The University of Manchester

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June 2023

Advanced UK Instrumentation Training 2022

Diamond Detectors

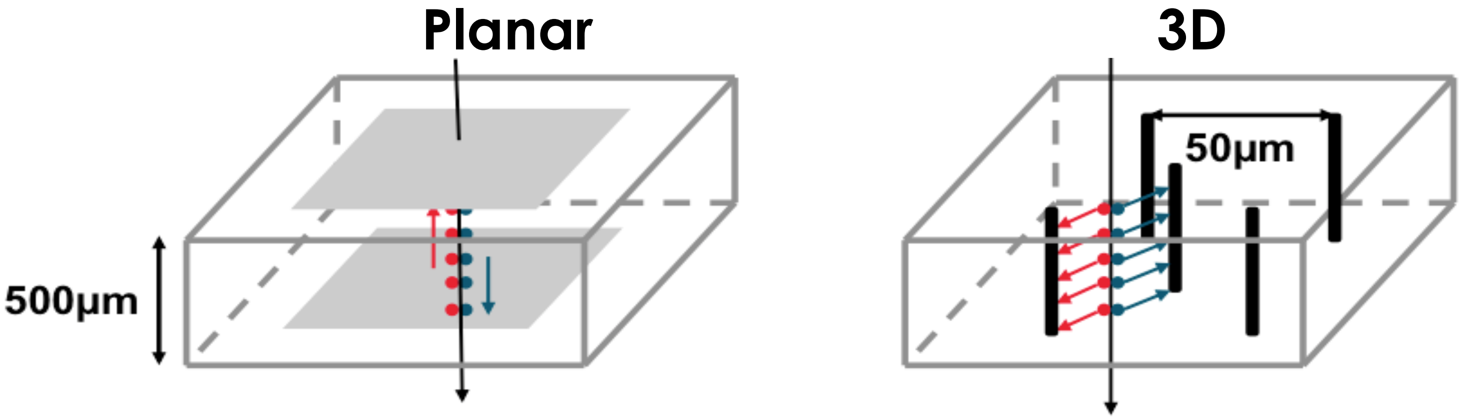
Alexander Oh
University of Manchester

PART 2

- 3D Diamond detectors
- Application of diamond detectors in HEP

3D diamond detectors

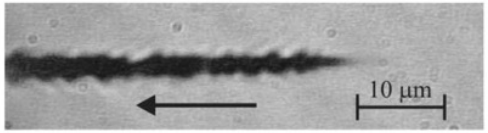
3D Diamond Detectors



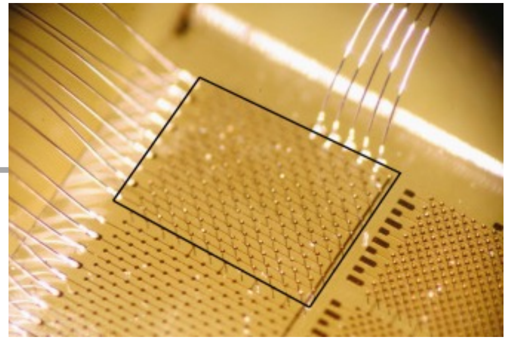
- Electrode spacing determines drift distance to induce 1e charge.
- 3D has shorter electrode spacing compared to planar.
- Charge carriers need less drift distance (and time) in 3D then in planar to induce equal signal.
- Influence of traps and resulting limited lifetime suppressed in 3D.

3D Diamond Research - A relatively young field

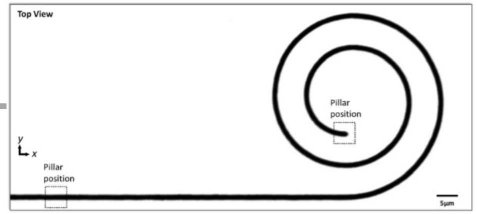
- Laser induced phase change in diamond.
  - E.g. T.V. Kononenko et al, Diamond & Related Materials 18 (**2009**) 196–199 "***Femtosecond laser microstructuring in the bulk of diamond*** "



- 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"***

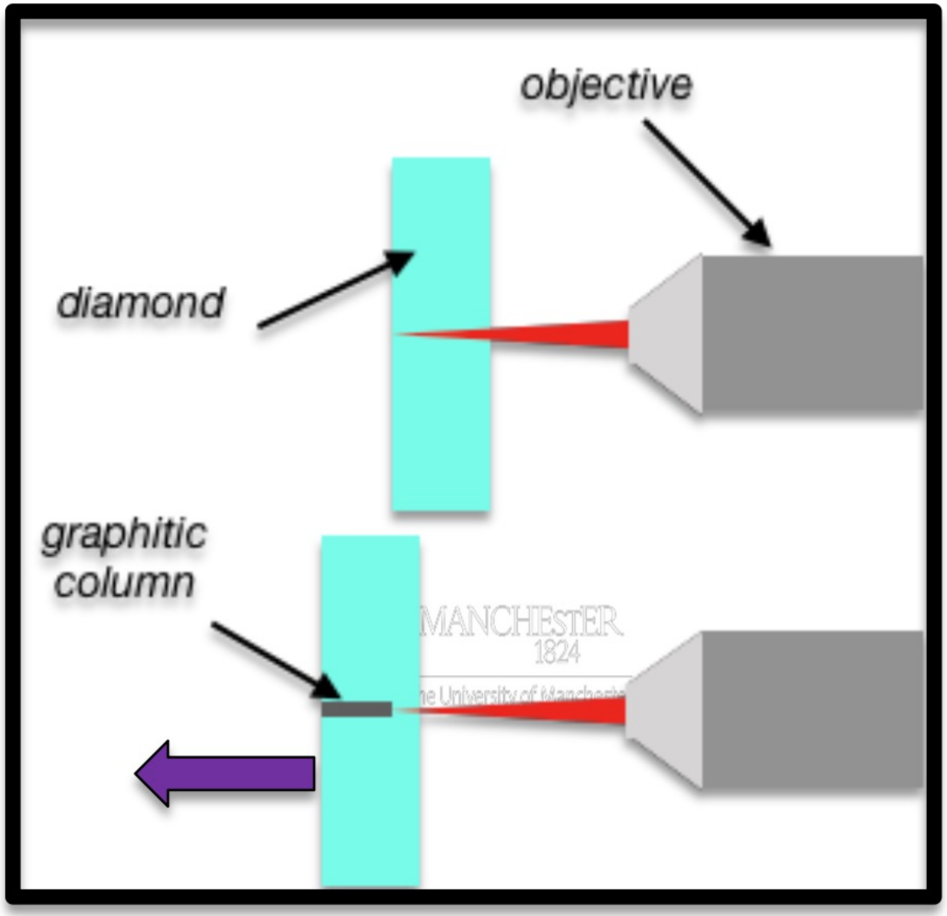


- Radiation damage studies.
  - Eg. S. Lagomarsino et al, Applied Physics Letters **106**, 193509 (**2015**) "***Radiation hardness of three-dimensional polycrystalline diamond detectors"***
- Improvements in graphitization process.
  - Eg. B. Sun et al., Applied Physics Letters **105**, 231105 (**2014**), "**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:

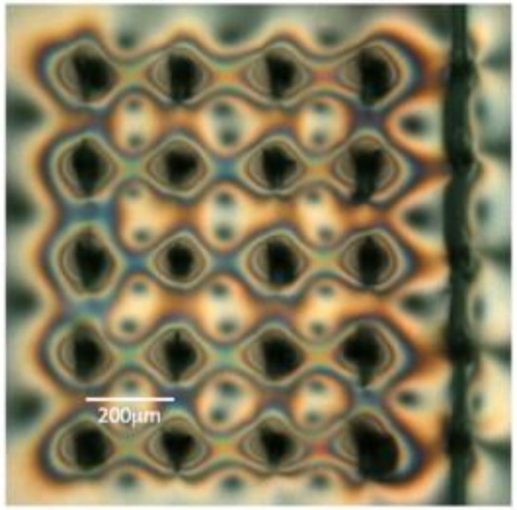


Laser graphitisation of diamond

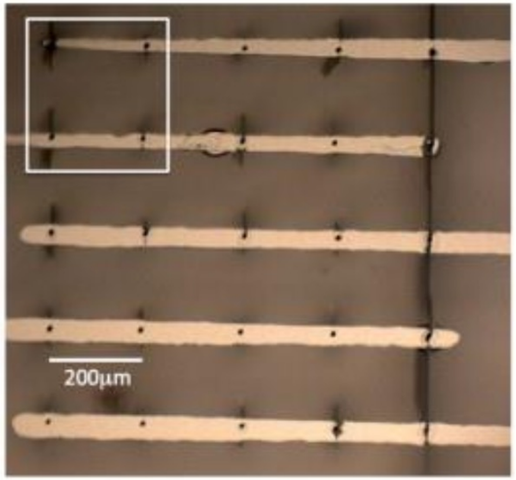
FIRST 3D DIAMOND DEVICE

- 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**

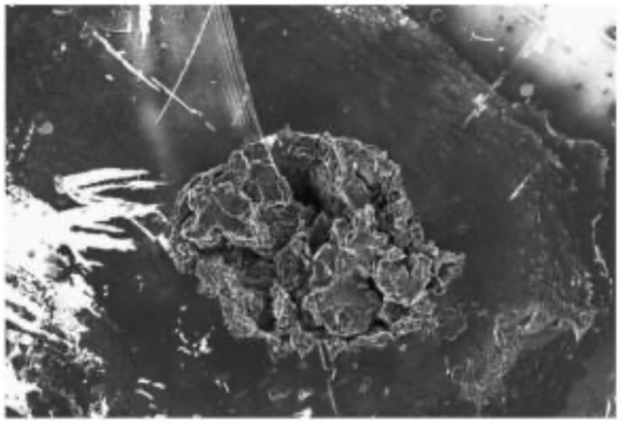
(a)Birefringence microscopy.



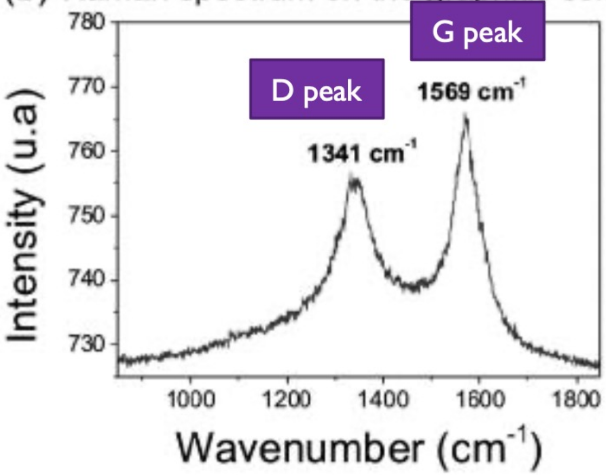
(b) Photograph after metallisation.



(a) SEM picture of a graphitic column.

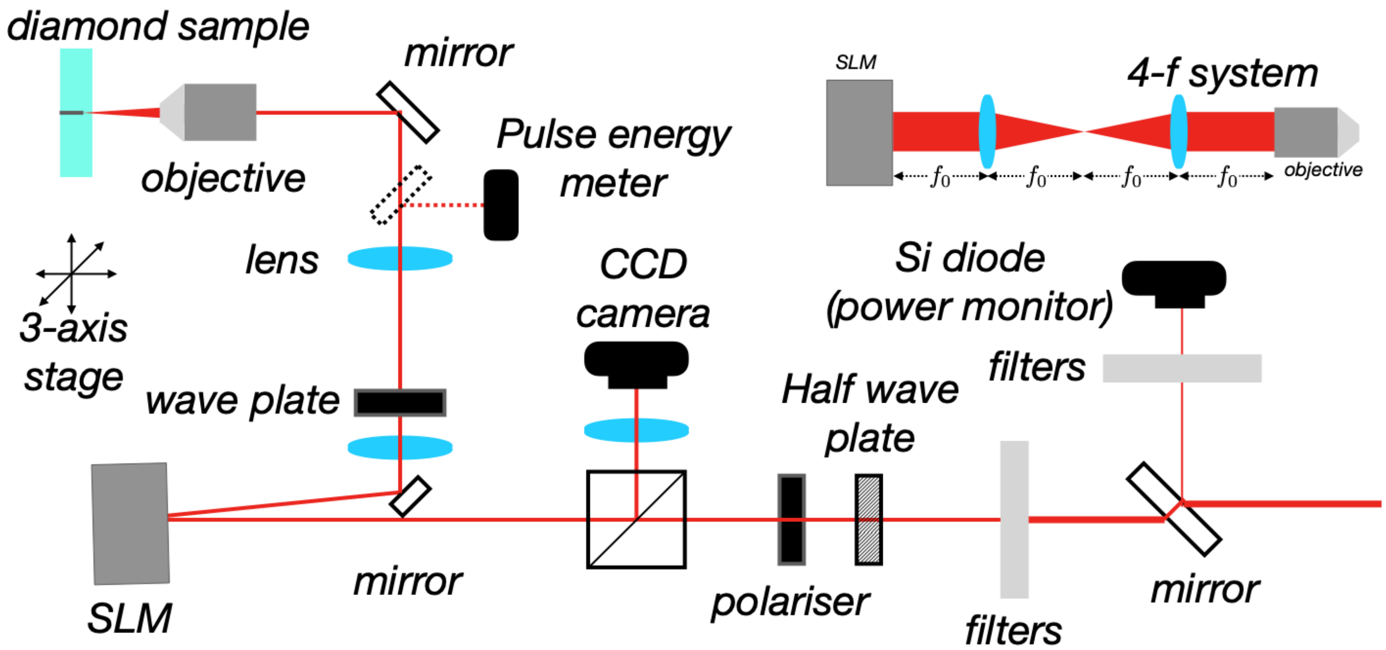


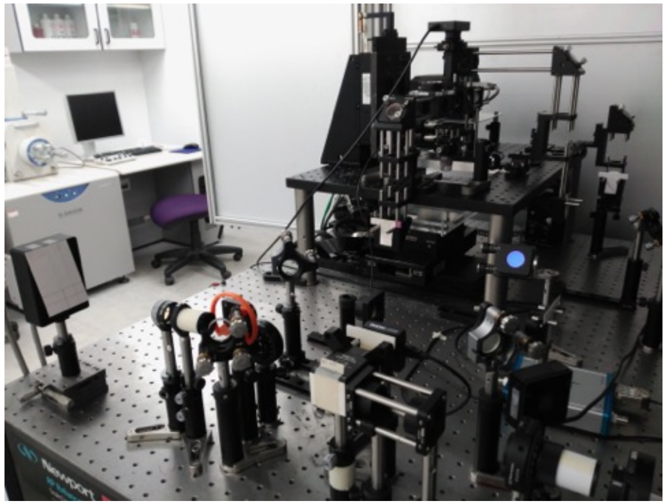
(b) Raman spectrum on the graphitic column.



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





Just moved to MECD!

Laser specs:

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

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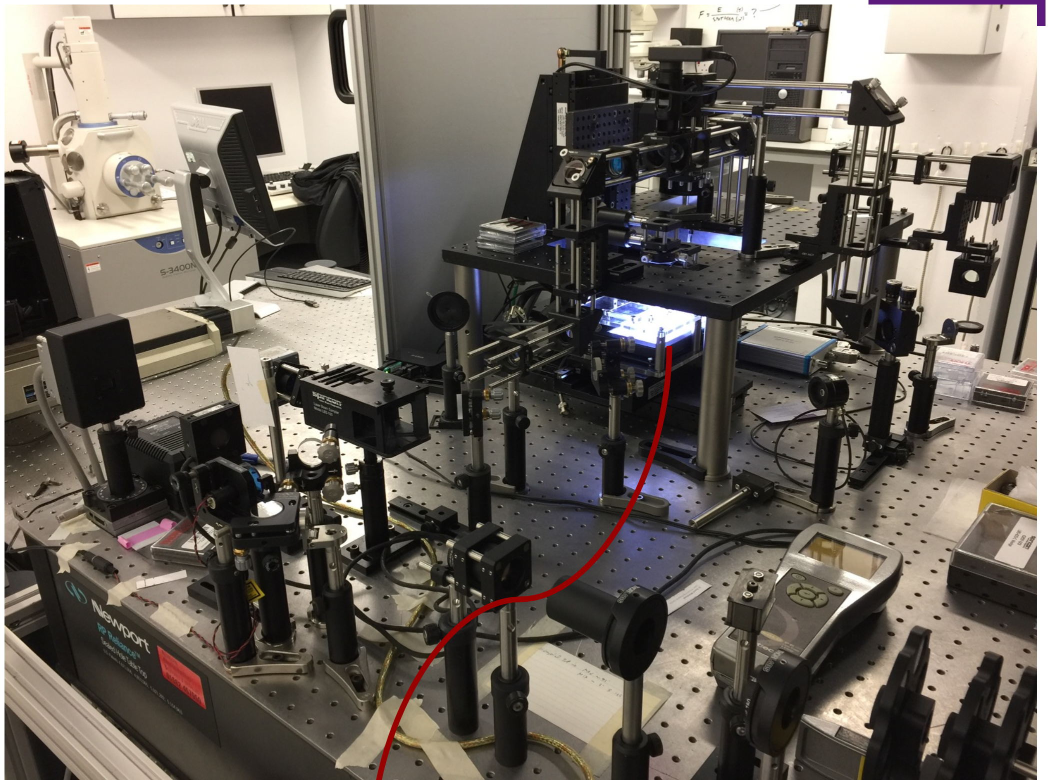
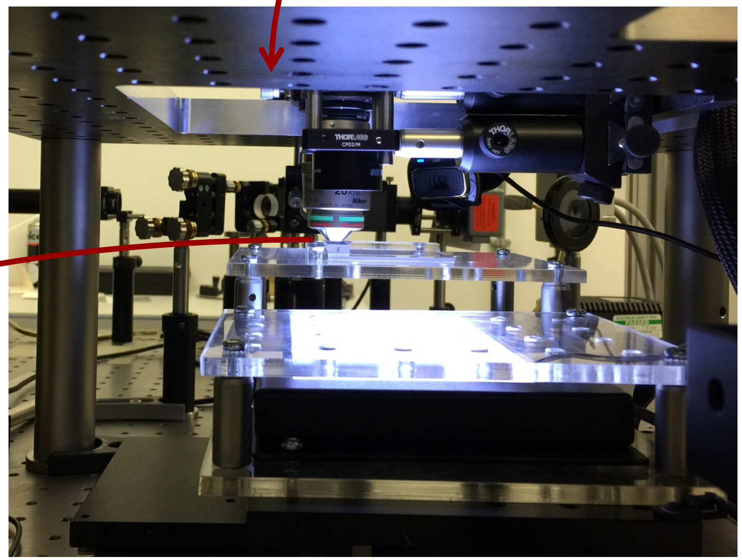
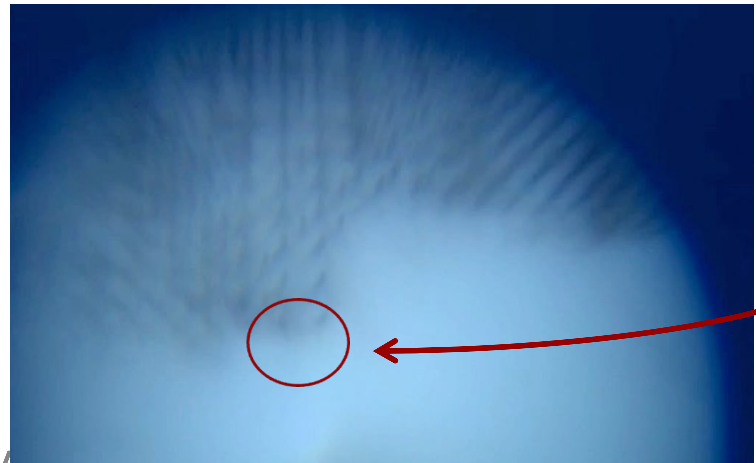
University of Manchester, Laser Processing Research Center.

