RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Radiation damage of beryllium: MIAMI irradiation test plans

Slava Kuksenko[1], Chris Densham[2], Patrick Hurh[3], Steve Roberts[1]

[1] University of Oxford, UK
[2] Rutherford Appleton Laboratory, UK
[3] Fermi National Accelerator Laboratory, USA

Collaboration with:

Graeme Greaves and Stephen Donnelly from the University of Huddersfield

Xiaoou Yi *University of Oxford*

What do we study and why?

Beryllium - Grade PF-60

Max impurities, appm	
Al	170
C	450
Fe	130
Mg	810
O	2900
Si	130
N	195
Be	balance

Long-Baseline Neutrino Experiment (LBNE)

Application	Operating conditions					Proton beam parameters
	Avg. T (°C)	Peak T (°C)	Total DPA	Gas production (appm/DPA)		
				He	H	
Beam window (vacuum to air)	200	300	~ 0.23/yr	>2000	>2500	700 kW; 120 GeV; ~1 Hz; σ_{rms} = 1.3 mm
Target	375	450	~ 0.23/yr	>2000	>2500	700 kW; 120 GeV; ~1 Hz; σ_{rms} = 1.3 mm

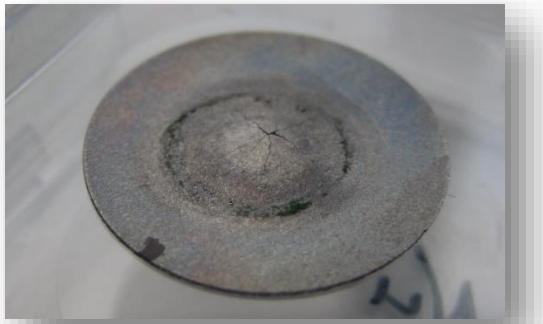
Environment: elevated temperature + radiation + pulsing loads

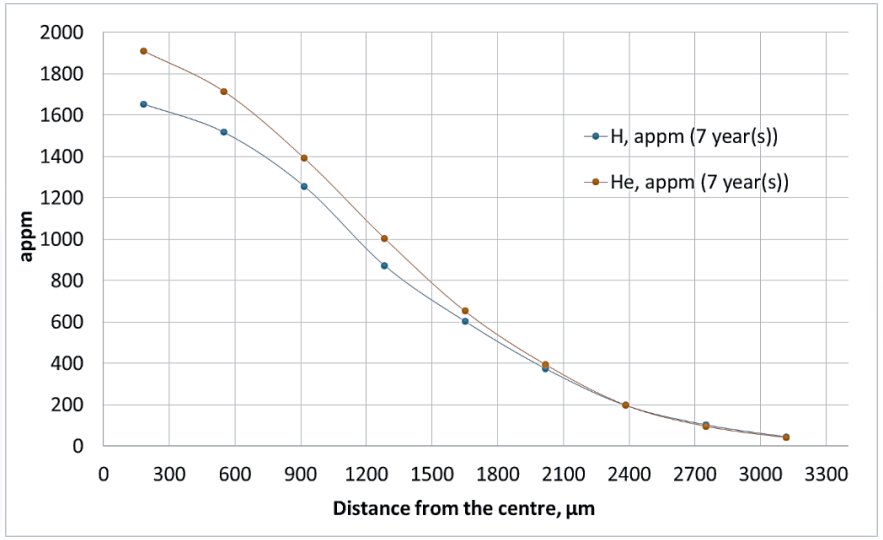
300 kW NuMI beam window

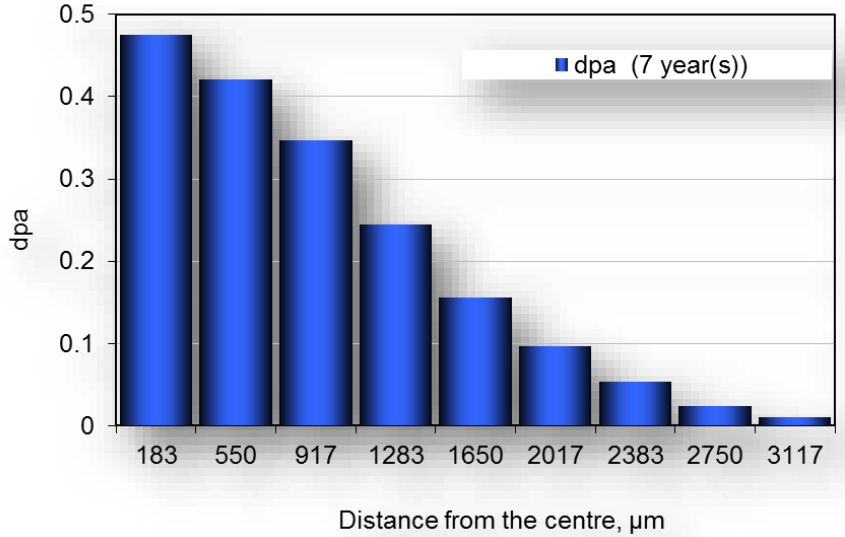
120GeV proton beam

about 3×10^{13} protons per pulse, 0.5 Hz

T ≈ 50ºC







Simulation with ion irradiation experiments

Low energy in-situ irradiation:

- easy variation of irradiation parameters;
- reasonable correspondence of He/dpa ratio.
- observation of evolution of microstructure structure vs dose/appm;

High-energy irradiation + PIE

- microstructural and micromechanical tests data will be available

But: **validity of the simulation should be confirmed**

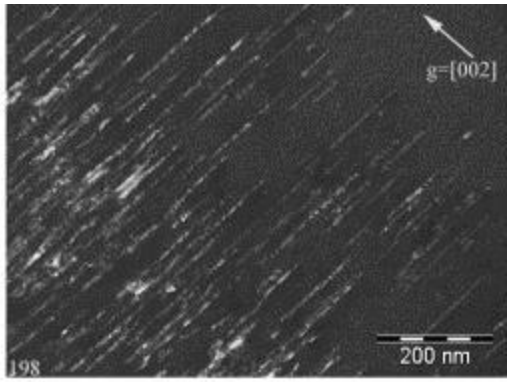
Be under irradiation

n-irradiation:

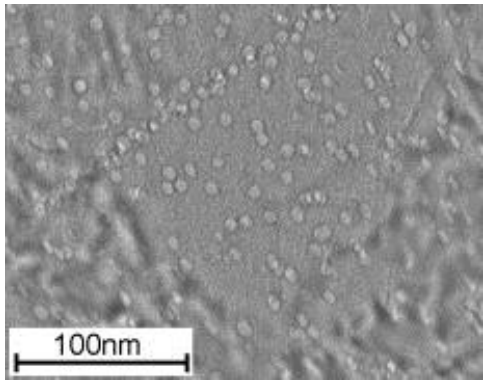
• At low T_{irr} below ~ 200ºC (Chakin et al. JNM 2009) or 400ºC (Gelles et al. JNM 1994): “black dots” and dislocation loops.

• At higher T: mainly He babbles

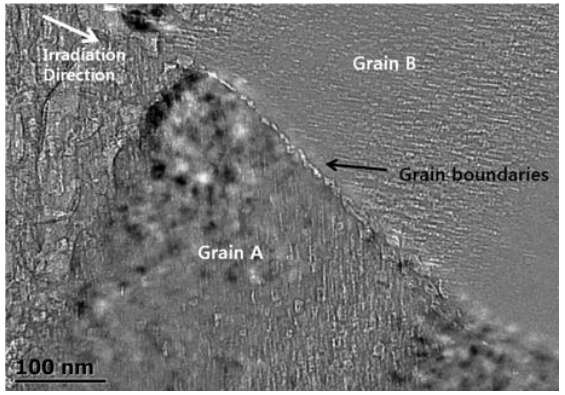
Implantation of He and H: bubbles can dominate even at RT



Irr. Be, TEM, DF, dislocation loops, Tirr.=70 °C, $F = 6\times10^{22}$ cm^{-2} (E > 0.1 MeV) (Chakin et al. JNM 2009)



Irr. Be, TEM, BF, He bubbles, Tirr.=413 °C, $F = 6.5\times10^{21}$ cm^{-2} (E > 1 MeV) (Klimenkov et al. JNM 2013)



S-200-F, H implantation (120keV, RT. 2×10^{18} ions/cm^2), (from Kang et al. Journal of the Korean Physical Society, 63, 2013)

Irradiation Source	He gas production in Be (appm/DPA)
Mixed spectrum fission reactor	10-500
Fusion reactor	550
High energy proton beam (NuMI)	~ 4000
Ion implantation	~ 35000…50000

What can we expect from GeV protons?

