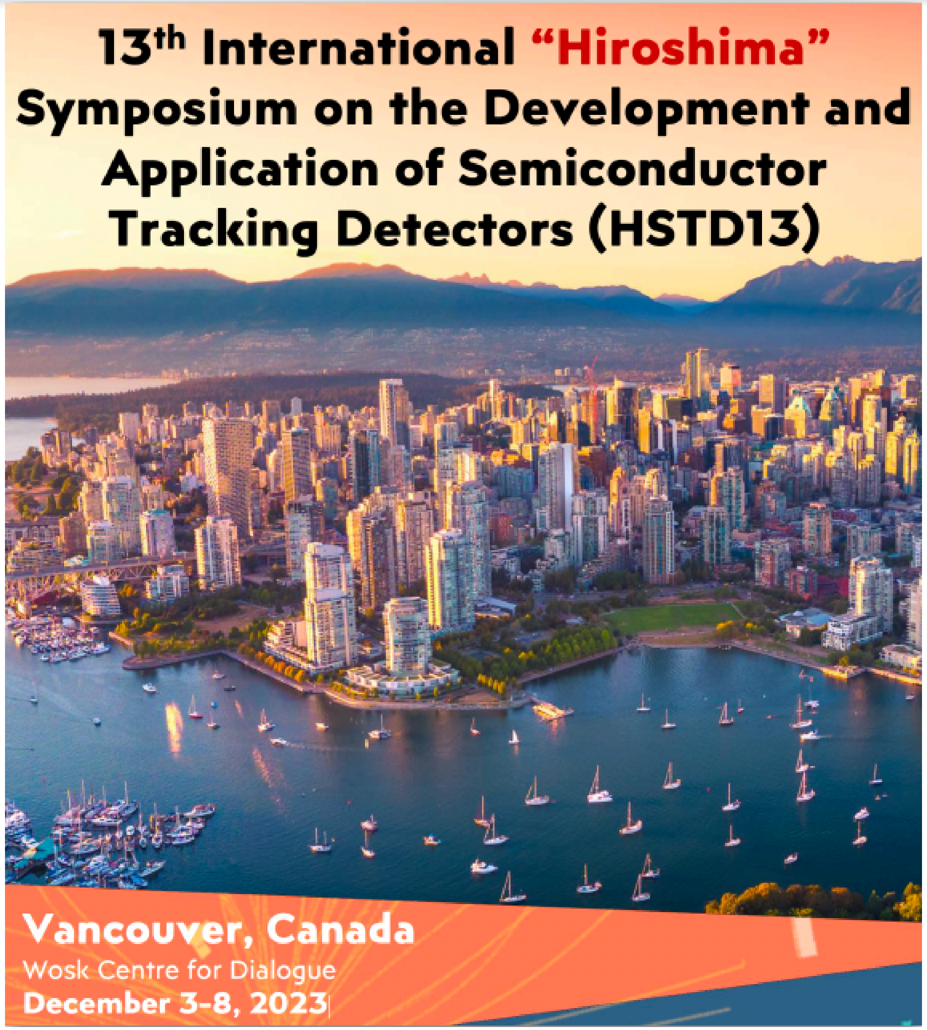
Recent Results from Diamond Detectors

Harris Kagan

Ohio State University

On behalf of the RD42 Collaboration

The help of my RD42 colleagues is gratefully acknowledged



RD42 Collaboration (2023)

The 2023 RD42 Collaboration

M. Artuso[16], L. Bäni[20], M. Bartosik[3], V. Bellini[2], B. Bentele[15], P. Bergonzo[27], A. Bes[23], J-M. Brom[6], G. Chiodini[22], D. Chren[14], V. Cindro[8], G. Claus[6], J. Collot[23], J. Cumalat[15], A. Dabrowski[3], D. Dauvergne[23], S. Ditalia Tchernij[11], G. Eigen[26], V. Eremin[5], P. Everaere[23], J. Forneris[11], L. Gallin-Martel[23], M-L. Gallin-Martel[23], K.K. Gan[9], M. Gastal[3], A. Gentry[17], M. Goffe[6], J. Goldstein[13], A. Golubev[7], A. Gorišek[8], E. Grigoriev[7], J. Grosse-Knetter[19], B. Hiti[8], D. Hits[20], C. Hoarau[23], M. Hoeferkamp[17], J. Hosselet[6], F. Hügging[1], C. Hutson[13], R. Jackman[27], R. Jennings-Moors[27], H. Kagan[9,◊], K. Kanxheri[24], M. Kis[4], G. Kramberger[8], M. Kruger[28], S. Kuleshov[7], A. Lacoste[23], E. Lukosi[21], C. Maazouzi[6], M. Mali[8], I. Mandić[8], S. Marcatili[23], A. Marino[15], C. Mathieu[6], M. Menichelli[24], M. Mikuž[8], R. Molle[23], A. Morozzi[24], F. Moscatelli[24], J. Moss[25], R. Mountain[16], J-F. Muraz[23], E.A. Narazyanan[17], A. Oh[18], P. Olivero[11], D. Passeri[24], H. Pernegger[3], R. Perrino[22], F. Picollo[11], A. Porter[18], A. Portier[23], R. Potenza[2], A. Quadt[19], F. Rarbi[23], A. Re[11], M. Reichmann[20], S. Roe[3], O. Rossetto[23], P. Salter[28], D.A. Sanz Becerra[20], C. Schmidt[4], S. Schnetzer[10], S. Seidel[17], L. Servoli[24], R. Shivaraman[28], S. Smith[9], B. Sopko[14], V. Sopko[14], J. Sorenson[17], S. Spagnolo[22], S. Spanier[21], K. Stenson[15], R. Stone[10], B. Stugu[26], C. Sutera[2], M. Traeger[4], W. Trischuk[12,◊], M. Truccato[11], C. Tuve[2], J. Velthuis[13], E. Verbitskaya[5], S. Wagner[15], R. Wallny[20], J. Welch[27], T. Wengler[3], M. Yamouni[23], J. Zalieckas[26], M. Zavrtanik[8]

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Outline

Outline

- Diamond as a radiation detector
- 3D diamond pixel detectors
  - → Concept and motivation
  - → Results
- Rate Dependence of pCVD diamonds
- Conclusions and Outlook

Nucl. Instr. Meth. A **786** 97 (2015)

ETH Thesis 28688 (2023)
Micha Reichmann

https://rd42.web.cern.ch/rd42/publications/publications.html

Backup Slides

- Summary of RD42 radiation tolerance results

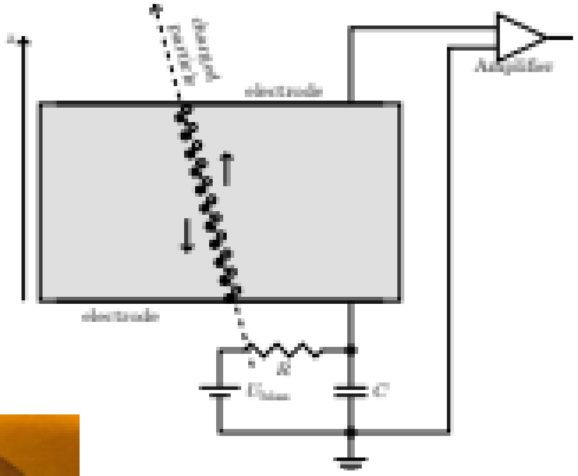
J. Phys. D: Appl. Phys. **52** 465103 (2019)

Sensors **20** 6648 (2020)

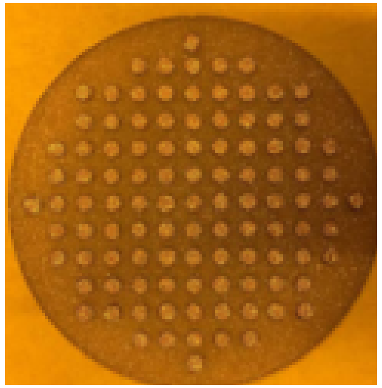
Diamond as a radiation detector

- Diamond detectors are operated as ionization chambers
  - 1 electron-hole pair generated per 13 eV ionizing energy loss
  - On average 36 electron-hole pairs per µm per MIP
  - Large (5.47 eV) bandgap ensures no thermal carriers

Working principle



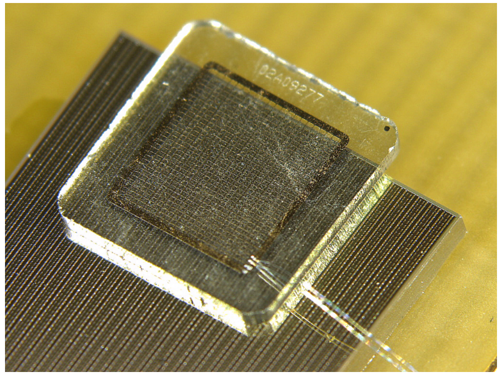
- Poly-crystalline material comes in large wafers
  - Wafers are grown 2-3x the final part thickness
  - Parts are cut out with a laser
  - Parts are thinned from the substrate side to the final thickness
  - RIE/ICP performed on both surfaces of all parts (critical)
  - Collection distance ~300 µm can be achieved on finished parts
  - Single-crystal sensors still confined to 4.5 mm x 4.5 mm size



15 cm diameter pCVD diamond wafer

- Devices can be made in any configuration
  - Pad, Strip, Pixel, 3D

3D pCVD diamond sensor with pixel readout

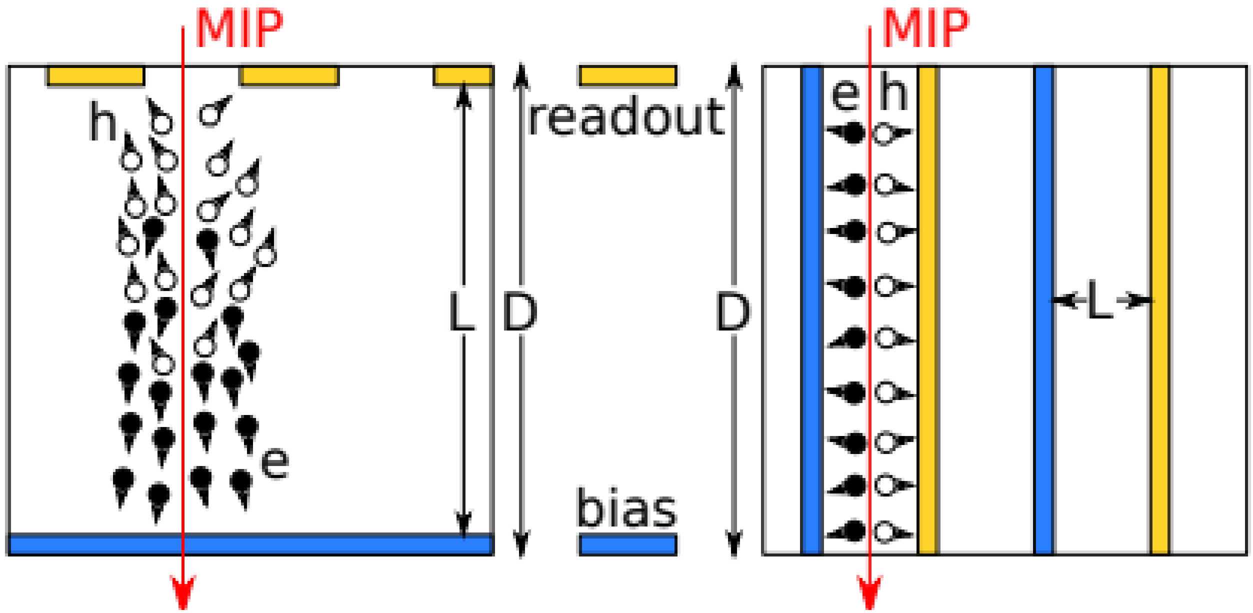


3D Diamond
Pixel Detectors

Principle of a 3D detector

Parker et al., NIM A395 (1997)