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



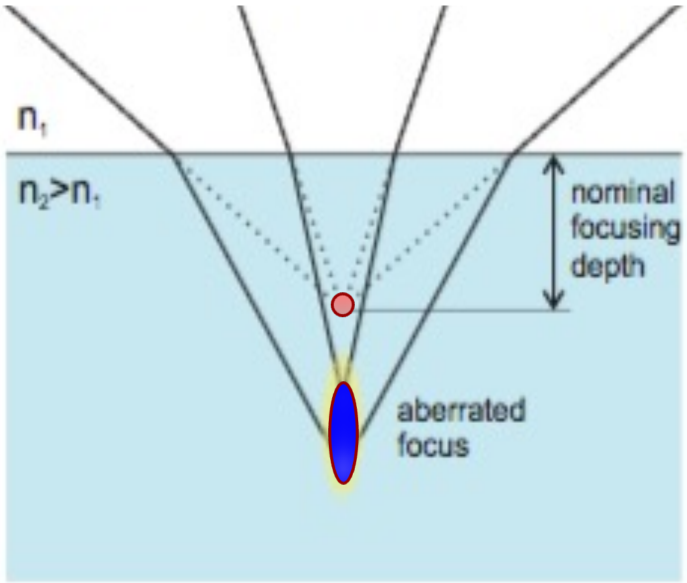




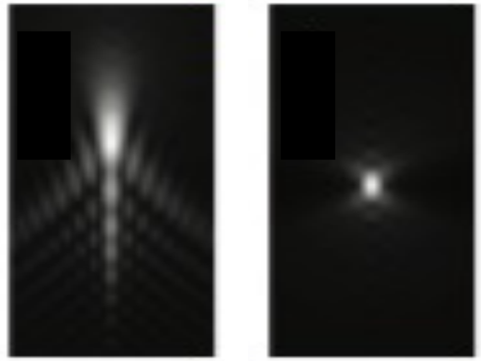
SLM – Phase **S**patial **L**ight **M**odulation

- Comparison SLM vs standard process.

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



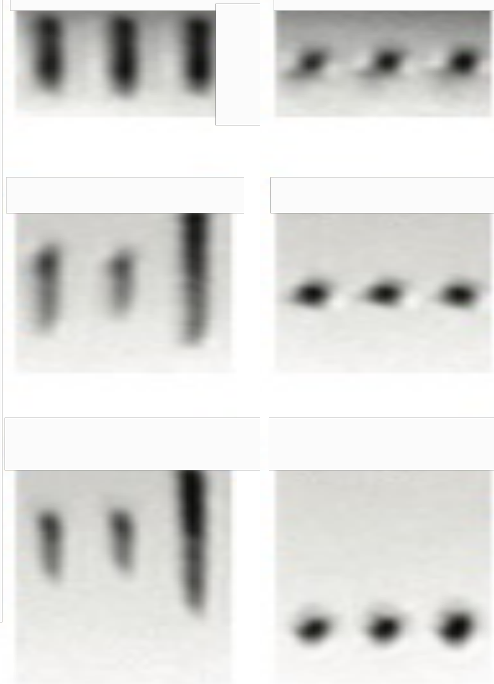
Simulated depth = 40µm



Measured depth = 40µm

depth = 80µm

depth = 130µm



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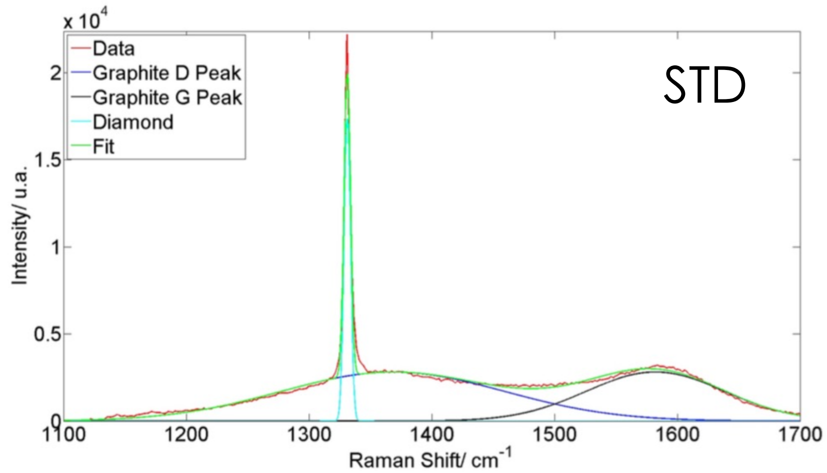
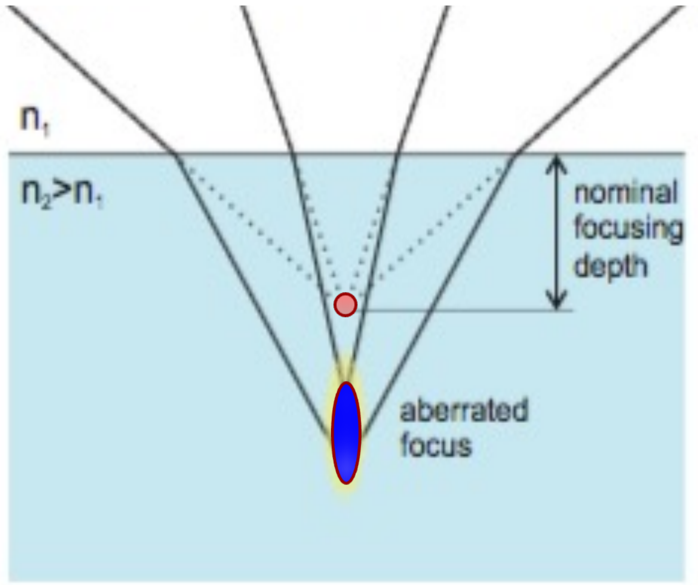
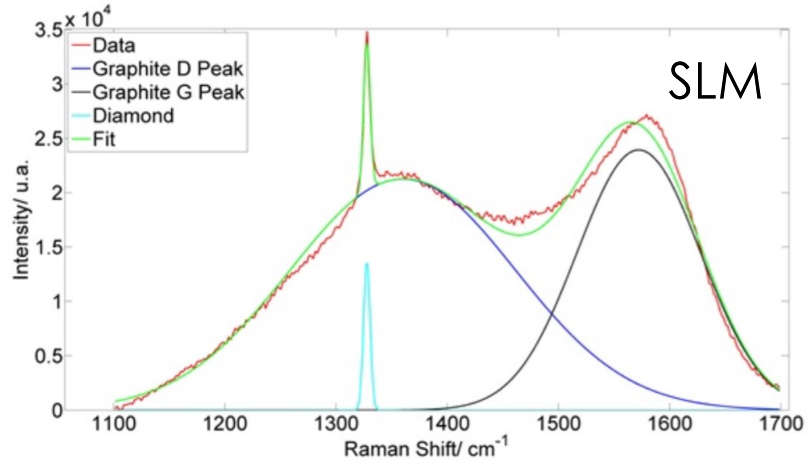
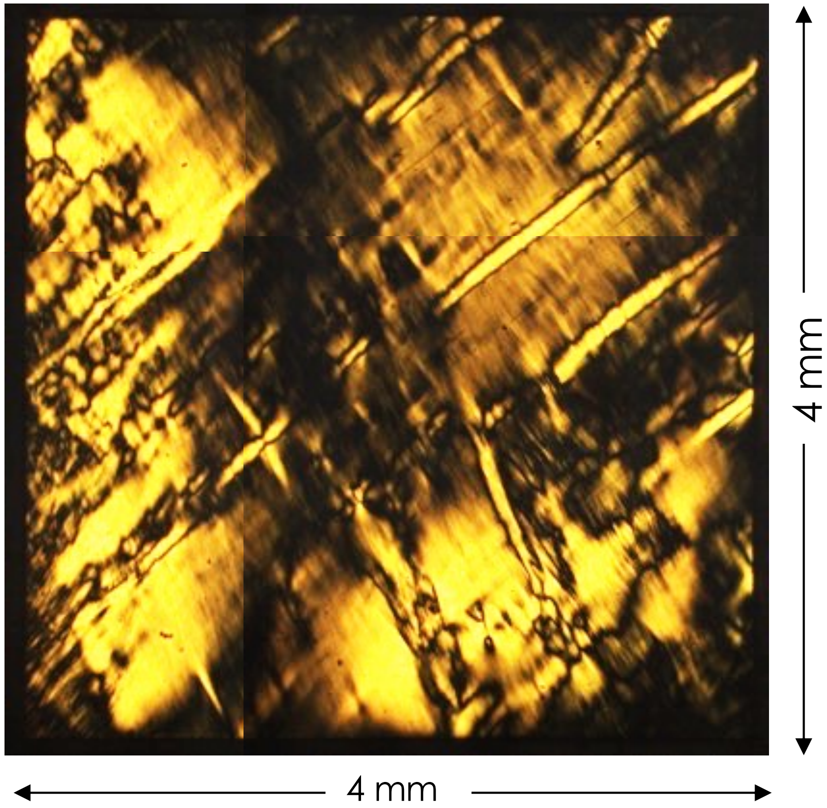


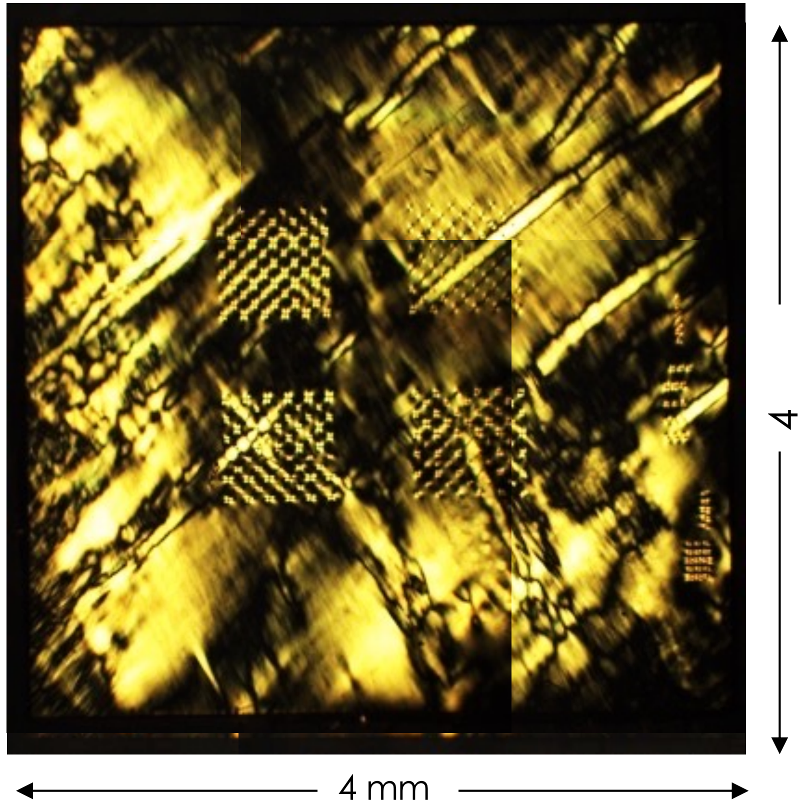
(a)





X-polariser image



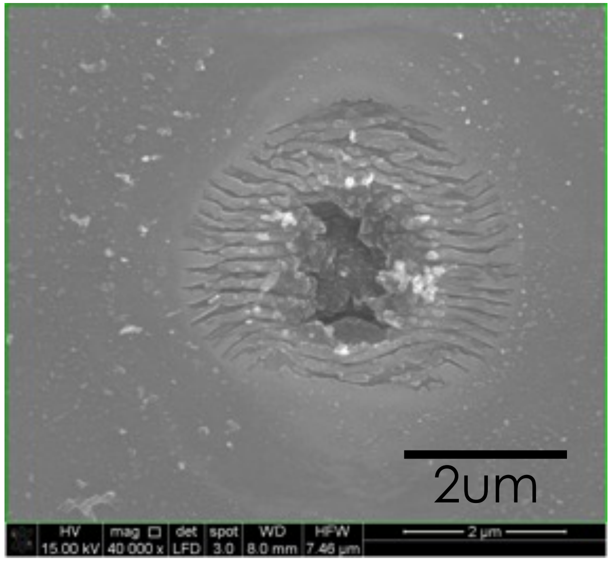


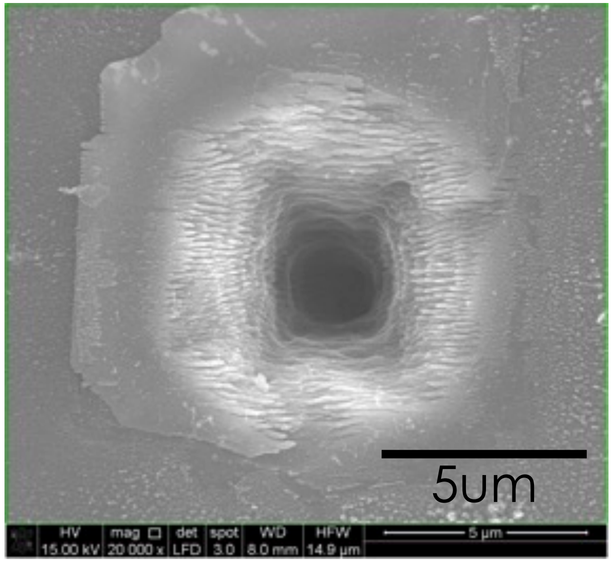
- Optical grade scCVD diamond.
- Post processing.

SEM surface image

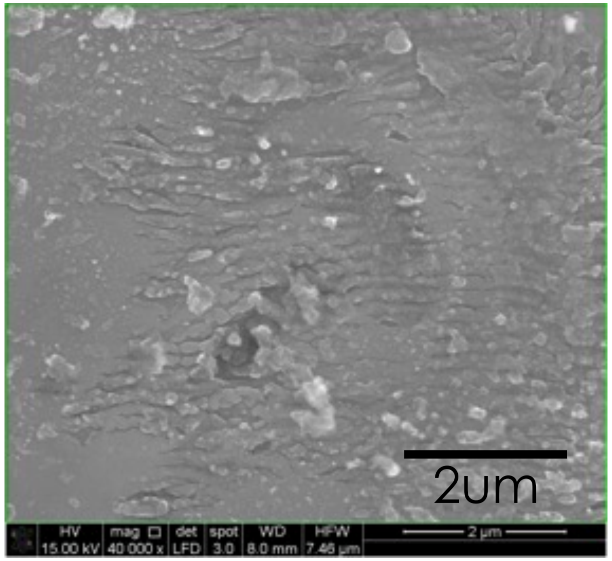
- Seed surface
- Exit surface

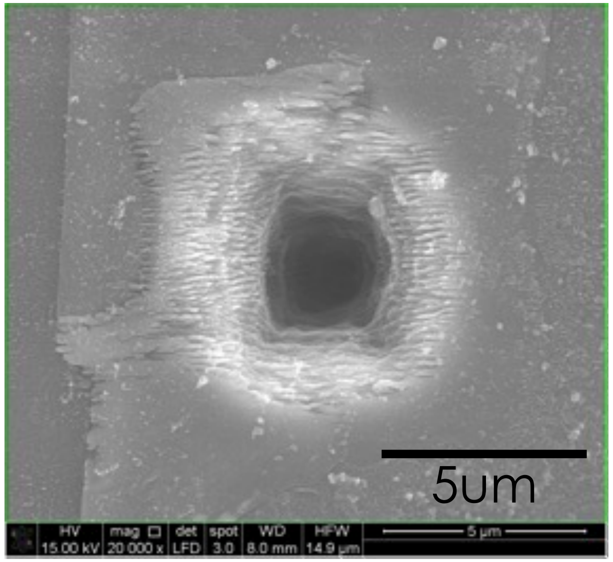
With SLM
10um/s
400nJ





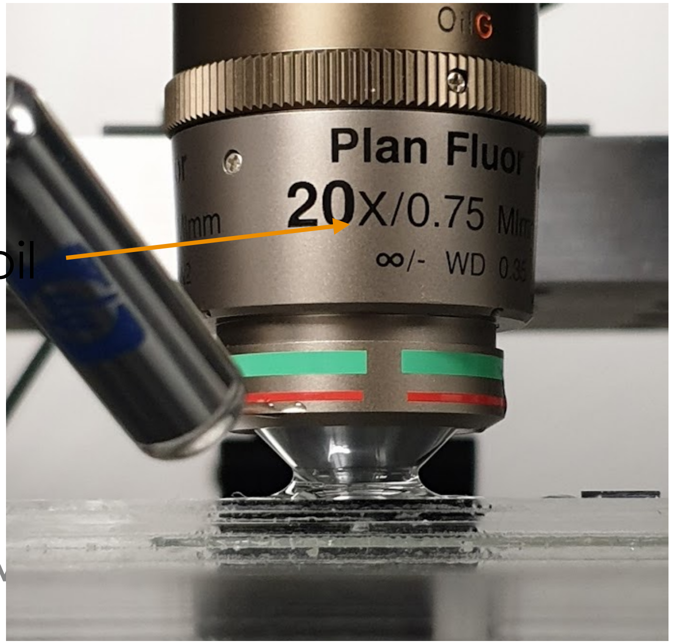
Without SLM
10um/s
400nJ

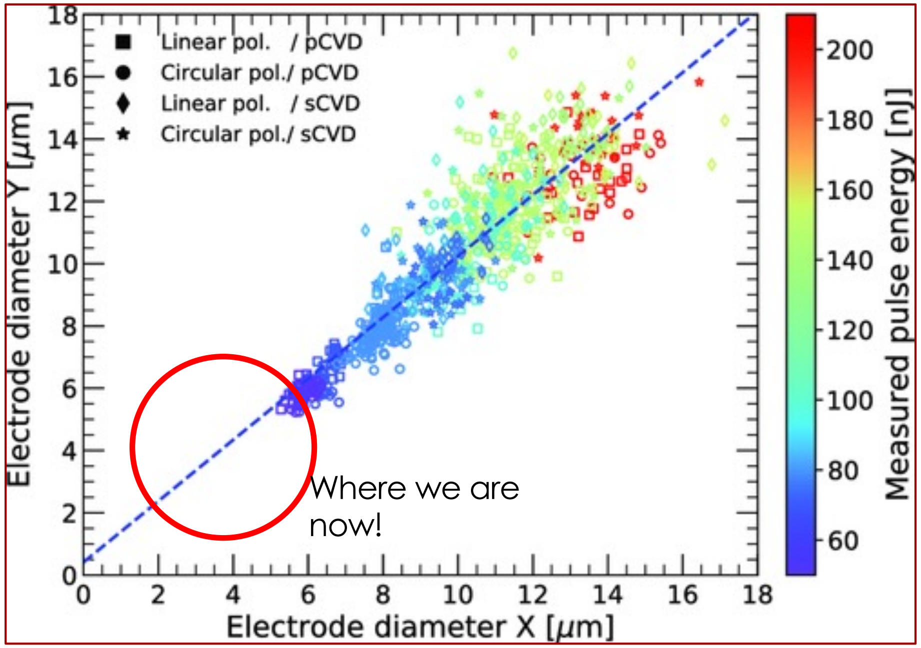




Making the thinnest column

- 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!

