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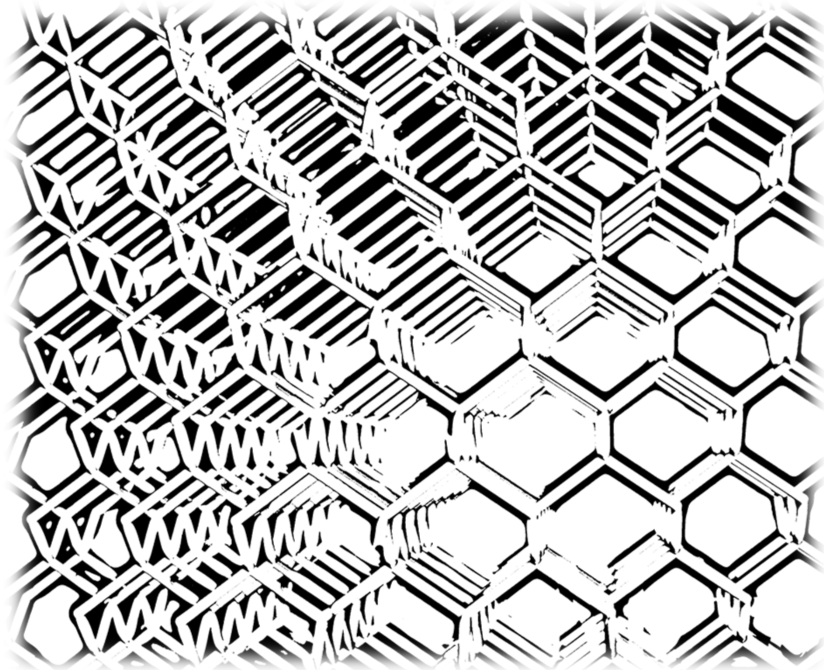
30.5.2018

Diamond Detectors - Status and Perspectives

Alexander Oh
University of Manchester

Outline

- Diamond Detectors
- Installations in experiments
- Radiation Hardness
- 3D Diamond detectors



Thanks for the material from the RD42 and ADAMAS collaborations!

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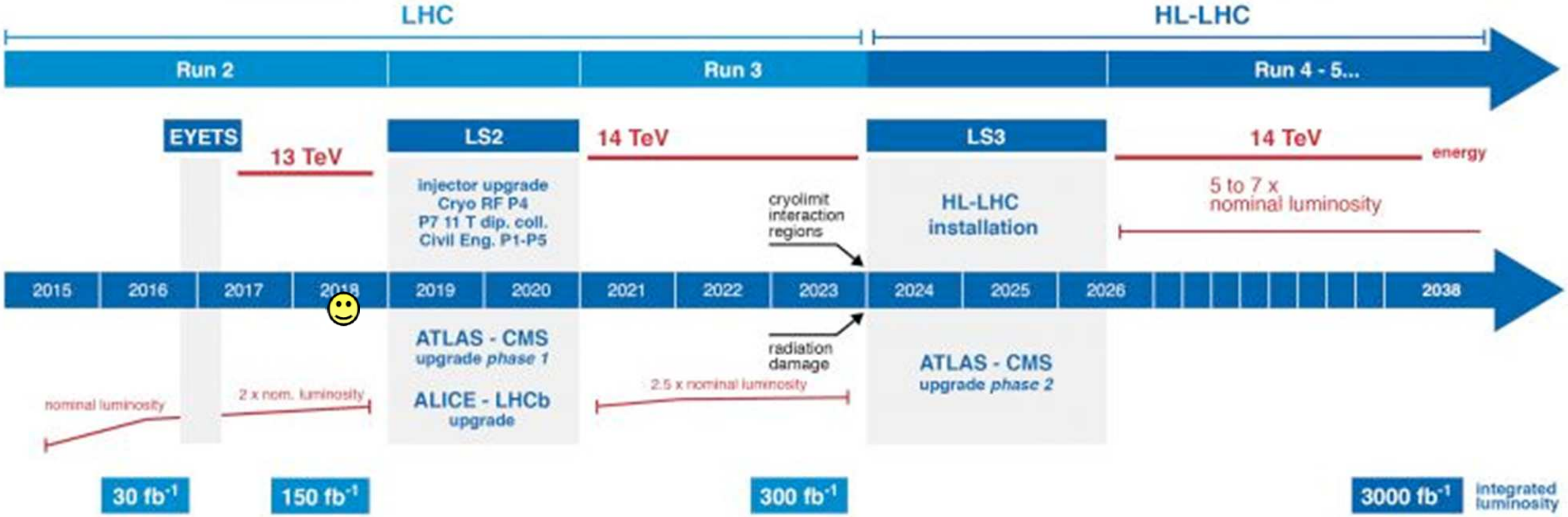
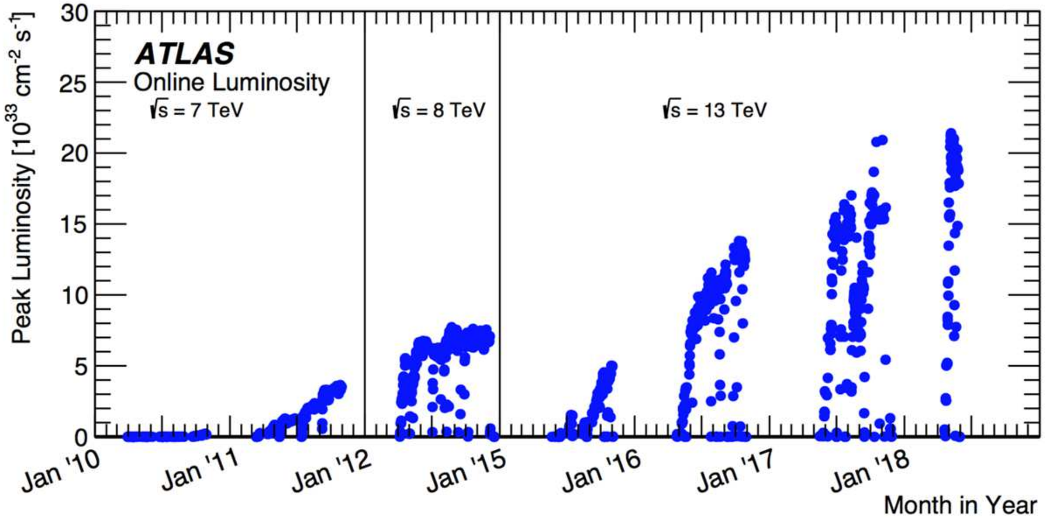
Challenges Ahead



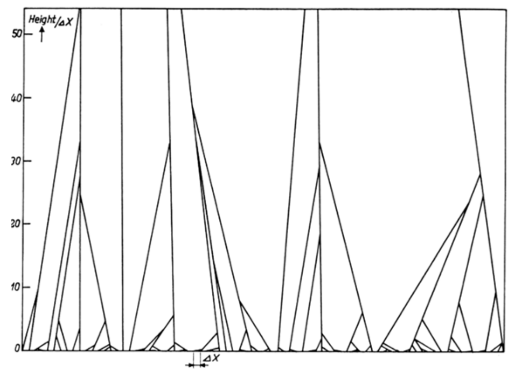


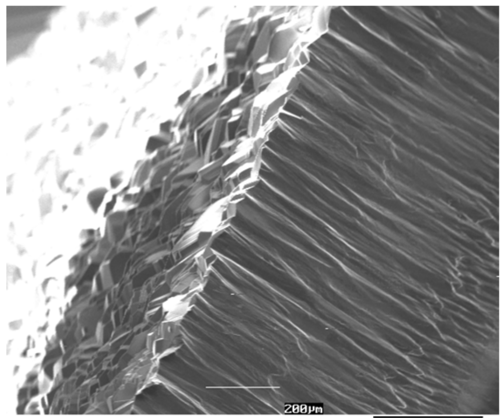
- Luminosity upgrades of the LHC will increase the luminosity by factor ~3.
- Luminosity ~ Radiation damage.
- Need new technologies in the innermost layers to survive the radiation levels.

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.
- 1995 – first diamond strip detector
- 1996 – first diamond pixel detector
- 2011 – first 3D diamond detector

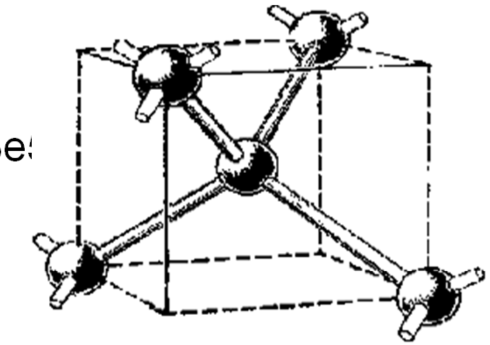




Diamant_DESS8_Seite-gekippt 300μm

Diamond properties

Property	Diamond	Silicon
band gap	5.47	1.12
mass density [g/cm^3]	3.5	2.33
dielectric constant	5.7	11.9
resistivity [Ωcm]	>10^{11}	2.3e
breakdown [kV/cm]	1e3...20e3	300
e mobility [cm^2/Vs]	2150	1350
h mobility [cm^2/Vs]	1700	480
therm. conductivity [W / cm K]	10..20	1.5
radiation length [cm]	12	9.4
Energy to create an eh-pair [eV]	13	3.6
ionisation density MIP [eh/mm]	36	89
ion. dens. of a MIP [eh/ 0.1 ‰ X_0]	450	840

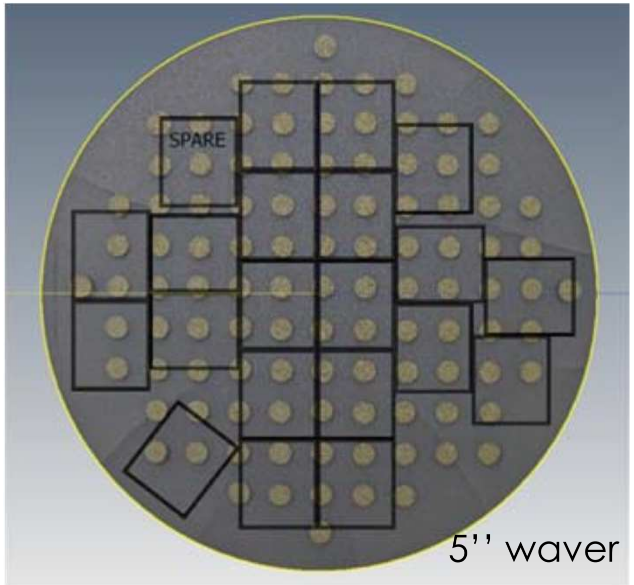


- Low dielectric constant ➔ low capacitance
- Low leakage current ➔ low noise
- Room temperature operation
- Fast signal collection time

- MIP signal ~2 smaller at same X_0
- Efficiency < 100% (pCVD)

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.**



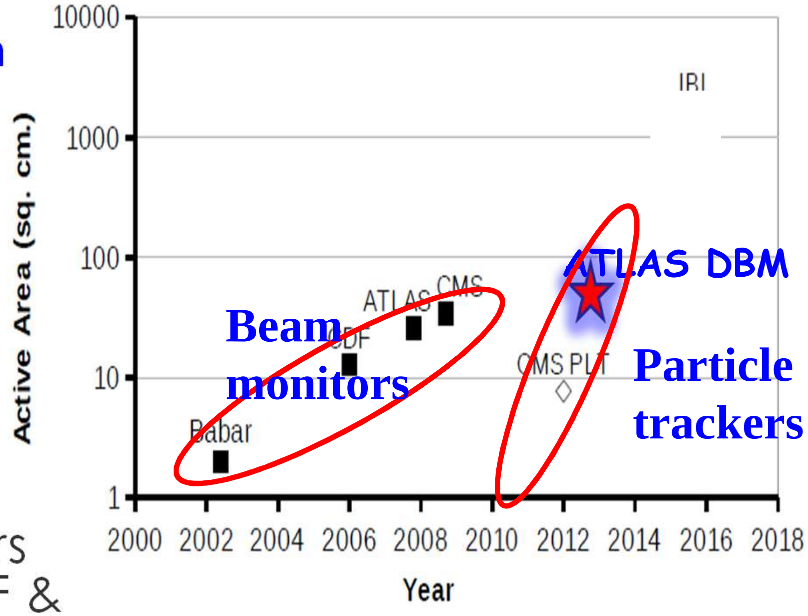
5'' waver

single crystal

DoI, 155ct

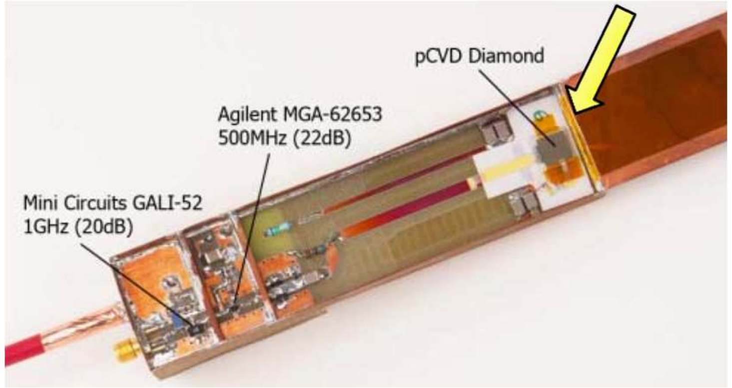
Diamond in current HEP experiments

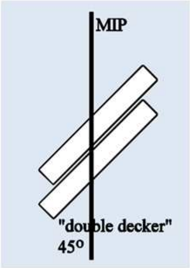
- **Beam monitors** to protect experiments against **beam losses** at the LHC, CERN.
  - For Silicon Vertex systems careful monitoring is crucial.
  - Beam monitors have to be **radiation hard.**
  - Abort beam when monitors signal dangerous beam conditions.
  - False signals must be avoided.
- During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

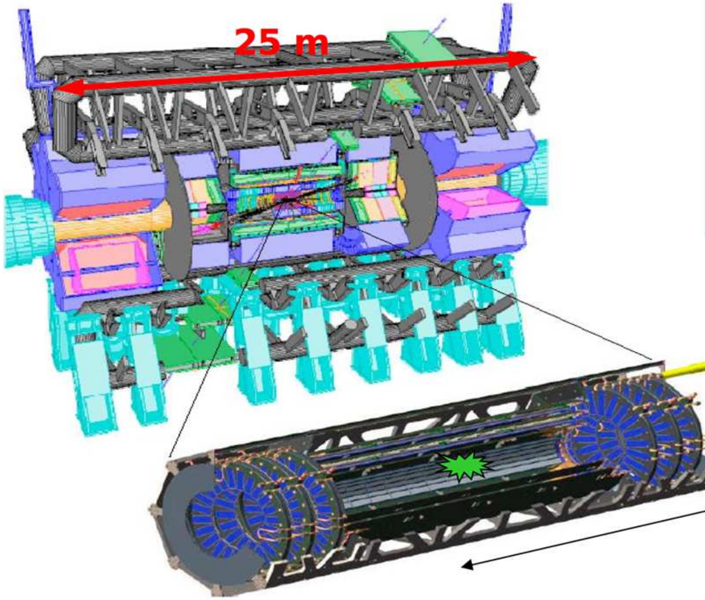


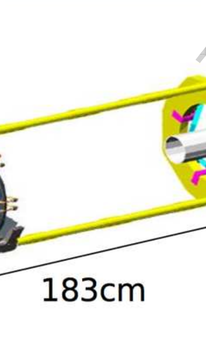
ATLAS beam conditions monitor

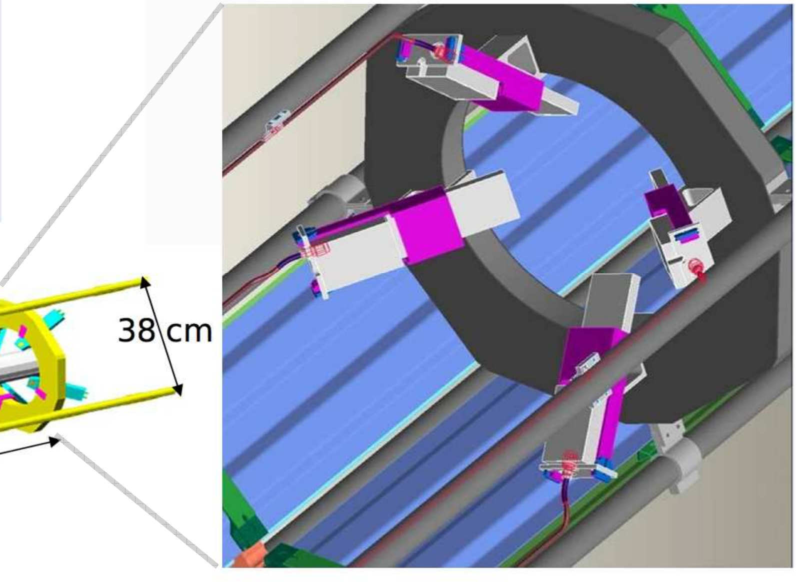
- Use 2x polycrystalline CVD diamonds per station (10 x 10 mm).
- 4 stations on each side of the ATLAS pixel detector
  - z = ±183.8 cm (~12.5ns) and r ~ 5 cm





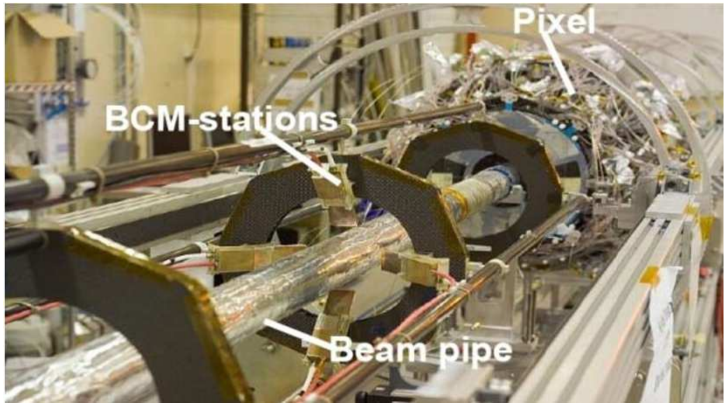


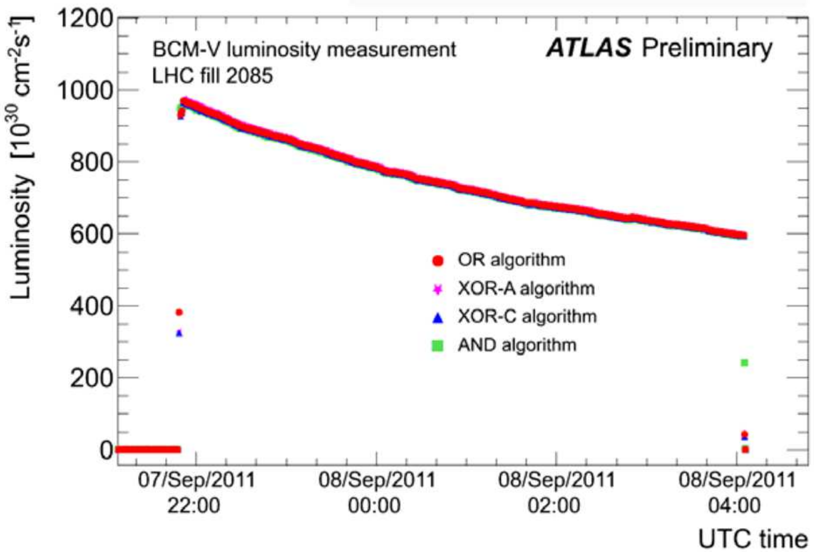


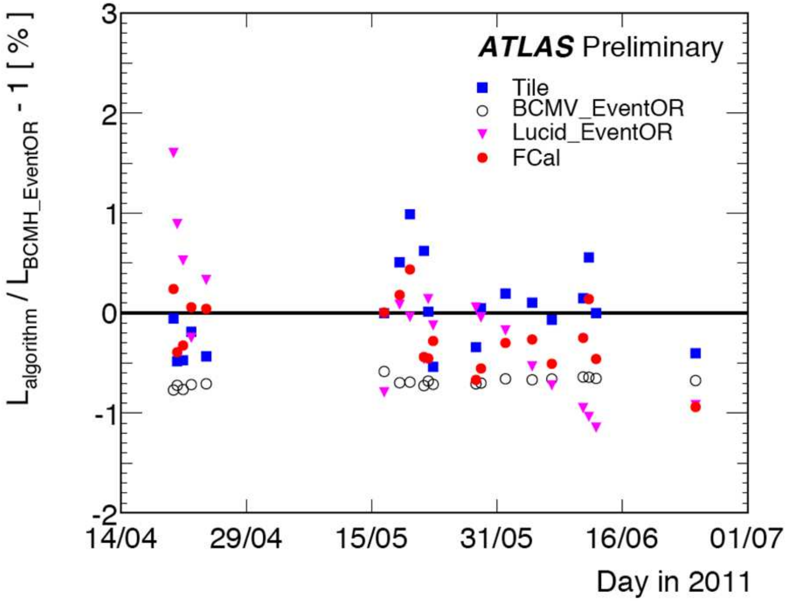


ATLAS beam conditions monitor

- Single particle counting with σ=0.7ns.
  - Distinguish between collision events and out-of-time background.
- Good stability in run-1
  - Used for luminosity determination.

