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PERFORMANCE OF THE CRYOGENIC BEAM LOSS MONITORS DEVELOPED AT THE LHC

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Abstract

Several systems protect the superconducting magnets of the Large Hadron Collider (LHC), which operate at −271.3 °C. The Beam Loss Monitoring (BLM) system is critical for detecting lost particles around the machine and reacting on their quantity and associated energy. It protects the machine from quenching and irreversible damage. To measure these losses, various detectors are used, primarily Ionisation Chambers (IC), but also other types of monitor depending on the intensity loss or time structure that needs to be detected. As an example, in injection and extraction areas, fast poly-crystalline Chemical Vapour Deposition (pCVD) diamond detectors measure time structured losses. To increase sensitivity, a new detector, the Cryogenic Beam Loss Monitor (CryoBLM), based on single-crystalline diamond (sCVD), was developed. It is mounted inside the cryostat between two superconducting magnets in the vicinity of the beam pipes and operates at cryogenic temperatures. Two CryoBLM locations in the LHC target different loss scenarios: betatron halo cleaning and luminosity losses from the CMS physics debris. This contribution presents the CryoBLM performance and comparisons with the ionisation chambers.

DETECTOR TYPES AND DESCRIPTION

Beam losses along the CERN accelerator complex are monitored with a distributed system with close to 4 500 ionisation chambers (IC) connected and read out by different electronics depending on the accelerator. The most widely used detector is the LHC-type IC [1] shown in Fig. 1. It is a 60 cm-long ionisation chamber filled with N_2 gas at 1.1 bar with 61 electrodes spaced every 5 mm.

Despite the differences, all the readout electronics have common design choices; they are based on the usage of integrator input circuits [2–4] with high dynamic range of around 120 dB. The time resolution of the different systems depends on the integration window of the used electronics, which is typically 2 µs, 10 µs or 40 µs.

However, in some areas and applications, it is necessary to measure losses with either higher time resolution down to the order of tens of nanoseconds or higher sensitivity. In this case, pCVD and sCVD diamond detectors (see Fig. 2) are used. They are read out with fast Analog-to-Digital Converters (ADCs) with a sampling rate up to 650 MHz. This is the configuration used in the LHC injection and collimation regions. However, in other areas, such as the LHC dispersion suppressor region, there is the need to measure very small losses. For this purpose, the CryoBLM system was developed. The system operates at cryogenic temperatures and can be installed inside the magnet cryostats, closer to the beam pipe, thereby enhancing sensitivity. The CryoBLM is based on the sCVD diamond which provides superior energy resolution and charge collection efficiency compared to the pCVD [6].

Figure 1: LHC type IC [5].

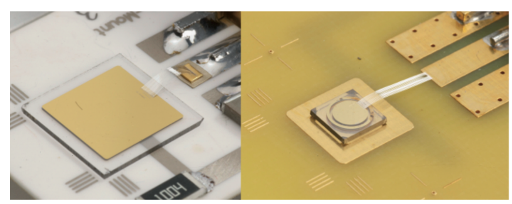

Figure 2: pCVD and sCVD Diamond Detector [7].

CryoBLM DESIGN AND INSTALLATION

The installation of these detectors inside the magnet cryostat restricts the choice of used materials, since they operate at a cryogenic temperature of around −271.3 °C in vacuum. The carrier Printed Circuit Board (PCB), made of ceramic (Al_2O_3), connects and encloses the sCVD substrate. The detectors themselves are fixed with a support on the cryostat between two superconducting magnets, see Fig. 3. Two CryoBLM prototypes were installed in the LHC Cell 9L5 in IP5, colliding point of the Compact Muon Solenoid (CMS) detector, and in Cell 9R7 in IP7, main betatron collimation region. These detectors are read out with standard LHC BLM front-end electronics, publishing data at 1 Hz for 12 different integration windows, so-called running sums (RS). More details about the complete installation can be found in [8].

In order to validate the performance and calibration of the diamond-type detectors, a sCVD and a pCVD diamond

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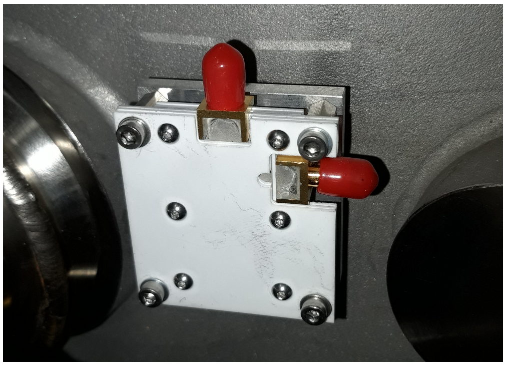

Figure 3: CryoBLM fixed on on of the LHC main dipole's cryostat.

were installed at both locations (9R7 and 9L5) outside the cryostat close to a standard IC, at ambient temperature. It is assumed that, as these detectors are only few centimeters apart, they will measure similar dose levels. While the dose measured by the CryoBLM will be potentially different and sensitive to the differences between Beam 1 and Beam 2. Figure 4 shows a sketch of the detector installation in 9R7 close to the magnet interconnect, identifying the CryoBLM in blue, sCVD in green, the pCVD in grey and the IC in yellow.

