Diamond Detector Technology: Status and Perspectives

Lukas Bäni, on behalf of the RD42 collaboration

Position Sensitive Detectors 11 2017, Milton Keynes

The RD42 Collaboration

The 2017 RD42 Collaboration

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Outline

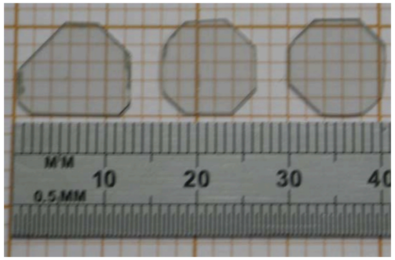
- Diamond as a sensor material
- Radiation tolerance
- 3D detectors
- Rate studies

Motivation

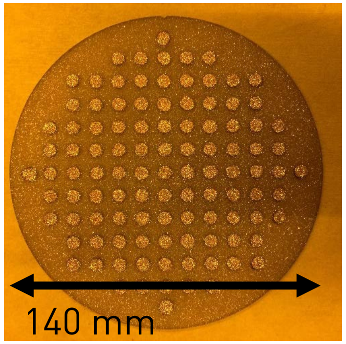
- Innermost layers of LHC experiments are exposed to a large particle fluence
- At the **High Luminosity LHC** a fluence of $\mathbf{2 \times 10^{16}\ n_{eq}/cm^2}$ is expected for the inner most layers of the tracker
- New **radiation tolerant concepts** are needed

Diamond as a Sensor Material

- Distinct properties interesting for HEP applications
  - Large band gap → low leakage current and noise
  - High thermal conductivity → good heat spread
  - Low dielectric constant → low capacitance, low noise
  - Large displacement energy → high radiation tolerance
- Disadvantages
  - Large band gap → ~1/2 signal of Si
- Diamonds grown with chemical vapour deposition (CVD)
  - Single-crystalline CVD (sCVD)
    available size: ~5×5 mm^2
  - Polycrystalline CVD (pCVD)
    large wavers of 5'' to 6'' ⌀



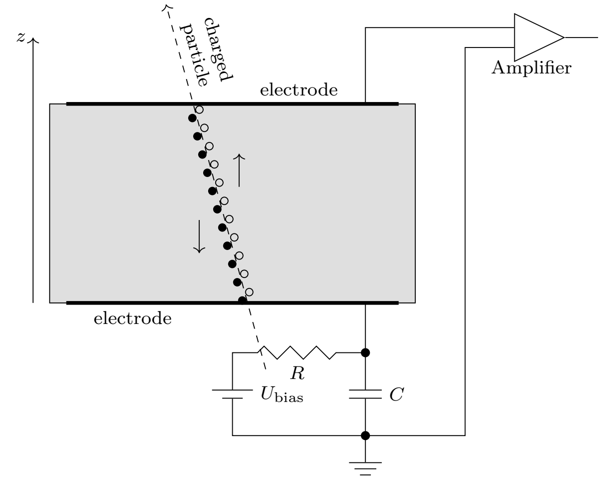
Single-crystalline CVD (courtesy of E6)

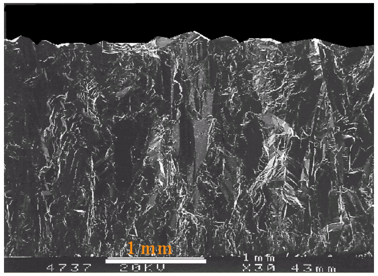


Poly-crystalline CVD (courtesy of II-IV)

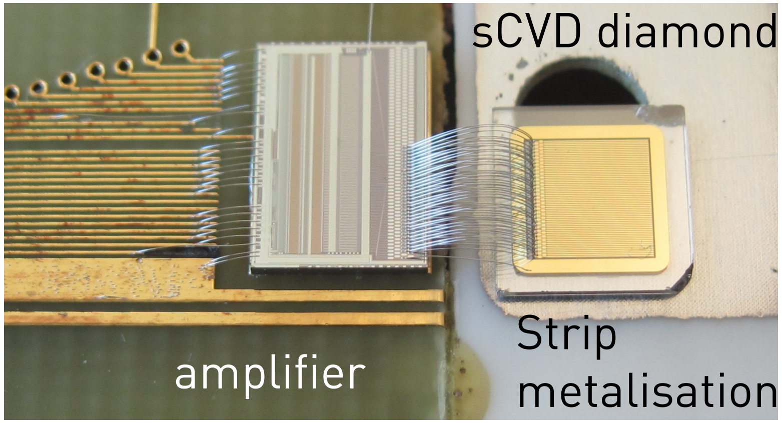
Diamond as a Particle Sensor

- Diamond detectors are operated as ionisation chambers
- Metalisation on both sides
  - **Pad**
  - **Strip**
  - Pixel
- Readout with low noise electronics