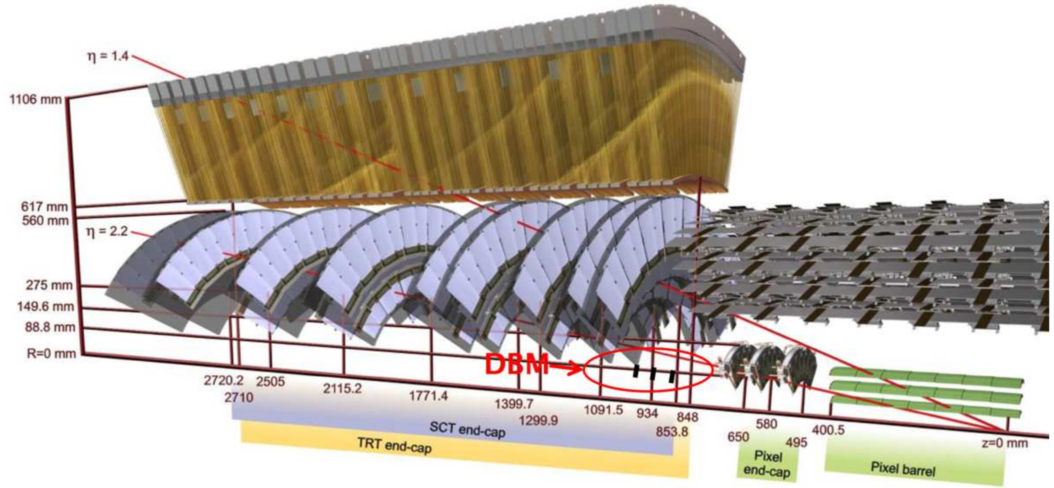






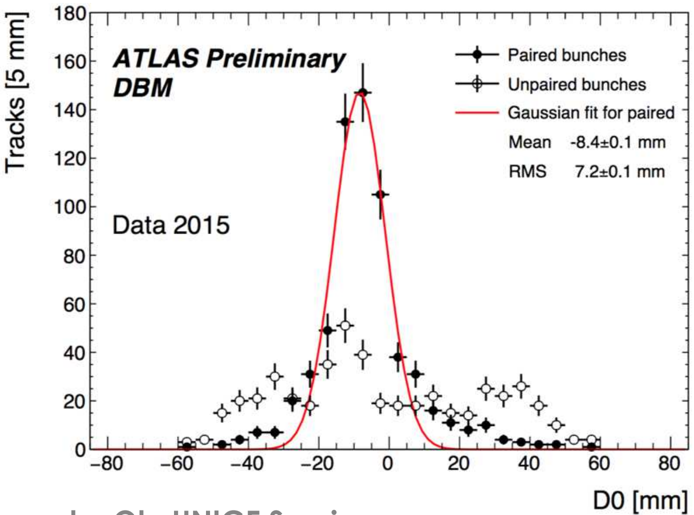
Run 2:
ATLAS Diamond Beam Monitor

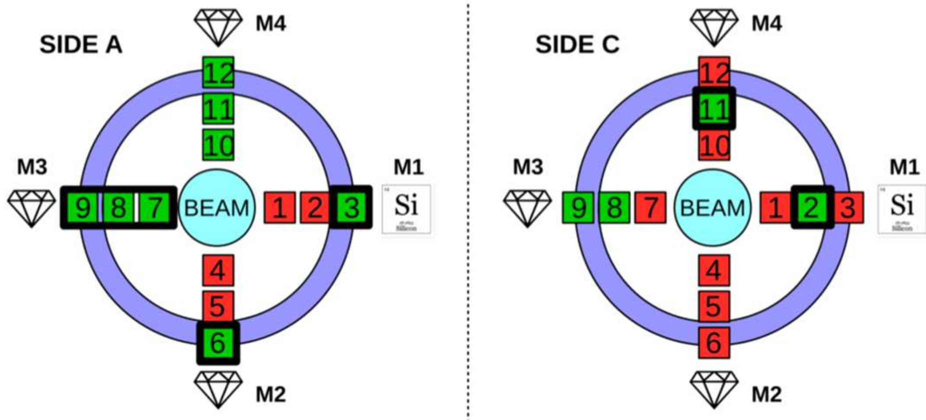
- 8 mini-trackers of 3 planes each using pixel-detectors.
- polycrystalline diamond sensors, 18mm x 21mm, δ>250μm.
- bump-bonded to FE-I4 pixel read-out chip.
  - 336 x 80 pixels
  - pixel size : 50μm x 250 μm
- Purpose:
  - Bunch-by-bunch luminosity monitor (aim < 1 % per BC per LB)
  - Bunch-by-bunch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





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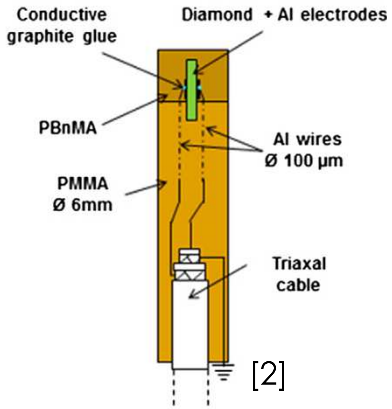
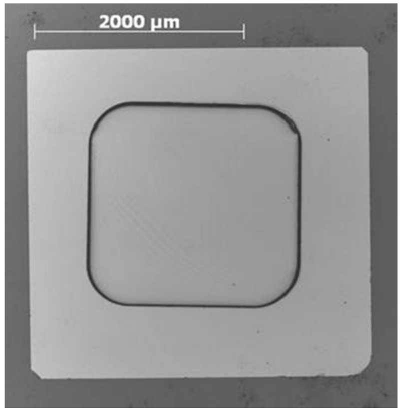
Examples of diamond detectors in related areas

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



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



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

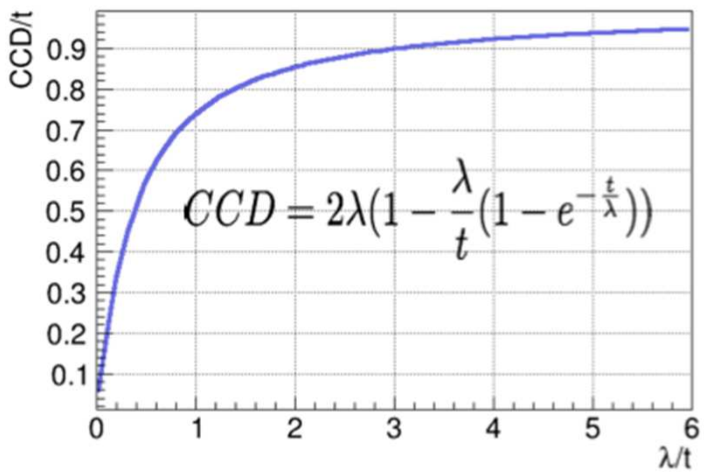
[1] M. Pomroski, CEA-LIST, MRS Fall meeting, Boston 28/11/2012
[2] F. Marsolat et al. / Diamond & Related Materials 33 (2013) 63-70

Radiation Hardness

- **Irradiated polycrystalline and single crystal CVD diamond.**
  - Protons 25MeV, 70MeV, 300MeV, 800MeV, 24GeV
  - Pions 300MeV
- **Signal response tested in test-beam.**
  - 120 GeV proton
  - strip-detector pattern, E = ±2V/µm
  - Samples pre-exposed to Sr90 to fill traps (aka *pumping*)
  - Require track on active area, no threshold on strip signals.
  - Build signal of two highest signals within 10 strips around the track.

Radiation Hardness

- "Charge Collection Distance" (*CCD*) is measured.
- Traps reduce the life-time of charge carriers, or "Schubweg" (λ).
  - Relation between *CCD* and λ:



Radiation damage is fitted with simple damage model:

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

damage constant (k_λ)

particle flux (Φ)

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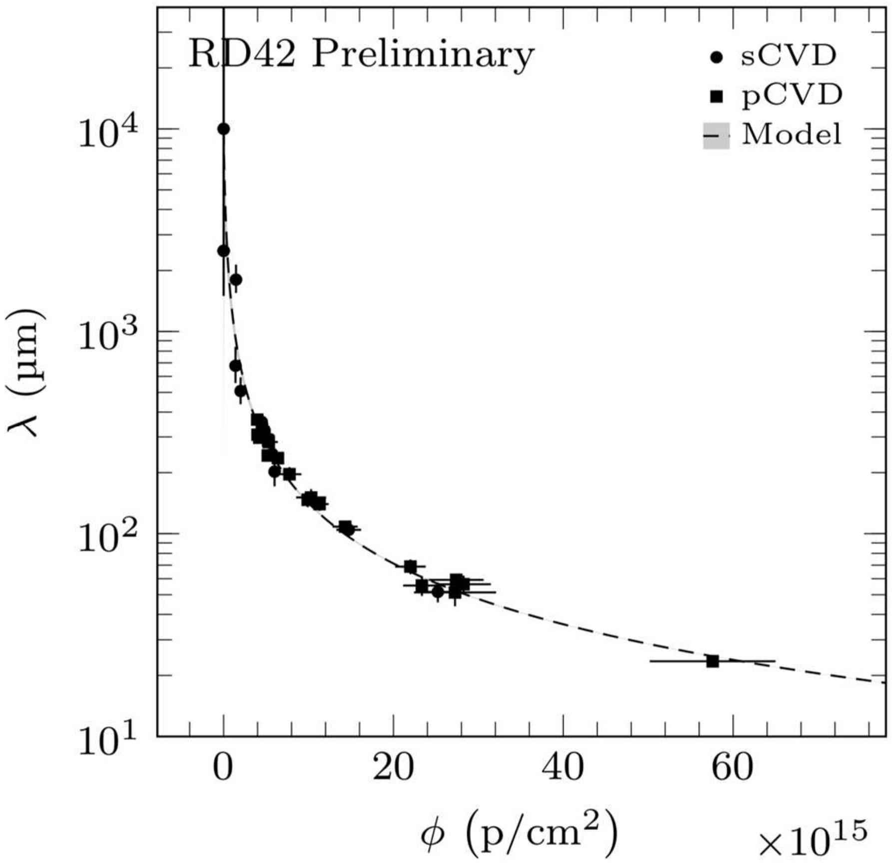
Radiation Hardness

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



https://www.research-collection.ethz.ch/handle/20.500.11850/222412

Radiation Hardness

- Summary of RD42 irradiation results:

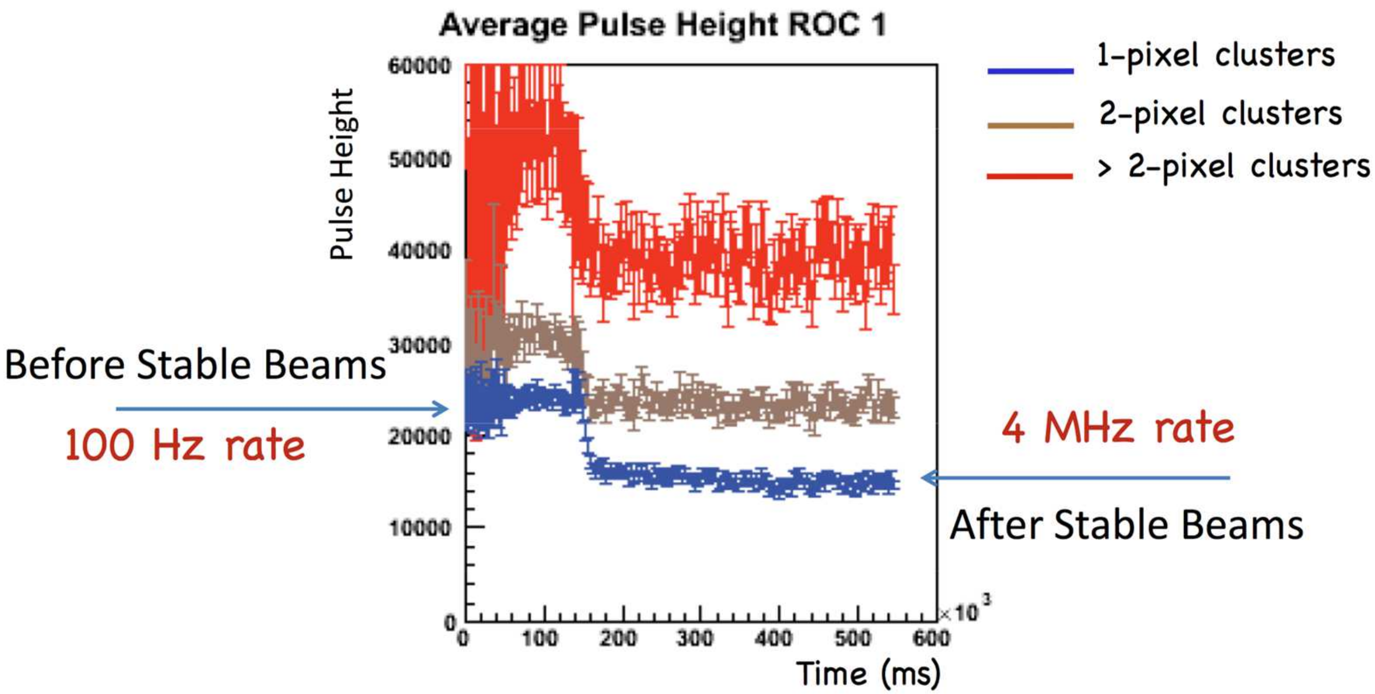
Particle Species	Relative Damage Constant, κ
24 GeV p	1
800 MeV p	1.85 ± 0.13
70 MeV p	2.5 ± 0.4
25 MeV p	4.5 ± 0.6
fast neutrons	4.5 ± 0.5
200 MeV π	2.5 - 3

*normalized to 24GeV protons

High Rate tests

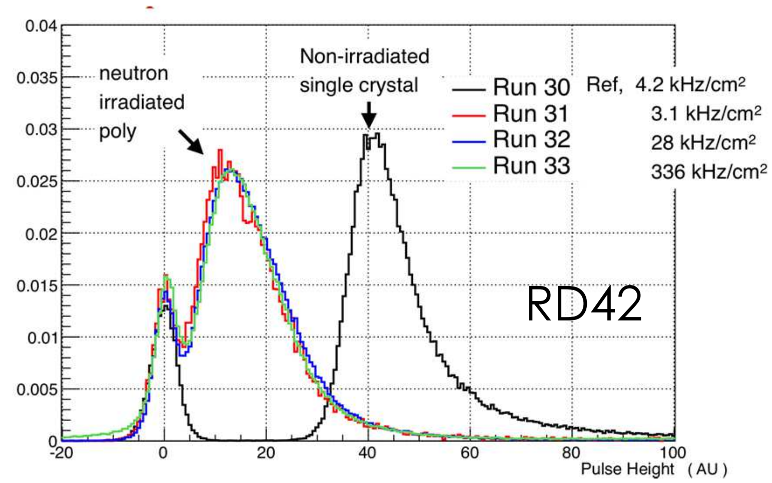
- Tests the pulse height as function of particle rate.
- Test single and poly crystalline diamond.
- Irradiated and un-irradiated.

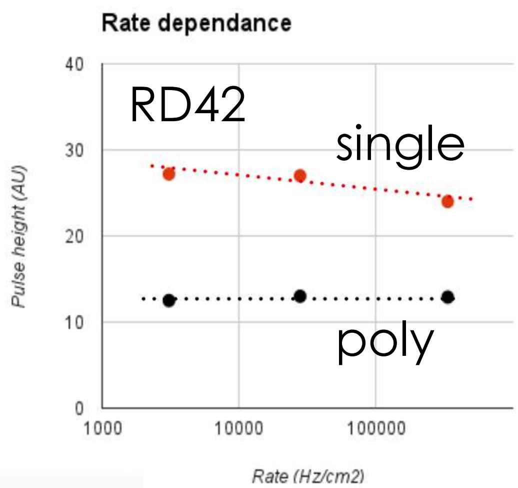
Investigations triggered by indication of rate dependence of of single crystal diamond pixel detector installed in CMS in 2012.

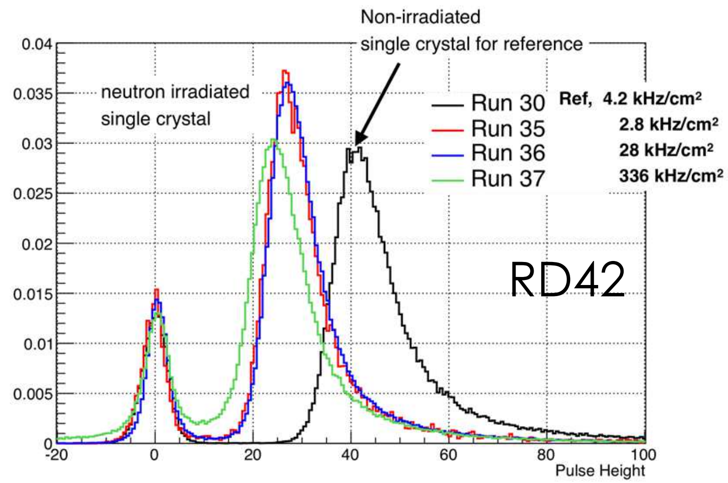


High Rate tests

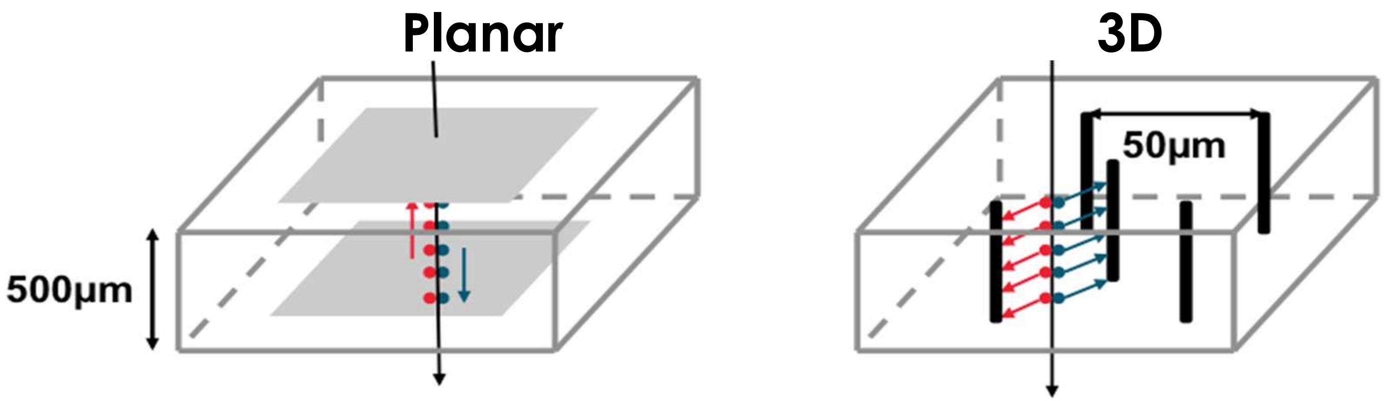
- single and poly sample irradiated with $5{\times}10^{13}$ reactor n.
- Tested with 250MeV pions.
- Slight rate dependence observed in irradiated **single crystal** sample.
- No rate dependence observed for irradiated **polycrystalline** sample.







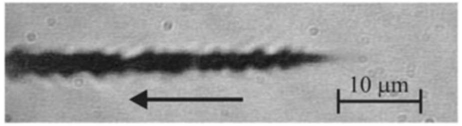
3D Diamond Detectors



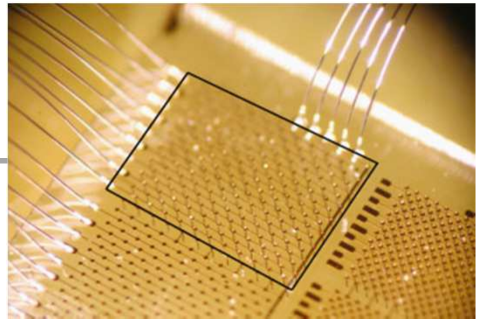
- Electrode spacing determines drift distance to induce 1e charge.
- 3D has shorter electrode spacing compared to planar.
- Charge carriers need less drift distance (and time) in 3D then in planar to induce equal signal.
- Influence of traps and resulting limited lifetime suppressed in 3D.

