

## Diamond detector technology, status and perspectives

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#### 50 Abstract

Detectors based on Chemical Vapor Deposition (CVD) diamond have been used extensively 51 and successfully in beam conditions/beam loss monitors as the innermost detectors in the highest 52 radiation areas of Large Hadron Collider (LHC) experiments. The startup of the LHC in 2015 53 brought a new milestone where the first polycrystalline CVD (pCVD) diamond pixel modules 54 were installed in an LHC experiment and successfully began operation. The RD42 collaboration 55 at CERN is leading the effort to develop polycrystalline CVD diamond as a material for tracking 56 detectors operating in extreme radiation environments. The status of the RD42 project with 57 emphasis on recent beam test results is presented. 58

59 Keywords: Chemical Vapor Deposition, pCVD diamond, diamond detectors, 3D diamond

60 detectors, radiation tolerant detectors

#### 61 **1. Introduction**

The RD42 collaboration [1, 2] at CERN is leading the effort to develop radiation tolerant 62 devices based on pCVD diamond as a material for tracking detectors operating in harsh radiation 63 environments. Diamond has properties which make it suitable for such detector applications. 64 During the last few years the RD42 group has succeeded in producing and measuring a number 65 of devices to address specific issues related to use at the HL-LHC [3, 4]. This paper presents 66 the status of the RD42 project with emphasis on recent beam test results. In particular, results 67 are presented on the status of the first diamond pixel detector based on pCVD material, on the 68 independence of signal size on incident particle rate in pCVD diamond detectors over a range of 69 particle fluxes up to 20 MHz/cm<sup>2</sup> and on the 3D diamond detectors fabricated in pCVD diamond. 70

#### 71 2. Status of the ATLAS Diamond Beam Monitor

The startup of the LHC in 2015 brought a new milestone for diamond detector development 72 where the first planar diamond pixel modules based on pCVD diamond were installed in an 73 LHC experiment, the ATLAS experiment [5], and successfully began operation. The ATLAS 74 Diamond Beam Monitor (DBM) [6, 7] was designed to measure the instantaneous luminosity, 75 the background rates and the beam spot position. A single DBM module consists of an 18 mm  $\times$ 76 21 mm pCVD diamond 500  $\mu$ m thick instrumented with a FE-I4 pixel chip [8]. The 26,880 pixels 77 are arranged in 80 columns on 250  $\mu$ m pitch and 336 rows on 50  $\mu$ m pitch resulting in an active 78 area of 16.8 mm  $\times$  20.0 mm. This fine granularity provides high precision particle tracking. The 79 deposited charge from a particle is measured in the FE-I4 by Time-over-Threshold. 80

The ATLAS DBM uses diamonds with a charge collection distance (the average distance an electron-hole pair move apart under the influence of the applied electric field) of 200-220  $\mu$ m at an applied bias voltage of 500 V. Three telescopes each with 3 diamond DBM modules (plus 1 telescope with silicon sensors) mounted as a three layer tracking device were installed inside the pixel detector services on each side of the ATLAS interaction point at 90 cm < |z| < 111 cm,

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 $3.2 < |\eta| < 3.5$  and at a radial distance from 5 cm to 7 cm from the center of the beam pipe. The 86 modules have an inclination of  $10^{\circ}$  with respect to the ATLAS solenoid magnetic field direction 87 to suppress erratic dark currents [9] in the diamonds. The ATLAS DBM data-acquisition system 88 is shared with the ATLAS IBL [10]. After initial installment, data were collected in the July 2015 89 run. These data have been analyzed and the first results of the ATLAS DBM tracking capabilities 90 are shown in Fig. 1. A clear separation between background particles from unpaired bunches 91 (open circles) and collision particles from colliding bunches (filled circles) is observed. After 92 two electrical incidents in 2015 with consequent loss of several silicon and diamond modules, 93 the DBM has now been re-commissioned and is again in the operation phase. 94



Figure 1: Radial distance (left plot) and longitudinal distance (right plot) of the closest approach of the projected particle tracks to the interaction point as recorded by a single DBM telescope with preliminary alignment.