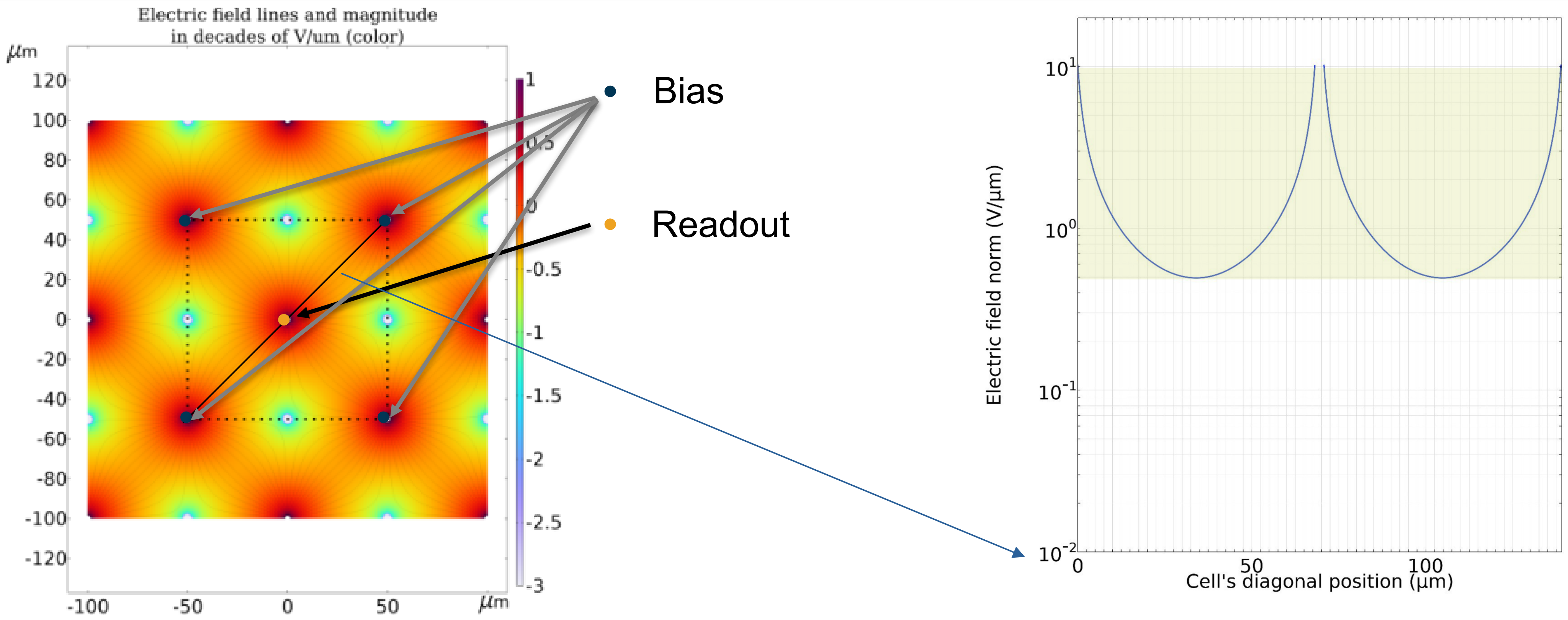
Planar



3D

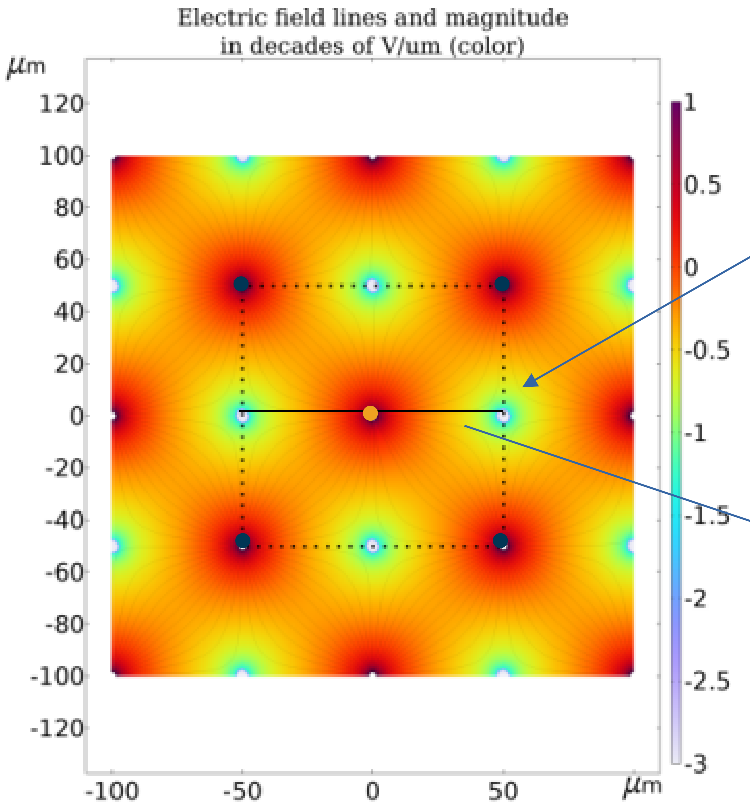
- After large radiation fluence all detectors become trap limited
  - mean drift distance in diamond ~26 μm after 10^{16} n/cm^2
- In 3D detectors: bias and readout electrodes are inside the bulk detector material
- Same thickness D → same amount of generated charge but 3D has shorter drift distance L
  - 18 μm between the columns of a 25 μm x 25 μm cell
- In 3D detectors, collected charge is larger when drift distance < limited mean drift distance
  - However, low field regions are introduced

Principle of 3D detector

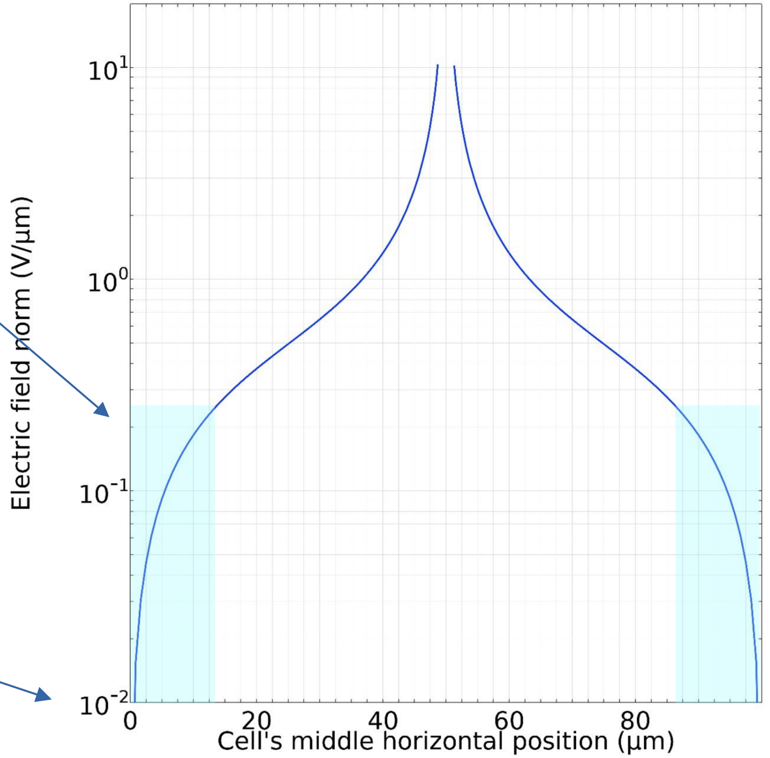


- Simulation with 90 V bias voltage and periodic boundary conditions
  - 100 μm x 100 μm cell
- Electric field between ~0.5 – 10 V/μm along the diagonal line

Principle of 3D detector

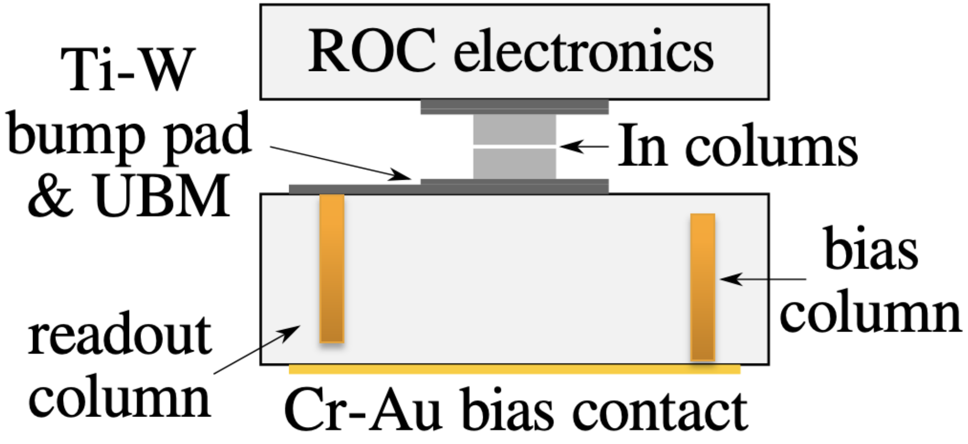


Low Field Region



- Simulation with 90 V bias voltage and periodic boundary conditions
  - 100 μm x 100 μm cell
- Electric field between ~0.01 – 10 V/μm along the horizontal line
  - Low field region (<0.25 V/μm) in between the electrodes and sizable (>25%)

3D diamond pixel detectors

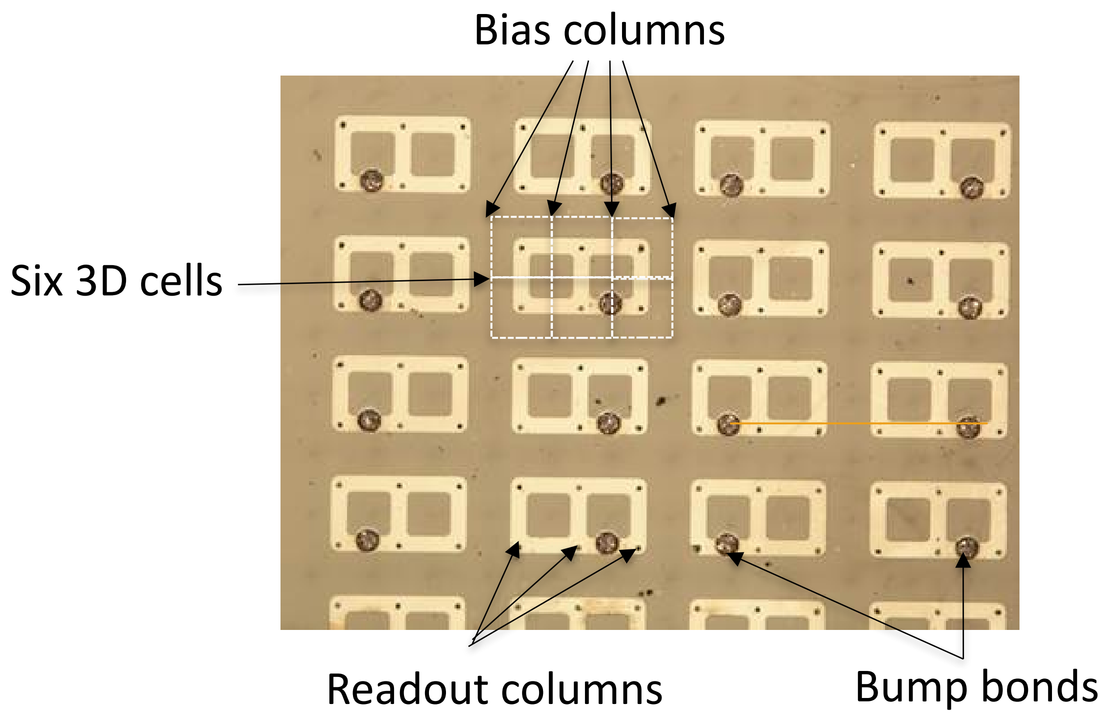


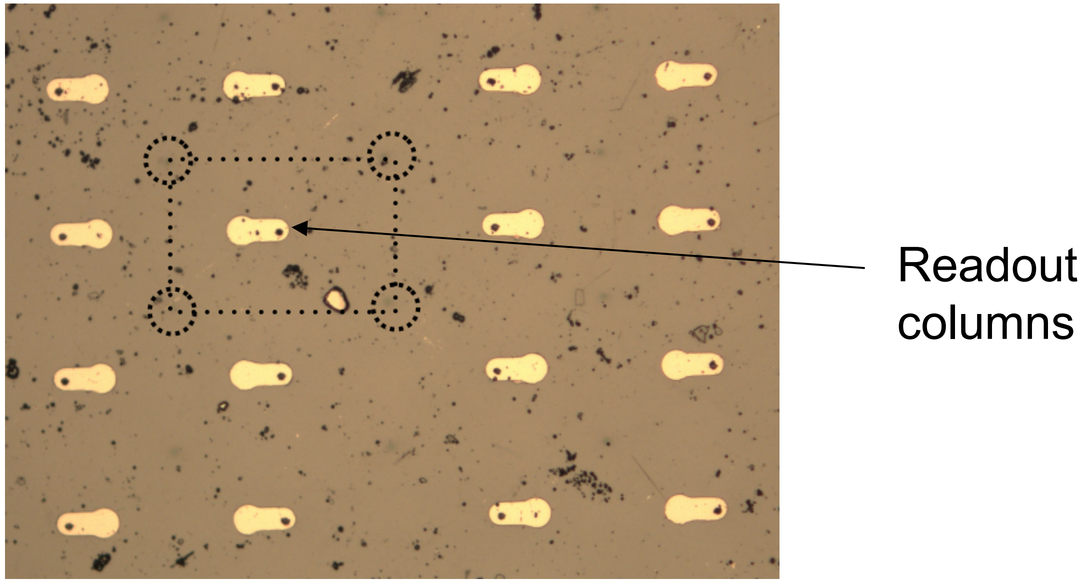
Two prototypes were built:

- One with 50 µm x 50 µm cells and one with 100 µm x 150 µm cells
- Bump bonding to CMS chip (PSI46dig2) at Princeton (Indium without reflow)
- Both readout and bias columns have a small gap (~15 µm) to the opposite surface
- Column diameter 2.6 µm (50 µm x 50 µm)
- Laser drilling efficiency 99.7%

3D diamond pixel detectors

Connection to readout columns with surface metallization





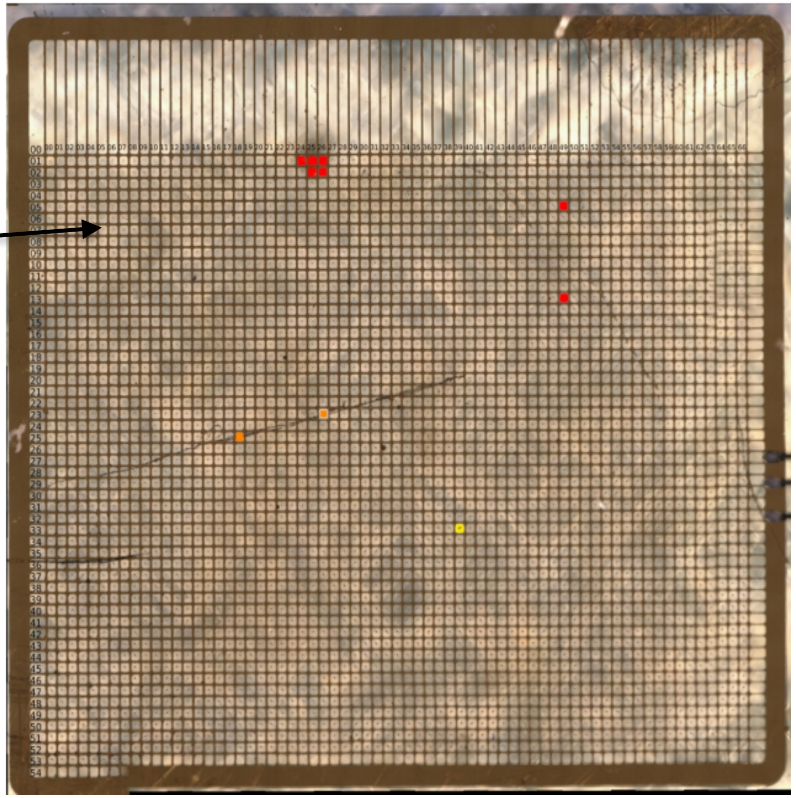
50 µm x 50 µm cells
Readout side
6 cells ganged to match the readout pitch