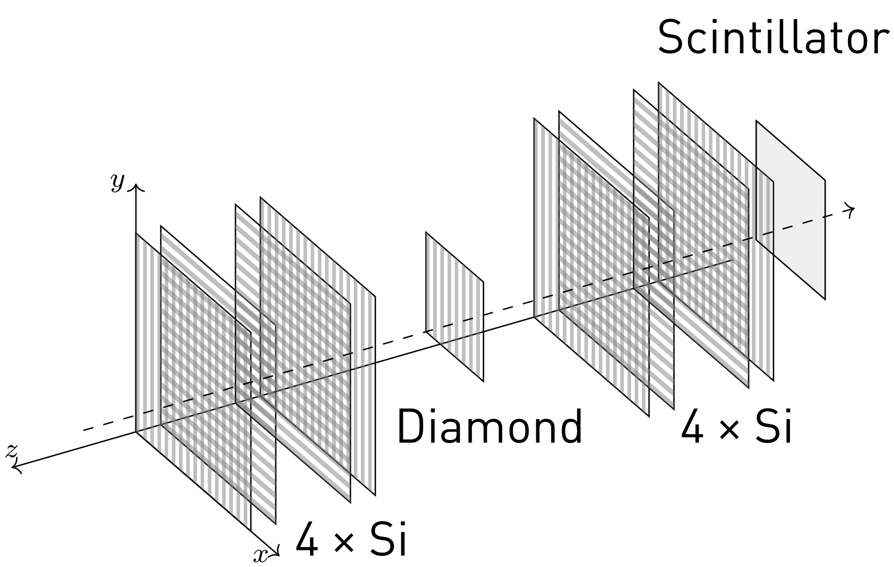


Poly-crystalline CVD



Testbeam Experimental Setup

- Characterisation of devices with
  - 120 GeV π/p beam at CERN
  - 260 MeV π^+ beam at PSI
- Use telescope prediction for unbiased measurements
- Measurements include
  - Signal response as a function of the predicted track position
  - Spatial resolution



Analysis Strategy

- Measure the signal response as a function of predicted position
  → Direct measurement of **charge collection distance (CCD)** = average distance e-h pairs move apart under the influence of an electric field
- Convert CCD into **mean free path (MFP)**, assuming same MFP for electrons and holes

$$\mathrm{CCD} = \sum_{\mathrm{e,\ h}} \lambda_i \left(1 - \frac{\lambda_i}{d}\left(1 - \exp\left(-\frac{d}{\lambda_i}\right)\right)\right)$$

- Damage equation

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

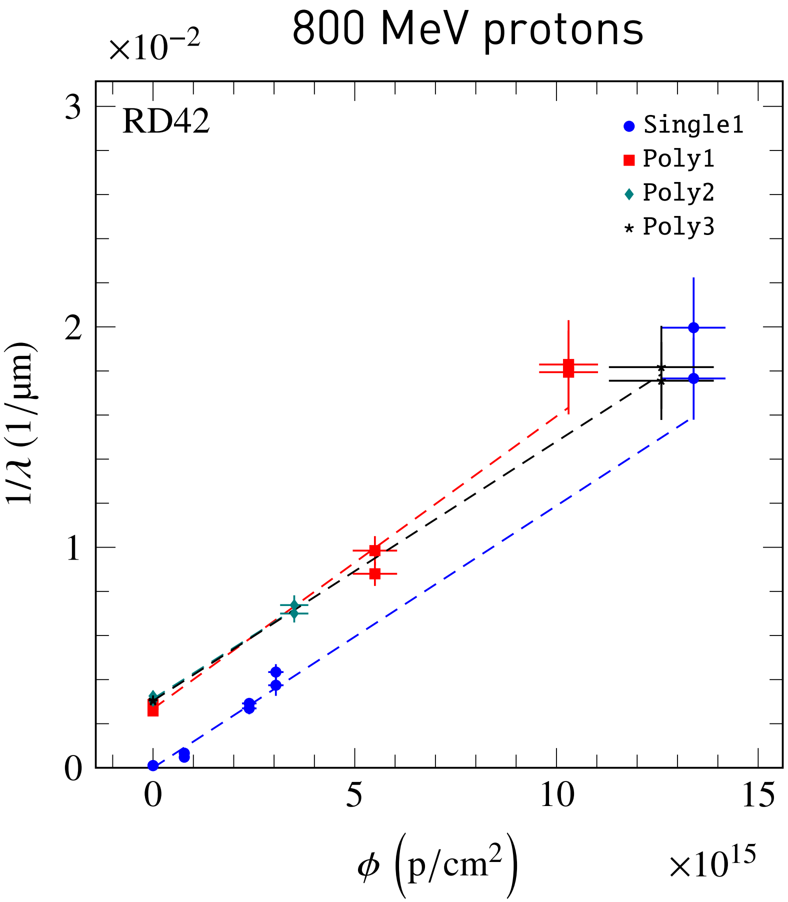
$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi$$

