Recent Developments in Diamond Detectors

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Vertex 2022
Tateyama, Japan
October 25, 2022

Outline of Talk

- Introduction – Motivation, Diamond Detectors, RD42
- Radiation Tolerance
- Rate Tolerance
- Device Development – Test beam results of 3D diamond pixel devices
- Development of the Atlas BCM'
- Summary

Introduction - Motivation

Present Situation at CERN LHC:

- Innermost layers → highest radiation damage, highest particle rate
- Current detectors designed to survive ~12 months in HL- LHC

→ R&D for more radiation tolerant detector designs and/or materials

Diamond as a Detector Material:

- Properties:

  Inherent radiation tolerance – large displacement energy
  insulating material with high thermal conductivity
  high charge carrier mobility
  Smaller signal than in same thickness of silicon

RD42 work:

- Investigate signals and radiation tolerance in various detector designs:

  pad → full diamond as a single cell readout
  pixel → diamond sensor on pixel chips
  3D → strip/pixel detector with design to reduce drift distance

Introduction - The 2022 RD42 Collaboration

The 2022 RD42 Collaboration

M. Artuso[20], L. Bäni[24], M. Bartosik[3], V. Bellini[2], B. Bentele[19], P. Bergonzo[31], A. Bes[27], J-M. Brom[7], G. Chiodini[26], D. Chren[18], V. Cindro[9], G. Claus[7], J. Collot[27], J. Cumalat[19], A. Dabrowski[3], D. Dauvergne[27], S. Ditalia Tchernij[15], M. Dunser[3], G. Eigen[30], V. Eremin[6], P. Everaere[27], J. Forneris[15], L. Gallin-Martel[27], M-L. Gallin-Martel[27], K.K. Gan[13], M. Gastal[3], A. Gentry[21], M. Goffe[7], J. Goldstein[17], A. Golubev[8], A. Gorišek[9], E. Grigoriev[8], J. Grosse-Knetter[23], B. Hiti[9], D. Hits[24], C. Hoarau[27], M. Hoeferkamp[21], J. Hosselet[7], F. Hügging[1], C. Hutson[17], R. Jackman[31], R. Jennings-Moors[31], H. Kagan[13,◊], K. Kanxheri[28], M. Kis[5], G. Kramberger[9], M. Kruger[32], S. Kuleshov[8], A. Lacoste[27], E. Lukosi[25], C. Maazouzi[7], M. Mali[9], I. Mandić[9], S. Marcatili[27], A. Marino[19], C. Mathieu[7], M. Menichelli[28], M. Mikuž[9], R. Molle[27], A. Morozzi[28], F. Moscatelli[28], J. Moss[29], R. Mountain[20], J-F. Muraz[27], E.A. Narazyanan[21], A. Oh[22], P. Olivero[15], D. Passeri[28], H. Pernegger[3], R. Perrino[26], F. Picollo[15], A. Porter[22], A. Portier[27], R. Potenza[2], A. Quadt[23], F. Rarbi[27], A. Re[15], M. Reichmann[24], S. Roe[3], O. Rossetto[27], P. Salter[32], D.A. Sanz Becerra[24], C. Schmidt[5], S. Schnetzer[14], S. Seidel[21], L. Servoli[28], R. Shivaraman[32], S. Smith[13], B. Sopko[18], V. Sopko[18], J. Sorenson[21], S. Spagnolo[26], S. Spanier[25], K. Stenson[19], R. Stone[14], B. Stugu[30], C. Sutera[2], M. Traeger[5], W. Trischuk[16,◊], M. Truccato[15], C. Tuve[2], J. Velthuis[17], E. Verbitskaya[6], S. Wagner[19], R. Wallny[24], J. Welch[31], T. Wengler[3], M. Yamouni[27], J. Zalieckas[30], M. Zavrtanik[9]

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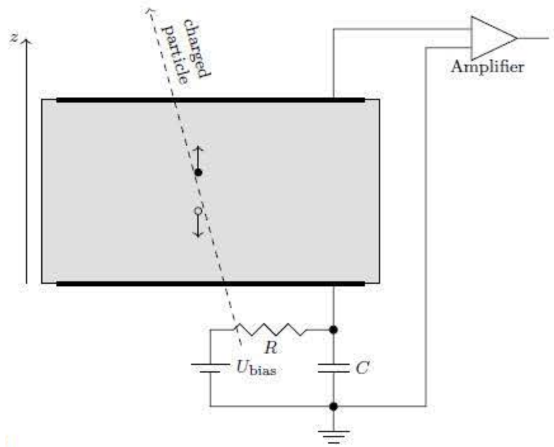
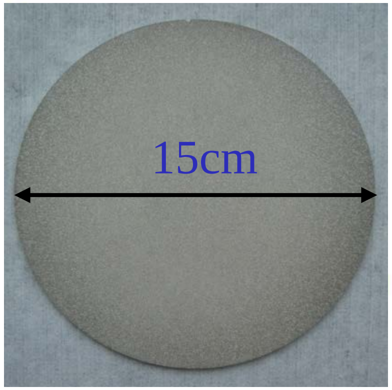
110 participants

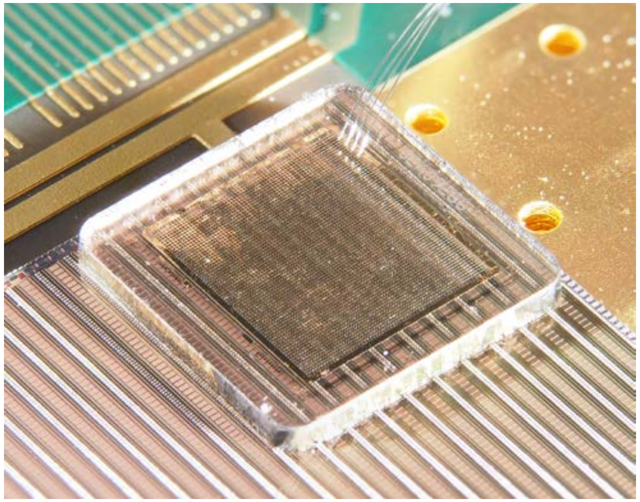
28 institutes

Introduction – 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
- Connected to low noise electronics





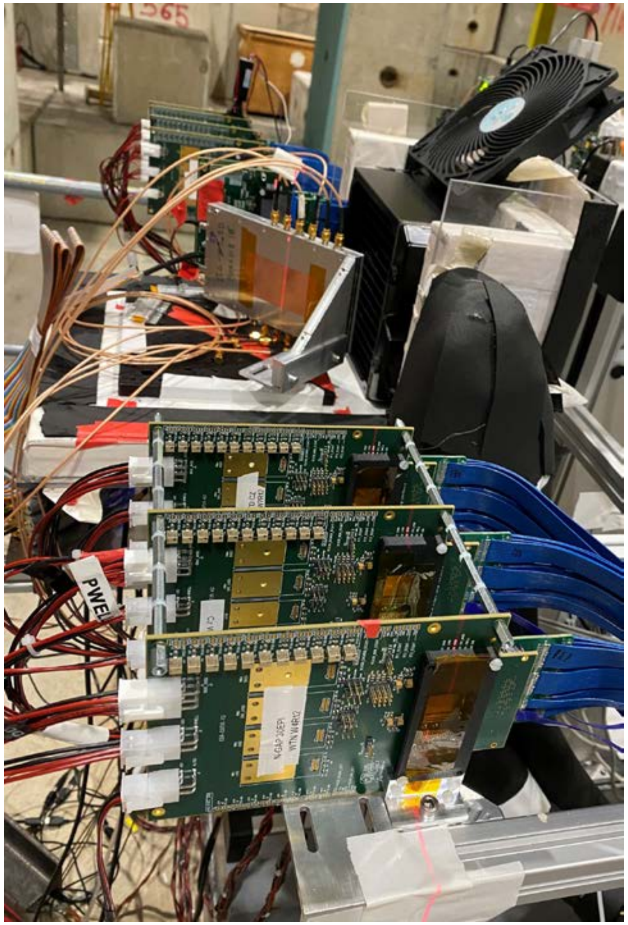


pCVD diamond with 3D pixel device bump-bonded to FE-I4

Introduction – Diamond as a Particle Detector

CERN Test Beam Setup
(MALTA Telescope)

- characterization of devices using test beams
- transparent or unbiased hit prediction from telescope
- tracking precision at detector under test: ~2-3μm
- talk by Heinz Pernegger on the Malta Telescope



Radiation Tolerance

Radiation Tolerance - Analysis Strategy

- Measure signal response as a function of predicted position
  Direct measurement of charge collection distance (CCD)
  CCD = average distance e-h pairs drift apart under E-field
- Convert CCD to "schubweg" (λ) – the mean free drift distance before being trapped in an infinite material – assume same λ for e,h

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

- Damage equation: $n = n_0 + k\phi$

$$\downarrow \qquad \downarrow$$

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

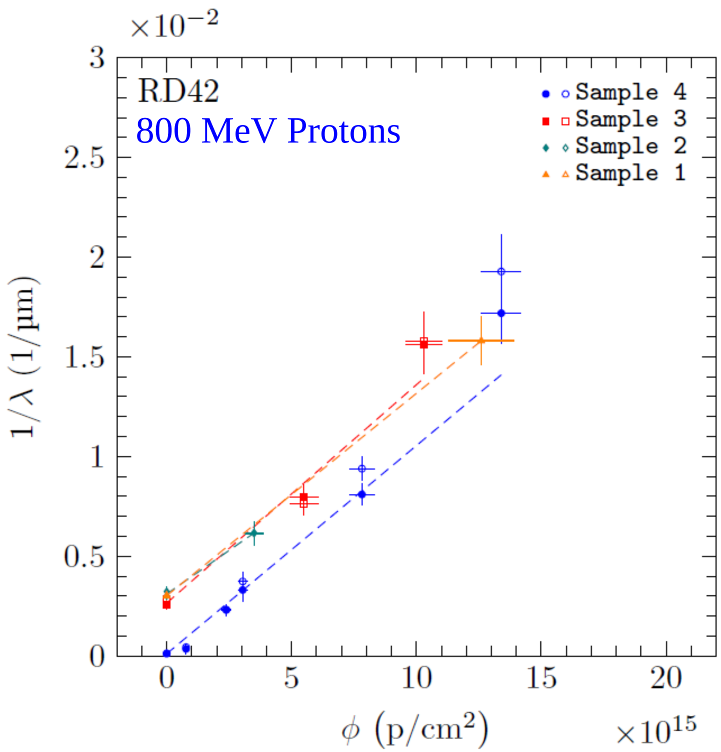
n number of traps
n_0 initial traps in material
k damage constant
ϕ fluence
λ MFDD
λ_0 initial MFDD

