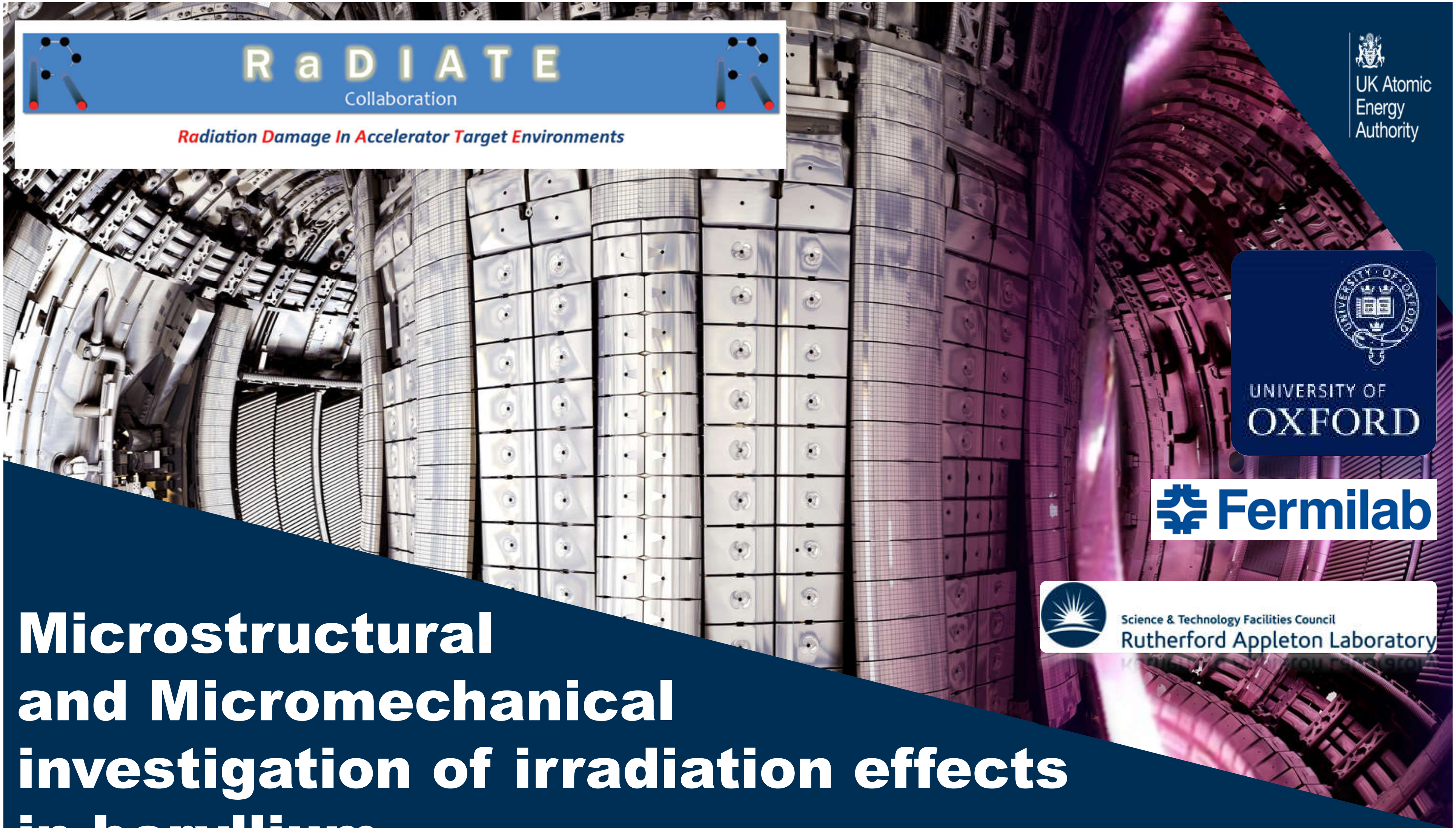
RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments



Microstructural and Micromechanical investigation of irradiation effects in beryllium