- Fit in **$1/\lambda$ vs ϕ space**

n Number of traps
n_0 initial traps
ϕ fluence
λ MFP
λ_0 initial MFP

Radiation Tolerance

- Irradiations with different particle species and energies
  - 800 MeV protons at LANSCE, Los Alamos, USA
  - 70 MeV protons at CYRIC, Tohoku, Japan
  - Fast neutrons (>100 keV) at Jožef Stefan Institute, Ljubljana, Slovenia
- Fit each sample in 1/λ vs ϕ space
  → linear fit, k = slope
- Average slopes



Summary of Radiation Tolerance Study
Combined Damage Curve

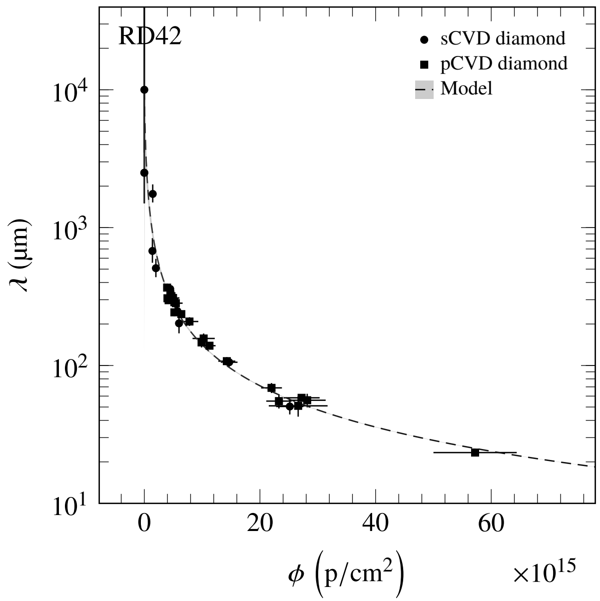
- Obtained radiation damage constants are compared to 24 GeV protons
- Combined damage curve
  - Shift pCVD sample by

$$\varphi_0 = \frac{1}{\lambda_0 k}$$

  - Scale fluence by relative k

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

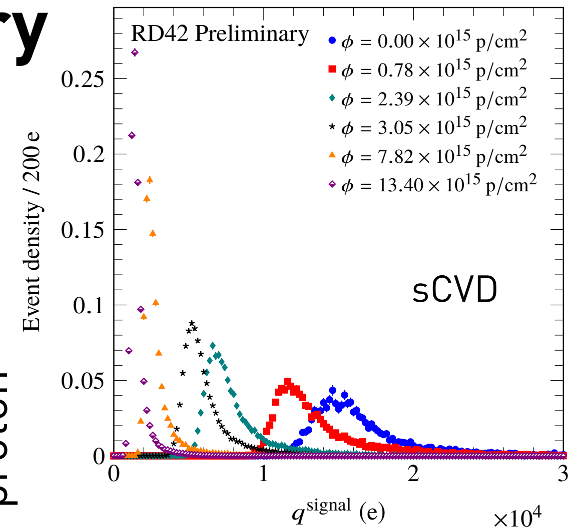
Particle species	Relative k
24 GeV protons	1
800 MeV protons	1.85 ± 0.13
70 MeV protons	2.5 ± 0.4
Fast neutrons	4.5 ± 0.5

