Latest Results on the Radiation Tolerance of Diamond Detectors

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The 2019 RD42 Collaboration

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113 participants

30 institutes

Introduction

RD42

Radiation bulk damage poses a major problem for semiconductor detector operation at future colliders (HL-LHC, FCC, …). Dominant contribution from pions/charged hadrons close to the IP and neutrons further out (r>30 cm).

Diamond has been looked at for a very long time as a replacement for Si and is in fact the only other material up to now used at LHC as semiconductor sensing material (beam monitors, telescopes):

- large **band gap** (5.5 eV) – large E_g/k_BT also means that (G-R) processes can be very slow and state of operation can depend on the history (similar to Si at cryogenic temperatures)
- **low leakage current -> low noise**
- lower signal (~1/2 of Si)
- **drift velocities** of e and h are larger (comparable) to silicon
- low **capacitance** -> low noise
- high **thermal conductivity** -> good heat spread
- very high resistivity – no need for junction

Is it more radiation hard than silicon – displacement energy is larger than for Si (42eV vs. 25 eV), but the defects that formed matter?

There is no general statement on that as it depends very much on application!

Production of the sensors

Production of material with Chemical Vapour Deposition Technique. Choice of right substrate (HTHP for scCVD, sapphire for pCVD) is important:

- sCVD: expensive and limited area (very pure, high CCD)
- pCVD: less expensive, larger growing area but more intrinsic charge traps

Thickness of typical diamond detectors ~400–1000 µm.

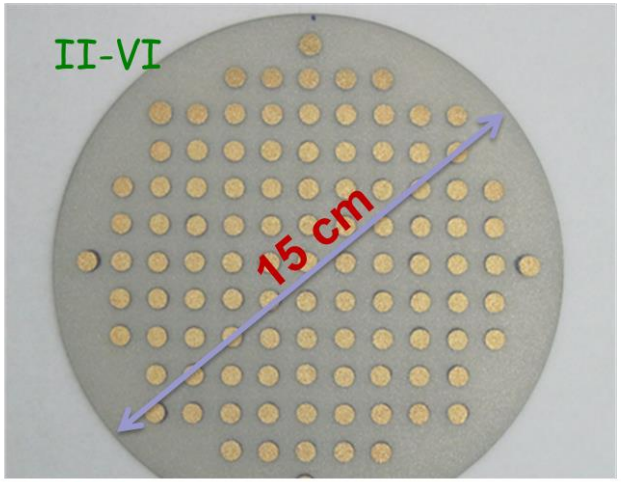
Metallization plays and important role for the detector operation (proprietary procedures):

- accumulation of charge underneath the electrodes
- resistivity of the electrode
- mechanical/chemical properties

Any kind of electrode is possible, in recent years also 3D diamond detectors – see talk from Harris Kagan.

Unlike silicon – diamond can be reused – metallized many times!

Unfortunately the number of producers is limited – at least those interested in diamond detectors



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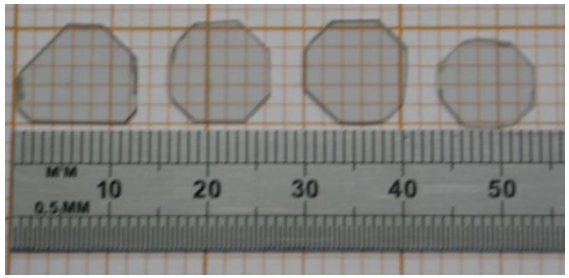
pCVD wafer

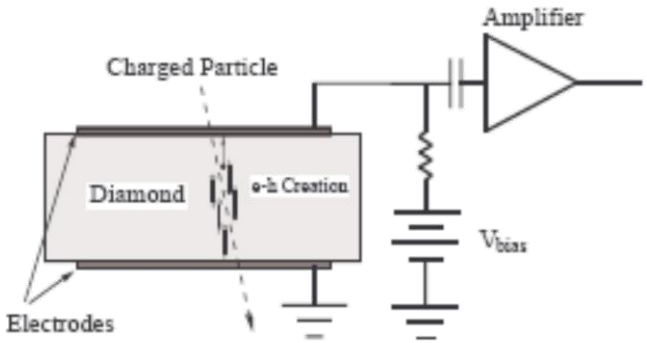


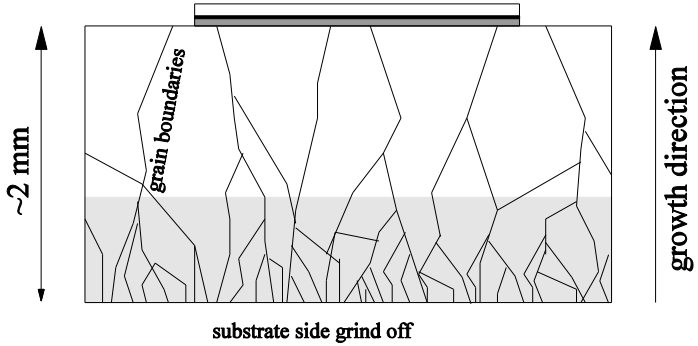
Single-crystalline CVD (courtesy of E6)

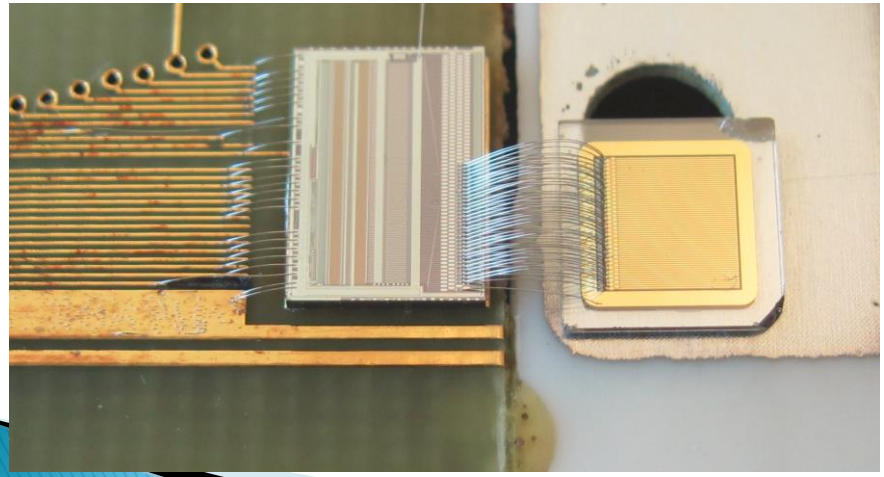
Diamond as particle detector

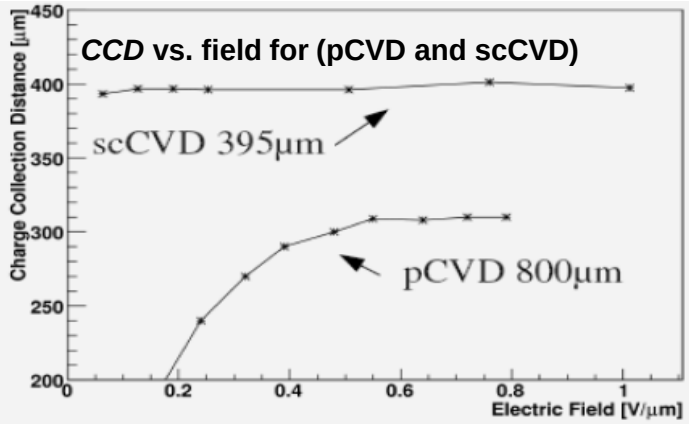
- Operation as any other semiconductor detector
- Trapping on grain boundaries (pCVD) and in bulk (scCVD and pCVD) determines most of the detector properties
- Historically the performance is parameterized with Charge Collection Distance

