The University of Manchester

3D Diamond Development for tracking and dosimetry measurements

Iain Haughton, PhD
The University of Manchester
iain.haughton@cern.ch

TIPP - 2017

MANCHESTER 1824

The University of Manchester

Authors

[1] The University of Manchester – Manchester, UK

Alex Oh, Iain Haughton, Steve Murphy, Giulio Forcolin, Francisca Munoz Sanchez, Olivier Allegre, David Whitehead

[2] The University of Oxford – Oxford, UK

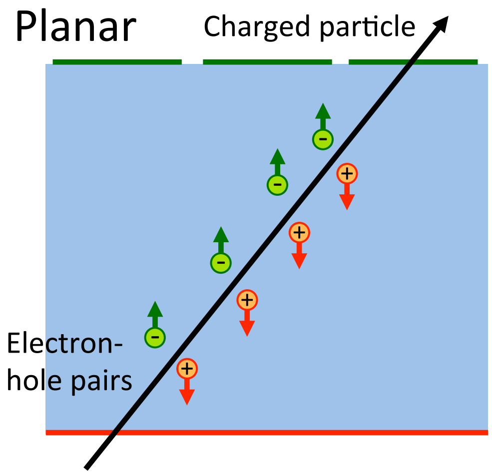
Martin Booth, Patrick Salter

[3] Ruder Boskovic Institute – Zagreb, Croatia

Milko Jaksic, Natko Skukan

Introduction – why 3D?

1. Build an ultra radiation tolerant particle detector.
2. Improve the performance of polycrystalline diamond for high precision particle detectors.



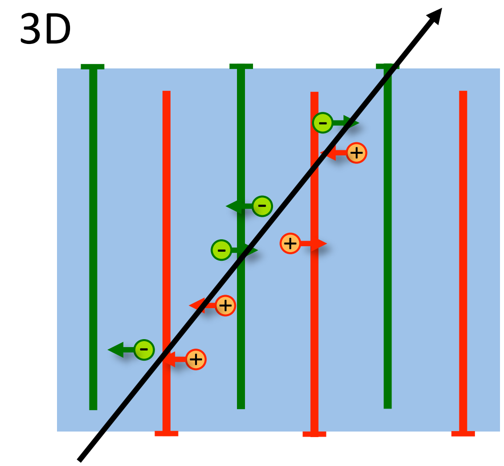
Instantaneous current — Carrier charge

$$i = E_w q v$$

Weighting field — Carrier velocity

Induced charge

$$Q = \int i \, dt$$



- Carriers have to travel a much shorter distance in 3D to get equivalent charge induced.

Number of carriers

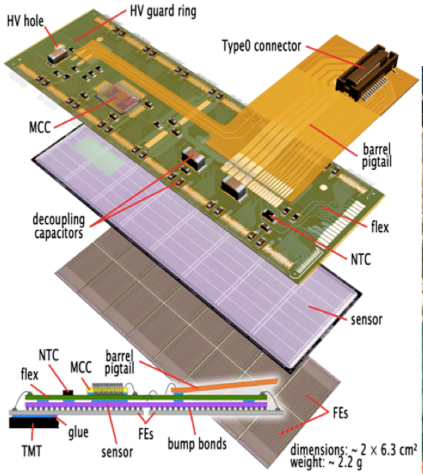
$$n(t) = n_0 e^{-t/\tau}$$

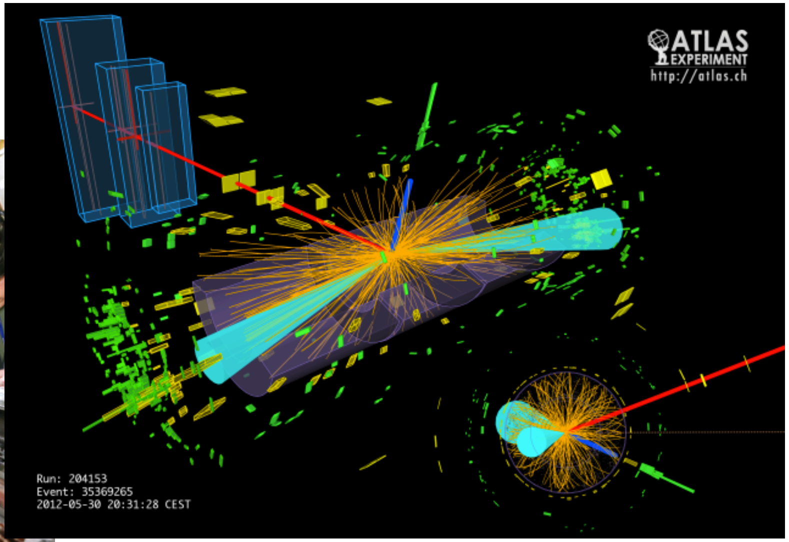
Carrier lifetime

- τ decreases with radiation exposure.
- τ is smaller in polycrystalline diamond than in single crystal diamond.

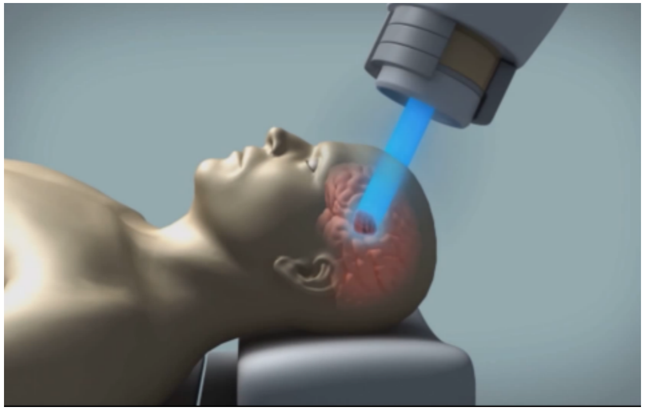
Introduction - applications

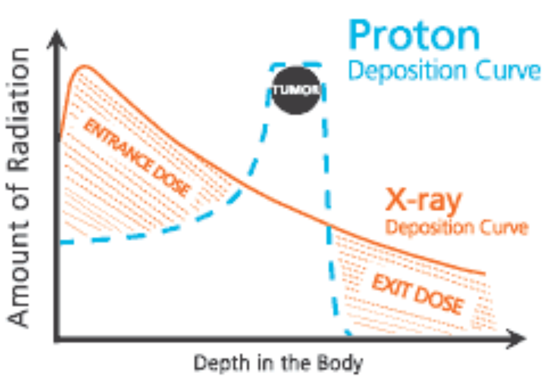
- High energy physics:





- Medical dosimetry (proton therapy):





MANCHESTER 1824

The University of Manchester

Fabrication

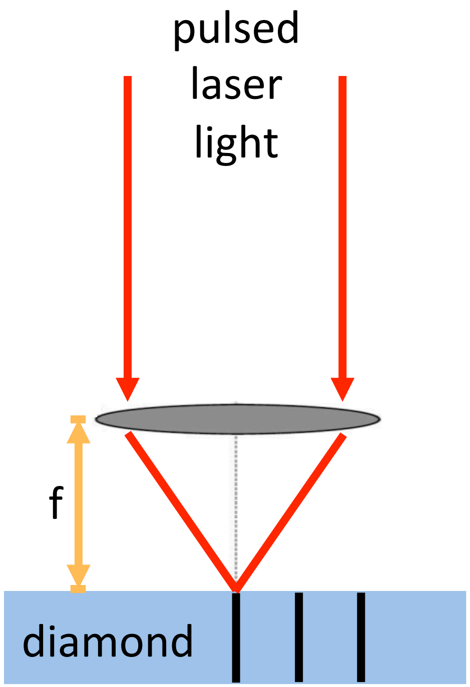
The University of Manchester – Manchester, UK

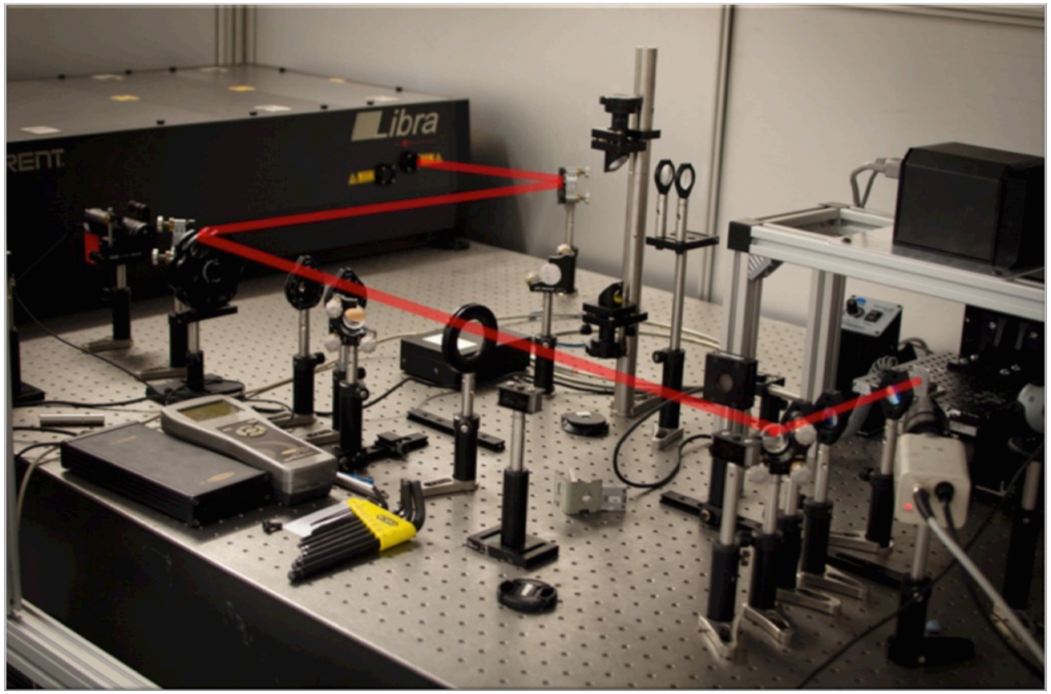
The University of Oxford – Oxford, UK

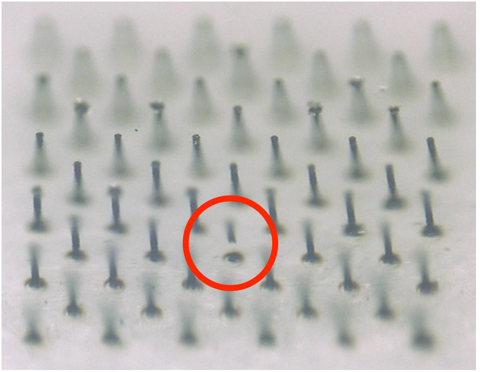
[4] M. Booth et al, "Three dimensional laser micro fabrication in diamond a using dual adaptive optics system", Opt. Express (2011).

[5] M. Booth and A. Jesacher, "Parallel direct laser writing in three dimensions with spatially dependent aberration correction", Opt. Express (2010).

Column formation - laser processing

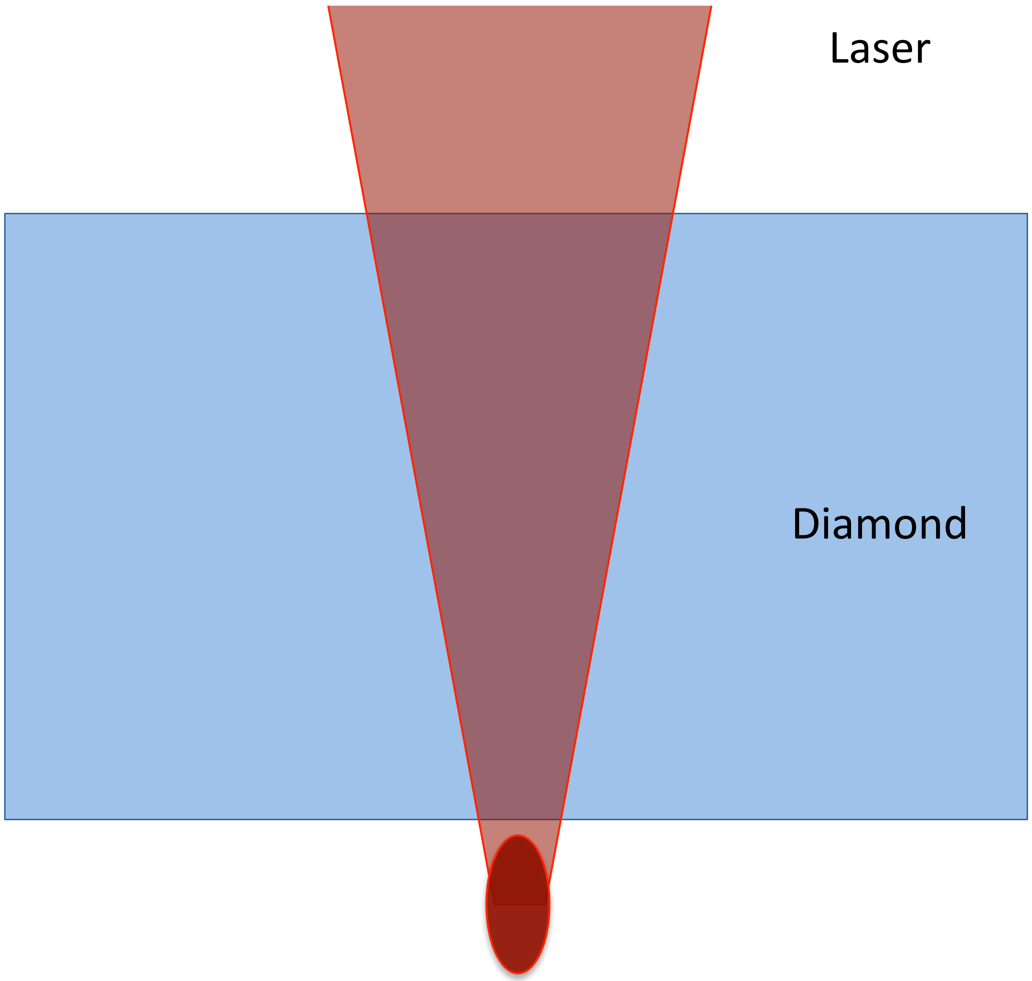




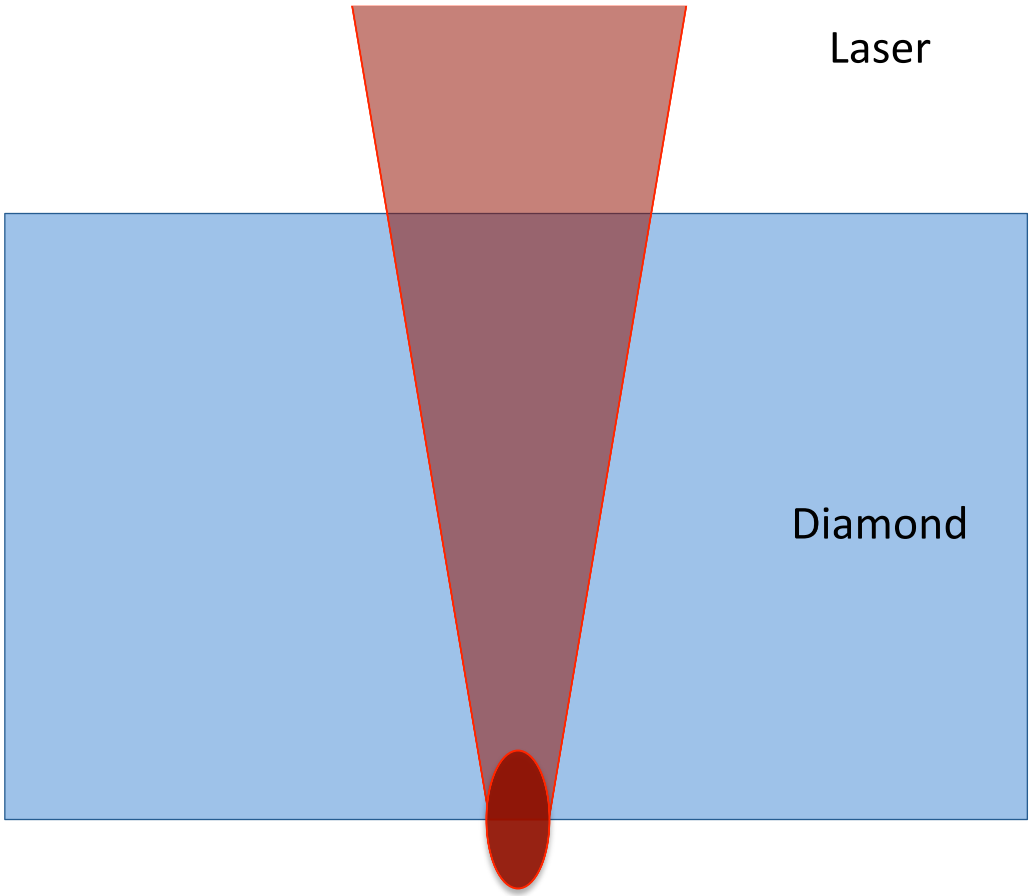


- Laser wavelength = 800nm.
- Laser pulse length = 120fs.
- Transform sp^3 diamond (non conductive material) into a combination of diamond-like carbon, amorphous carbon and graphite (conductive material).