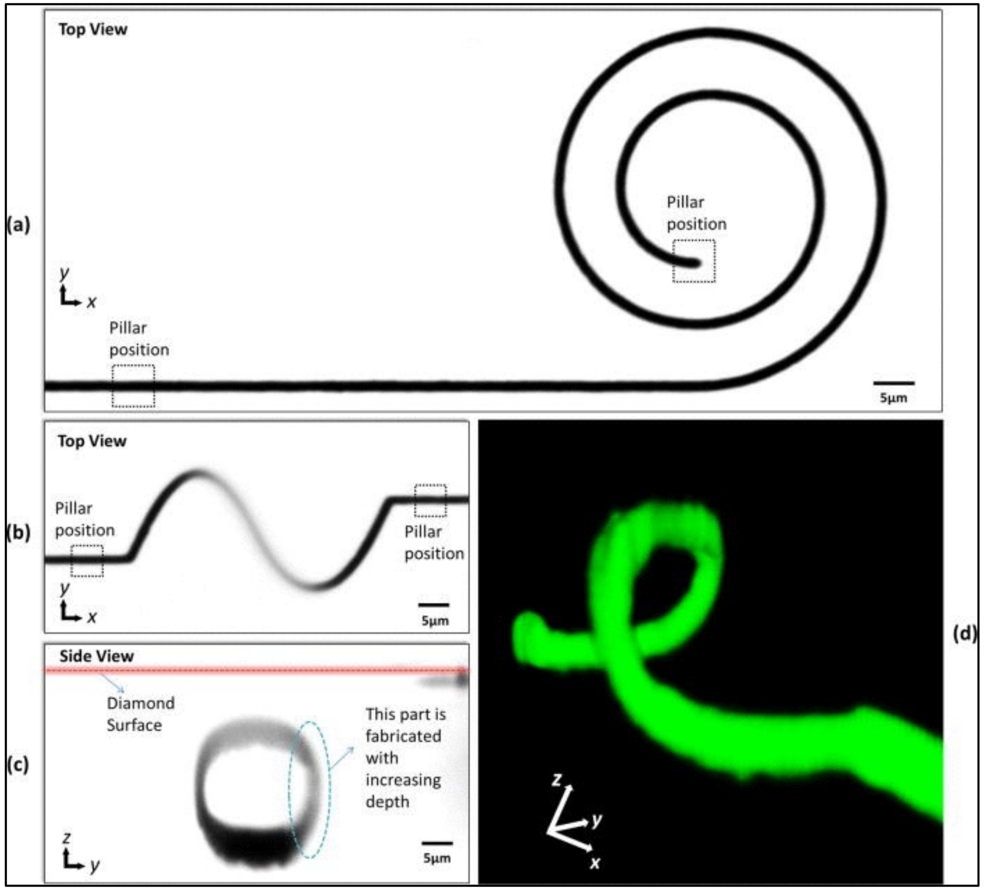




Lopez Paz, I., Allegre, O., Li, Z., Oh, A., Porter, A. and Whitehead, D. (2019), Study of Electrode Fabrication in Diamond with a Femto-Second Laser. Phys. Status Solidi A, 216: 1900236.

Moving sideways

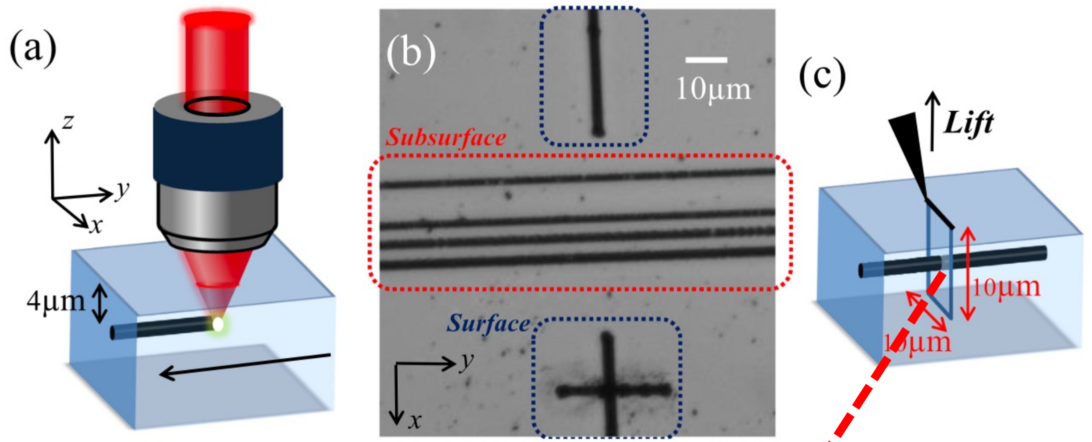
- Also have the possibility to move in **arbitrary** direction
- Wavefront correction needs to be tailored in real-time
  - For vertical columns have mainly spherical corrections
  - For horizontal processing, the correction is ~elliptical
  - Gets even trickier at depth >200μm

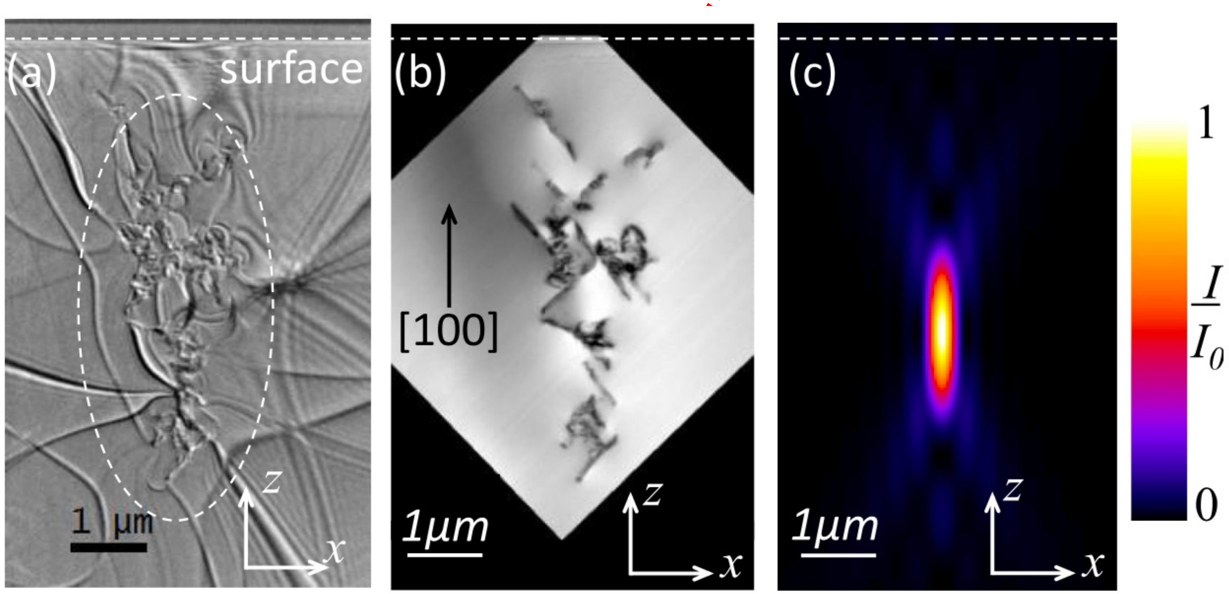


Sun, B., Salter, P. S., & Booth, M. J. (2014). High conductivity micro-wires in diamond following arbitrary paths. *Applied Physics Letters*, *105*(23), 231105.

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

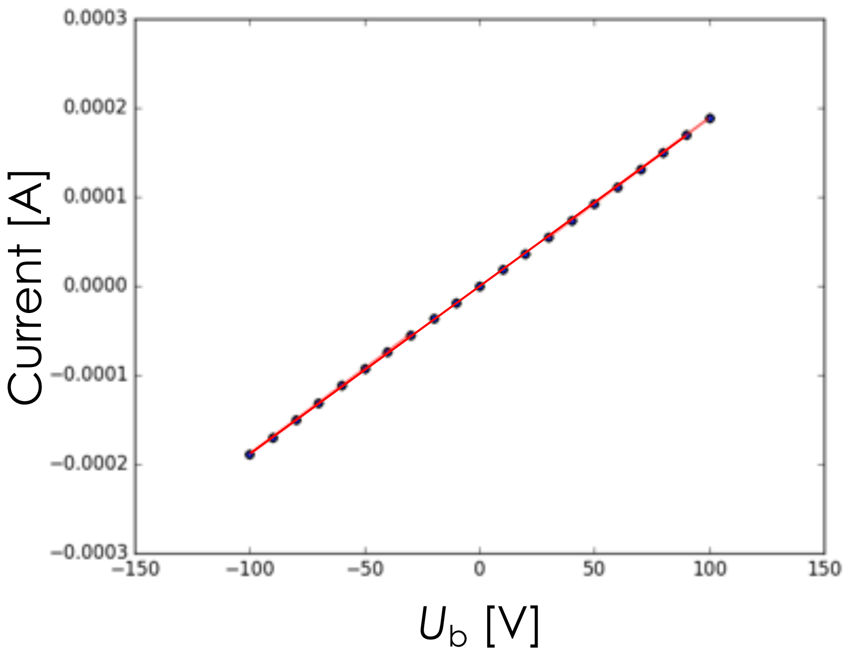
Patrick Salter, Oxford
Iain Haughton, AO, Manchester

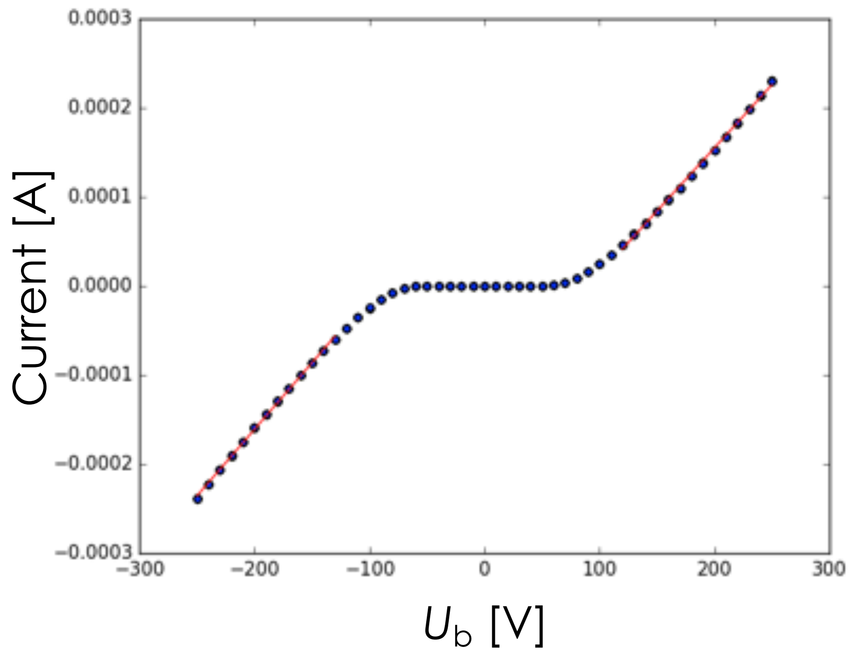
Laser beam energy		Laser translation speed			
		5um/s	10um/s	20um/s	30um/s
	100nJ	x	x		
	200nJ	x	x	x	
	300nJ		x	x	x
	400nJ		x	x	x
	500nJ			x	x
	600nJ				x

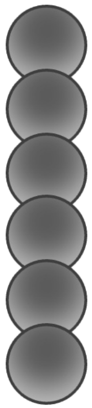
- Repeat **with** and **without** SLM correction.

IV curves

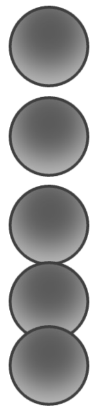
- Ohmic and barrier potential curves observed.





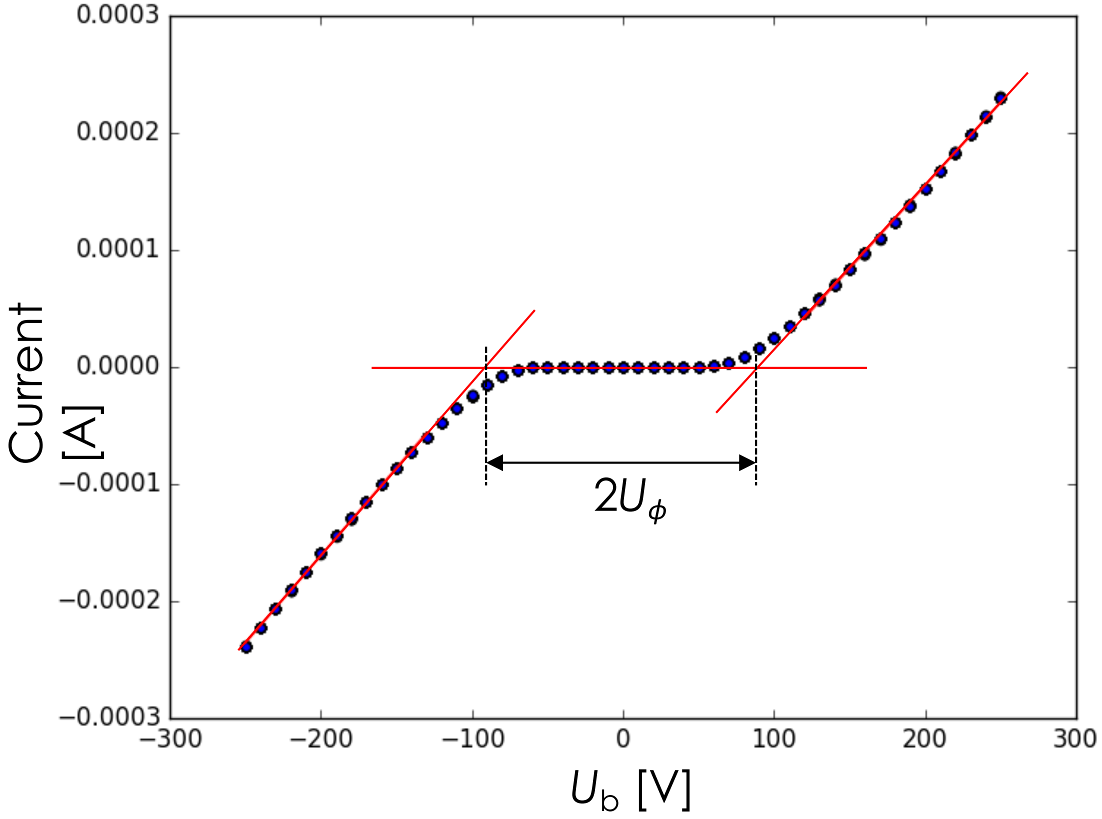


Continuous.

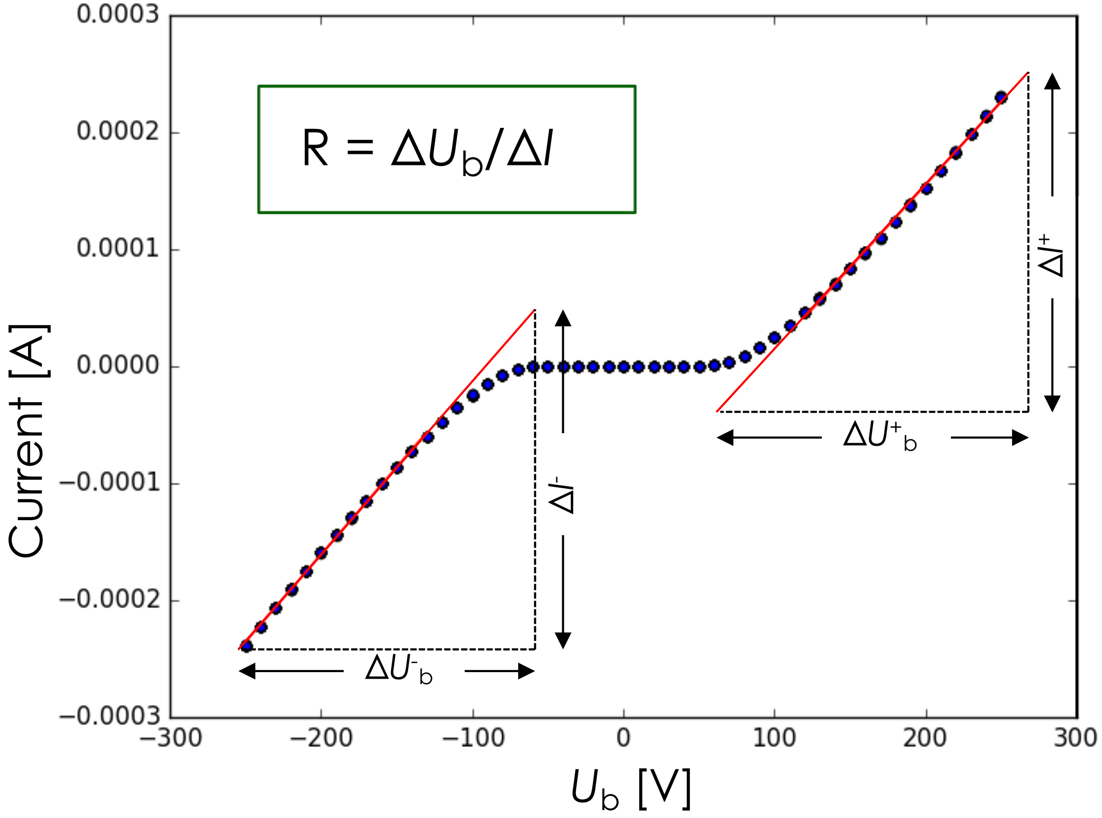


Bulk effect?
Micro gaps?

