Radiation Tolerance of Diamond Detectors

International Conference on Technology and Instrumentation in Particle Physics

Lukas Bäni
on behalf of the RD42 Collaboration

26.05.2021
Motivation

- Estimated particle fluence for the innermost layers
  - $\mathcal{O}(\sim10^{15} / \text{cm}^2)$ at the LHC
  - $\mathcal{O}(\sim10^{16} / \text{cm}^2)$ at the HL-LHC
  - $\mathcal{O}(\sim10^{17} / \text{cm}^2)$ at the FCC
  - Above $10^{16} / \text{cm}^2$ all materials are trap limited
    → need for more radiation tolerant detector designs/materials
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- Diamond as a detector material
  - intrinsic radiation tolerance due to large displacement energy
  - insulating material with high thermal conductivity
  - high charge carrier mobility
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    $\rightarrow$ 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
$\rightarrow$ complete characterisation of diamond radiation tolerance
The 2021 RD42 Collaboration


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3 CERN, Geneva, Switzerland
4 INFN/University of Florence, Florence, Italy
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6 Ioffe Institute, St. Petersburg, Russia
7 IPHC, Strasbourg, France
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28 INFN-Perugia, Perugia, Italy
29 California State University - Sacramento, USA
30 University of Bergen, Bergen, Norway
31 University College London, London, UK

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
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* Tracking precision at detector under test: $\sim 2–3 \mu m$
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- 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

Event density / 100 e

-2 V/µm

+2 V/µm

Analysis Strategy

* Measure the signal response as a function of predicted position
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* Derive mean free drift path ($\lambda$) from measured signals
**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

\[
\begin{align*}
  n &= n_0 + k' \phi \\
  \frac{1}{\lambda} &= \frac{1}{\lambda_0} + k \phi
\end{align*}
\]

- Fit in $1/\lambda$ vs $\phi$ space to determine $k$, $\lambda_0$
Radiation Tolerance

- Plot single-crystalline (sCVD) and poly-crystalline (pCVD) data on same graph.

Due to initial traps in poly.

24 GeV proton

**Radiation Tolerance**

- 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

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Radiation Tolerance

* 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

24 GeV proton

Universal Damage Curve

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

[Sensors 20 (2020) 6648, DOI: 10.3390/s20226648]
Universal Damage Curve

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  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

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

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<td>3.2 ± 0.8</td>
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  Shifted pCVD samples by their individual $1/\lambda_0$

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

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

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Signal Response Prediction

- One-parameter description lends itself to universal damage curve
**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

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**Signal Response Prediction**

* One-parameter description lends itself to universal damage curve

* Normalise damage to 24 GeV proton fluence

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

* \( \lambda \) 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 $\lambda$
3D Detector Concept

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- Comparison of planar and 3D devices
  - 3D design has bias and readout electrodes inside detector material
**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
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

* $3.5 \times 10^{15}/\text{cm}^2$: $(5 \pm 10)\%$ reduction in signal with 3D sensors

* $3.5 \times 10^{15}/\text{cm}^2$: $(45 \pm 5)\%$ reduction in signal with planar

![Irradiation of pCVD diamond with 800 MeV protons: 3D vs Planar](image-url)
Rate Studies

Study the pulse height dependence on the particle flux
Setup

* Increasing particle rate: LHC $\rightarrow$ HL-LHC $\rightarrow$ FCC
**Setup**

* Increasing particle rate: LHC $\rightarrow$ HL-LHC $\rightarrow$ FCC
* Characterization in 260 MeV $\pi^+$ beam at PSI
Setup

* Increasing particle rate: LHC $\rightarrow$ HL-LHC $\rightarrow$ FCC
* Characterization in 260 MeV $\pi^+$ beam at PSI
* Measure rate dependence of irradiated devices (up to $8 \times 10^{15} \, n/cm^2$)
Setup

