Development of CVD Diamond Tracking Detectors for Experiments at High Luminosity Colliders

RD42 Status Report

Harris Kagan
for the RD42 Collaboration

LHCC Open Session – November 30, 2022

Outline of Talk

- The RD42 Collaboration
- Highlights of Work Accomplished
- Status of RD42 2022 Program Milestones
- Summary

The 2022 RD42 Collaboration

The 2022 RD42 Collaboration

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110 participants

28 institutes

The RD42 Areas of Work, Publications, and more

Areas of work in RD42:

- Materials work (characterization of diamond)
- Work with manufacturers (feedback)
- Development of detectors (pad, strip, pixel, 3D)
- Development of machine devices (BLM, lumi)
- Irradiation (JSI, FNAL) and Beam tests (CERN, PSI)
- Work with LHC experiments

RD42 meetings: https://indico.cern.ch/category/3177/

- 11 papers published in 2019, 6 in 2020, 6 in 2021
- 5 conference talks in 2019, 3 in 2020, 3 cancelled in 2021
- 2-3 Ph.D. students expect to graduate in 2022
- 5 Ph.D. students continuing in 2023

The RD42 Program

The RD42 program consists of the following elements:

7.1: 3D Diamond Sensor Fabrication and Characterisation

- Develop reduced column spacing + internal/external connection – issues are rad tolerance + redundancy

7.2: HL-LHC Beam Monitoring Proof-of-Principle

- Development of planar+3D diamond sensors plus dedicated ASIC development – issues are rad tolerance + calibration. Moving to $10^{17}/cm^2$ - Two publications of rad tolerance so far with 1916/1276 total downloads to date

7.3: Development of pCVD Material

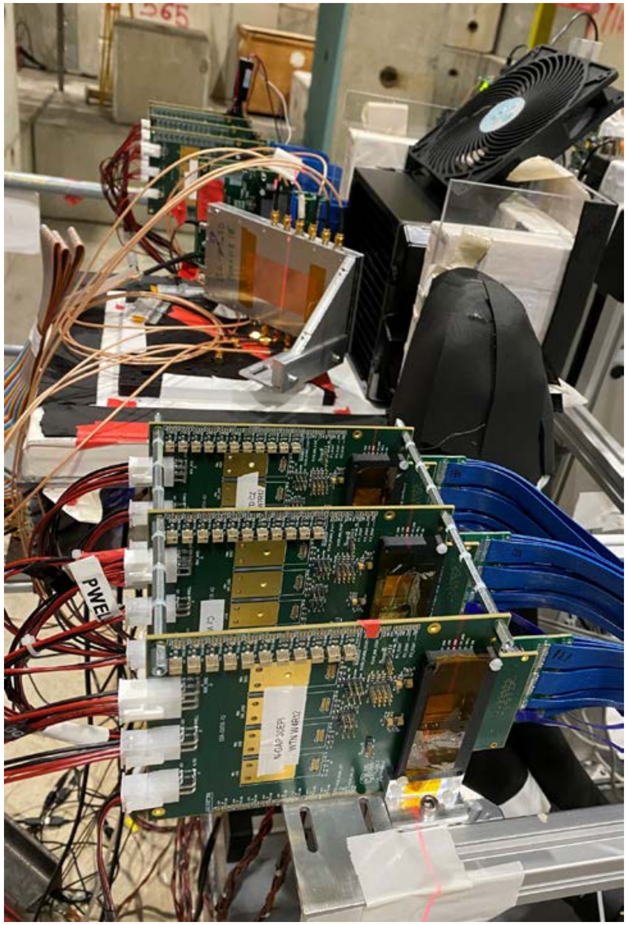
7.4: Development of 3D Diamond Pixel Modules

- Using existing ASICs

Highlights of Work Accomplished

Test Beam Studies at CERN (using the MALTA Telescope)

- characterization of devices without multiple scattering
- relatively high rate ~4000 events/spill
- transparent or unbiased hit prediction from telescope
- tracking precision at detector under test: ~2-3μm



Highlights of Work Accomplished

Radiation Tolerance Studies (published)

- 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:

$$n = n_0 + k\phi$$

$$\downarrow \qquad \downarrow$$

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

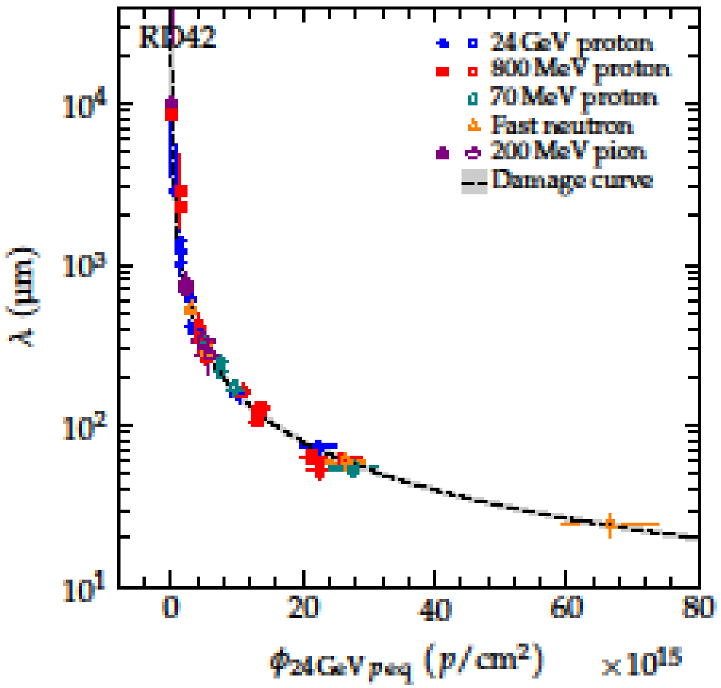
n number of traps
n_0 initial traps in material
k damage constant
ϕ fluence
λ MFDD
λ_0 initial MFDD

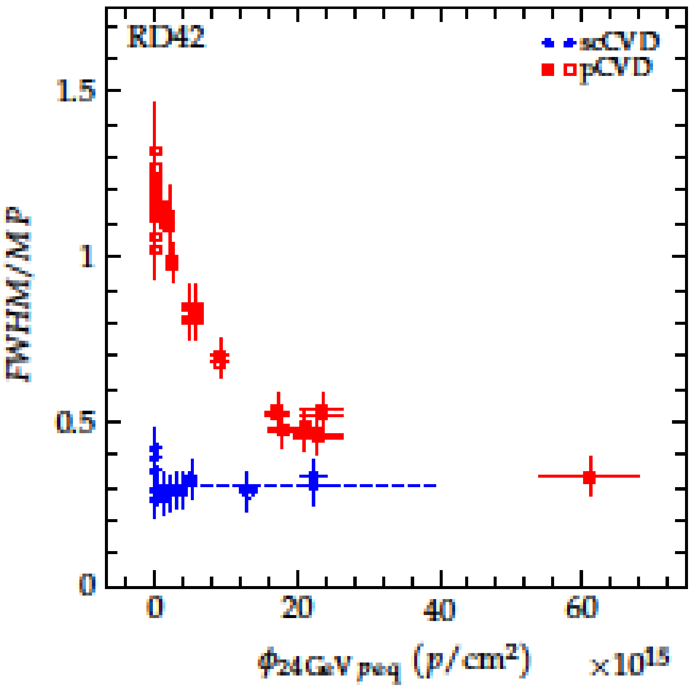
- Fit in $1/\lambda$ vs ϕ space to determine k, λ_0

Highlights of Work Accomplished

Radiation Tolerance Studies (published)

1-Study 24GeV p, 800 MeV p, 70 MeV p, 25 MeV p, Fast n, 200 MeV π
2-Determine damage constant for each using 1st-order model
3-Determine Universal Damage Curve scaling parameters
4-Quantify signal response (λ) and uniformity (FWHM/MP) vs dose