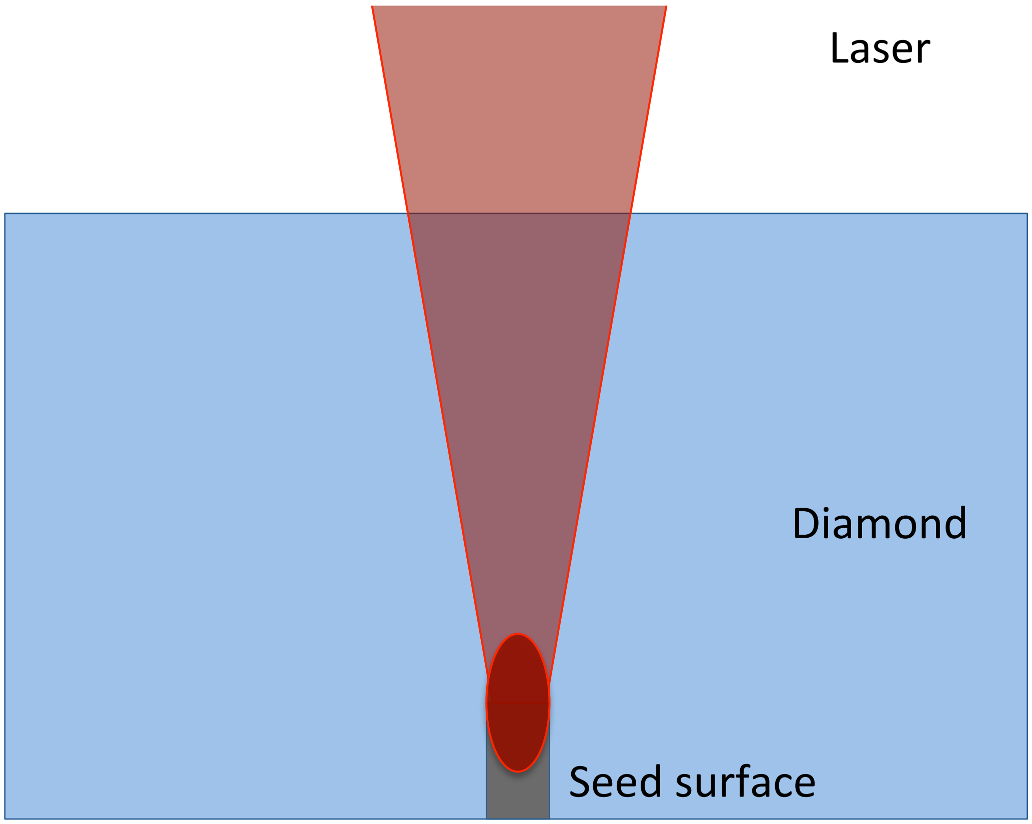
Column production



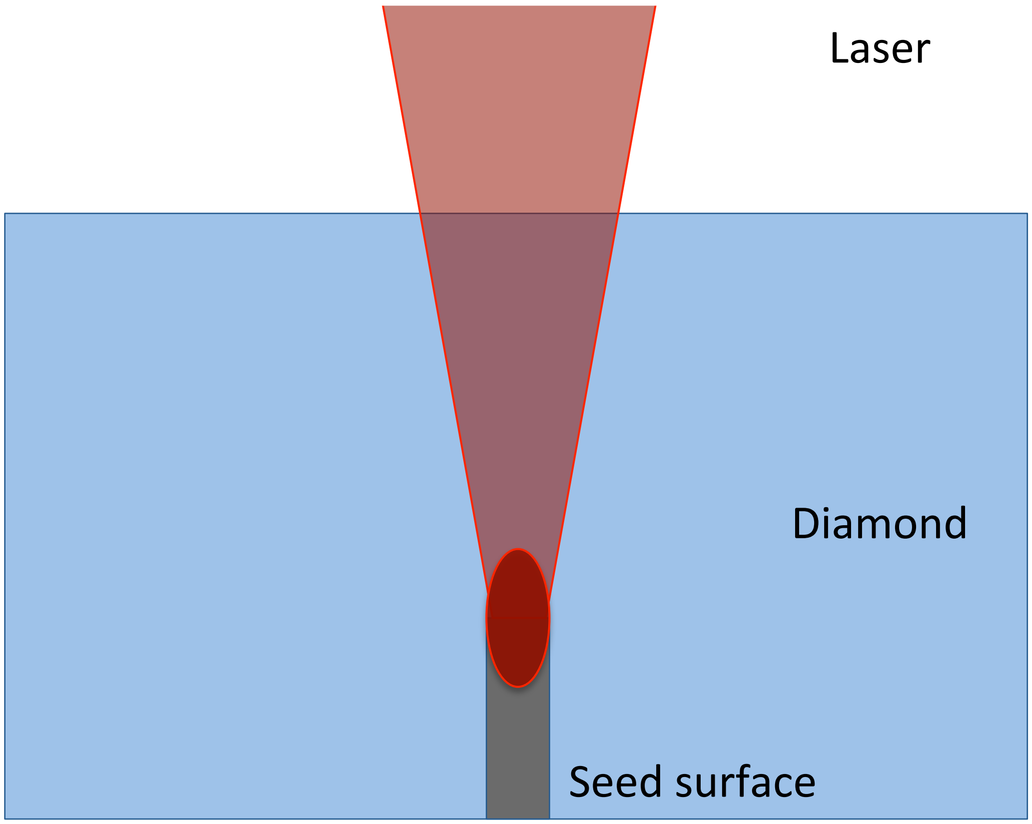
Column production



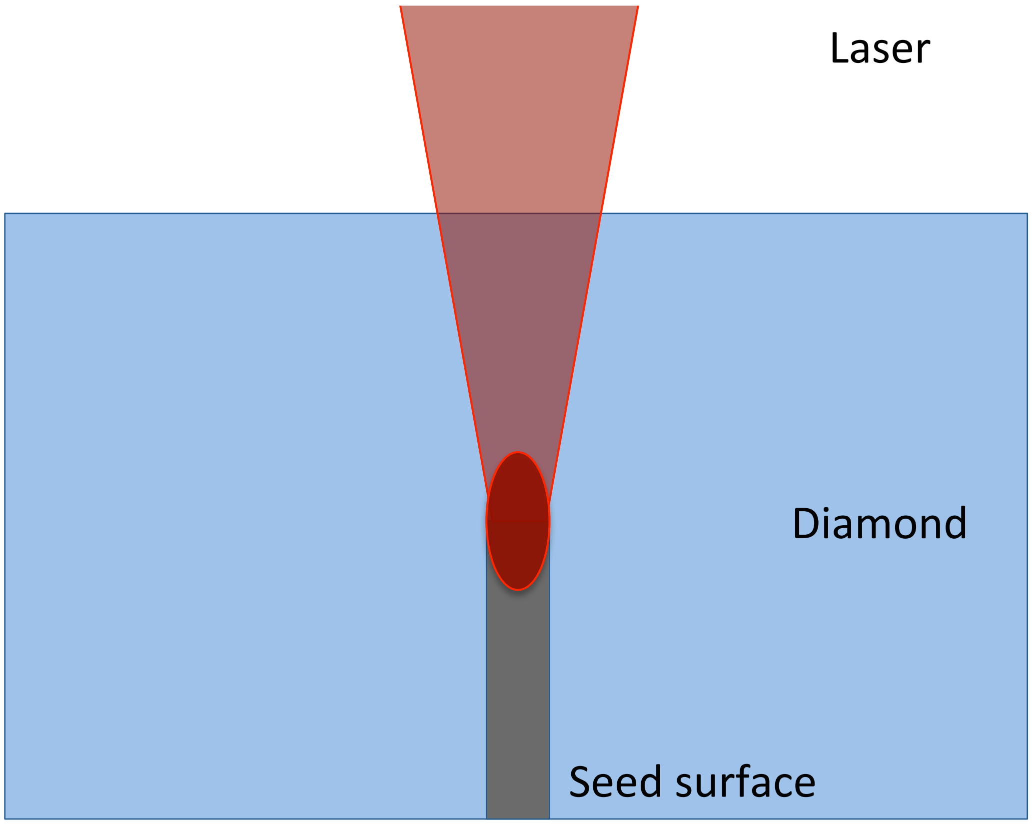
Column production



Column production



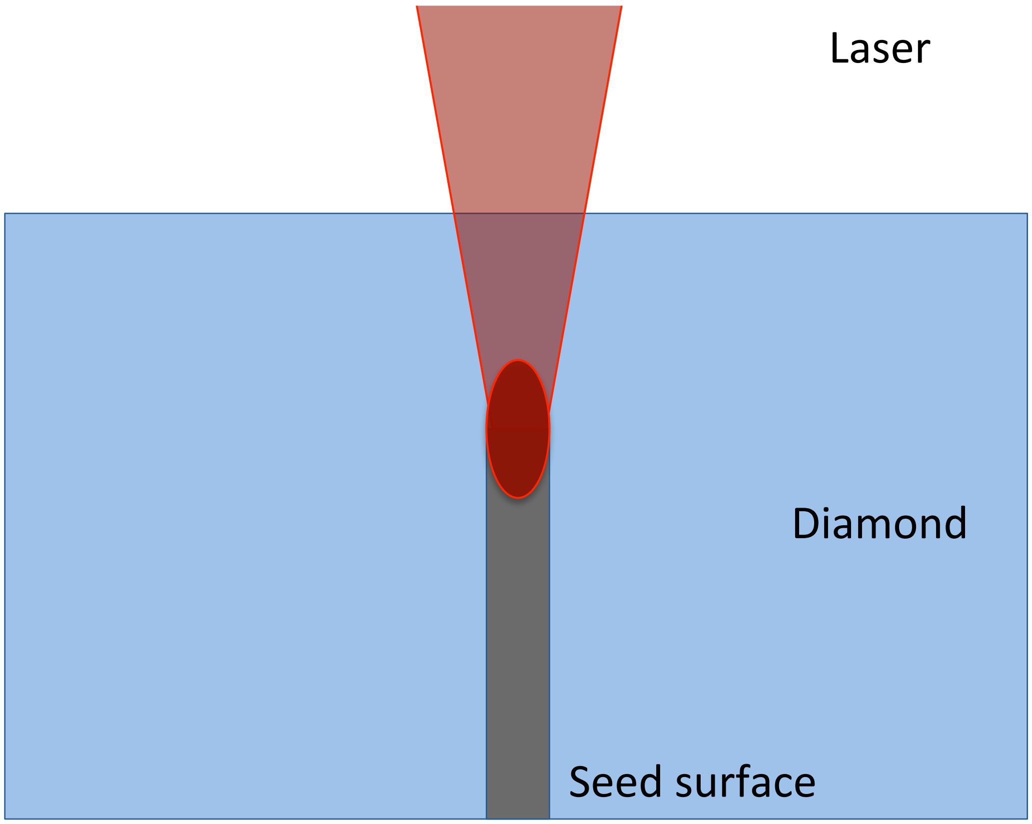
Column production



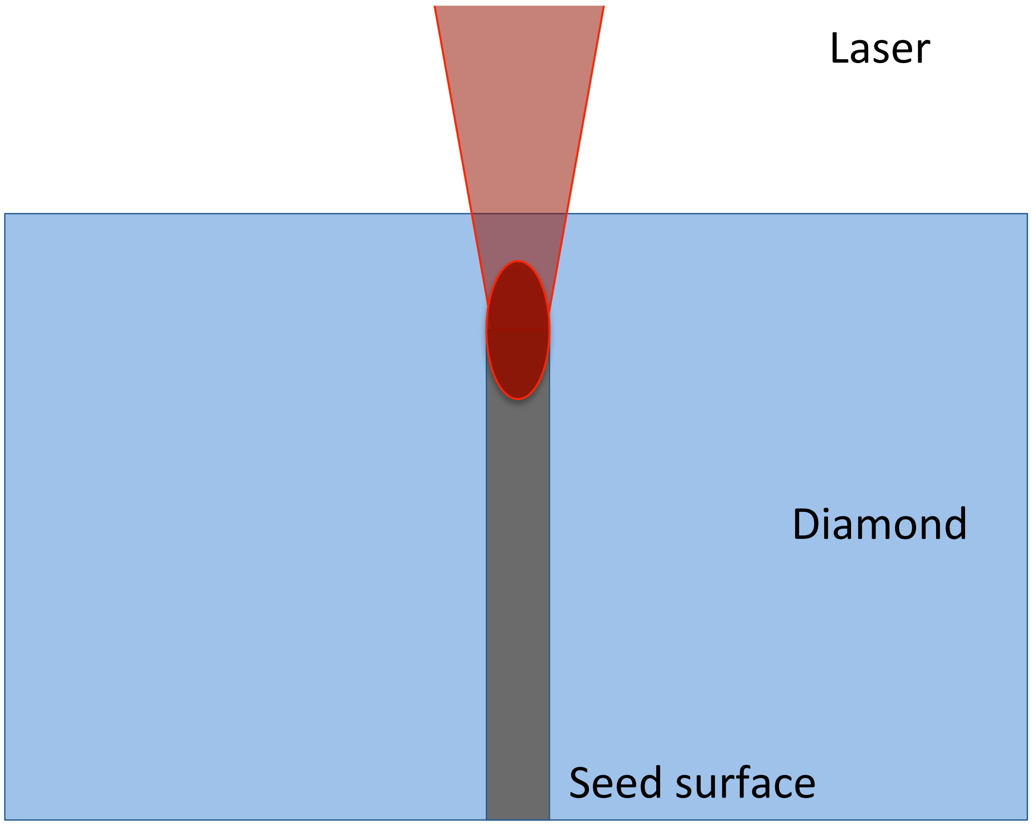
MANCHESTER 1824

The University of Manchester

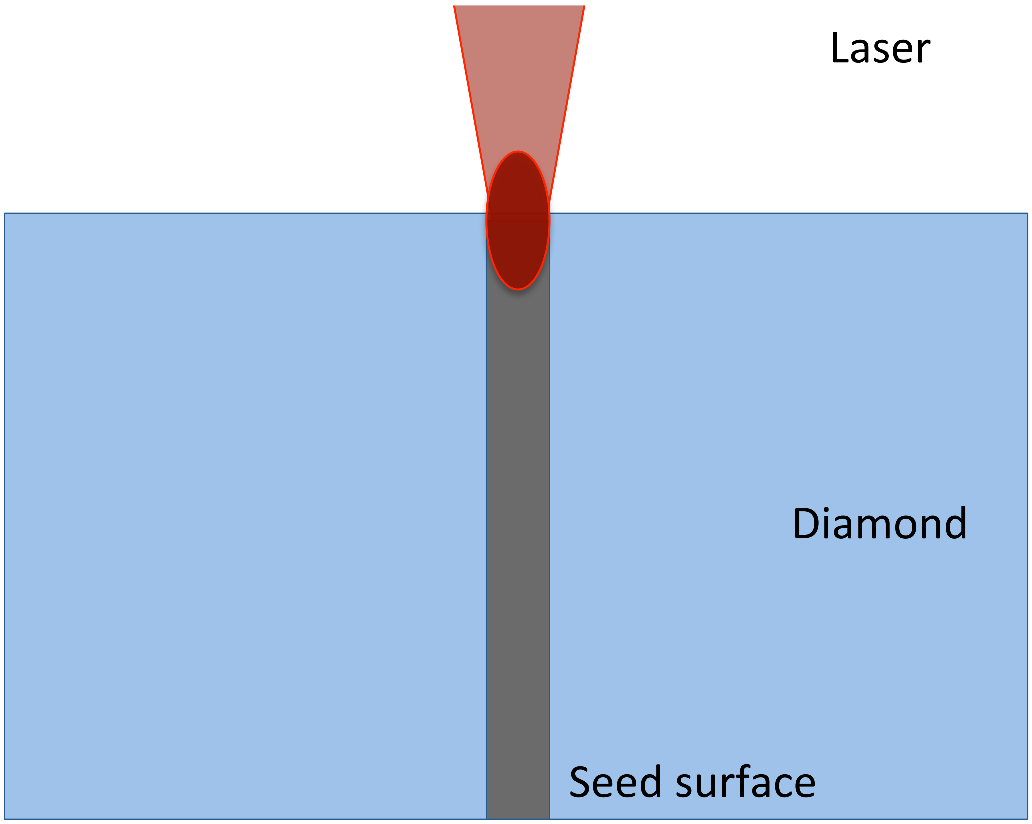
Column production



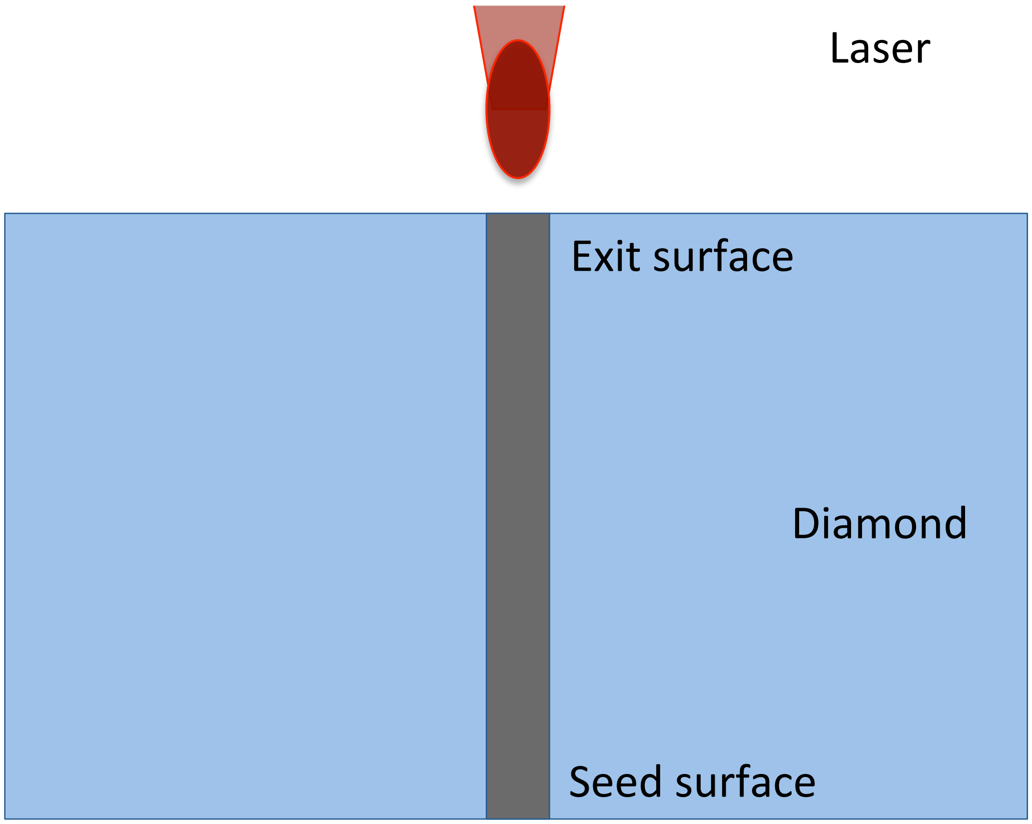
Column production



Column production



Column production



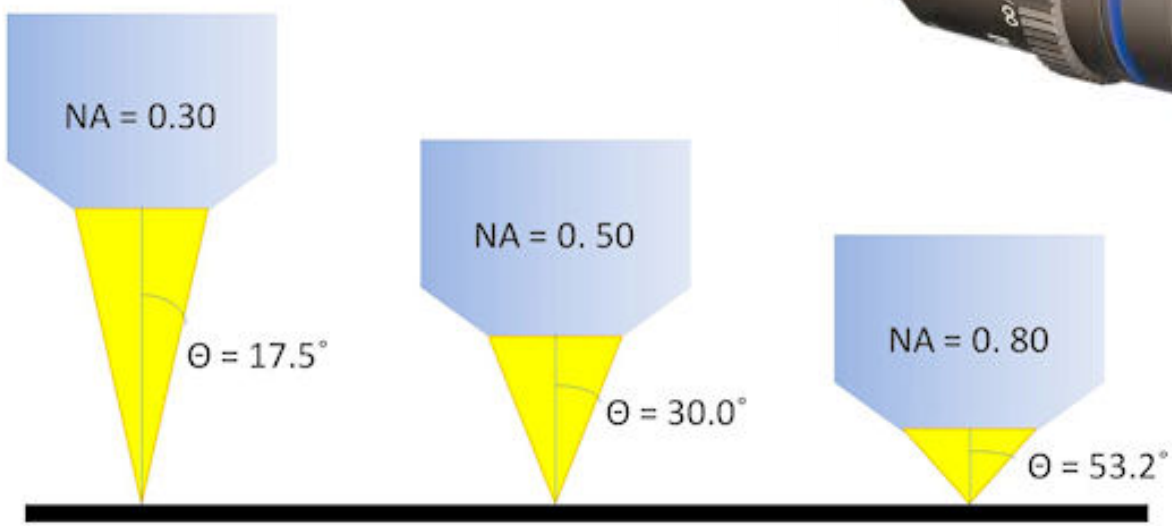
Objective lens

Numerical Aperture (NA):

- Higher NA → Increased focal resolution.

Refractive index — Focal length — Pupil radius

$$NA = n.\sin\Theta = f.R$$

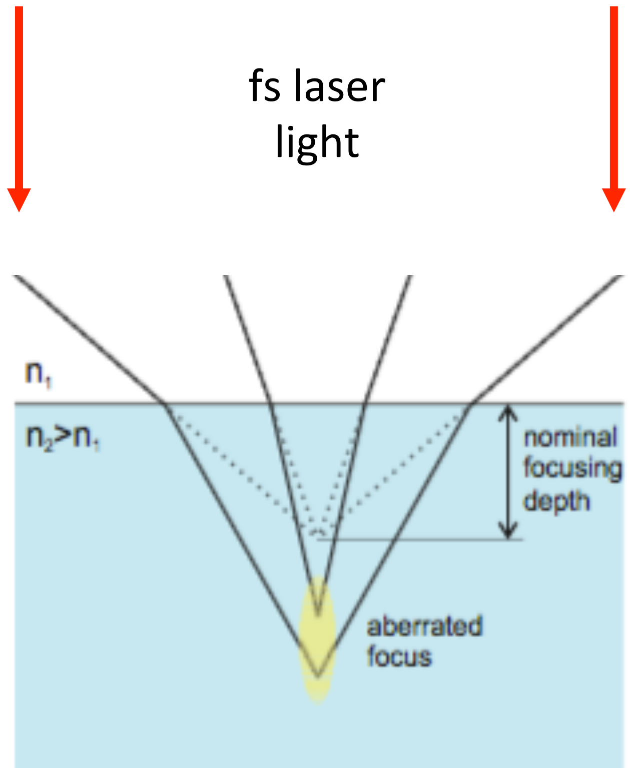


[6] Kroto Imaging Facility, The University of Sheffield.

MANCHESTER 1824

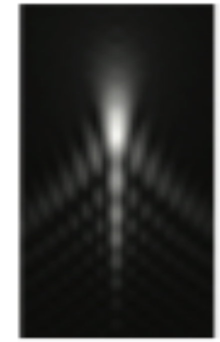
The University of Manchester

Light aberration



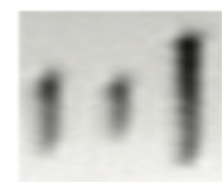
Drilling efficiency (best achieved)	~ 90 %
Resistivity	~ 1Ω cm
Diameter	~ 6 µm