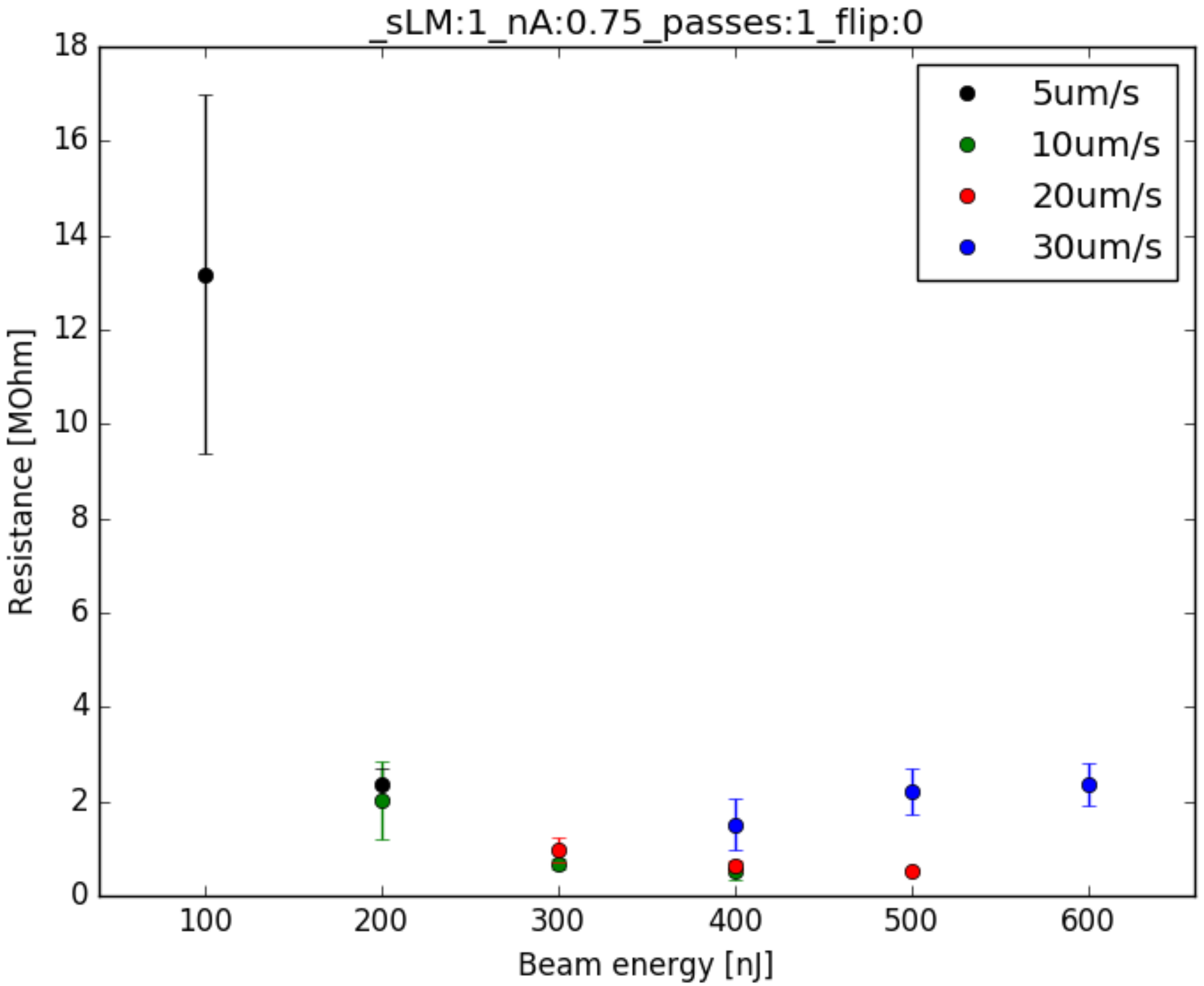
Barrier potential



Resistance measurement

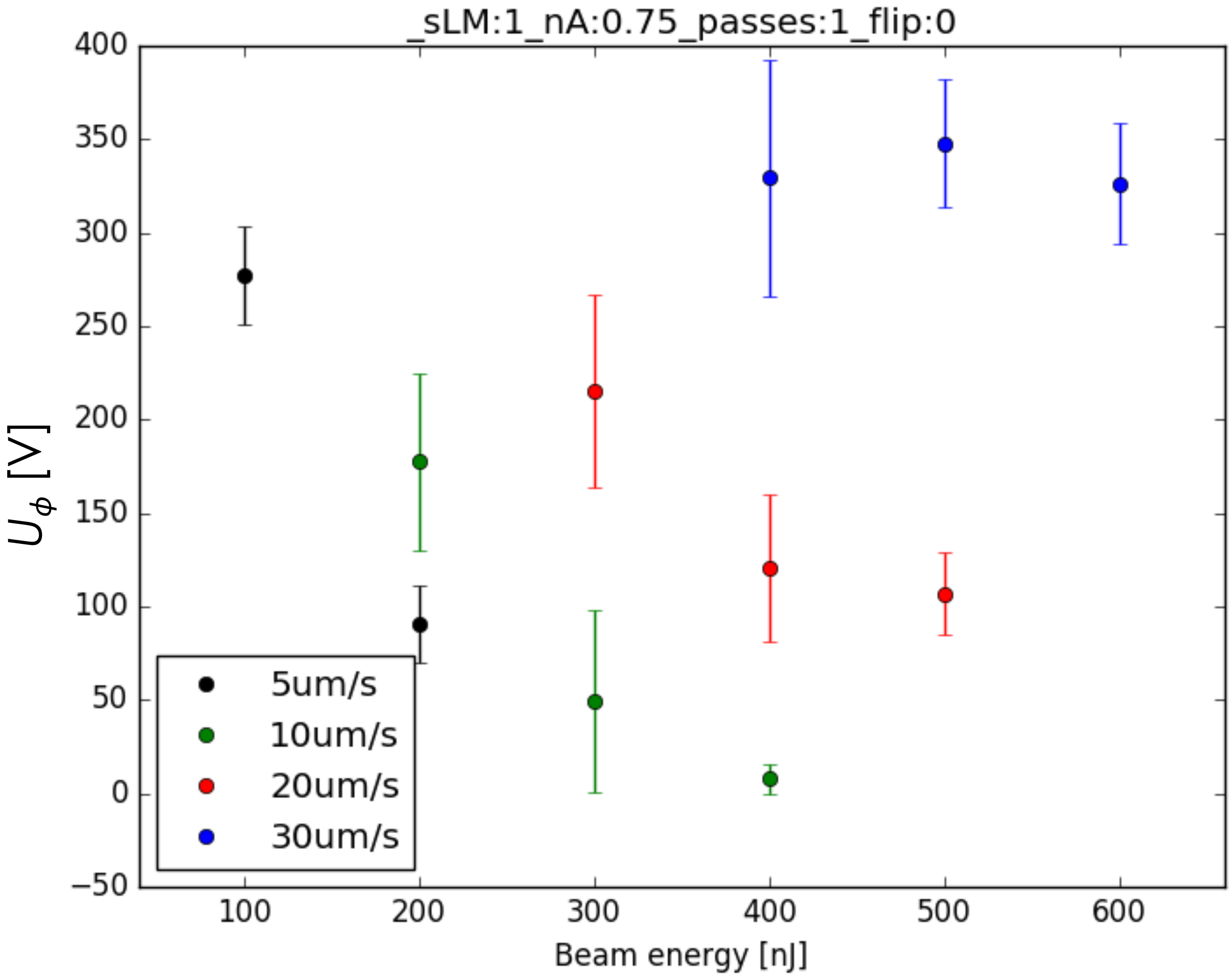


Resistance



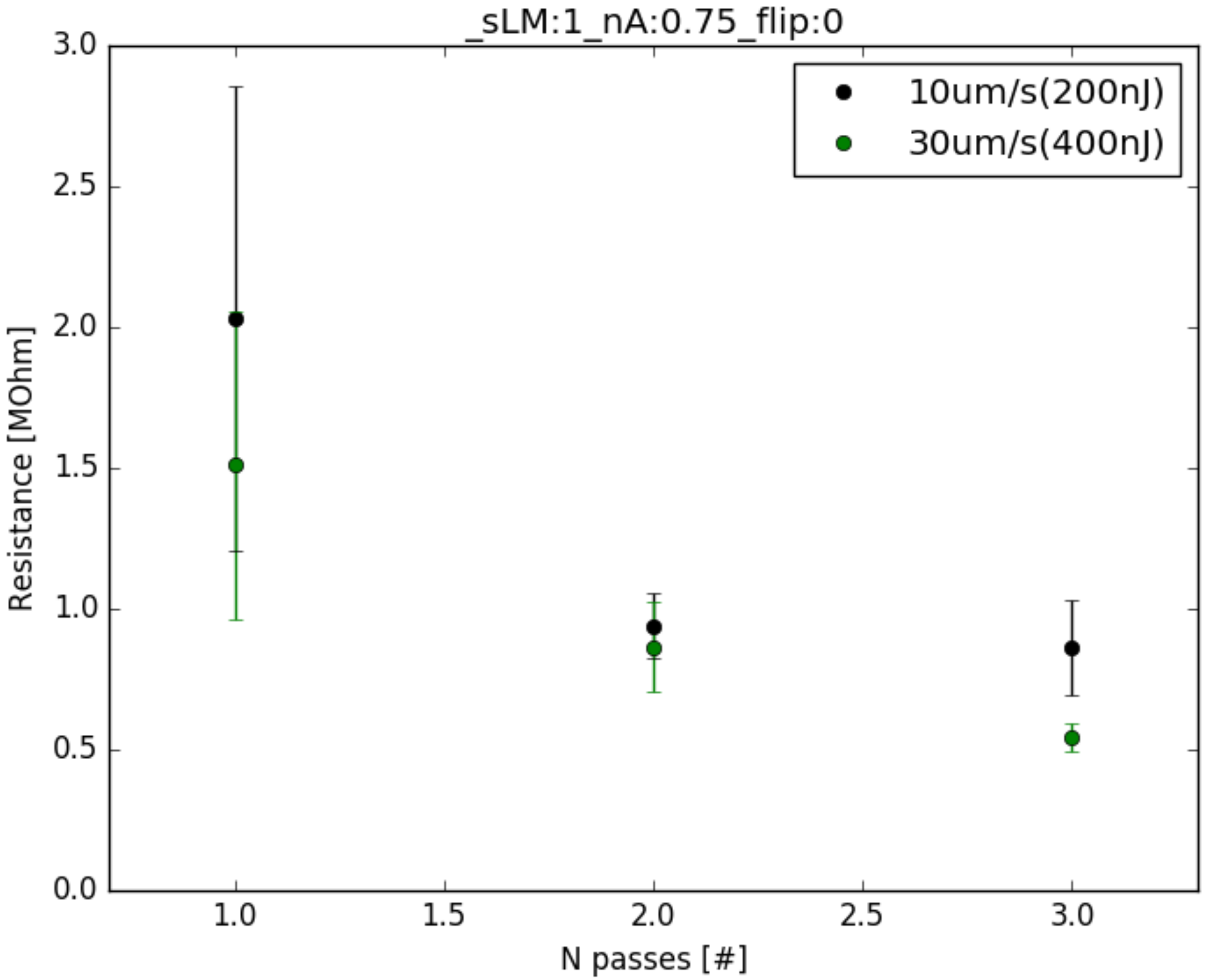
- Resistance increase as power law → multi-photon process.
- Clear discrepancy at 30um/s.

Barrier energy



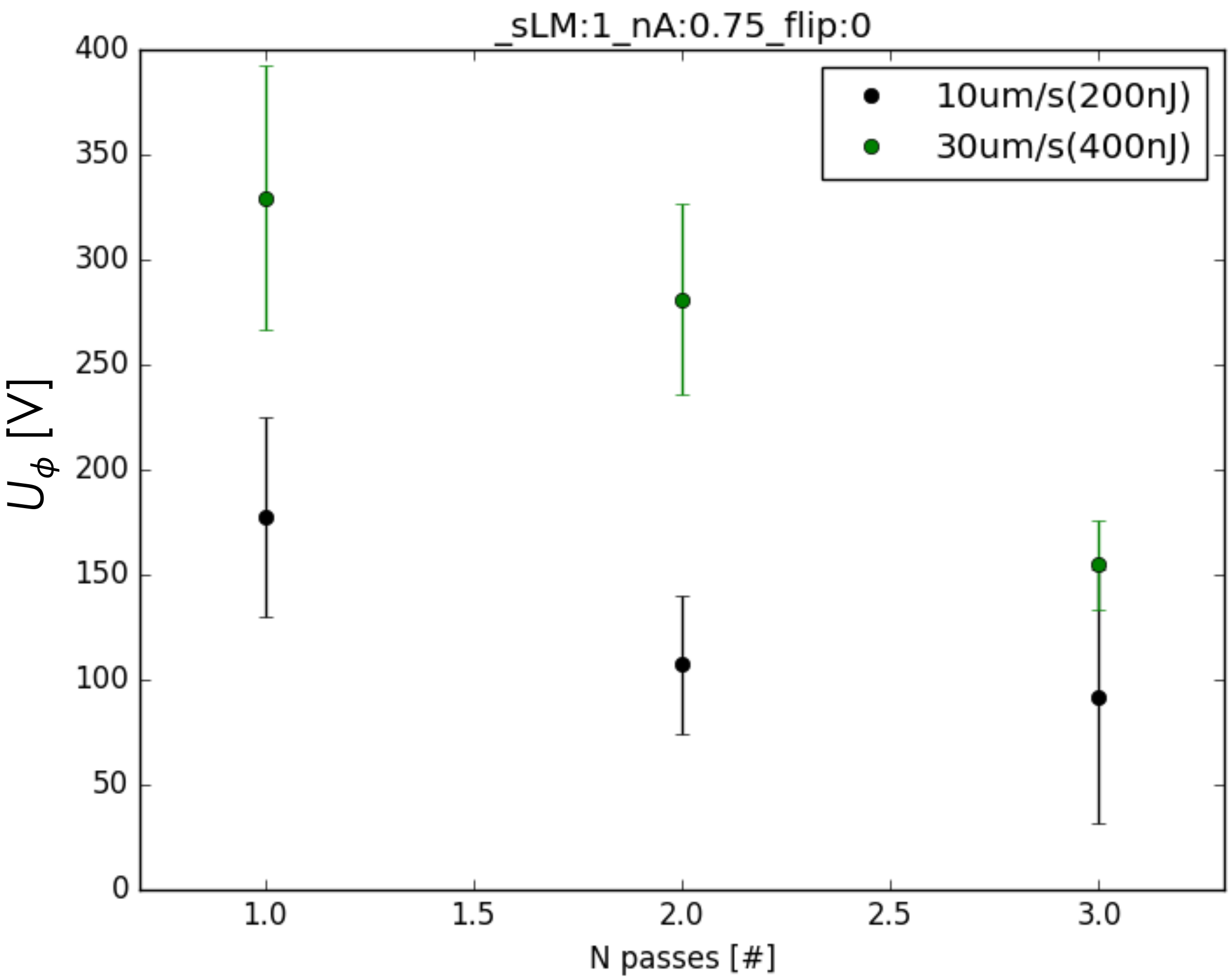
- Reduction in barrier with increased energy.
- Discrepancy at 30um/s.

Multiple passes



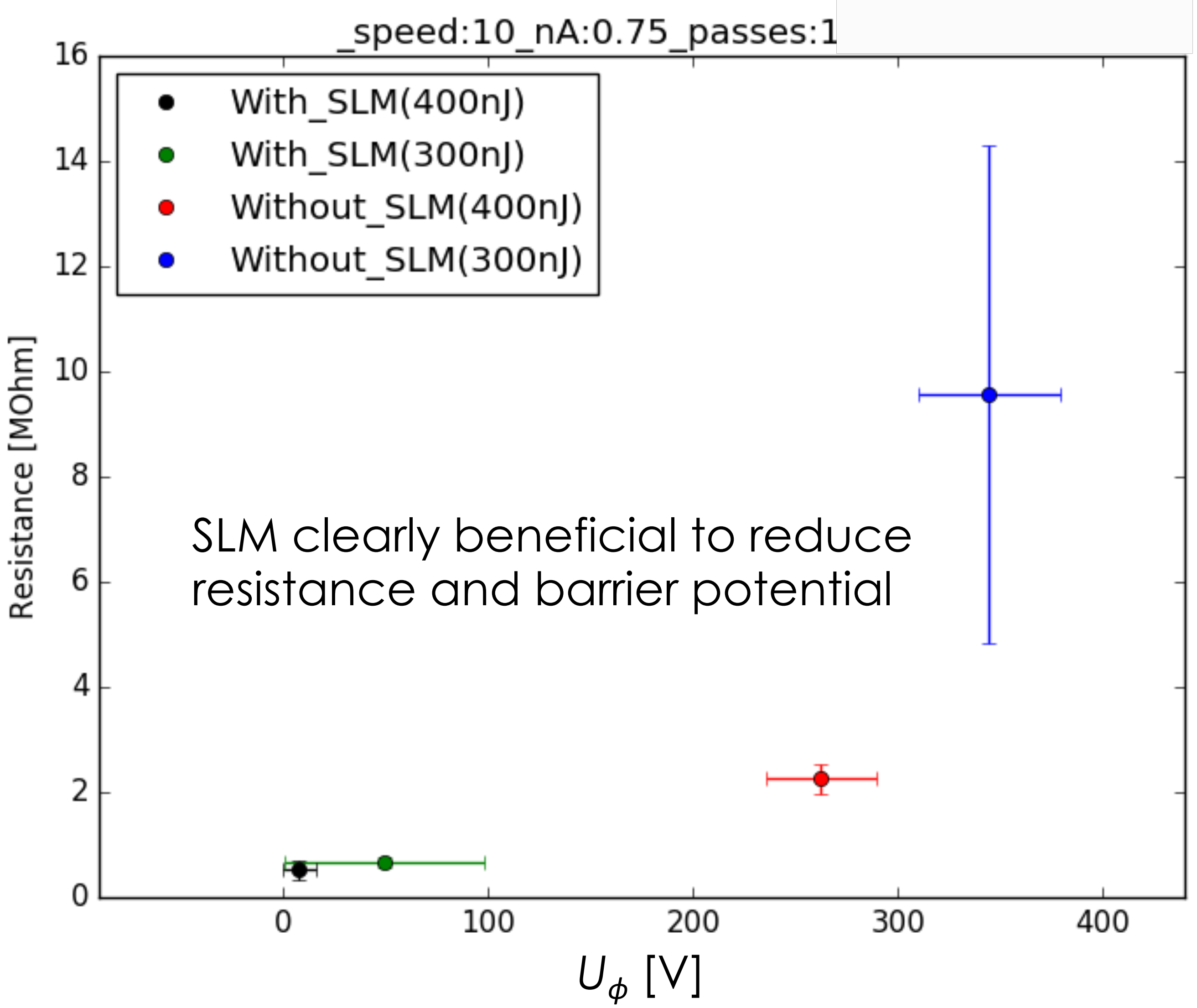
- Multiple passes reduces resistance and increases uniformity of the columns.