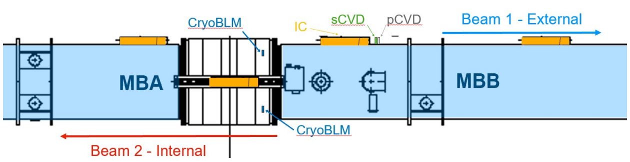

Figure 4: Sketch of the detector installation in 9R7, MBA and MBB are LHC main dipole superconducting magnets.

CALIBRATION FACTORS

The theoretical calibration factor to convert from measured charge (in Coulomb) to absorbed dose (in Gray) can be assessed from the detector geometry and the properties of the active medium: the material density and the average energy needed to create an electron-hole (or electron-ion) pair (i.e. Ionisation Energy). For CVDs, the active volume is assumed to be the whole detector envelope and not only the area covered by the electrodes, with a density of 3.5 g cm^{-3}. For the IC, the active material is precisely known to be the gas volume within the electrodes. The density of Nitrogen in the IC, at a pressure of 1.1 bar and an operating temperature 20 °C, is 1.26×10^{-3} g cm^{-3}. The detector parameters are summarized in Table 1. The absorbed dose D needed to create an ion-electron pair or electron-hole pair and the corresponding charge created f_{Gy} can be expressed as:

$$D = \frac{\mathrm{IE}}{m}\ [\mathrm{eV/kg}]\ \text{ and }\ f_{\mathrm{Gy}} = \frac{1}{D}[\mathrm{C/Gy}]\ , \tag{1}$$

where IE is the ionization energy and m the active material mass.

Table 1: Detector Parameters

Parameter	IC	sCVD	pCVD
Ionizing Mat.	N_2	C	C
Density [g/cm^3]	1.26×10^{-3}	3.5	3.5
Electrode [mm]	ø75	4 × 4	8 × 8
Active V. [mm^3]	1.5×10^6	10.125	50
Pressure [bar]	1.1	-	-
Mass [g]	1.89	0.0354	0.175
IE [eV]	35	13	13

The conversion factor f_{count} from absorbed dose to counts for the Current-to-Frequency Converter (CFC) [9] is determined from the expected charge of 200 pC/count. This value is obtained assuming a maximum input current of 1 mA, an integrator capacitance of 100 pF, a recharge voltage of 2 V, and an output rate of 5×10^6 count/s. The factor is then written as:

$$f_{\mathrm{count}} = \frac{200\ \mathrm{pC/count}}{f_{\mathrm{Gy}}}\ [\mathrm{Gy/count}], \tag{2}$$

which, divided by the ADC resolution (1024 bits), gives the conversion from dose to bits equal to:

$$f_{\mathrm{bit}} = \frac{f_{\mathrm{count}}}{1024}\ [\mathrm{Gy/BLMbit}]. \tag{3}$$

Combining the detector parameters in Table 1 with Eqs. (1) to (3) allows to calculate the calibration and conversion factors reported in Table 2.

Table 2: Calibration and Conversion Factors

Factor	IC	sCVD	pCVD
f_{bit}	3.62×10^{-9}	7.17×10^{-8}	1.45×10^{-8}
f_{Gy}	5.4×10^{-5}	2.725×10^{-6}	1.35×10^{-5}

MEASUREMENTS

During these tests, the CryoBLM, ICs, pCVD and sCVD are all connected to the input of a CFC card. The card transmits the digitized values to the surface electronics, processing the data and sending results to the logging database. At present, the measured signals are published in BLMbits and calibrated to dose using the same calibration factor, the one of the standard IC (3.62×10^{-9} Gy/BLMbits); these miss-calibrated values are stored in the database in Gy/s units.

To compare the theoretical calibration, two physics periods were selected where the losses are expected to be higher or with a special pattern. For 9R7, the data showed corresponds to a specific beam test where the primary collimators in Beam 1 were scraping the beam in small steps, slowly increasing the losses in steps.

For 9L5, a standard LHC fill was used, where collision physics debris at CMS detector was measured. Most of

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the period the luminosity is kept constant but we selected a fill where the beams were separated for a short period and therefore shows a decrease of luminosity.

The integration window of ≈20.9 s (RS11) was used for this study. The measured values were offset corrected and calibrated using the theoretical factors in Table 2. After calibration, one should expect that the IC, sCVD and pCVD measure the same absorbed dose, but that the CryoBLM that is located closer to the beam pipe measures higher dose. Figure 5 shows on top the raw signals, in Amperes, and on bottom the calibrated signals to dose for the beam loss scenario of 9R7. Similarly, Fig. 6 shows the uncalibrated signals on top and the calibrated signals on bottom for the physics debris beam loss scenario of 9L5. For the analysed periods, the signal levels in 9R7 are a factor 10 lower than those measured in 9L5, and they are very close to the lower limits of the electronic. This has an impact on the error of the measured signal.

