28.05.24

Advanced UK Instrumentation Training 2024

Diamond Detectors

Alexander Oh
University of Manchester

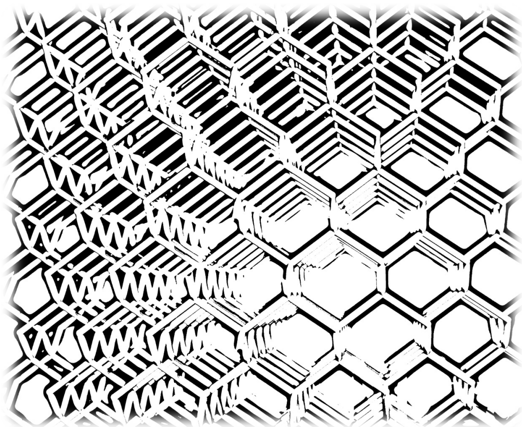
Outline

Part 1

- Diamond basics and detector principle
- Diamond strip and pixel detectors
- Radiation Hardness

Part 2

- 3D Diamond detectors
- Current and future diamond detector installations

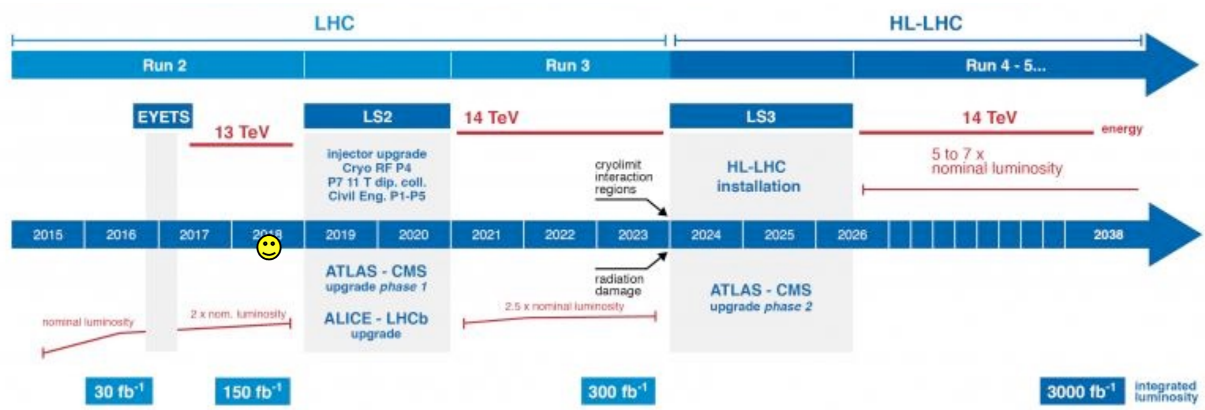


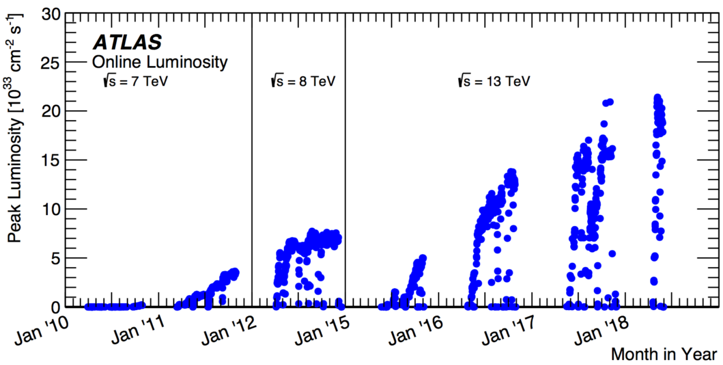
Thanks for the material from the RD42 and ADAMAS collaborations!
Very soon new working group organisation: **DRD3 WG6**

PART 1

- Introduction to Diamond detectors
  - properties
  - principle of operation
- Strip and Pixel detectors
- Radiation tolerance
- High rate capability

Challenges Ahead





- Luminosity upgrades of the LHC will increase the luminosity by factor ~3.
- Luminosity ~ Radiation damage.
- Need new technologies in the innermost layers to survive the radiation levels.

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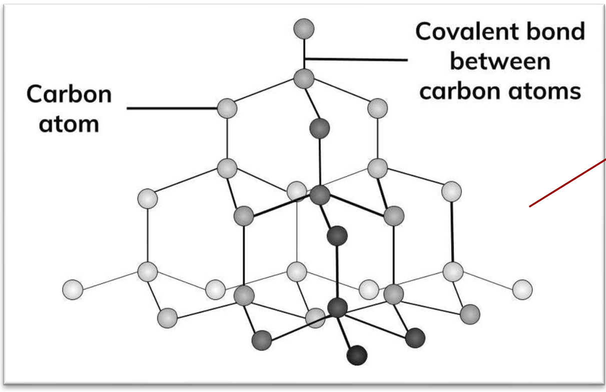
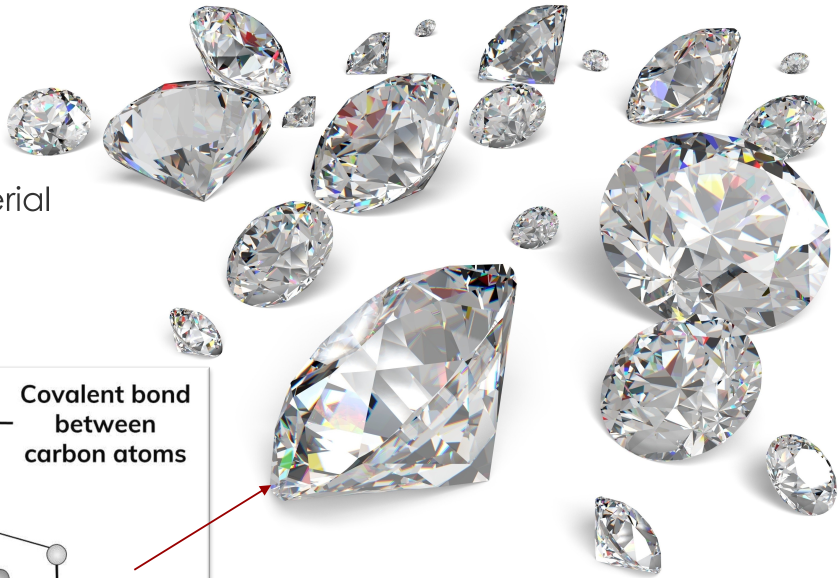
diamond

- Allotrope of Carbon
- Hardest natural material
- Tetrahedral structure
  - Sp3 bonds





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	Diamond	Silicon
Band Gap [eV]	5.5	1.1

→ Lower leakage current

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Average Ionisation Density for MIP [eh/μm]	36	81

→ Lower leakage current

→ Lower signal

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Displacement Energy [eV]	43	25

→ Lower leakage current

→ Lower signal

→ Radiation Hardness

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Displacement Energy [eV]	43	25	→ Radiation Hardness
Thermal Conductivity [W/cm.K]	10-20	1.5	→ Room temperature operation

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Atomic Number	6	14	→ Tissue equivalence
Electron Mobility [cm²/V.s]	1900-3800	1350	→ Fast signal (Electron and Hole Mobility)
Hole Mobility [cm²/V.s]	2300-4500	480	

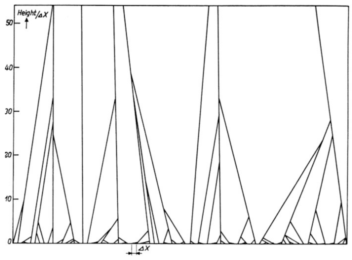
Natural and synthetic diamond

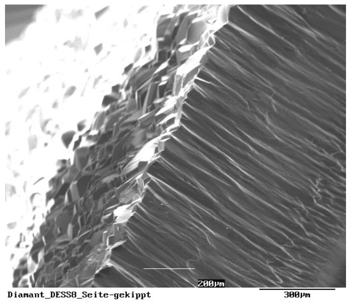
- Natural diamonds have a **high defect concentration**
  - Grow in different structure to synthetic diamonds
  - Compete with jewellery market
  - There are radiation sensors using natural diamond!