Simulated
depth = 40 µm



Measured
depth = 40 µm

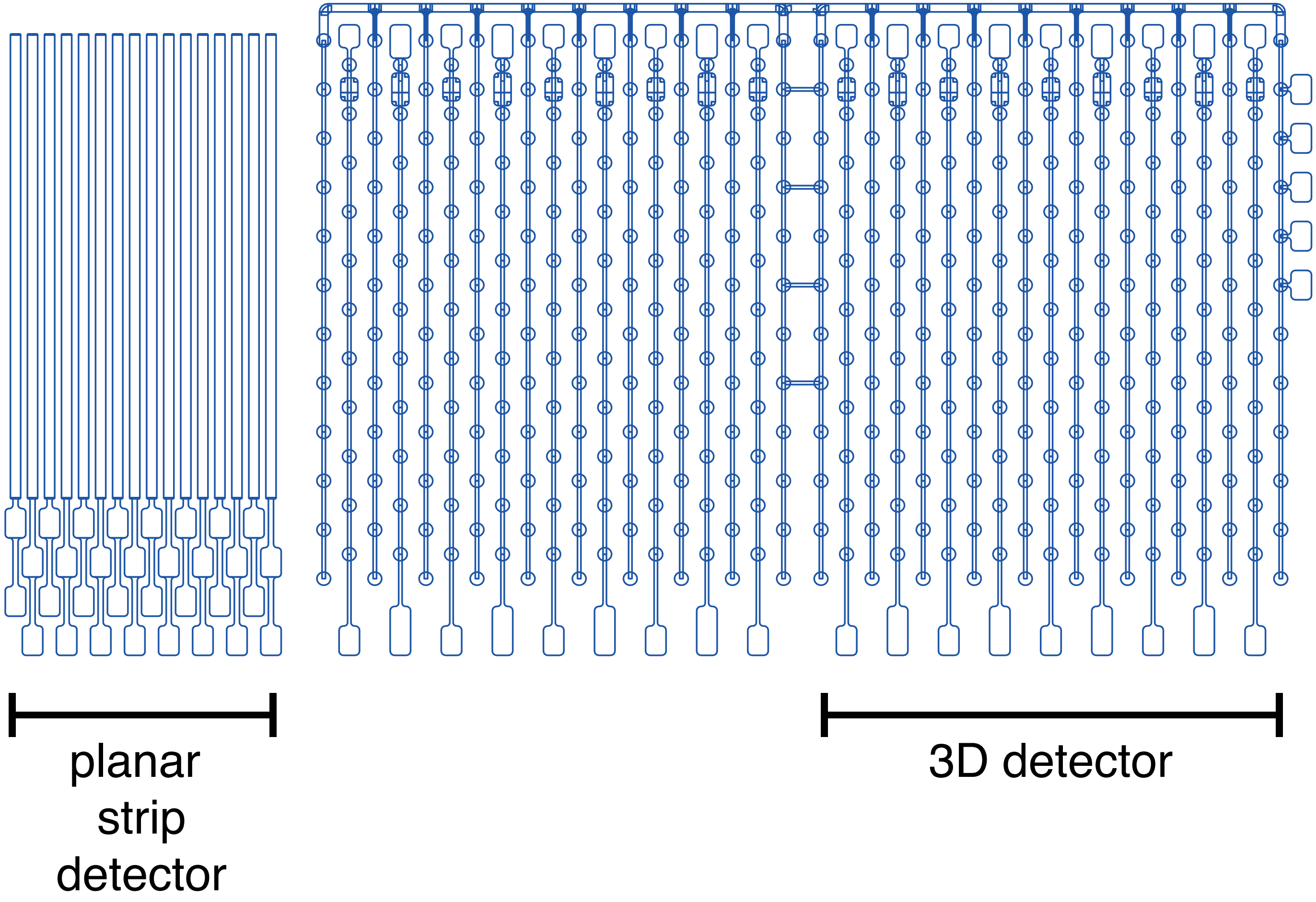
depth = 80 µm



depth = 130 µm

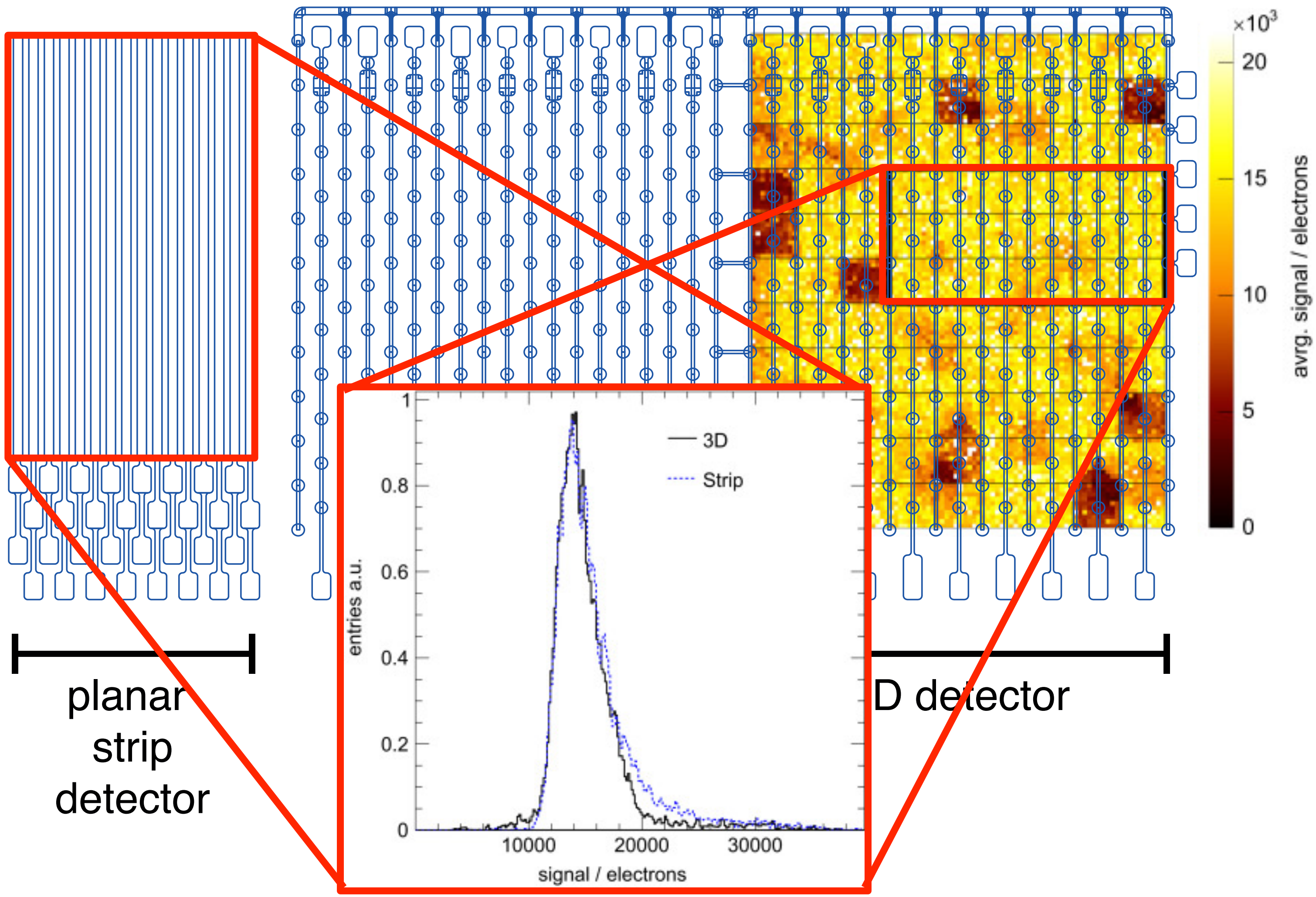
[4], [5]

First particle tracking measurement



[7] F.Bachmair et al., NIMA 786 (2015) 97-104

First particle tracking measurement

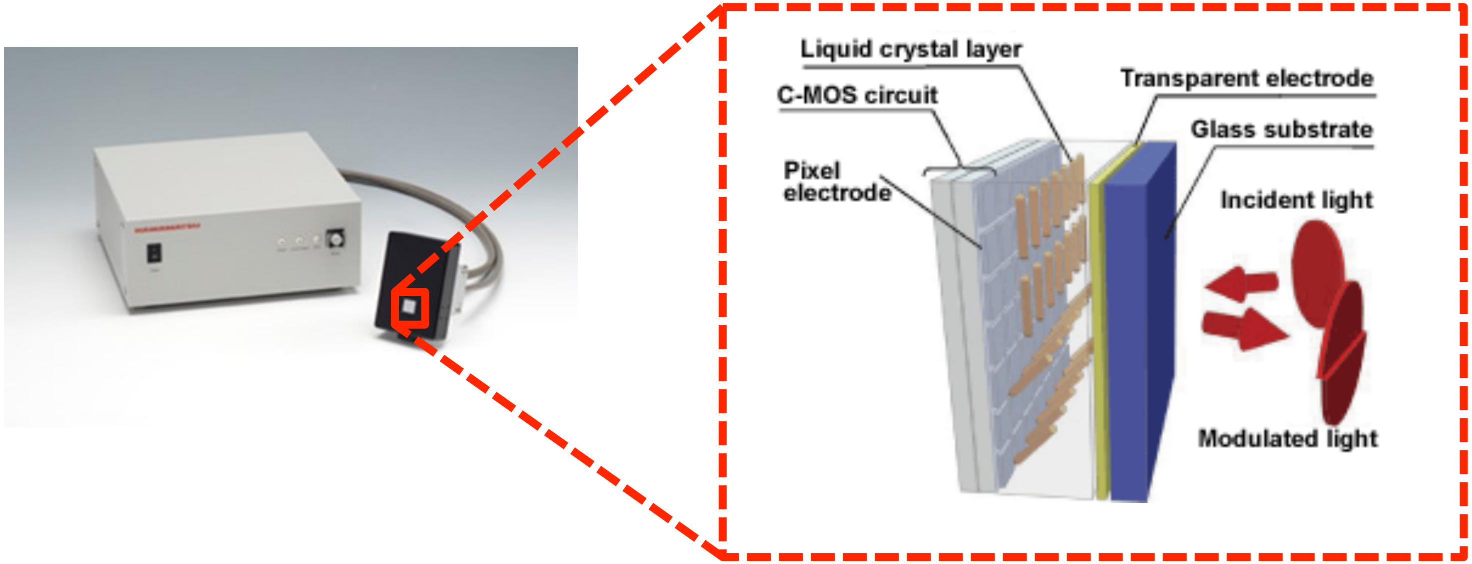


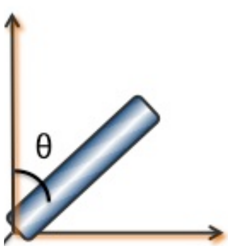
[7] F.Bachmair et al., NIMA 786 (2015) 97-104

MANCHESTER 1824

The University of Manchester

Spatial Light Modulator (SLM) correction

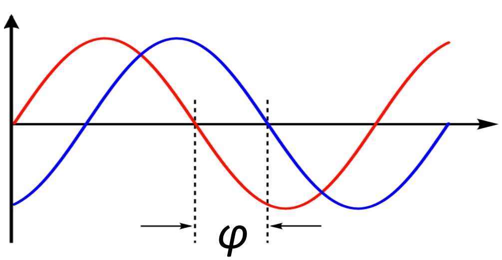


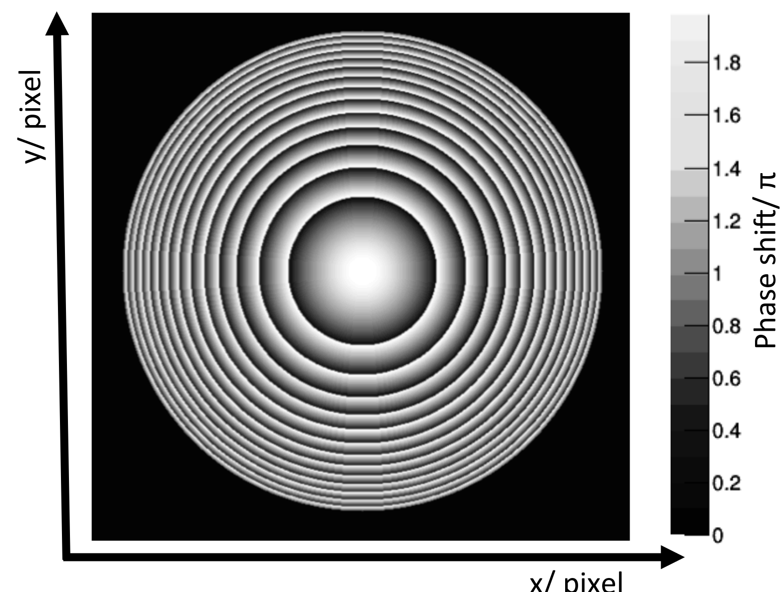


Speed of light in medium

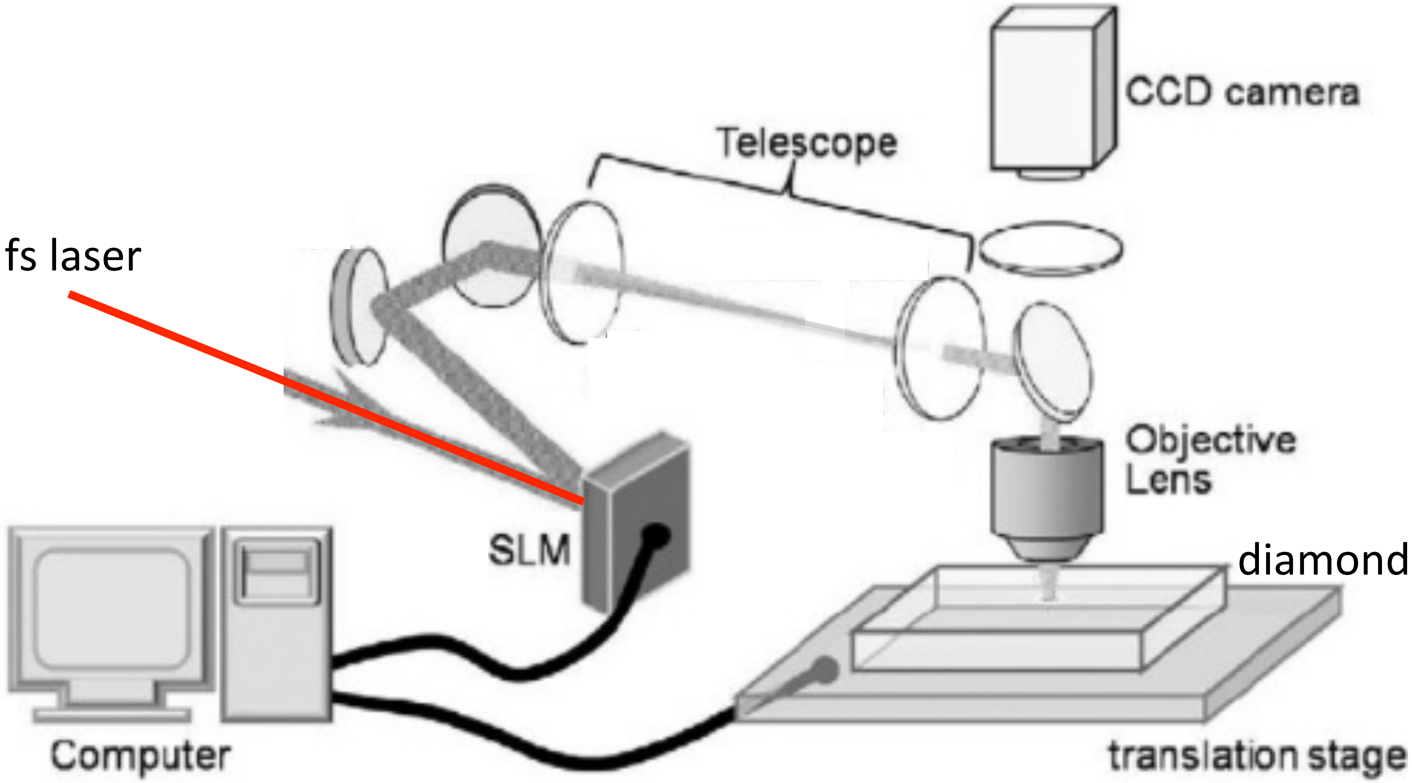
$$v = c/n(\theta)$$

Refractive index



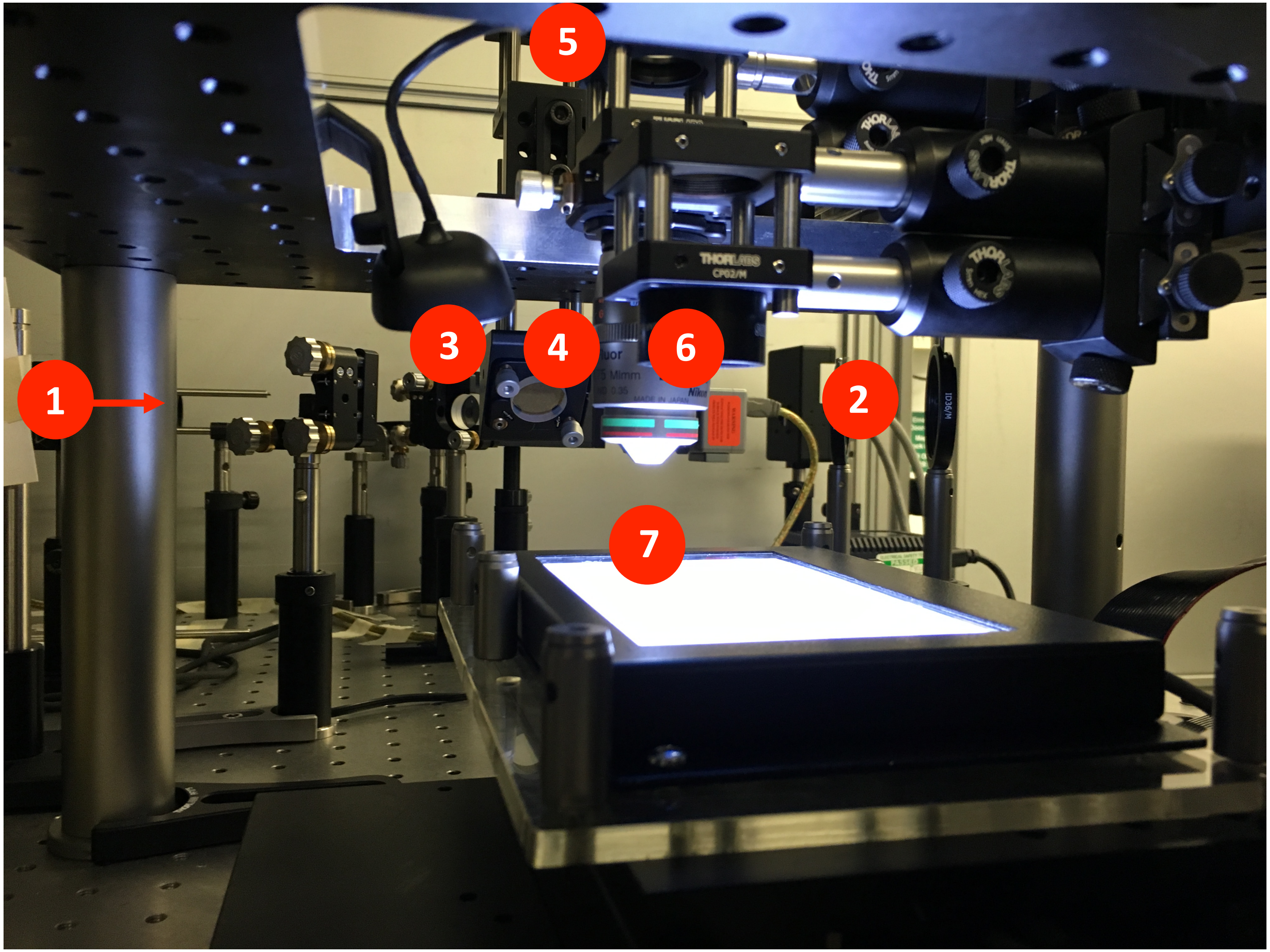


Laser setup



fs laser
Telescope
CCD camera
Objective
Lens
SLM
diamond
Computer
translation stage

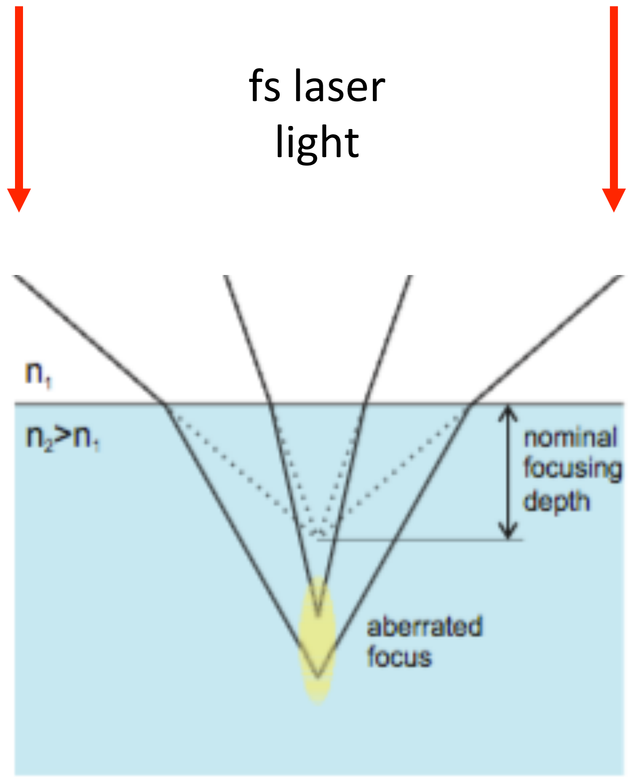
Laser setup – Manchester



MANCHESTER 1824

The University of Manchester

Light aberration – SLM corrected



Simulated depth = 40 µm

Measured depth = 40 µm

depth = 80 µm

depth = 130 µm

Drilling efficiency (consistent)	~ 100 %
Resistivity	~ 0.1 Ωcm
Diameter	~ 1 µm

[4], [5]

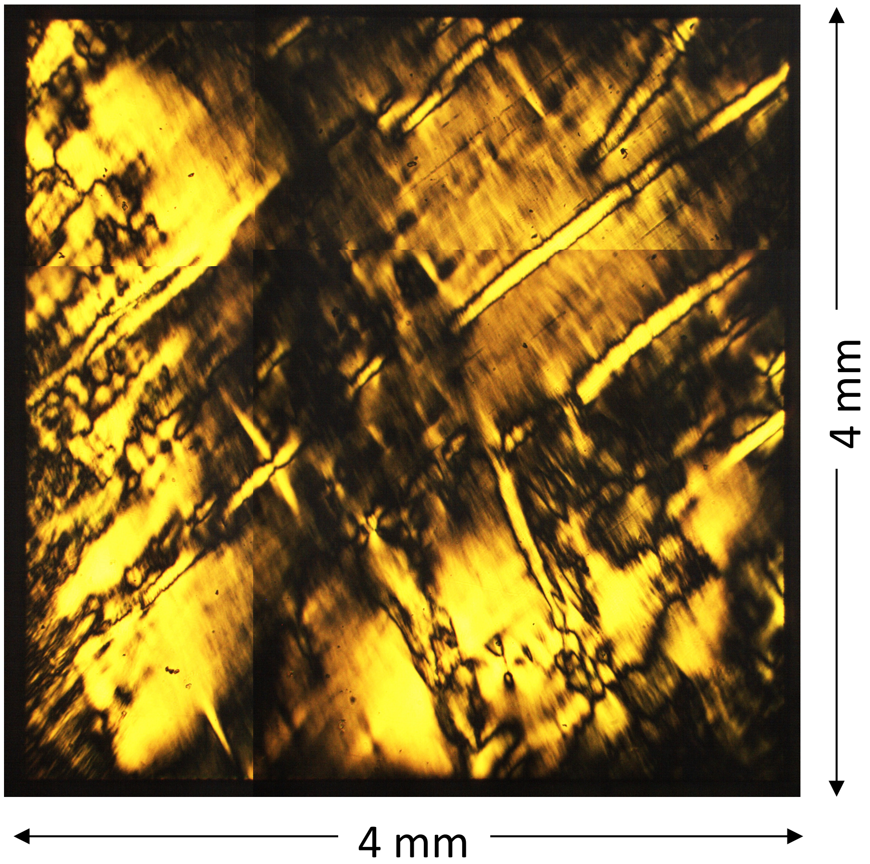
Parameter space scan

		Translation speed			
		5um/s	10um/s	20um/s	30um/s
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.

The University of Manchester

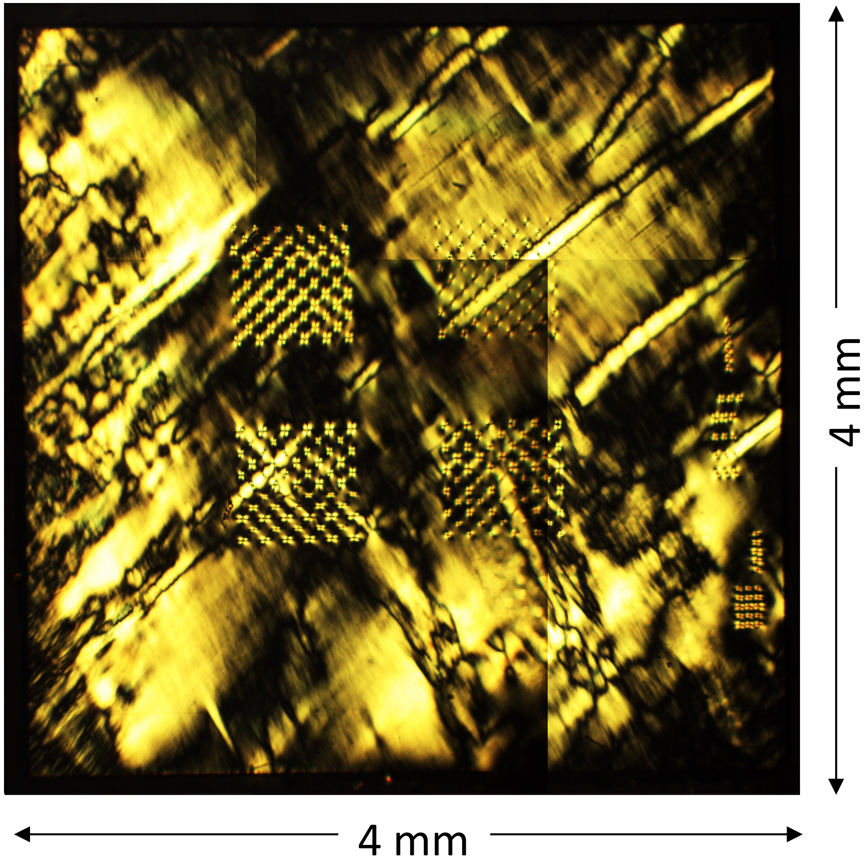
X polarisers



- Optical grade single crystal diamond.

