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

RD42 Status Report

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for the RD42 Collaboration

LHCC Meeting – September 2, 2020

Outline of Talk

- RD42 Collaboration
- Research milestones for 2020
- Beam monitors for LHC experiments
- Results from 3D pixel devices
- Irradiation and Rate studies in diamond
- Plans and Request

The 2020 RD42 Collaboration

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118 Participants

31 Institutes

RD42 Research Priorities for 2020

- Develop high rate beam monitors
  - Dedicated dual-gain readout chip (lumi/abort)
  - Includes 3D sensors for added radiation tolerance
- Advancing 3D sensors
  - Study irradiated sensors
  - Develop 3D diamond pixel modules
  - Develop reduced column spacing to further improve rad tolerance
- Radiation tolerance of pCVD and scCVD planar sensors
  - Publication of irradiation studies submitted
    - Includes 70 MeV protons, neutrons and pions

7.2 HL-LHC Beam Monitoring Proof-of-Principle

7.2.1 Milestones

2019

- Produce the first RD42 65 nm HL-LHC beam loss/lumi chip
- Assemble first HL-LHC beam loss monitor station
- Test at PSI with fluxes up to 20 MHz
- Irradiate one station to a fluence of 10^{15} — Analysis in progress

2020

- Production HL-LHC beam loss readout chip — Submitted August 2020
- Test un-irradiated beam loss station with production chip in beam at CERN
- Test irradiated beam loss station (from previous year) with MIPs at CERN — No beams at CERN ☹
- Irradiate one station to a fluence of 10^{16} — Will be done in 2021 at JSI

2021

- Work with manufacturers to produce pCVD diamond for HL-LHC systems
- Preselect, metalise diamond for the ATLAS BCM' project (and similar for CMS)
- Beam test of BCM' modules using the RD42 65 nm chip — CMS will use chip, silicon sensors

7.1 3D Diamond Sensor Fabrication and Characterisation

7.1.1 Milestones

2019

- Complete testbeam analysis of early 3D prototypes to quantify HV and I operating points, charge collected, efficiency.
- Irradiation of two early 3D prototype sensors configured as pad detectors to 10^{15}.
- Laser drilling of 50 μm $\times$ 50 μm 3D cells with 2.5 μm diameter columns with $>99.9\%$ yield.
- First 3D columns from etching process produced and evaluated.

99% yield achieved (2019)

2020

- Testbeam studies of irradiated 3D sensors configured as pad detectors.
- Assess performance after 10^{15} fluences
- Scale up of 3D columns produced by laser and etching
- Irradiation of 50 μm $\times$ 50 μm cells to 10^{16}

Still working on this

Will be done in 2021 at JSI

2021

- Final scale of column production – produce 10 cm^2 sensors
- Testbeam studies of sensors irradiated to 10^{16}
- Transfer column production procedures to industry
- Irradiation to fluences of 10^{17}

On Track for these

Postponed until 2022

7.4 Development of 3D Diamond Pixel Module Prototypes

7.4.1 Milestones

2019

- Fabricate and characterize a number of 3D diamond pixel devices with the latest advances with 50 $\mu m \times 50$ μm cell size.
- Irradiate a small number of these 3D diamonds pixel devices up to $10^{15}/cm^2$. One to 3.5 x10 ^{15}
- Characterise radiation tolerance of 3D pixel devices in beam tests with the RD53 chip.

Have chip, need to bump-bond – will be done in 2021/22

2020

- Fabricate and characterize a number of 3D diamond pixel devices with the latest advances with 25 $\mu m \times 25$ μm cell size.
  - Going to 25x25 um cells only needed for 10^{17}
- Irradiate a small number of these 3D diamonds pixel devices up to $10^{16}/cm^2$.
- Directly compare the 25 μm cells with the 50 μm cells in a beam test.

2021

- Confirm radiation hardness of 3D diamond devices in beam tests up to 10^{17} hadrons/cm^2.
- Technology transfer.
- Construct and test pCVD diamond pixel based beam monitoring devices.