100 µm x 150 µm cells
Readout Side

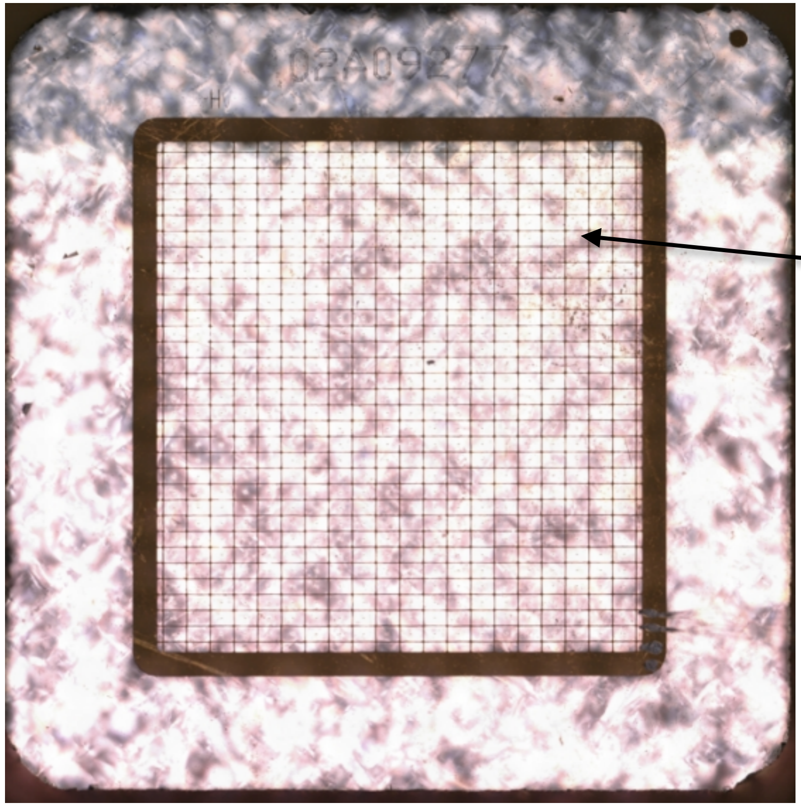
3D diamond pixel detectors

Connection to bias columns with surface metallization

Bias grid



50 µm x 50 µm cells
Bias side

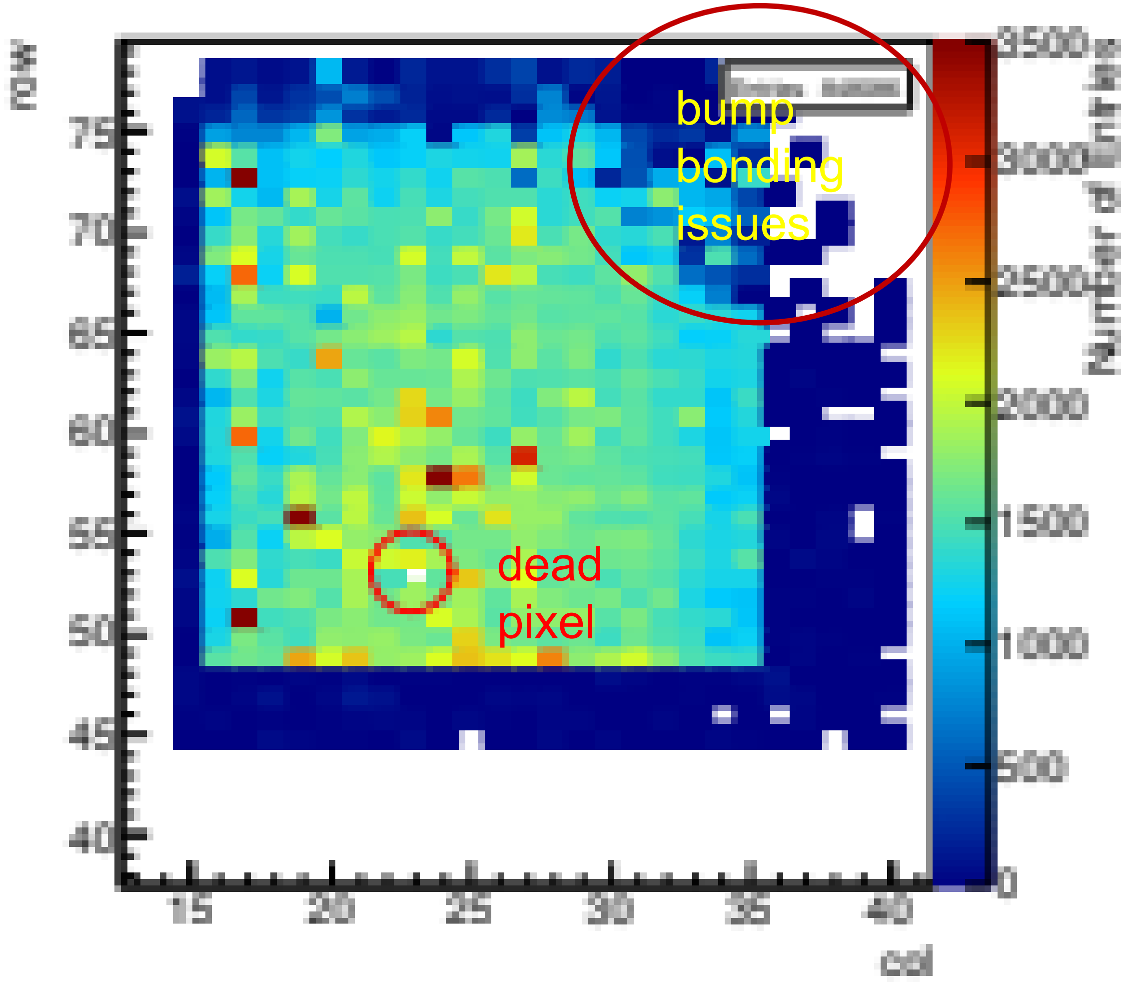


Bias grid

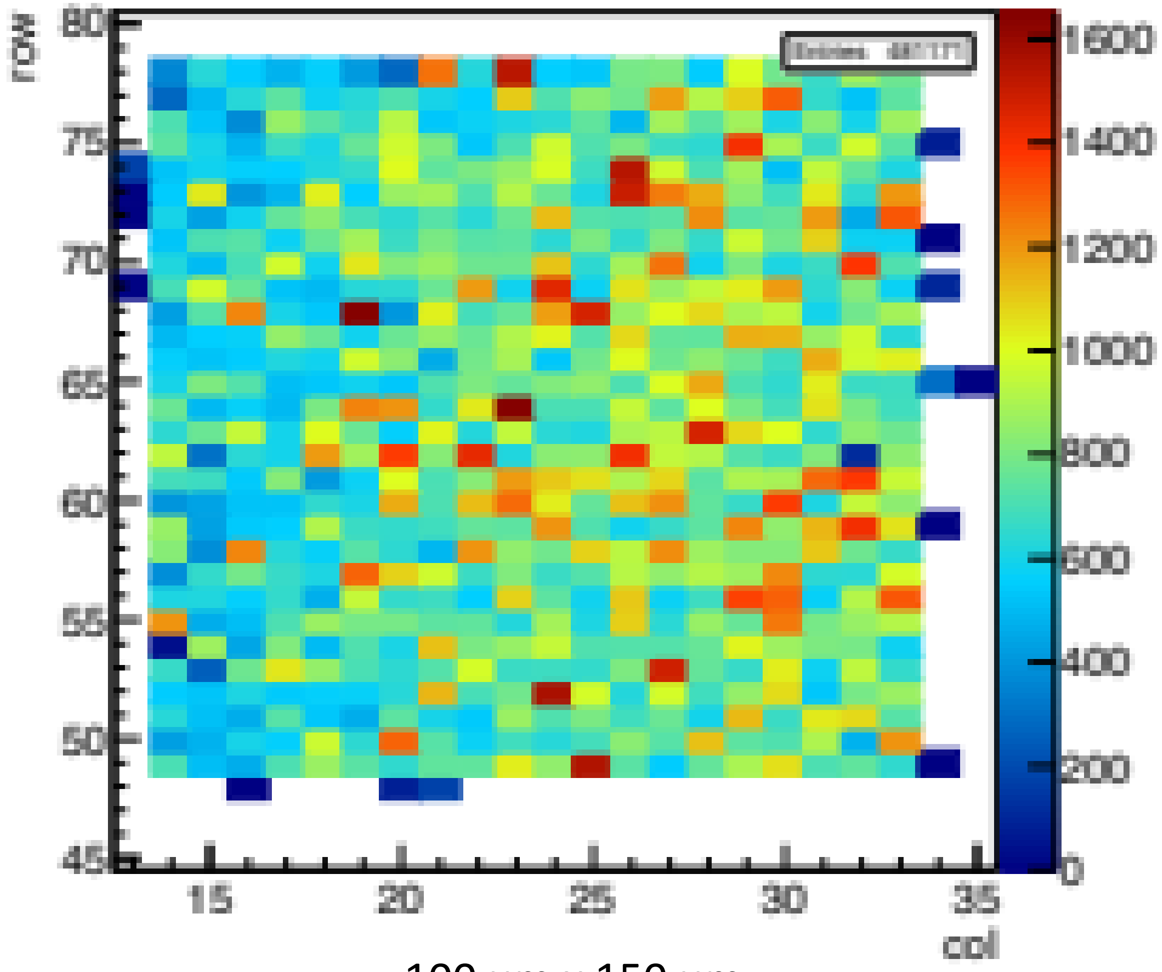
100 µm x 150 µm cells
Bias Side

Hit Occupancy

PSI Testbeam



50 µm x 50 µm

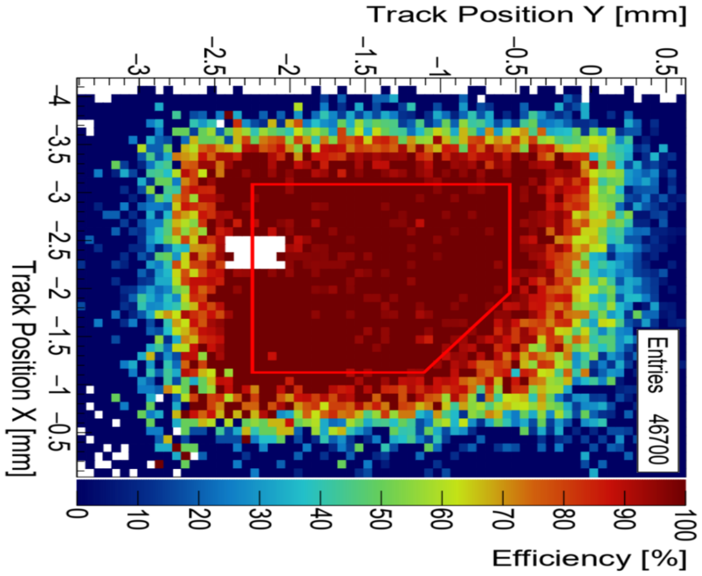


100 µm x 150 µm

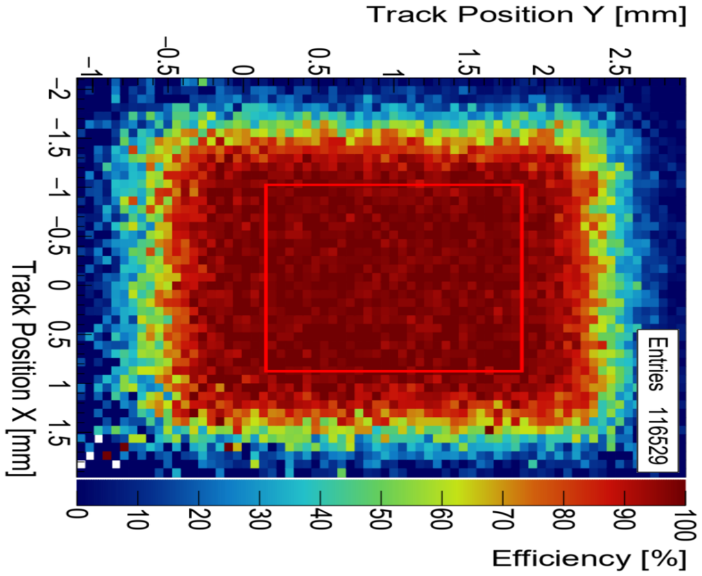
Efficiency

PSI Testbeam

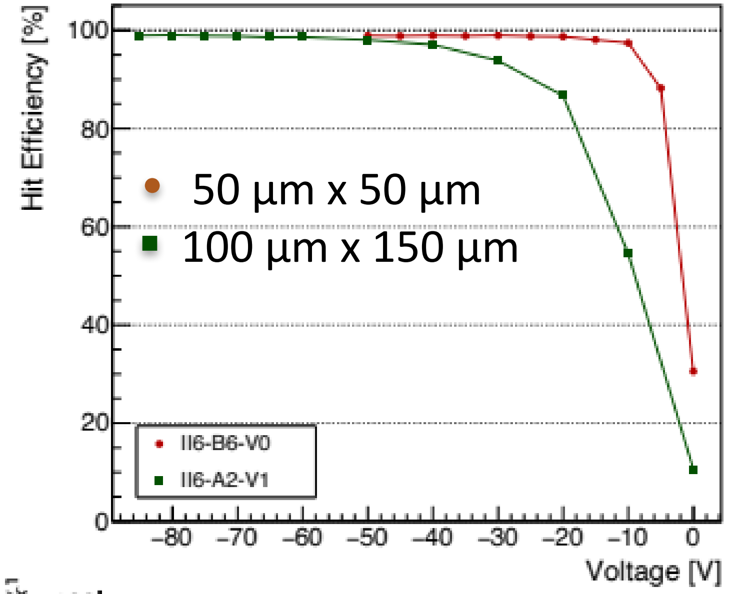
- Readout with PSI46dig v2.1-respin CMS chip
  - threshold ~2000 electrons
- Testing at **PSI** (using 260 MeV π^+ beam)
  - telescope resolution ~60 µm (multiple scattering)
- Fiducial selection avoids known problems

