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Beam test results of the dependence of signal size on incident particle flux in diamond pixel and pad detectors

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ABSTRACT: We present results of beam tests of charged particle detectors based on single-crystal and poly-crystalline Chemical Vapor Deposition (CVD) diamond. We measured the signal pulse height dependence on the particle flux. The detectors were tested over a range of particle fluxes from 2 kHz/cm\textsuperscript{2} to 20 MHz/cm\textsuperscript{2}. The pulse height of the sensors was measured with pad and pixel readout electronics. The pulse height of the non-irradiated single-crystal CVD diamond pad sensors was stable with respect to flux, while the pulse height of irradiated single-crystal CVD diamond pad sensors decreased with increasing particle flux. The pulse height of the non-irradiated single-crystal CVD diamond pixel detectors decreased slightly with increasing particle flux while the pulse height of the irradiated single-crystal CVD diamond pixel detectors decreased significantly with increasing particle flux. The observed sensitivity to flux is similar in both the diamond pad sensors constructed using diamonds from the Pixel Luminosity Telescope (PLT) irradiated during its pilot run in the Compact Muon Solenoid (CMS) detector and in neutron irradiated diamond pad sensors from the same manufacturer irradiated to the same fluence of neutrons. The pulse height for irradiated poly-crystalline CVD diamond pad sensors proved to be stable with respect to particle flux.

KEYWORDS: Particle tracking detectors; Solid state detectors; Diamond Detectors; Radiation-hard detectors

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1 Introduction

For two decades the CERN-based RD42 collaboration has investigated Chemical Vapor Deposition (CVD) diamond as a radiation tolerant alternative for precision tracking detectors [1]. The basic properties of diamond, such as large displacement energy and large band gap are the main factors influencing its radiation hardness. The RD42 collaboration has measured the signal response of single-crystal and poly-crystalline CVD diamond detectors irradiated to particle fluences up to $1.8 \times 10^{16}$ protons/cm$^2$ [2]. As a consequence of these measurements, diamond pixel tracking detectors have been proposed and already implemented as beam condition and luminosity monitors for both general purpose Large Hadron Collider (LHC) experiments: the Compact Muon Solenoid (CMS) and the A Toroidal LHC ApparatuS (ATLAS) whose radiation environments require use of radiation tolerant sensor materials.

The first diamond pixel detectors installed in a running collider experiment were used in the pilot run of the Pixel Luminosity Telescope (PLT) operating in CMS in 2012-2013 [3]. This device was based on single-crystal CVD diamonds that were limited in area ($4.5 \times 4.5$ mm$^2$) and read out with a standard CMS PSI46v2 pixel readout chip (ROC) [4]. The ATLAS experiment chose to use the larger area polycrystalline CVD diamonds ($18 \times 21$ mm$^2$) for its Diamond Beam Monitor (DBM) upgrade [5] which is now installed and awaiting the 2015 LHC run. During the pilot run the PLT devices experienced particle fluxes much higher than in any previous beam test, in excess of 4 MHz/cm$^2$. The total integrated particle fluence received by the PLT sensors during the entire run was estimated by a FLUKA [6, 7] calculation to be $\sim 5 \times 10^{13}$ n/cm$^2$ and $\sim 5 \times 10^{13}$ charged hadrons/cm$^2$ [8], a relatively low fluence. In early running, after receiving a relatively low fluence of $\sim 1 \times 10^{13}$ hadrons/cm$^2$, the PLT sensors exhibited a pulse height dependence on particle flux with the observed pulse height decreasing with increasing particle flux [9].
pulse heights at low rate (100 Hz) had similar values to those predicted by the damage curve derived from RD42 beam test data, while those at higher rate (4 MHz) had 1/4 of the predicted pulse height from the RD42 beam test data. This unexpected effect prompted this systematic study. In this paper we present the first steps of the study. We irradiated poly-crystalline and single-crystal CVD diamond sensors to known neutron fluences similar to that observed by the PLT during the pilot run in CMS. We then measured the response of those diamond sensors along with non-irradiated single-crystal CVD diamond sensors to a controllable flux of 250 MeV/c pions, approximately minimum ionizing particles. We tested two different detector geometries: a pad geometry to test the effect of electrostatics on charge collection and a pixel geometry to test the effect of the readout threshold and of the weighting field on charge collection. Each geometry was read out by a different system. The results were compared under the same test beam conditions to non-irradiated single-crystal CVD diamond sensors and single-crystal CVD diamond sensors irradiated during the PLT pilot run.

