# 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 17, 2021

Outline of Talk

- The RD42 Collaboration
- The RD42 2019-2021 Program Milestones and Status
- Highlights of Recent Work
- The RD42 3 Year Proposal
- Summary

# The 2021 RD42 Collaboration

## The 2021 RD42 Collaboration

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31 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, LANL) and Beam tests (CERN, PSI)
- Work with LHC experiments

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

- 11 papers published in 2019, 4 papers published in 2020
- 3 conference talks in 2019, 3 conference talks in 2020
  3 conference talks in 2021, (3 talks cancelled)
- 3 Ph.D. student expect to graduate in 2022
- 5 Ph.D. students continuing in 2022

# RD42 Priorities of Research - 2021

- Develop High Rate Beam Monitors
  - Dedicated dual-gain readout ASIC (lumi/abort)
  - Includes ganged 3D sensors for added rad tolerance
- Advancing 3D Sensors
  - Study irradiated sensors
  - Develop 3D diamond pixel modules
  - Develop internal graphitic connections for added redundancy
  - Develop reduced column spacing to further improve rad tolerance
- Radiation tolerance of pCVD and scCVD planar sensors
  - Two complete publications of irradiation studies

# 2019-2021 Program Milestones and Status

## 2.1 Milestones: 3D Diamond Sensor Fabrication and Characterisation

2019

- Complete testbeam analysis of early 3D prototypes to quantify operating points, collected charge, efficiency – Done
- 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 Modulators is the key)
- 3D columns from etching process produced and evaluated – Done

2020

- Testbeam studies of irradiated 3D sensors configured as ganged detectors – Done
- Assess performance after fluence of $10^{15}$ – Done

# 2019-2021 Program Milestones and Status

- Scale up 3D columns produced by laser– Done
- Irradiation of 50 μm x 50 μm cells to $10^{16}$ – In progress

2021

- Final scale up of column production – produce 10 $cm^2$ sensors – Postponed due to shutdown of production lab
- Testbeam studies of sensors irradiated to $10^{16}$ – Postponed due to shutdown of resources
- Transfer column production procedures to industry – Postponed due to shutdown of resources
- Irradiation to fluences of $10^{17}$ – postponed due to shutdown of resources

# 2019-2021 Program Milestones and Status

## 2.2 Milestones: HL-LHC Beam Monitoring Proof-of-Principle

2019

- Produce first RD42 65nm HL-LHC beam loss/lumi ASIC – Done
- Assemble first HL-LHC beam loss monitor station – Done
- Test at PSI with fluxes up to 20 MHz– Done
- Irradiate one station to a fluence of $10^{15}$ – Done

2020

- Produce second 65 nm HL-LHC beam loss/lumi ASIC – Done
- Test un-irradiated beam loss station with CalypsoC ASIC in test beam at CERN – Done (results in this talk)
- Test irradiated beam loss station w/MIPs at CERN – Postponed waiting for material

# 2019-2021 Program Milestones and Status

2021

- Work w/manufacturers to produce pCVD diamond for HL-LHC systems – Done
- Preselect, metalise diamond for the ATLAS BCM’ project – In progress, waiting for material from manufacturer
- Beam test of BCM’ modules using the RD42 65nm CalypsoC ASIC – Done (results in this talk)

# 2019-2021 Program Milestones and Status

## 2.3 Milestones: Development of pCVD Diamond Material

2019

- Develop edge-TCT to measure the internal electric field configuration of CVD material – Done
- Work w/manufacturers to reduce surface imperfections and voids to less than $1/cm^2$ – Done

2020

- Work w/manufacturers to produce first pCVD material with 400 μm collection distance in finished 500 μm part – In progress, waiting for material

2021

- Work w/manufacturers to reduce the as-grown charge collection distance uniformity across 12 cm wafers to < 2% - In progress

# 2019-2021 Program Milestones and Status

## 2.4 Milestones: Development of 3D pCVD Pixel Module Prototypes

2019

- Fabricate and characterize a number of 3D diamond pixel devices with the latest advances with 50 μm x 50 μm cell size – Done
- Irradiate a small number of 3D diamond pixel devices up to $10^{15}/cm^2$– Done
- Characterize radiation tolerance of 3D pixel devices in beam tests with the RD53 chip – Postponed

2020

- Fabricate and characterize a number of 3D diamond pixel devices with the latest advances with 25 μm x 25 μm cell size – Postponed
- Irradiate a small number of 3D diamond pixel devices up to $10^{16}/cm^2$ – In progress

# 2019-2021 Program Milestones and Status

- Directly compare the 25 μm cells with the 50 μm cells in a beam test – Postponed to this proposal

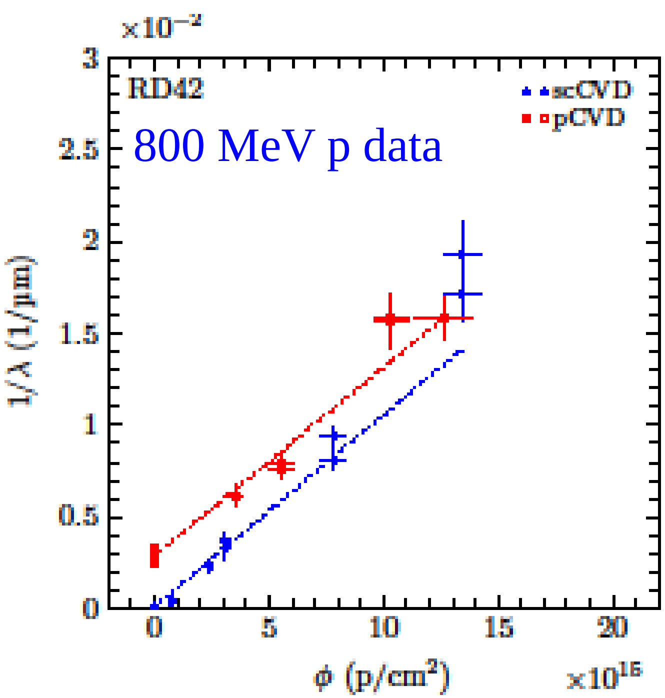
2021

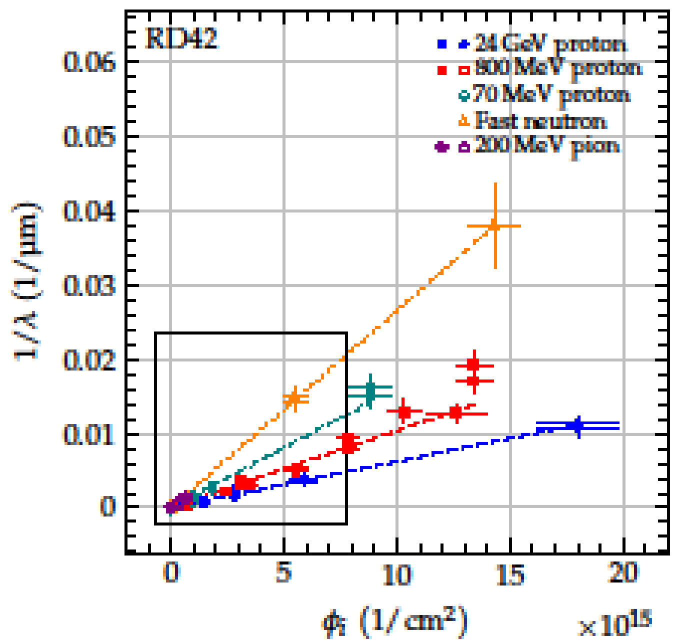
- Confirm radiation hardness of 3D diamond devices in beam tests up to $10^{17}$ hadrons/$cm^2$ – Postponed to this proposal
- Technology Transfer – Postponed to this proposal
- Construct and test pCVD diamond pixel based beam monitoring devices – Done

# Highlights of Recent Work Accomplished

## Radiation Tolerance Studies

1-Study 24 GeV 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, uniformity vs dose




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

| Particle Species | Relative Damage Constant, κ |
|---|---|
| 24 GeV p | 1 |
| 800 MeV p | 1.67 ± 0.09 |
| 70 MeV p | 2.60 ± 0.29 |
| 25 MeV p | 4.4 ± 1.2 |
| Fast neutrons | 4.3 ± 0.4 |
| 200 MeV π | 3.2 ± 0.8 |

