The University of Manchester

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Advanced UK Instrumentation Training 2022

Diamond Detectors

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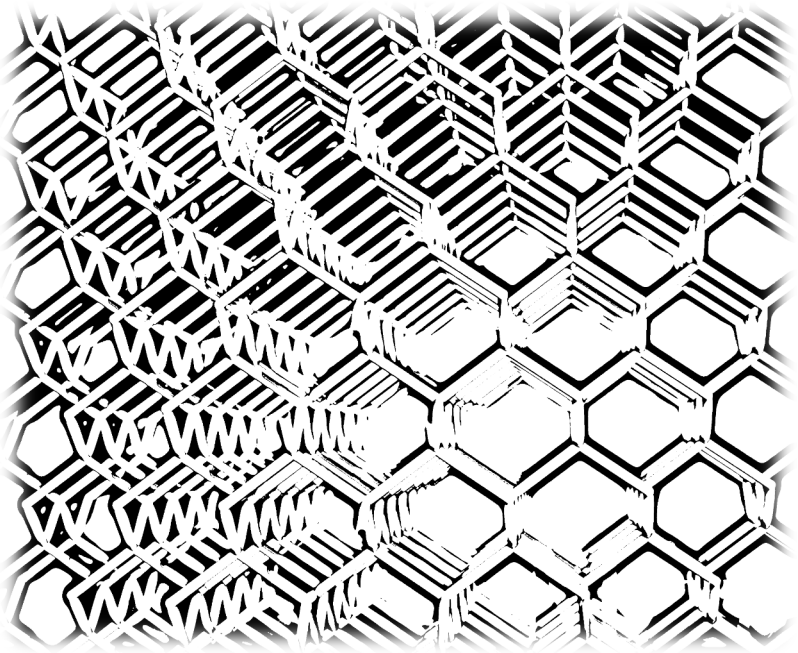
University of Manchester

Outline

Part 1

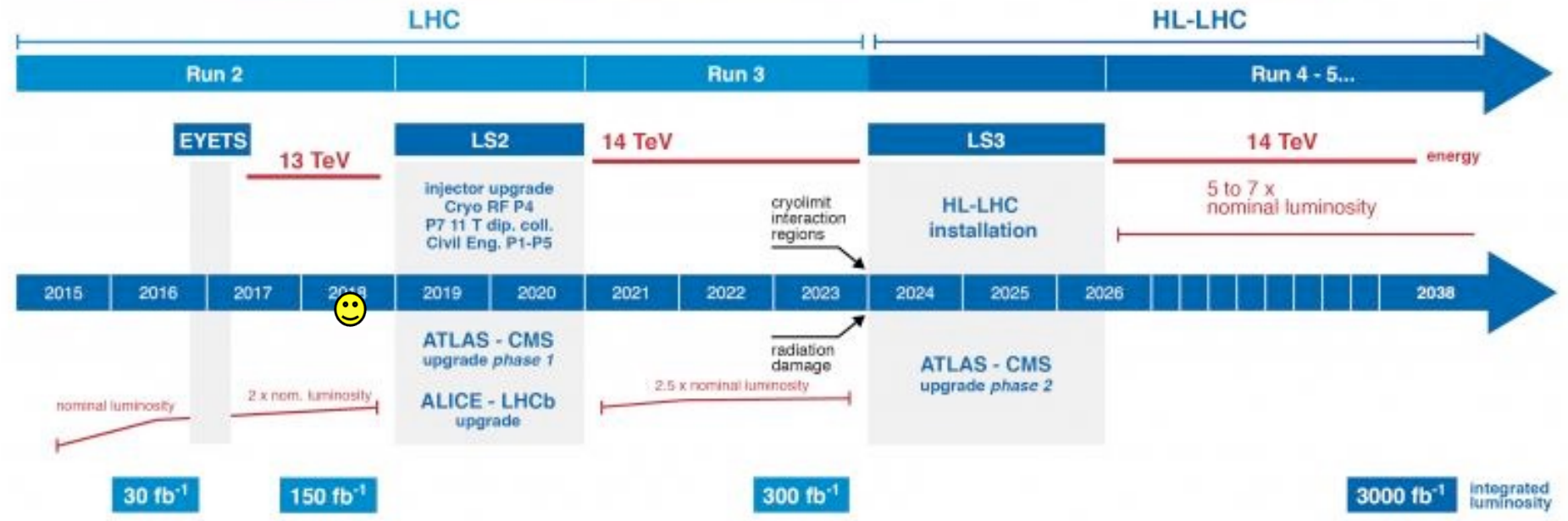
Part 2

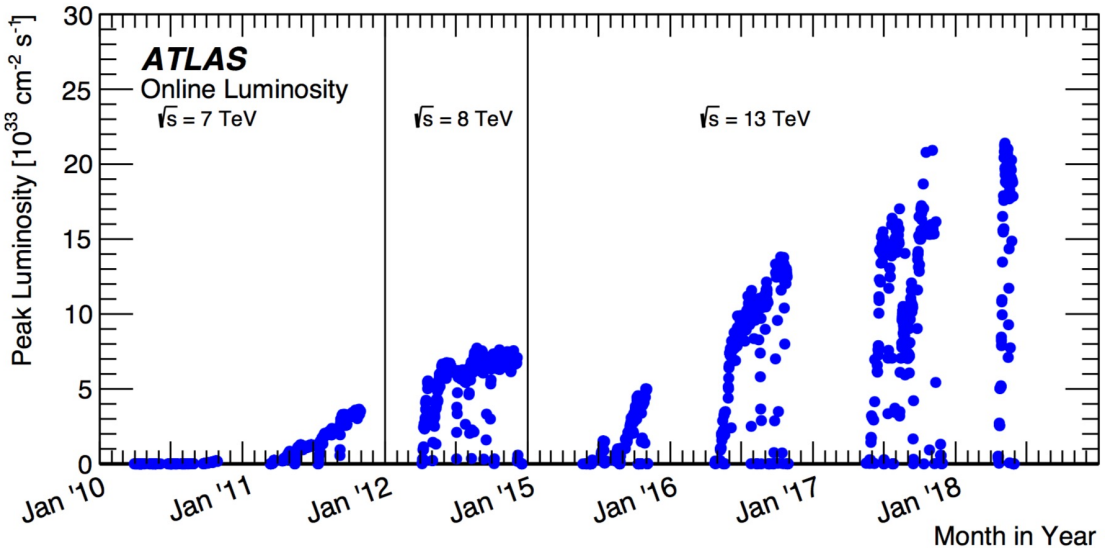
- Diamond basics and detector principle
- Diamond strip and pixel detectors
- Radiation Hardness
- 3D Diamond detectors
- Current and future diamond detector installations



Thanks for the material from the RD42 and ADAMAS collaborations!

Challenges Ahead

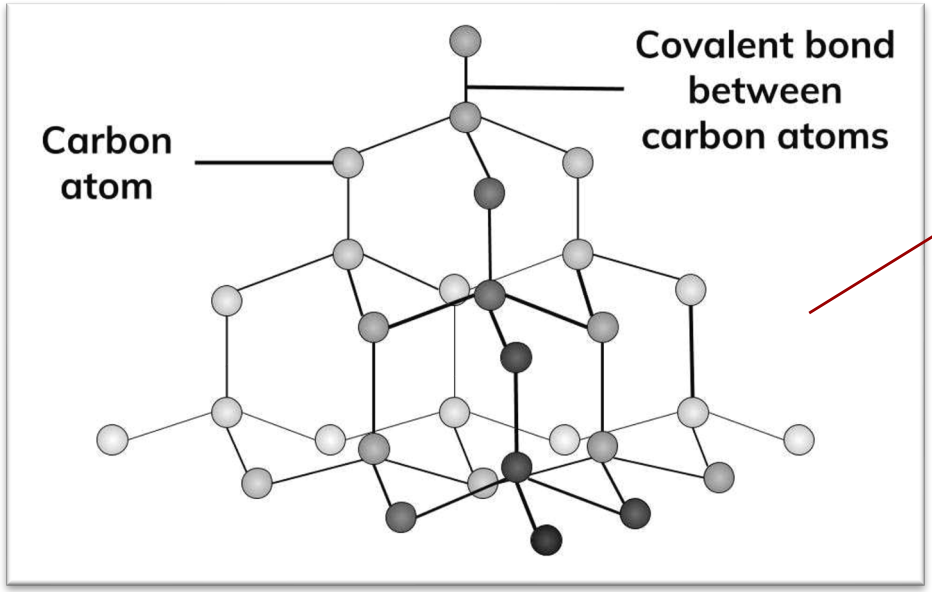




- Luminosity upgrades of the LHC will increase the luminosity by factor ~3.
- Luminosity ~ Radiation damage.
- Need new technologies in the innermost layers to survive the radiation levels.

diamond

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



	Diamond	Silicon
Band Gap [eV]	5.5	1.1

→ Lower leakage current

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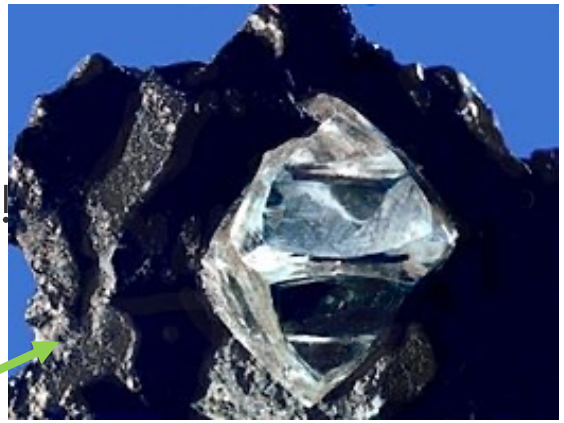
Electron Mobility [$cm^2/V.s$]	1900-3800	1350	→ Fast signal
Hole Mobility [$cm^2/V.s$]	2300-4500	480	

Natural and synthetic diamond

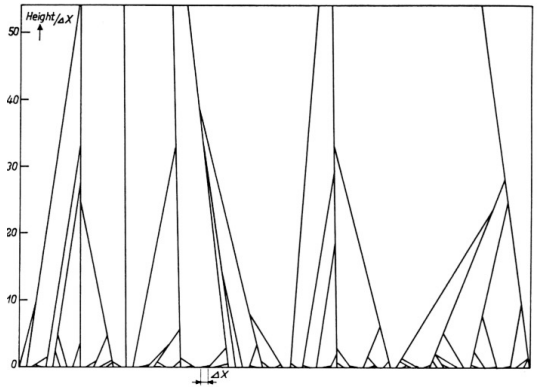
- Natural diamonds have a **high defect concentration**
  - Grow in different structure to synthetic diamonds
  - Compete with jewellery market
  - There are radiation sensors using natural diamond!

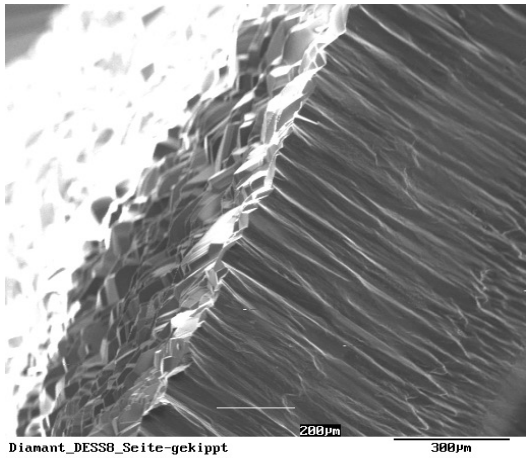


G. Stetter. Verhandl. deut. physik. Ges., 22:13, 1941.

Diamond

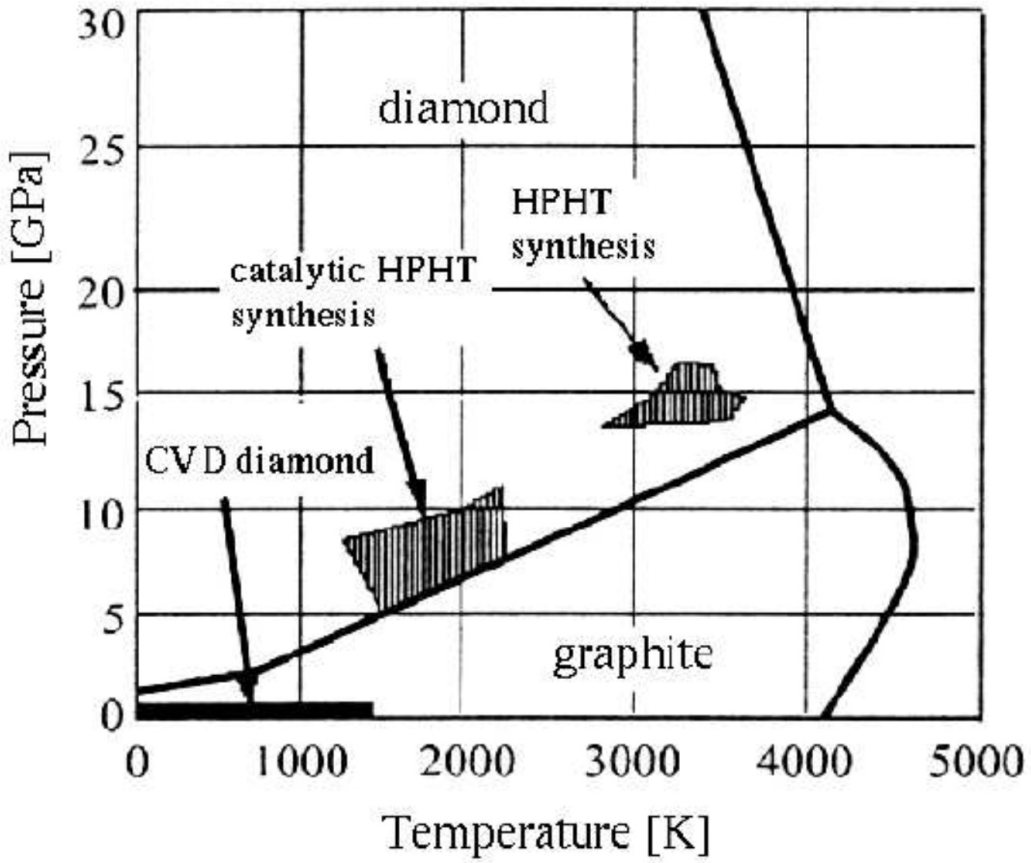
- 1941 – Diamond as particle detector (Stetter)
- 1953- CVD process, synthesis of diamond (Eversole)
- ~1980 – polycrystalline CVD diamond.
- 1994 – first diamond strip detector
- 1996 – first diamond pixel detector
- 2011 – first 3D diamond detector





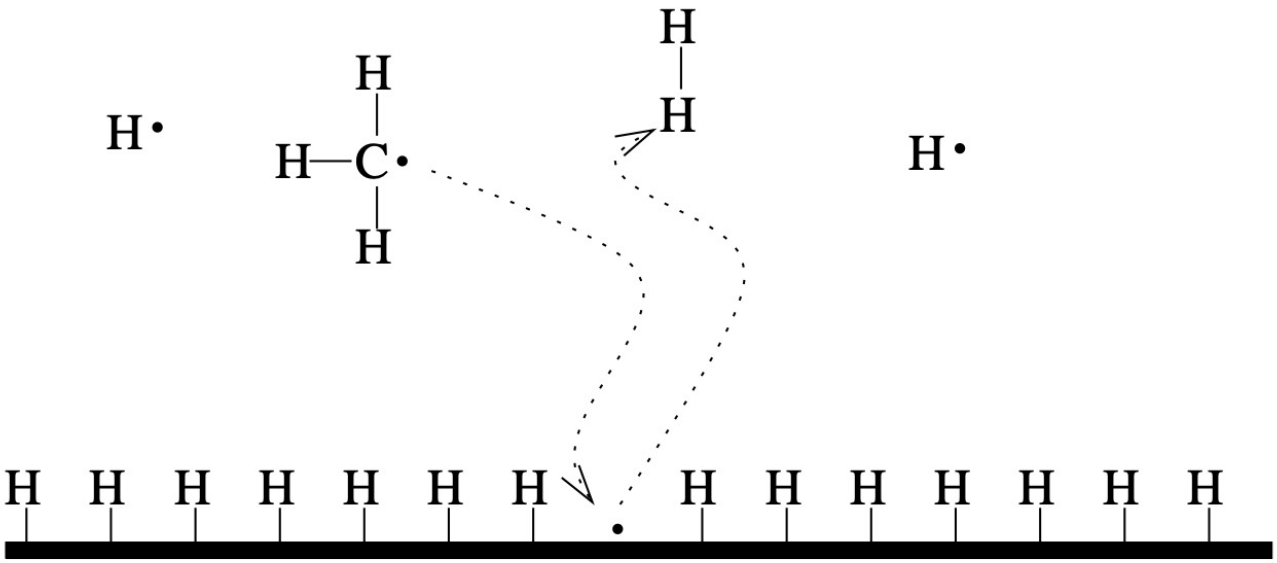
Synthesis of Diamond

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



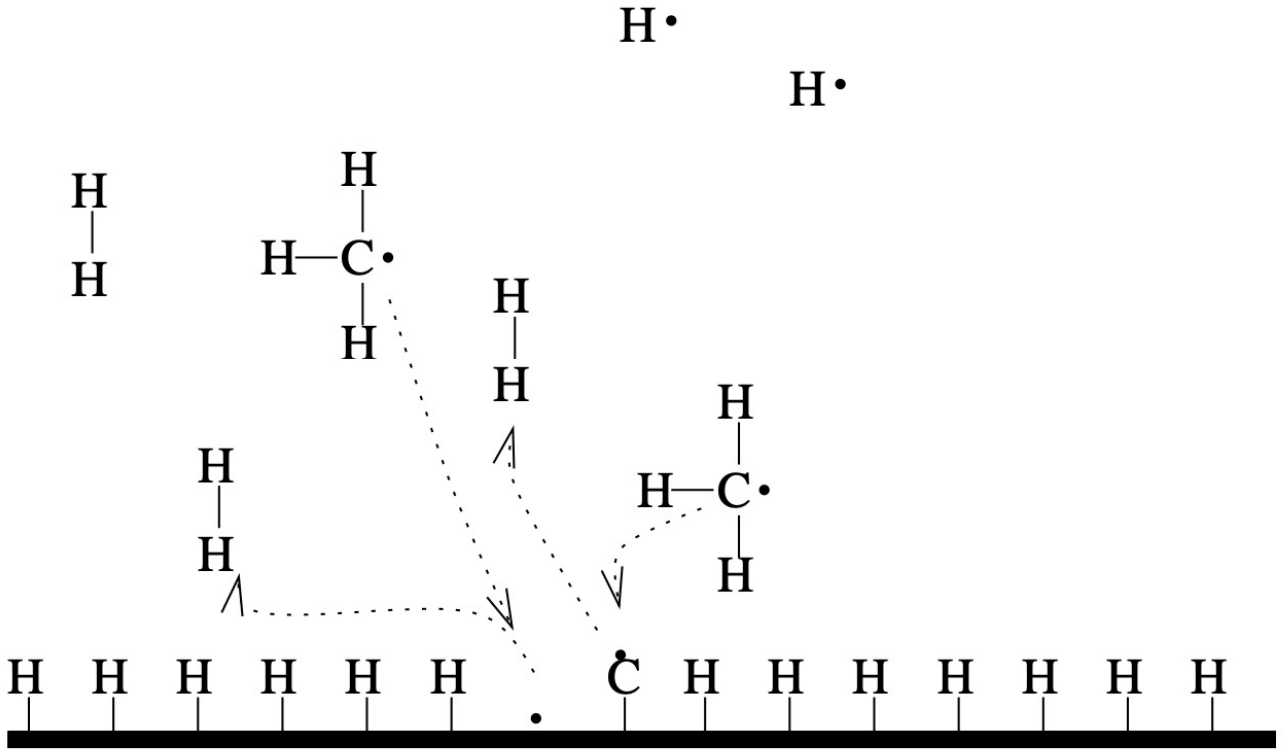
Synthesis of Diamond

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



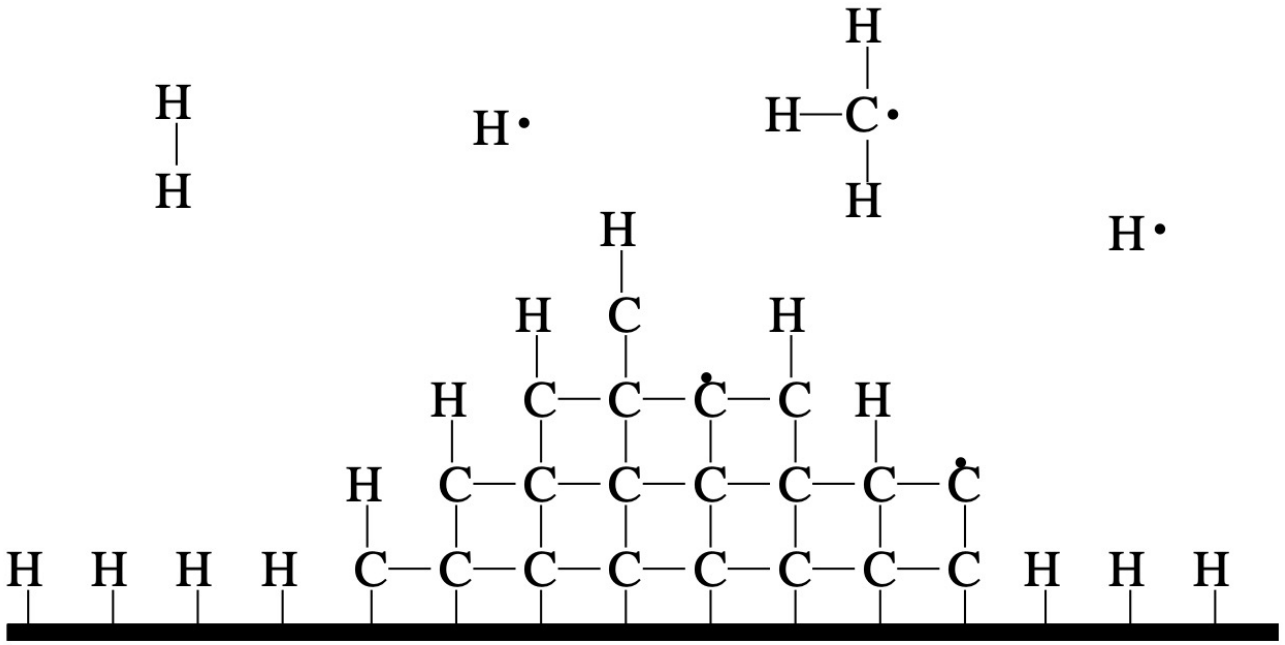
Synthesis of Diamond

- Hydrogen atoms are replaced with Carbon



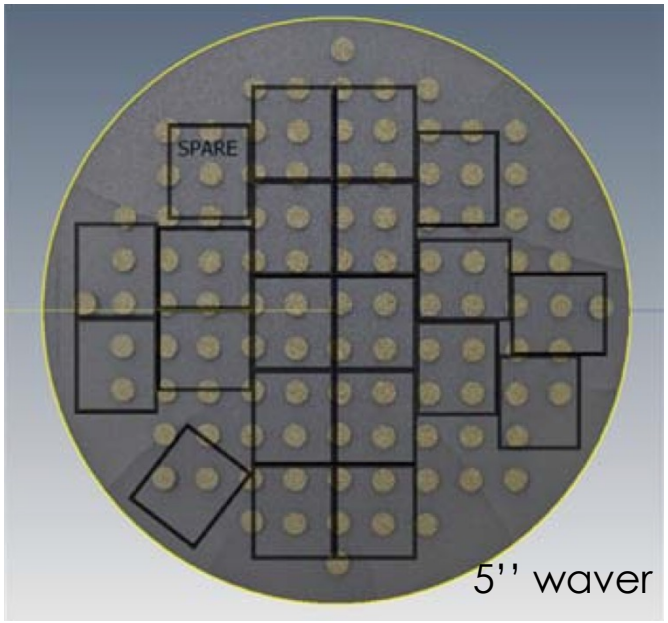
Synthesis of Diamond

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

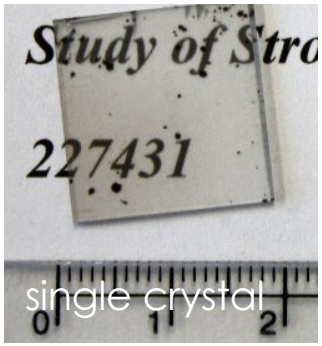


Development of CVD Diamond for detector applications

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



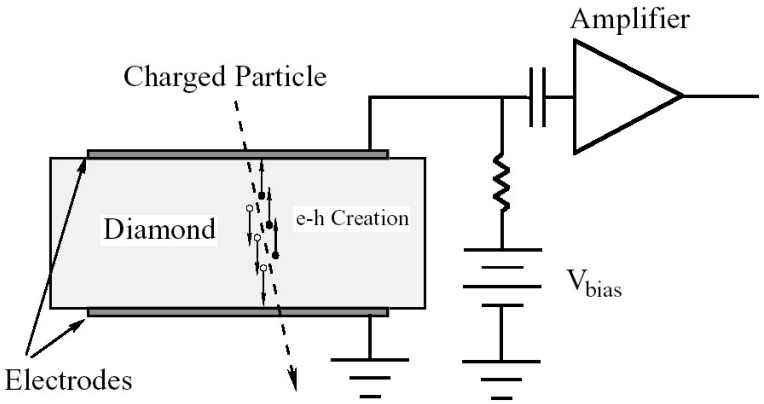
5'' waver

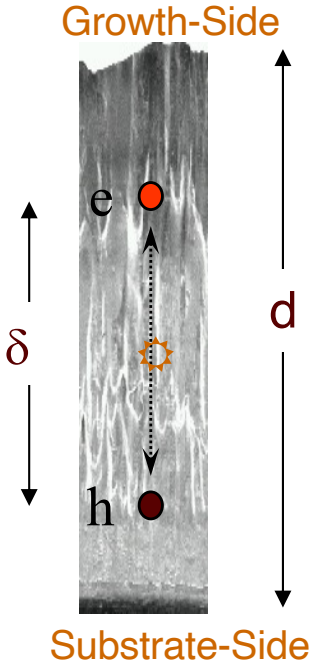


single crystal


DoI, 155ct

- Principle of detector operation





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

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

$$\varepsilon = Q / Q_0$$ collection efficiency

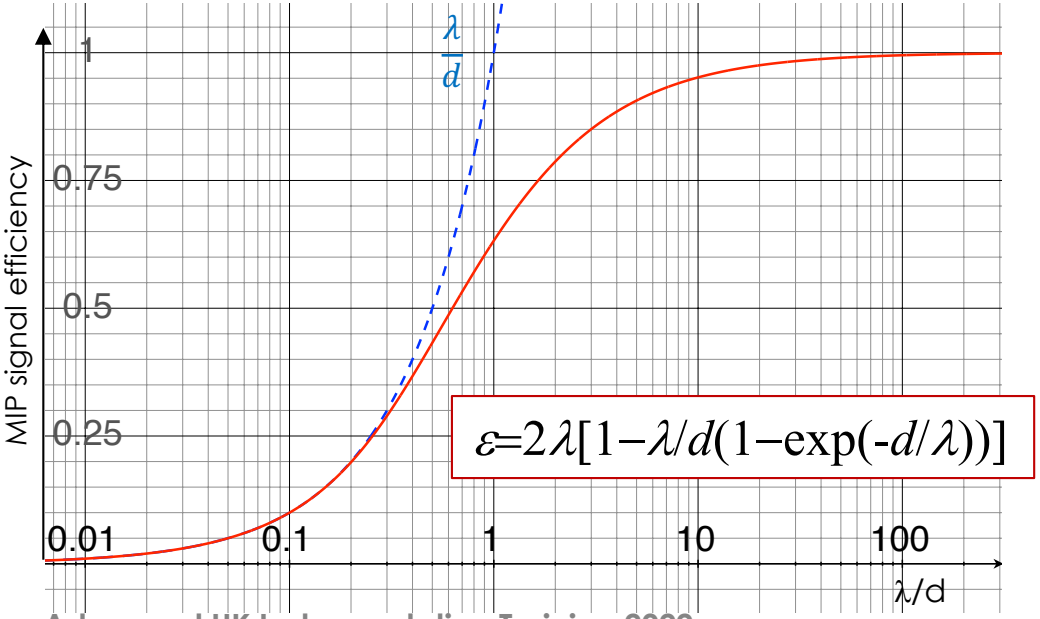
$$\mu = \mu_e + \mu_h$$
$$\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$$

- 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:

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

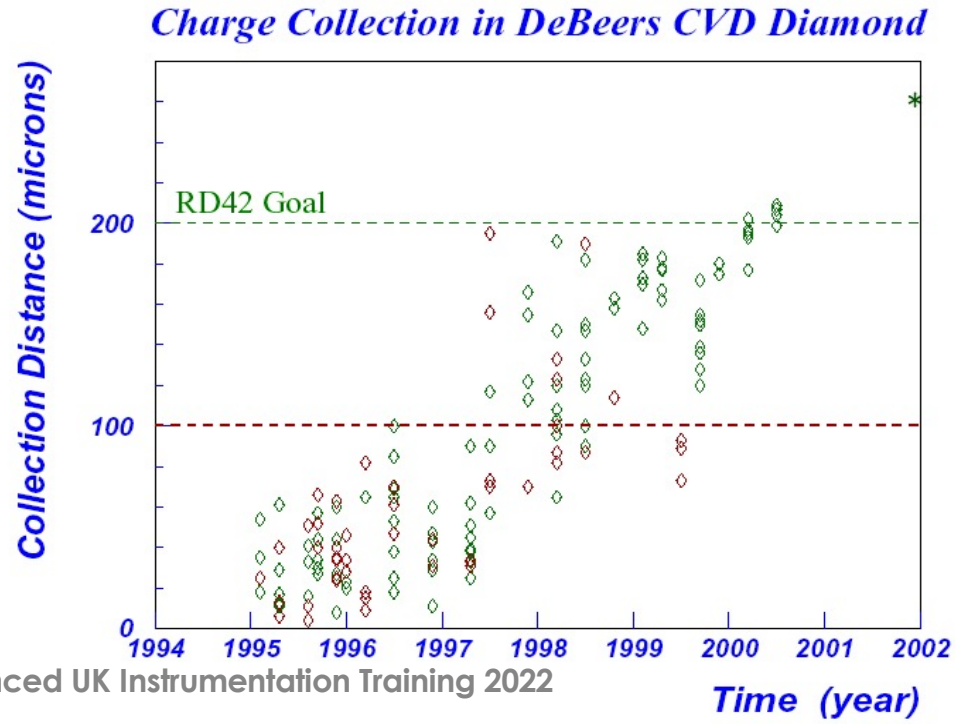
$$\delta = Q_m/36\ [e\mu\mathrm{m}^{-1}]$$

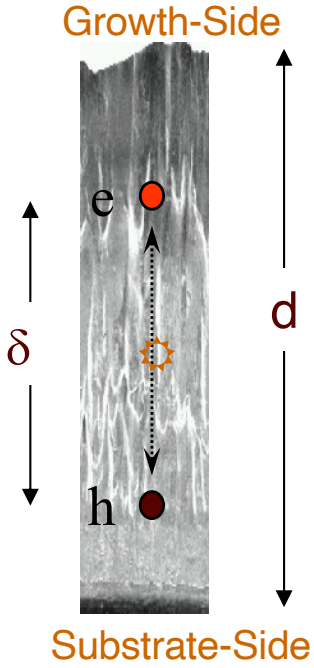
$$\epsilon = 2\lambda[1 - \lambda/d \cdot (1 - \exp(-d/\lambda))]$$



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.**

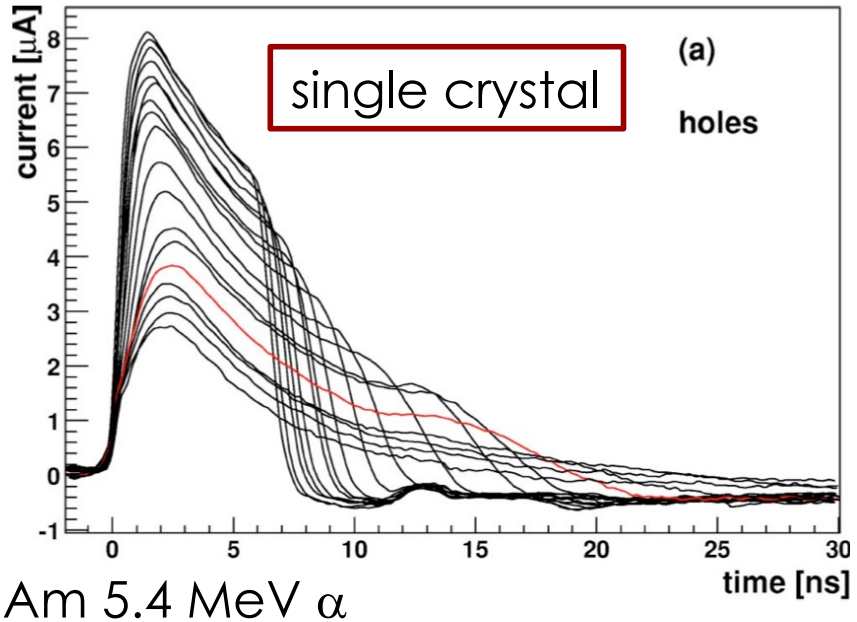




Development of CVD Diamond for detector applications

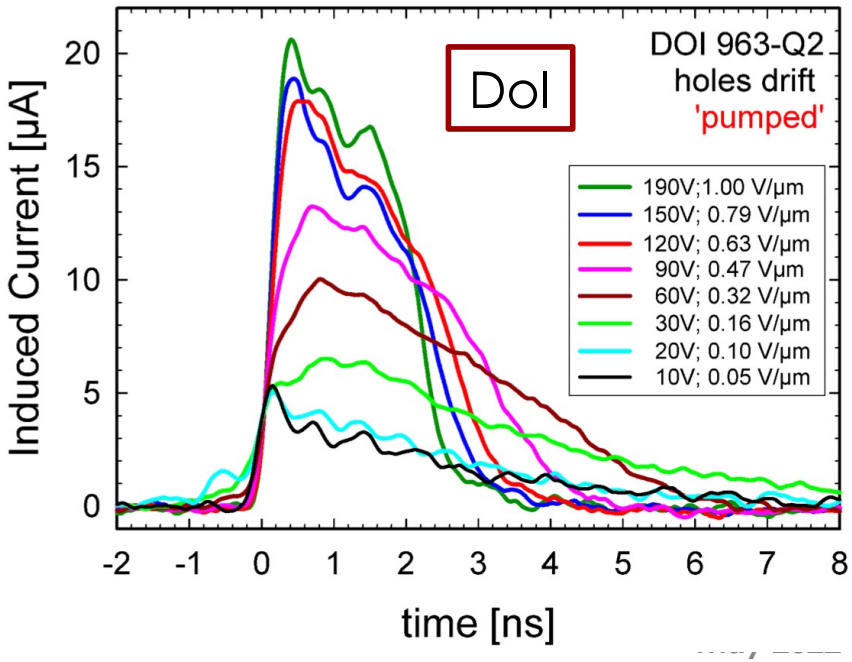
- Impressive progress over the last 20 years.
- **Single crystal diamond ~ 100% efficient**
- **Diamond on iridium ~ 97% efficient**

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



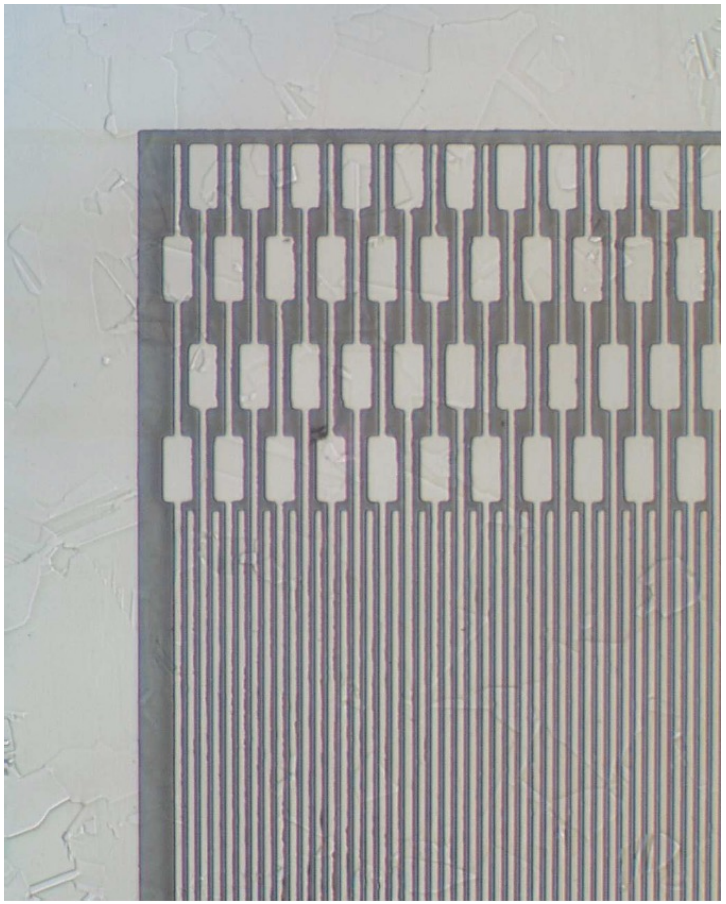
^{241}Am 5.4 MeV α

GSI annual report 2013

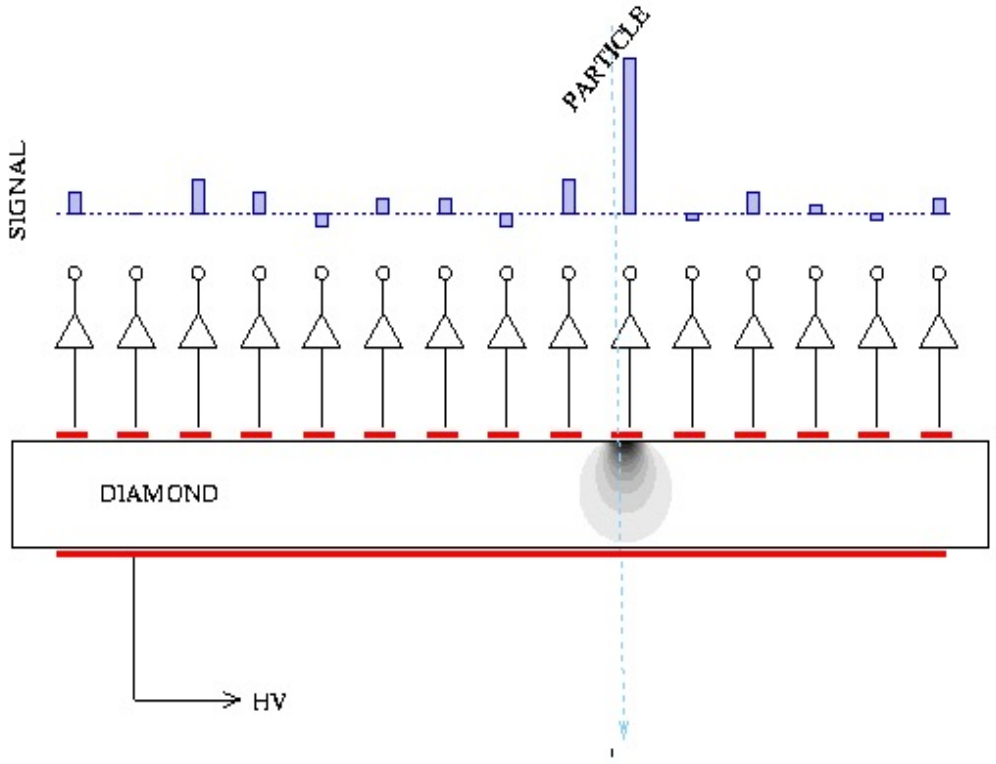


Strip Detectors

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

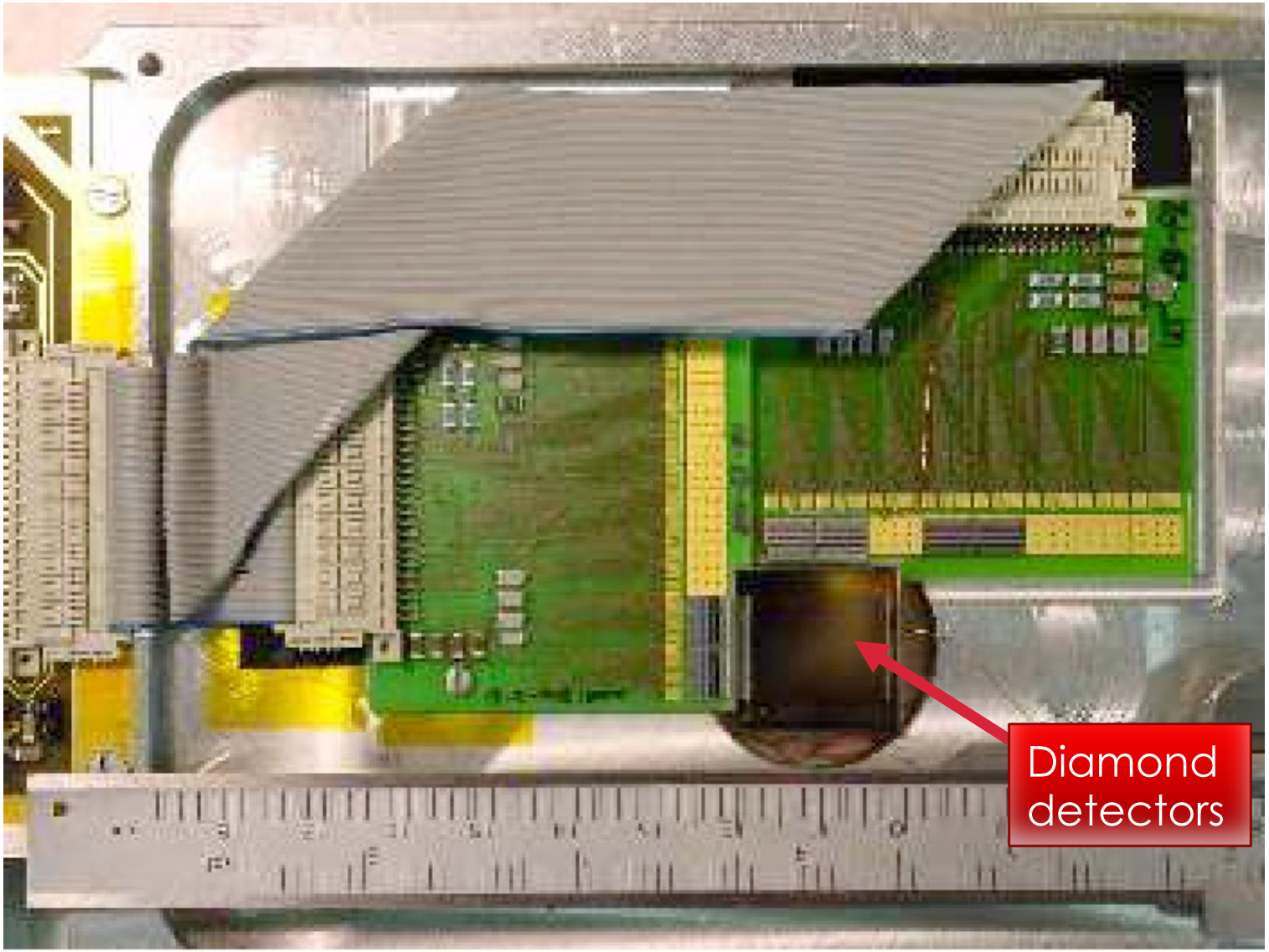


Principle

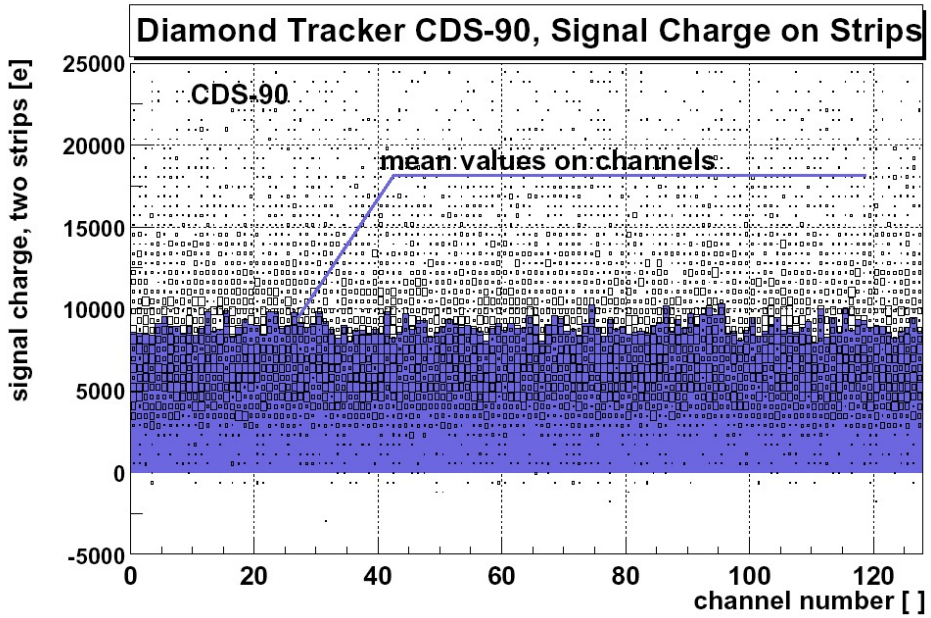


- The charge signal is picked up by the strip(s) next to the particle track.
- The charge is shared by multiple strips if the charge collection is incomplete.
- The position of the particle track can be reconstructed by calculating the charge weighted impact point **(Center of Gravity)**

- A Diamond Testbeam Telescope

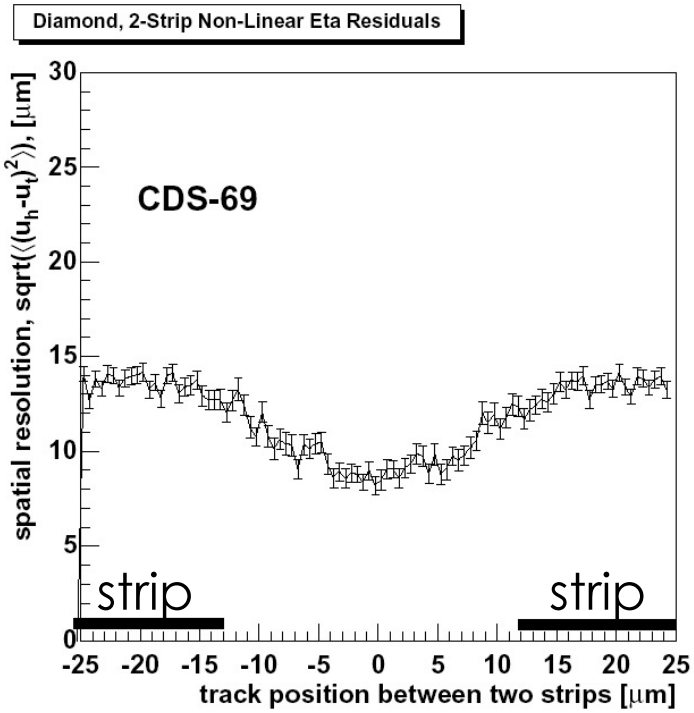


PH Distribution on each Strip



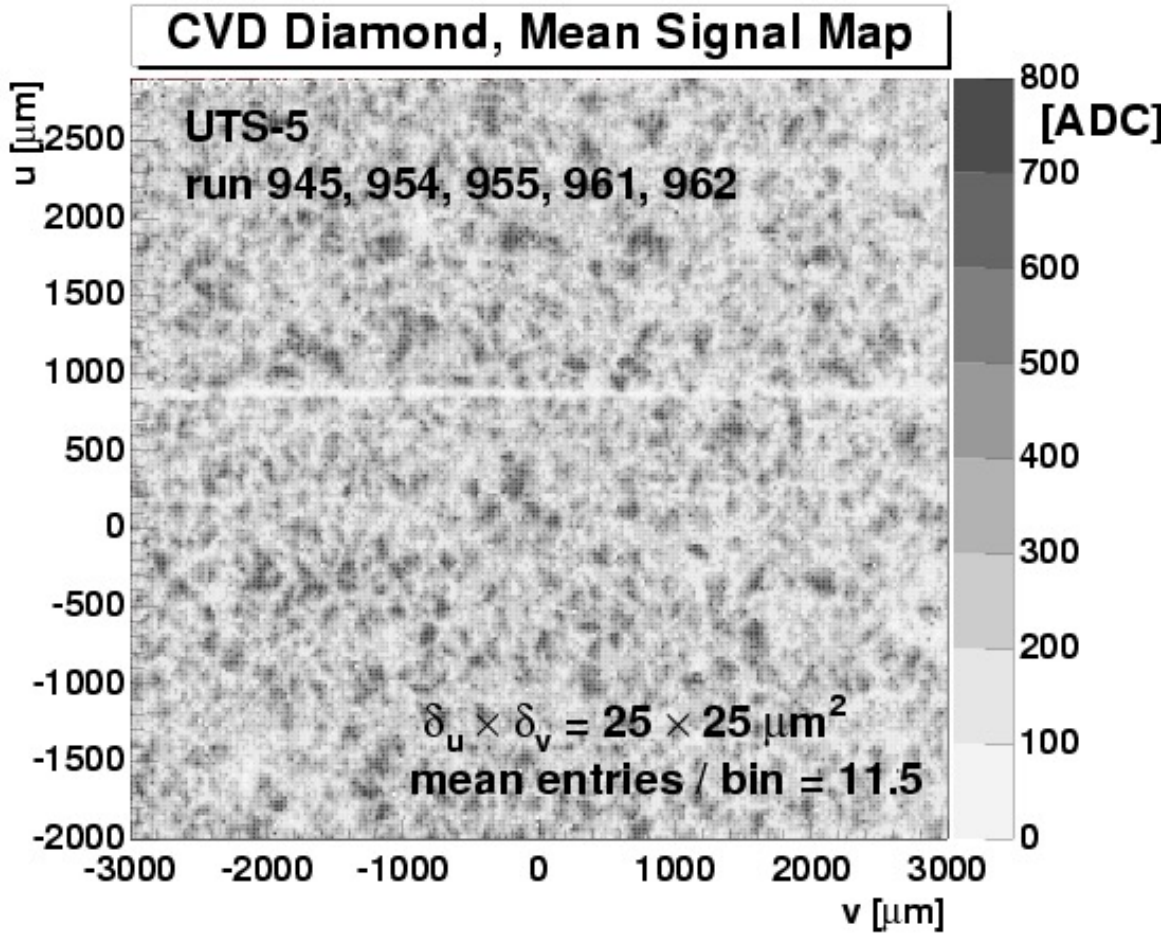
~10ke mean signal

Residual versus Track Position



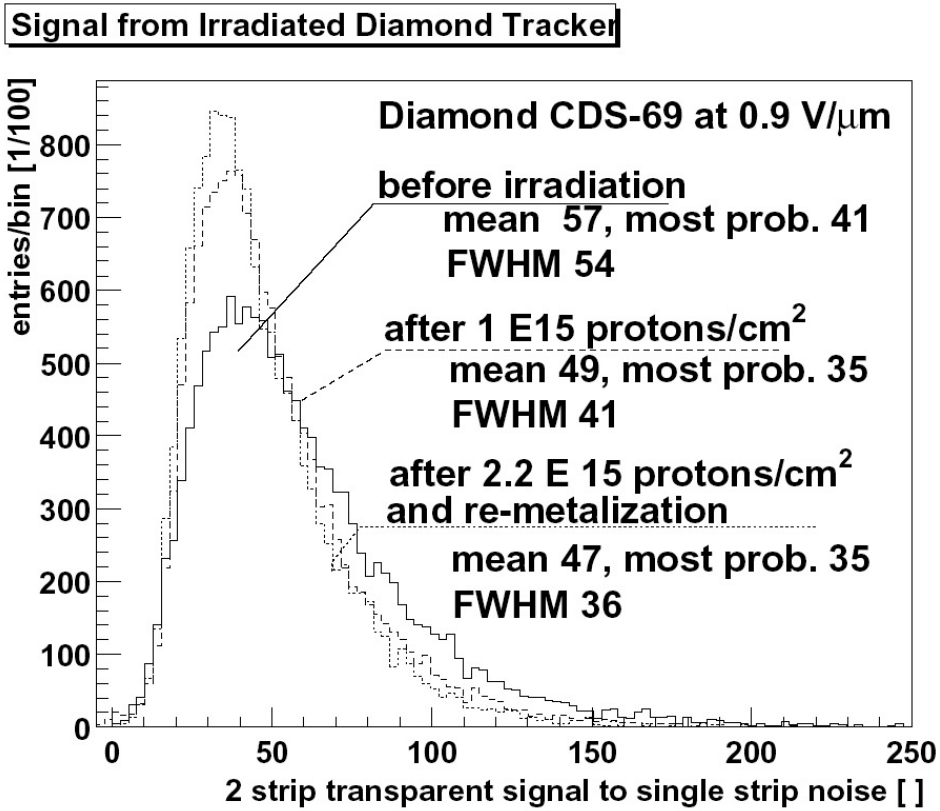
Uniformity in Charge Collection of CVD Diamonds

