RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

The experimental investigation of proton and ion irradiation damage in beryllium

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NBI2017

10TH INTERNATIONAL WORKSHOP ON NEUTRINO BEAMS & INSTRUMENTATION + RADIATE

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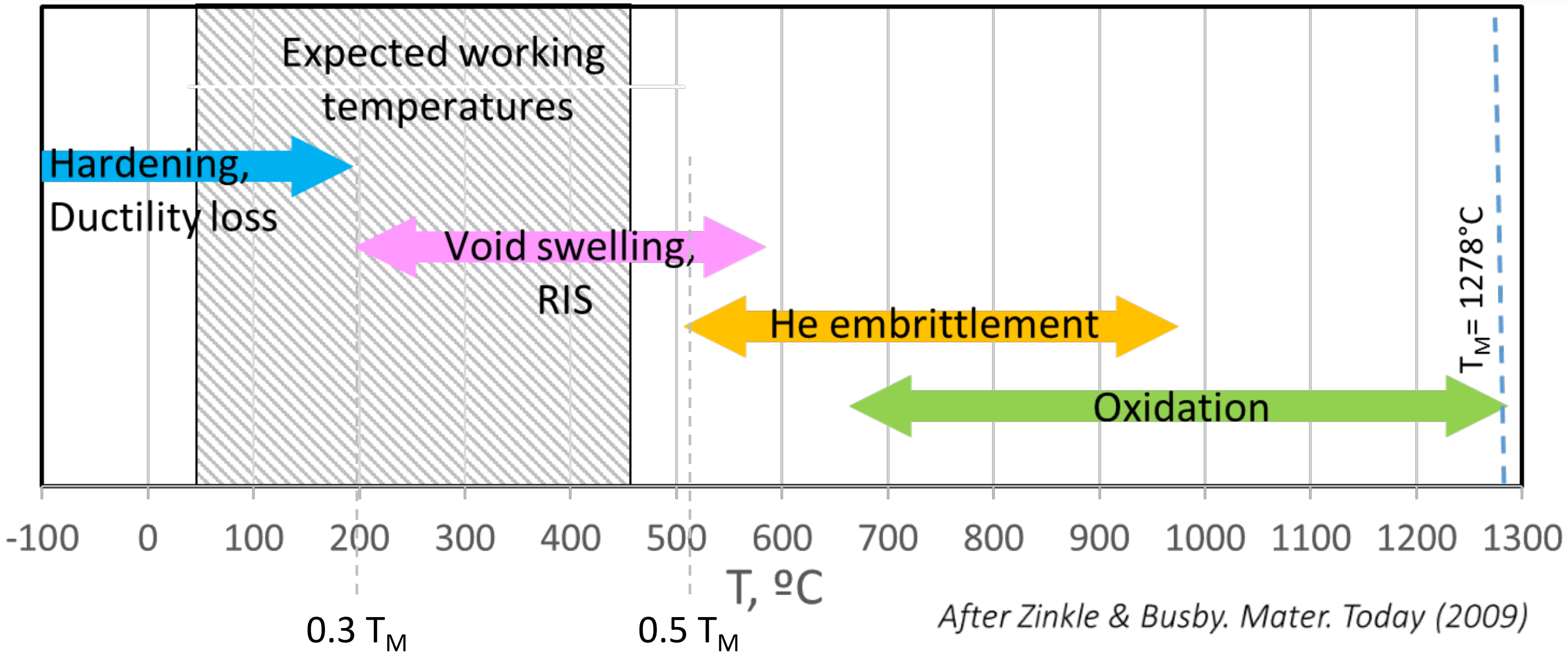
Beryllium

- is extensively used as a material of neutrino target parts, for example as beam windows;

- is a promising candidate for future high-power neutrino sources

Expected working conditions for some parts of LBNF

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	>2000	700 kW; 120 GeV; ~1 Hz; σ_{rms} = 1.3 mm
Target	375	450	~ 0.23/yr	>2000	>2000	700 kW; 120 GeV; ~1 Hz; σ_{rms} = 1.3 mm

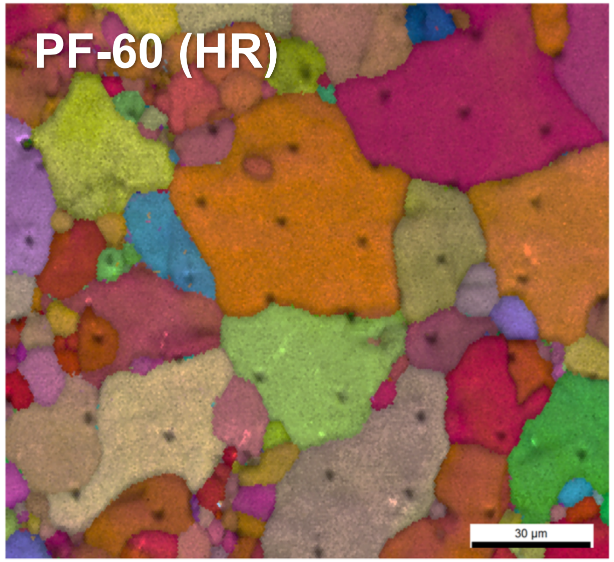


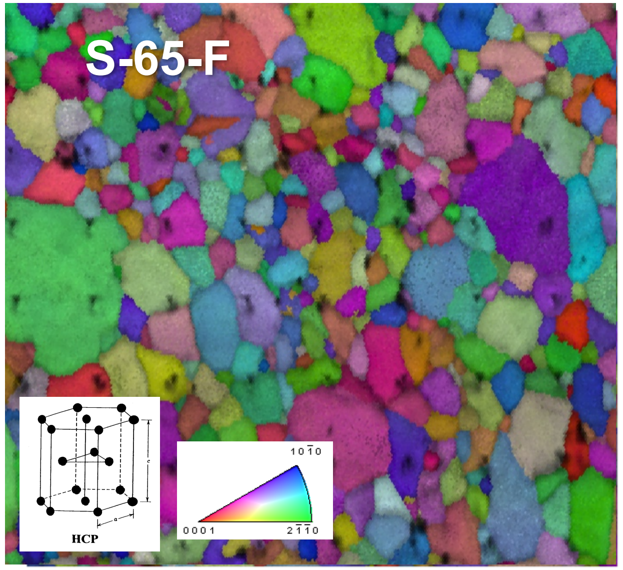
After Zinkle & Busby. Mater. Today (2009)

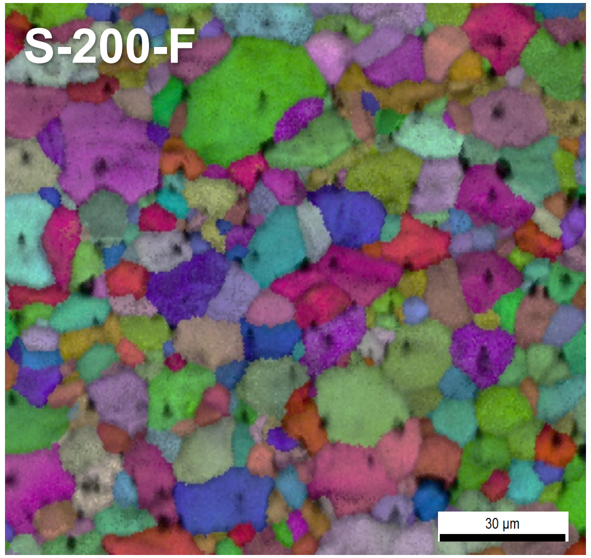
Outline

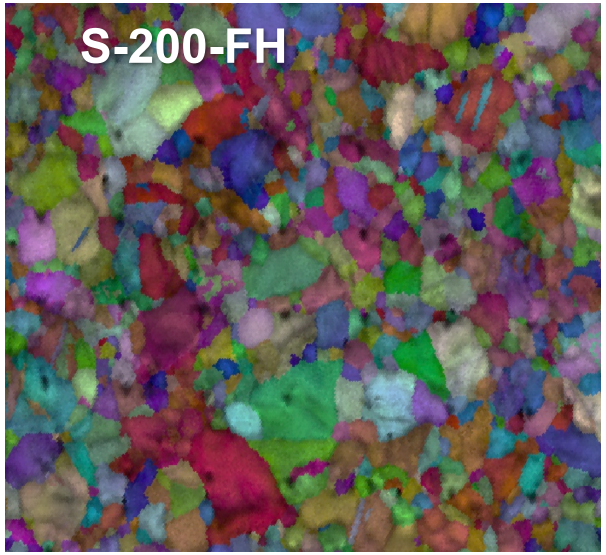
- As-received Be
- Investigation of the proton Be window (NuMI)
- Ion irradiation experiments

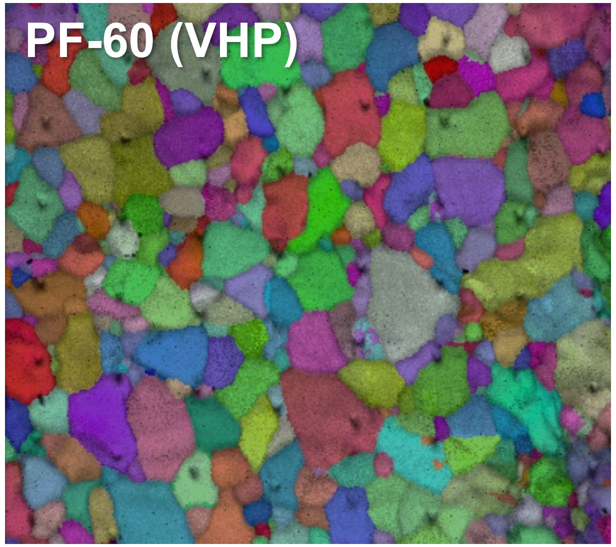
As-received beryllium: Microstructure











PF-60

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

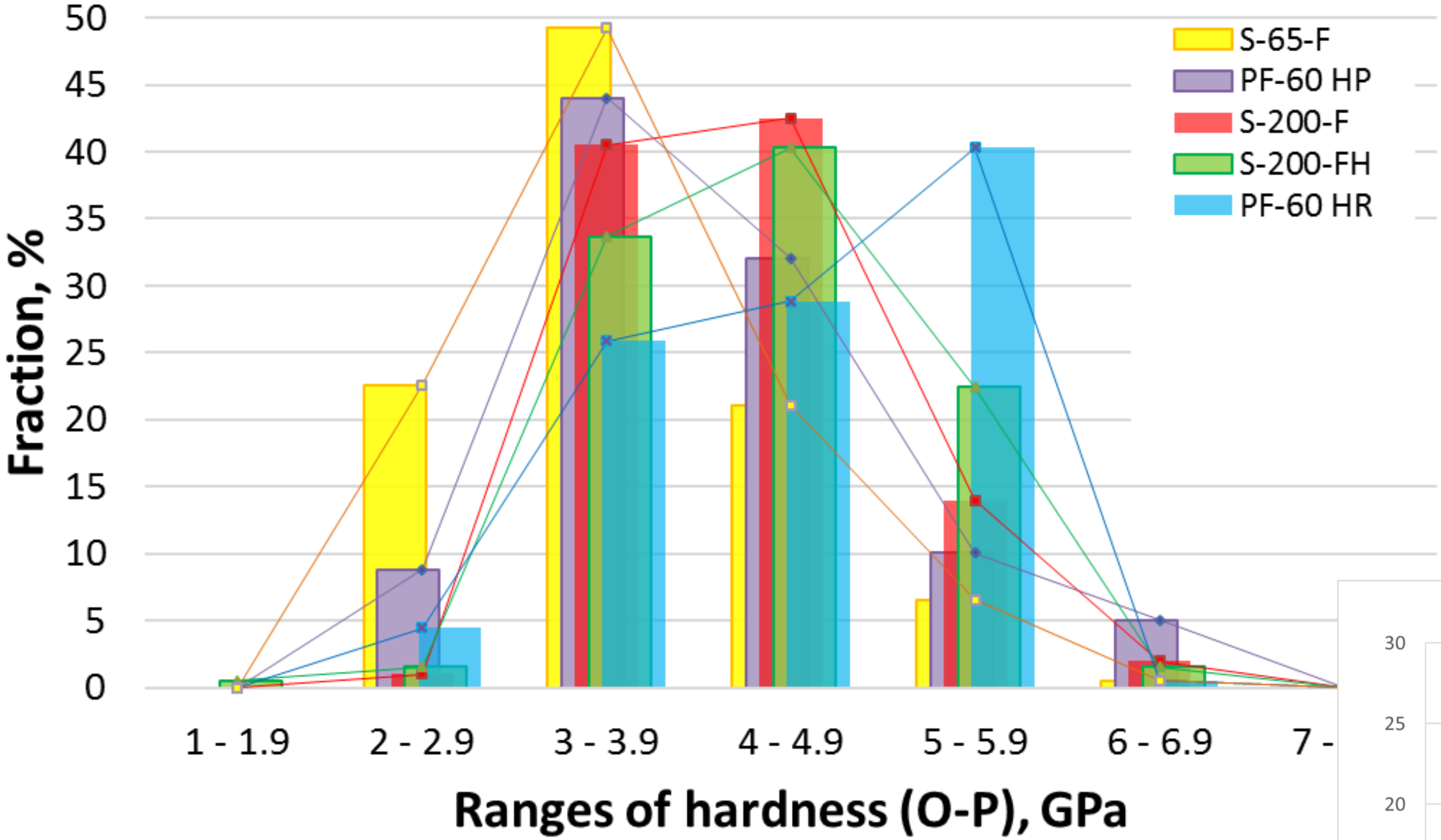
S-65-F

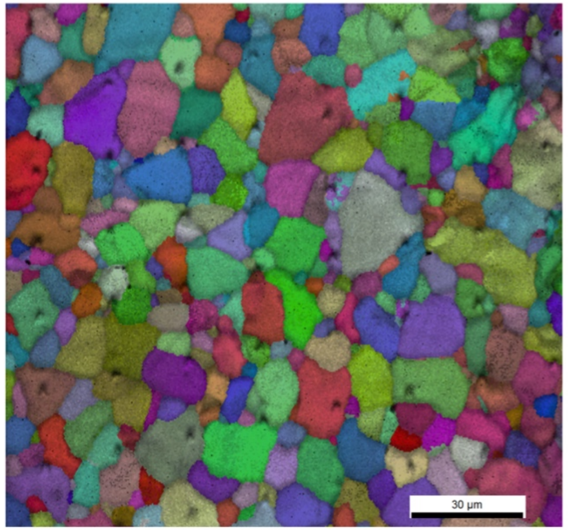
	Max impurities, appm
Al	170
C	680
Fe	130
Mg	15
O	**3260**
Si	145
Be	balance

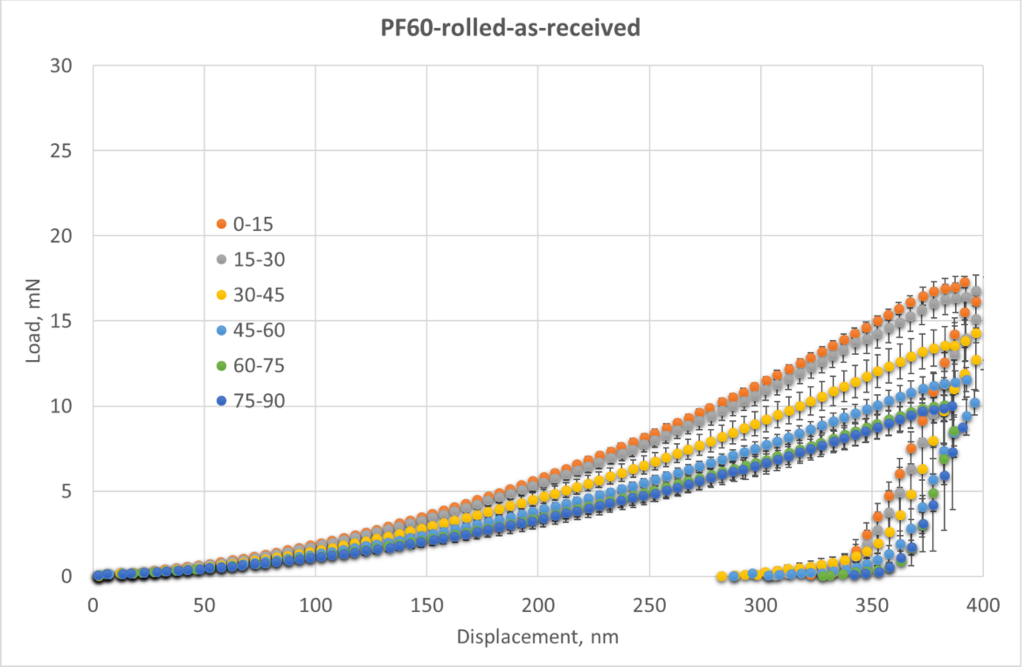
S-200-F/FH

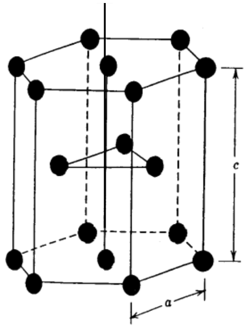
	Max impurities, appm
Al	335
C	**1130**
Fe	210
Mg	130
O	**5445**
Si	195
Be	balance