  $CCD = \langle Q_{col} \rangle / 36$ e-h/μm (for mip)-> average distance e-h pairs move apart
- In high quality scCVD CCD doesn't depend on E









G. Kramberger, HSTD12, Hiroshima 2019

Test beam measurements

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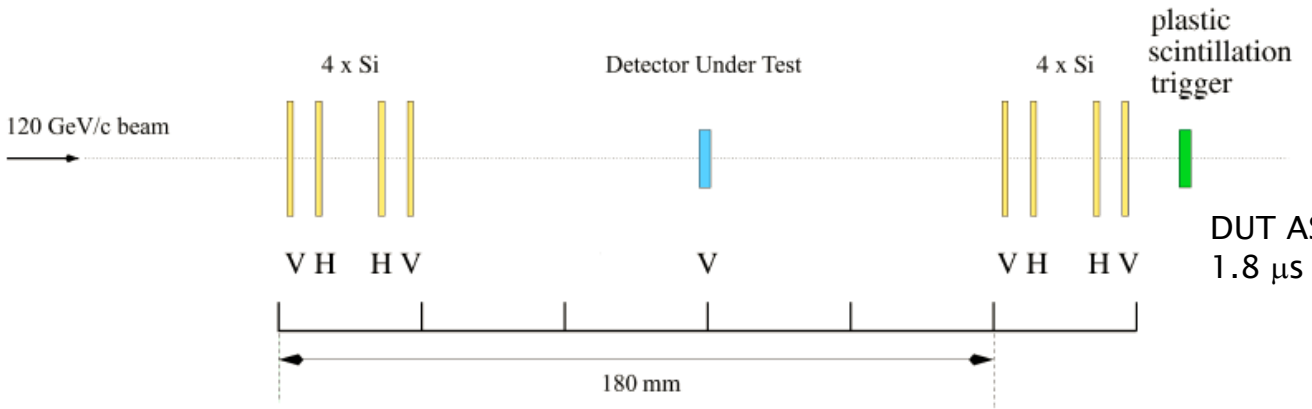
- irradiated diamond samples with various particle species and energies (5x5 mm^2 (scSVD) and 10x10 mm^2 (pCVD)
- metalized as strip detectors with 50 μm pitch
- characterization of irradiated devices in beam tests 120 GeV p,π at CERN
- transparent (unbiased;5 largest strips/10 strips ROI) hit prediction from telescope
- tracking precision at detector under test: ~ 2-3 μm



DUT ASIC – IDE AS VA2.2
1.8 μs shaping

- sensors pumped with ^{90}Sr source to fill lattice traps ("reset" the diamond)
- test of leakage current, $I < 10$ nA
- signal charge corrected for pedestal, noise, common mode noise
- signal calibration (ADC to electrons)
- measurement done with two polarities (at ± 1 V/μm and ± 2V/μm)

Radiation Damage Parameterization

- Radiation-induced traps decrease the mean free path
  $\lambda = \lambda_e + \lambda_h = v_e \tau_e + v_h \tau_h$

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

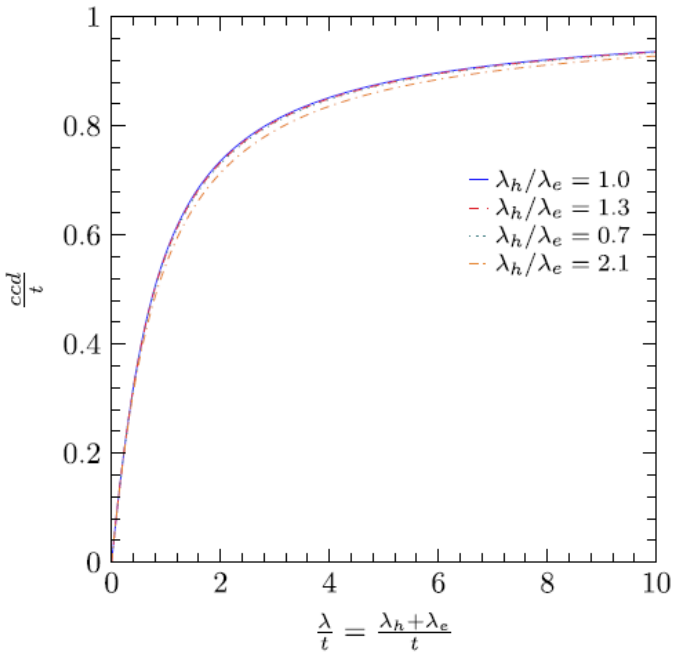
- Relation $CCD \leftrightarrow \lambda$ for homogeneous material

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

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

t	thickness
n	number of traps
n_0	initial traps in material
ϕ	fluence
λ	schubweg
λ_0	initial schubweg
k	damage constant

$CCD \sim \lambda$ for $t >> \lambda$



Measure CCD -> λ
λ (Φ) -> k and λ_0 from the fit of the model to the data

- due to lack of data we assume $\lambda_e = \lambda_h$, but for pad geometry it is quite robust
- Similar CCD for strip detectors after field reversal support the assumption, but more studies are needed