Multiple passes



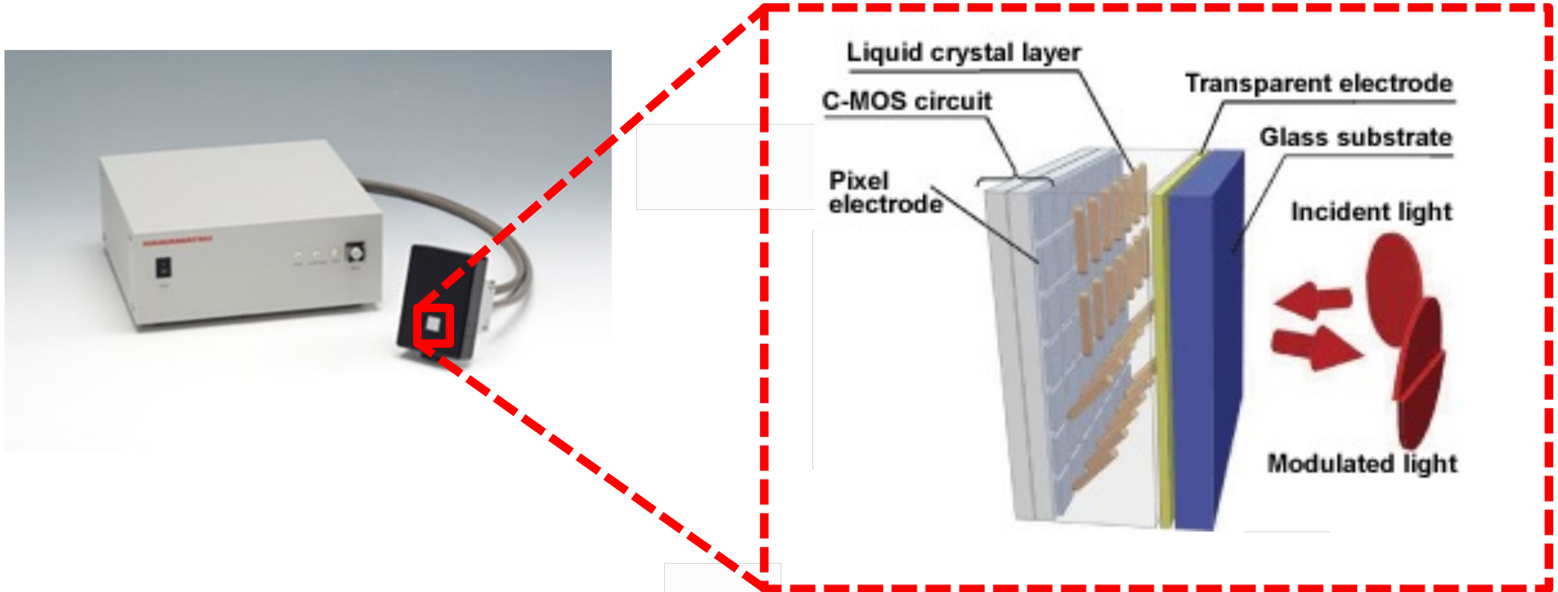
- Multiple passes also reduces U_ϕ.

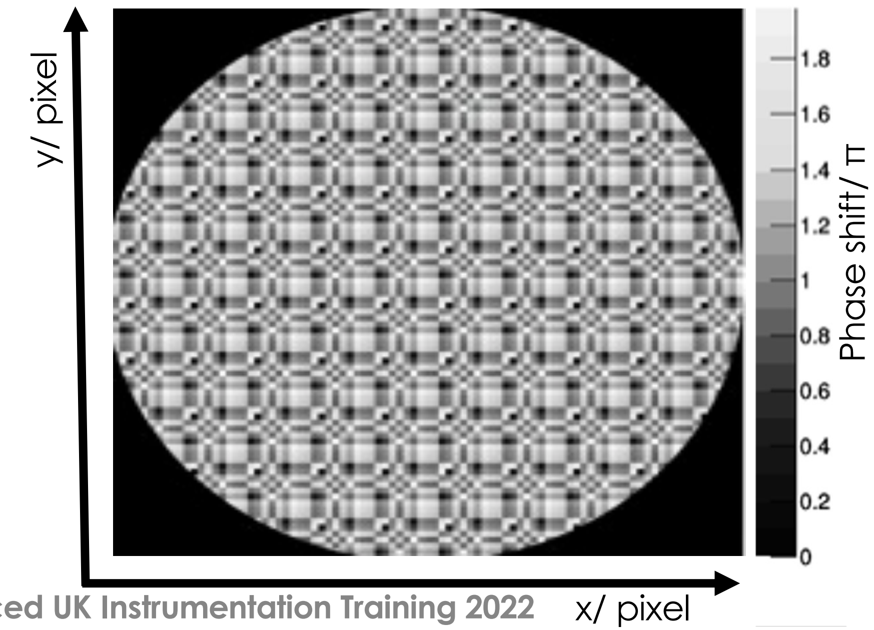
With and without SLM

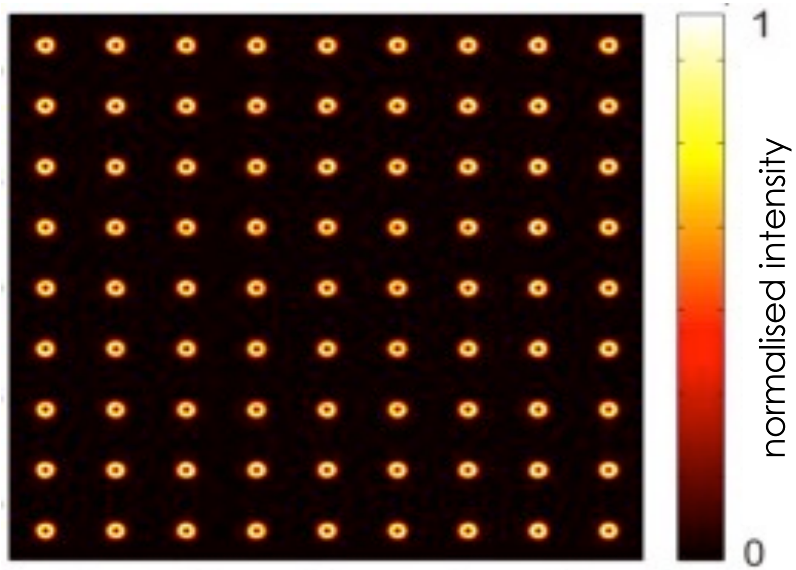


SLM clearly beneficial to reduce resistance and barrier potential

SLM parallel processing?







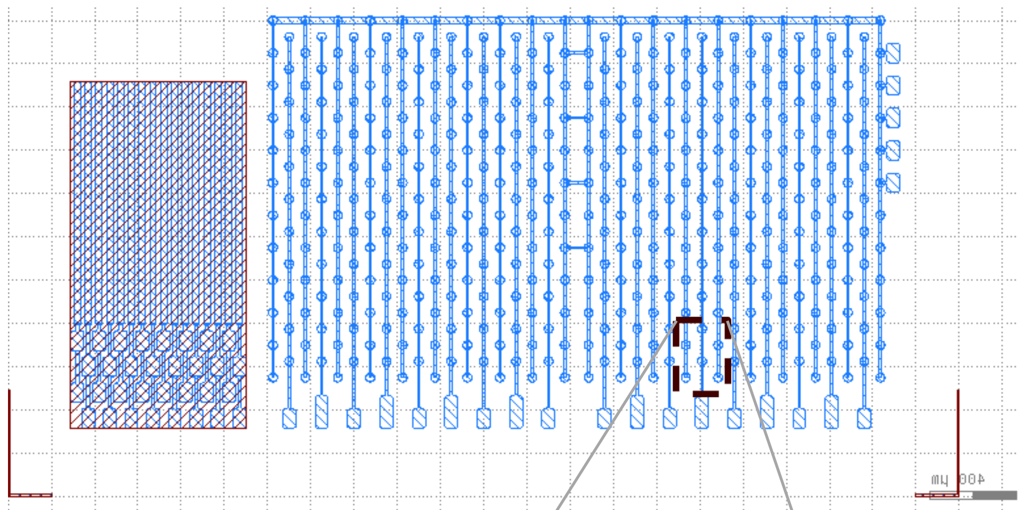
3D Diamond detector tests with relativistic charged particles

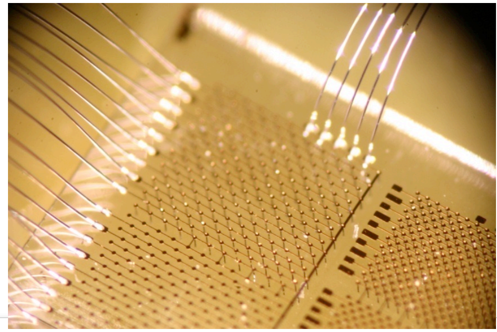
- Types
  - 100x100um cell size ganged to form strips
  - 100x100um cell size, bonded to pixel read-out
  - 50x50um cell size, bonded to pixel read-out
- All detectors made from polycrystalline diamond.
- Beam tests
  - CERN beam line H6 : protons ~ 120 GeV/c
  - PSI : pions ~ 250 MeV/c

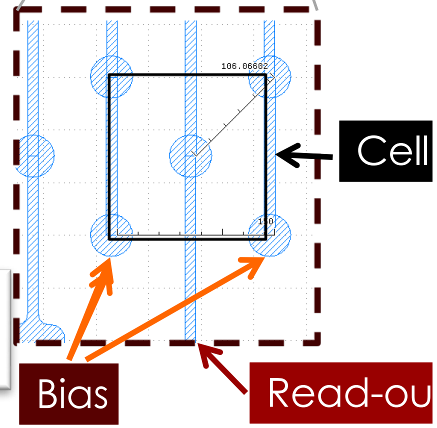
Thanks for material from the RD42 collaboration!

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]

Analysis steps

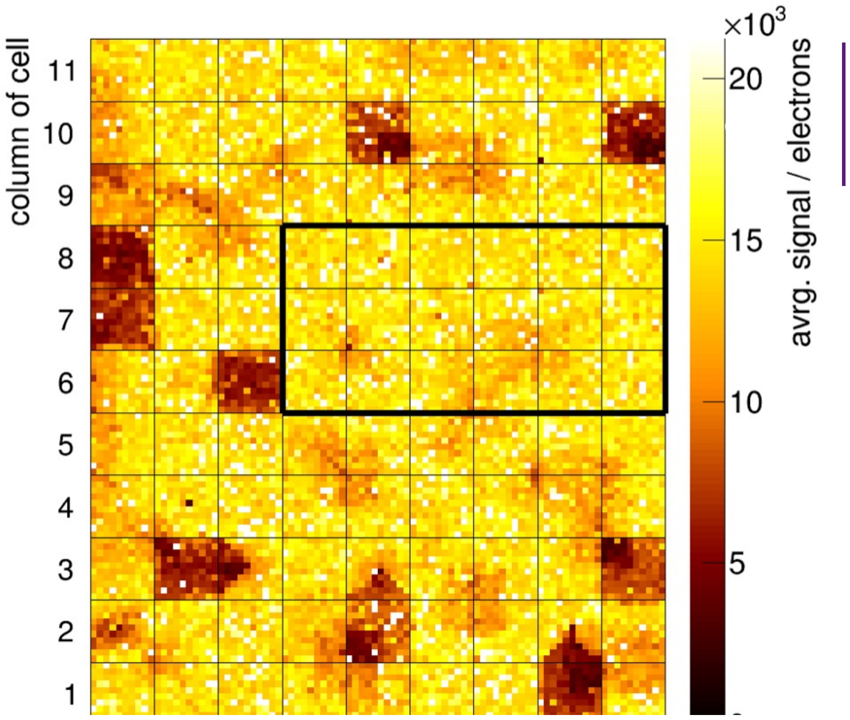
- U_b(3D)=40V
- U_b(strip)=500V

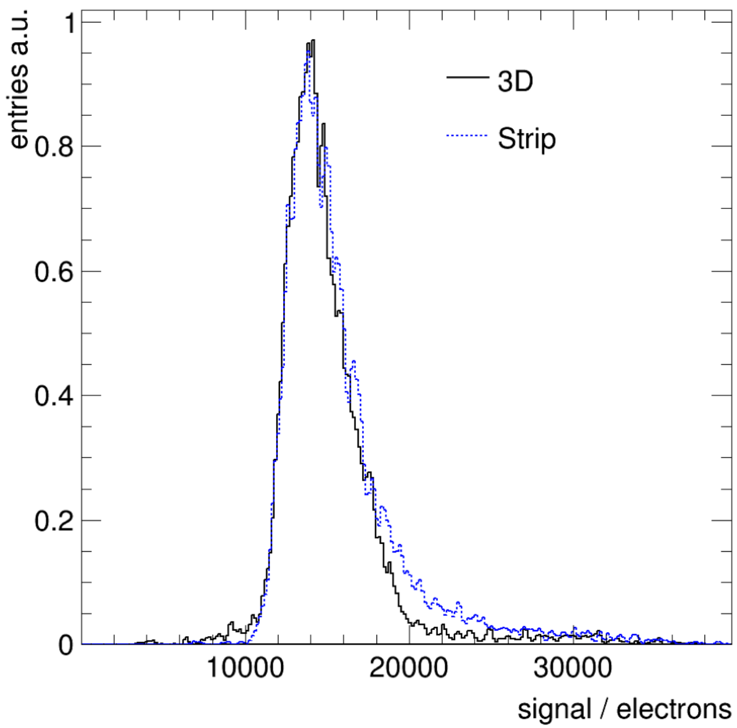
- Identify **continuous region** of intact cells for analysis.
- Exclude contribution of negative signals.

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

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

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





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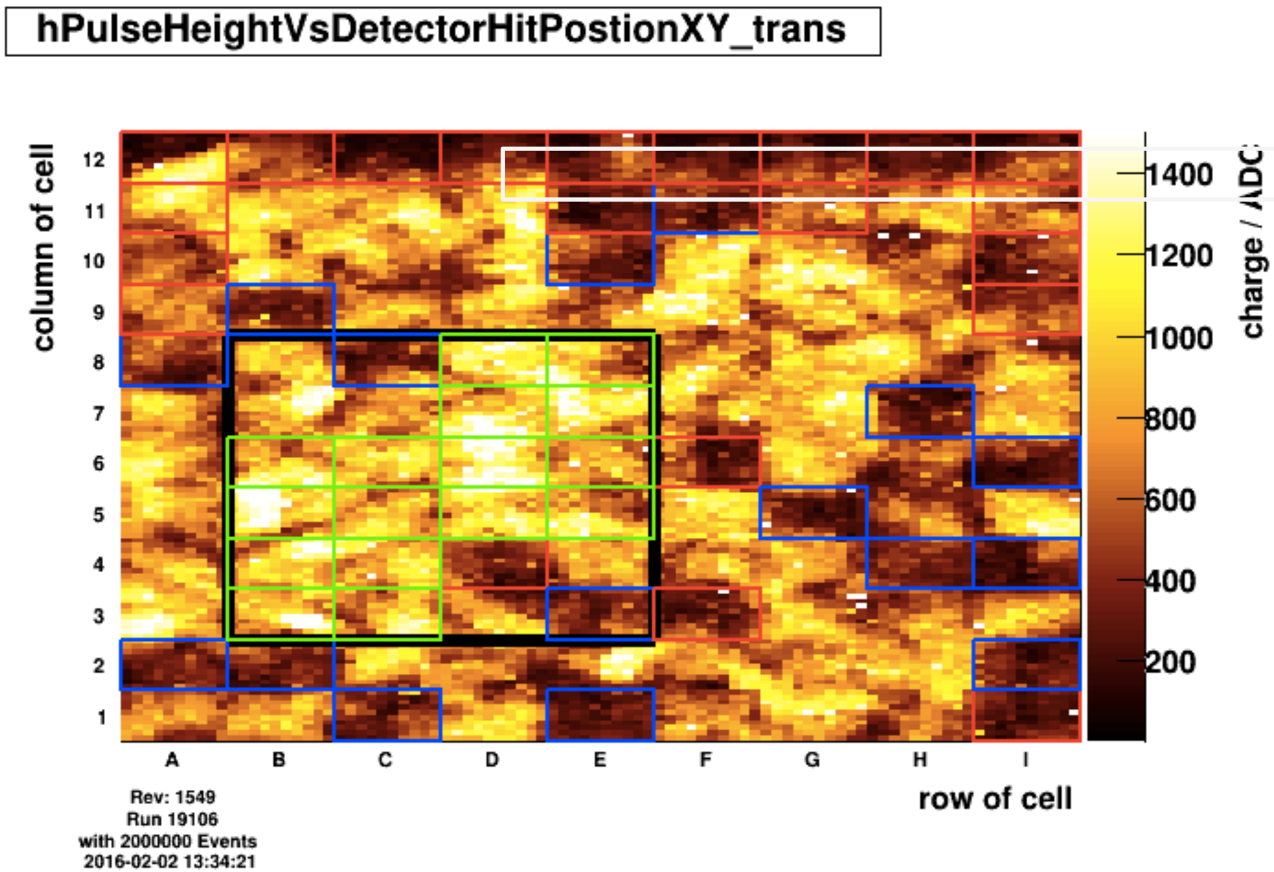
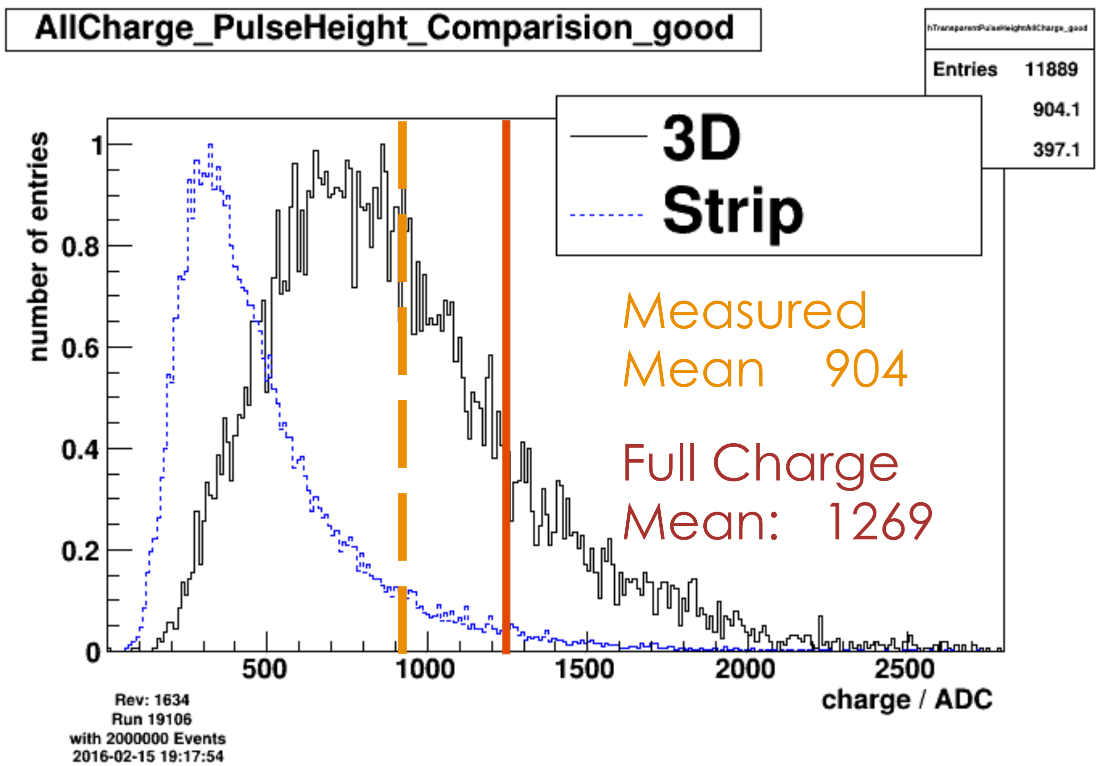
Test of first 3D pCVD diamond detectors



- 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.