Hardness: as-received



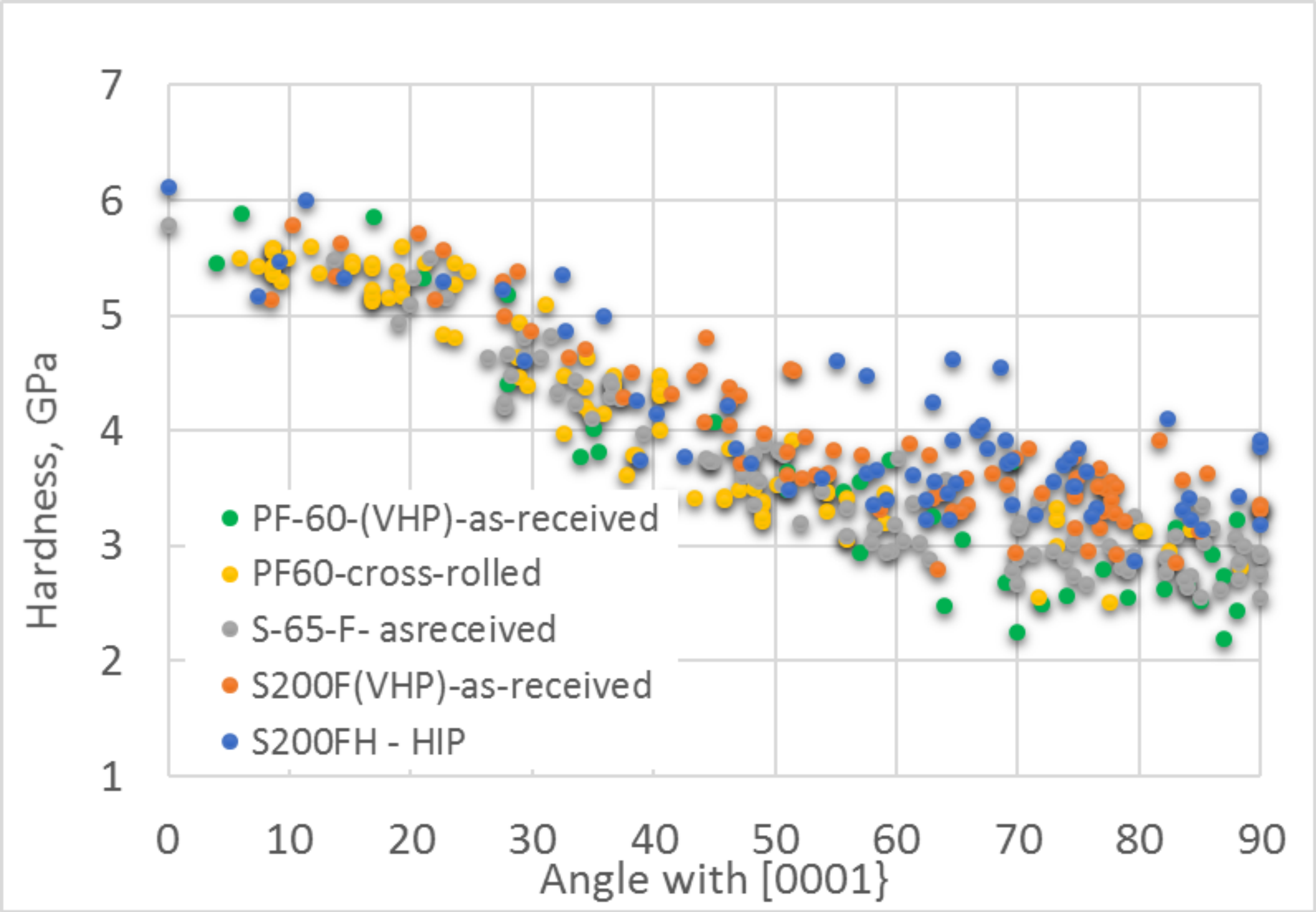


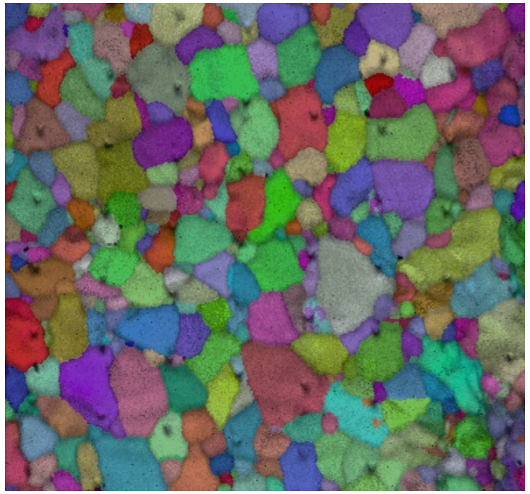




HCP

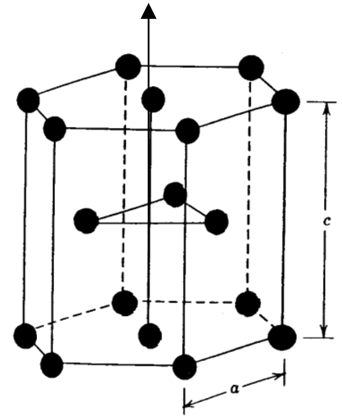
Nanoindentation data for different crystallographic orientations





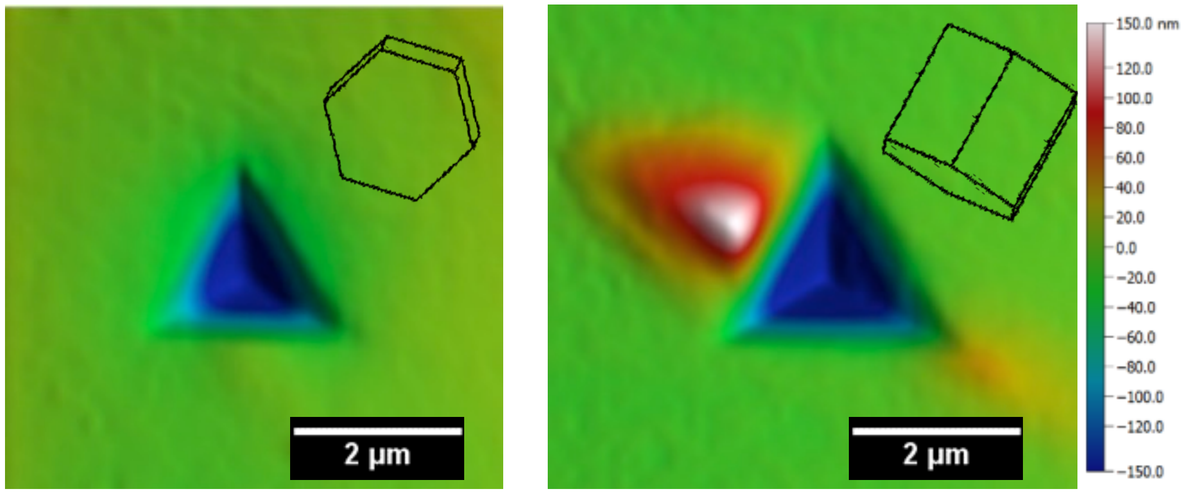
S-200-F/FH

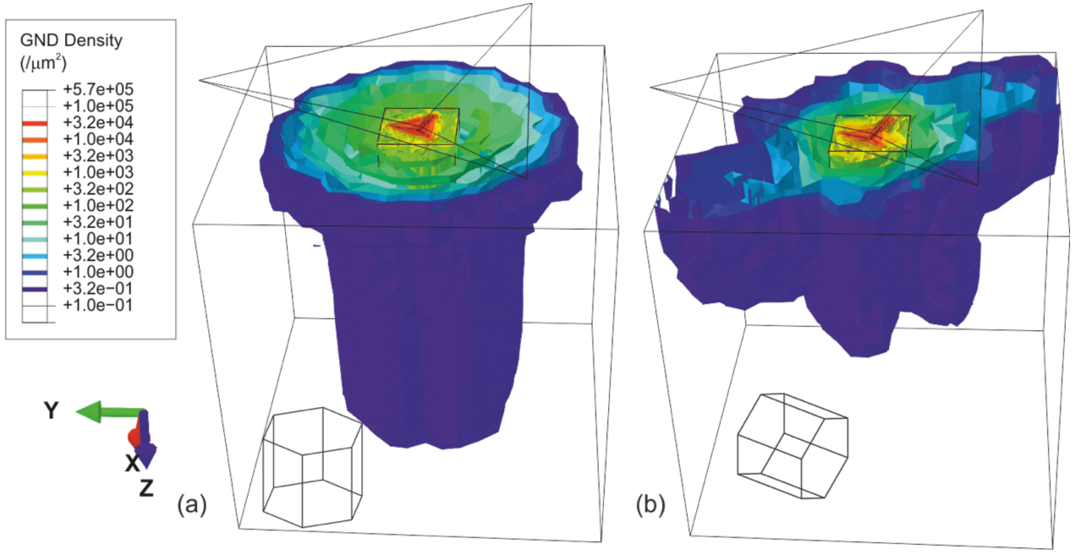
PF60 and S-65-F



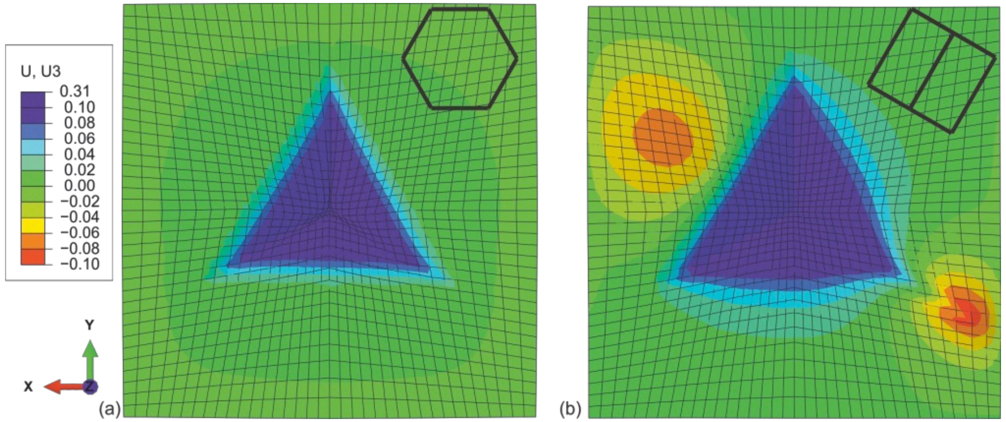
- Extremely high variation of nanoindentation hardness data was observed for grains with different crystallographic orientation in non-irradiated beryllium.

Modelling collaboration with Ed Tarleton (Oxford)

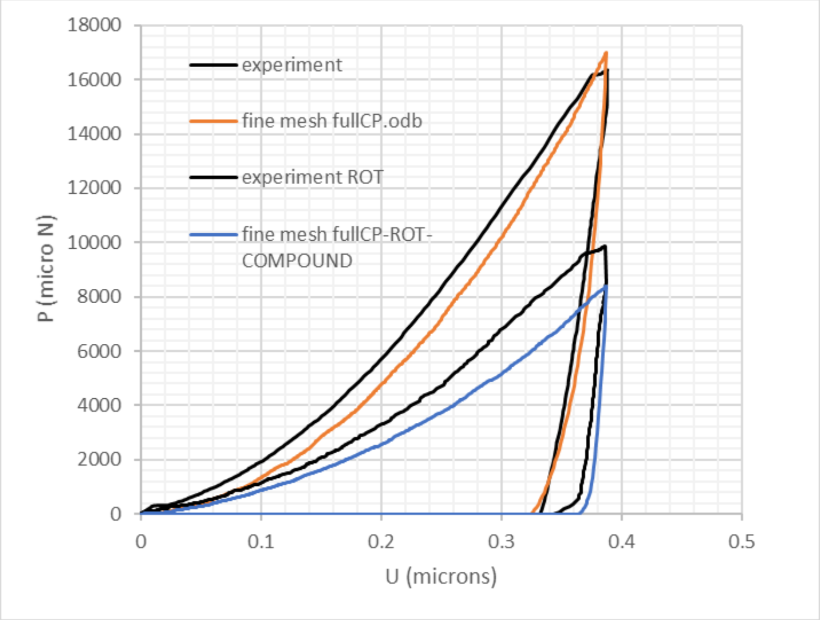




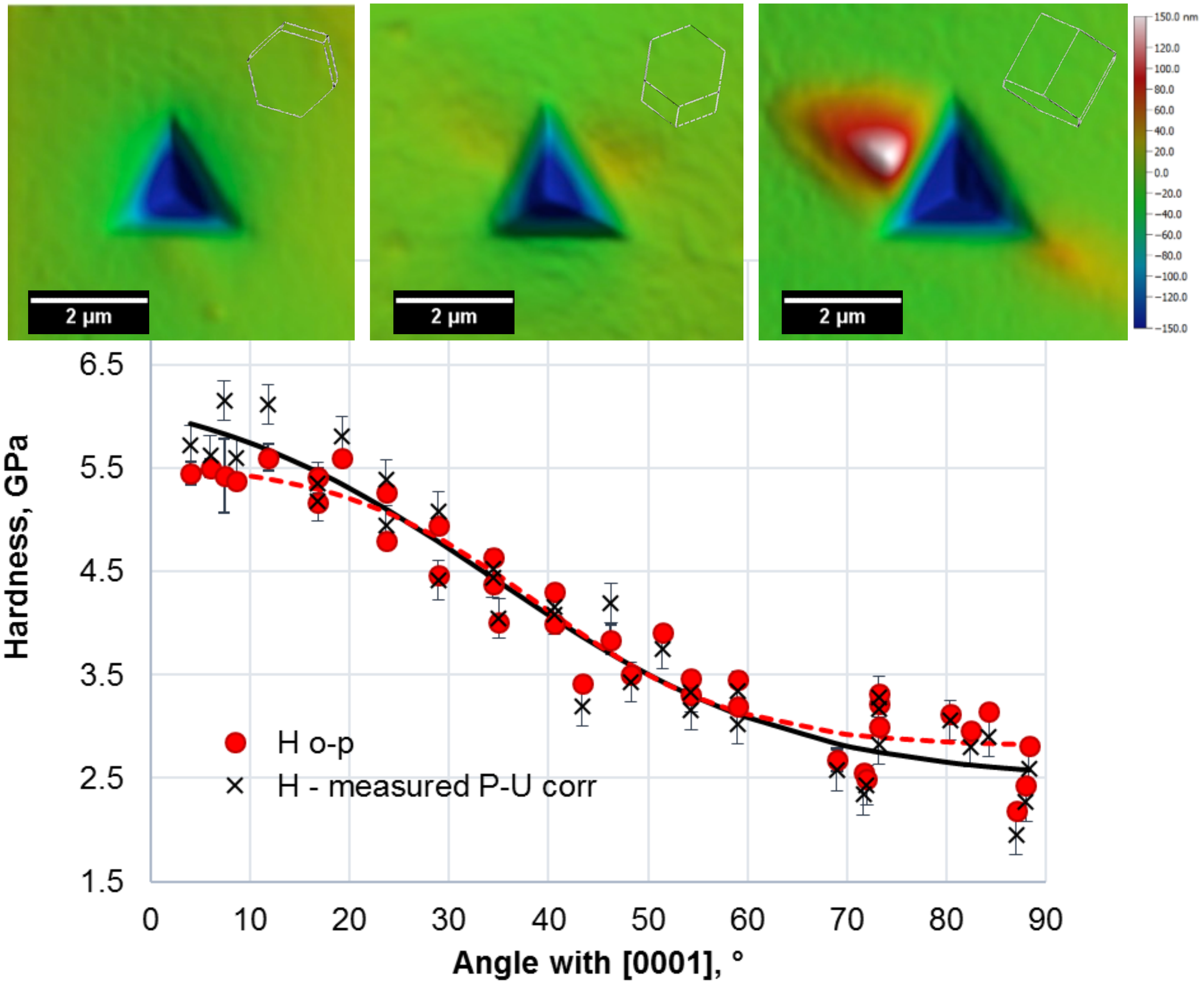
The total GND density (log scale) after unloading for the hard (a) and soft (b) orientations.