Fast charged hadrons

L Bäni et al 2019
J. Phys. D: Appl. Phys. 52 465103

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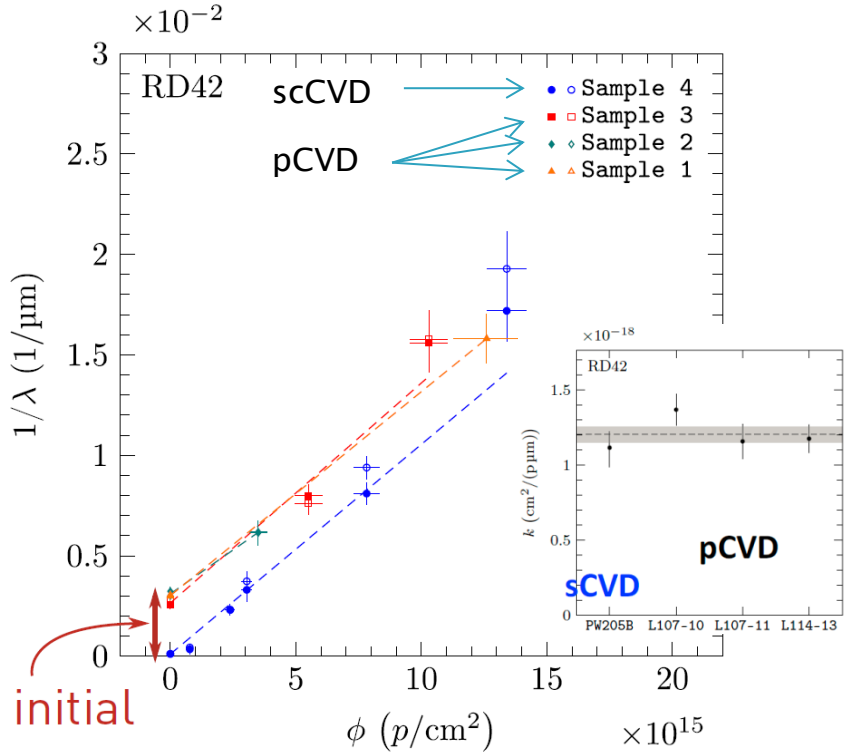
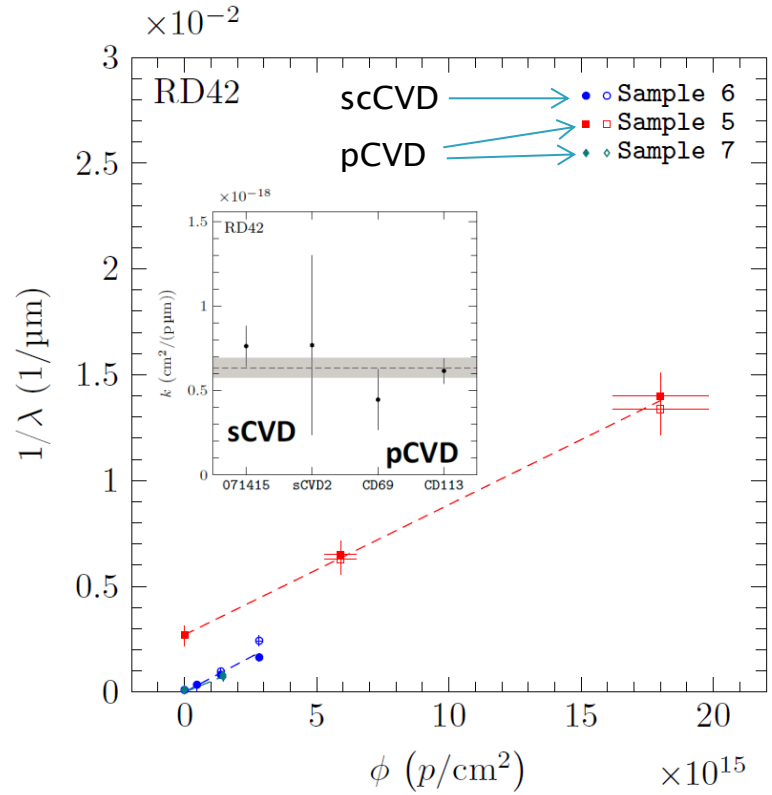
$k_{800\ MeV\ p} = 1.04$
± 0.02(stat.) ± 0.05 (syst.) 10^{-18} cm2 / (p µm)

$k_{24\ GeV\ p} = 0.62$
± 0.01 (stat.) ± 0.06 (syst.) $\cdot 10^{-18}$ cm2 / (p µm)



due to initial traps in poly

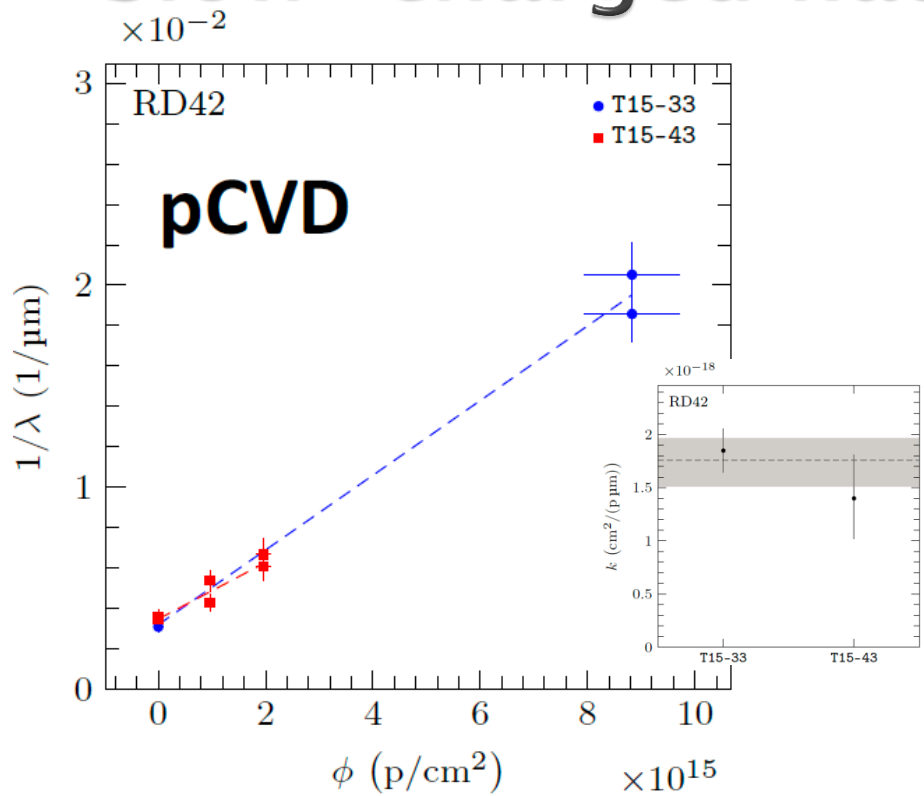
800 MeV proton

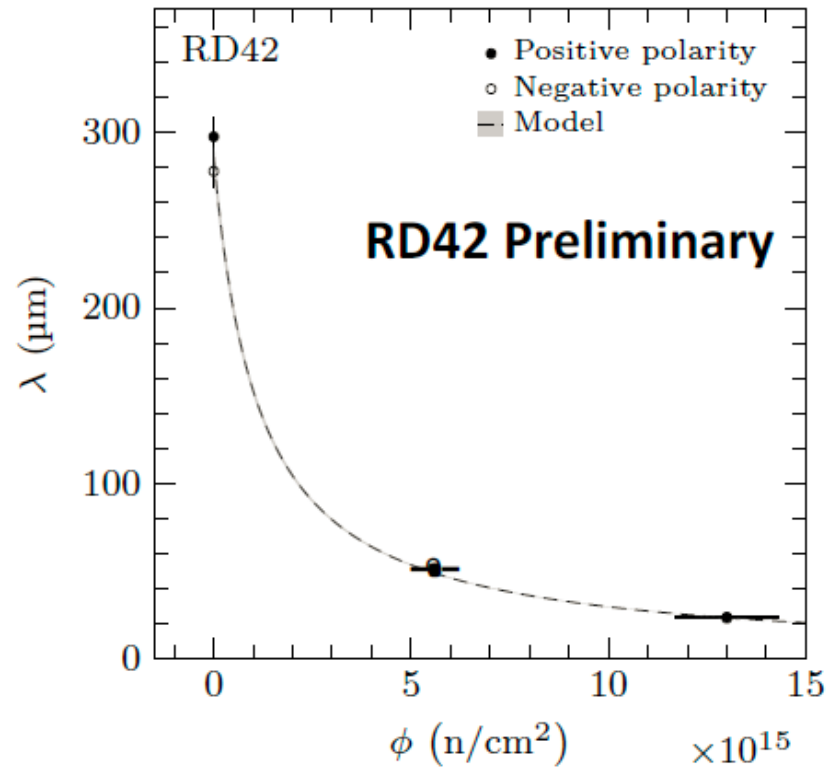


24 GeV proton

- Single *k* used in fits to all the data points – pCVD data are simply offset for the initial traps in the material