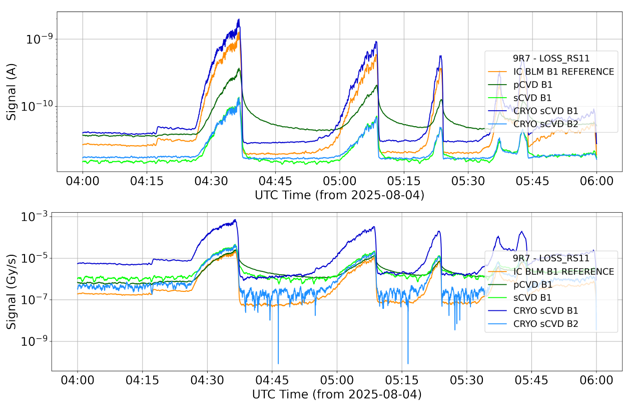

Figure 5: Detector signals of 9R7: (Top) raw-data in [A], (Bottom) offset corrected and calibrated in [Gy/s].

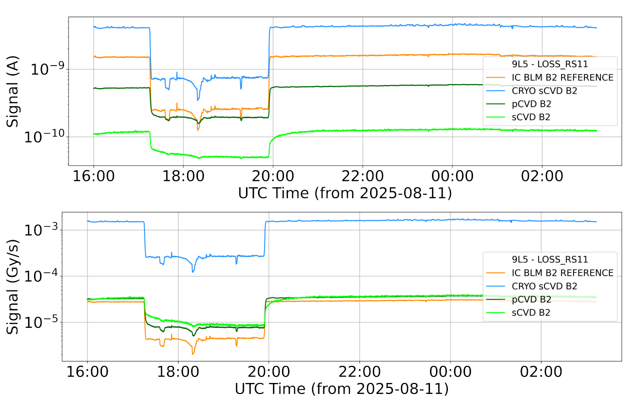

Figure 6: Detector signals of 9L5: (Top) in [A] , (Bottom) offset corrected and calibrated in [Gy/s].

The diamond and CryoBLM calibrated signals are then compared to the one of the reference IC, as shown in Fig. 7, for 9R7 on the left and 9L5 on the right. This allows calculating a set of measured calibration factors, $f_{\mathrm{Gy}}^{\mathrm{measured}}$ which are approximately

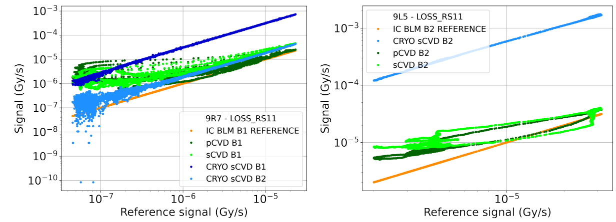

Figure 7: Calibrated detector signal vs reference IC in Gy/s of 9R7 (left) and 9L5 (right).

- $1.1 - 1.5 \times 10^{-5}$ C/Gy for the pCVD and
- $2.9 - 4.7 \times 10^{-6}$ C/Gy for the sCVD.

The measured factor for the pCVD is within the 20 % error compared to the theoretical calibration factor. While the relative difference between the measured and theoretical calibration of the sCVD is up to 70 %. However, the current delivered by this detector on the outside of the cryostat is below 0.1 nA both for the scraping beam test and the physics debris losses.

Another effect was observed on the diamonds located outside the cryostat. They present a very slow decay and rise time. This effect is particularly observable in Fig. 6 for the sCVD, when the luminosity drops rapidly down, the sCVD signal shows a long decay before reaching the final value. The same is observed when the luminosity goes up. In 9R7 (Fig. 5) it is also observed but the smooth rise of the beam losses makes this effect less visible. For the CryoBLM, however, this effect is not observed. The reason is still under-investigation.

When applying the theoretical sCVD calibraion factor to the CryoBLMs, installed inside the magnet interconnect, the signals are found to be 30 to 50 times higher than the dose measured outside the cryostat, depending on the location. This result is consistent with the expected increase in radiation due to the detectors being closer to the beam pipe.

CONCLUSION

CryoBLMs were installed inside the interconnect of the LHC superconducting magnets at two different locations in the accelerator. Additionally, in the vicinity of the closest ionisation chamber, a sCVD and pCVD detectors were also installed in order to use them as reference for the study of the detector calibration factor. The theoretical values were applied to the selected data. The error on the sCVD and pCVD was quantified to be below 70 % and 20 %, respectively, assuming that these detectors will measure the same dose as the reference ionisation chamber. After applying this calibration, the beam losses measured at the CryoBLMs were found to be a factor 30 to 50 higher than the IC outside the cryostat. This is compatible with the expected increase of radiation at the CryoBLM location.

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