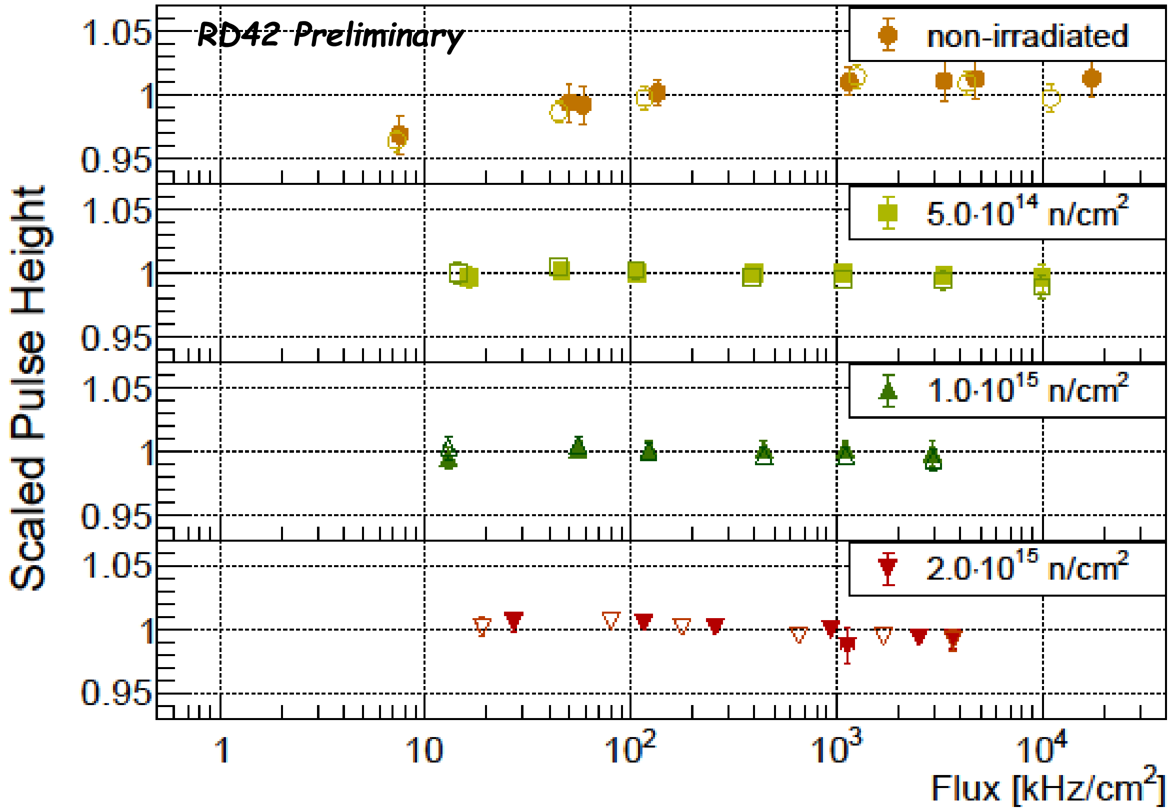




Highlights of Work Accomplished

Rate Studies

M. Reichmann
Ph.D. Thesis
ETH Zurich 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

Highlights of Work Accomplished

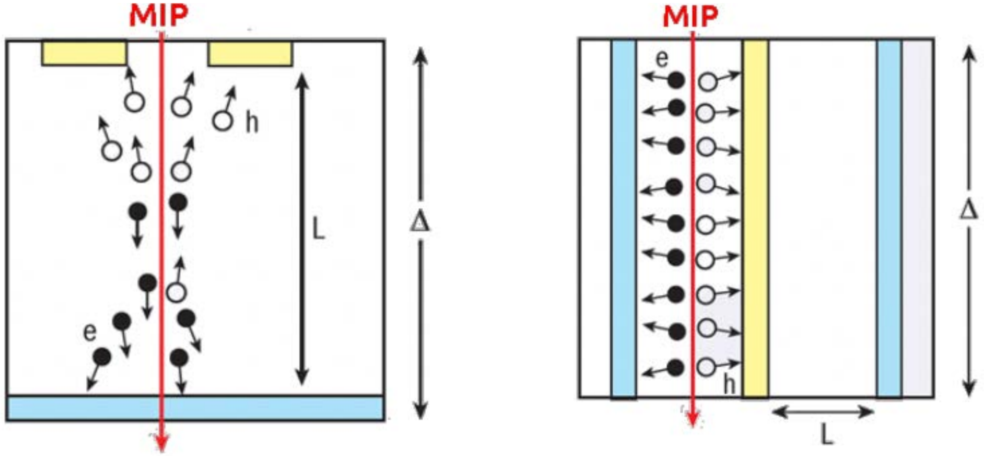
3D Device on pCVD Diamond

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 make 3D in pCVD diamond?



Planar 3D

Have to make resistive columns in diamond for this to work

-columns made with 800nm femtosecond laser

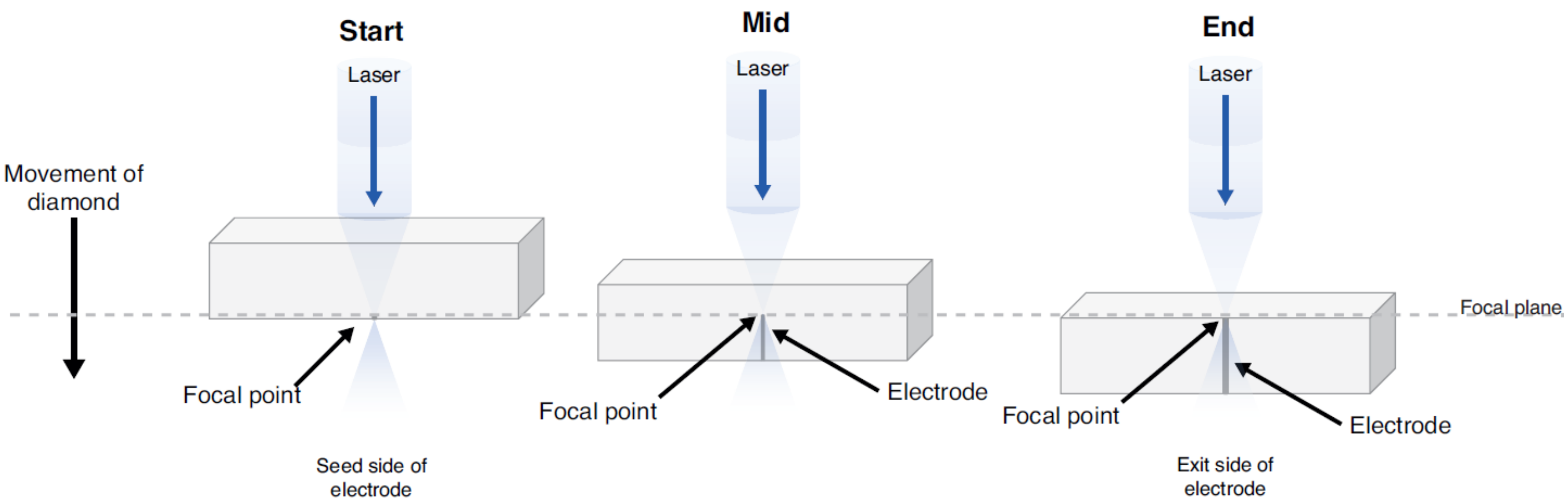
-initial cells 150μm x 150μm; columns 5-10μm diameter