3D Diamond Research - A relatively young field

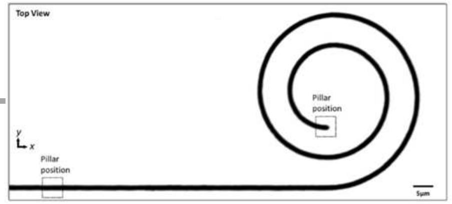
- Laser induced phase change in diamond.
  - E.g. T.V. Kononenko et al, Diamond & Related Materials 18 (**2009**) 196–199 "***Femtosecond laser microstructuring in the bulk of diamond*** "



- 3D "Pad" detector
  - E.g. S. Lagomarsino et al, Appl. Phys. Lett. 103, 233507 (**2013**), ***"Three-dimensional diamond detectors: Charge collection efficiency of graphitic electrodes"***

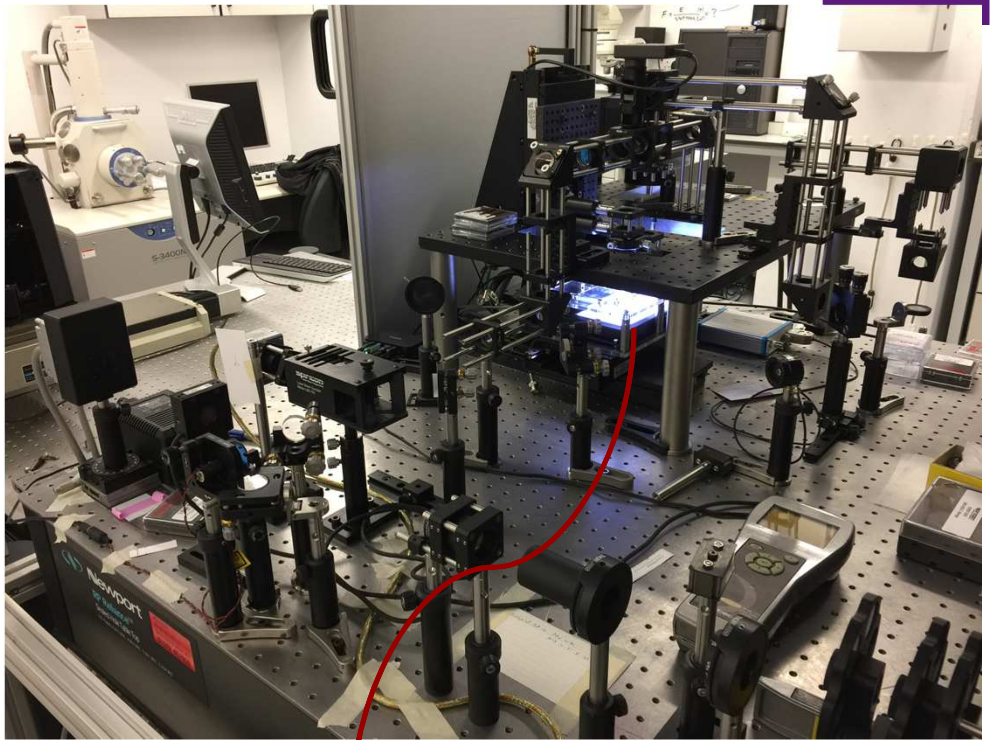


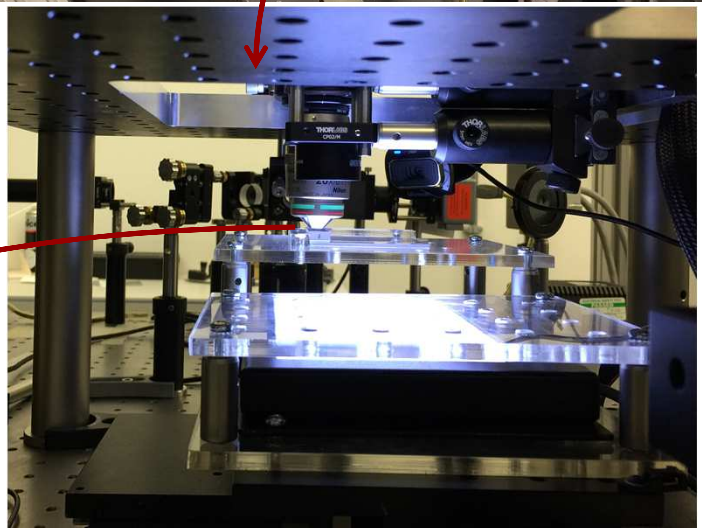
- 3D "strip array" detector with position resolution.
  - E.g. F. Bachmaier et al, NIM A, 786, (**2015**) 97-104, ***"A 3D diamond detector for particle tracking"***
- Radiation damage studies.
  - Eg. S. Lagomarsino et al, Applied Physics Letters **106**, 193509 (**2015**) "***Radiation hardness of 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**"

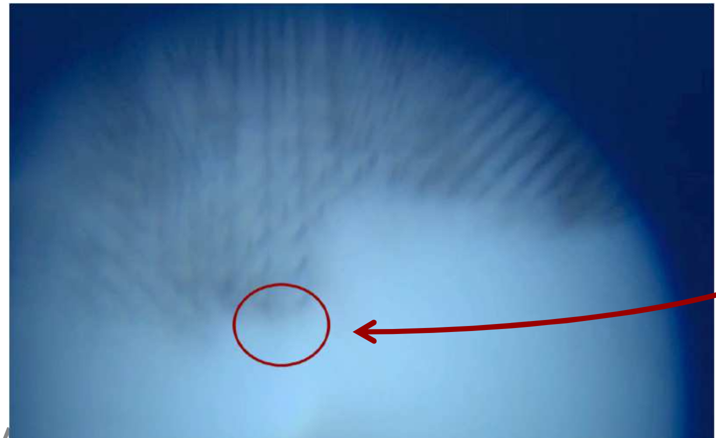


University of Manchester, Laser Processing Research Center.

- 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

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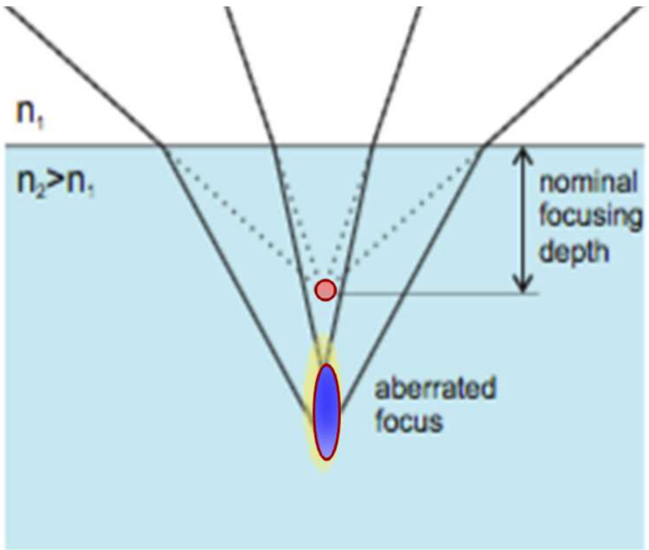
- Comparison SLM vs standard process.

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

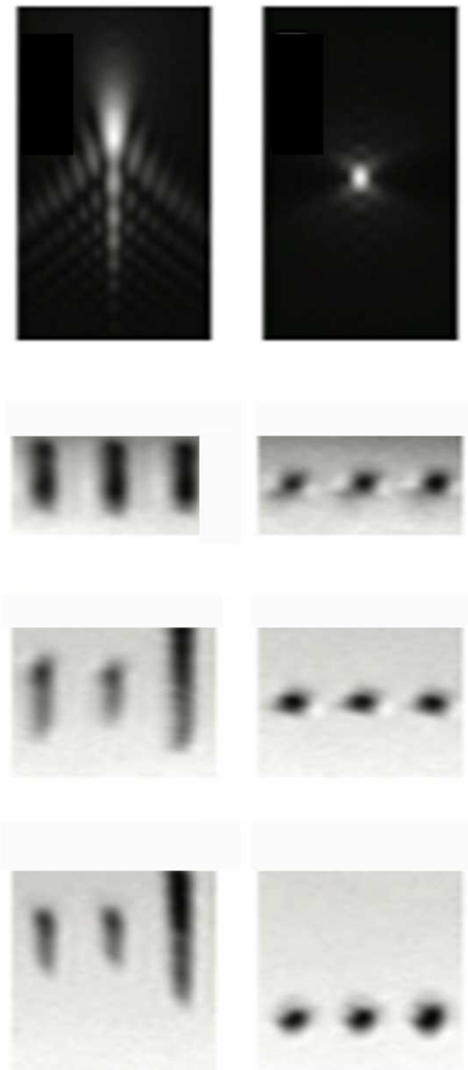


Simulated depth = 40µm

Measured depth = 40µm

depth = 80µm

depth = 130µm



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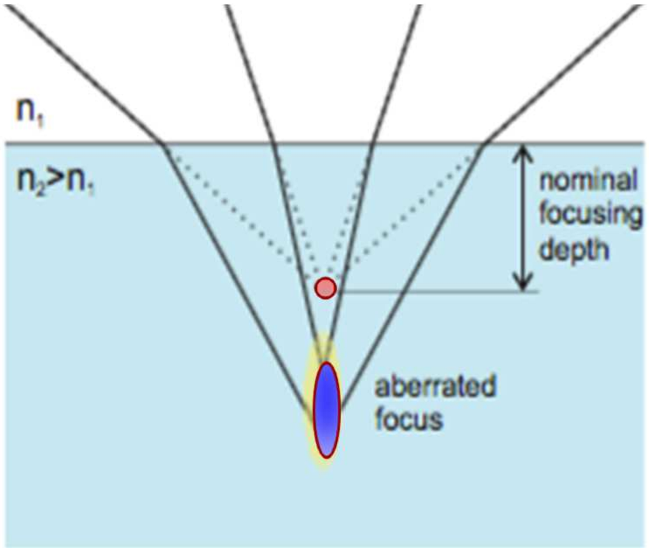
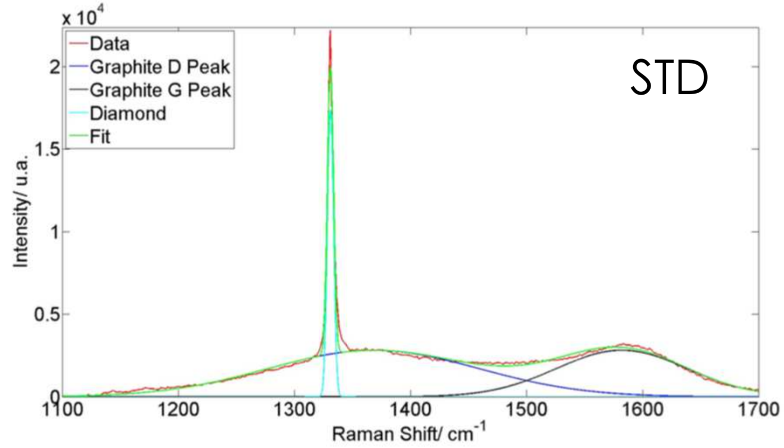
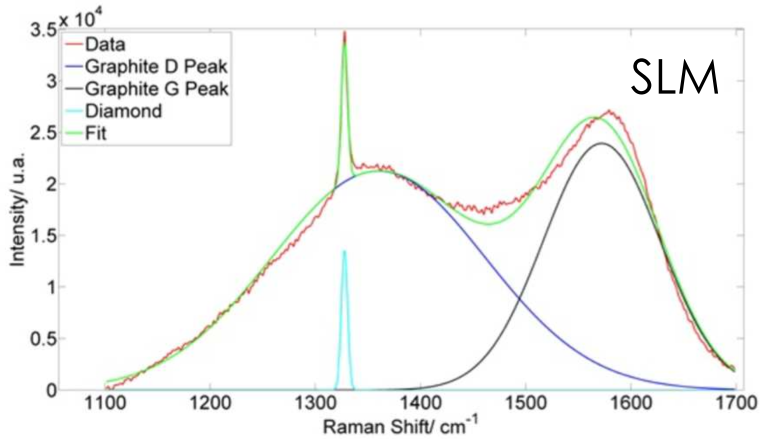
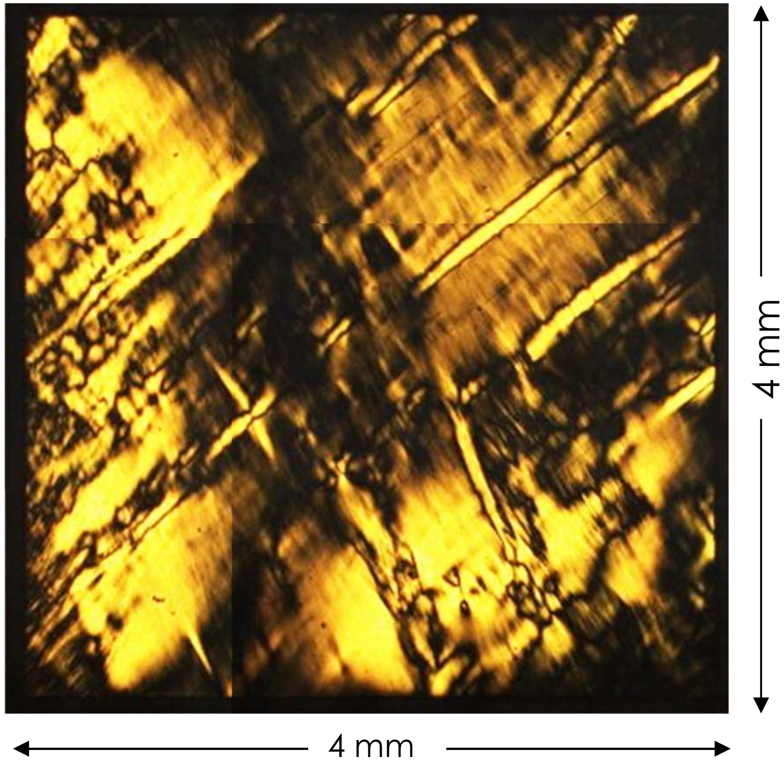


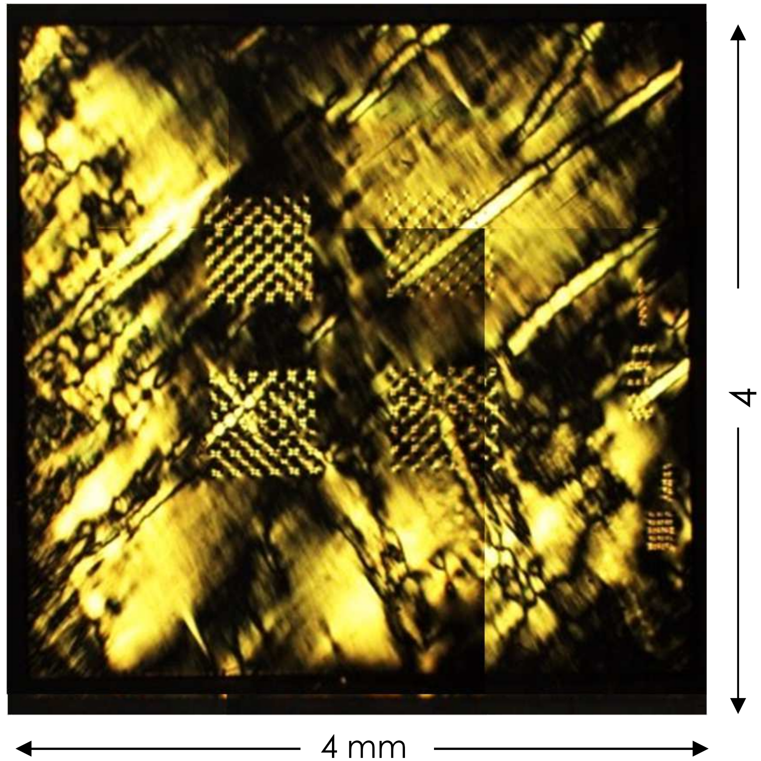


(a)



X-polariser image

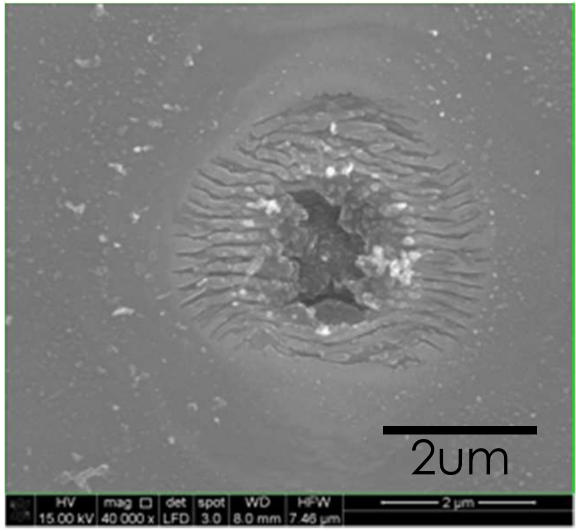




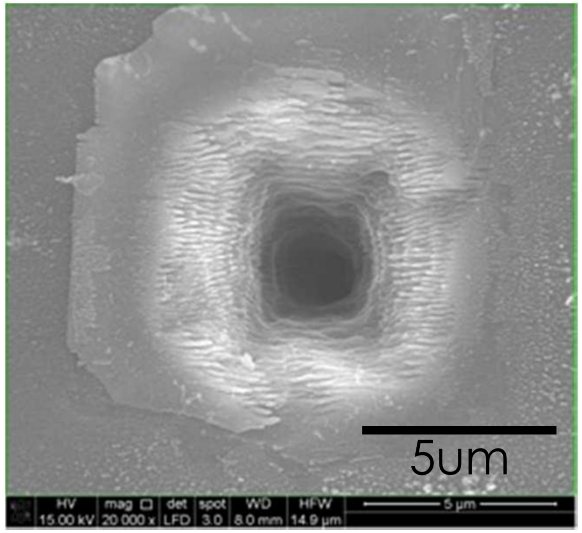
- Optical grade scCVD diamond.
- Post processing.

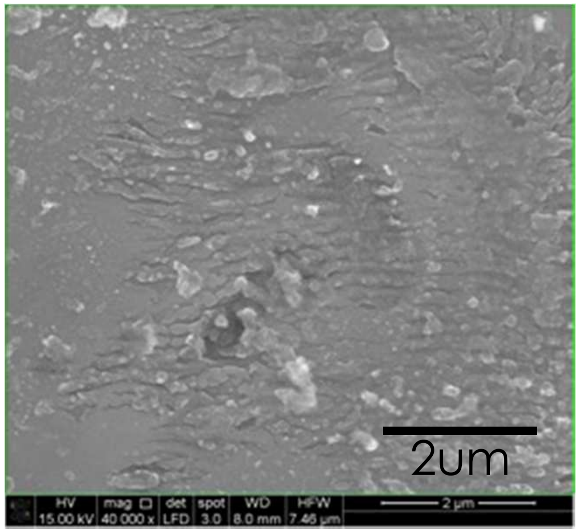
SEM surface image

- Seed surface
- Exit surface

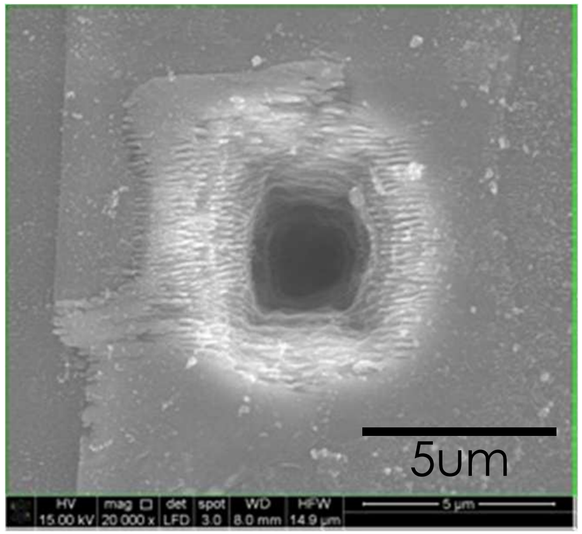


With SLM
10um/s
400nJ

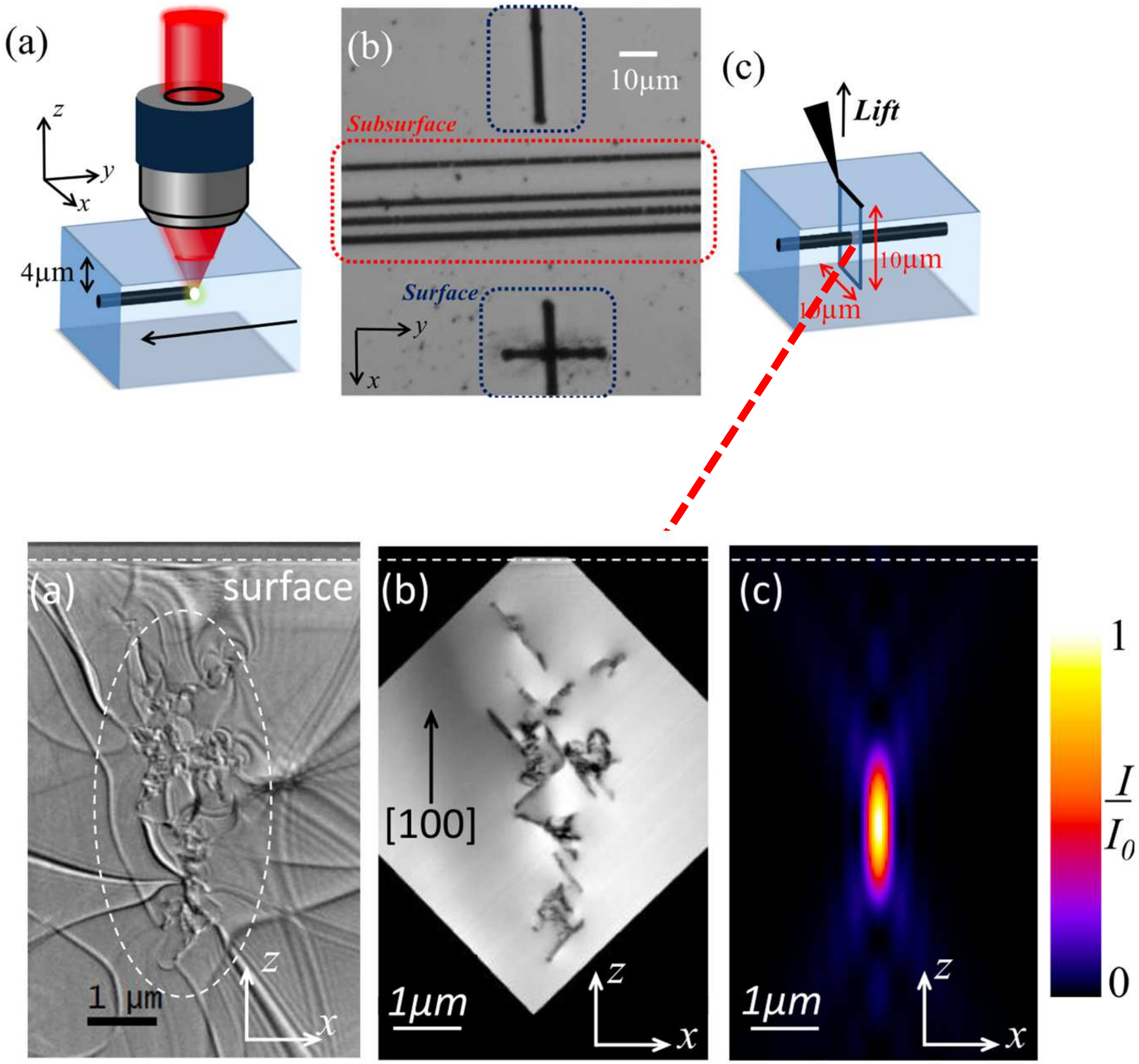




Without SLM
10um/s
400nJ



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!