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

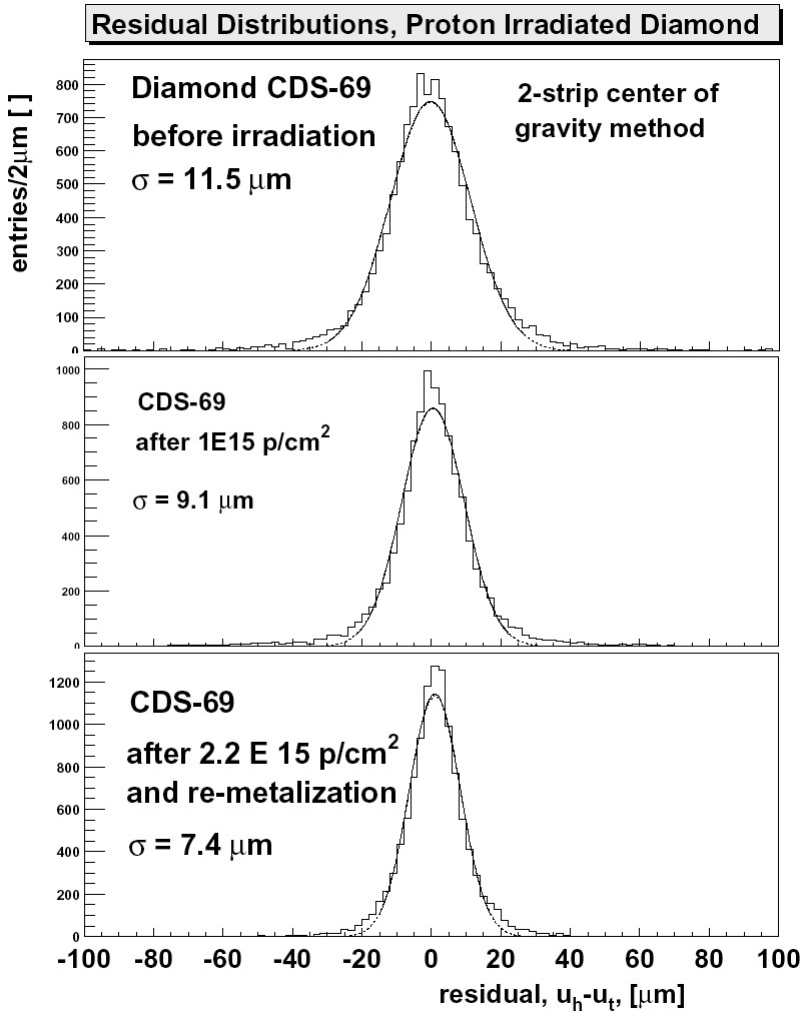


Irradiated Strip Detectors

- Proton Irradiation



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



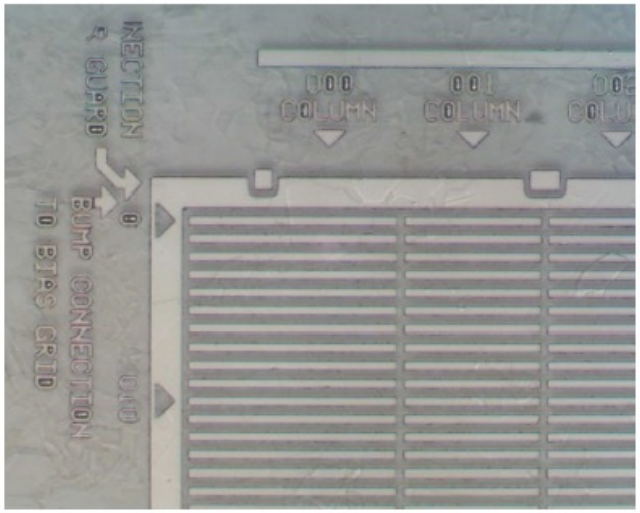
35% improvement in resolution

Pixel Detectors

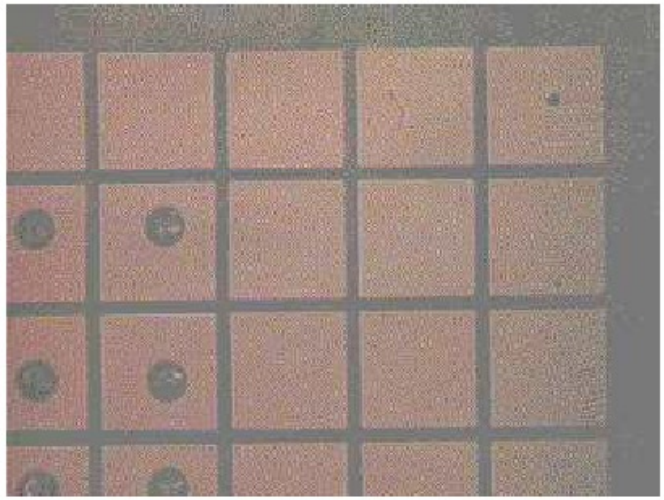
- Several prototypes of Diamond pixel detectors have been developped and tested since around 1996.
- Read-out chips use ROC (CMS), FE-I4 (ATLAS)
- More recently tested 3D pixel detectors (see later).
- Some historic examples in the following.

• Diamond Pixel Detectors

ATLAS FE/I Pixels (Al)



CMS Pixels (Ti-W)



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

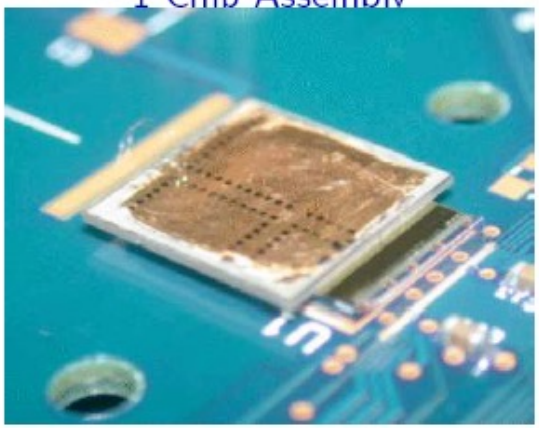
- CMS pixel pitch 125μm $\times$ 125μm
- Metalization: Ti/W
- Indium bumping at UC Davis

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

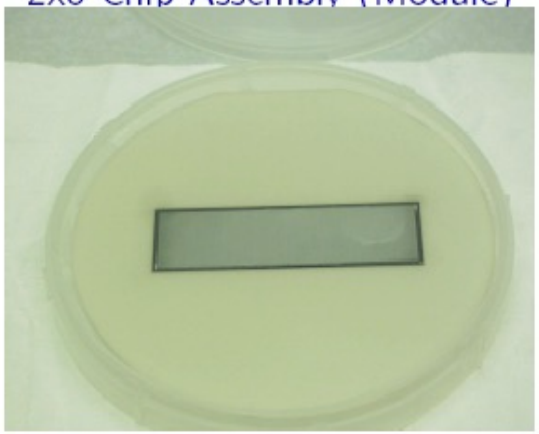
Diamond Pixel Detectors

Results from an ATLAS pixel detector

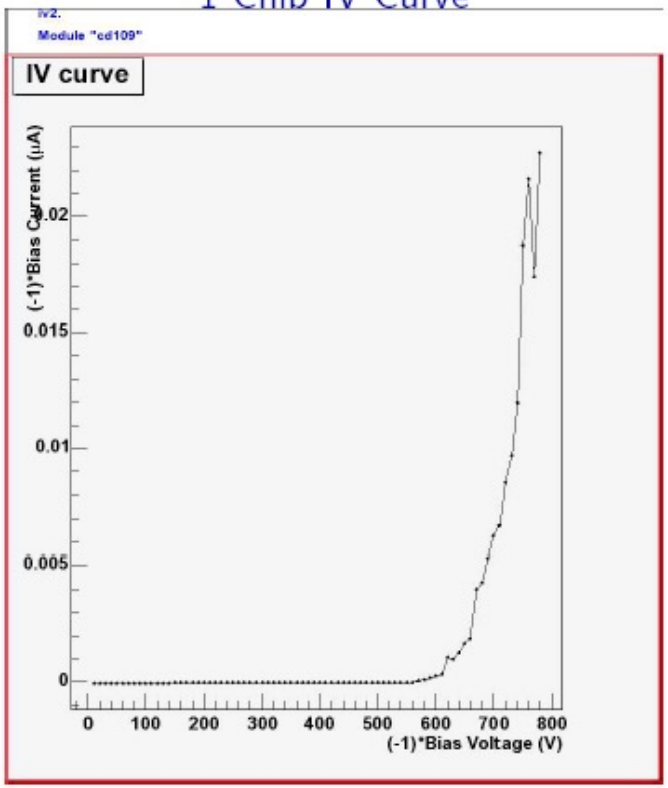
1 Chip Assembly



2x8 Chip Assembly (Module)



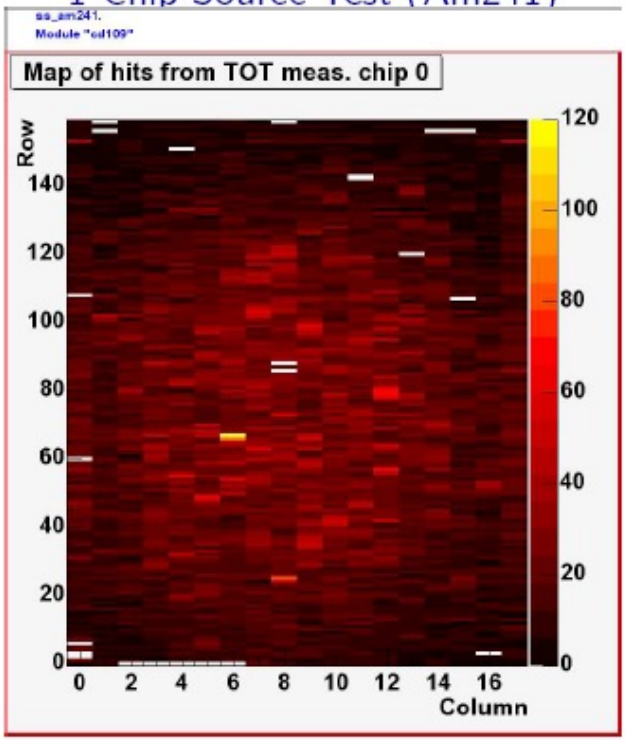
1 Chip IV Curve



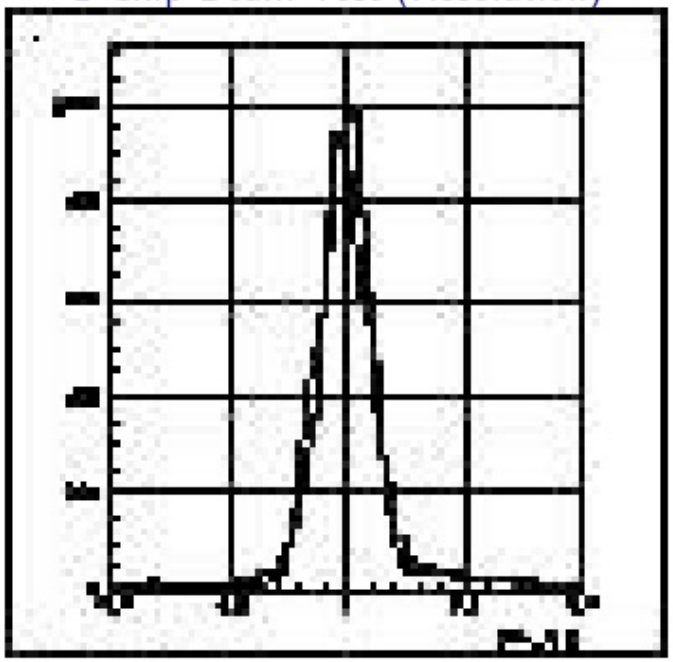
Diamond Pixel Detectors

Results from an ATLAS pixel detector

1 Chip Source Test (Am241)



1 Chip Beam Test (Resolution)

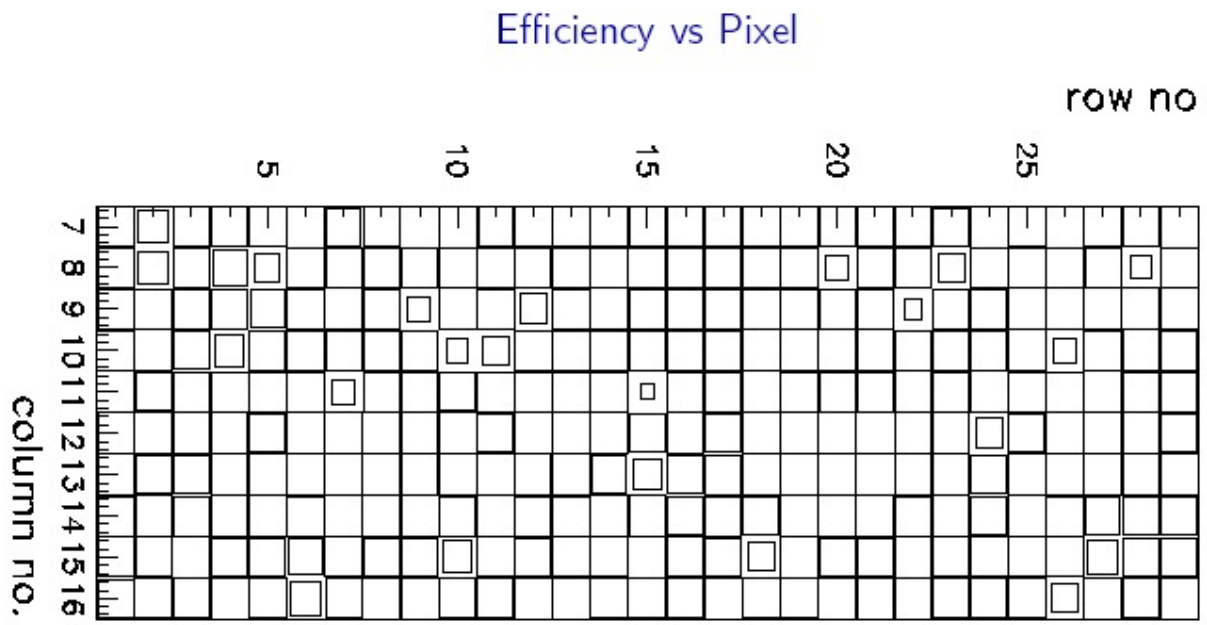


Americium 241 deposits $\approx 4600e$

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

Diamond Pixel Detectors

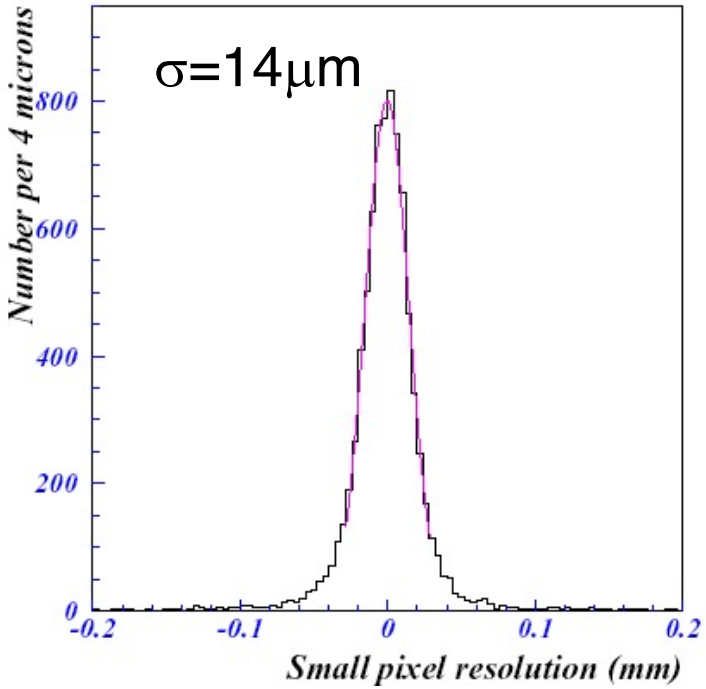
Results from a CMS pixel detector



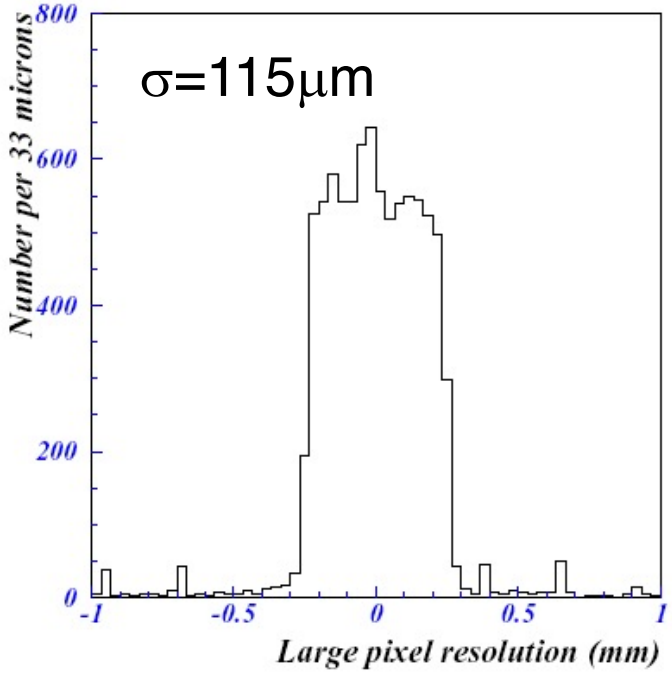
- Inefficient pixels due to bump bonding and/or electronics - shown in pulser tests
- Excellent correlation between beam telescope and pixel tracker data!

• Results from Atlas Diamond Pixel Detectors

Spatial Resolution – Short Direction

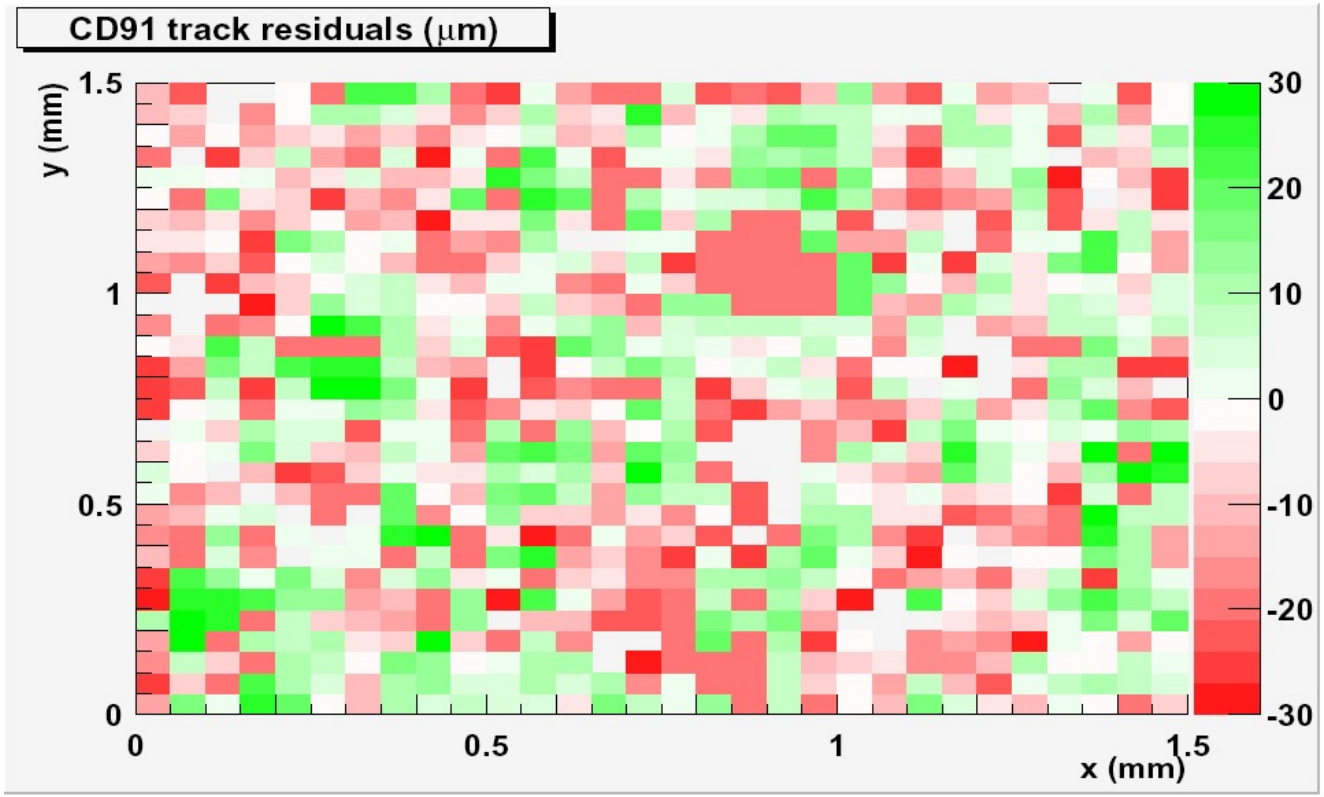


Spatial Resolution – Long Direction



- Efficiency = 80%
- Resolution = digital

• Results from Atlas Diamond Pixel Detectors



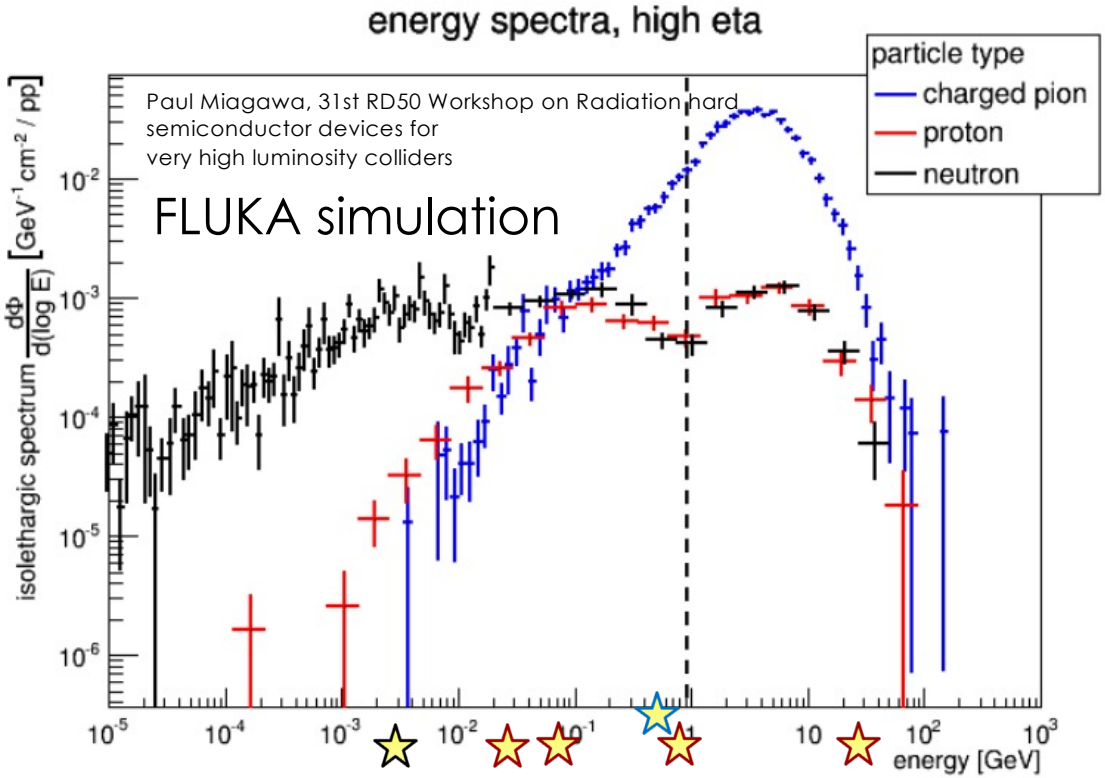
Tommaso Lari (INFN)
Alexander Oh (CERN)
Norbert Wermes (University Bonn)

- 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:

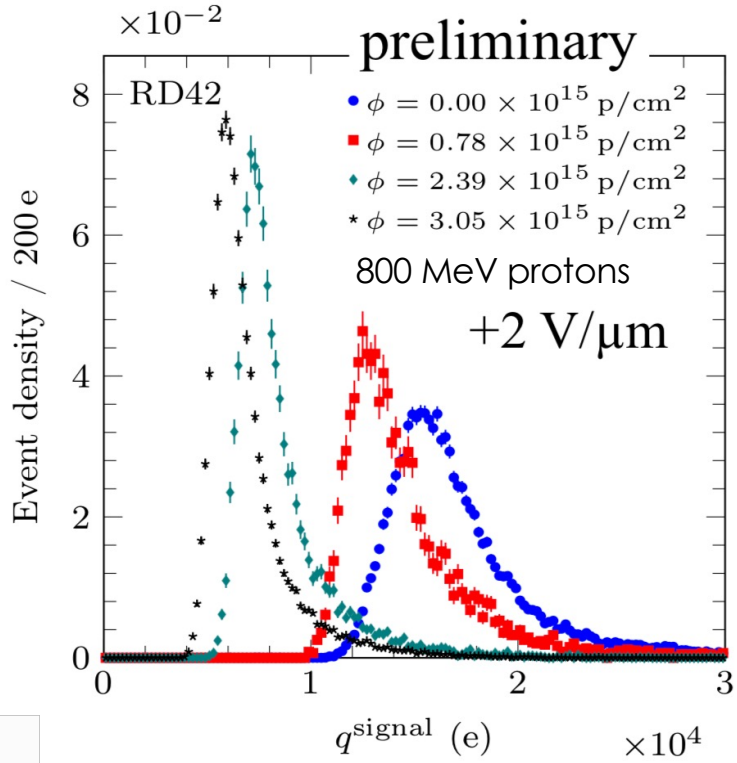
$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k_\lambda \Phi$$

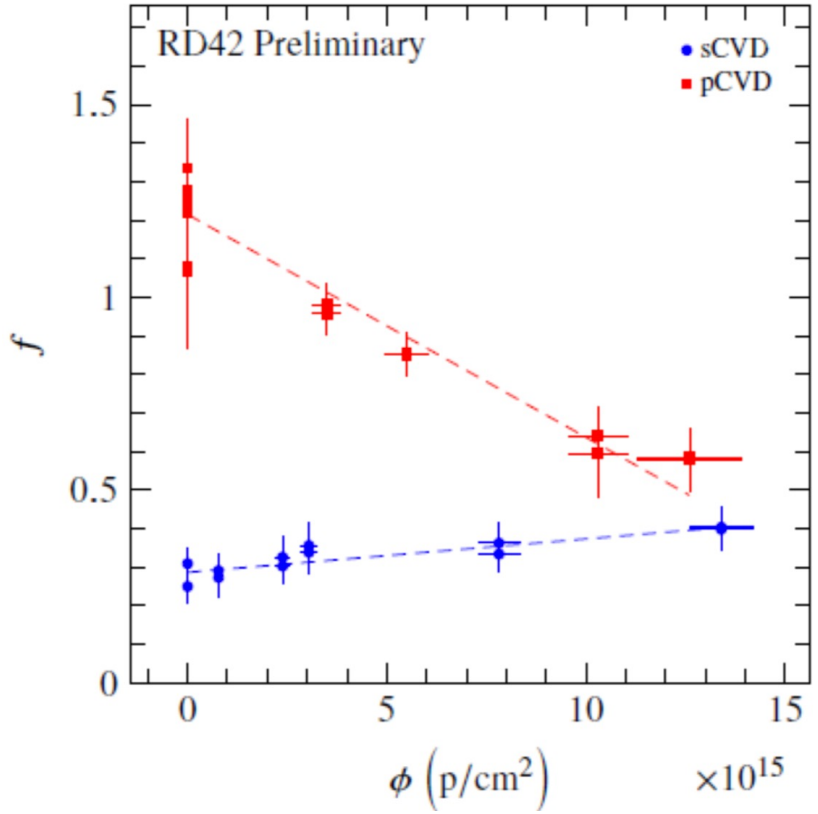
damage constant

particle flux

Radiation Tolerance: Characterization

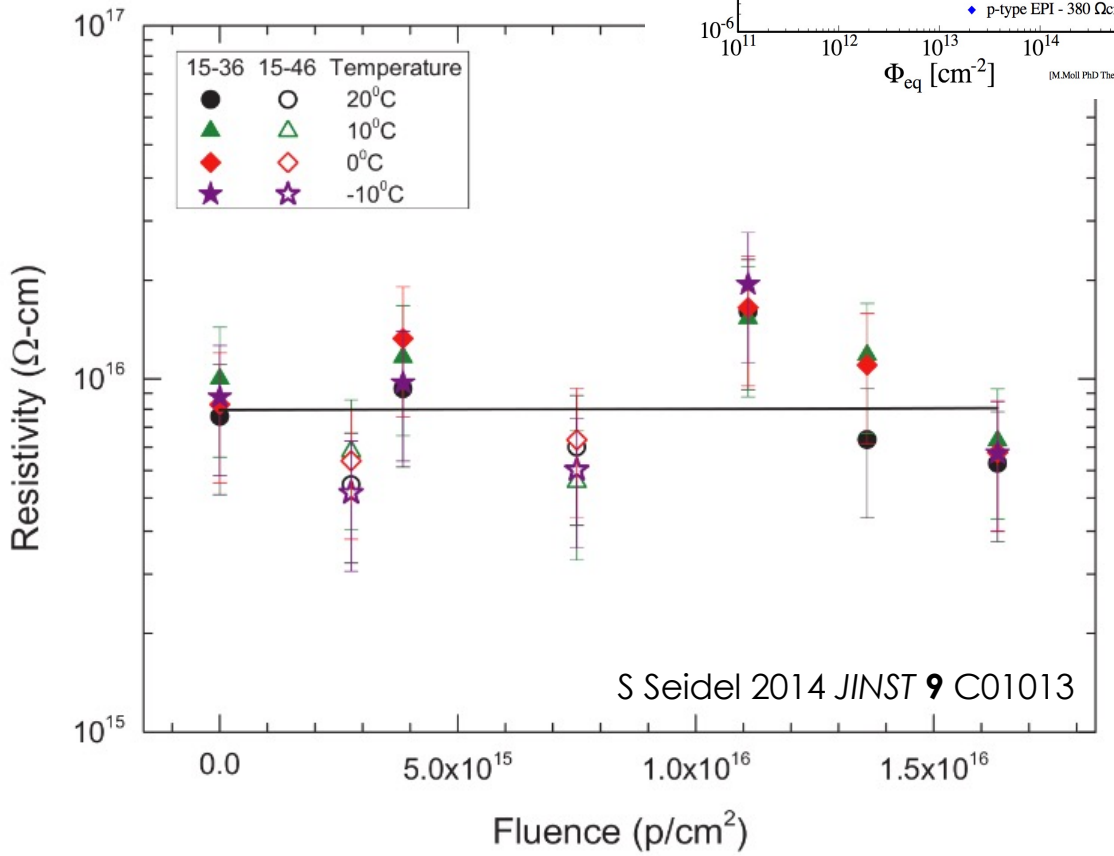
- Typical Landau Spectra after irradiation of pCVD.
- For pCVD see reduction of **FWHM / MP** with irradiation.
  - Expected from polycrystalline nature of material!
  - Single crystal material almost flat.



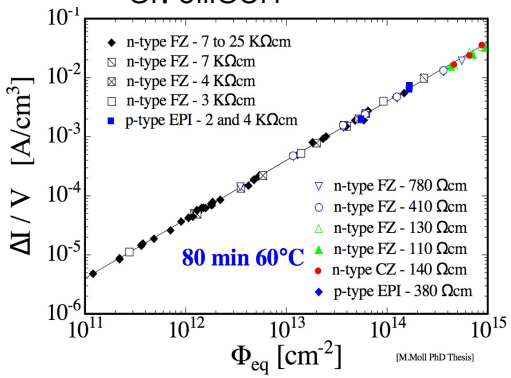


Radiation Tolerance: Characterization

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



cf. Silicon



MANCHESTER 1824

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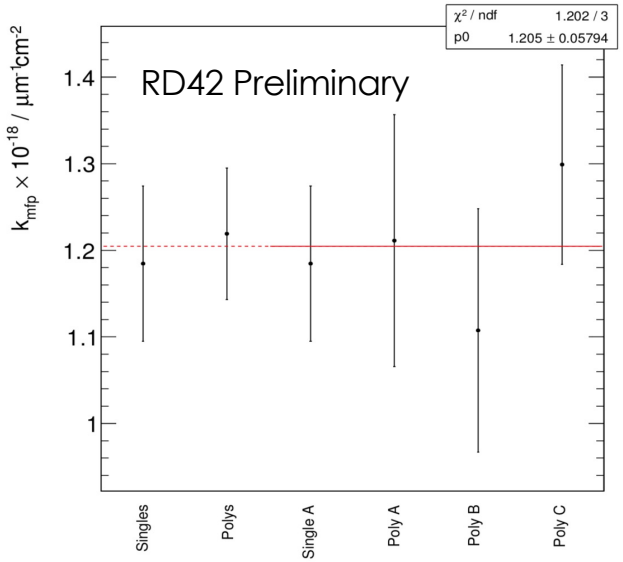
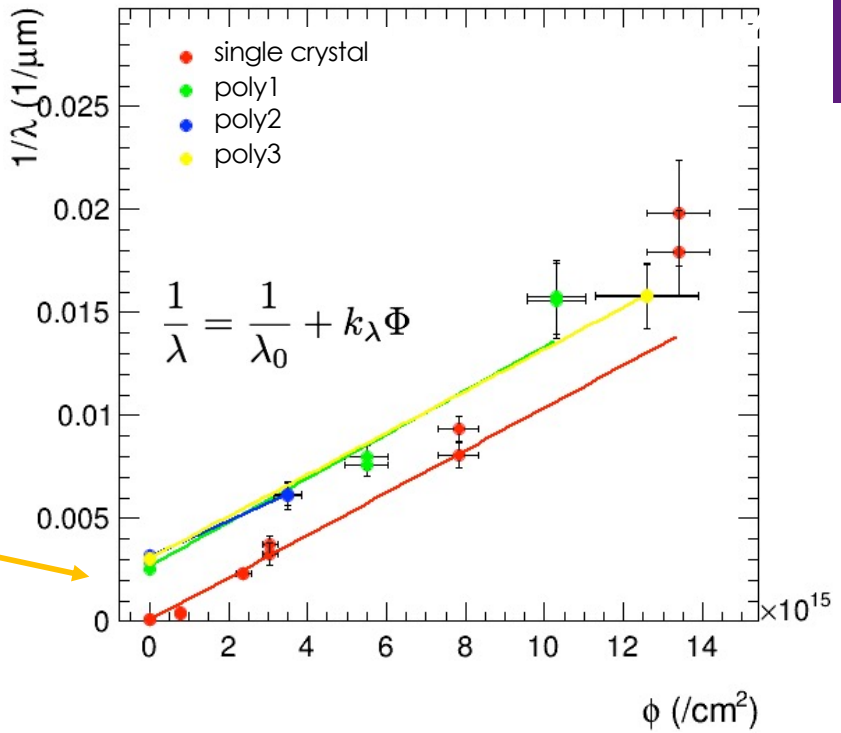
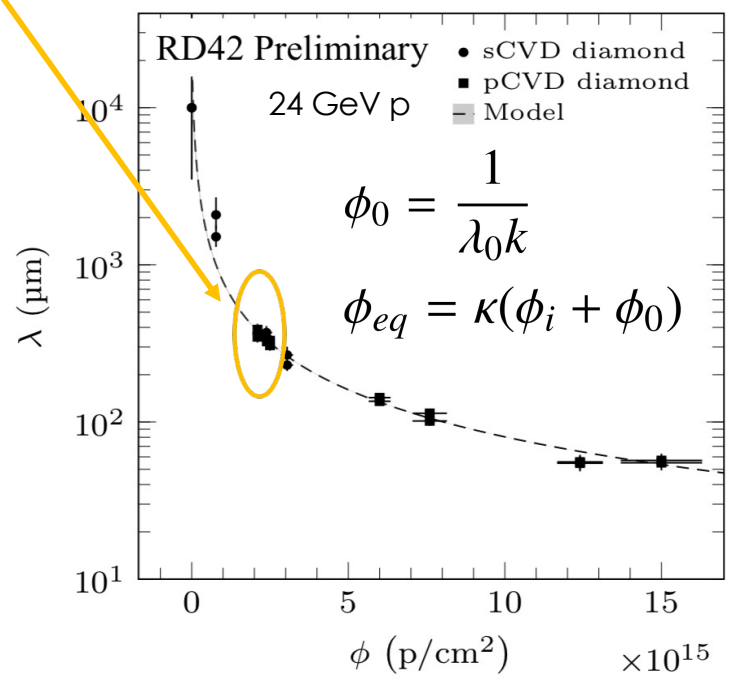
Radiation Tolerance: Characterization

- 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.

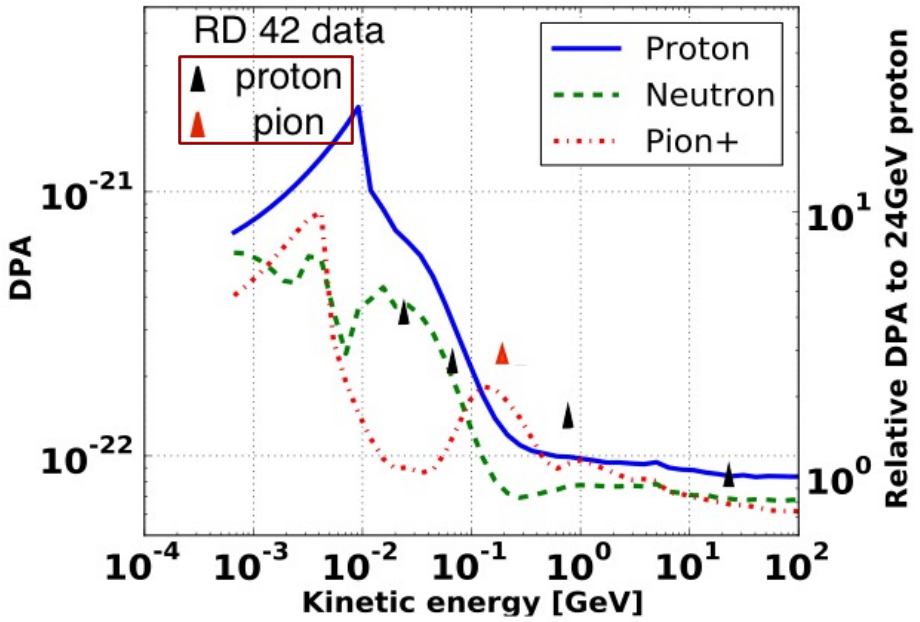






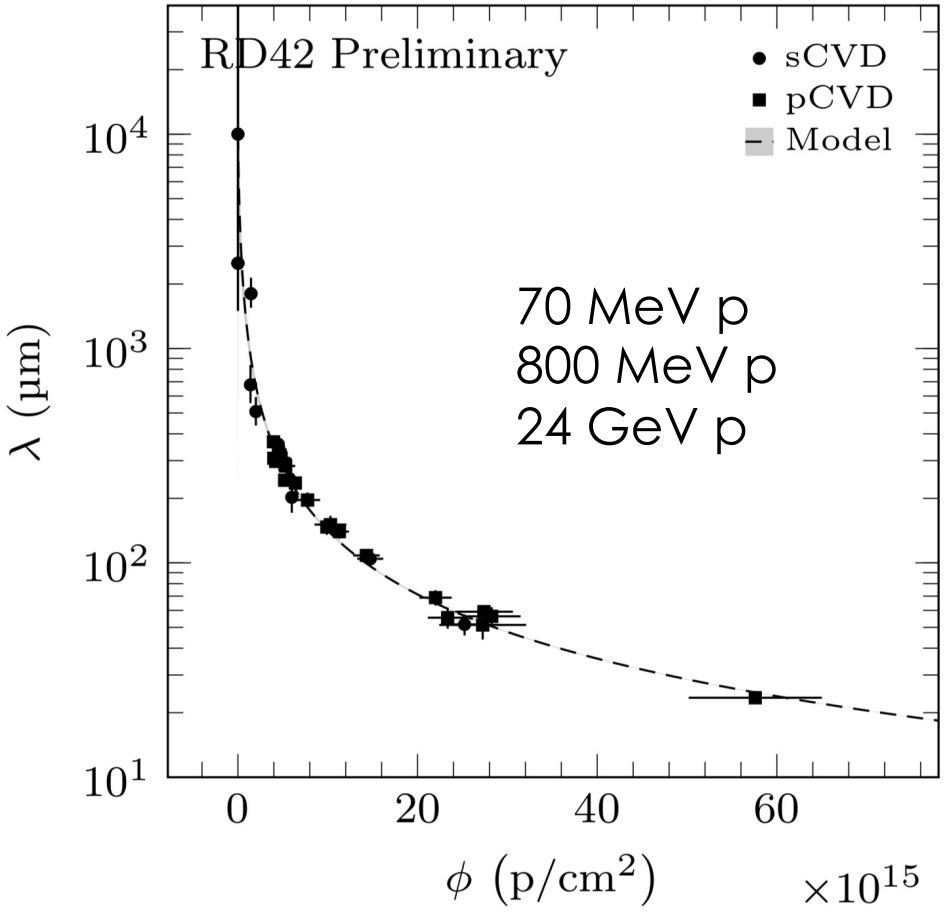
Radiation Hardness

- 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.



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

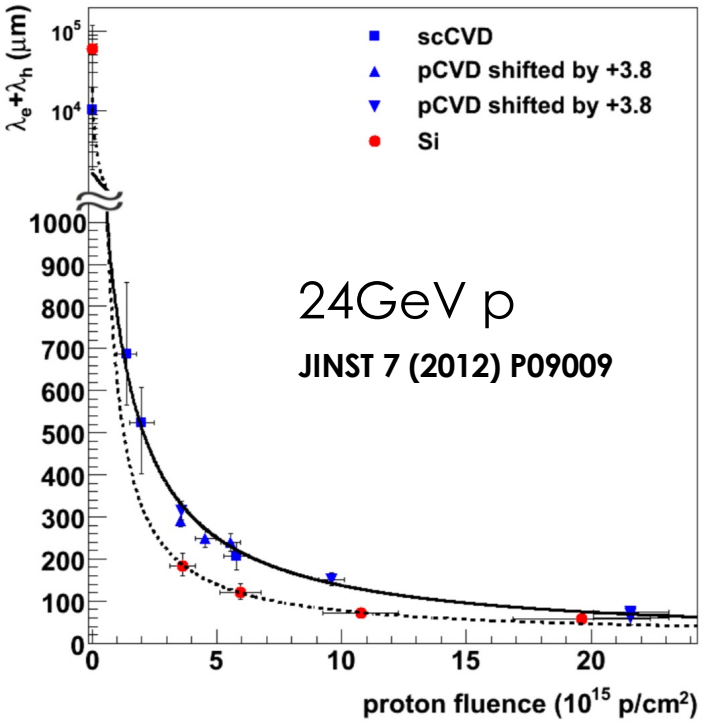
- Summary of RD42 irradiation results:

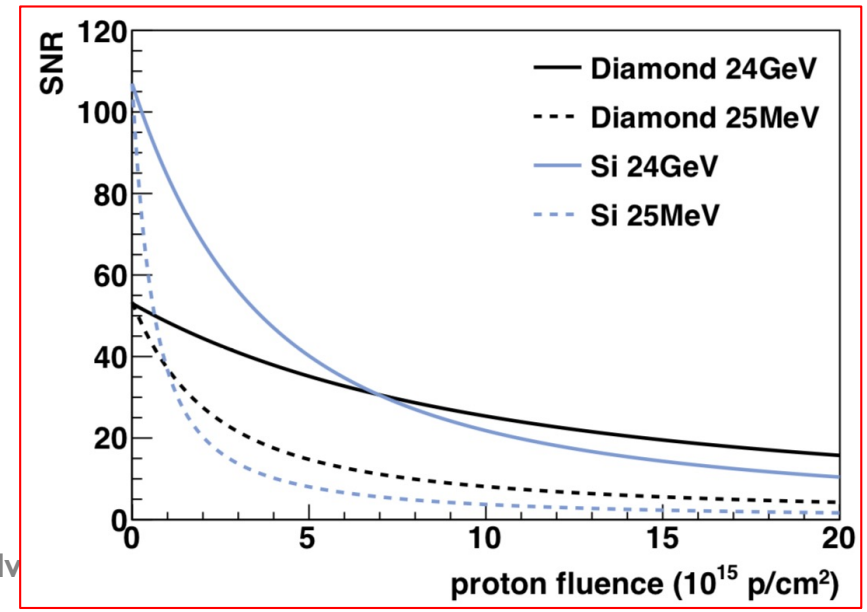
Particle Species	Relative Damage Constant, κ
24 GeV p	1
800 MeV p	1.54 ± 0.13
70 MeV p	2.5 ± 0.4
25 MeV p	4.5 ± 0.6
fast neutrons	4.5 ± 0.5

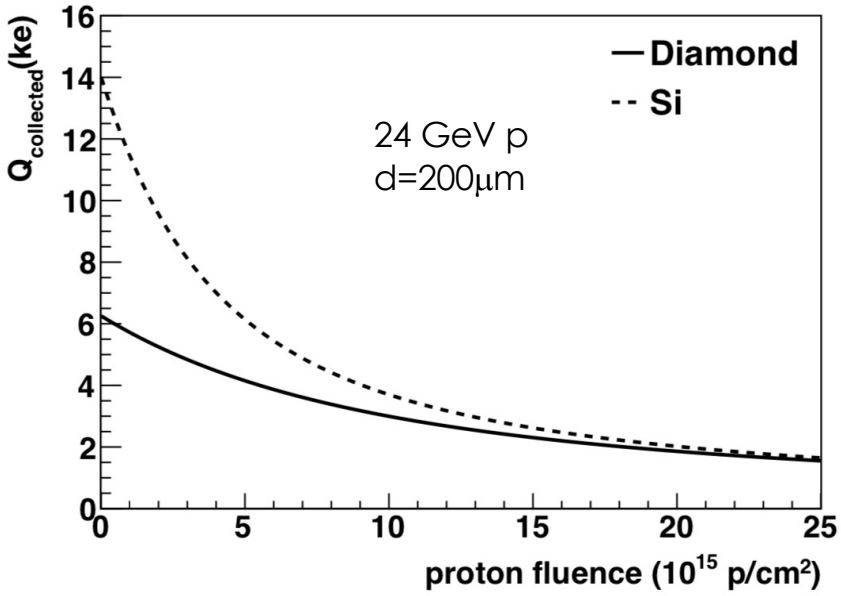
*normalized to 24GeV protons

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:





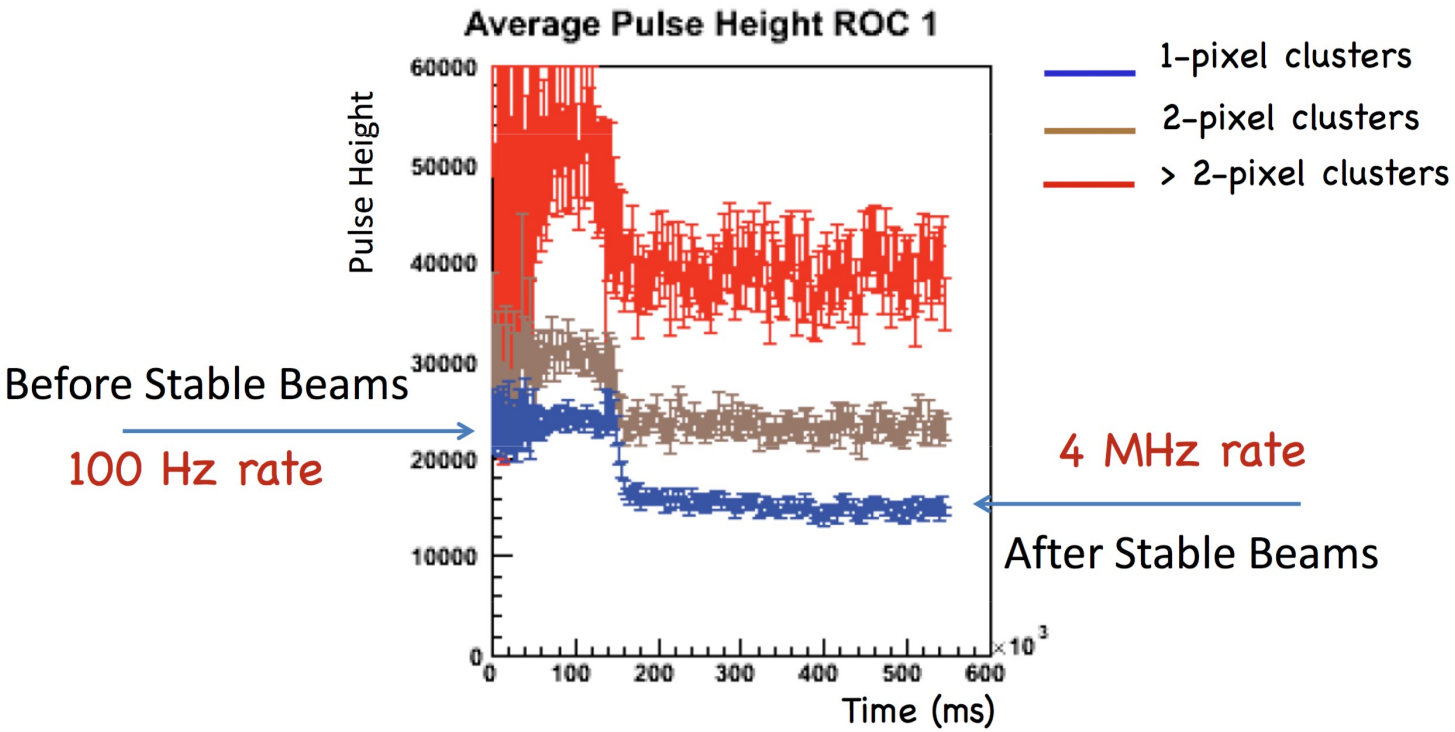


High rate capability

High Rate tests

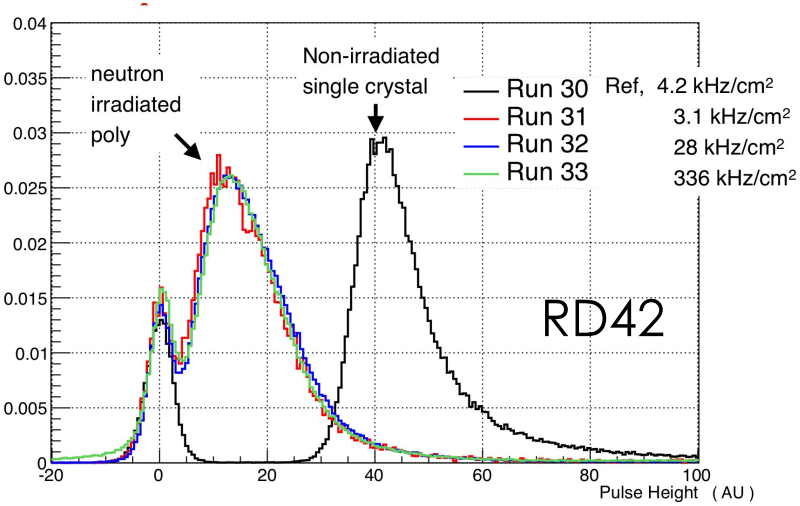
- Tests the pulse height as function of particle rate.
- Test single and poly crystalline diamond.
- Irradiated and un-irradiated.

