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CALIBRATION OF THE LHC DIAMOND BEAM LOSS MONITORS FOR LHC RUN 3

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Abstract

A set of twelve Polycrystalline Chemical Vapour Deposition (pCVD) diamond detectors are installed in the beam injection, extraction and betatron collimation areas of the Large Hadron Collider (LHC) as fast beam loss monitoring detectors. Their high-radiation tolerance and time resolution in the order of a few ns makes them an ideal candidate to monitor bunch-by-bunch losses in the LHC beams, which have a nominal bunch separation of 25 ns. Considering their location in some of the most critical areas for beam loss studies, a signal-to-lost-particle calibration of these detectors provides a useful insight of the various LHC bunch-by-bunch beam loss mechanisms. This contribution shows the principle of the calibration of the LHC diamond Beam Loss Monitors (dBLMs) as well as a description of the machine tests run to study and perform this calibration.

INTRODUCTION

The LHC at CERN is the most powerful accelerator ever built, and the restart of its operation in 2022 for Run 3 arrived with a record beam energy of 6.8 TeV. Combined with an intensity of more than 10^{14} protons [1], the LHC beams can be highly destructive if they reach machine elements.

In order to actively protect the LHC machine against damage from beam losses, around 4 000 detectors based on Ionization Chambers (ICs) are installed downstream the most probable loss locations as part of the LHC BLM system. These detectors provide an integrated signal which is updated every 40 µs and compared with predetermined beam loss thresholds. In the event that one of the measured signals reaches its respective threshold, the beams are extracted from the LHC in less than 3 turns, being 89 µs each [2].

Additionally, twelve dBLM detectors are installed in the regions that are expected to reach higher levels of beam losses regularly and would profit from a higher spatial resolution in the measurements. These detectors are high-radiation tolerant and with a fast signal response in the order of a few ns, therefore the perfect candidates to resolve bunch-by-bunch beam losses in the LHC, which nominal bunch separation is 25 ns.

There is one dBLM detector at the beginning and at the end of each one of the injection lines and one dBLM detector in each extraction line. The remaining six are located in the betatron collimation region, the only location where multi-turn beam losses are expected to be measured by the dBLM detectors regularly during nominal LHC operation.

A signal-to-beam-loss calibration of these six detectors was proven to be possible using Run 2 data. However, it could not reach the same level of accuracy as the similar calibration carried out with the IC BLMs located downstream the primary collimators [3].

Discrepancies observed between the IC BLM and dBLM detectors signals, in addition to the lack of un-preprocessed dBLM data and the unability to read the non-amplified channels motivated the proposal to test the dBLM detectors in the electron beam test facility CLEAR, awaiting for the restart of the rest of the CERN accelerator complex [4].

It was found that, even though the dBLM signal grows linearly with increasing beam losses, when the amplified channel saturates its signal drops drastically, providing negative readings and affecting the integrated beam loss values.

Following the analysis of the tests, and in view of improving the accuracy of the dBLM calibration, it was decided to start logging other quantities such as the non-amplified channels' signals, to increase the dynamic range of the system, and a histogram with the distribution of the raw signals, to identify when the amplified channels saturate.

This work explains the principle of the updated calibration of the dBLM detectors signals, as well as a description of the tests run in the LHC to acquire the calibration data.

LHC DIAMOND BLM SIGNALS

The working principle of the dBLM detector can be described as a solid state IC which is composed of a 10 mm-long, 0.5 mm-thick squared pCVD diamond detector coated on each side with an 8 mm-long, 200 nm-thick squared golden electrode.

The signal coming from the detector is then decoupled by an AC-DC splitter. The AC part is divided into two equivalent outputs, and one of them is connected to a 40 dB amplifier which provides a signal amplification of a factor of around 100. Both non-amplified and amplified signals are sampled at a frequency of 650 MHz by an ADC.