The residual out of plane displacement for the hard (a) and soft (b) orientations. A pile up was only observed in the soft orientation and was produced by the easy out of plane <a> slip



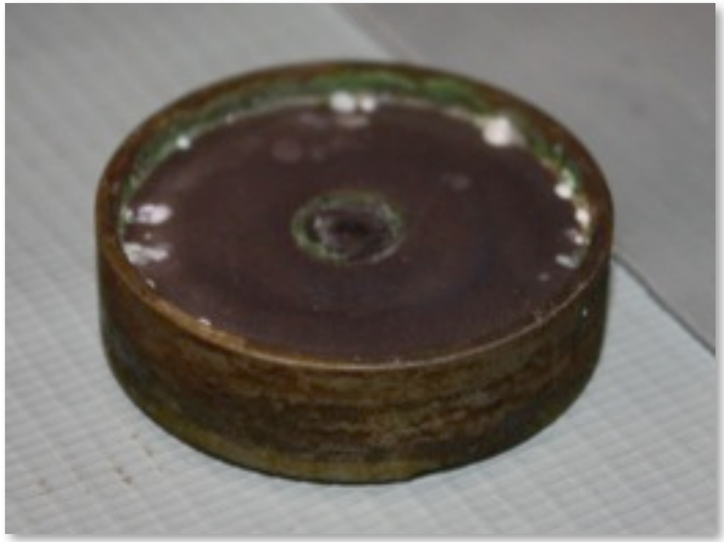
Correction of data – real nanoindentation data distribution is even broader

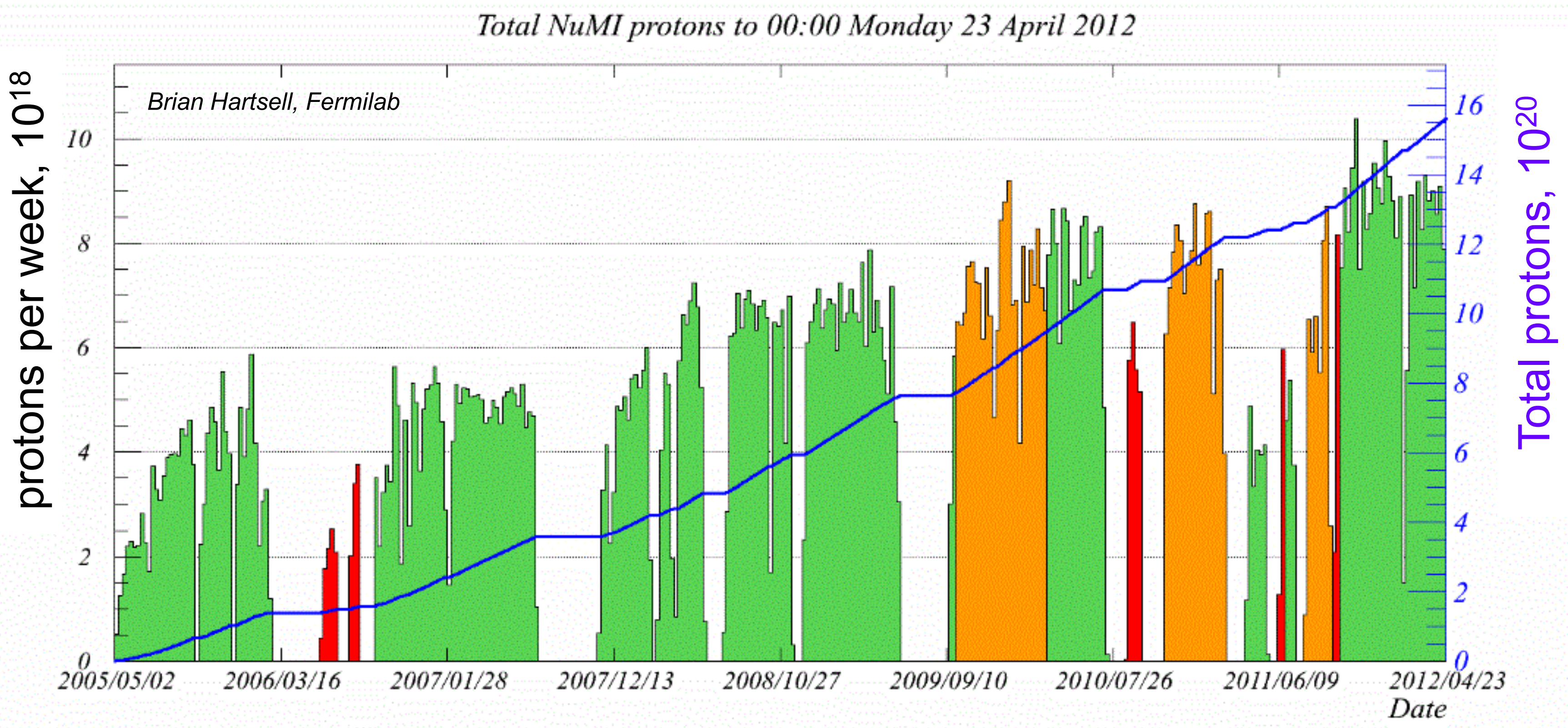


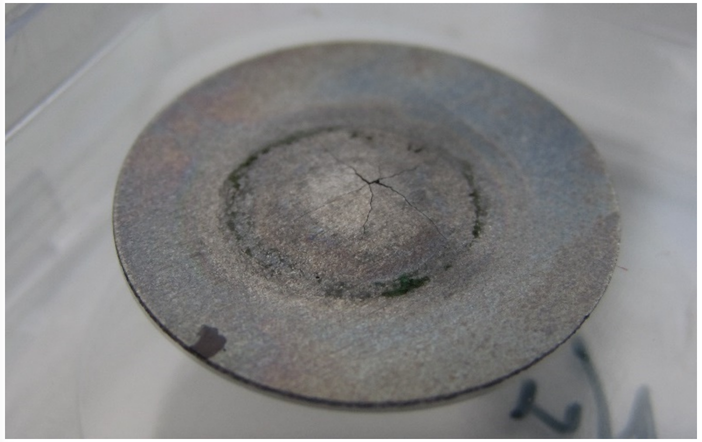
NuMI beam window experiments

300 kW NuMI beam window
(MARS calculations of Brian Hartsell, Fermilab)

- 120GeV proton beam
- about 3×10^{13} protons per pulse, 0.5 Hz
- 1.57×10^{21} protons during its lifetime
- 1.1mm beam sigma
- T ≈ 50°C

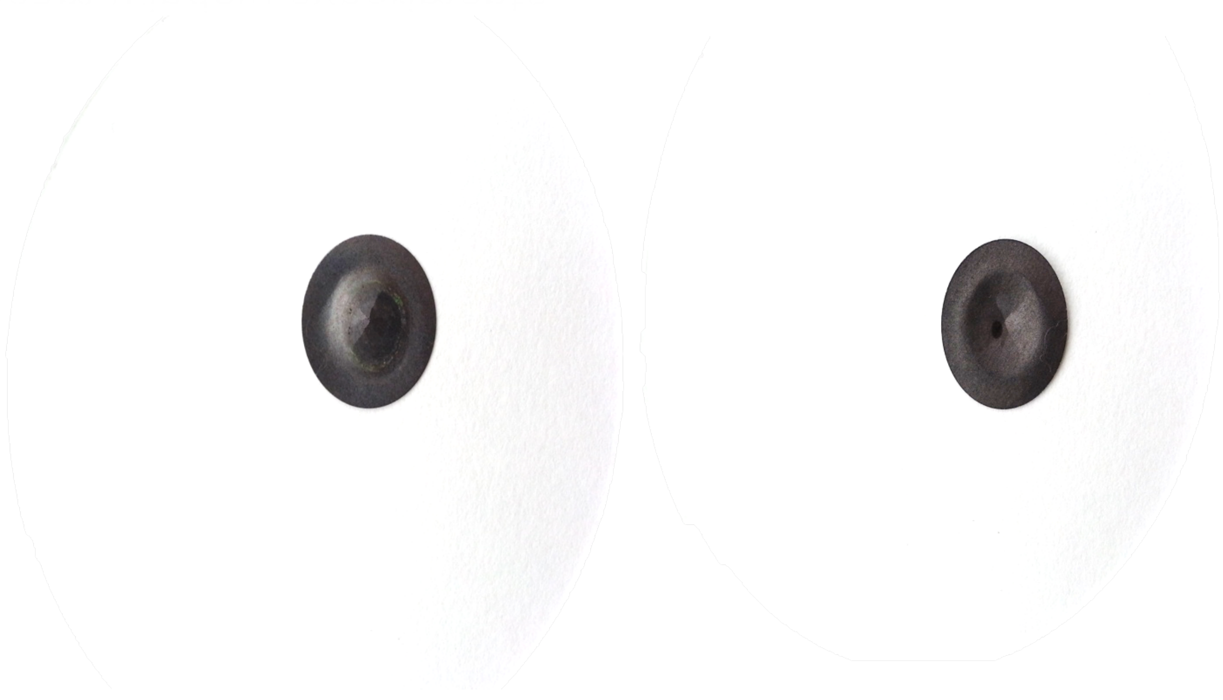




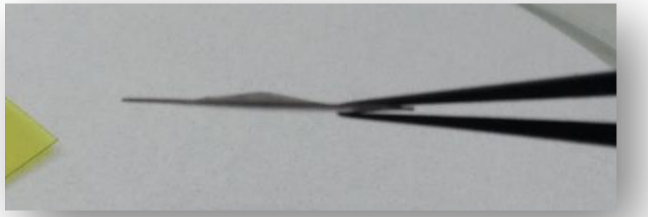


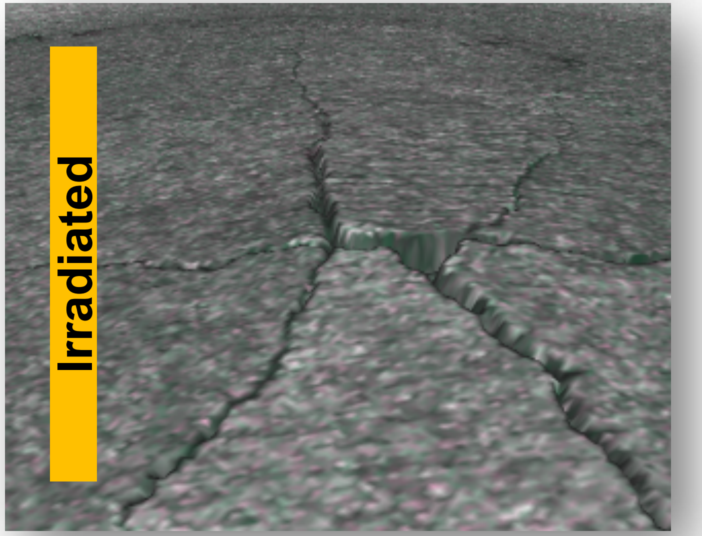
NuMI beam window experiments

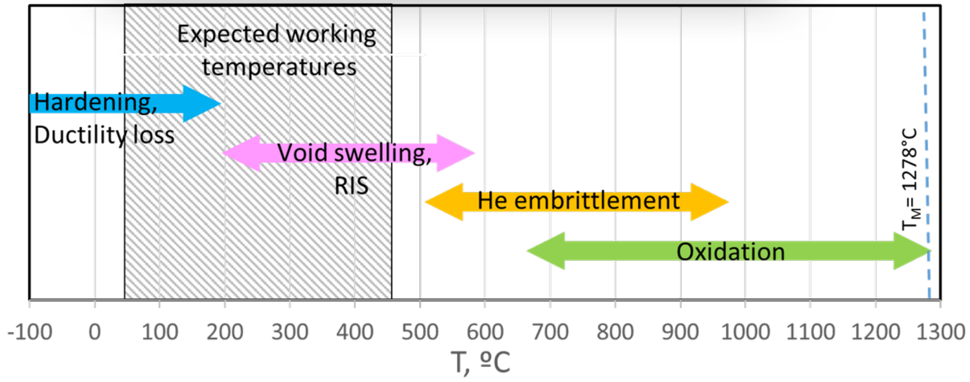
Irradiated



As-received



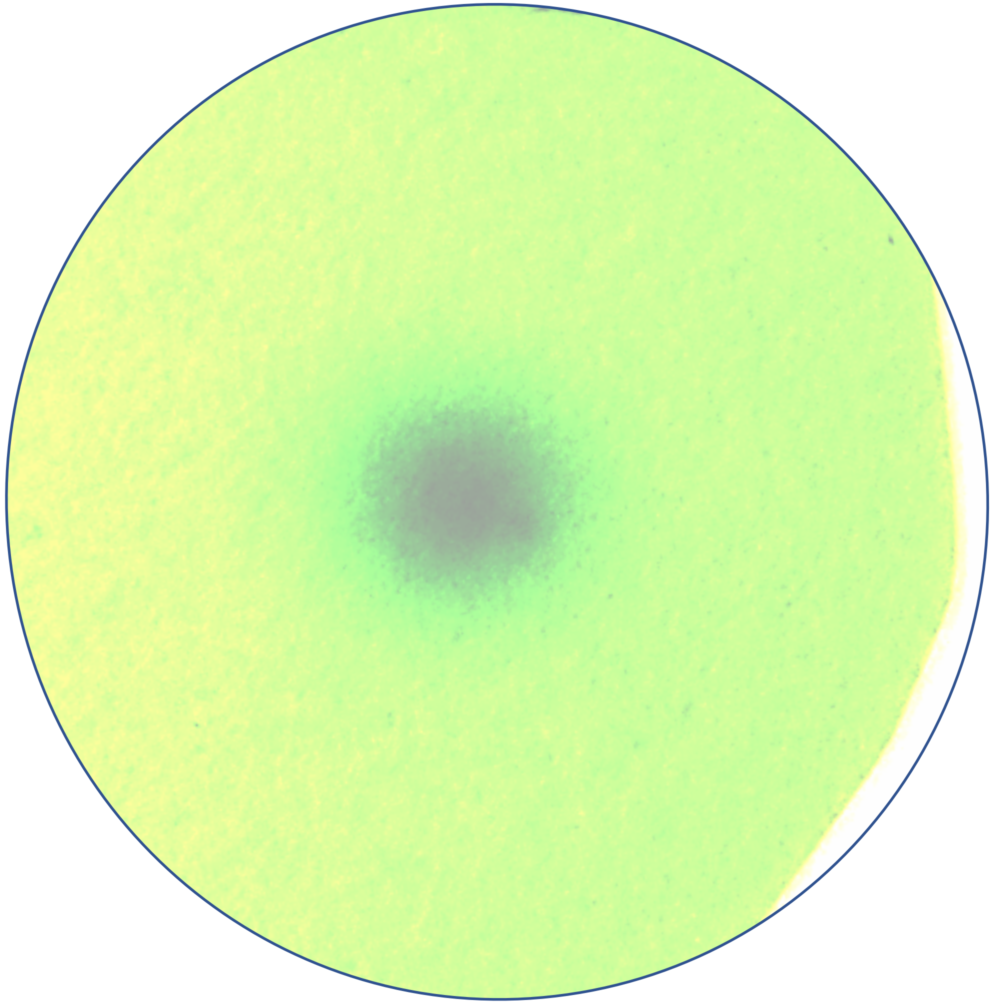




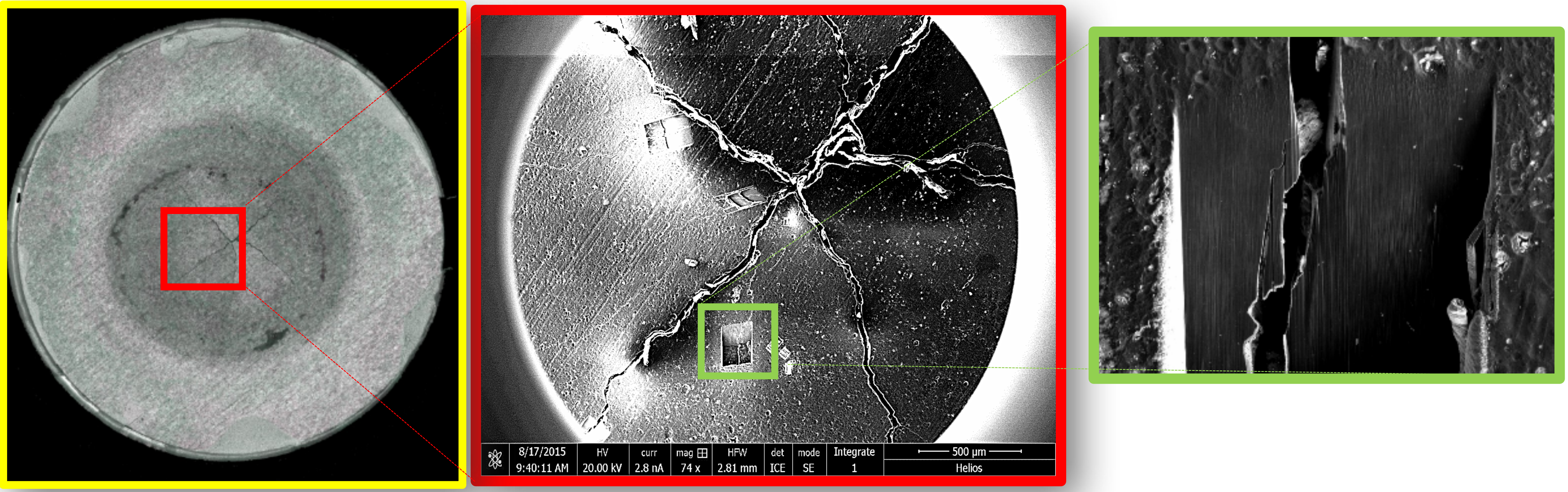
Radiation embrittlement?