G. Stetter. Verhandl. deut. physik. Ges., 22:13, 1941.

Diamond

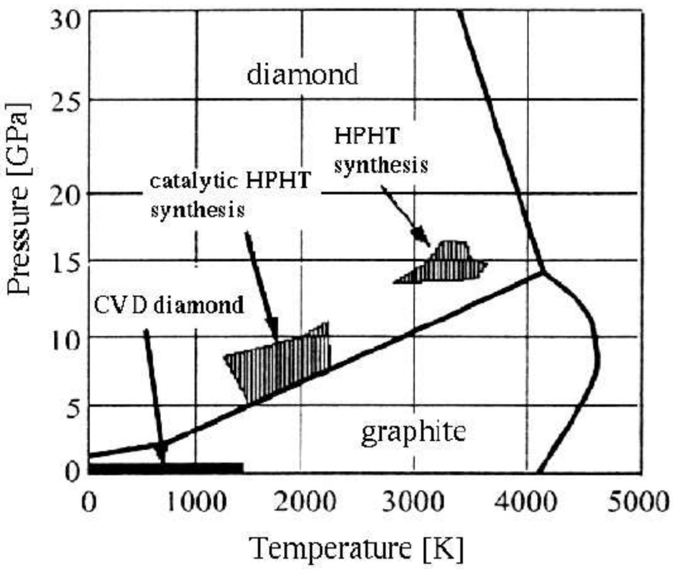
- 1941 – Diamond as particle detector (Stetter)
- 1953- CVD process, synthesis of diamond (Eversole)
- ~1980 – polycrystalline CVD diamond.
- 1994 – first diamond strip detector
- 1996 – first diamond pixel detector
- 2011 – first 3D diamond detector





Synthesis of Diamond

- Chemical Vapour Deposition (CVD) of diamond in the graphit phase space.



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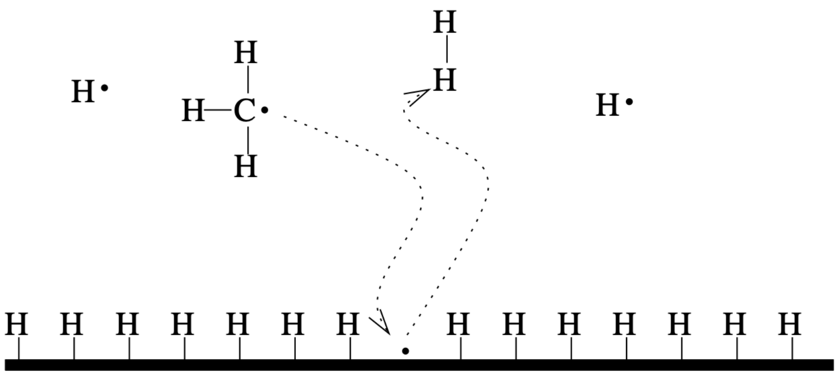
Synthesis of Diamond

- Hydrogen terminated substrate surface
- Methan and Hydrogen gas are heated with microwaves to form a plasma
- Radicals form



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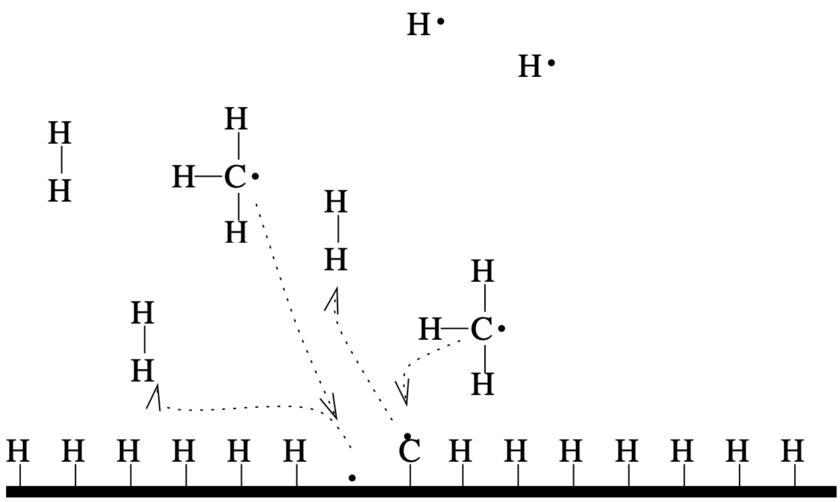
Synthesis of Diamond

- Hydrogen atoms are replaced with Carbon



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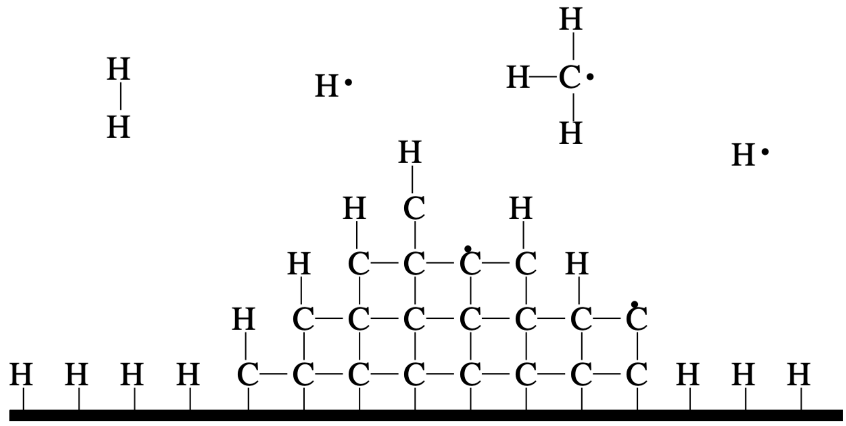
Synthesis of Diamond

- SP2 bonds (graphite) are weaker then SP3 bonds (diamond)
- Hydrogen radicals will etch away graphite, but leave diamond
- A diamond film is grown



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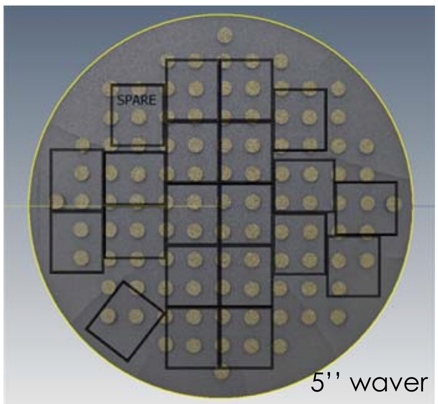
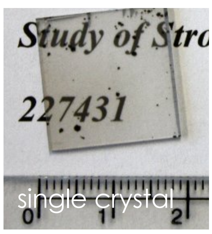
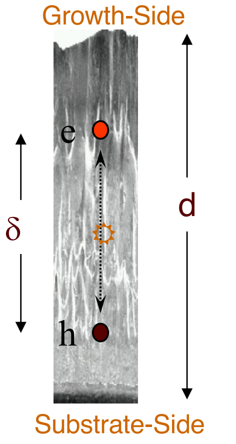
Development of CVD Diamond for detector applications