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Parameter space scan

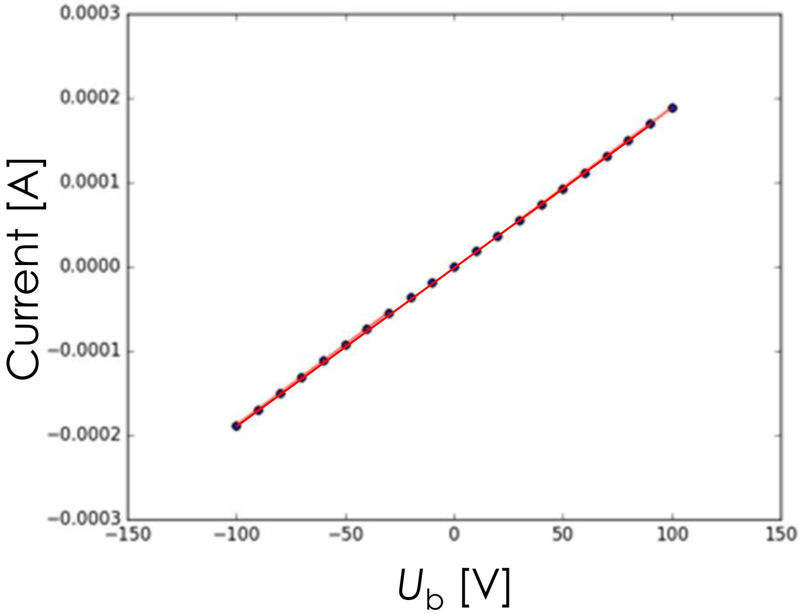
Patrick Salter, Oxford
Iain Haughton, AO, Manchester

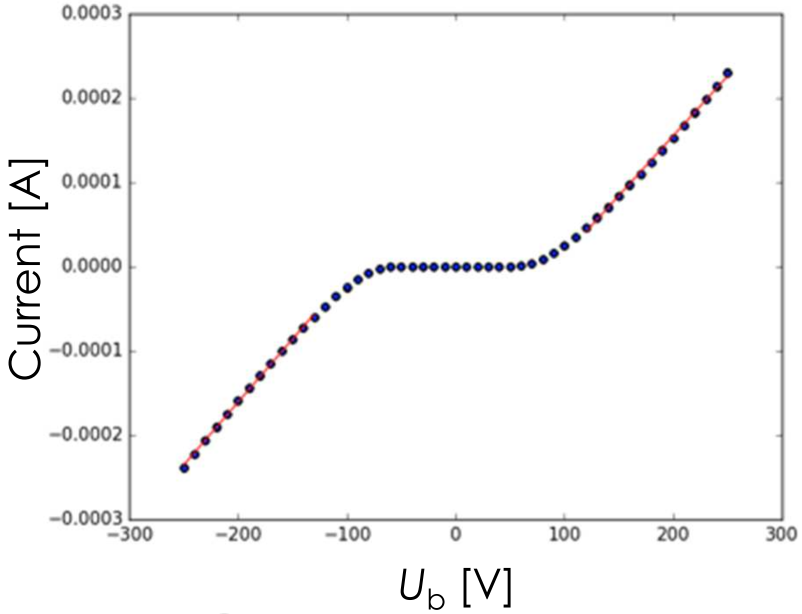
Laser beam energy		Laser translation speed			
		5um/s	10um/s	20um/s	30um/s
	100nJ	x	x		
	200nJ	x	x	x	
	300nJ		x	x	x
	400nJ		x	x	x
	500nJ			x	x
	600nJ				x

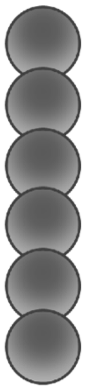
- Repeat **with** and **without** SLM correction.

IV curves

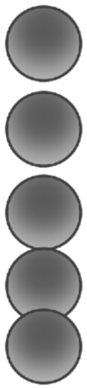
- Ohmic and barrier potential curves observed.





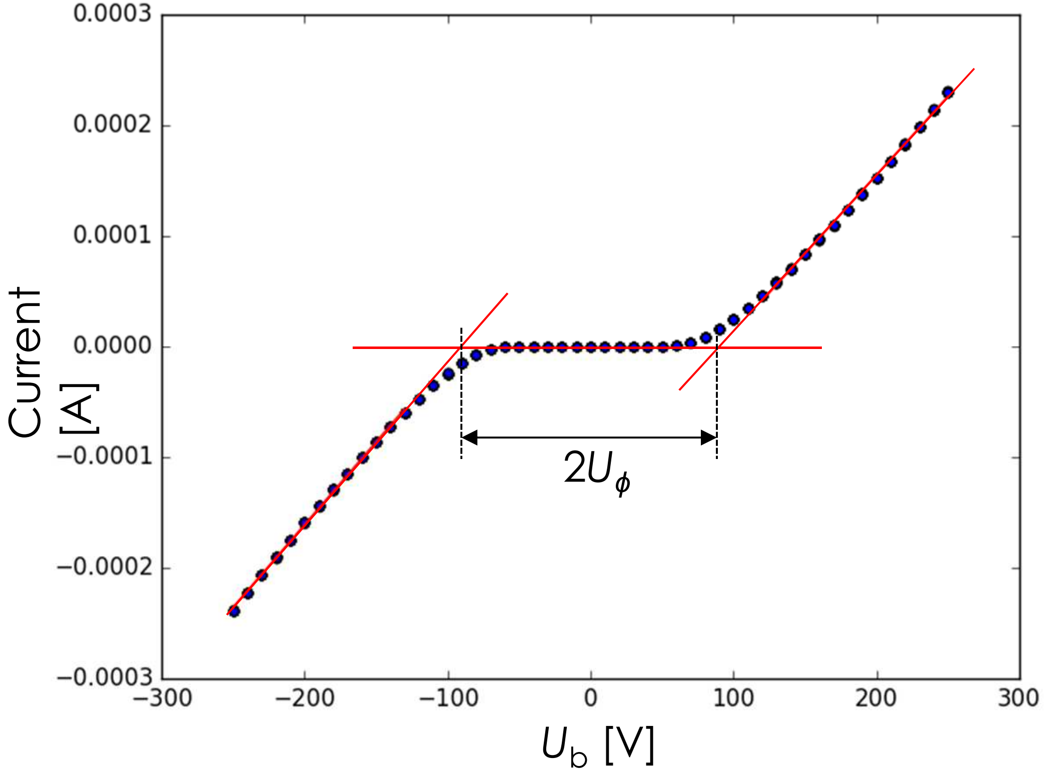


Continuous.

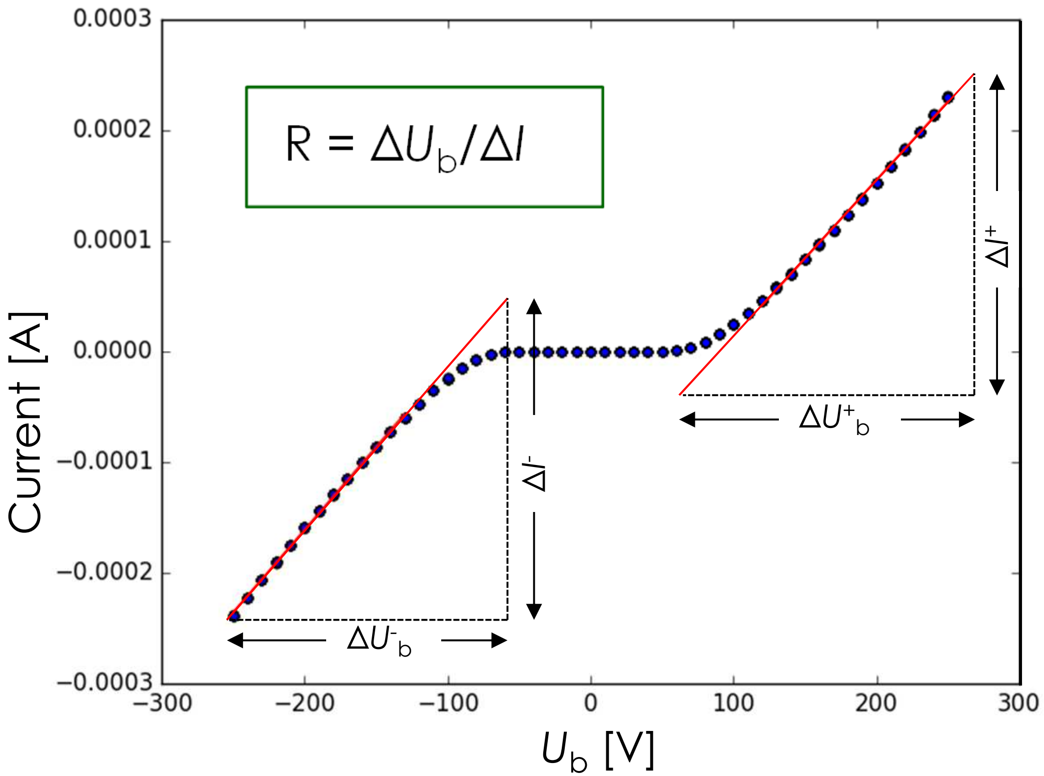


Bulk effect?
Micro gaps?

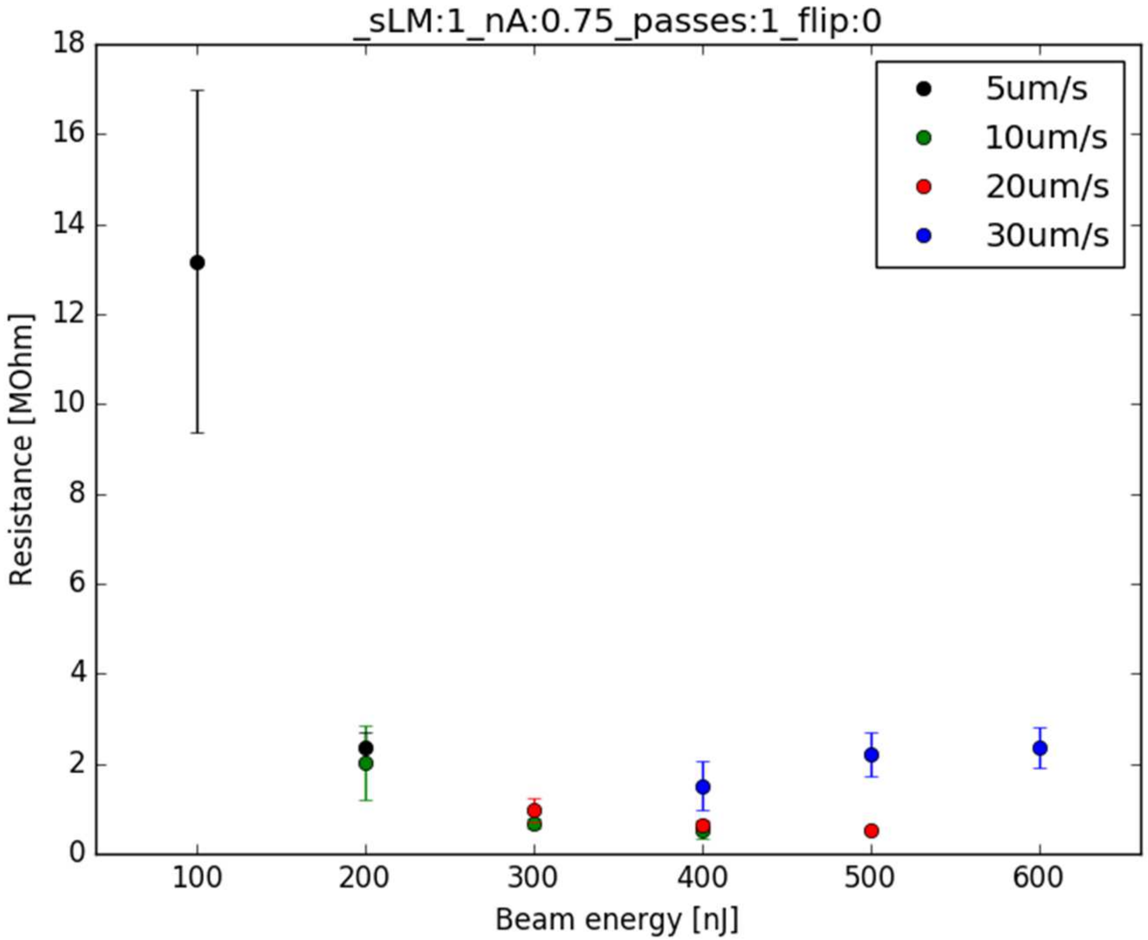
Barrier potential



Resistance measurement

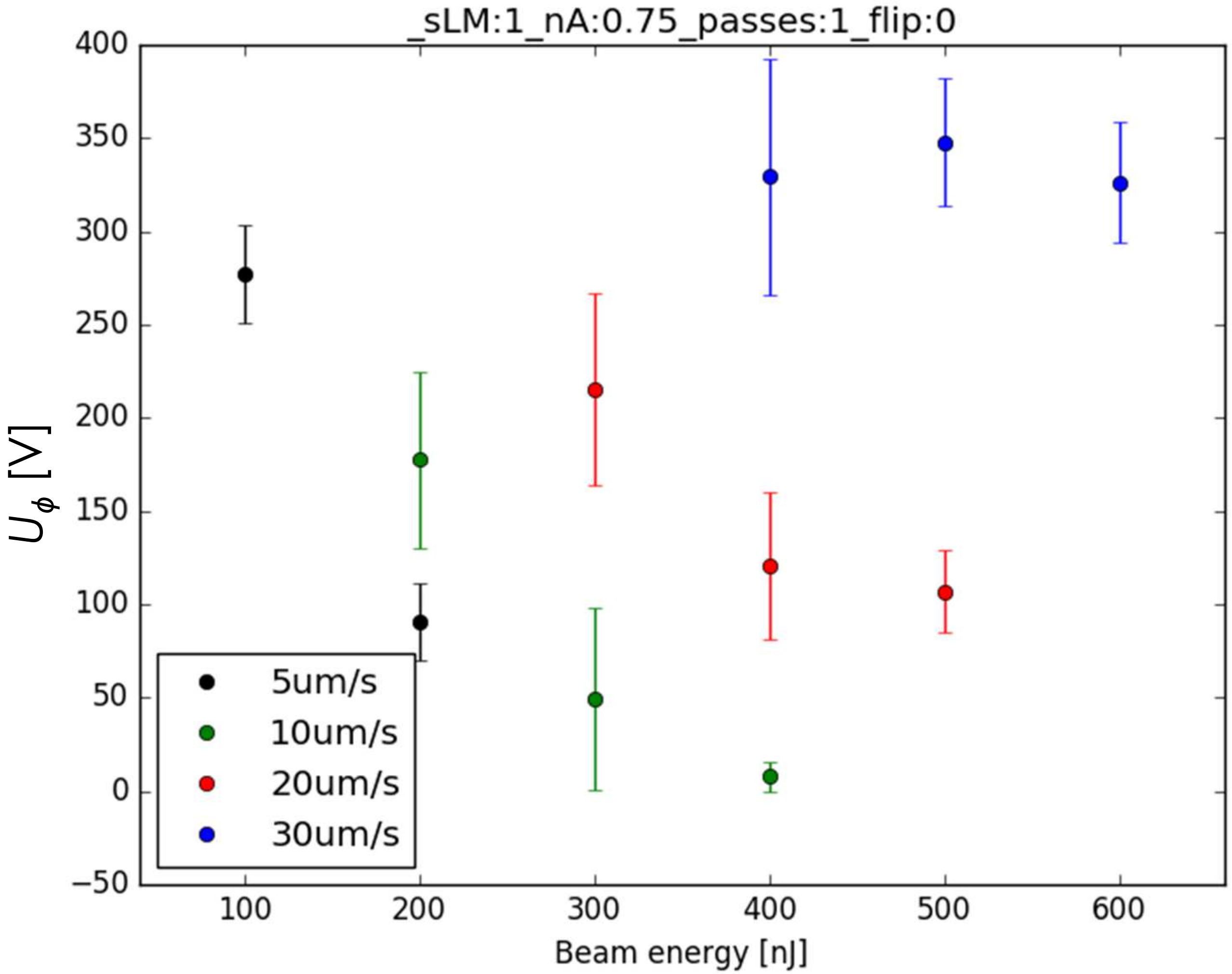


Resistance



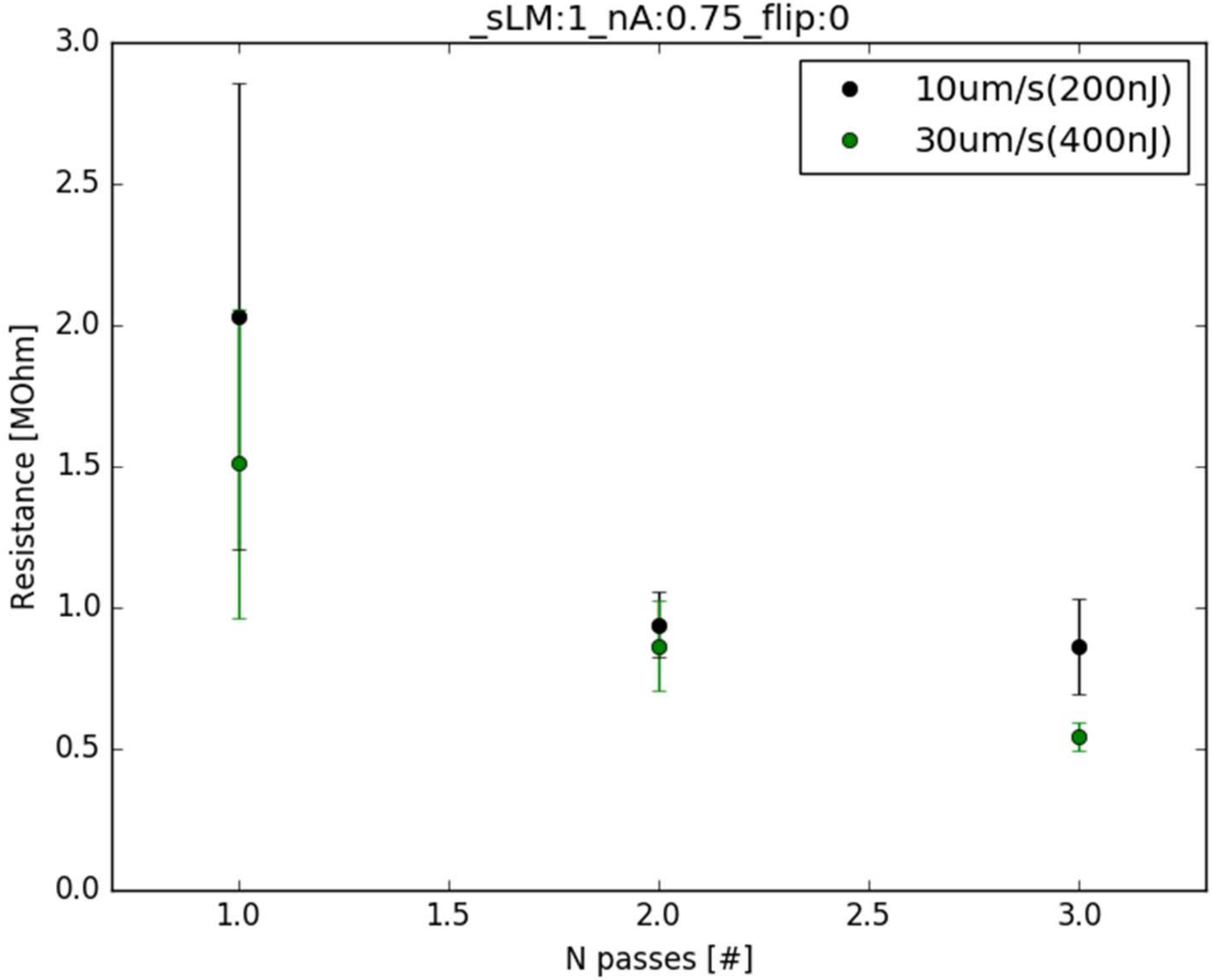
- Resistance increase as power law
  → multi-photon process.
- Clear discrepancy at 30um/s.