Six dBLM detectors are located in the betatron collimation region, three per beam. For both beams there is one detector installed downstream the primary vertical collimator to monitor the beam losses in the vertical plane, and another detector downstream the rest of primary collimators to monitor the beam losses in the horizontal plane. The extra detector is in both cases located downstream one of the crystal collimators used during the ion Runs [5].

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An example of the raw signal from the dBLM detector located downstream the primary vertical Beam 1 (B1) collimator is shown in Fig. 1. Four signal peaks, in blue, corresponding to the four proton bunches that were circulating in the machine at that moment can be clearly seen above the signal noise. The black vertical line marks an LHC turn, after which one of the signal peaks can be spotted again.

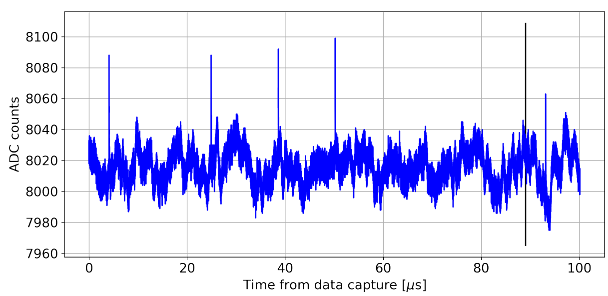

Figure 1: Raw signal from the dBLM detector located downstream the B1 primary vertical collimator with four proton bunches circulating in the LHC.

However, it is not possible to save this high amount of data continuously, and the raw signal is only captured on demand for a maximum of around 23 LHC turns. The rest of the time the data is pre-processed in the digital back-end by an FPGA which provides several measurements modes, two of which are used for the dBLM calibration.

The Raw Distribution mode provides a histogram showing the distribution of the raw dBLM signal, while the Integral mode provides its integrated values bunch-by-bunch. In both cases, the data is logged every 11 200 LHC turns, equivalent to around 1 s.

With a response decay in the order of some ns, the raw signals are expected to pile-up when the nominal 25 ns LHC bunch separation is used. This is taken into account by a correction mechanism that estimates the baseline in between bunches and subtracts it from the raw signal before performing the integration for the Integral mode.

Similarly to the IC BLM calibration performed for LHC Run 3, the dBLM calibration is based on the fact that the ratio between the dBLM detectors signals is different depending on the beam loss scenario. The first step for the calibration is to calculate the dBLM detectors responses, which are defined as the expected signal per proton lost in each one of the considered well-defined beam loss scenarios.

LHC BEAM TESTS FOR DIAMOND BLM CALIBRATION

In order to calculate the dBLM detector responses, it is needed to reproduce the well-defined beam loss scenarios that are considered in the calibration. These included for the first time the proton impacts on the jaws of all the primary B1 and Beam 2 (B2) collimators in the betatron region. The method selected was beam scraping, during which it is possible to generate controlled beam losses for some minutes by closing in small steps the jaws of a collimator.

Two dedicated beam tests were performed, one at injection energy with four nominal bunches per beam and another one at top energy, with three nominal bunches per beam. This selection on the number of bunches was done in order to stay under the safe beam intensity limit and be able to move the collimators jaws without triggering the beam extraction.

Figure 2 shows the bunch-by-bunch integrated signal from the dBLM detector located downstream the B1 primary vertical collimator during beam scraping with that collimator at injection energy. The signal corresponding to the four bunches circulating in the machine can be clearly seen.

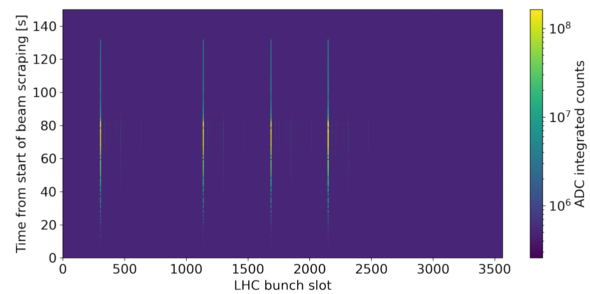

Figure 2: Bunch-by-bunch integrated signal from the dBLM detector located downstream the B1 primary vertical collimator during beam scraping.

