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
    $\rightarrow$ 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


1 Universitäät Bonn, Bonn, Germany
2 INFN/University of Catania, Catania, Italy
3 CERN, Geneva, Switzerland
4 INFN/University of Florence, Florence, Italy
5 GSI, Darmstadt, Germany
6 Ioffe Institute, St. Petersburg, Russia
7 IPHC, Strasbourg, France
8 ITEP, Moscow, Russia
9 Jožef Stefan Institute, Ljubljana, Slovenia
10 Universität Karlsruhe, Karlsruhe, Germany
11 CEA-LIST Technologies Avancees, Saclay, France
12 MEPhI Institute, Moscow, Russia
13 The Ohio State University, Columbus, OH, USA
14 Rutgers University, Piscataway, NJ, USA
15 University of Torino, Torino, Italy
16 University of Toronto, Toronto, ON, Canada
17 University of Bristol, Bristol, UK
18 Czech Technical Univ., Prague, Czech Republic
19 University of Colorado, Boulder, CO, USA
20 Syracuse University, Syracuse, NY, USA
21 University of New Mexico, Albuquerque, NM, USA
22 University of Manchester, Manchester, UK
23 Universität Goettingen, Goettingen, Germany
24 ETH Zürich, Zürich, Switzerland
25 University of Tennessee, Knoxville, TN, USA
26 INFN-Lecce, Lecce, Italy
27 LPSC-Grenoble, Grenoble, France
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
* Re-metalize after each irradiation step to fabricate a strip detector
* Characterization of irradiated devices in beam tests
* Tracking precision at detector under test: $\sim 2–3 \mu m$
* 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

![Graph](image)

Event density / 100 e

$E = 0 \times 10^{15}$ p/cm$^2$

$E = 0.78 \times 10^{15}$ p/cm$^2$

$E = 2.39 \times 10^{15}$ p/cm$^2$

$E = 3.05 \times 10^{15}$ p/cm$^2$

$E = 7.8 \times 10^{15}$ p/cm$^2$

$E = 13.4 \times 10^{15}$ p/cm$^2$

-2 V/µm

+2 V/µm

**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

\[ n = n_0 + k' \phi \]

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

* 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
- 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

![Graph showing radiation tolerance comparison between sCVD and pCVD diamonds](image)

“due to initial traps in poly 24 GeV proton”

Universal Damage Curve

* 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>
</tr>
</thead>
<tbody>
<tr>
<td>24 GeV protons</td>
<td>1.0</td>
</tr>
<tr>
<td>800 MeV protons</td>
<td>1.67 ± 0.09</td>
</tr>
<tr>
<td>70 MeV protons</td>
<td>2.60 ± 0.27</td>
</tr>
<tr>
<td>200 MeV pions</td>
<td>3.2 ± 0.8</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>4.27 ± 0.33</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

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

- \( \lambda \) 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 $10^{17}$/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
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 $8 \times 10^{15}$ $n$/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 × 10¹⁵ n/cm²

Lukas Bäni  
TIPP 2021
**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$^2$

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