Barrier energy



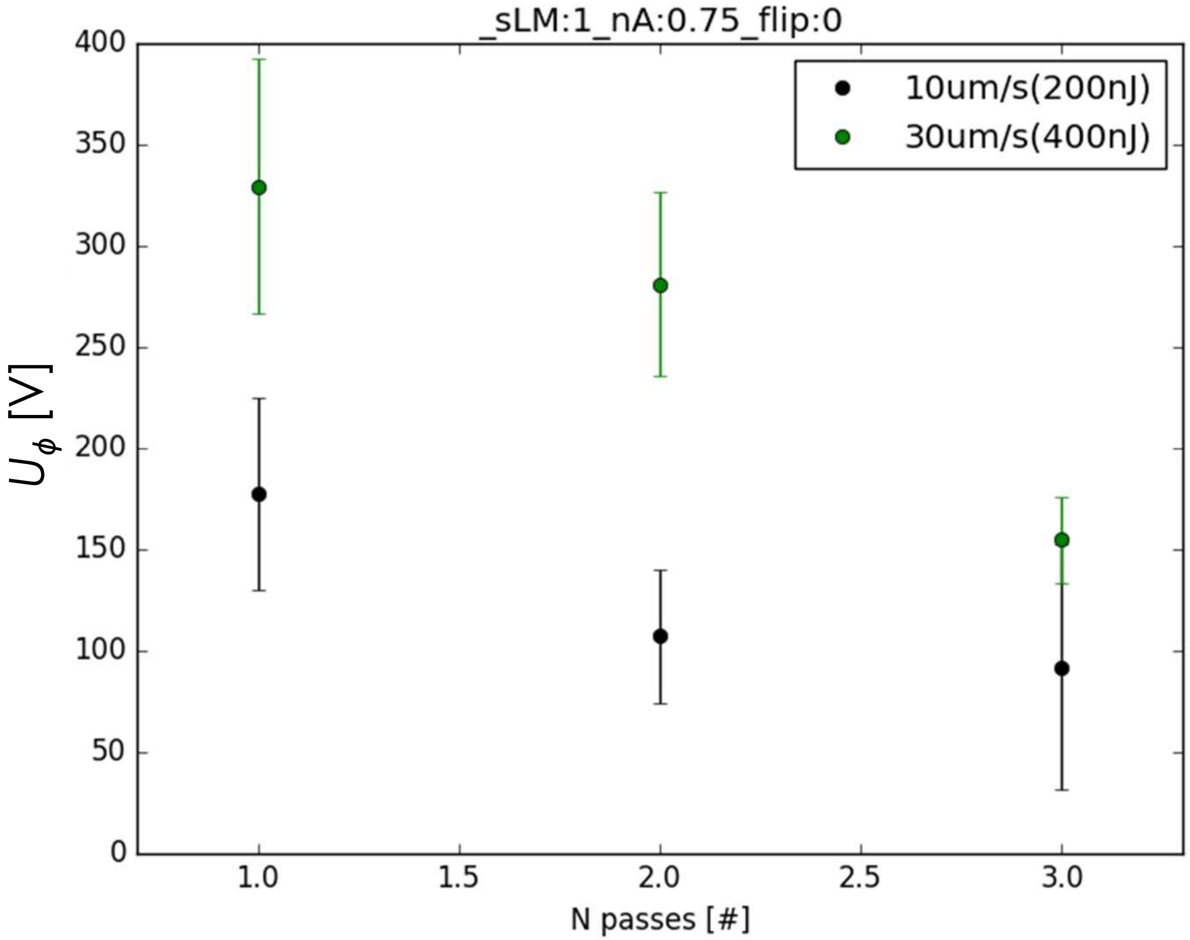
- Reduction in barrier with increased energy.
- Discrepancy at 30um/s.

Multiple passes



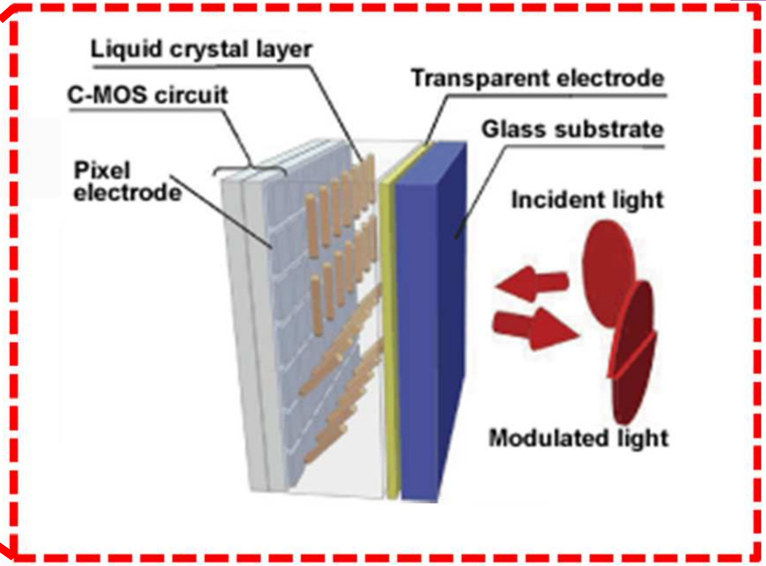
- Multiple passes reduces resistance and increases uniformity of the columns.

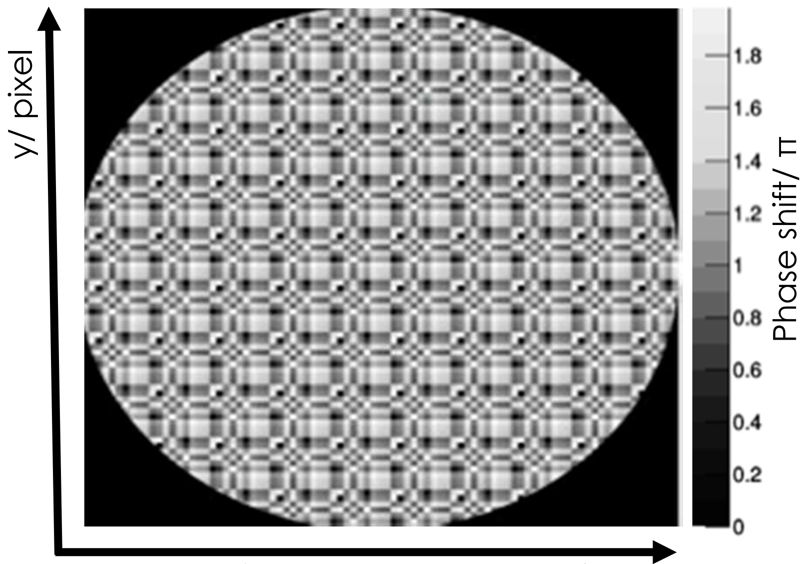
Multiple passes

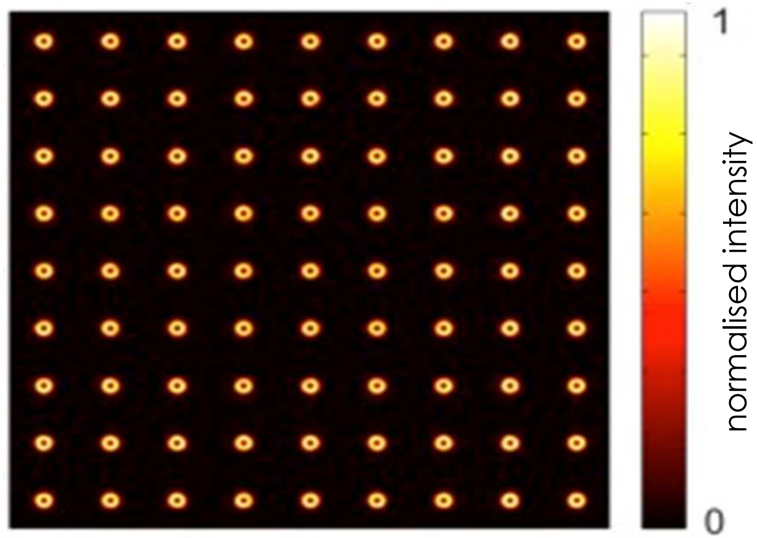


- Multiple passes also reduces U_ϕ.

SLM parallel processing?



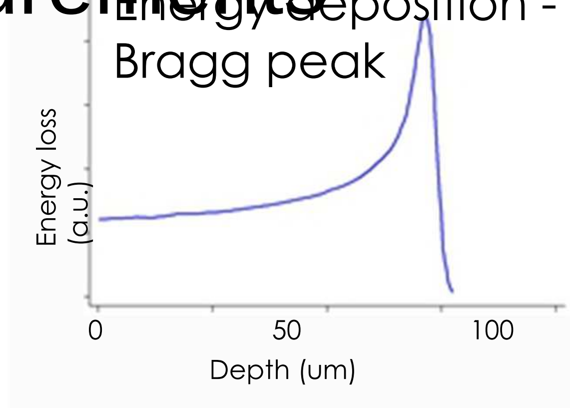




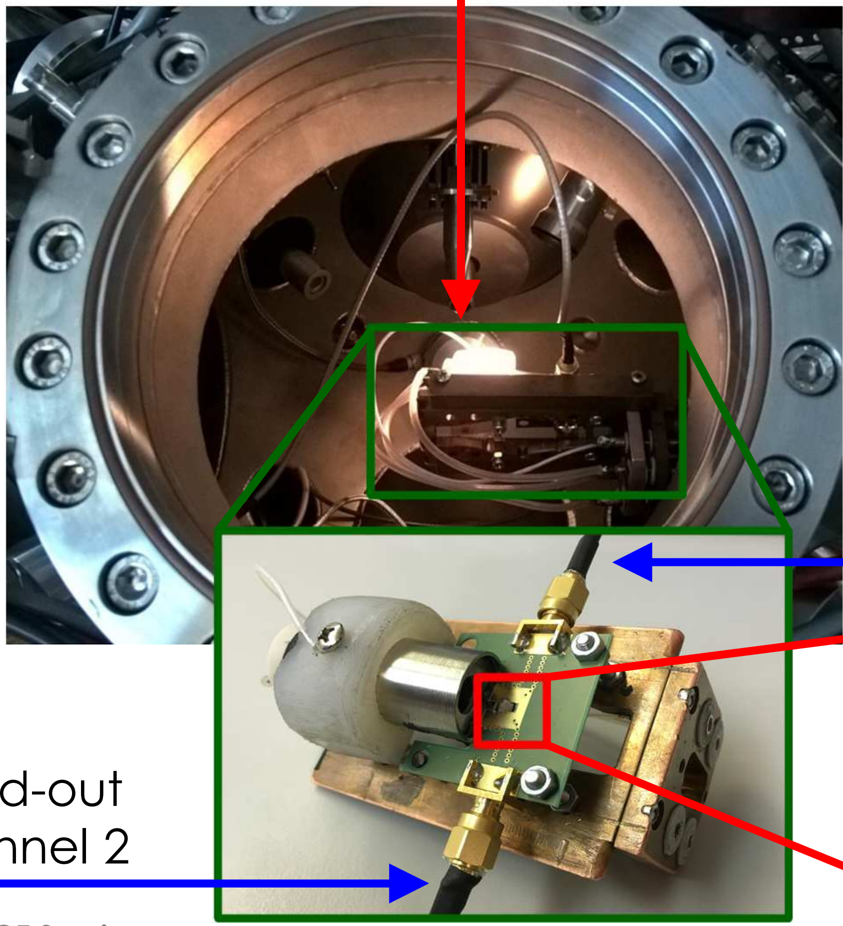
3D Detector Characterization

- Proton Micro-beam: 4.5 MeV p

Proton micro-beam measurements



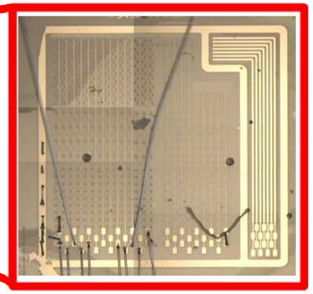
4.5 MeV protons



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

Read-out channel 1

Read-out channel 2

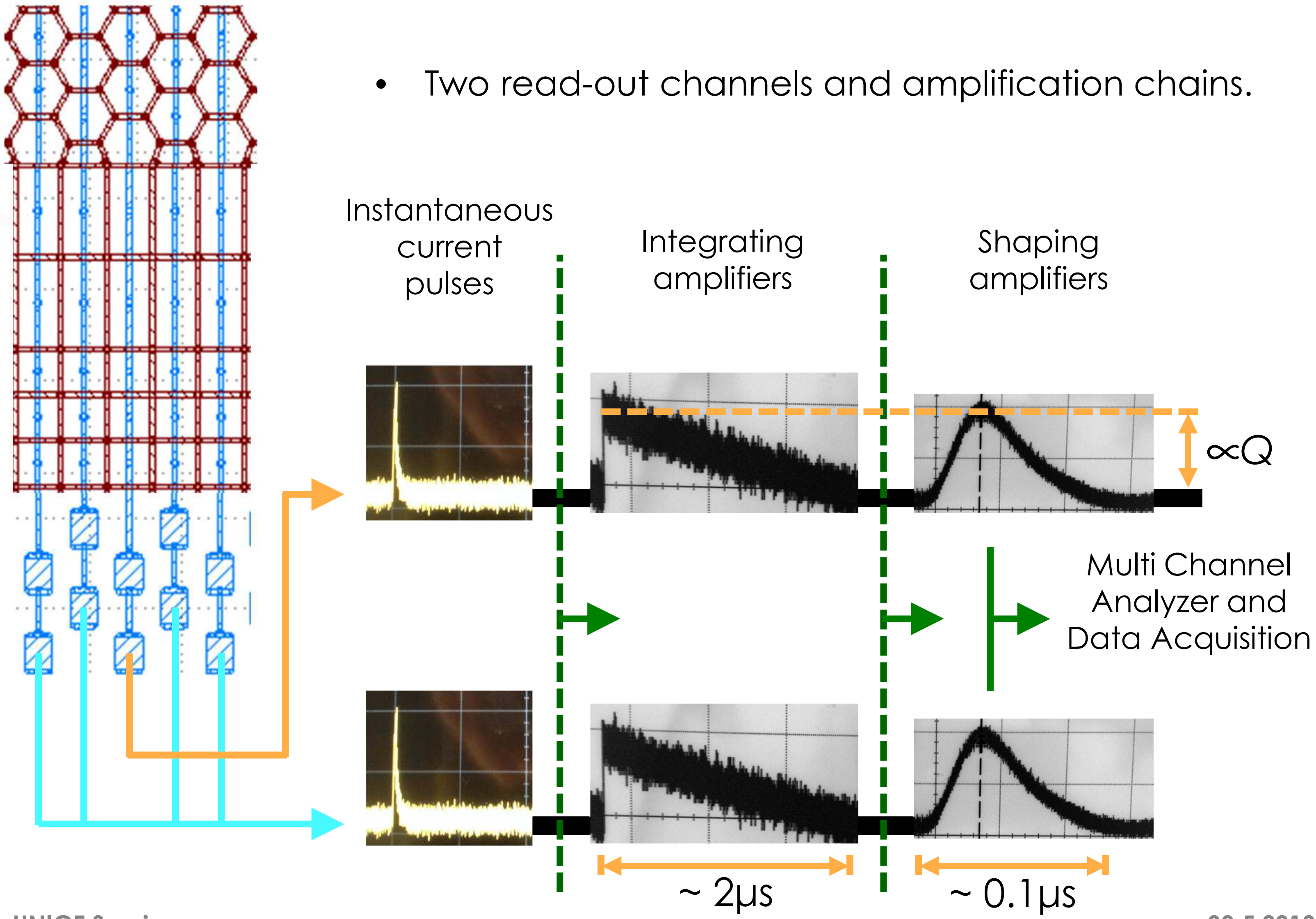


3D diamond detector

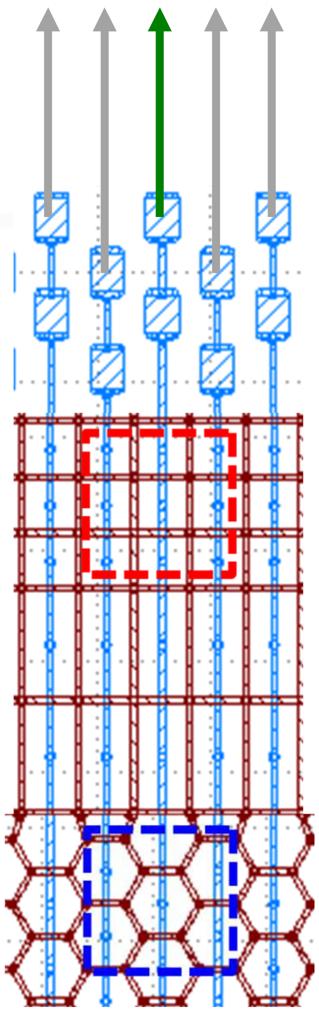
(TR)IBIC

(Time Resolved) Ion Beam Induced Current

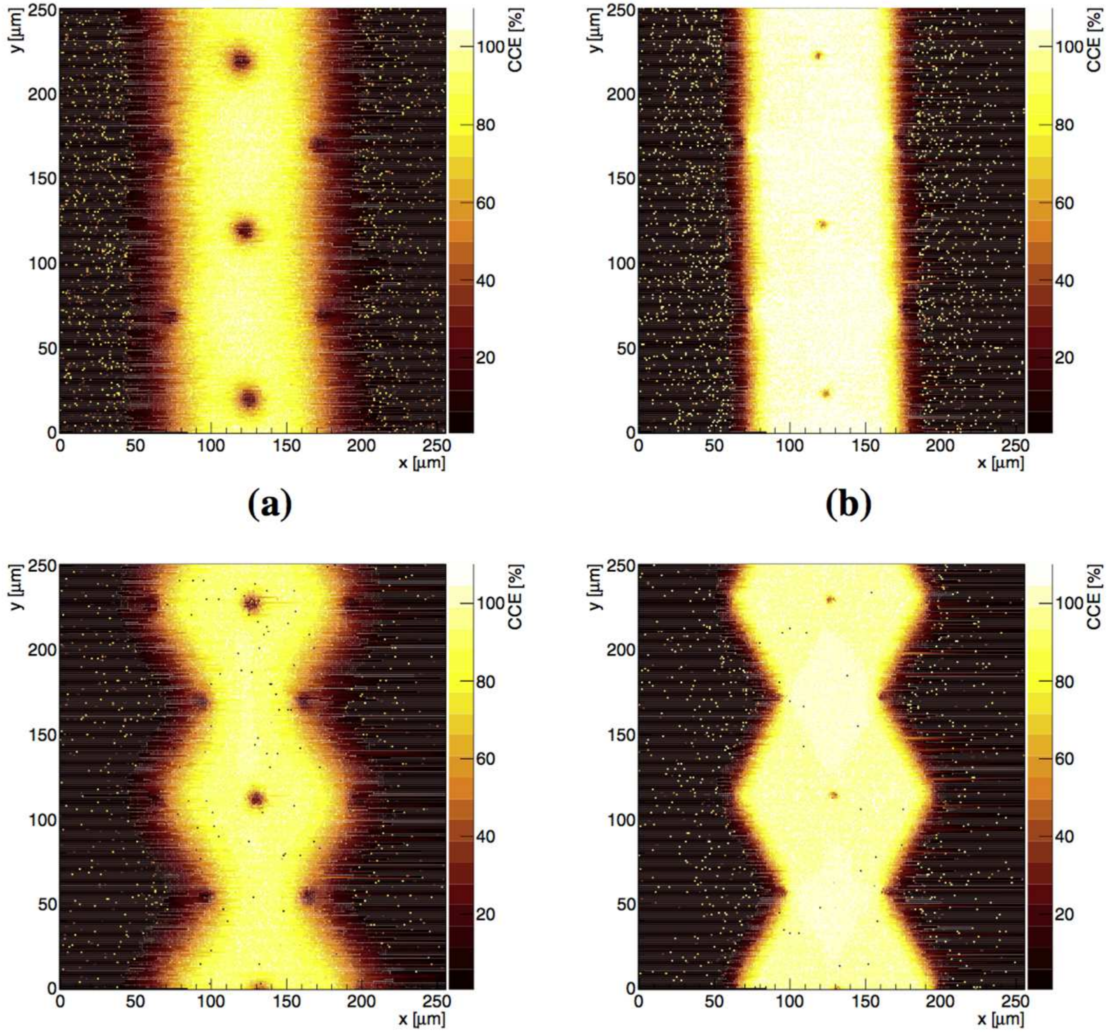
- Two read-out channels and amplification chains.