The University of Manchester

X polarisers

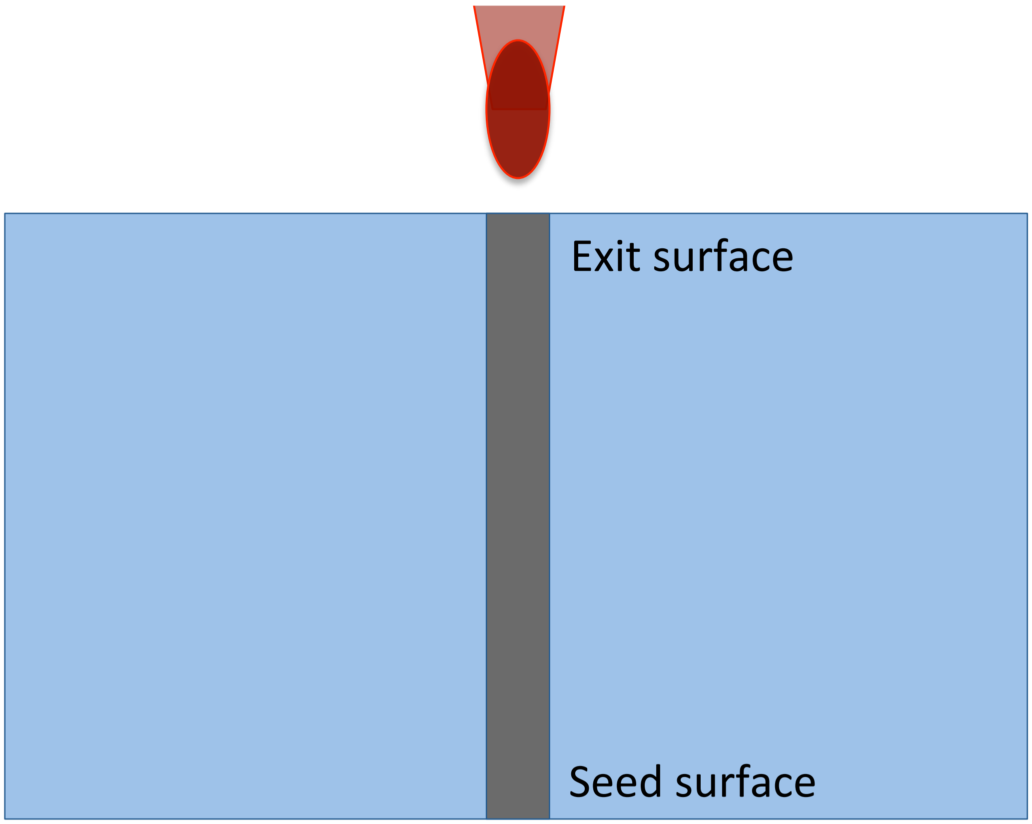


- Post processing.

MANCHESTER 1824

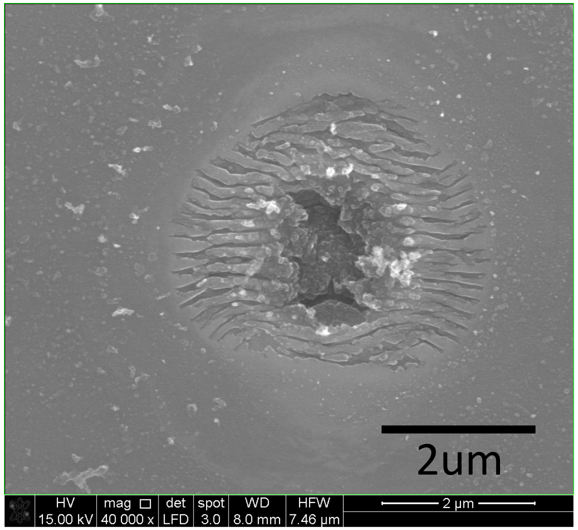
The University of Manchester

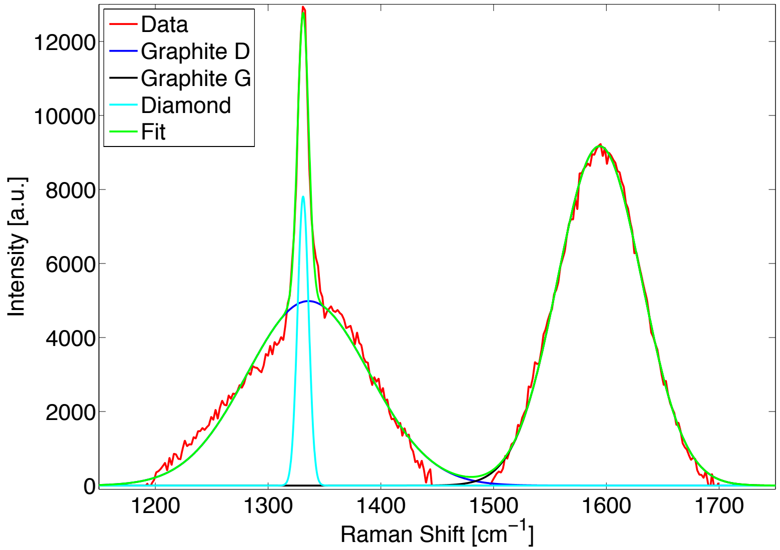
Column production



Surface measurement

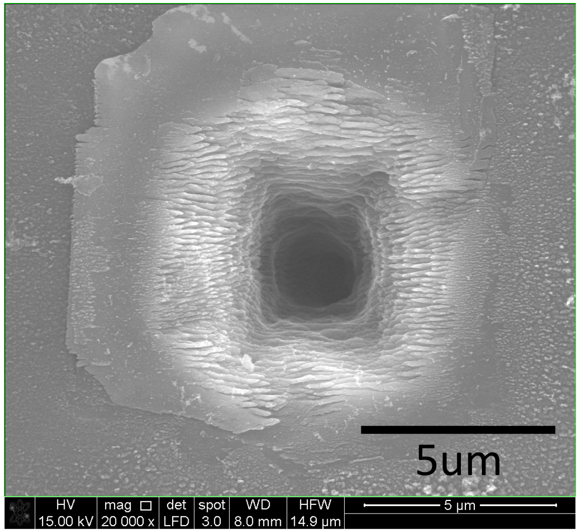
- Seed surface

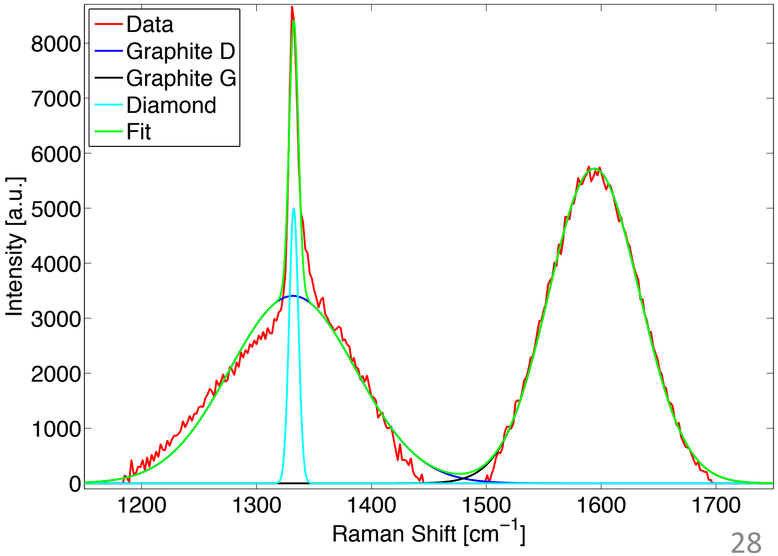




With SLM
10um/s
400nJ

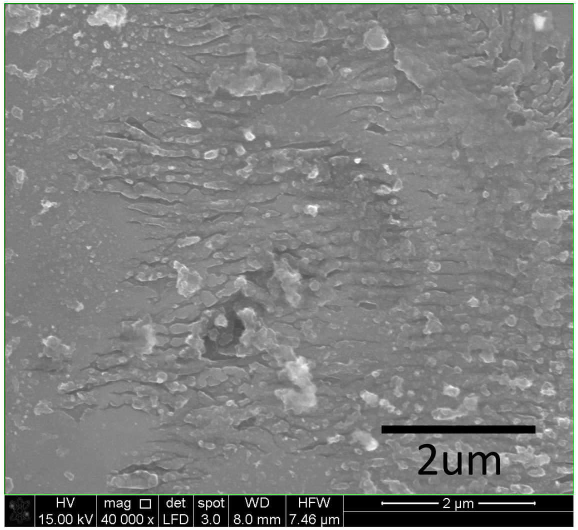
- Exit surface

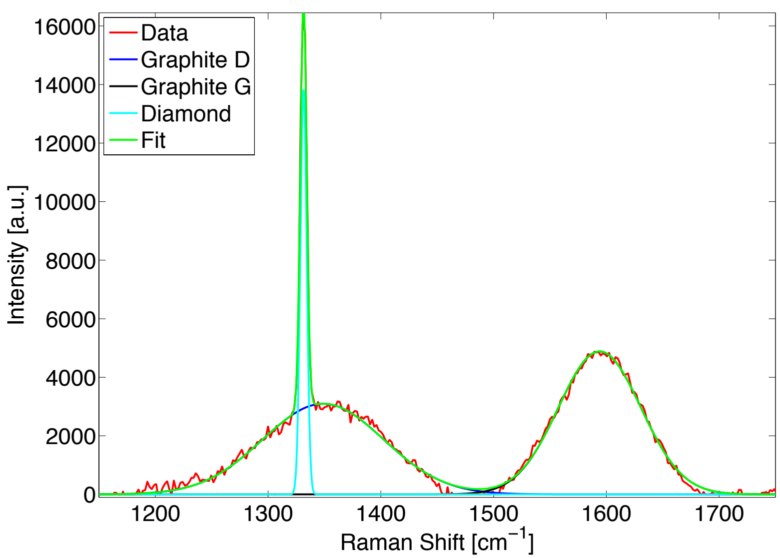




Surface measurement

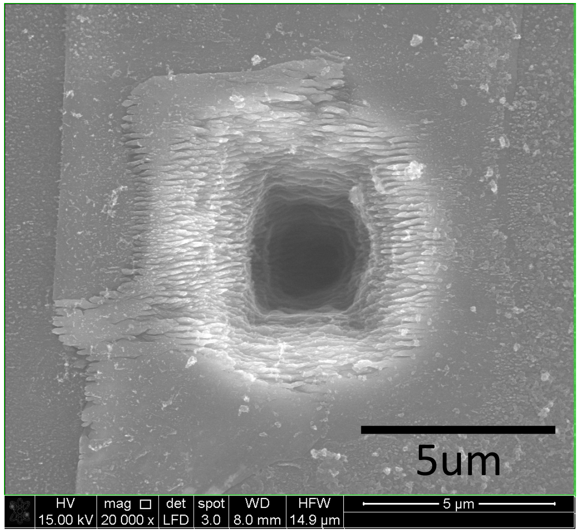
- Seed surface

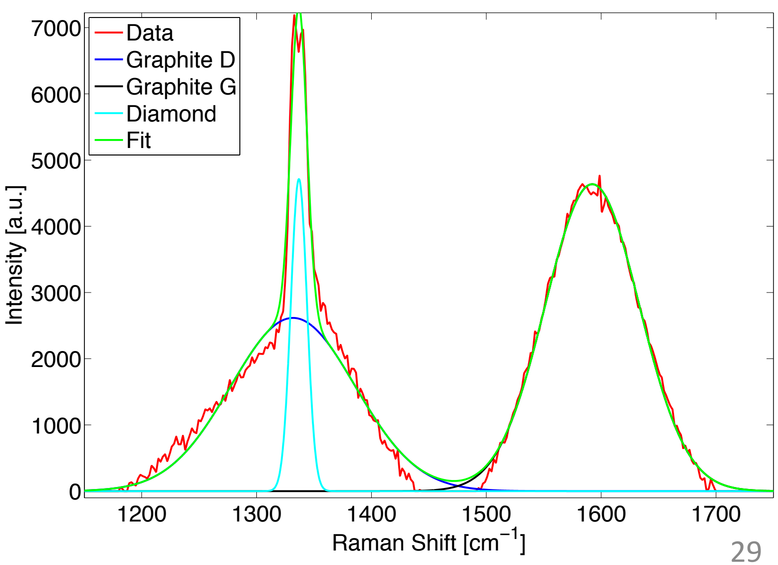




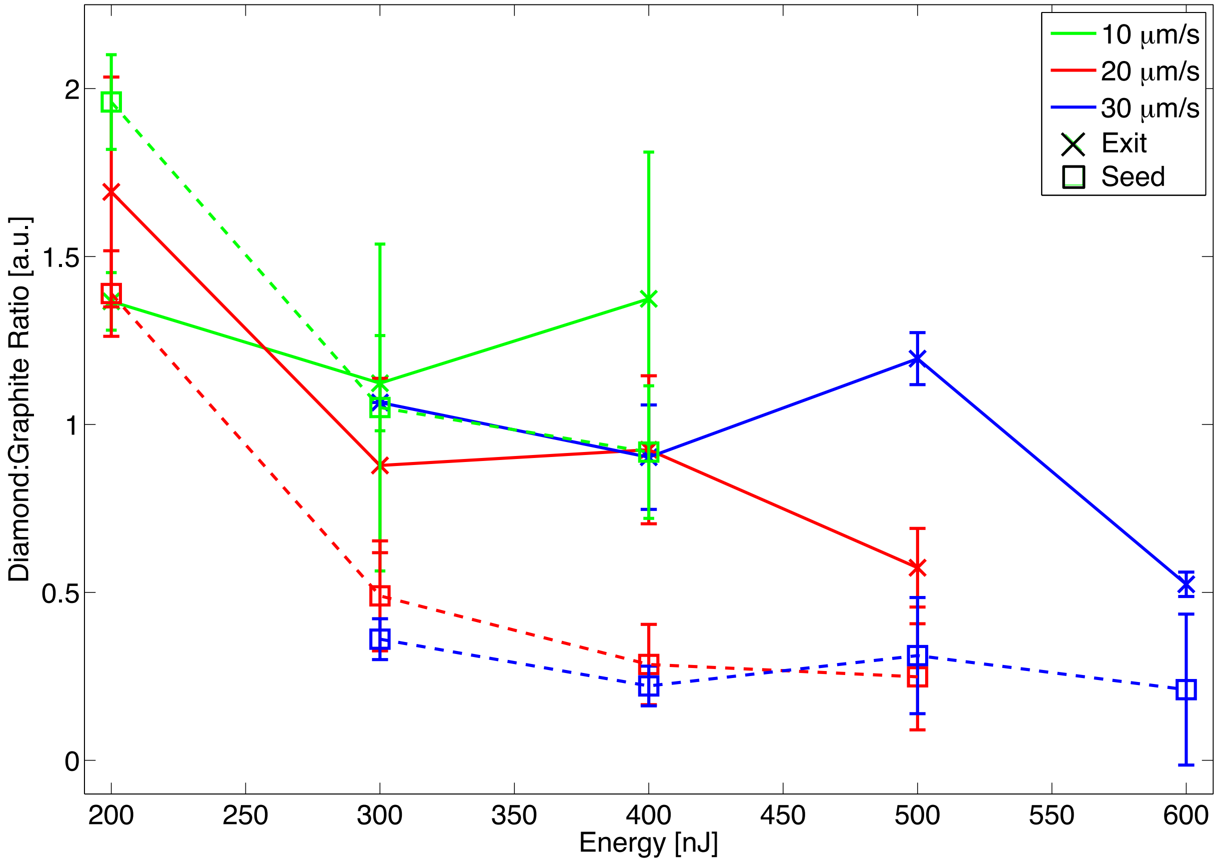
Without SLM
10um/s
400nJ

- Exit surface



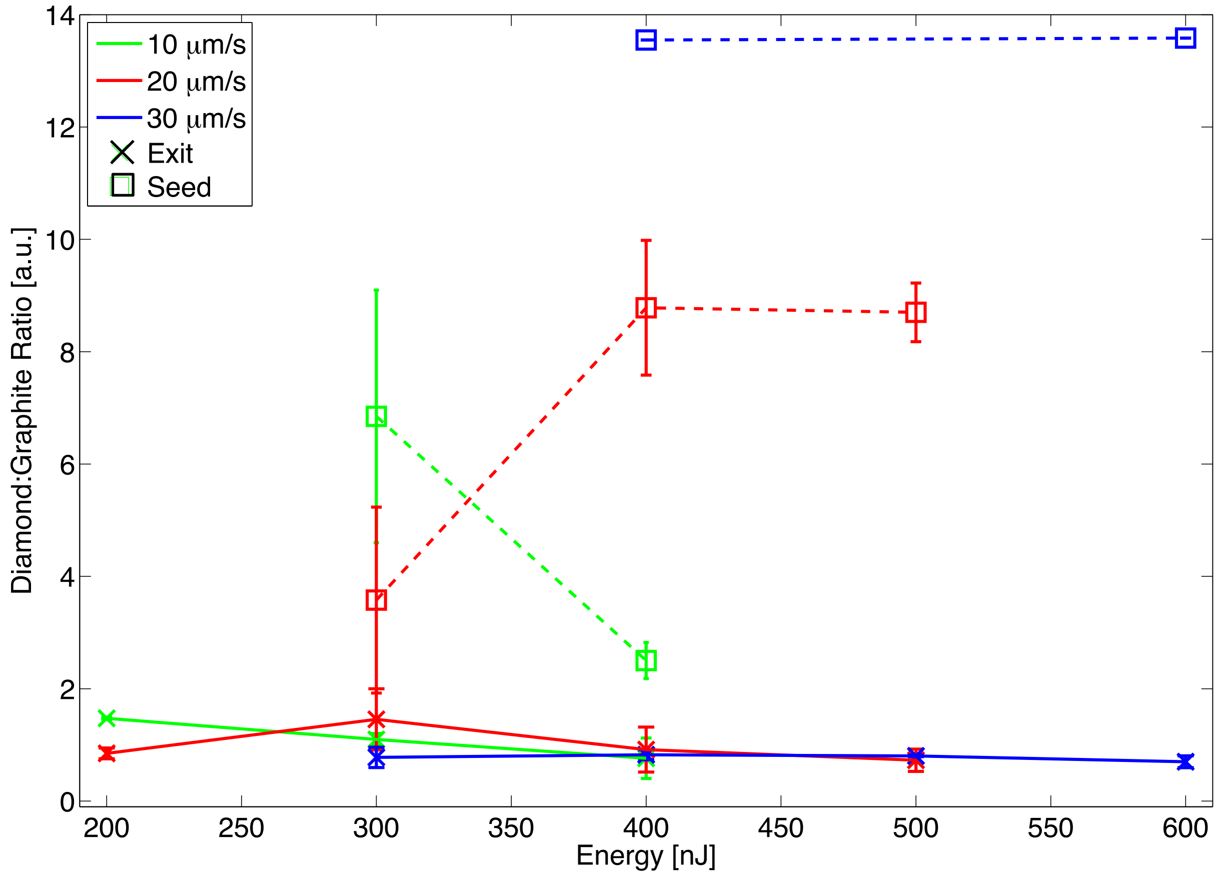


Raman – with SLM



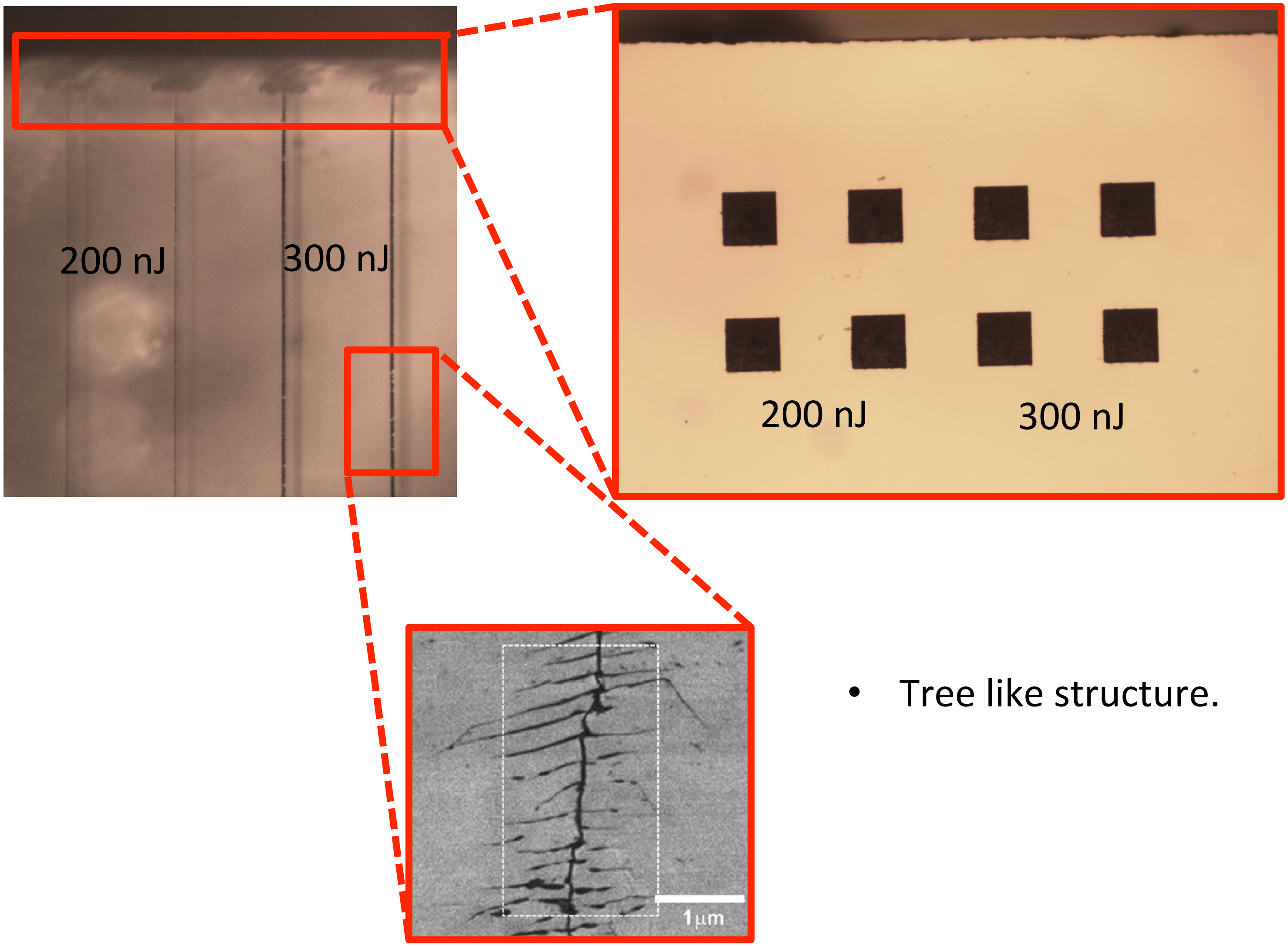
- Exit surface exhibits a higher ratio than the seed:
  → Possibly due to ejection of material.