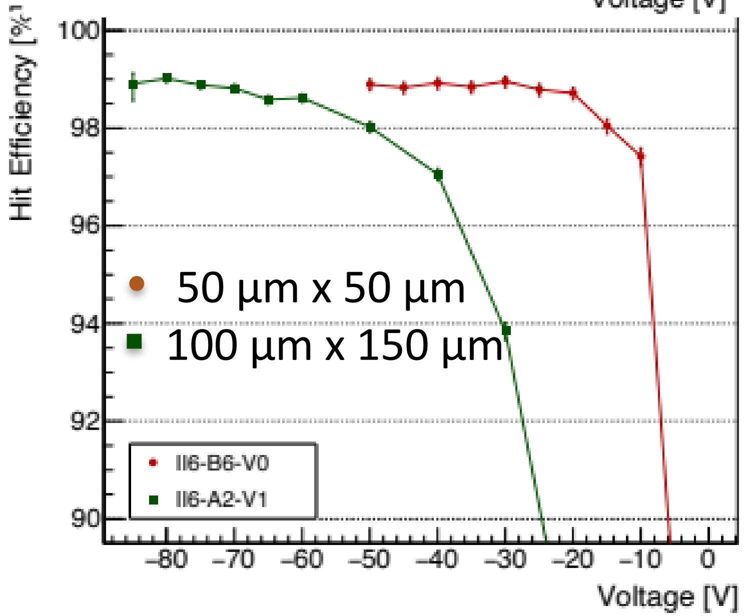


50 µm x 50 µm



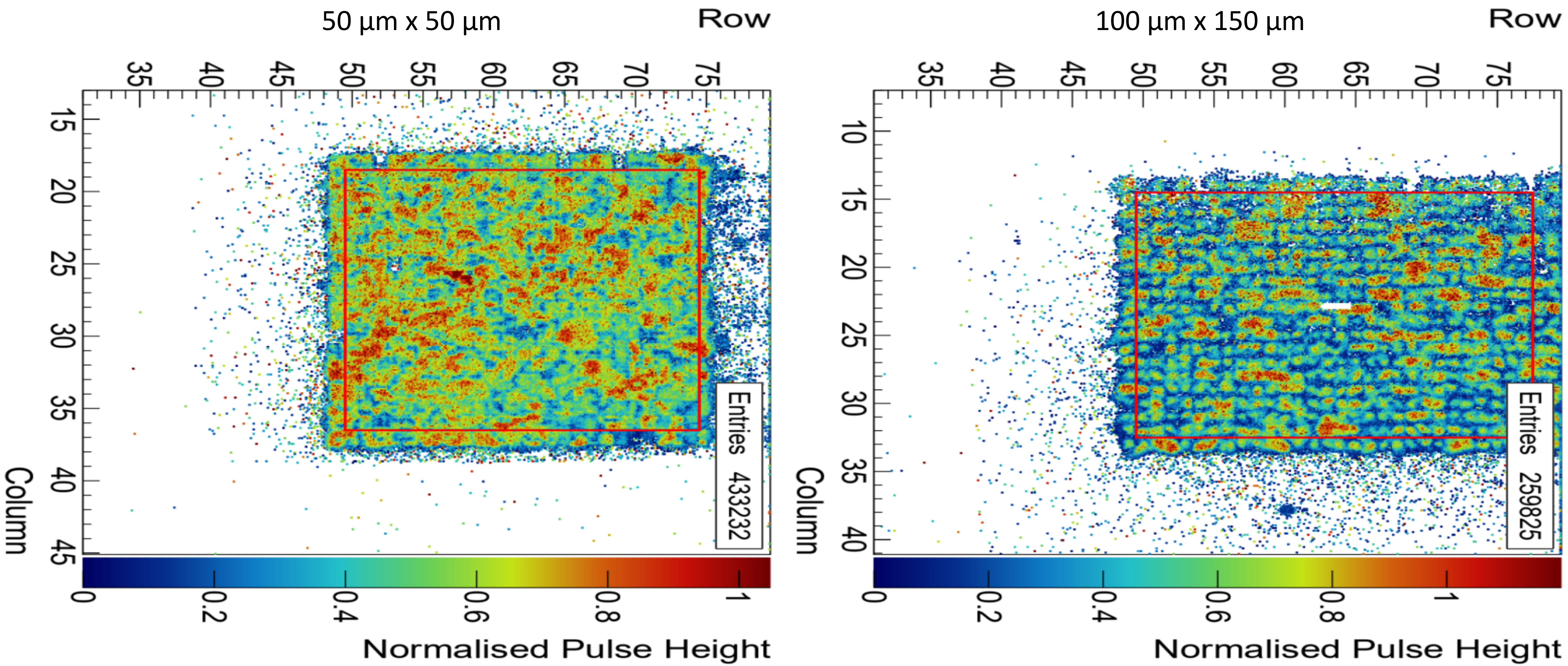
100 µm x 150 µm





Pulse Height vs Hit Position

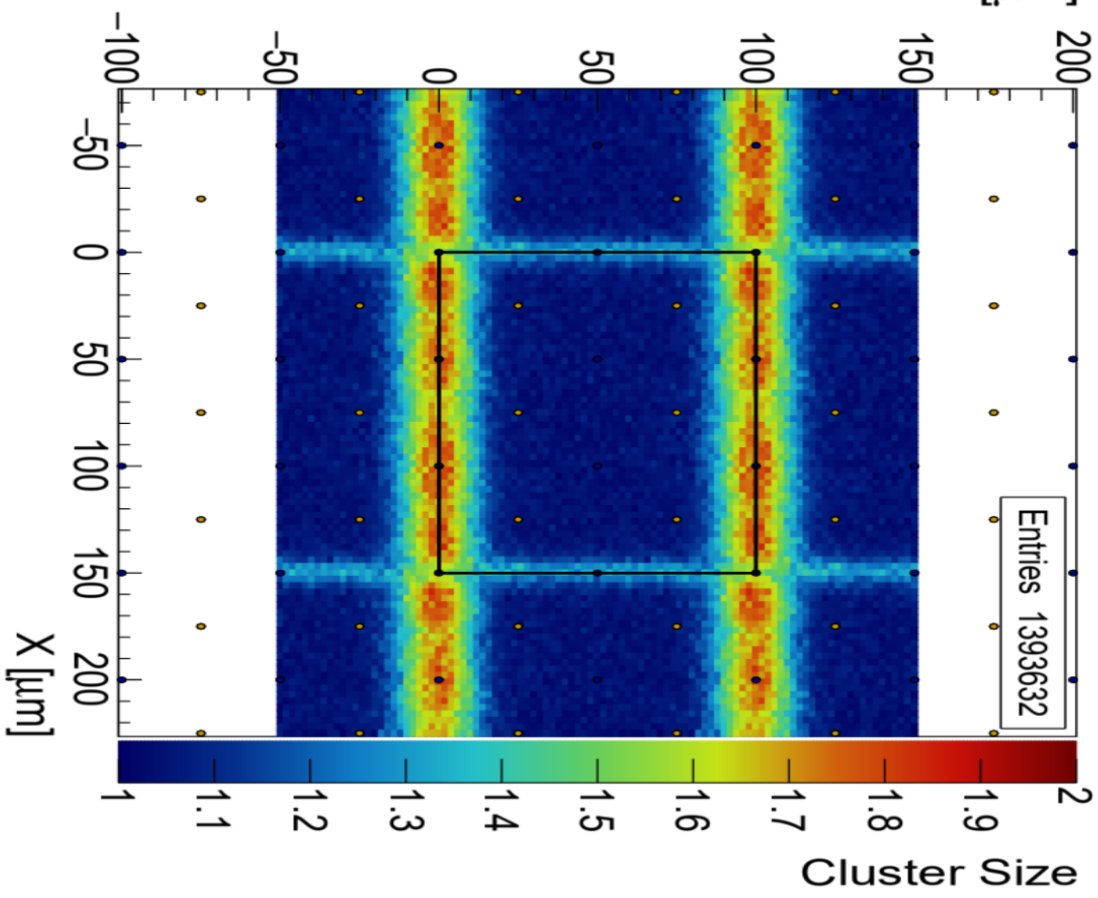
CERN Testbeam



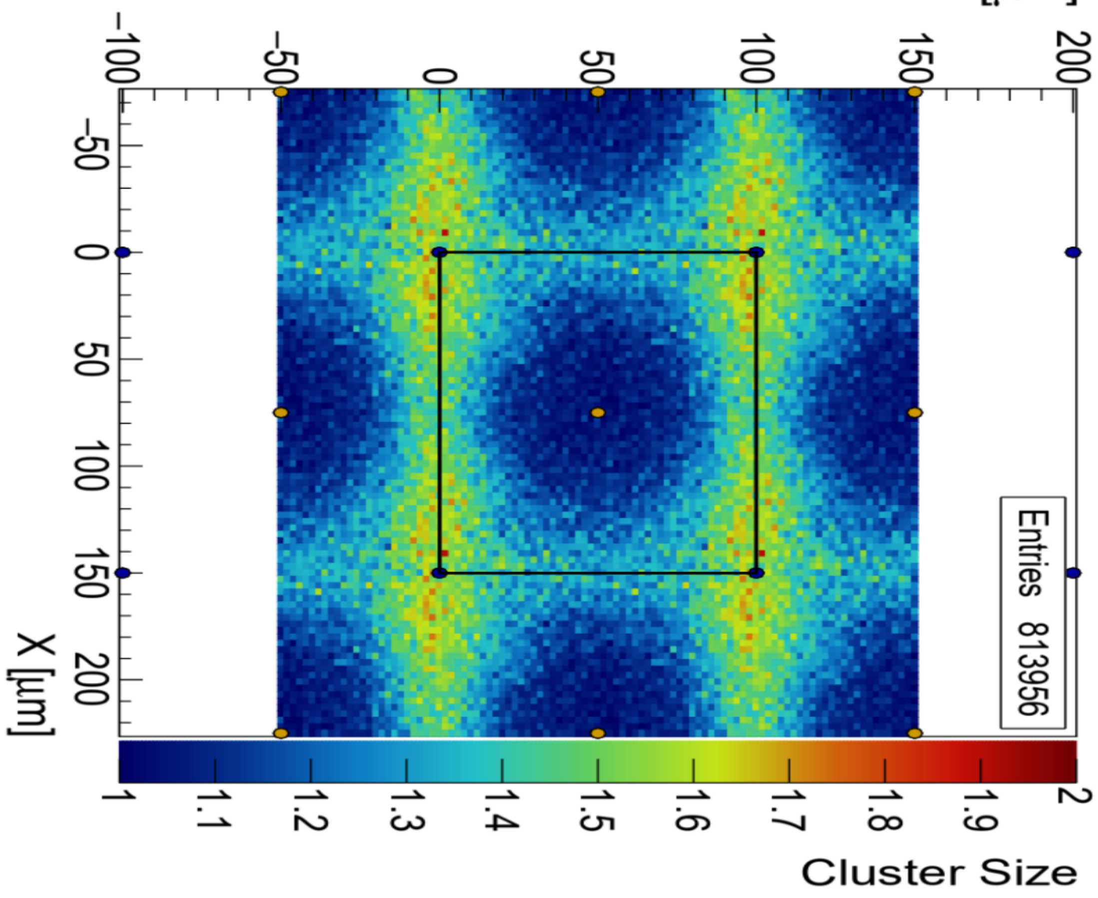
In-cell Cluster Size

CERN Testbeam

50 µm x 50 µm



100 µm x 150 µm

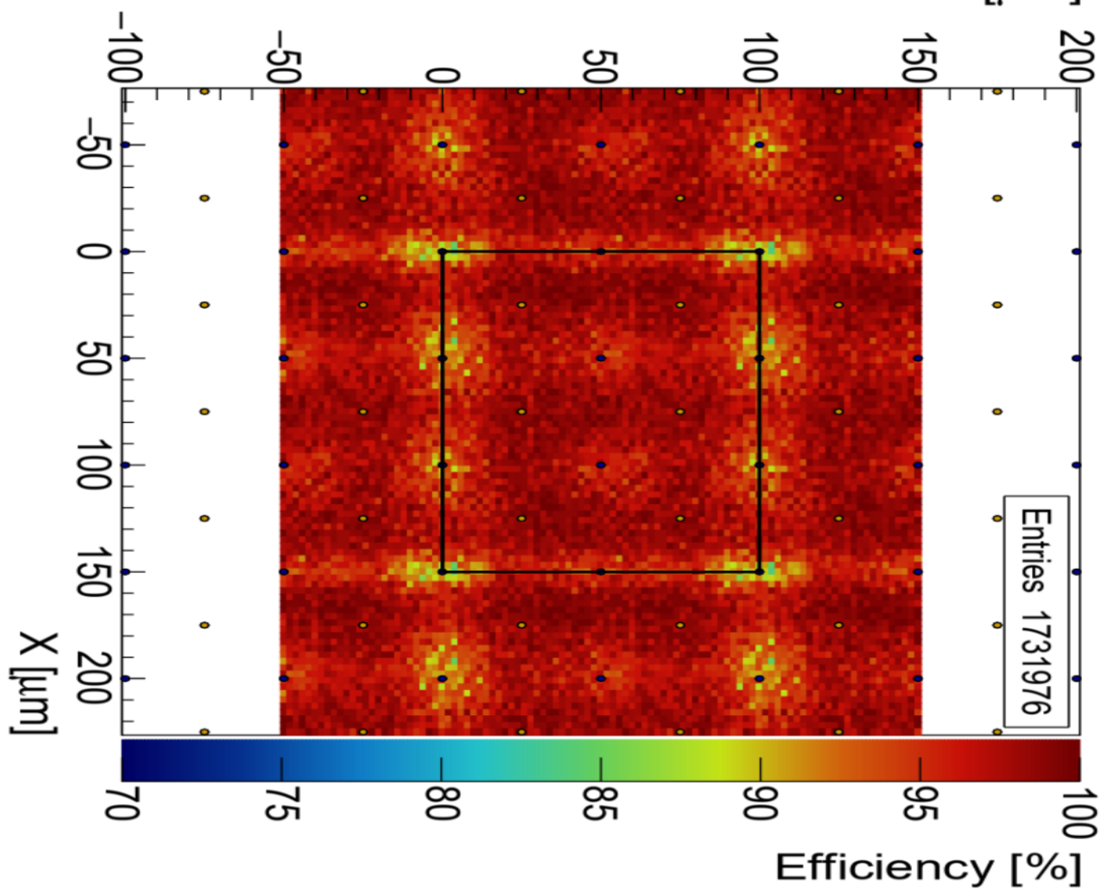


- Bias
- Readout

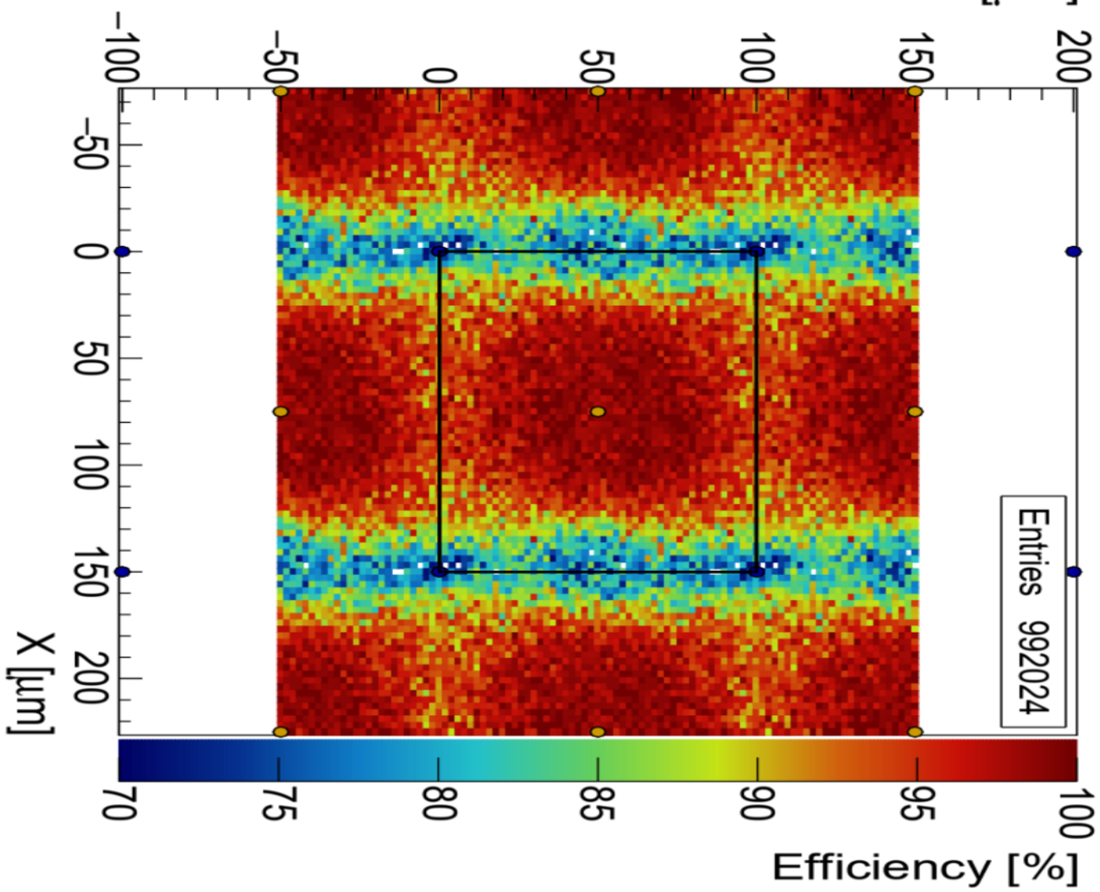
In-cell Efficiency

CERN Testbeam

50 µm x 50 µm



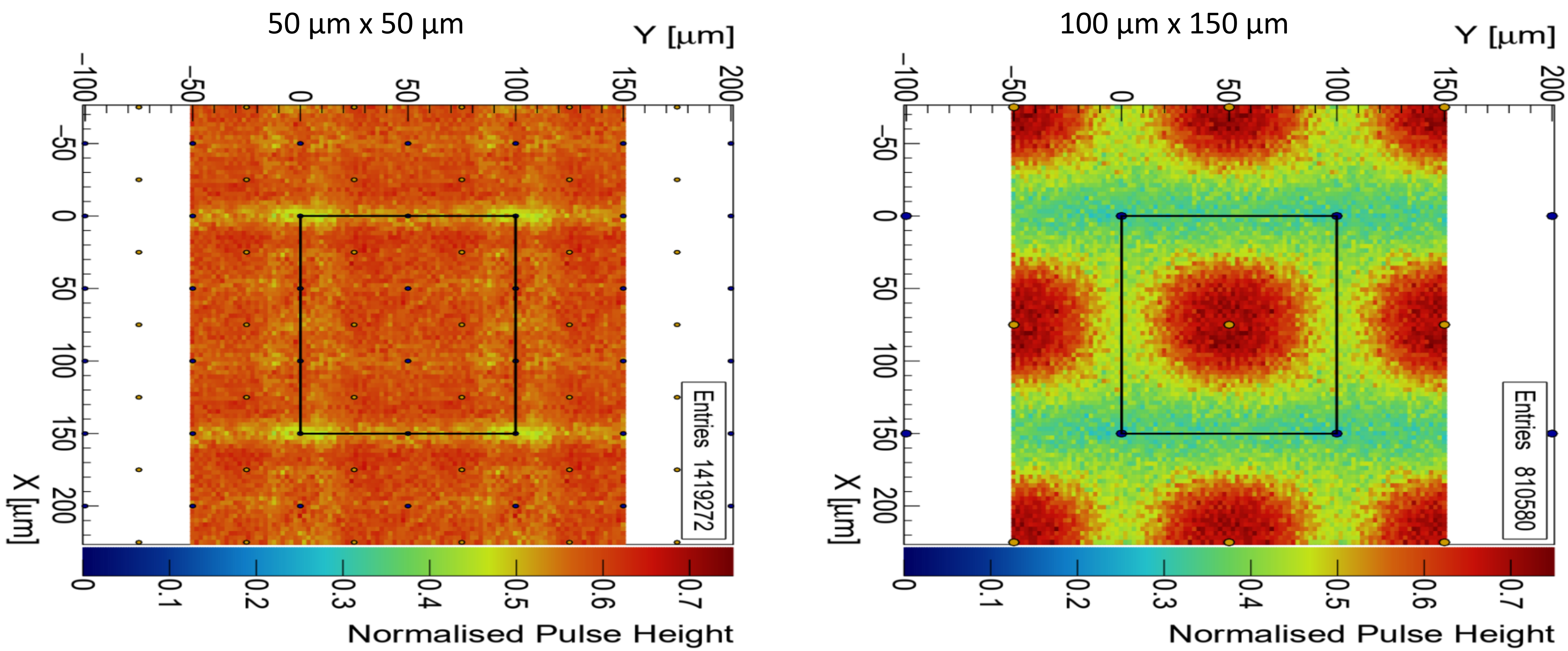
100 µm x 150 µm



- Bias
- Readout

In-cell Pulse Height

CERN Testbeam

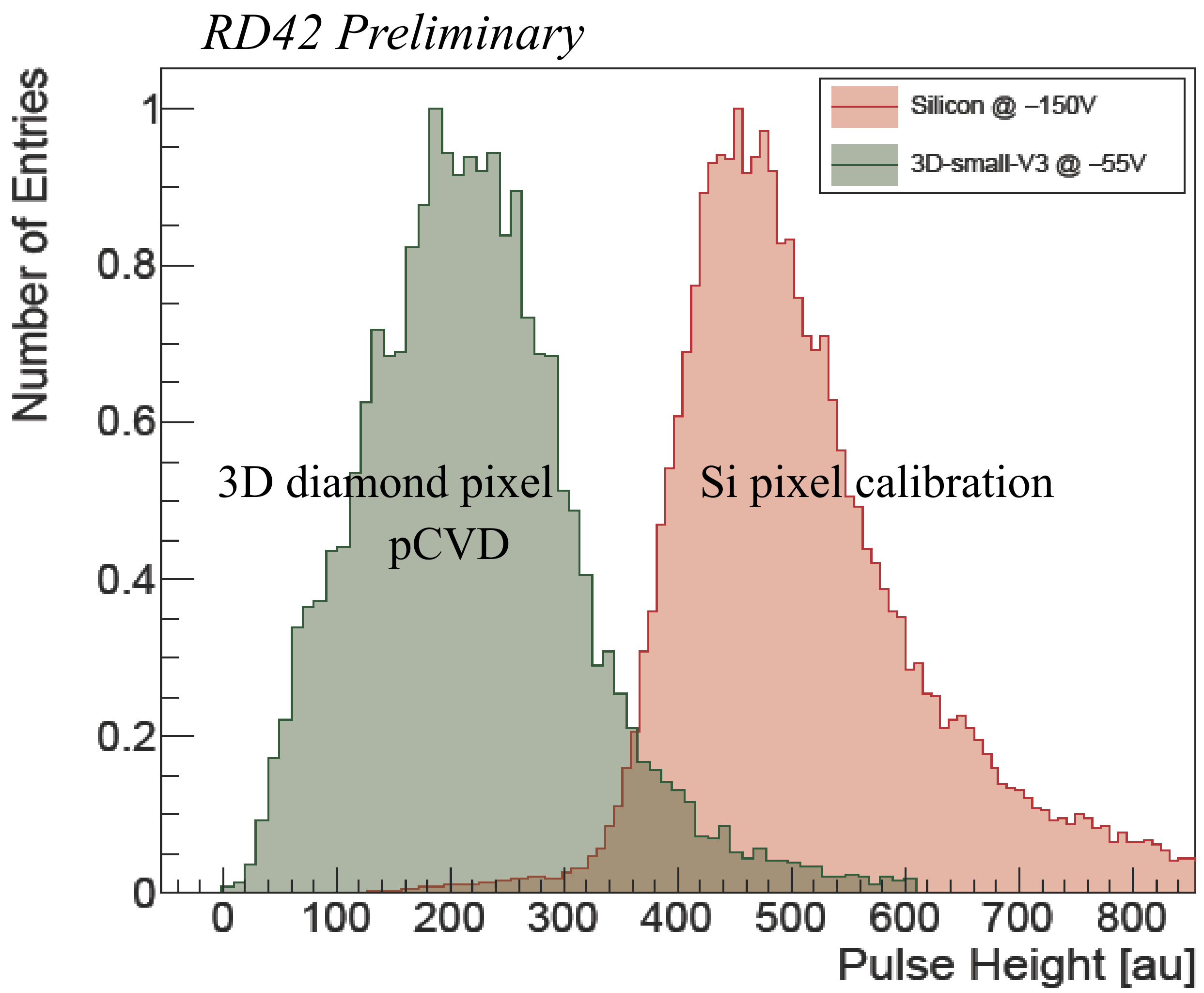


- Bias
- Readout

Pulse Height Distributions

CERN Testbeam

- 3D pCVD diamond collects >85% of charge
- efficiency in fiducial region: >99.2%
- In the 3D configuration, pCVD diamond looks single crystal like!



New Steps in Diamond Processing

RIE/ICP Processing

Reactive Ion Etching/Inductively Coupled Plasma (RIE/ICP) Processing is a plasma processing step which can be used to “repair” surface issues.

This is particularly necessary in diamond processing since most manufacturers use mechanical processing (grinding) to finish “final” detectors.

These mechanical steps can create sub-surface damage as deep as 12 μm beneath the surface. Such damage can become evident as visible surface defects, lower signals, larger leakage currents, HV breakdown, polarization and lower yield.

These effects can be mitigated with RIE/ICP processing.