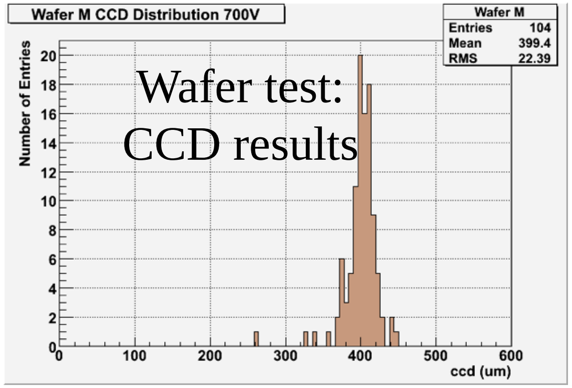
Beam Monitors for HL-LHC

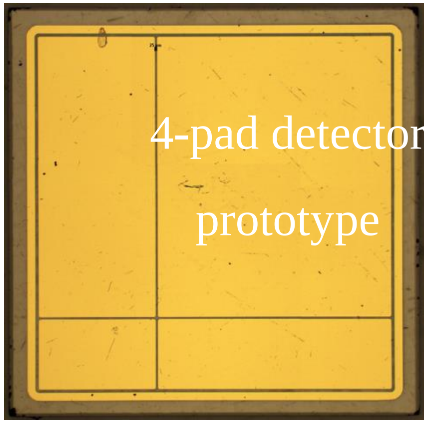
- ATLAS developing diamond based BCM'
  - Planar sensors for large area, low-lumi measurements
  - 3D sensors for improved radiation tolerance in small area
  - 65 nm readout chip with two different gains
    - MIP sensitivity for luminosity
    - kMIP sensitivity for beam aborts
- CMS considering RD42 readout chip with silicon sensors

- *Readout chip submitted later than anticipated*
  - *Europractice submission cancelled/delayed*

Sensors

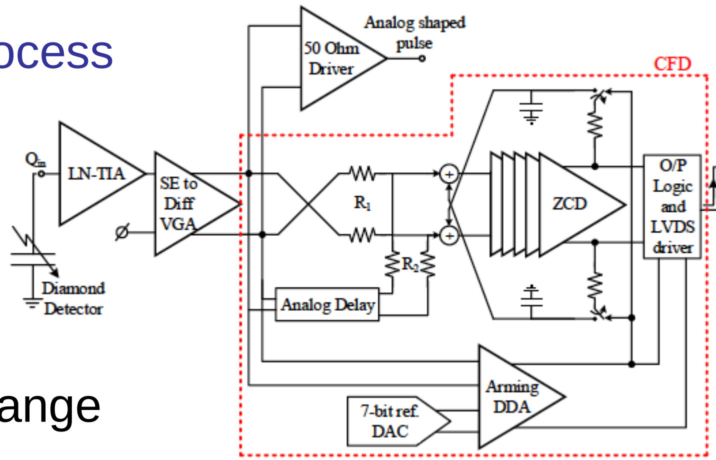
- pCVD diamond chosen as BCM' sensor material
- 3 types of sensors
  - 1x1 cm^2 (*lumi*), 5x5 mm^2 (*abort*), ~1x1 mm^2 (3D lumi)
  - aim for C < 5pF (challenging for 3D?)
- RD42 and ATLAS working to secure best possible pCVD diamond sensor quality (working with US vendor)
  - 2-3 wafers to be grown for the project
- Evaluation of charge collection (~9-11 ke @2V/µm) and long-term current stability
- Sensors and Readout chip delayed

