PERFORMANCE OF DETECTORS USING DIAMOND SENSORS AT THE LHC AND CMS

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Abstract

Diamond detectors are used as beam loss and luminosity monitors for CMS and LHC. A time resolution in the nanosecond range allows to detect beam losses and luminosities of single bunches. The radiation hardness and negligible temperature dependence allow the usage of diamond sensors in high radiation fields without cooling. Two different diamond detector types are installed at LHC and CMS. One is based on pcCVD (polycrystalline chemical vapor deposition) diamonds and installed at different locations in the LHC tunnel for beam loss monitoring. Measurements of these detectors are used to perform a bunch-by-bunch beam loss analysis. They allow to disentangle the origin of beam losses. The second type uses scCVD (single crystal chemical vapor deposition) diamonds and is located inside CMS for van-der-Meer scan, beam halo and online luminosity monitoring and around the LHC tunnel for beam loss observation. Results on the performance of these detectors will be presented and examples of the use for analyzing the beam conditions will be given. In order to persist the enhanced requirements of the LHC after the long shutdown, e.g. higher luminosity, an upgrade of the detectors is required. The concept of the new detectors will be presented and first results will be shown.

INTRODUCTION

Diamond detectors became very attractive in the field of particle detection because of various reasons. Diamond is a radiation hard material and can be used where other sensors fail. Additionally, the leakage current is low with a negligible temperature dependence due to the energy gap of 5.47 eV. Due to these advantages diamond detector are interesting for high energy particle detection, e.g. at LHC and CMS. The nanosecond time resolution allows bunch to bunch measurements, e.g. beam loss or luminosity measurements. Two different diamond detector systems are installed at the LHC. One is based on pcCVD diamond and used for beam loss measurements around the LHC ring. The other one is based on scCVD diamond. Eight scCVD diamond detectors are installed inside CMS for beam halo and luminosity measurements and six scCVD diamonds are located around the LHC ring for beam loss observation.

DIAMOND DETECTORS BASED ON pcCVD

Detectors equipped with pcCVD diamond sensors are used for beam loss measurements[1]. The detectors are installed above the beam pipe as shown in Fig. 1 and they are read out with an oscilloscope. The locations of the pcCVD diamond detectors at the LHC tunnel are:

- Injection area for beam loss observation due to the injection process.
- Momentum cleaning area for beam loss measurements during the cleaning process.
- Beam dump region for beam loss detection during the beam dump.
- Betatron cleaning region for observation of various beam losses.

The most important location is the betatron cleaning area where the aperture limitation is defined. Different beam loss origins can be distinguished as shown in [2, 3].

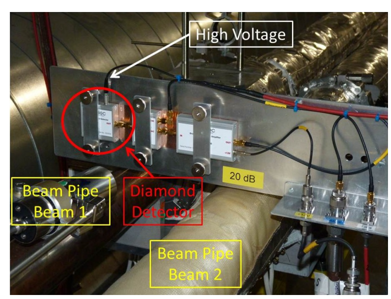

Figure 1: Diamond detector installed above the beam pipe.

BEAM LOSS MEASUREMENT USING pcCVD

The diamond detector at the betatron cleaning region is able to detect beam losses during the injection process from the pre-accelerator to the LHC. Injection oscillations cause beam losses in each injected bunch [4]. Figure 2 shows these beam losses during an injection of 12 bunches with a bunch spacing of 50 ns. An additional beam loss is observed before the 12 injected bunches. This beam loss is believed to be an unbunched beam from the previously injected circulating probe bunch. Unbunched protons of the

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probe bunch are deflected by the injection kicker magnet during the rise time of the magnet current. These beam losses can be measured in the betatron cleaning region due to the aperture limitation even though beam losses originate from the injection region.

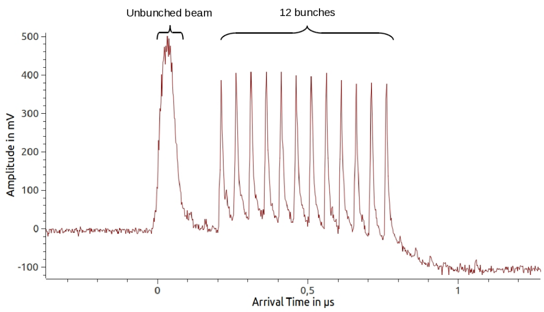

Figure 2: Beam losses after injection. The detected beam losses originate from unbunched beam and 12 injected bunches separated by 50 ns.

DIAMOND DETECTORS BASED ON scCVD

Detectors using scCVD sensors are located at several positions of the LHC:

- Injection Region for beam loss observation during injection.
- Beam instrumentation region for monitoring the abort gap population.
- Outside of CMS for collision and beam halo rate observation.
- Inside of CMS for luminosity and beam halo measurements.