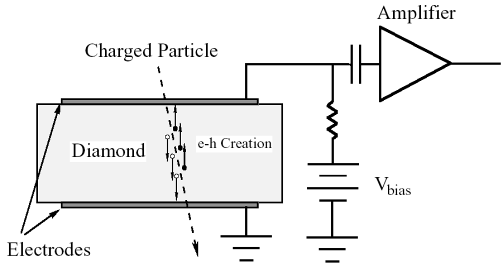
- Today two <u>main manufacturers</u> of detector grade diamond
  - **ElementSix Ltd**
    - large **polycrystalline** wafers
    - **single crystal** diamonds
  - **II-VI Semiconductors**
    - large **polycrystalline** wafers
    - relatively recent entry
- <u>Alternative sources</u>
  - Diamond on Iridium (DoI) (Audiatec, Germany)
  - Hetero-epitaxially grown -> **large area**
  - **Highly oriented crystallites**.





- Principle of detector operation





$Q = \frac{d}{t} Q_0$ collected charge

$\delta = \mu E \tau$ "collection distance"

$\varepsilon = Q / Q_0$ collection efficiency

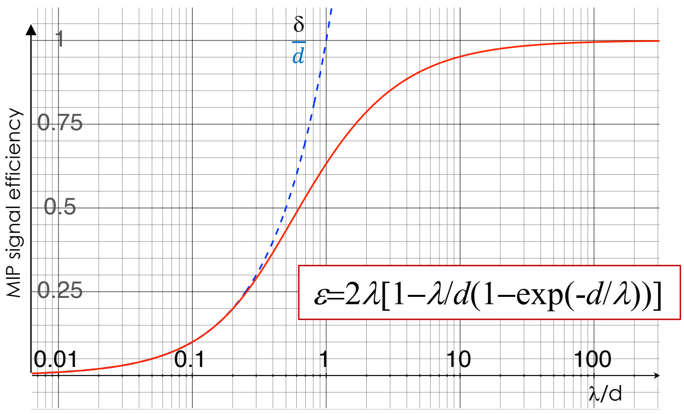
$$\mu = \mu_e + \mu_h$$
$$\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$$

- MIP signal is measured, expressed in charge collection distance defined as **δ [μm]=Q_m[e] / 36 [e/μm]**
- More accurately the "Schubweg" (λ).
  - Relation between *MIP signal efficiency* ε, "collection distance" δ, and "Schubweg" λ:

$$\epsilon = \frac{Q_m}{Q_0}$$

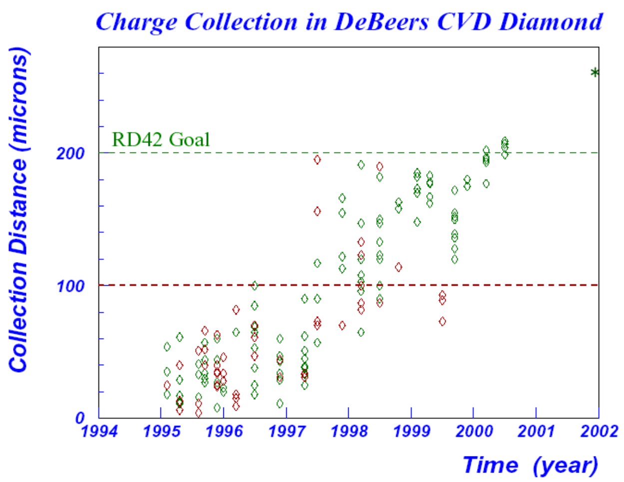
$$\delta = Q_m/36\ [e\mu\mathrm{m}^{-1}]$$

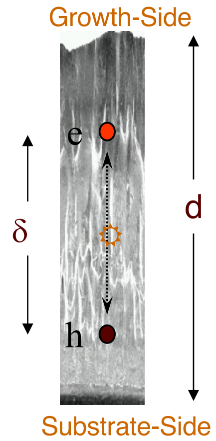
$$\epsilon = 2\lambda[1 - \lambda/d \cdot (1 - \exp(-d/\lambda))]$$



Development of CVD Diamond for detector applications

- Impressive progress over the last 20 years.
- Current state of the art for **polycrystalline** CVD diamond
  δ ~ **250 μm (~9000 e/MIP) commercially available.**

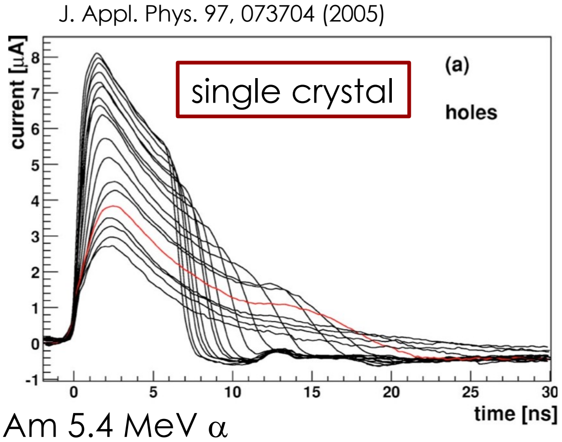




Development of CVD Diamond for detector applications

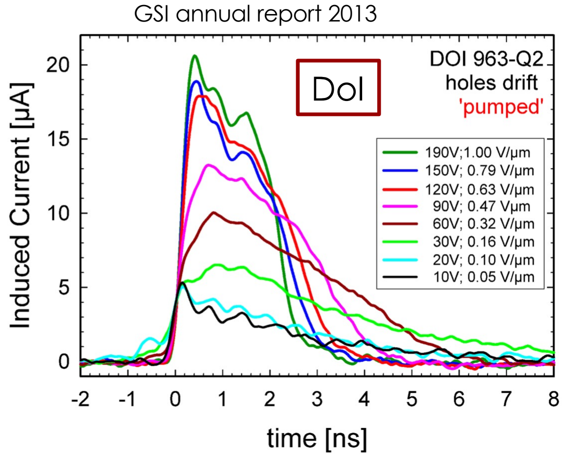
- Impressive progress over the last 20 years.
- **Single crystal diamond ~ 100% efficient**
- **Diamond on iridium ~ 97% efficient**