# Highlights of Recent Work Accomplished

## Radiation Tolerance Studies

1-Study 24GeV p, 800 MeV p, 70 MeV p, 25 MeV p, Fast n, 200 MeV $\pi$
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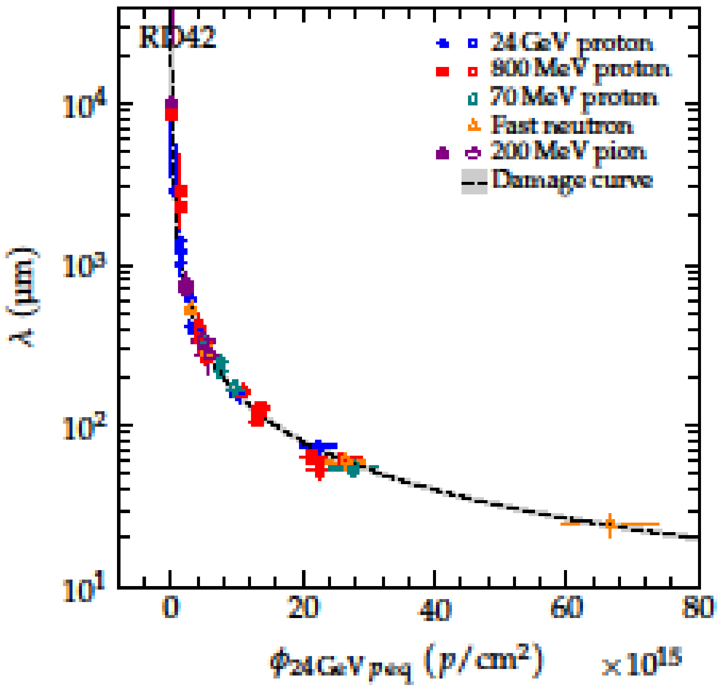
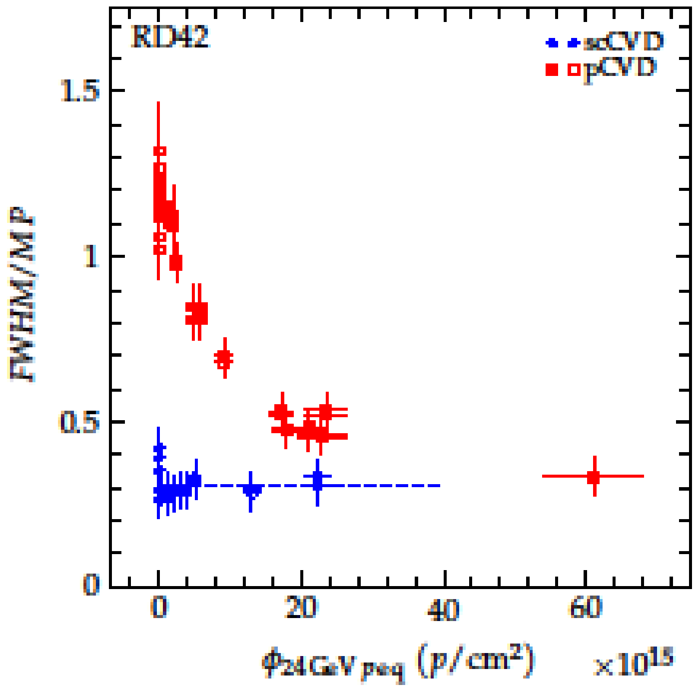


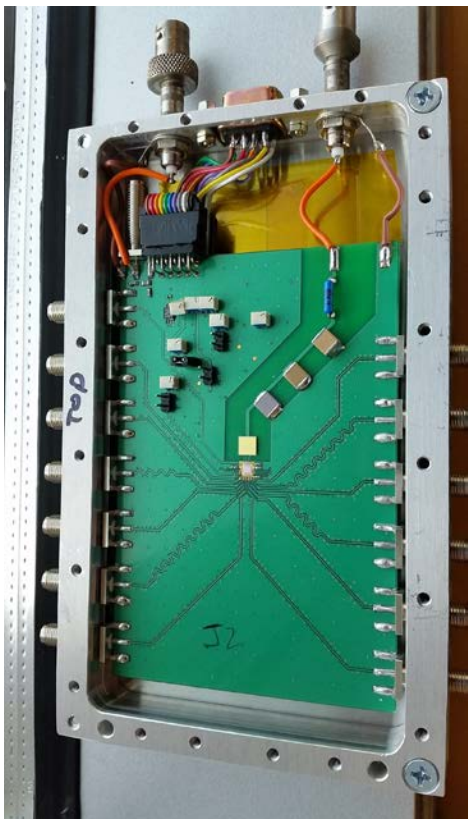



# Highlights of Recent Work Accomplished

## Collaboration with CERN/LHC Users - ATLAS

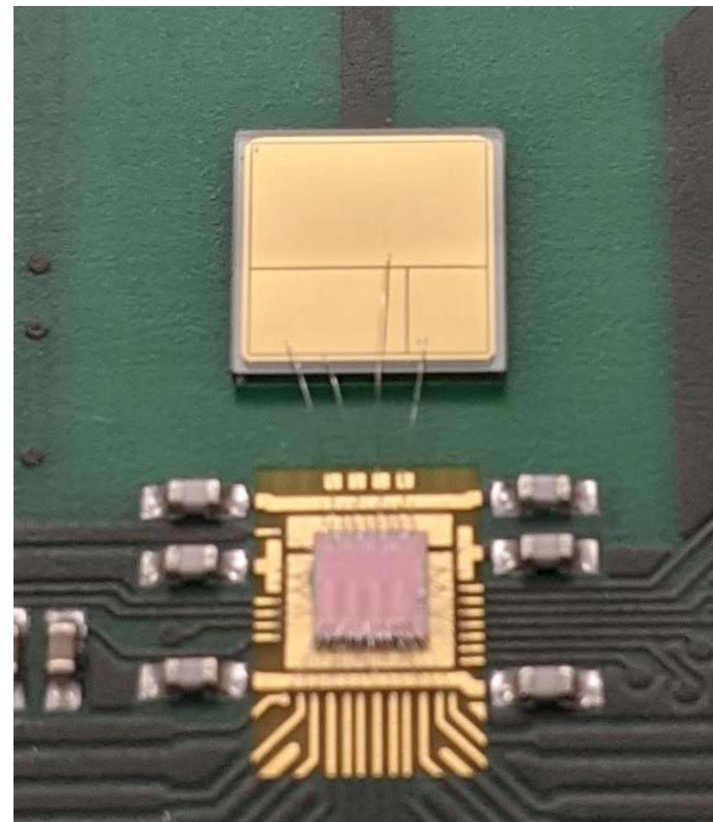
1-RD42 created Calypso ASIC for lumi/abort functionality
2-ATLAS BCM' will use Calypso ASIC w/diamond pad, 3D diamond, silicon
3-First beam test results (Aug, Oct, Nov 2021)

BCM' Module:
Pulser In,
Analog out(4),
LVDS+(4),
LVDS-(4)
→ SMA



BCM' 3-pad diamond detector
Area ratio 1:2:4.5

Calypso_C:



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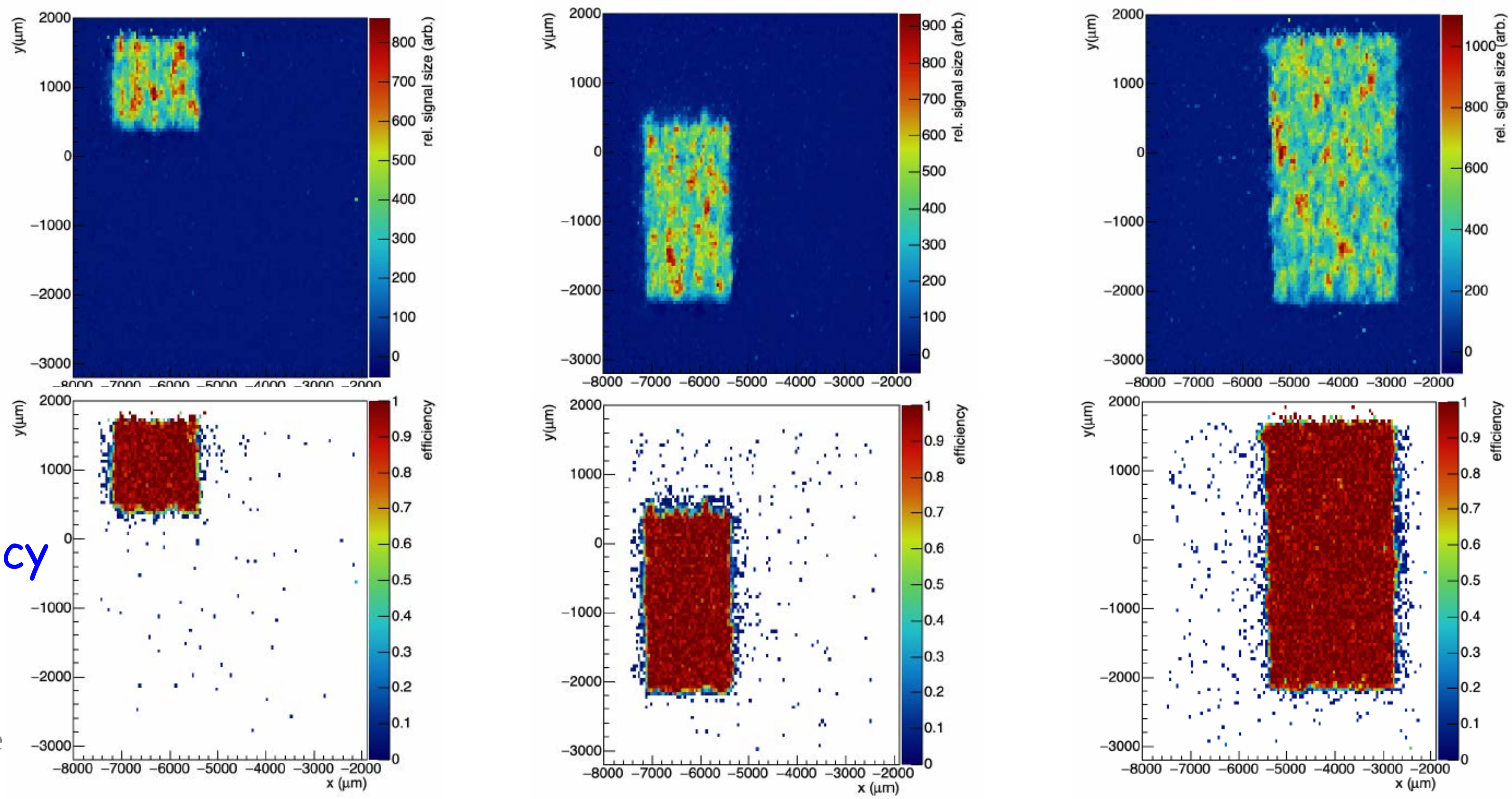
3-First beam test results in MALTA Telescope (Aug, Oct, Nov 2021)

BCM' Module: Pad A1 | BCM' Module: Pad A2 | BCM' Module Pad A4.5

Pulse Height for trk in pad

Efficiency

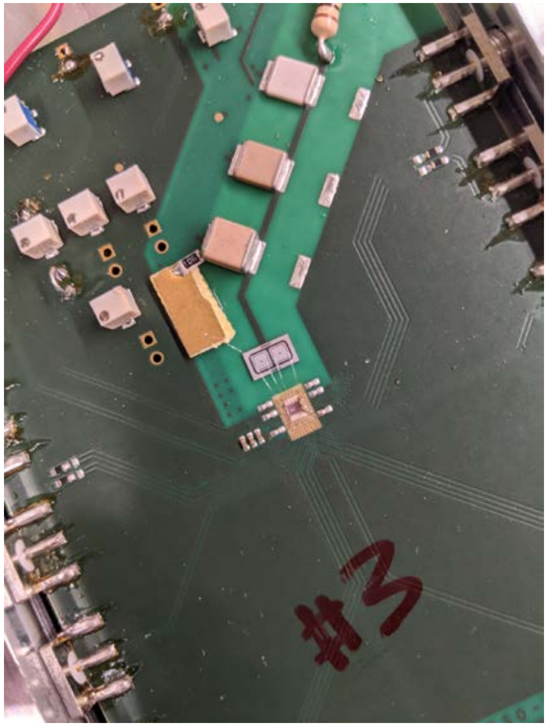


# Highlights of Recent Work Accomplished

## Collaboration with CERN/LHC Users - CMS

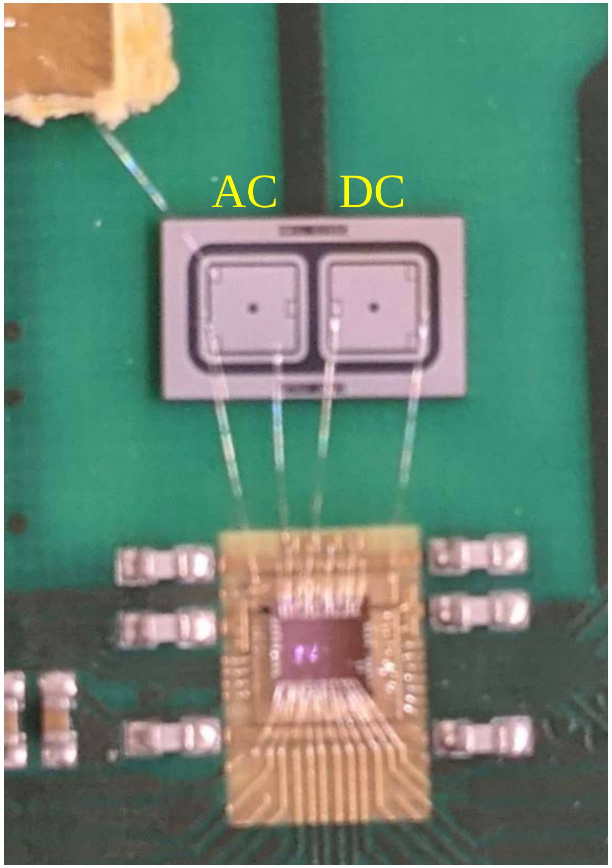
1-RD42 created Calypso ASIC for lumi/abort functionality
2-CMS BCM' may use Calypso ASIC w/silicon pad detectors
3-First beam test results in MALTA Telescope (Oct 2021)

CMS Module:
Pulser In,
Analog out(4),
LVDS+(4),
LVDS-(4)
→ SMA



CMS
Silicon pad
detector
AC/DC
coupled

Calypso_C:



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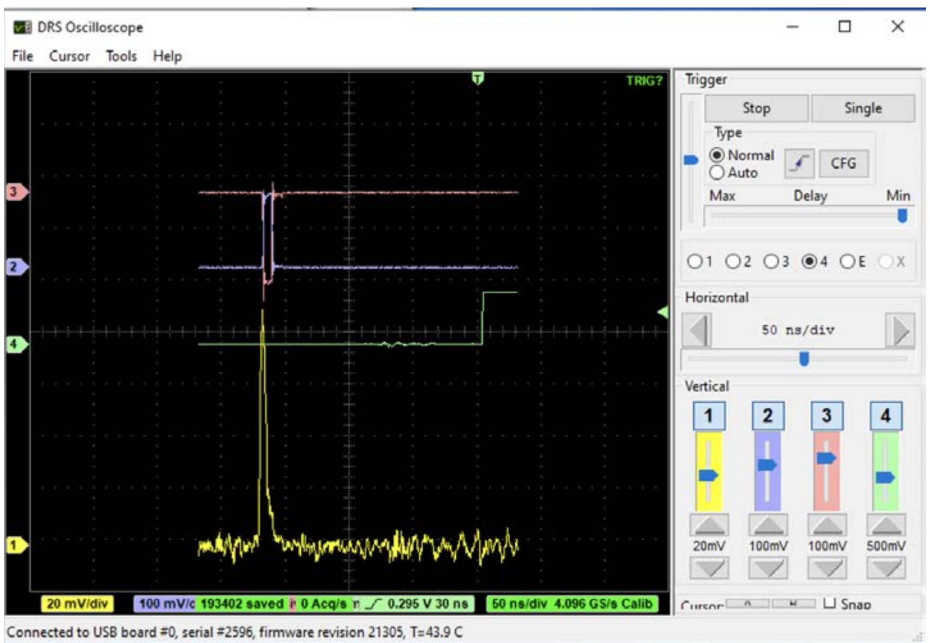
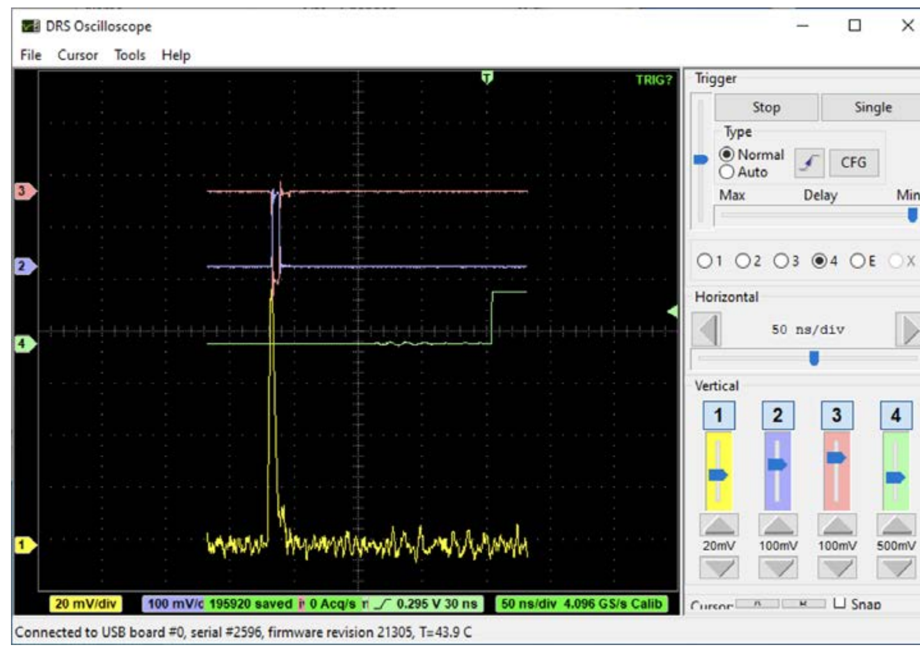
CMS Si-Pad, -900V w/FD Event 8




CMS Si-Pad, -900V w/FD Event 9



# Highlights of Recent Work Accomplished

## Collaboration with CERN/LHC Users - CMS

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2-CMS BCM' may use Calypso ASIC w/silicon pad detectors
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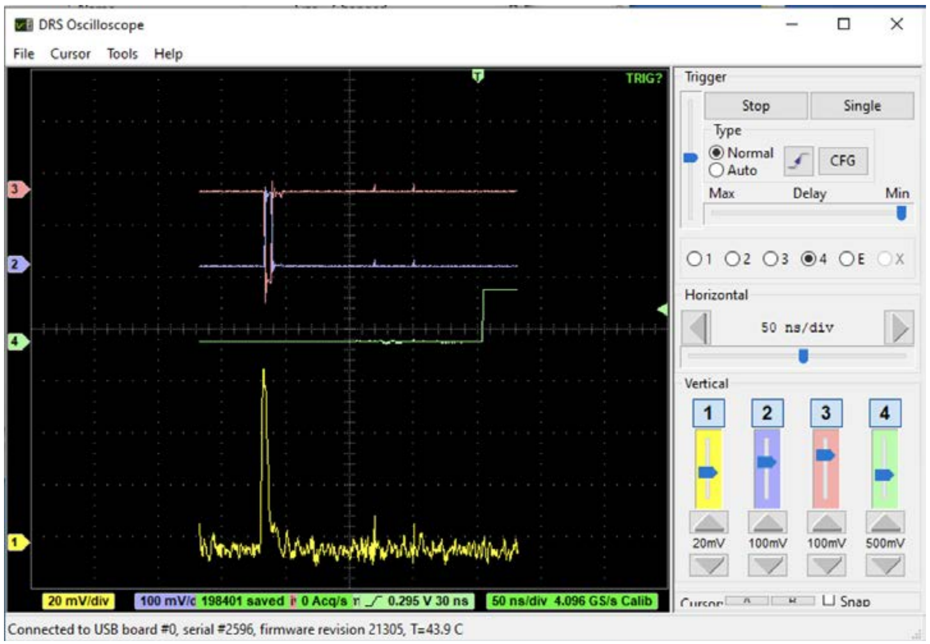
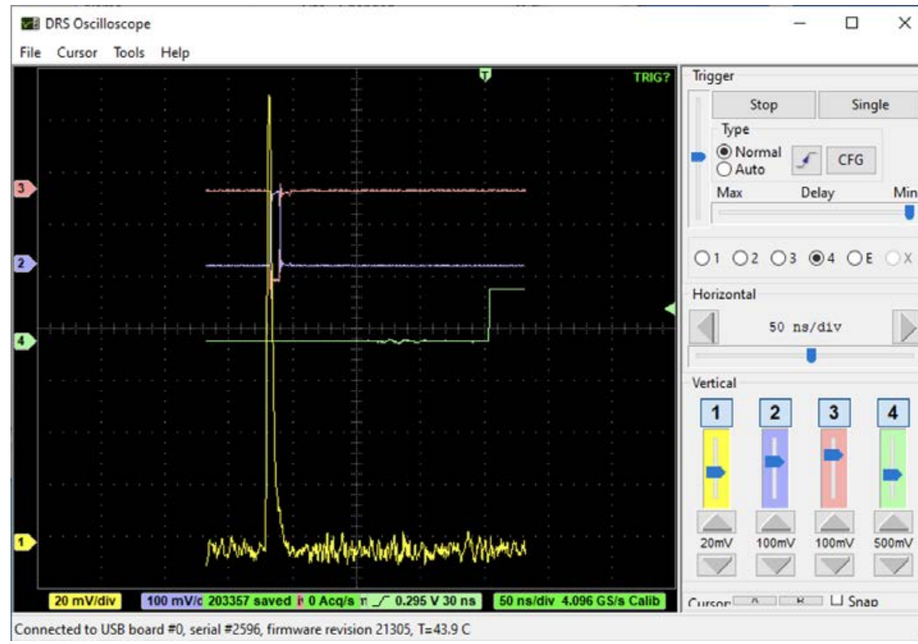
CMS Si-Pad, -900V w/FD Event 10