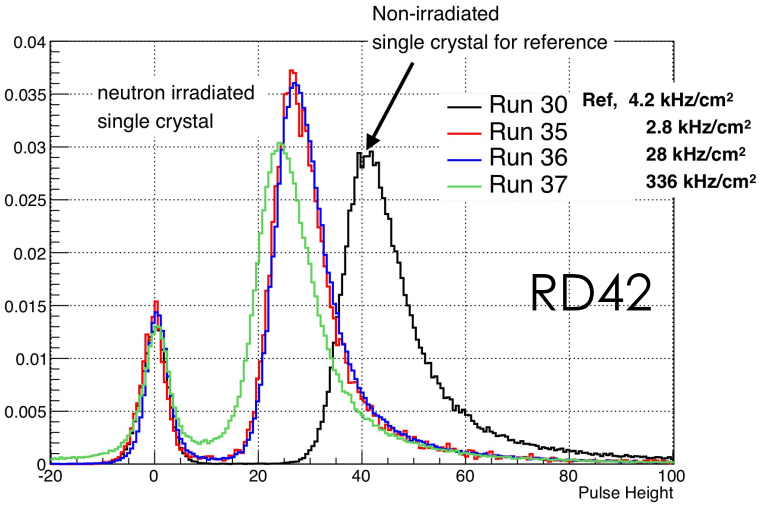
Investigations triggered by indication of rate dependence of of single crystal diamond pixel detector installed in CMS in 2012.

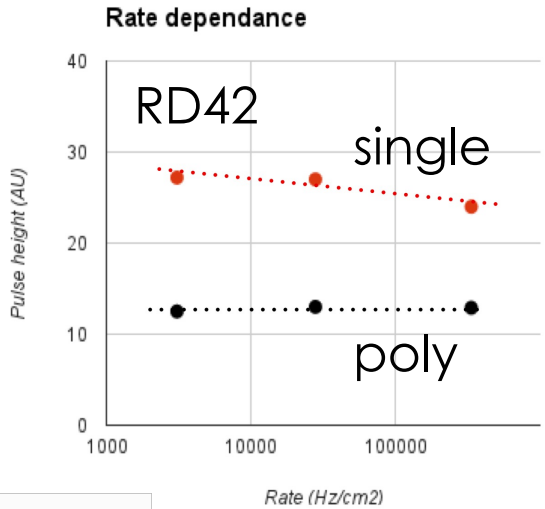


High Rate tests

- 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.

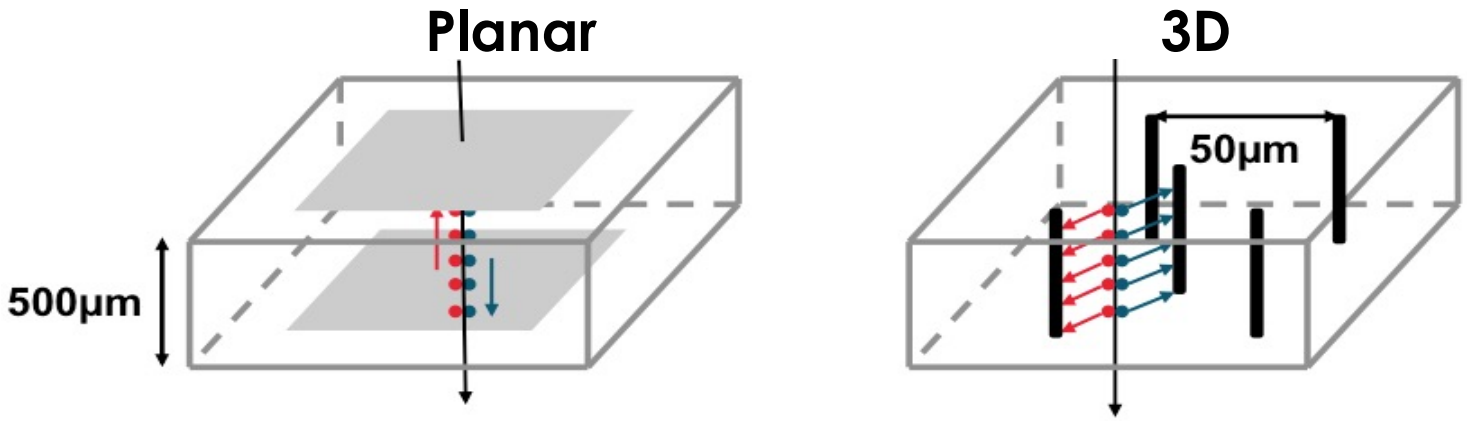






3D diamond detectors

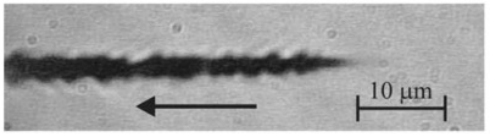
3D Diamond Detectors



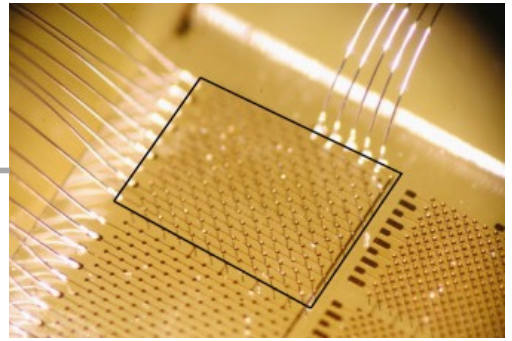
- Electrode spacing determines drift distance to induce 1e charge.
- 3D has shorter electrode spacing compared to planar.
- Charge carriers need less drift distance (and time) in 3D then in planar to induce equal signal.
- Influence of traps and resulting limited lifetime suppressed in 3D.

3D Diamond Research - A relatively young field

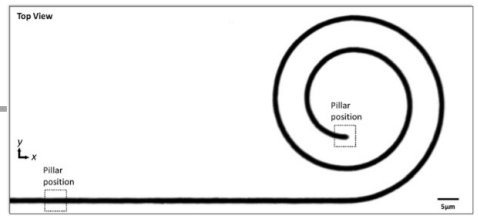
- Laser induced phase change in diamond.
  - E.g. T.V. Kononenko et al, Diamond & Related Materials 18 (**2009**) 196–199 "***Femtosecond laser microstructuring in the bulk of diamond* "**



- 3D "Pad" detector
  - A. Oh, B. Caylar, M. Pomorski, T. Wengler, Diamond and Related Materials, 38 , (**2013**), ***"A novel detector with graphitic electrodes in CVD diamond"***
  - S. Lagomarsino et al, Appl. Phys. Lett. 103, 233507 (**2013**), ***"Three-dimensional diamond detectors: Charge collection efficiency of graphitic electrodes"***

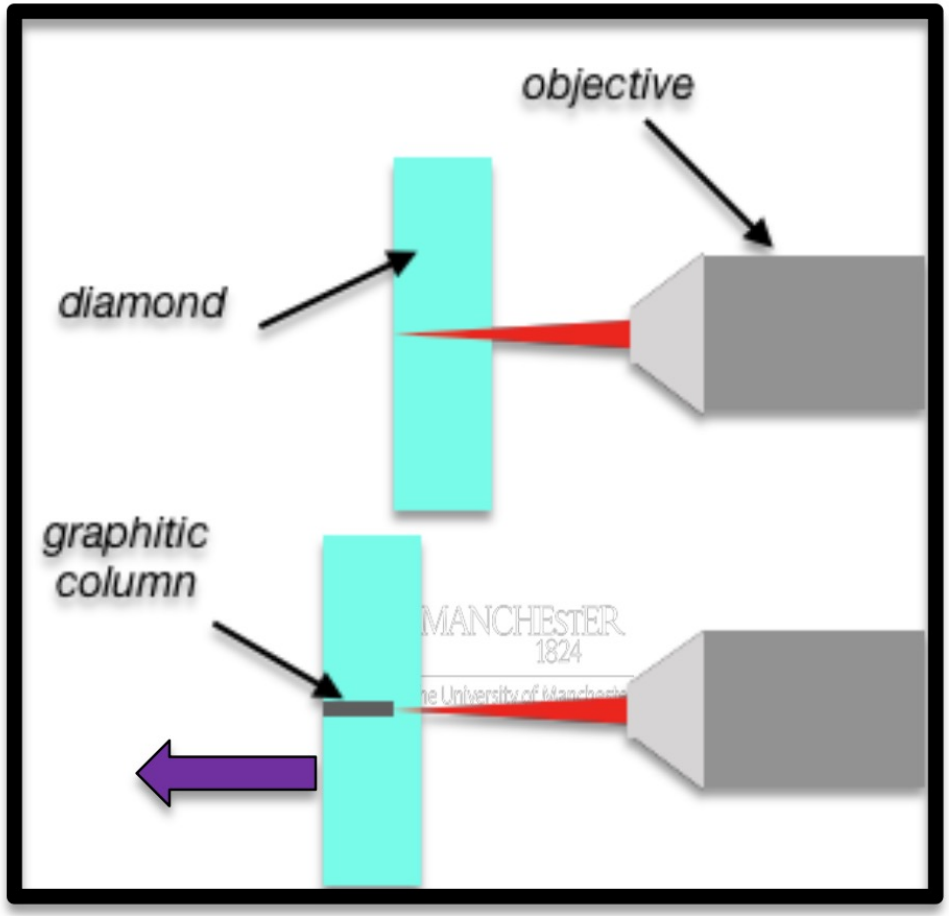


- 3D "strip array" detector with position resolution.
  - E.g. F. Bachmaier et al, *NIM* A, 786, (**2015**) 97-104, ***"A 3D diamond detector for particle tracking"***
- Radiation damage studies.
  - Eg. S. Lagomarsino et al, Applied Physics Letters **106**, 193509 (**2015**) "***Radiation hardness of three-dimensional polycrystalline diamond detectors"***
- Improvements in graphitization process.
  - Eg. B. Sun et al., Applied Physics Letters **105**, 231105 (**2014**), "**High conductivity micro-wires in diamond following arbitrary paths**"
- 3D pixel detectors
  - RD42, CERN-LHCC-2018-015 ((**2018**), **Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC, HL-LHC and Beyond**
  - L. Anderlini et al, Front. Phys., 04 November **2020**, **Fabrication and Characterisation of 3D Diamond Pixel Detectors With Timing Capabilities**



Fabrication

- Conductive columns are created by changing diamond into a graphitic material with a short laser pulse:

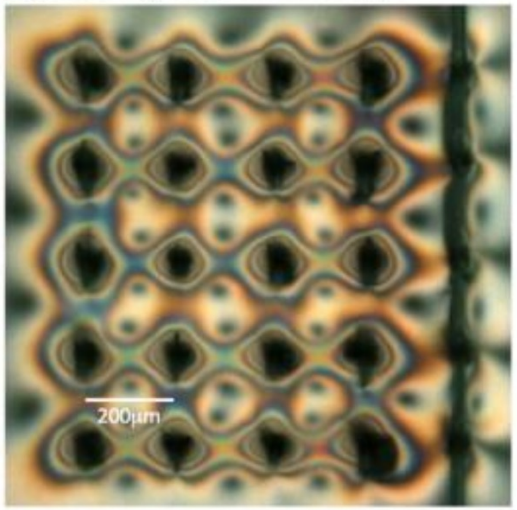


Laser graphitisation of diamond

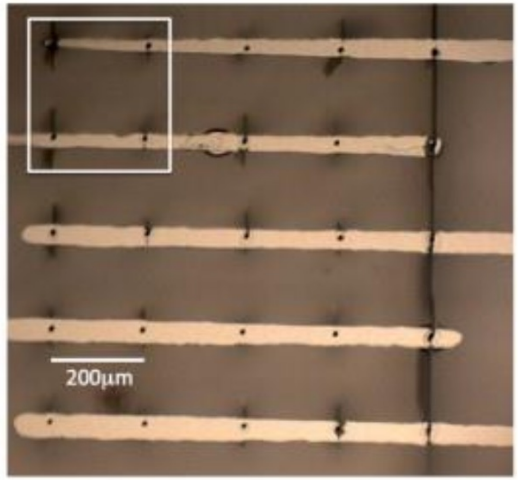
FIRST 3D DIAMOND DEVICE

- Collaboration of **Manchester**, CEA LIST and CERN
- Published **2013**
- Single crystal substrate
- First device made at LIST using **nano-second** pulse nitrogen laser with beam spot diameter of **10µm**

(a)Birefringence microscopy.



(b) Photograph after metallisation.



1824

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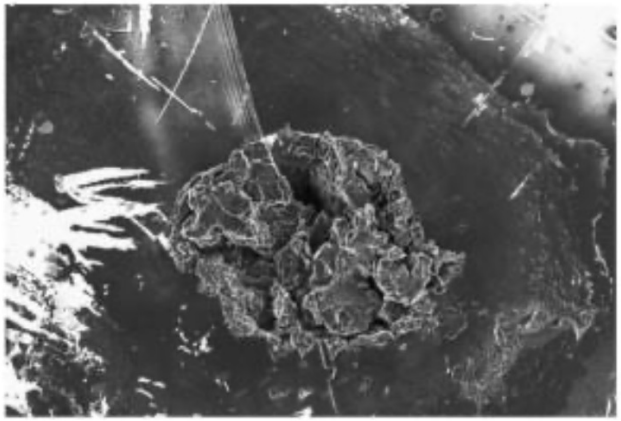
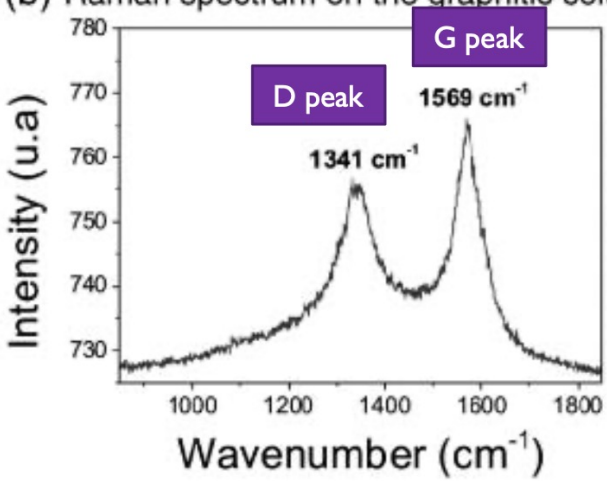
(a) SEM picture of a graphitic column.

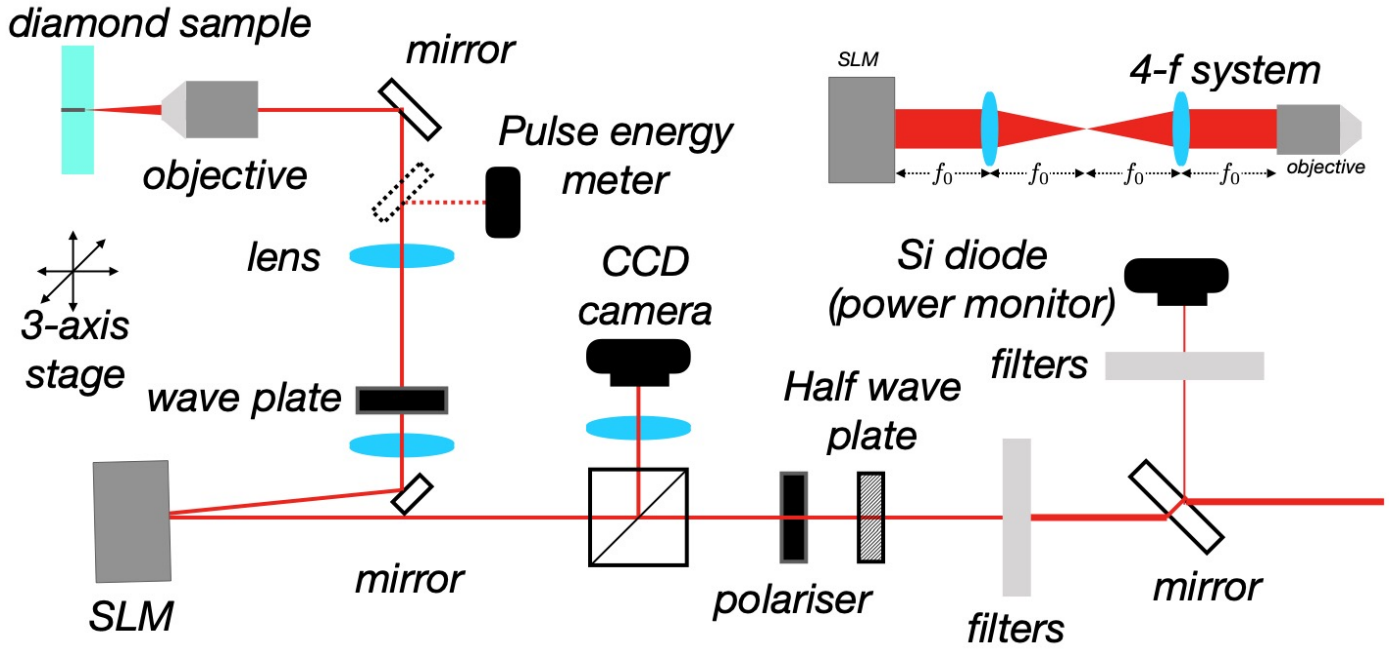


(b) Raman spectrum on the graphitic column.



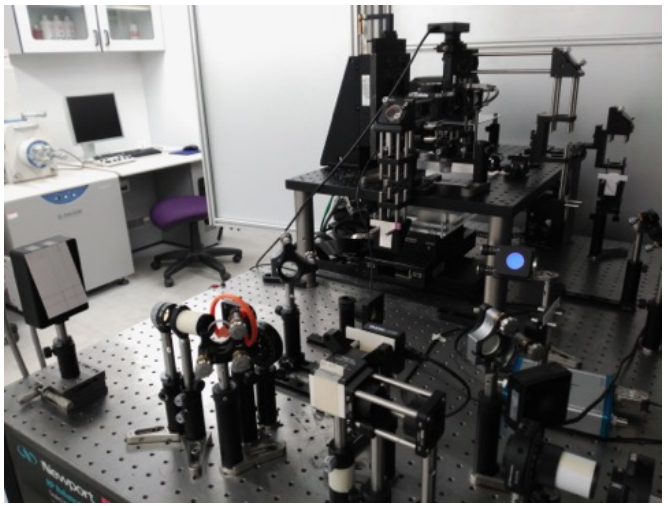
Oh, A., Caylar, B., Pomorski, M., & Wengler, T. (2013). A novel detector with graphitic electrodes in CVD diamond. *Diamond and Related Materials*, *38*, 9–13.

Laser Set-up in Manchester



Laser specs:

- Wavelength: 800 nm
- Repetition rate: 1 kHz
- Pulse duration: 100 fs
- Max power: 1 W

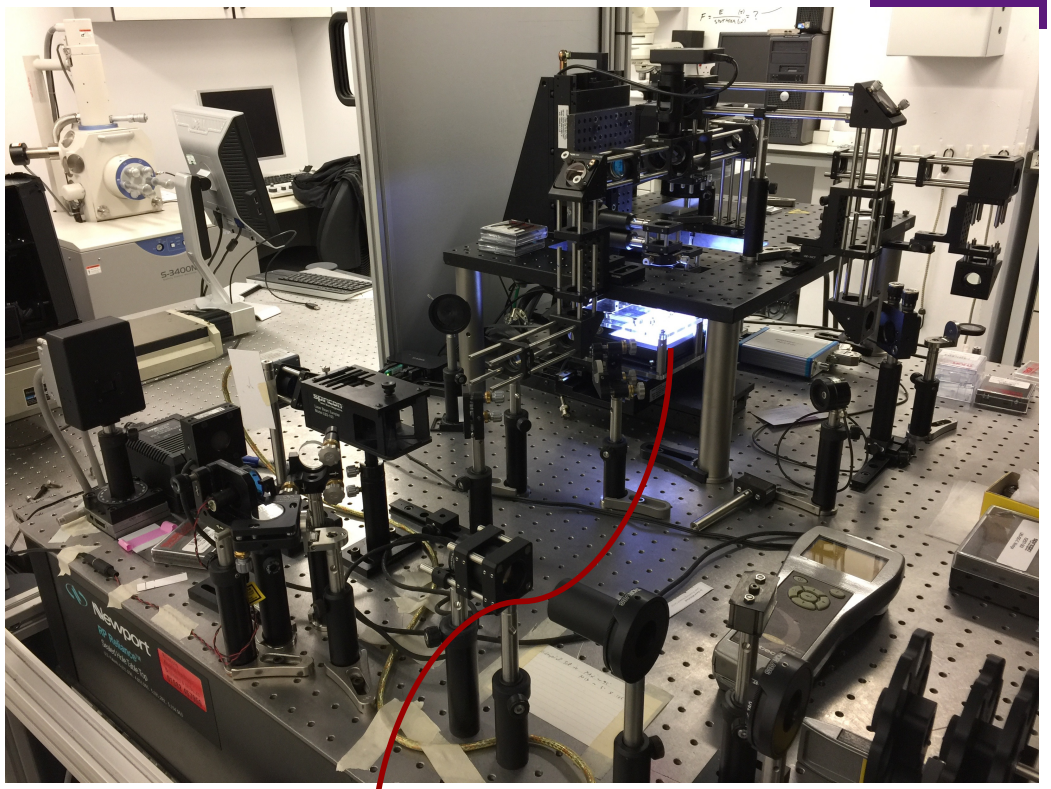


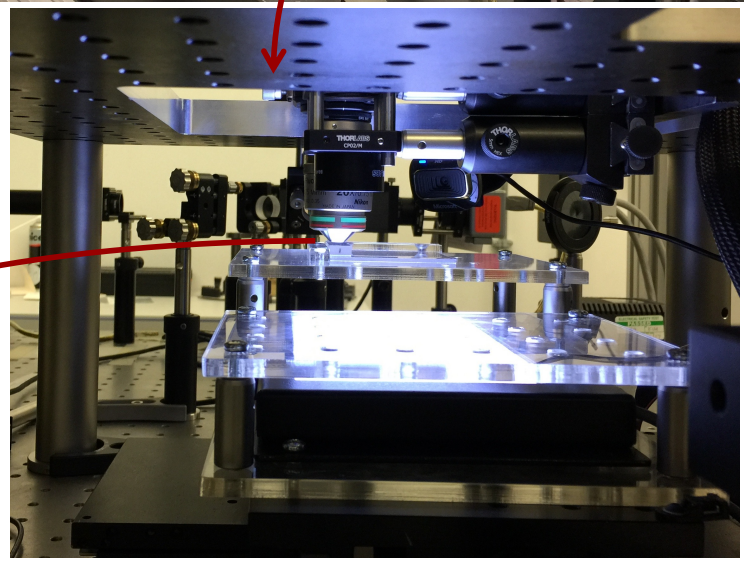
Just moved to MECD!

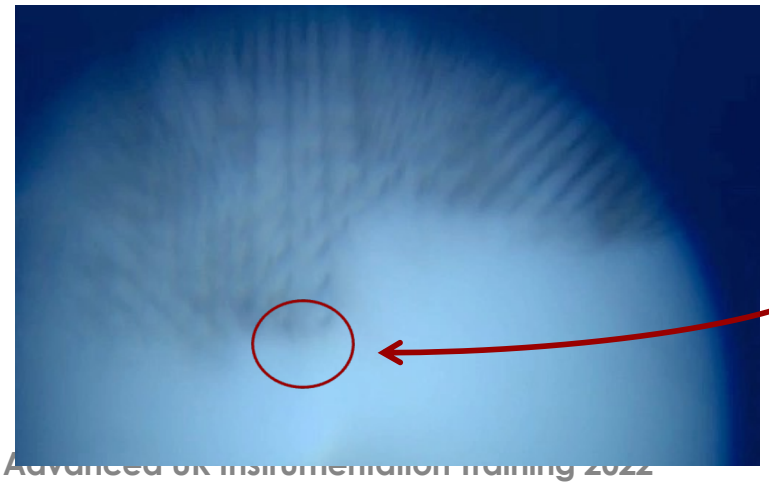
The University of Manchester

University of Manchester, Laser Processing Research Center.

- Wavelength = 800 nm
- Repetition rate = 1 kHz
- Pulse duration = 100 fs
- Spot size = 10µm
- Pulse Energy ~ 1 µJ
- **Spatial light modulator**



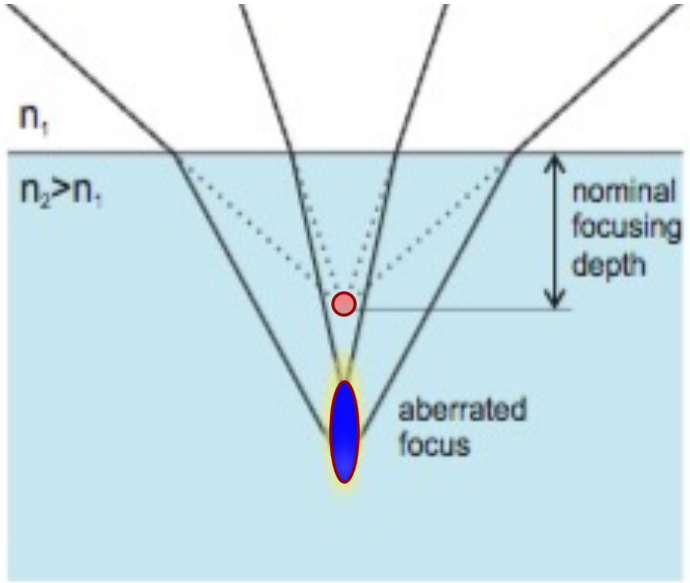


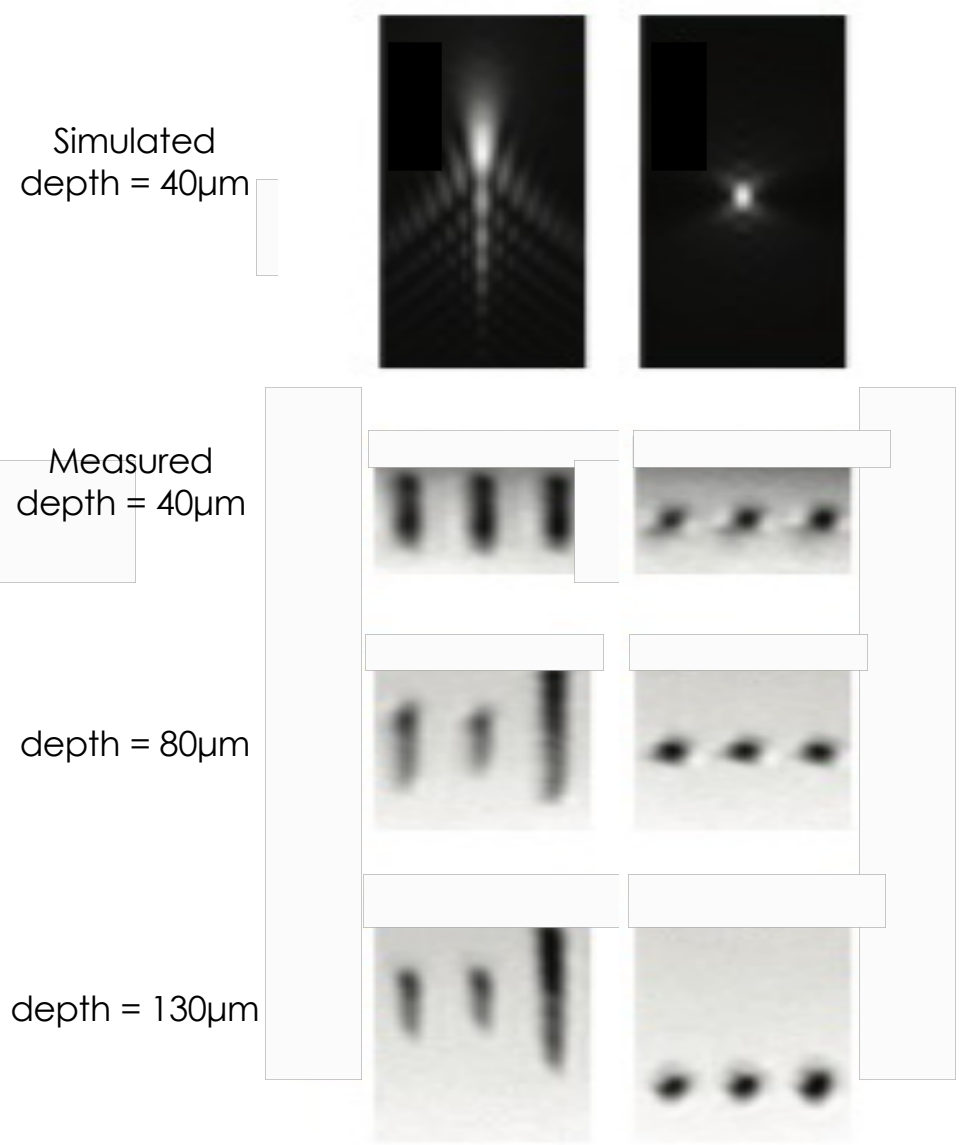


SLM – Phase **S**patial **L**ight **M**odulation

- Comparison SLM vs standard process.

	Std.	SLM
Resistivity	1 Ωcm	0.1 Ωcm
Diameter	~3μm	~1μm
Diamond to graphite ratio	~4	~0.2





SLM – Phase **S**patial **L**ight **M**odulation

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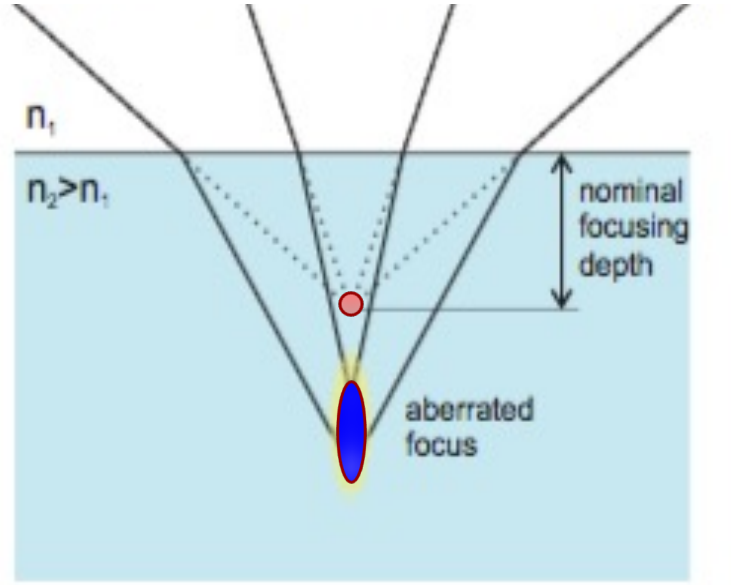
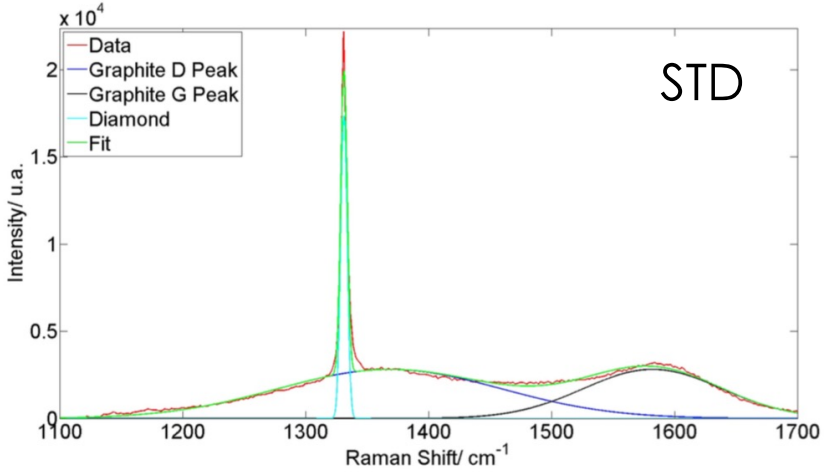
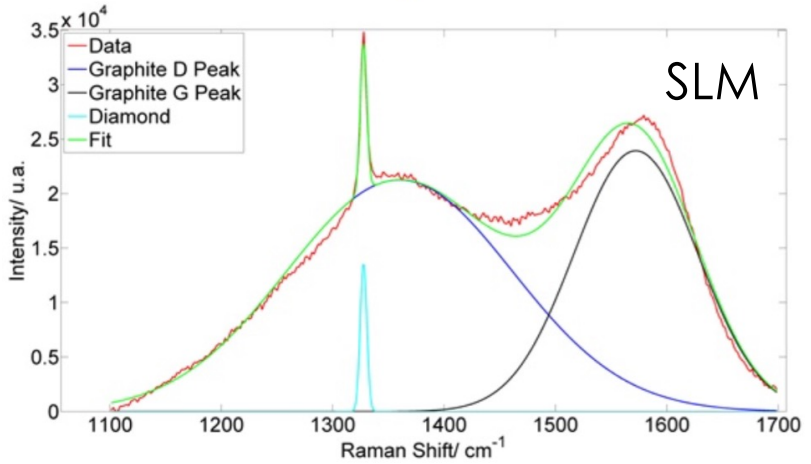
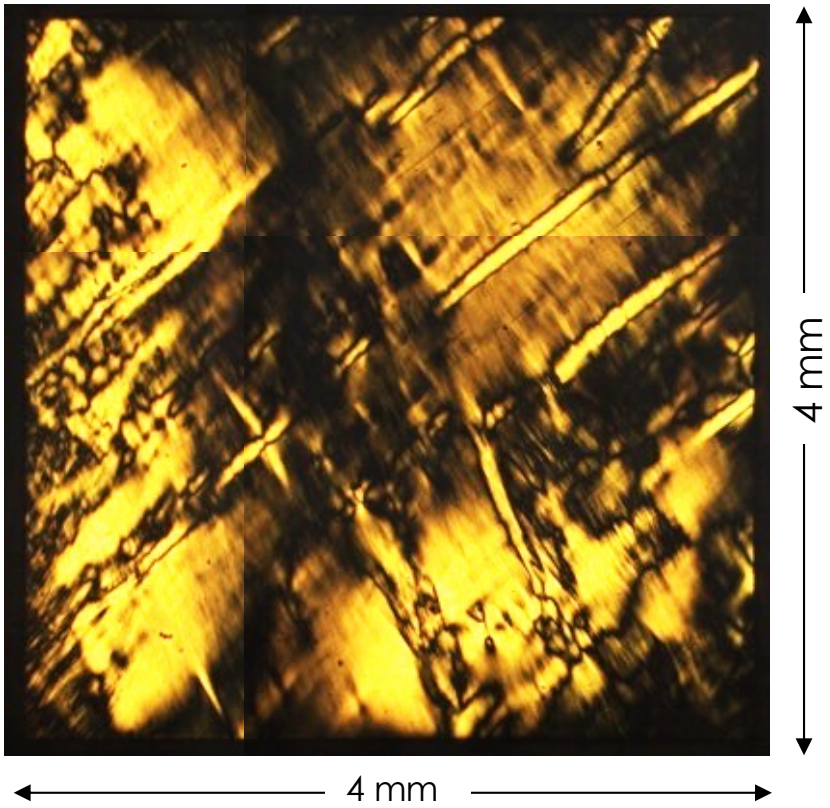


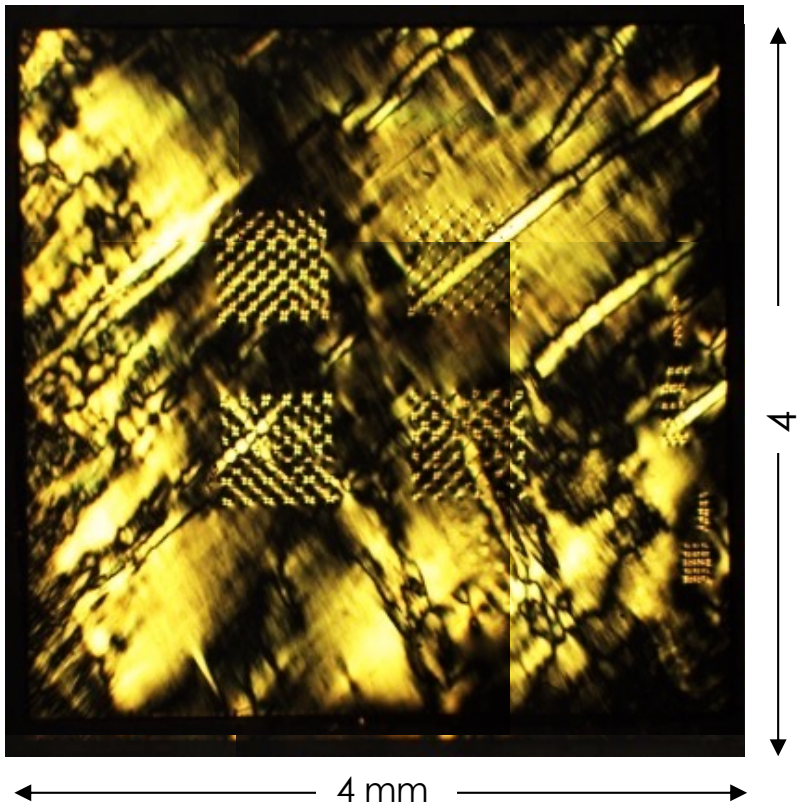


(a)



X-polariser image

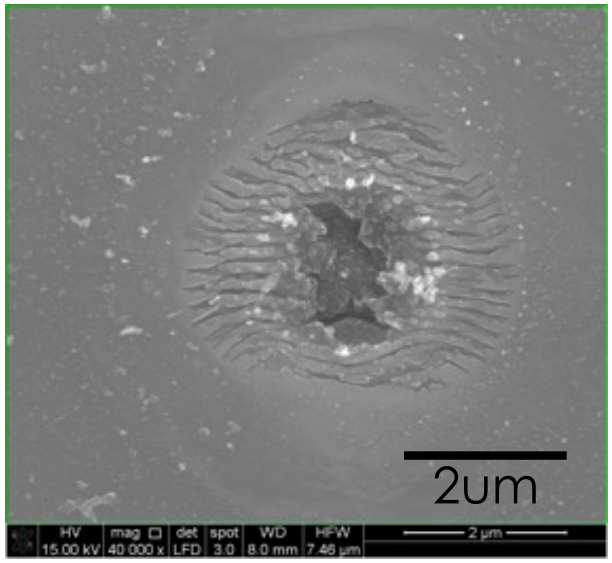


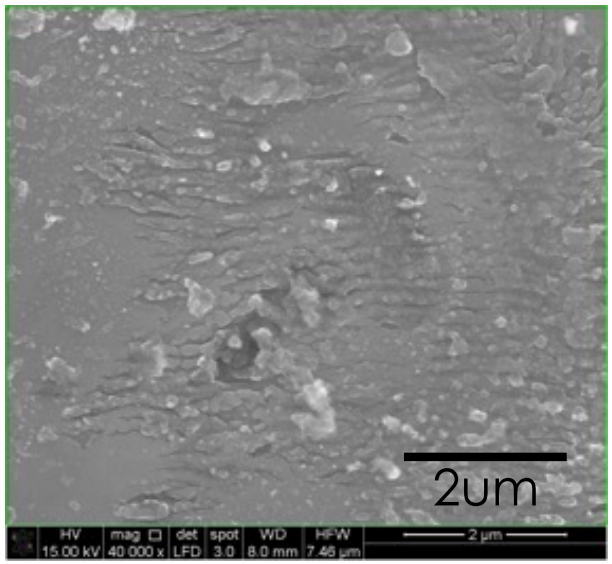


- Optical grade scCVD diamond.
- Post processing.

SEM surface image

- Seed surface

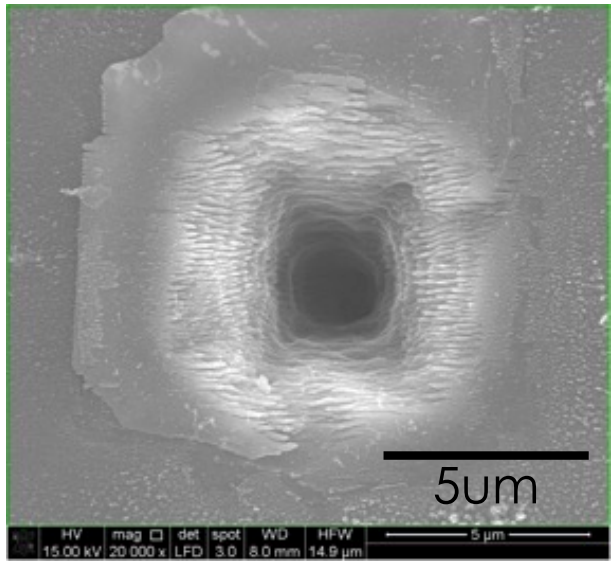


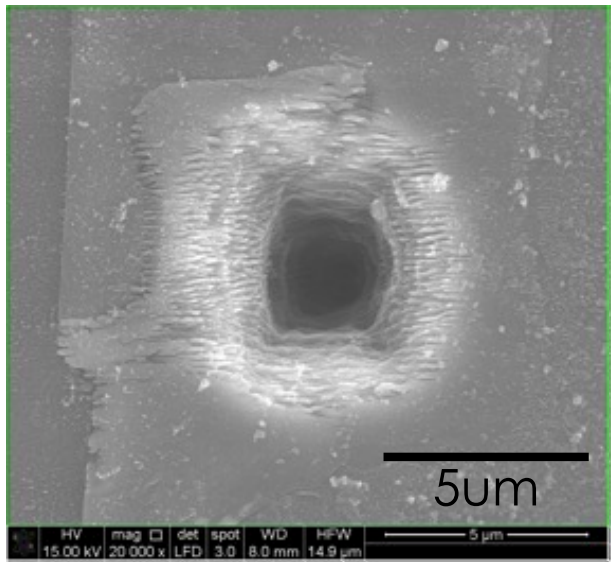


With SLM
10um/s
400nJ

Without SLM
10um/s
400nJ

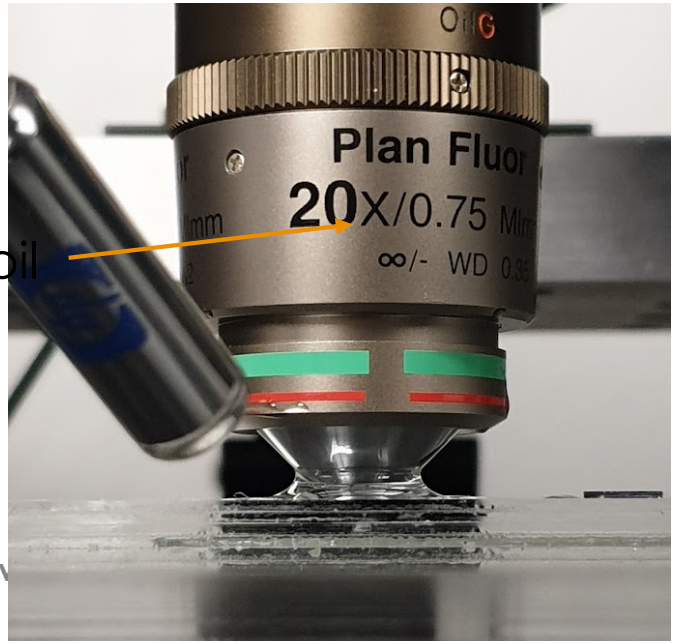
- Exit surface

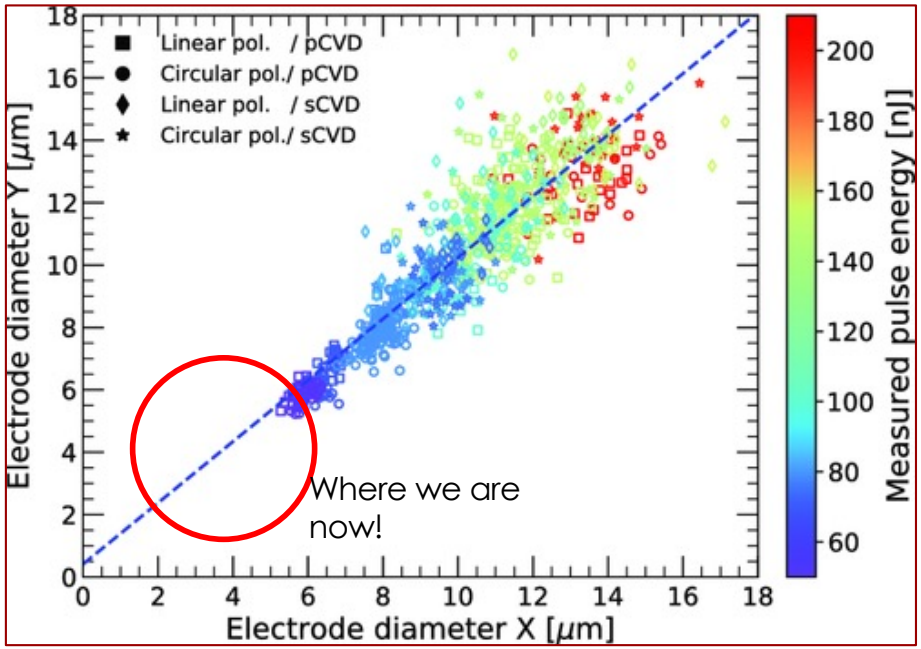




Making the thinnest column

- More energy = thicker column
- Non-linear breakdown of diamond
  - More focused beam spot at depth makes thinner column
  - Immersion Oil helps to reduce refraction loss from air-diamond interface
    - SLM still key!