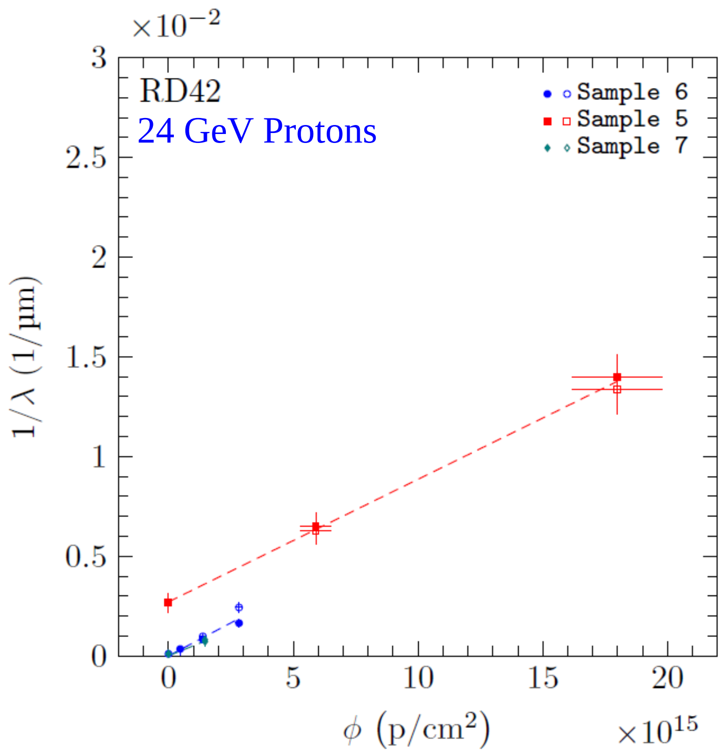
- Fit in $1/\lambda$ vs ϕ space to determine k, λ_0

Radiation Tolerance - Analysis Strategy

Example - 800 MeV protons, 24 GeV protons

- Plot single-crystalline and poly-crystalline on same graph
- Fit in $1/\lambda$ vs ϕ space
- Damage constant (=slope) the same for single-crystal and poly





Radiation Tolerance – Damage Curve Analysis

Summary of Radiation Tolerance Study
Combined Damage Curve

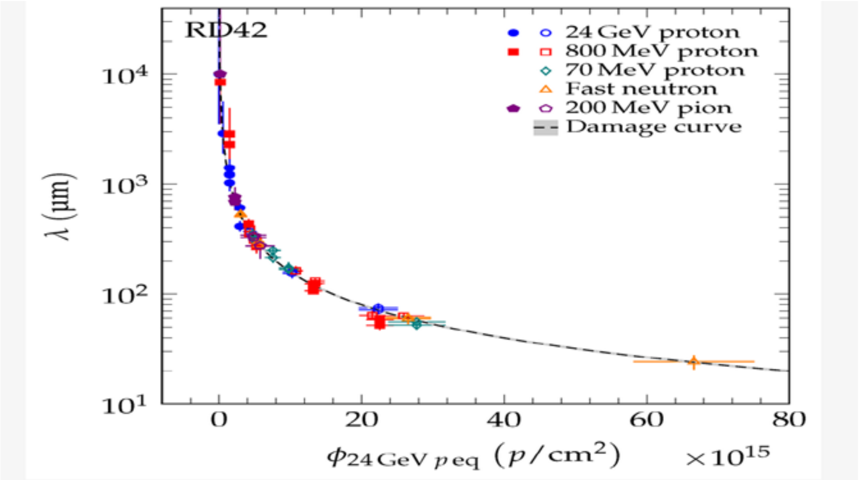
- Obtained radiation damage constants are compared to 24 GeV protons
- Combined damage curve
  - Shift pCVD sample by

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

  - Scale fluence by relative k

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

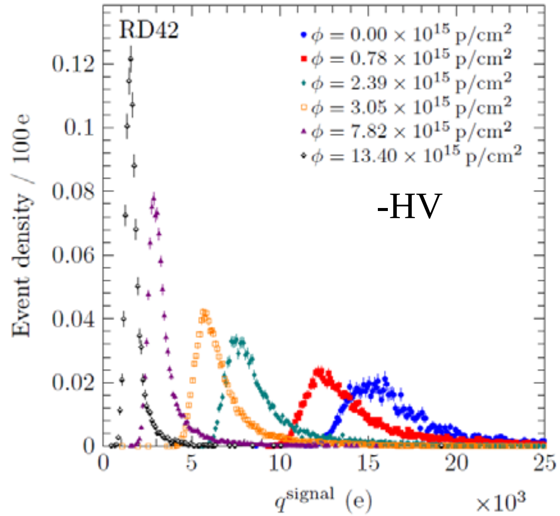
Particle Species	Relative Damage Constant, κ
24 GeV p	1
800 MeV p	1.67 ± 0.09
70 MeV p	2.6± 0.3
25 MeV p	4.4± 1.2
fast neutrons (>100keV)	4.3± 0.4

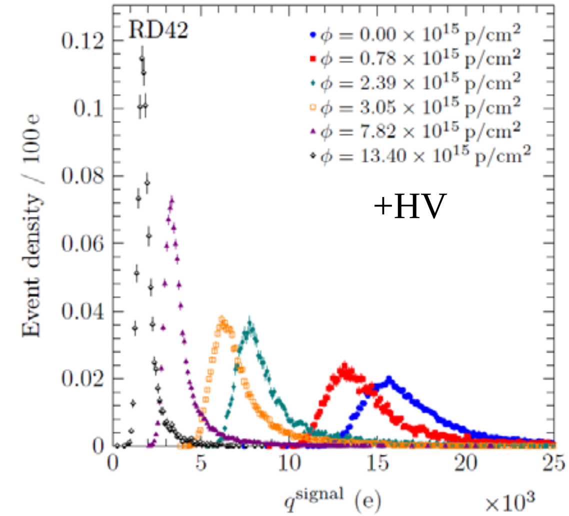


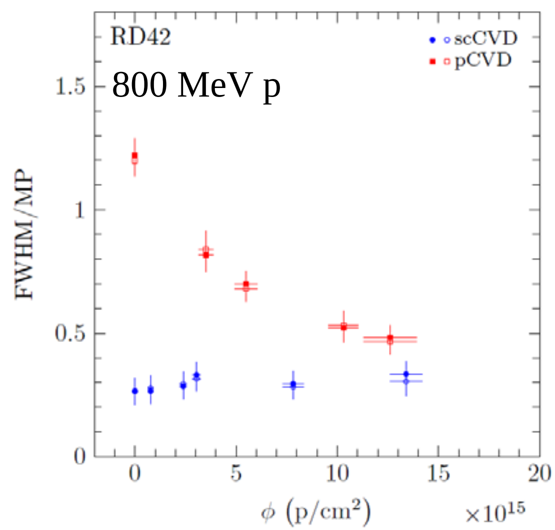
Radiation Tolerance - Shape Analysis

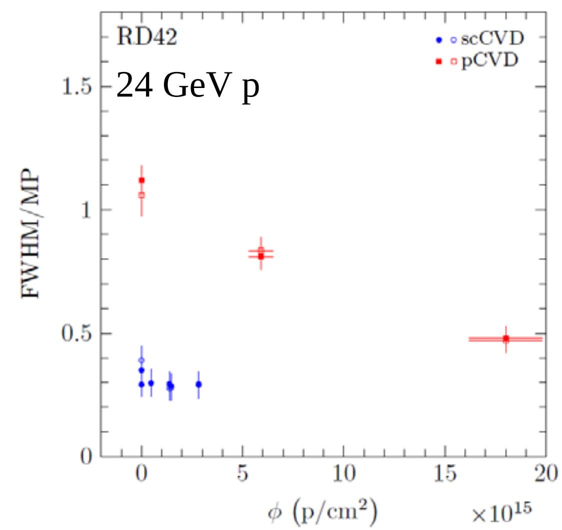
Signal Shape Analysis

- Study the shape of the pulse height distribution after irradiation (5/10 algorithm)
- Use the ratio FWHM/MP which is a measure of the uniformity of the material
- 800 MeV proton irradiated
  - pCVD samples
    - FWHM/MP decreases w/dose
  - scCVD samples
    - Smaller initial FWHM/MP
    - FWHM/MP is flat w/dose
- See similar results for other irradiation energies, species





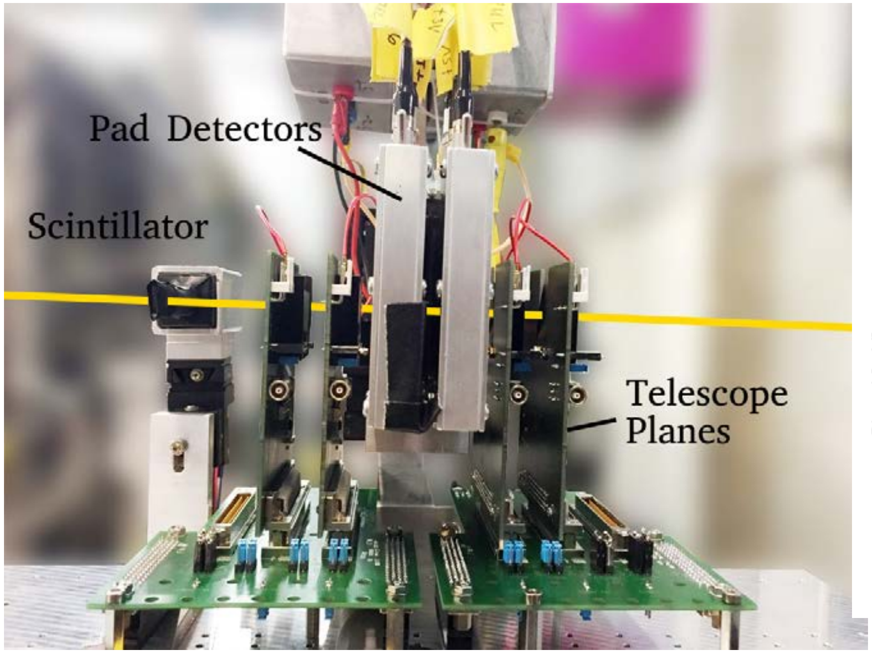


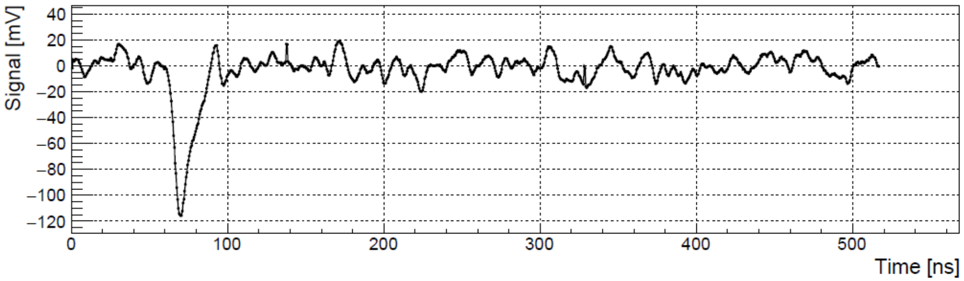


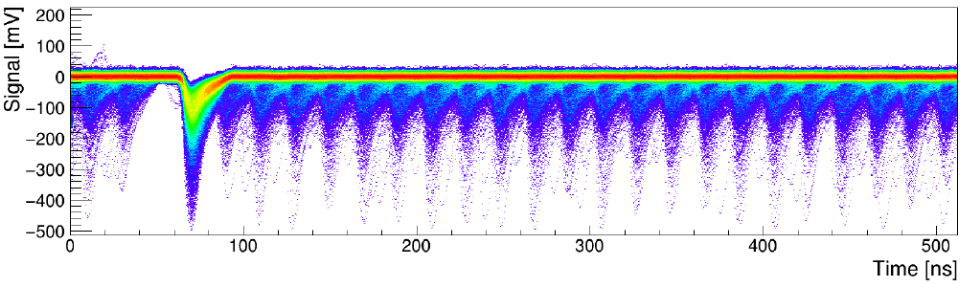
Rate Studies

Rate Studies in pCVD diamond

- First done@PSI - 5yrs ago published rates to 300kHz/cm^2
- 3 years ago w/new electronics, rates up to 10MHz/cm^2
- Recently measured rate after fluences of 2×10^{15}n/cm^2
- Pad detectors tested in ETH-Z (CMS Pixel) telescope
- Electronics is prototype for HL-LHC BCM/BLM