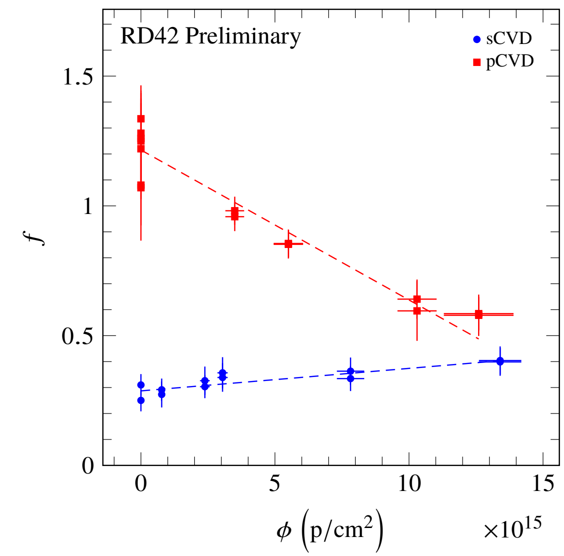


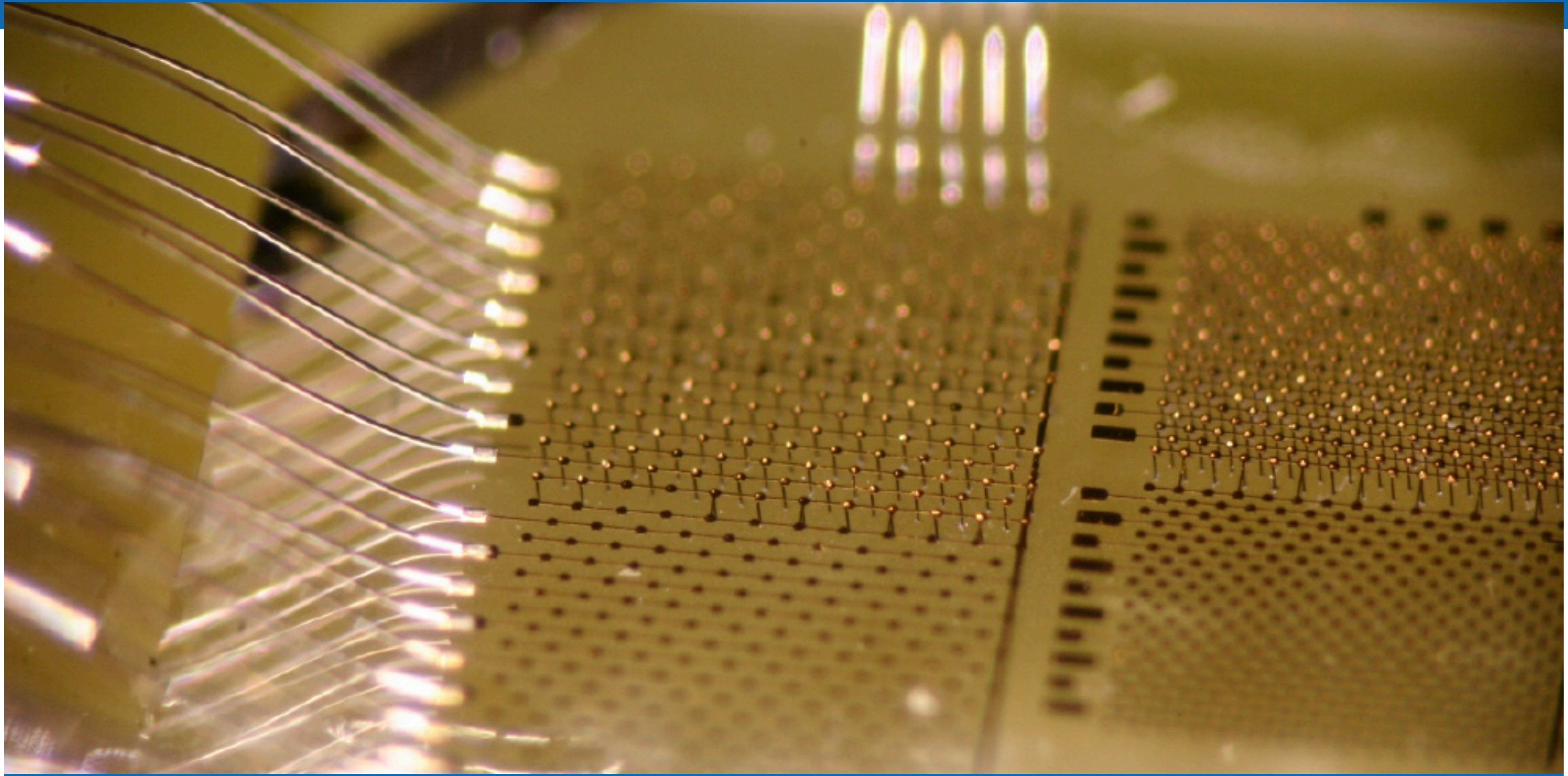
Signal Shape Analysis – Preliminary

- Study the shape of the pulse height distribution after irradiation
- Define the ratio f = FWHM / MP as figure of merit
- 800 MeV proton irradiated
  - pCVD diamond samples
    - Decrease of FWHM/MP
  - sCVD diamond
    - Smaller initial relative width (~0.3)
    - Increase towards the same value as the pCVD samples