"Slow" charged hadrons and neutrons





$k_{70\ MeV\ p} = 1.76$
$\pm$ 0.10 (stat.) $^{+0.18}_{-0.23}$ (syst.) $\cdot 10^{-18}$ cm^2 / (p μm)

$k_{fast\ n} = 3.05$
$\pm$ 0.23 (stat.) $\pm$ 0.14 (syst.) $\cdot 10^{-18}$ cm2 / (n μm)

Measurements done in the past also with 26 MeV p (KIT) – less accurate:
$k_{26\ MeV\ p} \sim 2.6 \cdot 10^{-18}$ cm^2/(p μm) for pCVD
Measurements done in the past with 200 MeV pions
$k_{200\ MeV\ \pi} \sim 2 \cdot 10^{-18}$ cm^2/(π μm) for pCVD

Summary of radiation damage results

RD42

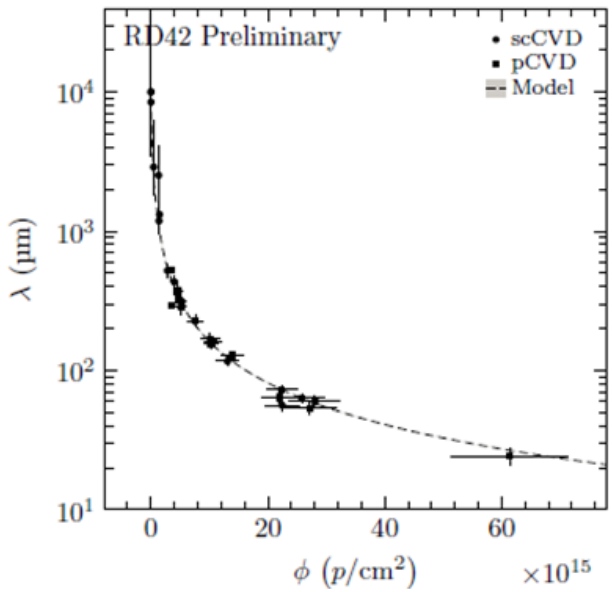
- pCVD and scCVD undergo the same degradation of performance with fluence – k_i is the same
- Initial $\lambda_{0,i}$ can be seen as shift in the fluence $\Phi_{0,i}$
- equivalent fluence defined with respect to 24 GeV p instead of 1 MeV neutrons

– Shift pCVD sample by

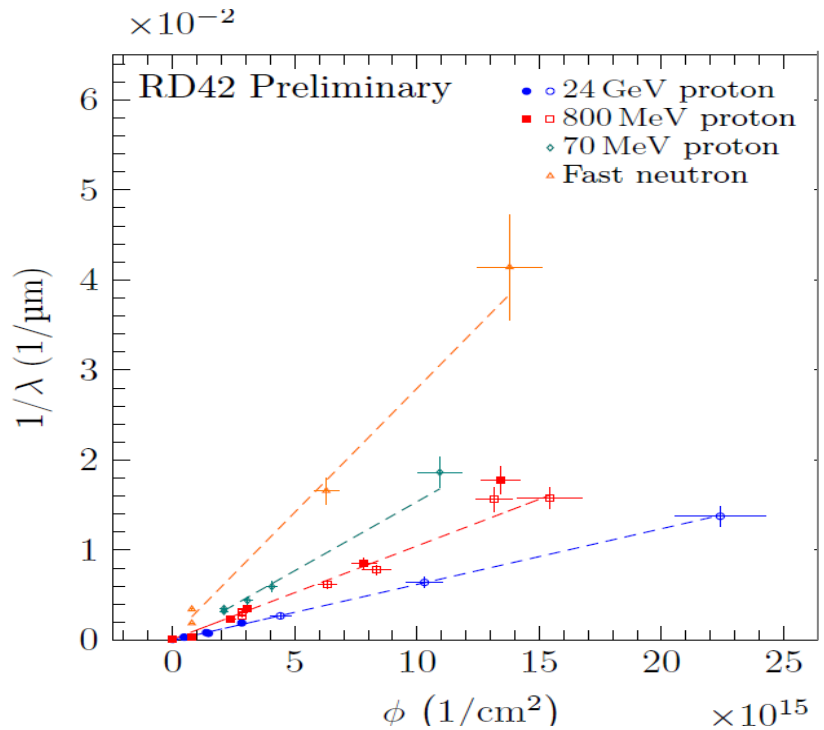
$$\phi_{0,i} = \frac{1}{\lambda_{0,i} k_i}$$

– Scale fluence by relative k

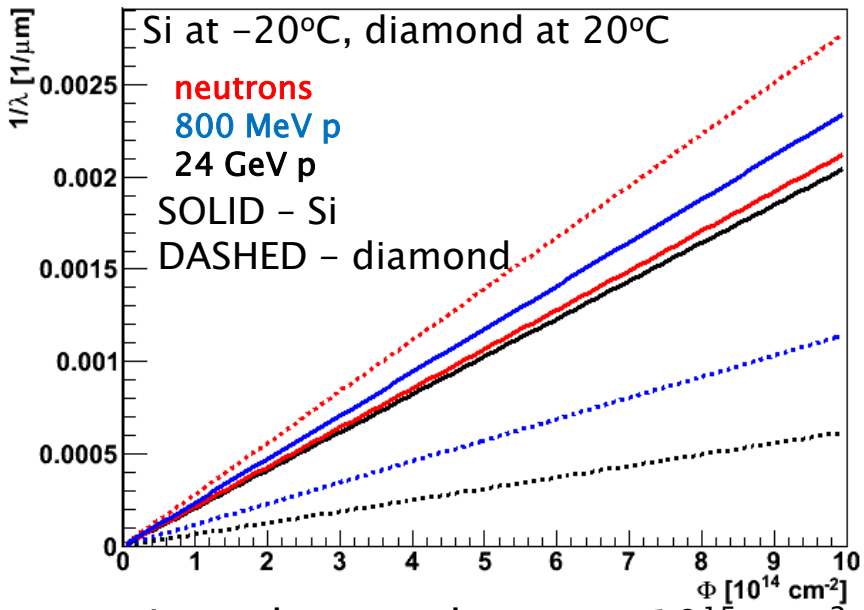
$$\phi_{\text{eq.}} = \frac{k_i}{k_{\text{24 GeV protons}}} \times \phi_i$$