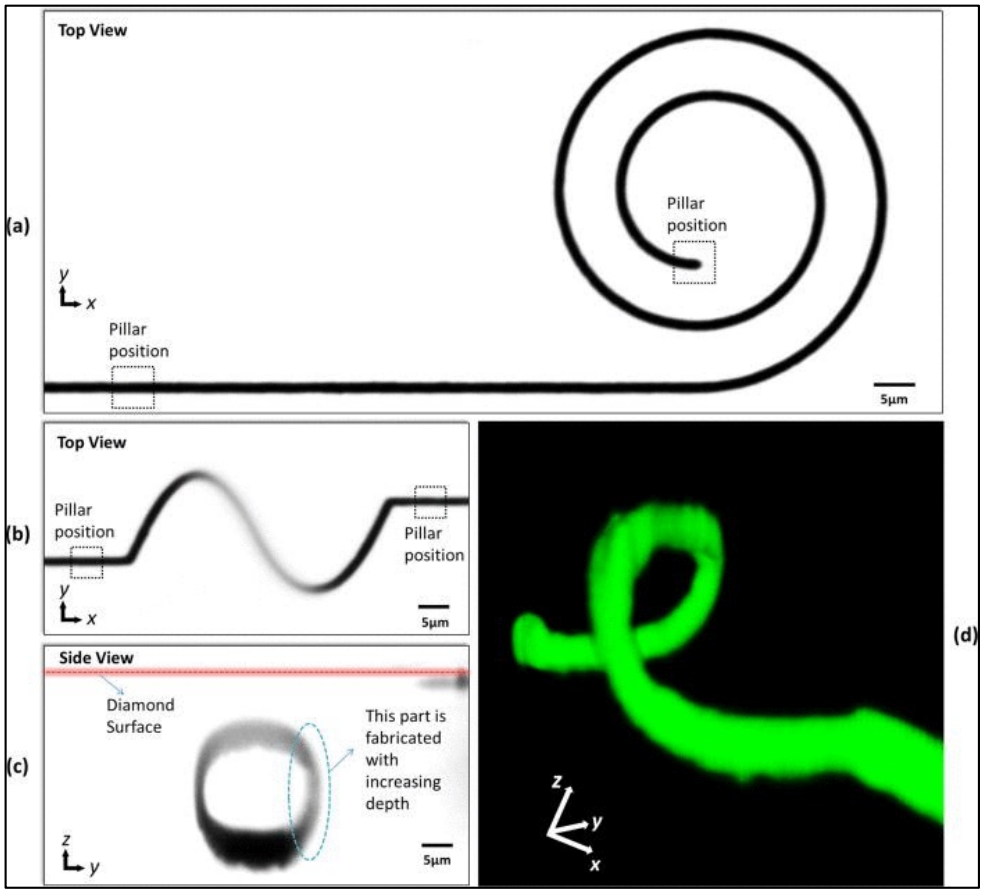




Lopez Paz, I., Allegre, O., Li, Z., Oh, A., Porter, A. and Whitehead, D. (2019), Study of Electrode Fabrication in Diamond with a Femto-Second Laser. Phys. Status Solidi A, 216: 1900236.

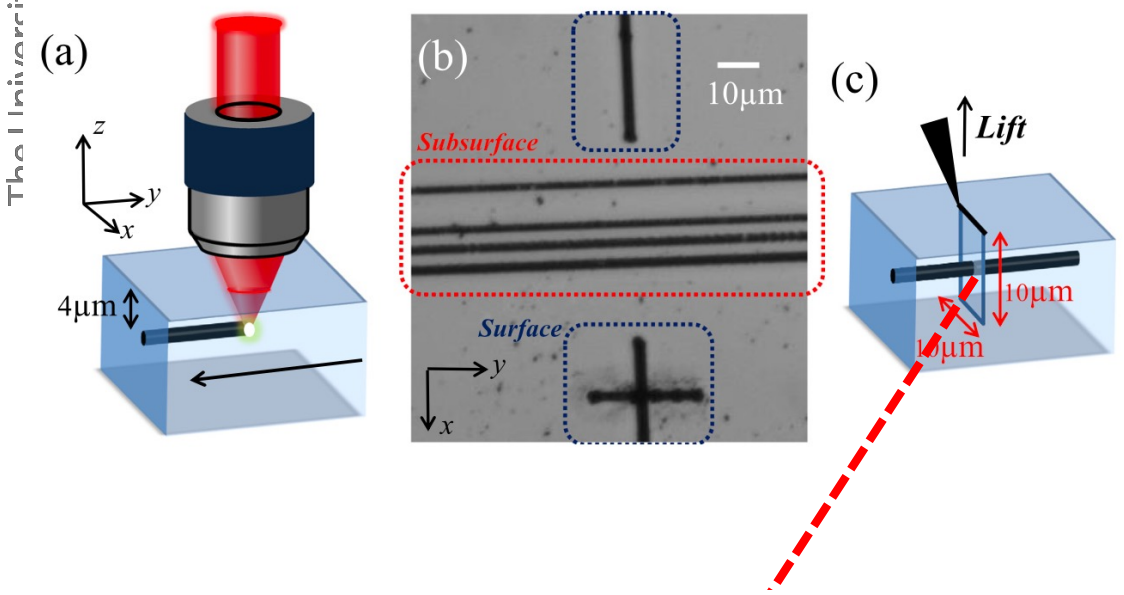
Moving sideways

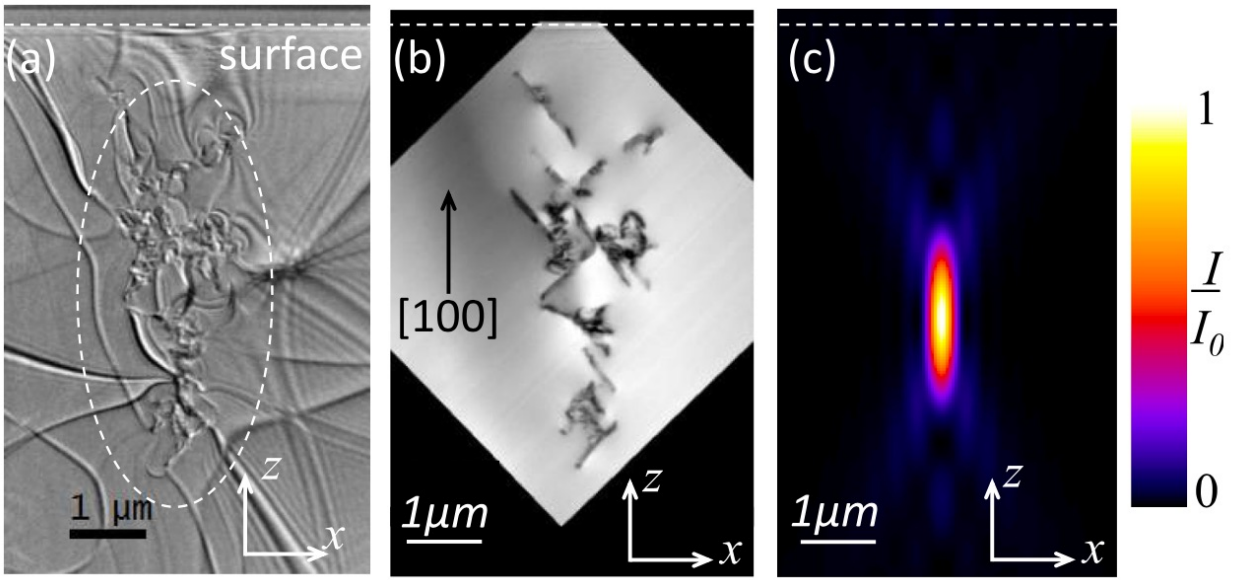
- Also have the possibility to move in **arbitrary** direction
- Wavefront correction needs to be tailored in real-time
  - For vertical columns have mainly spherical corrections
  - For horizontal processing, the correction is ~elliptical
  - Gets even trickier at depth >200µm



Sun, B., Salter, P. S., & Booth, M. J. (2014). High conductivity micro-wires in diamond following arbitrary paths. *Applied Physics Letters*, *105*(23), 231105.

Internal structure





Patrick S. Salter et al., APPLIED PHYSICS LETTERS 111, 081103 (2017)

- Prepare sample with horizontal graphitic wires.
- STEM image of wire cross section.
- Optical and spectral data points to micro-cracks and nano-clusters of sp^2 bonded carbon.
- Micro wires are not macroscopic structures!

Parameter space scan

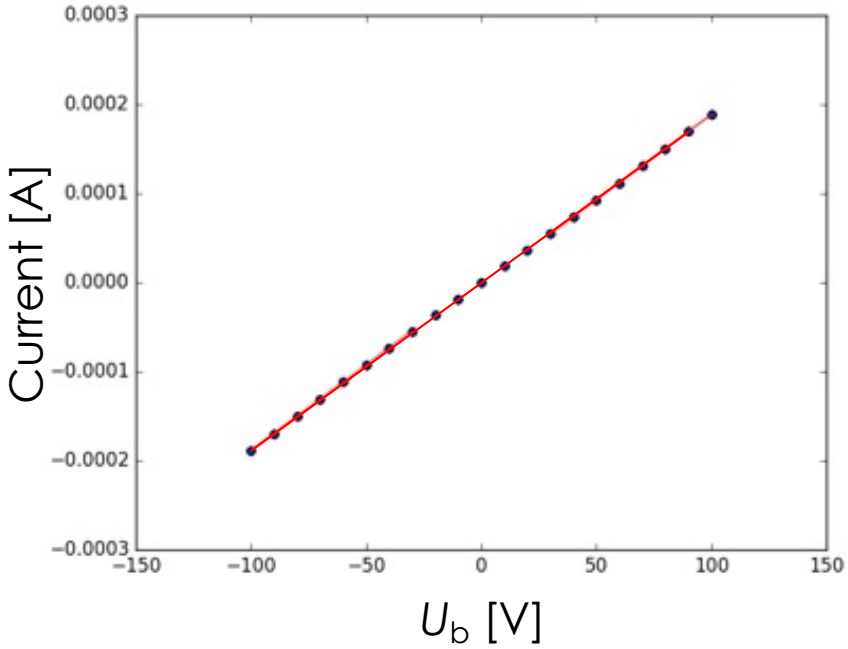
Patrick Salter, Oxford
Iain Haughton, AO, Manchester

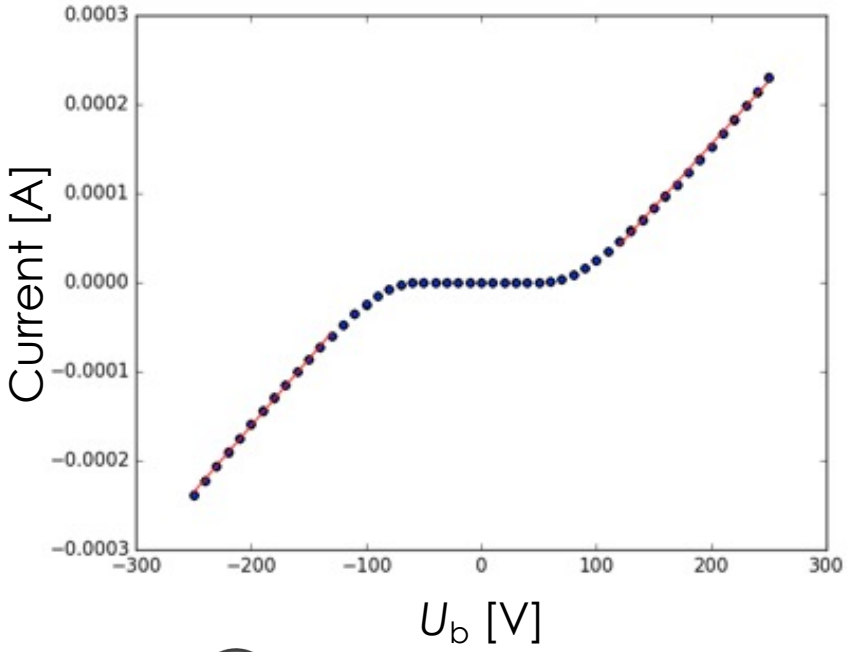
		Laser translation speed			
		5um/s	10um/s	20um/s	30um/s
Laser beam energy	100nJ	x	x		
	200nJ	x	x	x	
	300nJ		x	x	x
	400nJ		x	x	x
	500nJ			x	x
	600nJ				x

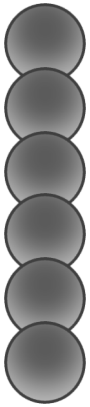
- Repeat **with** and **without** SLM correction.

IV curves

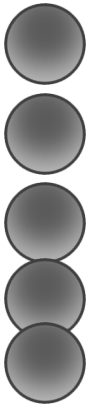
- Ohmic and barrier potential curves observed.





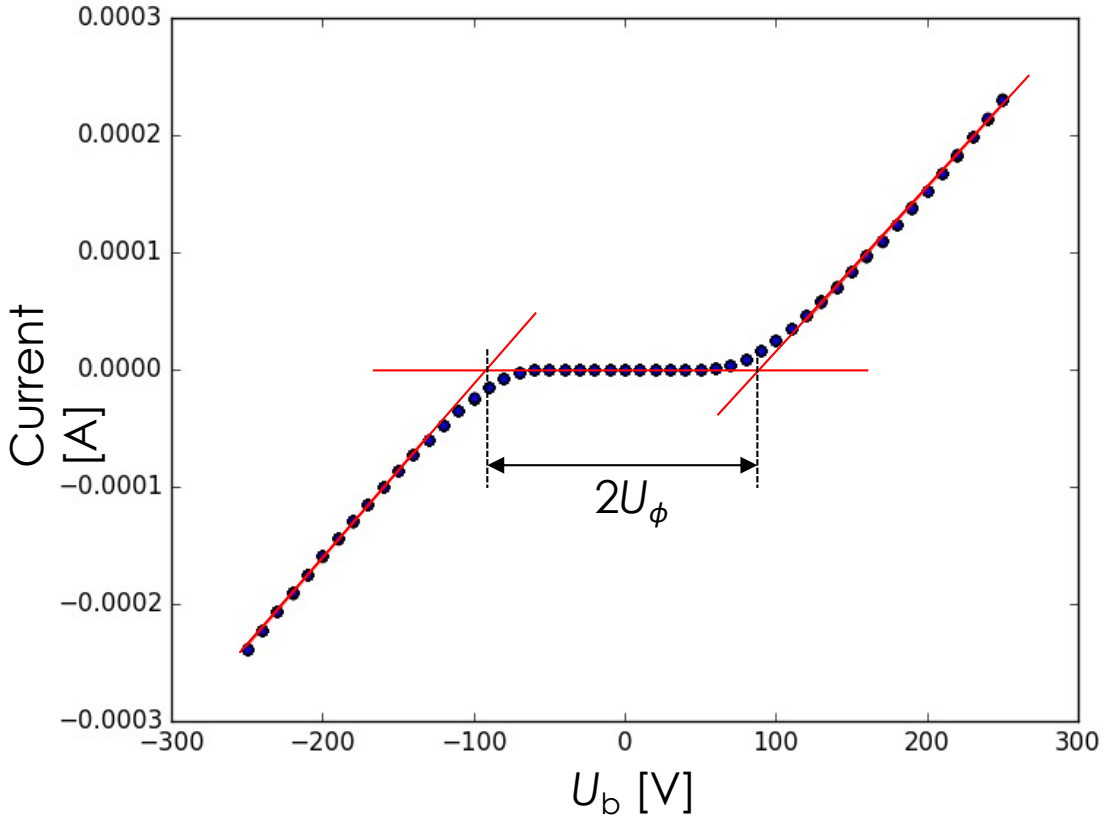


Continuous.

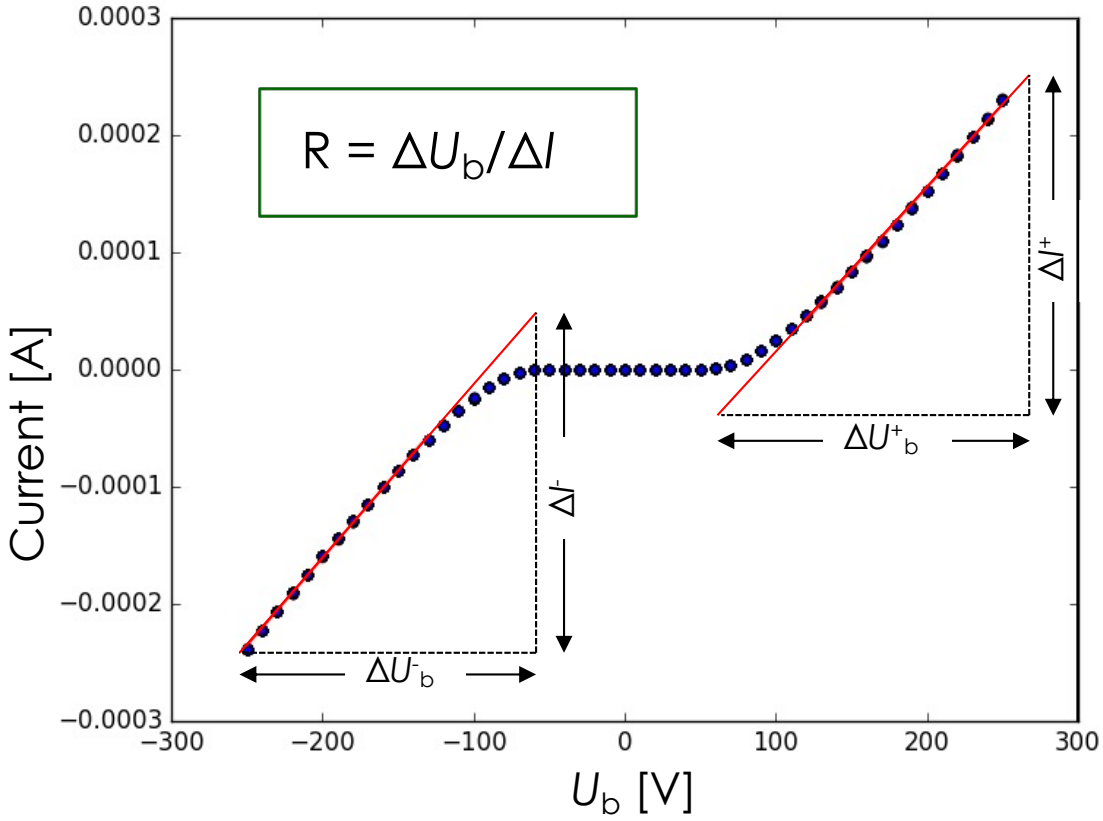


Bulk effect?
Micro gaps?

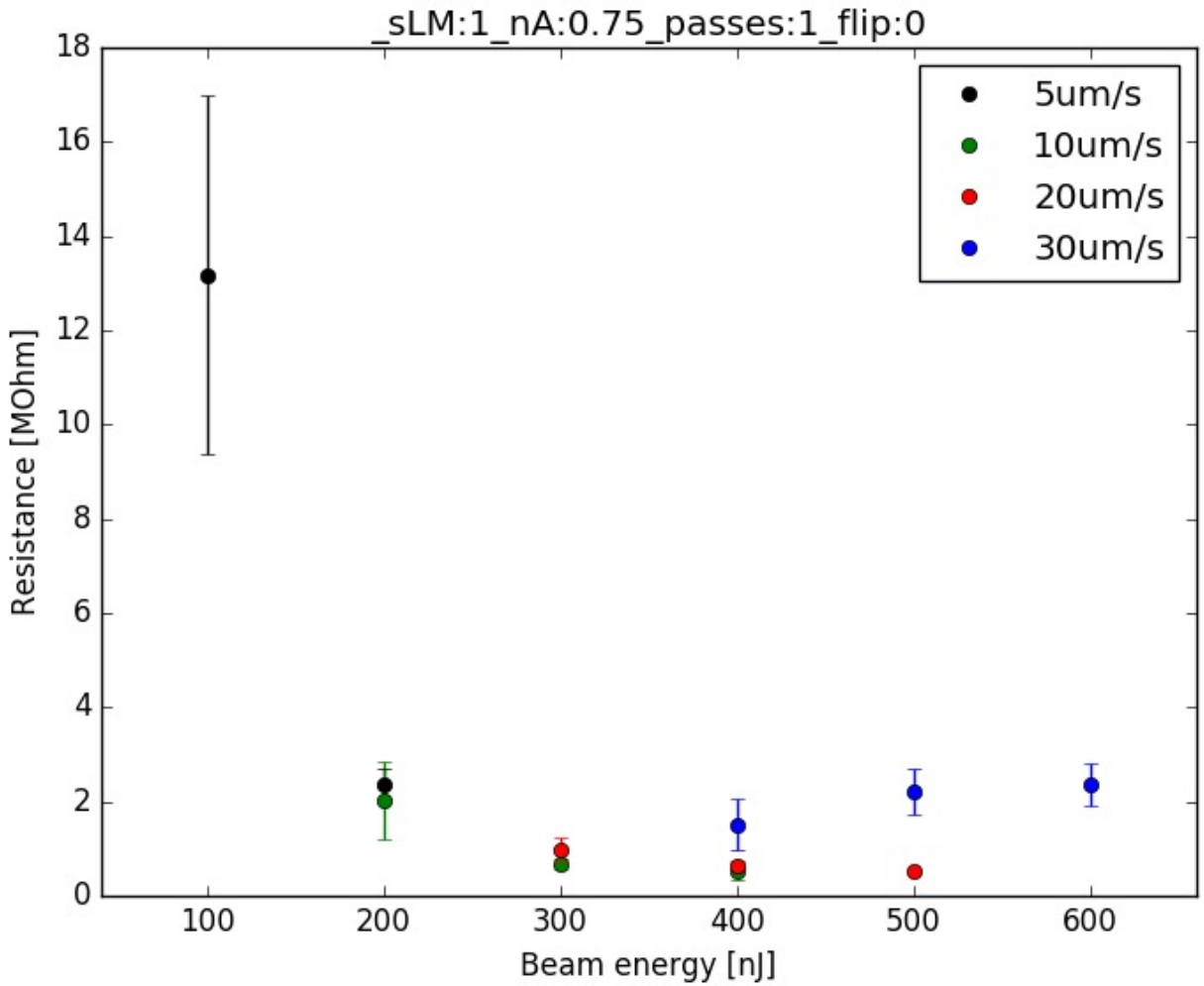
Barrier potential



Resistance measurement

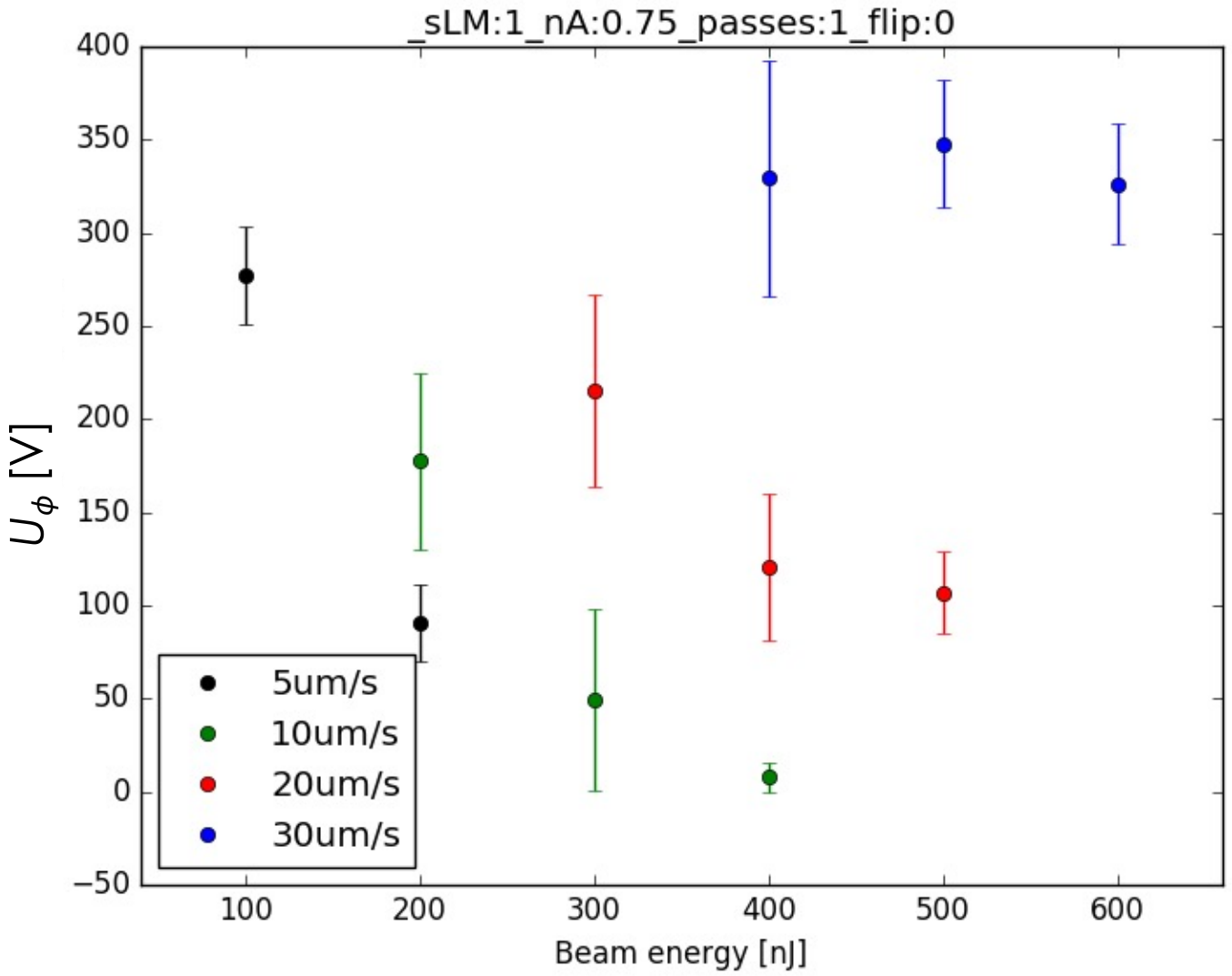


Resistance



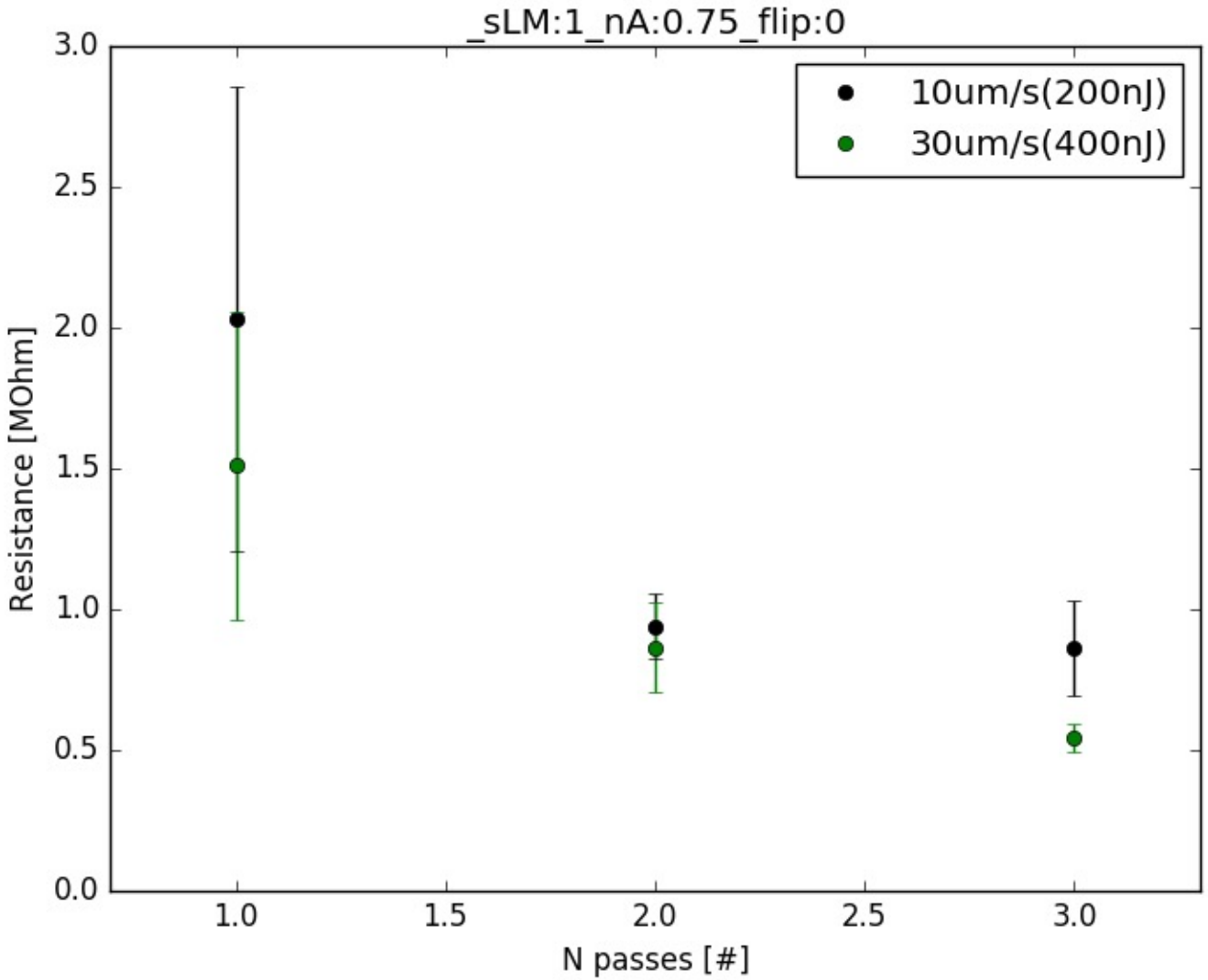
- Resistance increase as power law → multi-photon process.
- Clear discrepancy at 30um/s.

Barrier energy



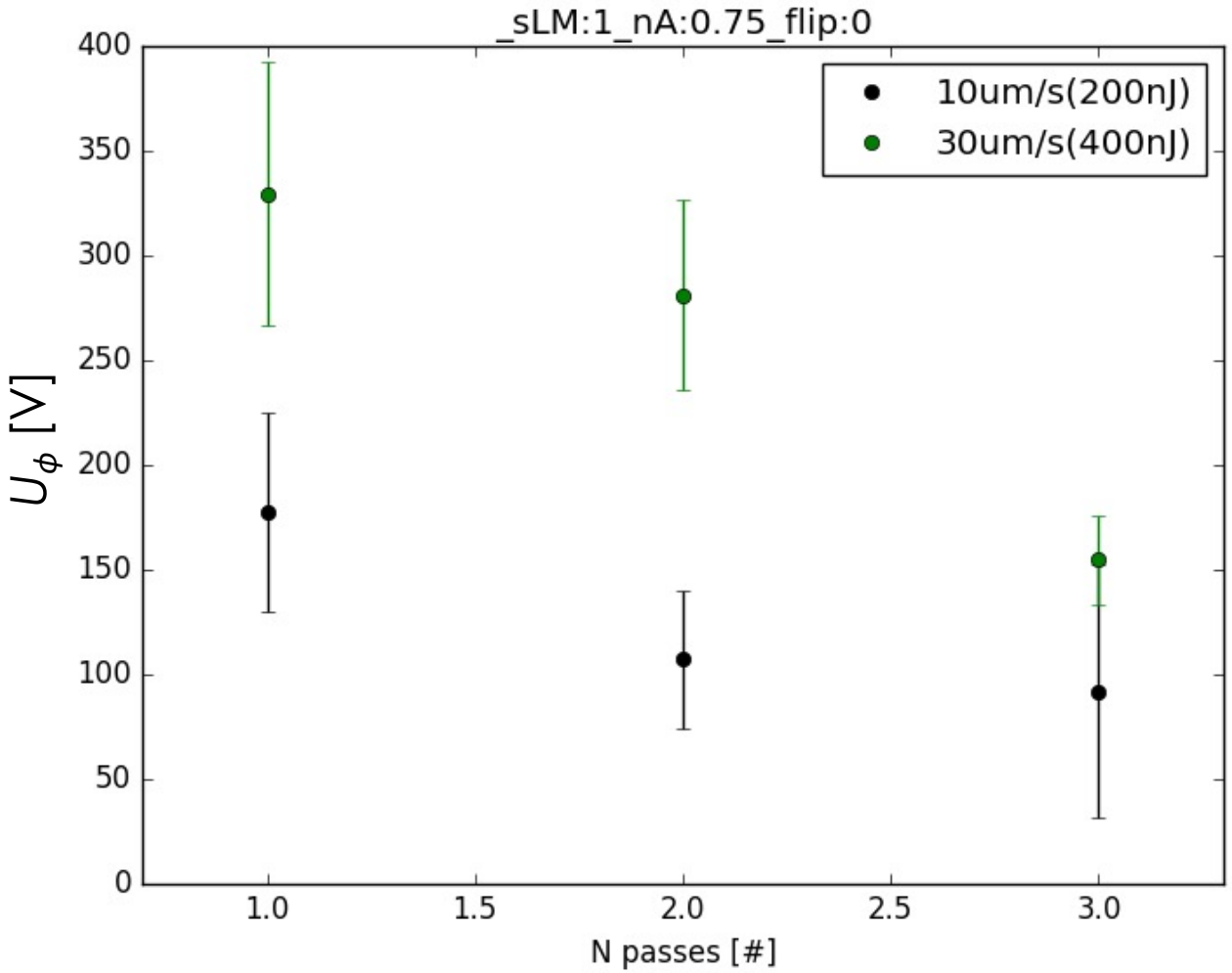
- Reduction in barrier with increased energy.
- Discrepancy at 30um/s.

Multiple passes



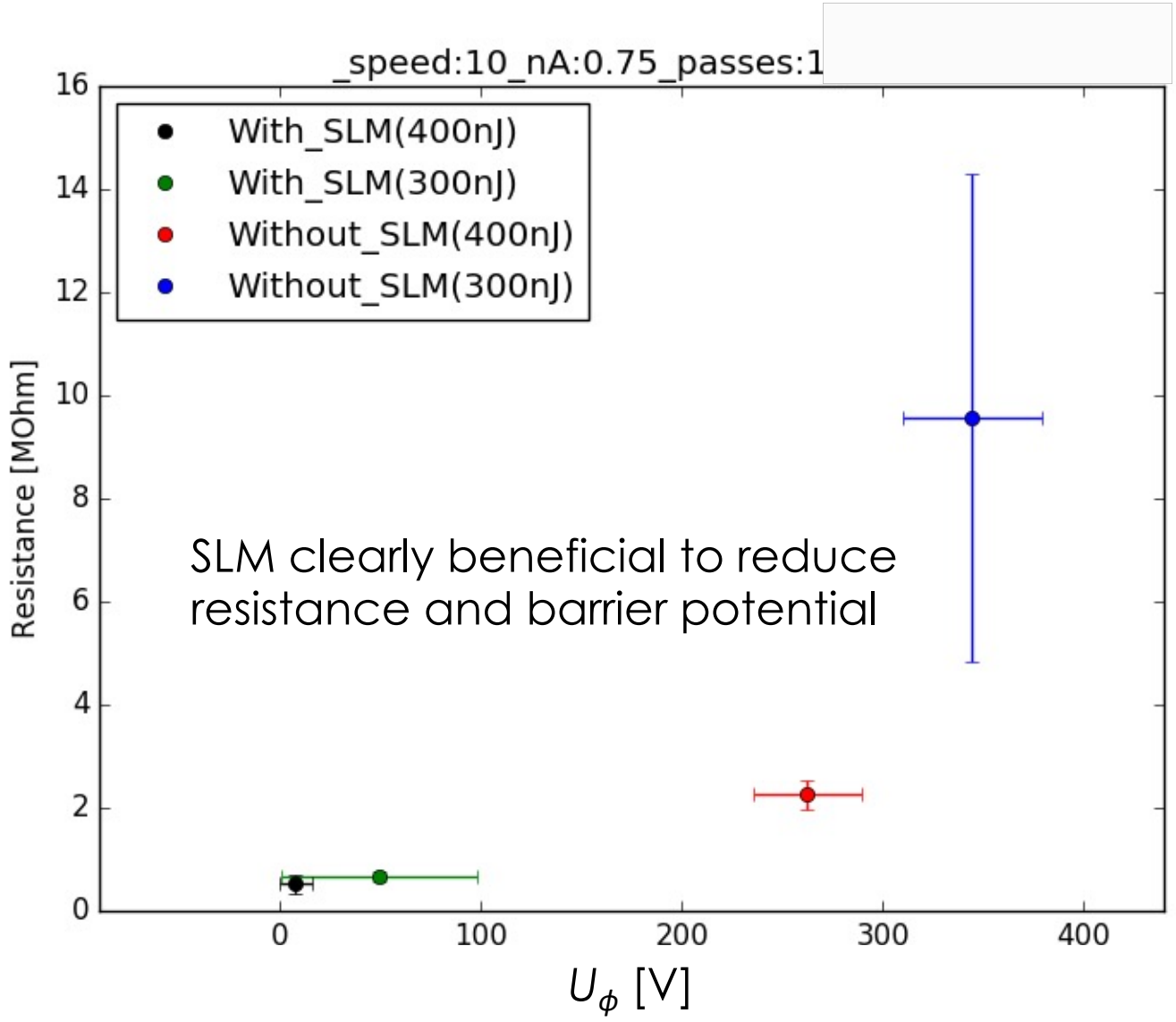
- Multiple passes reduces resistance and increases uniformity of the columns.

Multiple passes



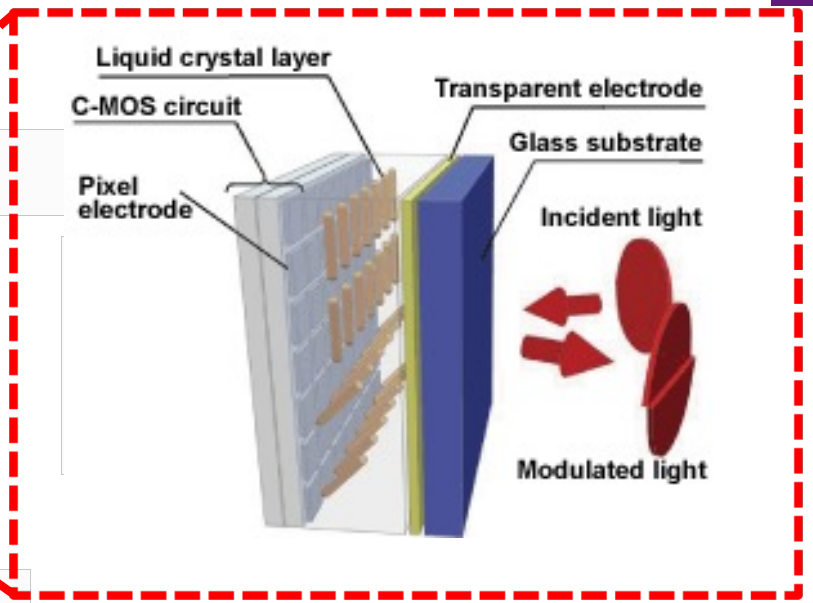
- Multiple passes also reduces U_ϕ.

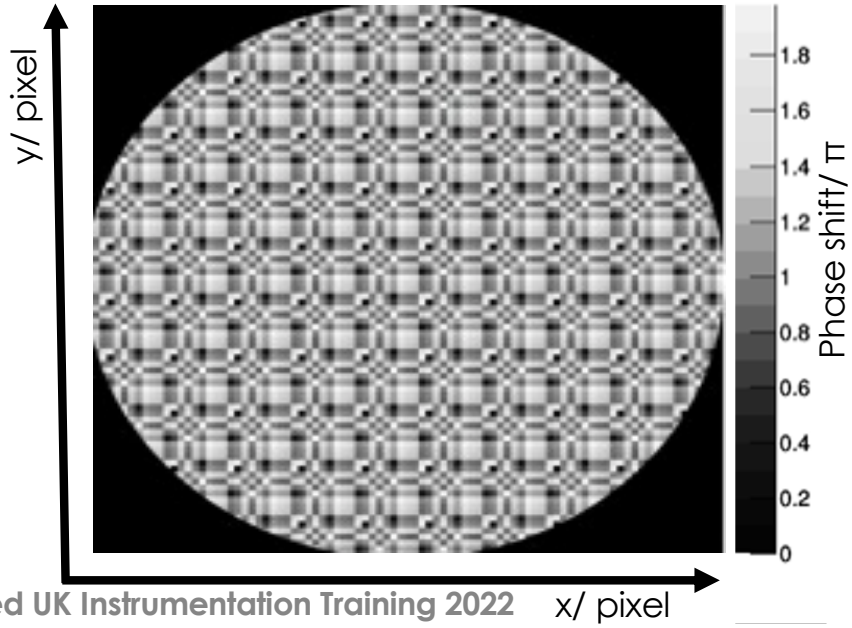
With and without SLM

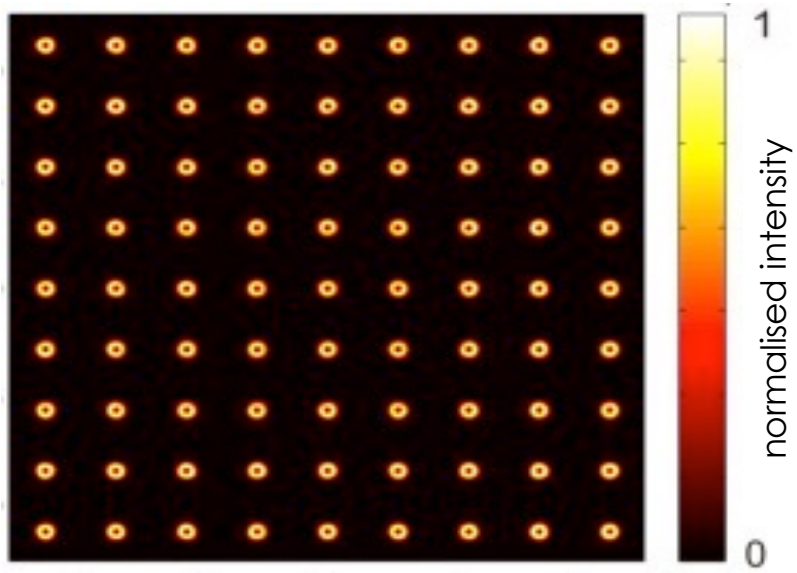


SLM clearly beneficial to reduce resistance and barrier potential

SLM parallel processing?







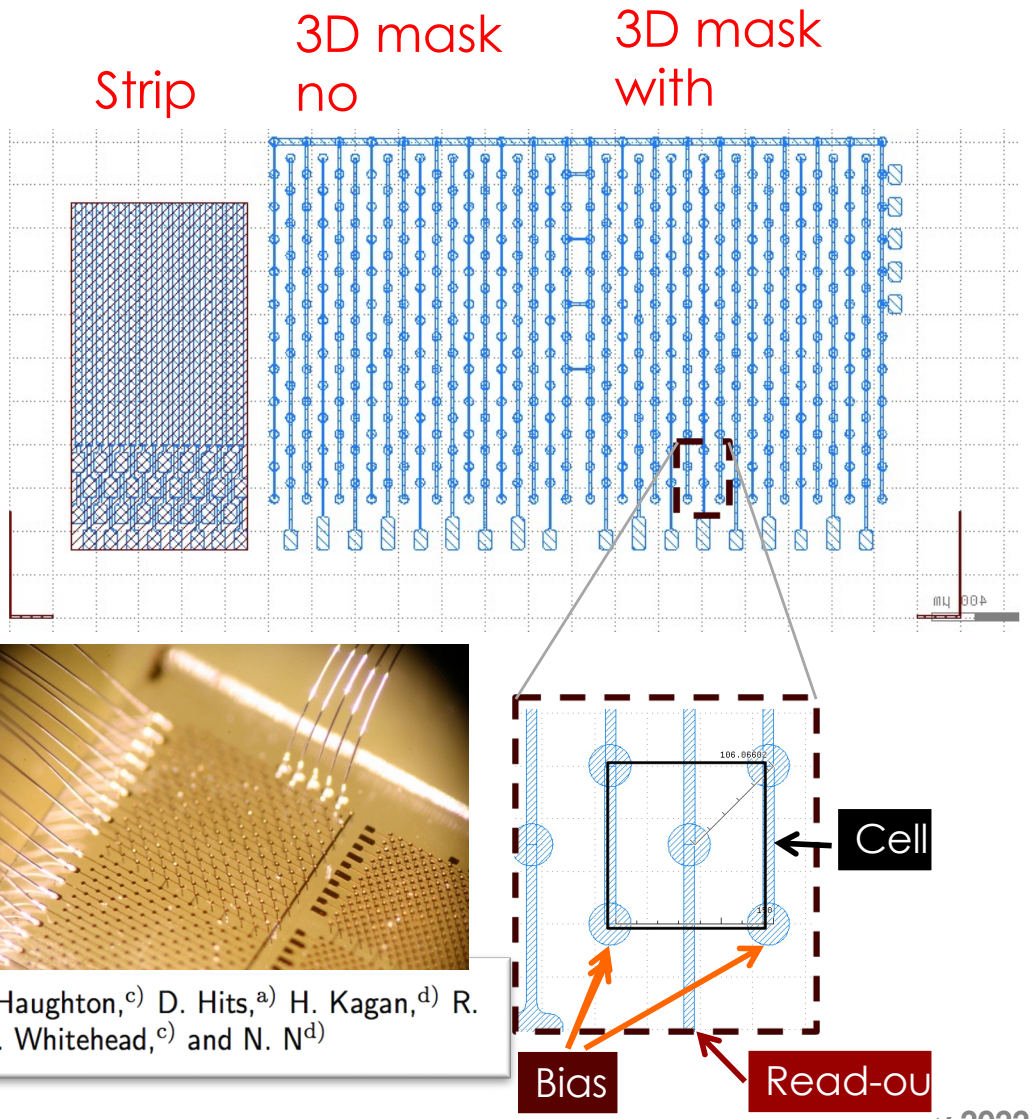
3D Diamond detector tests with relativistic charged particles

- Types
  - 100x100um cell size ganged to form strips
  - 100x100um cell size, bonded to pixel read-out
  - 50x50um cell size, bonded to pixel read-out
- All detectors made from polycrystalline diamond.
- Beam tests
  - CERN beam line H6 : protons ~ 120 GeV/c
  - PSI : pions ~ 250 MeV/c

Thanks for material from the RD42 collaboration!

3D Diamond prototype

- **Proto-type**
  - Strip detector with back side contact
  - 3D metal only pattern
  - 3D metal + graphitic columns
  - Cubic cell base size 150μm
  - 99 cells
- Measure response with 120 GeV protons.
- Paper published NIMA
  "A 3D diamond detector for particle tracking", NIM A, 786 (2015)



F. Bachmair,[a] L. Baeni,[a] P. Bergonzo,[b] B. Caylar,[b] G. Forcolin,[c] I. Haughton,[c] D. Hits,[a] H. Kagan,[d] R. Kass,[d] L. Li,[c] A. Oh,[c] M. Pomorski,[b] V. Tyzhnevyi,[c] R. Wallny,[a] D. Whitehead,[c] and N. N[d]

MANCHESTER 1824

The University of Manchester

Analysis steps

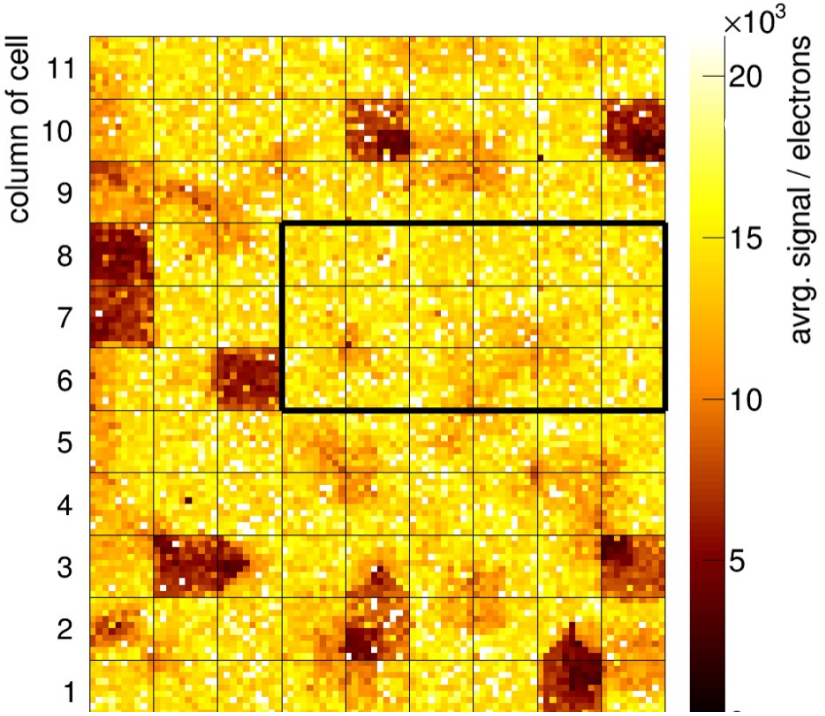
- U_b(3D)=40V
- U_b(strip)=500V

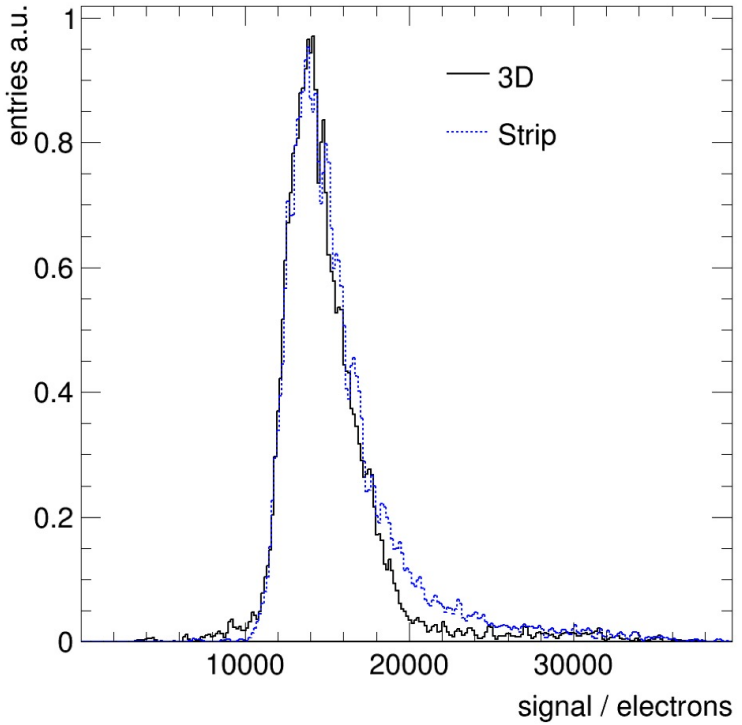
- Identify **continuous region** of intact cells for analysis.
- Exclude contribution of negative signals.

