PROCEEDINGS OF SCIENCE

Diamond Detector Technology: Status and Perspectives

Michael Reichmann[*†]
Eidgenoessische Technische Hochschule Zuerich (CH)
E-mail: michael.reichmann@cern.ch

Here could be your abstract ;-)

The European Physical Society Conference on High Energy Physics
5-12 July
Venice, Italy

[*] Speaker.
[†] The full list of RD42 authors is provided in the appendix.

© Copyright owned by the author(s) under the terms of the Creative Commons
Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

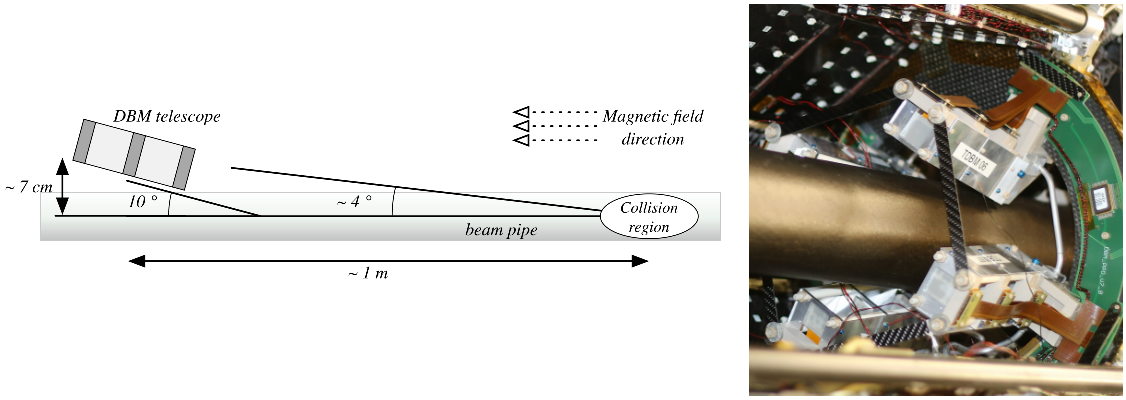
1. Introduction

The upgrade of the Large Hadron Collider (LHC) to the High Luminosity LHC (HL-LHC) from 2023 to 2025 [1] will push the luminosity limits even above the original design values of the LHC and will therefore hopefully give us even more insights in the fundamental nature of the universe. The in 2028 aspired instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ will be equivalent to a fluence of $2 \times 10^{16}\,\mathrm{n_{eq}/cm^2}$ [2] for the innermost tracking layer at a distance of $\sim$30 mm from the interaction point. In this environment pixel hit rates of $3\,\mathrm{GHz/cm^2}$ are expected. The current pixel detectors are designed to withstand $\sim 300\,\mathrm{fb^{-1}}$ and thus the full detector would have to be replaced about every semester. This fact lead to research and development of various radiation hard detector designs and materials.
Its large displacement energy and the high band gap (5.5 eV at 305 K) make diamond an excellent candidate for such a radiation tolerant detector which is why the RD42 Collaboration is investigating single-crystal (sc) and poly-crystalline (p) Chemical Vapour Deposition (CVD) diamond as an alternative for precision tracking detectors for over two decades. In order to grow high quality detector grade diamonds RD42 collaborates with industrial companies. All shown results are acquired with scCVD diamonds produced by Element Six Technologies [9] and pCVD diamonds produced by II-VI Incorporated [11]. The two companies use propriety CVD processes to fabricate their products. Both diamond types are grown on homo-epitaxial substrates with the difference that for scCVD another scCVD diamond is used as substrate and thus its size is limited to $\sim 0.25\,\mathrm{cm^2}$. However for the pCVD a diamond powder can be used as a substrate by what in can be grown to wafers of diameters up to 6 inch [4]. In various studies it was found out that diamond is minimum three times more radiation hard [7], has at least a two times faster charge collection [12] and its thermal conductivity is four times higher [13] than corresponding silicon detectors.
Due to the very high particle fluxes and radiation doses expected for the HL-LHC it is very important to understand the behaviour of future detectors in this environment. The RD42 Collaboration has studied CVD diamond detectors up to irradiation doses of $2.2 \times 10^{16}\,\mathrm{p/cm^2}$. In order to build even more radiation hard detectors a new technology - 3D detectors [3] - is investigated. The clever design of these detectors allows to heavily reduce the drift distance of the created charge carriers without reducing the total number of the electron-hole pairs. Since the behaviour at high fluxes is uncertain, high rate studies are performed at Paul Scherrer Institut (PSI) with nearly minimum ionising particles (MIPs) and tunable particle fluxes from the order of $1\,\mathrm{kHz/cm^2}$ up to the order of $10\,\mathrm{MHz/cm^2}$ are performed.