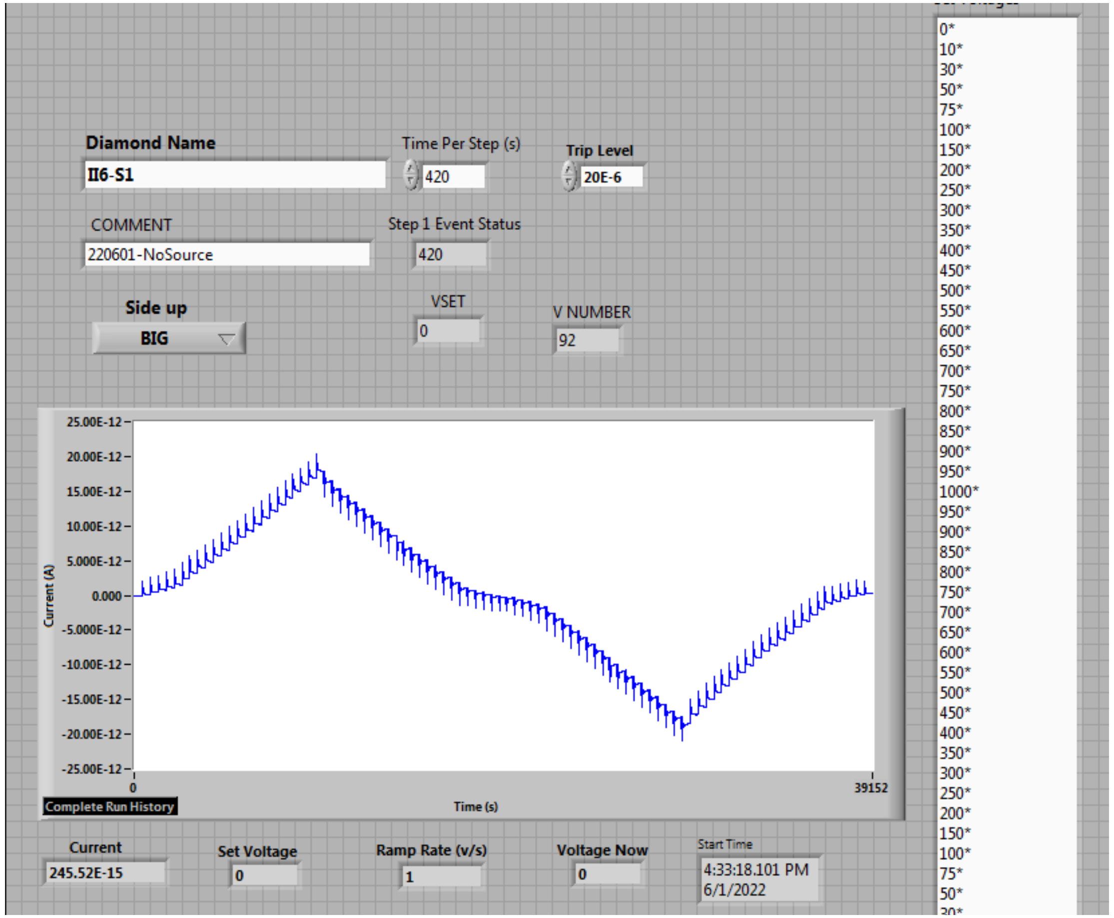
RIE/ICP Processing

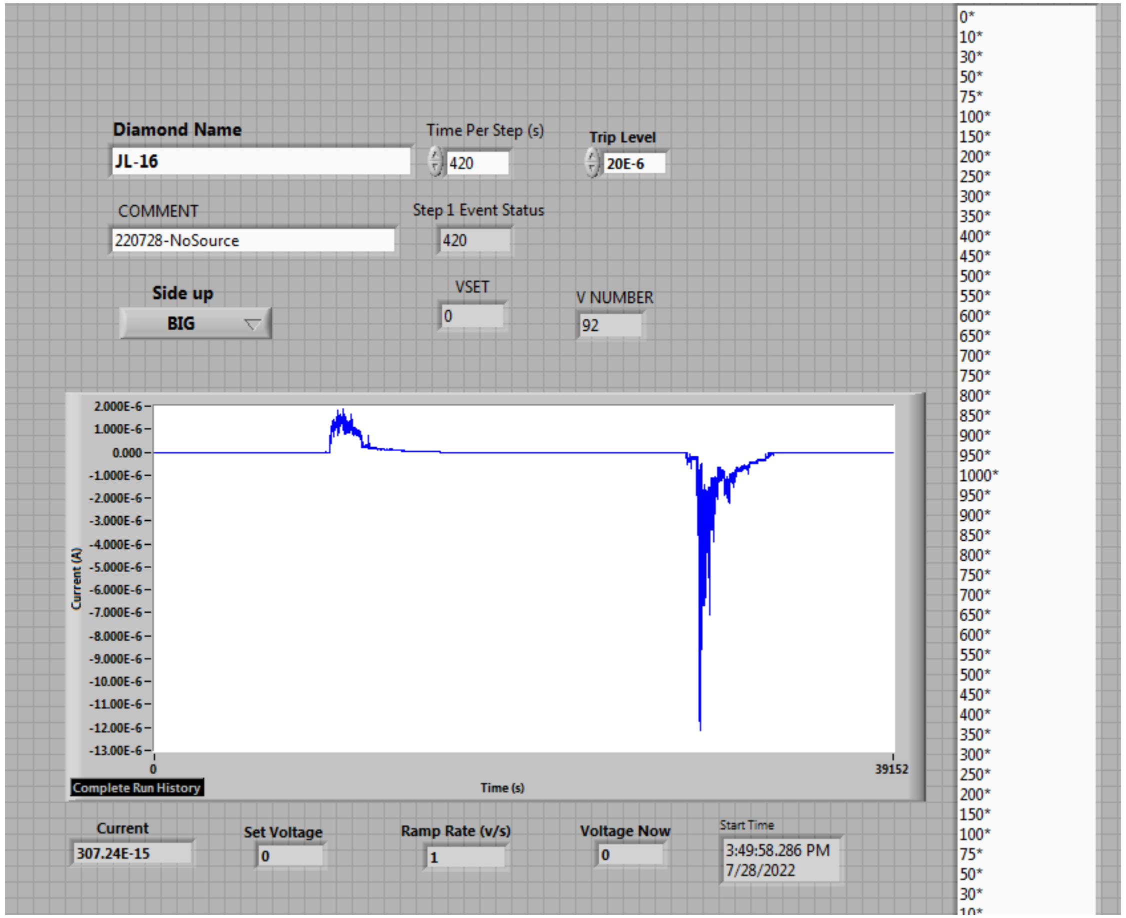
- Visible surface defects

Before RIE/ICP

RIE/ICP Processing

- Expected leakage currents (pA)
- Large leakage currents (µA)