2 Experimental setup

2.1 Devices and irradiations

We tested two types of CVD diamond sensors, poly-crystalline and single-crystal. Each type was tested with both pixel and pad detector geometries. All samples were ∼500 µm thick and ∼5 mm × 5 mm in lateral size. The contact electrodes for the pad detectors were made out of Cr/Au (Cr is the adhesive layer) and had a guard ring around the pad on the bias side. The metal contacts for the pixel detectors were Ti:W for both the pixel pattern and the backside bias electrode. The pixel pattern consisted of individual pixels with electrode size of 75 µm × 125 µm and 100 µm × 150 µm in pitch. After metalization both Cr/Au and Ti:W devices were annealed at 400 °C for 4 mins in a N₂ atmosphere. The bias electrode of the pad detectors was wire-bonded to an SMA connector. The pixel detector was bump-bonded to a standard CMS PSI46v2 pixel readout chip (ROC) [4] using indium bump technology without reflow.

In order to reproduce the neutron fluence obtained during the PLT pilot run, a series of detectors were irradiated. The irradiation was performed before the detector fabrication steps described above, to minimize the wait for detectors to “cool down” after the irradiation. Neutron irradiation was performed using the TRIGA Mark II research reactor at the Jožef Stefan Institute in Ljubljana [10]. A channel leading to the reactor core was used for irradiation. The total neutron flux in this channel at full power is ∼2×10^{13} n/(cm² s) with the flux of fast (>0.1 MeV) neutrons ∼1.8×10^{12} n/(cm² s), which can be scaled down by adjusting the power of the reactor. For our irradiation, a fraction of 10% of the reactor power was used. The dosimetry was established previously using various techniques, such as threshold activation, simulations of the reactor core, and leakage current measurements of standard silicon diodes [10]. The total dose of fast neutrons received by the diamond samples during the irradiation was determined to be 5.0±0.5×10^{13} n/cm². Summary information for all devices under test (DUTs), including the sensor material, the electrode type, irradiation fluence, and the type of irradiation, is shown in table 1.
Table 1. Summary table of the devices under test. The fluence received by samples 3 and 6 is estimated from a FLUKA calculation [8].

<table>
<thead>
<tr>
<th>sample #</th>
<th>material</th>
<th>electrode</th>
<th>fluence and irradiation particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>single-crystal diamond</td>
<td>pad</td>
<td>non-irradiated</td>
</tr>
<tr>
<td>2</td>
<td>poly-crystalline diamond</td>
<td>pad</td>
<td>$5 \times 10^{13}$ fast reactor neutrons</td>
</tr>
<tr>
<td>3</td>
<td>single-crystal diamond</td>
<td>pad</td>
<td>$\sim 5 \times 10^{13}$ n/cm$^2$ and $\sim 5 \times 10^{13}$ charged hadrons/cm$^2$</td>
</tr>
<tr>
<td>4</td>
<td>single-crystal diamond</td>
<td>pad</td>
<td>$5 \times 10^{13}$ fast reactor neutrons</td>
</tr>
<tr>
<td>5</td>
<td>single-crystal diamond</td>
<td>pixel</td>
<td>non-irradiated</td>
</tr>
<tr>
<td>6</td>
<td>single-crystal diamond</td>
<td>pixel</td>
<td>$\sim 5 \times 10^{13}$ n/cm$^2$ and $\sim 5 \times 10^{13}$ charged hadrons/cm$^2$</td>
</tr>
<tr>
<td>7</td>
<td>single-crystal silicon</td>
<td>pixel</td>
<td>non-irradiated</td>
</tr>
</tbody>
</table>