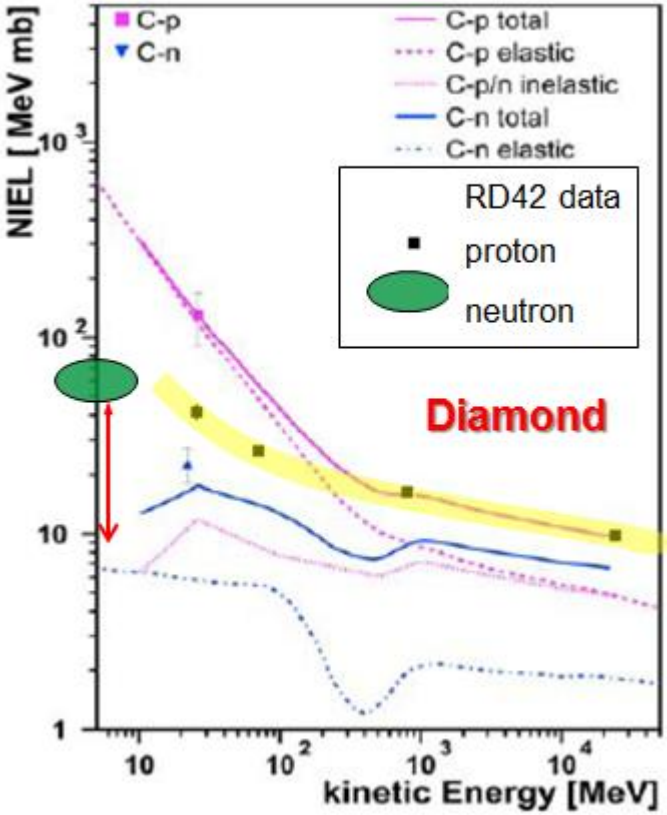


Particle species	κ
24 GeV protons	1.0
800 MeV protons	1.67 ± 0.09
70 MeV protons	2.48 ± 0.25
Fast neutrons	4.5 ± 0.4



Comparison with silicon



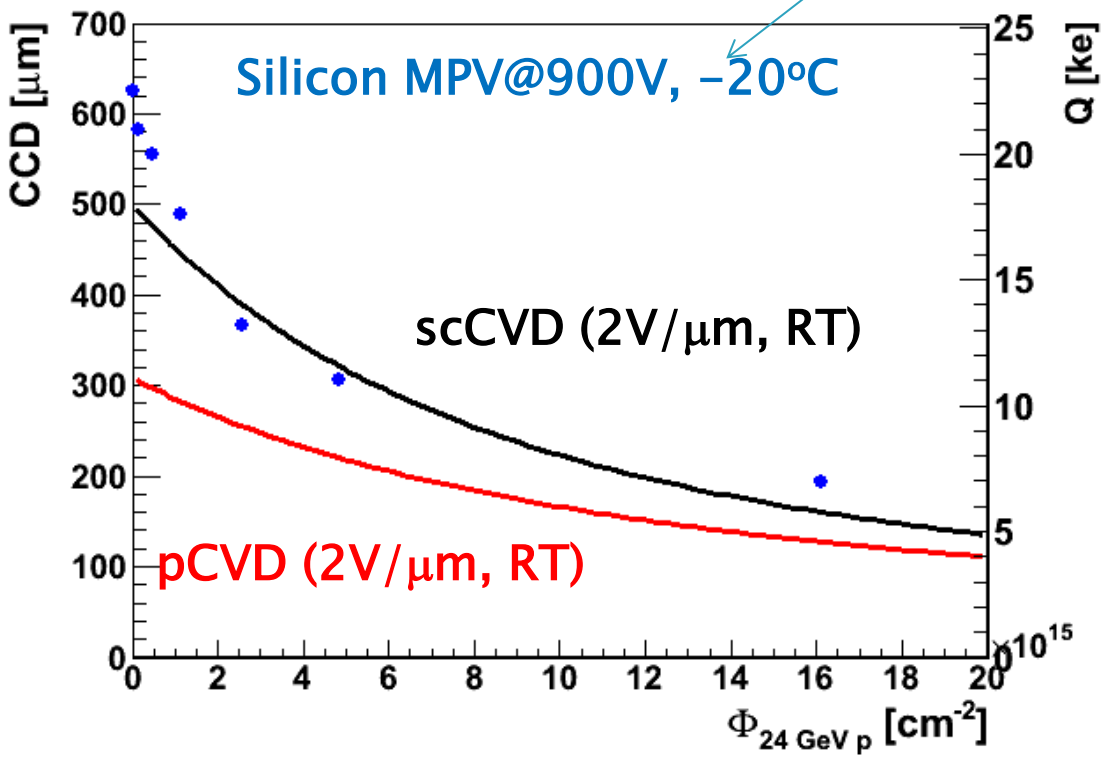


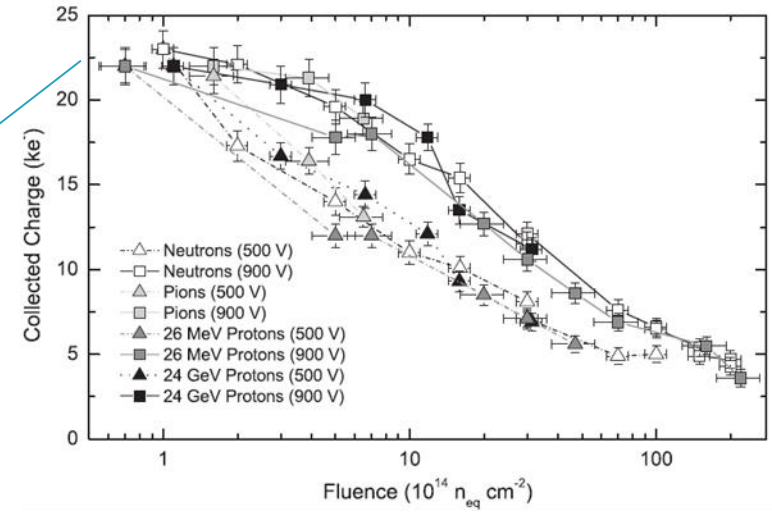
- comparison shown only up to ~10^{15} cm^{-2} –> reliable trapping time data from RD50
- detectors can be depleted with <E>=2V/μm (oxygen rich silicon material)
- In terms of λ diamond is better than silicon for charged hadrons and worse for neutrons
- In silicon the MFP starts exhibit saturation with fluence; seems not in diamond not for the investigated fluence range

Damage doesn't follow NIEL calculations.

How much charge can we expect?

- Less signal at all fluences of interest in diamond, but also less noise
- roughly around 3000 e is required for good efficiency (ok for 24 GeV p, on the limit for PSI π)





Si data:
T. Affolder et al., NIMA 623 (2010) 177.
I. Mandic et al., NIMA 603 (2009) 263.

Don't forget diamond has other advantages over silicon.