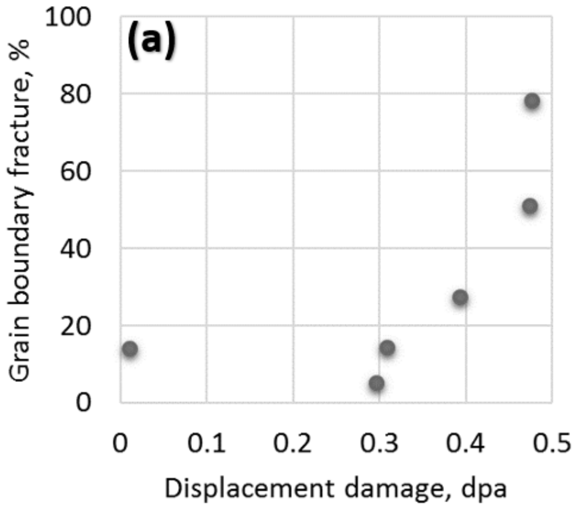
NuMI beam window experiments

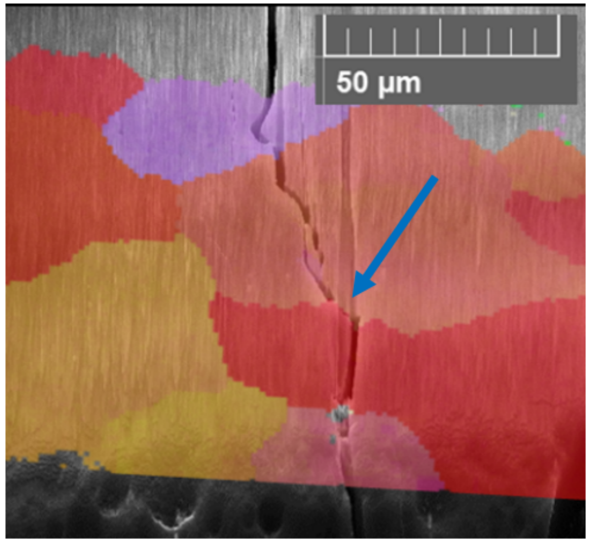
Dosimetry film, 5 days of exposure

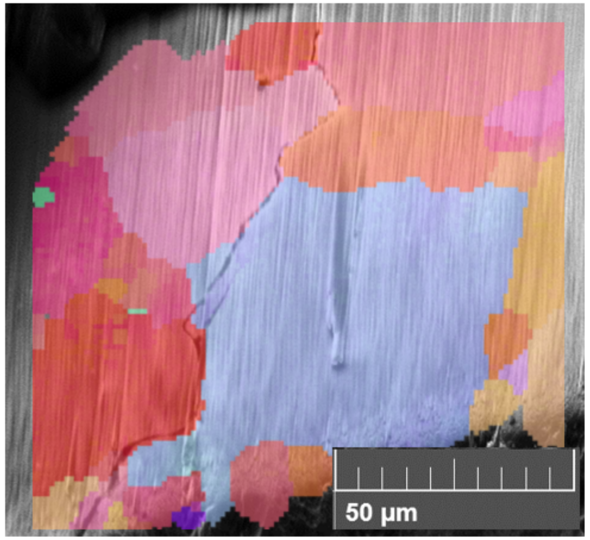


‘Gafchromic™ HD-V2 dosimetry film’



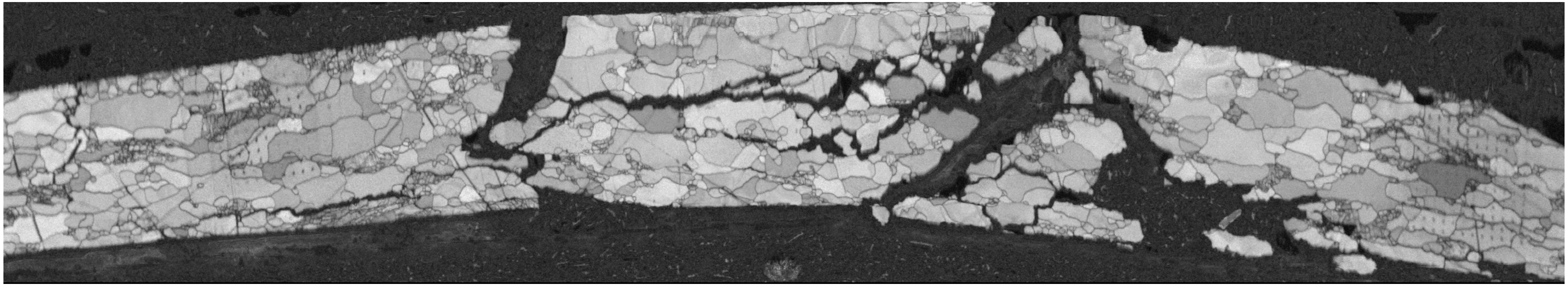


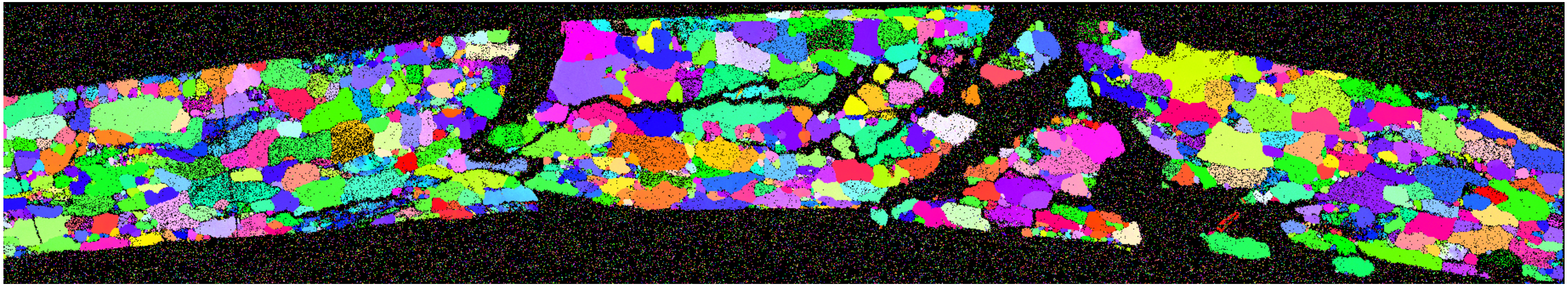




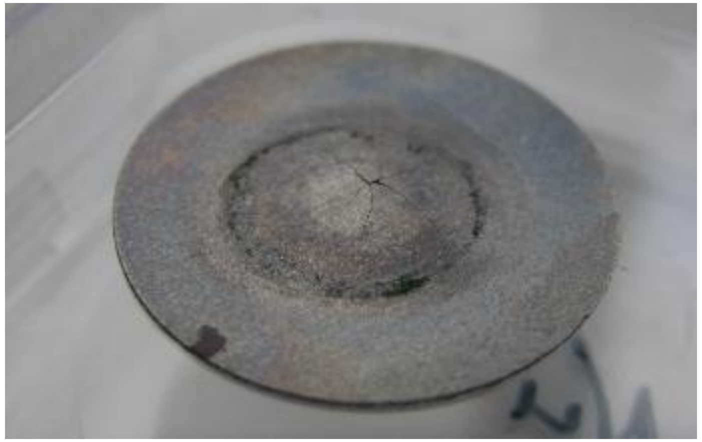
From cleavage to GB fracture

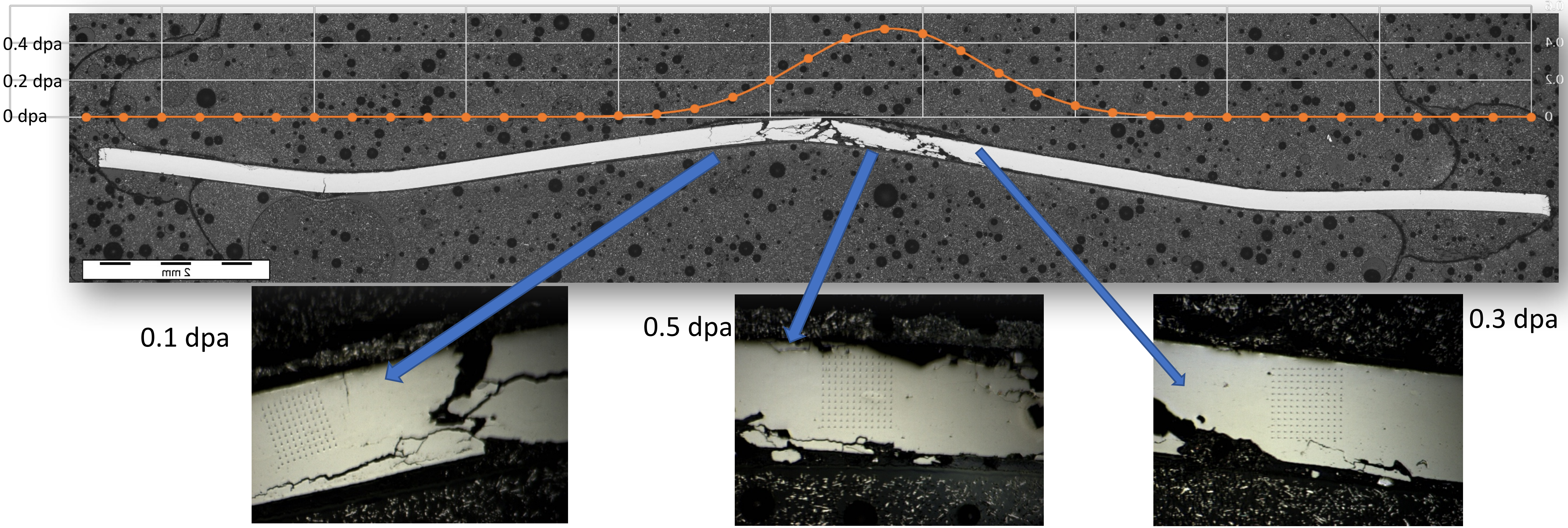
NuMI: a lot of GB fracture in the irradiated areas

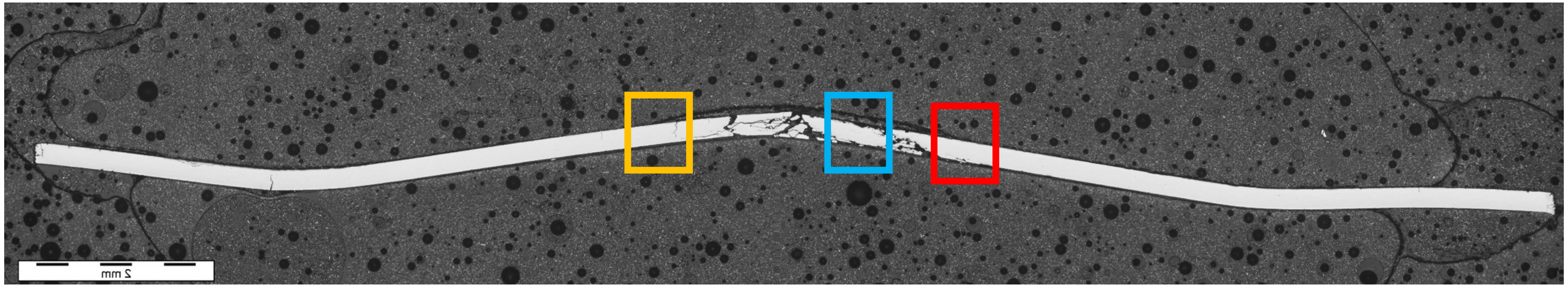


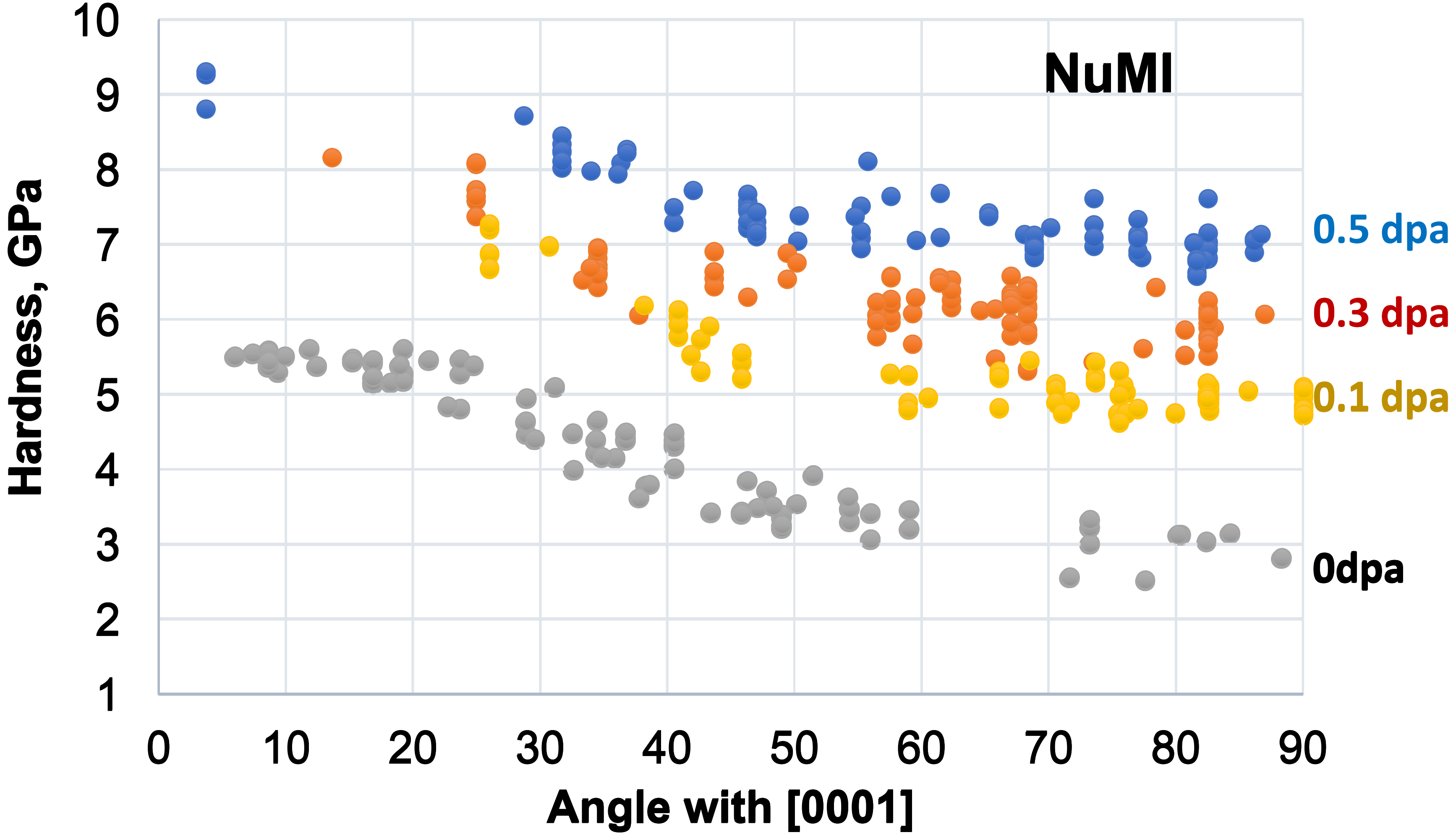


(1) Basal cleavage is a usual fracture mechanism for non-irradiated beryllium.
(2) We clearly see a lot of GB fracture in the irradiated sample