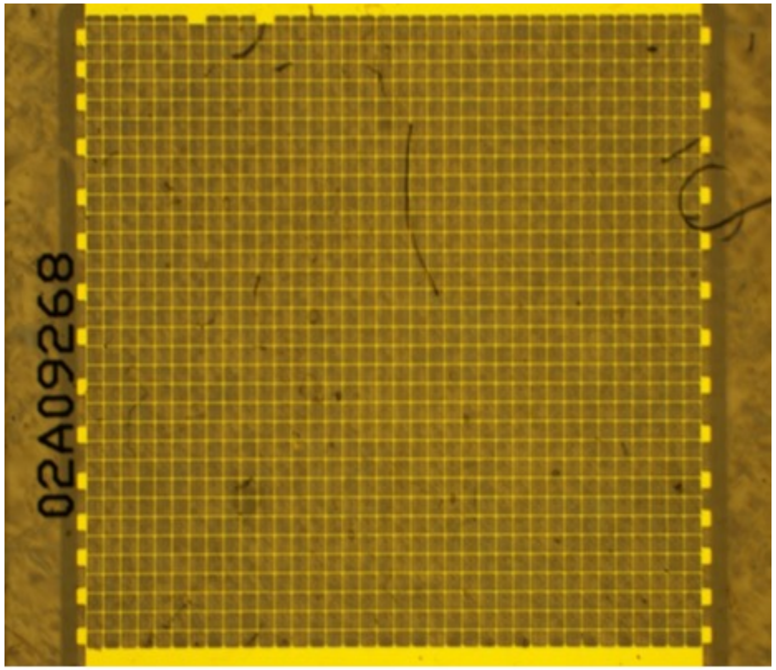
Highest charge collection ever measured for pCVD diamonds

Large area 3D, pCVD, 100x100

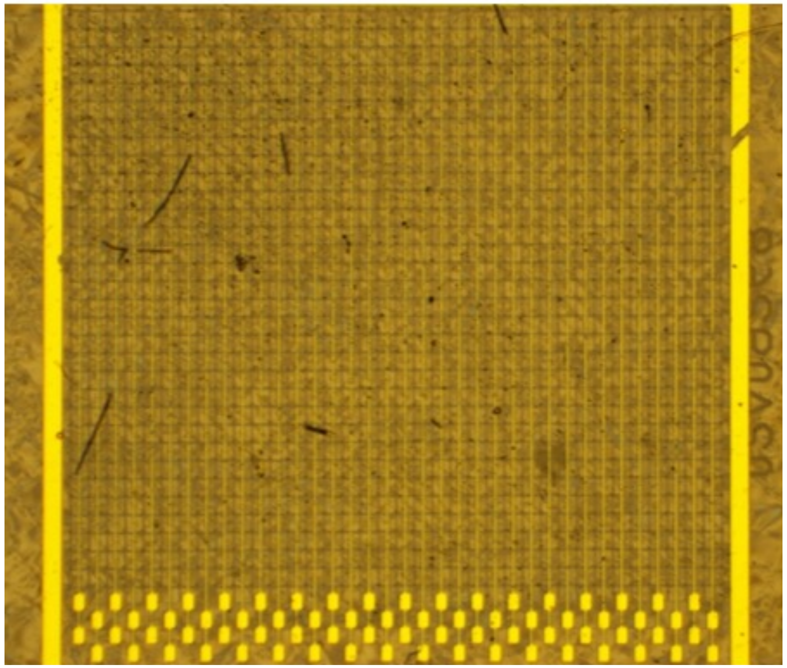
In May/Sept 2016 tested the first full 3D device fabricated in pcCVD with three dramatic improvements:

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

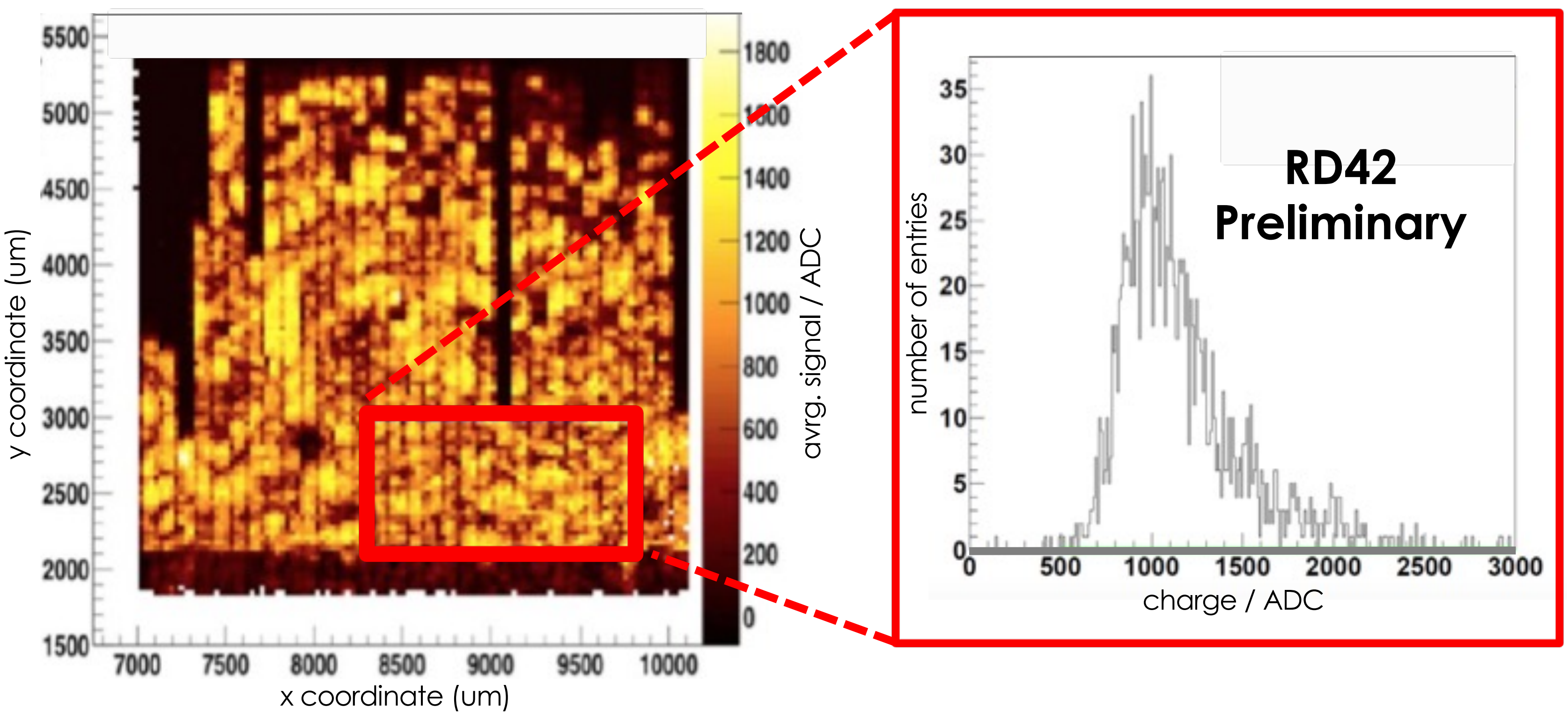


Readout side



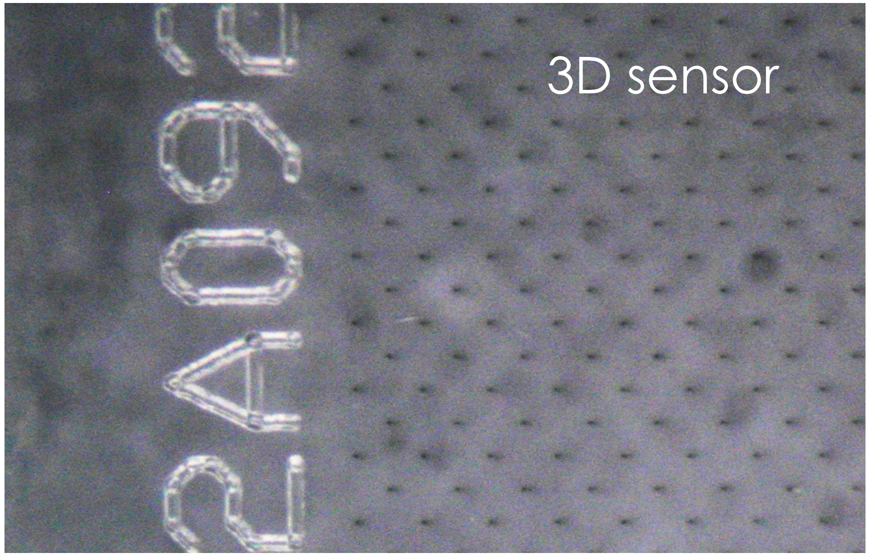
Large area 3D, pCVD, 100x100

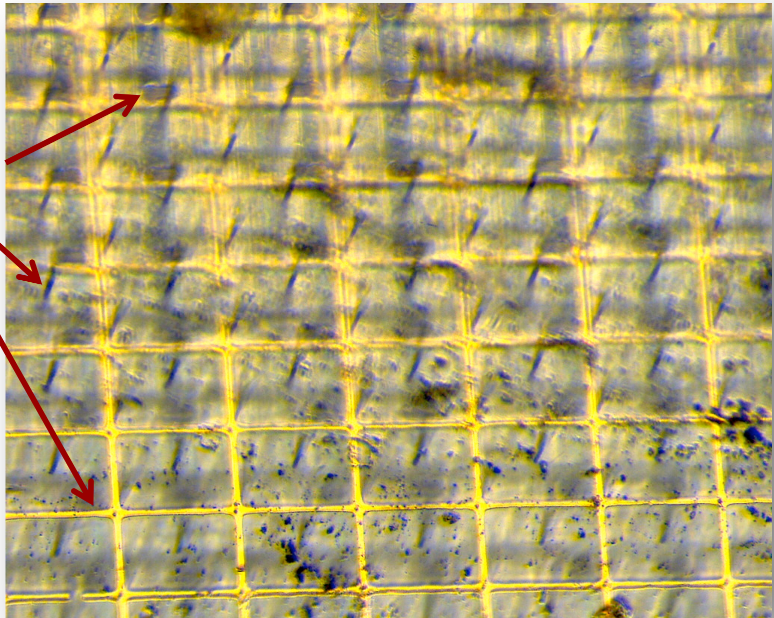
- Largest charge collection to date in pcCVD diamond!
  - >85 % of charge collected in continuous region, about twice as much as planar.

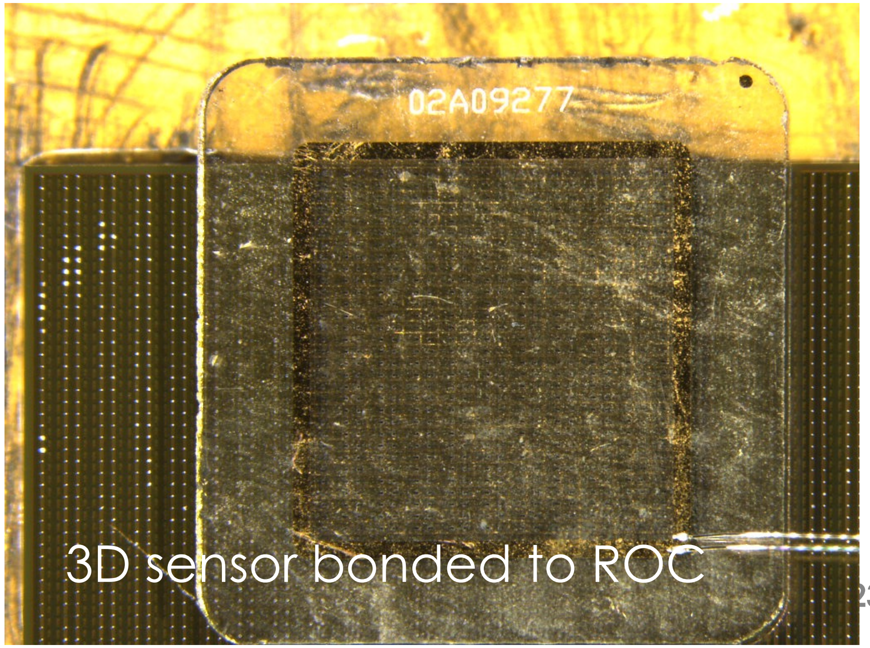


Pixel 3D, pCVD, 100x100

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

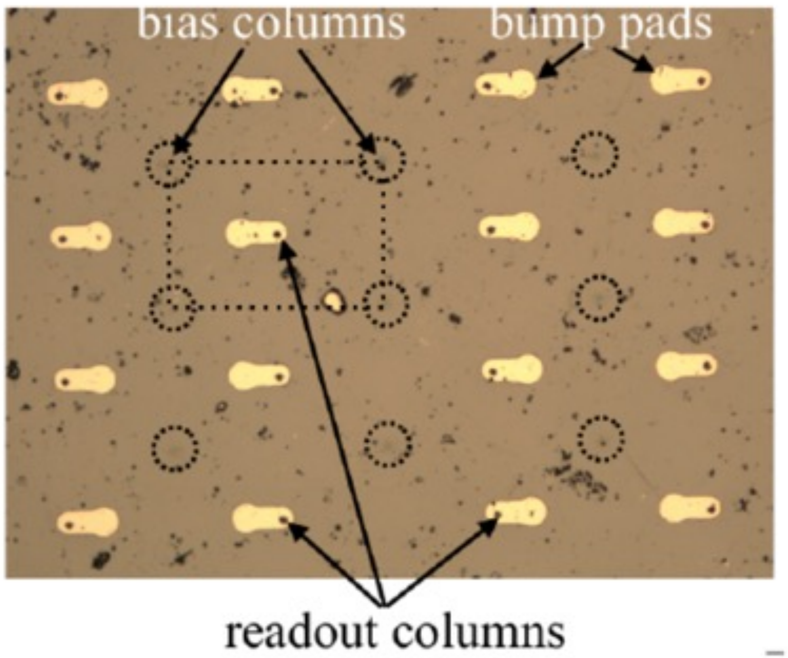


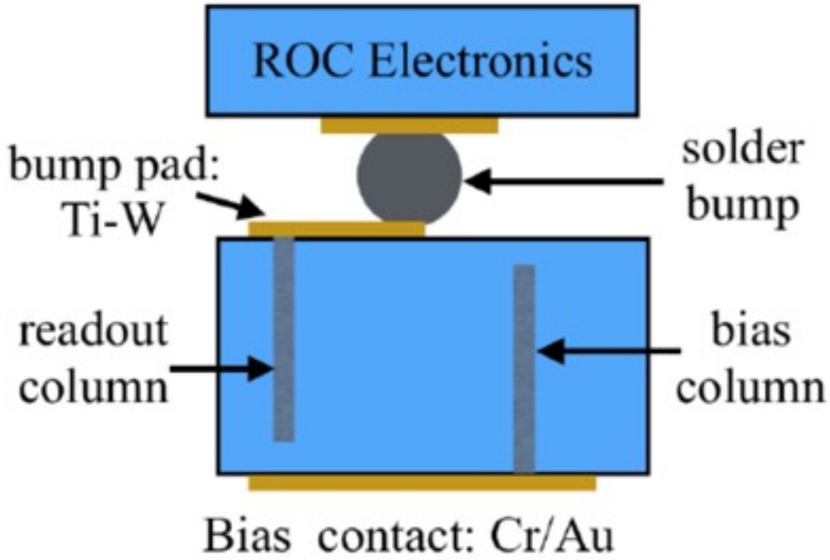




Pixel 3D, pCVD, 100x100

- Production of first pixel device using CMS readout electronics.

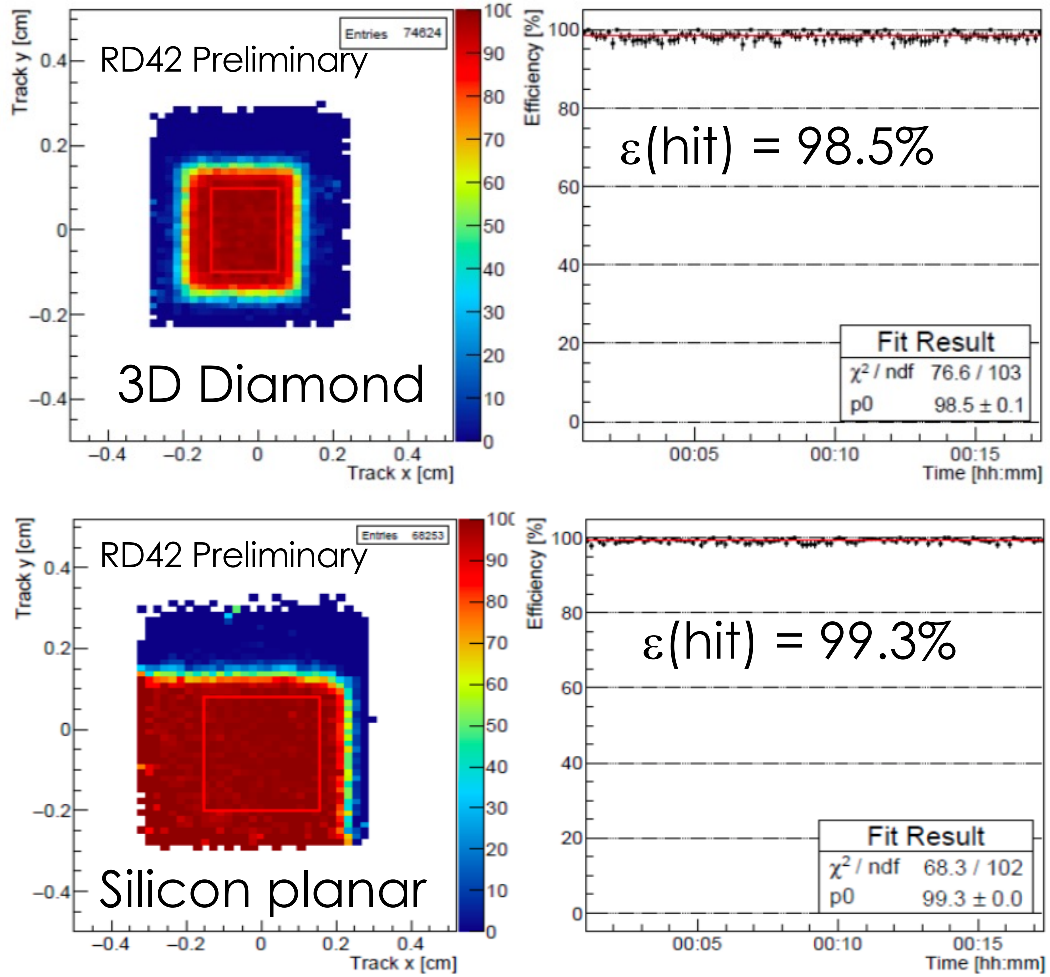




- Active region 3x3 mm with cell size ~100x100 um.