~2 GeV pions should be similar to 24 GeV protons

Spectra analysis

Nonhomogeneous collection over the surface – widening of the spectrum

pCVD samples

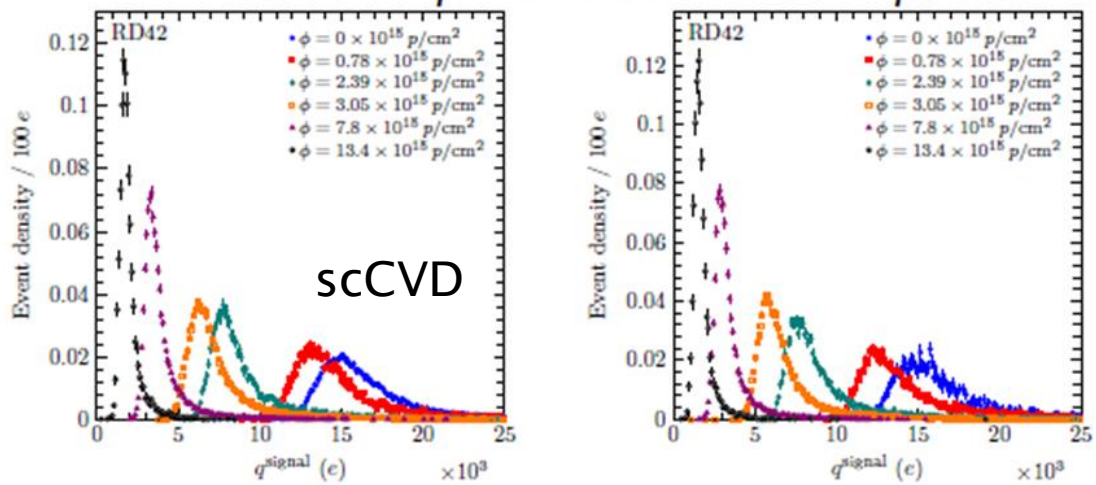
- *FWHM/MP* decreases with fluence

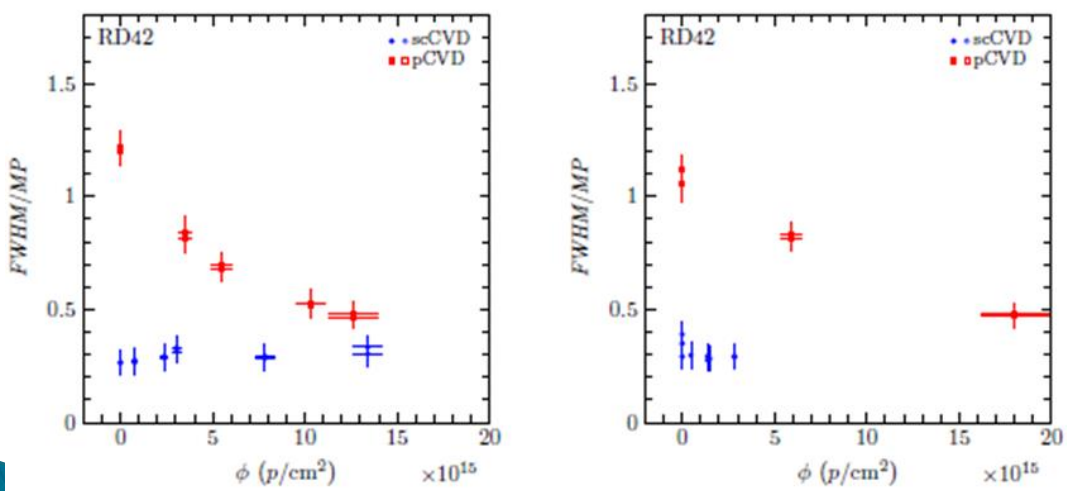
sCVD samples

- Smaller initial *FWHM/MP*
- *FWHM/MP* is flat with dose

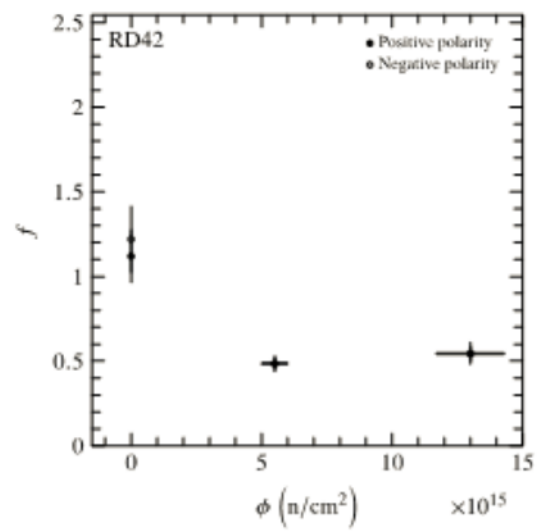
Determines the required threshold on readout chip – long tails!