Highlights of Work Accomplished

3D Device on pCVD Diamond

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

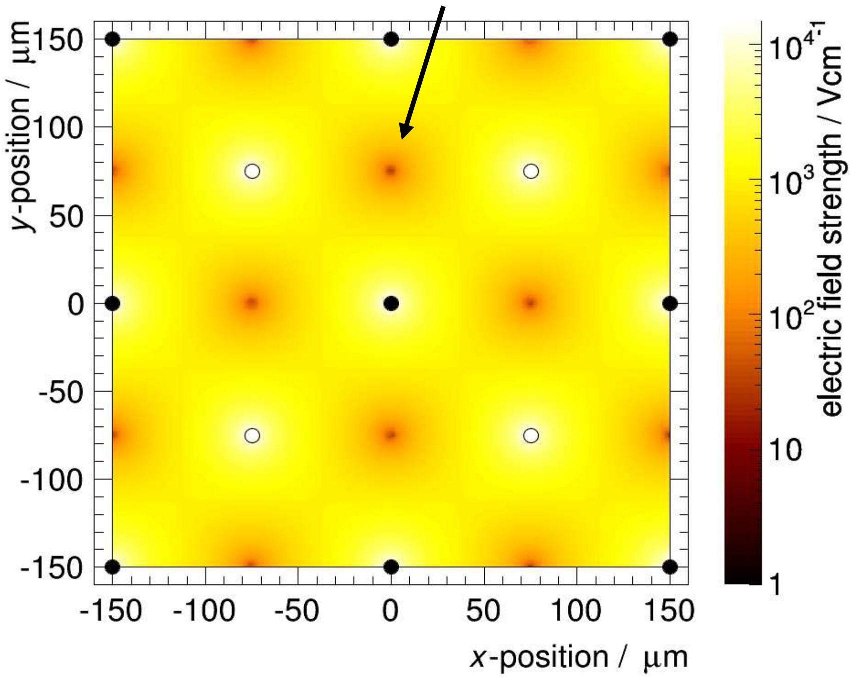
- Initial methods had 90% column yield → now >99% yield (Univ of Oxford) with Spatial Light Modulation (SLM)
- Initial column diameters 5-10μm → now 2.6μm (with SLM)



Highlights of Work Accomplished

3D Device on pCVD Diamond (reported previously)

- 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

Constructed pCVD 3DD pixel devices with various cell sizes

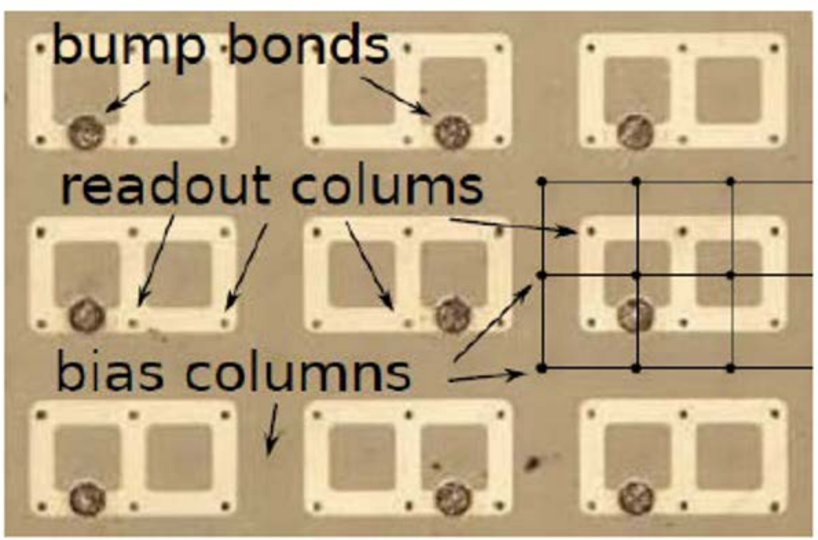
Highlights of Work Accomplished

3D Device on pCVD Diamond - 50µm x 50µm vs 100µm x 150µm

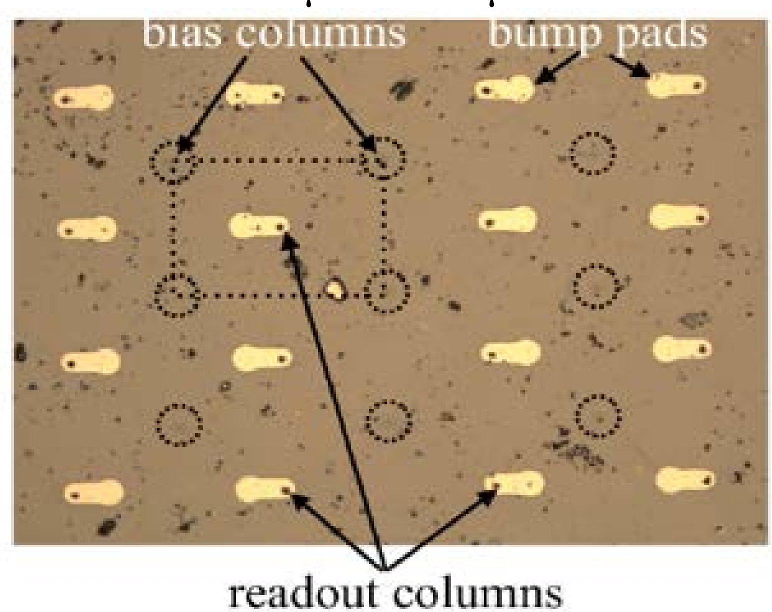
Produced 4000 cell pixel prototype w/50µm x 50µm pitch

- Both fabricated by University of Oxford
- 50µm x 50µm cells ganged for 2x3 (CMS) readout
- Bump bonding: CMS@Princeton (In)
- 50µm x 50µm ganged cells tested @PSI, DESY and CERN
- Compared to 100µm x 150µm tested @PSI

50µm x 50µm cells, ganged to 100µm x 150µm



100µm x 150µm

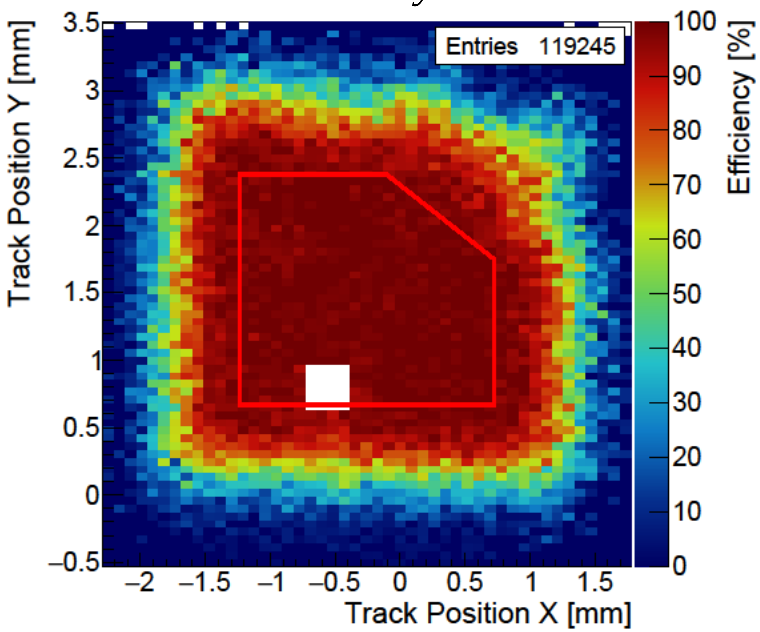


Highlights of Work Accomplished

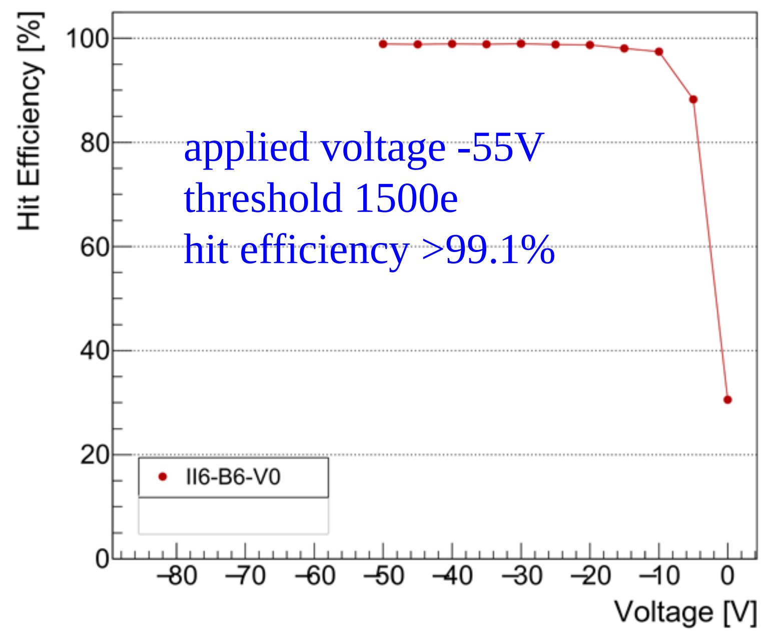
3D Device on pCVD Diamond - 50μm x 50μm cells, PSI results

- Readout w/PSI46digv2.1-respin CMS chip
  6 cells (3x2) readout w/1 pixel channel
- Efficiency >99.1% threshold ~1500e
- Collect >85% of charge!