J. Appl. Phys. 97, 073704 (2005)



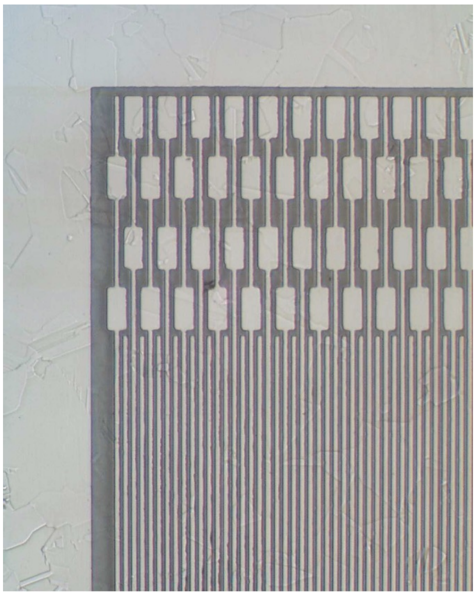
^{241}Am 5.4 MeV α

GSI annual report 2013

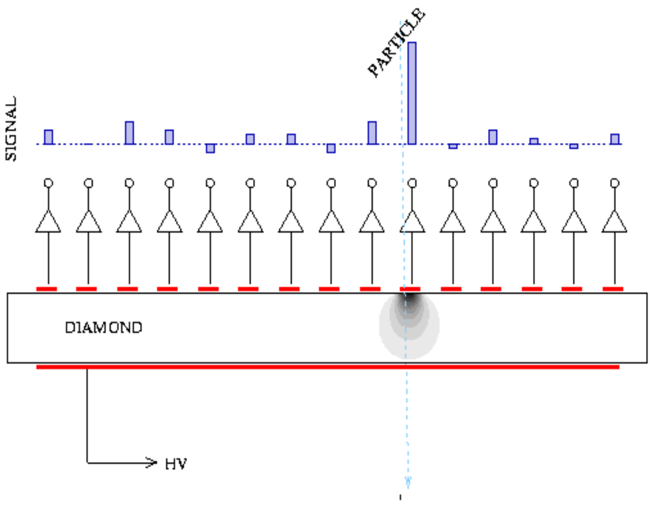


Strip Detectors

- First position sensitive diamond detectors where strip detectors.
- Many prototypes tested starting around 1994

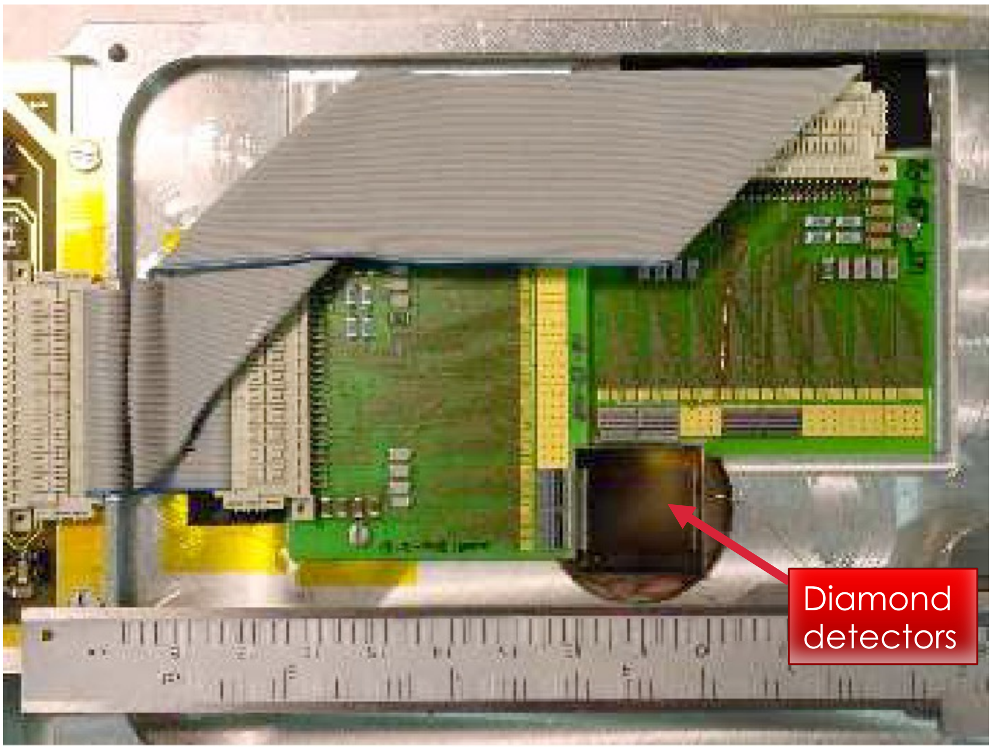


Principle

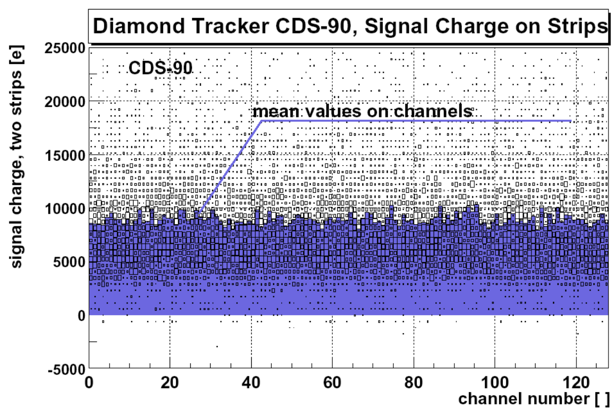


- The charge signal is picked up by the strip(s) next to the particle track.
- The charge is shared by multiple strips if the charge collection is incomplete.
- The position of the particle track can be reconstructed by calculating the charge weighted impact point **(Center of Gravity)**

- A Diamond Testbeam Telescope

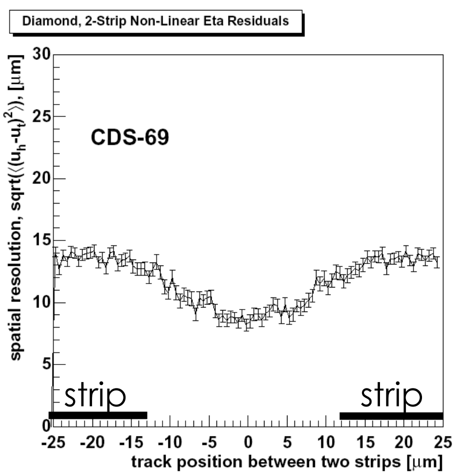


PH Distribution on each Strip



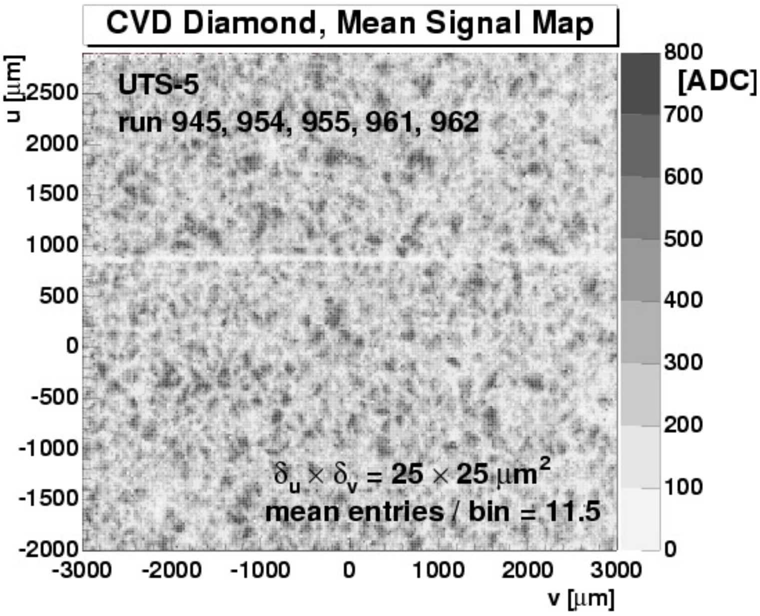
~10ke mean signal

Residual versus Track Position



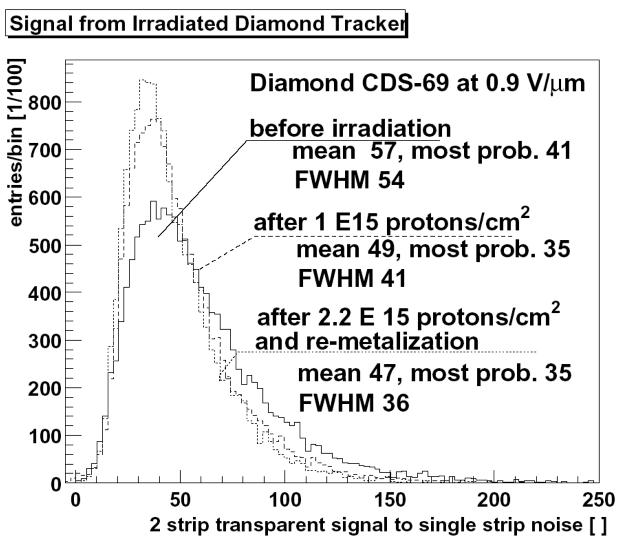
Uniformity in Charge Collection of CVD Diamonds

