Radiation Tolerance of Diamond Detectors

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on behalf of the RD42 Collaboration

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Motivation

* Estimated particle fluence for the innermost layers
  * $O(\sim 10^{15}/\text{cm}^2)$ at the LHC
  * $O(\sim 10^{16}/\text{cm}^2)$ at the HL-LHC
  * $O(\sim 10^{17}/\text{cm}^2)$ at the FCC
  * Above $10^{16}/\text{cm}^2$ all materials are trap limited
    → need for more radiation tolerant detector designs/materials

* Diamond as a detector material
  * intrinsic radiation tolerance due to large displacement energy
  * insulating material with high thermal conductivity
  * high charge carrier mobility

* RD42 collaboration investigates signals and radiation tolerance in various detector designs
  * pad (full diamond as a single cell)
  * strip (diamond segmented with multi-channel readout)
  * pixel (diamond sensor on pixel chips)
  * 3D to reduce drift distance in trap limited materials

→ complete characterisation of diamond radiation tolerance
The RD42 Collaboration


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116 Participants
31 Institutes
Diamond as a Particle Detector

- Diamond detectors are operated as ionization chambers
- Poly-crystalline material comes in large wafers
- Metalization on both sides
  - Pad
  - Strip
  - Pixel
  - 3D
- Connected to fast, low noise electronics
Radiation Tolerance

Study the pulse height dependence on the irradiation fluence
**Beam Test Setup**

- Irradiate diamond samples with various particle species and energies
- Re-metalize after each irradiation step to fabricate a strip detector
- Characterization of irradiated devices in beam tests
- Tracking precision at detector under test: \( \sim 2\text{–}3\ \mu\text{m} \)
- Transparent (unbiased) hit prediction from telescope
- Obtain position, pulse height correlation using strip detectors
Signal Response of Irradiated Detectors

* Sum of charge observed on 5 contiguous strips near predicted hit position
* Single-crystalline sample after 800 MeV proton irradiation

![Graphs showing signal response of irradiated detectors with different radiation flux densities and electric field strengths.](image)

**Analysis Strategy**

* Measure the signal response as a function of predicted position

* Derive mean free drift path ($\lambda$) from measured signals

* First order damage model

\[
\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi
\]

* Fit in $1/\lambda$ vs $\phi$ space to determine $k$, $\lambda_0$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>thickness</td>
</tr>
<tr>
<td>$n$</td>
<td>number of traps</td>
</tr>
<tr>
<td>$n_0$</td>
<td>initial traps in material</td>
</tr>
<tr>
<td>$k'$</td>
<td>damage constant</td>
</tr>
<tr>
<td>$\phi$</td>
<td>fluence</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>mean free path</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>initial mean free path</td>
</tr>
<tr>
<td>$k$</td>
<td>damage constant</td>
</tr>
</tbody>
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```
* Plot single-crystalline (sCVD) and poly-crystalline (pCVD) data on same graph

* Linear fit in $1/\lambda$ vs $\phi$ space

* Fit each sample separately to test agreement

* Observe same damage constant (=slope) for sCVD and pCVD diamond for all irradiation species and energies

Due to initial traps in poly 24 GeV proton

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Analysed proton, neutron, and pion irradiated samples
Shifted pCVD samples by their individual $1/\lambda_0$

Results are well described by first order damage model (one-parameter description), resulting in relative damage constants

$$\kappa = \frac{k_i}{k_{24\text{ GeV protons}}}$$

With this measurement it is possible to estimate the signal response of any irradiated diamond detector

<table>
<thead>
<tr>
<th>Particle species</th>
<th>$\kappa$</th>
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<tbody>
<tr>
<td>24 GeV protons</td>
<td>1.0</td>
</tr>
<tr>
<td>800 MeV protons</td>
<td>1.67 $\pm$ 0.09</td>
</tr>
<tr>
<td>70 MeV protons</td>
<td>2.60 $\pm$ 0.29</td>
</tr>
<tr>
<td>200 MeV pions</td>
<td>3.2 $\pm$ 0.8</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>4.3 $\pm$ 0.4</td>
</tr>
</tbody>
</table>

[Sensors 20 (2020) 6648, DOI: 10.3390/s20226648]
Signal Response Prediction

* One-parameter description lends itself to universal damage curve

* Normalise damage to 24 GeV proton fluence

\[
\phi_{\text{eq.}} = \frac{k_i}{k_{24\text{ GeV protons}}} \times \phi_i
\]

* \( \lambda \) vs \( \phi \) space

* Predicted mean free path at \( 10^{17} / \text{cm}^2 \): \( \sim 16 \mu\text{m} \)

[ Sensors 20 (2020) 6648, DOI: 10.3390/s20226648 ]
For $10^{17}/\text{cm}^2$: 3D Diamond Detectors

Device development for mean drift distance $\approx \lambda$
**3D Detector Concept**

- After large radiation fluence all detectors are trap limited
  - Mean free drift path $\lambda < 20 \, \mu m$
  - Need to keep drift distances ($L$) smaller than $\lambda$

- Comparison of planar and 3D devices
  - 3D design has bias and readout electrodes inside detector material
  - Same thickness $D \rightarrow$ same amount of induced charge
  - Shorter drift distance $L$
3D Diamond Detectors after Irradiation

- Program: measure radiation tolerance of 3D compared to planar diamond detectors
- Unirradiated: 3D sensors collect twice as much charge as planar
- $3.5 \times 10^{15}/cm^2$: $(5 \pm 10)\%$ reduction in signal with 3D sensors
- $3.5 \times 10^{15}/cm^2$: $(45 \pm 5)\%$ reduction in signal with planar

![Graph showing relative signal vs fluence for 3D vs Planar pCVD diamond after irradiation with 800 MeV protons. The graph includes error bars and a legend indicating 3D pCVD and Planar pCVD.]
Rate Studies

Study the pulse height dependence on the particle flux
**Setup**

- Increasing particle rate: LHC → HL-LHC → FCC
- Characterization in 260 MeV $\pi^+$ beam at PSI
- Measure rate dependence of irradiated devices (up to $8 \times 10^{15} \text{n/cm}^2$)
- Irradiated pad detectors tested in ETH (CMS Pixel) telescope

19.8 ns bunch spacing clearly visible
Rate Studies after Irradiation

- HV

No rate dependence (<2 %) observed in irradiated pCVD up to 10–20 MHz/cm²

+ HV

No rate dependence (<2 %) observed in irradiated pCVD up to $8 \times 10^{15}$ n/cm²
Summary

- Quantified understanding of radiation effects in diamond
  - Measured radiation tolerance up to fluences of $10^{16}/\text{cm}^2$ (relevant for tracker application in HL-LHC experiments)
  - Established universal damage curve
  - Devices now being studied up to $10^{17}/\text{cm}^2$

- Studied rate effects @2 V/μm
  - Irrad. pCVD diamond shows no rate effect (<2%) up to 20 MHz/cm²
  - Irrad. pCVD diamond shows no rate effect (<2%) up to $8 \times 10^{15} \text{n/cm}^2$
Thank you!