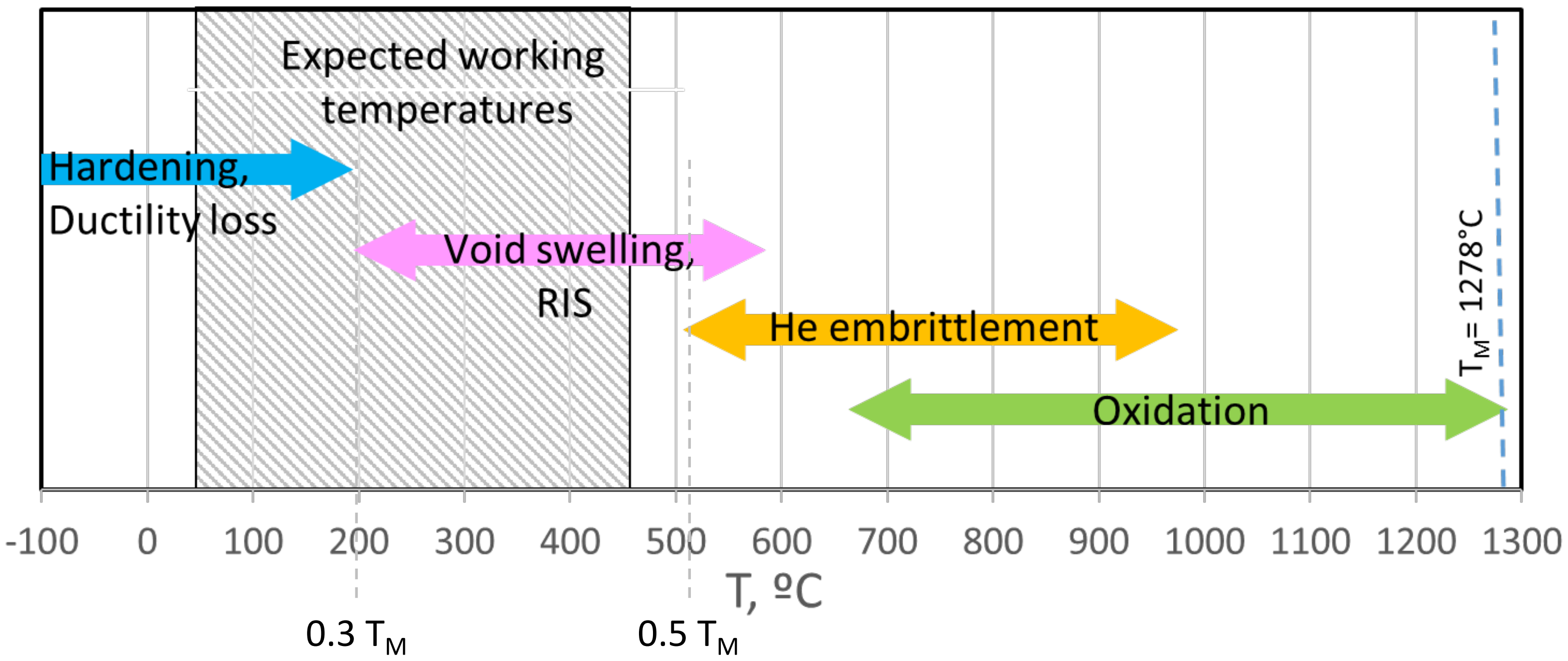

0.4 dpa
0.2 dpa
0 dpa
2 mm
0.1 dpa
0.5 dpa
0.3 dpa


2 mm


NuMI
Hardness, GPa
Angle with [0001]
0.5 dpa
0.3 dpa
0.1 dpa
0dpa
10
9
8
7
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90

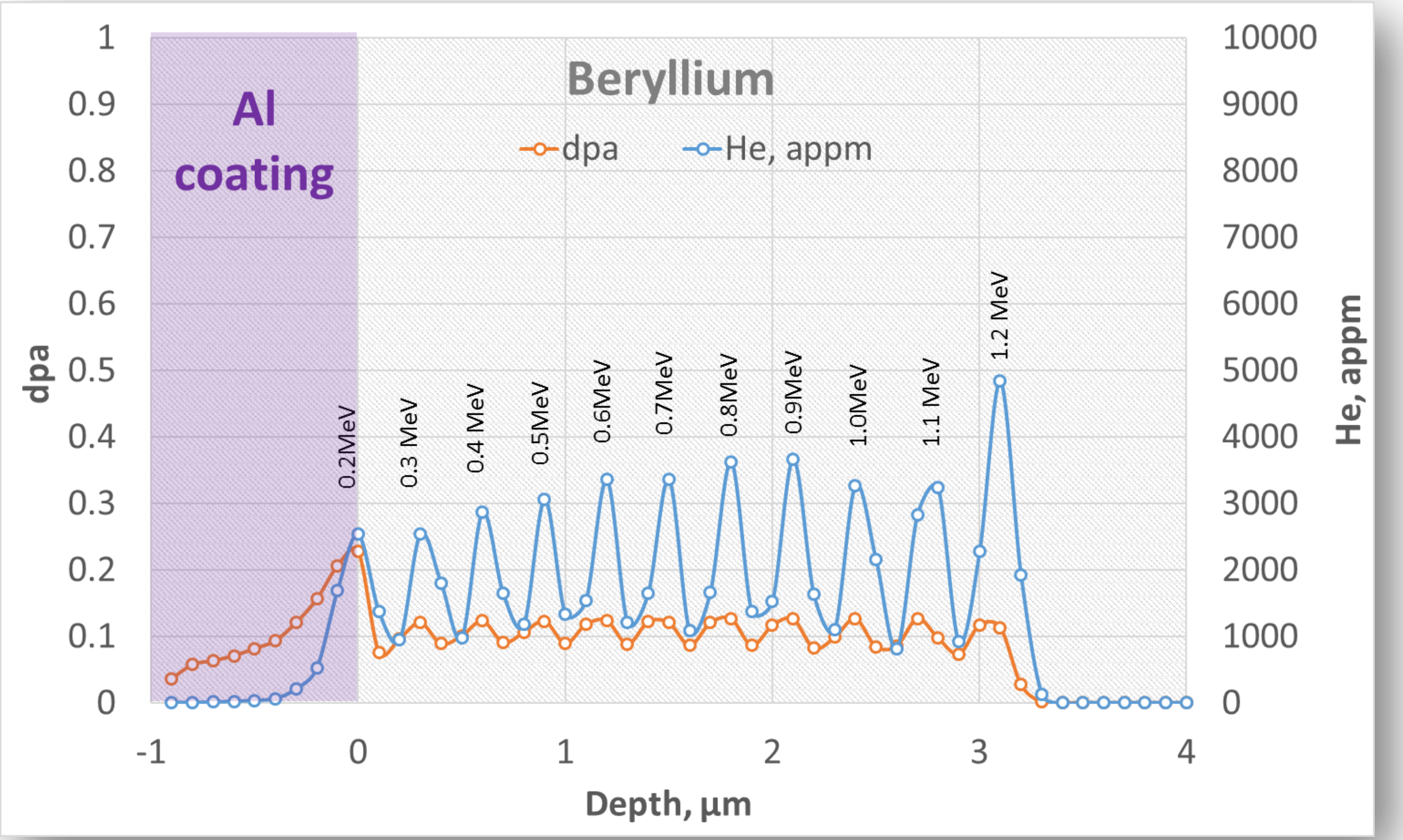
NuMI window

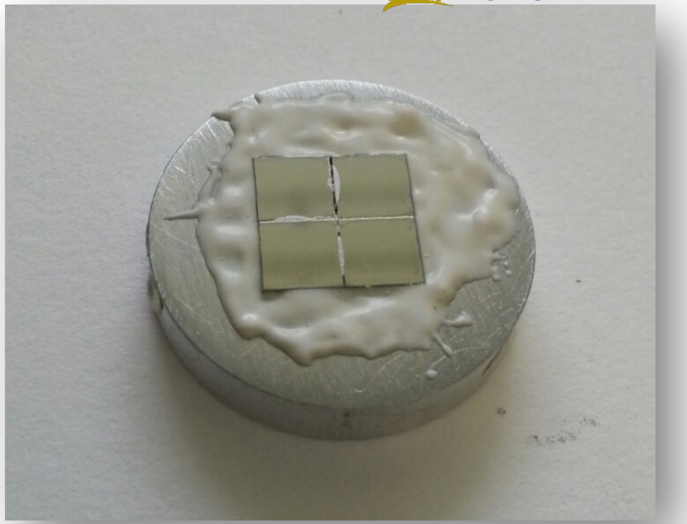
- Hardening was expected.
- What about ductility and fracture?
- What about higher T?

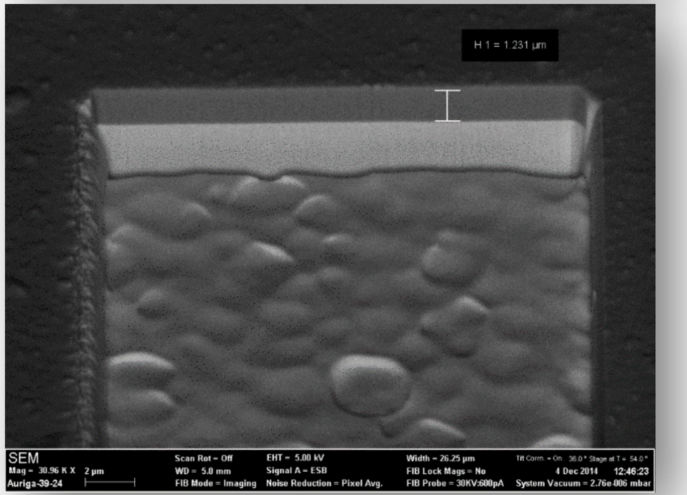


More micromechanics and ion implantation?