#### 95 3. Rate Studies in pCVD diamond

In order to study the dependence of signal size on incident particle rate, RD42 performed a series of beam tests in the  $\pi$ M1 beam line of the High Intensity Proton Accelerator (HIPA) at Paul Scherrer Institute (PSI) [11]. This beam line is able to deliver 260 MeV/c  $\pi^+$  fluxes from a rate of ~5 kHz/cm<sup>2</sup> to a rate ~20 MHz/cm<sup>2</sup> in bunches spaced 19.8 ns apart.

Sensors using pCVD material [12] were tested in a tracking telescope [13] based on 100  $\mu$ m 100  $\times$  150  $\mu$ m silicon pixel sensors read out by the PSI46v2 pixel chip [14]. The diamond signals 101 were amplified with custom-built front-end electronics with a peaking time of  $\sim 6$  ns, return-102 to-baseline in  $\sim 16$  ns and 550e noise with 2 pf input capacitance. The amplified signals were 103 recorded with a DRS4 evaluation board [15] operating at 2 GS/s. The entire system was triggered 104 with a scintillator which determined the timing of the beam particles with a precision of  $\sim 0.7$  ns. 105 A series of cuts were applied to the data including: removing 60 s of triggers at the beginning 106 of each run, removing triggers from heavily ionizing particles with saturated waveforms (mostly 107 protons), removing calibration triggers, removing triggers in the wrong beam bucket, removing 108 triggers with no tracks in the telescope and removing triggers with large angle tracks in the 109 telescope. After applying this procedure all telescope tracks which project into the diamond 110 fiducial region have a pulse height well separated from the pedestal distribution in the diamond 111 i.e. the diamond is 100% efficient at all rates. The same procedure was applied to all particle 112 flux points and the resulting mean pulse height (in arbitrary units) versus rate is shown in Fig. 2 113 for both positive and negative bias voltage. The uncertainty on the data points in the plot include 114 both statistical and systematic sources. The systematic uncertainty was determined by assuming 115 any deviations in pulse height for rates below 80 kHz/cm<sup>2</sup> were due to systematic effects. Thus 116

the spread in the data points at a given rate indicates the reproducibility of the data. Fig. 2 indicates the mean pulse height in pCVD diamond detectors irradiated up to  $5 \times 10^{14}$  n/cm<sup>2</sup> does

<sup>119</sup> not depend strongly on rate up to rates of 20 MHz/cm<sup>2</sup>.



Figure 2: The average pulse height versus rate for an un-irradiated and irradiated pCVD diamond pad detector at positive and negative bias. The beam line parameters were adjusted to set the different particle rates. The data was taken by scanning up and down in rate multiple times. The pulse height units are arbitrary since the un-irradiated and irradiated detectors used different readout electronics. The resulting electronics gain corrections and the relative gain correction for positive versus negative signals in the electronics is still being determined and has not been applied.

#### **4. 3D Diamond Pixel Detectors**

3D sensors with electrodes in the bulk of the sensor material were first proposed in 1997 [16] 121 in order to reduce the drift distance of the charged carriers to much less than the sensor thickness. 122 In order to achieve this goal a series of alternating + and – electrodes perpendicular to the read 123 out face were created in the bulk detector material. This idea is particularly beneficial in detectors 124 with a limited mean free path such as trap dominated sensor materials like heavily irradiated 125 silicon and pCVD diamond where the observed signal size is related to the mean free path divided 126 by the drift distance. Under these circumstances one gains radiation tolerance (larger signals) by 127 keeping the drift distance less than the mean free path. With this geometrical structure charge 128 carriers drift inside the bulk parallel to the surface over a typical drift distance of 25-100  $\mu$ m 129 instead of perpendicular to the surface over a distance of 250-500  $\mu$ m. 130

In 2015 RD42 published results of a 3D device fabricated in single-crystal CVD diamond [17] showing that the 3D structure works in diamond. In 2016 RD42 fabricated the first 3D device in pCVD diamond [18]. The electrodes in the bulk of the pCVD diamond 3D device were fabricated with lasers as described in [17]. The bias electrodes were placed at the corners and the readout electrodes were placed in the middle of the cells. This pCVD device was shown to collect more than 75% of the deposited charge which translates in more than a factor of two more charge than a planar diamond strip detector fabricated on the same pCVD diamond.