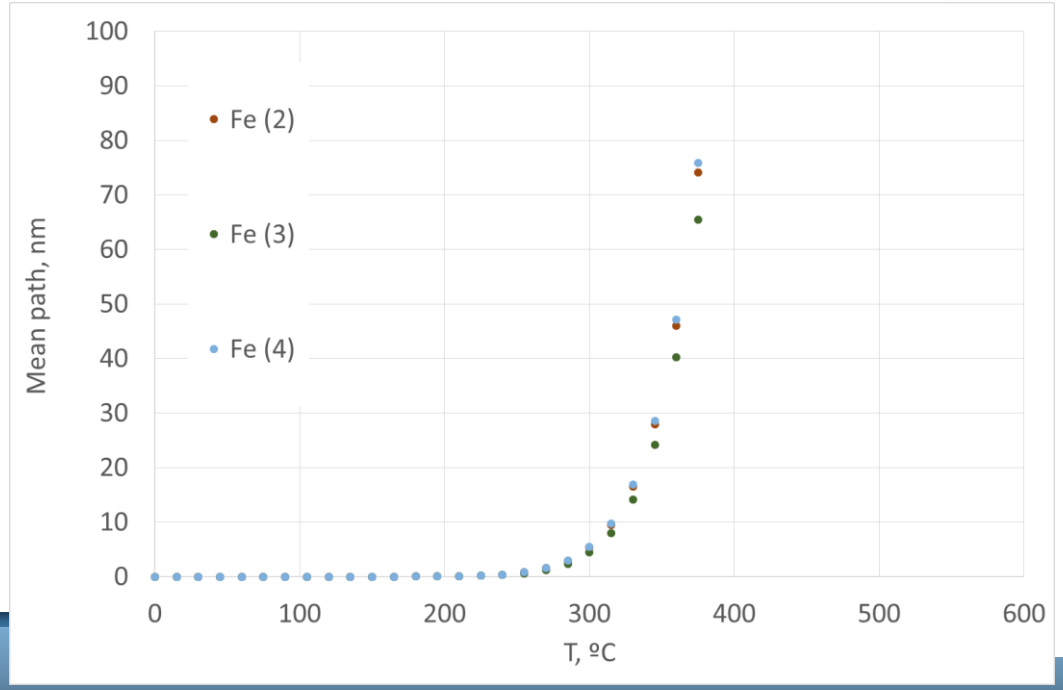
Consequences of supersaturation of defects:

1. Enhancement of phase transformation

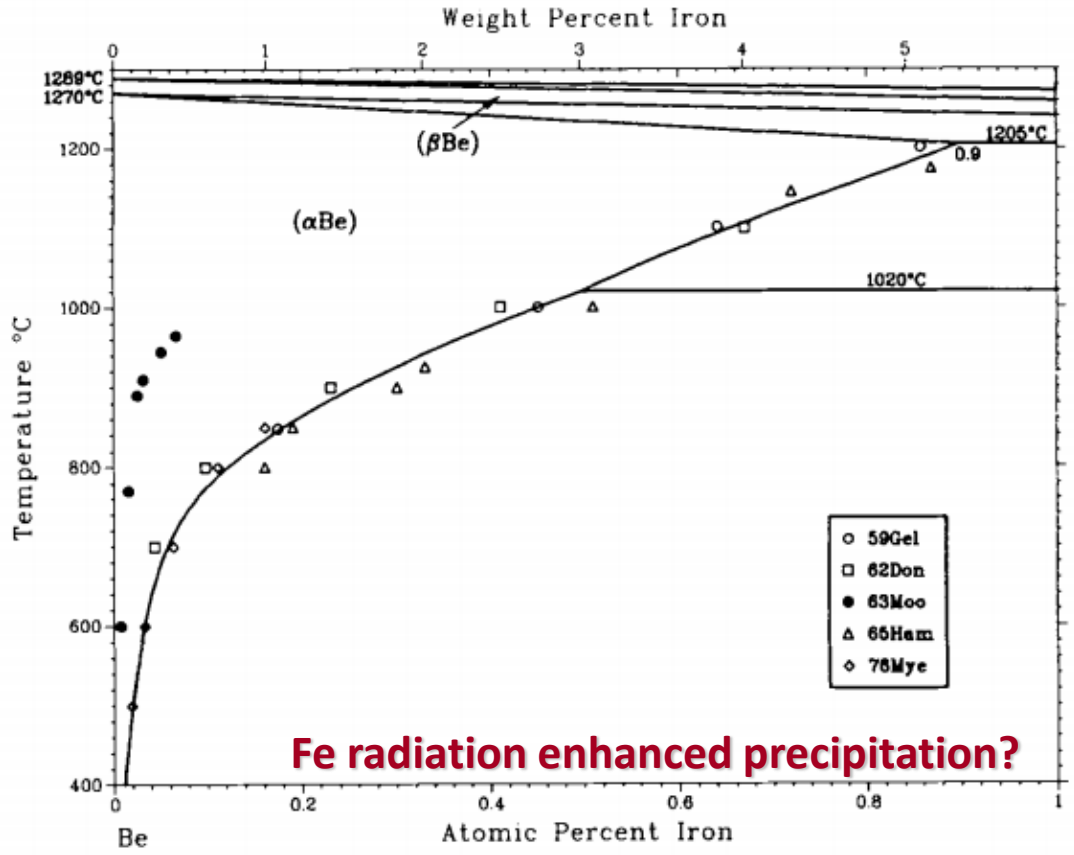
$$D^* = \alpha_V D_V C_V^* + \alpha_x D_x C_x^* \qquad C_V^* > C_V^T$$

X - self interstitial atom; clusters of point defects

Impurities in Beryllium matrix (preliminary)			
Fe, appm	Cu, appm	Ni, appm	O, appm
520±10	80±10	140±10	330±10

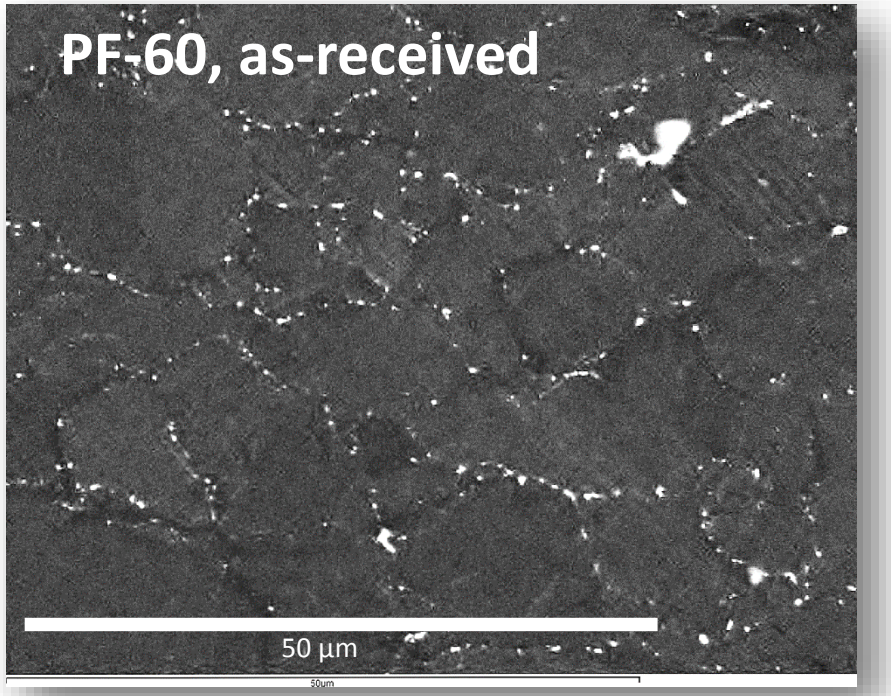


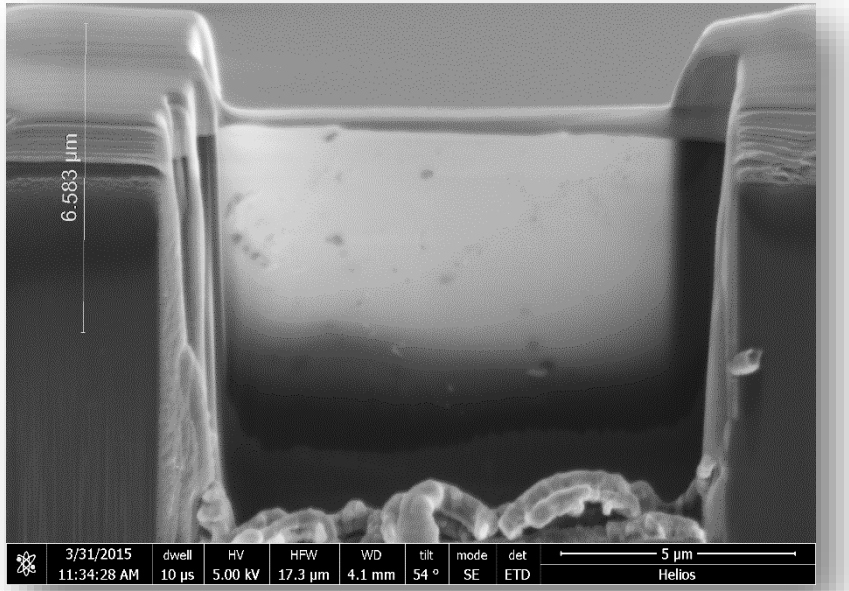
(αBe) Solvus Boundary of the Be-Fe Assessed Phase Diagram

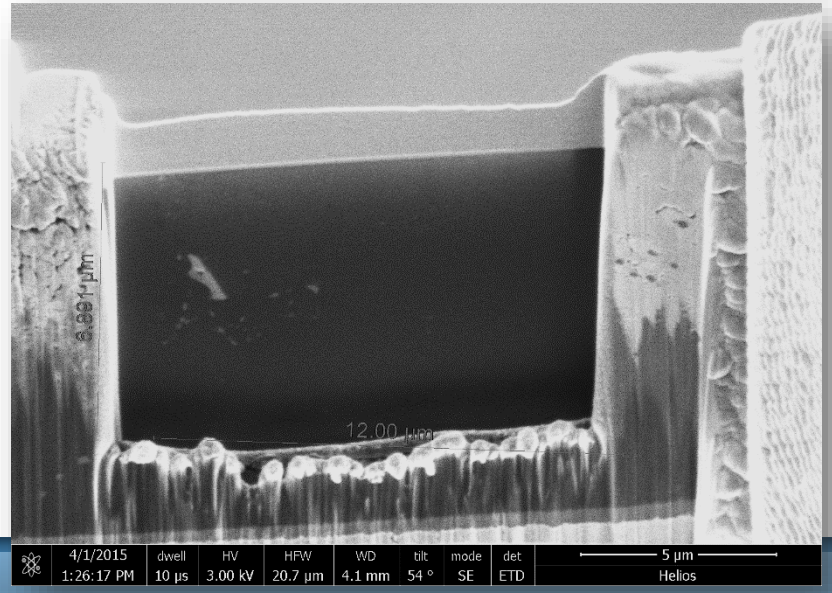


H. Okamoto and L.E. Tanner, 1988.

Samples preparation:



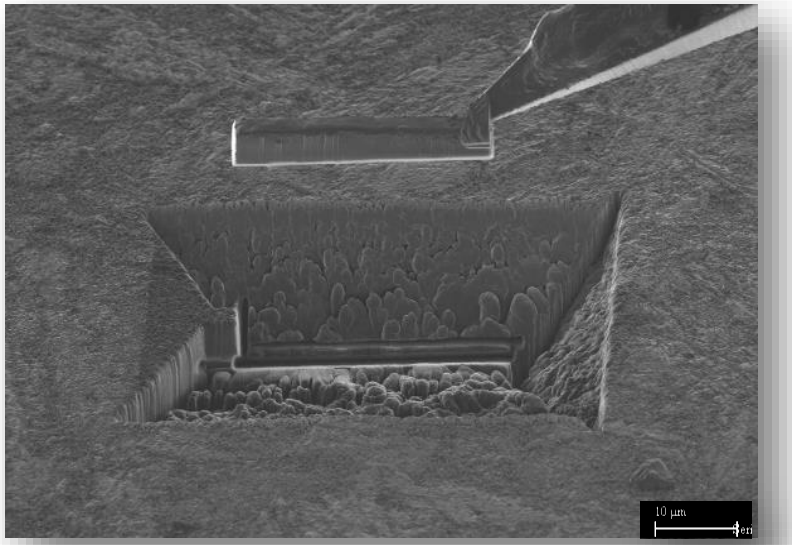


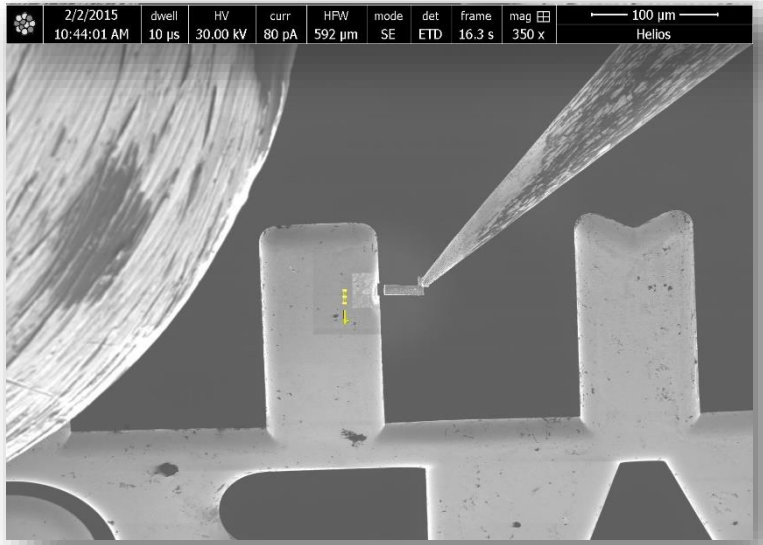


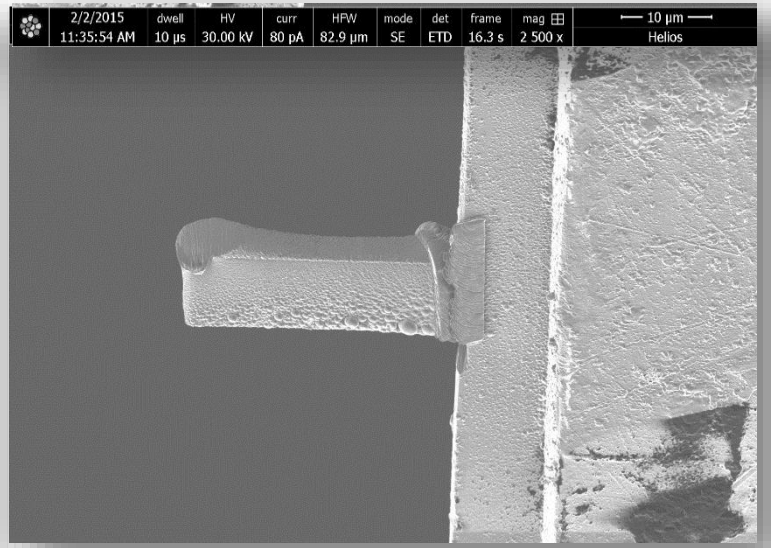
CCFE
CULHAM CENTRE FOR FUSION ENERGY

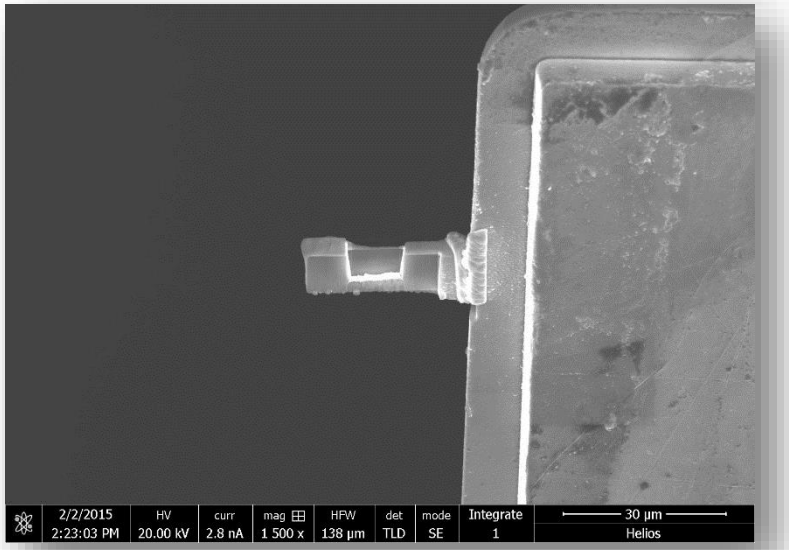
NNUF
National Nuclear User Facility

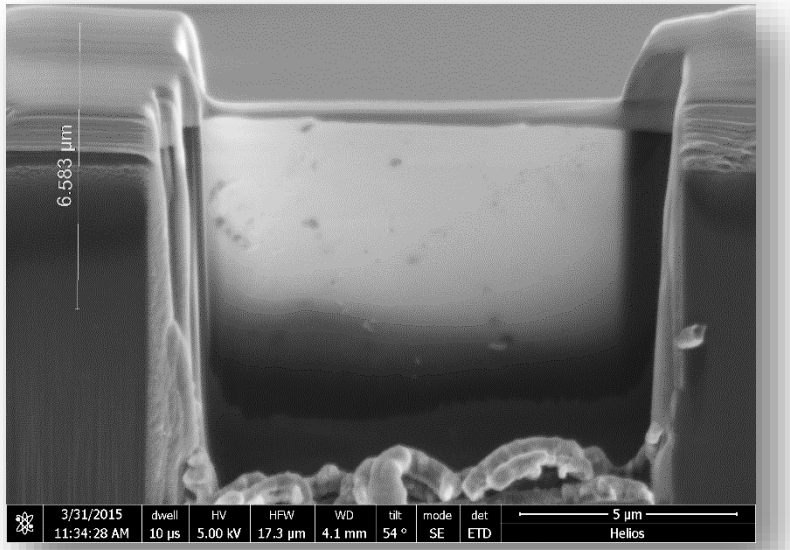
preparation of TEM samples