Signal efficiency at -2V and -20V



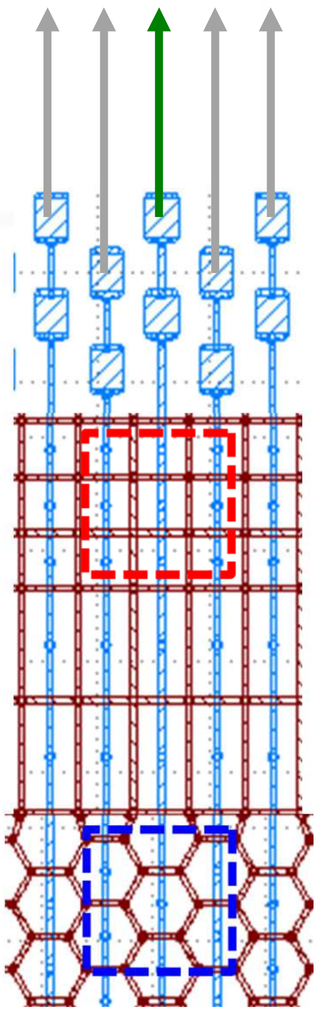
Square

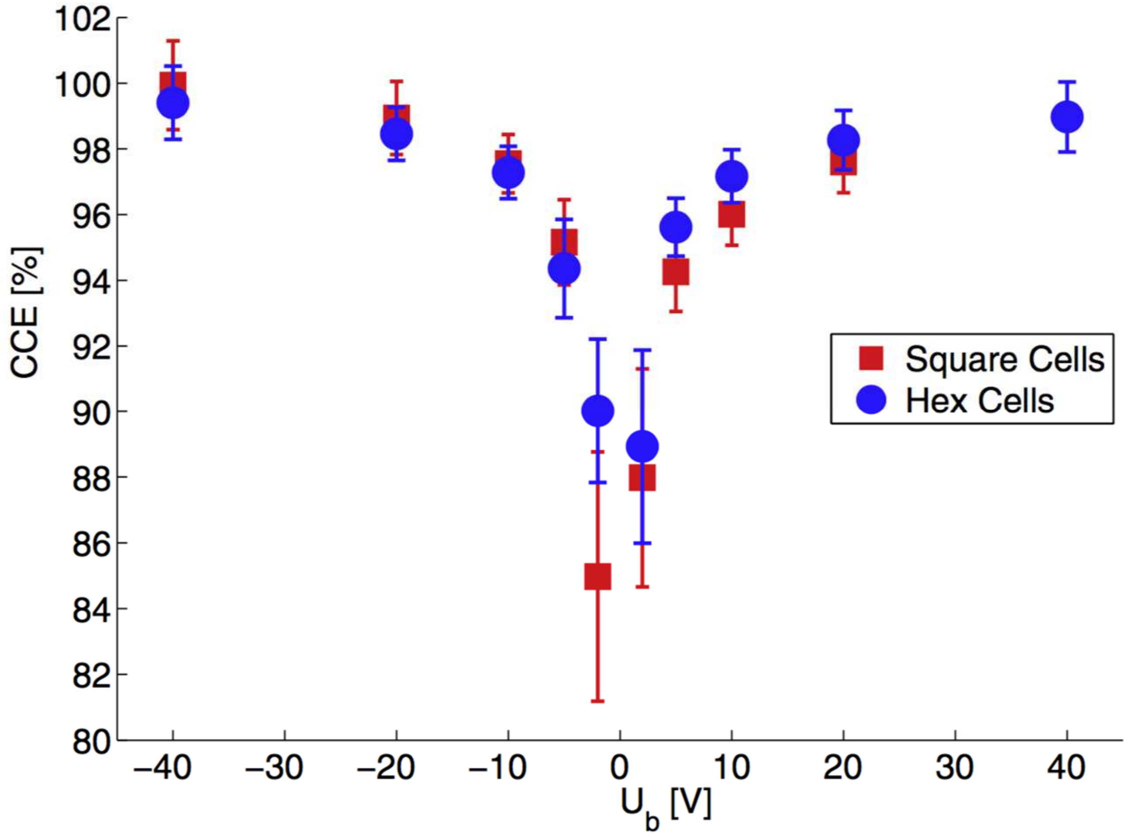


(a) (b) (c) (d)

Hexagonal

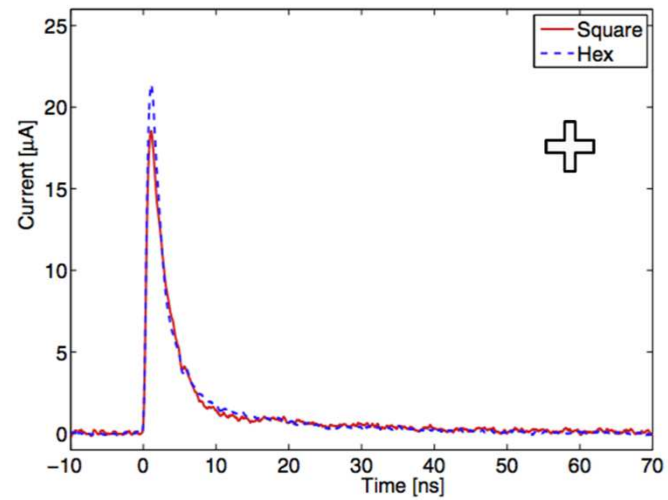
Signal efficiency at -2V and -20V

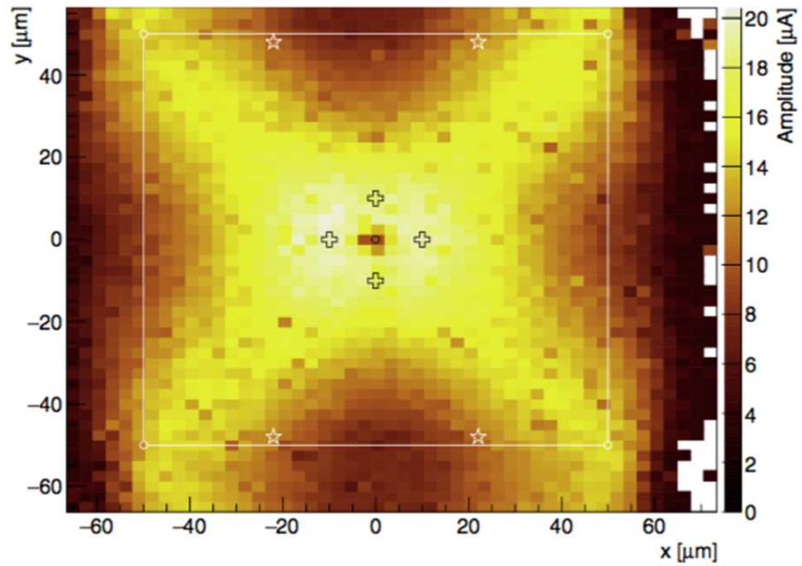


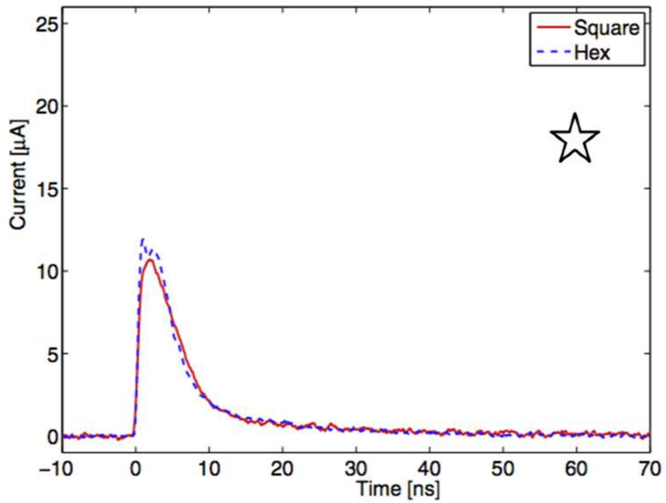


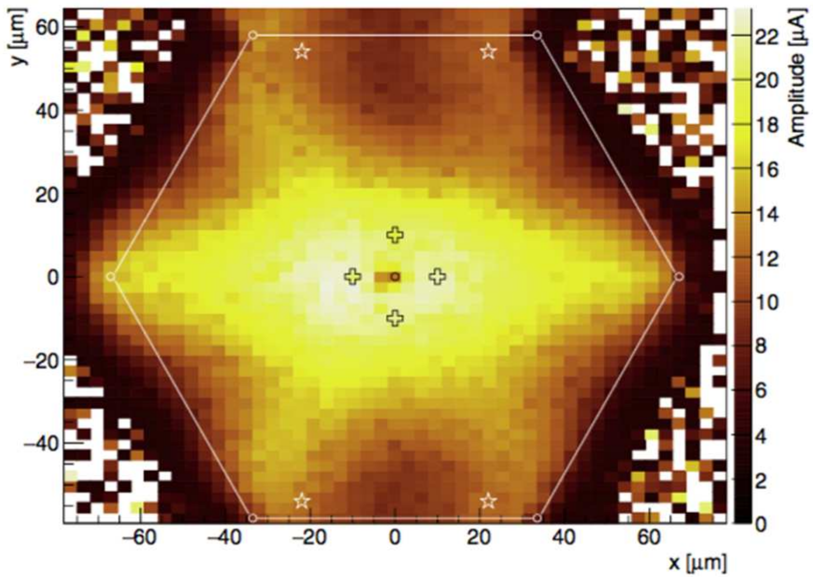
TRIBIC

U_b=-20V

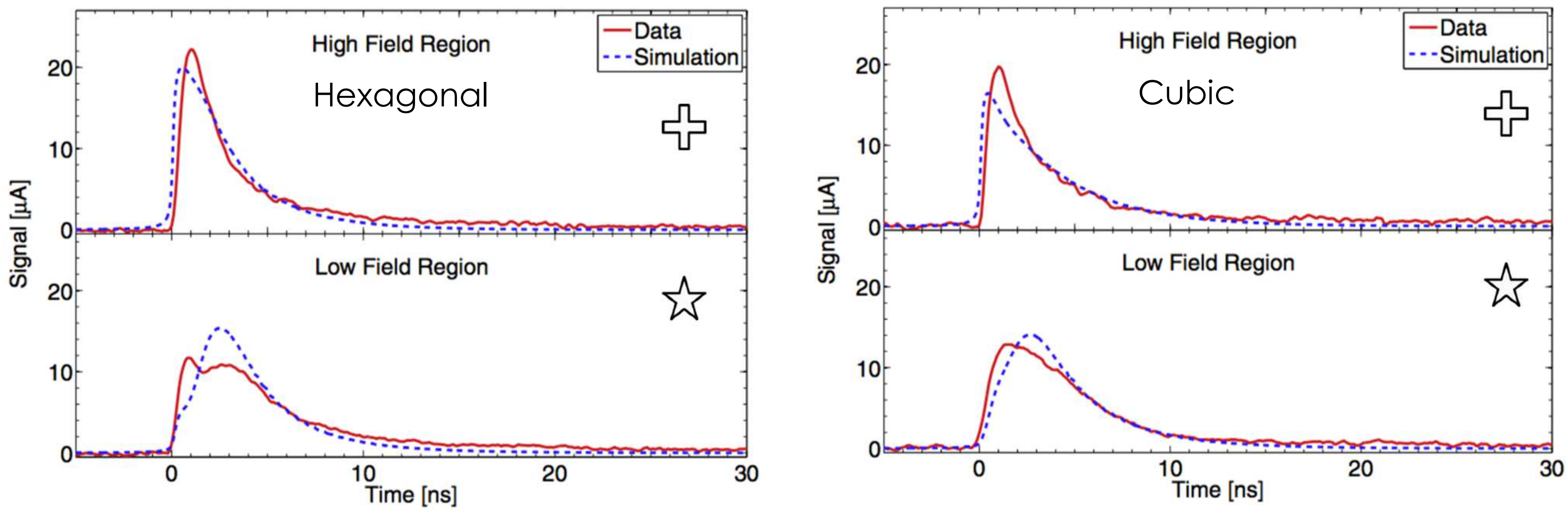








TRIBIC: Results



Comparison with TCAD Simulation model:

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

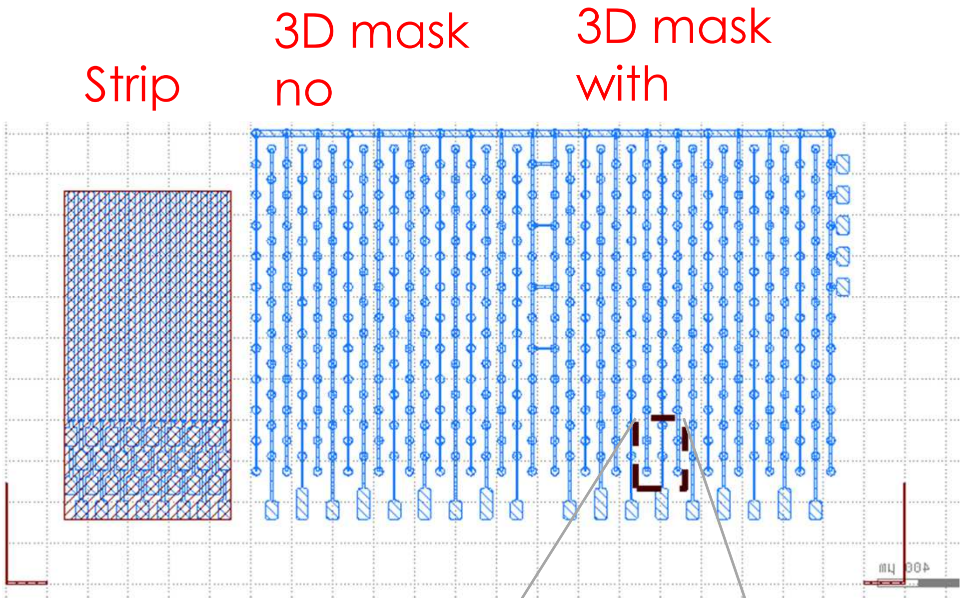
3D Diamond detector tests with relativistic charged particles

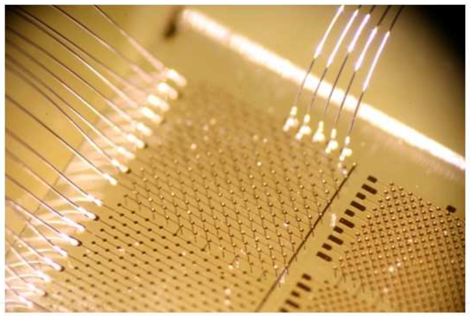
- Types
  - 100x100um cell size ganged to form strips
  - 100x100um cell size, bonded to pixel read-out
  - 50x50um cell size, bonded to pixel read-out
- All detectors made from polycrystalline diamond.
- Beam tests
  - CERN beam line H6 : protons ~ 120 GeV/c
  - PSI : pions ~ 250 MeV/c

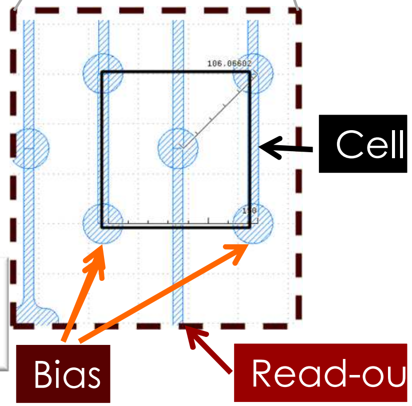
Thanks for material from the RD42 collaboration!

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]

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Analysis steps

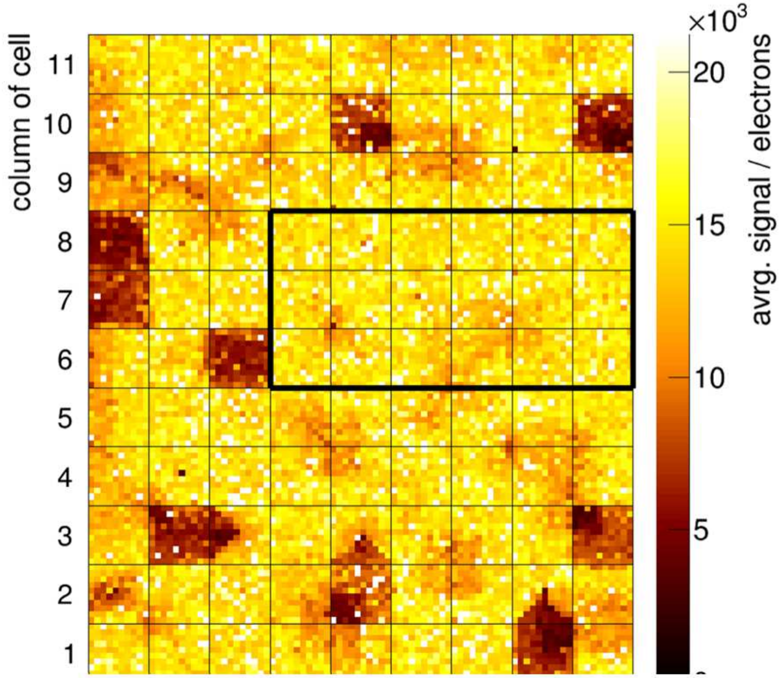
- $U_b(3D)=40V$
- $U_b(strip)=500V$

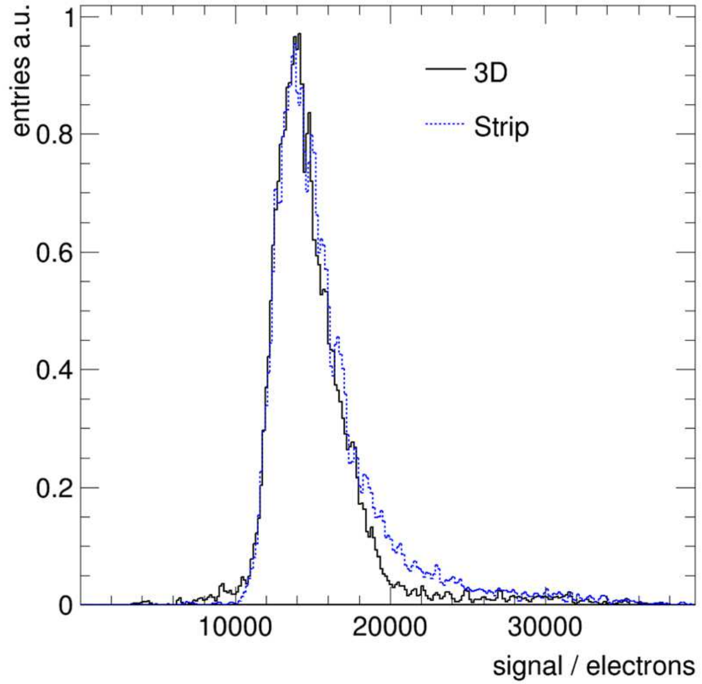
- Identify **continuous region** of intact cells for analysis.
- Exclude contribution of negative signals.

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

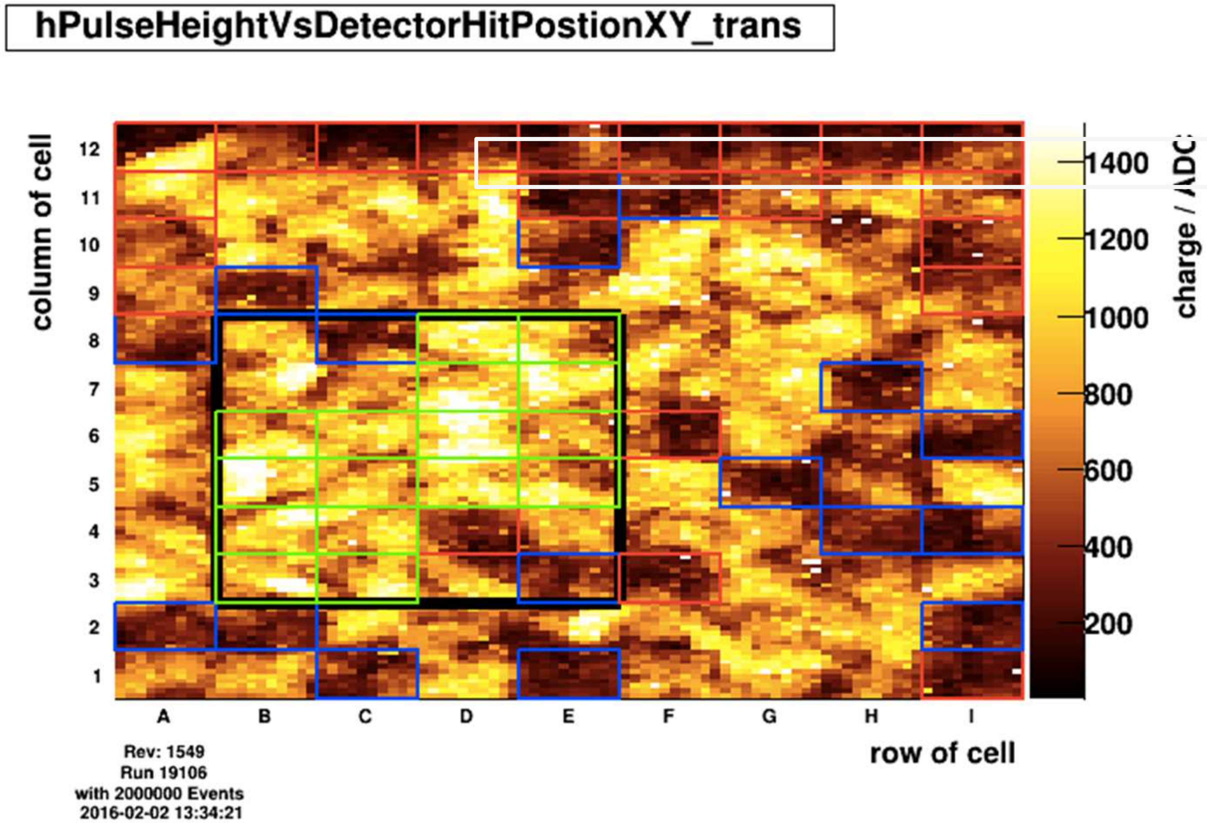
- **MP:**
  Strip: 14.7ke
  3D: 15ke

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





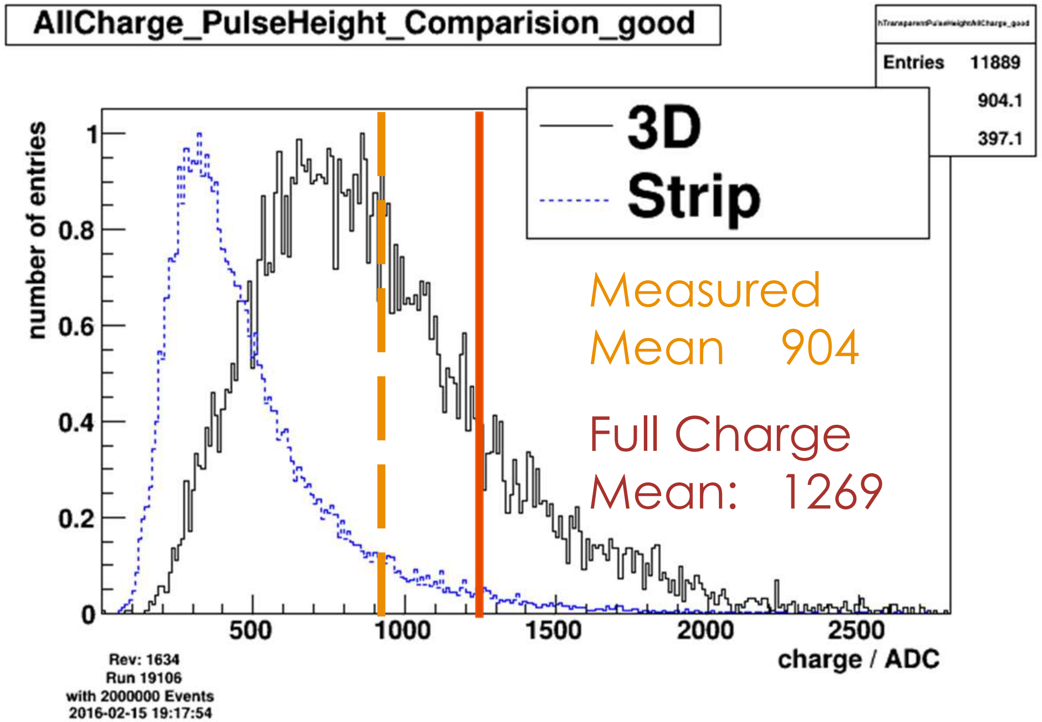
Test of first 3D pCVD diamond detectors



- 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.