The detectors installed in CMS, the Fast Beam Condition Monitor BCM1F, comprises 4 detector modules around the beam pipe at a radius of 4.5 cm at each side of the interaction point at a distance of 1.8 m. These BCM1F detectors are used to count particles from beam halo and collision products and deliver the count rates to CMS and the LHC [5, 6]. The readout and data acquisition system for BCM1F and the detectors installed around the LHC is sketched in Fig. 3. It comprises the:

- diamond sensors
- radiation hard front-end electronics (pre-amplifiers and optical drivers)
- back-end electronics (opt. receiver, ADCs, discriminators, scalers and logic units)

If a charged particle crosses the metallized diamond a signal is generated due to ionization. The signal is amplified and converted to an optical signal using front-end ASICs and laser drivers. The optical signal is transmitted to the counting room by optical fibers. In the counting room the signal is converted again to an electrical signal and processed by the readout modules. Luminosity and beam gas logics are used to measure beam halo rates and on-line luminosity [7].

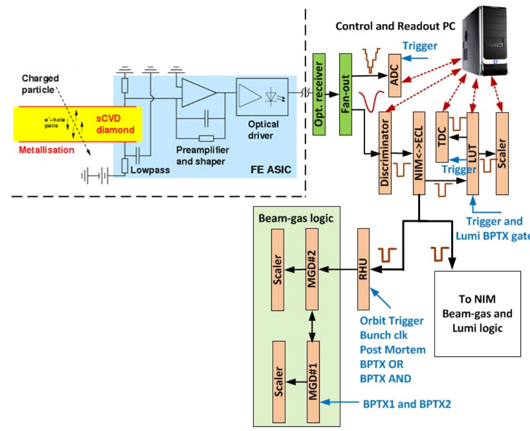

Figure 3: BCM1F readout system consisting of diamond sensors, ASICs, optical drivers and back-end modules.

MEASUREMENTS USING scCVD

The count rates of the scCVD diamond detectors are separated using the arrival time measurements from beam halo, beam gas and collision products [8]. Beam gas is caused by proton interaction with residual gas particles and characterize therefore the vacuum condition. Count rates of collision products are used for luminosity measurements.

Vacuum Conditions

The detector installed near to LHCb observed an increase of count rate during the proton collisions in LHCb as shown in Fig. 4a. Since the luminosity in LHCb is kept constant, the increase is due to proton interaction with residual gas particles in the vacuum pipe. Figure 4b shows the LHCb luminosity and vacuum pressure. A strong correlation of the diamond detector rates with the vacuum pressure measurement is observed.

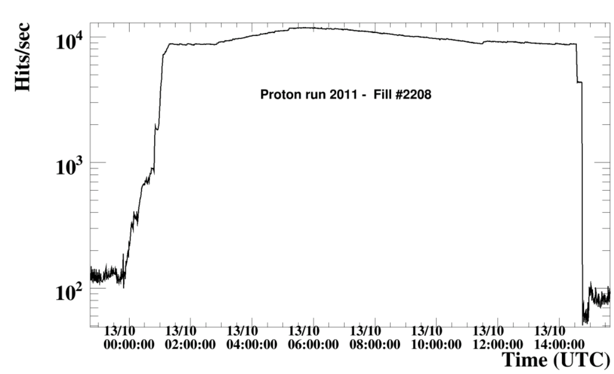

Figure 4a: Scaler rates over one LHC fill measured with scCVD sensor near to LHCb.

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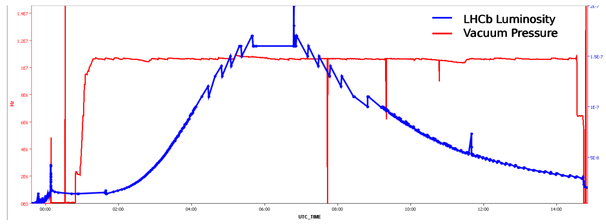

Figure 4b: Luminosity and vacuum pressure measurements for LHCb.

Luminosity Measurements with scCVD Sensors

The CMS luminosity is measured with several detectors, e.g. the Hadron Forward Calorimeter HF that is integrated to the main CMS DAQ. BCM1F provides an independent and fast measurement of the online luminosity. The BCM1F readout is decoupled from the main CMS DAQ and luminosity measurements are therefore available before the physics data is taken or in the case HF is not taking data. In order to monitor the luminosity with BCM1F it is necessary to measure the beam width with BCM1F since the luminosity is defined by

$$L = \frac{f_b N_1 N_2}{2\pi \Sigma_x \Sigma_y} ,$$

where f_b is the frequency od the orbit, $N_{1/2}$ the number of particles in the colliding bunches and $\Sigma_{x/y}$ the effective beam width in horizontal and vertical plane [9]. The beam width can be determined by Van der Meer scans [10]. These scans are done by colliding two beams with different horizontal and vertical beam separation.
A comparison between the beam width measured with HF and BCM1F shows good agreements as shown in Fig. 5. The BCM1F luminosity results are published in the CMS control room.

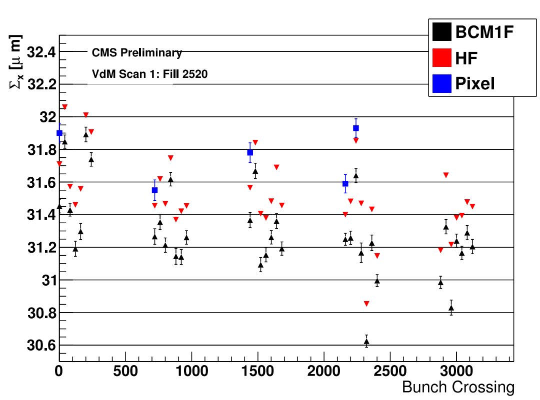

Figure 5: Measured beam width as a function of bunch crossing for BCM1F and HF. The beam width was obtained by Van der Meer scans.