- Measured with MIPS
- Polycrystalline CVD diamond exhibits non-uniform signal response due to crystallite structure.
- Similar patterns observed as with photon beam measurement

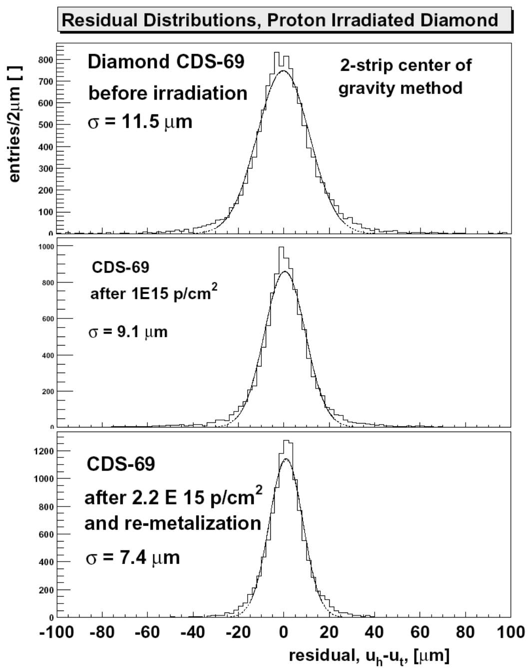


Irradiated Strip Detectors

- Proton Irradiation



15% loss of S/N after 2e15 p cm^{-2}



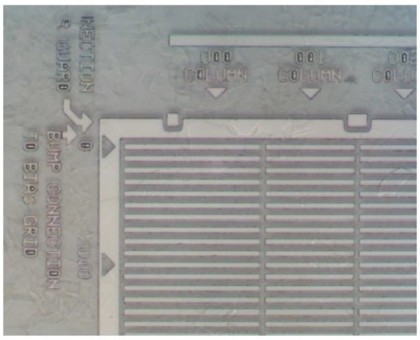
35% improvement in resolution

Pixel Detectors

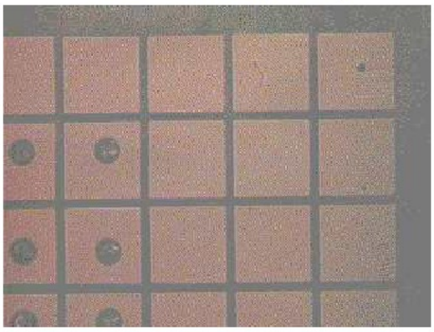
- Several prototypes of Diamond pixel detectors have been developped and tested since around 1996.
- Read-out chips use ROC (CMS), FE-I4 (ATLAS)
- More recently tested 3D pixel detectors (see later).
- Some historic examples in the following.

• Diamond Pixel Detectors

ATLAS FE/I Pixels (Al)



CMS Pixels (Ti-W)



- ✦ Atlas pixel pitch $50\mu m \times 400\mu m$
- ✦ Over Metalisation: Al
- ✦ Lead-tin solder bumping at IZM in Berlin

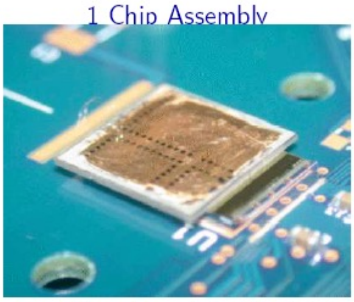
- ✦ CMS pixel pitch $125\mu m \times 125\mu m$
- ✦ Metalization: Ti/W
- ✦ Indium bumping at UC Davis

$\rightarrow$ Bump bonding yield $\approx$ 100 % for both ATLAS and CMS devices

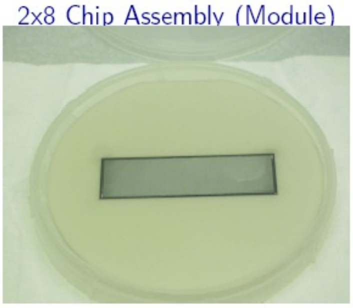
Diamond Pixel Detectors

Results from an ATLAS pixel detector

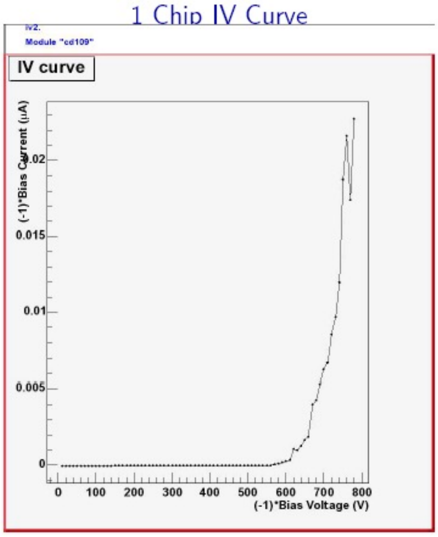
1 Chip Assembly



2x8 Chip Assembly (Module)



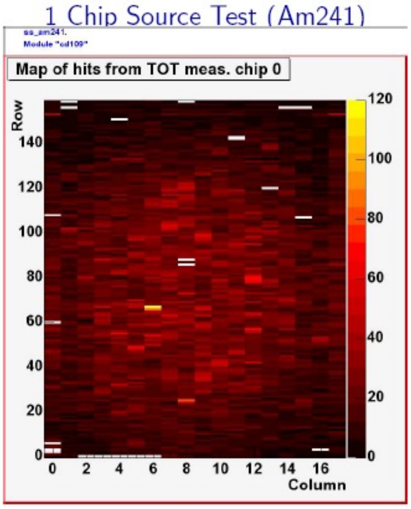
1 Chip IV Curve



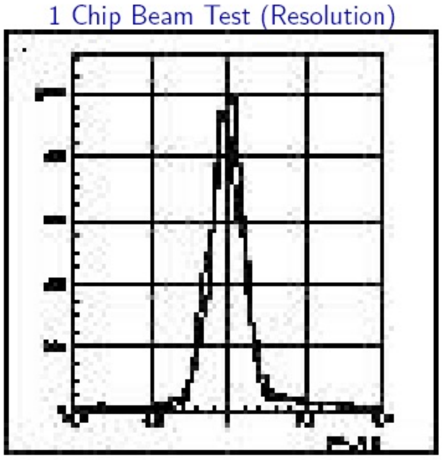
Diamond Pixel Detectors

Results from an ATLAS pixel detector

1 Chip Source Test (Am241)



1 Chip Beam Test (Resolution)



Americium 241 deposits $\approx 4600e$

Spatial Resolution $\approx$ pitch/$\sqrt{12}$ (pitch 50μm $\times$ 400μm)