2.2 Beam test setup

We performed the beam test in the $\pi M1$ beam line at the High Intensity Proton Accelerator (HIPA) Facility of the Paul Scherrer Institute (PSI) in Villigen, Switzerland [11]. The beam was tuned to provide $\pi^+$ particles with momentum 250 MeV/c and variable flux from $1 \text{ kHz/cm}^2$ – $20 \text{ MHz/cm}^2$, which was controlled by two sets of intermediate collimators.

Two detector geometries were tested: a pixel geometry and a pad geometry. For each detector geometry a separate configuration of the telescope was used. The front and the back telescope pixel planes were used for triggering. For the pixel geometry, the intermediate space between the trigger planes was populated with four additional pixel planes. For the pad geometry, the intermediate four planes were removed to provide a space for the pad detector box, which was placed in that position. The precise positioning of the pad detector within the sensitive area of the pixel planes was accomplished with an x-y positioning stage. The pad detector configuration is shown in figure 1.

The signal of the pad detector was first amplified by an Ortec 142A low noise charge sensitive preamplifier [12]. The preamplifier signal was further amplified and shaped by an Ortec 450 Research Amplifier. The shaped pad detector pulses had a peaking time of approximately 200 ns and were completely gone in 500 ns. Finally, the signal waveforms were digitized by a DRS4 evaluation board [13] and stored on a computer for further analysis. Figures 2a and 2b show an example of a hundred such waveforms overlayed at a low incident particle flux (3 kHz/cm$^2$) (figure 2a) and at a high incident particle flux (> 300 kHz/cm$^2$) (figure 2b).

In the pixel detector tests, the telescope consisted of six pixel planes. The first and last planes contained CMS silicon sensors [14] and the four intermediate planes contained detectors under test.
Figure 2. (2a) The raw pad detector signal at low 3 kHz/cm$^2$ flux with only one trigger plane in front of the pad detector and (2b) the raw pad detector signal at high > 300 kHz/cm$^2$ flux with two trigger planes: one in front and one in back of the pad detector. The addition of the second trigger plane eliminated particles which missed the pad detector under test. These show up in (2a) as a faint line under the peak.

The planes were read out by a standard CMS PSI46v2 pixel readout chip (ROC) [4]. A dedicated PSI46 test board was used to synchronize and to read out of all planes in the telescope.

The trigger in both pad and pixel configurations was derived from a coincidence between the “fast-OR” signals of the front and the back silicon planes. The “fast-OR” is a signal generated by a double-column of the ROC when one or more pixels in the double-column register a hit. Since the readouts of the telescope and a pad detector under test were not synchronized, we reduced the active area of the trigger planes to an area slightly smaller (∼ 0.5 mm on each side) than the sensitive area of the diamond pad sensor projected on those planes along the beam direction. This procedure assured that a particle that produced a trigger signal in both telescope planes would also pass through the sensitive area of the diamond plane.

In order to determine the pedestal level of the pad detector, two techniques were used. In one technique, the active area of the trigger planes was chosen outside of the projected active diamond area, in another technique the sampling point was shifted in time by an additional 2 µs away from the trigger point. Both techniques gave the same results for the value and the width of the pedestal. In most cases the temporal shift rather than the spatial shift technique was used, because the setup of the temporal shift was easier to implement. In the earlier beam test only one masked telescope plane was used for triggering. In this case, due to a slight divergence of the beam, some particles did not pass through the active area of the pad sensor under test, thus the pedestal and the signal appeared in the same dataset.