800 MeV proton



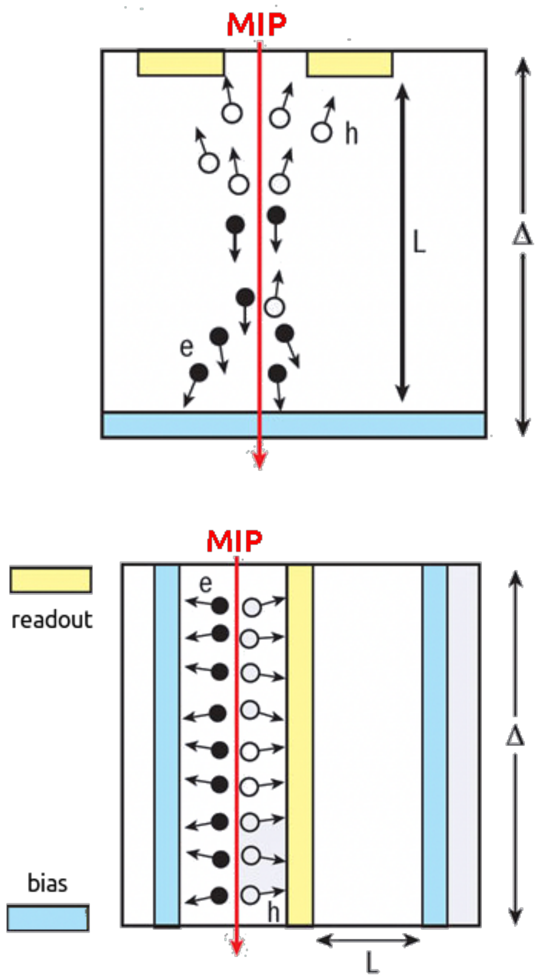




3D Diamond Detectors

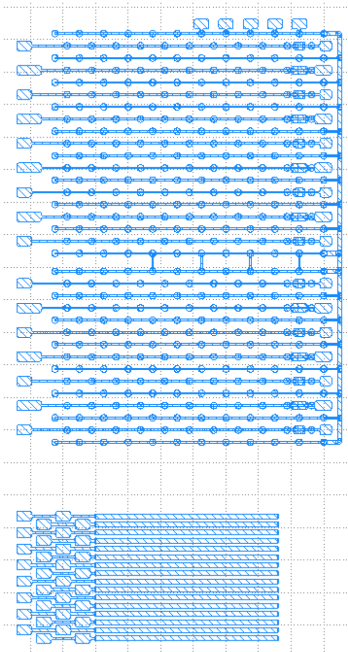
Concept

- MFP gets limited after large irradiations
- Use 3D geometry
- Place bias and readout electrodes inside diamond bulk
- **Drift length at the some order as MFP**
- Same thickness ➞ same amount of induced charge



Multi-region Device

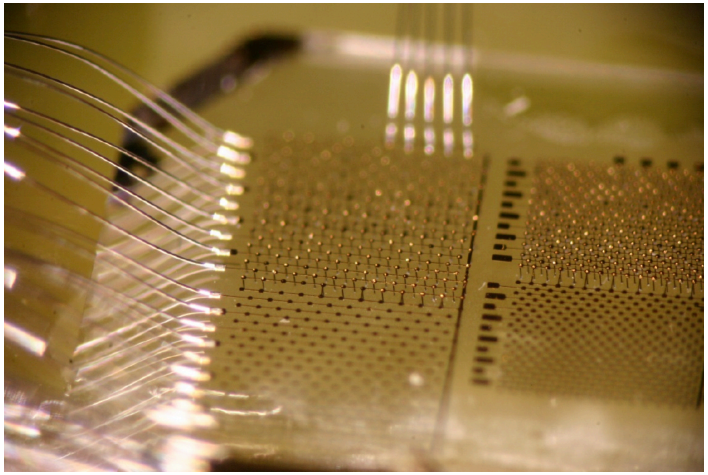
- Electrode columns drilled with a femtosecond laser
  → converts diamond into a resistive mixture of carbon phases
- pCVD diamond with 3 different regions
  - Strip detector for comparison @ 500 V
  - 3D phantom @ 60 V
    150 × 150 μm^2 cell size
  - 3D detector @ 60 V
    150 × 150 μm^2 cell size