RD42 Preliminary



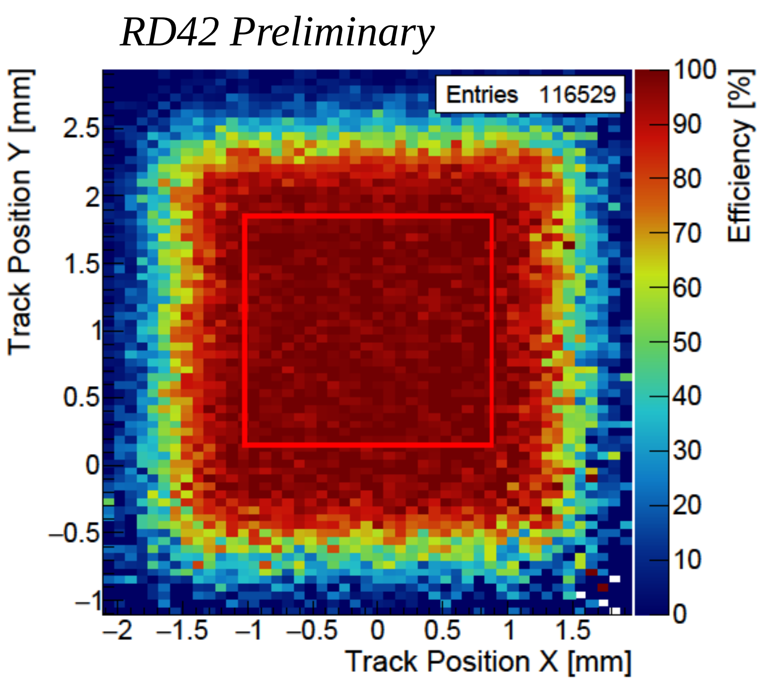
RD42 Preliminary

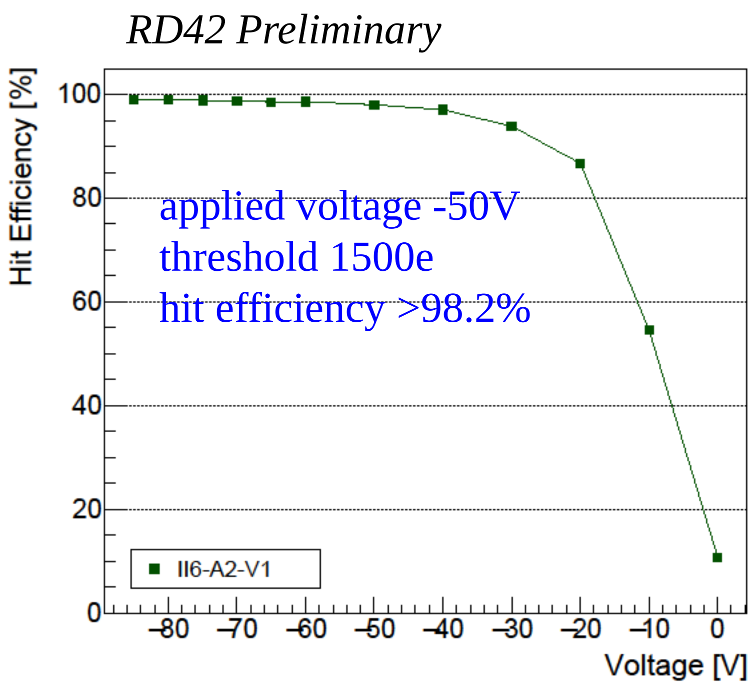


Highlights of Work Accomplished

3D Device on pCVD Diamond - 100μm x 150μm cell PSI results

- Readout w/PSI46digv2.1-respin CMS chip
  1 cell readout w/1 pixel channel
- Efficiency >98.2%, threshold ~1500e
- Collect >65% of charge!

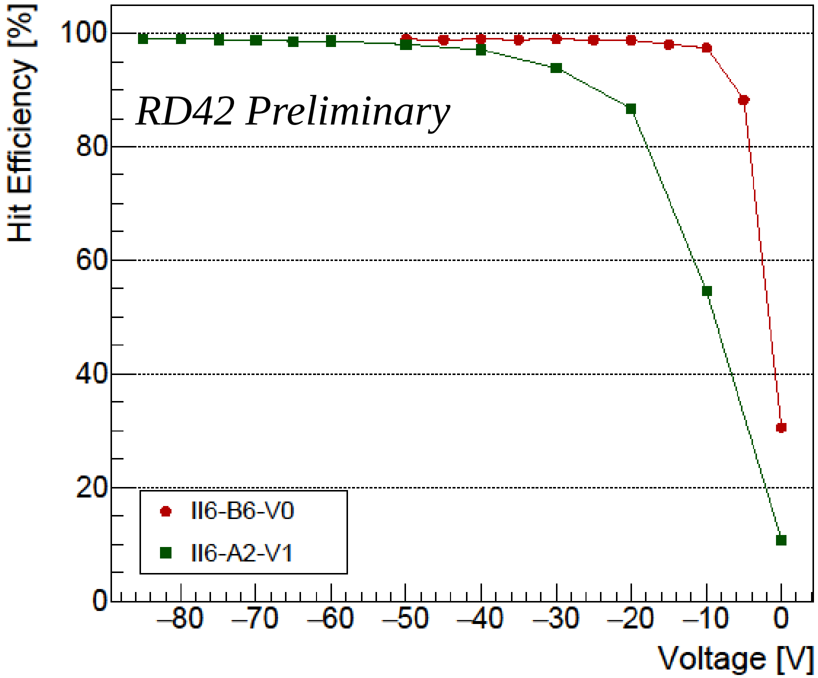




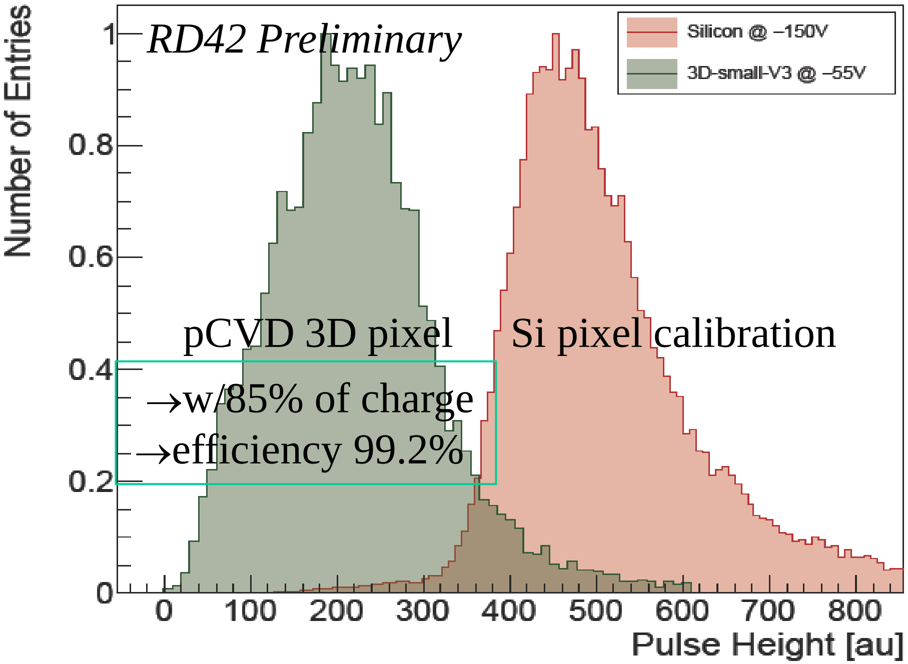
Highlights of Work Accomplished

Conclusion of 3D Pixel Devices in pCVD Diamond

- 3D devices in pCVD material work well! Can collect 85% of the charge from a pCVD diamond w/pixel electronics
- Efficiency >99% attainable. Small cells more efficient than large cells
- Small cells require less voltage to reach 99% efficiency