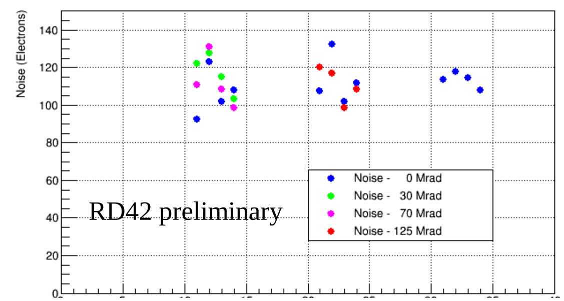


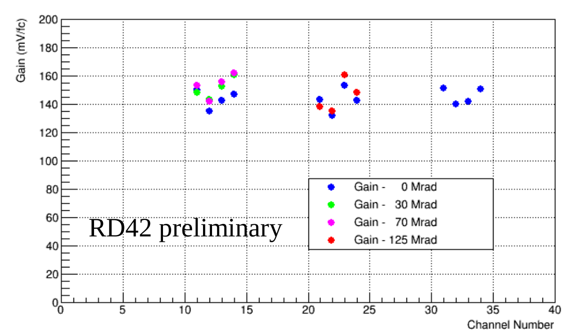


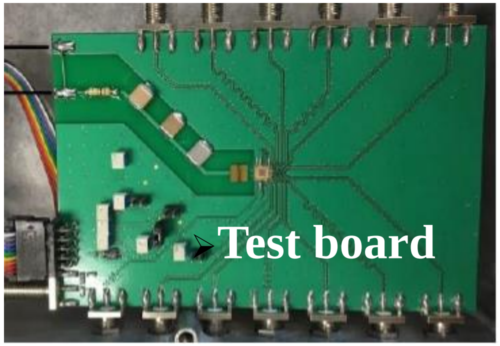
65nm RD42 Front-End - Calypso

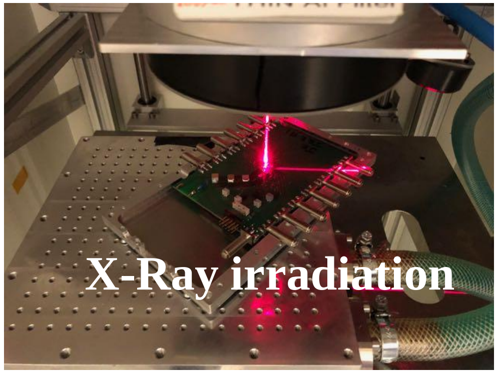
- 4-channel FE designed in MPW, TSMC 65 nm process
- Specs of 2 inputs/channel: *lumi* /*abort*
  - optimized for 2-5 pF detector capacitance
  - <1.5 ns peak, <15 ns settling time @2pF
  - <100 ps time jitter @2pF for >3.6 ke signals
  - *lumi*: (110 + 55/pF)e noise , ±50ke dynamic range
  - *abort*: 830 ke noise @2pF, ± 750Me dynamic range
- 2nd iteration Calypso B meets all specifications
  - TID radiation (125 MRad) shows no effects
- 3rd iteration Calypso C was submitted August 2020