Raman – without SLM



- Seed surface exhibits a much higher ratio than the exit:
  → Light aberration is maximum at the seed surface.

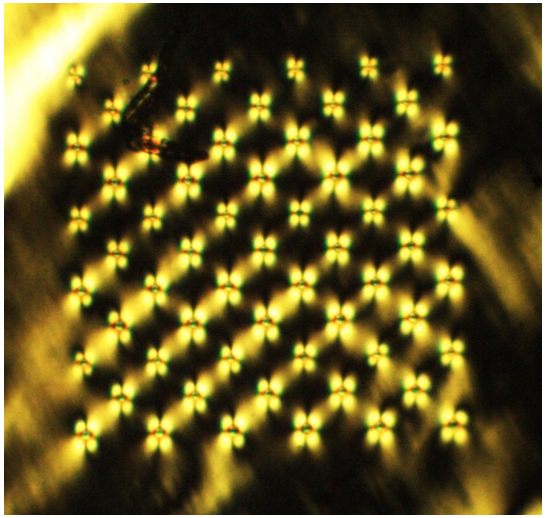
Internal structure



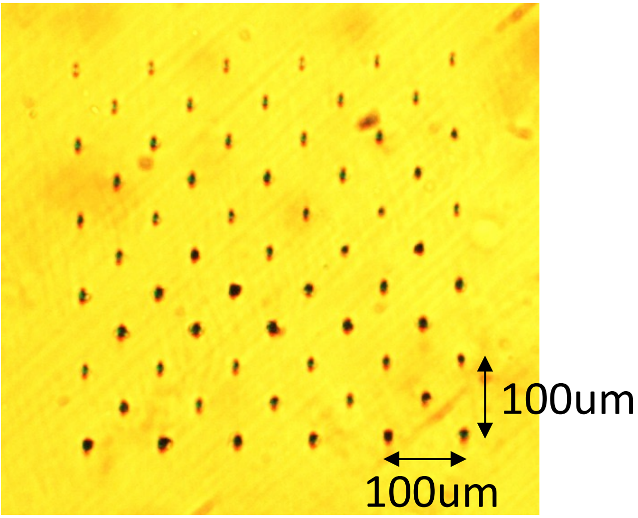
- Tree like structure.

[5] K.K. Ashikkalieva et al., Carbon 102 (2016) 383-389

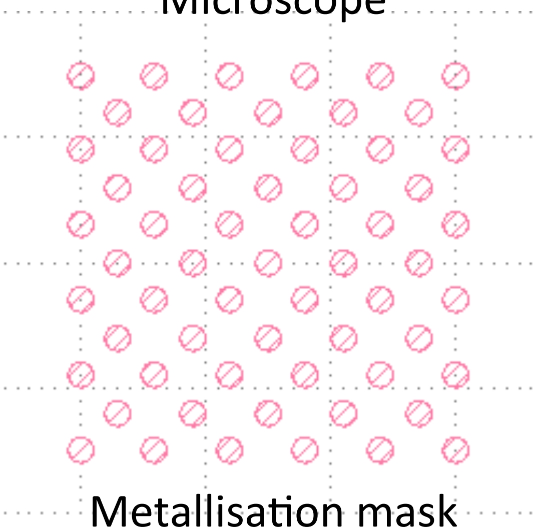
Metallisation



X polarisers



Microscope



Metallisation mask
(Seed surface)

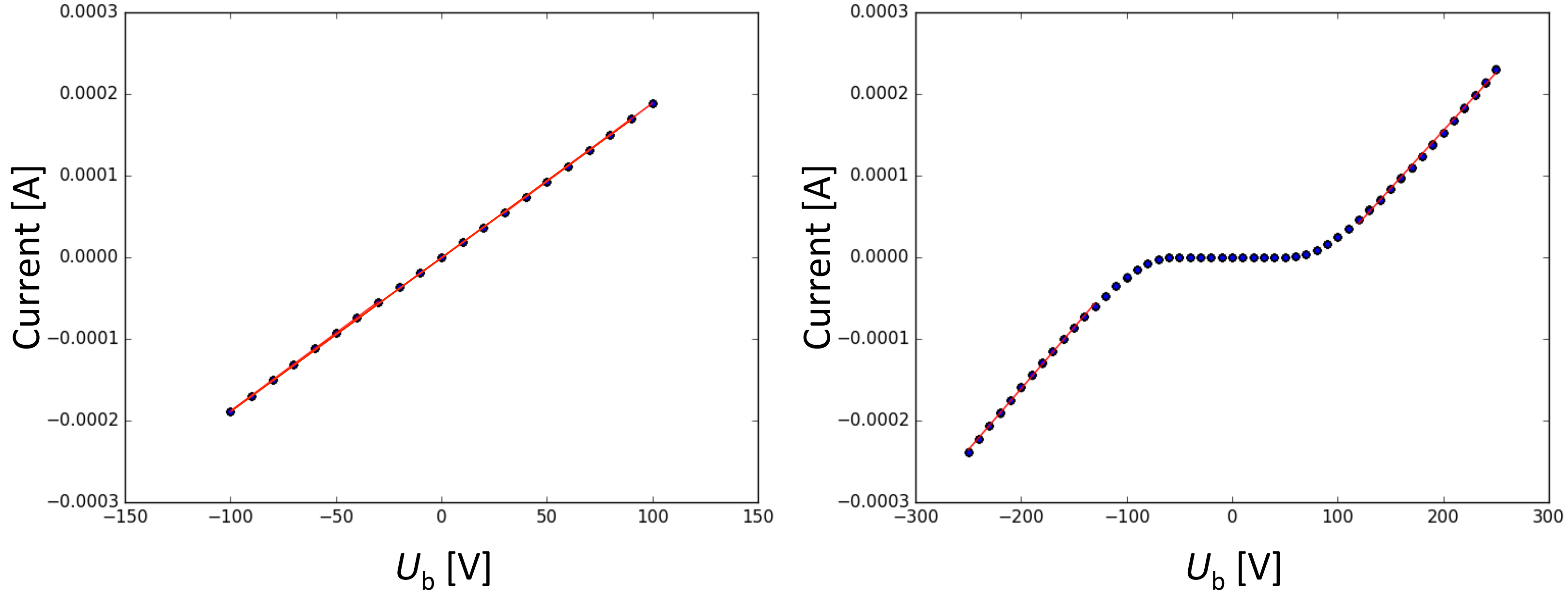
Metallisation in Manchester:

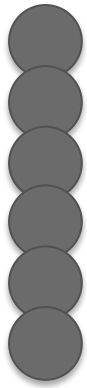
- Chromium
- Gold

Seed surface structured.
Exit surface pad.

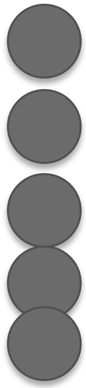
IV curves

- Ohmic and barrier potential curves observed.



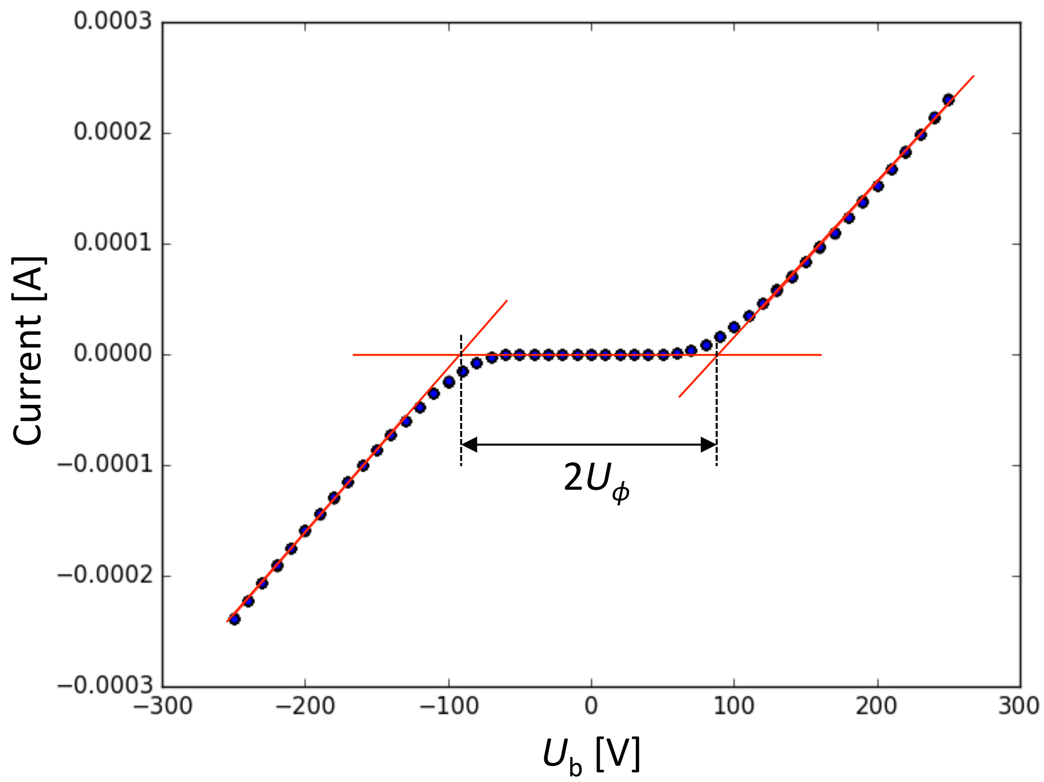


Continuous.

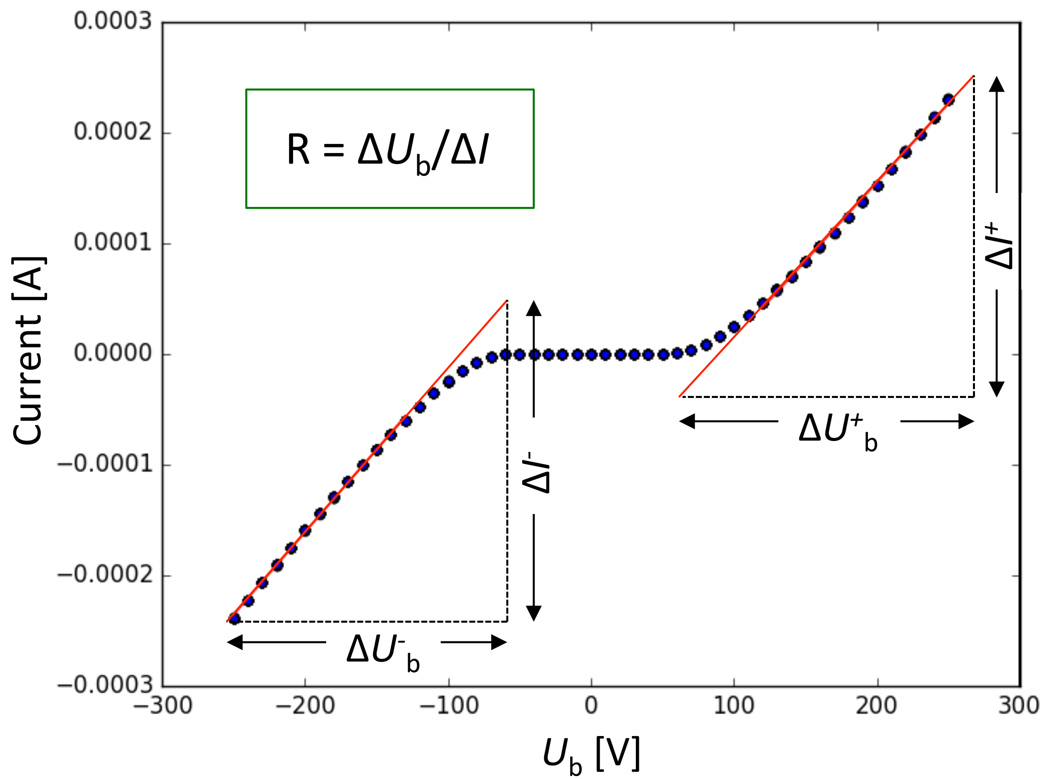


Micro gaps?

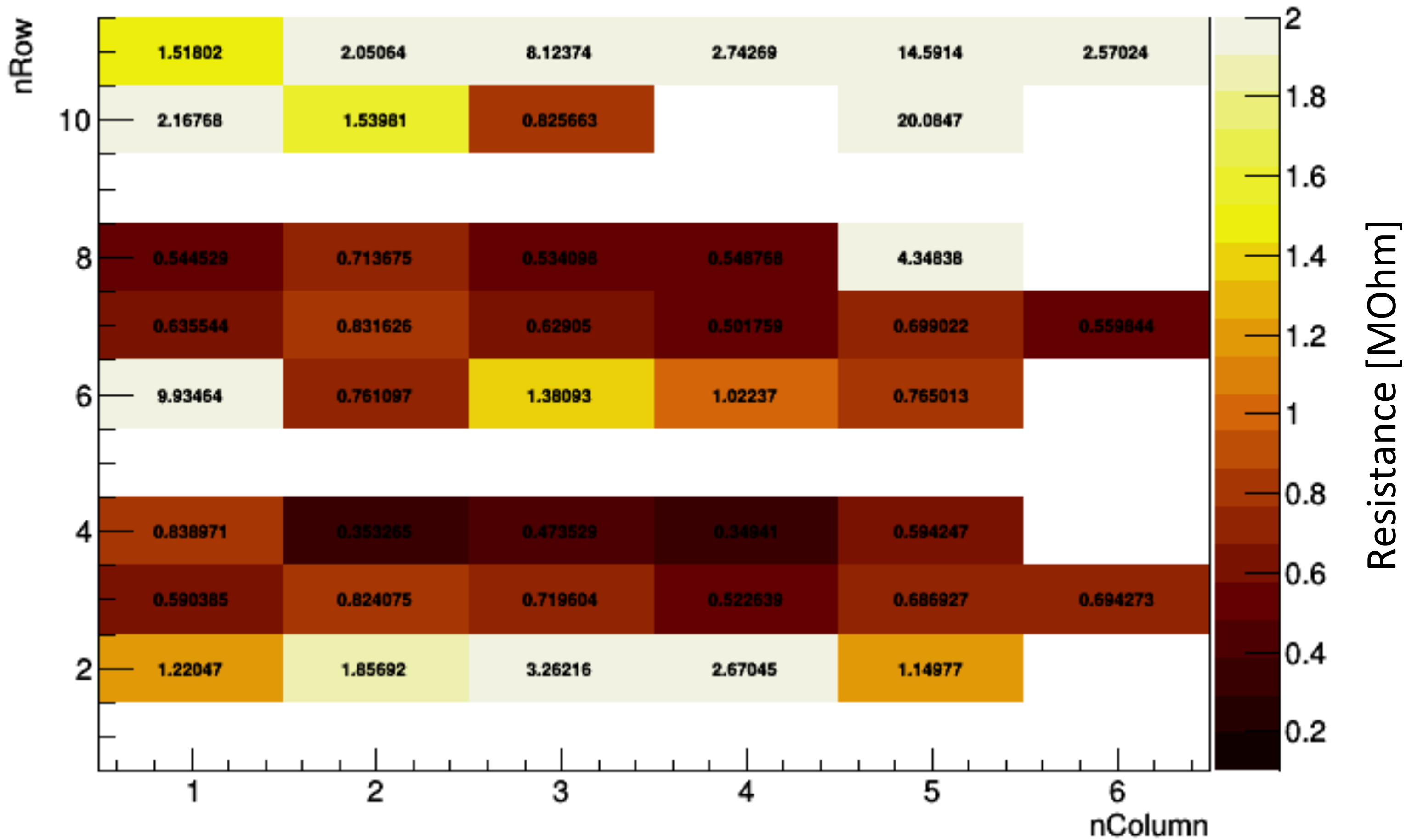
Barrier potential



Resistance measurement

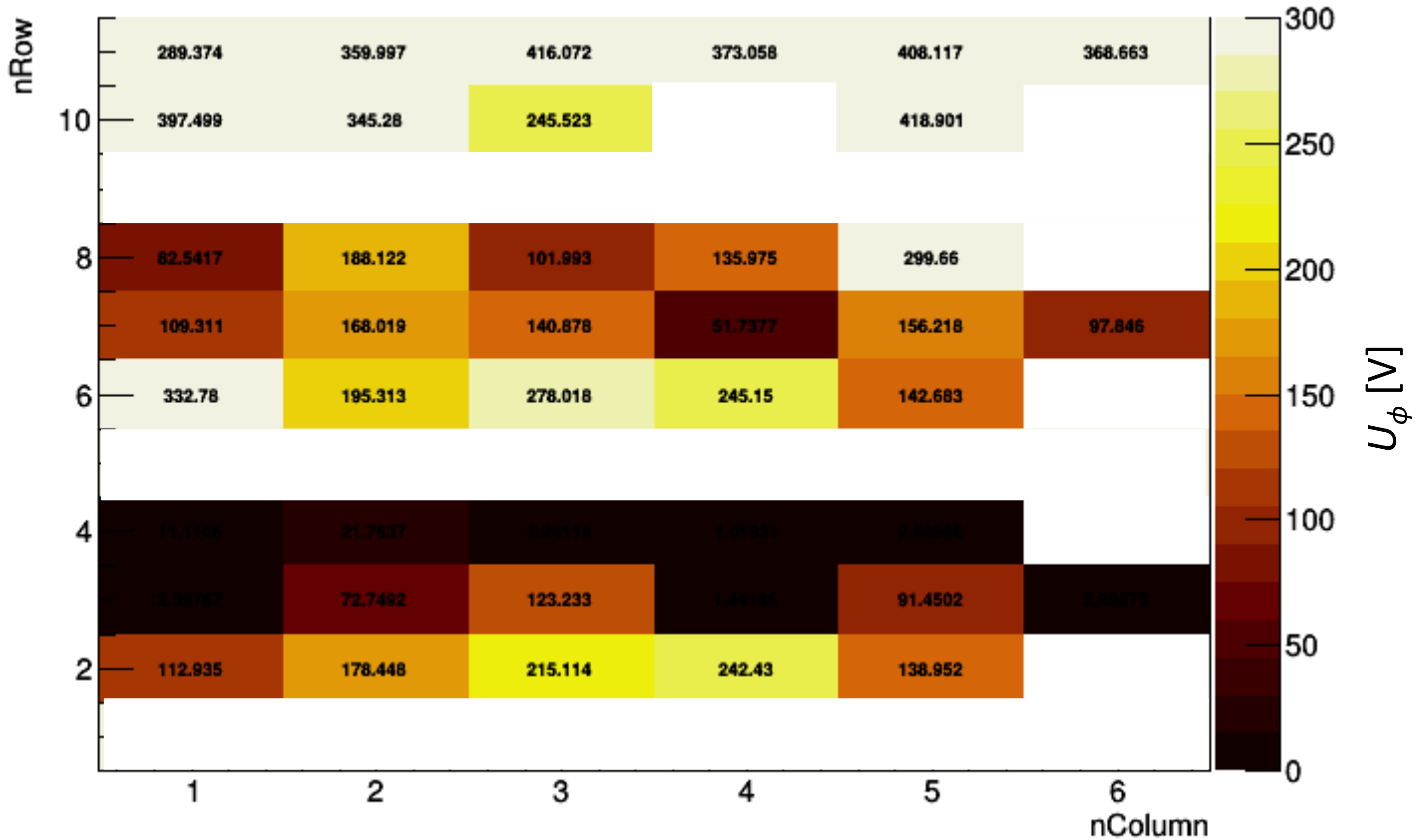


With SLM

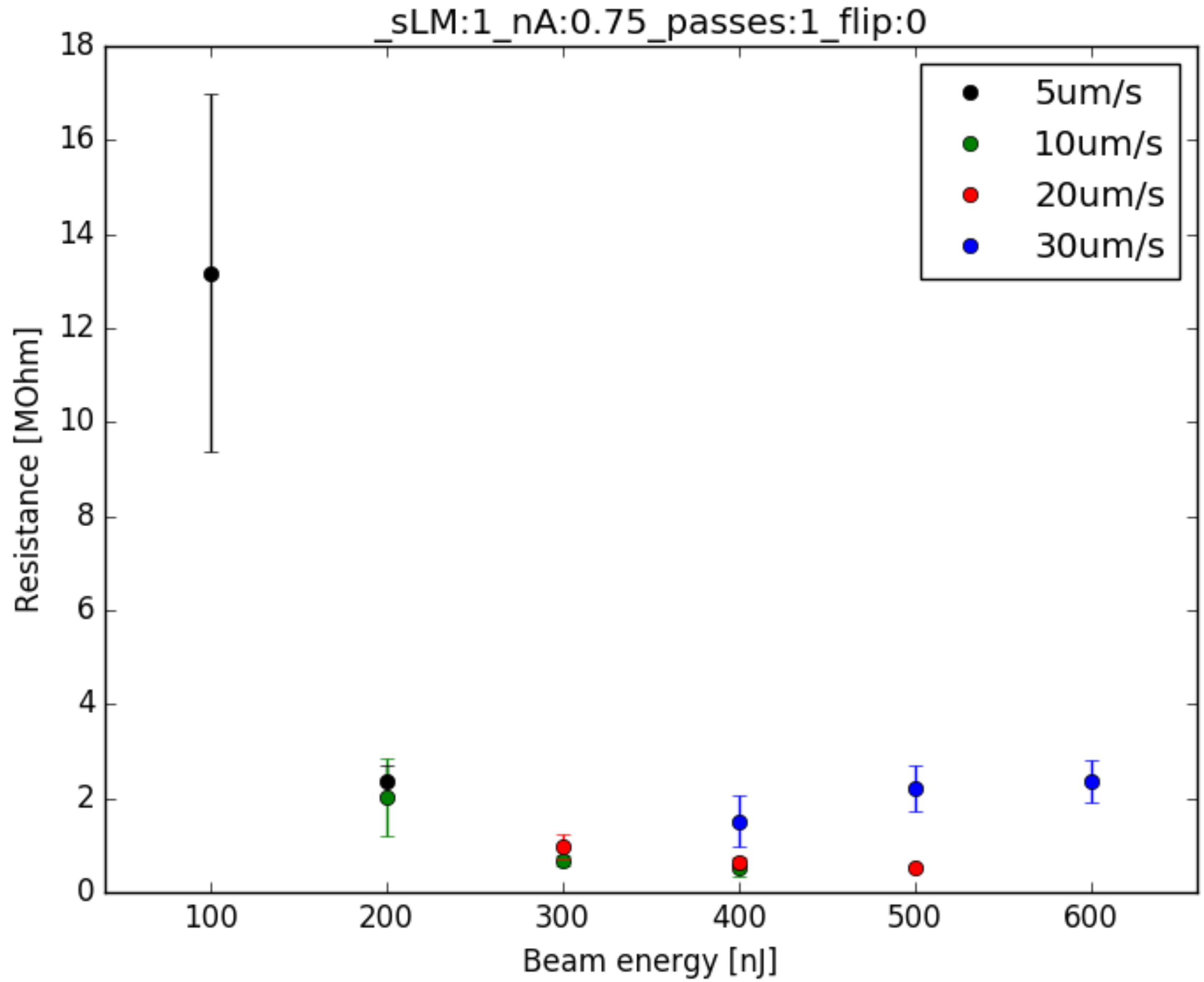


nRow
1.51802
2.05064
8.12374
2.74269
14.5914
2.57024
2.16768
1.53981
0.825663
20.0847
0.544529
0.713675
0.534098
0.548768
4.34838
0.635544
0.831626
0.62905
0.501759
0.699022
0.559844
9.93464
0.761097
1.38093
1.02237
0.765013
0.838971
0.353265
0.473529
0.34941
0.594247
0.590385
0.824075
0.719604
0.522639
0.686927
0.694273
1.22047
1.85692
3.26216
2.67045
1.14977
nColumn
Resistance [MOhm]