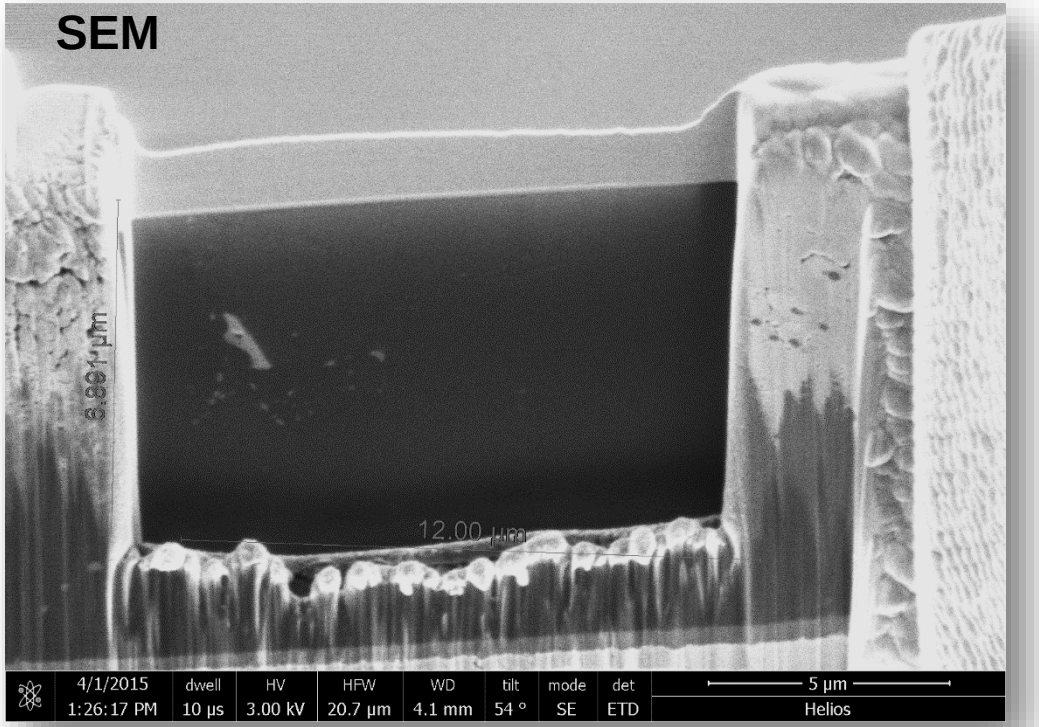


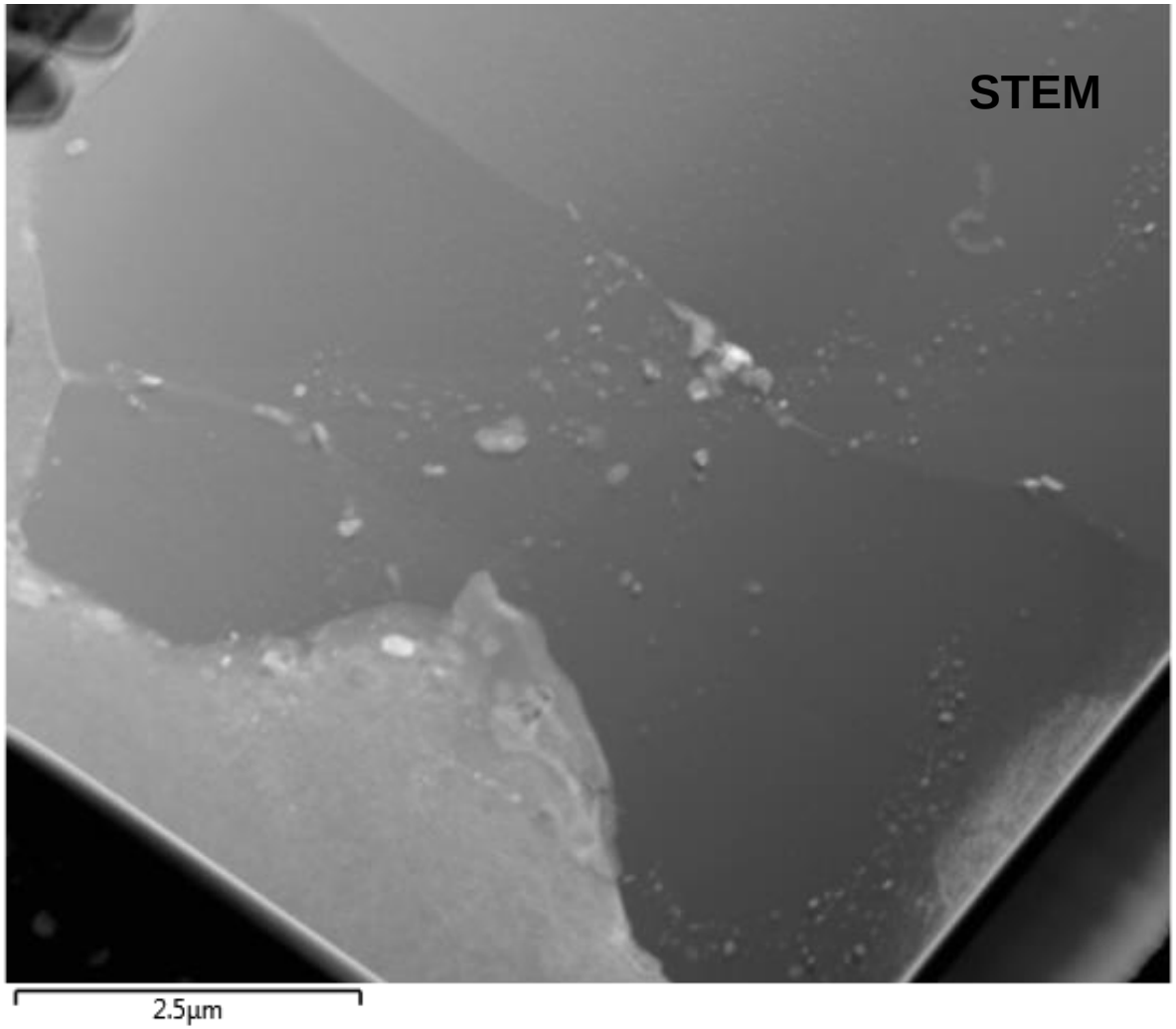


TEM lamella:

Size ~ 10×7 µm
Thickness ~ 100 nm

Pre-examination of TEM samples





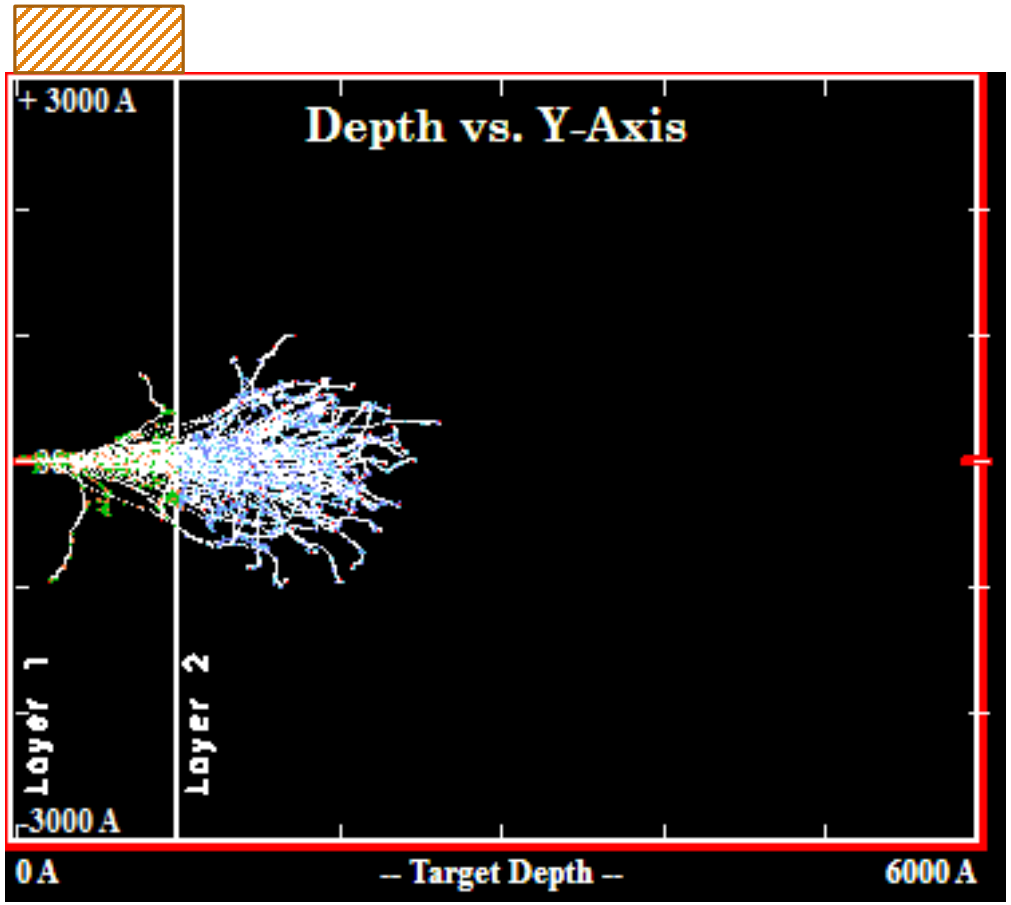
Microscope and Ion Accelerator for Materials Investigations facility (MIAMI) University of Huddersfield , UK