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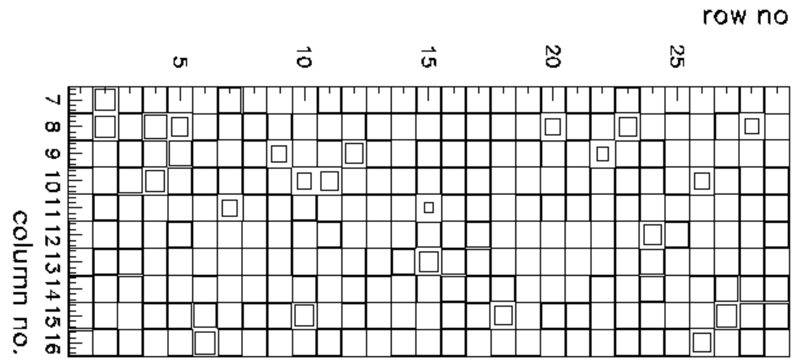
Diamond Pixel Detectors

Results from a CMS pixel detector

Efficiency vs Pixel



- Inefficient pixels due to bump bonding and/or electronics - shown in pulser tests
- Excellent correlation between beam telescope and pixel tracker data!

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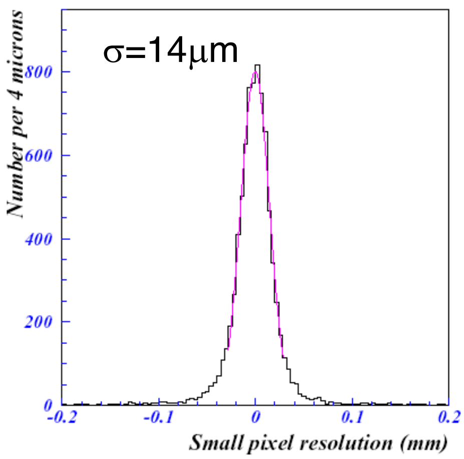
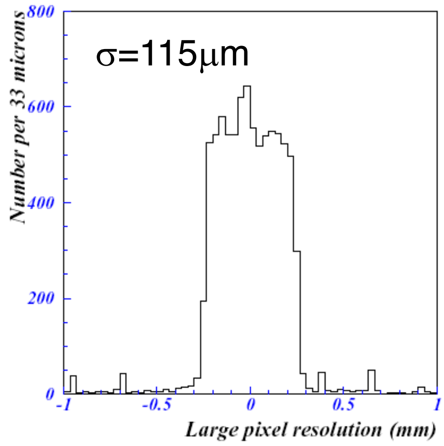
- Results from Atlas Diamond Pixel Detectors

Spatial Resolution – Short Direction

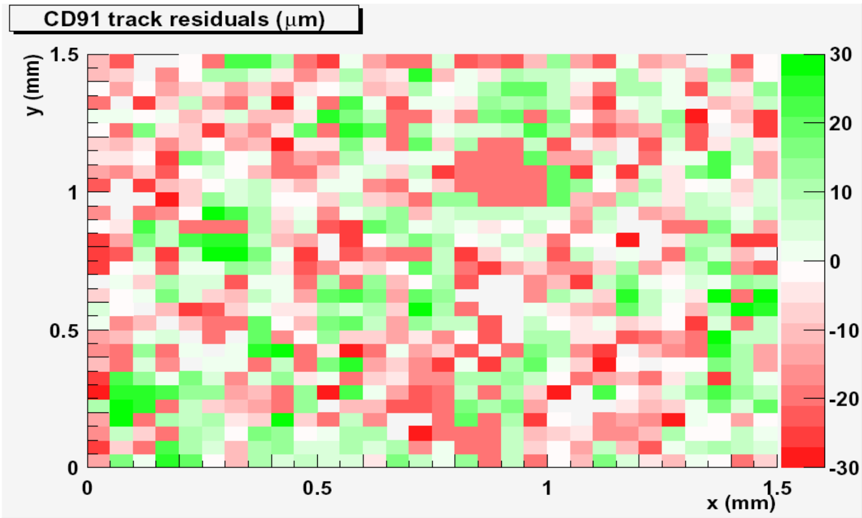


Spatial Resolution – Long Direction



- Efficiency = 80%
- Resolution = digital

- Results from Atlas Diamond Pixel Detectors



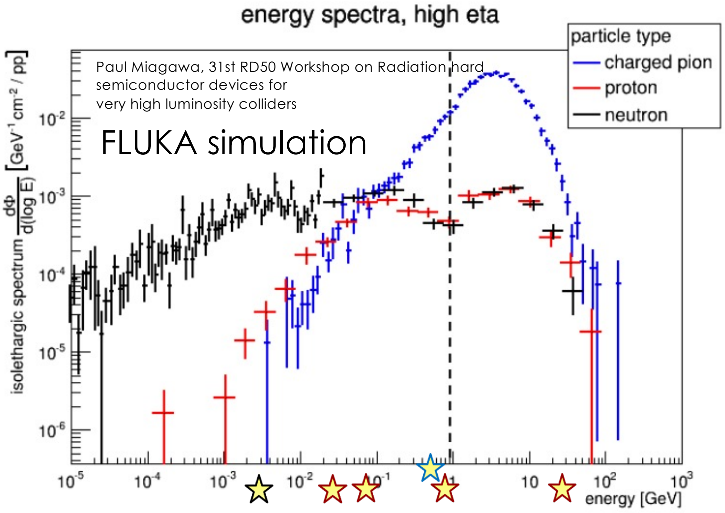
Tommaso Lari (INFN)
Alexander Oh (CERN)
Norbert Wermes (University Bonn)

- Large track residuals
- Non-uniformity of response qualitatively reproduces by modeling

Radiation Tolerance

Tests of Radiation Tolerance

- Irradiate with **proton**, **pions** and **neutrons**.
  - Energies within the expected radiation profile at HL-LHC.
  - HL-LHC fluence requirement about $2e10^{16}$ neq.



	Proton ☆	Pion ☆	Neutron ☆
Energy	25MeV – 24GeV	300 MeV	1-10 MeV
Fluence	1.27e16 p cm^{-2}	6e14 π cm^{-2}	1.3e16 n cm^{-2}

- Assume simple effective model for radiation damage:

Radiation damage constant is fitted with simple model:

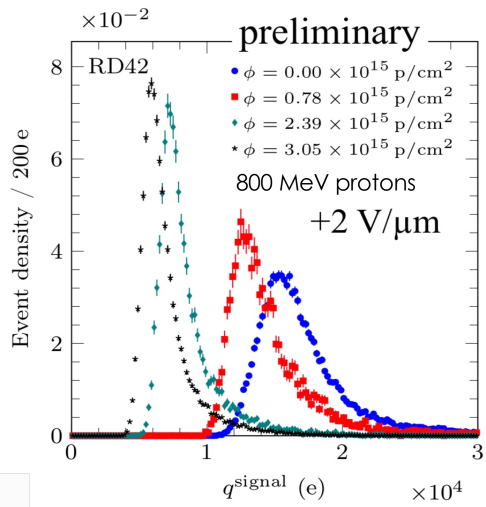
$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k_\lambda \Phi$$