3D detector

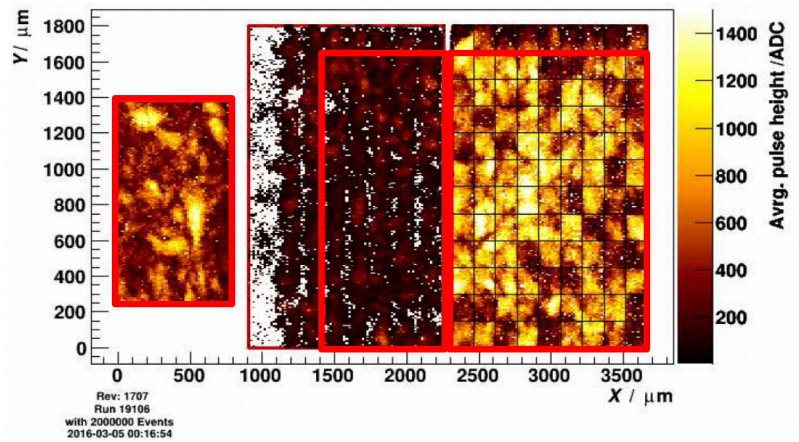
3D phantom

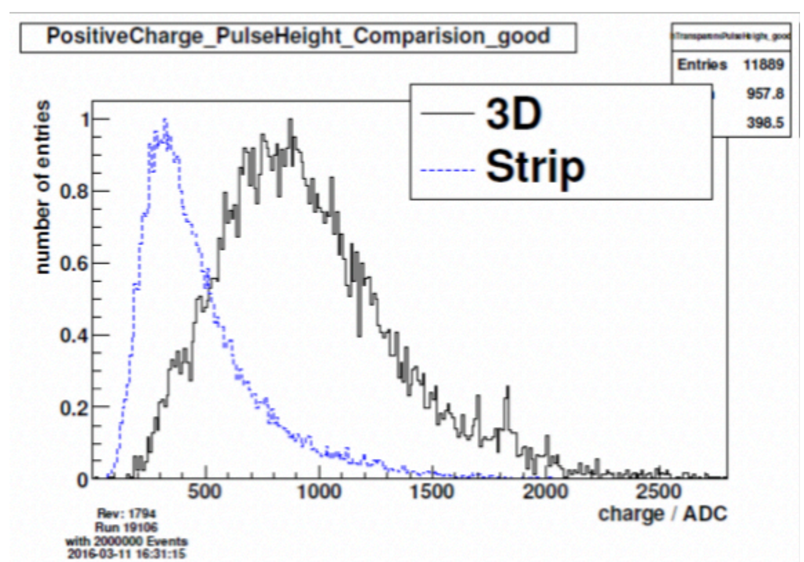
Strip



Signal Response

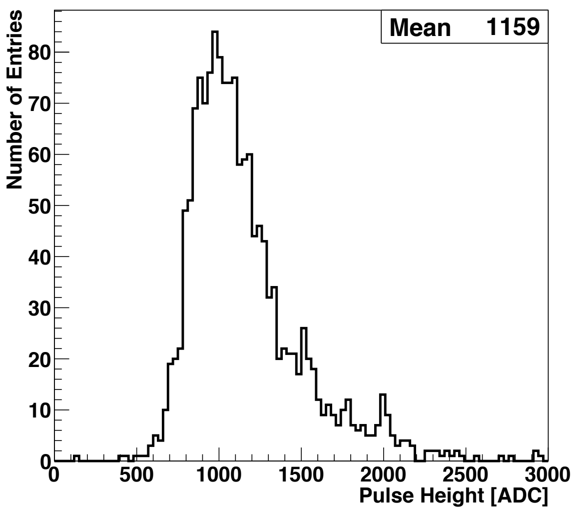
- Average pulse height maps
  - Verify working device
  - Phantom detector: less signal since columns are not connected
  - 3D detector: ~9 broken readout columns
- Observed signals (preliminary)
  - Strip: 6900 e → CCD = 192 μm
  - 3D: 13500 e → CCD* = 350-375 μm
    * equivalent CCD to observe same charge in planar device
  - **Collected 75 % charge with pCVD diamond for the first time!**

