LINEARITY AND RESPONSE TIME OF THE LHC DIAMOND BEAM LOSS MONITORS IN THE CLEAR BEAM TEST FACILITY AT CERN

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Abstract

Chemical Vapour Deposition (CVD) diamond detectors have been tested during the Run 2 operation period (2015-2018) as fast beam loss monitors for the Beam Loss Monitoring (BLM) system of the Large Hadron Collider (LHC) at CERN. However, the lack of raw data recorded during this operation period restrains our ability to perform a deep analysis of their signals. For this reason, a test campaign was carried out at the CLEAR beam test facility at CERN with the aim of studying the linearity and response time of the diamond detectors against losses from electron beams of different intensities. The signal build-up from multi-bunched electron beams was also analyzed. The conditions and procedures of the test campaign are explained, as well as the most significant results obtained.

INTRODUCTION

The LHC is the largest and most powerful particle accelerator ever built. Sitting in a tunnel located around 100 m underground and with a circumference of 27 km, it is designed to accelerate protons up to an energy of 7 TeV. The LHC beams are foreseen to contain up to 2 700 bunches with up to $1.4{\times}10^{11}$ protons each during the first year of the Run 3 operation period, starting in 2022 [1].

The LHC BLM system is in charge of actively protecting the machine against energy deposition from beam losses, which could provoke a quench in the superconducting magnets, leading to an accelerator downtime in the order of weeks [2]. The LHC BLM system provides updated beam loss signals every 40 µs that may trigger a fast extraction of the beams from the main ring towards beam dumps when losses are measured above predetermined thresholds. Around 4 000 BLM detectors, most of them Ionization Chambers (ICs), are part of the system and installed downstream from the most probable loss locations [3].

Additionally, a set of CVD diamond detectors has been installed in specific LHC locations during Run 2 (2015-2018) with the aim of studying their feasibility as fast beam loss monitors. They are commonly referred to as diamond Beam Loss Monitors (dBLMs). Considering their high-radiation tolerance and their time resolution in the order of ns, they resolve bunch-by-bunch losses, being the LHC bunches typically spaced by 25 ns [4].

A signal-to-beam-loss global calibration of a set of LHC IC BLM detectors has proven to be useful to follow-up the performance of the machine, e.g. by online beam lifetime calculation [5]. However, a similar calibration of the LHC dBLMs was not able to reach the same level of accuracy, i.e. it overestimated the beam losses by a factor of approximately 4, while the calibration of the LHC IC BLMs also overestimates the beam losses, but only by a factor of 1.25 [6].

Later on, a comparison between beam losses obtained by integrating IC BLM and dBLM signals suggested a potential non-linearity of the latter with increasing beam losses. Unfortunately, the unavailability of unprocessed data prevented us from finding if this was due to the response of the detectors themselves, the presence of high levels of noise in the signals or if it was related to a possible bias induced during the pre-processing of the signals.

Taking advantage of the fact that the stand-alone electron beam facility CLEAR was operational during CERN's accelerator complex shutdown period, we had the opportunity to perform a series of beam tests with relativistic electrons. The purpose of these tests was to study the dBLM signal linearity, its response function and the signal build-up from multi-bunched beams.

The tests setup and procedures are detailed in this paper, together with the most significant observations.

DIAMOND BEAM LOSS MONITORS

The dBLM is based on a squared, 10-mm side, 0.5-mm thick CVD diamond detector. It is coated on each side with an 8-mm long and 200-nm thick squared gold electrode. The whole is protected by an RF-shielding aluminium housing and operated with a bias voltage of 500 V.

The resulting signal is connected to an AC-DC splitter that decouples the DC part from the AC part and at the same time divides the AC part into two equivalent output signals. One of them is then connected to a 40-dB amplifier, which amplifies the signal by a factor of approximately 100 and saturates at ±1 V. This allows to increase the dynamic range of the system, being sensitive to single MIP particles.

The raw signal is digitised by an ADC at a frequency of 650 MHz. It is then pre-processed by an FPGA, which sends the resulting values to be saved for offline analysis. Among the different measurement modes provided, the most useful for our studies is the so-called Integral mode, which performs a bunch-by-bunch integration of the measured beam losses approximately every second. At the same time, the signal's baseline, i.e. the amplitude of the signal in between bunches, is measured and subtracted from the integrated signal.

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TESTS IN CLEAR

CLEAR stands for CERN Linear Electron Accelerator for Research. This facility has been in operation since 2017, running in parallel with the main CERN accelerator complex [7]. With several locations along the machine equipped with test benches, CLEAR provides a testing platform for accelerator R&D, including the development of novel beam instrumentation. It is composed of a 20-m long linear accelerator providing relativistic electrons that are then sent in an experimental beamline. CLEAR may offer a wide range of possible parameters regarding beam energy, bunch intensity and number of bunches per pulse among others.