Data taken at DESY



Highlights of Work Accomplished

Collaboration with CERN/LHC Users - 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 $\leq$ 2x10^{15} hadrons/cm^2
- TID $\leq$ 200Mrad

ATLAS requires a 50% safety margin

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, <12ns recovery)
- Everything rad tolerant (65nm TSMC)

Highlights of Work Accomplished

Collaboration with CERN/LHC Users – ATLAS BCM'

RD42 helped the BCM' group in the following ways:

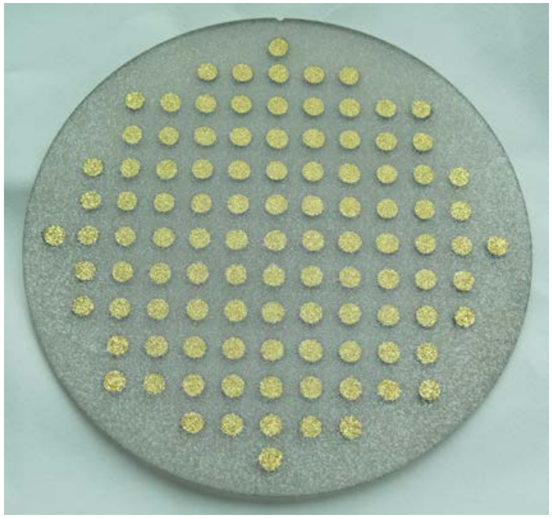
- Interface with vendor (II-VI Inc)
- Wafer Characterization
- Part Delivery
- Sensor Pre-selection and Characterization
- Repair of Sensor Production (ccd from 70μm → 220μm)
- Sensor Cleaning and Surface Preparation
- Mask Design and Metalization
- Device Testing and Selection
- Calypso_B and Calypso_C ASIC Development
- Provided 3D Diamond Detectors for BCM' to Test
- Beam Tests

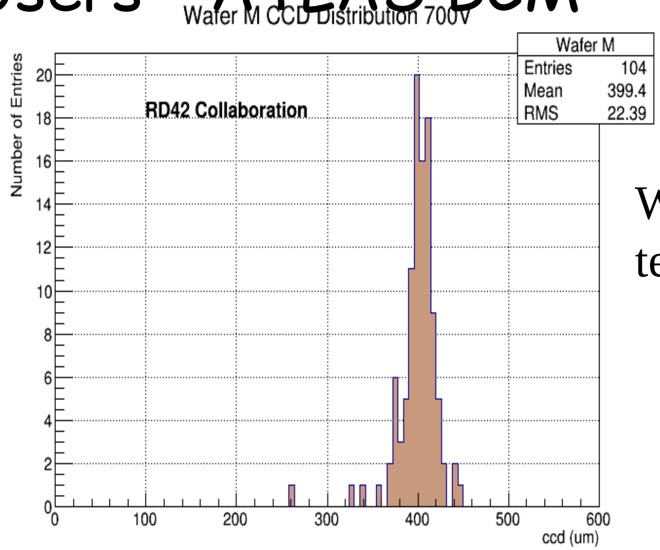
Similar to our work with CMS for BCM1F ~3 yrs ago

Highlights of Work Accomplished

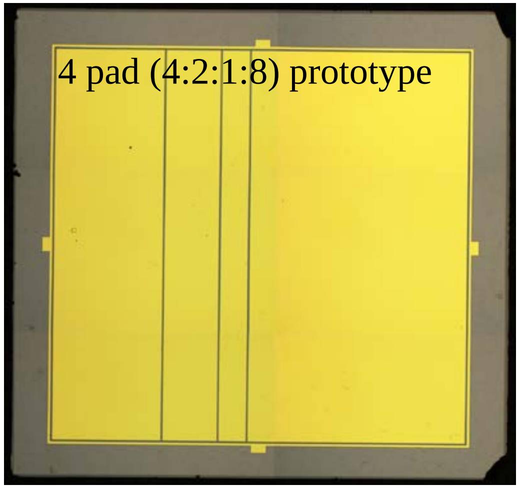
Collaboration with CERN/LHC Users – ATLAS BCM'

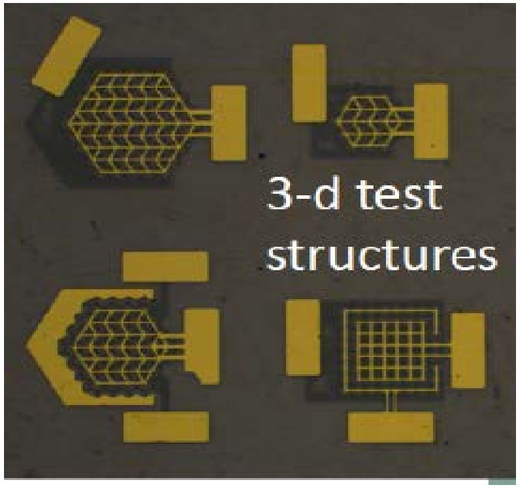
5.5” pCVD Wafer with test dots

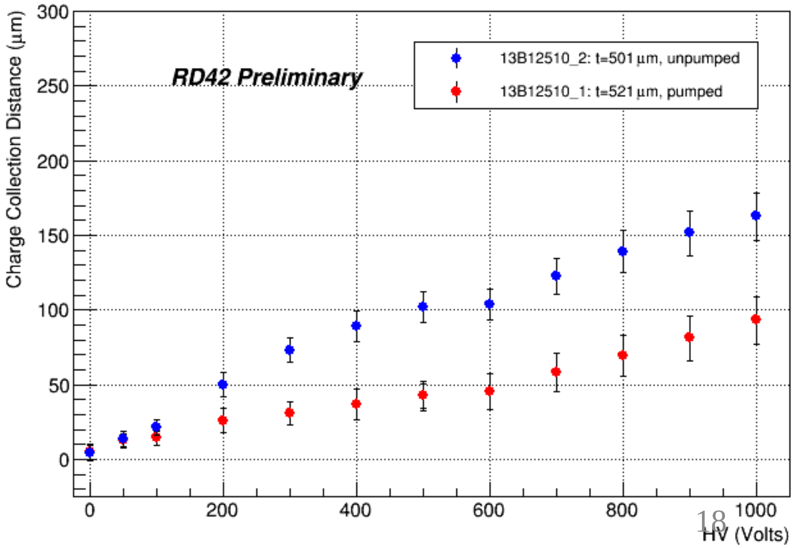




Wafer ccd test







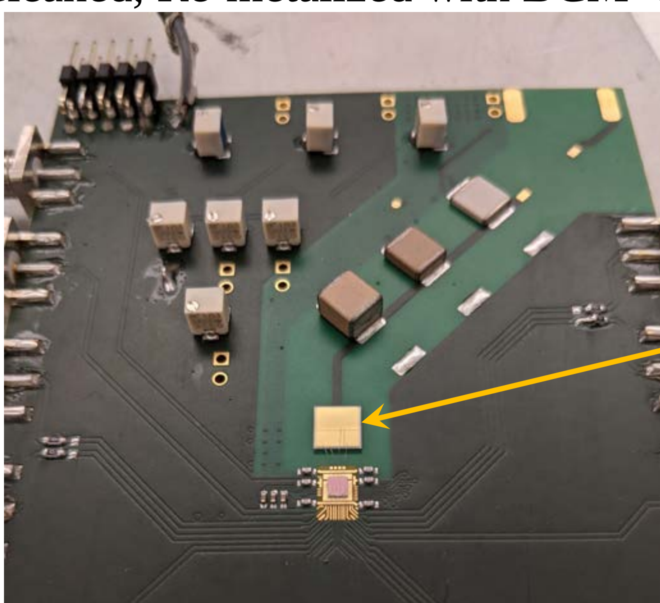
Highlights of Work Accomplished

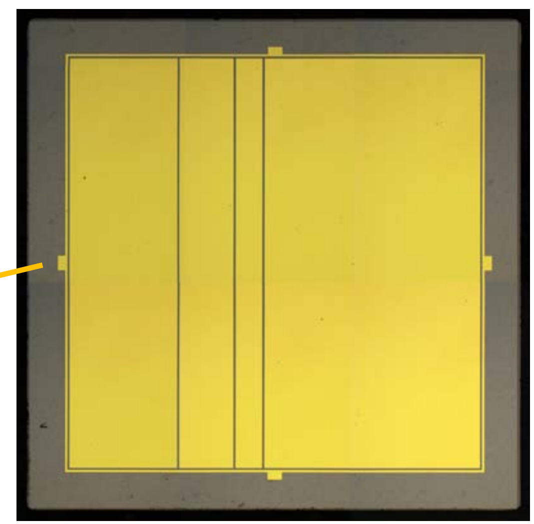
Collaboration with CERN/LHC Users – ATLAS BCM'