With SLM

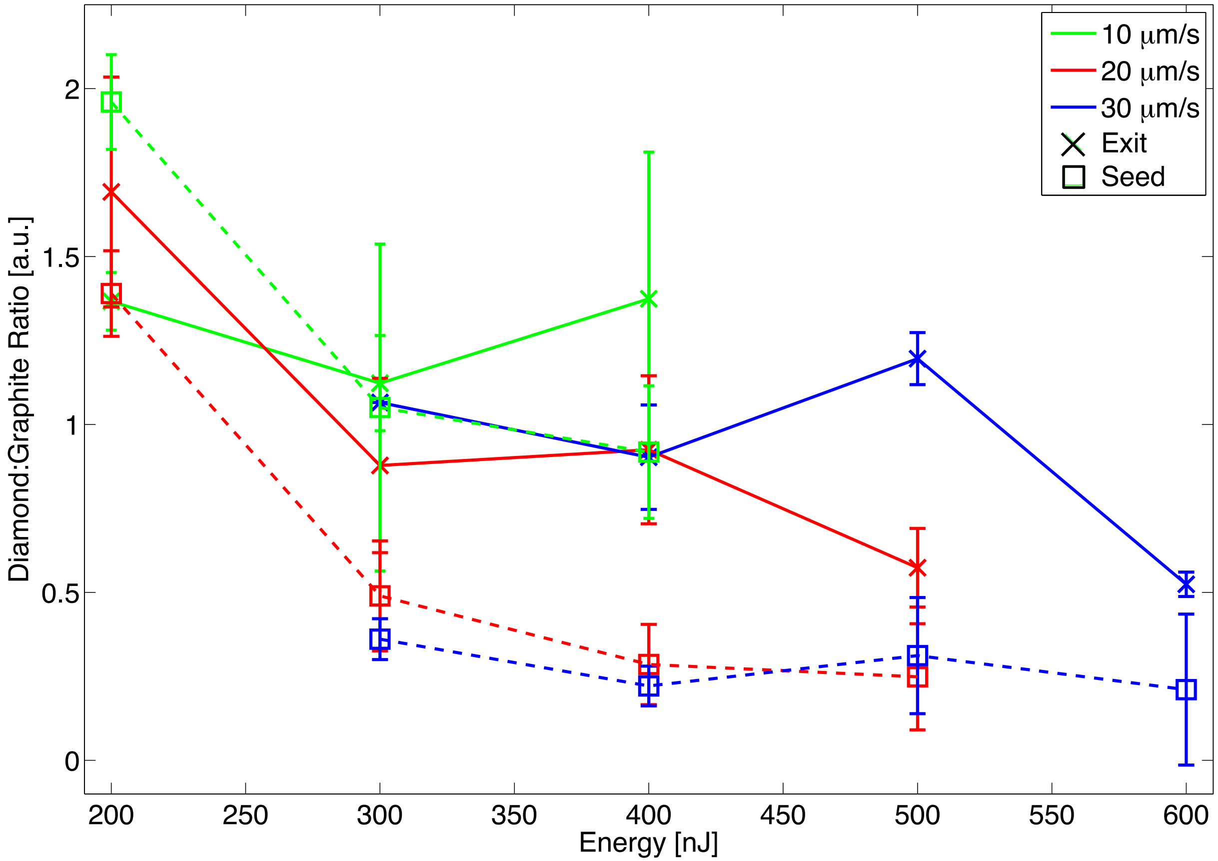

nRow
289.374
359.997
416.072
373.058
408.117
368.663
397.499
345.28
245.523
418.901
82.5417
188.122
101.993
135.975
299.66
109.311
168.019
140.878
51.7377
156.218
97.846
332.78
195.313
278.018
245.15
142.683
11.1106
21.7637
72.7492
123.233
91.4502
112.935
178.448
215.114
242.43
138.952
nColumn
U_ϕ [V]

Resistance



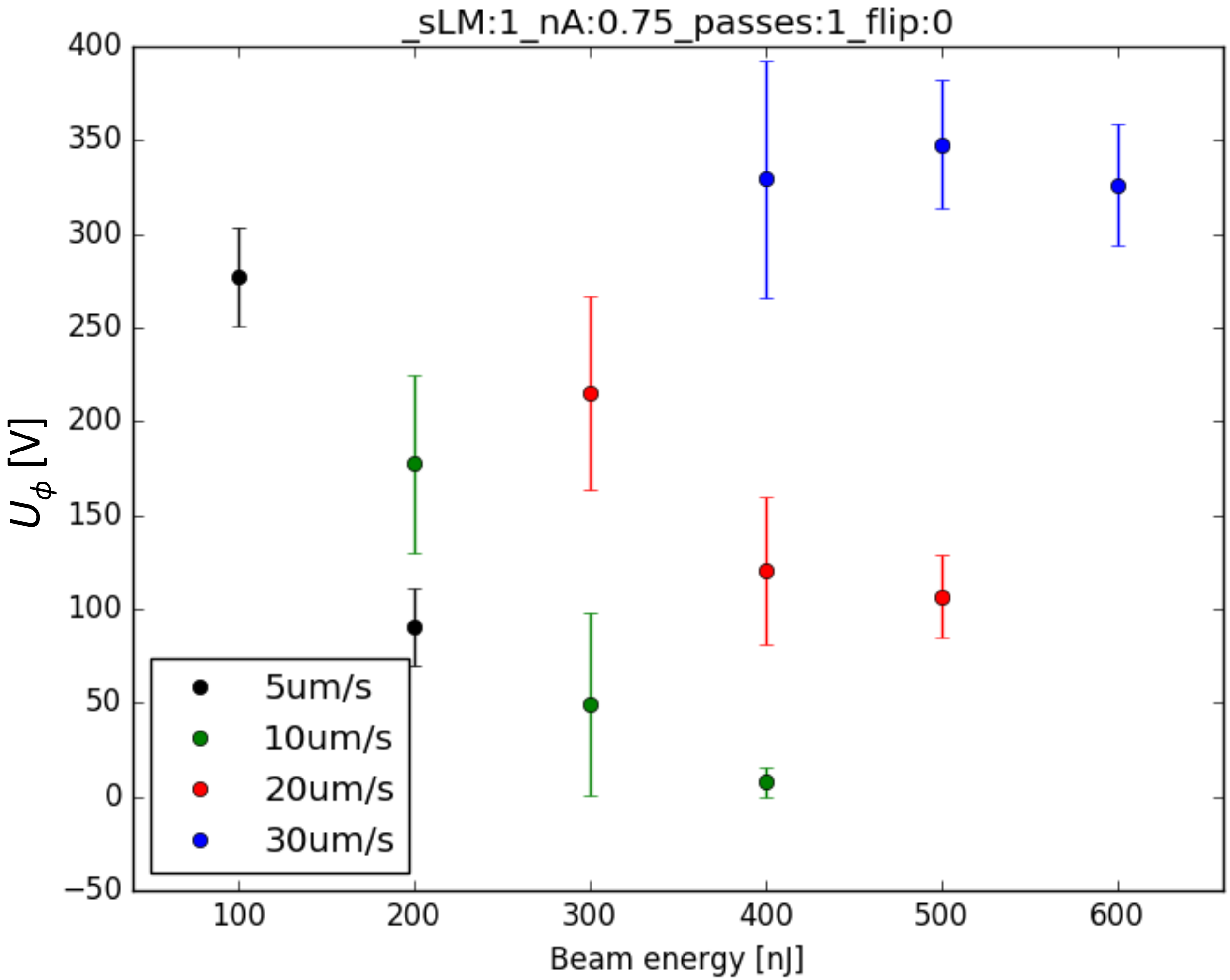
- Decreases as a power law → multi-photon absorption.
- Clear discrepancy at 30um/s.

Raman – with SLM

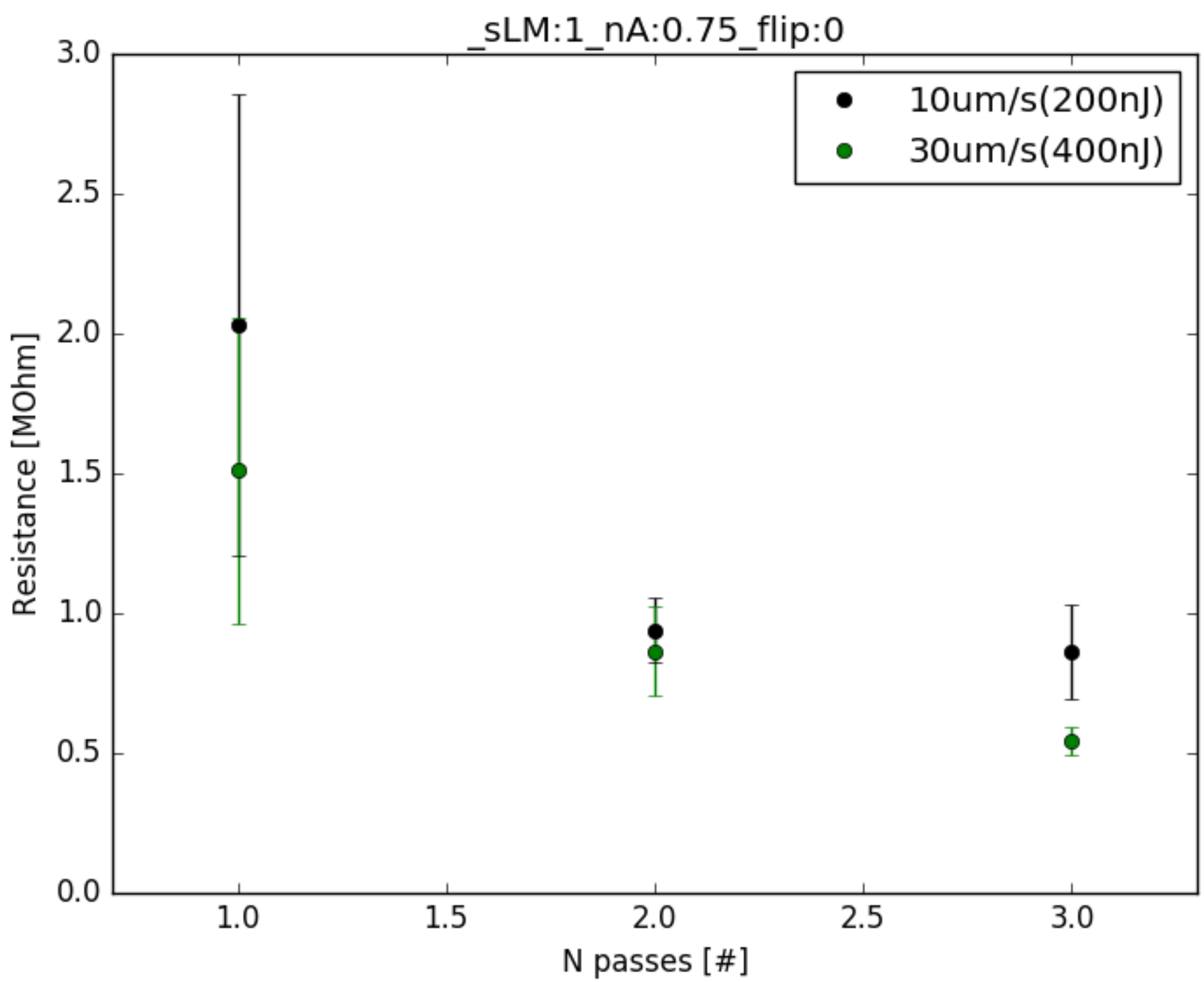


- No discrepancy seen in Raman at 30um/s.
  → Surface measurement.

Barrier energy

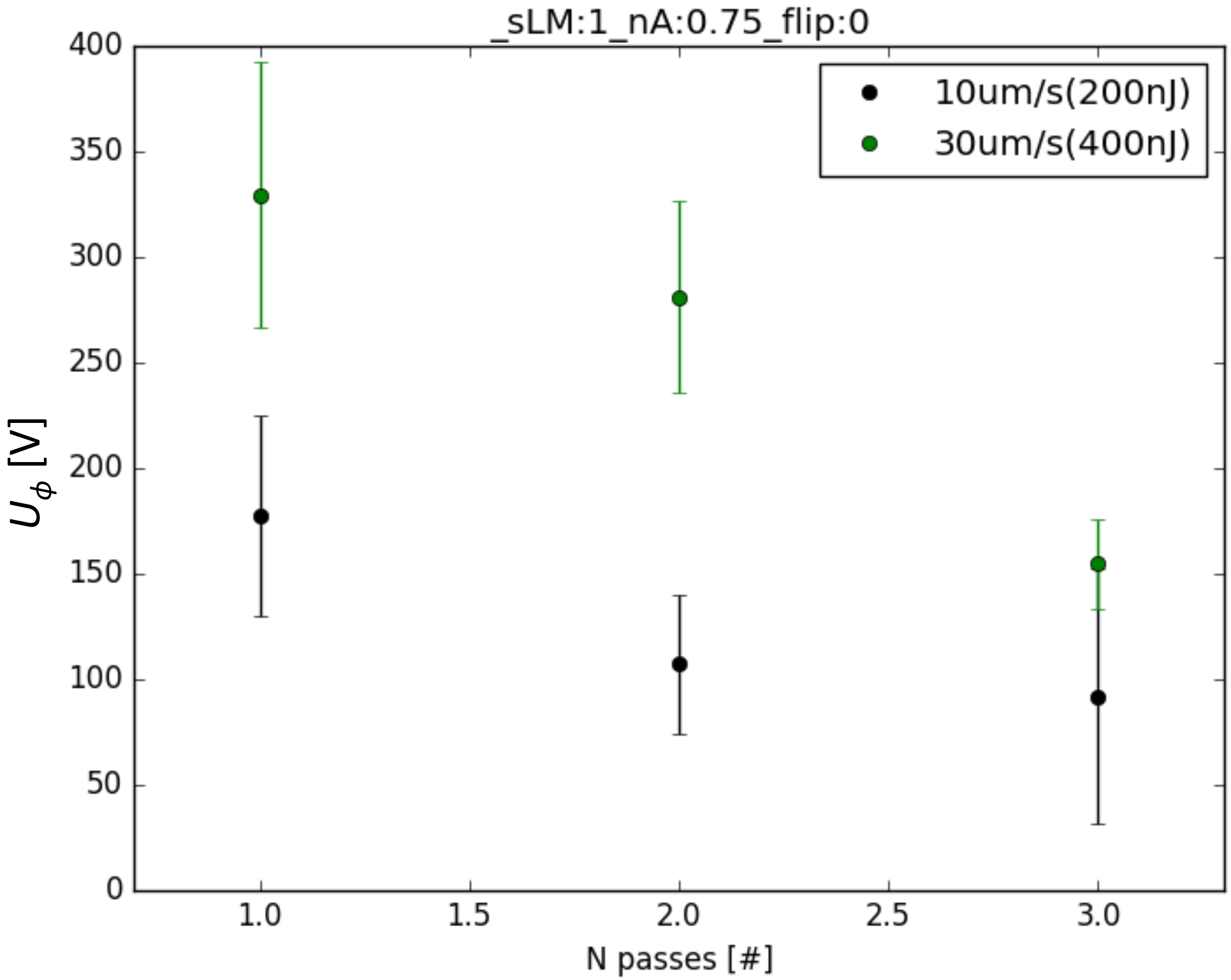


Multiple passes



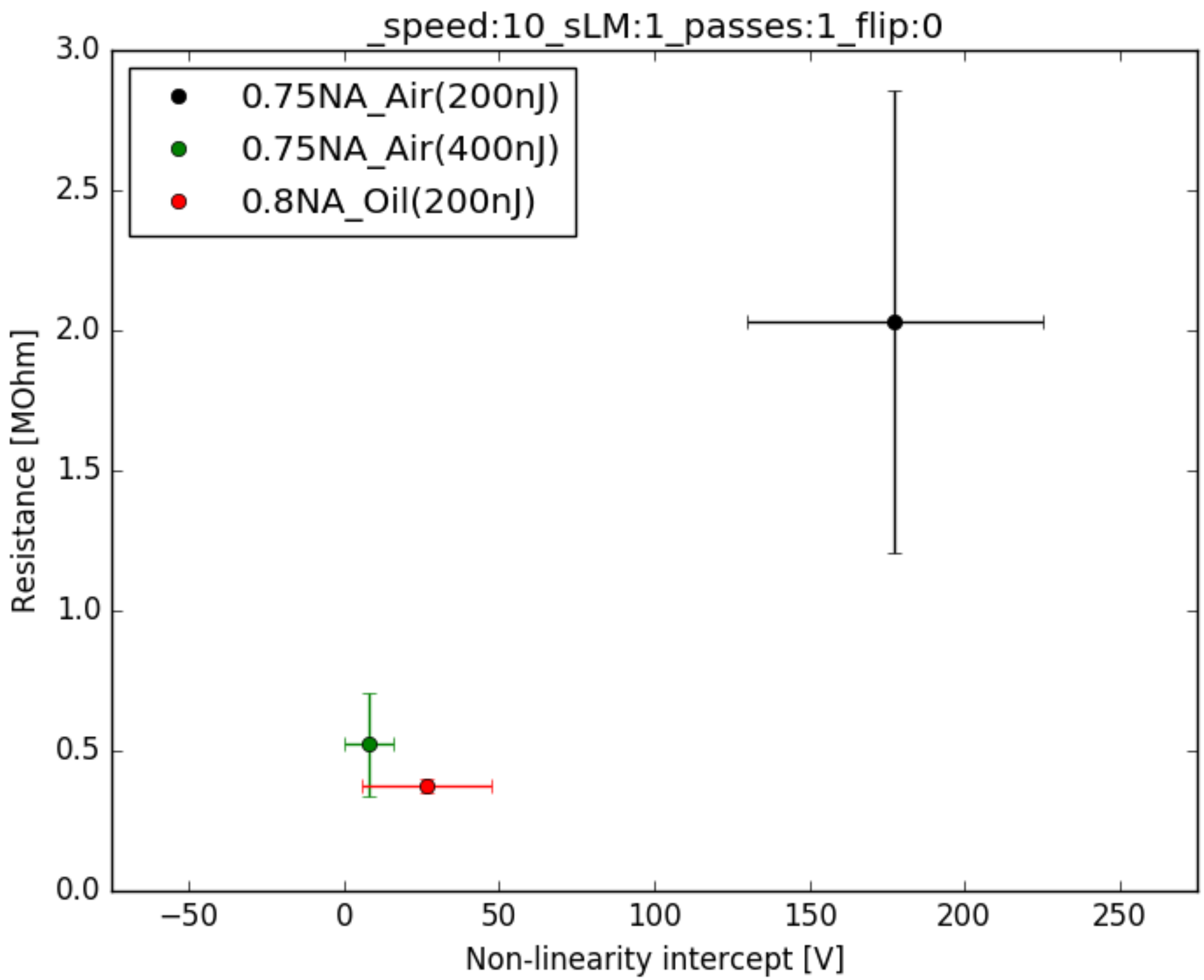
- Multiple passes reduces resistance and increases uniformity of the columns.