2. Diamond Detectors at CERN

It is essential for all modern collider experiments to have an online monitoring of the beam conditions. Since it is important to have these detectors as close as possible to the beam all of the four main experiments at the LHC are using detectors with diamond sensors. ATLAS [10], ALICE, CMS [5] and LHCb [8] all make use of various Beam Condition Monitors (BCMs) and/or Beam Loss Monitors (BLMs) based on both CVD type diamonds for live background estimations and luminosity measurements.
As an upgrade of the BCM during the long shutdown in 2014 ATLAS installed the Diamond Beam

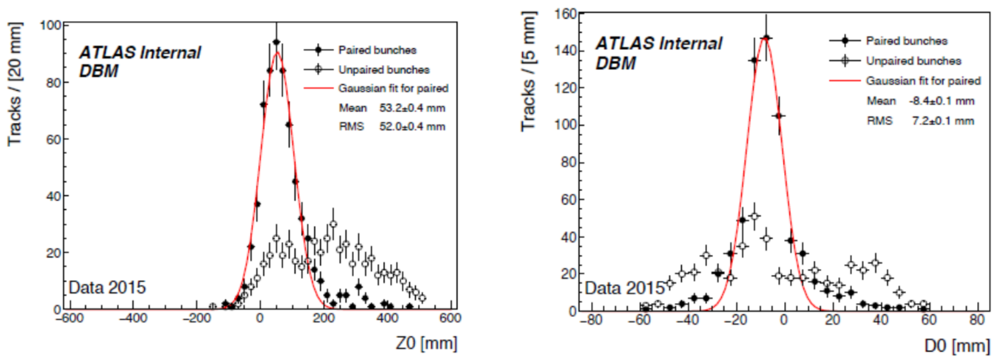
Monitor (DBM). Its purpose is to measure an instantaneous (bunch-by-bunch) luminosity and the bunch-by-bunch position of the beam spot. With its eight telescopes à three detector planes it adds tracking capability to the existing precise time-of-flight (ToF) measurements of the eight pad detectors of the BCM. The usage of state of the art pixel detectors based on the FE-I4b readout chip strongly increases the spatial resolution of the monitor and due to its projective geometry pointing towards the interaction region it also can distinguish particles coming from collisions and background [6]. The telescopes whereof the sensors of two are made out silicon and the other six out of pCVD diamond are positioned symmetrically around the beam pipe on both sides of the interaction point (IP) and are shown in figure 1. A total number of 45 diamonds with a thickness of 500 µm was available for the project of which the best for chosen for the detector.



(a) positioning and alignment (b) four mounted telescopes

Figure 1: DBM telescope

Shortly after the installation some of the modules broke (both silicon and diamond)and the DBM became non-operational. Nevertheless the first results already look promising as the plots in figure 2 proof. They show a clear discrimination between collision and background events. During the shutdown of the LHC in the beginning of 2017 the surviving modules were successfully recommissioned and became now a part of the ATLAS data taking.



(a) longitudinal distance to the IP (b) radial distance to the IP

Figure 2: Reconstruction of tracks from three modules using the initial alignment.