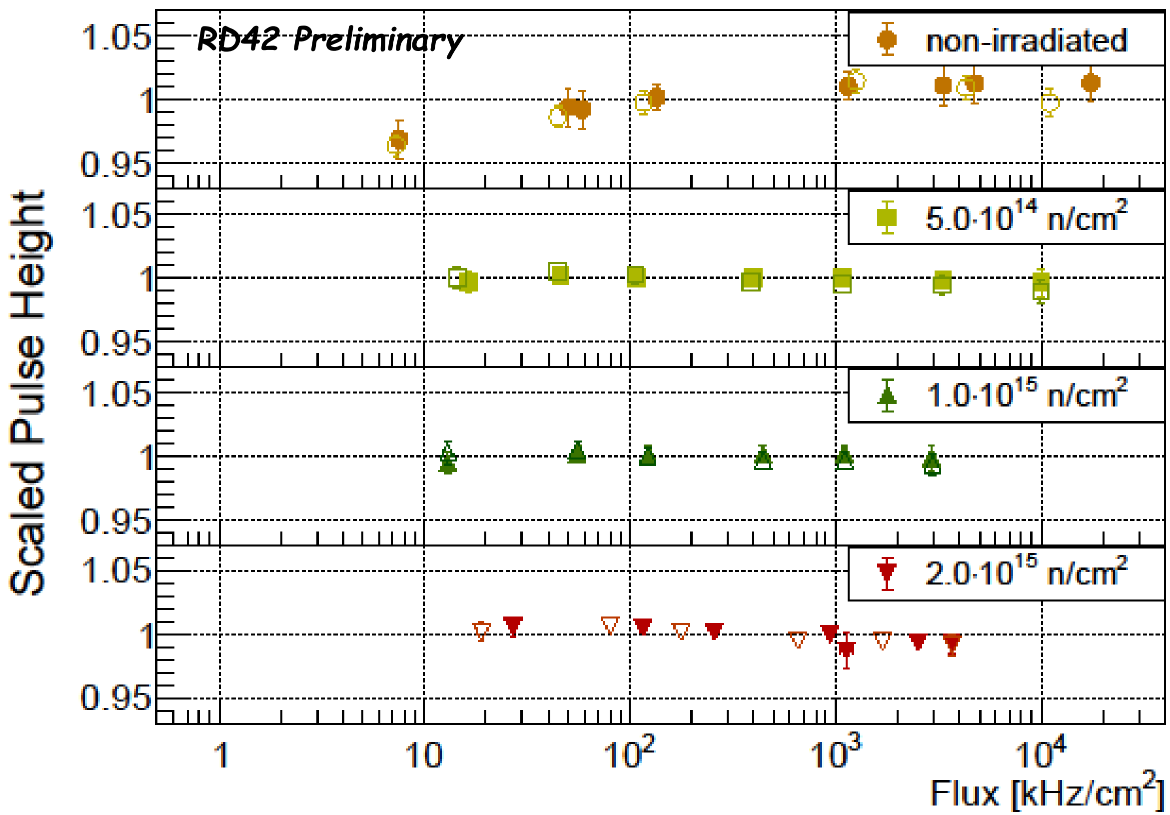




19.8ns bunch spacing clearly visible

Rate Studies in pCVD diamond

M. Reichmann
Thesis 2022



No rate dependence observed in pCVD up to 3-20MHz/cm^2
No rate dependence observed in pCVD up to 2x10^{15}n/cm^2
Now extending dose to 10^{16} n/cm^2 then 10^{17} n/cm^2

Device Development for more radiation tolerance: 3D diamond pixel detectors

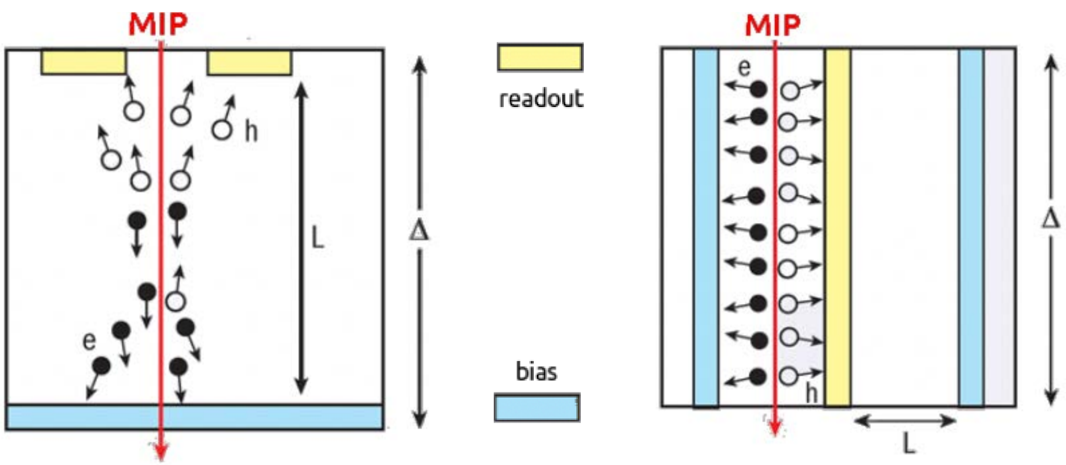
3D Device in pCVD Diamond

After large radiation fluence all detectors are trap limited

- Mean carrier "schubweg" λ < 50μm
- Need to keep drift distances (L) smaller than (λ)

Comparison of planar and 3D devices

Can one do this in pCVD diamond?



Planar 3D

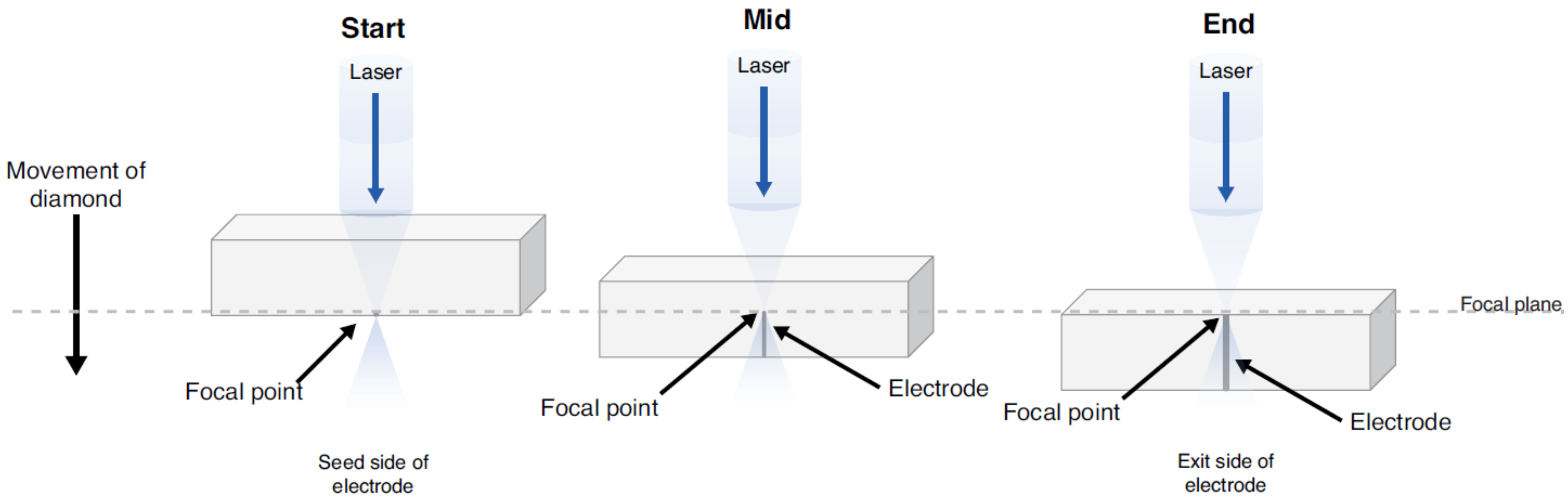
Have to make resistive columns in diamond for this to work

- -columns made with 800nm femtosecond laser
- -initial cells 100μm x 150μm; columns 4-6μm diameter

3D Device in pCVD Diamond

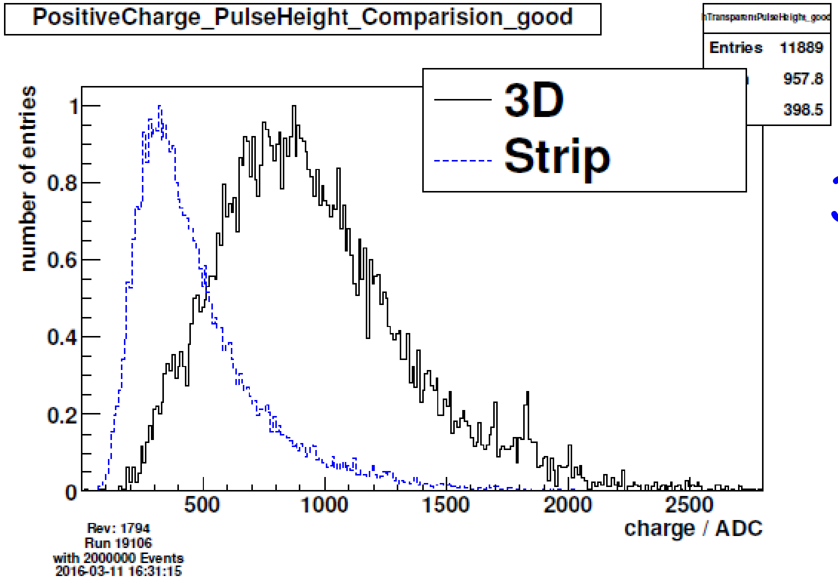
Femtosecond laser converts insulating diamond into resistive mixture of various carbon phases: amorphous carbon, DLC, nano-diamond, graphite.