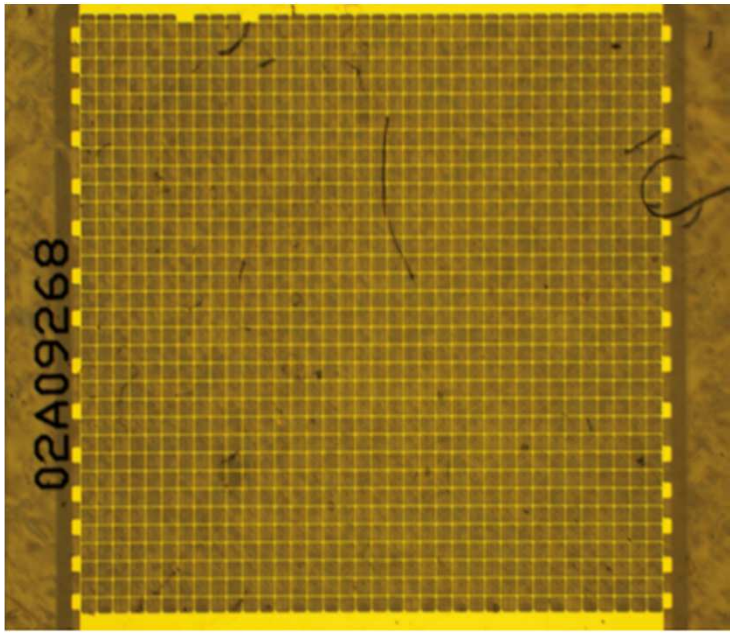
Highest charge collection ever measured for pCVD diamonds

Large area 3D, pCVD, 100x100

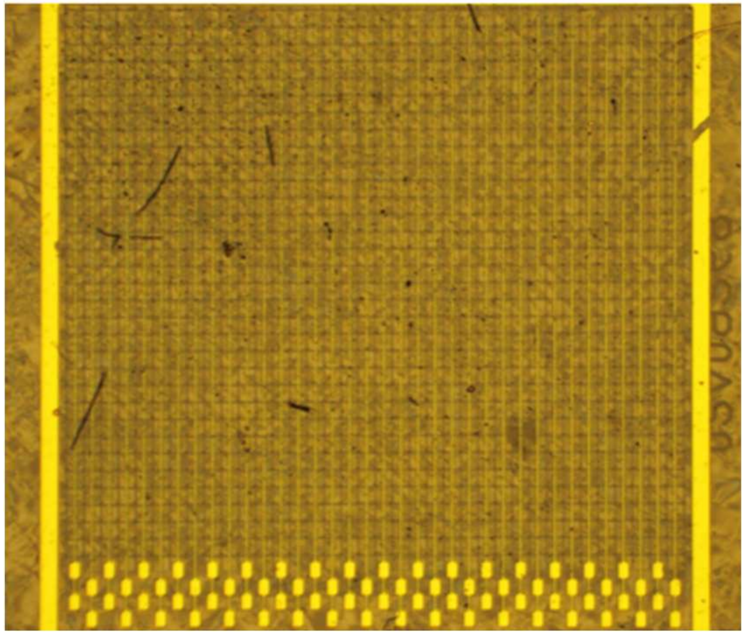
In May/Sept 2016 tested the first full 3D device fabricated in pcCVD with three dramatic improvements:

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

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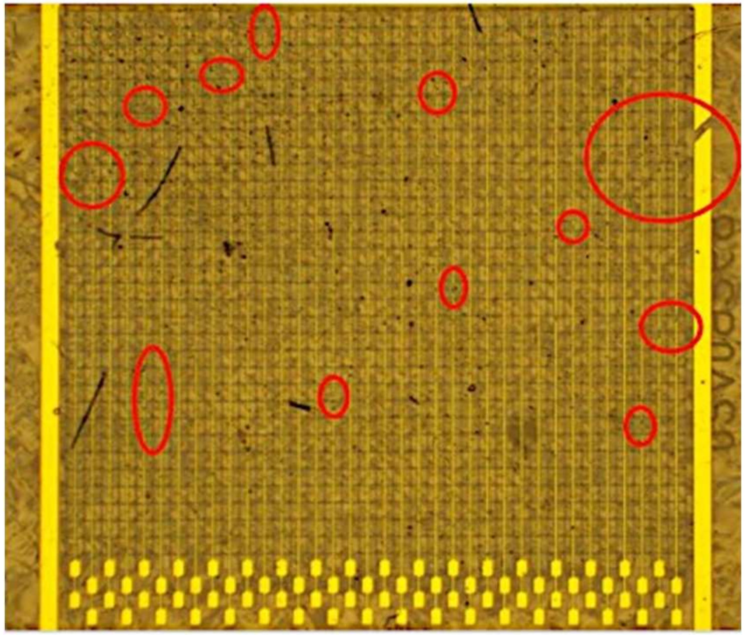
Readout side



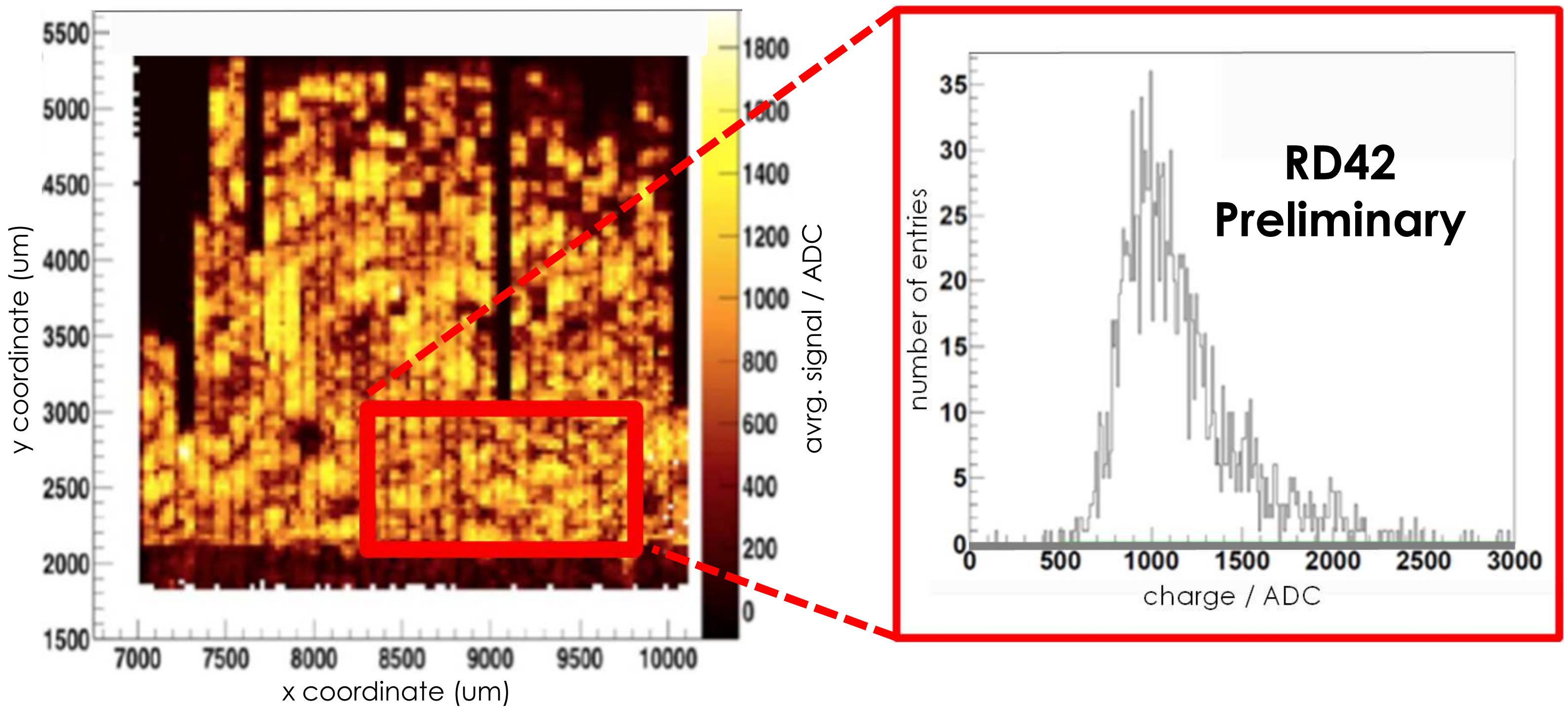
Some issues with handling procedures led to:

- Surface contamination.
- Some breaks in surface metallisation.

→ All fixable!

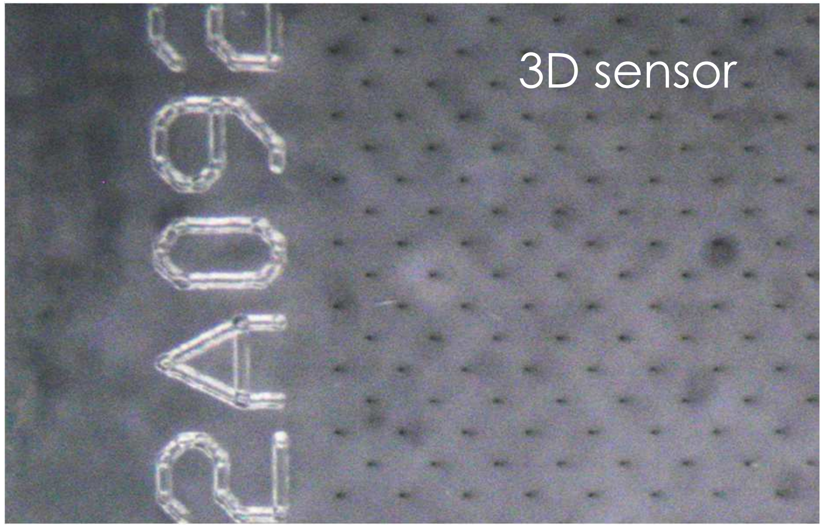
Large area 3D, pCVD, 100x100

- Largest charge collection to date in pcCVD diamond!
  - >85 % of charge collected in continuous region.
- Analysis in progress on full detector.

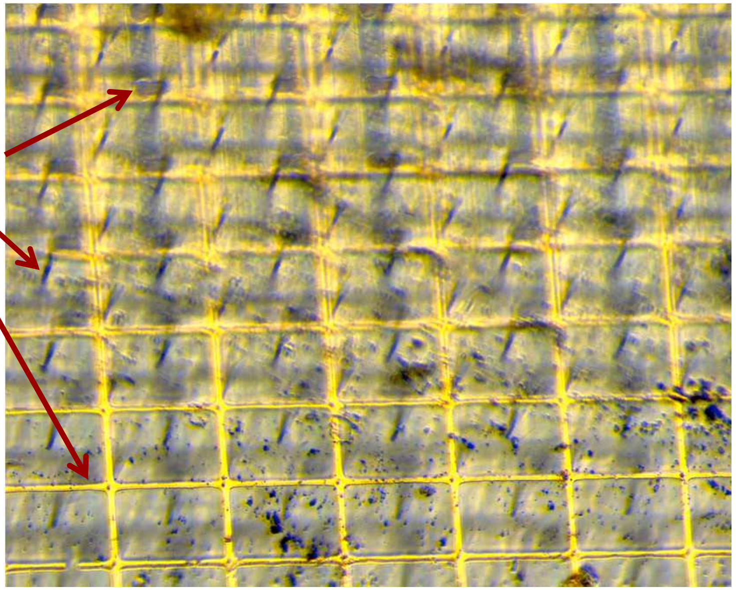


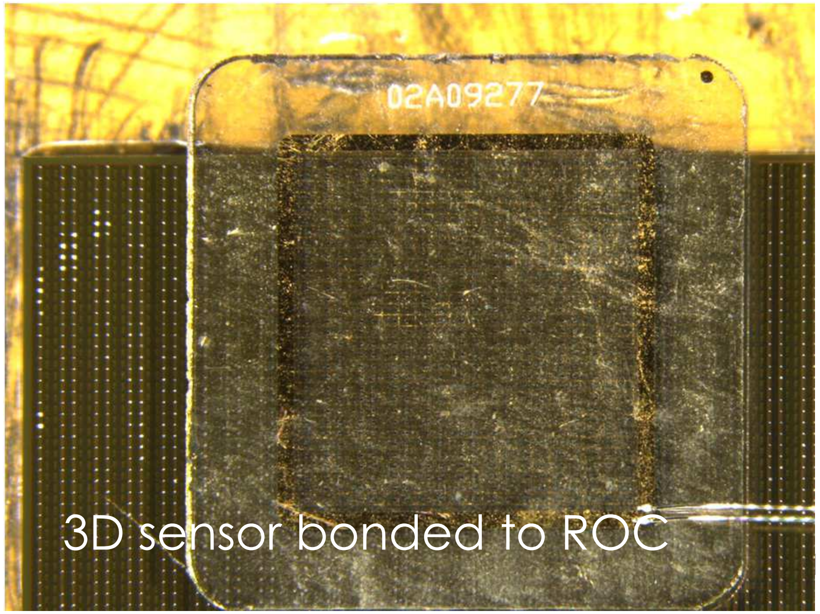
Pixel 3D, pCVD, 100x100

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



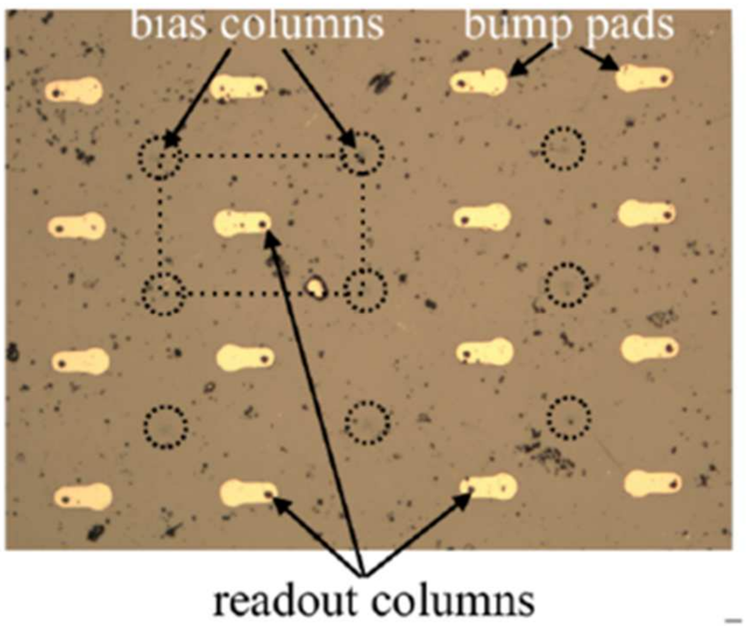
Bump pads
Columns
Bias grid

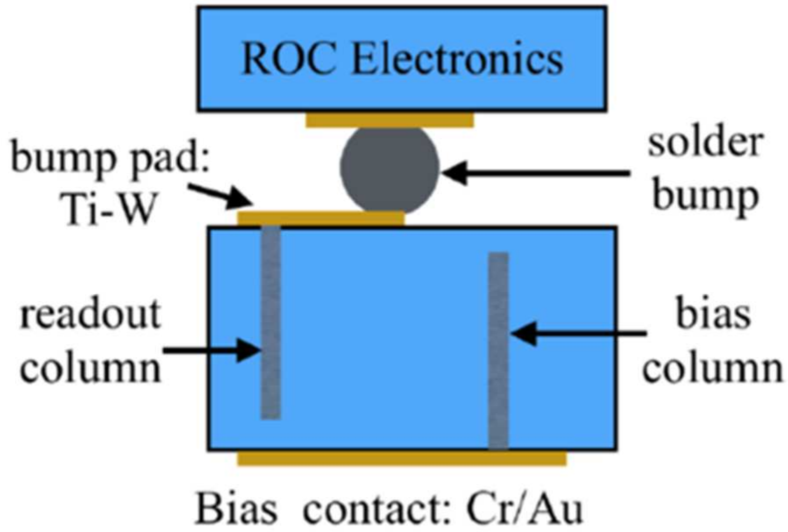




Pixel 3D, pCVD, 100x100

- Production of first pixel device using CMS readout electronics.

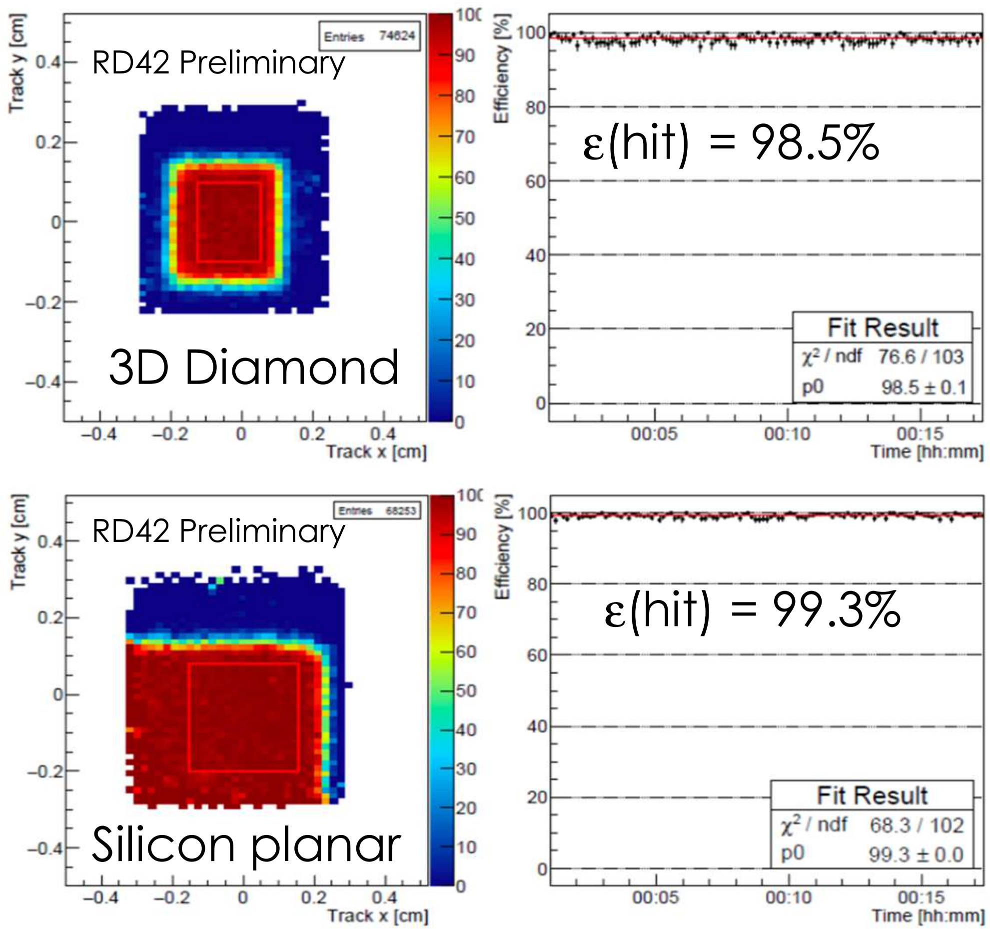




- Active region 3x3 mm with cell size ~100x100 um.

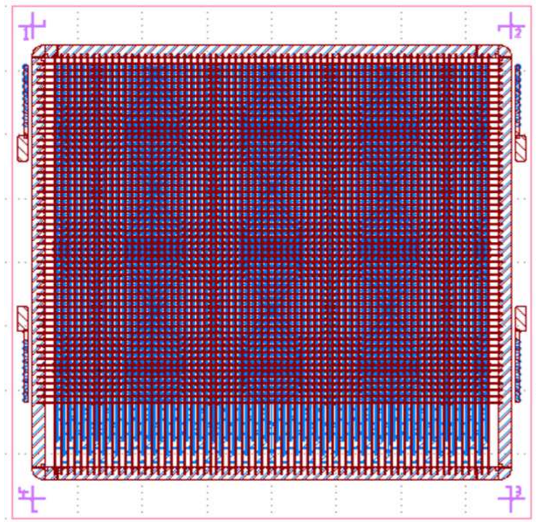
Pixel 3D, pCVD, 100x100

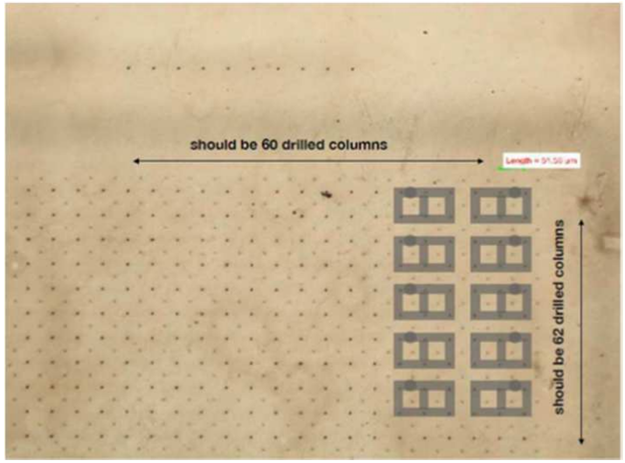
- Tested at PSI testbeam.
  - 3D diamond device and Silicon reference planar device.
  - Pixel threshold 1500e.
  - Check hit efficiency over time.
  - Device works!