- **Average charge**
  Strip: 16.8ke
  3D: 15.9ke

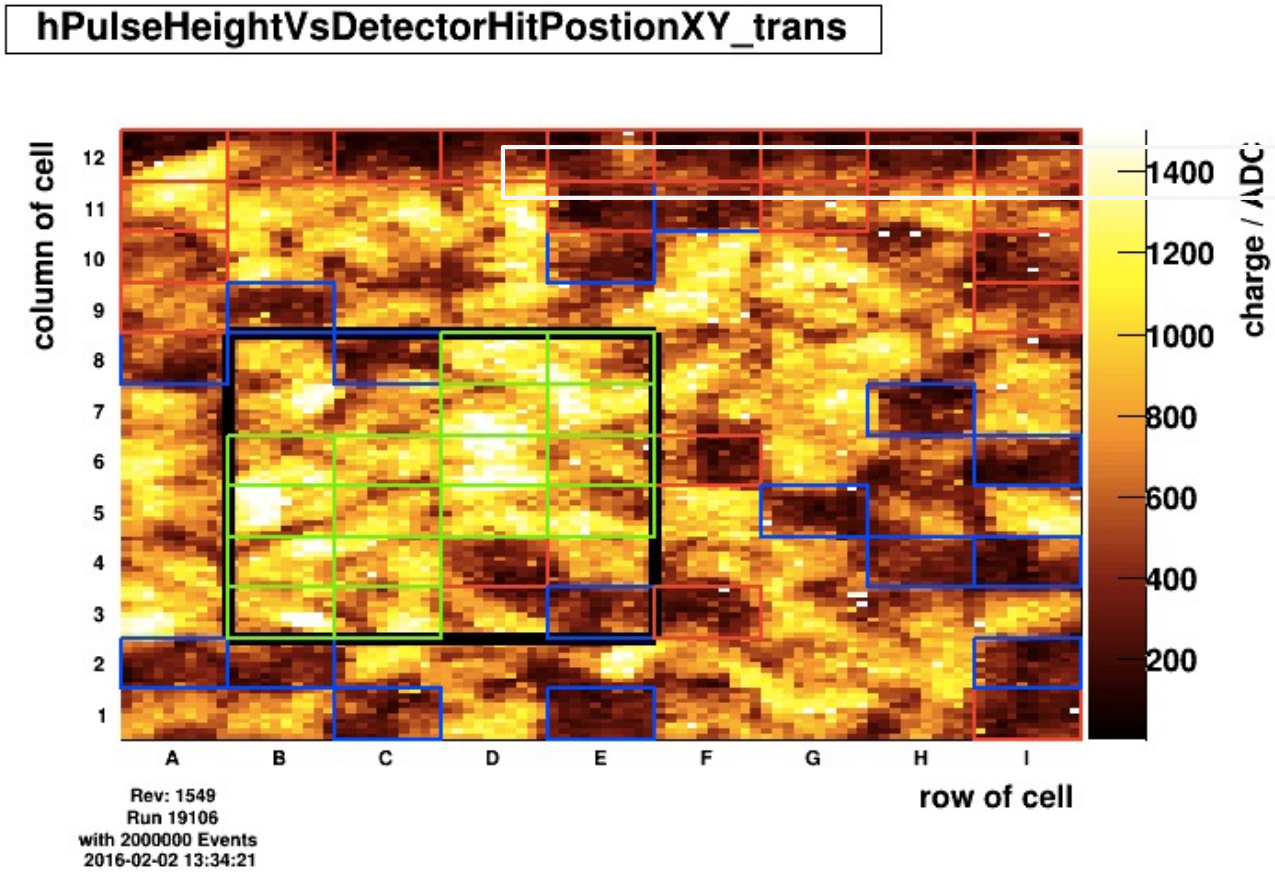
- **MP:**
  Strip: 14.7ke
  3D: 15ke

3D and Strip show comparable response.
Conclusion -> 3D works!





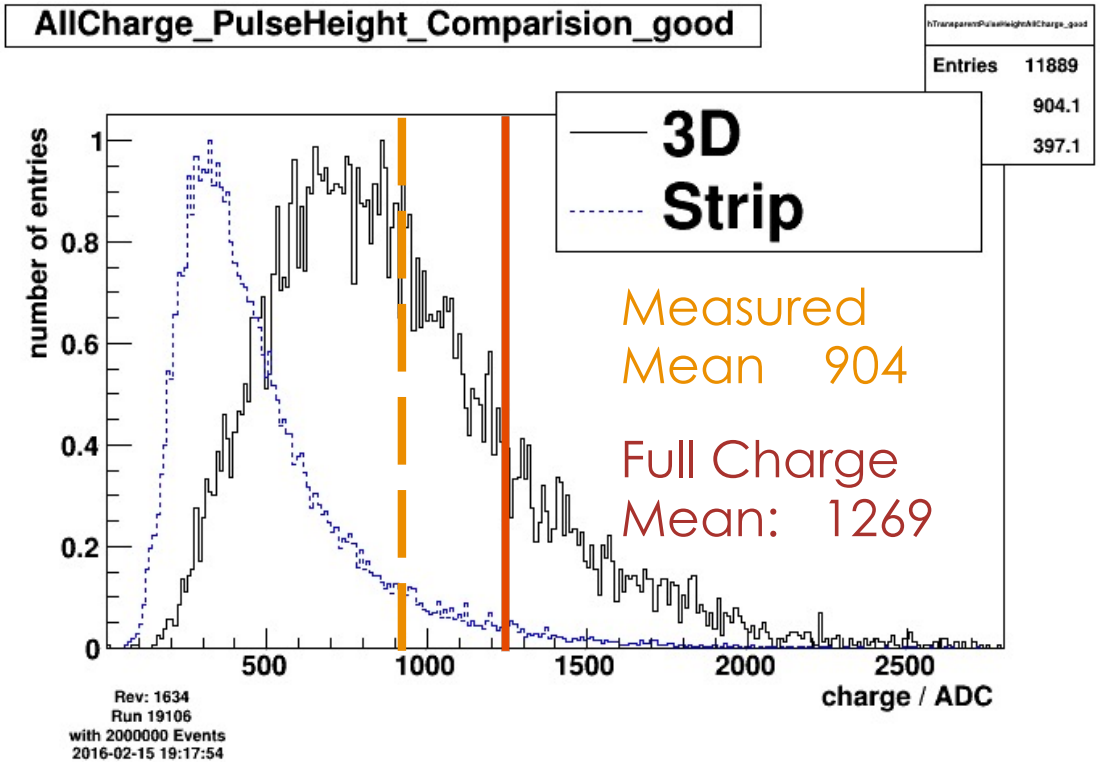
Test of first 3D pCVD diamond detectors



- U_b(3D)=75V
- U_b(strip)=500V
- Selected 16 adjacent cells

Test of first 3D pCVD diamond detectors

- Red line estimate the Mean for Full Charge Collection (100%)



71% of Full Charge Collection, corresponding to ~13 ke.

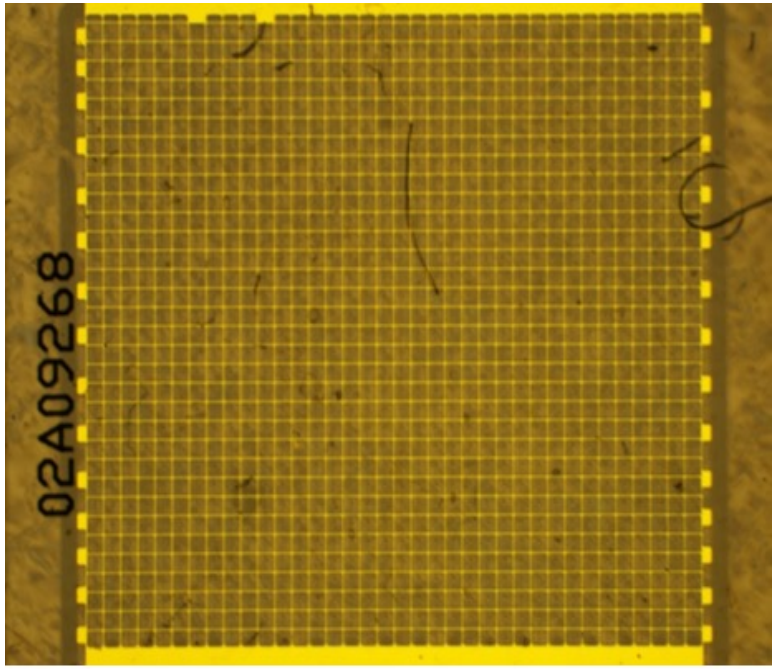
Highest charge collection ever measured for pCVD diamonds

Large area 3D, pCVD, 100x100

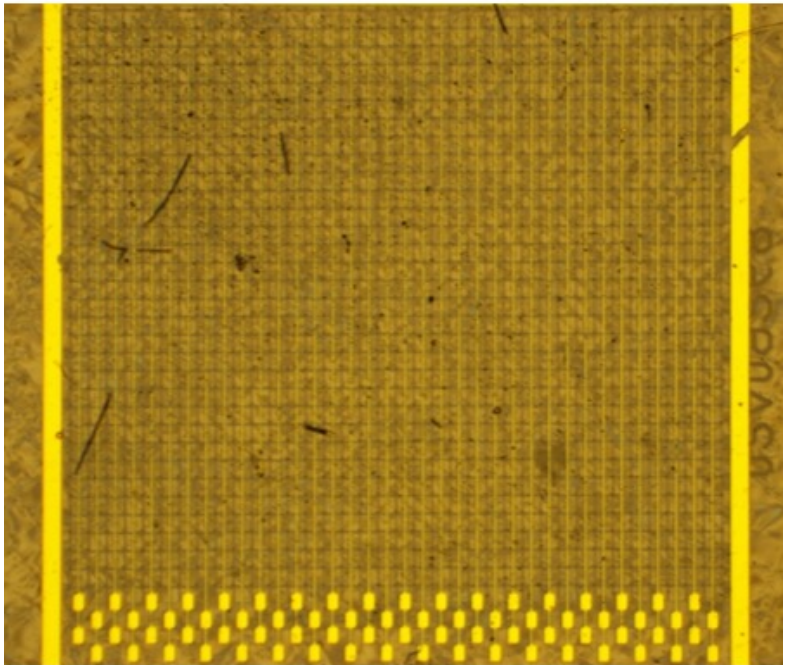
In May/Sept 2016 tested the first full 3D device fabricated in pcCVD with three dramatic improvements:

1. An order of magnitude more cells (1188 vs 99).
2. Smaller cell size (100um vs 150um).
3. Higher column production efficiency (>99% vs ~90%).

HV side

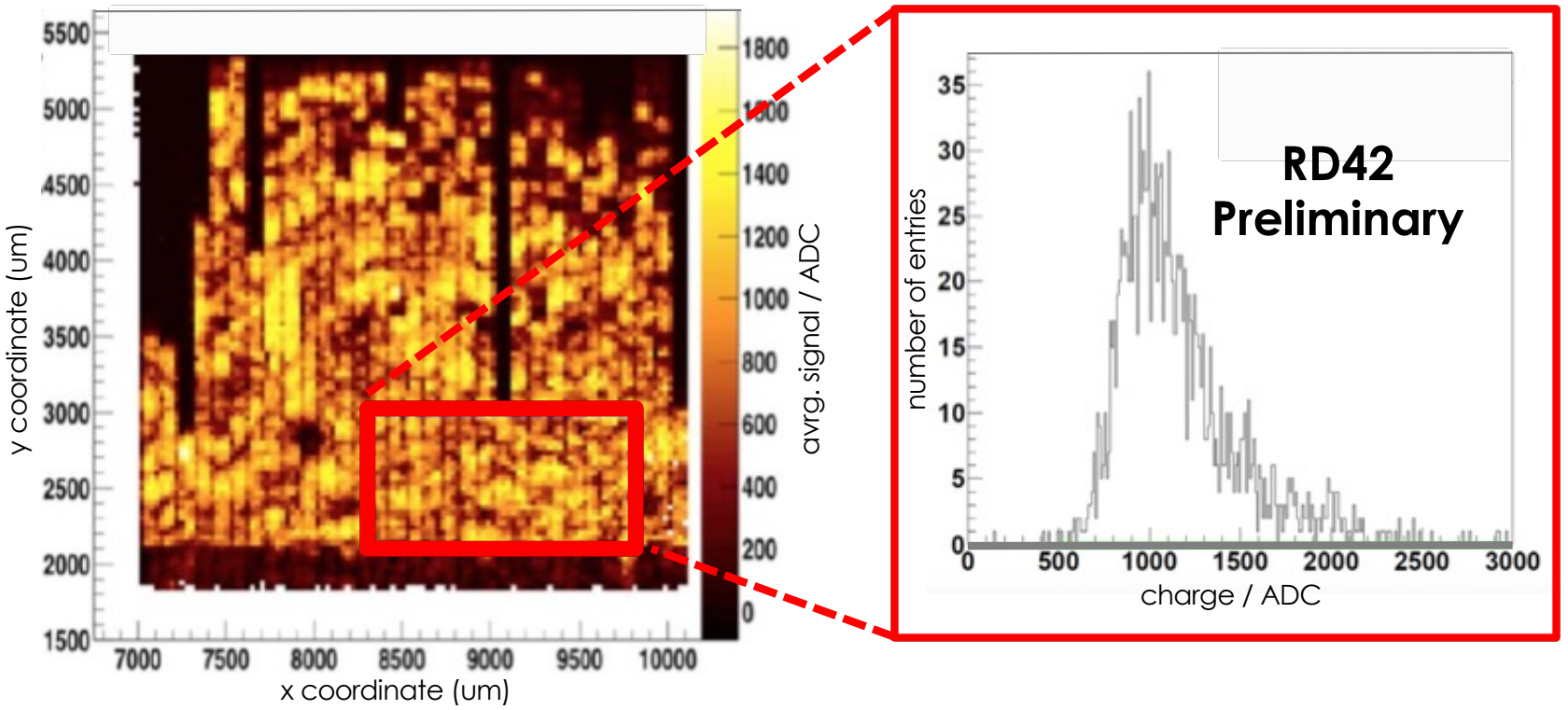


Readout side



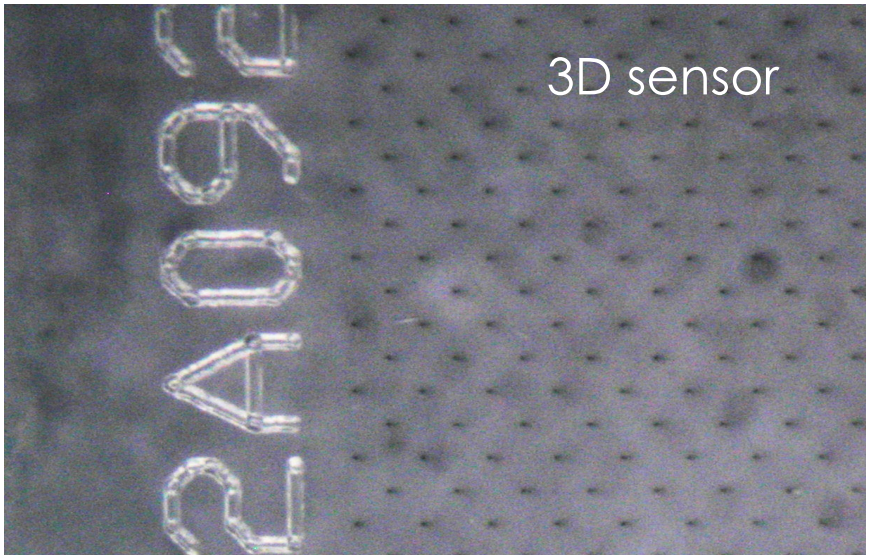
Large area 3D, pCVD, 100x100

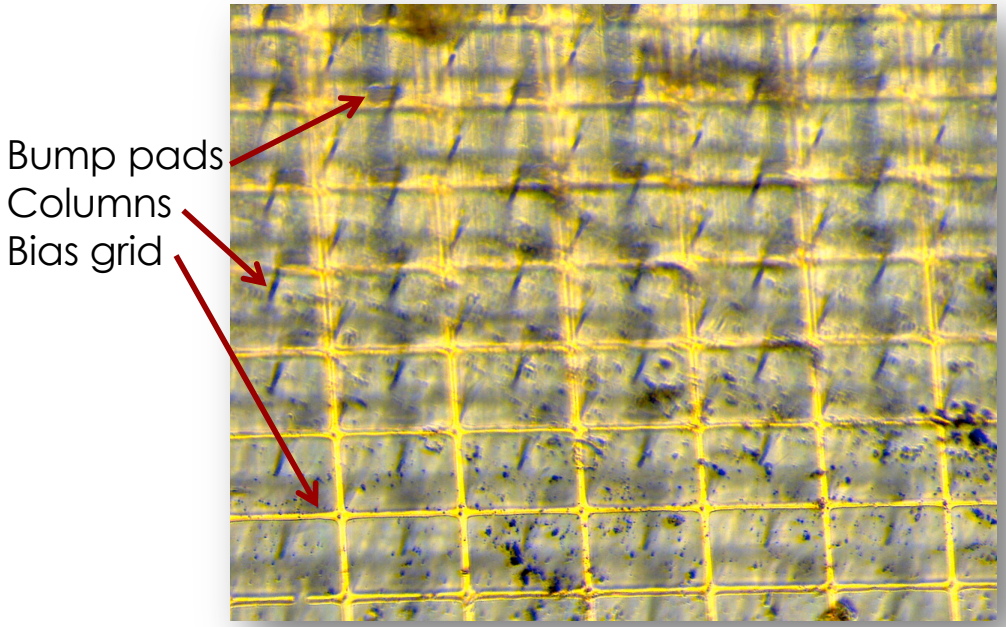
- Largest charge collection to date in pcCVD diamond!
  - >85 % of charge collected in continuous region, about twice as much as planar.

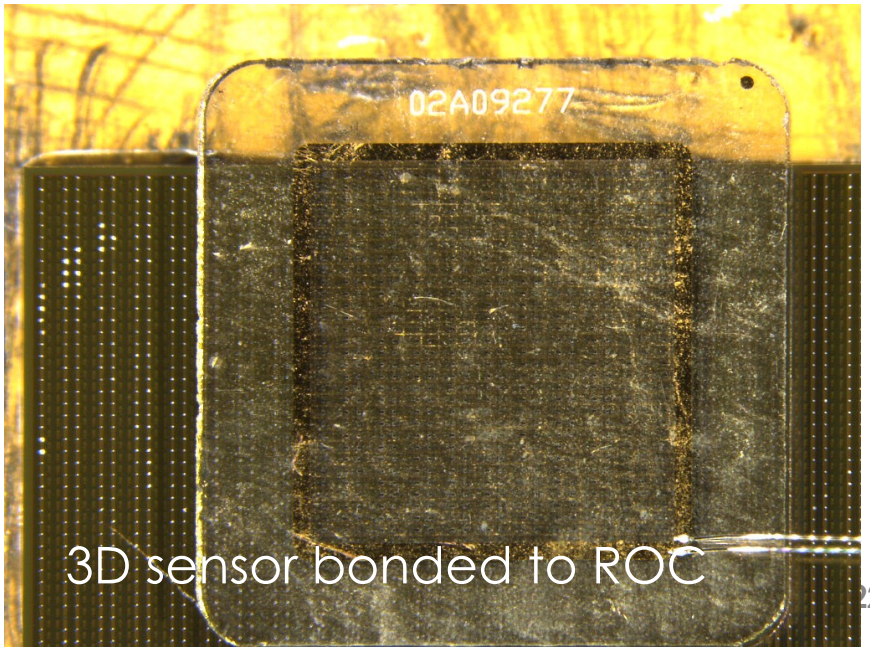


Pixel 3D, pCVD, 100x100

- First assembly with ROC chip produced.
  - Bump bonded in Princeton.
  - Cr-Au on bias side.
  - Ti-W under-bump metal.
  - Indium bumps on sensor.

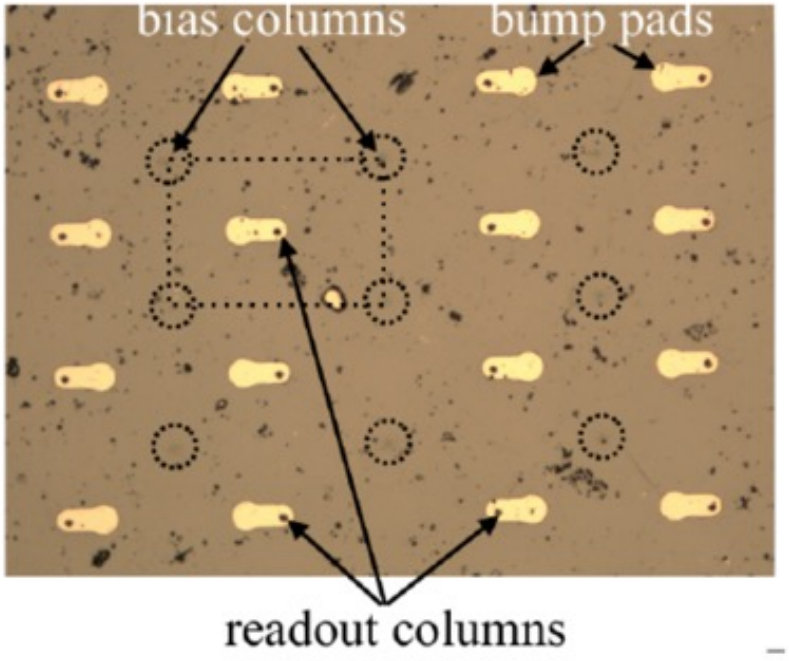


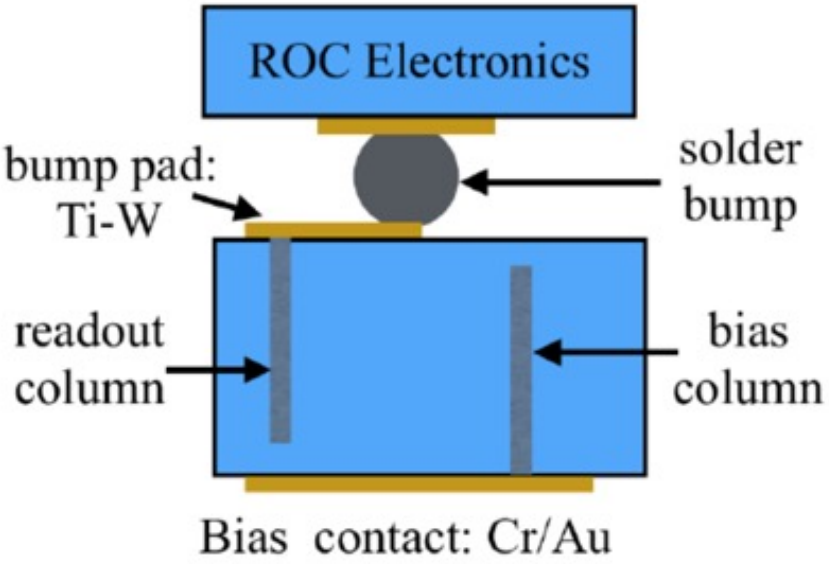




Pixel 3D, pCVD, 100x100

- Production of first pixel device using CMS readout electronics.

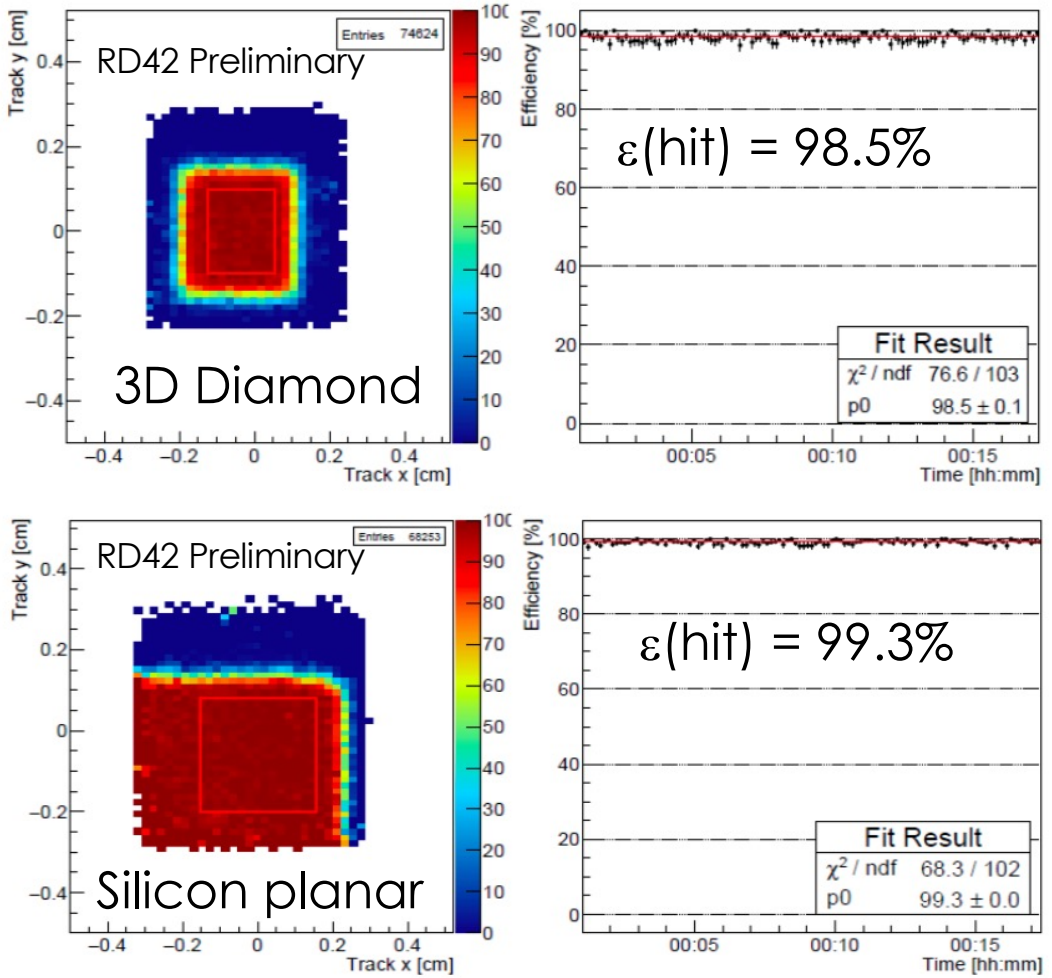




- Active region 3x3 mm with cell size ~100x100 um.

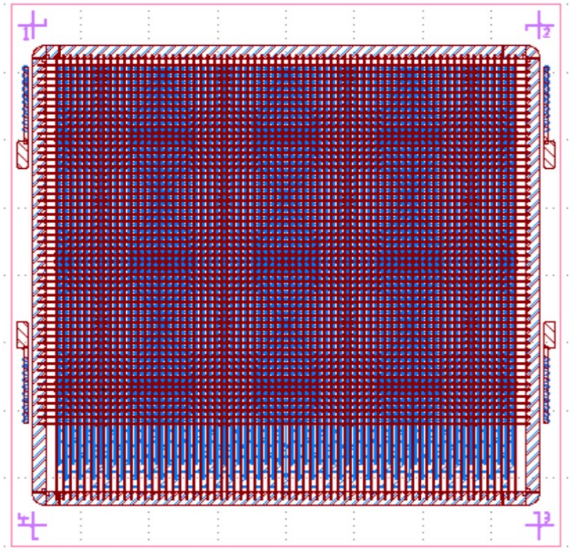
Pixel 3D, pCVD, 100x100

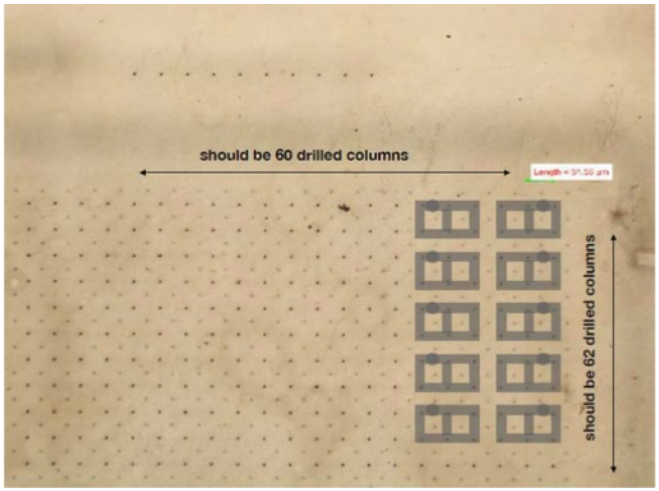
- 3D diamond device and Silicon reference planar device.
- Pixel threshold 1500e.
- Check hit efficiency over time.
- Device works!



Next generation 3D Diamond

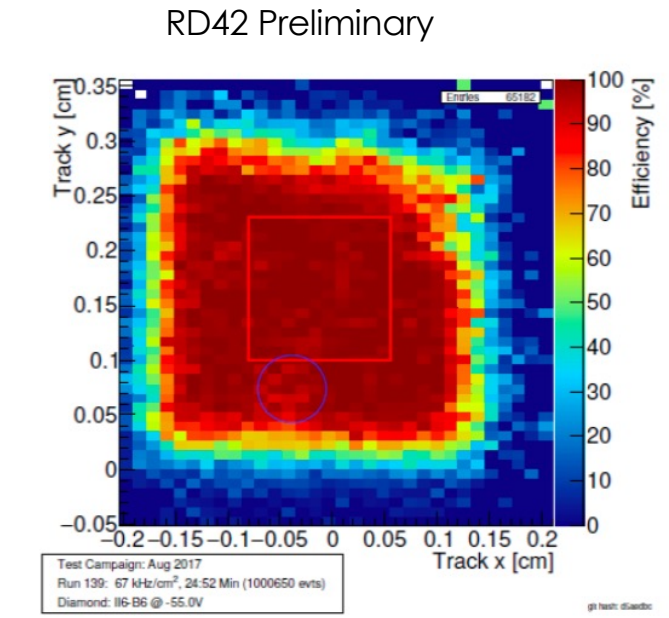
- Produced 3500 Cell pixel protoype, 50x50um cell size.
- Sample production:
  - Oxford (2x cubic cells)
  - Manchester set-up in progress (expected production date end of month.)
  - Bump bonding
    - For ROC (CMS) Princeton.
    - For FE-I4 (ATLAS) IFAE.
- Data taking in August 2017 at PSI.

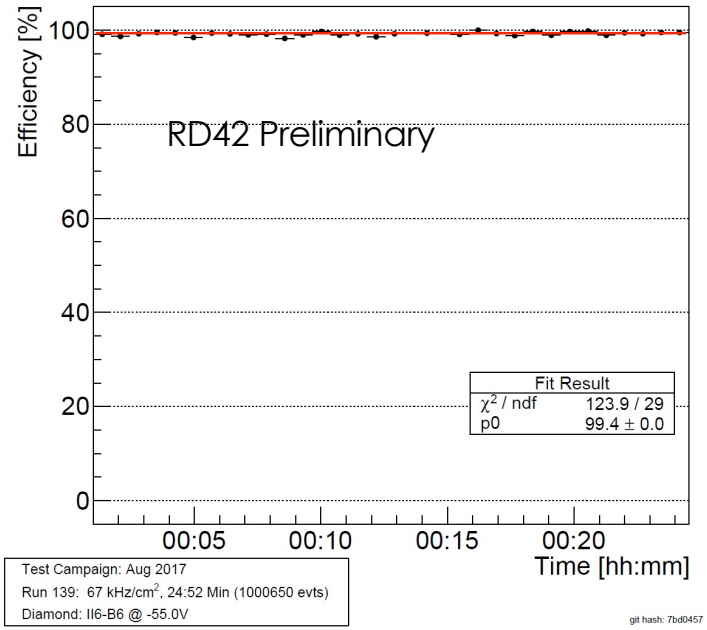




First 50x50 μm cell 3D Diamond (2017)

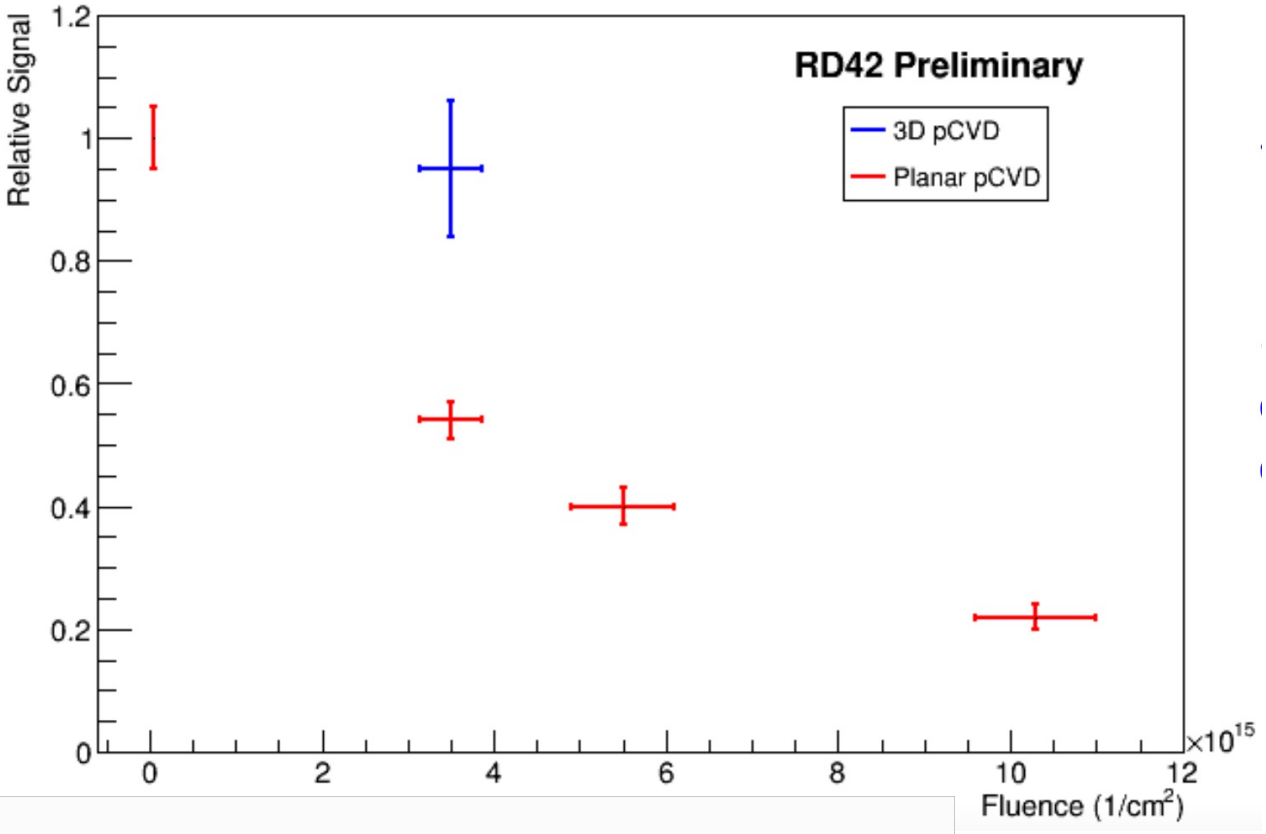
- Readout with CMS pixel readout.
- Bump bonding issue in upper right edge (Indium bump deposition machine not working properly)
- 6 columns (3x2) ganged together.
- Preliminary hit efficiency 99.2%
- Preliminary: Collect >90% of charge!
- Rate dependence tested with 10 kHz/cm^{-2} and 10 MHz/cm^{-2} -> no dependence observed.





3D diamond radiation tolerance

- Tested a 3D device irradiated to 3.5e15 p/cm^2 and compare to a planar diamond device at same fluence.
- Signal reduction:
  Planar $45 \pm 5\%$
  3D $5 \pm 10\%$
- Assuming scaling is similar 3D should operate at 10e17 p/cm^2



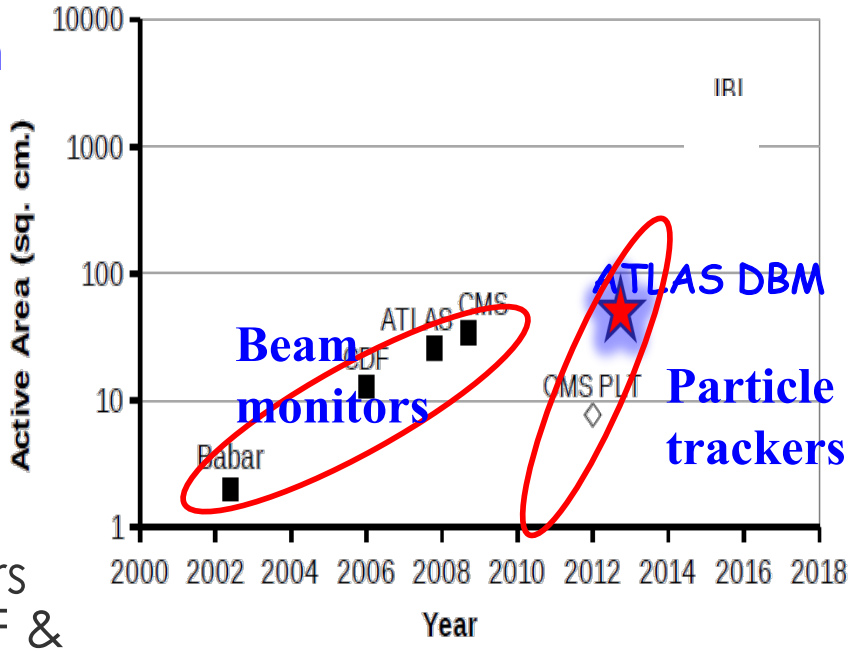
Applications in HEP

Applications in HEP

- Vertex detectors with CVD Diamond are not considered yet as an option for LHC.
- For Beam monitoring CVD Diamond is used at CMS and ATLAS at the LHC.
  - BaBar and Belle test already CVD Diamond in their beam monitoring system.

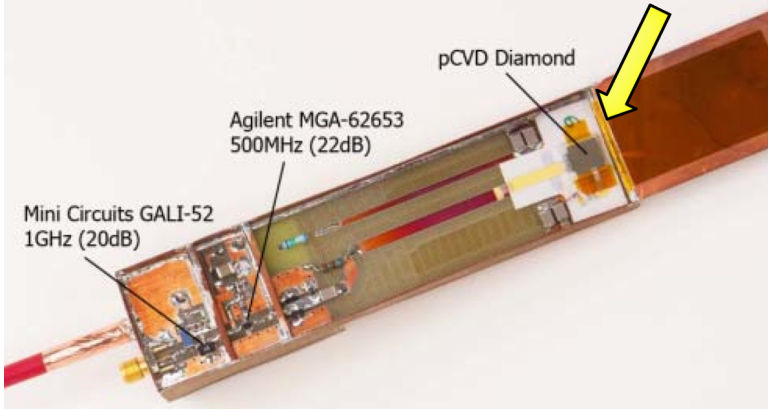
Diamond in current HEP experiments

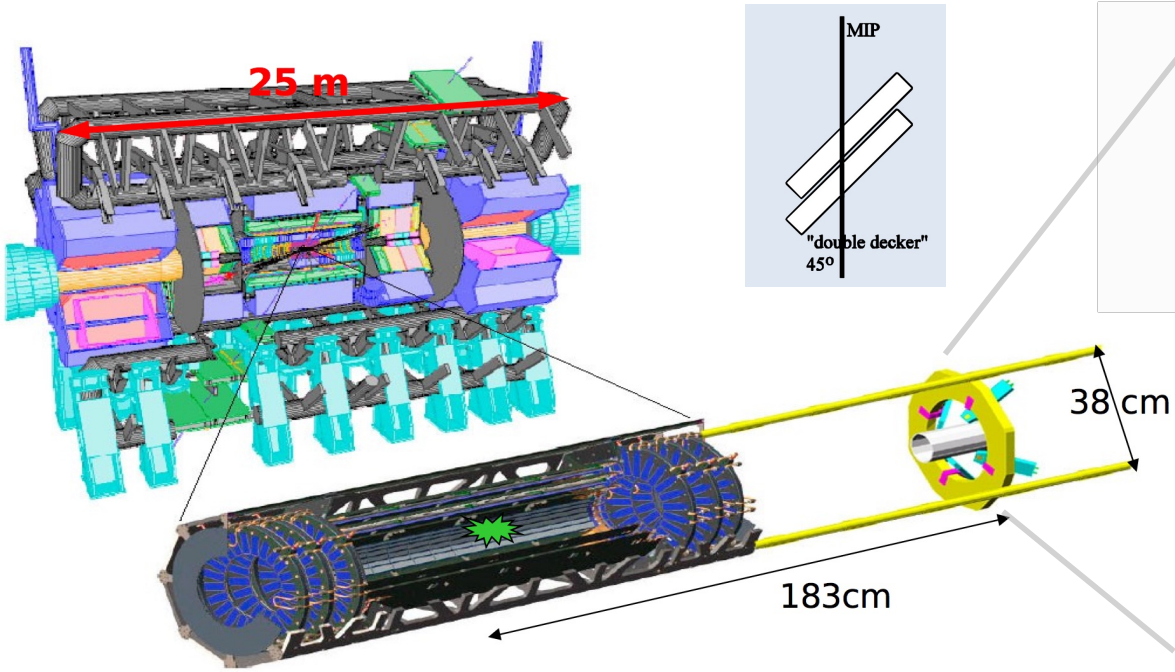
- **Beam monitors** to protect experiments against **beam losses** at the LHC, CERN.
  - For Silicon Vertex systems careful monitoring is crucial.
  - Beam monitors have to be **radiation hard.**
  - Abort beam when monitors signal dangerous beam conditions.
  - False signals must be avoided.
- During run-1 **diamond beam monitors operated** in ATLAS, CMS, and LHCb.
- Previously diamond beam monitors were installed in BaBar(SLAC), CDF & D0 (Tevatron).

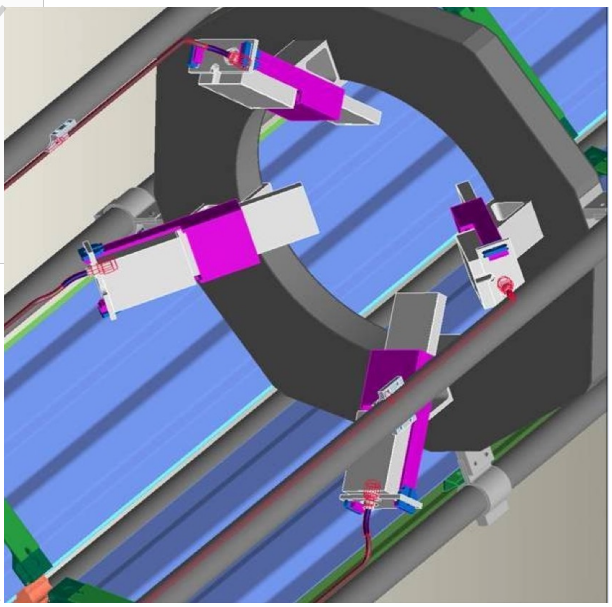


ATLAS beam conditions monitor

- Use 2x polycrystalline CVD diamonds per station (10 x 10 mm).
- 4 stations on each side of the ATLAS pixel detector
  - z = ±183.8 cm (~12.5ns) and r ~ 5 cm

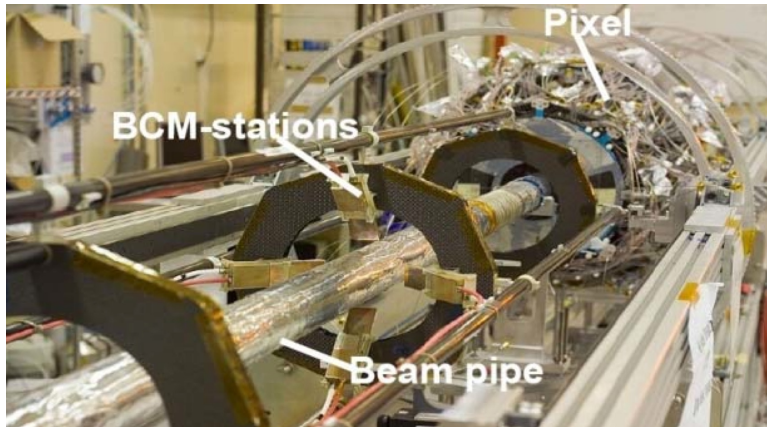


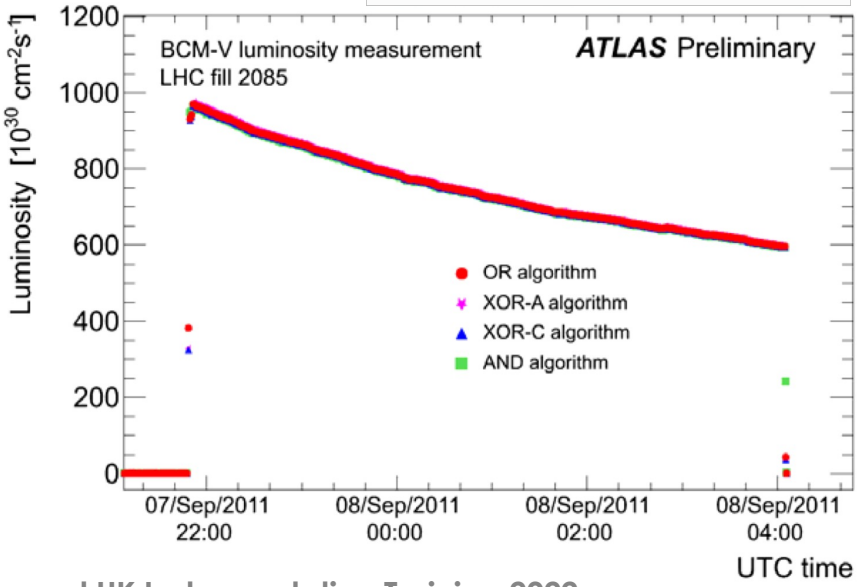


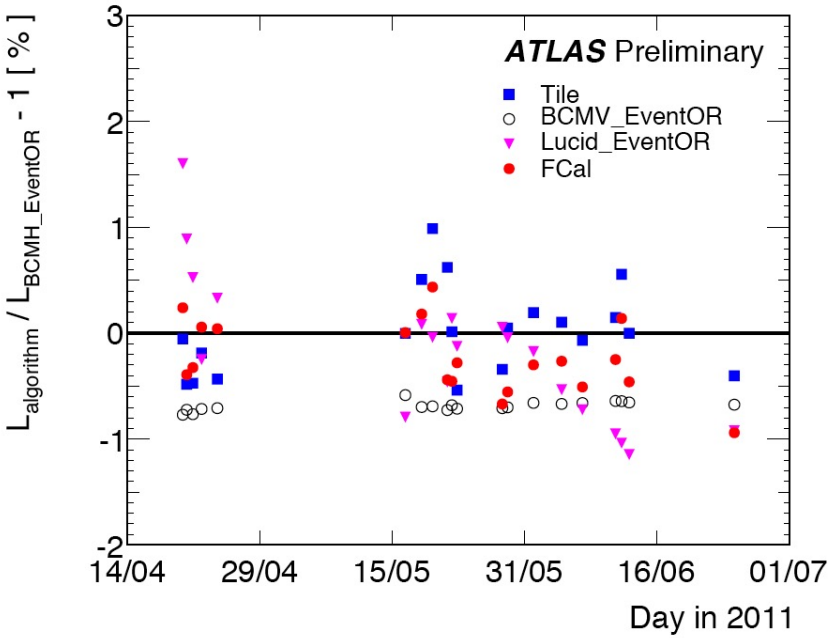


ATLAS beam conditions monitor

- Single particle counting with σ=0.7ns.
  - Distinguish between collision events and out-of-time background.
- Good stability
  - Used for luminosity determination.