800 MeV p: 0–13.4 × 10^{15} p/cm^2





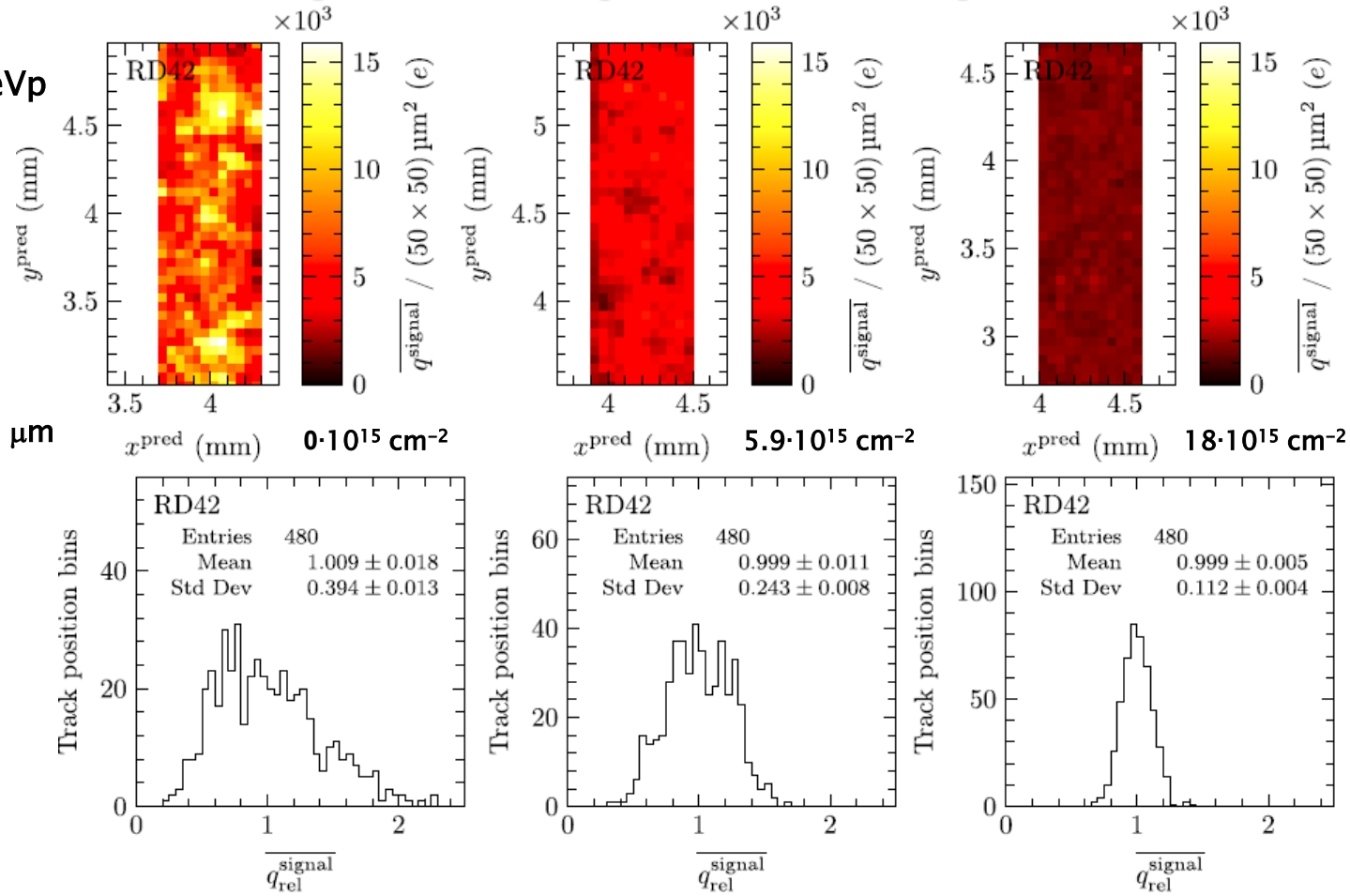
800 MeV p 24 GeV p



reactor neutrons

Uniformity of response in pixel sensor

Φ_{24GeVp}



CCD_0=239 μm

$0 \cdot 10^{15}$ cm^{-2} $5.9 \cdot 10^{15}$ cm^{-2} $18 \cdot 10^{15}$ cm^{-2}

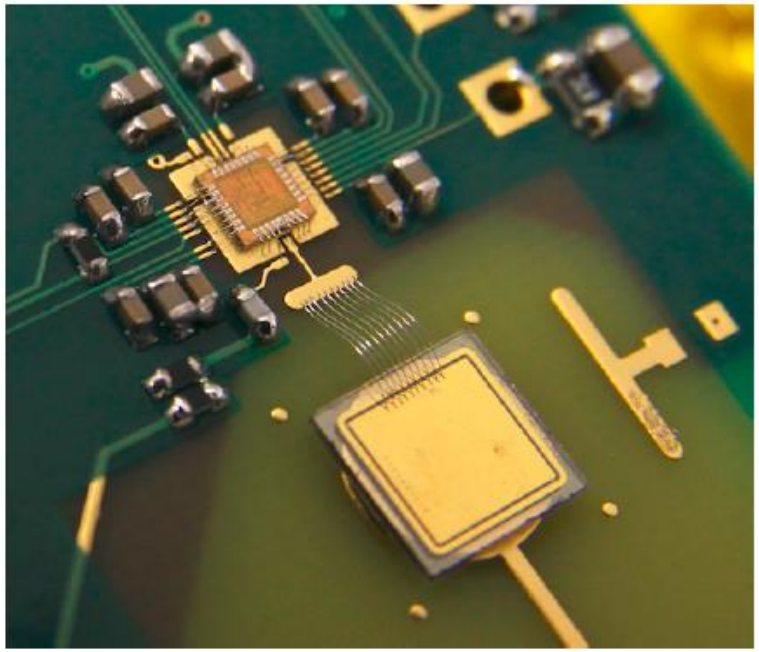
- *FWHM/MP* is a measure of the uniformity of the material
- Observe regions of different signal (λ) in un-irradiated poly-crystalline diamond
- Derivative of damage equation:

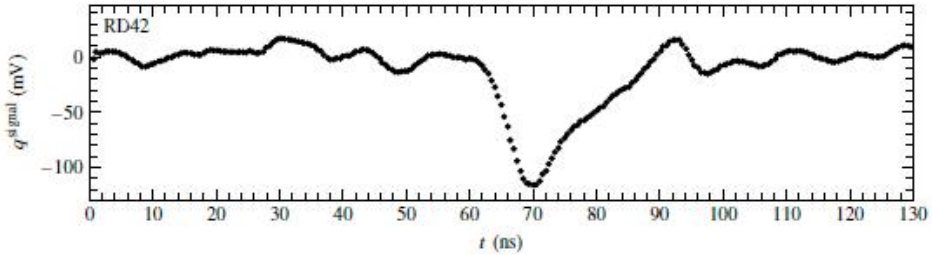
  $d\lambda/d\Phi = -k\lambda^2$ → portions of material with the largest λ have faster decrease

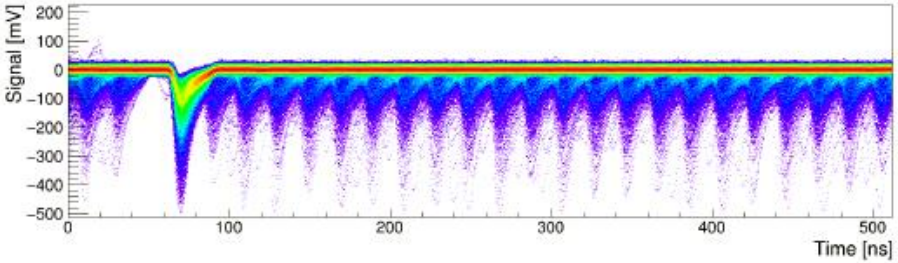
Rate effects

Study the pulse height dependence on the particle flux

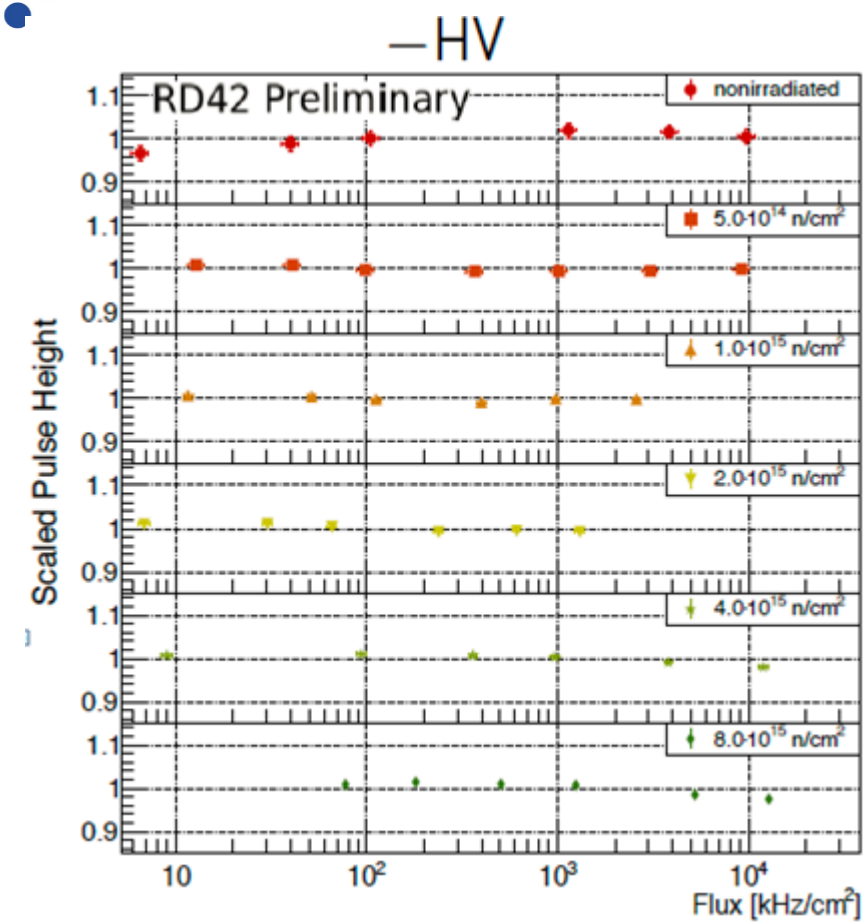
- Characterization in 260 MeV π^+ beam at PSI
- 5 years ago published rates up to 300 kHz/cm^2
- 4 years ago with new electronics, rates up to 10–20 MHz/cm^2
- Recently measured rate after fluences up to 8 $\times 10^{15}$ n/cm^2
- Pad detectors tested in ETH (CMS Pixel) telescope