DEGRADATION OF scCVD CHARGE COLLECTION EFFICIENCY

The BCM1F diamond sensor are 1.8 m away from the CMS interaction point and 4.5 cm away from the beam center. Therefore, the scCVD diamonds are exposed to high radiation of around 24 GeV proton equivalent ($3.5 \cdot 10^{12}$ proton equivalent per fb^{-1})[11, 12]. The impact of the radiation on the sensor performance was observed during the operation from 2008-2013.
The non-irradiated scCVD diamonds of BCM1F have a charge collection efficiency of 100% measured before installation. Additionally, all diamonds showed a saturation of charge collection efficiency above 100 V (0.4 V/μm) (see Fig. 6). After the absorbed radiation the charge collection efficiency decreased to around 75% at 500 V and a saturation is not reached up to 500 V (1.0 V/μm).

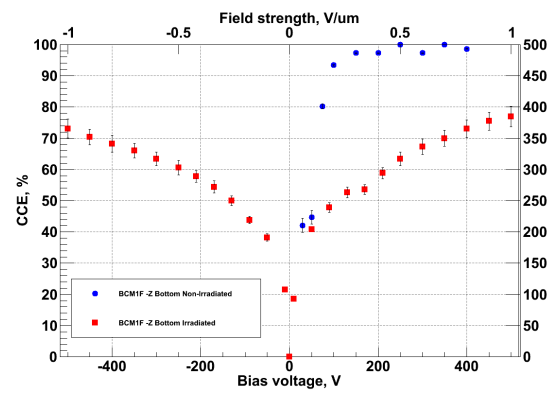

Figure 6: Charge collection efficiency for BCM1F diamond before and after irradiation.

BCM1F UPGRADE PLANS

After the long shut down one of the LHC the bunch spacing will be reduced to 25 ns and a higher luminosity is expected. In order to tackle higher rates the BCM1F components must be modified and upgraded.

Upgrade of Diamond Sensors

To improve the robustness of the system and to increase the efficiency, needed for the luminosity measurement, the number of diamond sensors will be increased to 12 on each side of the CMS interaction point (see Fig. 7). Additionally, each diamond will have two metallization pads on both sides to decrease the occupancy for each sensor (see Fig. 8). Currently the new sensors are characterized in the laboratory and simulations of luminosity measurements with 24 diamond sensors are ongoing.

Upgrade of the Front-End and Back-End Electronics

A dedicated preamplifier was developed with a peaking time of about 7 ns, an amplification of 50 mV/fC and two

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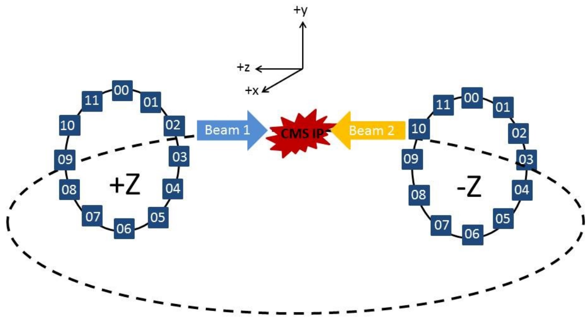

Figure 7: BCM1F diamond scheme for the upgrade.

Figure 8: New Diamond Metallization for BCM1F Sensors.

MIP separation better than 12.5 ns. To reduce the radiation load, the laser drivers will be installed at a larger distance from the beam center to 16 cm. Additional Bragg fibers will be installed to monitor the temperature at the laser driver.
The type of modules that are used for the back-end part are partially the same as in the last year of operation. The basic modules are ADCs, discriminator, scalers and logic units. Additional look-up tables and real time histogramming units with programmable FPGA logic chips are used for luminosity measurements and beam halo counting. Dedicated online data processing using FPGAs is also under development.

SUMMARY

Measurements from pcCVD based diamond detectors are used for various beam loss observations. The nanosecond time resolution allows a bunch-to-bunch beam loss analysis that is crucial to understand the origin of the beam losses and their mechanisms. Due to the performance of the diamond detectors losses from unbunched beam were observed right before the injected bunches. This observation can be used for further beam loss investigation during the injection process.
Measurements using scCVD demonstrate the successful applications of diamond sensors for beam loss and luminosity measurements. The diamond detectors installed near to LHCb show the sensitivity to vacuum changes and therefore the possibility of beam condition monitoring. BCM1F diamonds are used for beam halo and luminosity measurements and provide beam parameter to CMS and LHC. This system is operational since 2008 and illustrates the capability of diamond sensors in high energy physics. An upgrade of the BCM1F system is planned to increase the efficiency for luminosity measurements and to decrease the radiation damage. First upgrade concepts are implemented and also under further development.

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