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

19.8 ns bunch spacing clearly visible
Rate Studies after Irradiation

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

- 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 $10^{16}$/cm$^2$ (relevant for tracker application in HL-LHC experiments)
  - Established universal damage curve
  - Devices now being studied up to $10^{17}$/cm$^2$
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!
**CCD vs Schubweg**

CCD vs mean free drift distance before being trapped in an infinite material

\[
\frac{ccd}{t} = \sum_{i=e,h} \frac{\lambda_i}{t} \left[ 1 - \frac{\lambda_i}{t} \left( 1 - \exp\left(-\frac{t}{\lambda_i}\right) \right) \right]
\]

![Graph showing the relationship between \( \frac{ccd}{t} \) and \( \lambda \), with different values of \( \lambda_h/\lambda_e \).](image)
## Characteristics

<table>
<thead>
<tr>
<th>Property</th>
<th>Silicon</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant</td>
<td>11.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Thermal conductivity (W/(cm K))</td>
<td>1.3</td>
<td>6–22</td>
</tr>
<tr>
<td>Band gap (eV)</td>
<td>1.12</td>
<td>5.48</td>
</tr>
<tr>
<td>Electron mobility (cm²/(V s))</td>
<td>1450</td>
<td>2000</td>
</tr>
<tr>
<td>Hole mobility (cm²/(V s))</td>
<td>370</td>
<td>2100</td>
</tr>
<tr>
<td>Breakdown field (V/µm)</td>
<td>30</td>
<td>100–1000</td>
</tr>
<tr>
<td>Intrinsic resistivity (Ωm)</td>
<td>3200</td>
<td>&gt;10⁴⁰</td>
</tr>
<tr>
<td>Displacement energy (eV)</td>
<td>15–20</td>
<td>37.5–47.6</td>
</tr>
<tr>
<td>Radiation length (cm)</td>
<td>9.370</td>
<td>12.13</td>
</tr>
<tr>
<td>Nuclear interaction length (cm)</td>
<td>46.52</td>
<td>24.38</td>
</tr>
<tr>
<td>e-h pair creation energy (eV)</td>
<td>3.62</td>
<td>13.19</td>
</tr>
<tr>
<td>e-h pairs per MIP (av.) (1/µm)</td>
<td>90</td>
<td>36</td>
</tr>
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</table>
**Experimental Setup**

- Irradiate diamond samples with various particle species and energies
- Re-metalize after each irradiation step to fabricate a strip detector
- Beam tests
  - Tracking telescope (precision at detector under test: \( \sim 2–3 \, \mu m \))
  - Calibration with unirradiated devices
  - Characterization of irradiated devices
Uniformity in pCVD Diamond

* Observe regions of different signal ($\lambda$) in unirradiated poly-crystalline diamond

* Rewrite $\lambda$-$\phi$ relation:

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

* Expected damage with fluence using first order damage model:

\[
\frac{d\lambda}{d\phi} = -k \lambda^2
\]

→ Portions of material with the largest $\lambda$ are damaged most for given fluence $d\phi$

unirradiated $\phi = 18 \times 10^{15}$ p/cm$^2$
- Drilling columns with an 800 nm femtosecond laser
- Convert diamond into resistive mixture of various carbon phases (amorphous carbon, DLC, graphite, ...) $\mathcal{O}(50 \, \Omega)$
- Column diameter: 2.6 $\mu$m
- Cell size: 50 $\mu$m $\times$ 50 $\mu$m
- Number of columns per detector: $\mathcal{O}(1000)$
**Bump Bonding**

- Fabricated 4000 cell pixel prototype with $50 \mu m \times 50 \mu m$ pitch (3 devices)
- $50 \mu m \times 50 \mu m$ cells ganged for $3 \times 2$ (CMS) and $5 \times 1$ (ATLAS) readout
- Bump bonding: CMS @Princeton (In); ATLAS @IFAE (Sn/Ag)
- $3 \times 2$ ganged tested in Aug 2017 @PSI, Sep, Oct 2018 @CERN
- $5 \times 1$ ganged tested in Sep, Oct 2018 @CERN

3 × 2 bump pads

5 × 1 bump pads