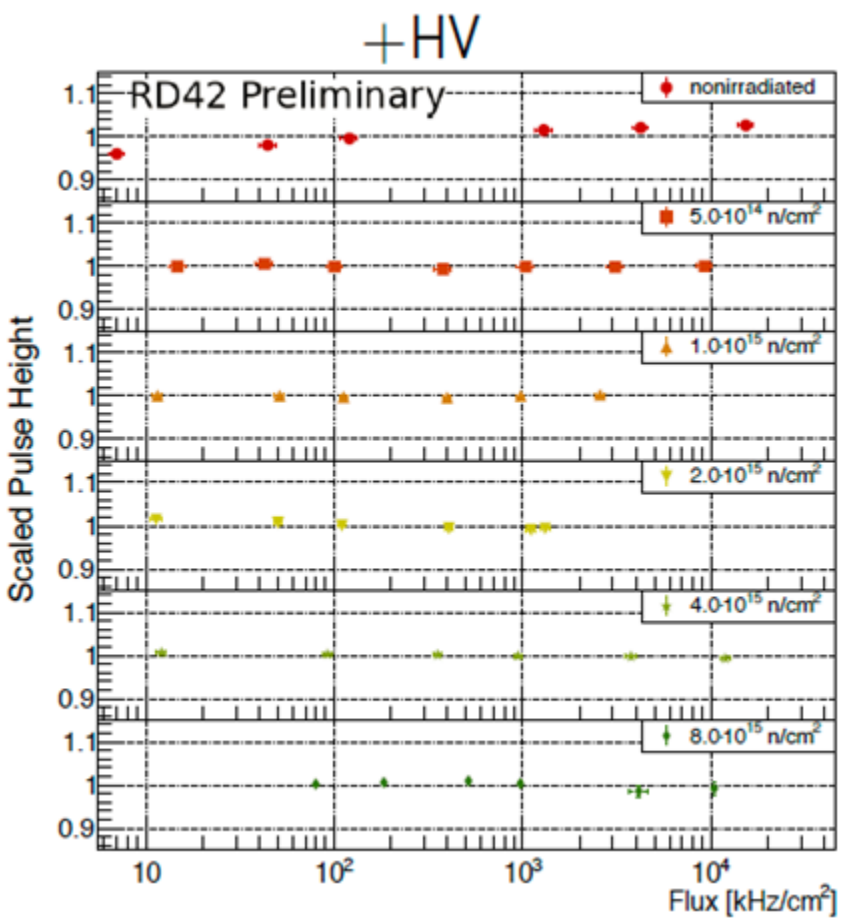






19.8 ns bunch spacing clearly visible





- 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
- Rate effects observed are very likely related to surface effects (cleaning and remetalizing of the surface cures the problem)

Conclusions

Quantified understanding of radiation effects

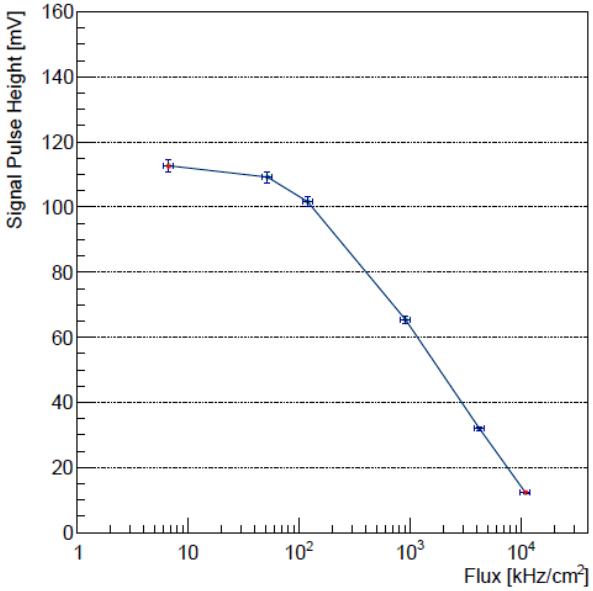
- radiation damage up to fluences relevant for tracker application in HL-LHC experiments
- analysed signal uniformity of single- and poly-crystalline CVD diamond after irradiation

The decrease of the mean free path doesn't follow NIEL.

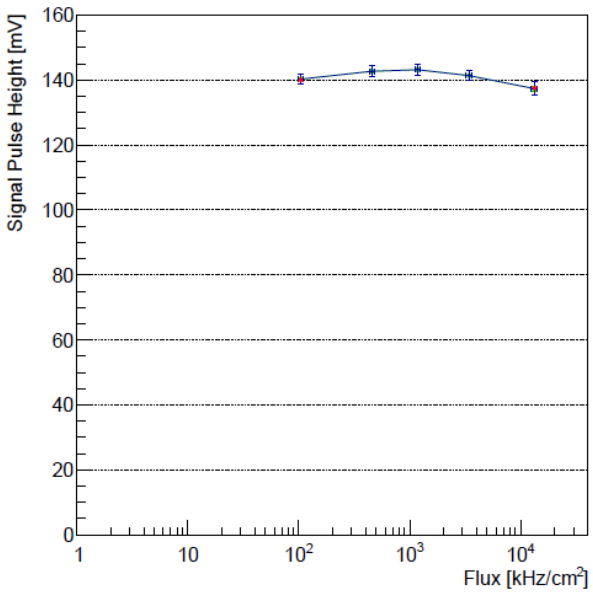
Quantified understanding of rate effects @2 V/µm

- 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

Repair of Rate Dependence



(a) First measurement



(b) After reprocessing

- Very large rate dependence of PH for some diamonds at first measurement (>90%)
- After reprocessing and surface cleaning with RIE, very stable behavior (2%)
- This is clearly a surface issue
- Feasible to “fix” some fraction of diamonds with rate dependent PH
- Less than 20% of the diamonds show rate dependence >10%