Ions: He+

Beam energy: ~ 18keV

Temperature: 50ºCc

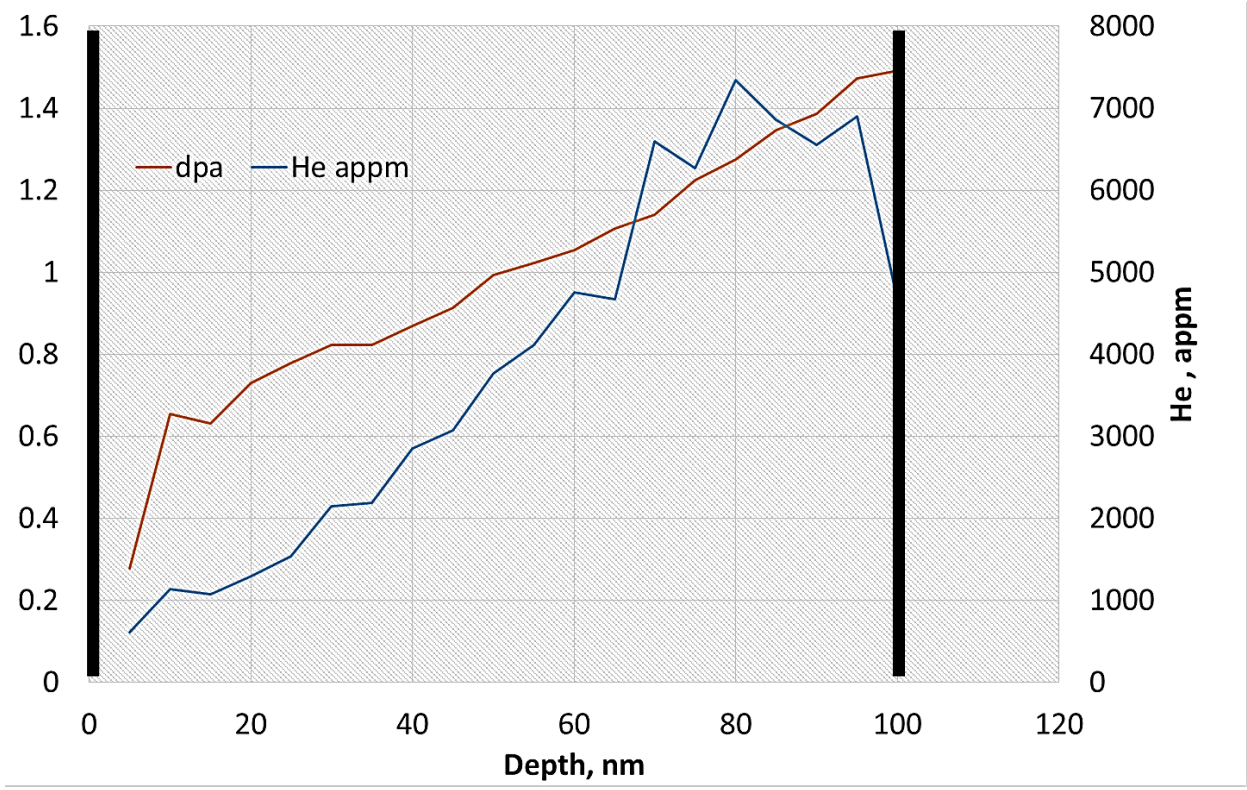
TEM foil



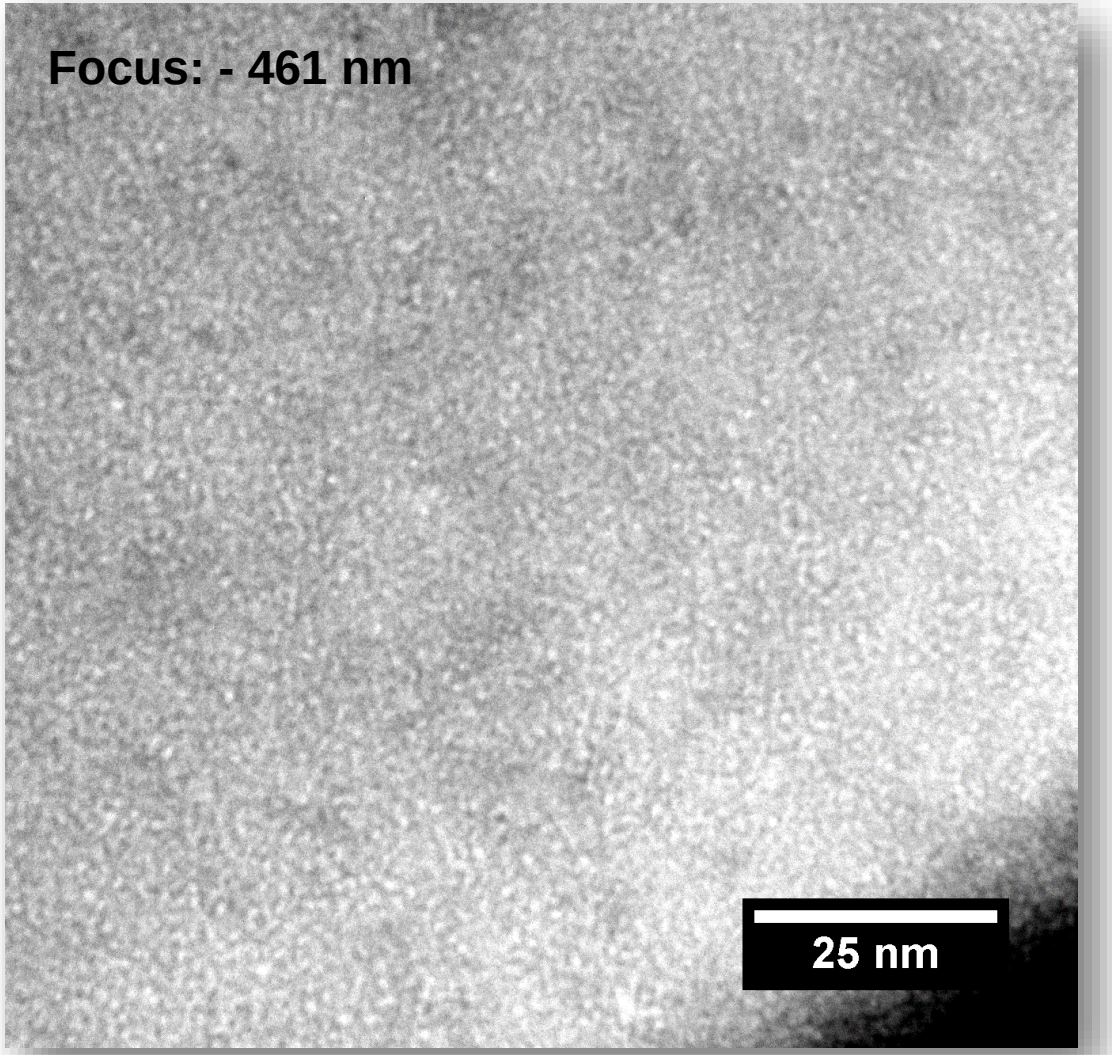
Ions: He+

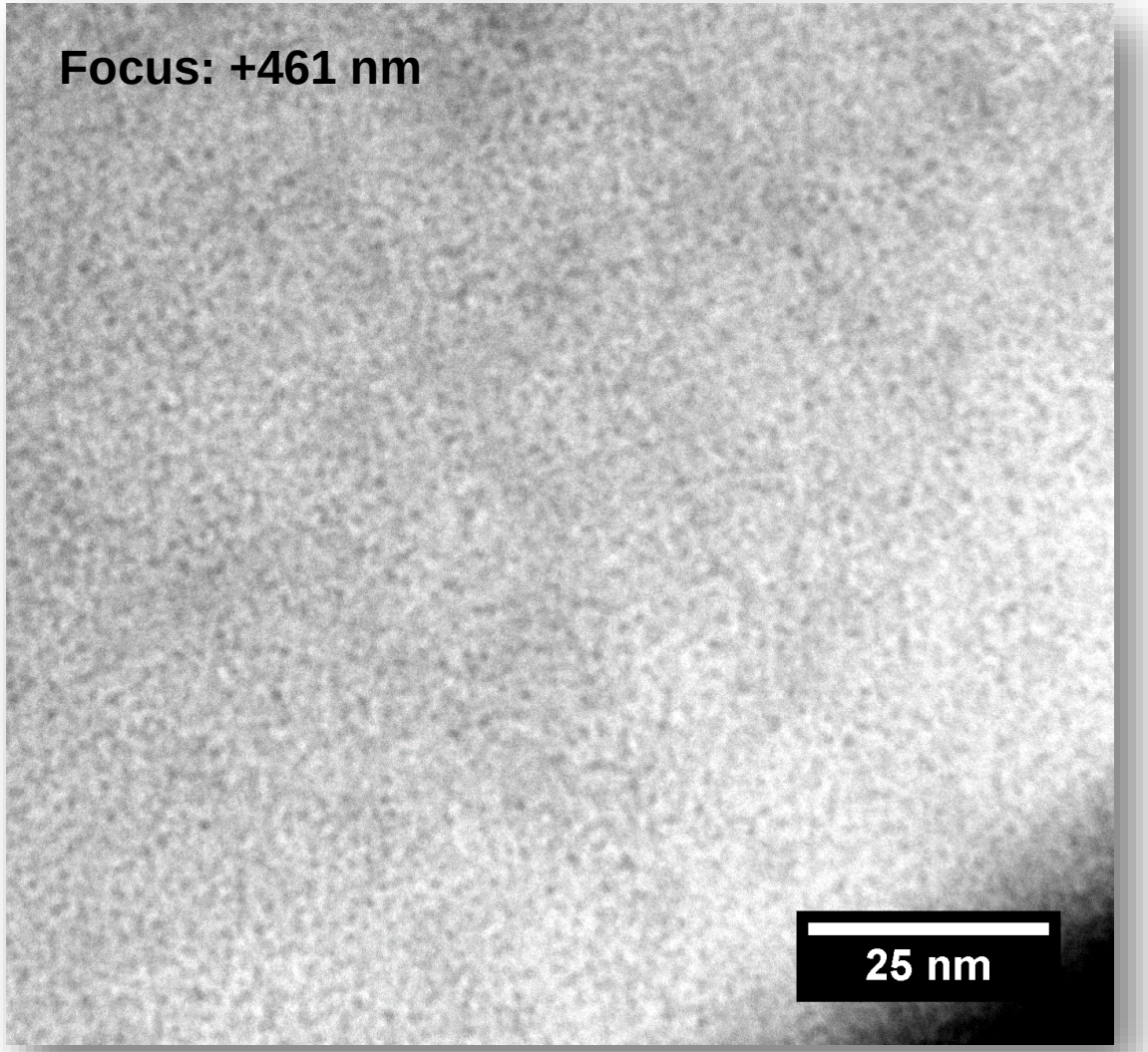
Beam energy: ~ 18keV

Mean He/dpa = 4000



Defocus contrast (preliminary)