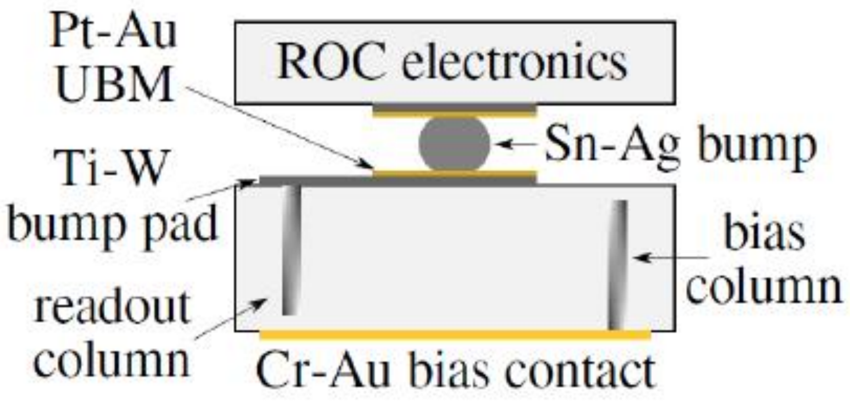


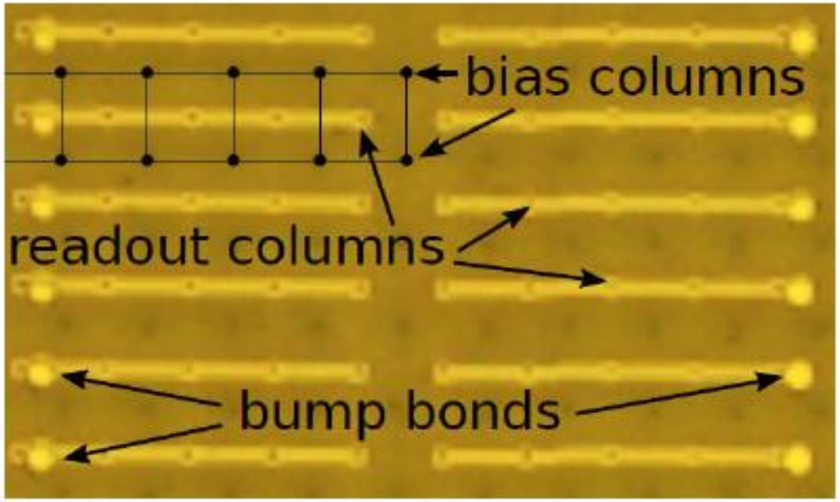


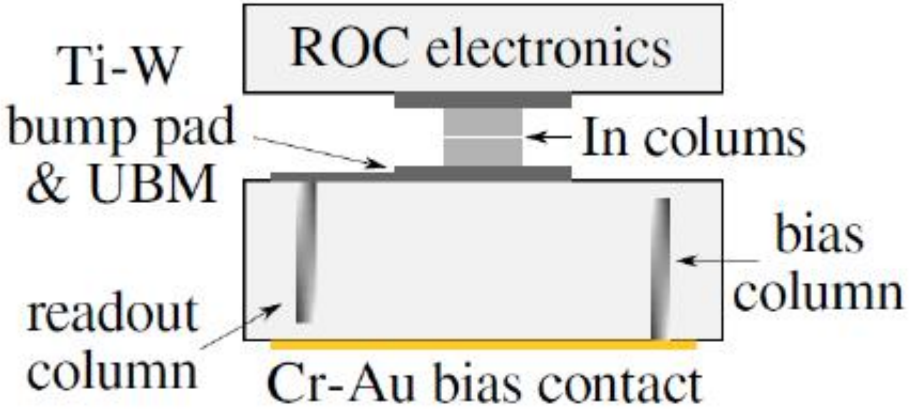


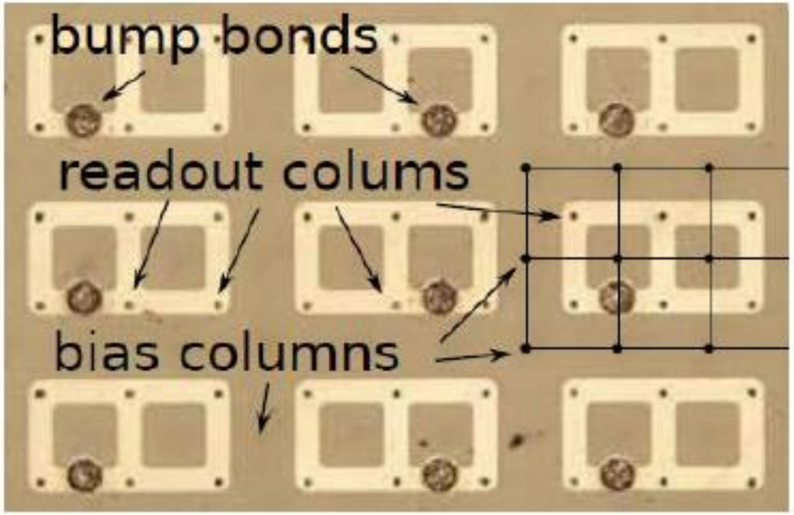


3D Diamond Tracker Prototypes (ATLAS/CMS)