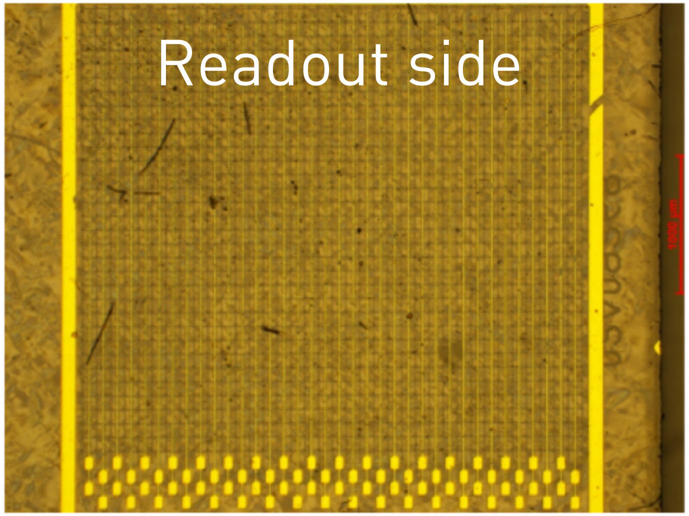


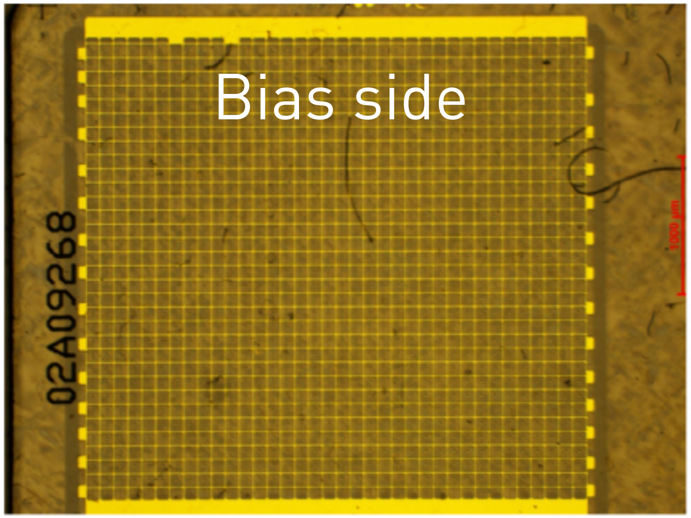


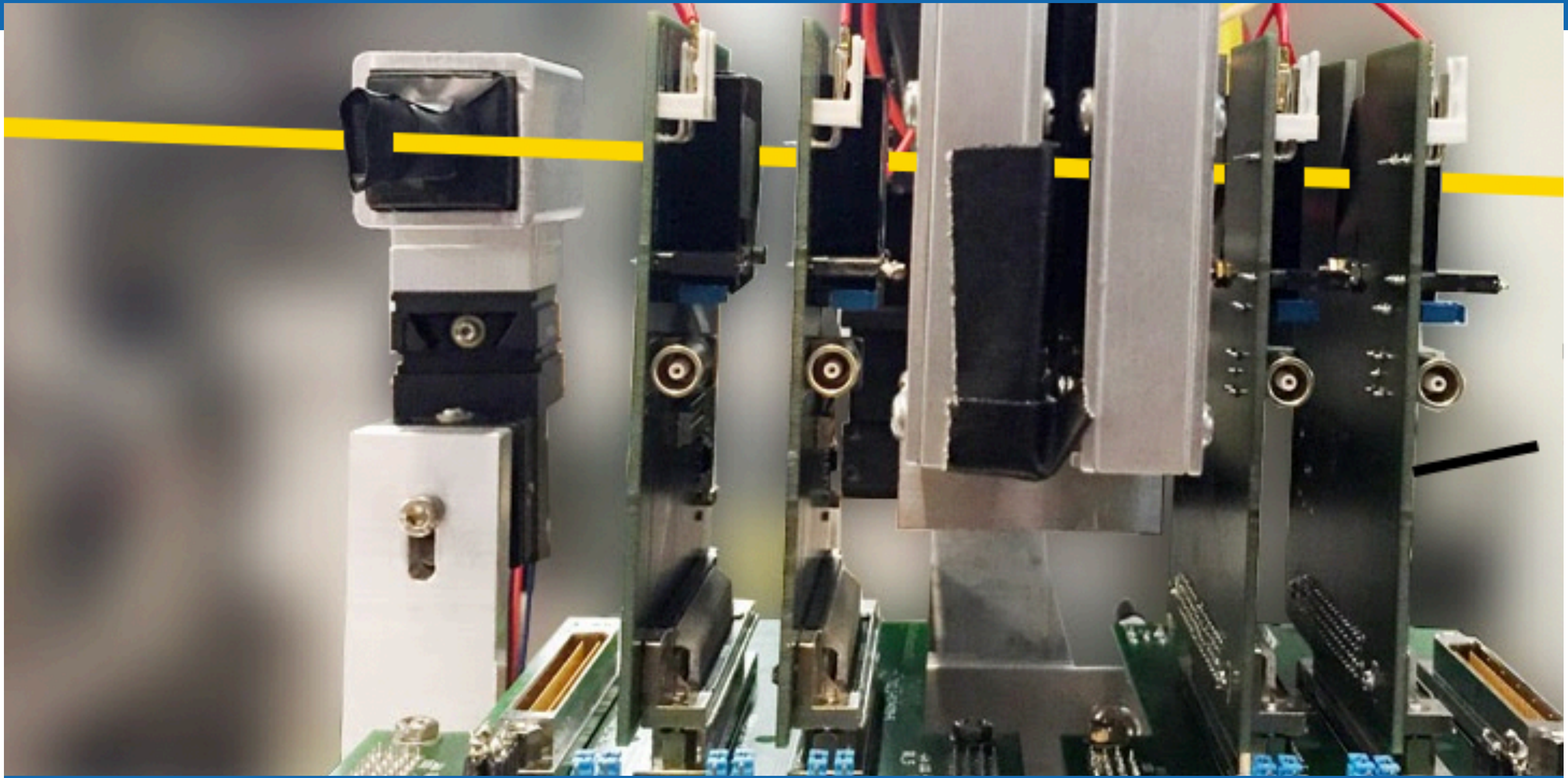
Single 3D Device

- pCVD diamond with one single 3D metalisation
  - Smaller cell size: 100 × 100 μm^2
  - More cells: 99 → 1188
  - Improved column production efficiency: 92 % → 99 %
- Collected **85 %** of charge