CMS Si-Pad, -900V w/FD Event 11



# Highlights of Recent Work Accomplished

## Collaboration with CERN/LHC Users - CMS

1-RD42 created Calypso ASIC for lumi/abort functionality
2-CMS BCM' may use Calypso ASIC w/silicon pad detectors
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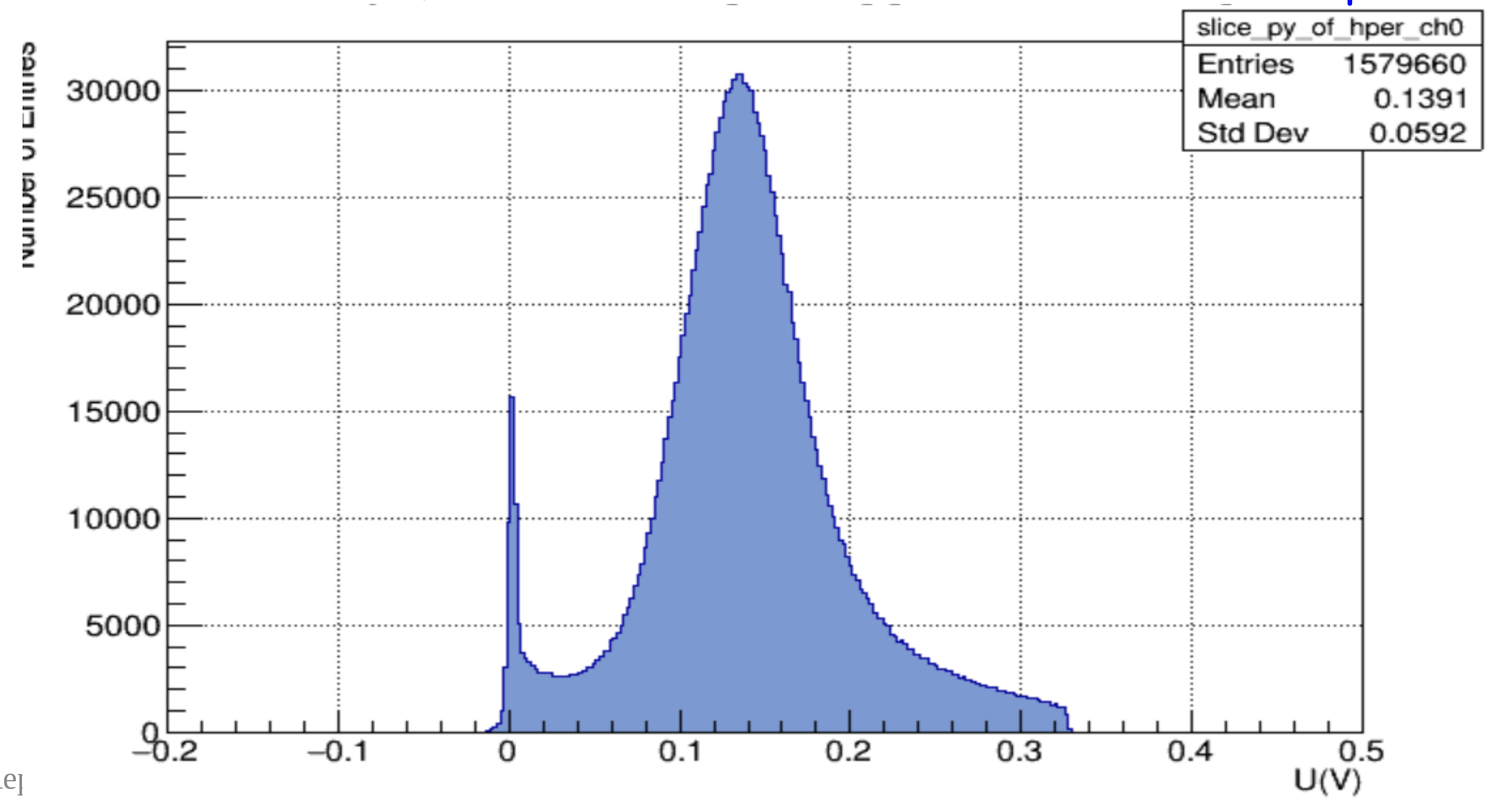
CMS Si-Pad, -900V w/FD PH Distribution for trks in pad

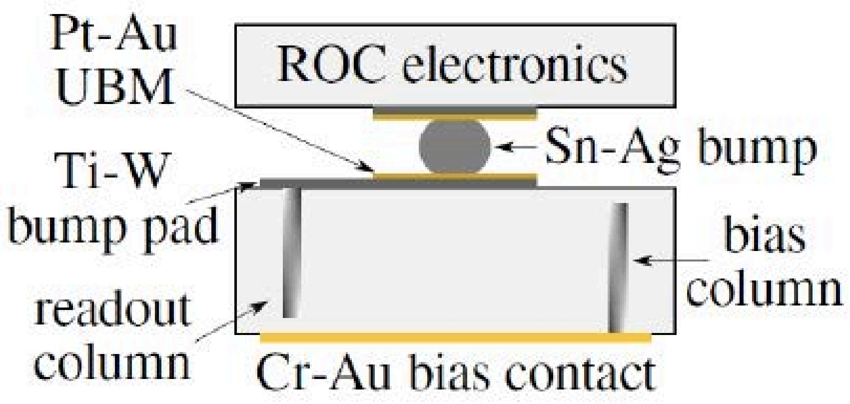


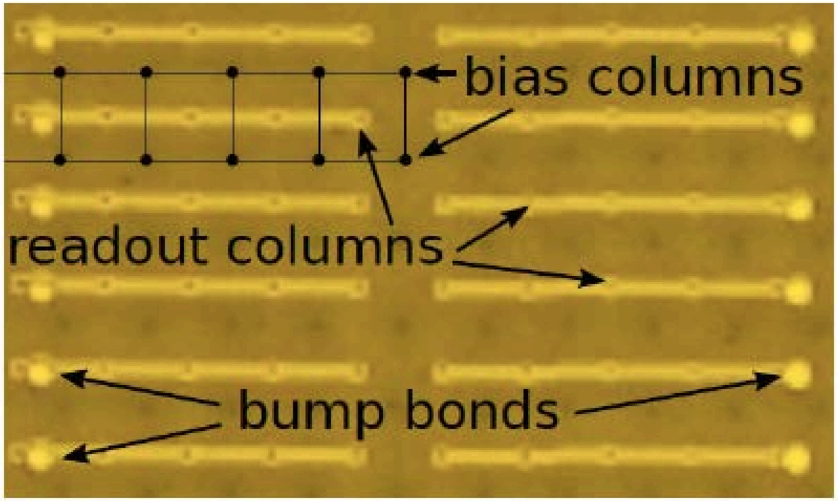
# Highlights of Recent Work Accomplished

## 3D Diamond Pixel Detectors

1-RD42 showed 3D devices work first in scCVD then pCVD diamond
2-RD42 fabricated 50μm x50μm pixel detectors read out by ganging with (1x5) ATLAS or (3x2) CMS ASICs
3-In 2019 RD42 characterized the rad tolerance of 3D diamond devices
4-This past year RD42 constructed the first cage/grid structure

ATLAS 3D diamond pixel device (1 x 5 ganging)



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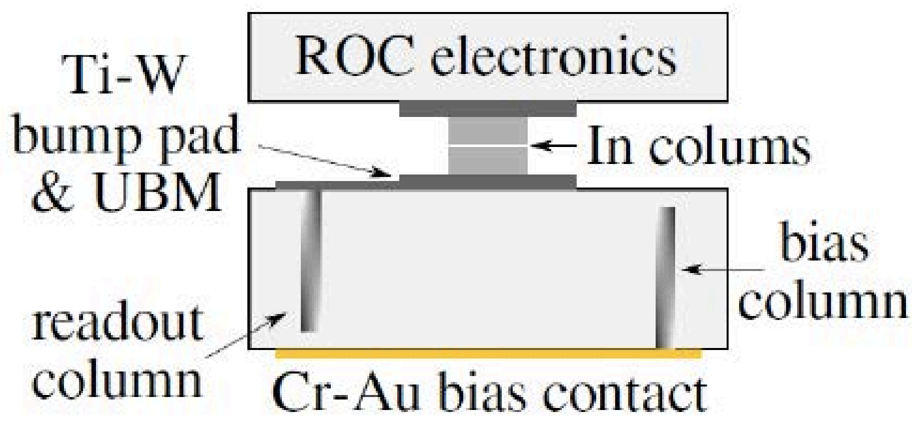
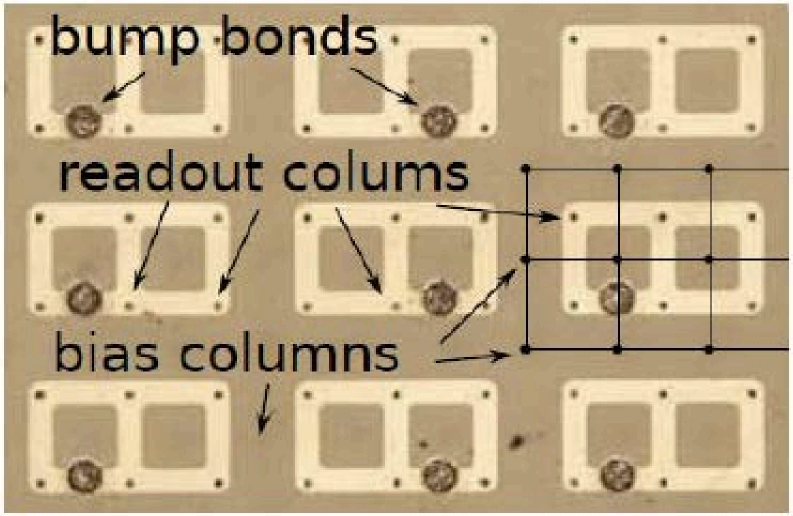
3-In 2019 RD42 characterized the rad tolerance of 3D diamond devices
4-This past year RD42 constructed the first cage/grid structure