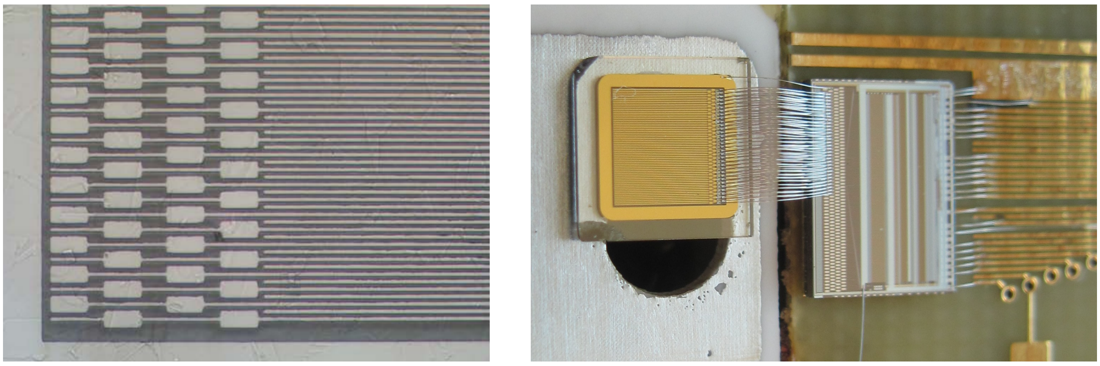
Du to the increasing particle fluence and excellent properties it is likely that diamond detectors become more popularin the future. The current research concentrates on 3D diamond detectors which will be described in section 5 on the following page as a possible candidate for the innermost tracking detectors of the LHC. But there is also work towards an upgrade of the BCM to the BCM' which is designed to provide a fast (bunch-by-bunch) abort system for ATLAS as well as precise luminosity measurement for the HL-LHC.

3. Radiation Tolerance

In order to probe the radiation tolerance of CVD diamond sensors several radiation studies have been performed varying the types and energies of damaging particles. The sensors were irradiated with protons with energies of 24 GeV, 800 MeV, 70 MeV and 25 MeV, 1 MeV neutrons and 200 MeV pions up to a maximum dose of $2.2 \times 10^{16}\,\mathrm{p/cm^2}$.

3.1 Preparation of the Detector

In a first step the surface of the raw diamond sensor has to be polished, cleaned and prepared for photo-lithography. Using the photo-lithography a metallisation pattern is then brought on the surface of the diamond. Depending on the pattern three types of detectors can be created: pad, strip and pixel detectors. This process is done for both of the sides of the diamond sensor whereby an almost edgeless design is obtained. By using a segmentation of the detector one can probe the charge of the detector depending on the position of the sensor which is critical for radiation studies. In this case solely strip detectors were used which were then mounted and connected to an amplifier to read out the charge of each strip. An image of the metallisation pattern and an example of a final detector are shown in figure 3.



(a) Strip metallisation pattern (b) A mounted diamond detector with amplifier

Figure 3: Detector for radiation studies

3.2 Setup

The characterisation of the irradiated devices was performed at the Super Proton Synchrotron (SPS) beam line at CERN with MIPs with momenta of the order of 100 GeV/c. By using a customised beam telescope with a spacial resolution of $\sim$2 μm one obtains an unbiased or transparent hit prediction of the particle track in the diamond sensor. The schematic setup is shown in figure 4. Two pairs of crossing silicon strip detectors are positioned equally spaced in front and after the device under test (DUT). At the end of the telescope is a scintillator as reference.

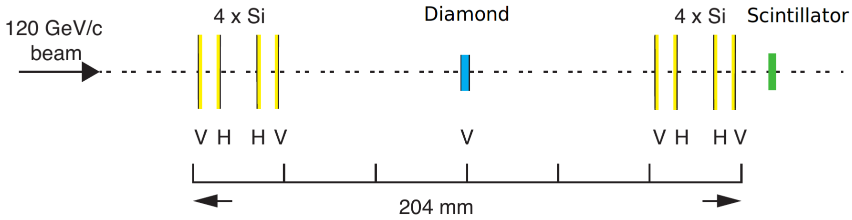


Figure 4: Schematic beam test setup

3.3 Results

The signal behaviour of irradiated material follows the simple damage equation where n_0 is

$$n = n_0 + k\phi \tag{3.1}$$

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k\phi \tag{3.2}$$

the initial number of traps, mfp_0 is the initial mean free path, k a damage constant and ϕ the fluence.