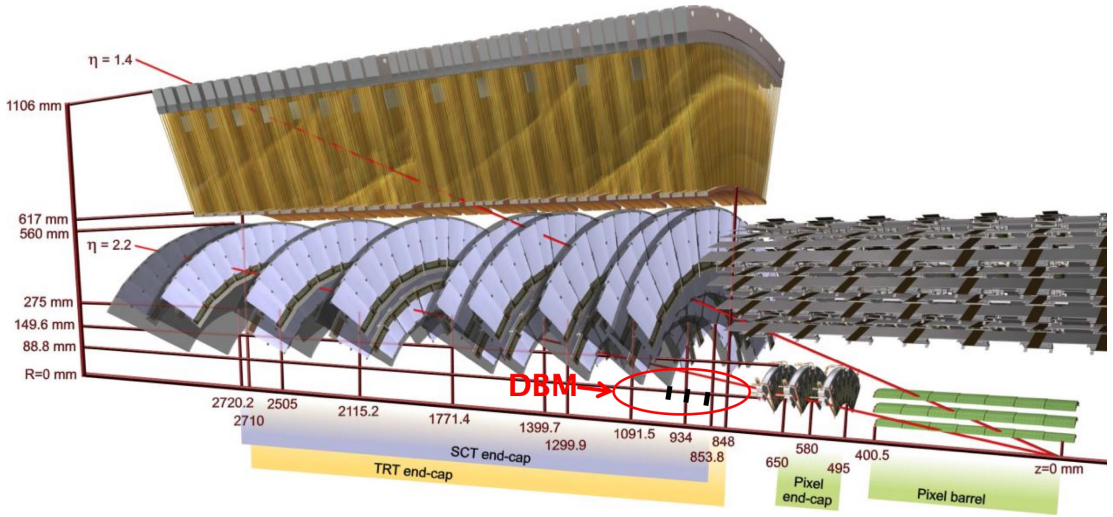






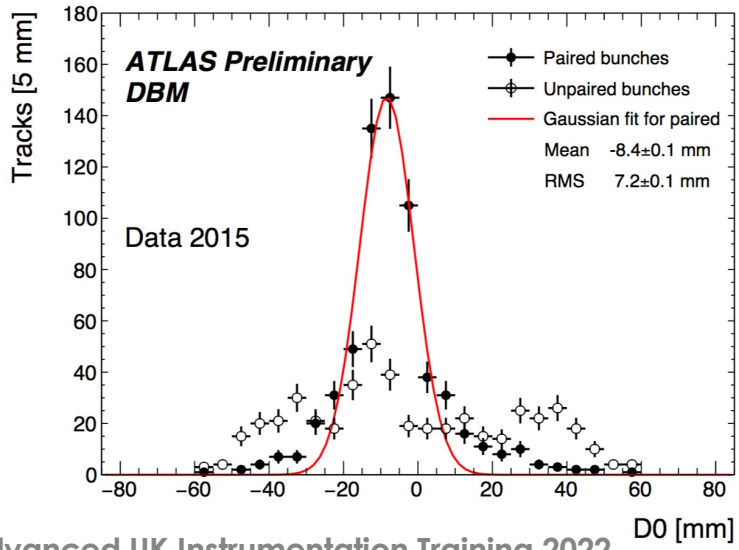
Run 2: ATLAS Diamond Beam Monitor

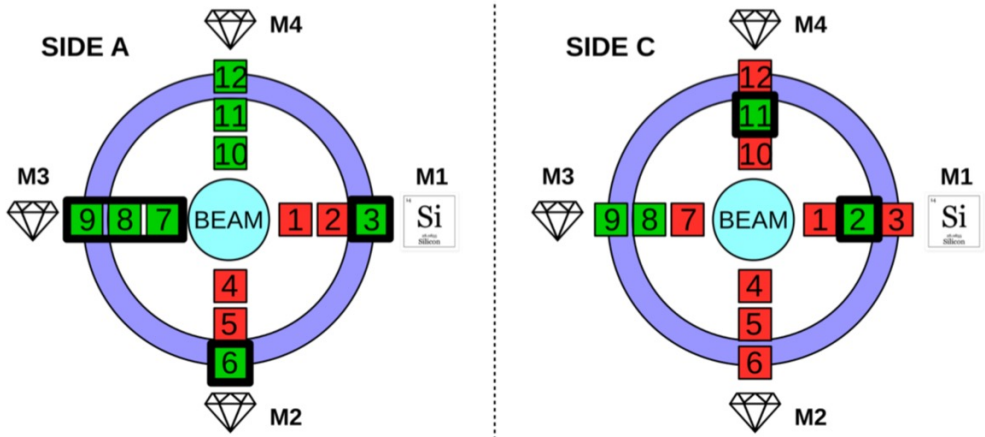
- 8 mini-trackers of 3 planes each using pixel-detectors.
- polycrystalline diamond sensors, 18mm x 21mm, δ>250μm.
- bump-bonded to FE-I4 pixel read-out chip.
  - 336 x 80 pixels
  - pixel size : 50μm x 250 μm
- Purpose:
  - Bunch-by-bunch luminosity monitor (aim < 1 % per BC per LB)
  - Bunch-by-bunch beam spot monitor



Run 2:
ATLAS Diamond Beam Monitor

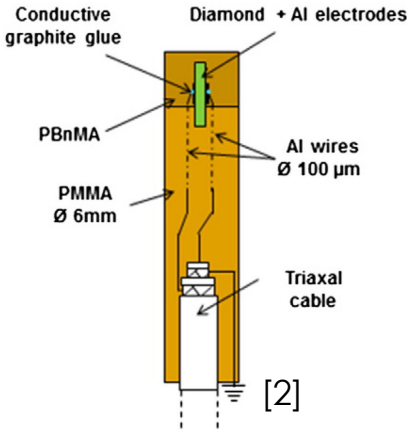
- Installed in ATLAS during LS1, but switched off due to unexpected death of Si and Diamond modules.
- DBM recommissioned in 2017/18 with 50% working modules.





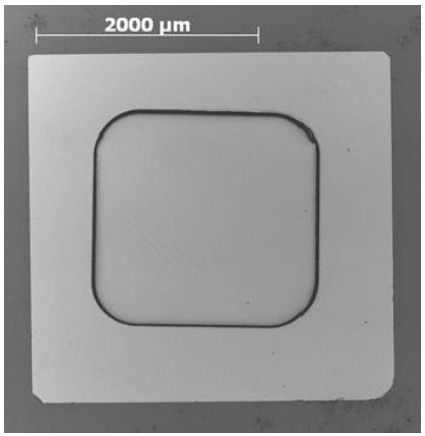
Examples of diamond detectors in related areas

- Synchrotron labs
  - beam position monitor
- Radiation Therapy
  - small field dosimetry
- Heavy Ion (GSI, FAIR)
  - beam diagnostic
  - particle tracking and TOF
  - hadron spectroscopy



[2]

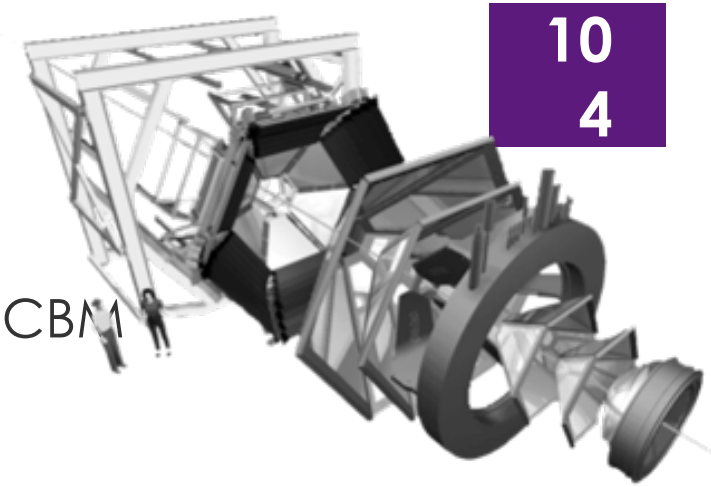
scCVD dosimeter, 0,4 mm^3 active vol. [2]



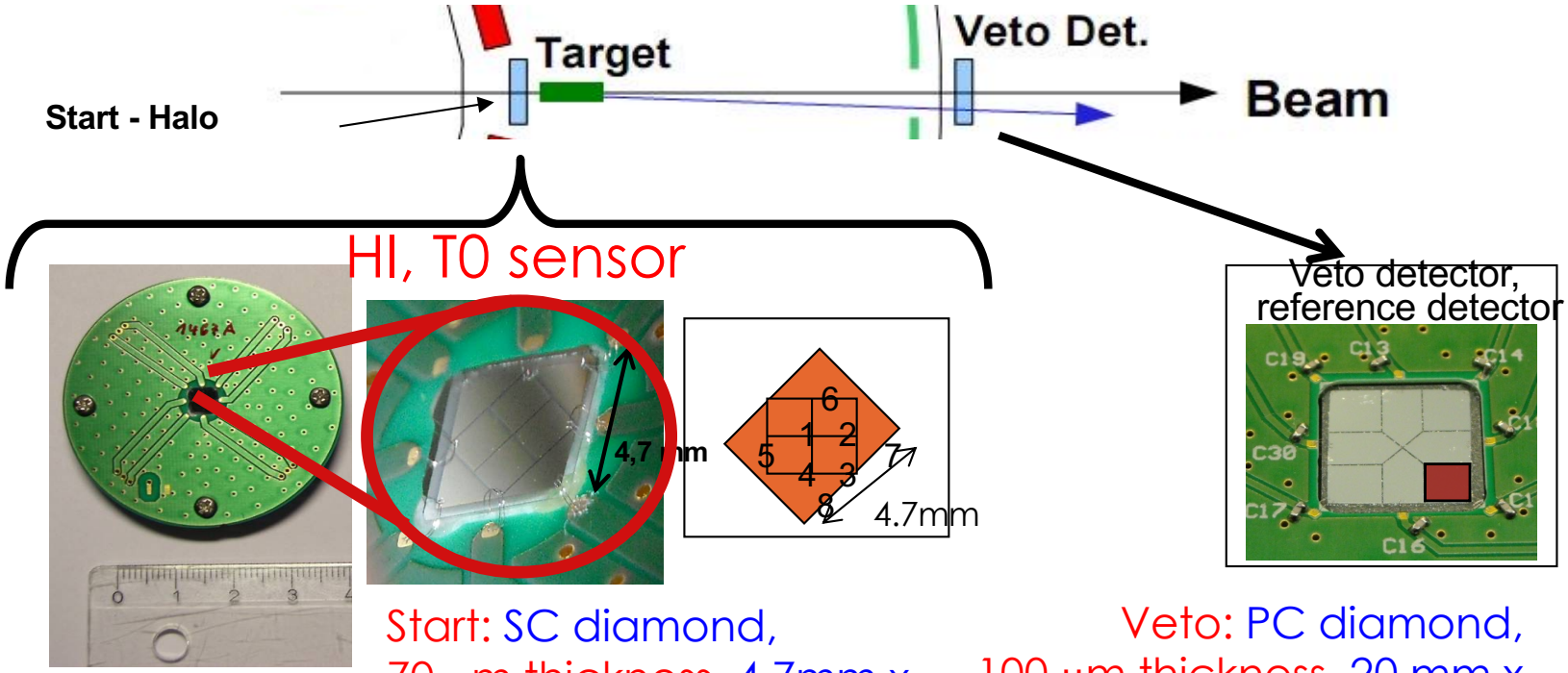
3 µm thick membrane in 40 µm thick scCVD [1]

[1] M. Pomroski, CEA-LIST, MRS Fall meeting, Boston 28/11/2012
[2] F. Marsolat et al. / Diamond & Related Materials 33 (2013) 63–70

Detectors for Heavy Ion



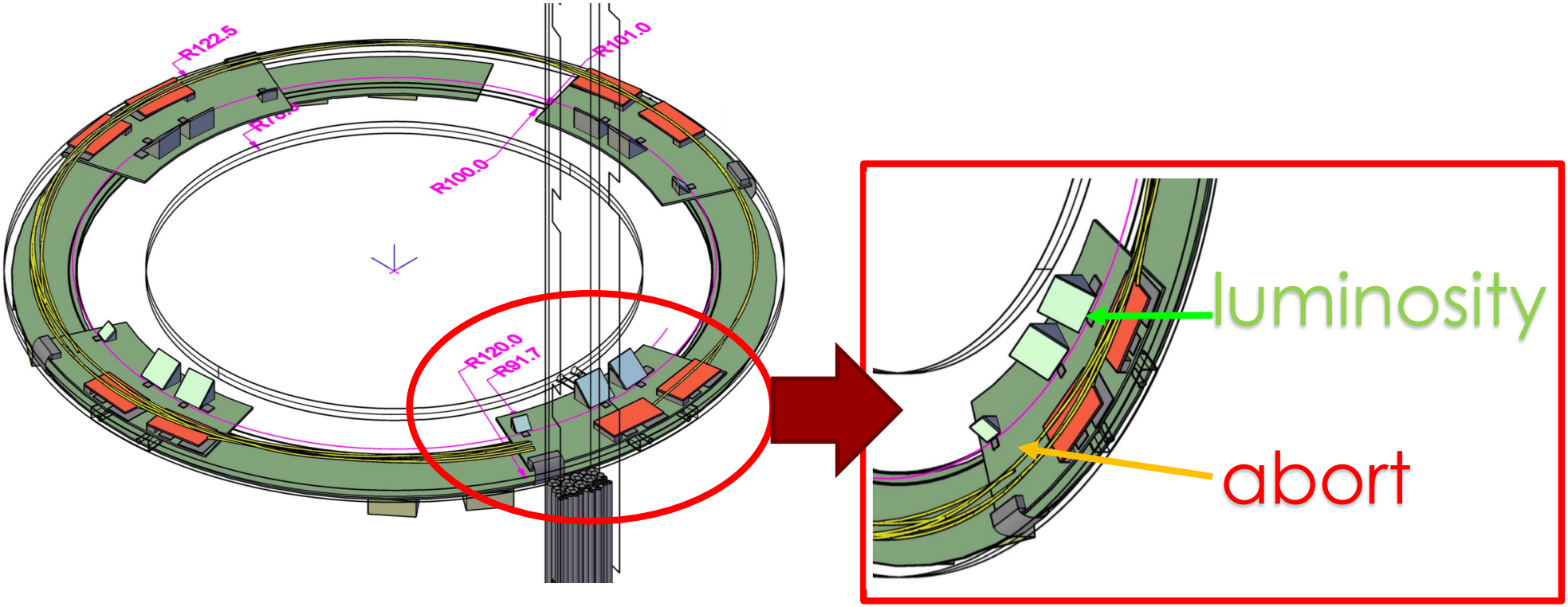
- In-beam START-VETO detectors for HADES and CBM
  - High beam intensities (10^7 #/s).
  - Protons (MIPS) up to very heavy ions (Au, U)
  - Excellent time resolution (30-100 ps)
  - Radiation hard up to 10^{12} /cm Au ions



Start: SC diamond, 70 μm thickness, 4.7mm x 4.7mm

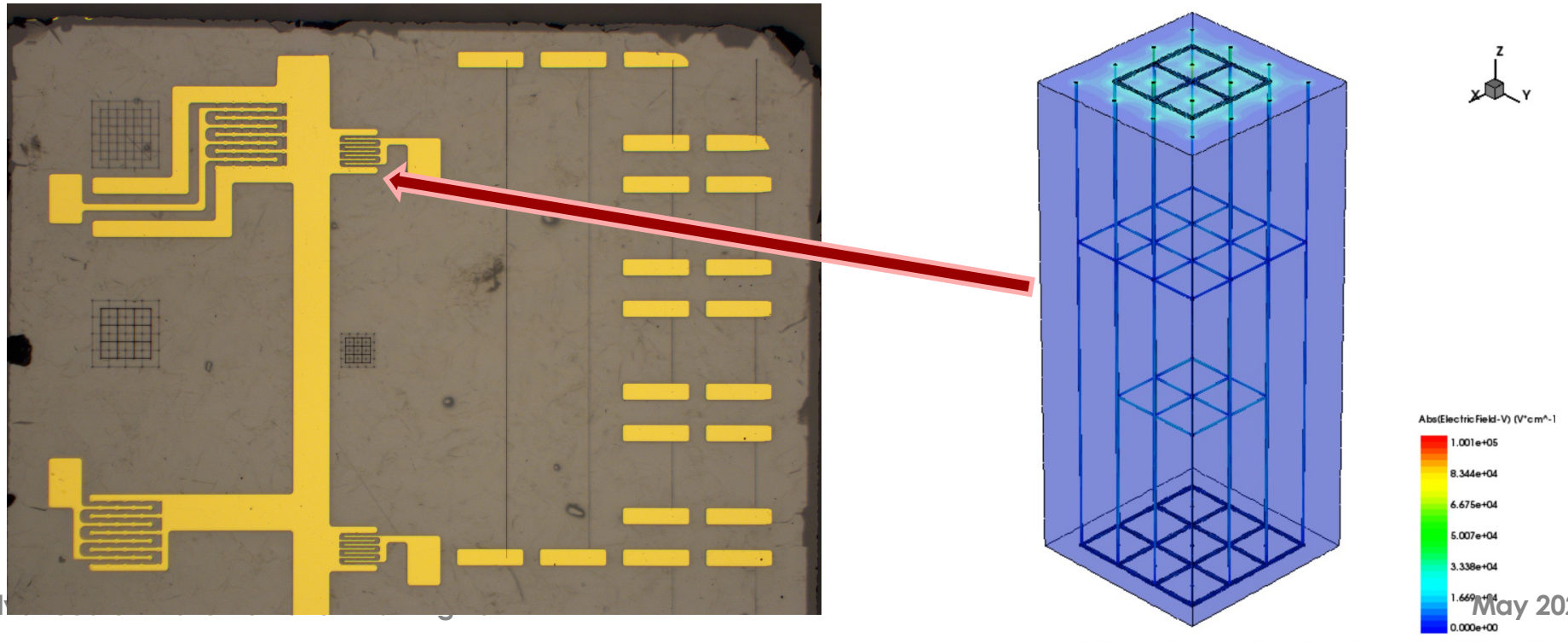
Veto: PC diamond, 100 μm thickness, 20 mm x 20 mm

Upgrade for LHC Phase-2: BCM' modules



First BCM' 3D test structure with new "cage" design

- Fabricated March 2020 (~week of UK Lockdown) first 3D diamond device with horizontal ganging
- Test structure has horizontal wires at depths of 125 and 375 µm in a 500 µm thick substrate (ρ measurement)
- Metallised 3D detector with alternating ganging (~model) read out in current mode in **RD42 Zagreb Testbeam 06-2021, second version tested April 2022**



Summary

- Diamond systems are used as beam and luminosity monitors in current HEP experiments and foreseen for future experiments.
- Radiation hardness and rate dependence has been studied.
- 3D diamond has been demonstrated to work.
- The understanding of diamond as a detector material is advancing.

EXTRA MATERIAL

3D Detector Characterization

- Proton Micro-beam: 4.5 MeV p

Proton micro-beam measurements

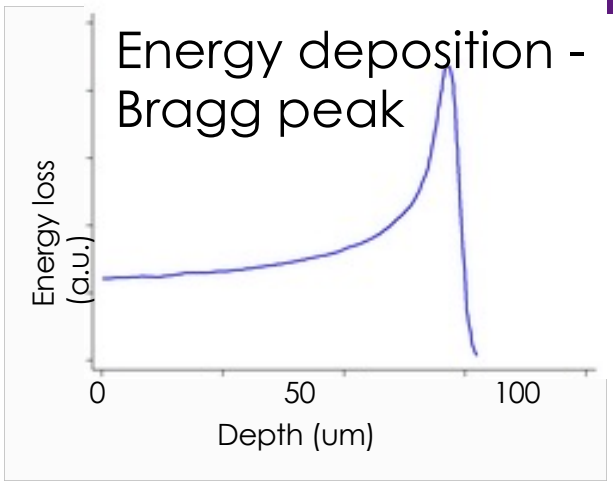
MANCHESTER 1824

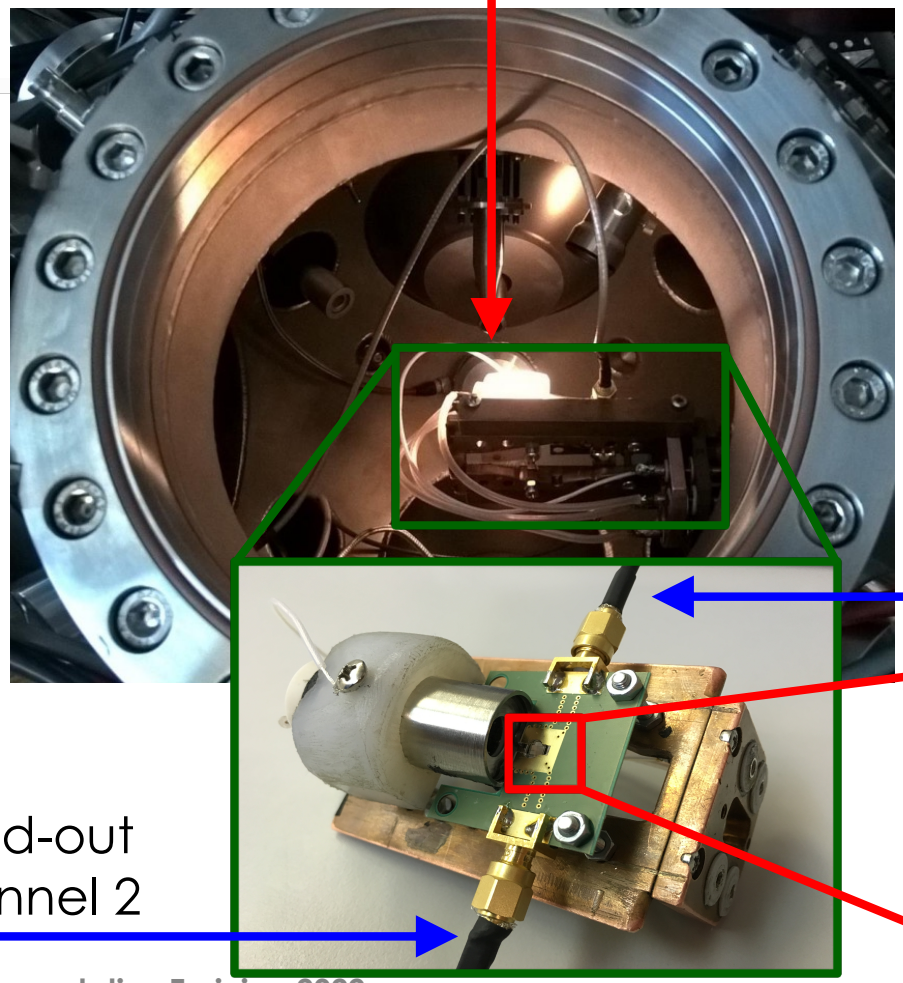
The University of Manchester

Ruđer Bošković Institute

AIDA 2020

4.5 MeV protons

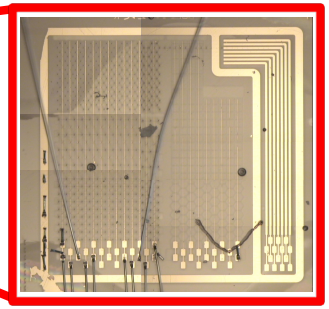




- Single particle beam.
- Rate ~ 1kHz.
- Beam position resolution < 2μm.

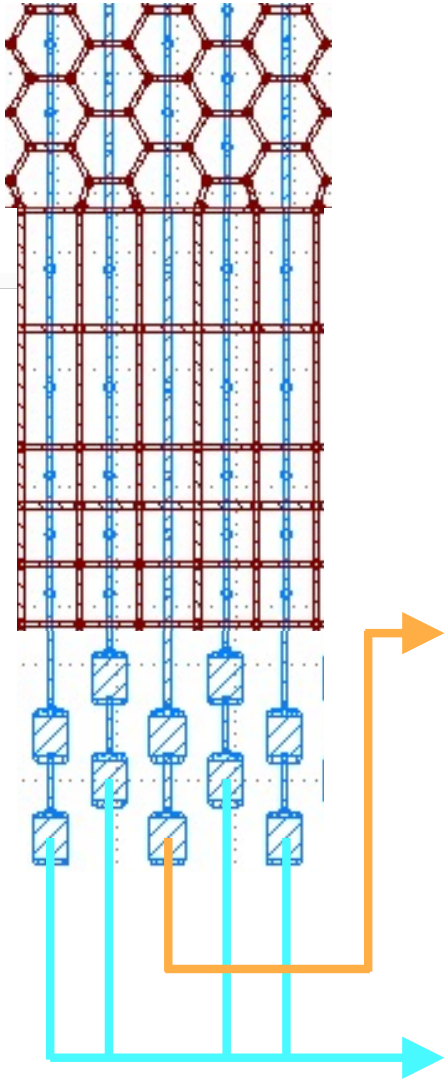
Read-out channel 1

Read-out channel 2

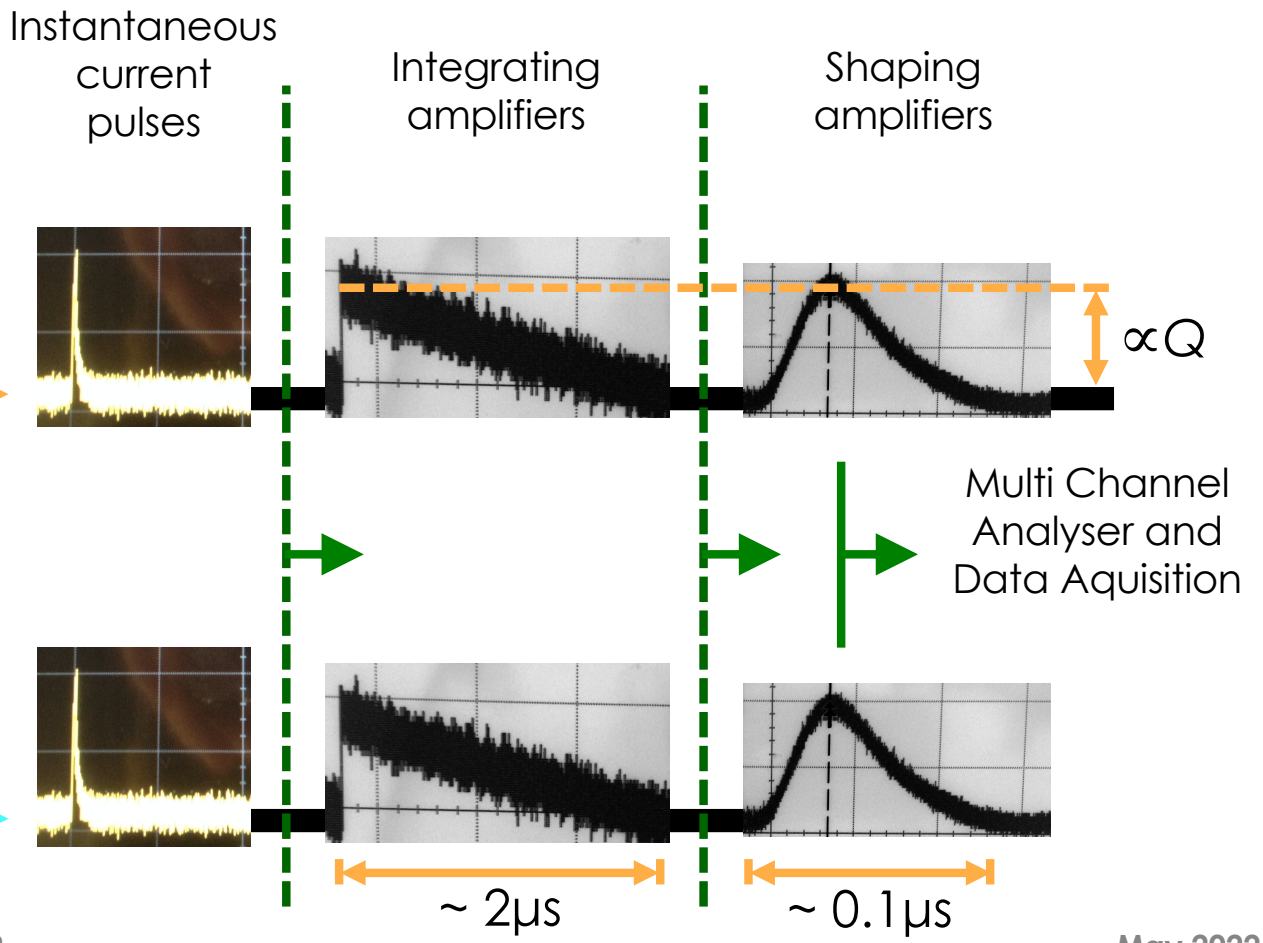


3D diamond detector

IBIC - setup



- Two read-out channels and amplification chains.



Proton micro-beam measurements

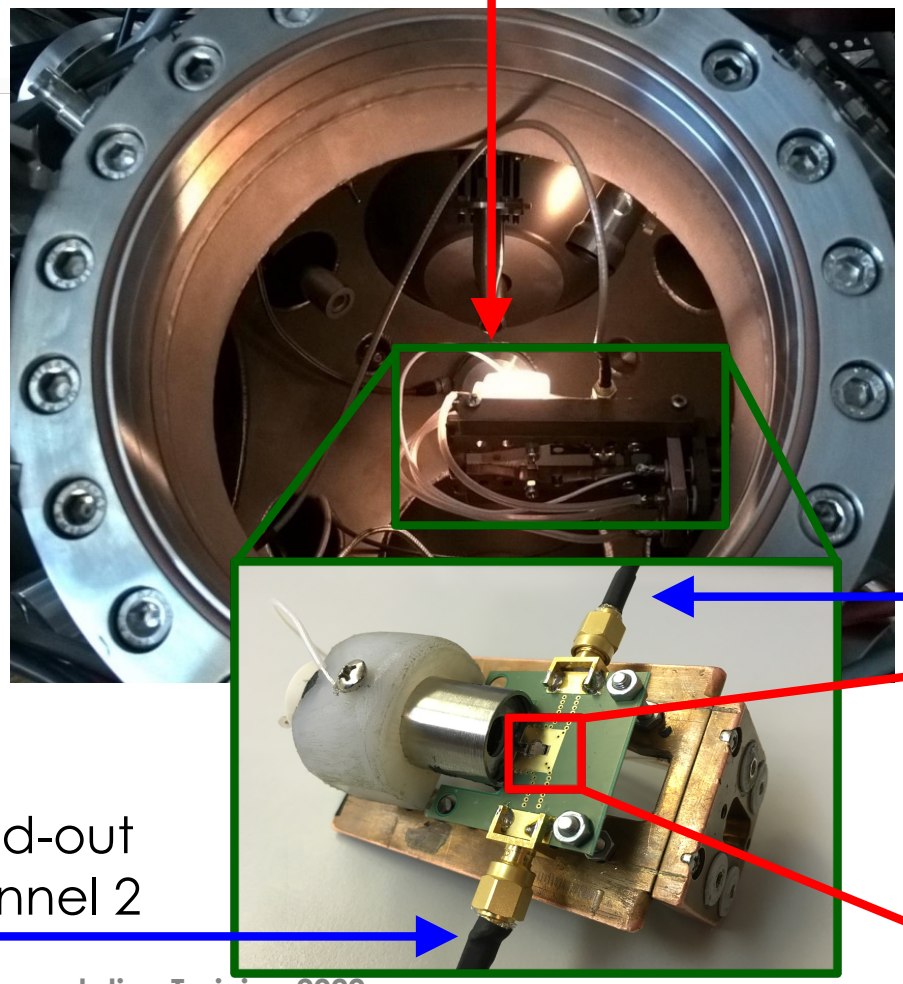
The University of Manchester

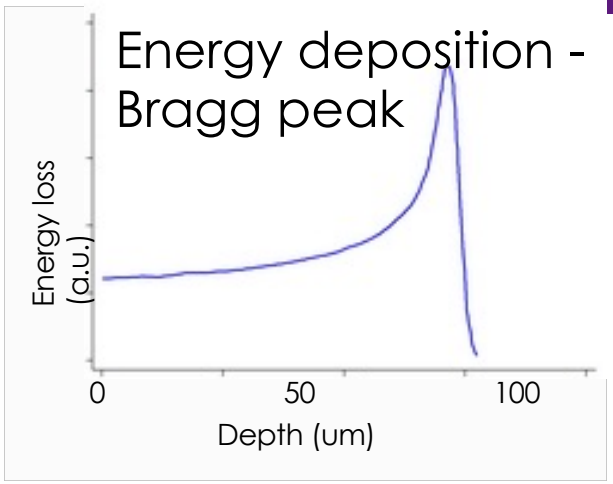
MANCHESTER 1824

Ruđer Bošković Institute

AIDA 2020

4.5 MeV protons





- Single particle beam.
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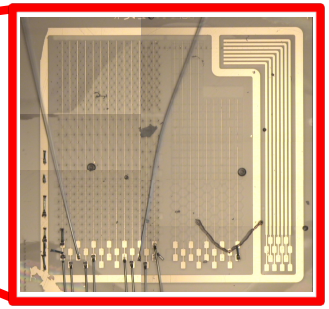
Read-out channel 1

Read-out channel 2

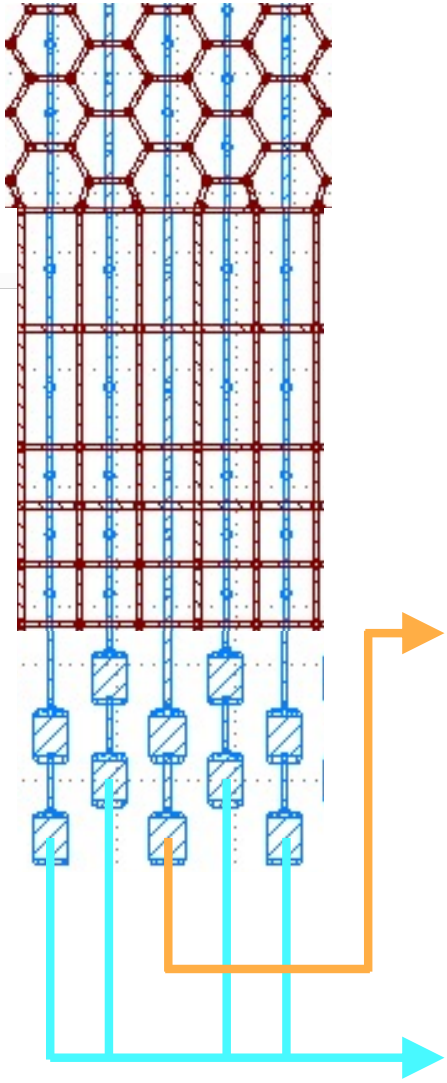


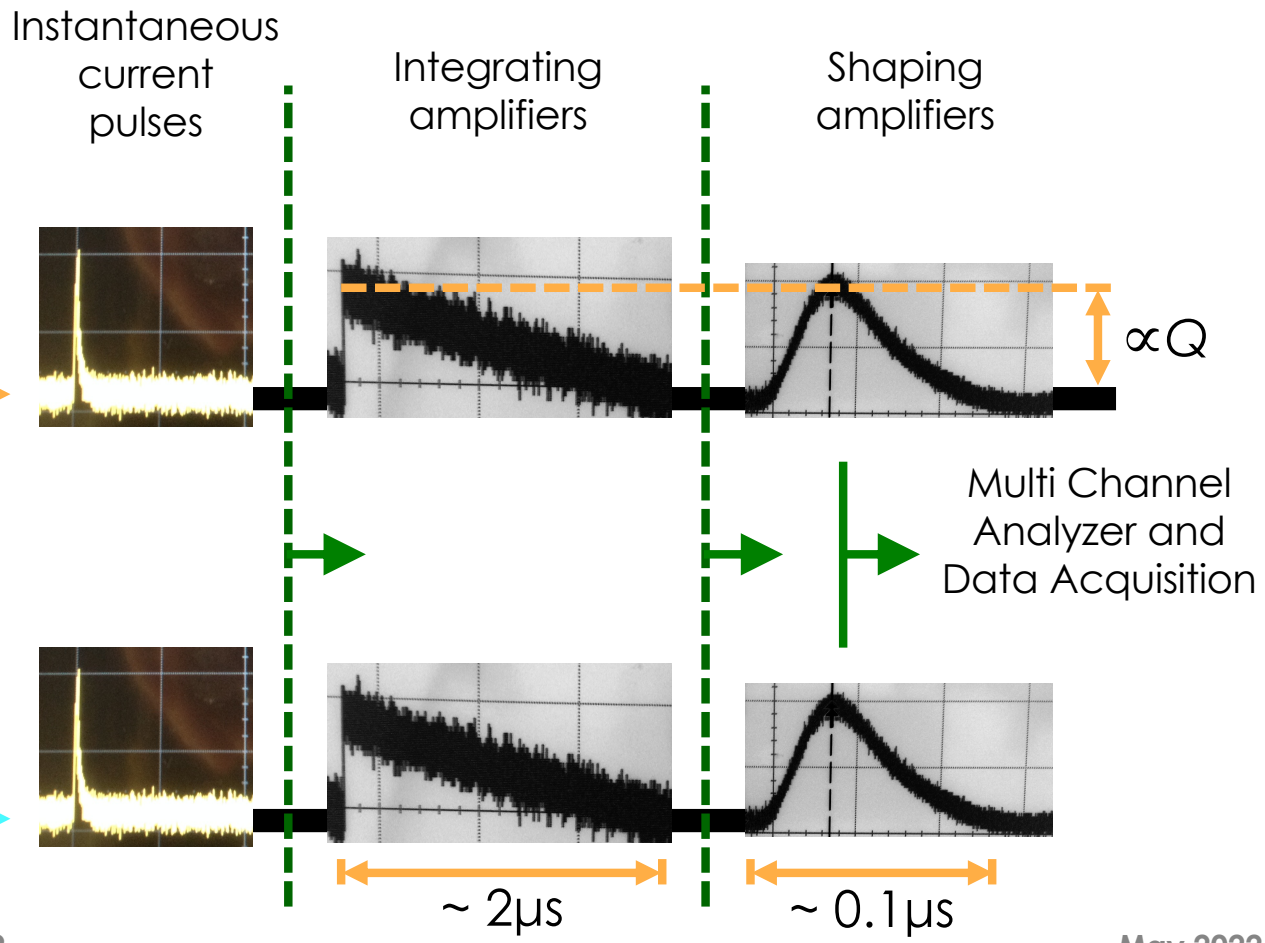
3D diamond detector

(TR)IBIC

(Time Resolved) Ion Beam Induced Current

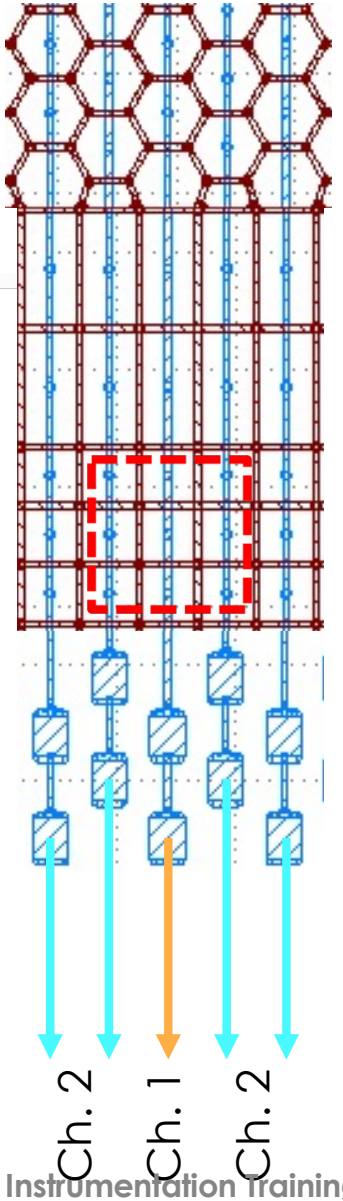
- Two read-out channels and amplification chains.



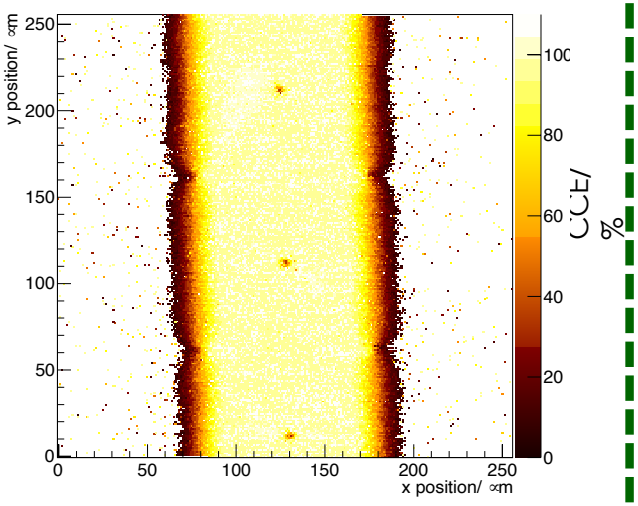


Signal efficiency at +20V

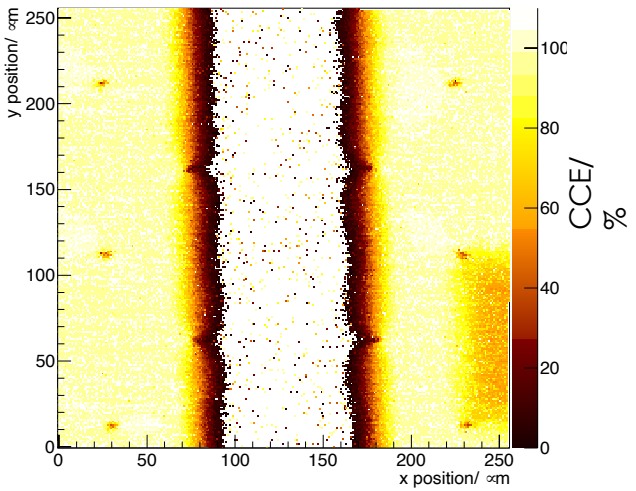
- Electronics chain calibrated with silicon detector.