On the other hand, Fig. 3 shows the bunch-by-bunch integrated signal for all the LHC turns in a single second from the same beam scraping period. The four proton bunches are again clearly visible, but also some secondary peaks which appear in all cases shifted by 163 bunches and are believed to be signal reflections between the detector and the acquisition card.

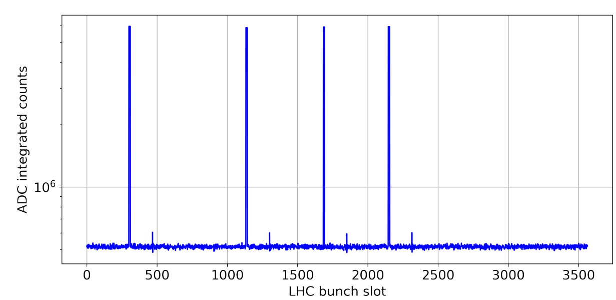

Figure 3: Bunch-by-bunch integrated signal from the dBLM detector located downstream the B1 primary vertical collimator for one second from beam scraping.

Considering the nominal 25 ns LHC bunch separation, it would correspond to the arrival of the signal to the card around 4.1 μs later, equivalent to a distance of 1004 m. This is comparable to the extra cable length the signal would do if it went back to the detector and got reflected again before arriving to the card. These possible reflections are to be studied in more detail and mitigated if possible.

LHC DIAMOND BLM CALIBRATION

For each one of the considered beam loss scenarios during the beam scraping tests, the dBLM detector response is

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calculated from a linear fit of the integrated signal versus the lost intensity measured by the Fast Beam Current Transformer (FBCT) [6], independently for every bunch that was circulating in the machine. Figure 4 shows the integrated signal of one bunch from the dBLM detector located downstream the B1 primary vertical collimator and the respective lost bunch intensity measured with the FBCT during beam scraping with that collimator. A comparison is done to verify that the response is similar in all circulating bunches, and it is then averaged.

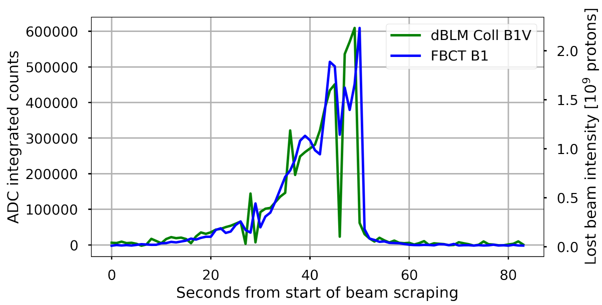

Figure 4: One-bunch integrated signal from the dBLM detector located downstream the B1 primary vertical collimator and lost bunch intensity measured with the FBCT during beam scraping.

This dBLM detector response is calculated for both the non-amplified and the amplified channels. Unluckily, it was not possible to obtain good-quality signal in either of the dBLM detectors located downstream the crystal collimators. Therefore, they could not be included in the calibration and it was decided to keep only the horizontal and vertical loss plane scenarios.

A study of the IC BLM detector responses at all the collimators concluded that the positions of these dBLM detectors were not ideal. A proposal was made (and accepted) to move them to other positions were they are expected to provide better measurements both during regular proton operation and ion operation with crystal collimators.

Once the dBLM detectors responses were calculated, a response matrix, $\boldsymbol{M}$, was built at injection and top energy. During nominal LHC periods, the horizontal and vertical bunch losses, $\overrightarrow{dI/dt}$, are obtained from the dBLM detectors bunch signals, $\overrightarrow{dBLM}$, as $\overrightarrow{dI/dt} = \boldsymbol{M}^{-1} \times \overrightarrow{dBLM}$.

The most remarkable addition to the calibration method in view of improving its accuracy with respect to Run 2 is the possibility to also access the data from the non-amplified channels signals and the distribution of the raw signals data. On a second-by-second basis, it is checked if the amplified channels signals are saturated. In case they are, the inverse response matrix is multiplied by the non-amplified channels signals instead of the amplified ones.