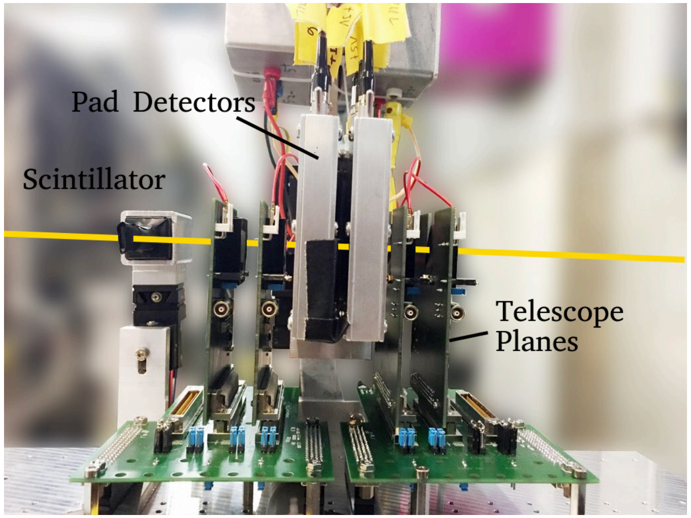




Rate Studies

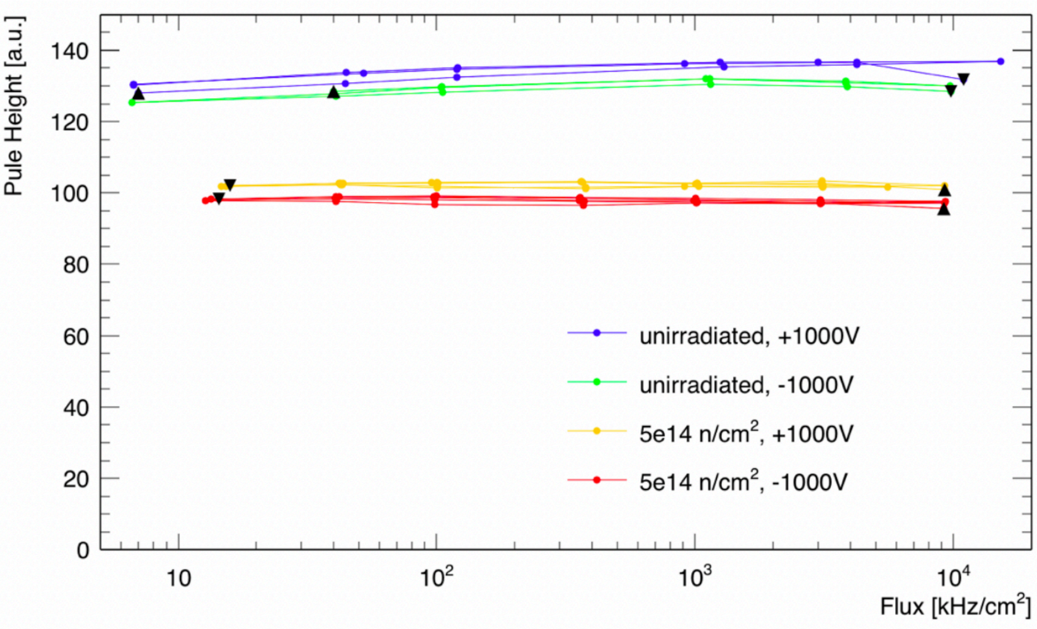
Setup

- Characterisation in 260 MeV π^+ beam at PSI with fluxes from $\mathcal{O}$(1 kHz/cm^2) to $\mathcal{O}$(10 MHz/cm^2)
- Telescope with 4 pixel planes
- pCVD diamond with pad electrodes
  - Unirradiated
  - Neutron irradiated (5 × 10^{14} /cm^2)



Rate Studies

- No rate dependence observed in pCVD diamond up to 10 MHz/cm^2
- Further test after several neutron fluences up to 2×10^{16} $/cm^2$



Conclusion

- Studied radiation damage up to fluences relevant for tracker application in HL-LHC experiments
- Ongoing analysis of signal shape of CVD diamond after irradiation
- Verified working 3D detector with pCVD diamond material
- Tested particle rate independence of CVD diamond detectors up to 10 MHz/cm^2