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[2] University of Oxford

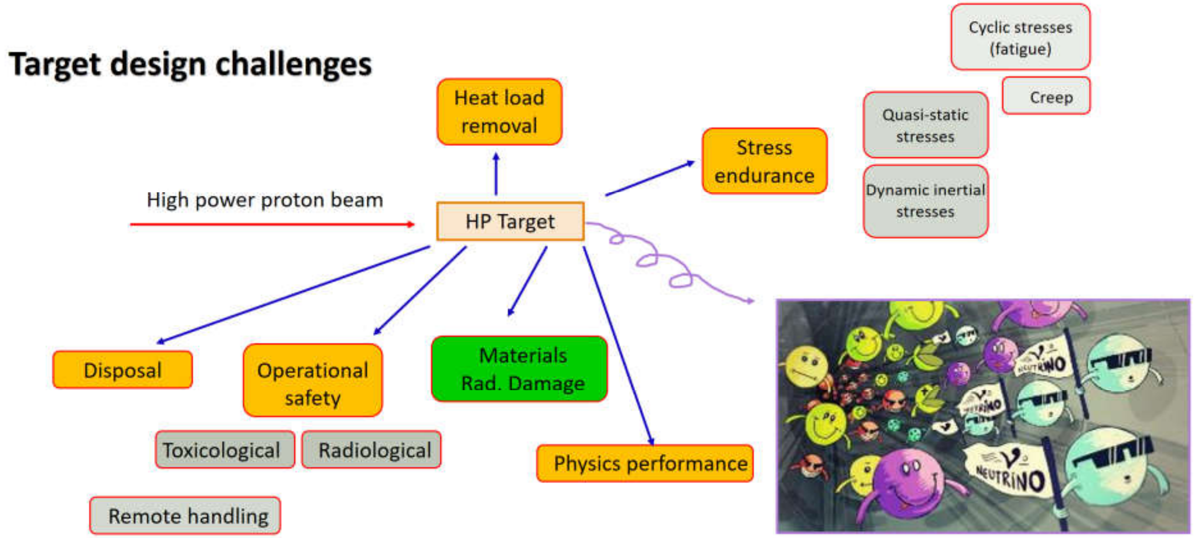
[3] Rutherford Appleton Laboratory, UK

[4] Fermi National Accelerator Laboratory, USA

Beryllium in high power target systems

- 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



After Otto Caretta, HTPW, May 2014

Application	Operating conditions		
	Avg. T (°C)	Peak T (°C)	Total DPA
Beam window NUMI	50	<100	~ 0.08/yr
Beam window LBNF	200	300	~ 0.23/yr
Target LBNF	375	450	~ 0.23/yr

	Approximate He production in beryllium, appm/dpa
SM-3 high-flux reactor (Russia)	330
BOR-60 reactor (Russia)	280
HFR, HIDOBE-01 irradiation campaign (Petten, Netherlands)	160
Beryllium reflectors in the ISIS neutron source (RAL, UK)	220 (TS1)
	110 (TS2)
DEMO fusion reactor	600
NuMI beam window (FNAL, USA)	4000

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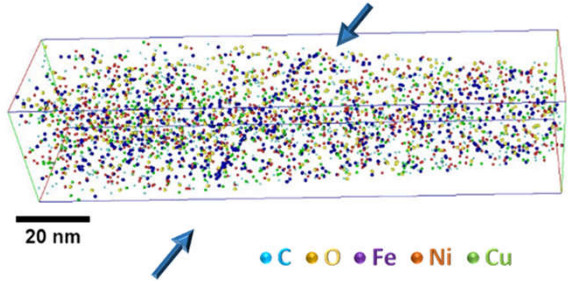
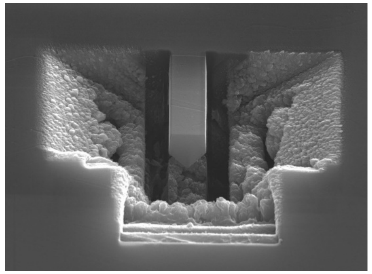
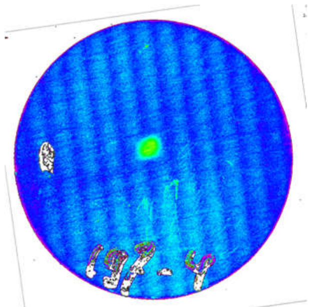
Radiation Damage In Accelerator Target Environments

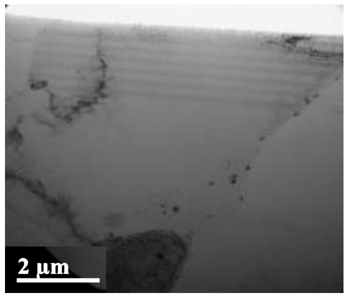
Experimental investigation: microstructure vs properties