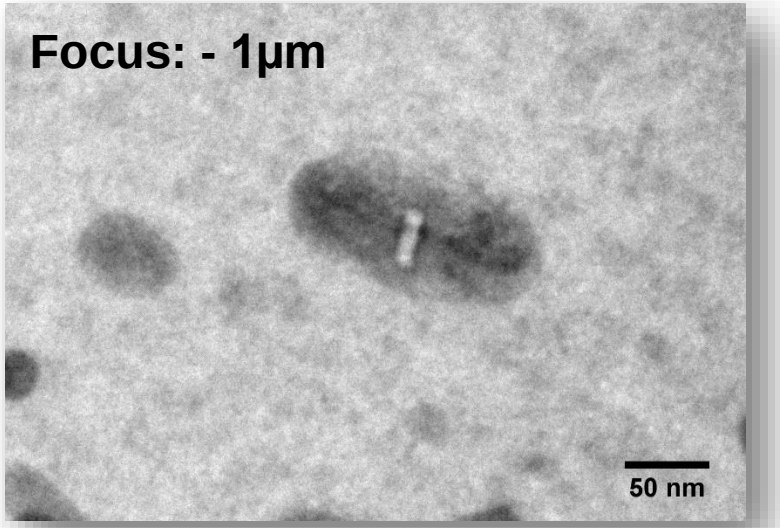


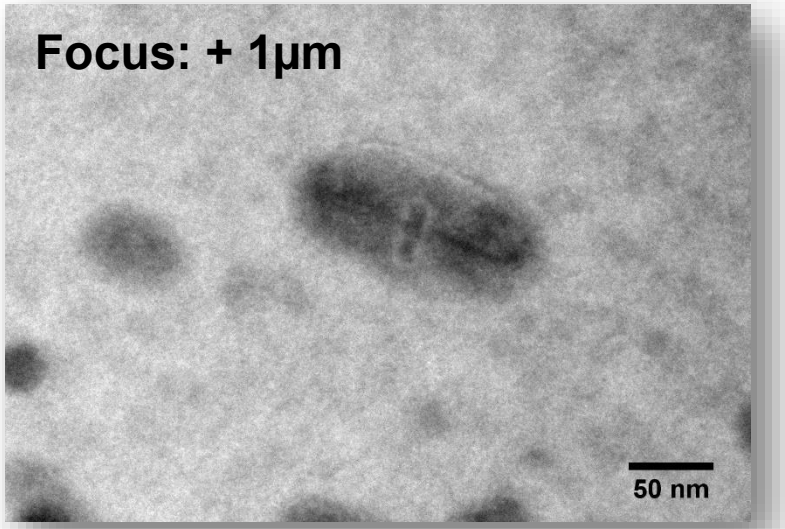


Size: up to 1…2 nm
ND ~ $5 \cdot 10^{23} \ldots 1 \cdot 10^{24}$ m^{-3}

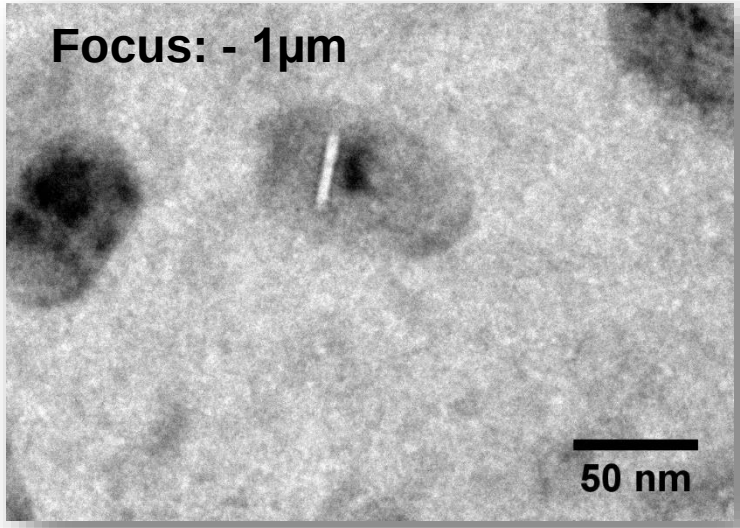
Defocus contrast (preliminary)

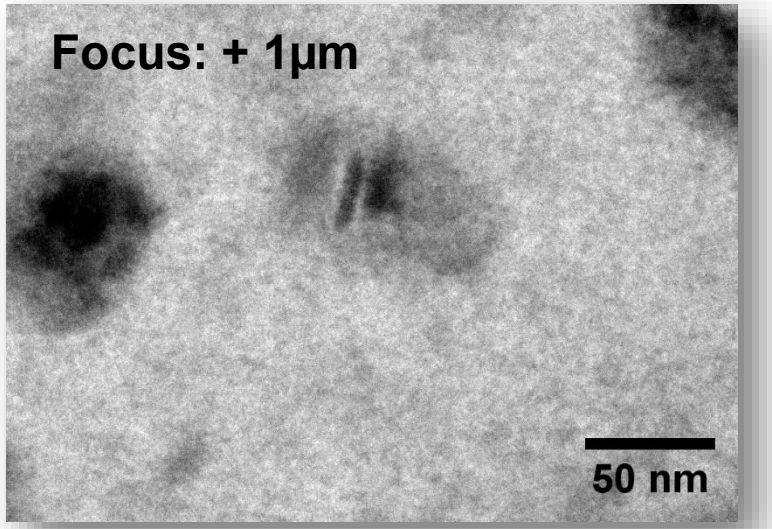
6000 appm / 1.5dpa





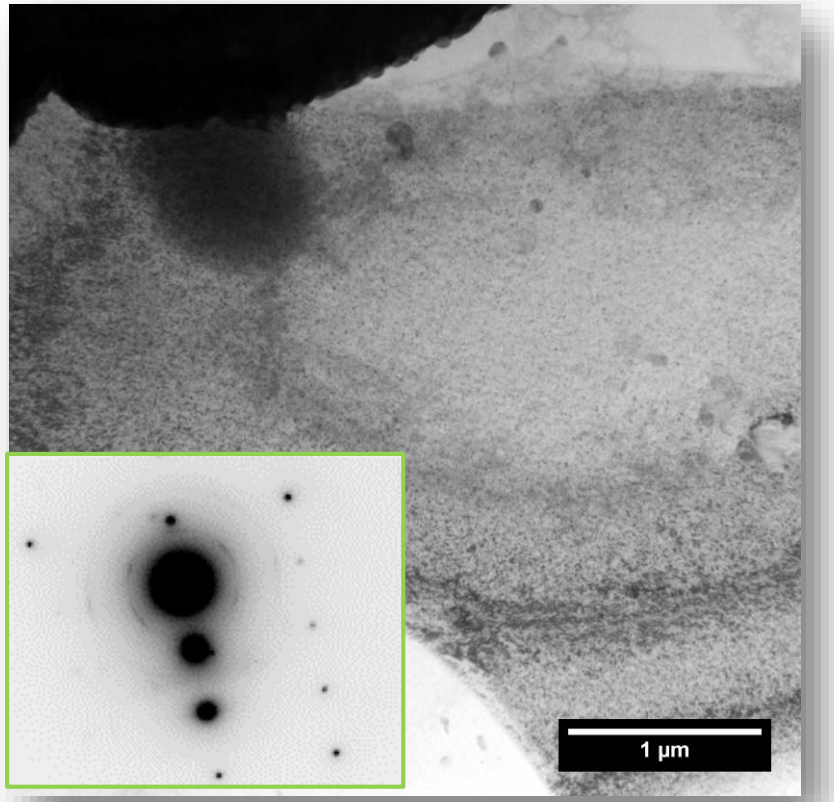
8000 appm / 2dpa



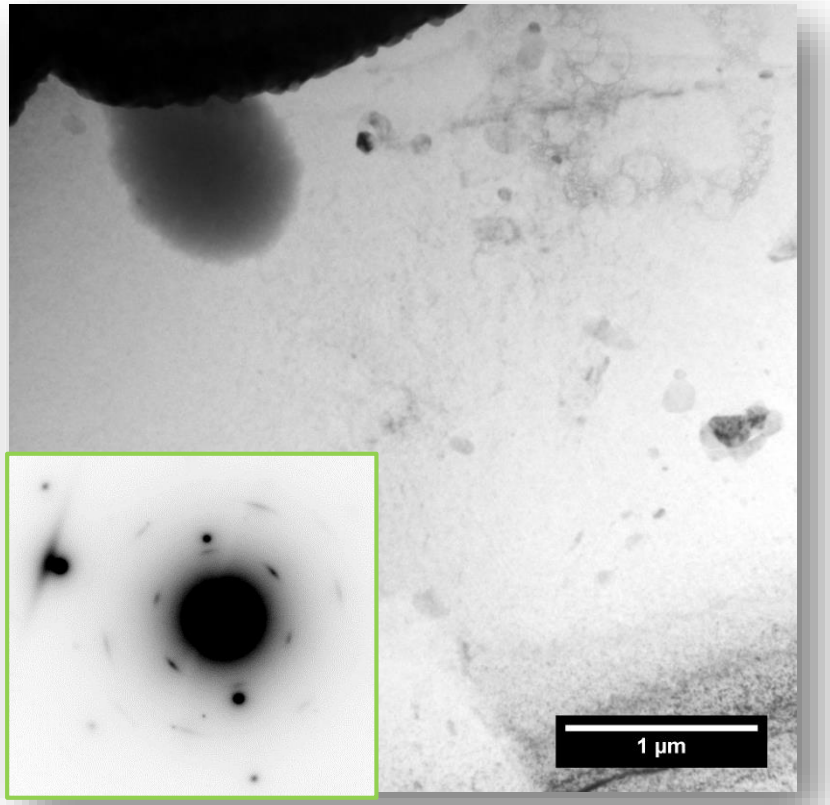


Dislocation loops (preliminary)

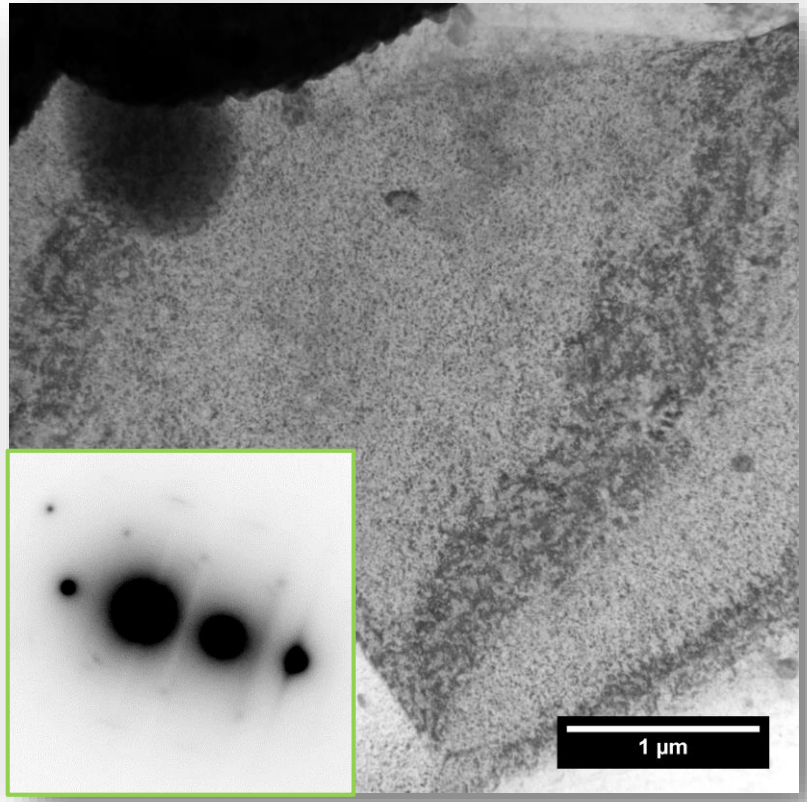
PF60.
1.5dpa/6000appm of He, T=50°C



g = [0 1 -1 0]