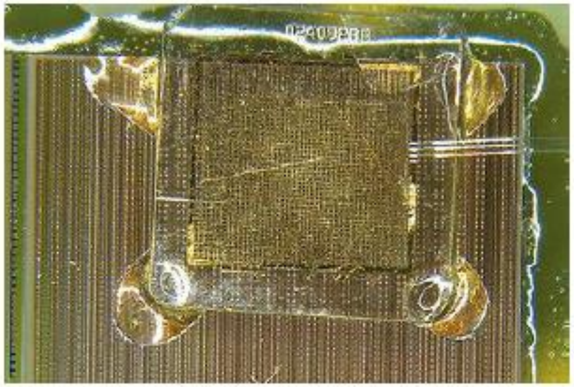


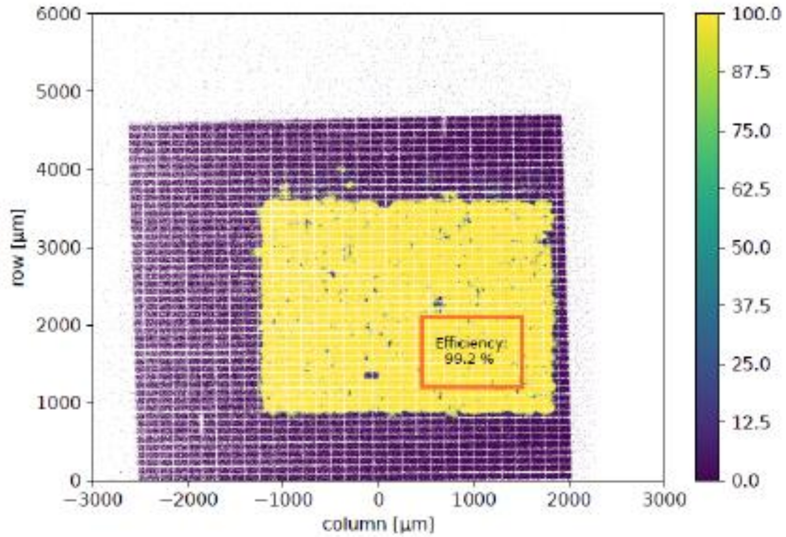


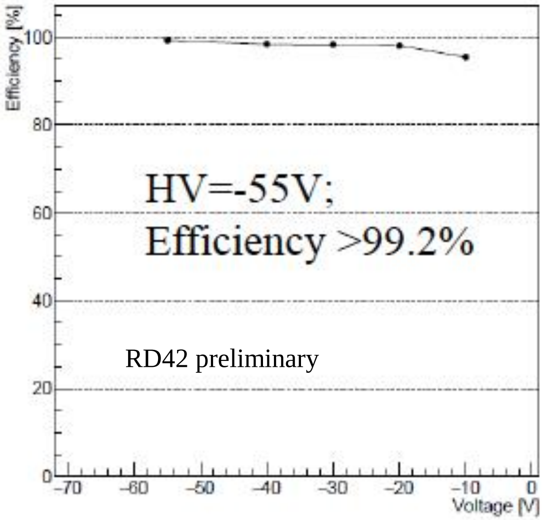
Testbeam results from CMS prototype

Preliminary Results (50μmx50μm cells)

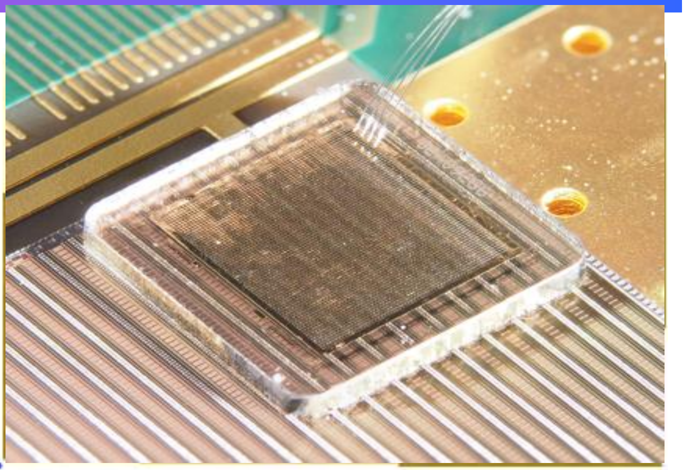
- CMS pixel readout (3x2) ganging
- Indium bumps, re-bump-bonded
- LJU telescope (resolution ~3 μm)
- Red box-efficiency 99.2%