Figure 5 shows the total beam losses with circulating beam at injection for a selection of LHC fills measured with the FBCT, the dBLM and the IC BLM calibrations. A much better agreement is observed between the BCT and both the IC BLMs and dBLMs calibrations with respect to the Run 2 results. For the dBLM calibration in particular, the relative error with respect to the FBCT measurements is around 60%, while it was around 300% in the past.

Still, a systematic offset between the beam losses measured by the FBCT and the dBLM calibration is observed. This could be due to the Integral mode correction mechanism not being optimized and calculating a higher baseline between bunches than it should when having 25 ns-spaced LHC bunch trains. A poor synchronization between the bunch arrival and the assigned bunch slot during the signal processing could also distort the measurement of this baseline. It is planned to study the effect of the baseline correction mechanism on the final Integral mode data and implement regular checks to make sure that the bunch arrival is synchronized with the dBLM signal bunch slots.

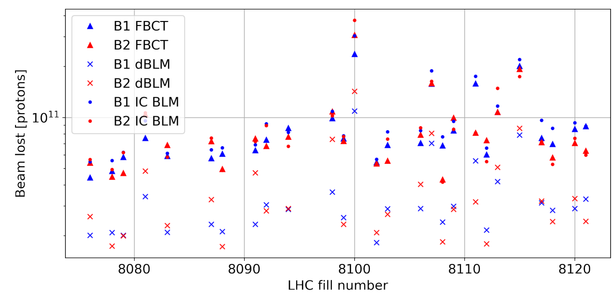

Figure 5: Comparison between the total beam losses in selected LHC fills during injection measured with the FBCT, the IC BLM and the dBLM calibrations.

CONCLUSION

Following the analysis of the results from the dBLM calibration with Run 2 data and the later tests run at CLEAR to characterize the dBLM signal, it was decided to start logging other quantities to improve the calibration in view of Run 3. Beam scraping tests were performed to get the required data for the calibration. Potential signal reflections were observed, which will need to be studied in more detail. It was not possible to obtain good-quality signal in the dBLM detectors located downstream the crystal collimators. Therefore, they were not considered in the calibration and it was decided to move them to new positions, where they are expected to provide better beam loss measurements. Still, the new calibration method showed a better agreement with the FBCT compared with the Run 2 results. However, a systematic offset was observed between the FBCT and the dBLM measurements, which still needs to be understood and is expected to be due to the Integral mode baseline correction method not being optimized for LHC bunch trains.

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REFERENCES

[1] M. Lamont, “LHC "Chamonix" Workshop Summary”. https://indico.cern.ch/event/1262929/

[2] E. B. Holzer *et al.*, “Beam loss monitoring system for the LHC”, in *IEEE Nuclear Science Symposium Conference Record*, Fajardo, PR, USA, Oct. 2005, pp. 1052–1056. doi:10.1109/NSSMIC.2005.1596433

[3] S. Morales Vigo *et al.*, “Beam Loss Signal Calibration for the LHC Diamond Detectors During Run 2”, in *Proc. IBIC'21*, Pohang, Korea, Sep. 2021, pp. 290–293. doi:10.18429/JACoW-IBIC2021-TUPP33

[4] S. Morales Vigo *et al.*, “Linearity and Response Time of the LHC Diamond Beam Loss Monitors in the CLEAR Beam Test Facility at CERN”, in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 355–358. doi:10.18429/JACoW-IPAC2022-MOPOPT046

[5] E. Calvo Giraldo *et al.*, “The Diamond Beam Loss Monitoring System at CERN LHC and SPS”, in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 202–206. doi:10.18429/JACoW-IBIC2022-TU2C2

[6] O. Bruning *et al.* (editors), “LHC Design Report Vol 1: The Main LHC Ring”, CERN, Geneva, Switzerland, 2004. doi:10.5170/CERN-2004-003-V-1