- Initial methods had 90% column yield → now >99% yield with Spatial Light Modulation (SLM)
- Initial column diameters 4-6μm → now 2.6μm (with SLM)



3D Device in pCVD Diamond

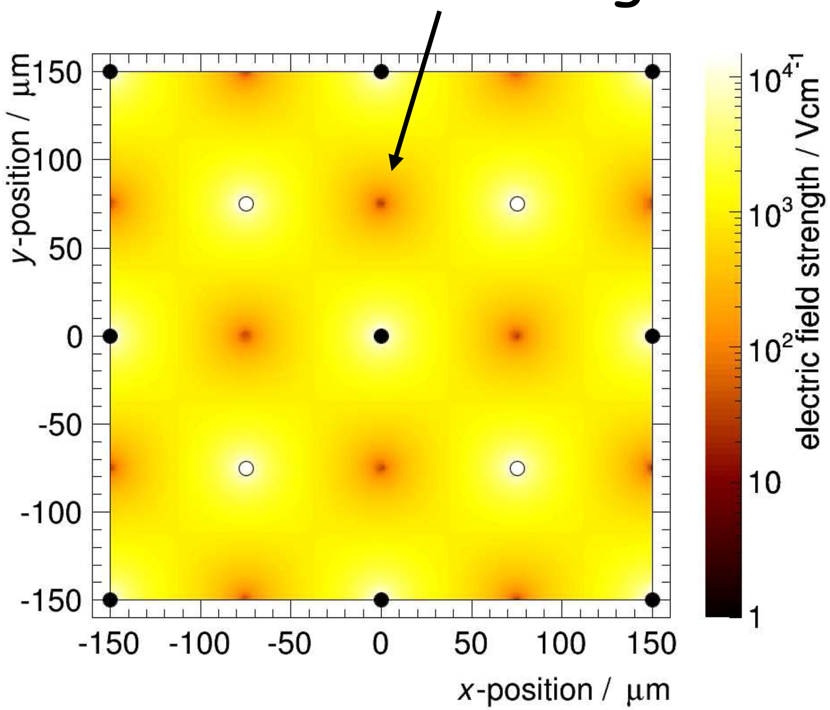
- Measured signal (diamond thickness 500µm):
  - Planar Strip ave charge
    6,900e or ccd=192µm
  - 3D ave charge
    13,500e or ccd_{eq}=350-375µm
- First time we collected >75% of deposited charge in pCVD



3D cell size:
150µm x 150µm

3D Device in pCVD Diamond

- Measurements consistent with TCAD simulations:
  - Large cells, large diameter columns → lower field regions in saddle points



Cell size: 150µm x 150µm
Voltage: 25V

from: G. Forcolin, Ph.D. Thesis
Manchester University 2017

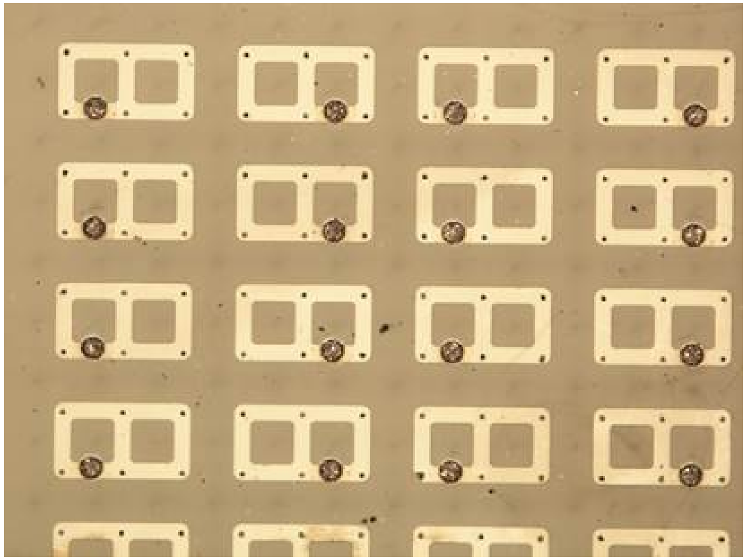
This part was understood well enough to construct pCVD 3D diamond pixel devices with various cell sizes.

Results of CMS 3D pCVD Pixel Devices

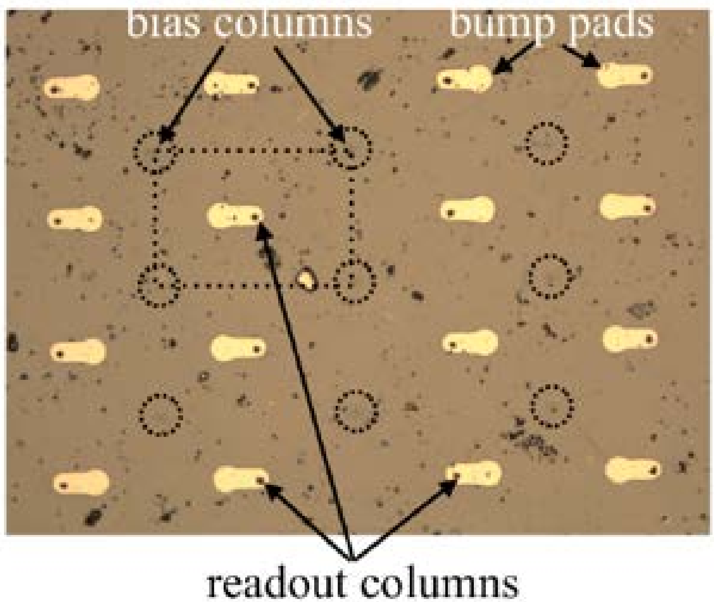
Produced 4000 cell pixel prototype w/50µm x 50µm pitch

- Three fabricated: Oxford 2, Manchester 1
- 50µm x 50µm cells ganged for 3x2 (CMS) readout
- Bump bonding: CMS@Princeton (In)
- 3x2 ganged tested in Aug 2017@PSI, Sep, Oct 2018@CERN
- Compared to 100µm x 150µm tested in Aug 2017@PSI

50µm x 50µm cells, ganged



100µm x 150µm

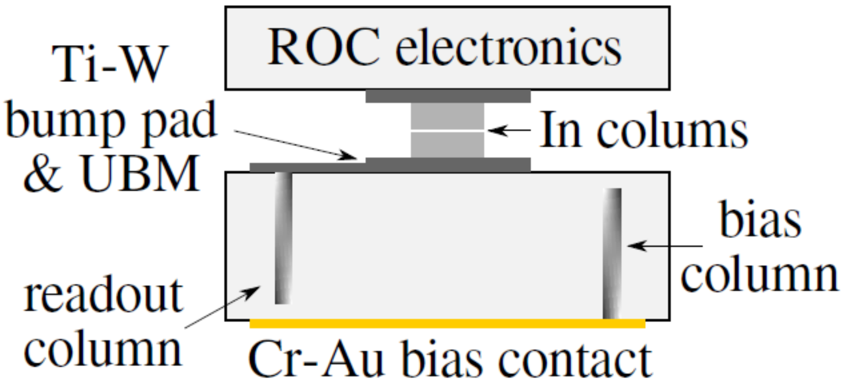


Comparison of CMS 3D pCVD Pixel Devices

3D pixel device structures [50μm x 50μm] compared to [100μm x 150μm] cells

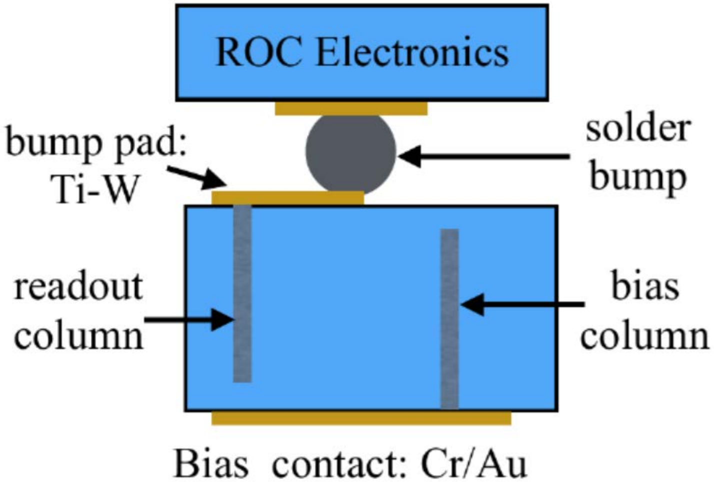
- Produced cells with 100μm x 150μm size for CMS pixel readout chip
- Cleaning, photolithography, metal contact to pixel and bias – RD42
- Bump and wire bonding - Princeton

[50μm x 50μm]



(a) Bump bond schematics

[100μm x 150μm]

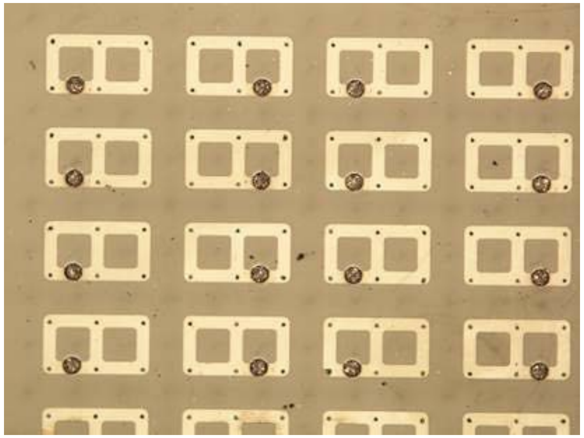


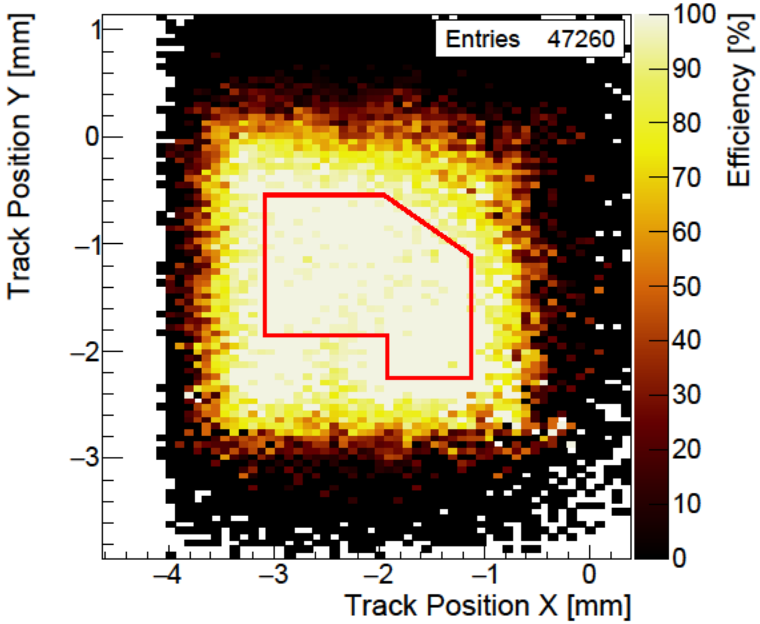
(b) final scheme

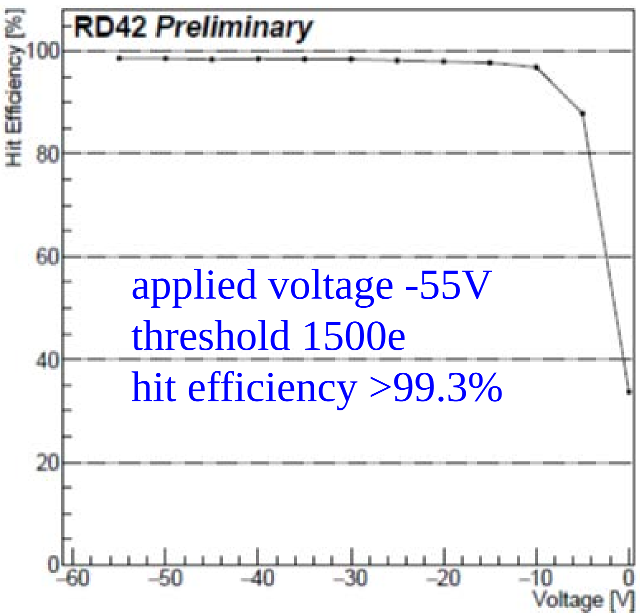
Results of CMS 3D pCVD Pixel Devices

Results (50µmx50µm cells)