Multiple passes



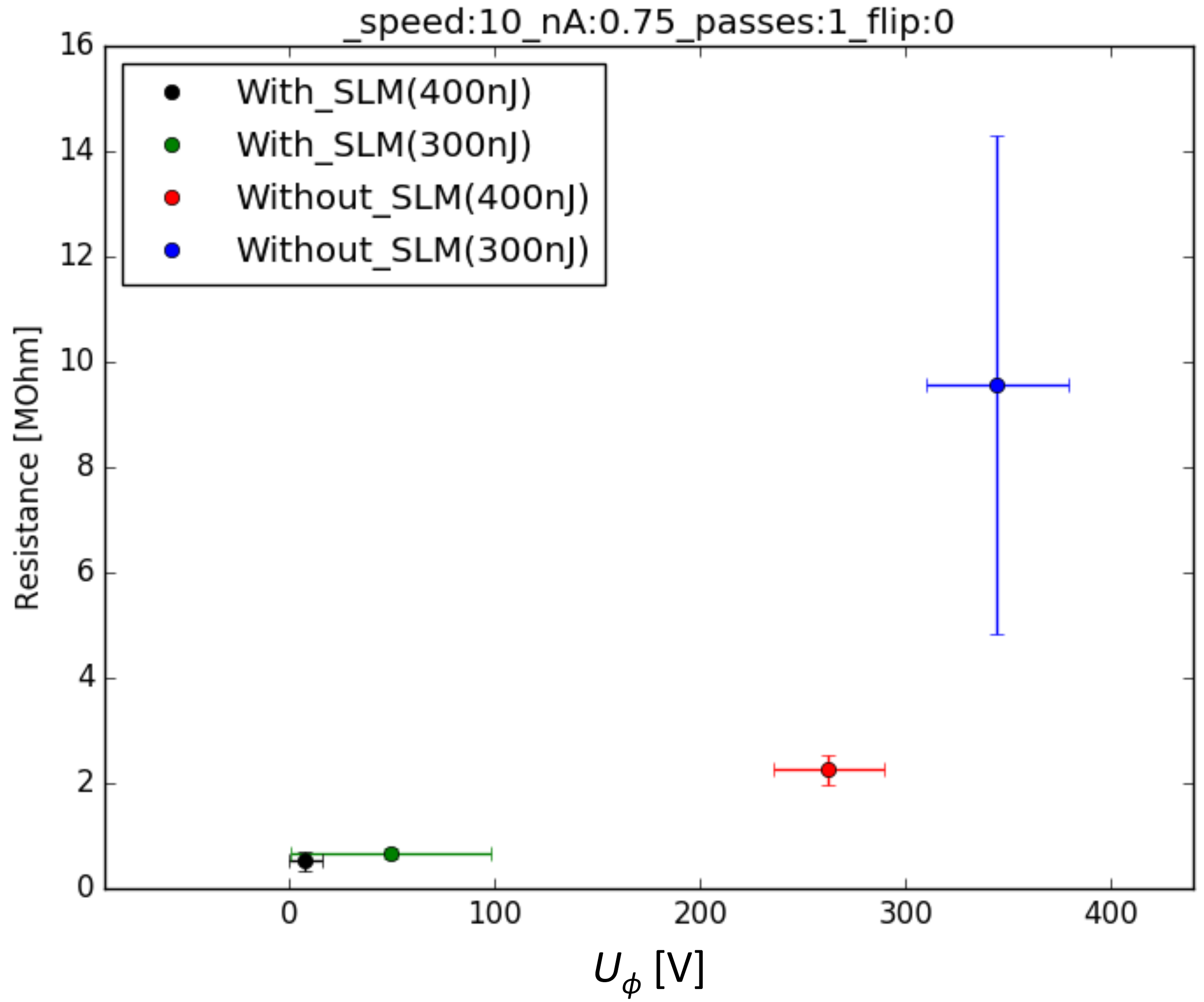
- Multiple passes also reduces U_ϕ.

Lens NA



- Higher NA oil immersion lens increases focal resolution.
  → Reduced resistance at 200nJ.

With and without SLM



The University of Manchester

MANCHESTER 1824

Summary

The method of column production has been vastly improved using an SLM.

→ However, high column resistivity is still a problem.

I've shown preliminary results for a comprehensive study of drilling parameters, including the measurement of:

- Surface diamond:graphite ratios.
- Morphology.
- IV characteristics.

- SLM is key to maintain the effective lens NA with depth.
- Higher NA → higher focal resolution → lower column resistivity.
- Speed needs to be tuned in order to minimise barrier potential.

Resistivity can be reduced further, but it takes much longer to form columns.

Future → lower resistivity in manageable timescales.

Thank you

Back up

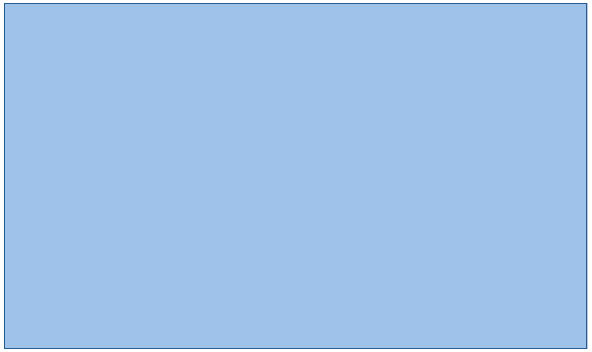
The University of Manchester

Introduction – why diamond?

Property (relative to silicon)	Silicon	Diamond
Energy gap	1	5 (3.5 *e-h* creation)
Dielectric constant	1	0.5
Thermal conductivity	1	13.5
Thermal expansion coefficient	1	0.03
Electron mobility	1	3.0
Hole mobility	1	6.3
Displacement energy	1	1.4

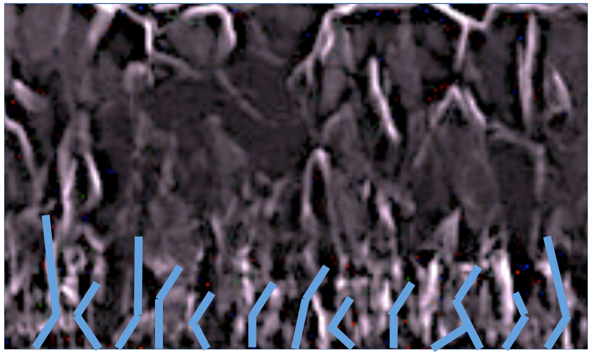
Introduction – types of diamond

Single Crystal



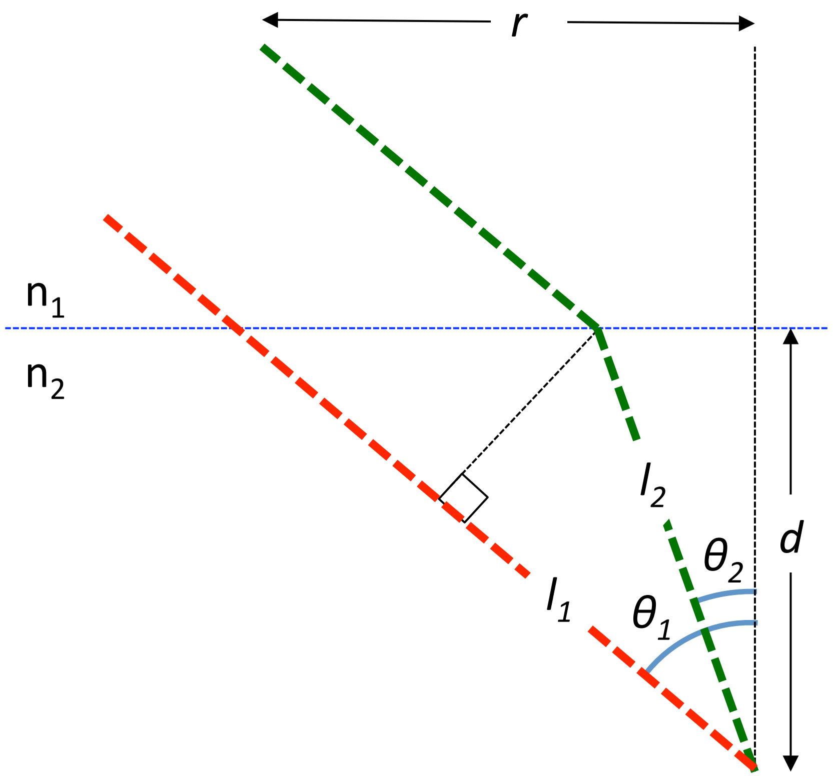
- Very good carrier properties.
- Small areas available.

Polycrystalline



- Reduced mean free path of carriers.
- Large areas available.

Spherical aberration



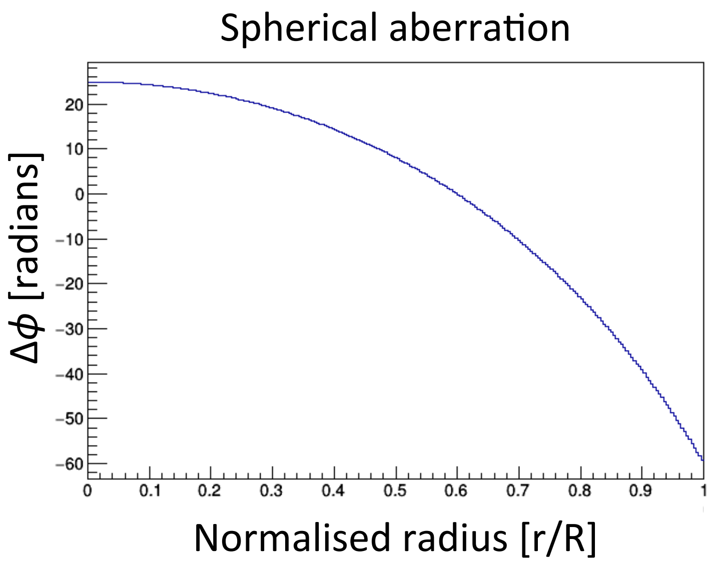
$$\Delta\phi = n_2 l_2 - n_1 l_1$$

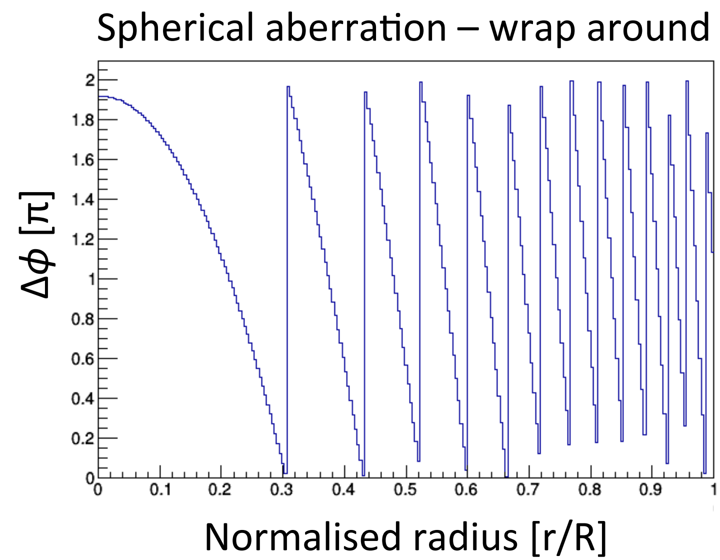
- Apply Snell's law.
- Assume lens obeys sine condition.

$$\Delta\phi(r) = -\frac{2\pi d}{\lambda_0 f}\left[\sqrt{f^2 n_2^2 - r^2} - \sqrt{f^2 n_1^2 - r^2}\right]$$

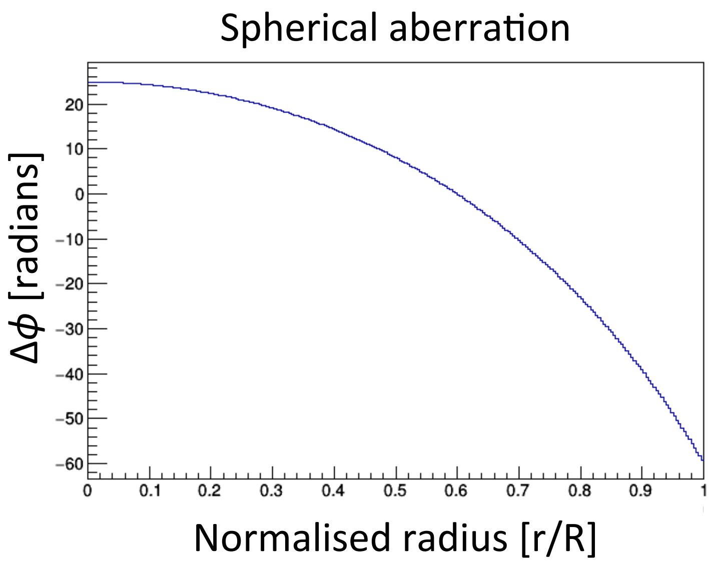
[5], [6]

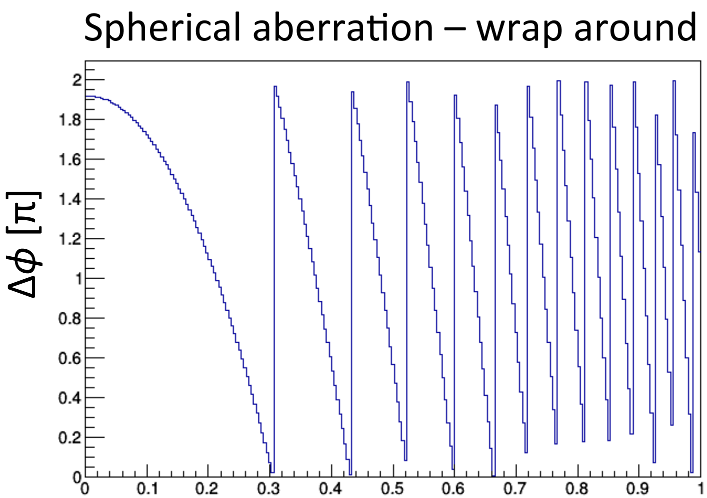
Spherical aberration

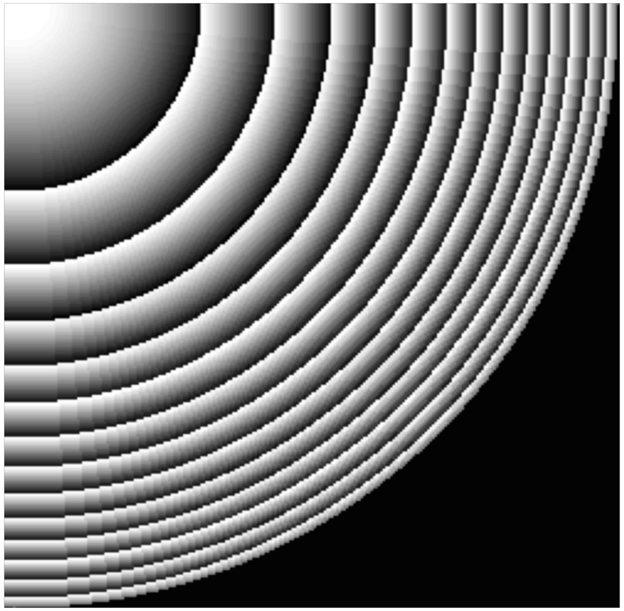




Spherical aberration



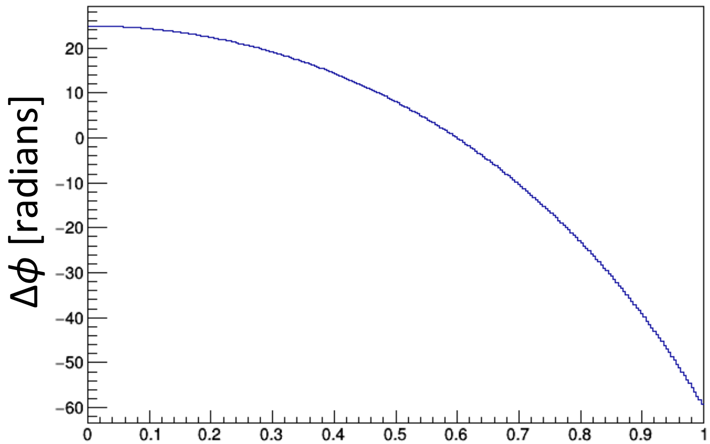




- Integrate around the optical axis.