In 2017 RD42 successfully constructed the first pCVD diamond 3D pixel detector with  $50\mu m$ ×  $50 \mu m$  cells. This pixel device is designed to be read out with the RD53 pixel readout chip [19] which is not yet available. In order to read this device out with an existing pixel readout chip a small number of cells were ganged together to match the pitch of the pixel readout chip. RD42 is proceeding to make 3D diamond pixel devices compatible with both the CMS pixel readout

chip (3  $\times$  2 ganging) and the ATLAS pixel readout chip (1  $\times$  5 ganging). The first 50  $\mu$ m  $\times$  50 143  $\mu$ m pCVD diamond 3D pixel device which was bump-bonded used the CMS pixel readout chip. 144 This first diamond 3D pixel device was tested during the Aug 2017 beam test at PSI at a 145 single voltage and with rates from 7 kHz/cm<sup>2</sup> to 7 MHz/cm<sup>2</sup>. During the initial lab test it was 146 discovered that the bump bonding had a small issue on one edge. We decided to take data with the 147 device rather than try to repair this small bump bonding issue. Fig. 3 (left) shows the preliminary 148 efficiency as a function of xy position for every cell in the device with a 1500e pixel threshold. 149 The red box marks the fiducial region used to measure the hit efficiency. The blue circle indicates 150 the position of the one non-working pixel cell in the central region of the device. Fig. 3 (right) 151 shows the hit efficiency in the fiducial region with the 1500e pixel threshold as a function of time 152 during an up-down scan of incident particle rates from 7 kHz/cm<sup>2</sup> to 7 MHz/cm<sup>2</sup> and back to 7 153 kHz/cm<sup>2</sup>. The overall measured efficiency is 99.2% and no change in efficiency as a function of 154 rate is observed. The corresponding efficiency for a planar silicon CMS pixel detector in this test 155 was 99.7% with no change in efficiency as a function of rate. The slight loss of efficiency (0.5%), 156 assuming it holds through the completion of the analysis, is most likely due to charge loss in the 157 column electrodes. If this explanation is correct, then this effect can be easily remedied by tilting 158 the detector at a small angle with respect to the incident beam. 159



Figure 3: The hit efficiency of the first  $50\mu m \times 50 \mu m$  cell pCVD 3D pixel detector with  $3 \times 2$  ganged cells read out with CMS pixel electronics with a 1500e threshold. The left plot shows the efficiency of each ganged cell as a function of *xy* position in the device. The right plot shows the average efficiency in the fiducial region (the red box in the left plot) as a function of time during the run at  $67 \text{ kHz/cm}^2$ .

#### 160 5. Conclusions

The recent progress in the design, fabrication and testing of polycrystalline CVD diamond 161 detectors was presented. The following milestones have been achieved: successful operation of 162 the first pCVD diamond planar pixel detector in the ATLAS experiment at the LHC; demonstra-163 tion that the average signal pulse height of pCVD diamond detectors irradiated up to  $5 \times 10^{14}$ 164  $n/cm^2$  is independent of the particle flux up to ~20 MHz/cm<sup>2</sup>; successful fabrication and opera-165 tion of the first pCVD diamond 3D pixel detector with 50  $\mu$ m  $\times$  50  $\mu$ m pixels read out with CMS 166 pixel electronics where the efficiency for a MIP was >99% and the average charge collected in 167 the device was >90% of the deposited charge. In the future RD42 plans to study the pulse height 168 dependence of CVD diamond sensors with pad and pixel electrodes with radiation doses up to 169

<sup>170</sup>  $10^{17}$  n/cm<sup>2</sup> and continue the development of 3D diamond detectors with the production of a 50 <sup>171</sup>  $\mu$ m × 50  $\mu$ m cell pCVD diamond 3D pixel detector compatible with ATLAS readout electronics.

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