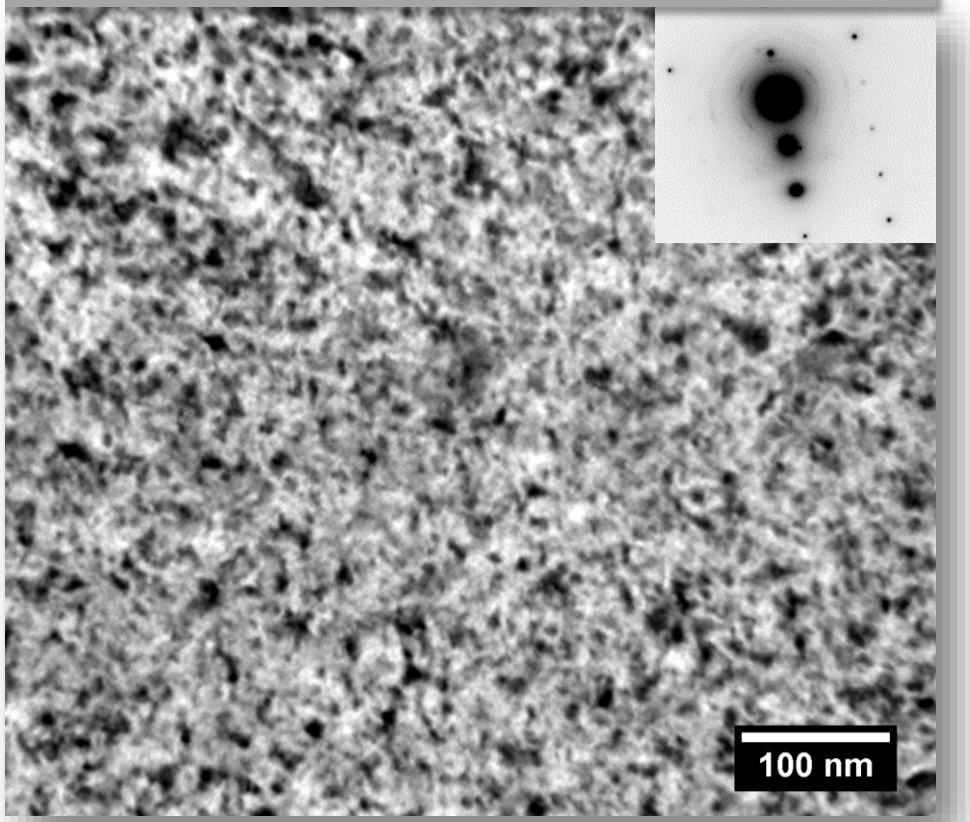
g = [-2 2 0 1]



g = [1 -1 0 0]

Dislocation loops (preliminary)

PF60.
1.5dpa/6000appm of He, T=50°C

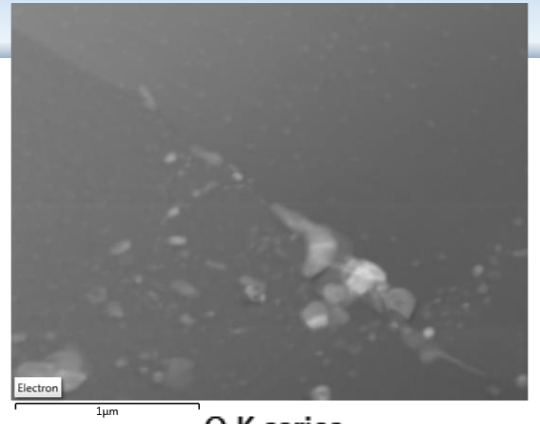


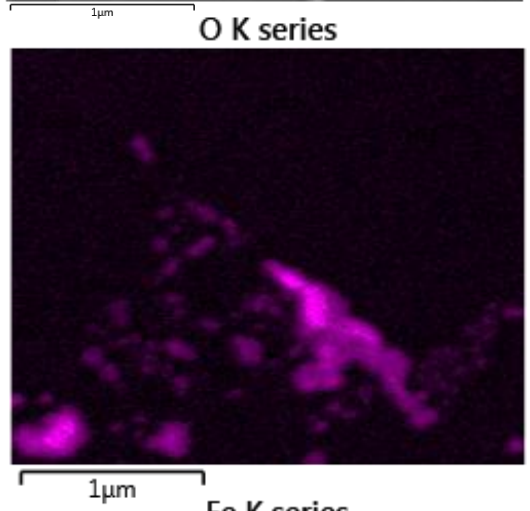
Preliminary, only one lamella, 1.5 dpa

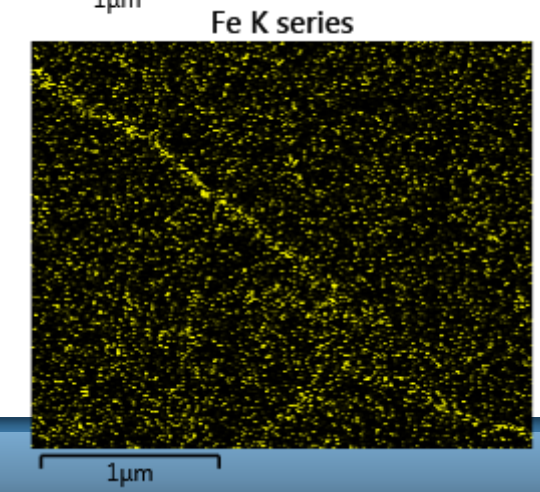
Size: up to 10 nm
ND ~ $5 \cdot 10^{23}$ m^{-3}
Dislocation density ~ $5 \cdot 10^{16}$ m^{-2}
b = 1/3 < 1 1 -2 0>

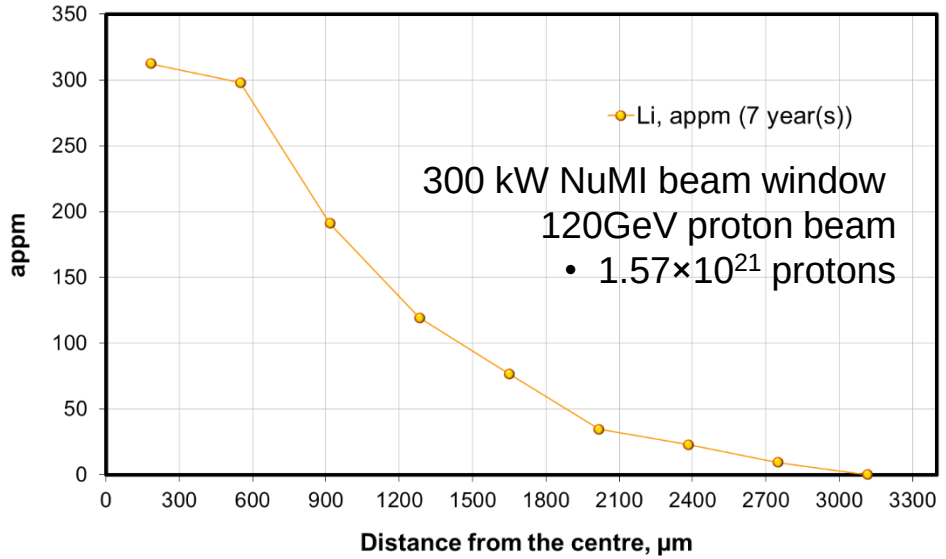
Future plans:

- Finish the ex-situ analysis (dislocations, bubbles, precipitates)
- Repeat 50°C irradiation up to 0.5 dpa (NuMI conditions)
- Perform irradiations at 200°C (future LBNF conditions)
- H and Li irradiations
- High-energy implantation





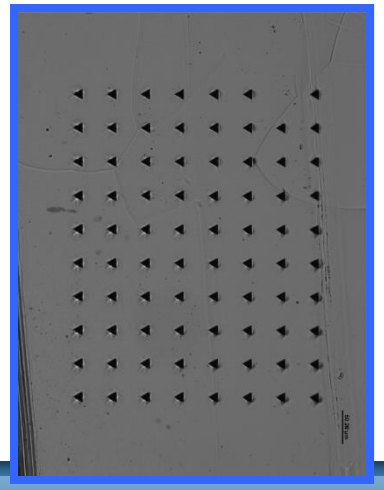


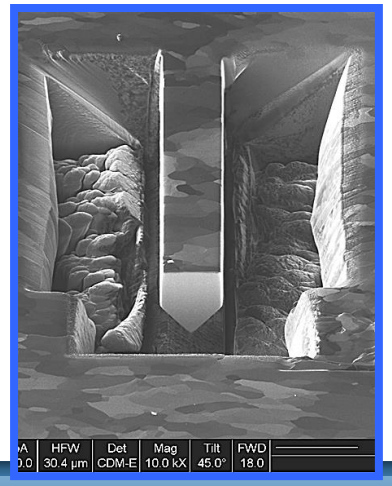


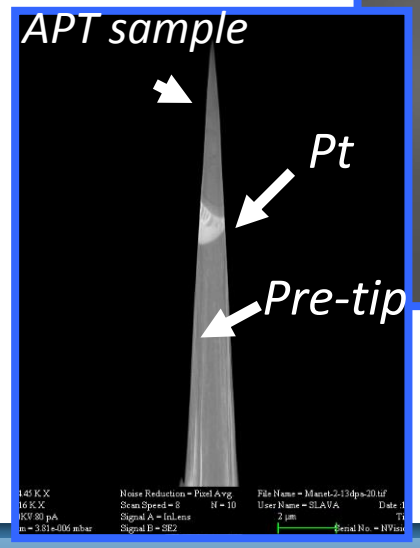
Surrey Ion Beam Centre, UK
(collaboration with Prof. R.Gwilliam)