- Readout w/PSI46digv2.1-respin CMS chip
  6 cells (3x2) readout w/1 pixel channel
- Preliminary efficiency >99.3% threshold 1500e
- Collect >85% of charge!



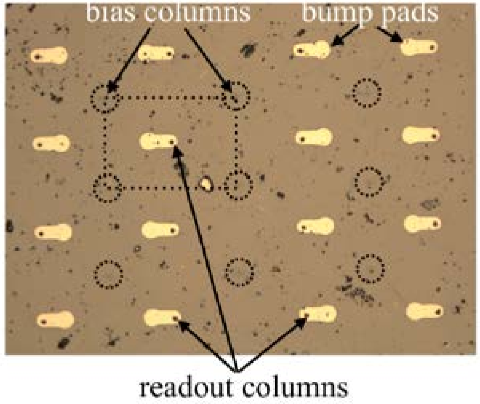


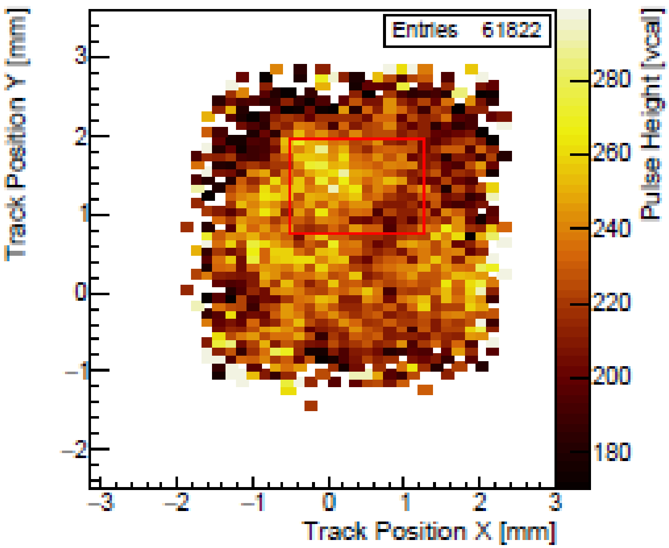


Results of CMS 3D pCVD Pixel Devices

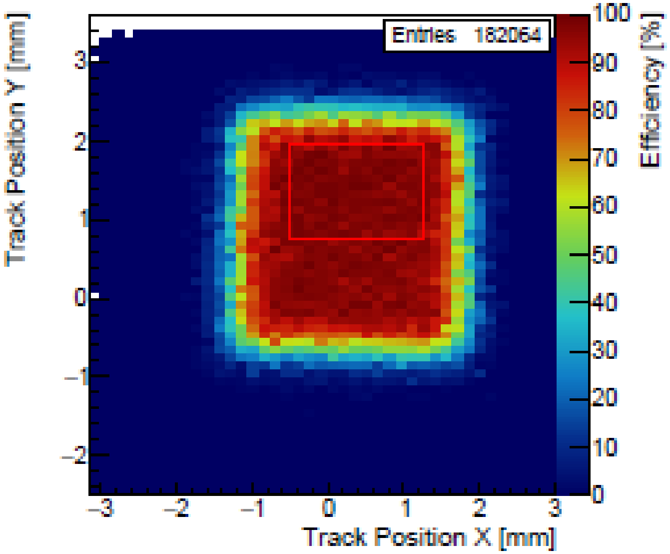
Results (100μmx150μm cells)

- Readout w/PSI46digv2.1-respin CMS chip
  - 1 cell readout w/1 pixel channel
- Efficiency >90.0%, threshold 1500e
- Collect >55% of charge!





(a) Pulse height map.



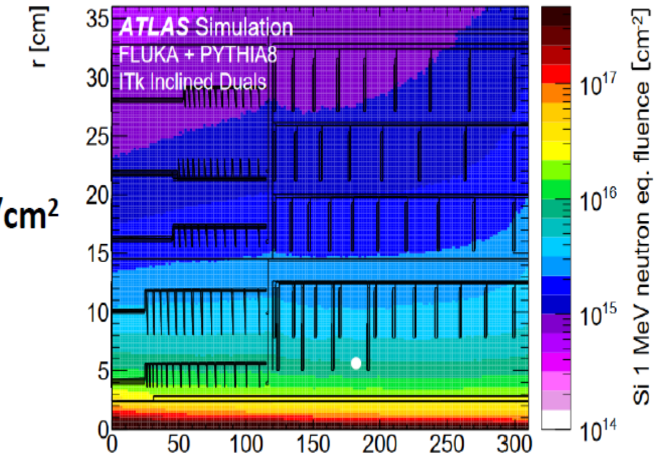
(b) Hit efficiency map.

Development of the ATLAS BCM' system for Beam Abort and Luminosity Determination

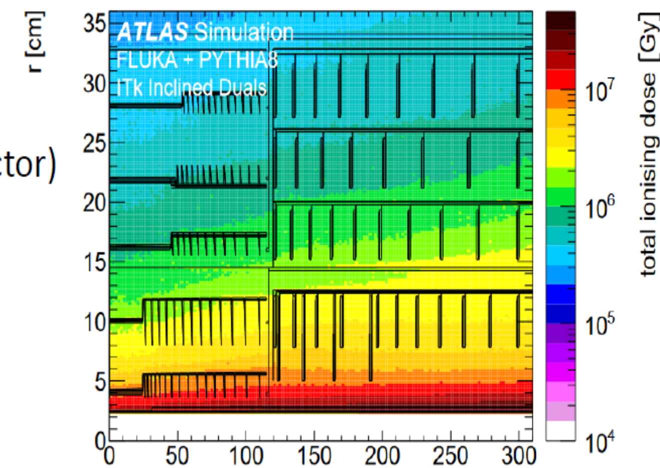
Development of the ATLAS BCM'

- Beam Conditions Monitor (BCM) in ATLAS at the LHC:
  - Based on radiation tolerant diamond sensors
  - Installed since 2008
  - Located in the Pixel Detector at $z = \pm 184$ cm, $r = 5.5$ cm
    - **NIEL 1 x 10^{15} n_{eq}/cm^2, TID 50 Mrad**, charged particle flux up to **60 MHz/cm²**
- BCM provides bunch-by-bunch detection for **Beam Protection and Luminosity measurement:**
  - Per-bunch fast safety system *(abort)*
  - Background monitoring
  - Per-bunch luminosity meter (*lumi)*

  } Can abort LHC beam to protect the tracking detector
- HL-LHC: particle density will increase by almost an order of magnitude
  - Charged particle flux up to **230 MHz/cm²** at pile up **μ = 200**
  - **NIEL 3 x 10^{15} n_{eq}/cm^2, TID 300 Mrad** after **2000 fb^{-1}** (including x 1.5 safety factor)



[ATLAS ITk Pixel TDR]



> A new **BCM'** system will be installed in ATLAS ITk in 2024
> BCM' group: OSU, JSI, Manchester, Wiener Neustadt, CERN

Development of the ATLAS BCM'

BCM' should provide for $\mu \leq 200$:

- Fast bunch-by-bunch safety system for ATLAS
- Background monitoring
- Luminosity measurement

In an environment of:

- Flux $\leq$ 220 MHz/cm^2
- NIEL $\leq 2 \times 10^{15}$ hadrons/cm^2
- TID $\leq$ 200Mrad

BCM' Solution is:

- Multiple detectors by function (BCM, BLM, Abort, Lumi)
- Multiple detectors with same functionality for cross-check
- Fast electronics (<1.5ns rise-time, <15ns recovery)
- Everything rad tolerant (65nm TSMC)

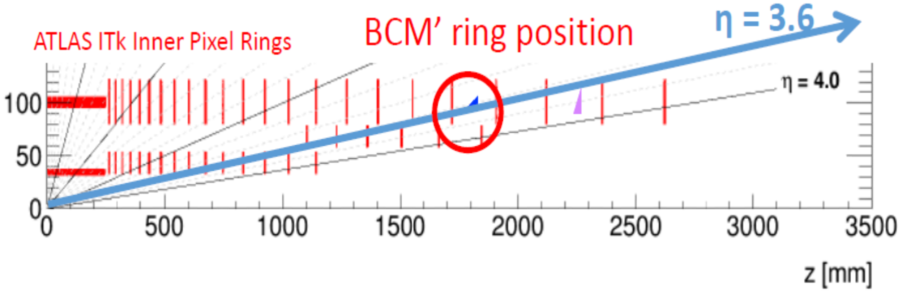
Development of the ATLAS BCM'

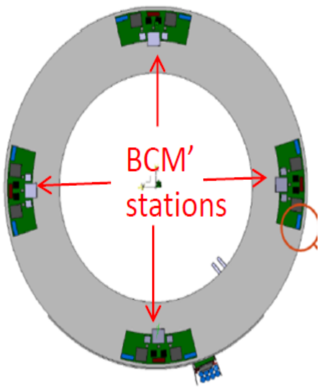
- Good S/N with 1 detector/ch @45°
  - ✓ electronics in 65nm technology for extra gain-bw
  - ✓ preamp is differential after 1st stage
  - ✓ preamp noise should be <400e for initial signal of ≥8000e
- Individual preamps for Abort (Me) and Lumi (ke)
  - ✓ electronics with 2 preamps/ch
  - ✓ low gain preamp (Abort) with adjustable thresholds
  - ✓ high gain preamp (Lumi) with adjustable thresholds
  - ✓ differential design + independent ch V, gnd to minimize crosstalk
  - ✓ preamp output directly coupled to on-chip CF discriminator
- Baseline threshold stability, voltage stability and rate
  - ✓ preamp should be able to handle μ=200
  - ✓ preamp recovery to <2% in 15ns for PH up to saturation
  - ✓ preamp output semi-digital (leading edge: TOA, width: TOT)