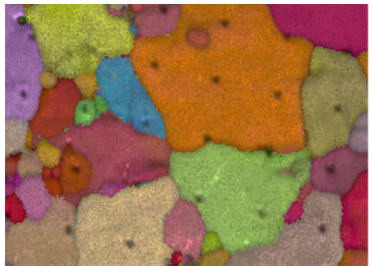
- Investigation of as-received beryllium
- Proton irradiation effects — Fermilab
- Ion irradiation experiments (He implantation) — University of Surrey
- Thermal shock effects in beryllium — CERN











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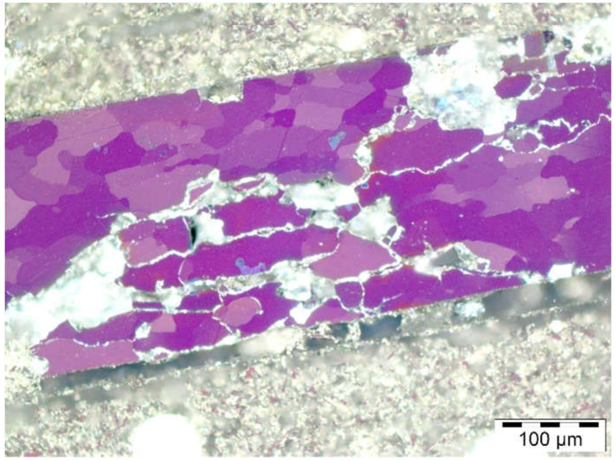
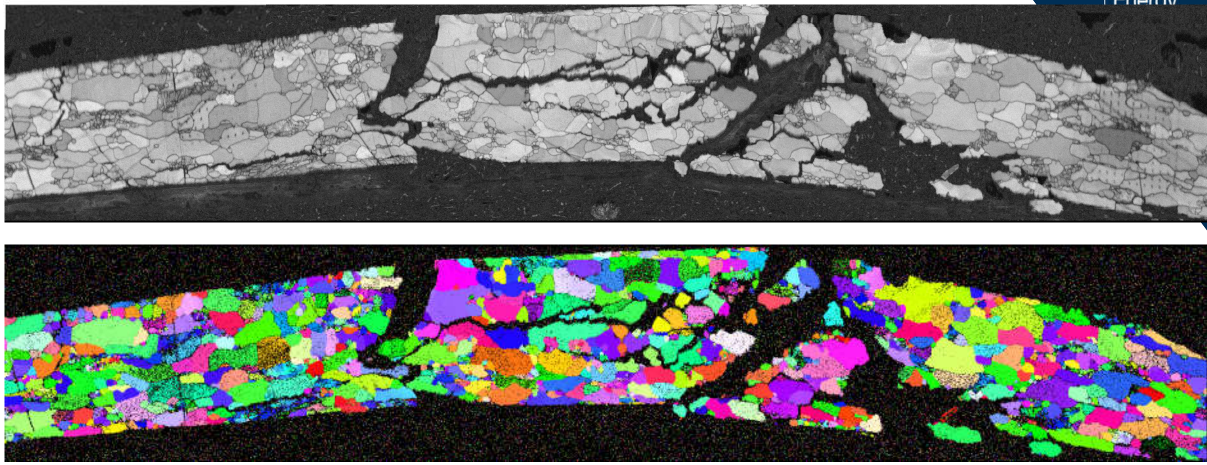
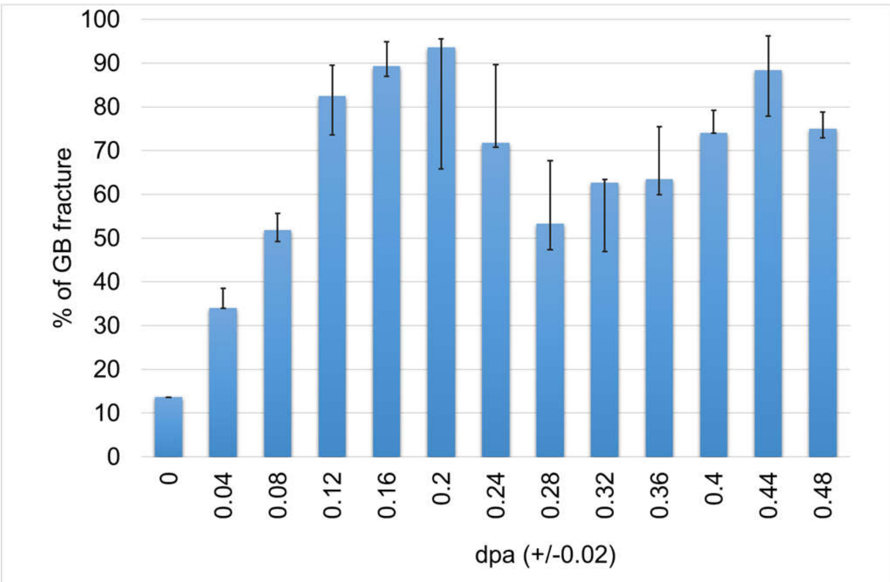
NuMI beam window: fracture mechanism