Experimental Setup

The test setup was installed in the In-Air Test Area, a 1-m long optical table located at the end of the experimental beamline, right before the dump. A picture of the setup is shown in Fig. 1. The electron beam travels from right to left, with the beam dump visible on the left side of the picture. The experimental setup included a 3 cm-diameter and 2 cm-thick copper target mounted on a support installed on the optical table which could be moved closer or further away from the beam to generate the losses. The diamond detector, the AC-DC splitter and the 40-dB amplifier were mounted on a standing metallic support positioned on the side of the optical table. The signals were directly connected to an acquisition card so that the raw data could be displayed and saved at every beam pulse.

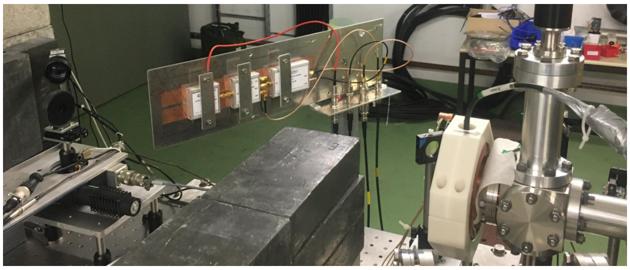

Figure 1: Experimental setup installed in the In-Air Test Area in CLEAR.

Test Procedure

Three independent intensity scans were performed, each starting with the minimum possible intensity per bunch (i.e. 5 pC) and increasing it gradually in 11 steps up to an intensity of 400 pC per bunch. Three different configurations were used as described below:

- 1st: Single-bunch-beam pulses, Cu target away
- 2nd: 20-bunch-train-beam pulses, Cu target away
- 3rd: Single-bunch-beam pulses, Cu target intercepting the beam

For all the intensity scans, each intensity step included 10 beam pulses with a repetition rate of 1.2 s between them. In all the cases the bunch length was less than 10 ps, with an energy of around 200 MeV. For the 20-bunch-train-beam pulses, the distance between bunches was of 0.666 ns.

TESTS RESULTS

During the three intensity scans both the non-amplified and amplified dBLM signals were acquired. In the three intensity scans the amplified dBLM signal reached saturation values from a certain intensity step. In the first intensity scan this was already visible at a beam intensity of around 200 pC, while during the second and third intensity scans the amplified dBLM signal was even over-saturated most of the time. Figure 2 shows examples of the amplified dBLM signal for a 20-bunch-train-beam pulse in different intensity steps. It can be seen that after the signal reaches over-saturation values, it drops drastically and provides negative readings. Furthermore, this effect aggravates with higher beam intensities.

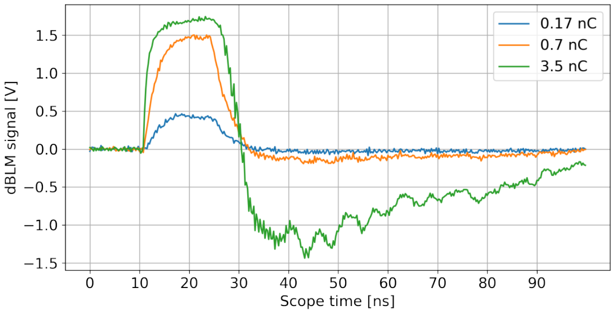

Figure 2: Amplified dBLM signal for a 20-bunch-train-beam pulse in different intensity steps.

Linearity of the dBLM Signal

The study of the linearity of the dBLM has been performed using two target positions which provided different loss conditions: a low beam loss regime, when the beam is not impacting on the target, and a high beam loss regime, when the beam impacts on the target producing a large electromagnetic shower. The amplified signal was not considered for this study as it was saturated in most cases.

First, the offset of the non-amplified dBLM signal was calculated for every beam pulse by averaging the signal values right before the detection of the pulse. After that, the offset-corrected signal was integrated for every pulse. Figure 3 shows the results of a linear fit for the integrated and offset-corrected signals versus the beam intensity in every beam pulse. As expected, it is clearly visible in the two configurations that the dBLM signal grows linearly with increasing beam intensities. Furthermore, it can be seen that the slope of the linear fit is more than 500 times higher in the case where the target was intercepting the beam.

dBLM Response Time

The dBLM response time was studied from the signals acquired with the single-bunch-beam pulses. At CLEAR, the bunch length is typically a few ps long, considerably shorter