CMS 3D diamond pixel device (3 x 2 ganging)



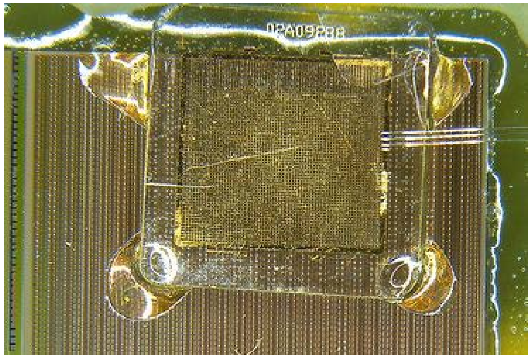



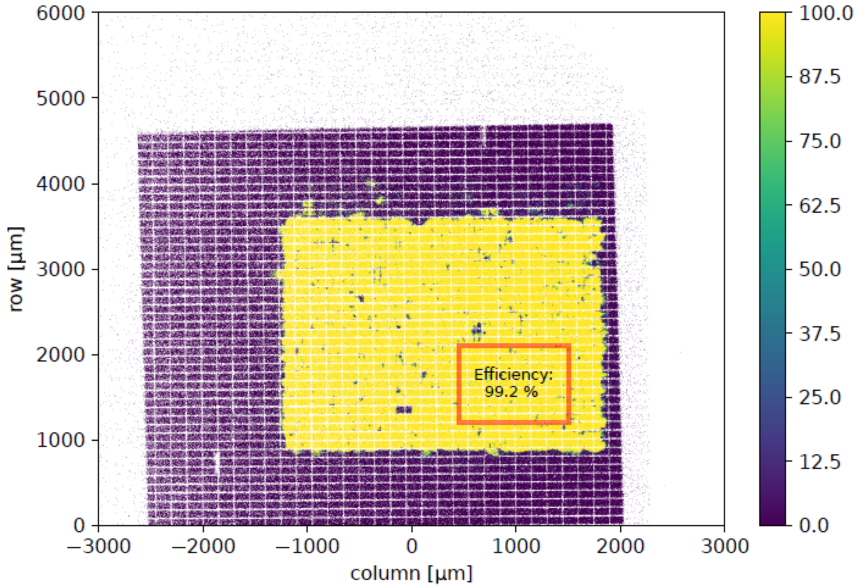
# Highlights of Recent Work Accomplished

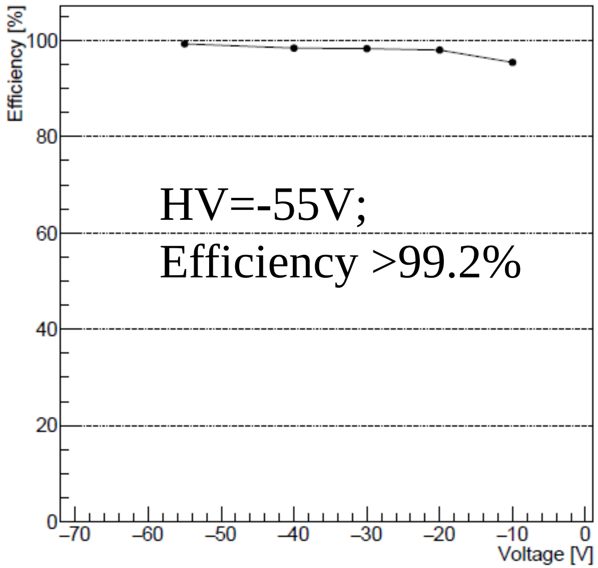
## 3D Diamond Pixel Detector Results

Preliminary Results (50μmx50μm cells)

- CMS pixel readout (3x2) ganging
- Indium bumps
- LJU telescope (resolution ~3 μm)
- Red box-efficiency 99.2%





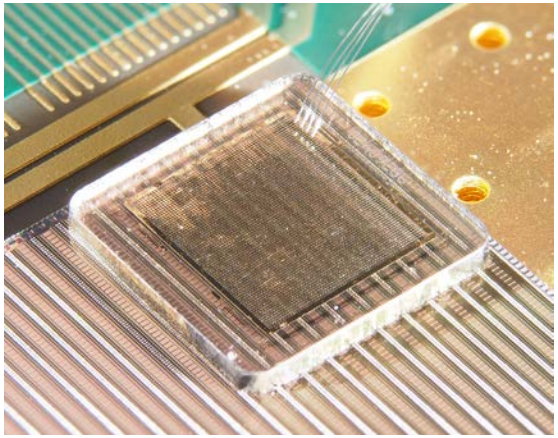



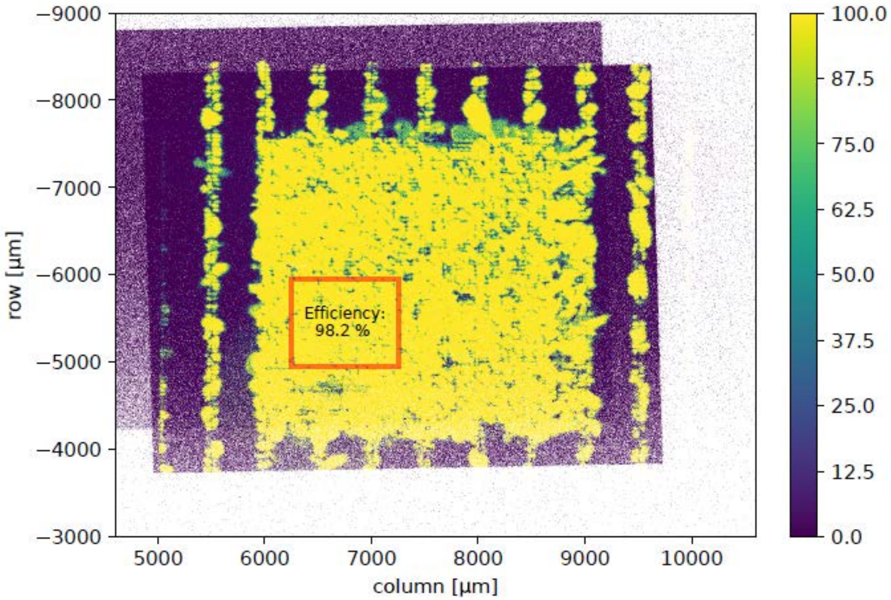
# Highlights of Recent Work Accomplished

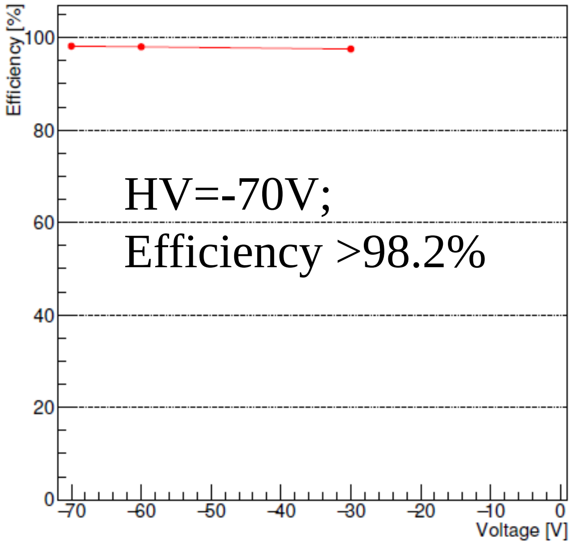
## 3D Diamond Pixel Detector Results

### Preliminary Results (50μmx50μm cells)

- Atlas pixel readout (1x5) ganging
- Tin-Silver bumps
- LJU telescope (resolution ~3 μm)
- Red box-efficiency 98.2%
- Inefficiencies most likely due to processing