Sample preparation and light microscopy done at KIT

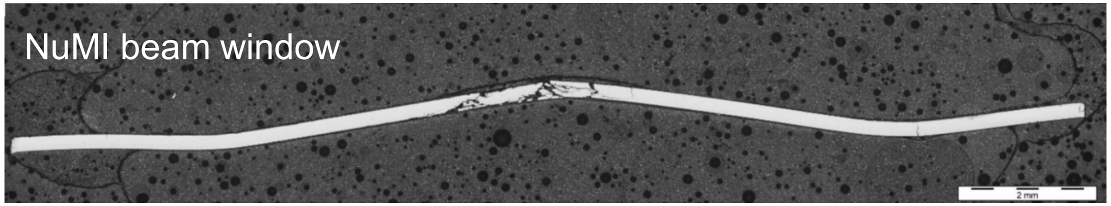


Transition form transgranular fracture to grain boundary/mixed mode fracture

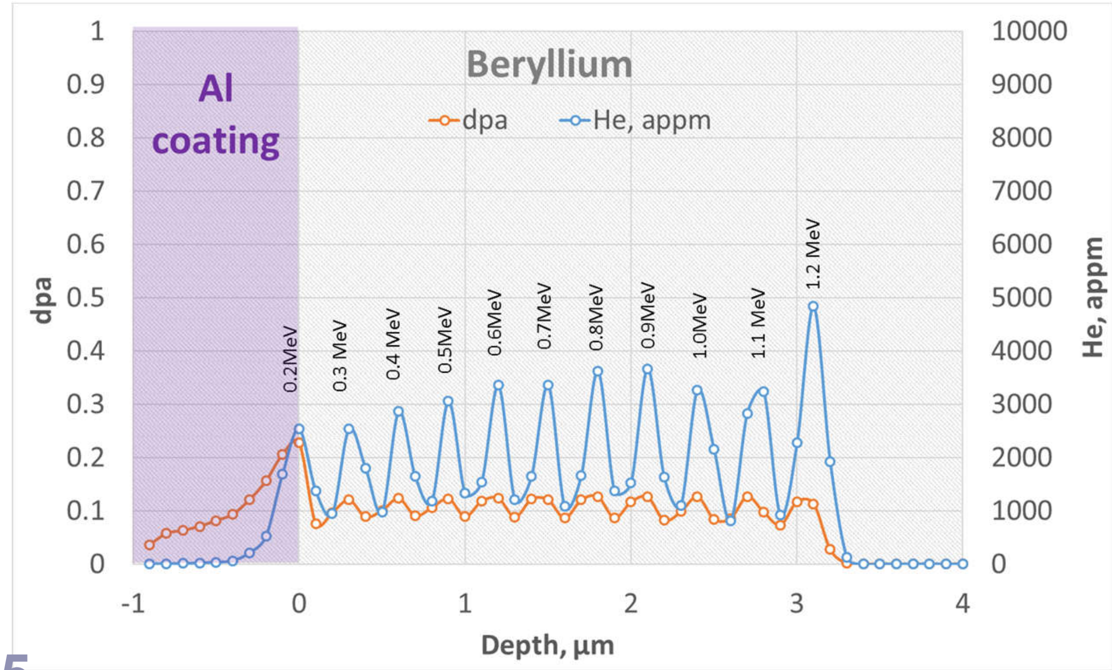
- Non-irradiated beryllium – mainly transgranular cleavage
- Grain-boundary fracture may be caused by strengthening of the matrix or “weakening” of GBs

Why nanoindentation?