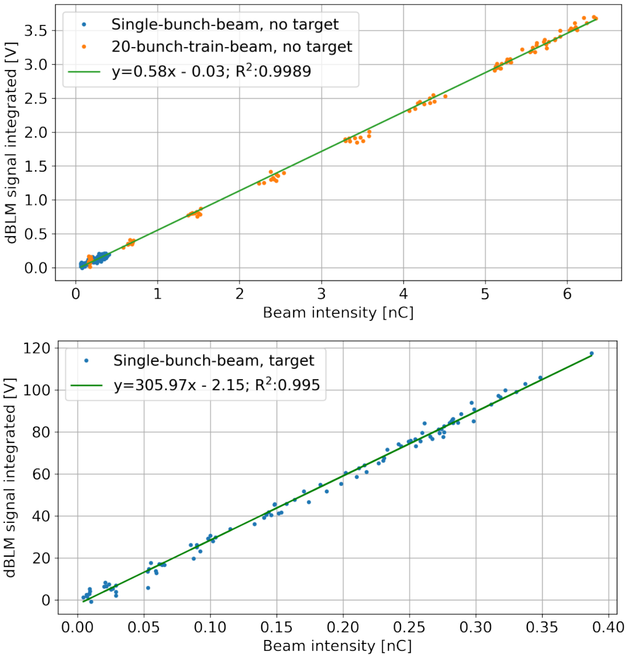

Figure 3: Integrated and offset-corrected non-amplified dBLM signal versus beam intensity in every beam pulse for (top) the first and second intensity scans (target away from the beam) and (bottom) the third intensity scan (target intercepting the beam).

than the expected rise time and fall time of the detector. Figure 4 shows some examples of both the amplified and non-amplified signals during the single-bunch-beam intensity scans. For the non-amplified signal, the best examples to analyze correspond to when the beam directly hit the target, as the signal was in general too small in the other case. On the other hand, the amplified channel only provided non-saturated signals when the target was sitting far away from the electron beam.

The decay of the signal can be fitted by a function of the type $a + b \times e^{-t/\tau}$. For the non-amplified signal, the average value of τ is of 5 ns. However, as it can be seen in Fig. 4, when the signal reaches higher values, i.e. with a 319 pC beam intercepted by the target, the shape of its decay is distorted and changes with time. This behaviour is still to be analyzed further. For the amplified signal, the average value of τ is of 3.1 ns. It was noticed that in most cases the signal presented a second peak around 2 or 3 ns after the first, which would correspond to electrons travelling an additional distance of between 50 and 60 cm. This could be due to the detection of back-scattering from the dump, which was closer than 1 m from the detector.

dBLM Signal Multi-Bunched Beams

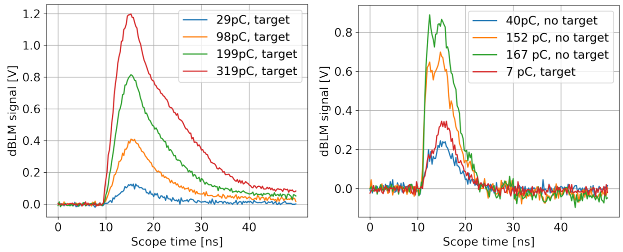

Figure 4: Non-amplified (left) and amplified (right) signals for single-bunch-beam pulses of different intensities, for the two used target positions.

Given the fact that the decay of the dBLM response takes longer than the distance between bunches, it was expected to see a signal build-up in the 20-bunch-train-beam intensity scan. In order to understand the mechanism behind this, the convolution between the dBLM response function and a simulated 20-bunch-train-beam pulse was calculated and compared with the measured signal. This is shown in Fig. 5. It can be seen that the convoluted and the measured signals are well-matched. However, this still needs further analysis and understanding of how it should be treated during the pre-processing of the signal.

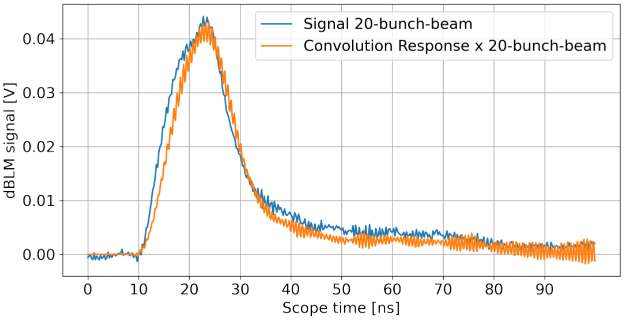

Figure 5: Non-amplified signal for a 20-bunch-train-beam pulse (blue) and convolution of dBLM response with a simulated 20-bunch-train-beam pulse (orange).

CONCLUSION

A test campaign was carried out at the CLEAR beam test facility at CERN to understand the results from the calibration of the LHC dBLMs. The linearity and response time of the detectors were studied with losses from electron beams of different intensities. It was found that, as expected, the dBLM signal grows linearly with increasing beam losses in the range considered in the test. Furthermore, the signal build-up from a train of 20 consecutive bunches spaced by 0.666 ns was also studied and found in good agreement with our expectations. Some saturation effects and temporal distortions of the signals were observed and would require further analysis and possibly additional beam tests to be fully understood and cured.

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