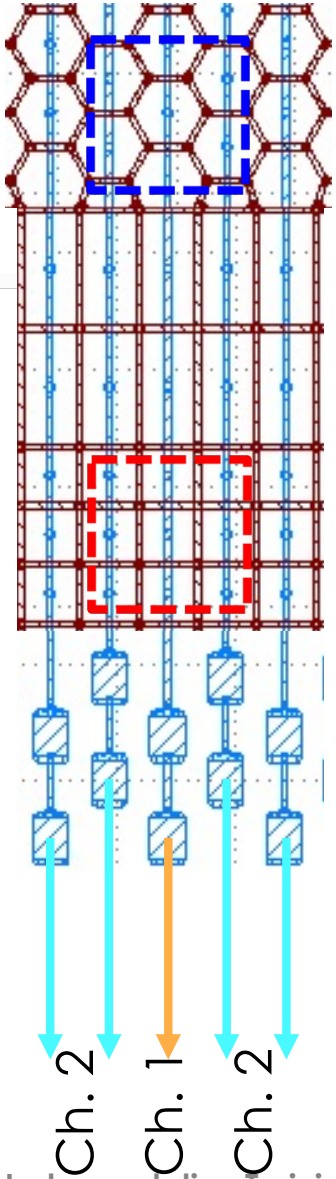
Channel 1



Channel 2



Charge sharing

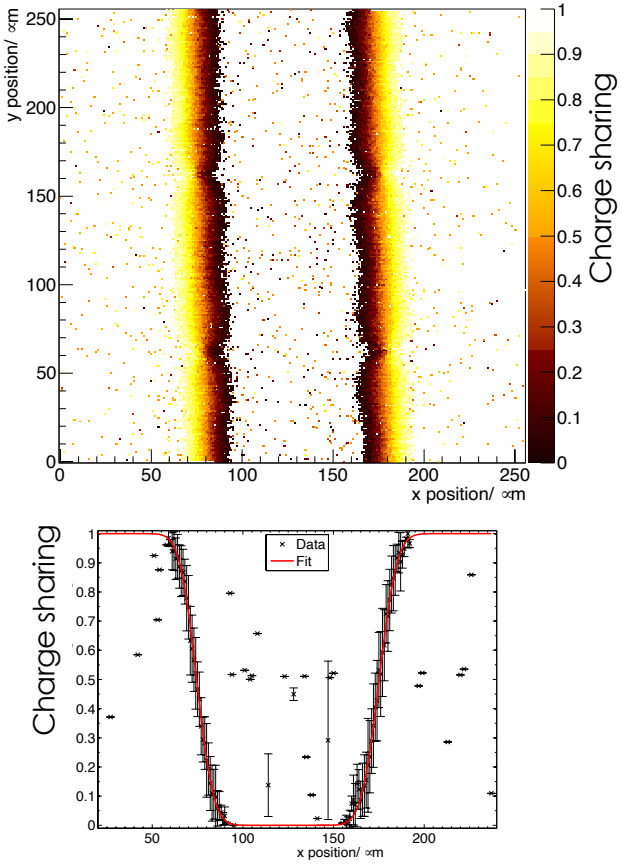


Charge Sharing

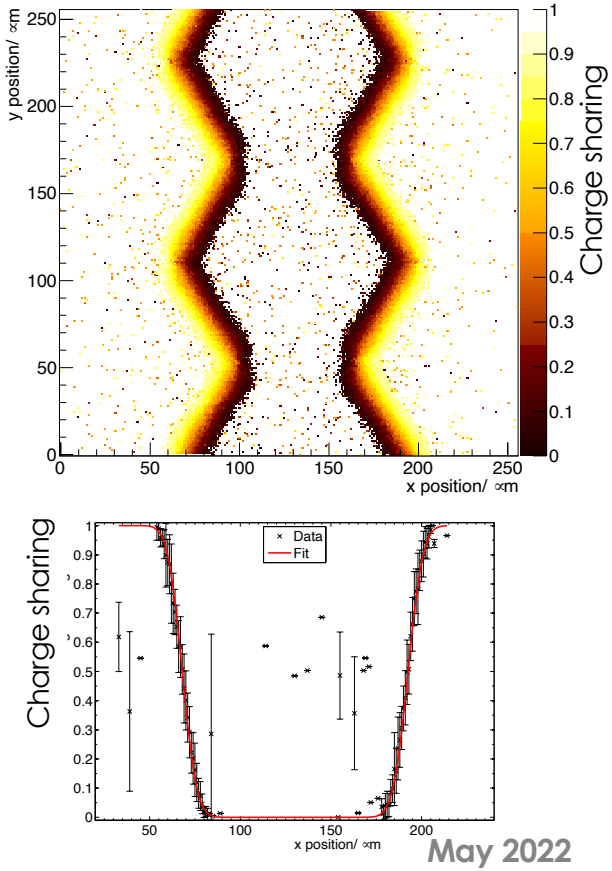
$$\rho = Q_2/(Q_1+Q_2)$$

Induced charge on Ch. 2 — Induced charge on Ch. 1

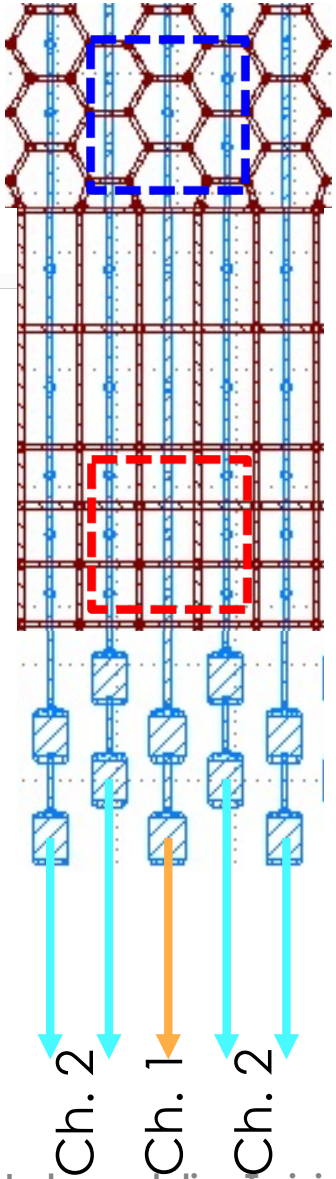
Square

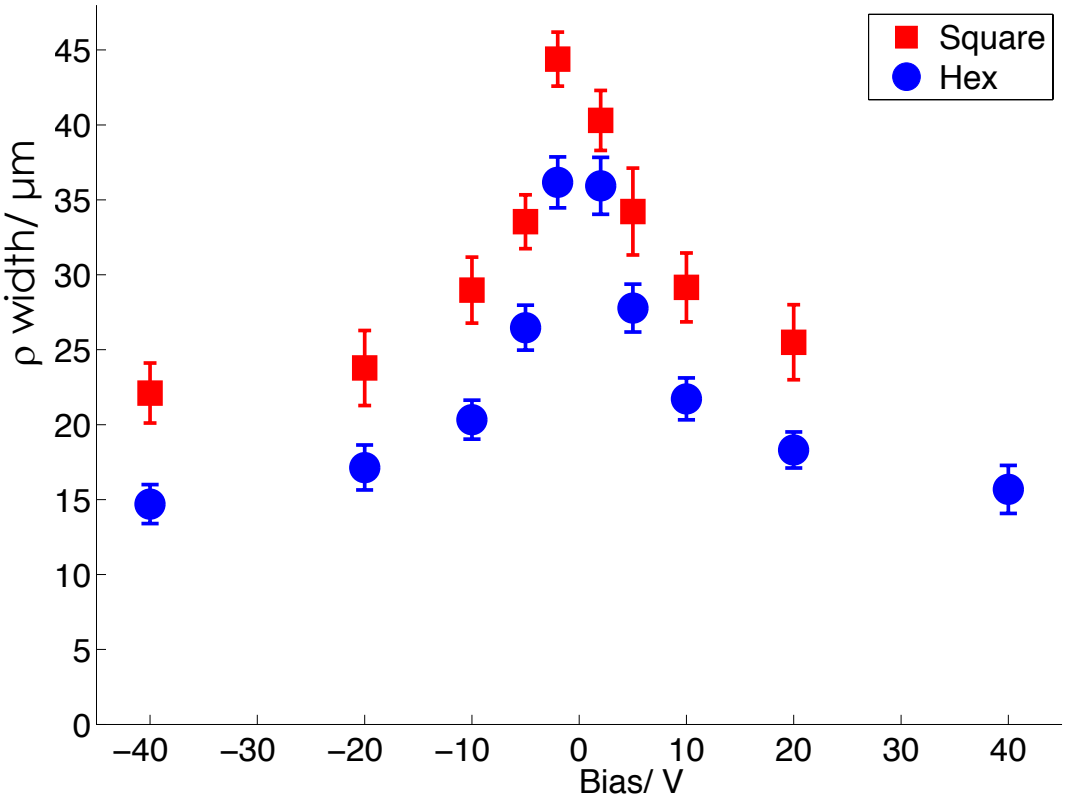


Hexagonal

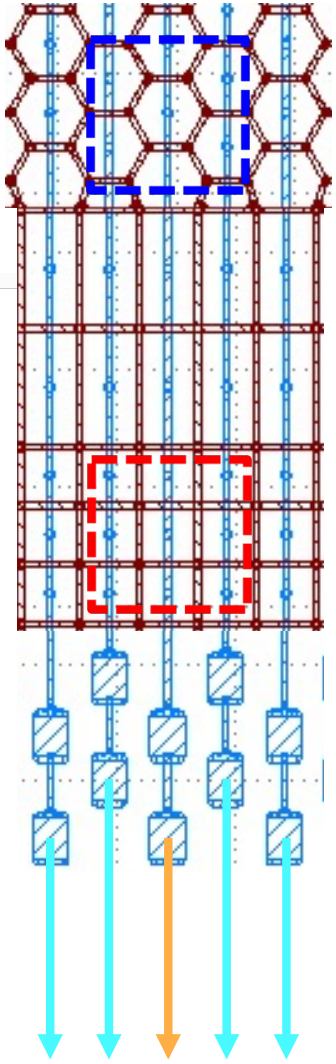


Charge sharing comparison



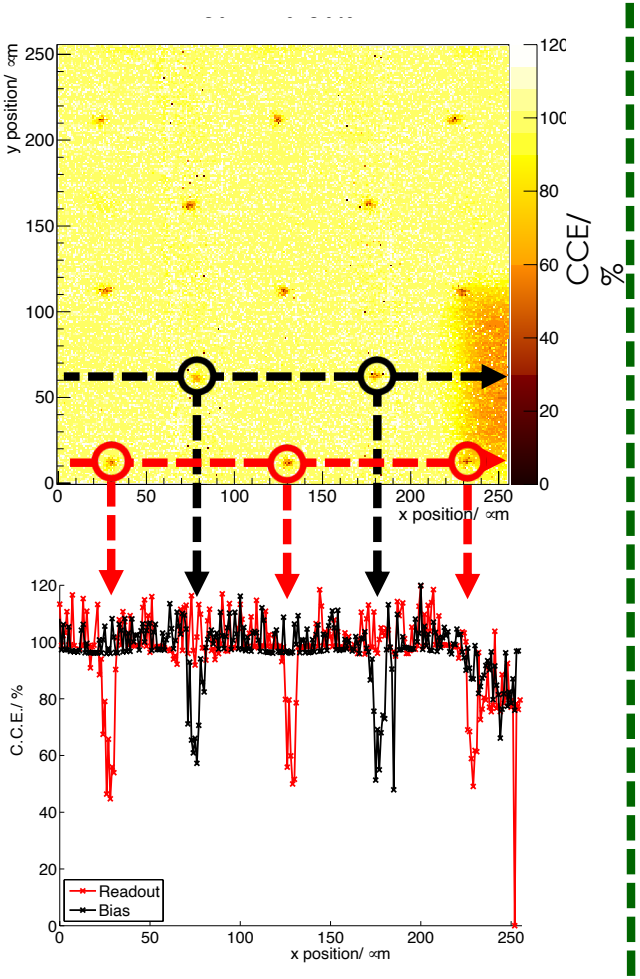


Combined Ch. 1 and Ch. 2 at +20V

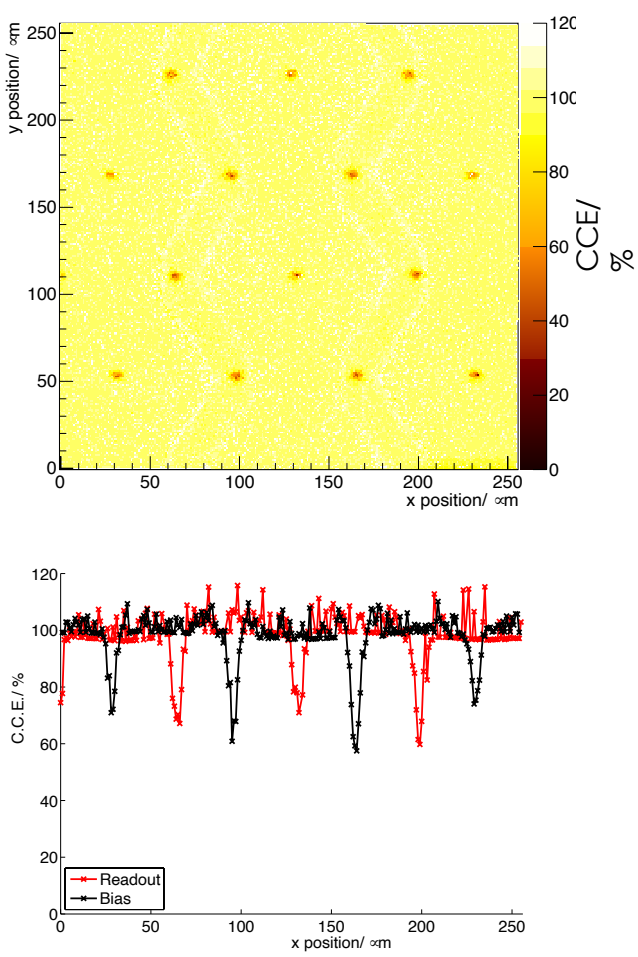


Combine

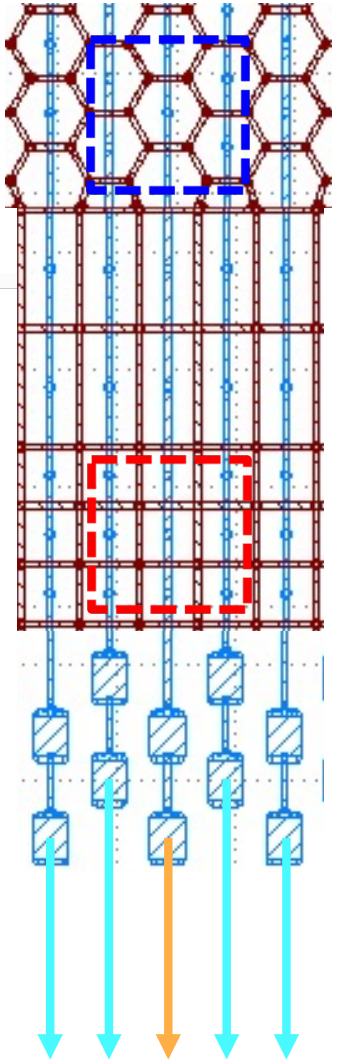
Square



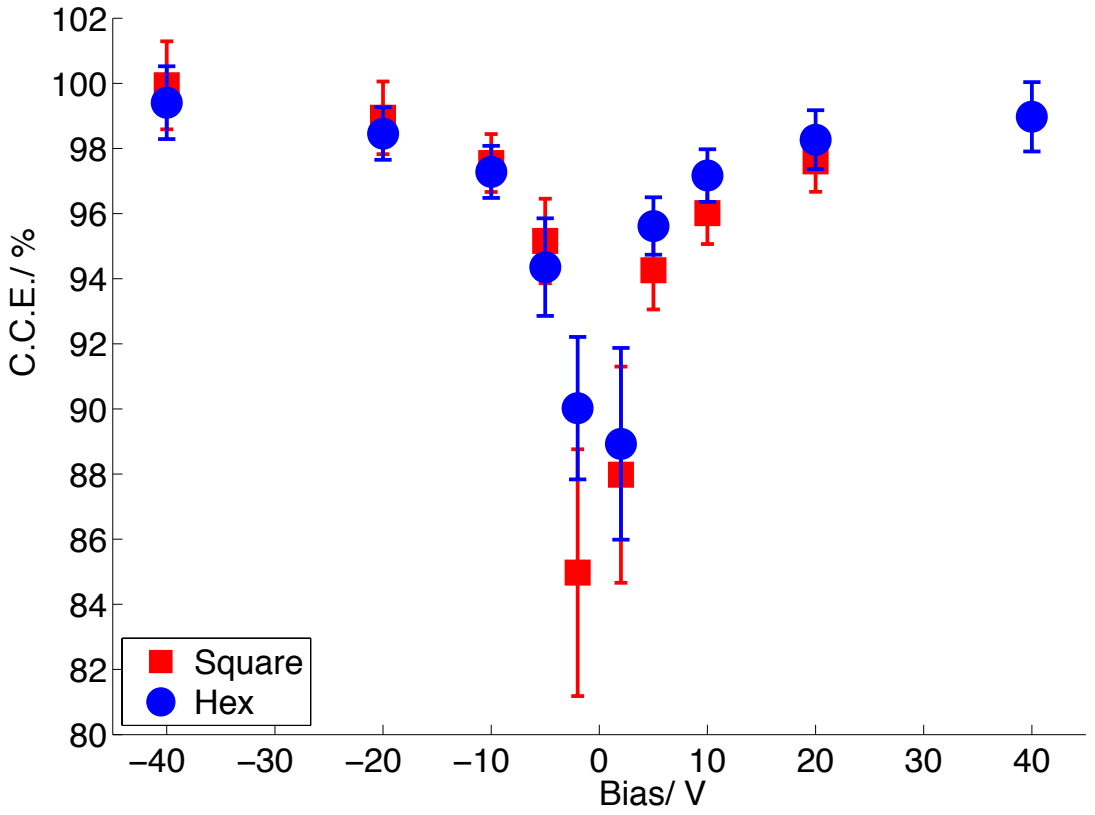
Hexagonal



Signal efficiency comparison



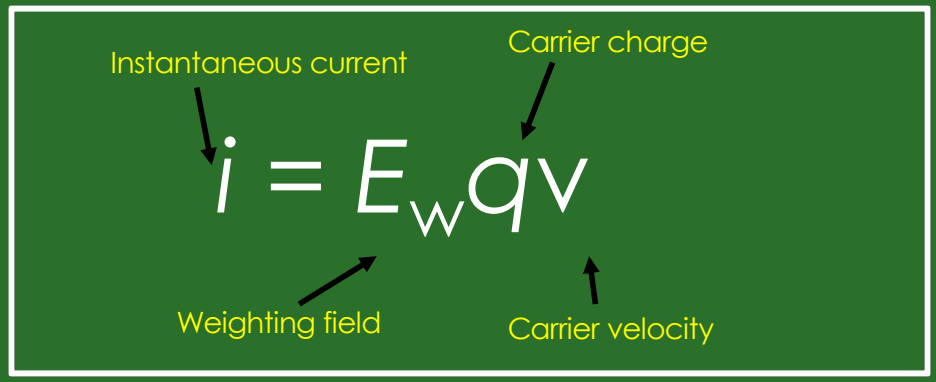
Combine



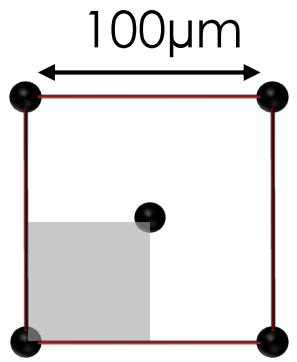
Summary IBIC

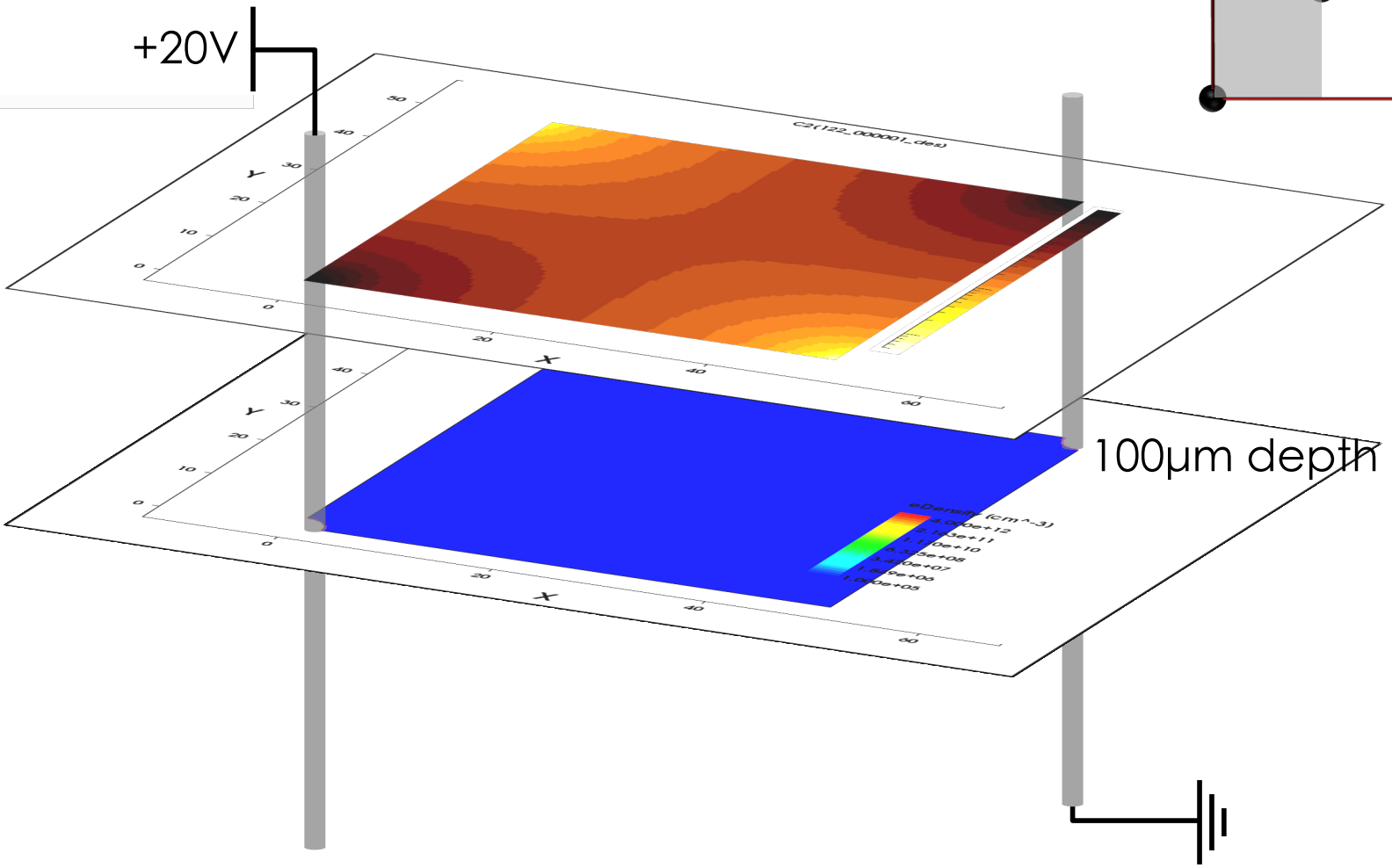
- Measured the Signal Efficiency versus position.
- Both geometries show > 98% CCE above 20V.
- There is a measured drop in signal due to columns of diameter ~ 6µm.
- A small region of charge sharing, ~ 20µm, is observed in both geometries.

Time Resolved IBIC (TRIBIC)

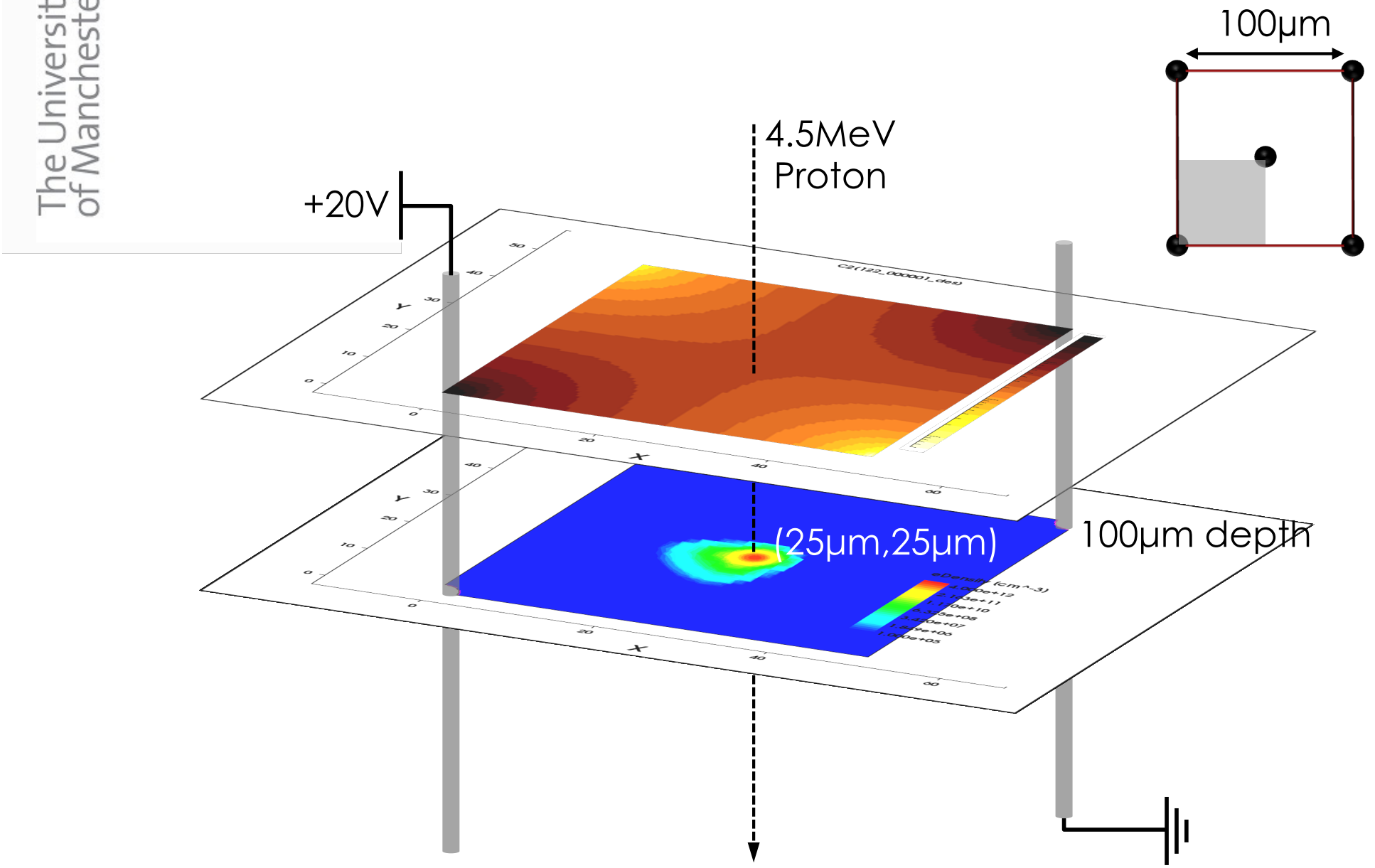


Simulation

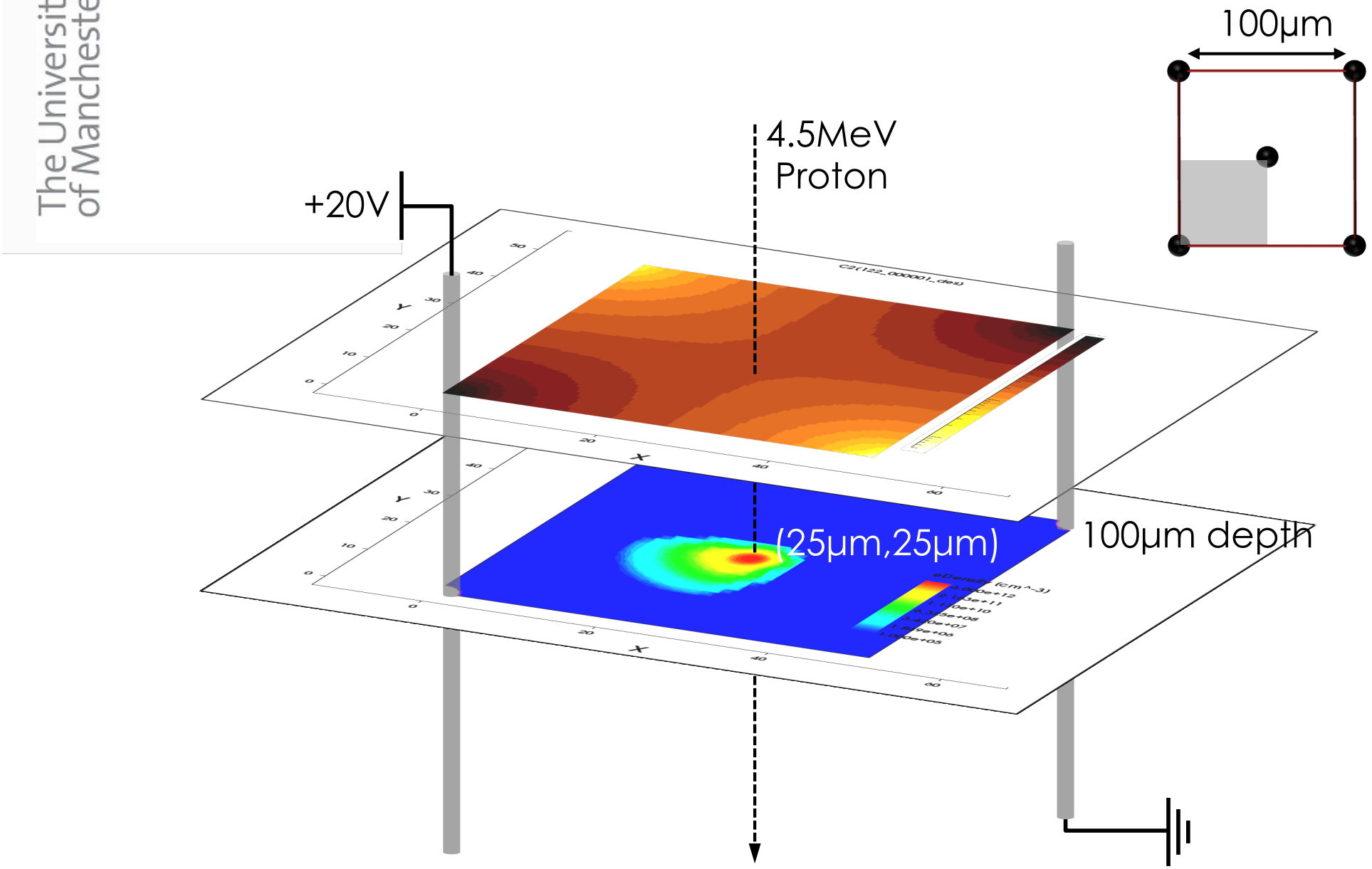




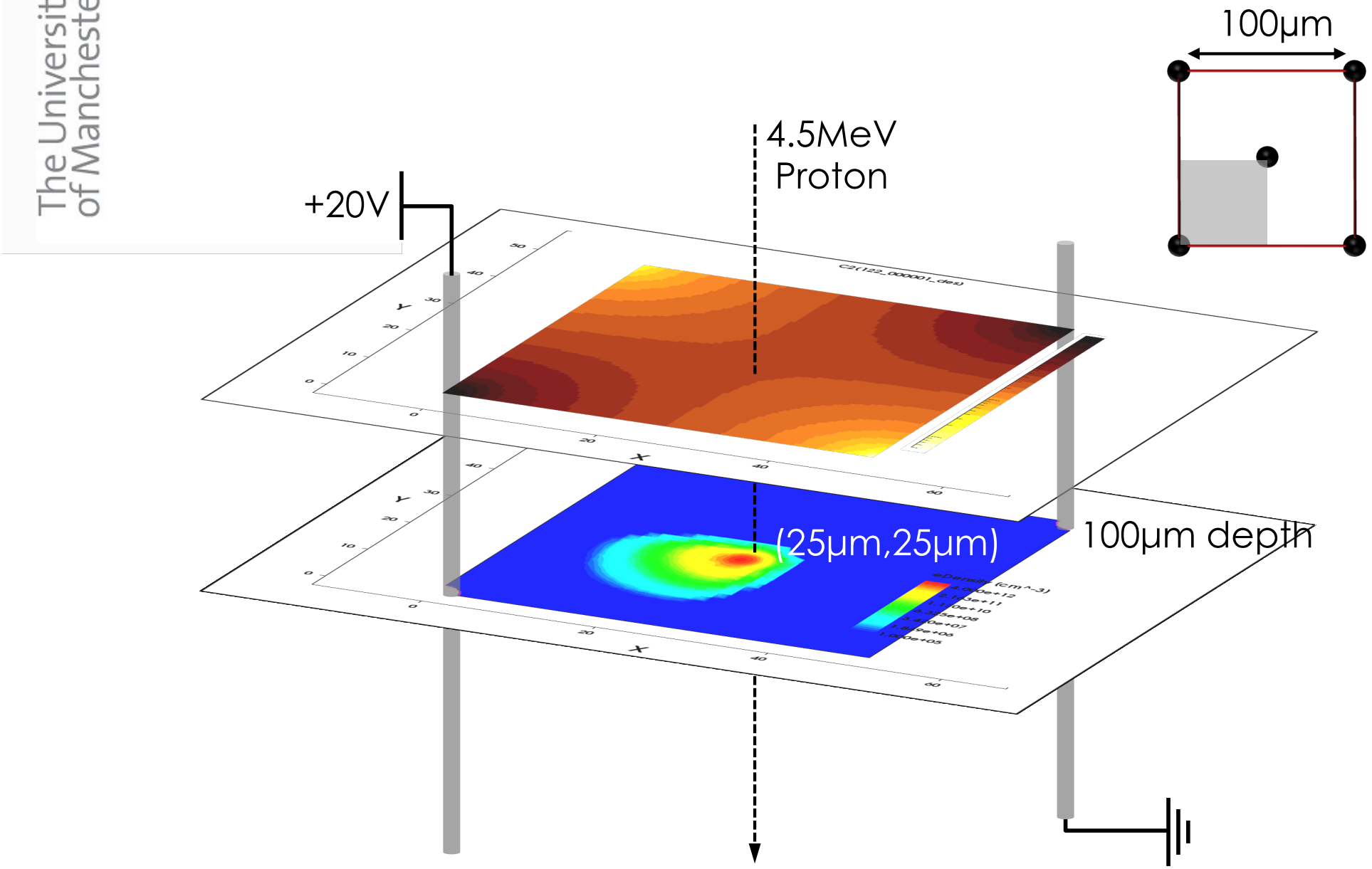
Simulation



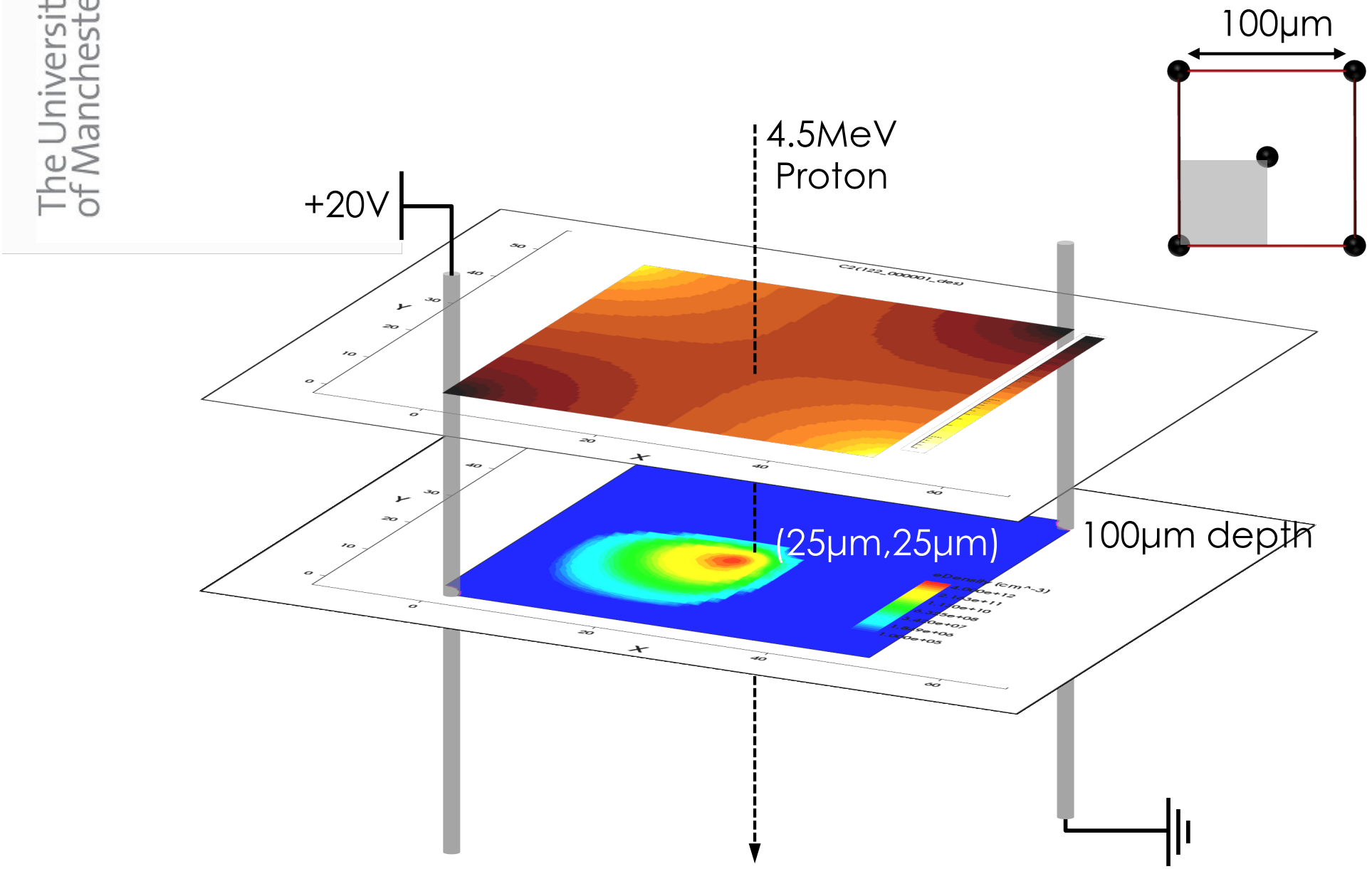
Simulation



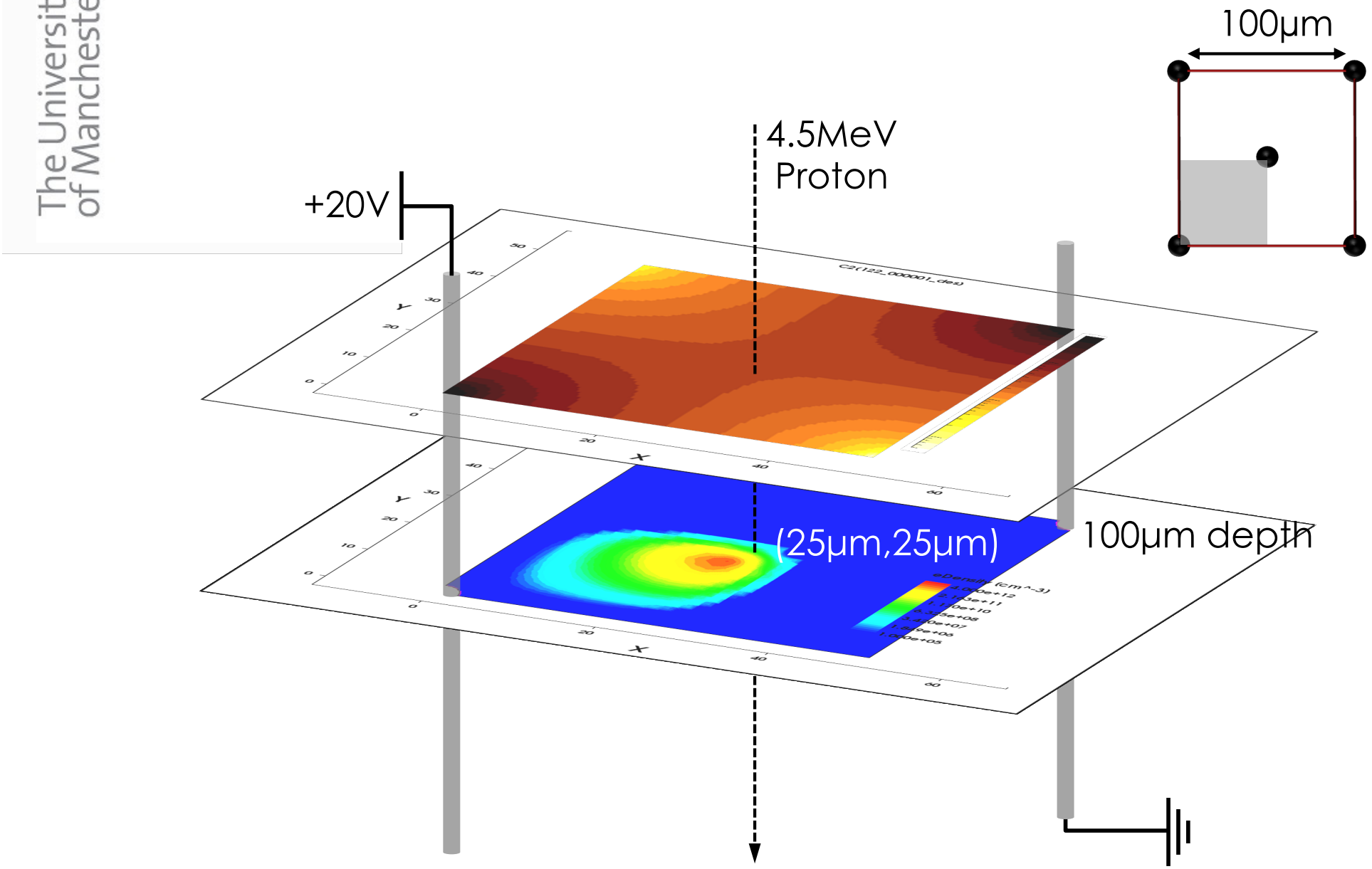
Simulation



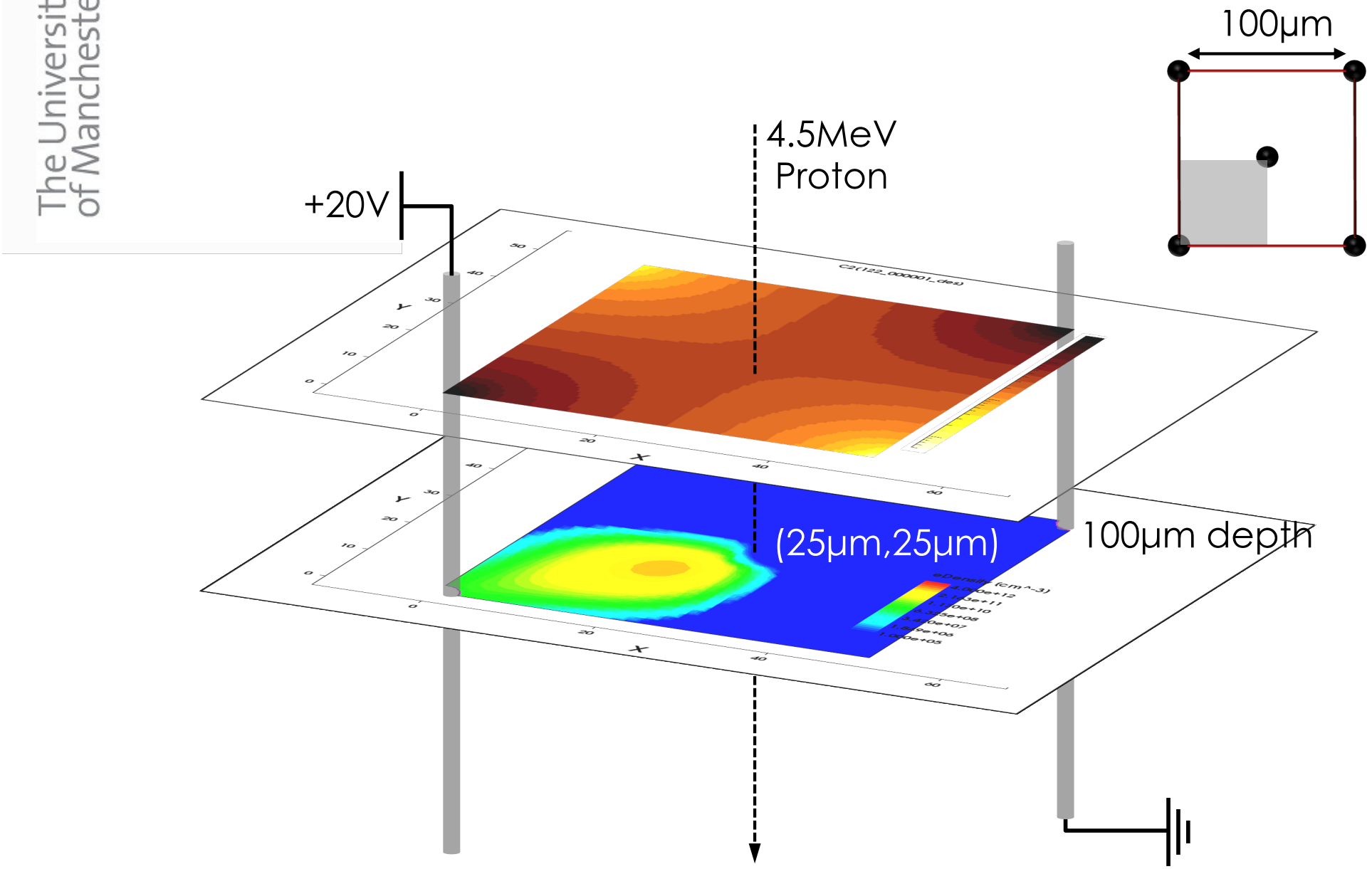
Simulation



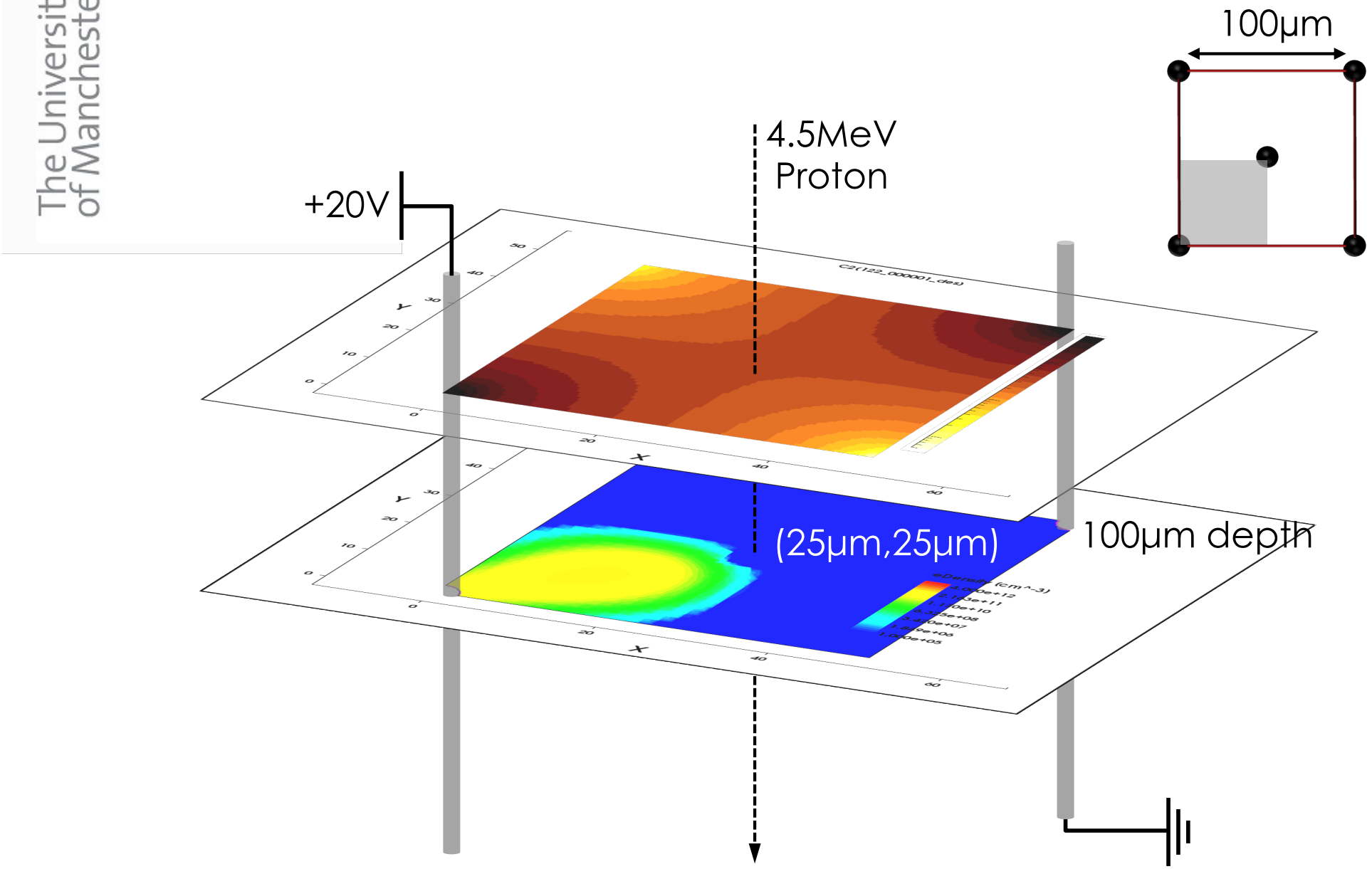
Simulation



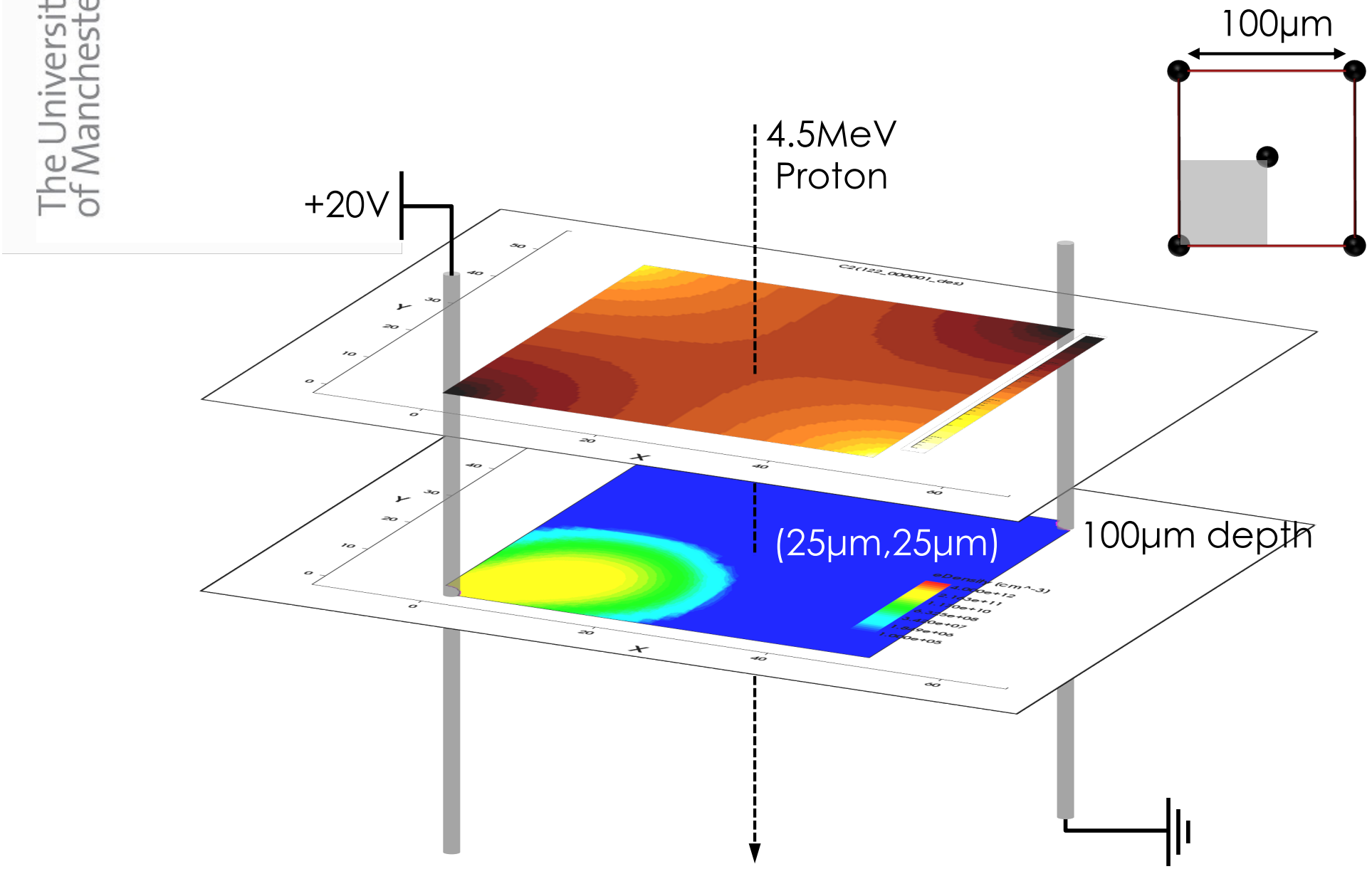
Simulation



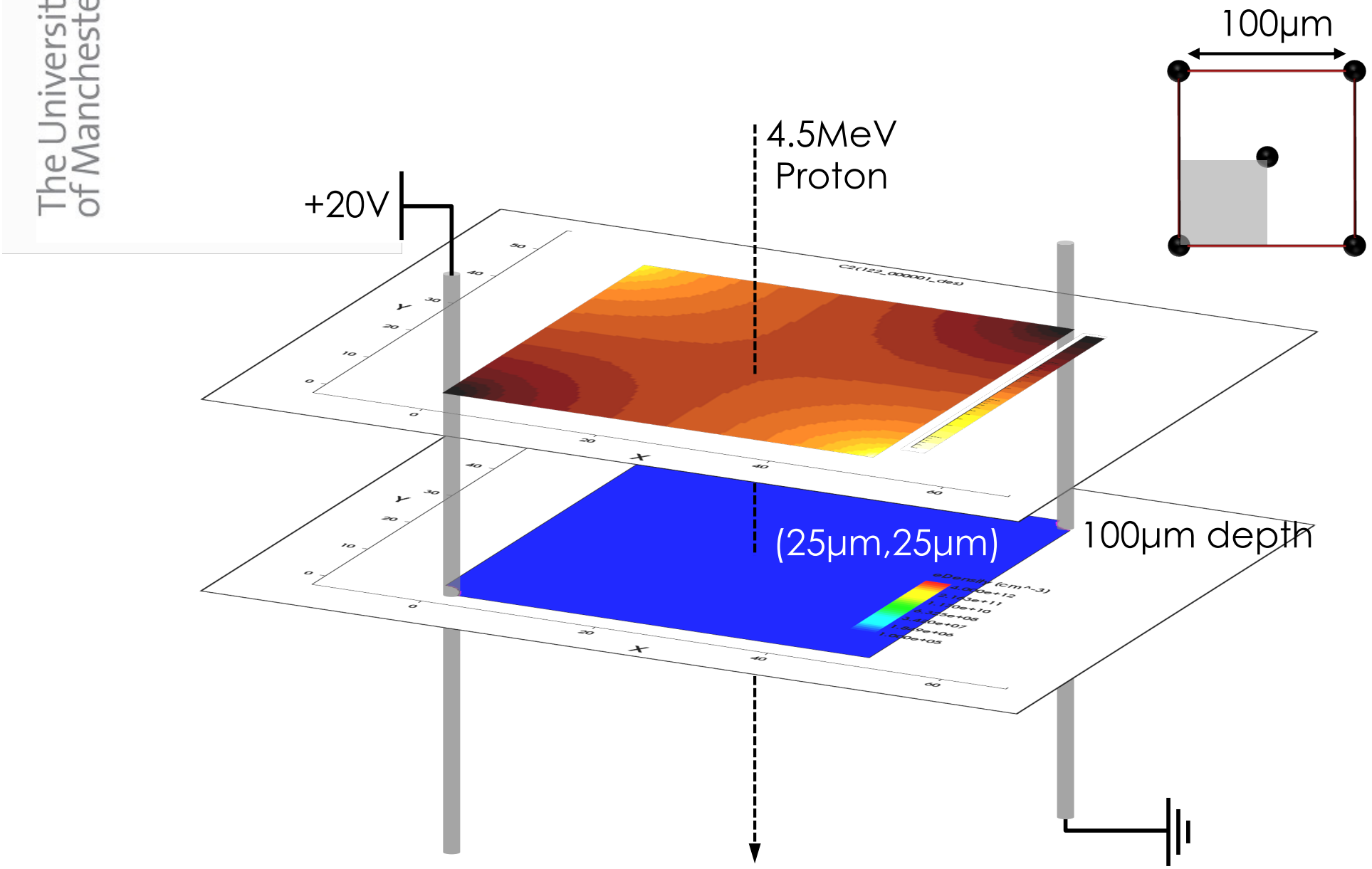
Simulation



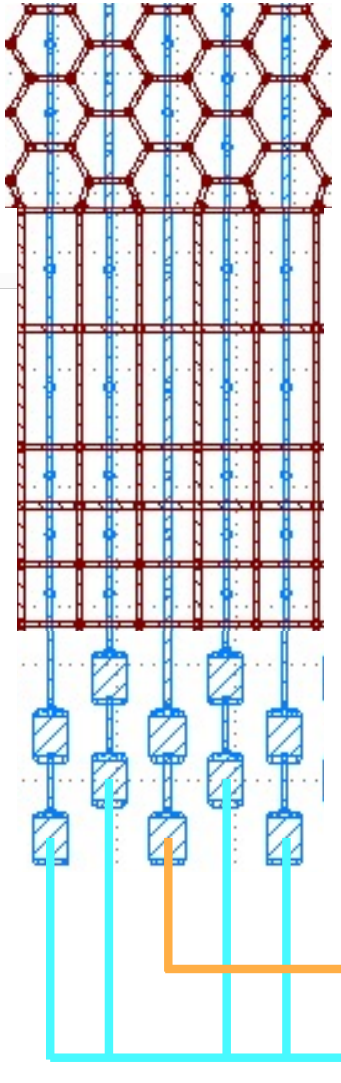
Simulation



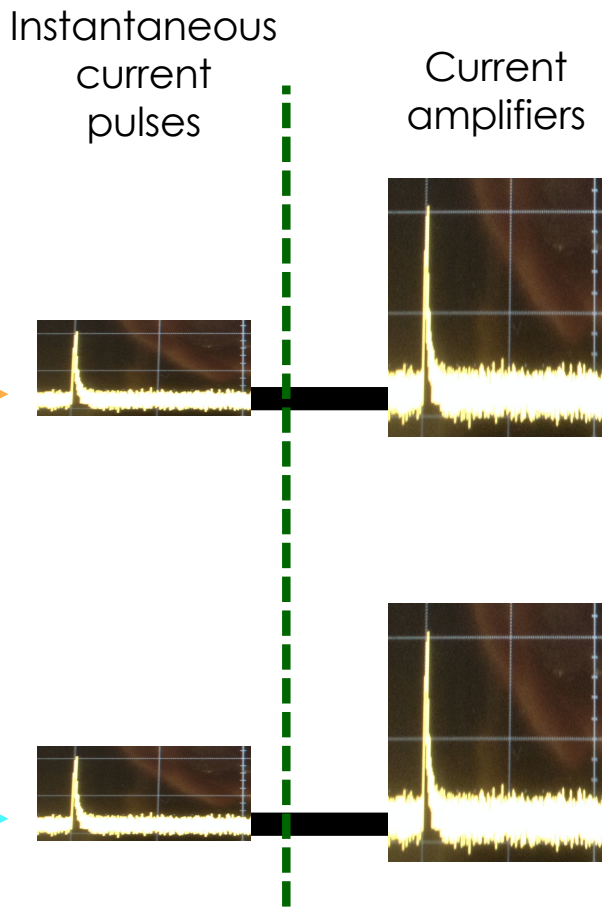
Simulation



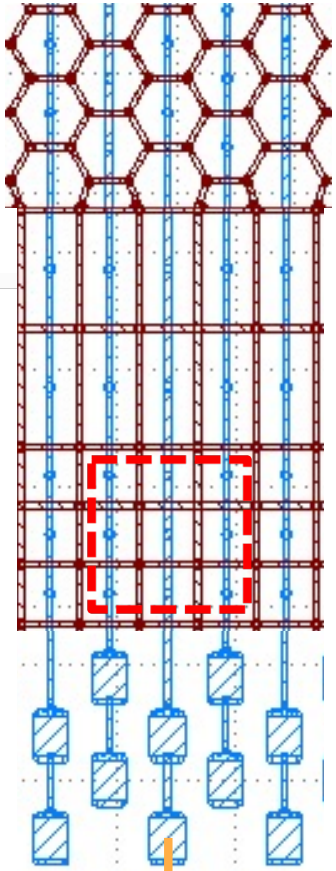
TRIBIC - setup



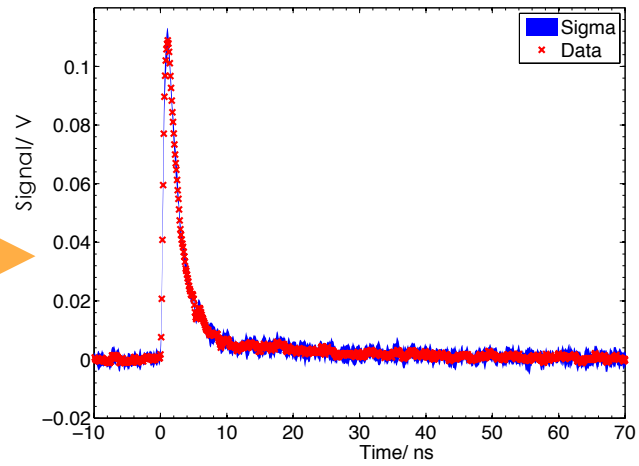
- Two read-out channels and amplification chains.