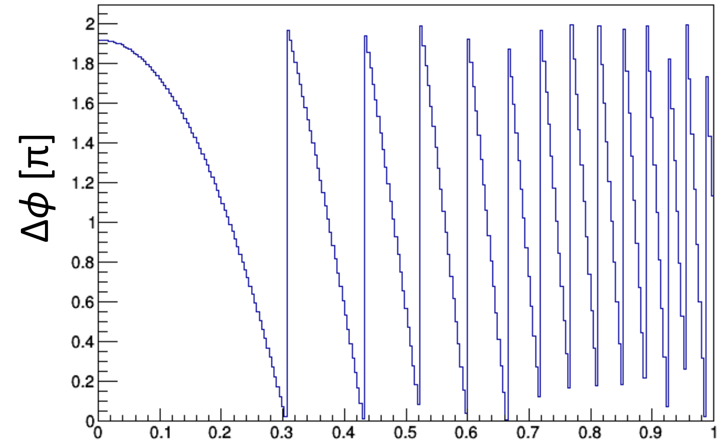
Spherical aberration

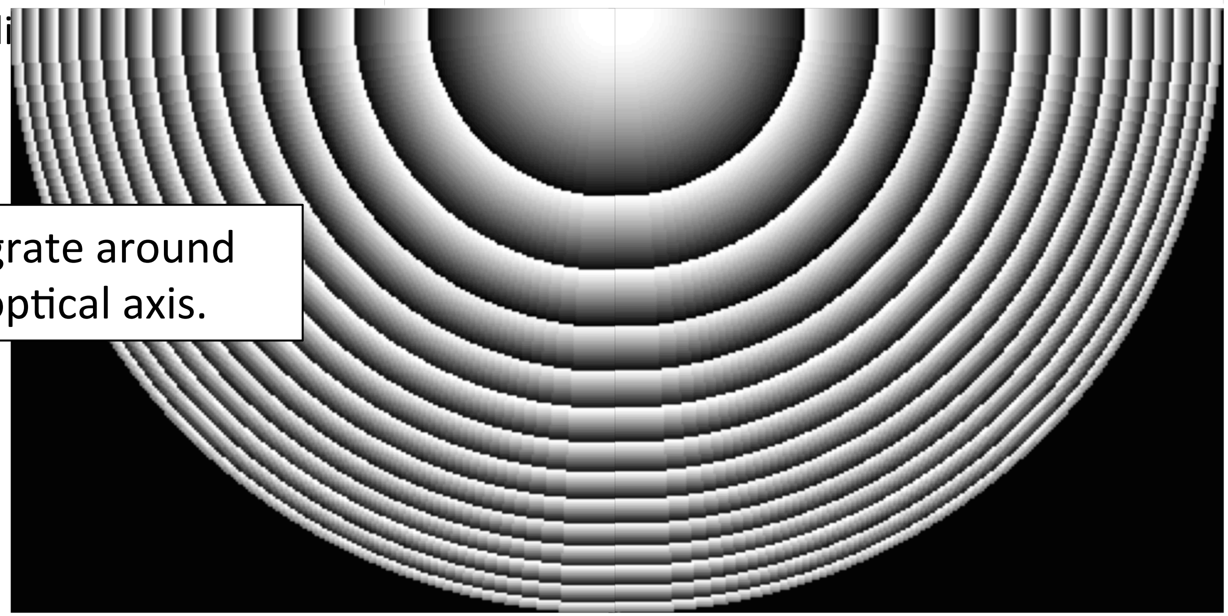
Spherical aberration



Normali

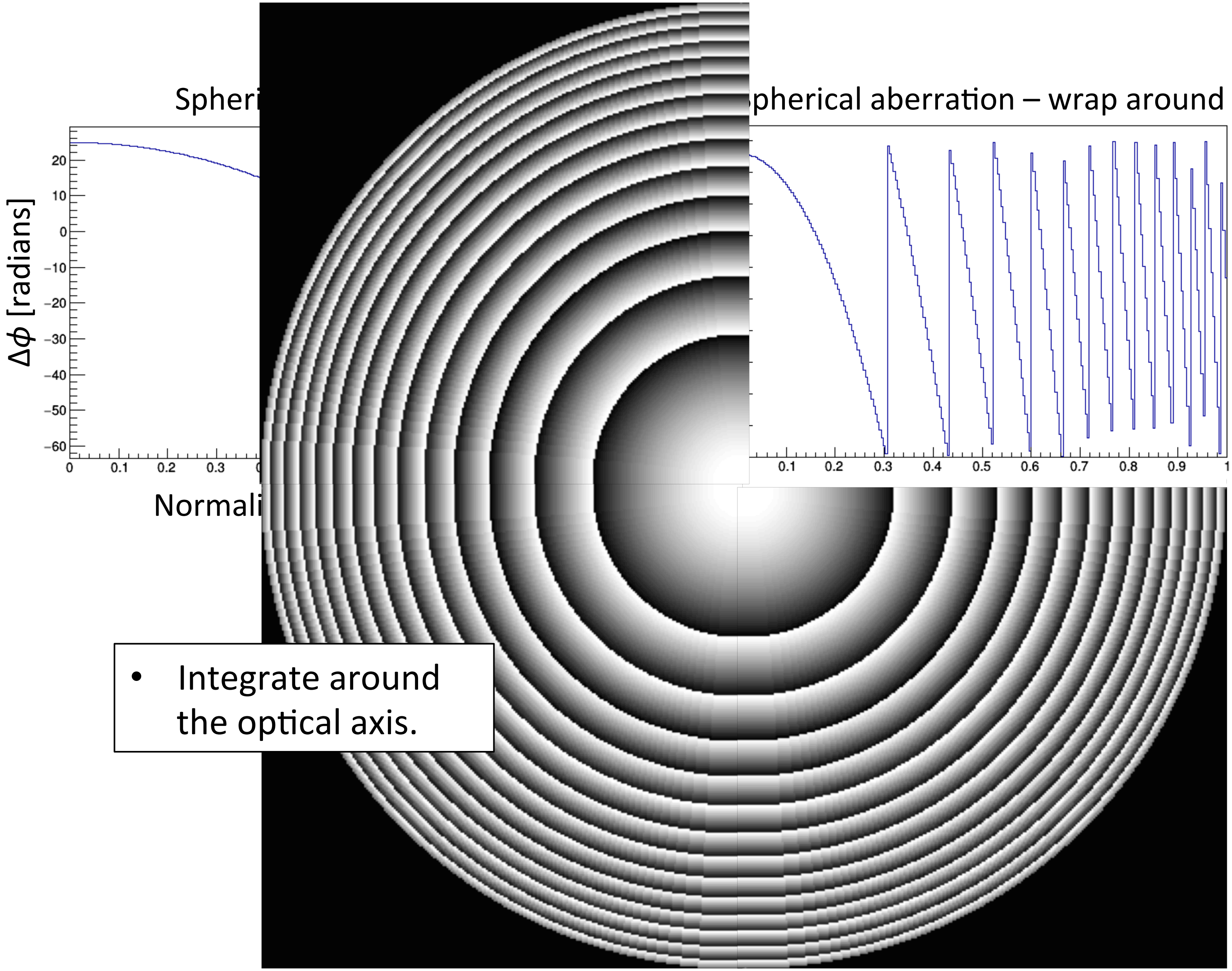
Spherical aberration – wrap around





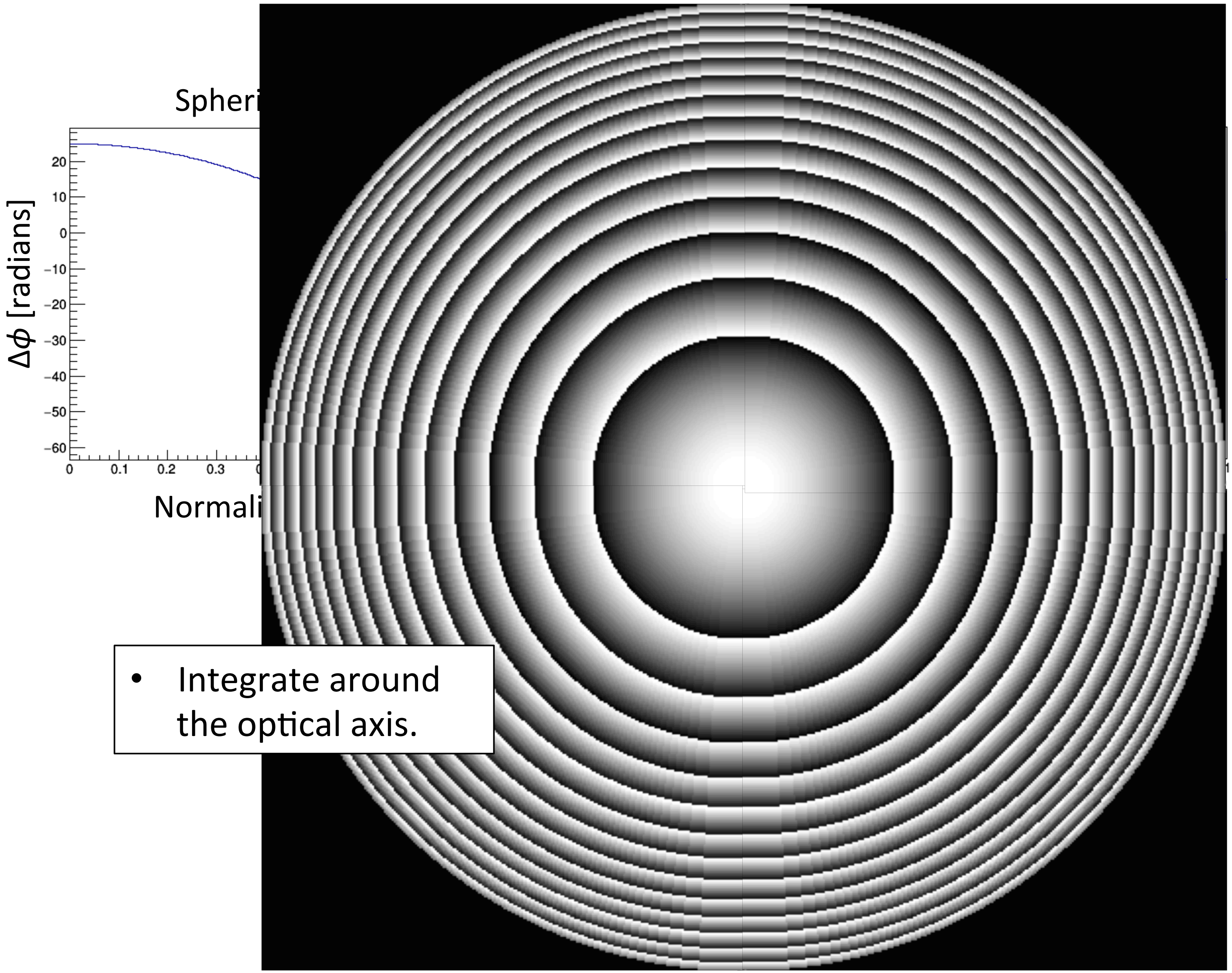
- Integrate around the optical axis.

Spherical aberration



- Integrate around the optical axis.

Spherical aberration

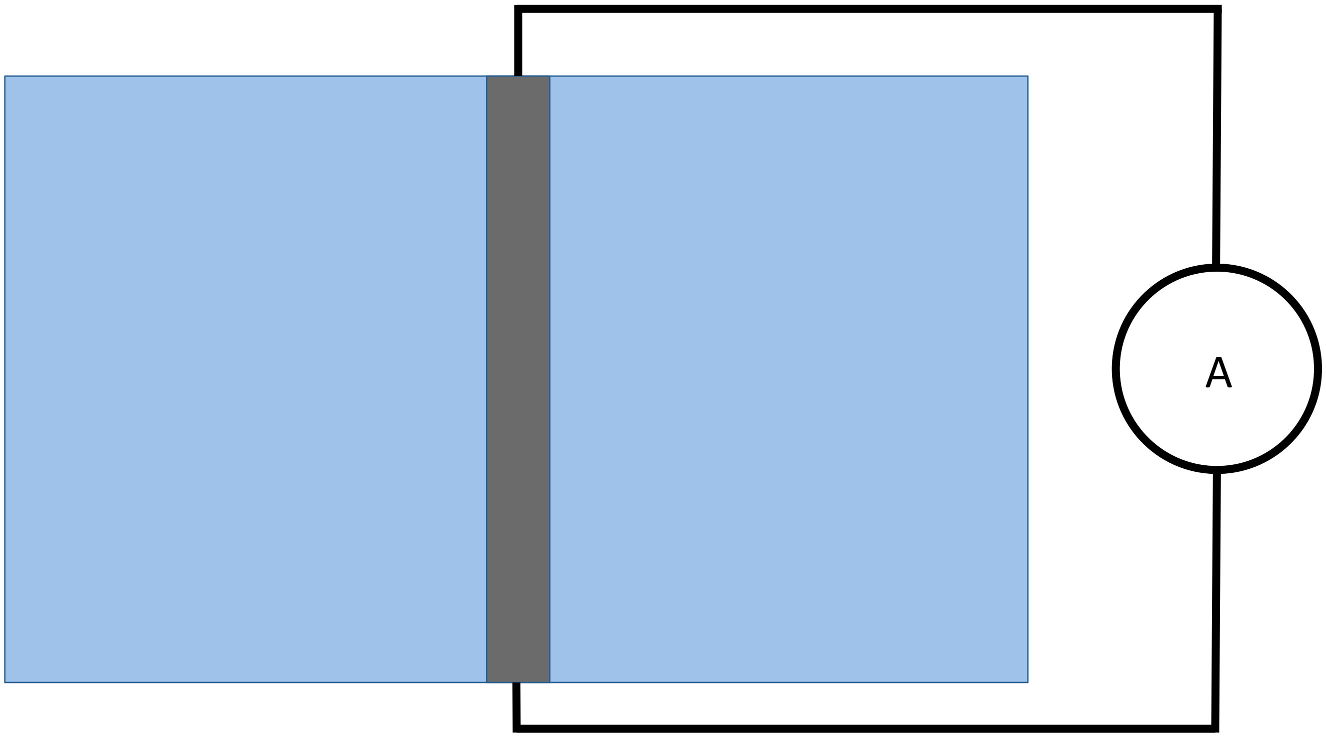


- Integrate around the optical axis.

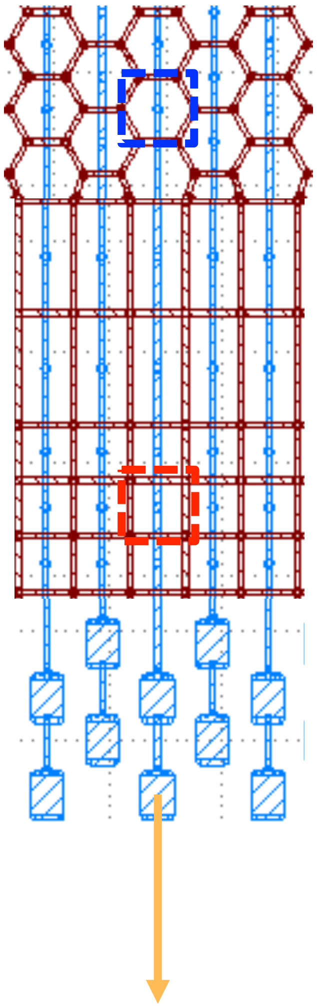
Internal measurement

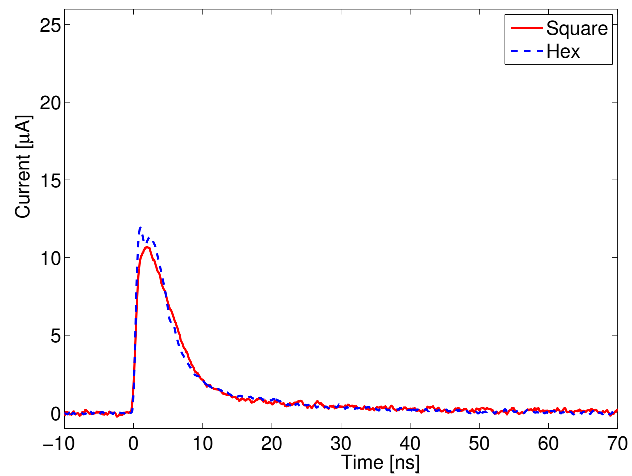
Current (I) versus applied bias voltage (U_b) measurement:

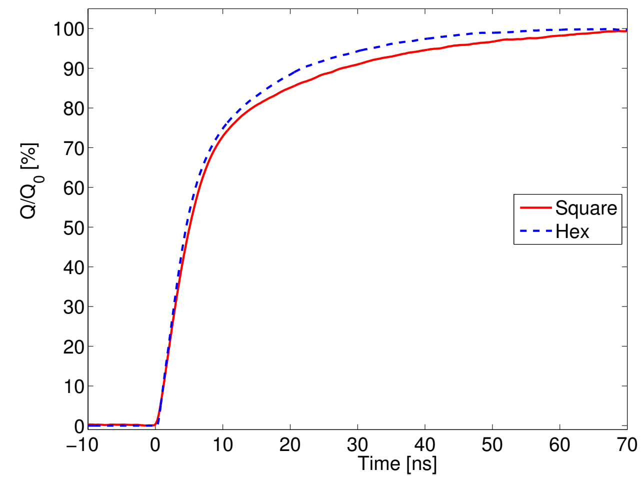
- *Keithley* 2410 source meter.
- Exit surface grounded.
- Seed surface probed.



Transient current signals at 20V

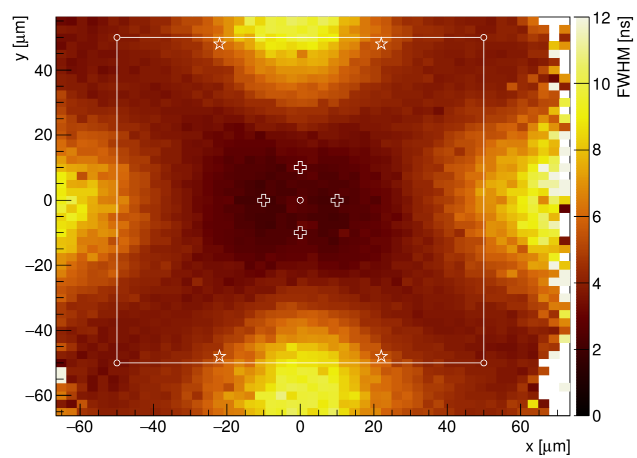


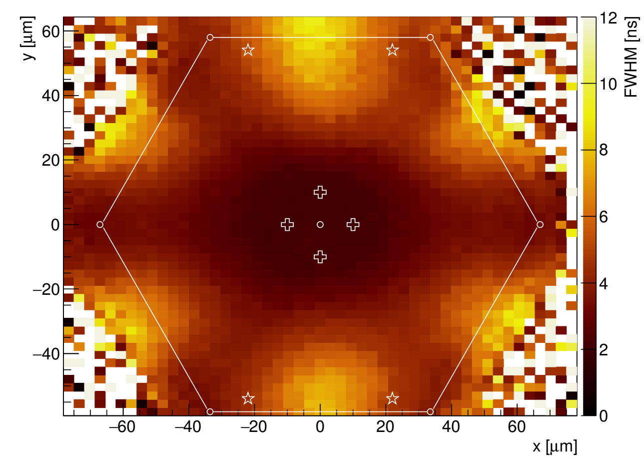




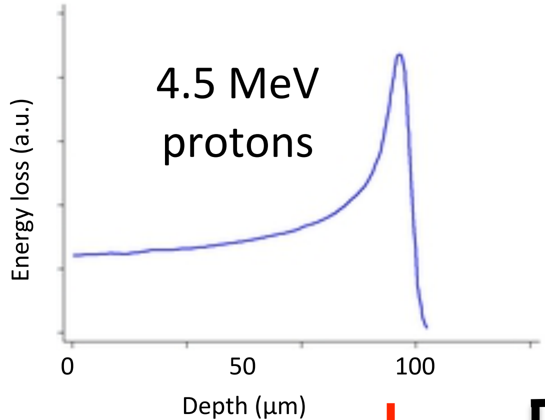
Square

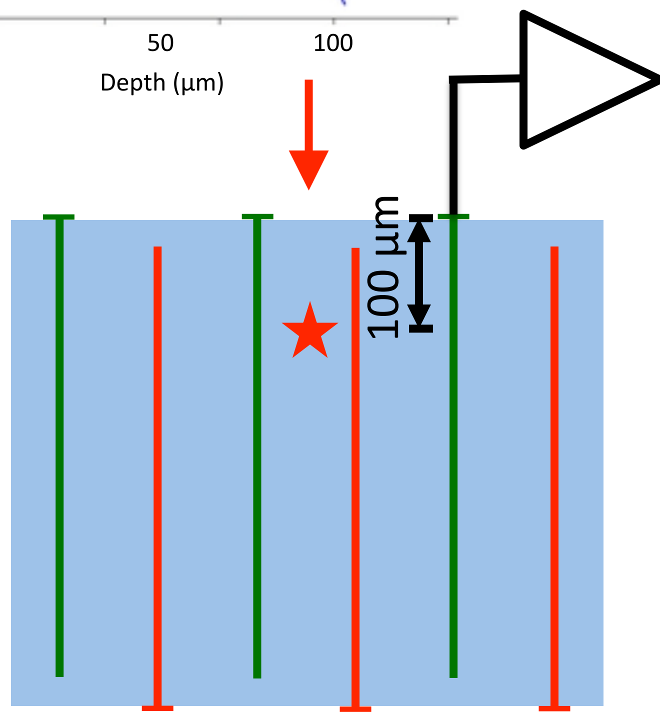
Hexagonal

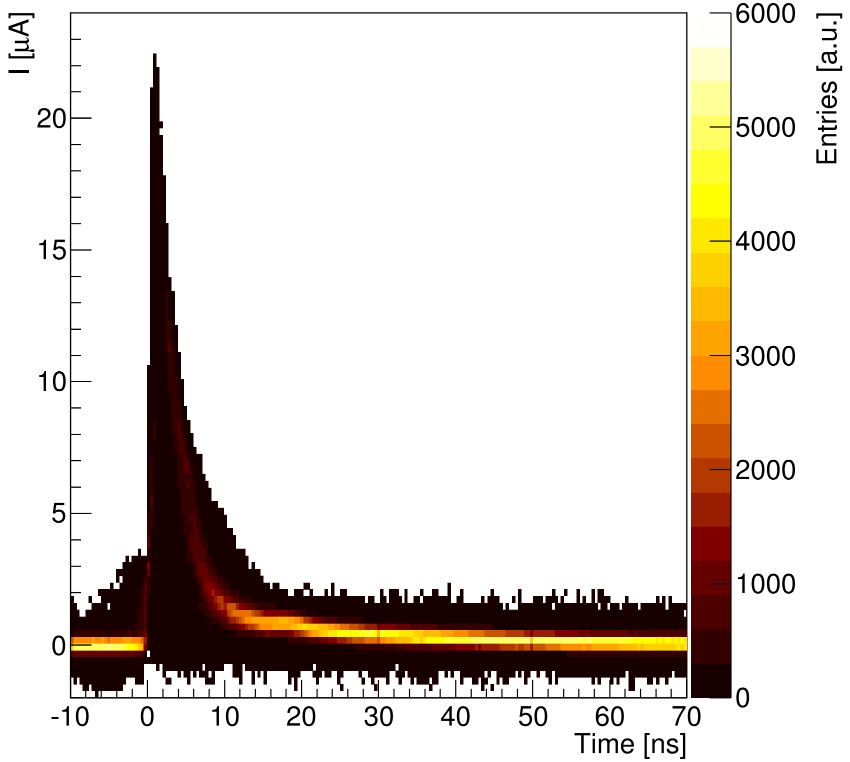




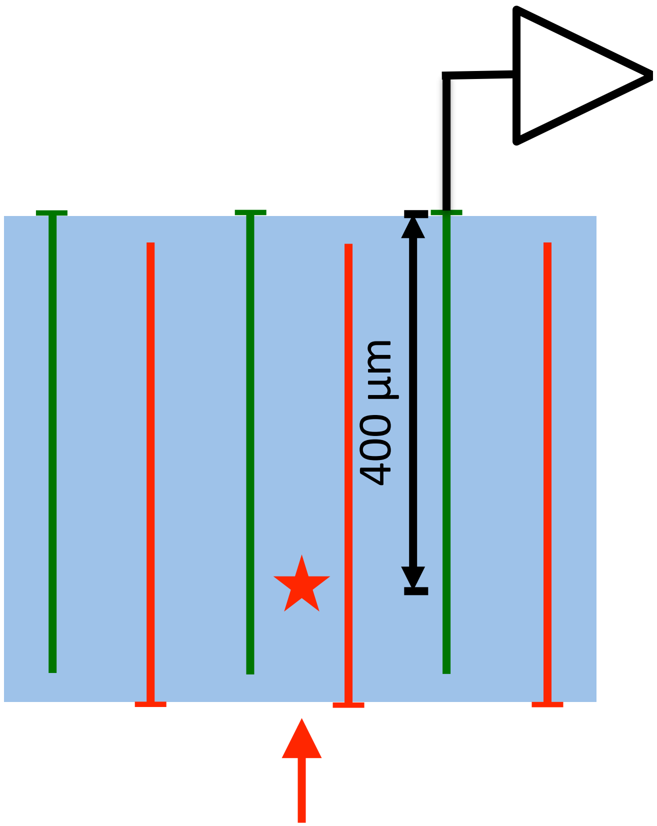
Charge production at depth

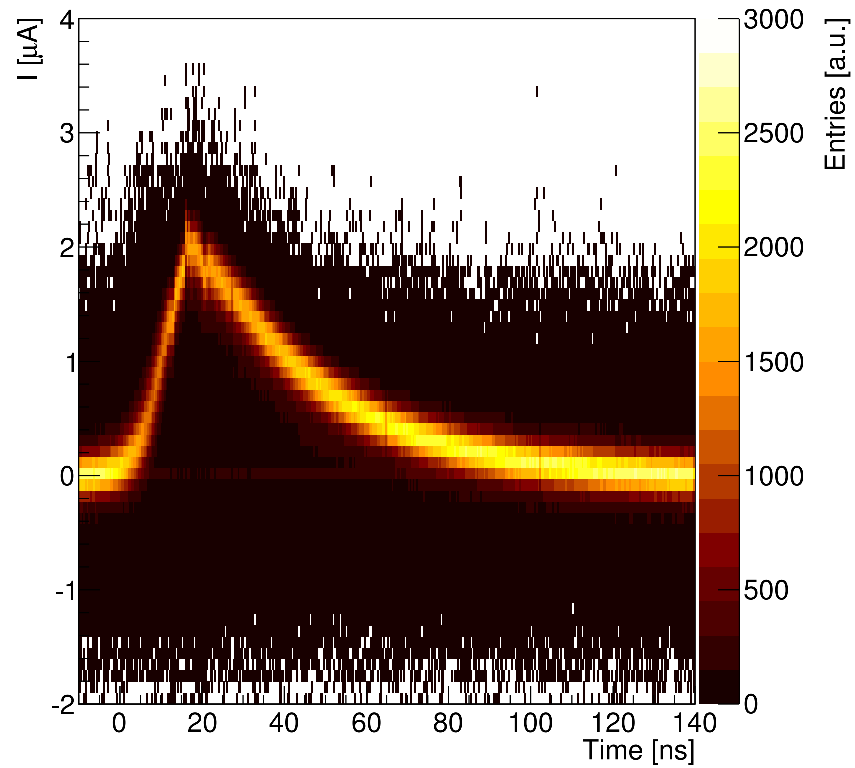


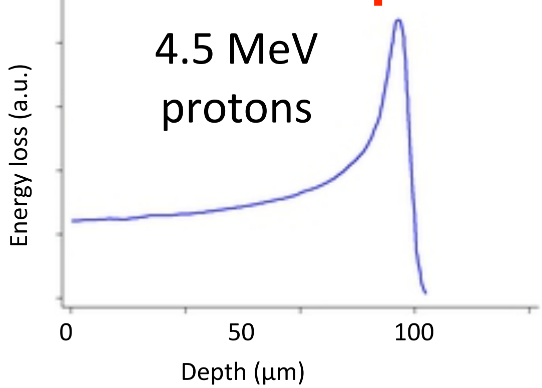




Column resistance







Sample flipping