3 Analysis and results

3.1 Pad detector results

The following data analysis procedure was applied to all pad detector data. First, the waveforms (as shown in figure 2) from all events were averaged together in order to determine the position of the signal peak. The position of the signal peak was assumed to stay constant throughout a run. The value of the pulse height was subsequently calculated by averaging 25 points of the trace on
each side of this sampling point. In total, 50 trace points (equivalent to a time window of 70 ns) were averaged. In the pedestal runs, the sampling point was chosen at the same position as in the corresponding signal runs. The number of integration points was chosen as a trade-off between the influences of pile-up and noise. Since we are primarily interested in relative changes of pulse heights, the peak of the pulse height distribution for the lowest flux was scaled to one separately for each device under test. The same factor was then used to scale the other pulse height distributions for this sample. The resulting pulse height distributions are shown in figure 3 through 5.

The pulse height distributions of the non-irradiated single-crystal diamond detector (sample #1 in table 1) are shown in figure 3. Figure 3a shows the pulse height distributions at +500 V bias for 3 kHz/cm$^2$ and 30 kHz/cm$^2$ fluxes and figure 3b shows the pulse height distributions at -500 V for 30 kHz/cm$^2$, and 300 kHz/cm$^2$ fluxes. We observe no dependence on either the flux of the incoming particles, or the polarity of the bias voltage.

Figure 3. The raw pulse height distribution for the non-irradiated single-crystal CVD diamond pad detector (sample #1) at various (3 kHz/cm$^2$, 30 kHz/cm$^2$, and 300 kHz/cm$^2$) fluxes for positive (3a) and negative (3b) biases. One scale factor (scaling to one the most probable pulse height of the data from 3 kHz/cm$^2$, +500 V) was used to scale all four data runs. The peak at 3.25 a.u. originates from very large pulses which saturate the electronics.

Figure 4 shows the pulse height distributions for single-crystal CVD diamond detectors for various incident particle fluxes: (4a) neutron irradiated (sample #4) and (4b) irradiated during the PLT pilot run (sample #3). Figure 5, shows the pulse height distributions for a neutron irradiated poly-crystalline CVD diamond detector (sample #2) for the same set of incident particle fluxes. The dependence of the pulse height distributions on the particle flux is different for poly-crystalline and single-crystal samples. For both irradiated single-crystal samples the pulse height is noticeably (∼10% to 15%) lower for the highest (∼300 kHz/cm$^2$) particle flux indicating the existence of a flux dependence of the signal pulse height. On the contrary, the pulse height distributions of the poly-crystalline sample (sample #2) lie on top of each other indicating no such dependence on the incoming particle flux. The flux dependences of the single-crystal CVD diamond detectors coincide with the behavior of the diamond pixel detectors of similar type used in the PLT pilot run [9].
However, the notable absence of any dependence for the neutron irradiated poly-crystalline sample indicates that the type of diamond (single-crystal versus poly-crystalline) does affect its performance after irradiation. The underlying cause of this effect remains to be clarified in upcoming studies.

Figure 4. The pulse height distributions for single-crystal CVD diamond sensors, pad geometry: (4a) neutron irradiated to a fluence of $5 \times 10^{13}$ n/cm$^2$ (sample #4) and (4b) in-situ irradiated during the 2012-2013 PLT pilot run (sample #3). For this data-taking the sensors were biased at +500 V.

Figure 5. The pulse height distributions for the poly-crystalline CVD diamond sensor neutron irradiated to a fluence of $5 \times 10^{13}$ n/cm$^2$ (sample #2). For this data-taking the sensors were biased at +500 V.