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

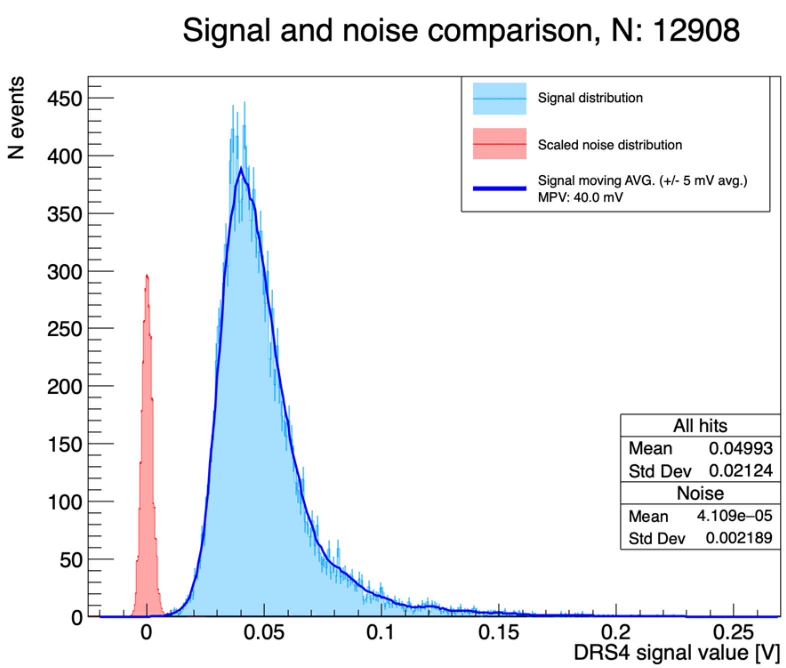
Highlights of Work Accomplished

Collaboration with CERN/LHC Users - ATLAS BCM'

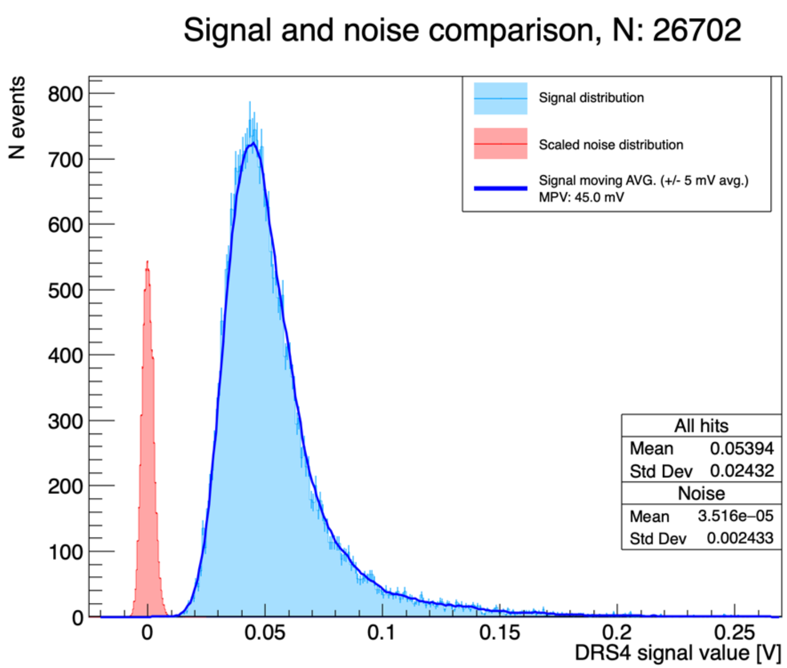
New S Modules read out with Calypso_C in MALTA telescope at CERN

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

- Results w/Calypso_C using AnalogOut and TOT with DRS4 waveform capture
- 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

Highlights of Work Accomplished

Collaboration with CERN/LHC Users – ATLAS BCM'

New S Modules read out with Calypso_C in MALTA telescope at CERN

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

- Results w/Calypso_C using AnalogOut and TOT with DRS4 waveform capture
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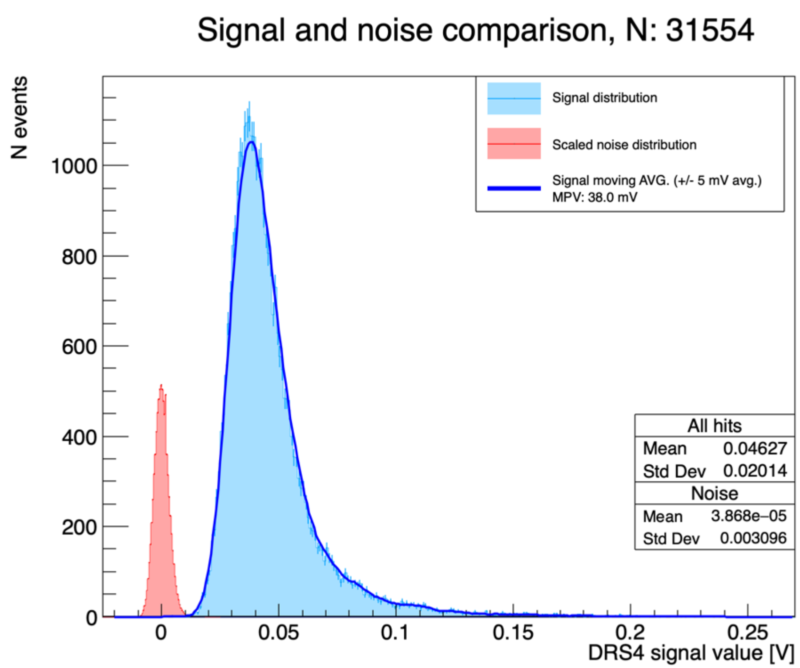
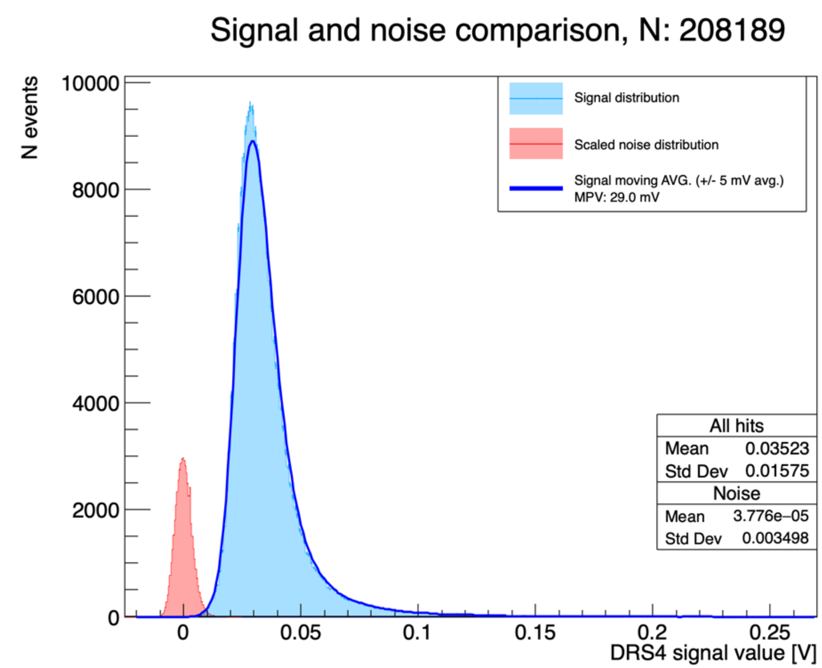