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



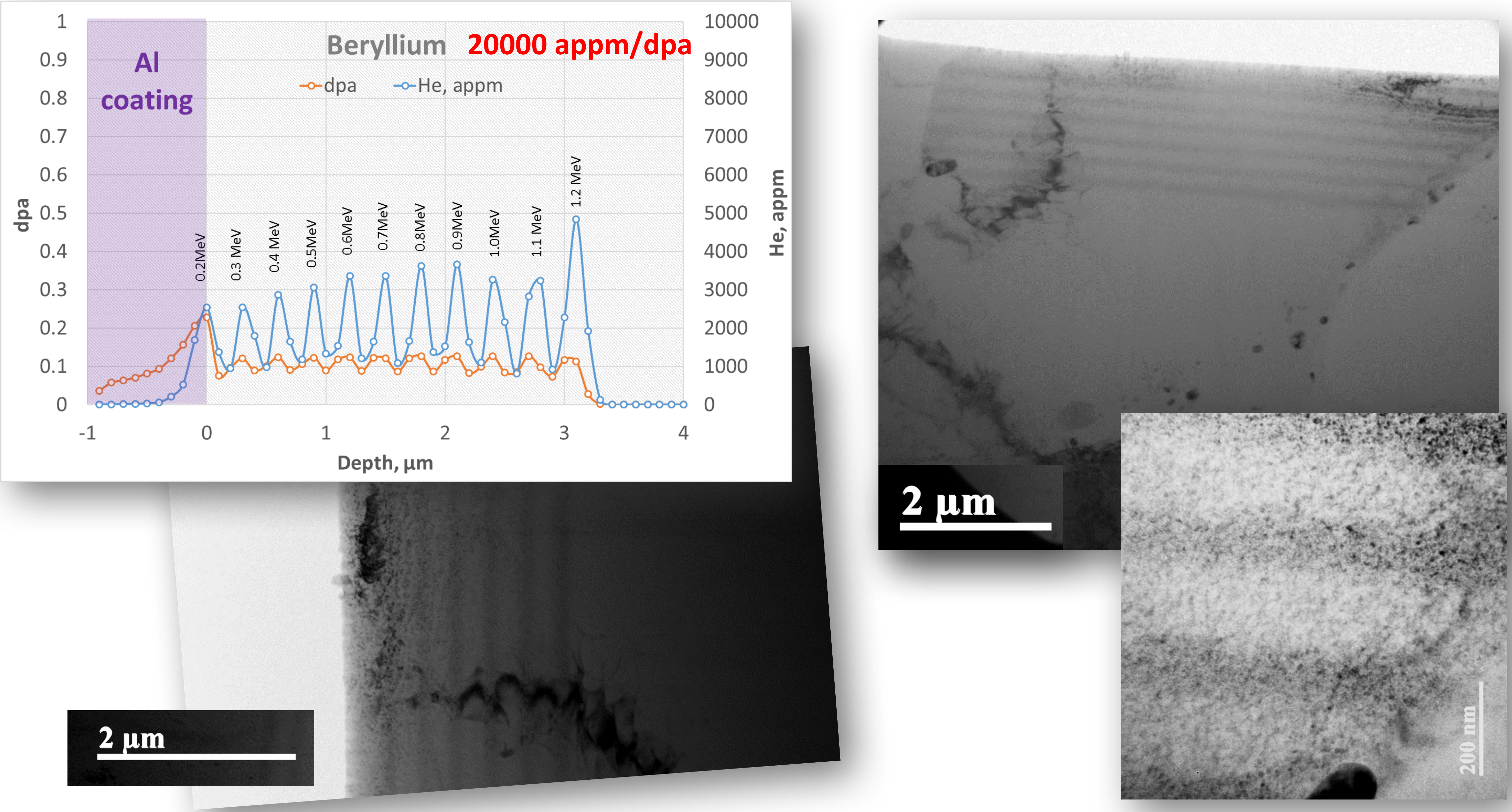




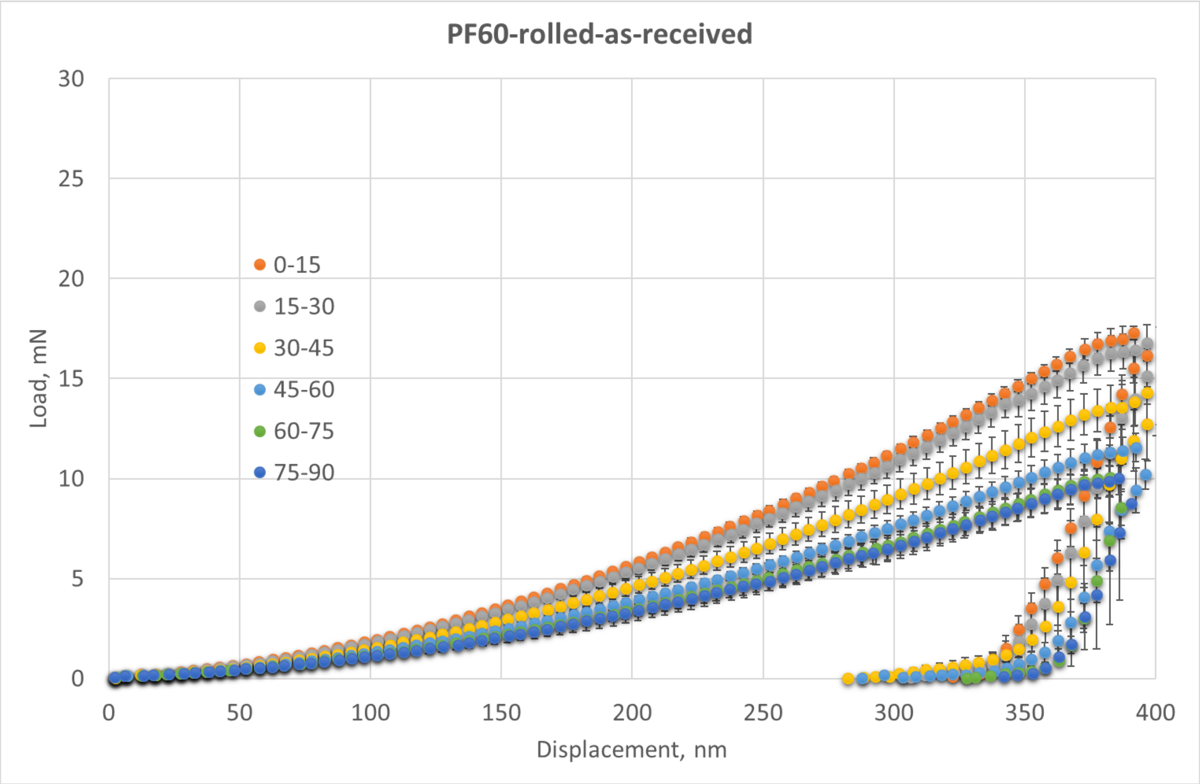
Ed(Al) = 25eV
Ed(Be) = 31 eV

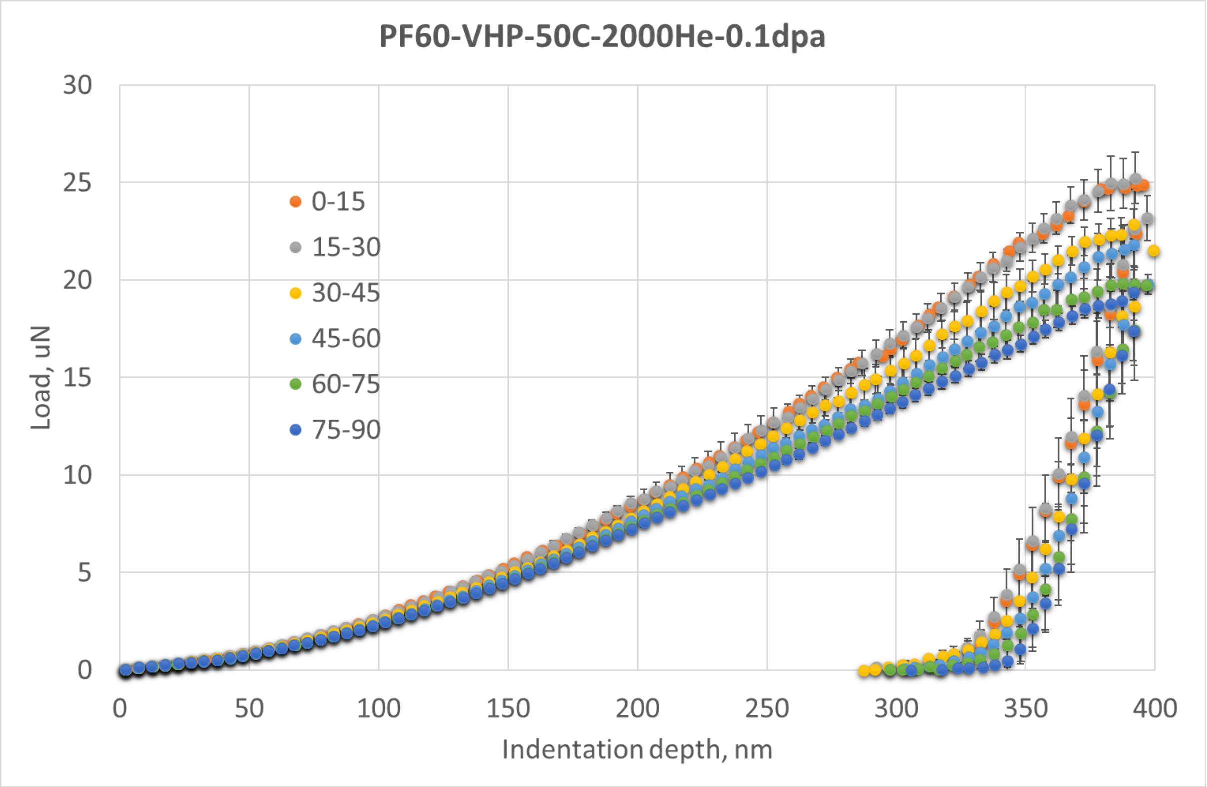
Steps	1	2	3	4	5	6	7	8	9	10	11
Energy, MeV	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
He ions/cm^2, ×10^{16}	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.83	0.83	0.90	1.20

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

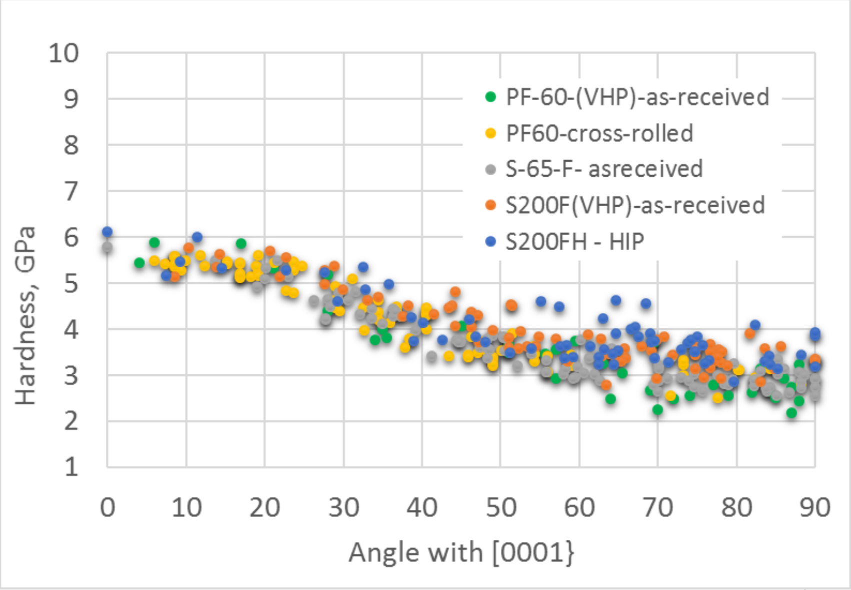


As-received vs Implanted

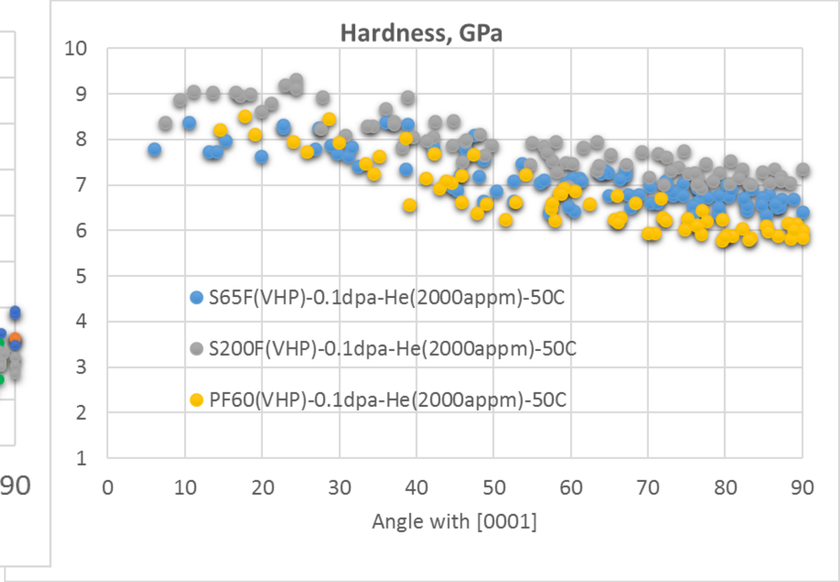




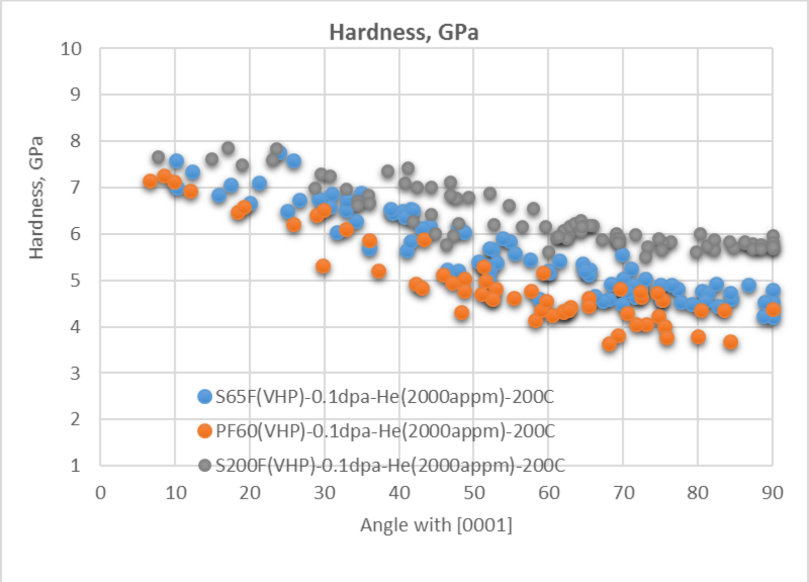
As-received

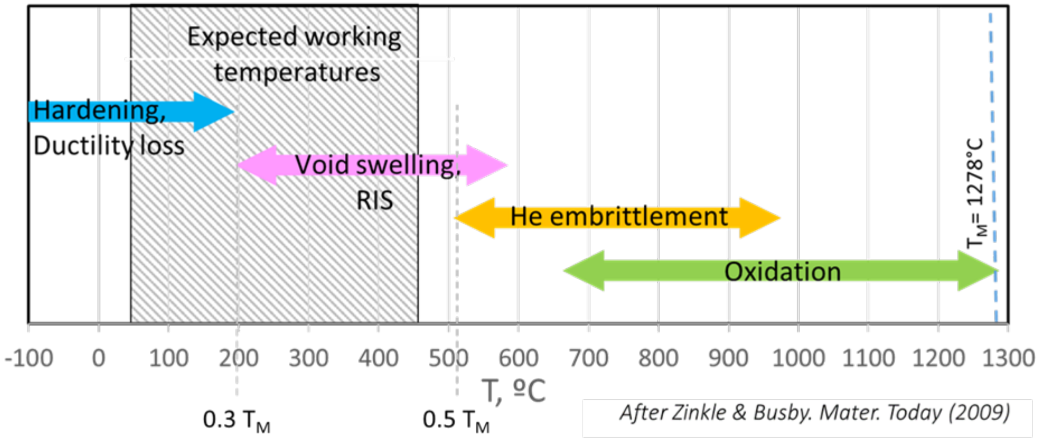


50°C implantation



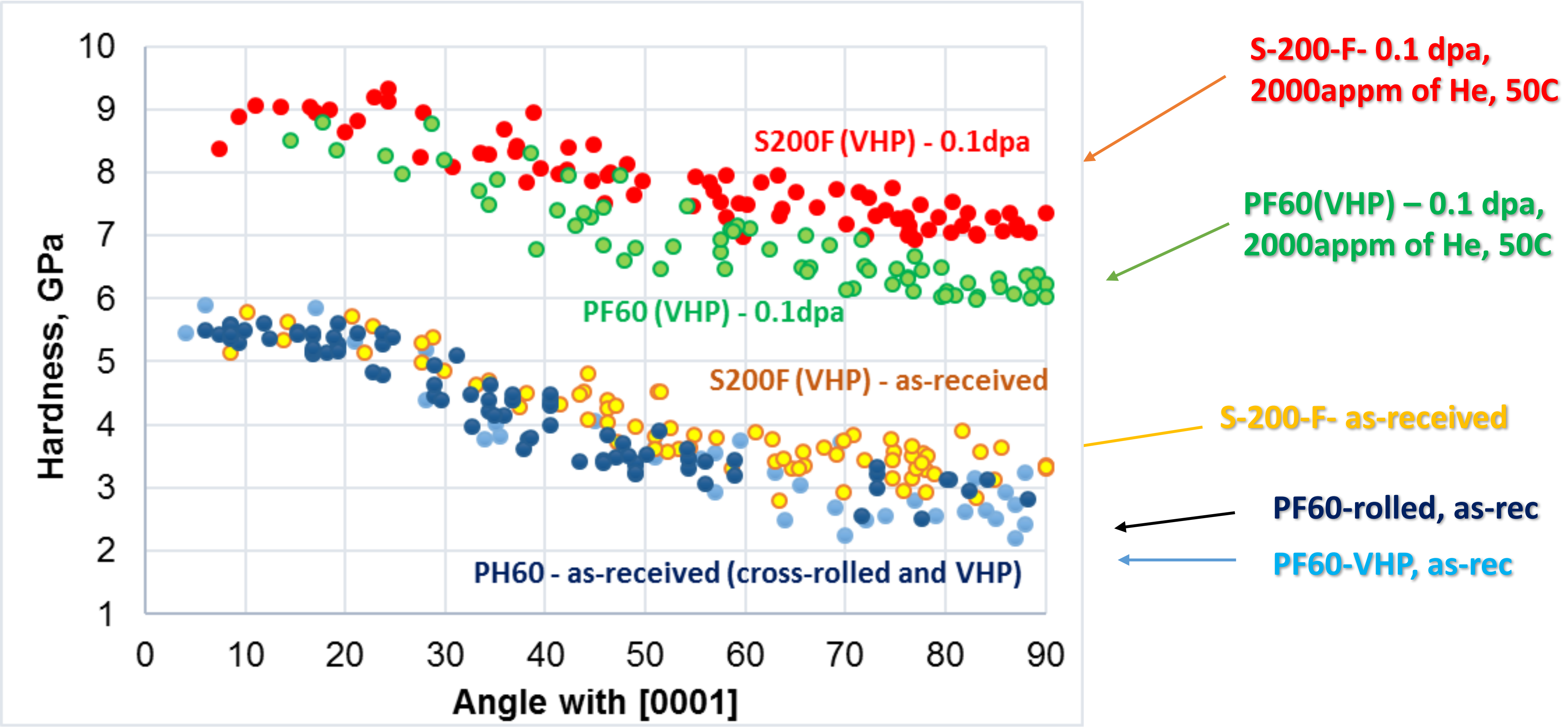
200°C implantation



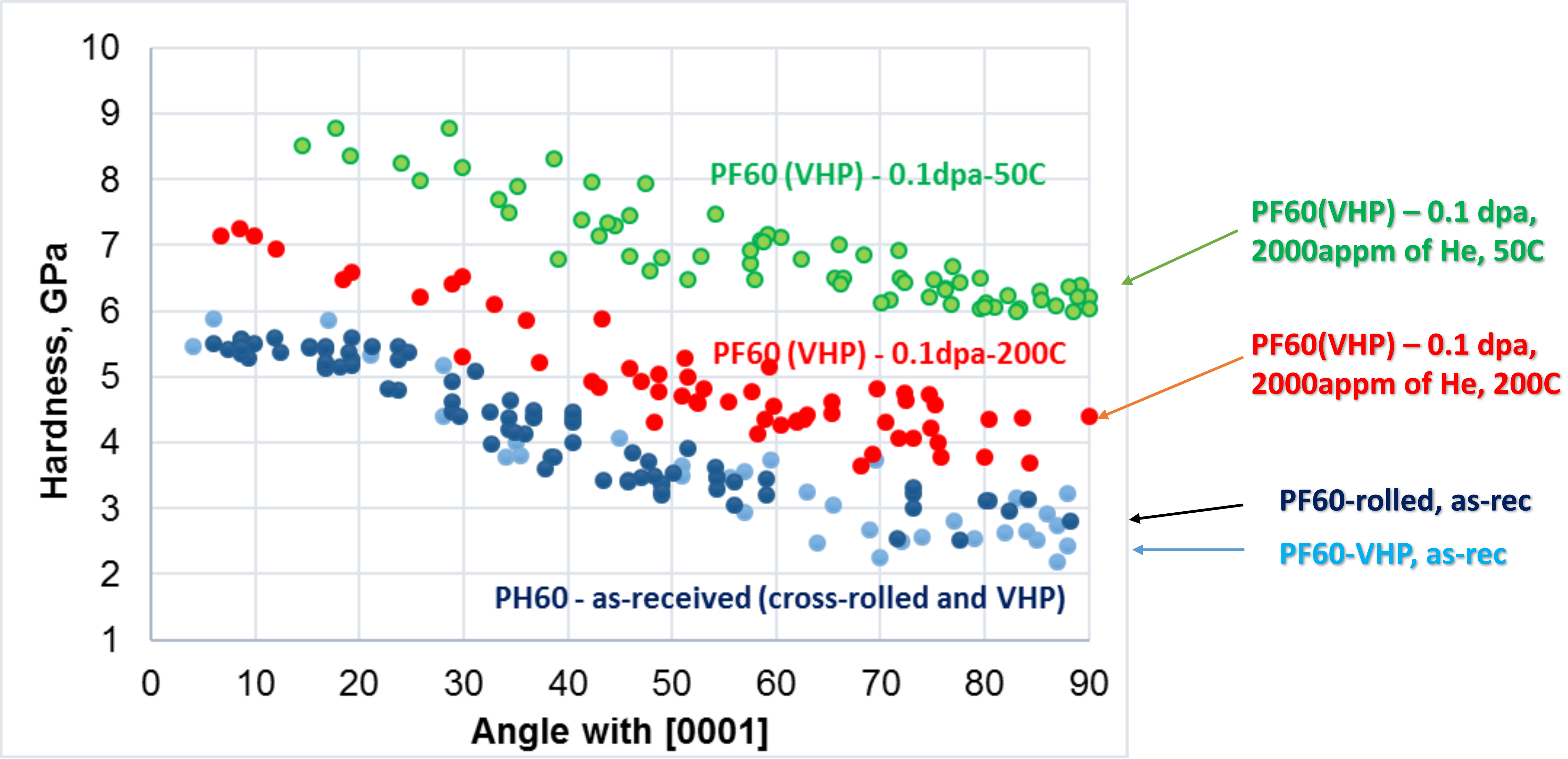


After Zinkle & Busby. Mater. Today (2009)