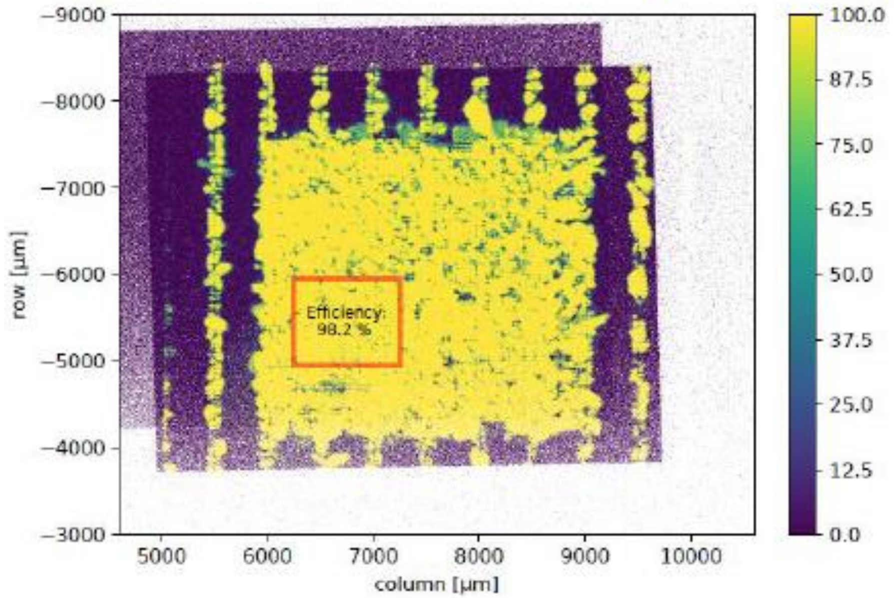


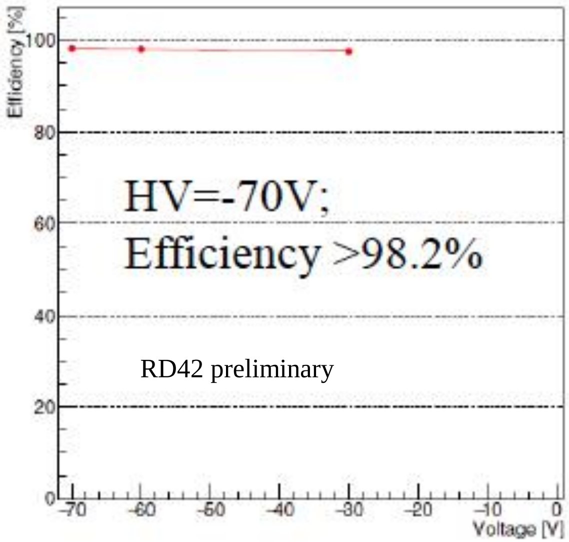
Testbeam Results from ATLAS Prototype



Preliminary Results (50μmx50μm cells)

- ATLAS pixel readout (5x1) ganging
- Tin-Silver solder bumps
- LJU telescope (resolution ~3 μm)
- Red box - efficiency >98.2%
- Inefficiencies most likely due to processing



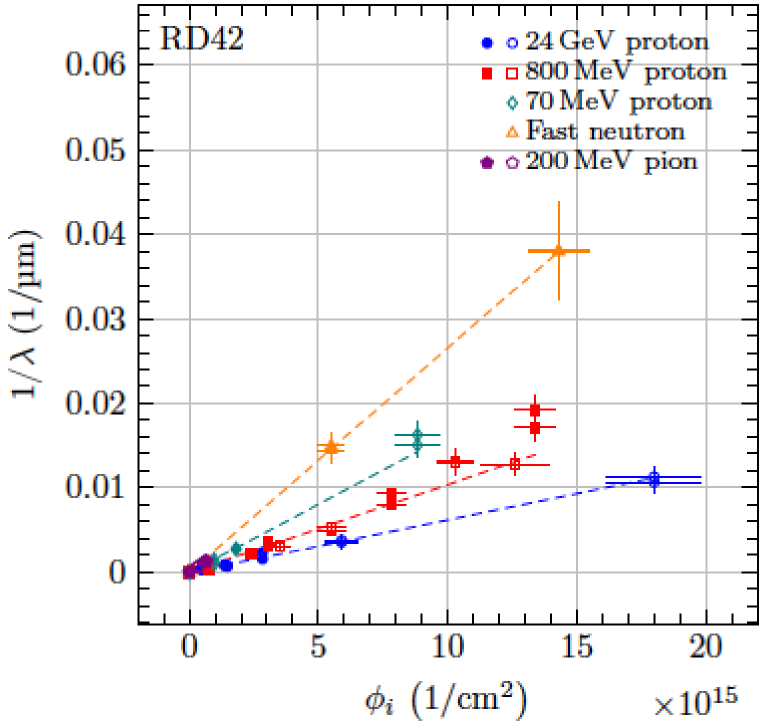


Mean Free Path vs. Irradiation species

- Irradiation introduces traps in the material
- Lowers carrier mean free path
- Effect depends on:
  - Traps in unirradiated material: λ_0
  - Proportional to fluence: ϕ
  - Irradiation species (protons, neutrons,…): k_i