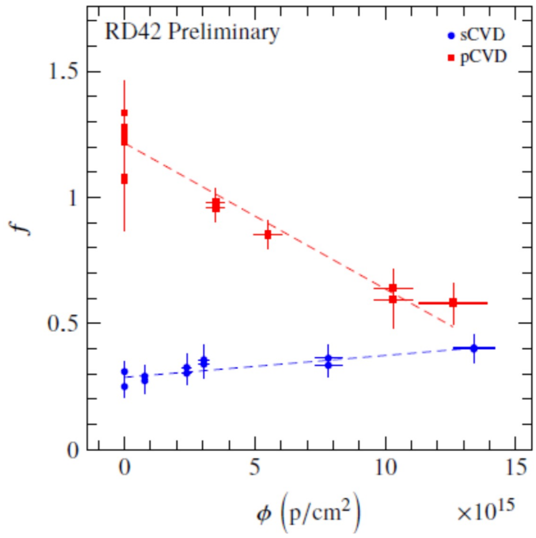
damage constant (k_λ)

particle flux (Φ)

Radiation Tolerance: Characterization

- Typical Landau Spectra after irradiation of pCVD.
- For pCVD see reduction of **FWHM / MP** with irradiation.
  - Expected from polycrystalline nature of material!
  - Single crystal material almost flat.

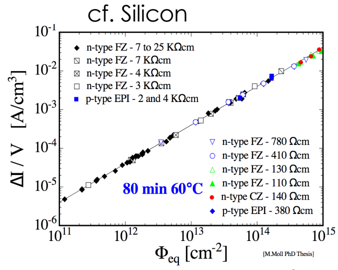


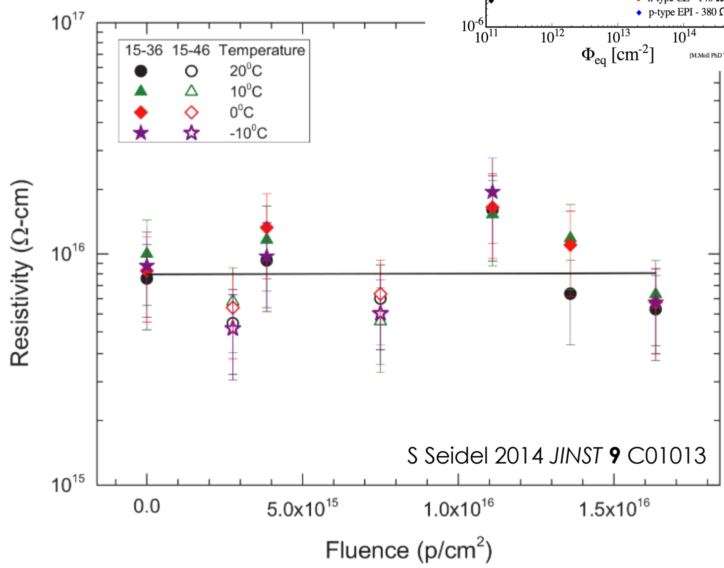


Radiation Tolerance: Characterization

- Resistivity
  - No dose dependence.
  - Due to large bandgap no significant temperature dependence at RT or below.

cf. Silicon





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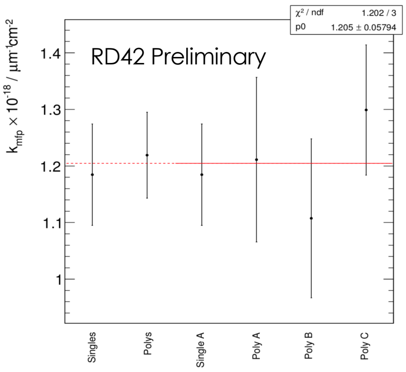
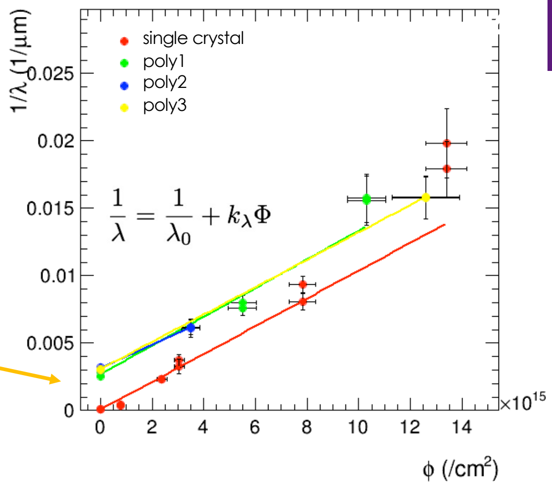
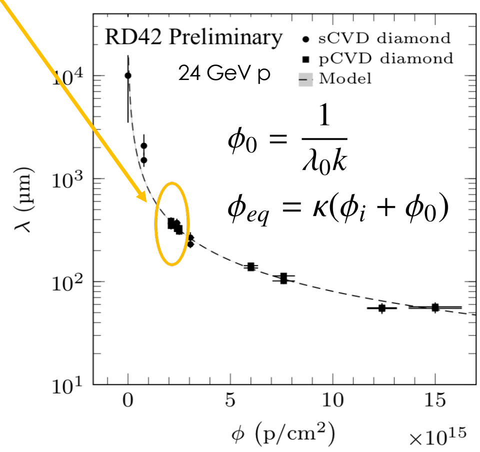
Radiation Tolerance: Characterization

- Damage factor k is determined for each sample.
- **pCVD** diamonds are offset by λ_0 to account for initial finite carrier lifetime.
- Final damage factor averaged over all samples.







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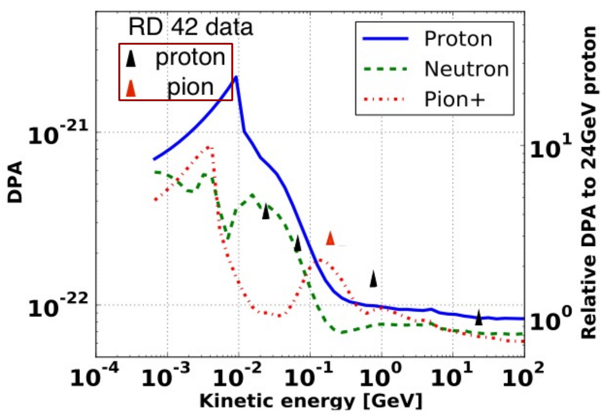
Radiation Hardness

- Describe radiation damage using Norget-Robinson-Torrens theorem to predict displacements per atom (DPA).
  - (M. Guthoff et al., arXiv:1308.5419)
  - Diamond displacement energy: 43.3 eV
  - Reasonable agreement for E>100MeV.



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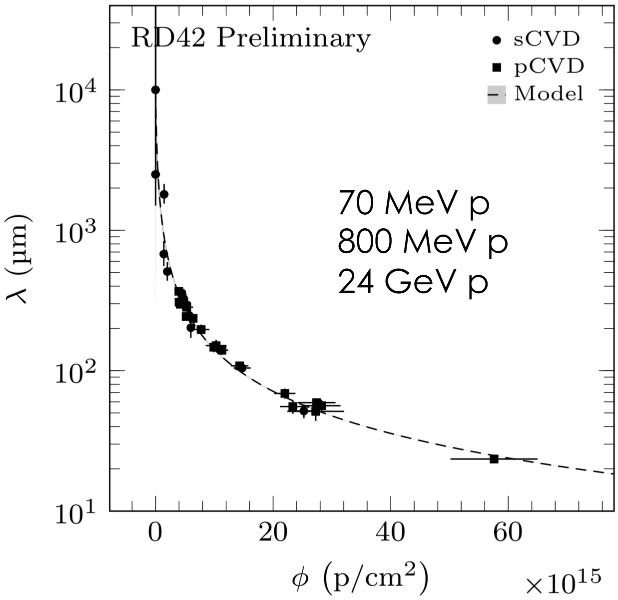
Radiation Tolerance

- **24 GeV protons**
  - $k_\lambda = 0.67 \pm 0.04 \times 10^{-18}\ cm^2 \mu m^{-1}$
  - polycrystalline diamond sample offset by $\Phi \sim 5\times10^{15}$ to account for existing traps.
  - Poly and single crystal diamond show consistent damage constants.



