Radiation Tolerance of Diamond Detectors

Meeting of the Division of Particles and Fields of the American Physical Society

DPF 2021

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on behalf of the RD42 Collaboration

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» Motivation

* Estimated particle fluence for the innermost layers
  * $\mathcal{O}(\sim 10^{15}/\mathrm{cm}^2)$ at the LHC
  * $\mathcal{O}(\sim 10^{16}/\mathrm{cm}^2)$ at the HL-LHC
  * $\mathcal{O}(\sim 10^{17}/\mathrm{cm}^2)$ at the FCC
  * Above $10^{16}/\mathrm{cm}^2$ 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 $\rightarrow$ A. Porter's talk

$\rightarrow$ complete characterisation of diamond radiation tolerance

» The RD42 Collaboration

The 2021 RD42 Collaboration

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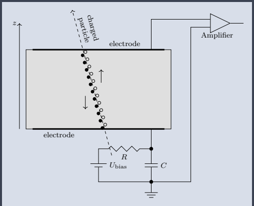
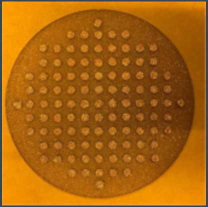
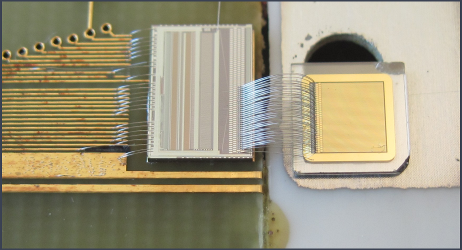
31 Institutes

» 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





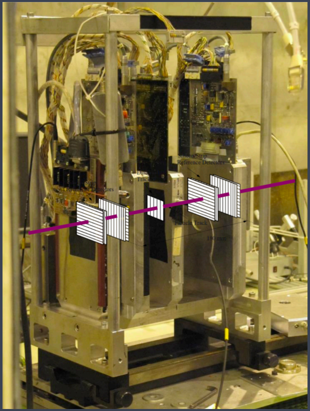


Radiation Tolerance

Study the pulse height dependence on the irradiation fluence

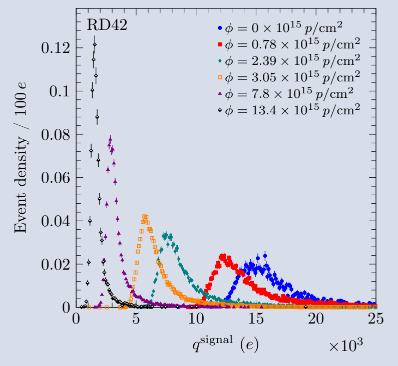
» Beam Test Setup

- 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 µm
- Transparent (unbiased) hit prediction from telescope
- Obtain position, pulse height correlation using strip detectors

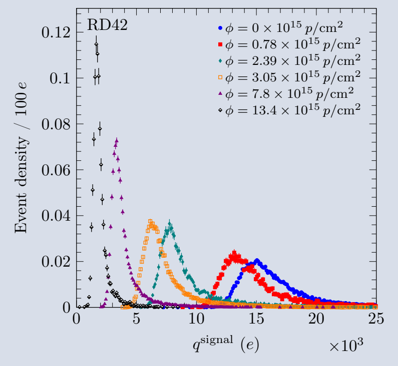


» Signal Response of Irradiated Detectors

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



−2 V/µm



+2 V/µm

[J. Phys. D: Appl. Phys. **52** (2019) 465103, DOI: 10.1088/1361-6463/ab37c6]

» Analysis Strategy

* Measure the signal response as a function of predicted position
* Derive mean free drift path (λ) from measured signals
* First order damage model

$$n = n_0 + k'\phi$$

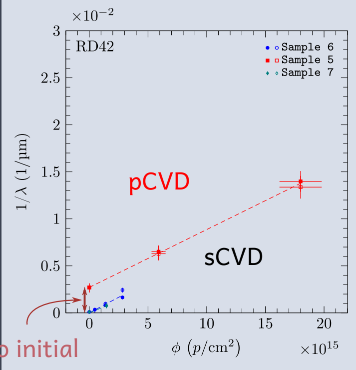
$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi$$

* Fit in $1/\lambda$ vs ϕ space to determine k, λ_0

t	thickness
n	number of traps
n_0	initial traps in material
k'	damage constant
ϕ	fluence
λ	mean free path
λ_0	initial mean free path
k	damage constant

