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New Beam Test Results of 3D Pixel Detectors Constructed With poly-crystalline CVD diamonds

The RD42 Collaboration

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The planned upgrade of the LHC to the High-Luminosity-LHC will push the luminosity limits above the original design values. Since the current detectors will not be able to cope with this environment ATLAS and CMS are doing research to find more radiation tolerant technologies for their innermost tracking layers. Chemical Vapour Deposition (CVD) diamond is an excellent candidate for this purpose. Detectors out of this material are already established in the highest irradiation regimes for the beam condition monitors at LHC. The RD42 collaboration is leading an effort to use CVD diamonds also as sensor material for the future tracking detectors. The signal behaviour of highly irradiated diamonds is presented as well as the recent study of the signal dependence on incident particle flux. There is also a recent development towards 3D detectors and especially 3D detectors with a pixel readout based on diamond sensors.

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1. Introduction

The upgrade of the Large Hadron Collider (LHC) to the High-Luminosity-LHC (HL-LHC) from 2023 $\sim$ 2025 [1] will push the luminosity limits even above the original design values of the LHC and will therefore hopefully give us more insights in the fundamental nature of the universe. In 2028 an instantaneous luminosity of $5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ is expected. In this environment the innermost tracking layer at a distance of $\sim$30 mm to the interaction point (IP) is expected to be exposed to a total fluence of $2 \cdot 10^{16}\,\mathrm{n_{eq}/cm^2}$ by 2028 [2]. This fluence is equivalent to an integrated luminosity of $\sim$3000 fb^{-1}, but since the current pixel detectors are designed to withstand $\sim$300 fb^{-1} the full detector would have to be replaced about every year. This led to research and development of new radiation tolerant detector designs and materials.

Its large displacement energy of 42 eV/atom and a high band gap of 5.5 eV 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 works together with industrial companies. All results in this paper were acquired with scCVD diamonds produced by Element Six Technologies [3] and pCVD diamonds produced by II-VI Incorporated [4]. The main difference between the two types of diamonds are their sizes of $\sim$0.25 cm^2 for scCVD and up to 6 inch for pCVD and the smaller signal in pCVD [5]. In various studies it was shown that compared to corresponding silicon detectors, diamond is at minimum three times more radiation hard [6], has at least a two times faster charge collection [7] and its thermal conductivity is four times higher [8].

It is essential for all modern collider experiments to have an online monitoring of the beam conditions as close as possible to the beam [1]. Due to the high radiation in that regime presently all of the four main experiments at the LHC are using detectors with diamond sensors. ATLAS [9], ALICE [10], CMS [11] and LHCb [12] 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.

Due to expected high particle flux and expected radiation dose 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 with irradiation doses up to $2.2 \cdot 10^{16}\,\mathrm{p/cm^2}$. In order to build more radiation tolerant detectors, a new technology - 3D detectors [13] - in diamond is being investigated [14] . The 3D design of these detectors heavily reduces the drift distance of the created charge carriers without reducing the total number of the created electron-hole pairs. Since the particle flux of the HL-LHC will be in completely new regime, 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 $10\,\mathrm{MHz/cm^2}$.

2. Conclusion

By now the technology of diamond detectors is well established in high energy physics. Many of the experiments are already using BCMs or BLMs based on CVD diamonds. As one of the first pixel projects the ATLAS Diamond Beam Monitor (DBM) was recommissioned for the 13 TeV collisions and started taking data.

The diamond material was proven to be very radiation tolerant and the signal behaviour after the irradiation with various particle species and energies is well understood for both scCVD and pCVD diamonds. In extensive studies it was found that pCVD diamond detectors work reliably and show no signal dependence up to an incident particle flux of $20\,\mathrm{MHz/cm^2}$. This was also shown for irradiated detectors up to fluence of $5 \cdot 10^{14}\,\mathrm{n_{eq}/cm^2}$.

There is also great progress in the development of more radiation tolerant devices. The working principle of both 3D strip and pixel detectors was proven with great success down to cell sizes of $100\,\mu\mathrm{m} \times 100\,\mu\mathrm{m}$. For the first time more than 80 % of the created charge in the material was read out. The efficiency of the column drilling process is now above 99 % and the relative efficiency of the 3D pixel detectors is 99.3 % compared to a silicon detector.

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