Figure 6 shows the mean values of the pedestal subtracted pulse height distributions from figure 3 through 5 as a function of the incident particle flux. The pedestal subtracted mean was calculated by fitting a double Gaussian to the pedestal and subtracting the fitted pedestal from the overall distribution. This technique removes the variation in the number of pedestal events from the various detector runs. In order to focus on the relative change in the pulse height with flux, the mean pulse height at the lowest flux was scaled to one. The mean pulse height for the other fluxes for the same sample was scaled by the same factor. In the top plot of figure 6 the average pulse height of the non-irradiated single-crystal diamond sensor versus flux is shown. Although both
Figure 6. The mean values of the pulse height distributions for all pad geometry detectors from figure 3, figure 4 and figure 5 versus the incident particle flux. The statistical uncertainty on the points is approximately 1%. We estimate a 3% systematic uncertainty by comparing several procedures used to estimate the mean.

polarities are plotted on the graph it is difficult to distinguish them because the markers overlap, this shows that the average pulse height of the non-irradiated single-crystal diamond detector is independent of both the flux and the bias polarity. The average pulse height of the neutron irradiated poly-crystalline diamond sensor, shown in the bottom plot of figure 6, is also independent of the flux. Conversely, the average pulse height of both, the neutron irradiated single-crystal diamond sensor (sample #4) and the PLT pilot run irradiated single-crystal CVD diamond sensor (sample #3), shown correspondingly in the top middle and the bottom middle plot of figure 6, experience a ∼10% decrease at the highest particle flux ∼300 kHz/cm².
3.2 Pixel detector results

The pulse height distributions of the pixel detectors were determined using the following procedure. First, the correspondence between ADC values of the pixel readout system and the collected charge was found by using an internal calibration procedure: a known value of an internal calibration signal was applied to the calibration capacitor of the pixel readout circuit and the corresponding ADC value was read out. Adjacent pixels above threshold were added to form a cluster. The charge of the cluster was calculated as the sum of the pixels’ charges.

As described in section 2.2, the pixelated diamond detectors were measured in the telescope using six planes. In the analysis we assigned five of the planes to be reference planes and the remaining plane to be the one under test. Events with one and only one cluster in each plane were used for the alignment of the telescope. One run at low flux was dedicated for alignment of the telescope. After alignment, all potential tracks were fit to hits in the five reference planes. If the track’s $\chi^2$ was less than 6.25 (removing roughly 10% of the tracks), this track was used in the data analysis and its hit position in the plane under test was reconstructed. No requirements on the hit were made for the plane under test. The pulse height of the detector under test was constructed by summing pulse heights of pixels within a four pixel radius of the predicted hit position from the reconstructed track. Because we are primarily interested in relative changes of pulse heights versus flux, for each device under test we scaled the most probable pulse height for the lowest flux to one. The scaling factor determined for each DUT was then used to scale the pulse height distributions at other fluxes. A similar procedure was used to scale the average pulse height: the average pulse height at the lowest flux for each DUT was scaled to one and then the same scale factor was applied for the average pulse heights at other fluxes for that DUT. These procedures were used in figures 7, 8 and 10.

A silicon plane (sample #7) was used to estimate the systematic uncertainty on the average pulse height. The pulse height of the silicon sensor was assumed to be constant with flux and the observed changes in the pulse height were attributed to the readout electronics. The average pulse height of the silicon sensor versus flux is shown in figure 7 indicating that the pulse heights are stable versus flux. A small variation (~0.4%) of the average pulse height for various fluxes is assumed to be due to systematic uncertainties.

The pixel readout system allowed us to measure the pulse height of the samples at higher particle fluxes than for the pad readout, with fluxes up to 20 MHz/cm$^2$. In our data-taking, we increased the particle flux from run to run, except for the runs with a silicon sensor plane where the flux was adjusted non-sequentially. Figure 8a shows cluster pulse height distributions at low (2 kHz/cm$^2$), medium (100 kHz/cm$^2$), and high (20 MHz/cm$^2$) fluxes and (8b) the average pulse height of the cluster versus particle flux for the non-irradiated single-crystal CVD diamond detector (sample #5). It manifests a small (~0.4% per decade) decrease in average pulse height versus flux. This effect may be explained by the observed increase in cluster size (figure 9) and the detector threshold. During the data-taking the individual pixel threshold was set at ~3000 electrons. This threshold may not seem high enough to affect the pulse height distribution of diamond sensors, however, one should take into account that the threshold effect is enhanced when the charge is shared between two or more pixels. As the flux is increased, we observe (figure 9) the charge is shared between more pixels, reducing the charge collected by an individual pixel. As the charge on
Figure 7. The average pulse height versus flux for the non-irradiated silicon sensor (sample #7). The average pulse height at the lowest flux is scaled to one, the average pulse heights at other fluxes were scaled by the same factor. The average variation of the pulse height for various fluxes is \( \sim 0.4\% \). For this data-taking the silicon sensor was biased at -150 V.