Medium-Large pad, size=4, C=1.8 pF



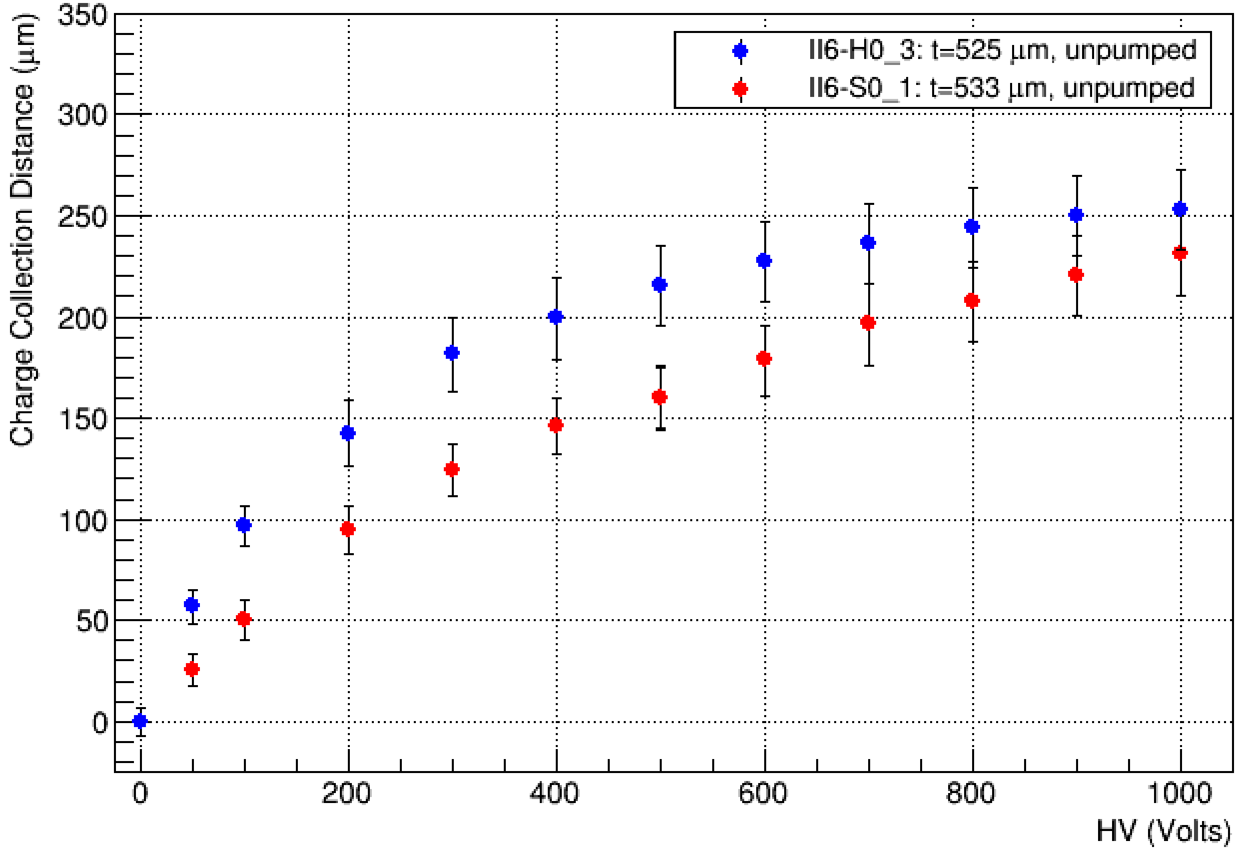
Large pad, size=8, C=3.6 pF

Highlights of Work Accomplished

Collaboration with CERN/LHC Users – ATLAS BCM'

Comparison of new S0, with old H0 read out in the source setup

H0 presently yields more charge than S0 (after 1 yr of work)



Status of RD42 2022 Program Milestones

7.1 Milestones: 3D Diamond Sensor Fabrication and Characterisation

- Complete testbeam analysis of early 3D prototypes to quantify operating points, collected charge, efficiency – Done (results in this talk)
- Irradiation of two early 3D prototype sensors configured as pad detectors to 10^{15} – Done
- Laser drilling 50 μm x 50 μm cells with 2.6 μm diameter columns with 99.9% yield – Done (Spatial Light Modulation is the key)
- Etched 3D columns produced and evaluated – In Progress

7.2 Milestones: HL-LHC Beam Monitoring Proof-of-Principle

- Produce third RD42 65nm HL-LHC beam loss/lumi ASIC – due in Dec
- Build first HL-LHC beam loss monitor station w/CalypsoD – In Progress
- Test CalypsoD at PSI with fluxes up to 20 MHz – postponed to 2023
- Test un-irradiated beam loss station with CalypsoC in test beam at CERN – Done (results in this talk)
- Irradiate one station (w/CalypsoC) to a fluence of 10^{15} – In Progress

Status of RD42 2022 Program Milestones

7.3 Milestones: Development of pCVD Diamond Material

- Work w/manufacturers to reduce surface imperfections and voids to less than $1/cm^2$ – was Done, now In Progress after processing changes

7.4 Milestones: Development of 3D pCVD Pixel Module Prototypes

- Fabricate and characterize a number of 3D diamond pixel devices with the latest advances with 50 μm x 50 μm cell size – Done (results in this talk)
- Irradiate small number of 3D diamond pixel devices to $10^{15}/cm^2$ – In Progress
- Characterize radiation tolerance of 3D pixel devices in beam tests with the RD42 CalypsoD – Postponed to 2023

Summary

Radiation Tolerance

- Universal curves for diamond understood and published
- Next milestone: 10^{16}, then 10^{17}

Beam Monitors for the HL-LHC

- ATLAS BCM' will use diamond planar, diamond 3D and silicon
- RD42 Calypso ASIC will be used by the ATLAS BCM'
- Problems with wafer manufacturing resolved by RD42
- Next milestone: production

3D Pixel Sensors

- 3D pixel devices in pCVD material work well
  - Small cells can collect 85% of deposited charge
  - Efficiency >99% now attainable
  - Small cells are more efficient than large cells
  - Small cells require less voltage to reach 99% efficiency
- Next milestone: 25μm x 25μm 3D cells with ganging

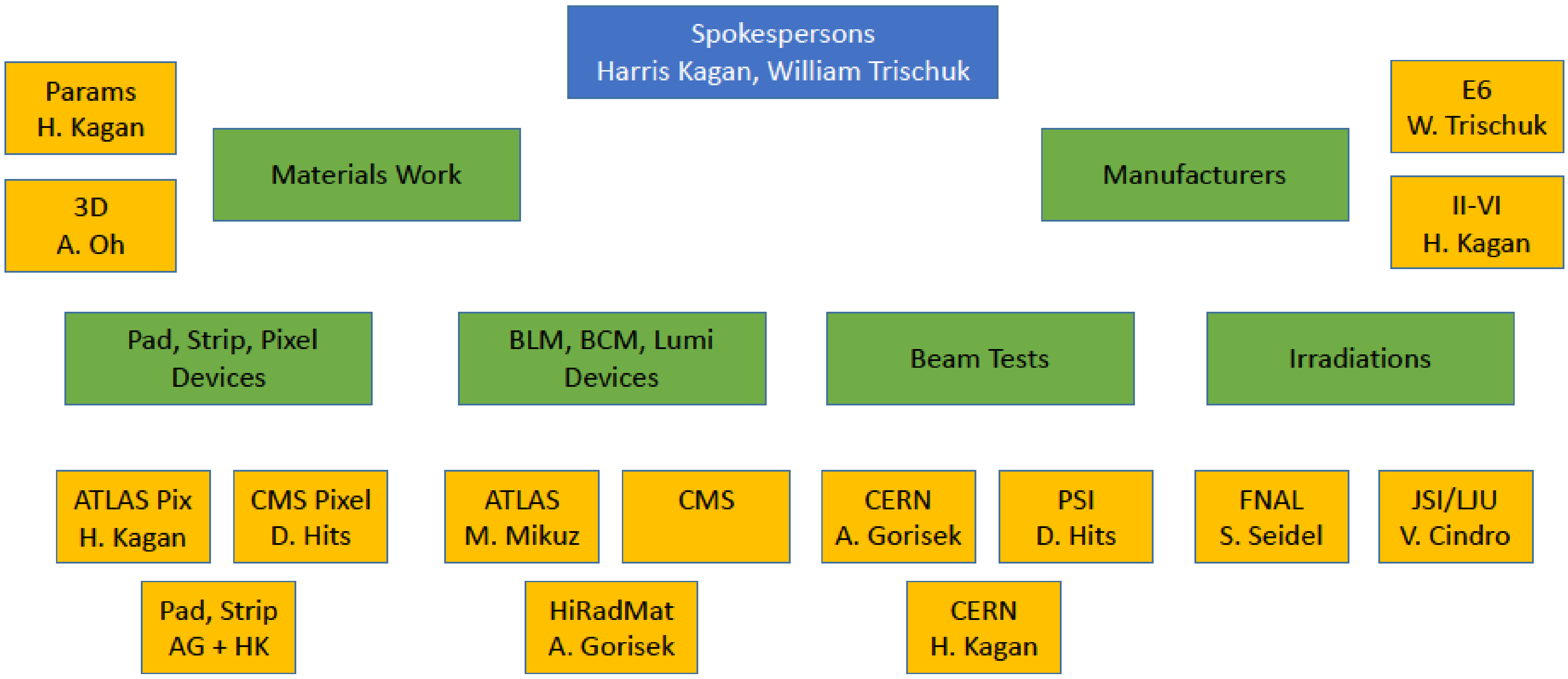
RD42 plays a pivotal role in diamond work at CERN