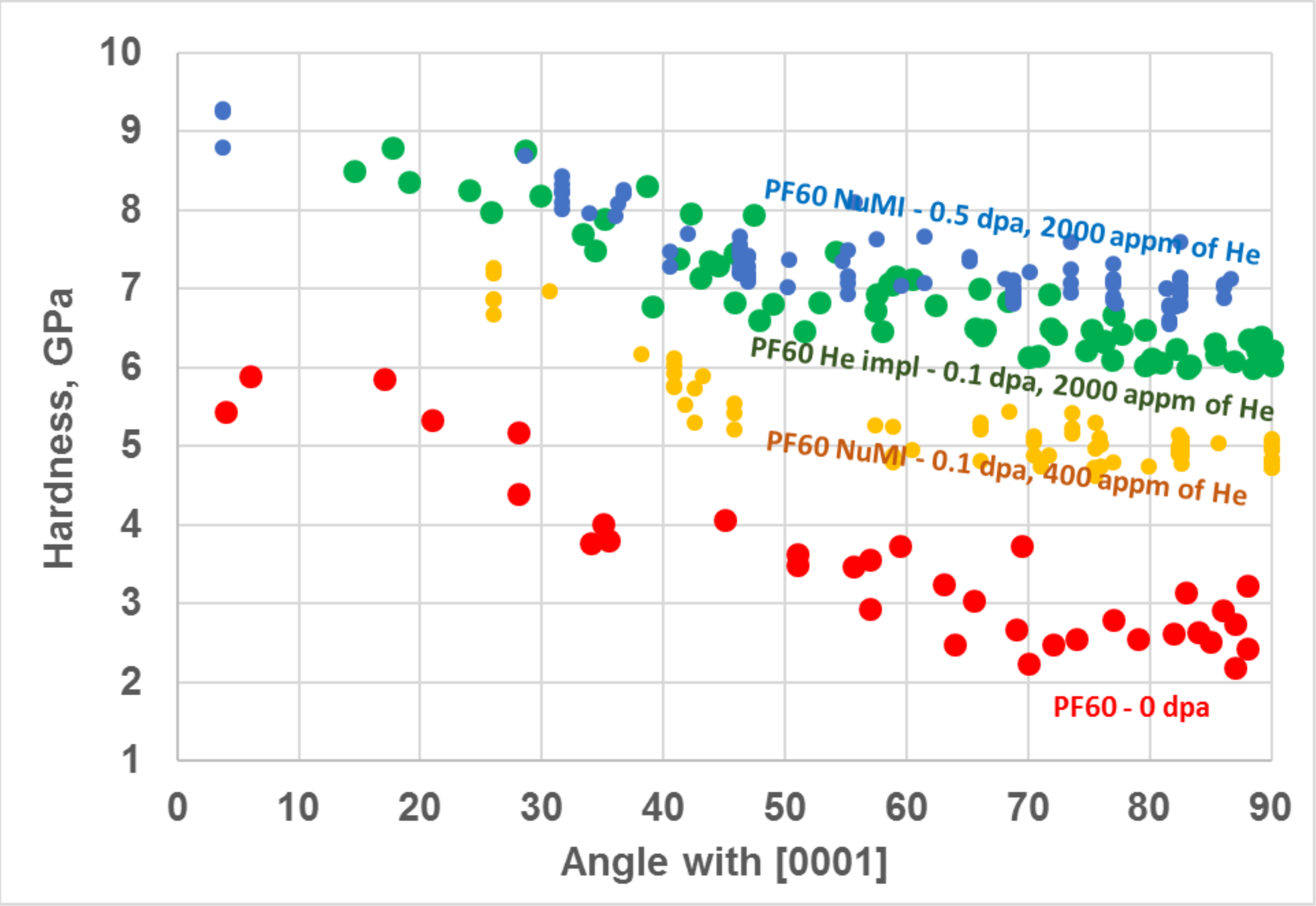
- Clear irradiation hardening effect
- Less hardening at higher temperature
- More hardening in the S-200 grade?



The average hardness was increased after helium implantation, while anisotropy of hardness was decreased

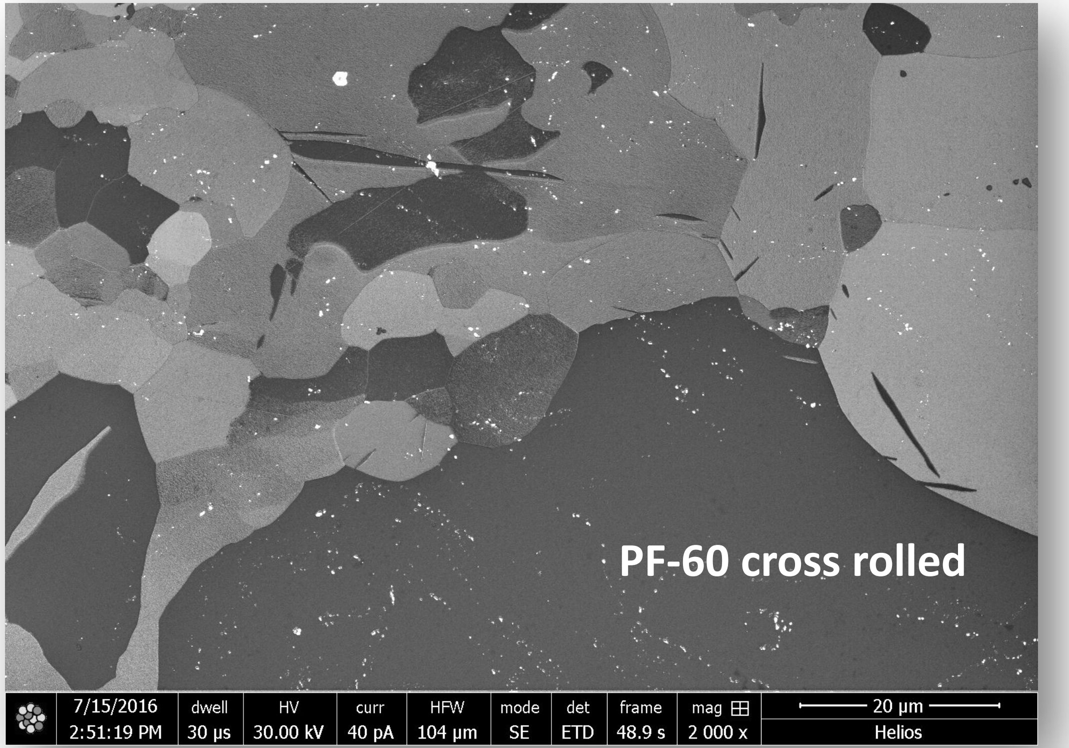


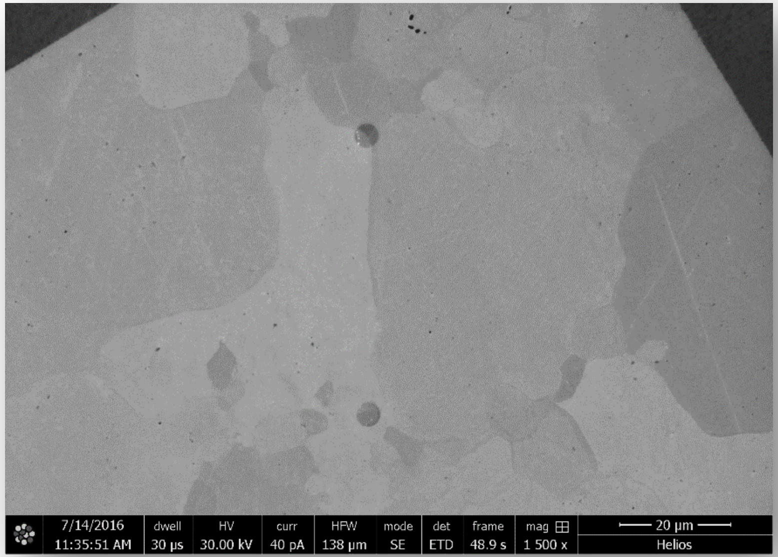
- Higher hardening at lower irradiation temperature

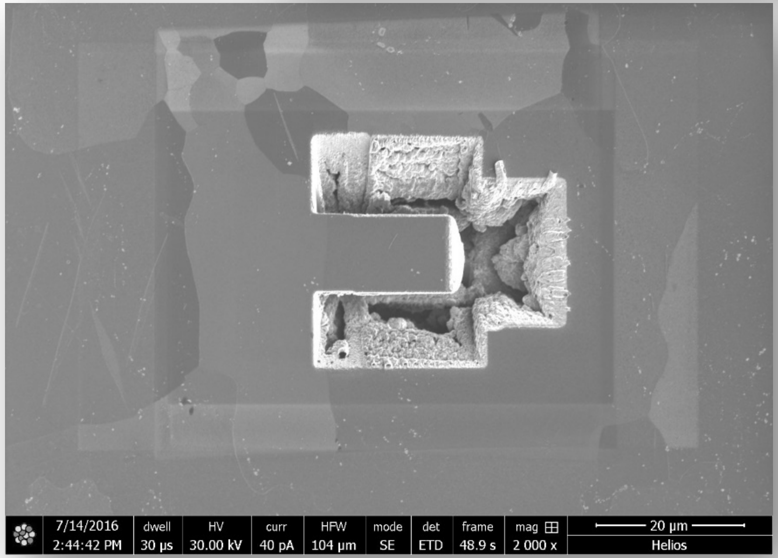


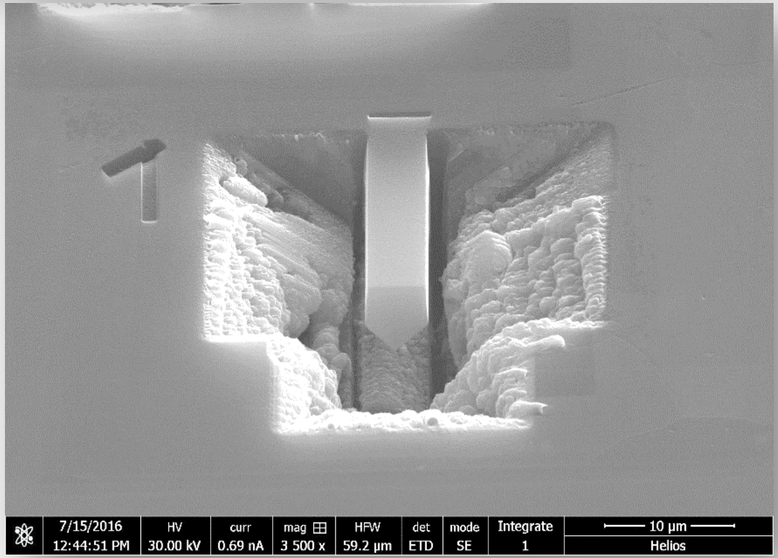
- Comparison of proton irradiation and He implantation data indicated dominating effect He content

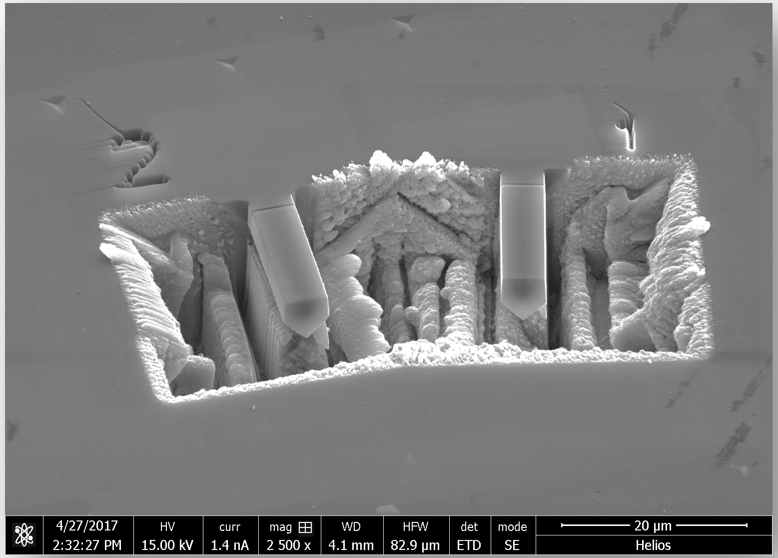
Micromechanical tests samples preparation