Development of the ATLAS BCM'

- Located within the new ATLAS ITk Pixel Inner system on both detector sides at r = 100 mm, z = ± 1800 mm (6.25 ns) from Interaction Point
- Collision/background separation based on Time of Flight
  - **Luminosity:** Collision products arrive simultaneously on both detector sides (in-time)
  - **Beam protection:** Background arrives out-of-time, 12.5 ns interval between two sides
- Four stations per each side of the detector
- Multiple detectors by function
  - Abort (dynamic range 10^5 MIP)
  - Beam Loss Monitor (BLM) – slow, integrating, electronics copied from LHC machine
  - Luminosity (single MIP sensitivity)

Each with own sensor





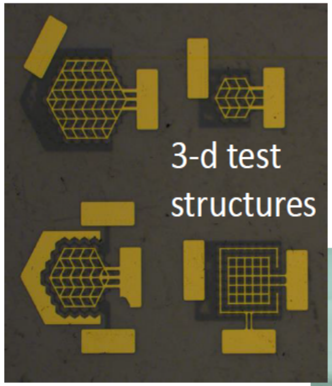
BCM TOF concept

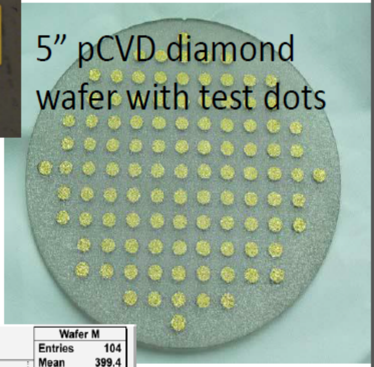
- **Collisions: in time**
- **Background: out of time**

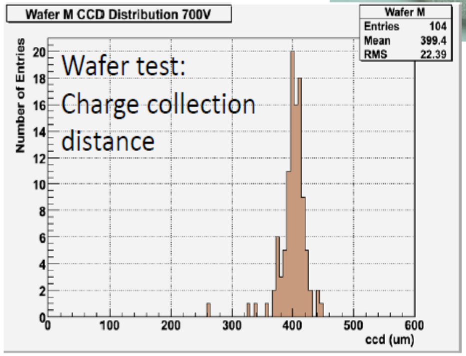
[2008 *JINST 3* P02004]

Development of the ATLAS BCM'

- Sensitivity on very broad range of particle fluxes required
  - Four orders of magnitude, $\mu_{vdM} = 0.01 \rightarrow \mu_{ultimate} = 200$
  - Dynamic range flexibility by segmenting the sensor into pads of varying size
- Three types of *polycrystalline chemical vapor deposition* (pCVD) diamond sensors and one silicon sensor per station:
  - **5 mm x 5 mm** (abort), four pads
  - **10 mm x 10 mm** (lumi), three pads (size 1 mm^2 – 50 mm^2)
  - **1 mm x 1 mm 3D** (lumi), single pad, hex or square electrode cells (53 µm sense-to-field electrode spacing), C = 5 pF, highest radiation tolerance
  - Small **Si pad/strip** (lumi), 10 mm^2, 5 pF
- Diamond sensors produced by US vendor II-VI (worked with RD42)
  - Three 500 µm thick 5-inch wafers have been grown for the project
  - Prototypes delivered Dec 2021
  - Promising first measurements of charge collection, long term current stability
- Preproduction will start in mid-2022







Development of the ATLAS BCM'

Parameter	Condition	Min	Typ	Max	Unit
Supply voltage	VDDFEX, VDDA, VDDDX	1.08	1.20	1.32	V
Current consumption per active channel (X)	VDDFEX		15.5		mA
	VDDA		16		
	VDDDX, with 50 Ω channel output termination.		6.5		
	Total		38		
Analog output offset (DC level)	With 50 Ω termination	90	120	170	mV
Analog output pulse P1dB	Peak Voltage – DC voltage. With 50 Ω termination.		325		mV
CFD LVDS output swing	Peak-to-peak differential swing		200		mVp-p
CFD LVDS common mode	With 100 Ω differential termination		600		mV
CFD LVDS transition time			100		ps
ABORT Gain	Independent of the sensor capacitance value		8.2		μV/fC
ABORT Rise time			1.5		ns
ABORT Settling time			13		ns
ABORT ENC			830		K e^-
LUMI Gain	At 2pF sensor capacitance		55		mV/fC
LUMI Rise time			1.6		ns
LUMI Settling time			14		ns
LUMI ENC			220		e^-
CFD intrinsic time walk	Over a linear output range			±20	ps
CFD threshold		-15		100	mV

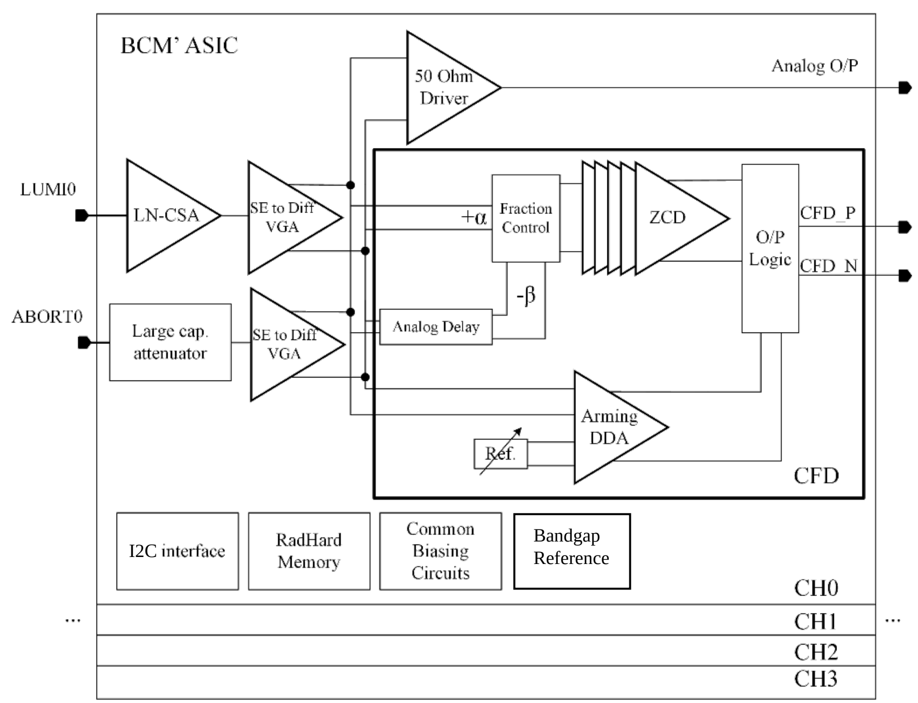
Measured parameters are within specifications

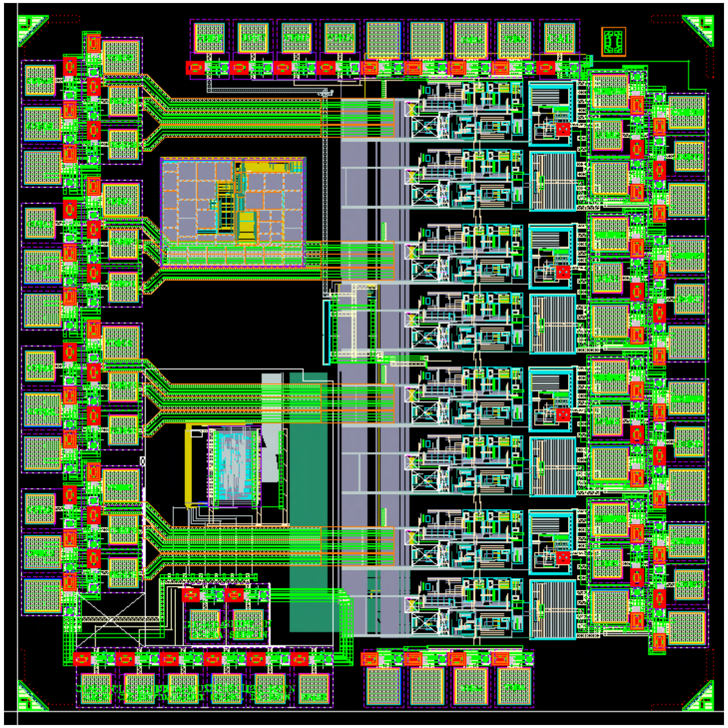
Development of the ATLAS BCM'

Present Version: Calypso_C ASIC

Calypso_B Data:

- Lumi design for 2pF load: Risetime 1.6ns, recovery 14ns, gain 55mV/fC, noise 220e
- Abort design independent of load: RT 1.5ns, recovery 13ns; gain 8.2μV/fC, noise 830ke



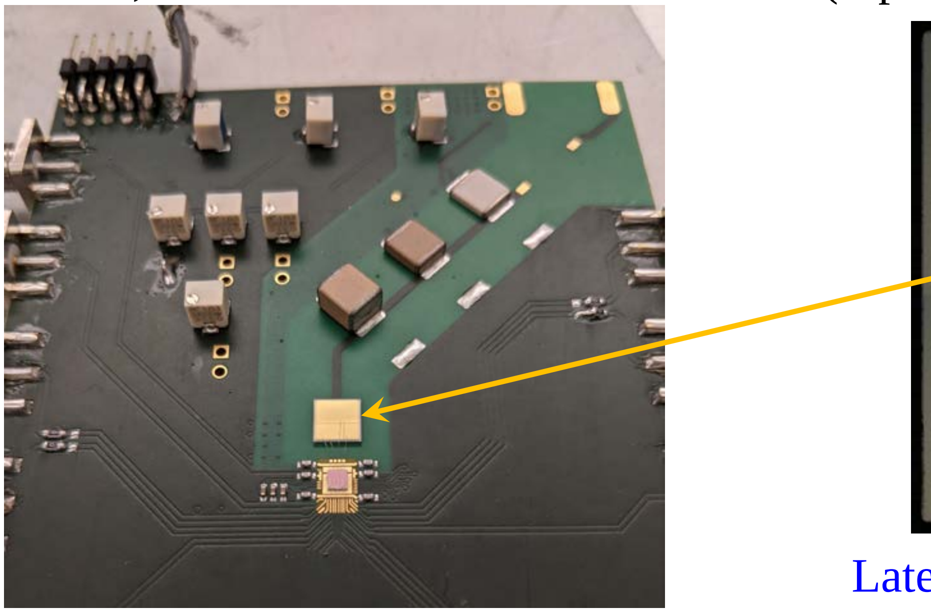


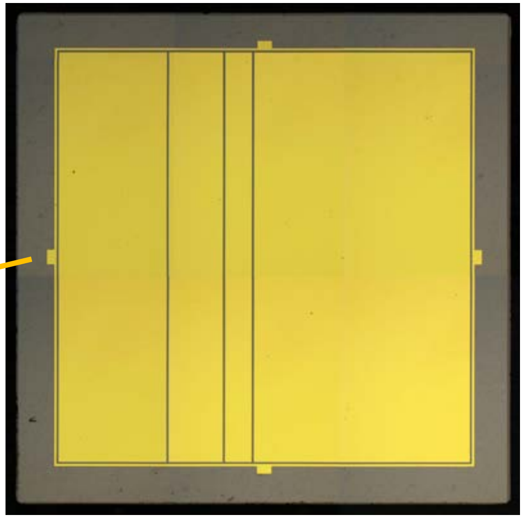
Development of the ATLAS BCM'

