Gy/s and keeps a history of the values by producing longer integration windows.

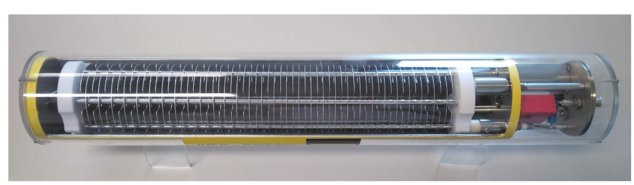

Figure 1: Internal part of an IC BLM detector showing the electrodes. The cables to the read-out electronics are located on the right side.

Diamond Detectors

The dBLM consists of a squared pCVD diamond detector which is 10 mm long and 0.5 mm thick. It offers a time resolution in the order of the ns which allows to record turn-by-turn and bunch-by-bunch beam loss measurements, as the nominal LHC bunches are separated by 25 ns [10]. These

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dBLM detectors were under test during the LHC Run 2 in certain specific locations. A dBLM detector and its analog front-end electronics are shown in Fig. 2. The signal induced in these detectors is digitized; about 57 802 samples per turn (i.e. approximately 89 µs long) are saved. The signals start being processed in the digital back-end, which provides various measurement modes. The one considered for this analysis is the Integral mode, which performs a bunch-by-bunch integration of the measured beam losses for every 11 200 turns (approximately every second) and calculates a baseline reconstruction within bunches that is subtracted from the integrated signal. An example of a dBLM bunch-by-bunch integrated beam loss signal during a Squeeze beam mode from a nominal LHC fill can be seen in Fig. 3.

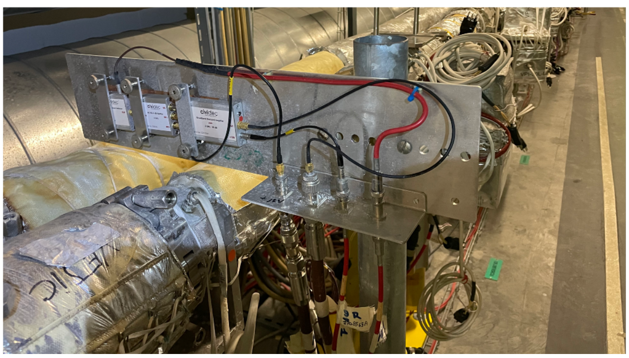

Figure 2: dBLM detector and analog front-end electronics located above the LHC beam pipes. From left to right a detector, AC-DC splitter and signal amplifier can be seen as well as the signal and high voltage cables.

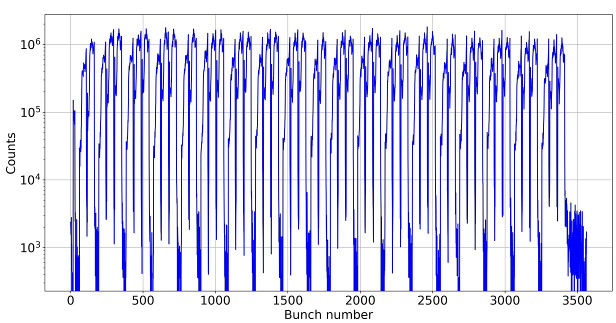

Figure 3: dBLM bunch-by-bunch integrated loss signal during a Squeeze beam mode from a nominal LHC fill.

LHC dBLM DETECTORS LAYOUT

During the LHC Run 2, 6 dBLM detectors were installed in the betatron collimation region, where the collimators which clean the beam from transverse halo particles are located. In Figs. 4 and 5 the dBLM layout in the LHC betatron collimation region is presented respectively for beam 1, which circulates clockwise in the LHC tunnel, and beam 2, which circulates counterclockwise. In both figures, the collimators located upstream the dBLM detectors are indicated with blue horizontal rectangles together with their beam cleaning orientation. The dBLM detectors are indicated

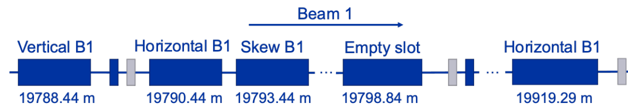

Figure 4: dBLM Layout in the LHC betatron collimation region for beam 1.

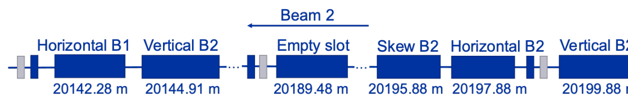

Figure 5: dBLM Layout in the LHC betatron collimation region for beam 2.

with grey vertical rectangles. Additionally, the IC detectors which are located closer to them are indicated with blue vertical rectangles.