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.
- This week in testbeam at CERN





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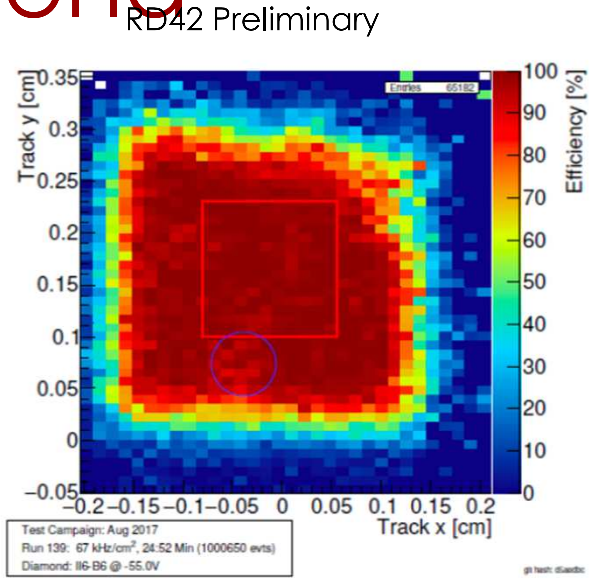
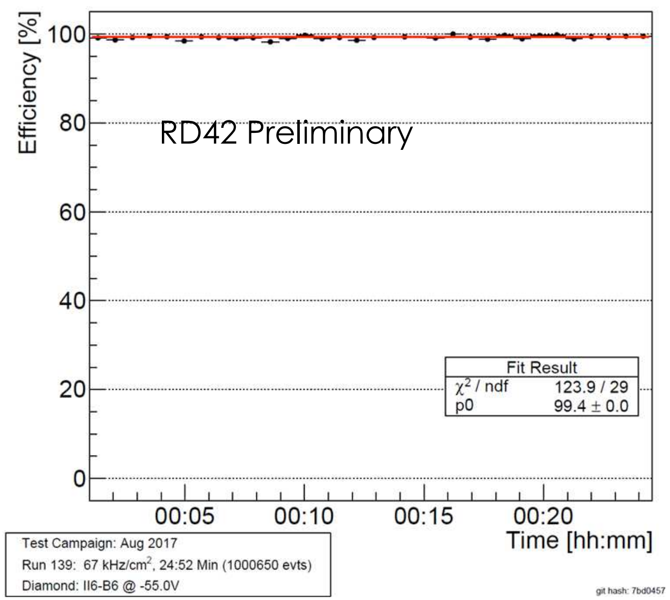
50x50 μm cell 3D Diamond

Preliminary Results (50μmx50μm pixels)

- 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.





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Summary

- Diamond systems are used as beam and luminosity monitors in current HEP 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.

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

Dosimetry application

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

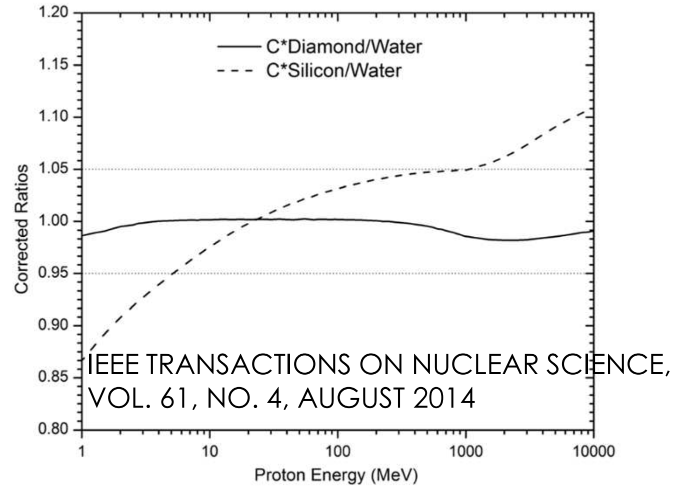

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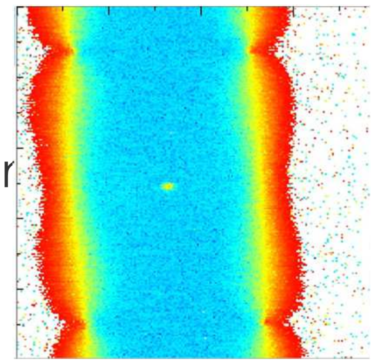
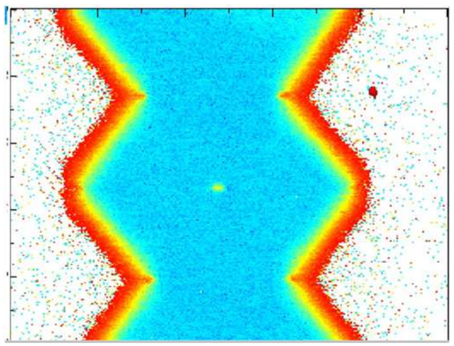
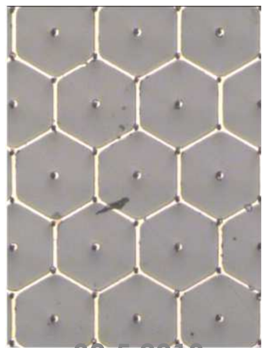
Fig. 14. Comparison of the corrected ratio of stopping powers for protons of diamond and silicon with water.

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

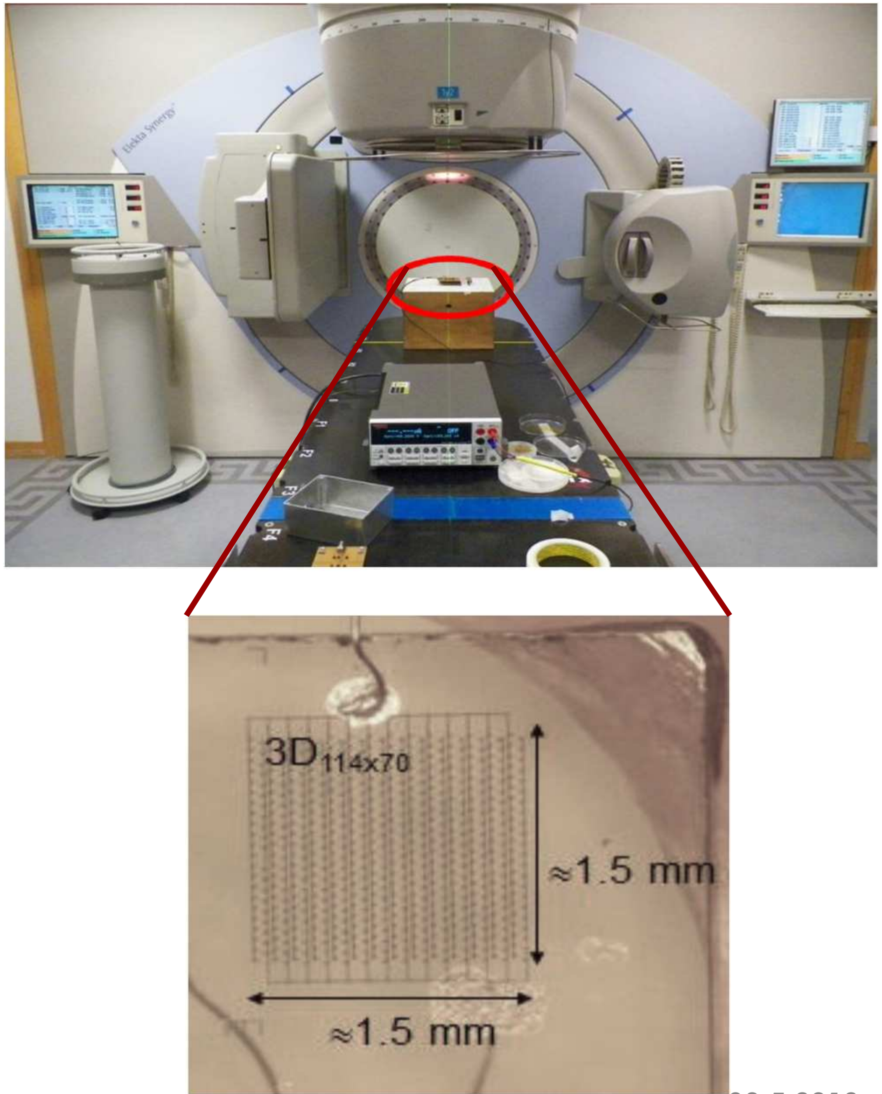






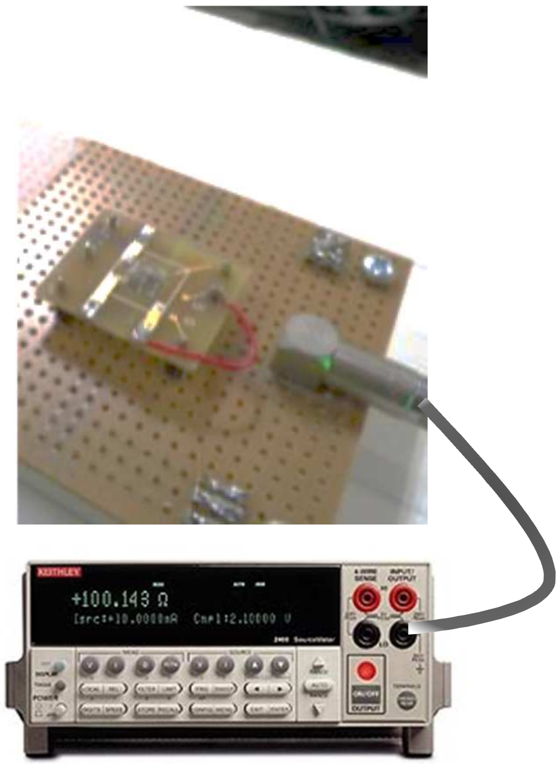
Dosimetry application

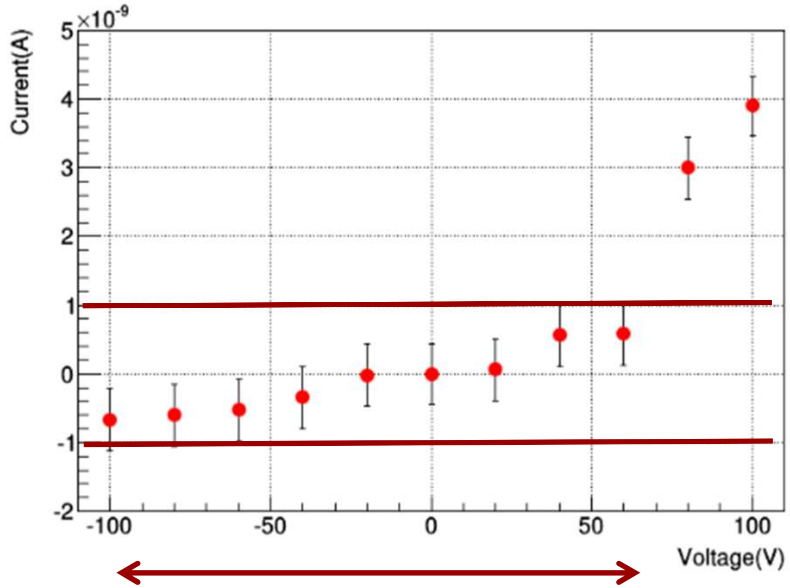
- **The Christie Hospital, Manchester**
  - medical linear accelerator (Elekta Synergy Sband)
  - 6MV and 10MV accelaration.
  - 10x10cm radiation field.
  - Dose rate dependence.
  - Photon beam profile.



Dosimetry application

- Test set-up:



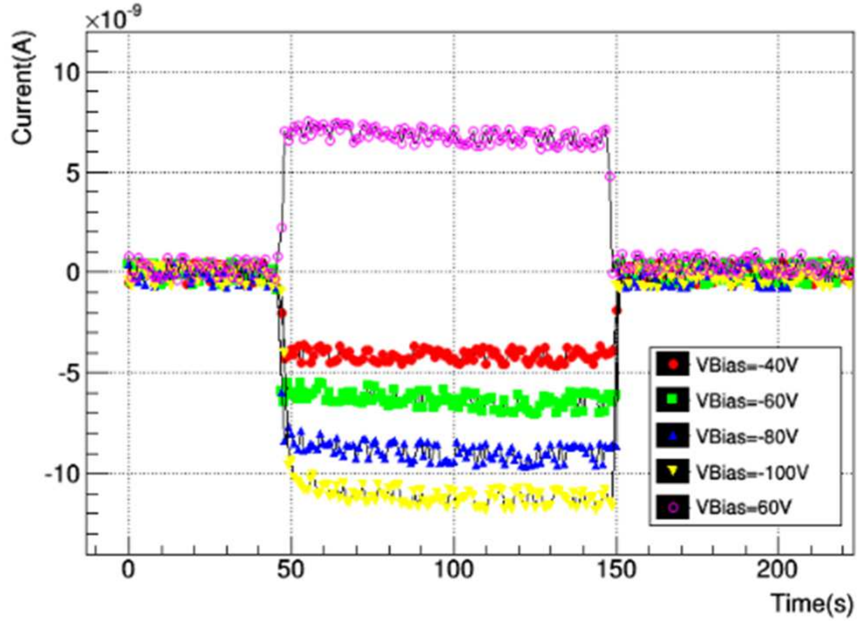


Asymmetric leakage current.
I_{leak} < 1nA for -100V to +60V

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.

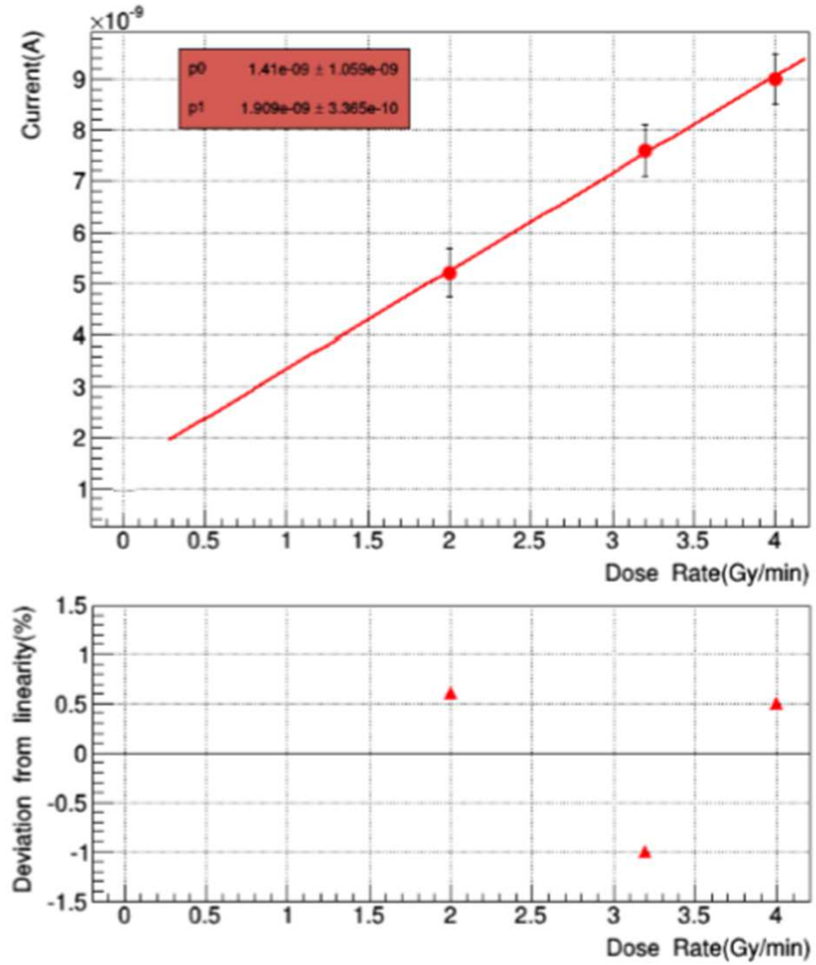


On-off response to 6MV photon beam with 4Gy/min. Variation of bias voltage.

Dosimetry application

First 3D diamond results:

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



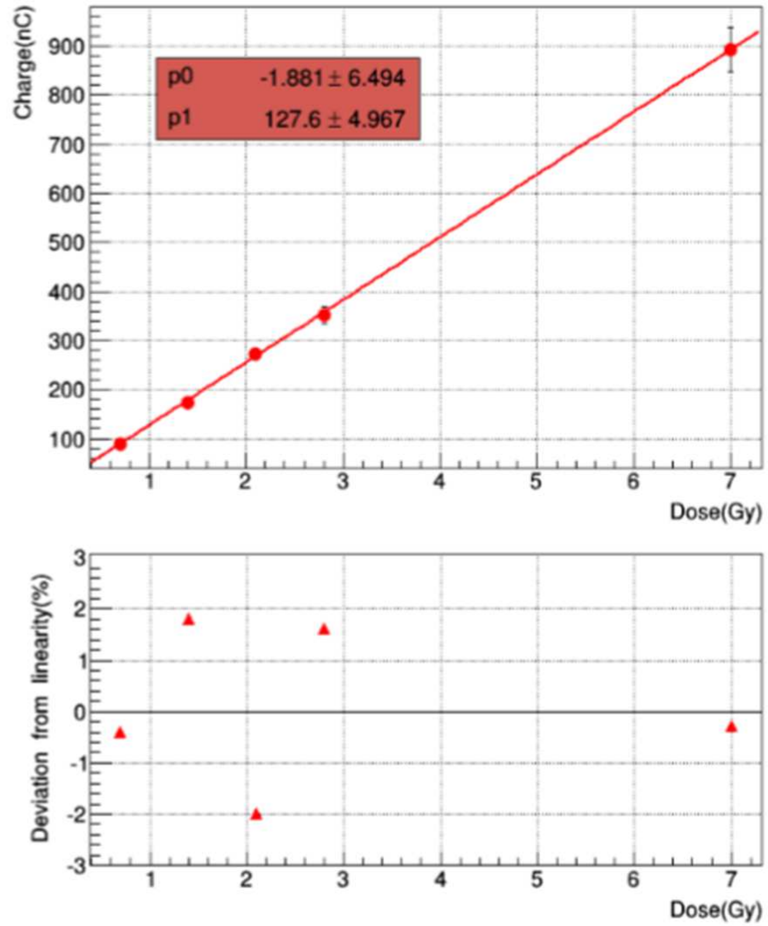
Dose rate linearity for 6MV photons at -80V

The Christie
Manchester
Florence
Perugia

Dosimetry application

<u>First 3D diamond</u> 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.



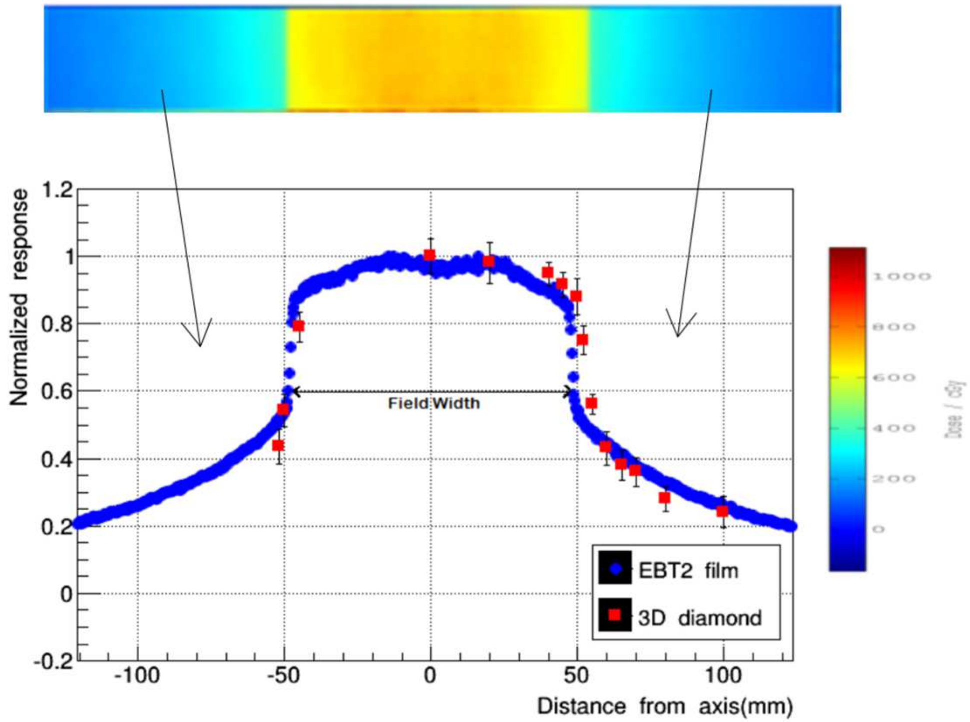
Dose linearity for 6MV photons at -80V

The Christie
Manchester
Florence
Perugia

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.