Prototype Modules Read Out with Calypso_C ASIC

4-Pad Abort Design Shown here:

- Material tested as described in Sensor PDR
- Photos, Xpol and DIC taken of all samples
- Edges characterized
- Pre-selection performed w/photo-lithographic contacts on active area of material
- Cleaned, Re-metalized with BCM' contacts (3-pad and 4-pad)





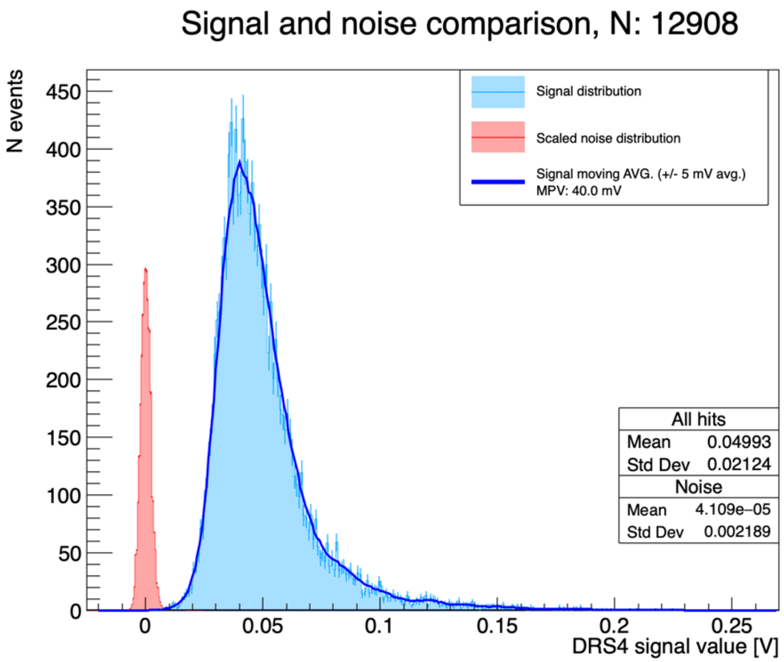
Latest Detector Design: 4:2:1:8

Development of the ATLAS BCM'

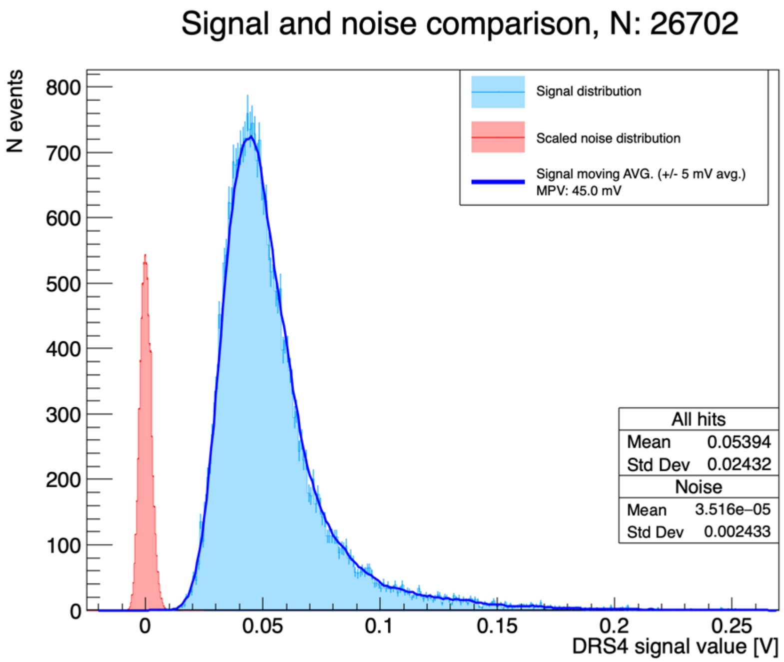
New S Modules read out with Calypso_C in beamtest at CERN

4-Pad Abort Design (4:2:1:8):

- Results w/Calypso_C using AnalogOut and TOT
- Tracking in MALTA Telescope in Jun, Aug, Oct 2022 Test Beam



Small pad, size=1, C=0.45 pF



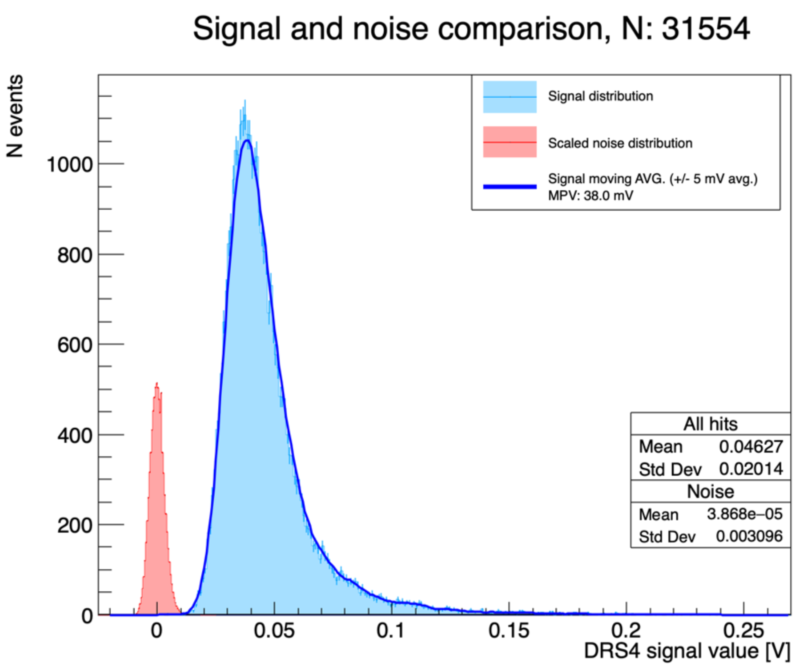
Medium-Small pad, size=2, C=0.90 pF

Development of the ATLAS BCM'

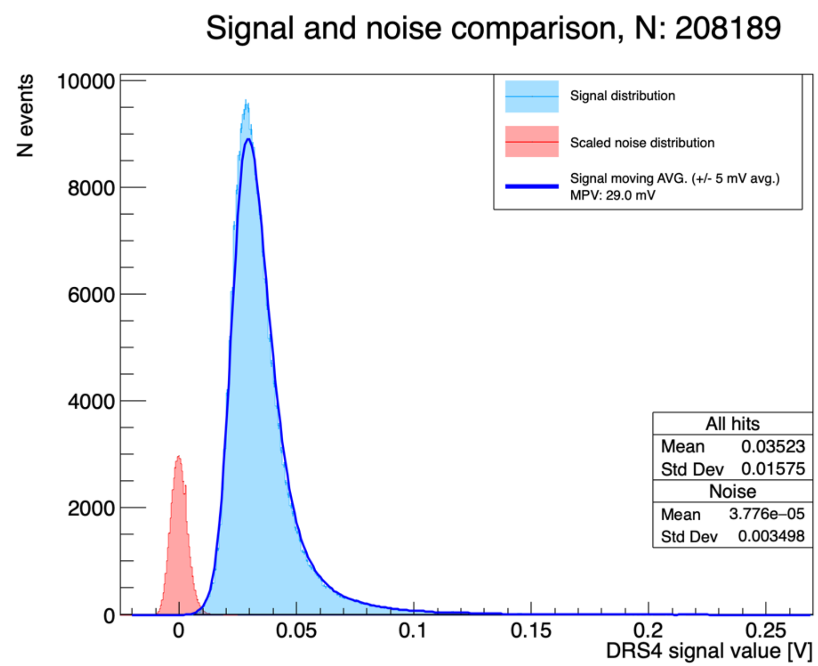
New S Modules read out with Calypso_C in beamtest at CERN

4-Pad Abort Design:

- Results w/Calypso_C using AnalogOut and TOT
- Tracking in MALTA Telescope in Jun, Aug, Oct 2022 Test Beam