As it can be seen in both figures, 3 dBLM detectors were installed per beam. In both beam lines there is a dBLM detector located downstream the primary vertical collimator, which is upstream the rest of the betatron collimation system for each beam. For this reason, the signals from both detectors are expected to be highly sensitive only to the beam particles lost in the respective primary vertical collimators, which is useful to identify whether the beam particles are lost in these collimators or elsewhere in the accelerator. Further downstream the primary collimators in both beam lines there is a dBLM detector located next to an empty slot and a dBLM detector located downstream additional collimators. Based on their positions, the signals from these 4 dBLM detectors are expected to be highly sensitive to the beam particles lost in the betatron collimation region, regardless of the type of the exact collimator where they are lost.

dBLM DETECTOR CALIBRATION

Obtaining a global calibration of the LHC dBLM detectors is key to the development of the loss pattern recognition algorithms that allow to study the LHC beam loss decomposition. These loss pattern recognition algorithms compare measured losses to well defined loss scenarios. Considering the total beam losses as a linear combination of those well studied loss scenarios, it is possible to obtain the loss vector decomposition using linear algebra.

Principle of the Loss Decomposition Algorithm

The signal of a BLM detector, S_i, is proportional to the total number of protons lost by different mechanisms in the LHC, ΔI, so that $S_i = \alpha_i \times \Delta I$. The constant α_i is called the monitor response factor.

For instance, in the case of protons lost in horizontal collimators, the signal of the same BLM detector is related to those lost protons by:

$$S_{i,\mathrm{H}} = \alpha_{i,\mathrm{H}} \times \Delta I_{\mathrm{H}}, \quad (1)$$

where $\alpha_{i,\mathrm{H}}$ is the monitor response factor for horizontal beam losses and ΔI_{H} represents the number of protons lost in the horizontal collimators.

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Considering a set of signals from different BLM detectors, $\vec{S} = (S_1, S_2, S_3, ...)$, and protons lost in different loss scenarios, $\overrightarrow{\Delta I} = (\Delta I_{\mathrm{H}}, \Delta I_{\mathrm{V}}, \Delta I_{\mathrm{S}}, ...)$, a so-called response matrix, $\boldsymbol{M}$, which includes all the monitor response factors for the different loss scenarios, can be defined as:

$$\vec{S} = \boldsymbol{M} \times \overrightarrow{\Delta I} \tag{2}$$

In nominal LHC fills it is possible to calculate the protons lost in different loss scenarios by applying the inverse response matrix to the BLM detector signals:

$$\overrightarrow{\Delta I} = \boldsymbol{M}^{-1} \times \vec{S} \tag{3}$$

Considering the capabilities of the LHC dBLM system to distinguish between particles lost in horizontal and vertical collimators, a preliminary and simplified version of a loss decomposition algorithm including their signals has been developed. Only horizontal and vertical particle loss scenarios are considered.

Data for Calibration: Lossmaps

The data for the calculation of the monitor response factors are collected from the so-called lossmaps. These are periods during which beam losses are generated on purpose with a low-intensity beam by exciting independently bunches with white noise in a selected plane (horizontal or vertical). This makes the beam transverse size to increase in a controlled way. As the beam size grows measurable beam losses start to appear at the collimators. The BLM detector signal and the beam intensity measured with the Beam Current Transformer (BCT) detector are extracted for that lossmap period and the monitor response factor for that loss scenario is calculated using Eq. (1).

For the simplified version of the algorithm, a set of horizontal and vertical lossmaps is required to calculate the monitor response factors. Furthermore, it is preferable to analyze the data from the lossmaps taking place during LHC Squeeze beam modes, as the beams are at top energy but not colliding, so the majority of the beam losses are expected to occur in the betatron collimation region. Therefore, for these lossmaps it is possible to crosscheck the total lost beam intensity calculated from the algorithm with the absolute measurements from the BCT detectors.

The signals of the LHC dBLM detectors were only logged during the last months of the LHC Run 2, from September 2018. For that period of time, a set of horizontal and vertical lossmaps that were performed after the LHC Technical Stop (17-21 September 2018) during a LHC Squeeze beam mode were selected for this analysis.

During that Technical Stop, the setups of some of the LHC dBLM detectors were modified, e.g. the amplified signal gain. Furthermore, the signals from the two LHC dBLM detectors installed downstream the empty slots stopped being logged after the Technical Stop. For that reason, those detectors were not considered in this analysis.

Using the data from the selected lossmaps the monitor response factors for horizontal and vertical loss scenarios

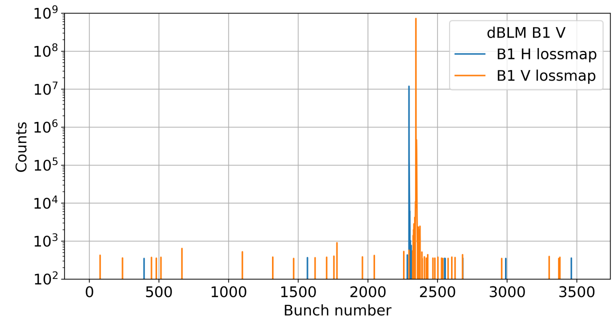

Figure 6: Bunch-by-bunch integrated signal of the beam 1 dBLM detector located downstream the primary vertical collimator for a horizontal and a vertical lossmap.