Backup Slides

Backup Slides

The 2022 RD42 Collaboration

RD42 Organization Chart



Highlights of Work Accomplished

Collaboration with CERN/LHC Users – ATLAS BCM'

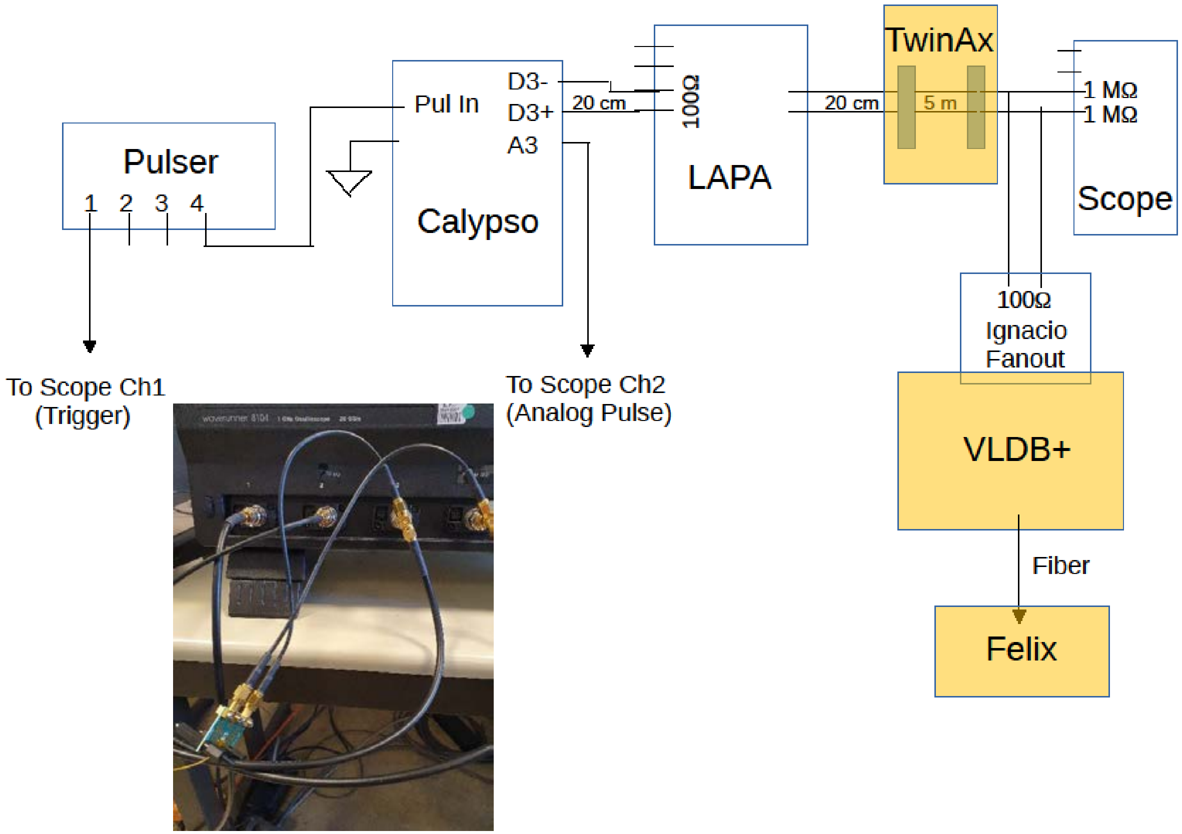
Parameter	Condition	Min	Typ	Max	Unit
Supply voltage	VDDFEX, VDDA, VDDDX	1.08	1.20	1.32	V
Current consumption per active channel (X)	VDDFEX		15.5		mA
	VDDA		16		
	VDDDX, with 50 Ω channel output termination.		6.5		
	Total		38		
Analog output offset (DC level)	With 50 Ω termination	90	120	170	mV
Analog 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

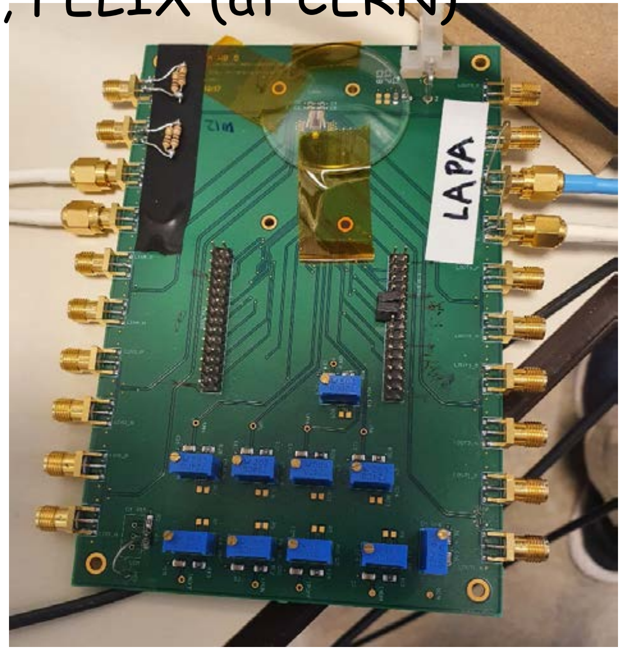
Measured parameters are within specifications

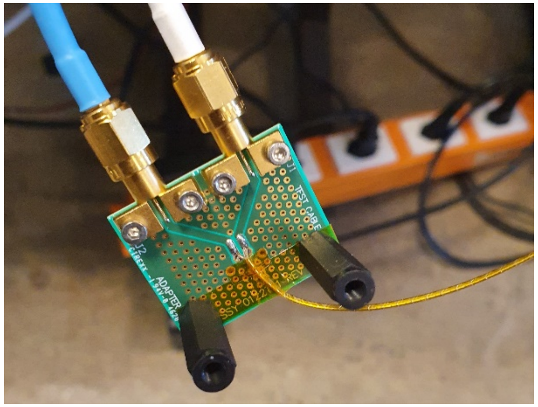
Highlights of Work Accomplished

Collaboration with CERN/LHC Users – ATLAS BCM'

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







RD42 Collaboration w/ATLAS, CMS, JLab

ATLAS

- Calypso submission with ATLAS specific designs - done
- Selection and qualification of BCM' diamond material
- Fabrication of BCM' 3D devices

CMS

- CMS is not under the same time pressure as ATLAS
- Operation of Si-pad detectors w/Calypso electronics

JLAB is also interested in using the Calypso design

- Operation of diamond based polarimeter
- We will provide a test system for evaluation
- Is interested in 32 channel Calypso ASIC