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

scCVD pCVD

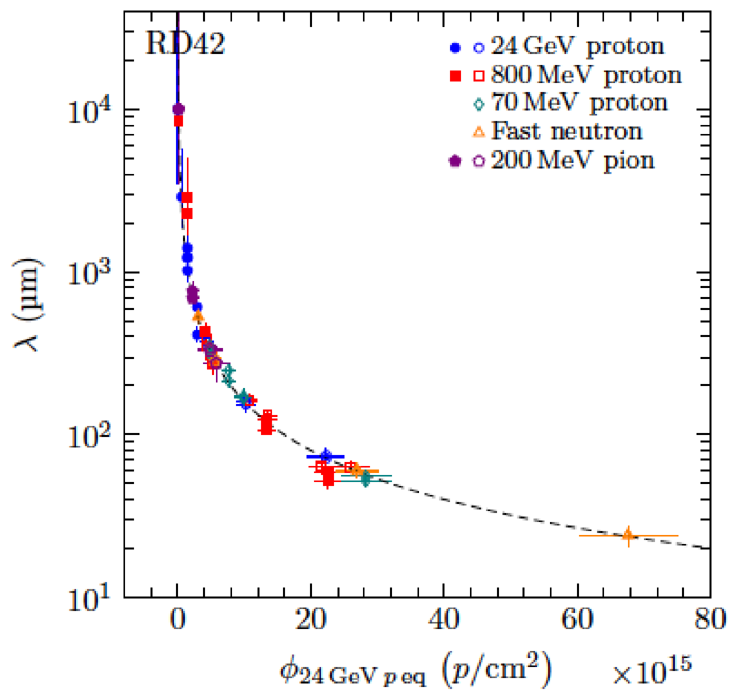


Adjust each species for relative damage

- Normalise to 24 GeV proton fluence
- Correct for λ_0 for each sample
- Universal signal degradation curve
-

Irradiation Species	k_i
200 MeV pions	3.2 ±0.8
Fast neutrons	4.27 ± 0.33
70 MeV protons	2.60 ± 0.27
800 MeV protons	1.67 ± 0.09
24 GeV protons	1

J. Phys. D: Appl. Phys. 52 465103



Publication of 70 MeV protons, pions & neutrons

A study of the radiation tolerance of CVD diamond to 70 MeV protons, fast neutrons and 200 MeV pions

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RD42 Pubs and Talks since last LHCC presentation

- Publications
  - LP2019 conference proceedings (2)
  - 3D sensor publication (Manchester group)
  - 70 MeV proton/fast neutron/pion paper
  - Vertex 2019 PoS proceedings
- Talks
  - TIPP2020 (Canada) 2 talks, 1 poster — Conf cancelled
  - ICHEP2020 (Prague) 3 talks — Virtual presentations
  - RAD8 - 2020 (Montenegro) 1 talk — Conf cancelled
  - Vertex 2019 (Croatia) 1 talk — Given
  - Hiroshima 2019 (Japan) 2 talks — Given
  - ....

Summary

- Beam monitors for HL-LHC advanced
  - Readout chip may be shared by ATLAS and CMS
  - ATLAS BCM' will use both planar and 3D sensors
- 3D diamond sensors working well
  - Unirradiated sensors show 80% charge collection
  - Irradiated sensors have significantly less loss in charge than planar
- Radiation tolerance and rate studies
  - Understood and published (*) up to 10^{16}
  - Next step is to go to 10^{17} and >20 MHz/cm^2
- Continuing to publish results in open-source literature
- RD42 played a pivotal role in making all this happen