4. Rate Studies

5. 3D Detectors

6. Conclusion

List of Acronyms

LHC Large Hadron Collider

HL-LHC High Luminosity LHC

PSI Paul Scherrer Institut

DUT device under test

SPS Super Proton Synchrotron

MIP minimum ionising particle

CVD Chemical Vapour Deposition

sc single-crystal

p poly-crystalline

BCM Beam Condition Monitor

BLM Beam Loss Monitor

DBM Diamond Beam Monitor

ToF time-of-flight

IP interaction point

References

[1] G Apollinari, I Béjar Alonso, O Brüning, M Lamont, and L Rossi. *High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2015.

[2] Georg Auzinger. Upgrade of the CMS Tracker for the High Luminosity LHC. Technical Report CMS-CR-2016-268, CERN, Geneva, Oct 2016.

[3] F. Bachmair, L. Bäni, P. Bergonzo, B. Caylar, G. Forcolin, I. Haughton, D. Hits, H. Kagan, R. Kass, L. Li, A. Oh, S. Phan, M. Pomorski, D.S. Smith, V. Tyzhnevyi, R. Wallny, and D. Whitehead. A 3d diamond detector for particle tracking. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 786:97 – 104, 2015.

[4] Felix Caspar Bachmair. *CVD Diamond Sensors In Detectors For High Energy Physics*. PhD thesis, Zurich, ETH, 2016.

[5] E. Bartz, J. Doroshenko, V. Halyo, B. Harrop, D.A. Hits, D. Marlow, L. Perera, S. Schnetzer, and R. Stone. The plt: A luminosity monitor for cms based on single-crystal diamond pixel sensors. *Nuclear Physics B - Proceedings Supplements*, 197(1):171 – 174, 2009. 11th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD08).

[6] Matevz Cerv. The atlas diamond beam monitor. 9:C02026, 02 2014.

[7] Wim de Boer, Johannes Bol, Alex Furgeri, Steffen Müller, Christian Sander, Eleni Berdermann, Michal Pomorski, and Mika Huhtinen. Radiation hardness of diamond and silicon sensors compared. *physica status solidi (a)*, 204(9):3004–3010, 2007.

[8] M. Domke, C. Ilgner, S. Kostner, M. Lieng, M. Nedos, J. Sauerbrey, S. Schleich, B. Spaan, and K. Warda. Commissioning of the beam conditions monitor of the lhcb experiment at cern. In *2008 IEEE Nuclear Science Symposium Conference Record*, pages 3306–3307, Oct 2008.

[9] elementsix - industry leading engineers. `https://e6cvd.com`, 2017.

[10] A. Goriek, V. Cindro, I. Dolenc, H. Frais-Kölbl, E. Griesmayer, H. Kagan, S. Korpar, G. Kramberger, I. Mandi, M. Meyer, M. Miku, H. Pernegger, S. Smith, W. Trischuk, P. Weilhammer, and M. Zavrtanik. Atlas diamond beam condition monitor. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 572(1):67 – 69, 2007. Frontier Detectors for Frontier Physics.

[11] Ii-vi incorporated : A global leader in engineered materials and optoelectronic devices and components. `http://www.ii-vi.com/`, 2017.

[12] H Pernegger, V Eremin, H Frais-Kölbl, E Griesmayer, H Kagan, S Roe, S Schnetzer, R Stone, W Trischuk, D Twitchen, Peter Weilhammer, and A Whitehead. Charge-carrier properties in synthetic single-crystal diamond measured with the transient-current technique. *J. Appl. Phys.*, 97(7):73704–1–9, 2005.

[13] Shu-lai Zhao. *Characterization of the electrical properties of polycrystalline diamond films*. PhD thesis, Ohio State U., 1994.