» Radiation Tolerance

- Plot single-crystalline (sCVD) and poly-crystalline (pCVD) data on same graph
- Linear fit in $1/\lambda$ vs ϕ 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

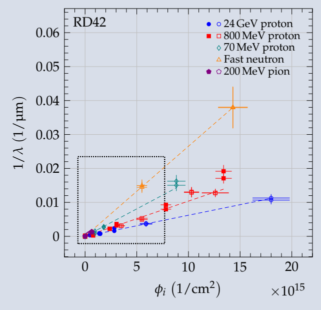
[J. Phys. D: Appl. Phys. **52** (2019) 465103, DOI: 10.1088/1361-6463/ab37c6]

» 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

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

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



[Sensors **20** (2020) 6648, DOI: 10.3390/s20226648]

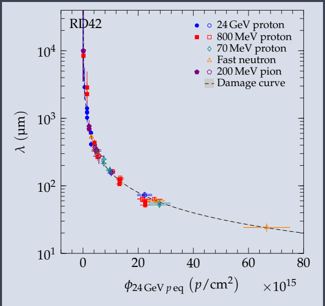
Particle species	κ
24 GeV protons	1.0
800 MeV protons	1.67 ± 0.09
70 MeV protons	2.60 ± 0.29
200 MeV pions	3.2 ± 0.8
Fast neutrons	4.3 ± 0.4

» Signal Response Prediction

* One-parameter description lends itself to universal damage curve
* Normalise damage to 24 GeV proton fluence

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

* λ vs ϕ space
* Predicted mean free path at $10^{17}/\text{cm}^2$: $\sim 16\,\mu\text{m}$



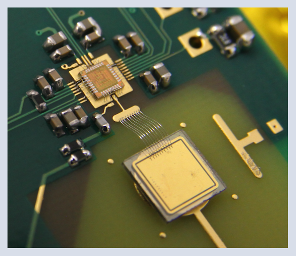
[Sensors **20** (2020) 6648, DOI: 10.3390/s20226648]

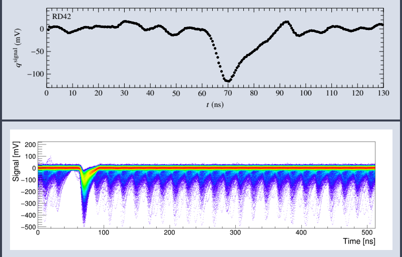
Rate Studies

Study the pulse height dependence on the particle flux

» Setup

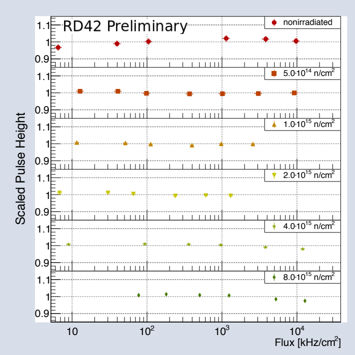
* Increasing particle rate: LHC → HL-LHC → FCC
* Characterization in 260 MeV π^+ beam at PSI
* Measure rate dependence of irradiated devices (up to $8 \times 10^{15}\ n/\mathrm{cm}^2$)
* Irradiated pad detectors tested in ETH (CMS Pixel) telescope



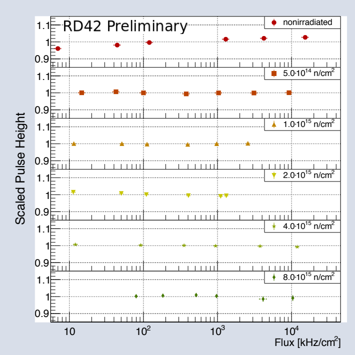


19.8 ns bunch spacing clearly visible

» Rate Studies after Irradiation



−HV



+HV

* No rate dependence ($<2\,\%$) observed in irradiated pCVD up to 10–20 $\mathrm{MHz/cm^2}$
* No rate dependence ($<2\,\%$) observed in irradiated pCVD up to $8 \times 10^{15}\ n/\mathrm{cm}^2$

» Summary

* Quantified understanding of radiation effects in diamond
  * Measured radiation tolerance up to fluences of $10^{16}/\mathrm{cm}^2$ (relevant for tracker application in HL-LHC experiments)
  * Established universal damage curve
  * Devices now being studied up to $10^{17}/\mathrm{cm}^2$
* 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 $8 \times 10^{15}\ n/\mathrm{cm}^2$

Thank you!