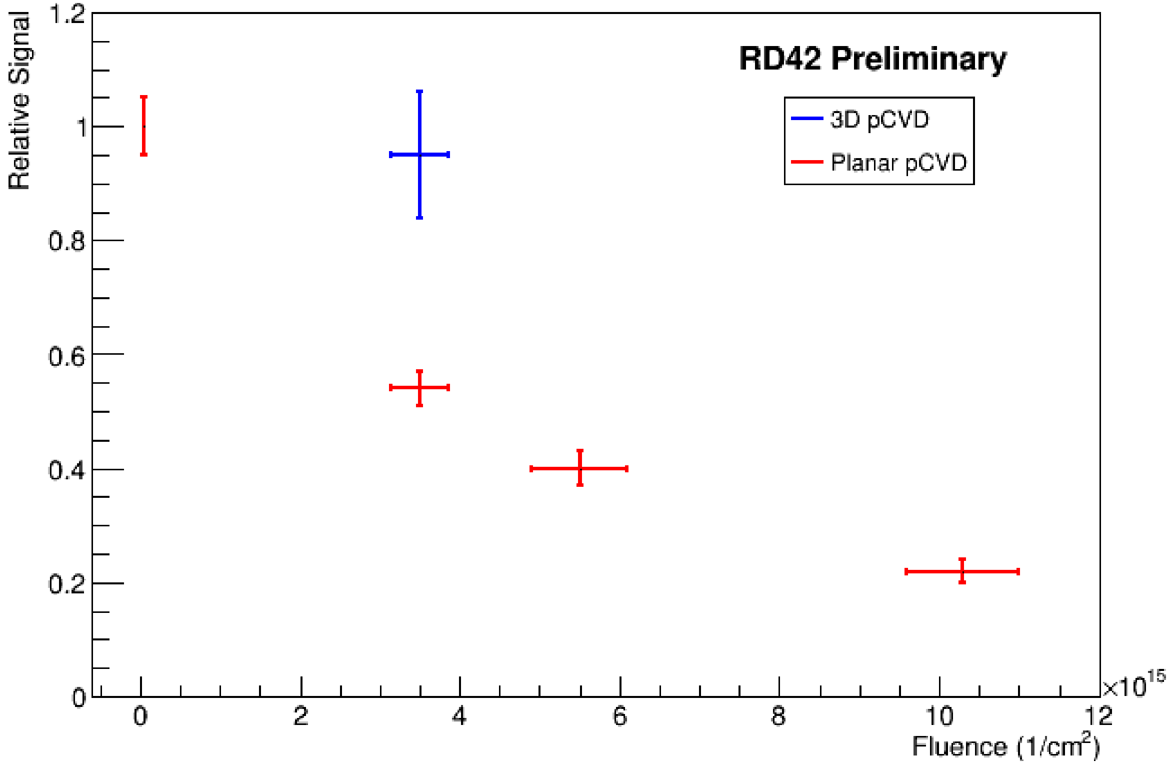



# Highlights of Recent Work Accomplished

## 3D Diamond Pixel Detector Radiation Tolerance Results

Compare signal loss in 3D pixels to published results from planar

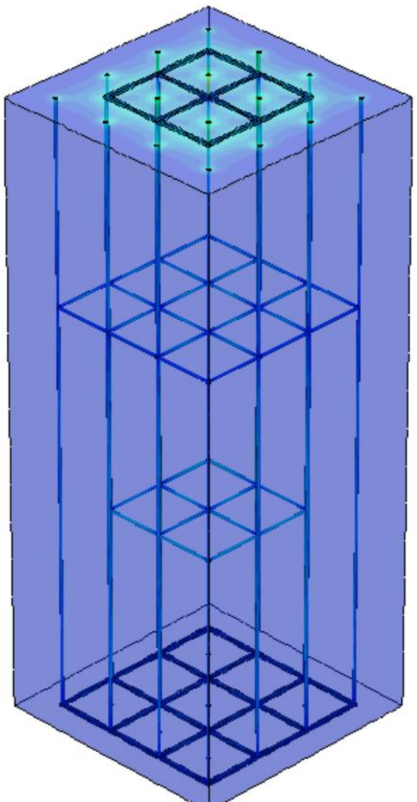
- 3D cells collect twice as much charge when unirradiated
- 3D sensors see 5±10% signal reduction at 3.5 x $10^{15}$ p/cm$^2$
- Planar sensors see 45±5% signal reduction at 3.5 x $10^{15}$ p/cm$^2$

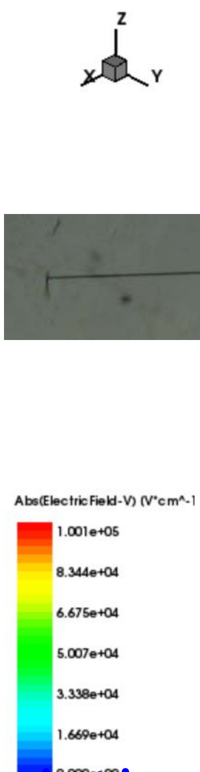



This result together with Universal curve imply 3D diamond devices should be able to operate at $10^{17}$/cm$^2$

# Highlights of Recent Work Accomplished

3D diamond devices are expected to make extreme radiation tolerant devices – What about redundancy?



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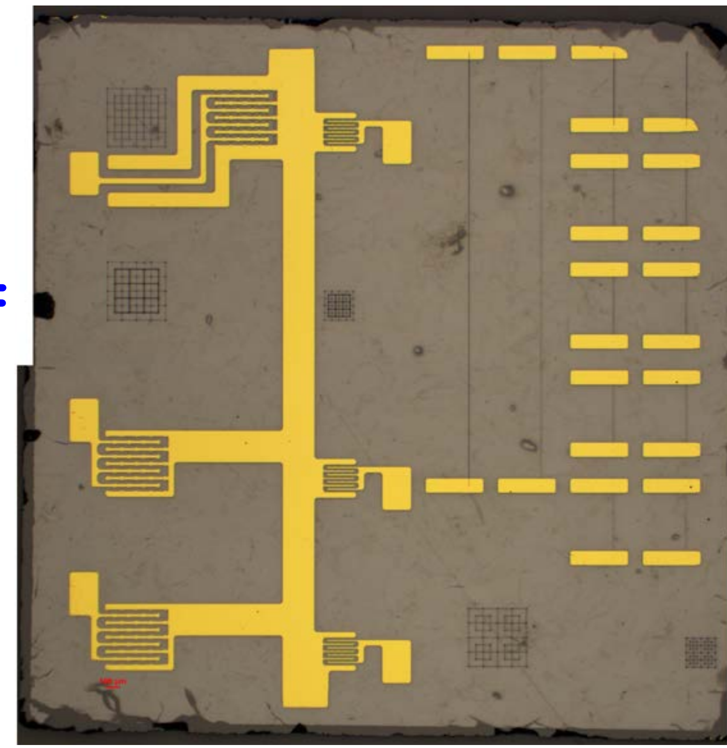


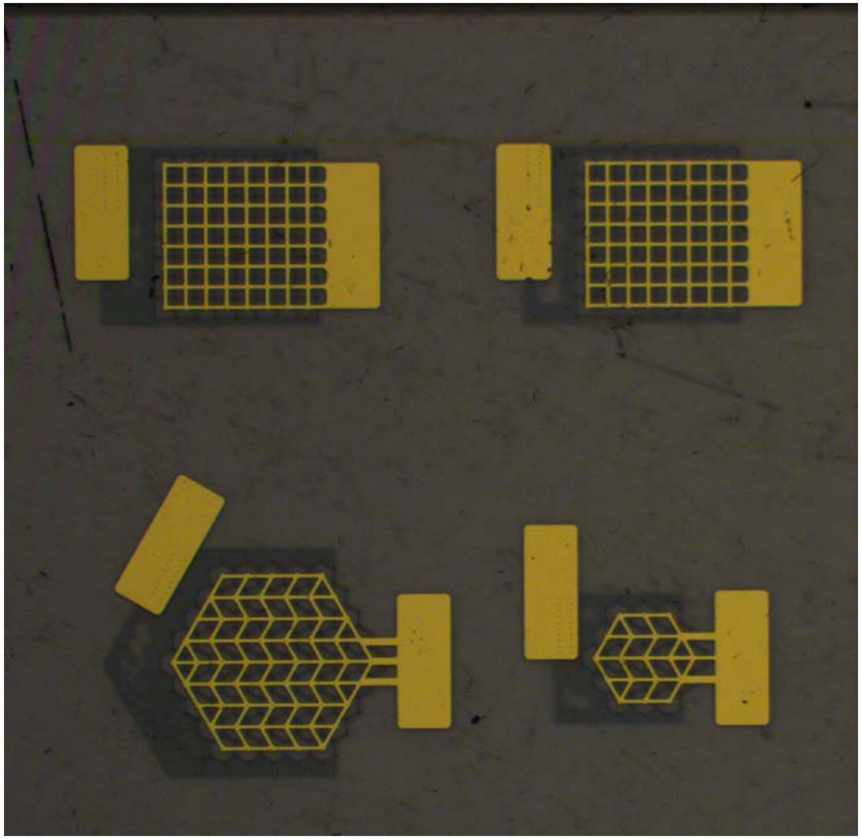
Can we make resistive lines in the diamond bulk? YES!!!