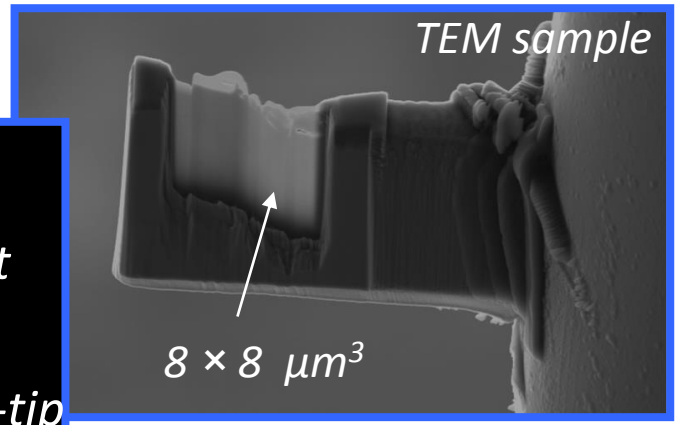
Ions: He+
Maximum beam energy: 2 MeV => 7.5µm implantation depth (SRIM)
Dose: up to 1 dpa
Temperature: 200ºC (100ºC, 500ºC)

Micromechanical tests



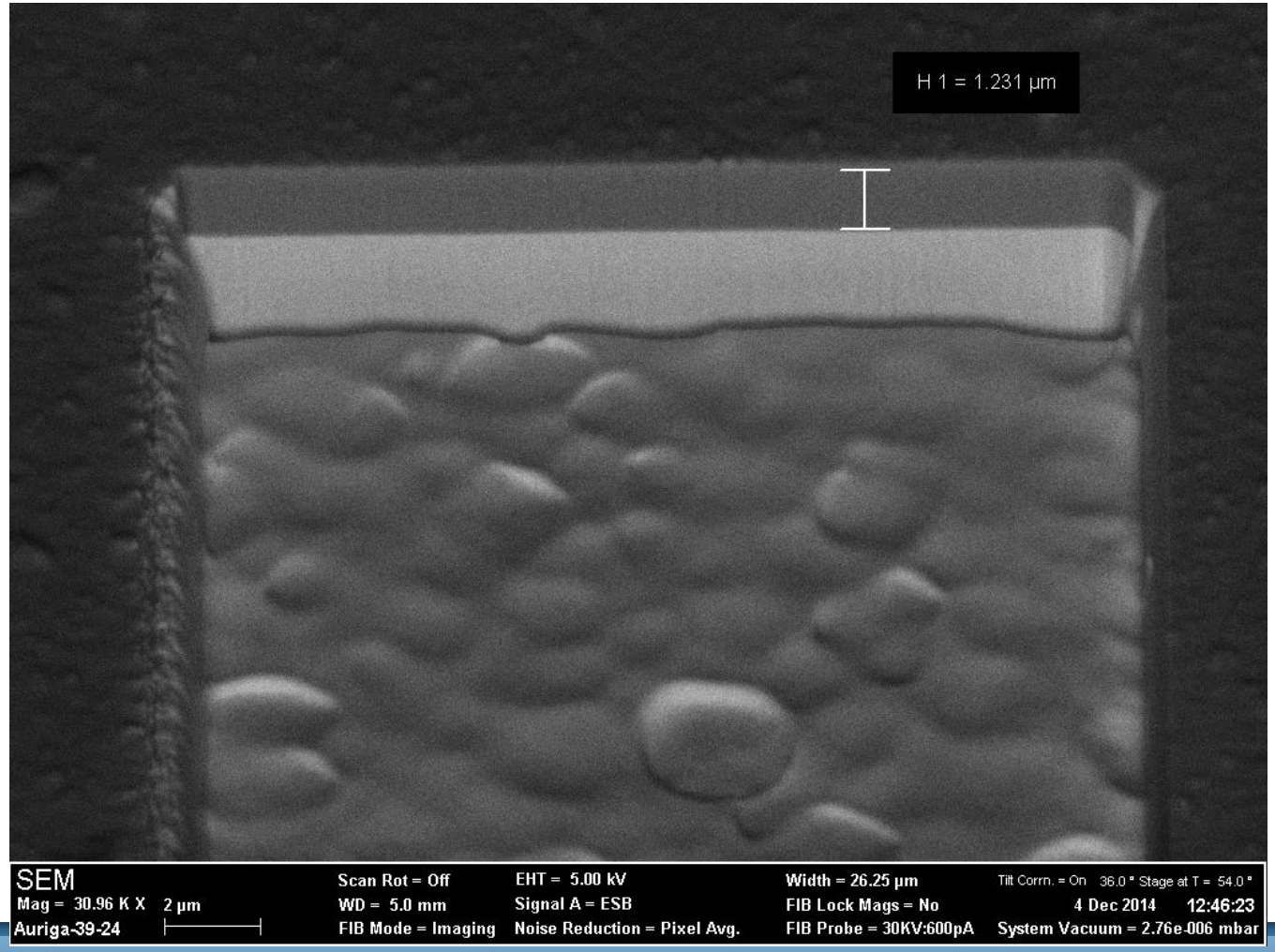






Issues:

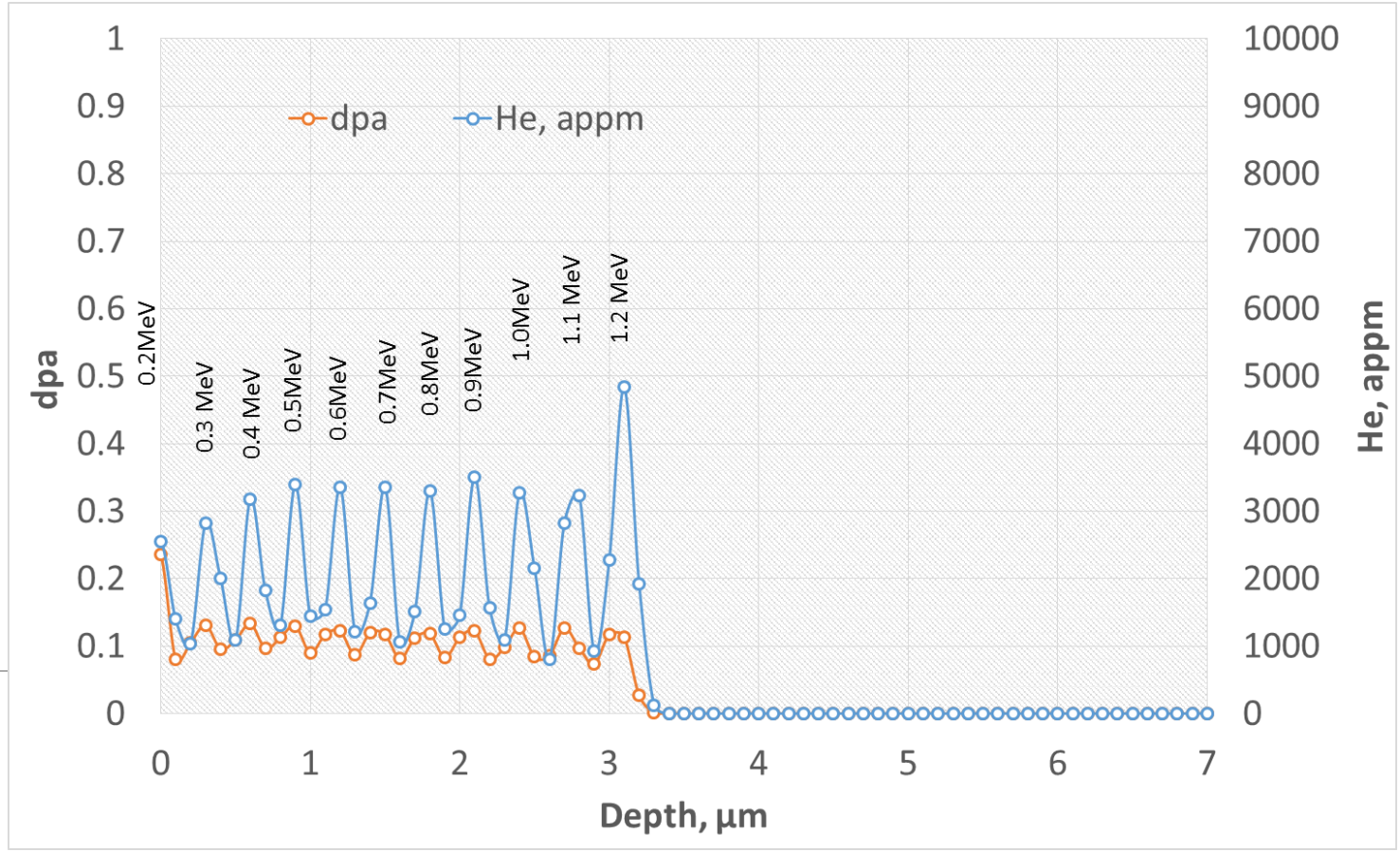
Al coating – how to remove then?



Issues:

15000 appm/dpa

He implantation in Be through Al degrader (1µm), high energy implantation



Ed(Al) = 25eV
Ed(Be) = 31 eV

Steps	1	2	3	4	5	6	7	8	9	10	11
Energy, MeV	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
He ions/cm^2, ×10^{16}	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.83	0.83	0.90	1.20

Thank you for your attention!