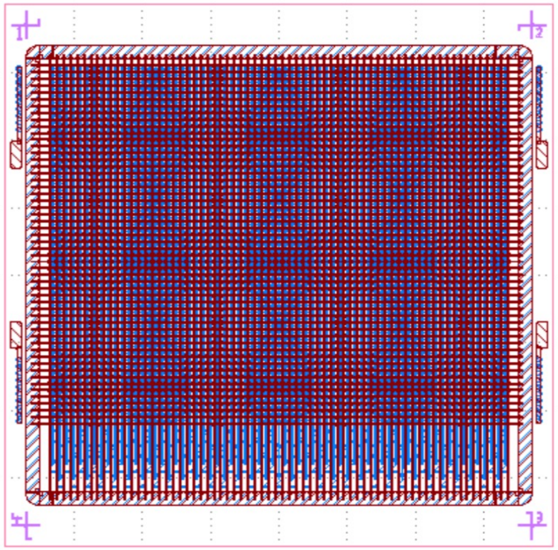
Pixel 3D, pCVD, 100x100

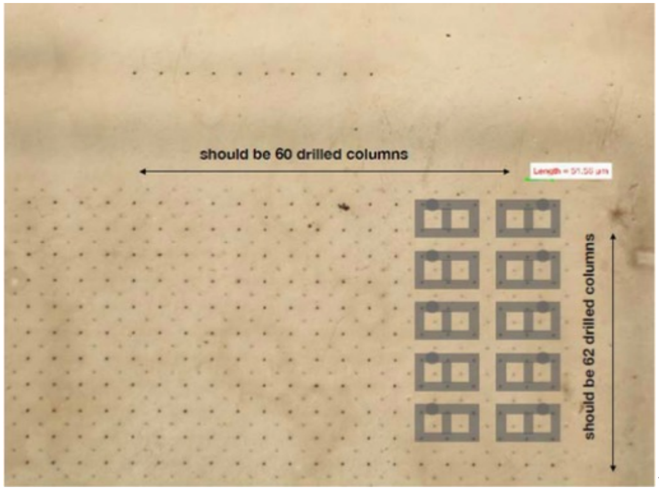
- 3D diamond device and Silicon reference planar device.
- Pixel threshold 1500e.
- Check hit efficiency over time.
- Device works!



Next generation 3D Diamond

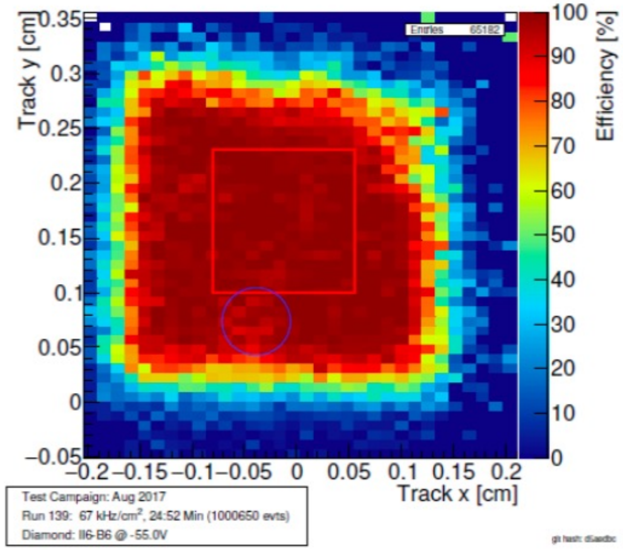
- Produced 3500 Cell pixel protoype, 50x50um cell size.
- Sample production:
  - Oxford (2x cubic cells)
  - Manchester set-up in progress (expected production date end of month.)
  - Bump bonding
    - For ROC (CMS) Princeton.
    - For FE-I4 (ATLAS) IFAE.
- Data taking in August 2017 at PSI.

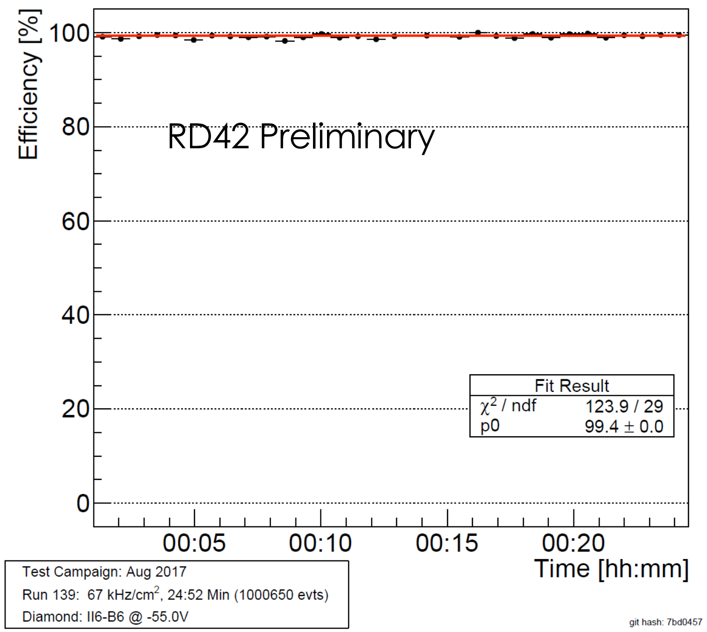




First 50x50 μm cell 3D Diamond (2017)

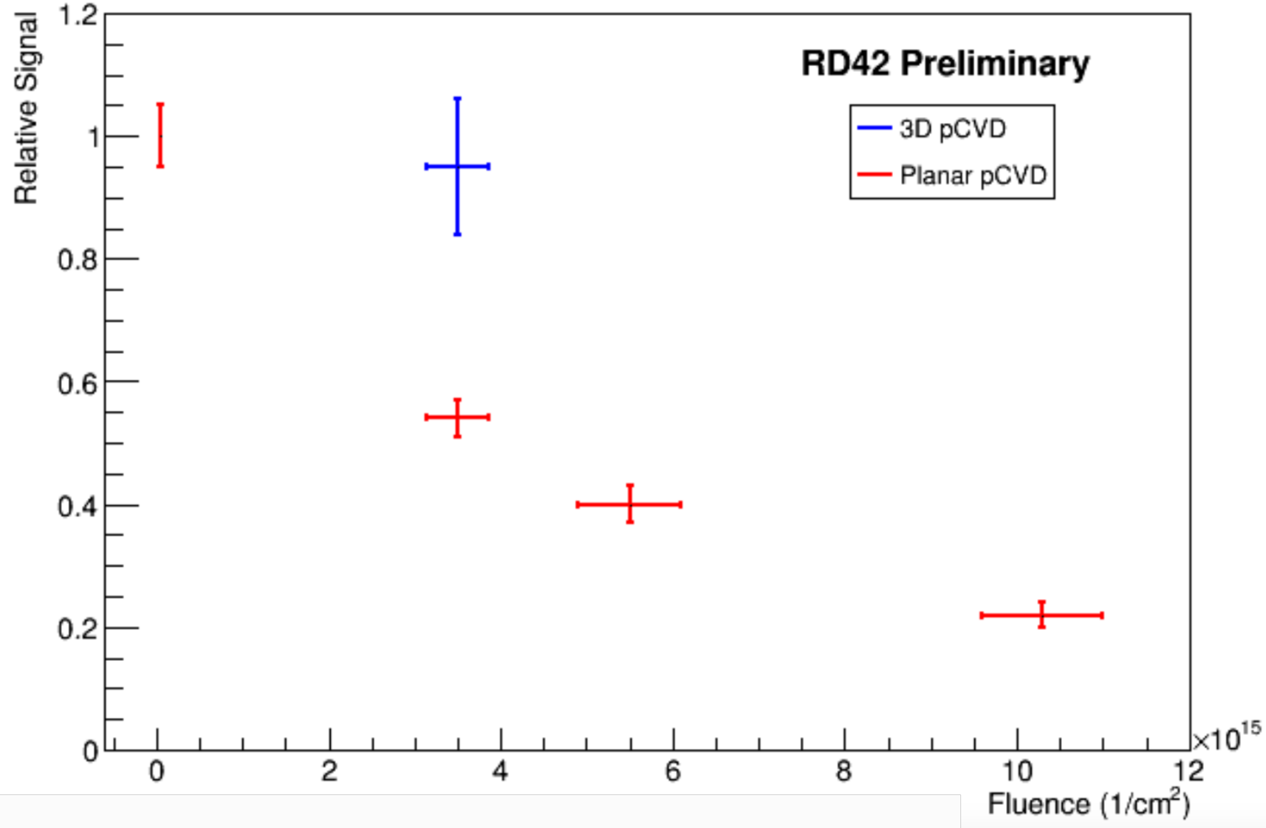
- Readout with CMS pixel readout.
- Bump bonding issue in upper right edge (Indium bump deposition machine not working properly)
- 6 columns (3x2) ganged together.
- Preliminary hit efficiency 99.2%
- Preliminary:
  Collect >90% of charge!
- Rate dependence tested with 10 kHz/cm^{-2} and 10 MHz/cm^{-2} ->
  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

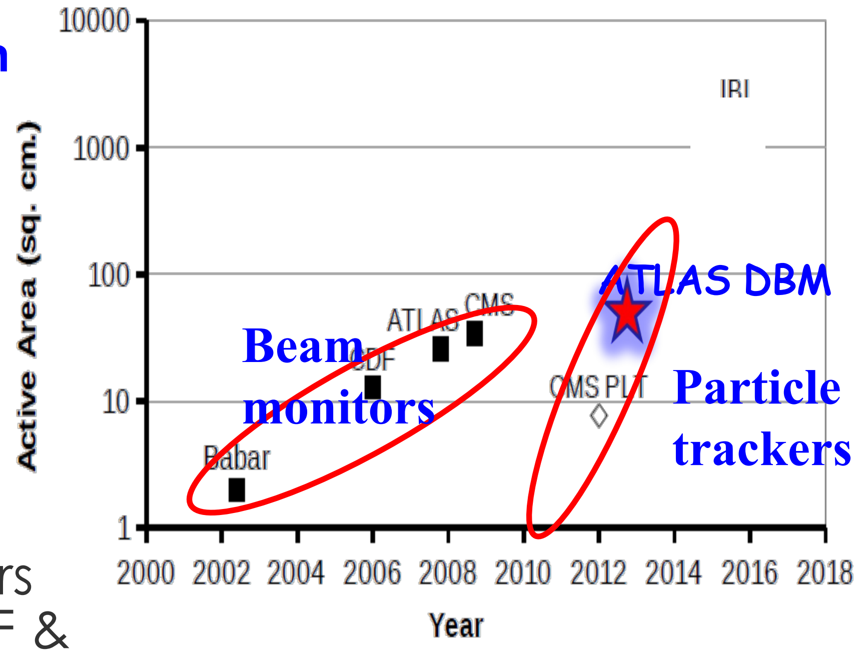
- Vertex detectors with CVD Diamond are not considered yet as an option for LHC.

- 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.

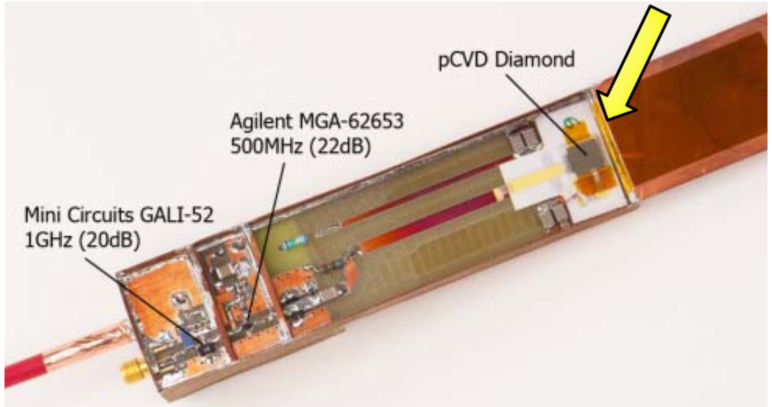
Diamond in current HEP experiments

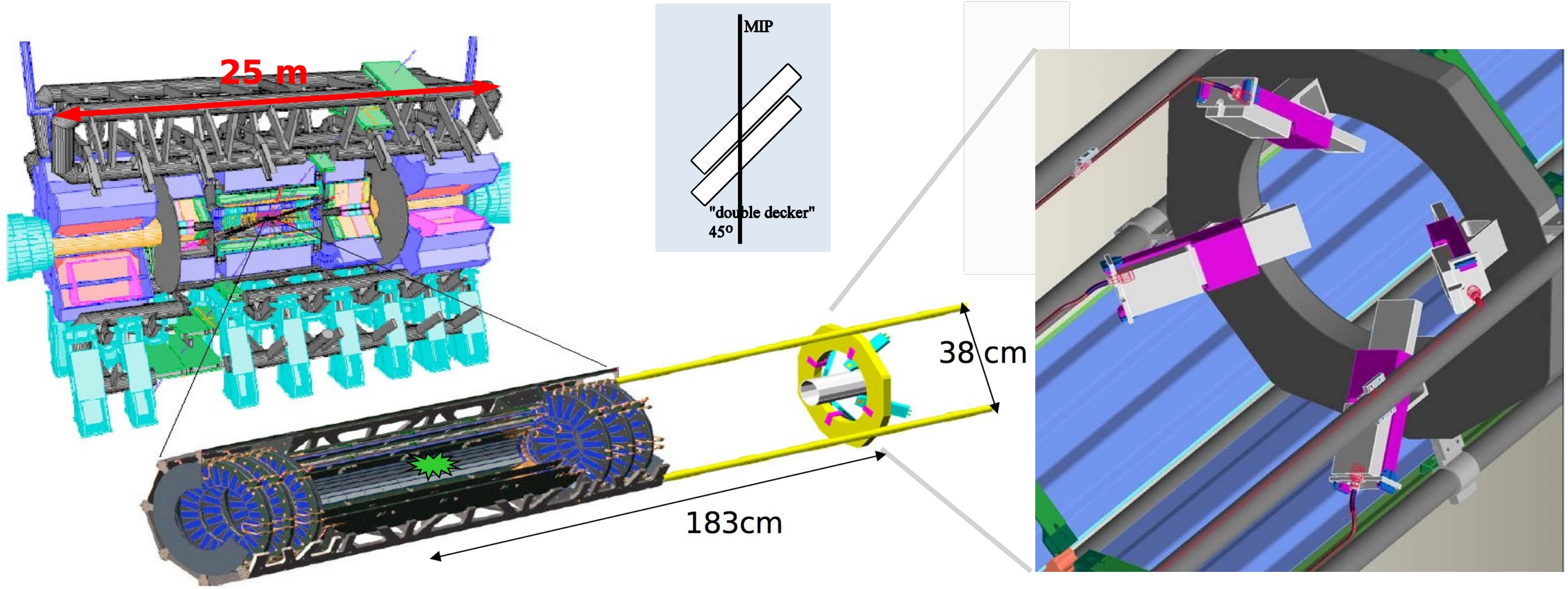
- **Beam monitors** to protect experiments against **beam losses** at the LHC, CERN.
  - For Silicon Vertex systems careful monitoring is crucial.
  - Beam monitors have to be **radiation hard.**
  - Abort beam when monitors signal dangerous beam conditions.
  - False signals must be avoided.
- During 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

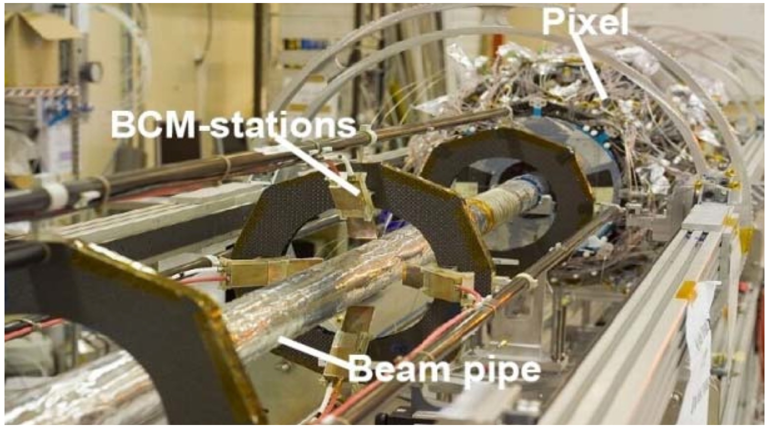
- Use 2x polycrystalline CVD diamonds per station (10 x 10 mm).
- 4 stations on each side of the ATLAS pixel detector
  - z = ±183.8 cm (~12.5ns) and r ~ 5 cm