Figure 8. (8a) The overlaid pulse height distributions for low, medium, and high fluxes and (8b) the average pulse height versus flux for the non-irradiated single-crystal CVD diamond sensor (sample #5). The average pulse height at the lowest flux is scaled to one, the average pulse heights at other fluxes were scaled by the same factor.

some pixels will be below the threshold and not read out, we observe an effective reduction of the measured charge.

Figure 10 shows the distributions for the in-situ irradiated single-crystal CVD diamond detector used during the 2012-2013 PLT pilot run (sample #6). During the PLT run the diamond sensor received on the order of \( \sim 5 \times 10^{13} \) n/cm\(^2\) and \( \sim 5 \times 10^{13} \) charged particles/cm\(^2\). Figure 10 shows a similar decrease of the pulse height (\( \sim 50\% \)) as observed in the PLT detector [9]. It is worth noting
Figure 9. The average cluster size in number of pixels versus flux for the non-irradiated single-crystal CVD diamond sensor (sample #5). The cluster size manifests $\sim 25\%$ increase from the lowest to the highest flux.

Figure 10. (10a) The pulse height distributions for several fluxes and (10b) the average pulse height versus flux for single-crystal CVD diamond detector irradiated during the PLT pilot run (sample #6). The average pulse height at the lowest flux is scaled to one, the average pulse heights at other fluxes were scaled by the same factor.

That already at a flux of 1 MHz/cm$^2$ the pulse height is close to the minimum, therefore implying that this particle flux was sufficient to study the effect of the decreasing pulse height using the slower pad electronics. One significant difference between these results and the result obtained with the pad detectors (cf. figure 6) is that the relative pulse height decrease is larger in the case of the pixel detector. This larger drop of the pulse height might be explained by the threshold imposed by the pixel electronics. In the pixel geometry the charge deposited by the incident particle is shared between multiple pixels. If one of the pixels in the cluster is below threshold, its charge is not added to the cluster, resulting in a lower cluster pulse height as explained above.
Although we measured both single-crystal and poly-crystalline CVD diamond detectors with the pixel readout system, the \( \sim 3000 \) electrons per pixel threshold prevented us from drawing conclusions about the behavior of the pulse height distributions of the poly-crystalline samples. The current CMS PSI46v2 ROC is not optimized for measurements with the diamond sensors. We plan to repeat the measurement in the future with a lower threshold readout system.

4 Conclusion

We have measured the pulse height dependence on the particle flux for non-irradiated and irradiated single-crystal CVD diamond pad and pixel detectors and for an irradiated poly-crystalline CVD diamond pad detector. For the single-crystal detectors we have obtained consistent results for both the pad and pixel readout electronics. The average pulse height of the non-irradiated single-crystal diamond pad detector did not depend on particle flux while the average pulse height of the non-irradiated diamond pixel detector decreased slightly with increasing particle flux. The average pulse height decreased with increasing particle flux for both the irradiated single-crystal CVD diamond pad detector and irradiated single-crystal pixel detectors. The pulse height of the neutron irradiated poly-crystalline CVD diamond detector measured with the pad readout showed no dependence on the particle flux. This result indicates that even though some diamonds do experience a drop in pulse height induced by particle flux, the effect is not present in all diamonds, therefore indicating that this effect possibly depends on the method of diamond growth. Future studies of diamonds as particle detectors should be focused on determining the underlying reason for this effect and communicating it to the manufacturers of detector grade diamond.

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