Can we make thru-hole vias? YES!!!

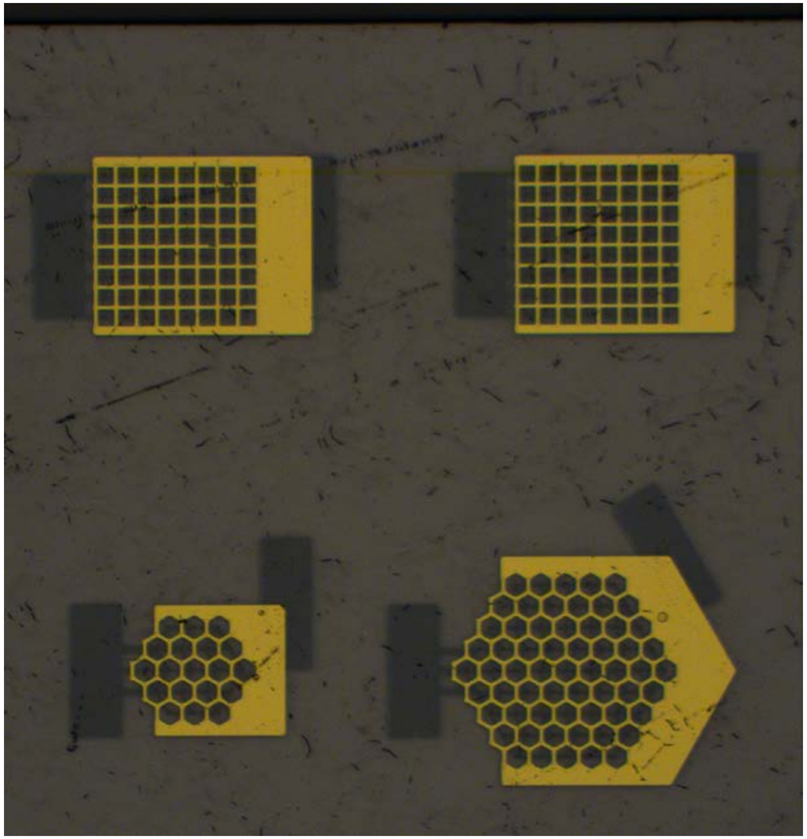
# Highlights of Recent Work Accomplished

New 3D Diamond Detector Designs w/grids and vias for extremely radiation tolerant reliable beam devices

BCM' Devices Top/Readout side

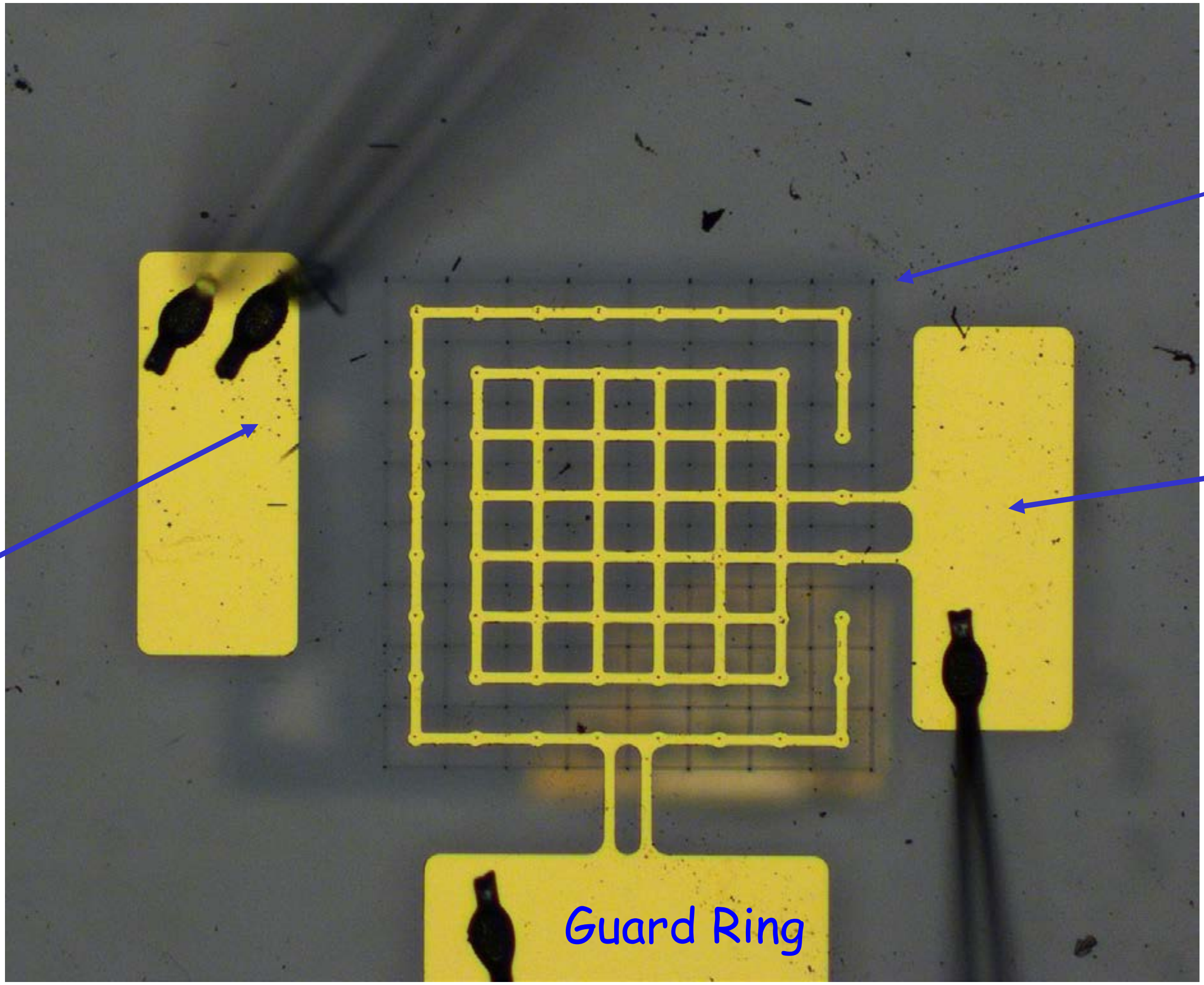


BCM' Devices Bot/HV side



# Highlights of Recent Work Accomplished

New 3D Diamond Detector Designs w/grids and vias



# Highlights of Recent Work Accomplished

## Possible Extensions of this Work

- Grids/cages together with through-hole-vias allow the possibility of biased structures in the bulk of the diamond
- This is a prerequisite for developing a gain structure based on Impact Ionization

# The RD42 Proposed Program

RD42 proposes a three-year program. The elements are:

7.1: 3D Diamond Sensor Fabrication and Characterisation

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

7.3: Development of pCVD Diamond Material

7.4: Development of 3D Diamond Pixel Modules

The program begins with the red and yellow milestones from the 2019-2021 program with additional milestones based on what we have recently learned. The details are in the report.

# RD42 Summary

- Radiation Tolerance
  - Understood and published up to $10^{16}$
  - Next step is to go to $10^{17}$
- Beam Monitors for the HL-LHC
  - Calypso readout chip will most likely be used by ATLAS and CMS
  - ATLAS BCM' will use diamond planar pads, diamond 3D and silicon
  - CMS BCM' will use silicon pads
- 3D diamond sensors work well
  - Unirradiated 3D sensors have twice the charge of planar sensors
  - Irradiated sensors have significantly less charge loss than planar
- RD42 played a pivotal role in making all this happen!