p^+ irradiation

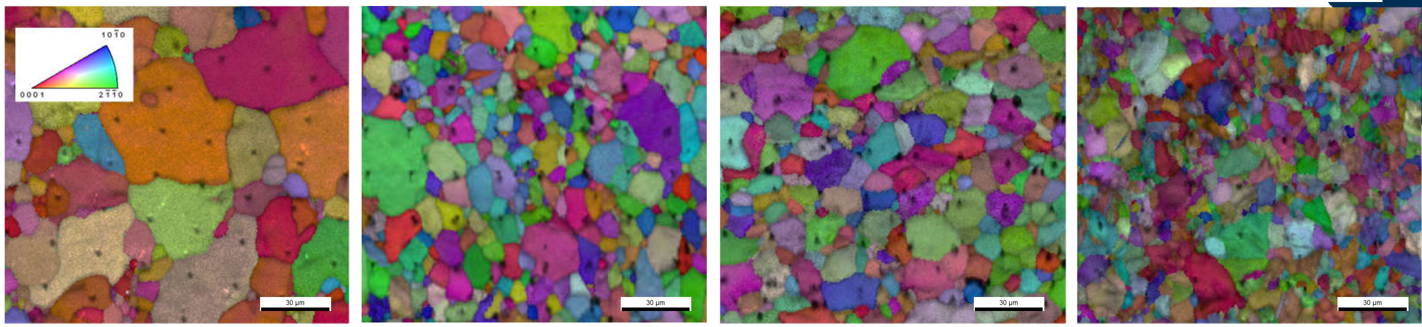


He implantation



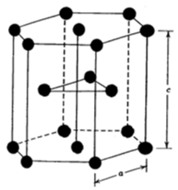
- The size and shape of irradiated accelerators components usually do not allow fabrication of samples for standardized tests
- Ion implantation creates only micrometric damage layer

miniaturized samples and nanoindentation hardness experiments and microcantilever fracture tests are used



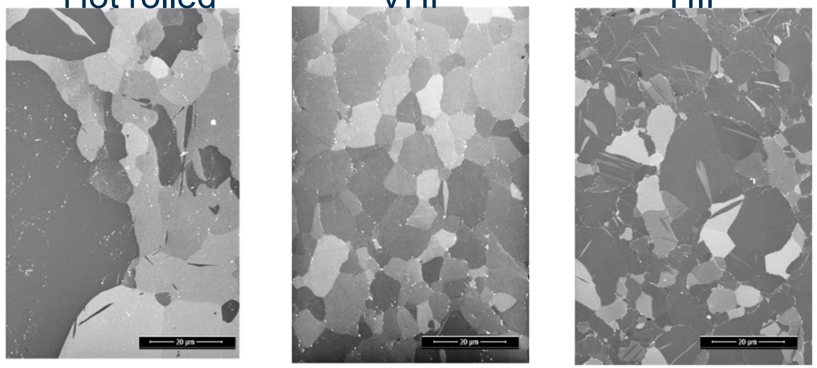
	PF-60 (Cross-rolled)	S-65 (VHP)	S-200-H (VHP)	S-200-FH (HIP)
Maximum impurities	1.0%	0.8%	1.5%	1.5%
Grain size, um	25 ± 14	7.3± 4.4	7.1 ± 4.1	5.3 ± 3.3

- Industrial beryllium is not pure: Be oxides and Fe, Al, Si, Mg etc… enriched impurities are mainly at GB - “White contrast particles” on SEM images (in the SE2 detector)
- Beryllium can be highly textured (hot rolled grades)
- Grain size is different in different grades