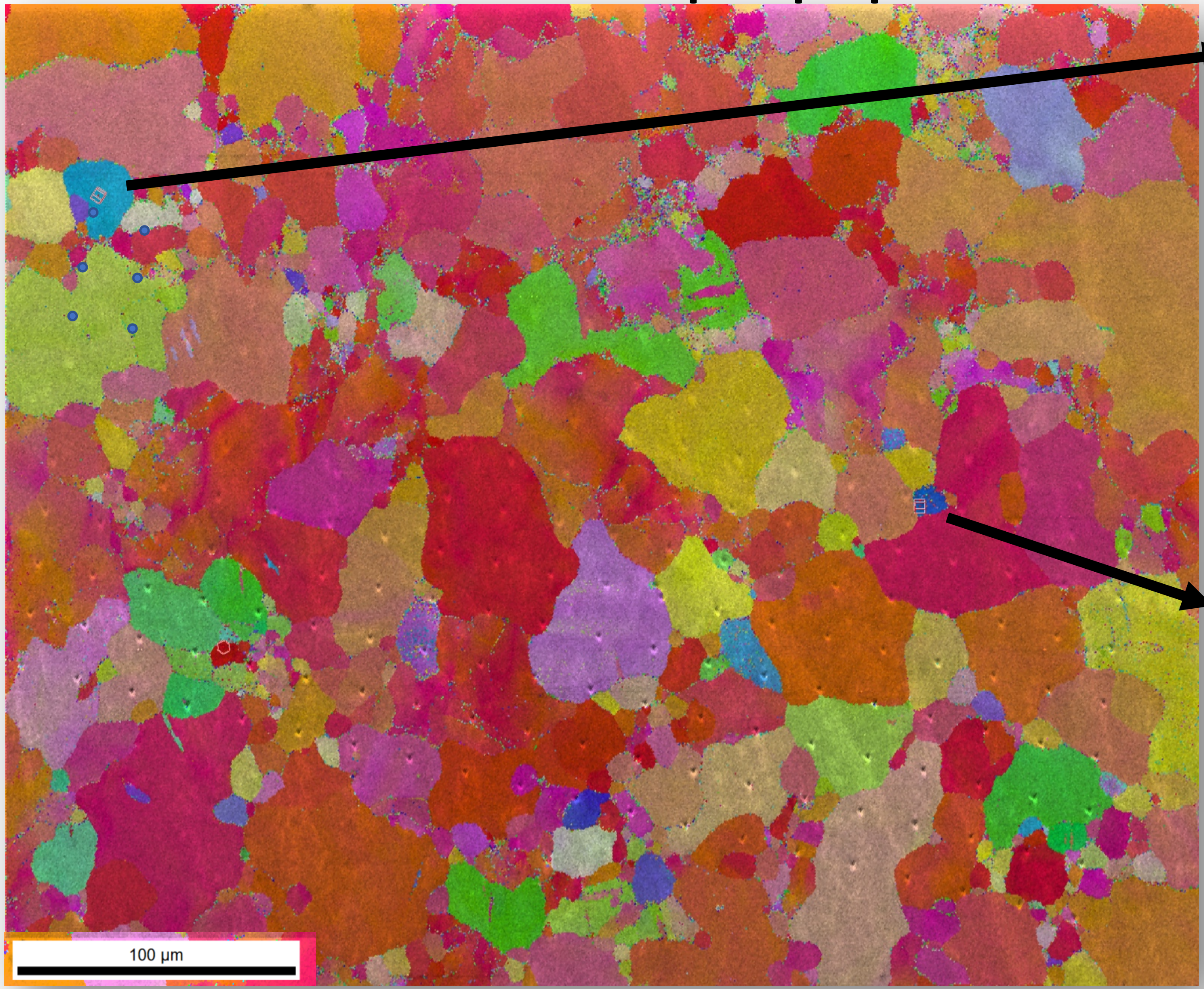


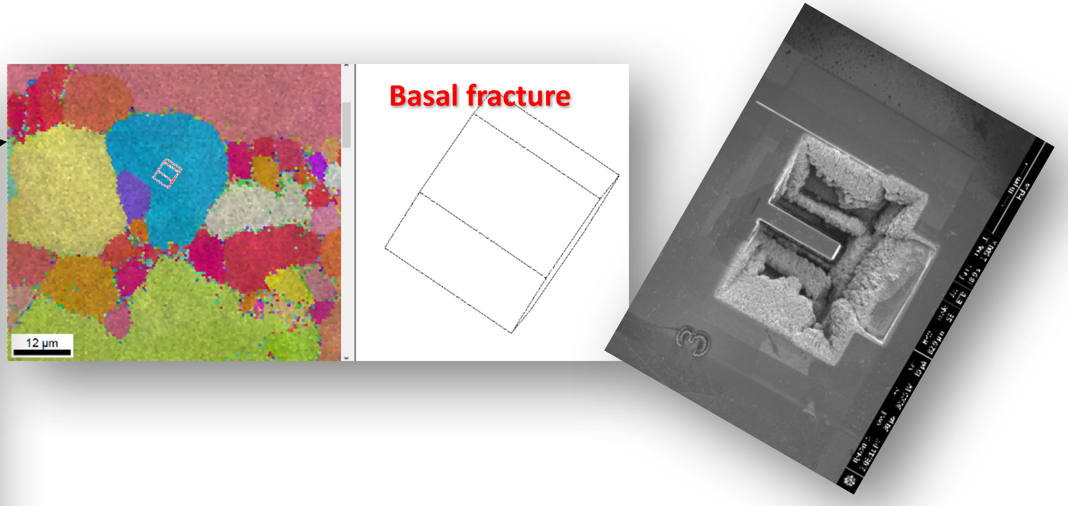


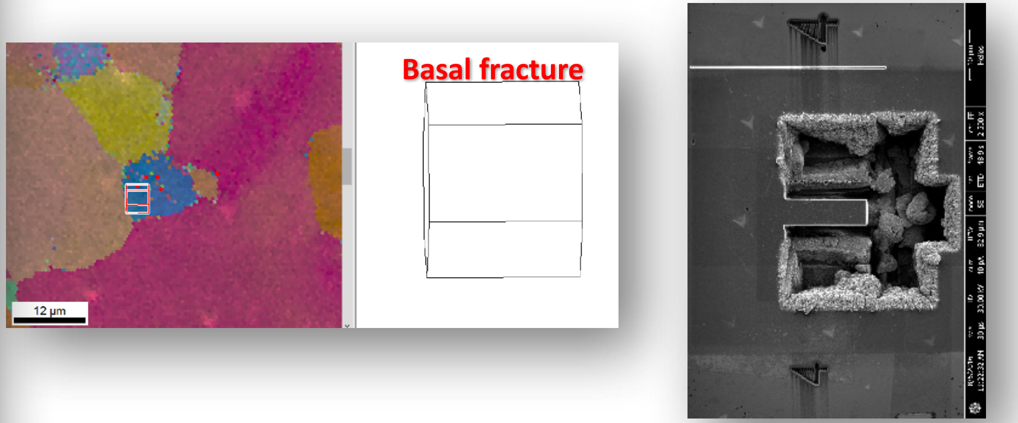




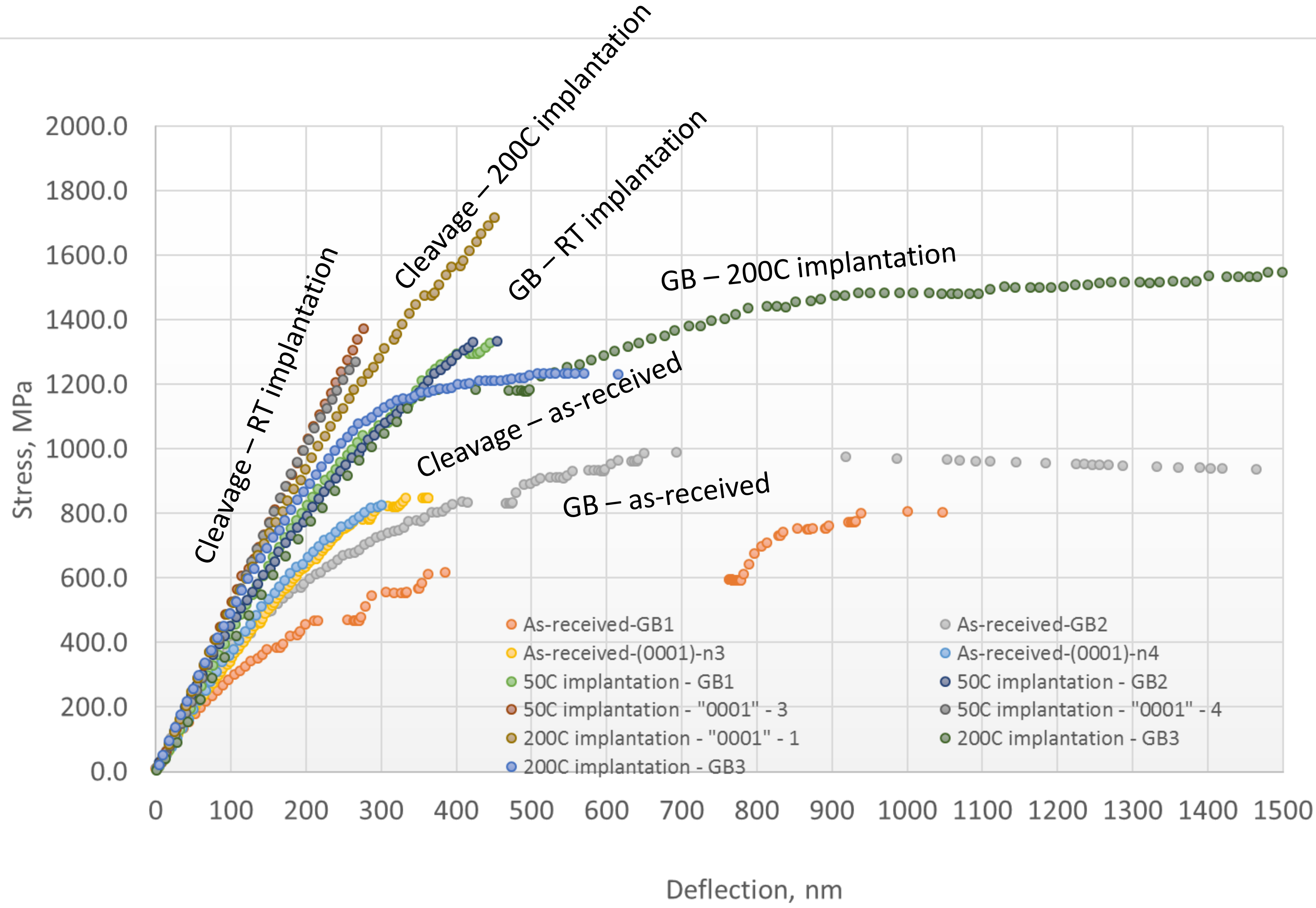
Micromechanical tests: samples preparation



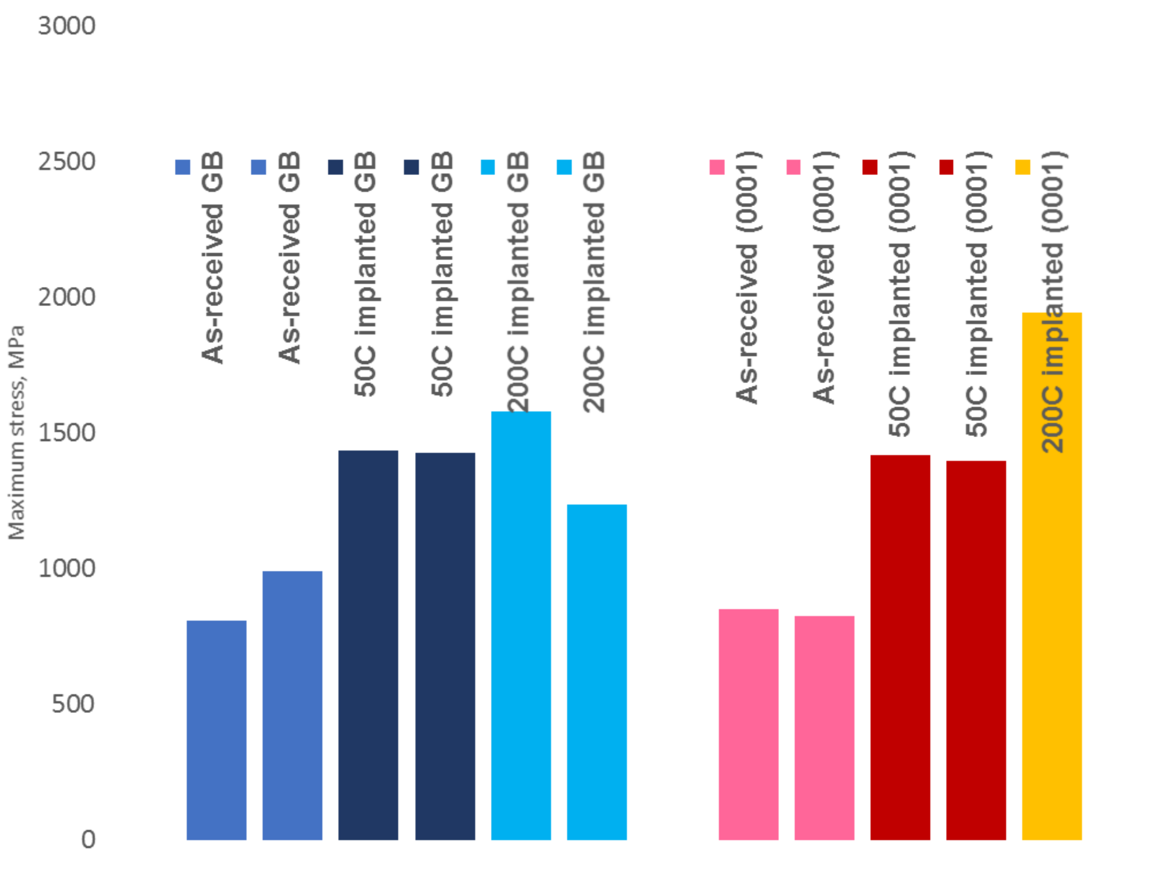


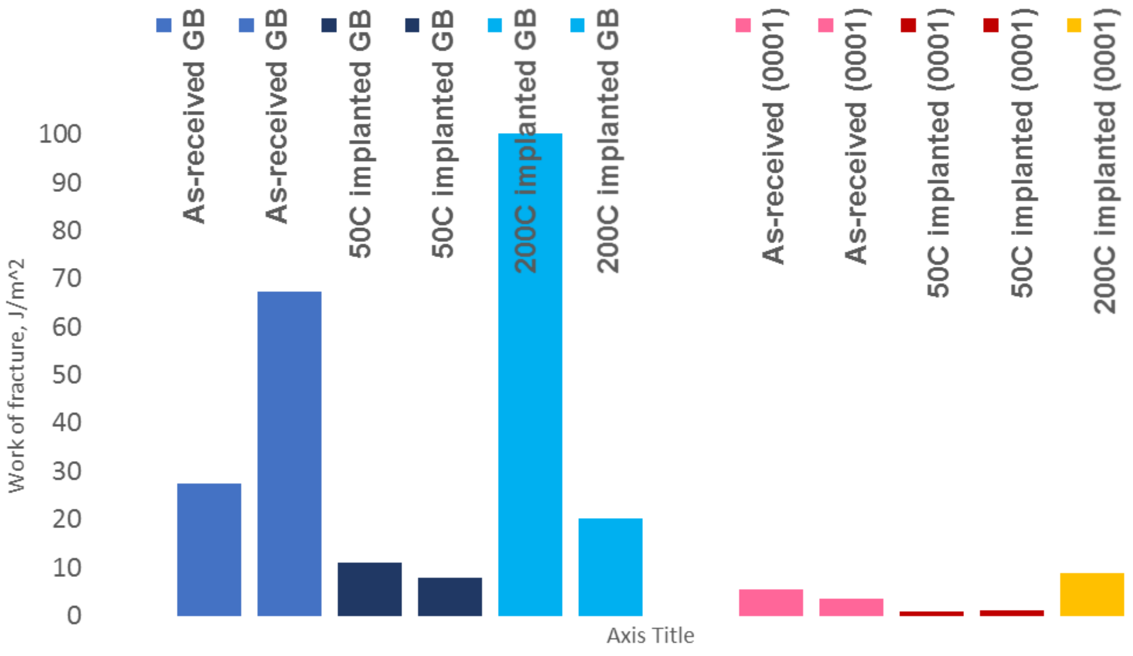


Microcantilevers were fabricated by FIB. Cantilevers were pre-notched so that the fracture properties of grain boundaries and basal cleavage plane, in both as-received and irradiated states, can be compared.



Cleavage – RT implantation
Cleavage – 200C implantation
GB – RT implantation
GB – 200C implantation
Cleavage – as-received
GB – as-received
Stress, MPa
Deflection, nm
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
As-received-GB1
As-received-GB2
As-received-(0001)-n3
As-received-(0001)-n4
50C implantation - GB1
50C implantation - GB2
50C implantation - "0001" - 3
50C implantation - "0001" - 4
200C implantation - "0001" - 1
200C implantation - GB3
200C implantation - GB3





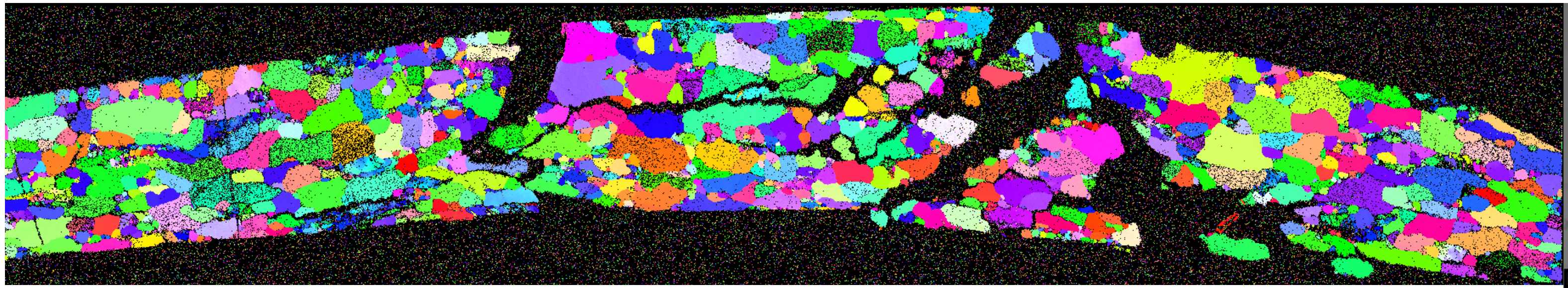
- Fracture load of both grain boundary and cleavage cantilevers increased significantly after irradiation.
- Work of fracture was found to be lower for cantilevers pre-notched in the basal cleavage plane, but the difference between two types of cantilevers was smaller in the irradiated state.

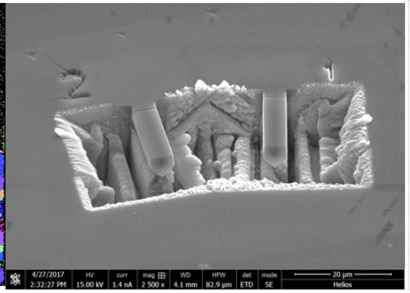
To do

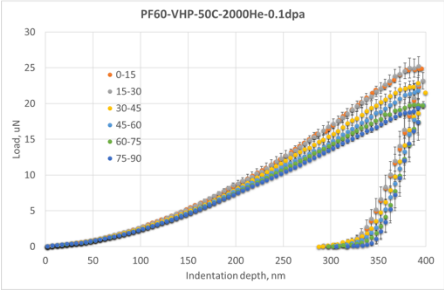
- More 200C implantation cantilevers;
- NuMI window cantilevers;

Conclusions

1. Radiation induces significant hardening of beryllium even at 0.1 dpa
2. We saw indications that less pure beryllium experience higher radiation induced hardening.
3. Irradiation at 200C leads to much lower hardening
4. Both displacement damage and He atoms cause hardening. We have indications that He content has a dominant effect.
5. He implantation led to increase of fracture strength of prenotched microcantilevers and decrease of work to fracture, with severe drop for 50C implantation.







Thank you!