were calculated for the 4 remaining LHC dBLM detectors and their closest IC BLM detectors for comparison purposes. As expected, the monitor response factors of the detectors located downstream the primary vertical collimators were much higher in the case of a vertical lossmap. Figure 6 shows the integrated bunch-by-bunch signal of the dBLM detector installed downstream the beam 1 primary vertical collimator during the selected beam 1 horizontal and vertical lossmaps. The signal peak is centered around a single particle bunch (only one particle bunch is excited per lossmap) and the signal during the vertical lossmap is around two orders of magnitude higher than during the horizontal lossmap, even if during both lossmaps the lost beam intensities measured by the BCT detector were around 5×10^9 protons. This behavior is expected, as the detected loss for different loss scenarios depends on the location of the detector.

CALIBRATION VALIDATION

After the calculation of the respective horizontal and vertical monitor response factors, the response matrices of the simplified dBLM and equivalent IC BLM decomposition algorithms were defined as in Eq. (2). The inverse matrices were calculated so that the algorithms could be applied to the dBLM and IC BLM signals as in Eq. (3) for regular LHC fills.

For the validation of the calibration, the decomposition algorithm was applied to the LHC Squeeze beam modes that took place during regular proton Physics periods after the Technical Stop in September 2018. That made a total of 27 Squeeze beam modes considered, each with a duration of around 11 minutes.

Figures 7 and 8 show the total lost beam intensity during each Squeeze period for beam 1 and beam 2 respectively. The red dots indicate the results obtained from the dBLM decomposition algorithm, while the blue stars indicate the results from the IC BLM decomposition algorithm and the green triangles the values measured with the BCT detectors. It can be seen that systematically the results obtained with the IC BLM algorithm show a better agreement with the lost intensity measured with the BCT detector but the dBLM method is able to follow the same trend.

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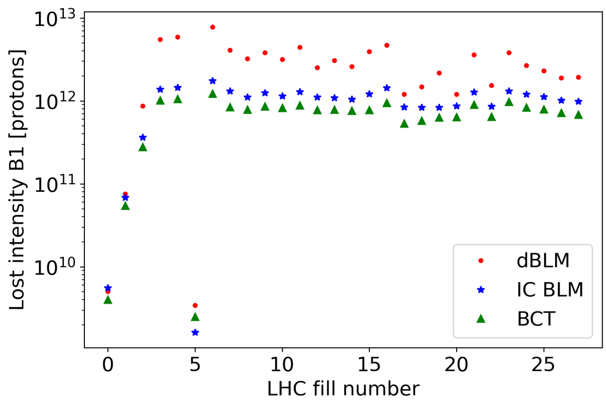

Figure 7: Total lost intensity in beam 1 during LHC Squeeze beam modes as calculated with the dBLM algorithm, the IC BLM algorithm and measured with the BCT detector.

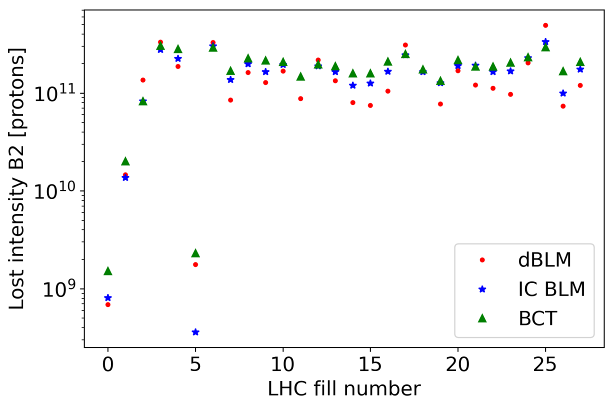

Figure 8: Total lost intensity in beam 2 during LHC Squeeze beam modes as calculated with the dBLM algorithm, the IC BLM algorithm and measured with the BCT detector.

CONCLUSION

Even though the BLM detectors are generally considered as a machine protection device against beam losses, their signals can also be used as a powerful diagnostics tool to improve the performance of the accelerator by providing a precise number of the lost beam intensity and identifying the beam loss mechanisms. In the past, this was only done with the signals from the IC BLM detectors. However, a set of dBLM detectors were installed and under test in the LHC betatron collimation region during the last months of Run 2. Their main advantage with respect to other types of BLM detectors is a time resolution of 1 ns which makes possible not only turn-by-turn, but also bunch-by-bunch loss measurements. A global calibration for the dBLM detectors was carried out. Even if the IC BLMs still show a higher accuracy for this kind of analysis, this paper shows that they can also be calibrated in such a way that the loss measurement is provided in total number of protons lost in the machine. A series of tests at the electron beam facility CLEAR at CERN are foreseen in order to study the response function of the dBLM detectors signals, the mix of signal from multi-bunched beams and the treatment of the signal noise. The aim of these studies is to achieve a better understanding of the dBLM detectors signals and improve their calibration results.

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