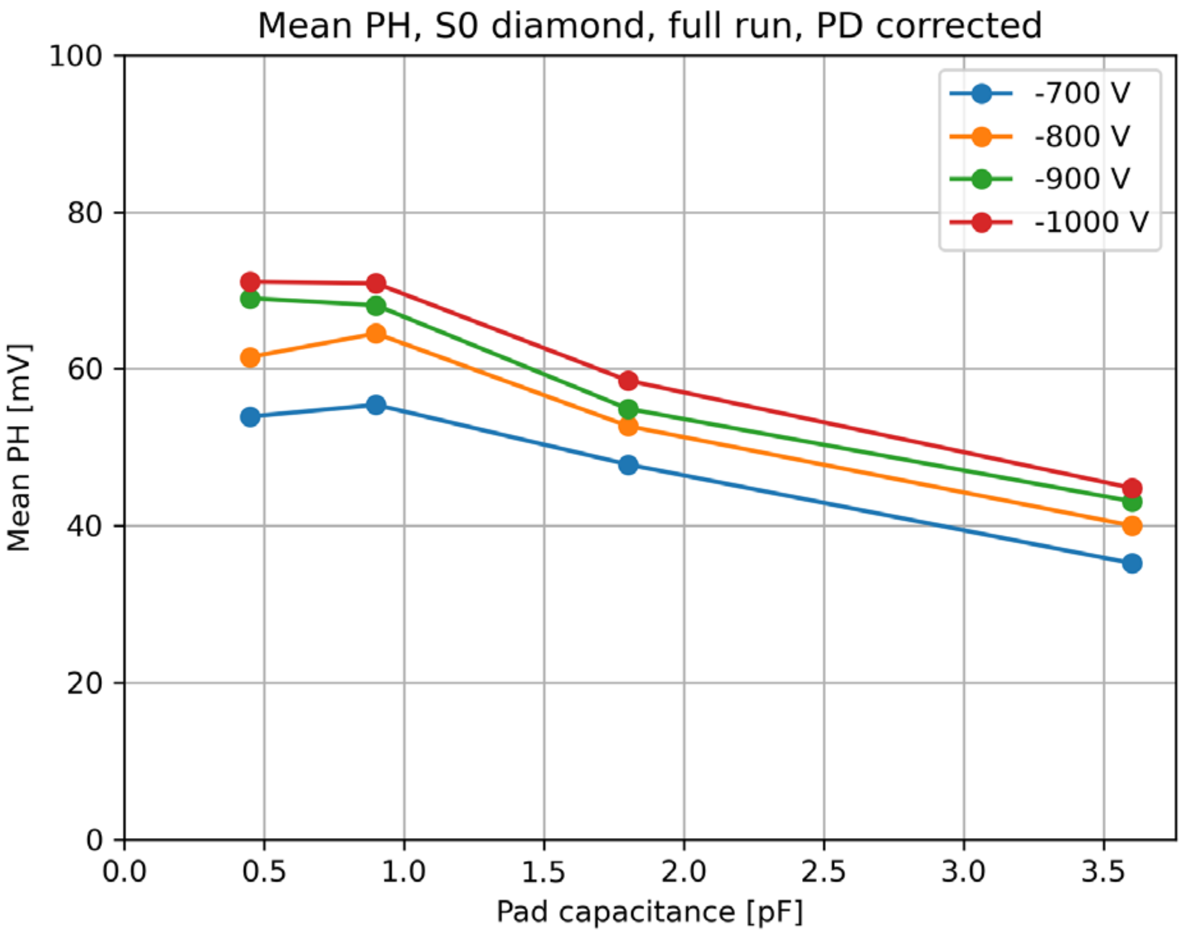
Medium-Large pad, size=4, C=1.8 pF



Large pad, size=8, C=3.6 pF

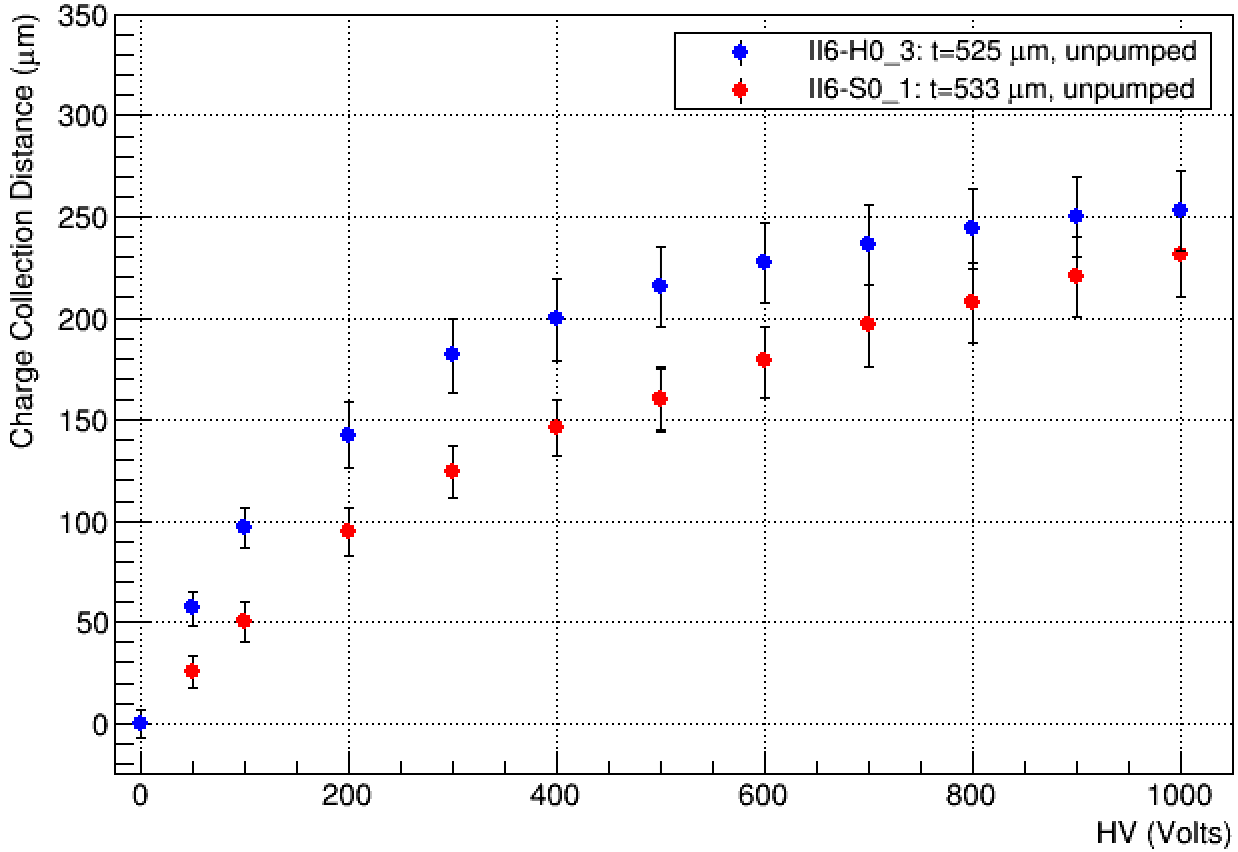
Development of the ATLAS BCM'

Mean PH - S0 read out with Calypso_C in Beam test at CERN



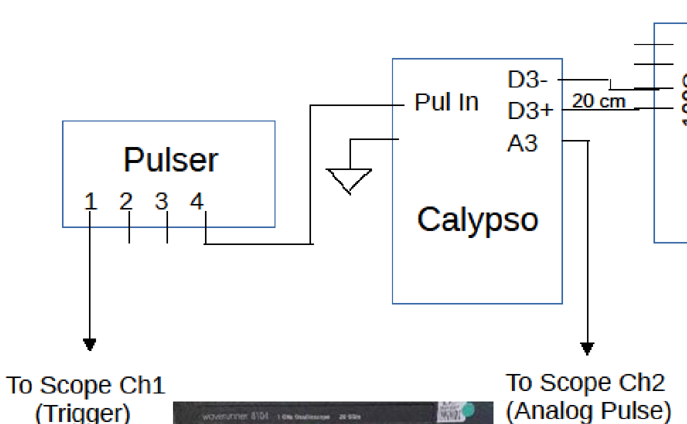
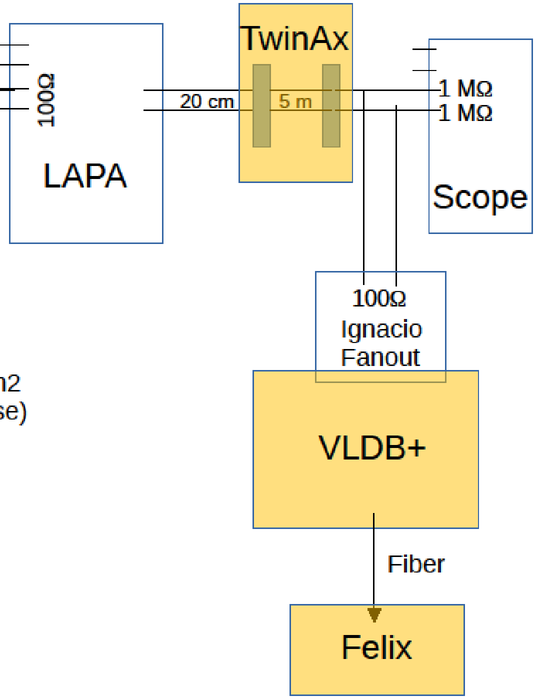
Development of the ATLAS BCM'

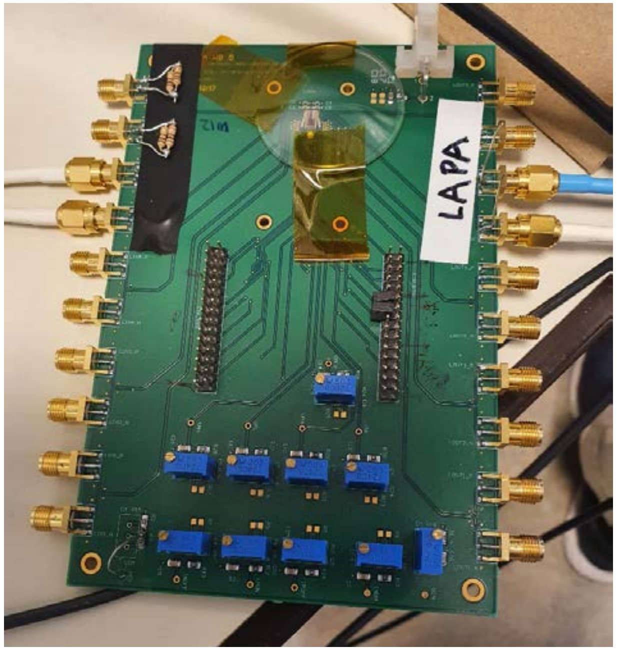
Comparison of new S0, with old H0 read out in the source setup at OSU
H0 presently yields more charge than S0 (after 1 yr of work)

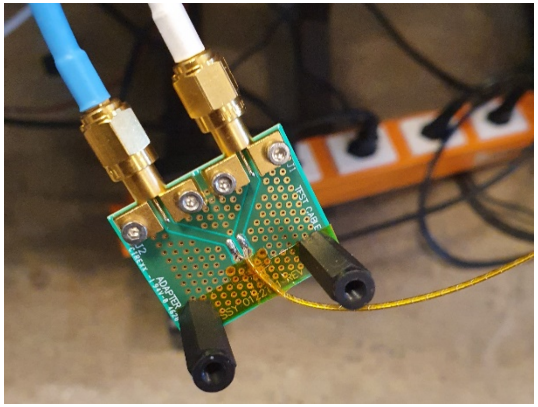


Development of the ATLAS BCM'

- System test w/Calypso_C driving Twinax, LAPA, VLDB+, FELIX (at CERN)





Summary of RD42 Work

Lots of progress in diamond with HL-LHC in view

- Quantified understanding of radiation and rate effects
  - pCVD shows no rate effect up to 10MHz/cm^2,8x10^{15}n/cm^2 @1000V
  - Irradiate devices to 2-4x10^{16} this year; continue rate studies
- 3D detector prototypes for 10^{17} operation - great progress
  - 3D works in pCVD diamond
  - Scale up (x40) worked; continue scale up (x10) this year
  - Smaller cells (50μm x 50μm) worked; test smaller cells (25μm)
  - Thinner columns (2.6μm) worked; try 2.0μm for 25μm x 25μm cells
- 3D diamond pixel devices being produced
  - All work as expected; just tested 50μm cells irrad@3.5x10^{15}p/cm^2
  - Visible improvements with each step
  - Efficiencies look good, still a bit to be understood w/charge
- BCM' design underway – nearly complete

Acknowledgements

The RD42 Collaboration gratefully acknowledges the staff at CERN for test beam time and their help in setting up beam conditions. We would also like to thank the beam line staff at the PSI High Intensity Proton Accelerator. The research leading to these results received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 654168. This work was also partially supported by Swiss National Science Foundation Grant #20FL20_154216, ETH Grant 51 15-1, Swiss Government Excellence Scholarship ESKAS No. 2015.0808, UK Science and Technology Facilities Council Grant ST/M003965/1 and U.S. Department of Energy Grant DE-SC0011726.