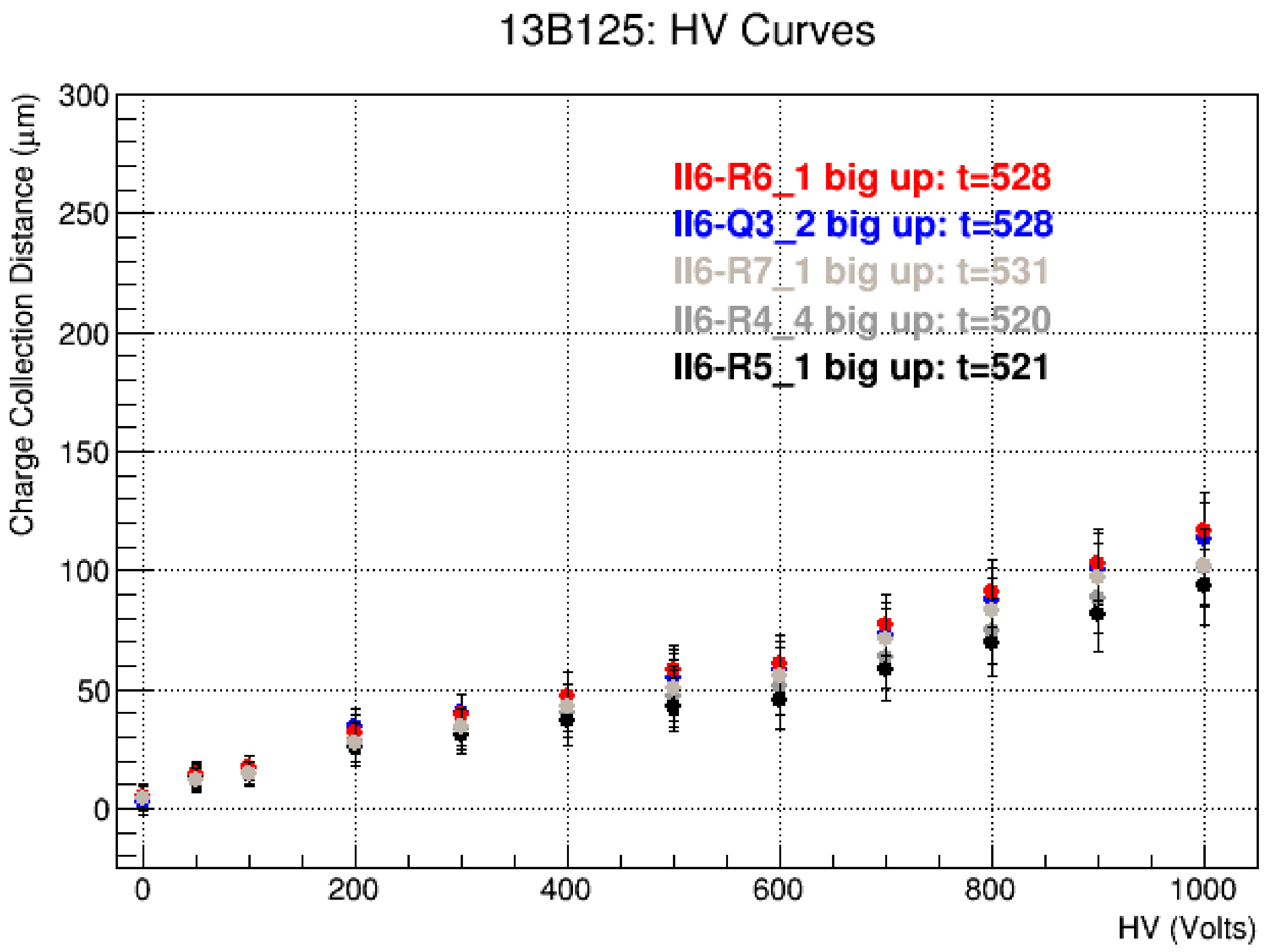




RIE/ICP Processing

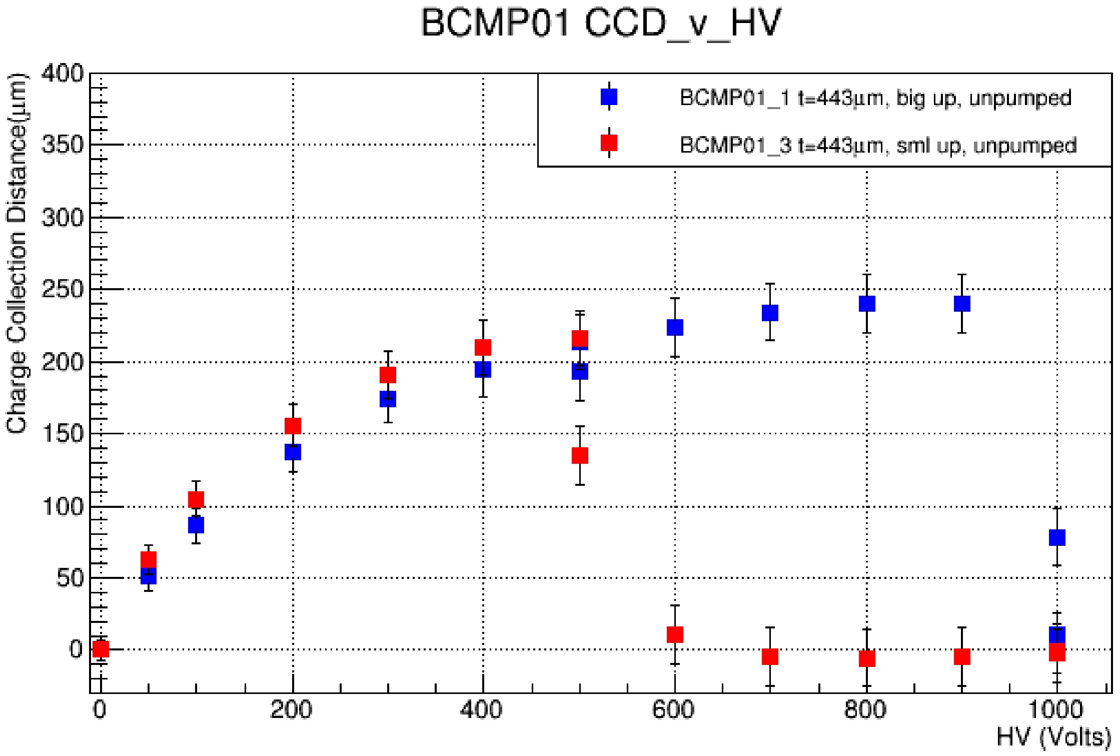
- Low signal size

Before RIE/ICP

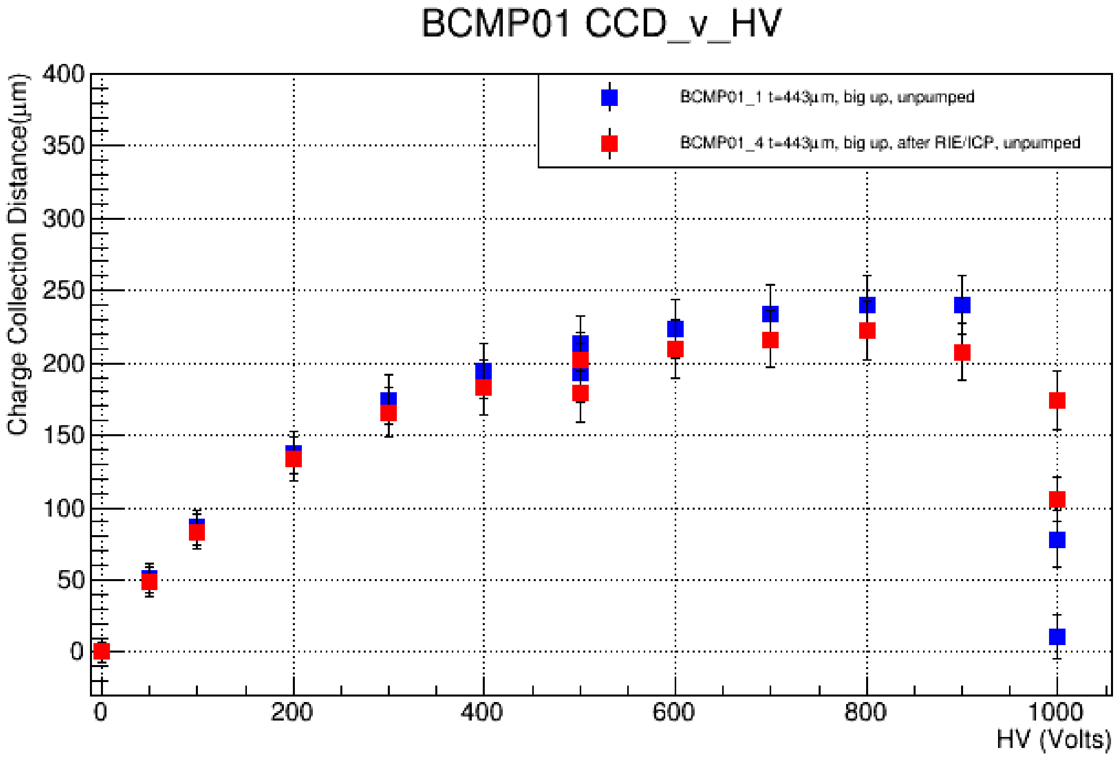


RIE/ICP Processing

- HV Issues



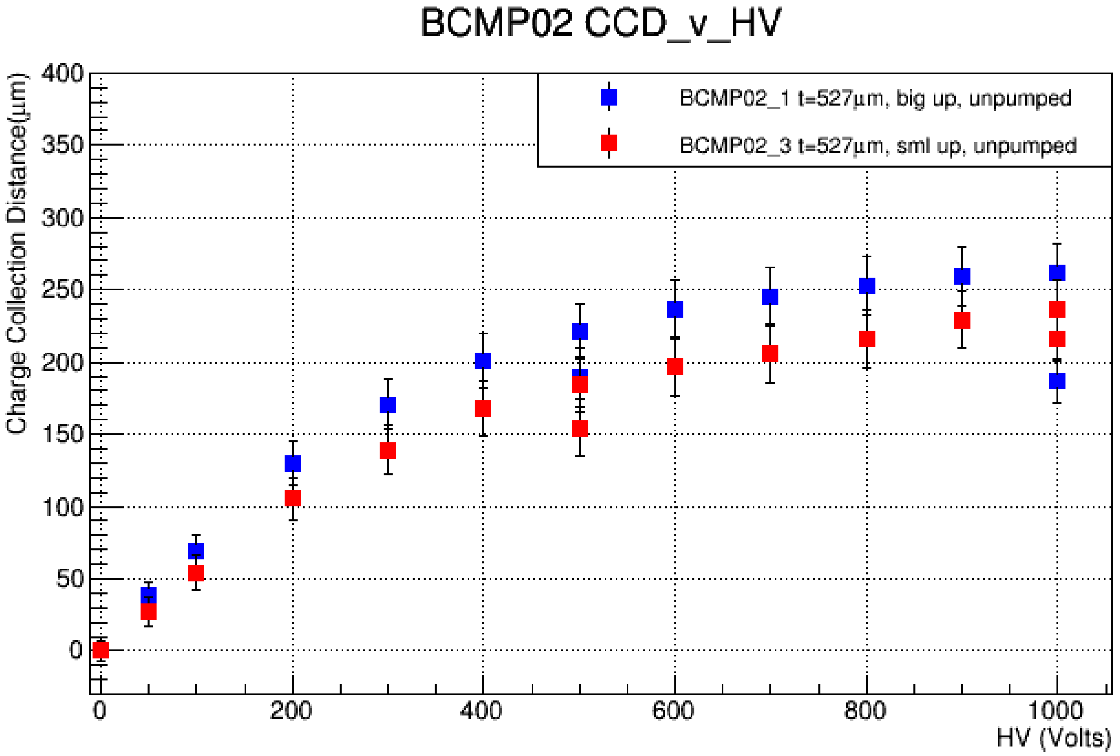
Before RIE/ICP



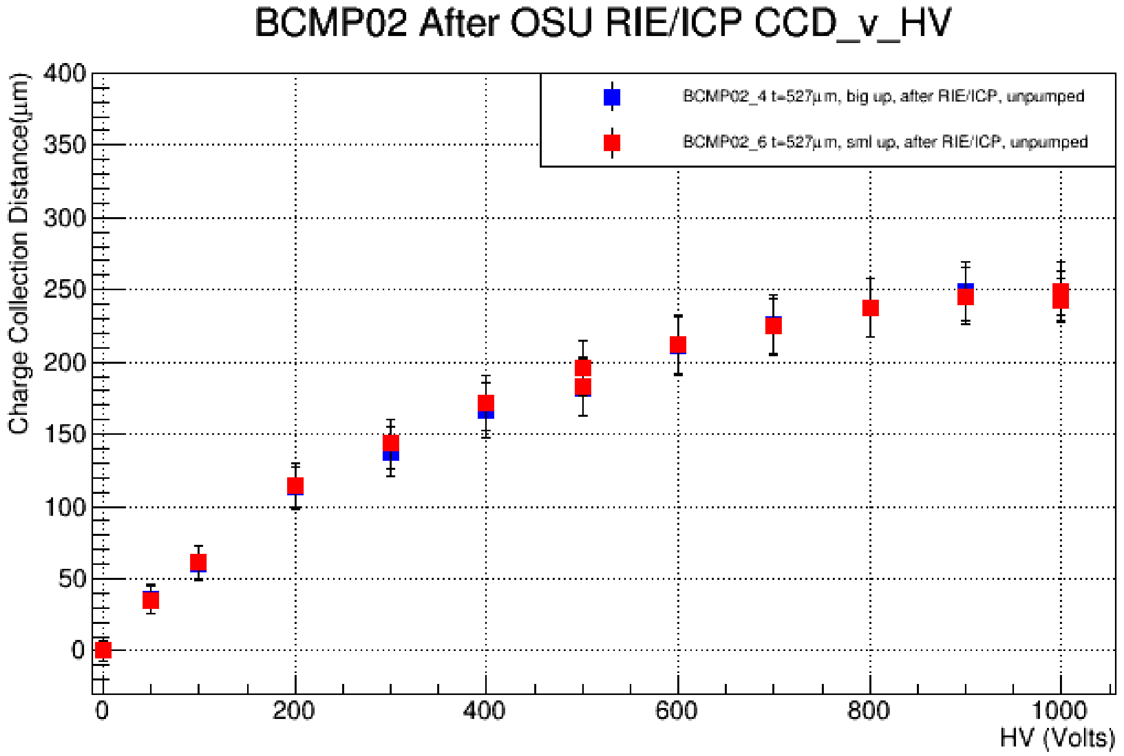
After RIE/ICP

RIE/ICP Processing

- Polarization Issues



Before RIE/ICP



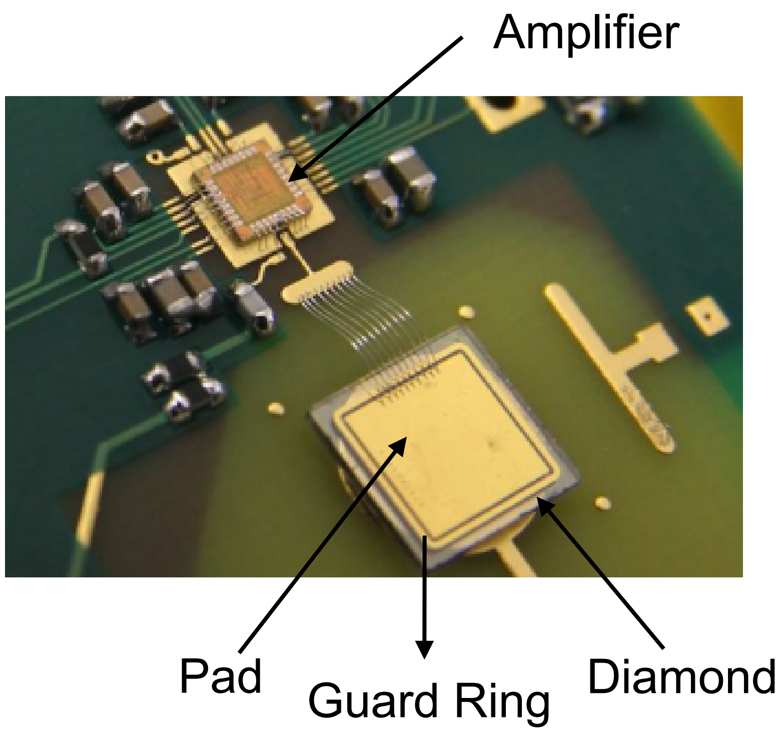
After RIE/IC

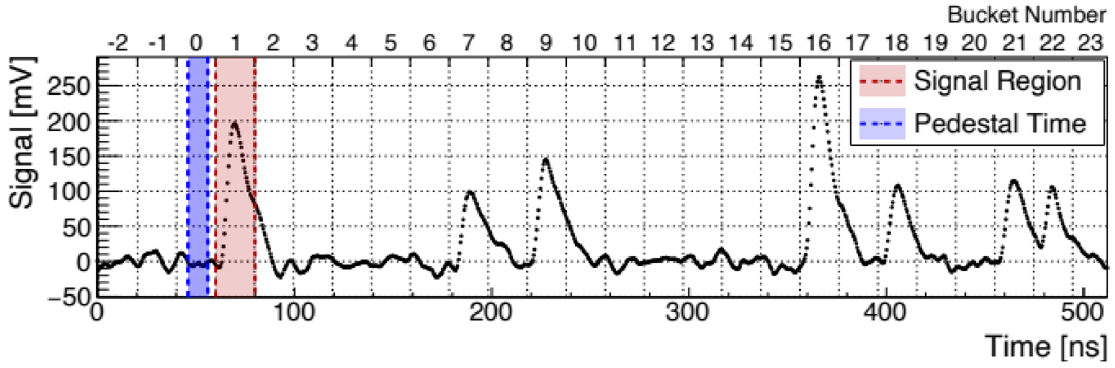
Rate Dependence of pCVD Diamonds

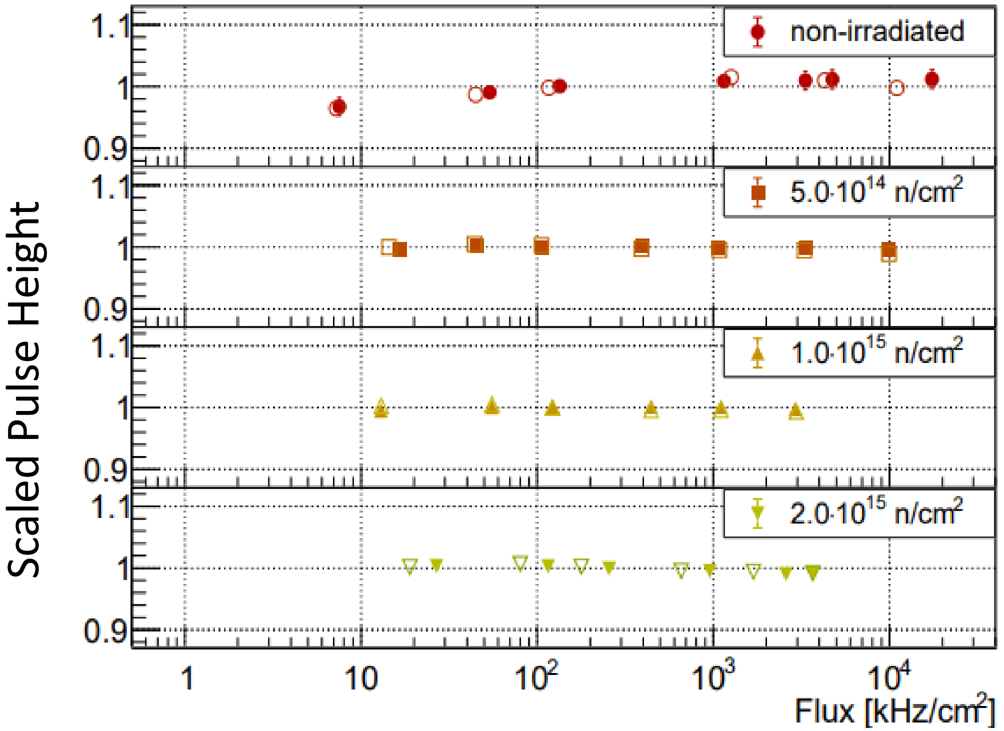
Rate dependence of pCVD diamonds

PSI Testbeam

ETH Thesis 28688 (2022):
M. Reichmann







No rate dependence observed in irradiated pCVD:

up to 20 MHz/cm^2

up to 2x10^{15} n/cm^2

Conclusions

- Two pCVD 3D pixel detectors with 50-µm x 50-µm and with 100-µm x 150-µm cells fabricated and compared
  - M. Reichmann, Ph.D. Thesis 28688 ETH Zurich (2022)
  - Laser drilling of ~2.6 µm diameter columns with >99.7% efficiency achieved
  - Hit detection efficiency >99% achieved with pixel electronics
  - 50 µm x 50 µm cells in pCVD diamond look very good; 100 µm x 150 µm cells are too large
  - 25 µm x 25 µm cells in pCVD diamond should give outstanding radiation tolerance