L. Baeni ETHZ Thesis
https://www.research-collection.ethz.ch/handle/20.500.11850/222412

Radiation Tolerance

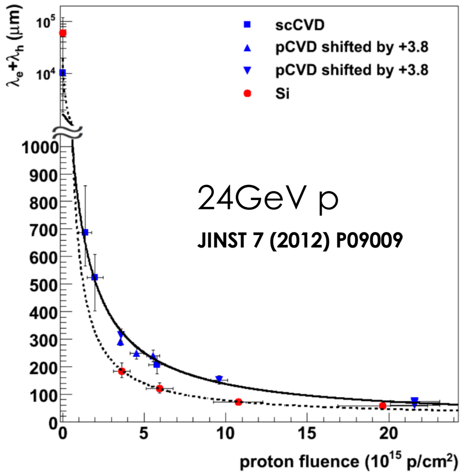
- Summary of RD42 irradiation results:

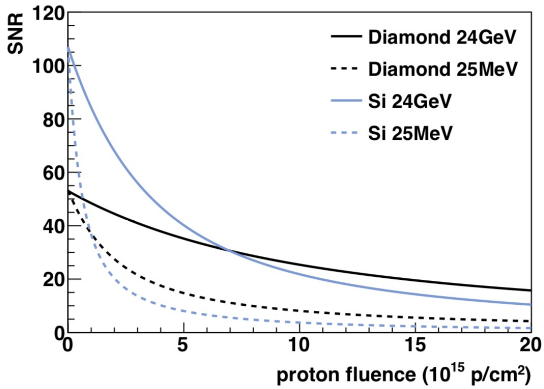
Particle Species	Relative Damage Constant, κ
24 GeV p	1
800 MeV p	1.54 ± 0.13
70 MeV p	2.5 ± 0.4
25 MeV p	4.5 ± 0.6
fast neutrons	4.5 ± 0.5

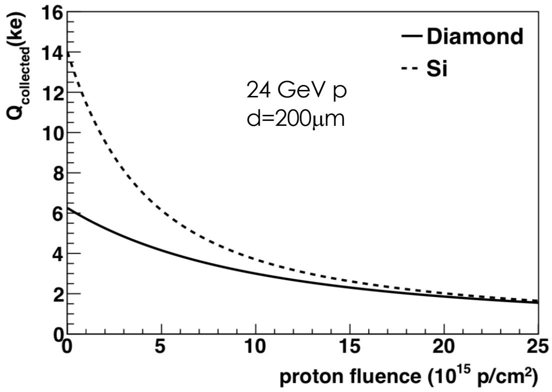
*normalized to 24GeV protons

Radiation Tolerance: Comparison to Si

- k factors typically 2-3 times higher for Silicon.
- A comparison to Si needs to take into account:
  - leakage current
  - capacitance
- Possible figure of merit Signal to noise ratio:





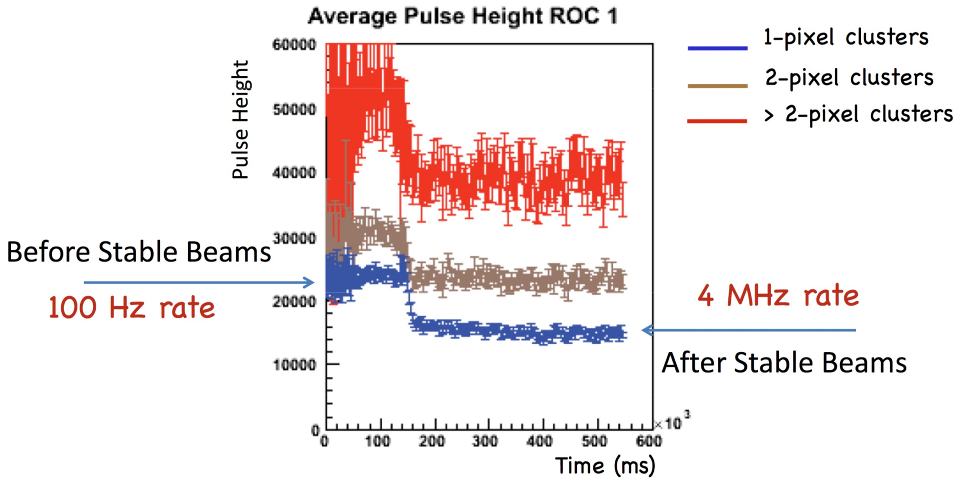


High rate capability

High Rate tests

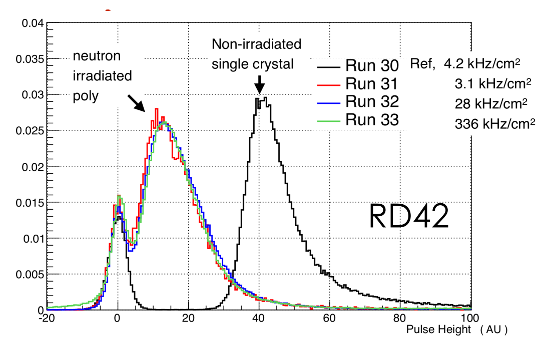
- Tests the pulse height as function of particle rate.
- Test single and poly crystalline diamond.
- Irradiated and un-irradiated.

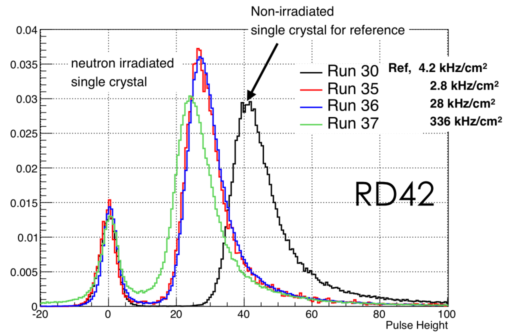
Investigations triggered by indication of rate dependence of of single crystal diamond pixel detector installed in CMS in 2012.

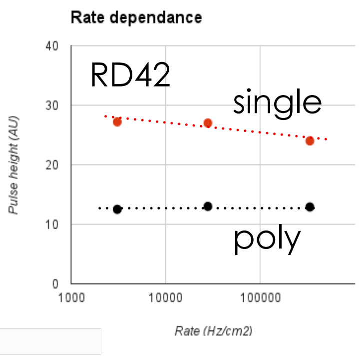


High Rate tests

- single and poly sample irradiated with 5×10^{13} reactor n.
- Tested with 250MeV pions.
- Slight rate dependence observed in irradiated **single crystal** sample.
- No rate dependence observed for irradiated **polycrystalline** sample.







END OF PART 1

- In part 2 next week we look at:
  - 3D Diamond detectors
  - Application of diamond detectors in HEP