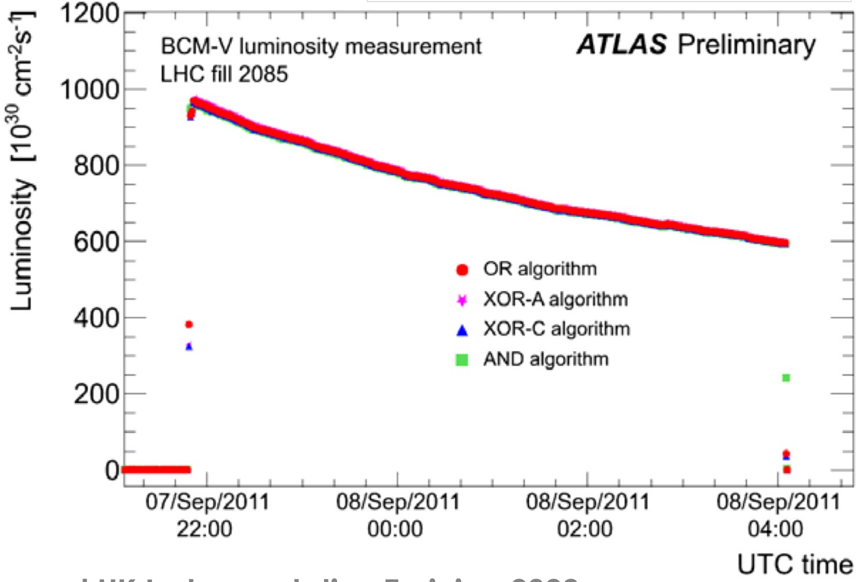


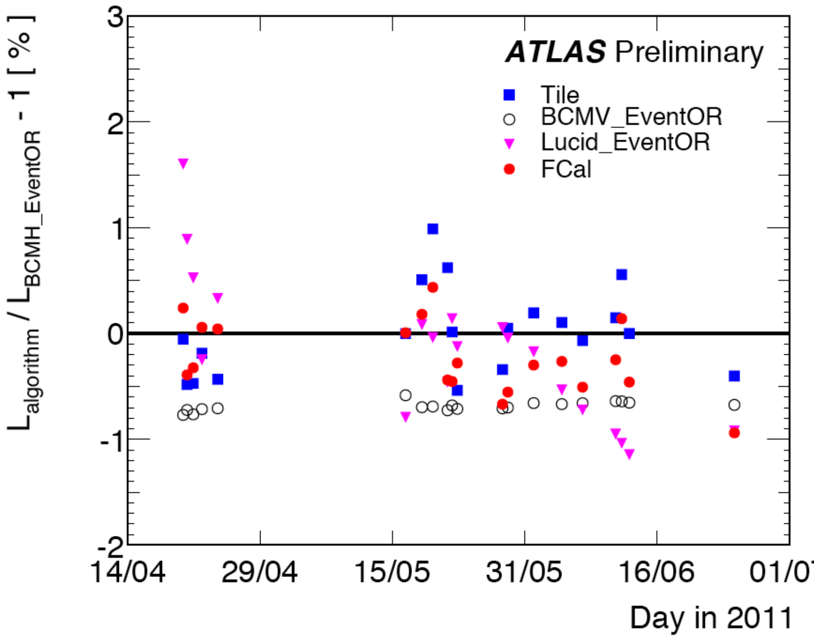


ATLAS beam conditions monitor

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

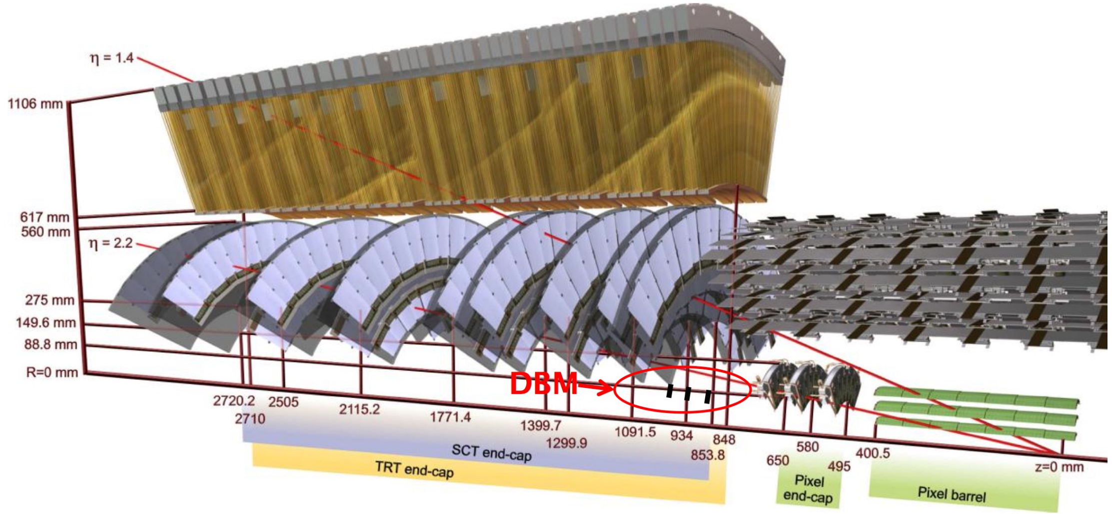






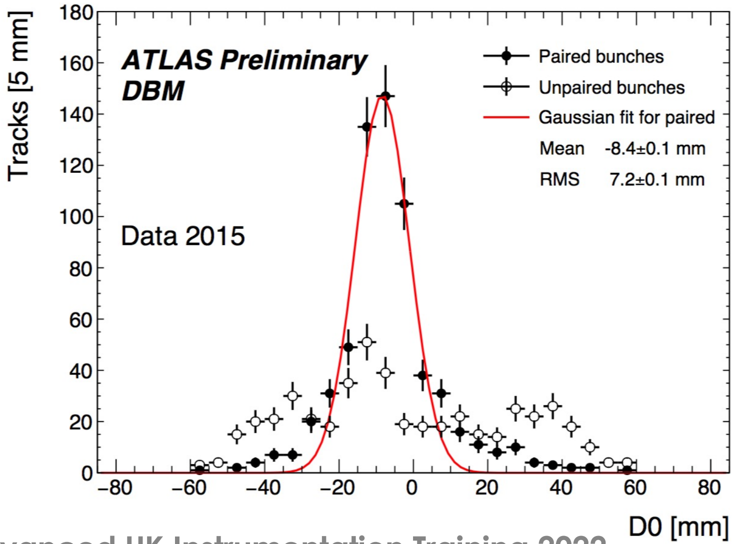
Run 2:
ATLAS Diamond Beam Monitor

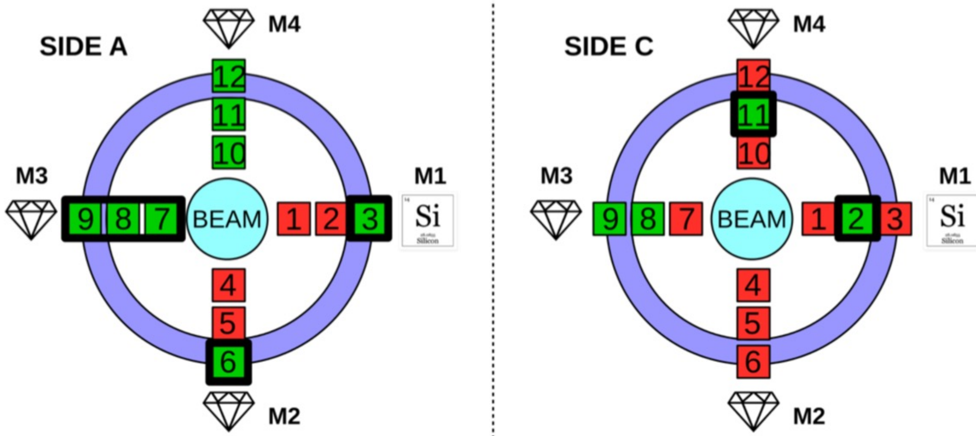
- 8 mini-trackers of 3 planes each using pixel-detectors.
- polycrystalline diamond sensors, 18mm x 21mm, $\delta > 250\mu m$.
- bump-bonded to FE-I4 pixel read-out chip.
  - 336 x 80 pixels
  - pixel size : $50\mu m$ x $250\ \mu m$
- Purpose:
  - Bunch-by-bunch luminosity monitor (aim < 1 % per BC per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



Run 2:
ATLAS Diamond Beam Monitor

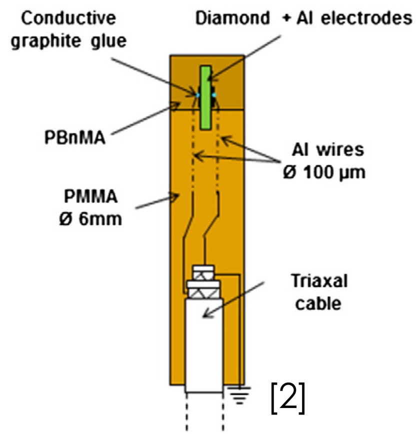
- Installed in ATLAS during LS1, but switched off due to unexpected death of Si and Diamond modules.
- DBM recommissioned in 2017/18 with 50% working modules.



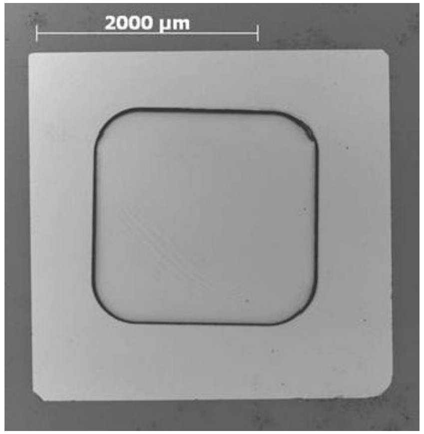


Examples of diamond detectors in related areas

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



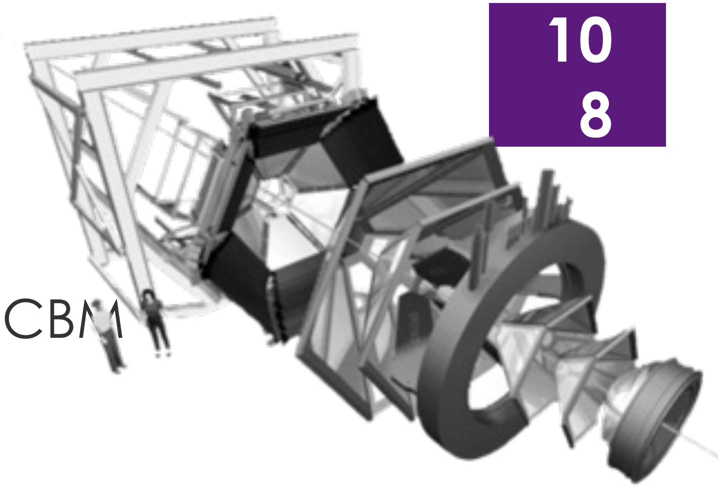
scCVD dosimeter,
0,4 mm^3 active vol. [2]



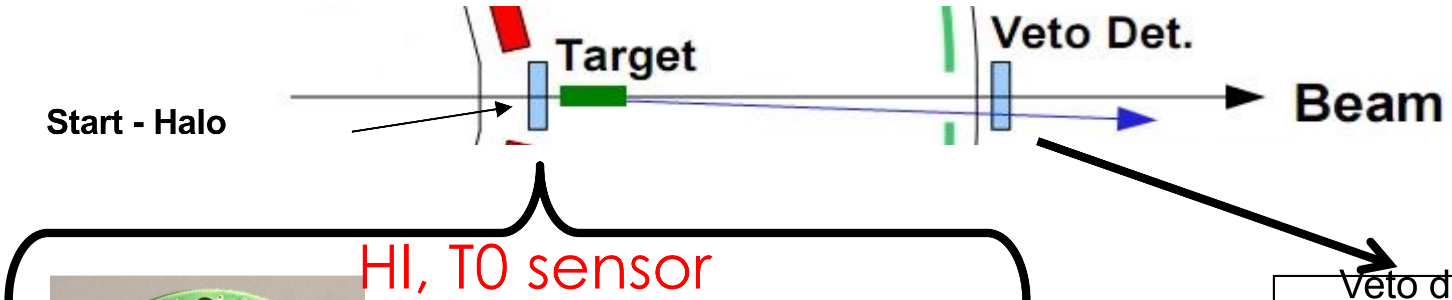
3 µm thick membrane in 40 µm thick scCVD [1]

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

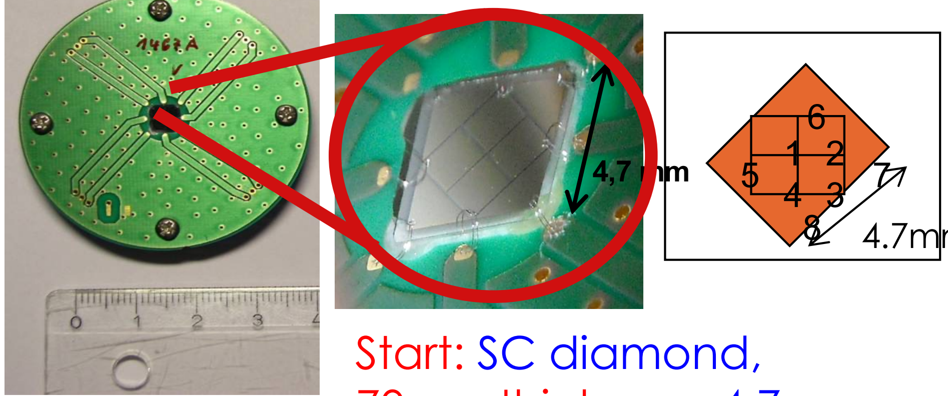
Detectors for Heavy Ion



- 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

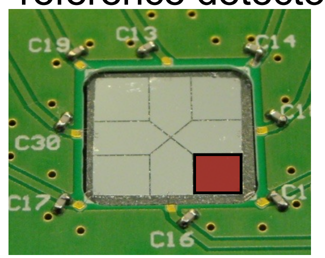


HI, T0 sensor



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

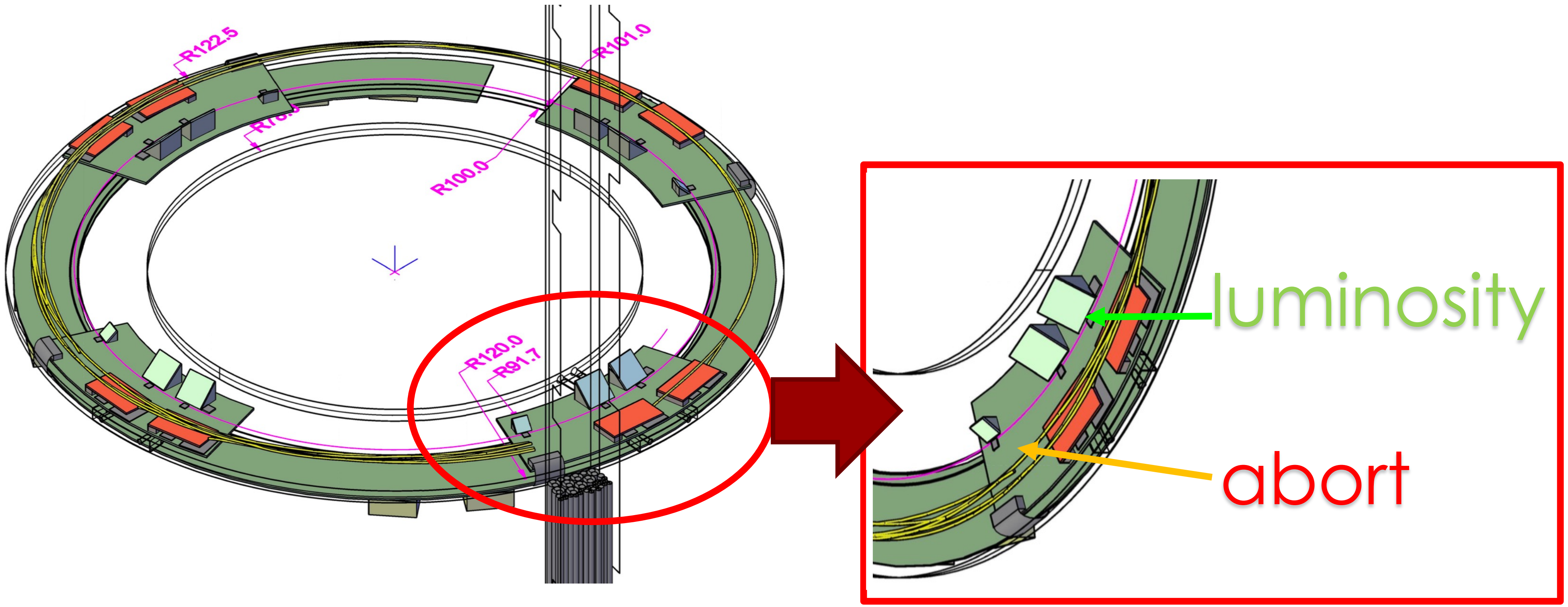
Veto detector,
reference detector



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

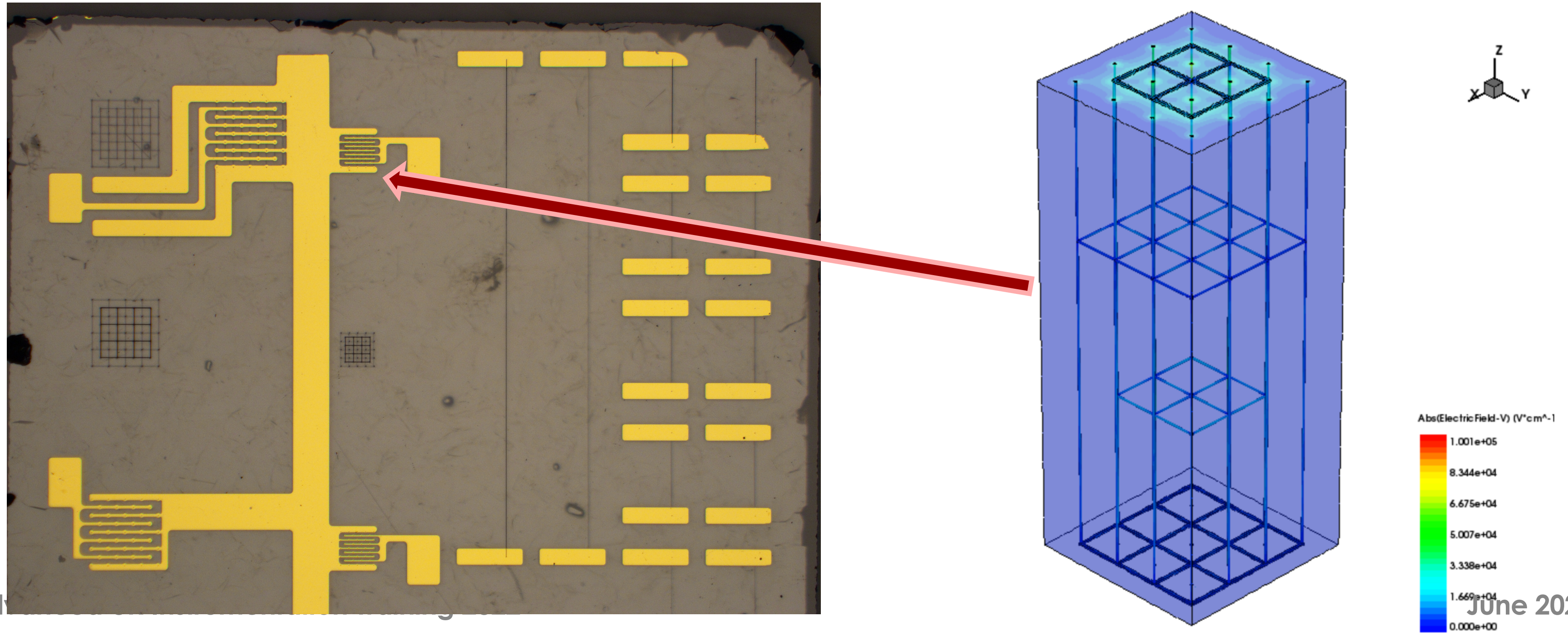
J.Pietraszko, 21st CBM Collab. Meeting

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.