- RIE/ICP can mitigate many production issues
  - In progress for ATLAS BCM’

- No rate dependence for irradiated pCVD diamonds for 10 kHz -20 MHz/cm^2, up to to 2x10^{15} n/cm^2
  - M. Reichmann, Ph.D. Thesis 28688 ETH Zurich (2022)

Conclusions and Future Plans

- Updated radiation hardness results of diamond to protons and fast neutrons up to fluences of $2x10^{16}$ protons/cm^2 plus a universal damage curve
  - Journal of Physics D: Applied Physics, Volume **52**, Number 46 (2019) [DOI: 10.1088/1361-6463/ab37c6]
  - Sensors, Volume **20**, p. 6648 (2020) [DOI: 10.3390/s20226648]

Future Plans

- Irradiate and assess performance of 3D diamond detectors after fluences of 10^{16} and 10^{17} n/cm^2
- Fabricate 25 µm x 25 µm 3D cells
- Scale up 3D column production using lasers
- Develop column etch process compatible with semiconductor industry

BACKUP

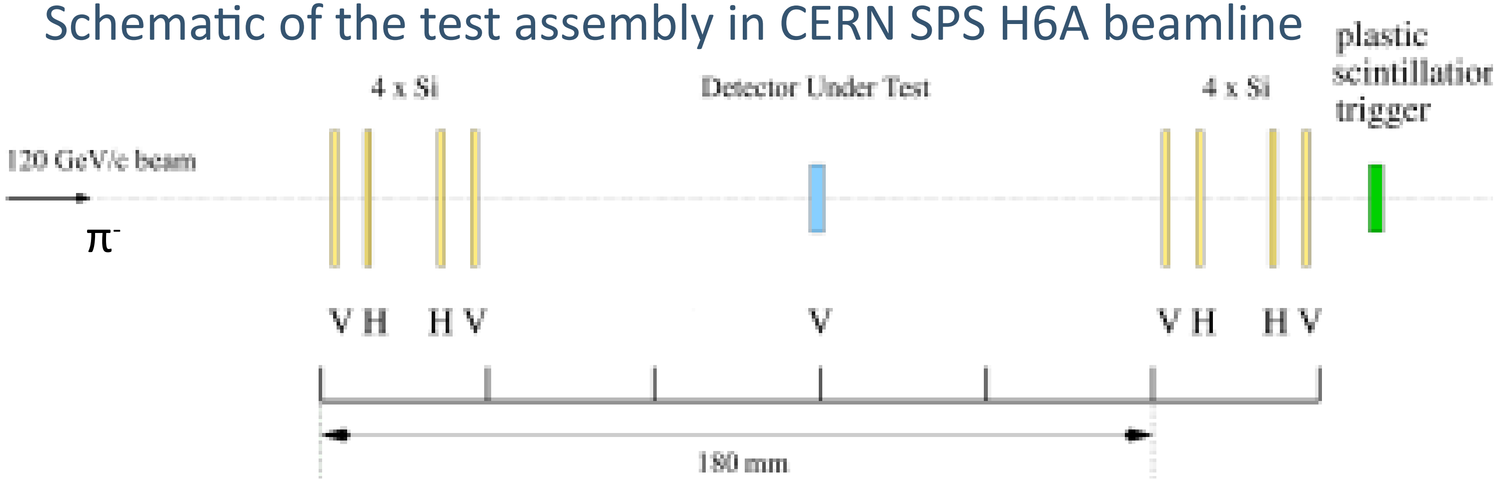
Summary of RD42 Results on Radiation Tolerance

Radiation tolerance of diamonds

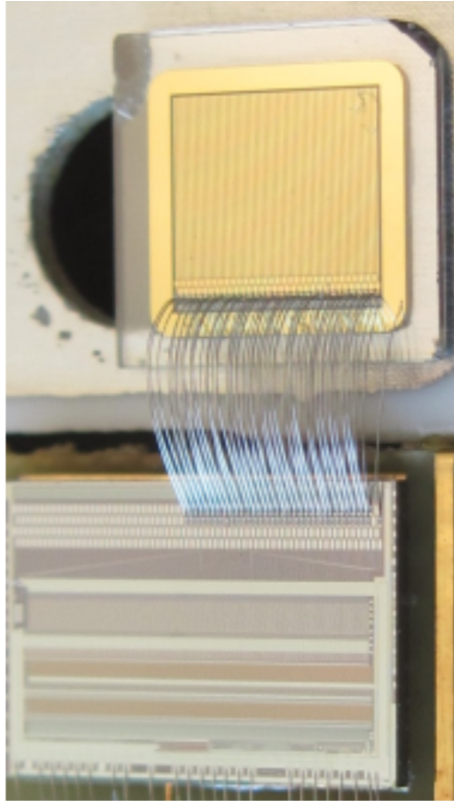
- Irradiate diamond samples with various particle species and energies
  - Re-metalize after each irradiation step to fabricate a strip detector
  - Readout with low (~80 electrons) noise VA2 chip

- Characterize irradiated devices in beam tests
  - Using hit prediction from telescope, collect charge in region of interest of up to 10 strips
  - Tracking precision at detector under test: ~ 2–3 µm

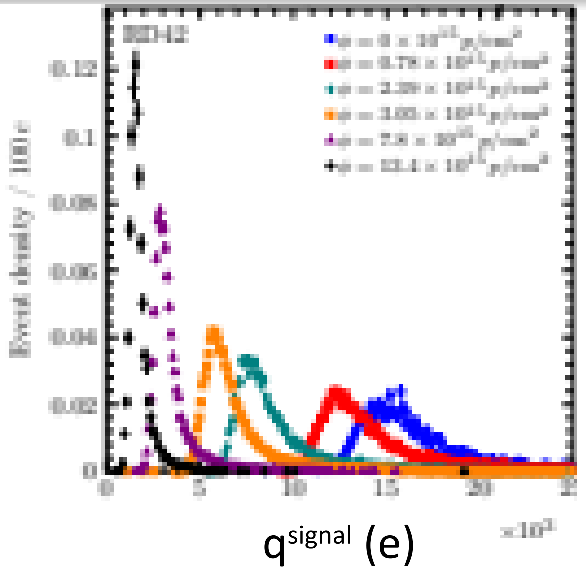
Schematic of the test assembly in CERN SPS H6A beamline

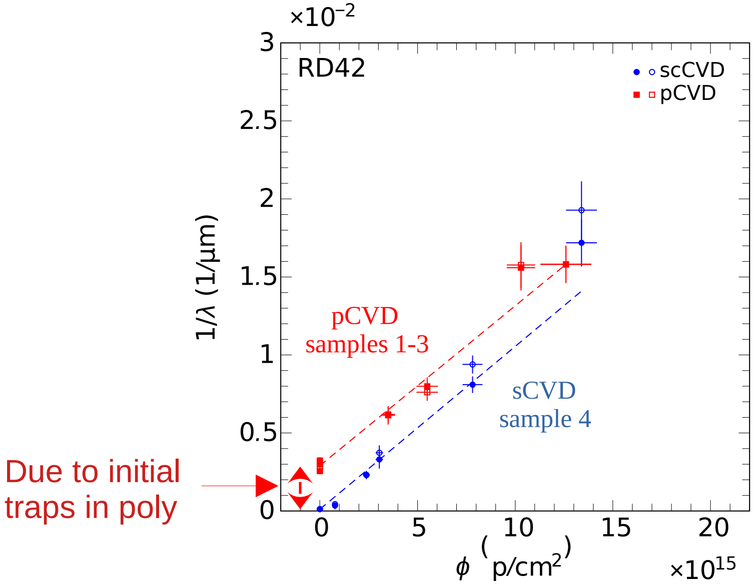


Diamond strip detector wire-bonded to a VA2 readout chip



Radiation tolerance of diamonds





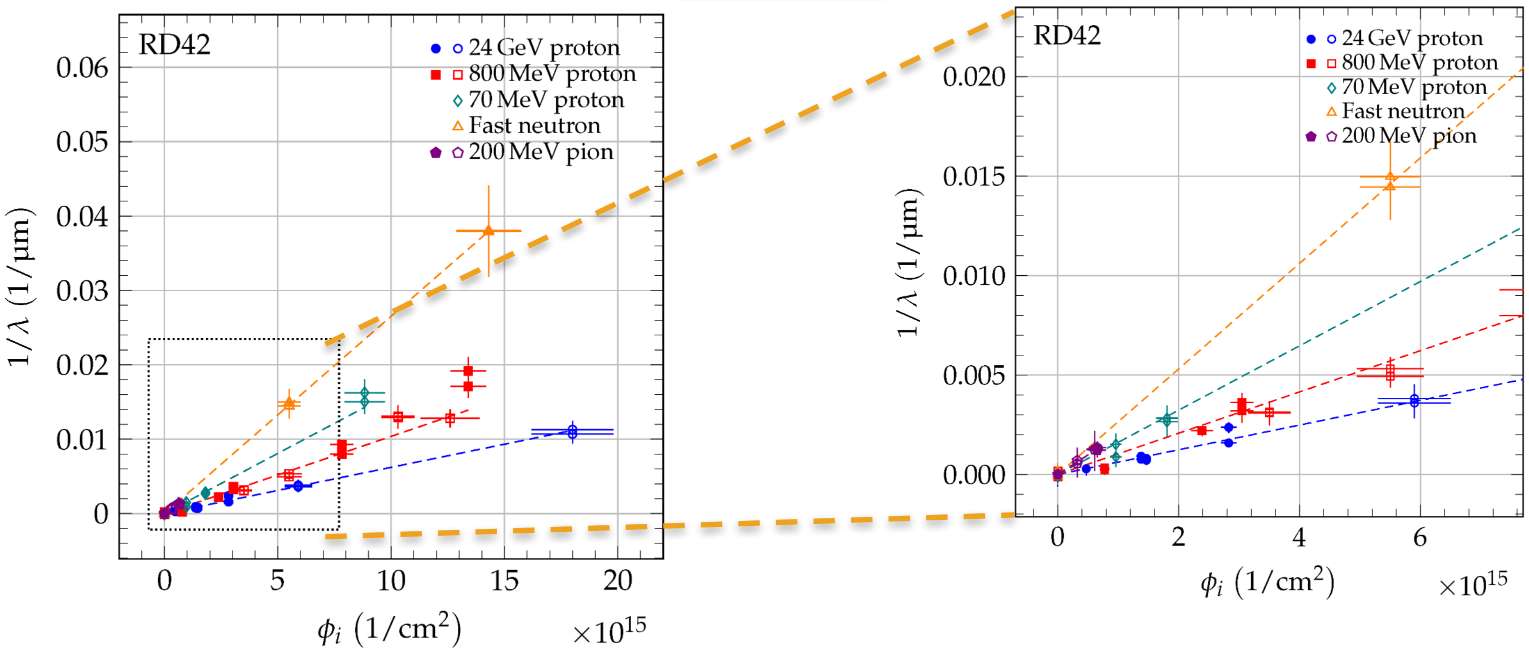
- Measure pulse height as a function of irradiation
  - Measure under both positive and negative bias
  - Convert mean pulse height to mean drift length before immobilization by trapping/annihilation - "Schubweg" (≈μEτ)

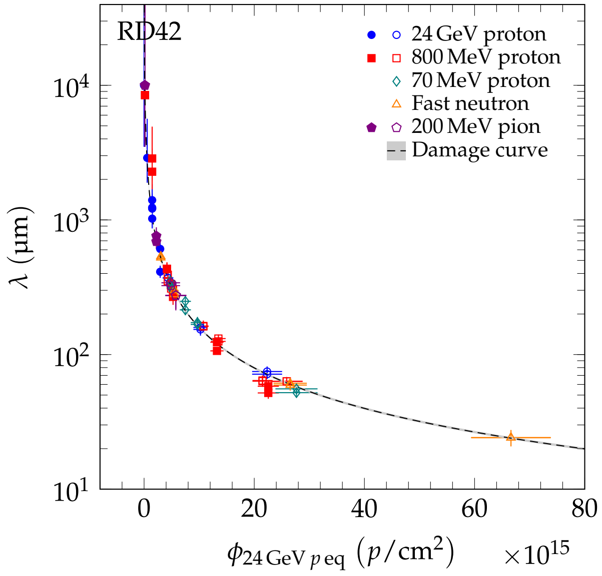
- Fit data with an empirical damage equation
  - n- number of traps, λ – Schubweg, k – damage constant, ϕ - fluence

$$n = n_0 + k'\phi \longrightarrow \frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi$$

  - The data for each sample are fit individually
  - Poly has a shorter initial Schubweg due to a higher initial trap concentration (offset in 1/λ at ϕ=0)
  - Slope for pCVD and scCVD are the same

Summary of RD42 radiation tolerance results





Particle	Energy	Relative k
proton	24 GeV	1
	800 MeV	1.67+/-0.09
	70 MeV	2.60+/-0.29
	25 MeV	4.4+/-1.2
pion	200 MeV	3.2+/-0.8
fast neutrons		4.3+/-0.4

Sensors **20** 6648 (2020)