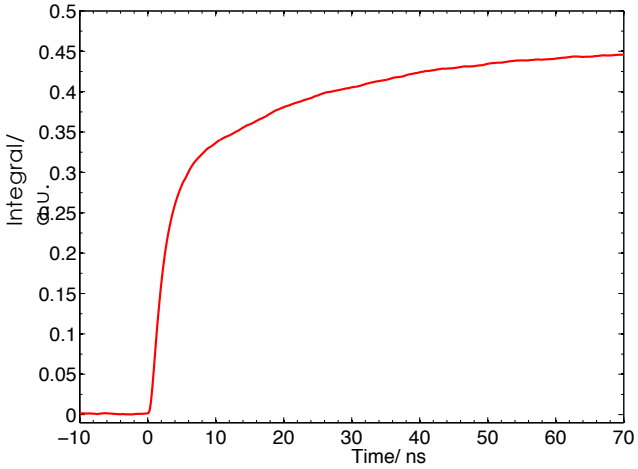
TRIBIC signals

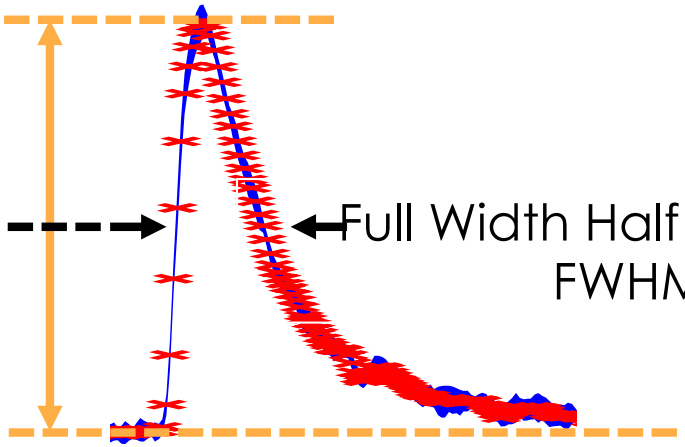


Instantaneous current pulse



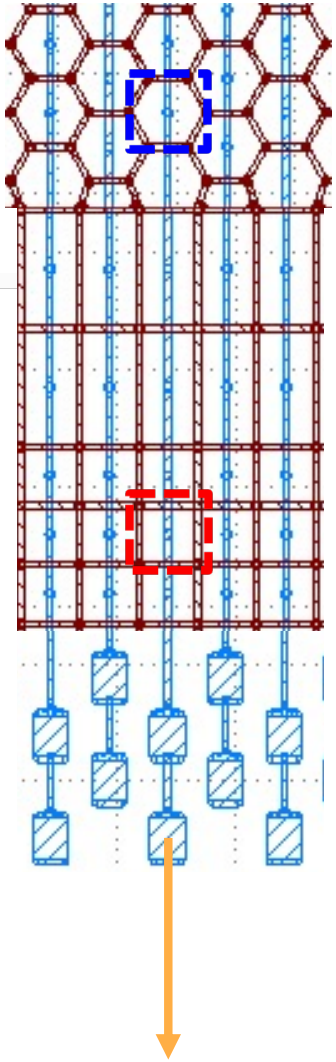
Integral





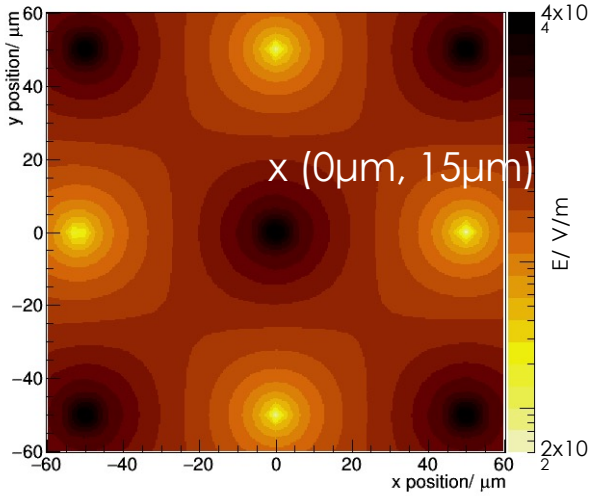
Full Width Half Maximum FWHM.

Position dependence – near electrode

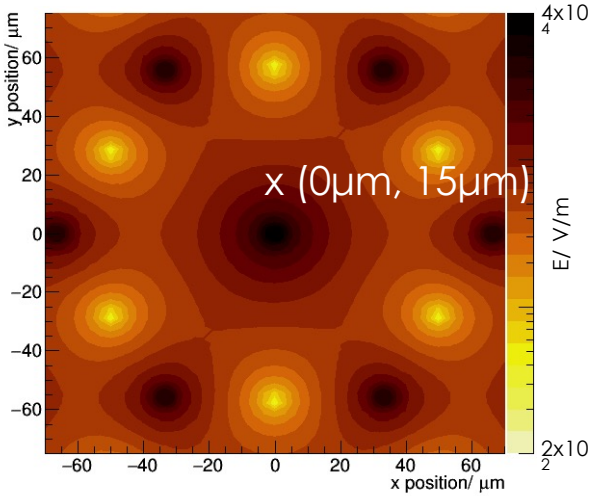


Simulated electric field at 20V

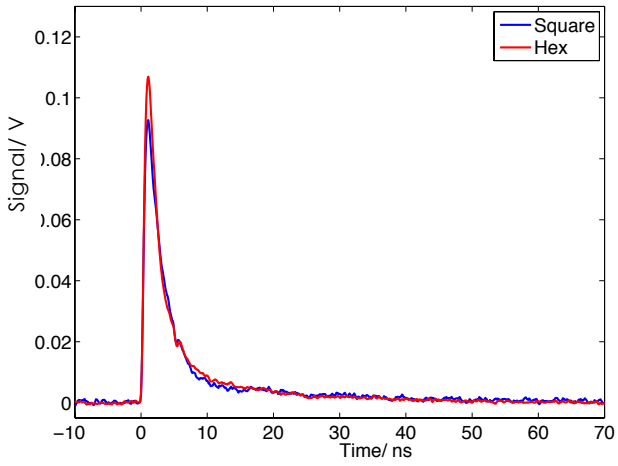
Square

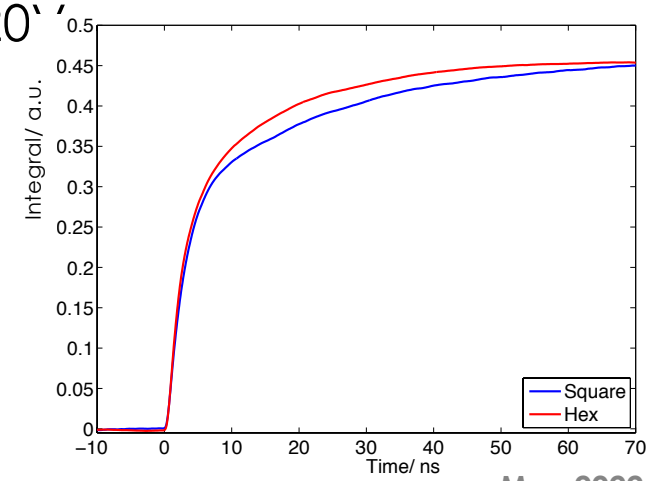


Hexagonal

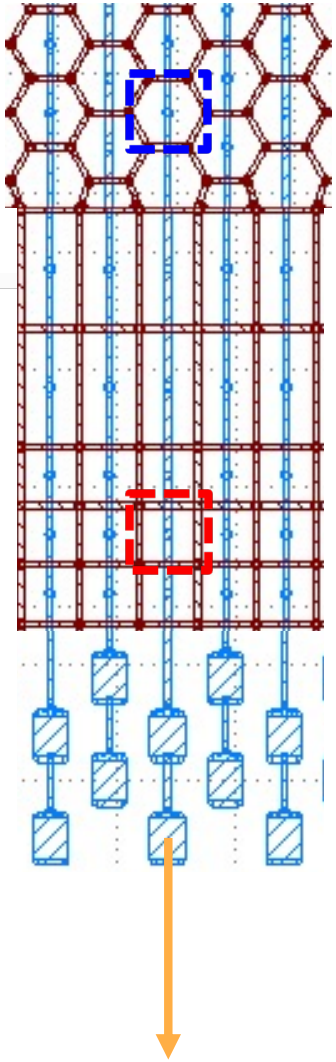


Measured current pulse at 20V

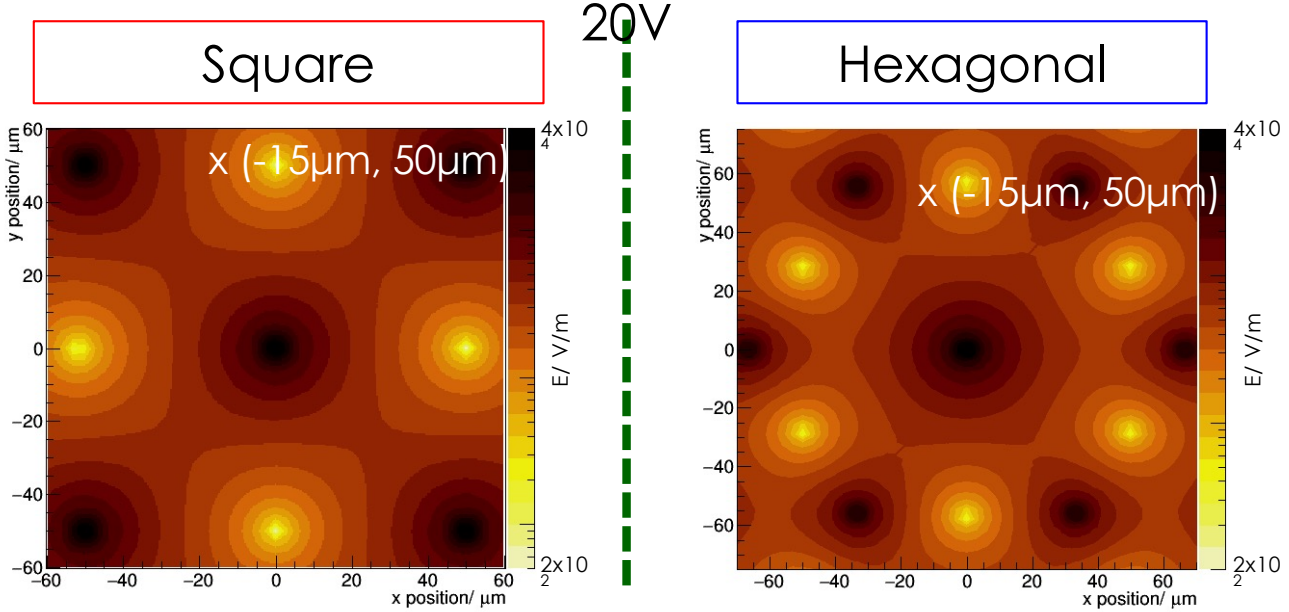




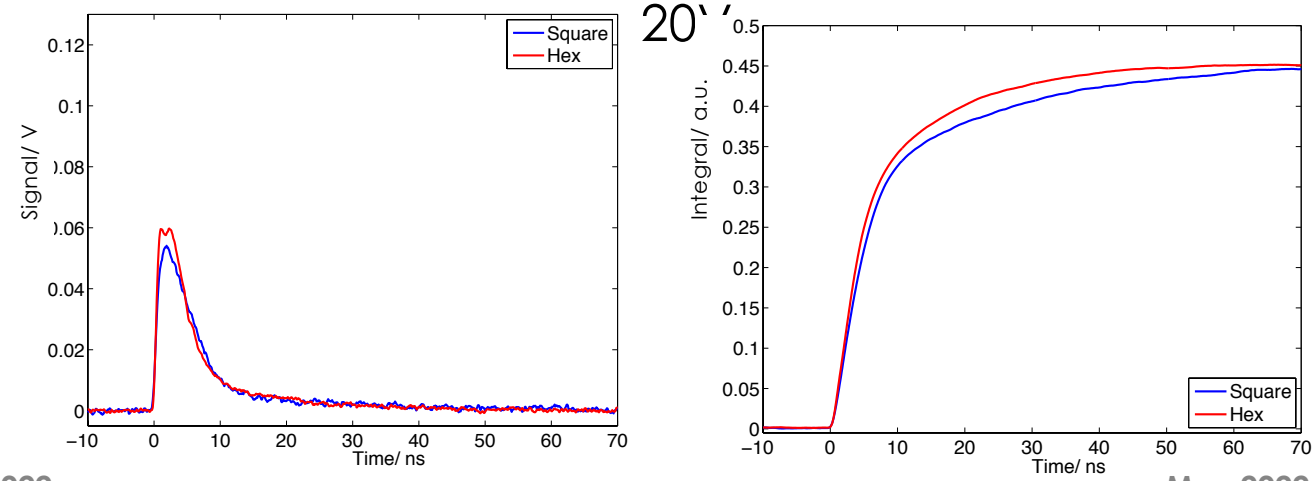
Position dependence – far from electrode



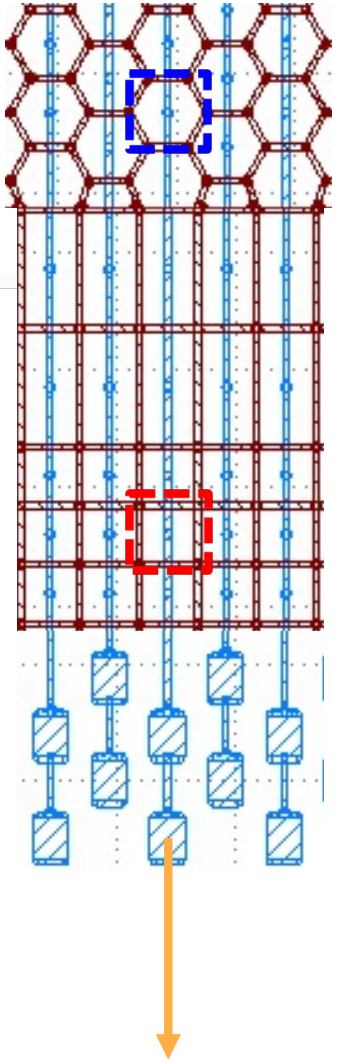
Simulated electric field at 20V



Measured current pulse at 20V

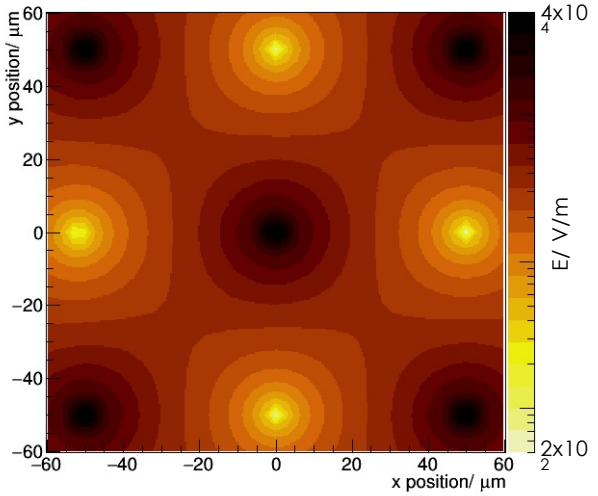


Position dependence - cell

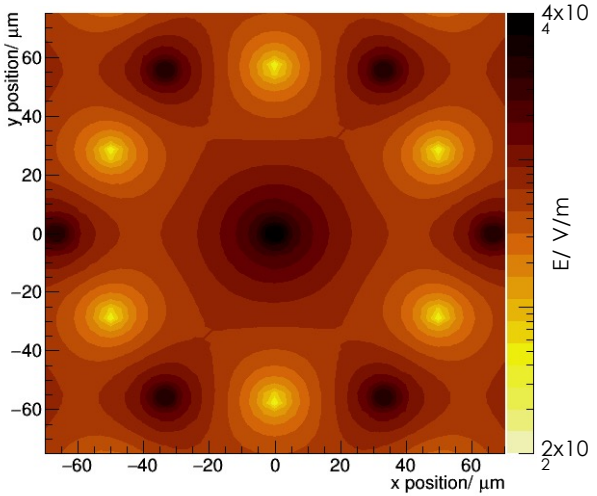


Simulated electric field at 20V

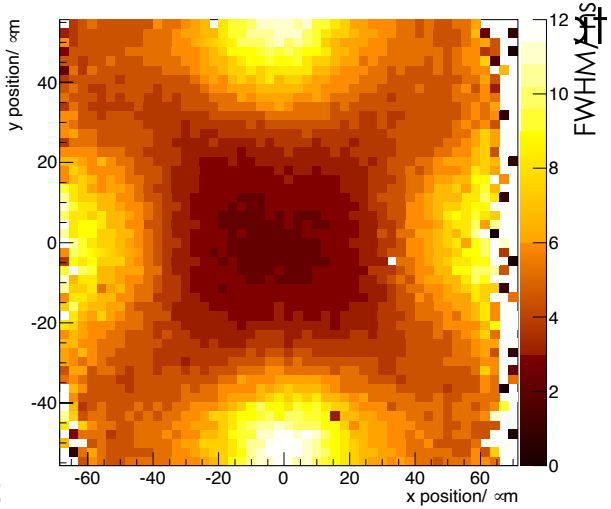
Square

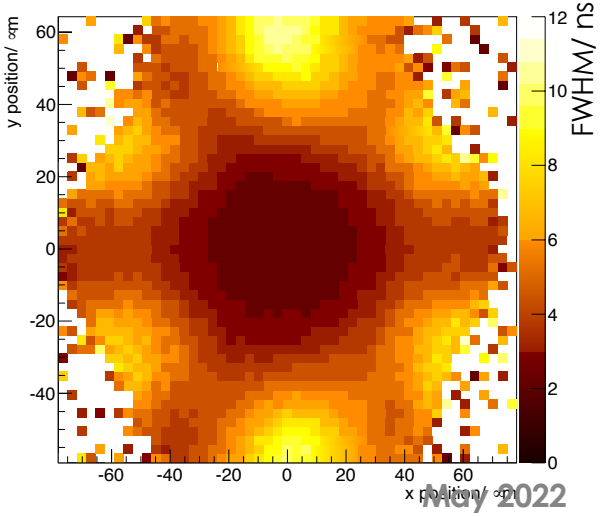


Hexagonal



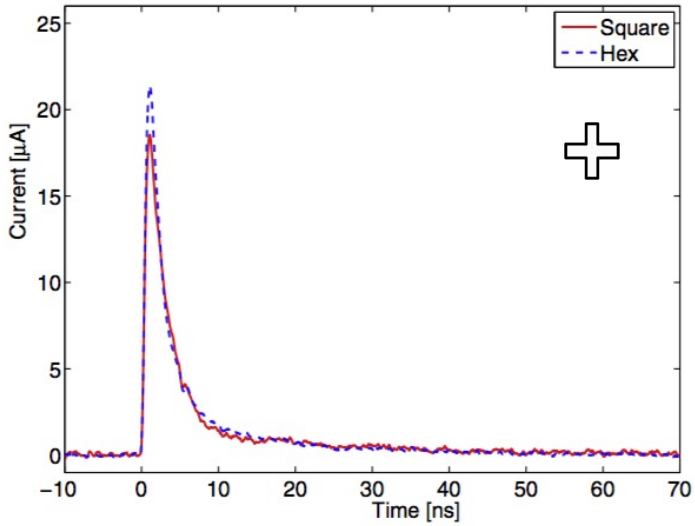
Measured FWHM of pulse at 20V

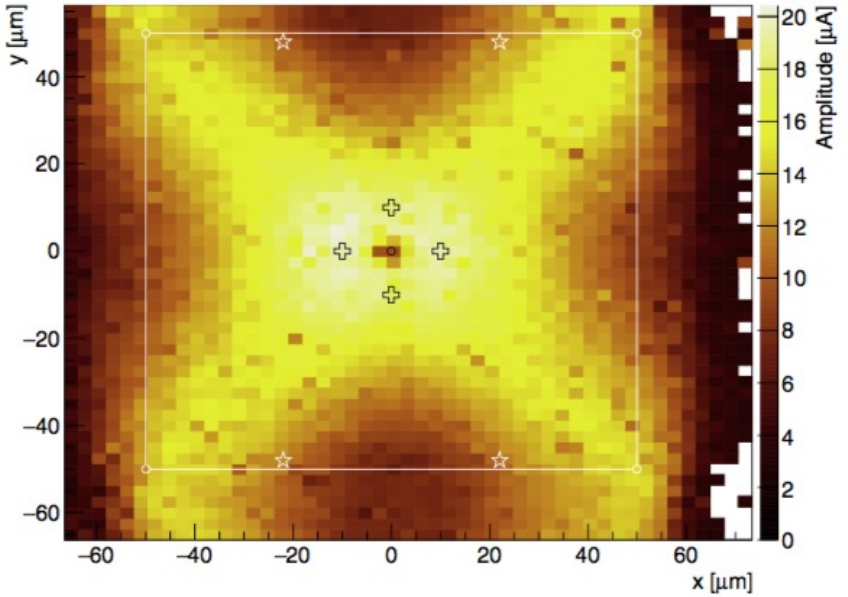


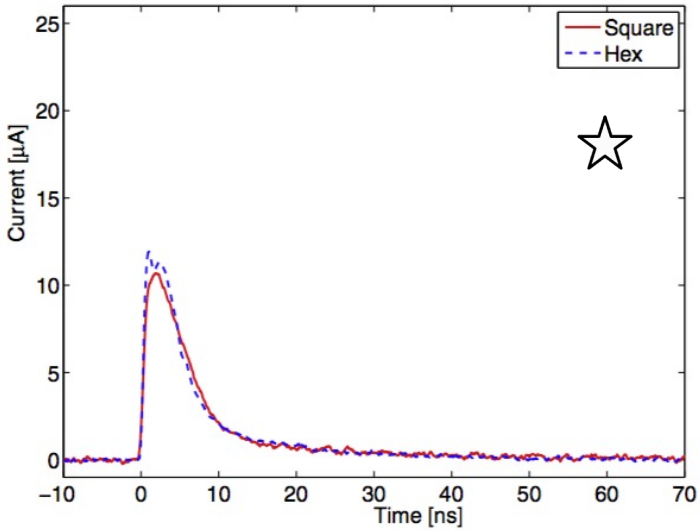


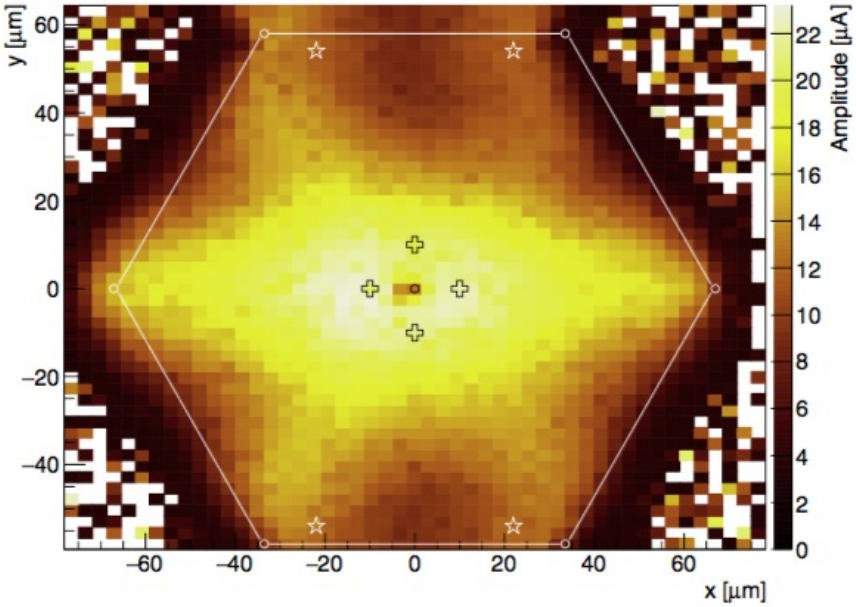
TRIBIC

U_b=-20V

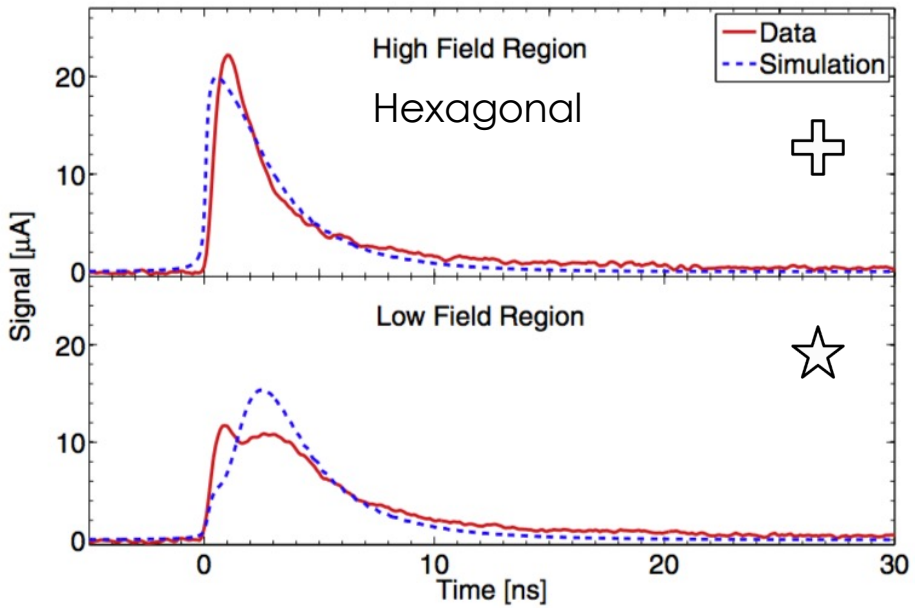


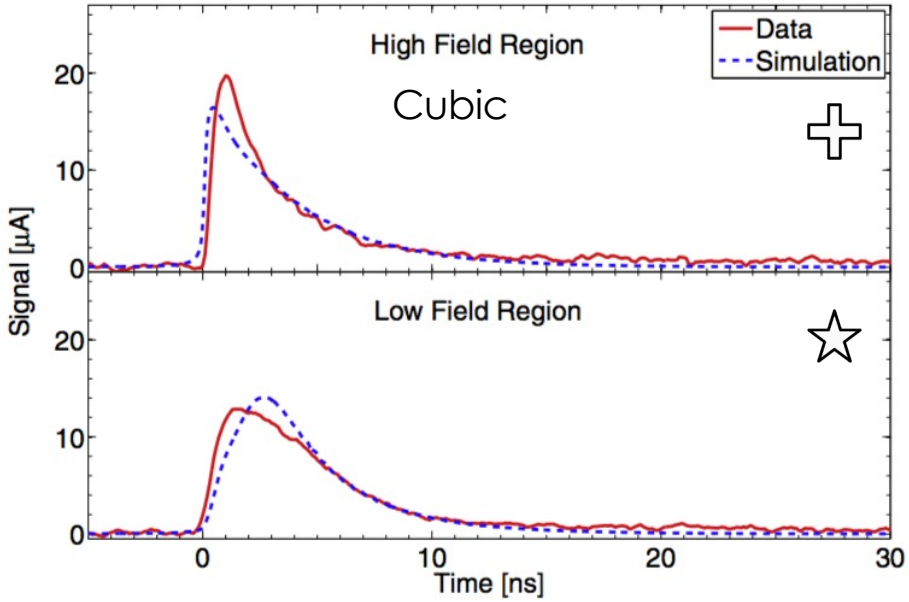






TRIBIC: Results





Comparison with TCAD Simulation model:

- basic features qualitatively reproduced.
- Reasonable agreement, but simplified model.

Summary TRIBIC

- First study of hexagonal and cubic 3D diamond cells with TRIBIC.
  - Hexagonal and cubic cells show expected characteristics.
  - Qualitative agreement with simulations.

- Results shown are preliminary, analysis ongoing.

- Next steps:
  - Quantitatively verify electrical field distribution.
  - Disentangle hole and electron contributions.
  - Radiation hardness studies.

BACKUP

3D Diamond detector for medical dosimetry

Dosimetry application

- Planning of dose distribution delivered dose distribution challenging with narrow field beams.
- Need high spatial resolution of tissue equivalent dose deposited.
- Target numbers:
  - Dose uncertainty <1%
  - Spatial resolution ~0.1mm

The University of Manchester

Dosimetry application

- **Diamond key properties for dosimetry**
  - Tissue equivalence
  - Radiation hardness
  - Room temperature operation
  - bio-compatibility

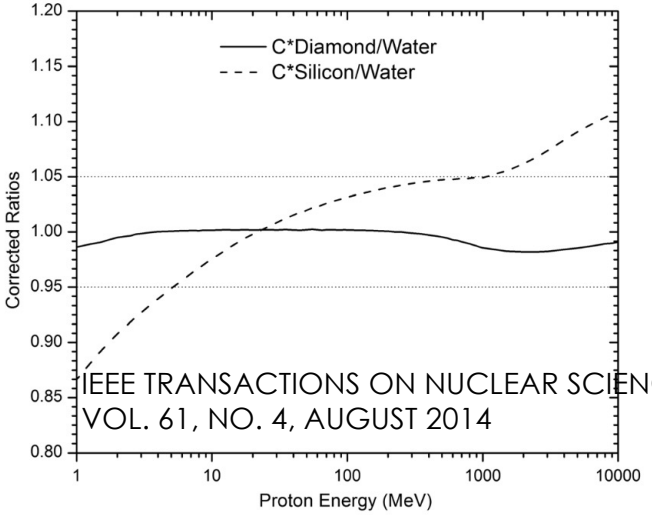
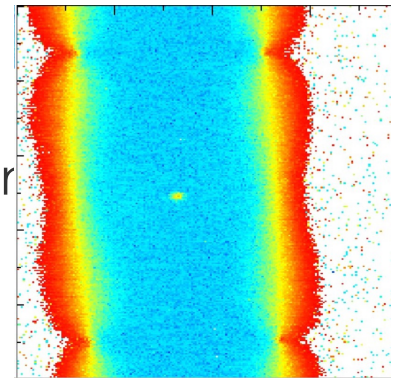
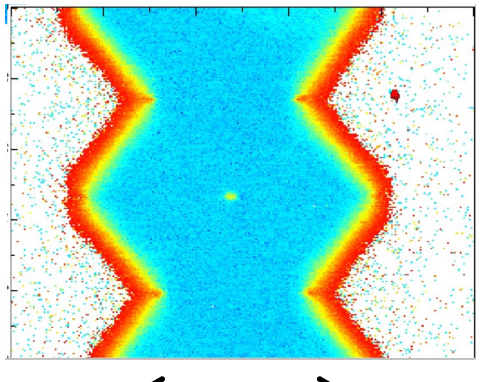
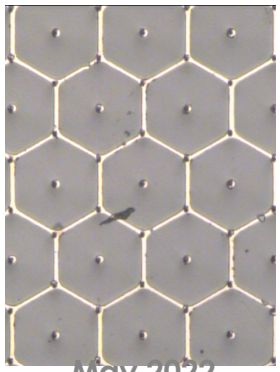


Fig. 14. Comparison of the corrected ratio of stopping powers for protons of diamond and silicon with water.

- **3D Advantage**
  - Flexible active volume
  - Radiation hardness
  - Potential for 3D position information

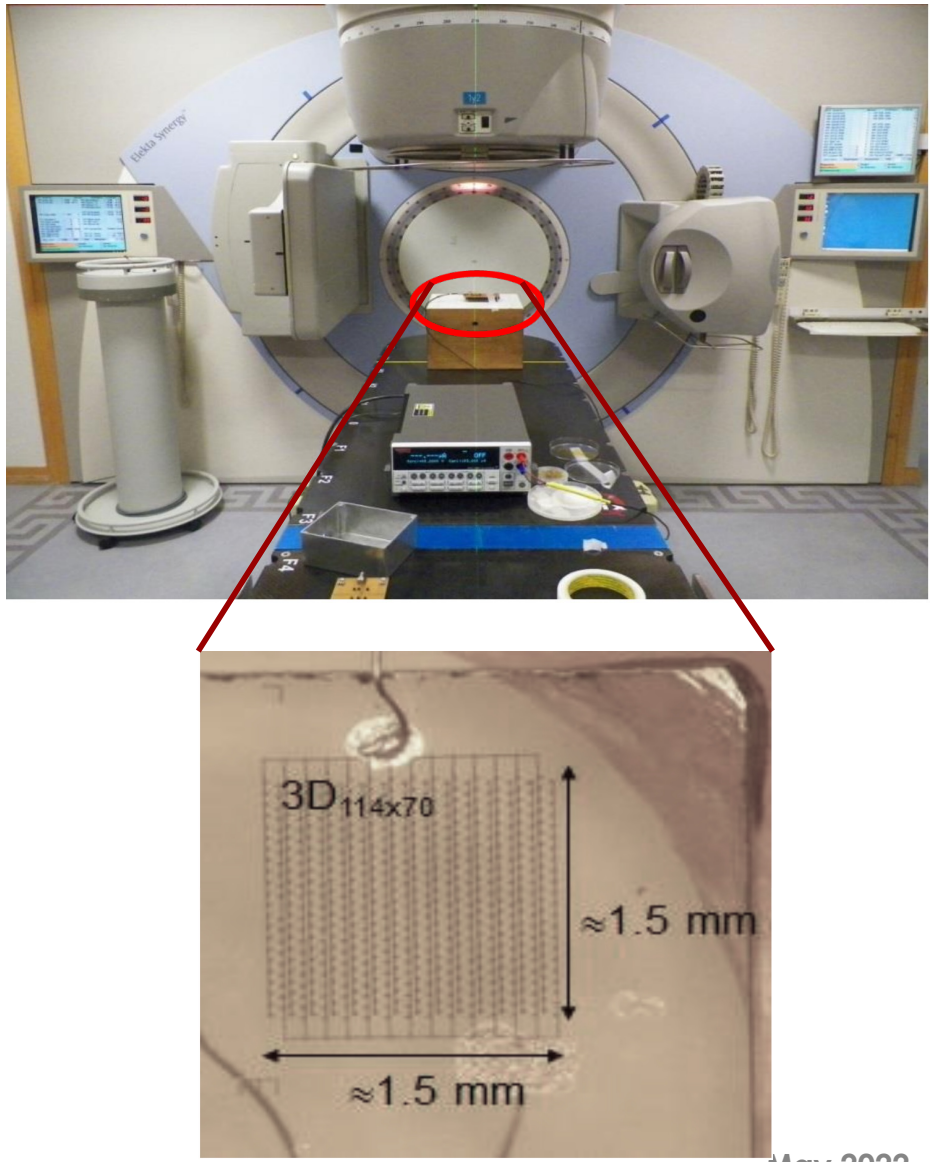






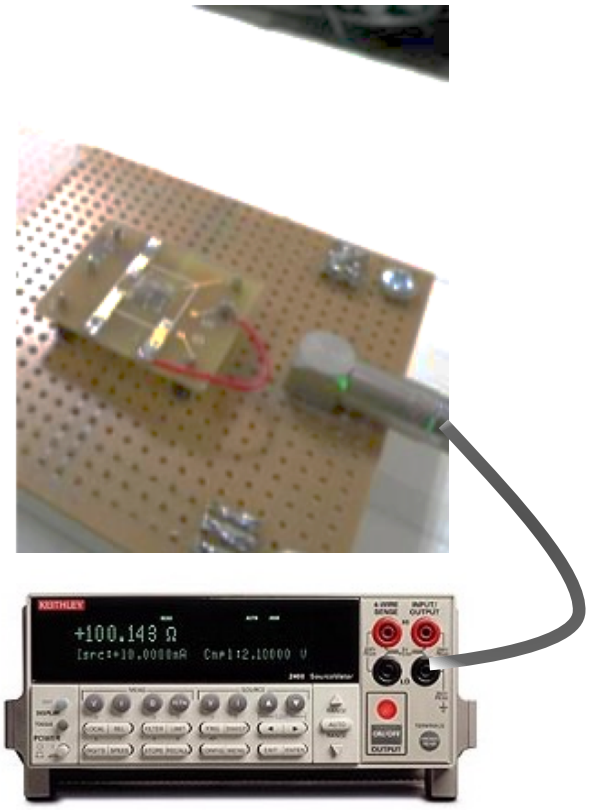
Dosimetry application

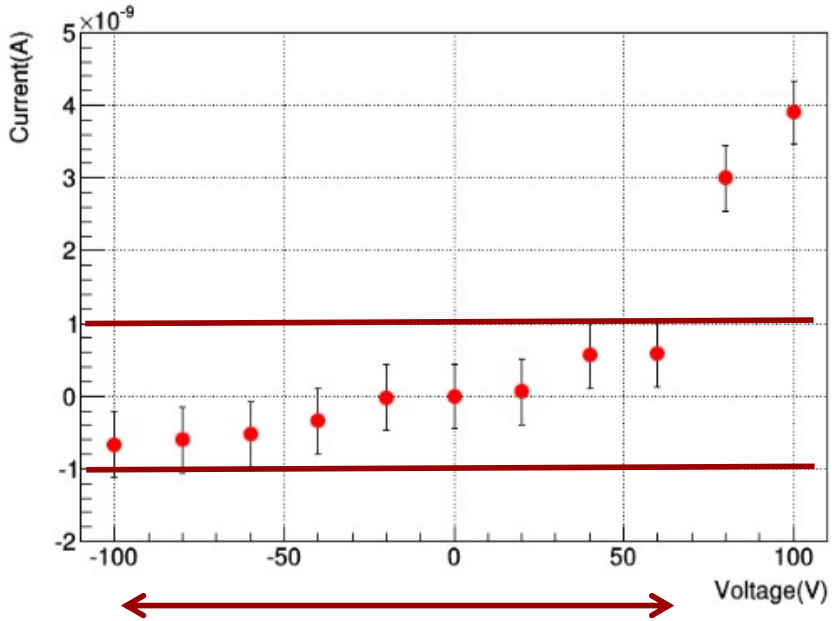
- **The Christie Hospital, Manchester**
  - medical linear accelerator (Elekta Synergy Sband)
  - 6MV and 10MV accelaration.
  - 10x10cm radiation field.
  - Dose rate dependence.
  - Photon beam profile.



Dosimetry application

- Test set-up:



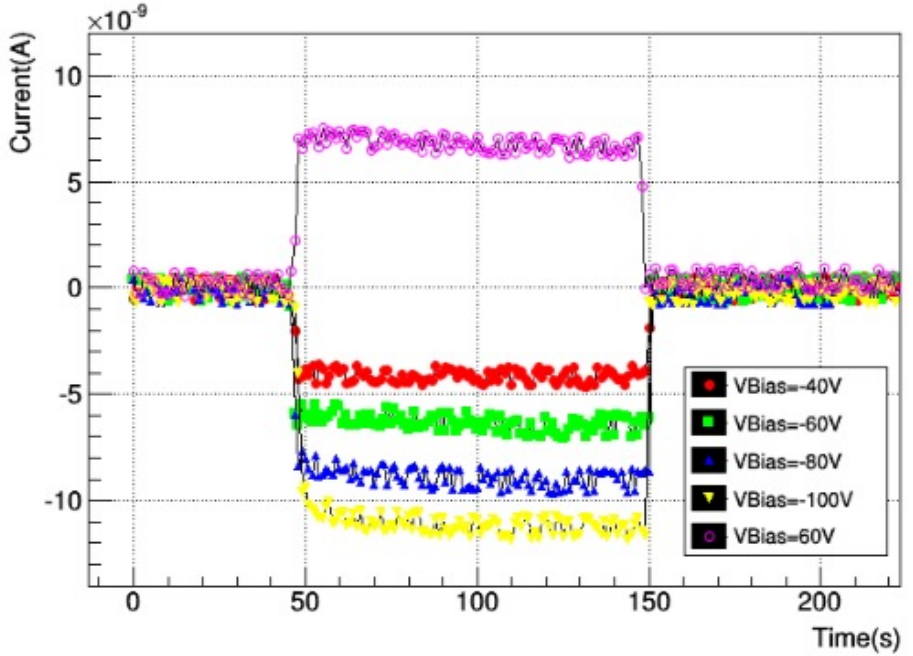


Asymmetric leakage current.
I_{leak} < 1nA for -100V to +60V

Dosimetry application

First 3D diamond results:

- Pre-irradiated with 5 Gy.
- Clear response to presence to 6MV photons.
- Return to baseline <1s, no significant baseline shift.
- Plateau stability needs further studies.

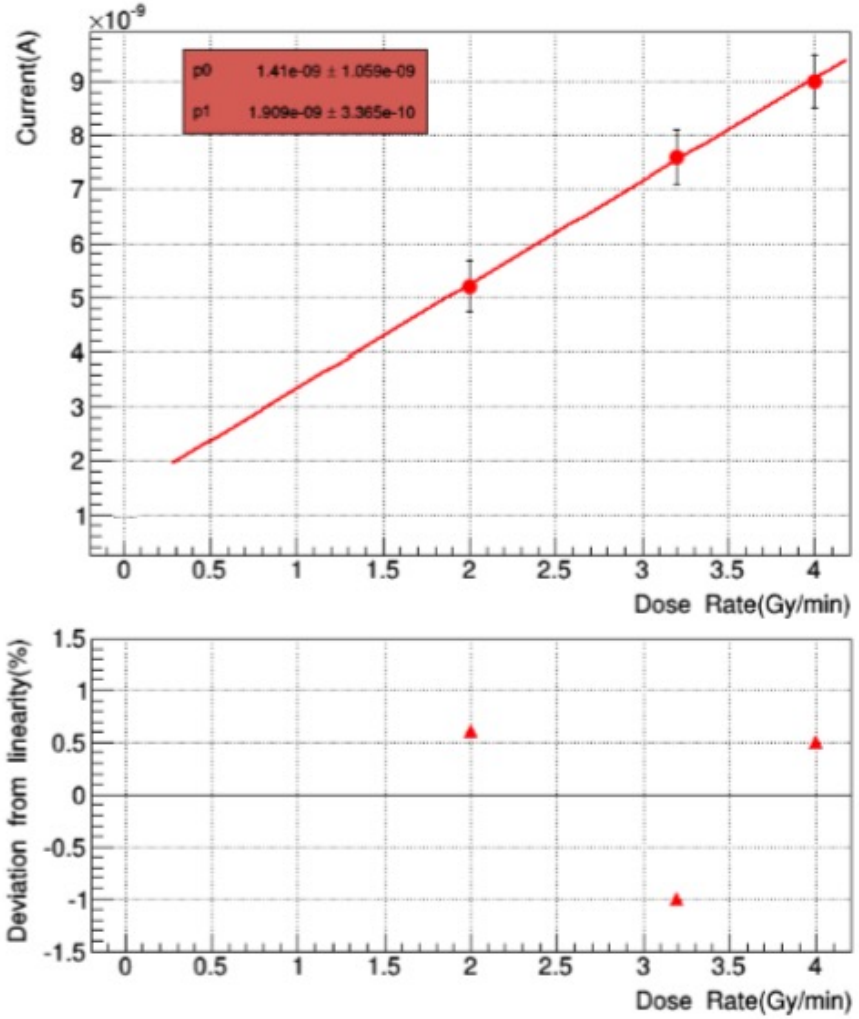


On-off response to 6MV photon beam with 4Gy/min.
Variation of bias voltage.

Dosimetry application

First 3D diamond results:

- Good linearity of ~1% over **dose rate** range of 2-4 Gy/min.

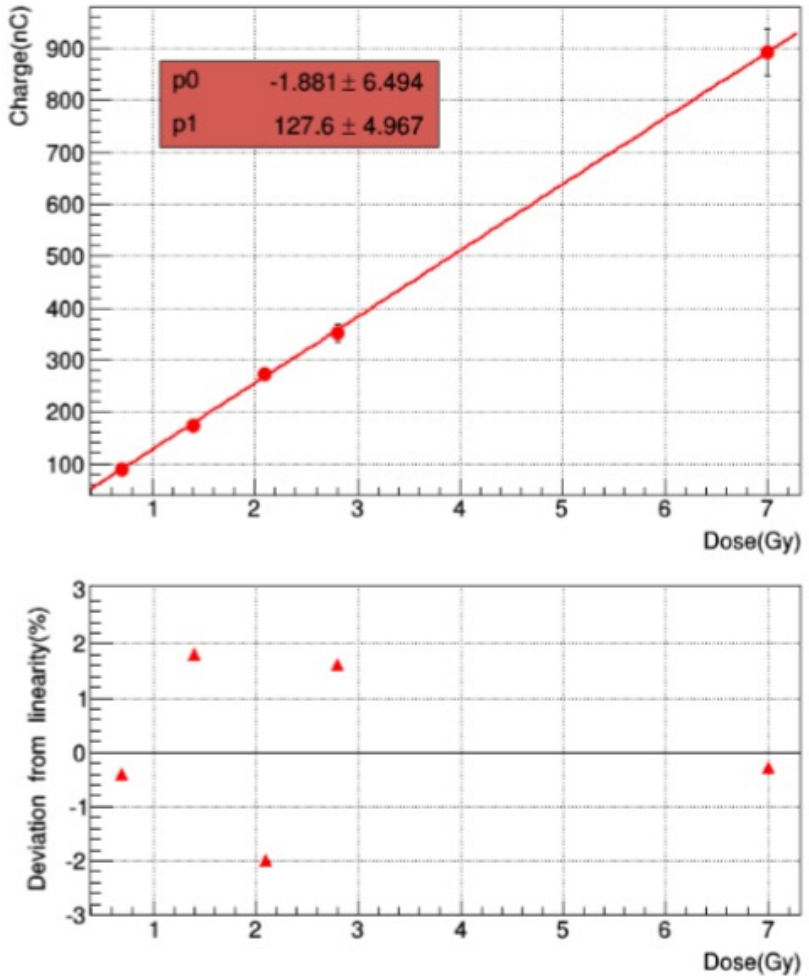


Dose rate linearity for 6MV photons at -80V

Dosimetry application

First 3D diamond results:

- Good linearity of ~1% over dose rate range of 2-4 Gy/min.
- Good linearity of ~2% over **dose range** of 0.5 to 7 Gy.

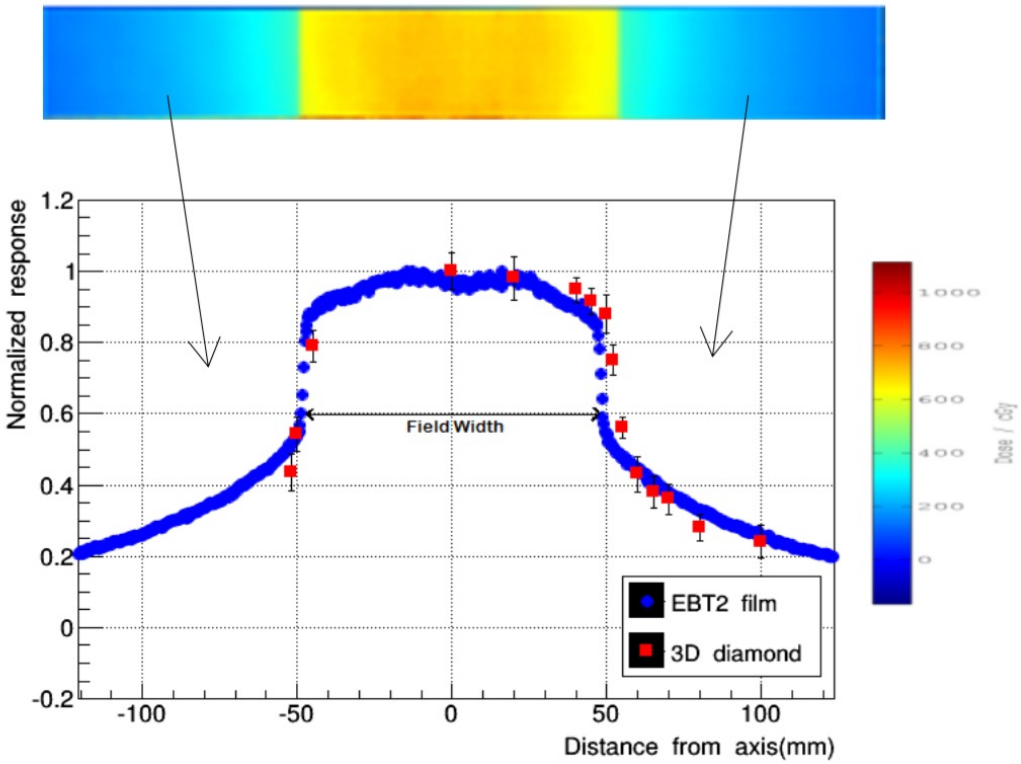


Dose linearity for 6MV photons at -80V

Dosimetry application

First 3D diamond results:

- Good linearity of ~1% over dose rate range of 2-4 Gy/min.
- Good linearity of ~2% over dose range of 0.5 to 7 Gy.
- **Beam width** well reproduced to 1% when compared to GafChromic film measurement.



10cm beam profile measured with 3D diamond at -80V, 4Gy/min and film.

Next generation:

- Next generation tests with variable array sizes.