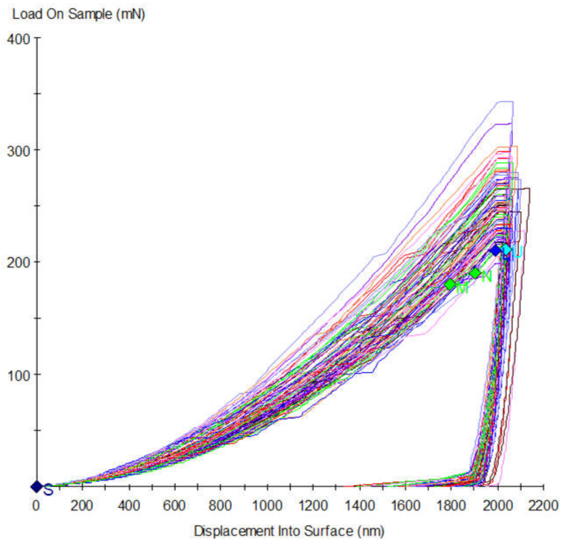


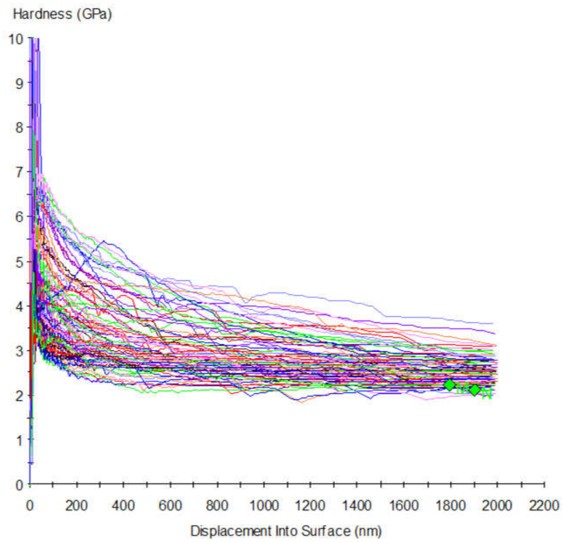
HCP

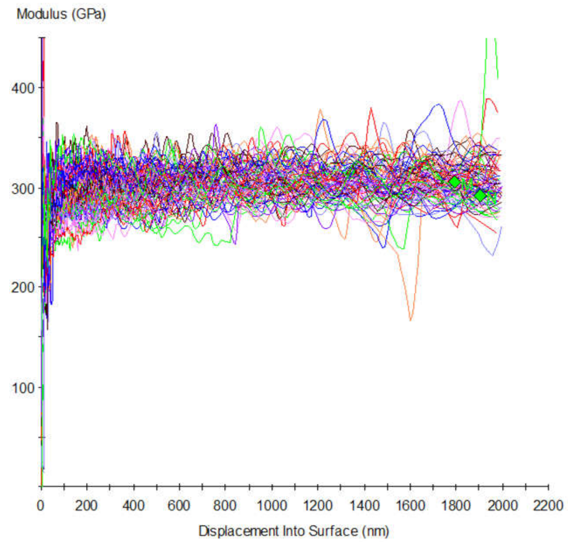
Hot rolled VHP HIP



S-200-H (VHP), 80 indents

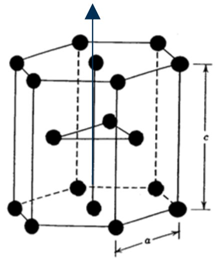




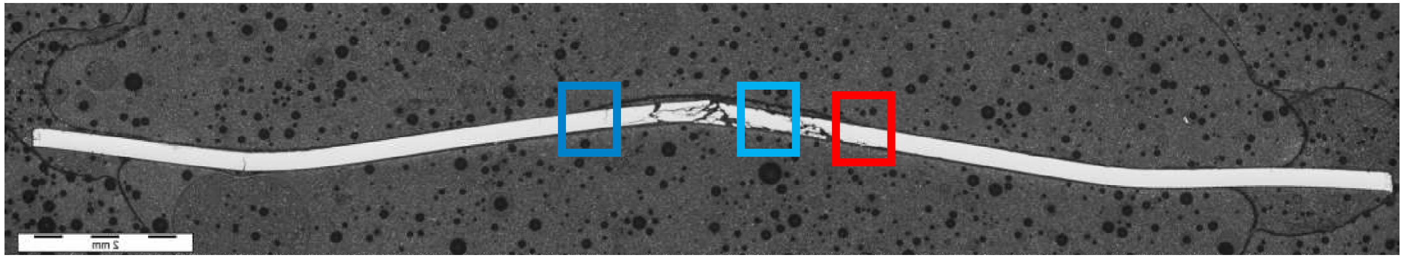


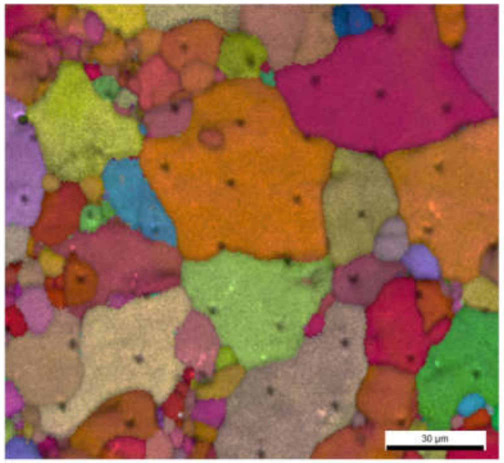
- Variations of indentation load, hardness and modulus are very broad

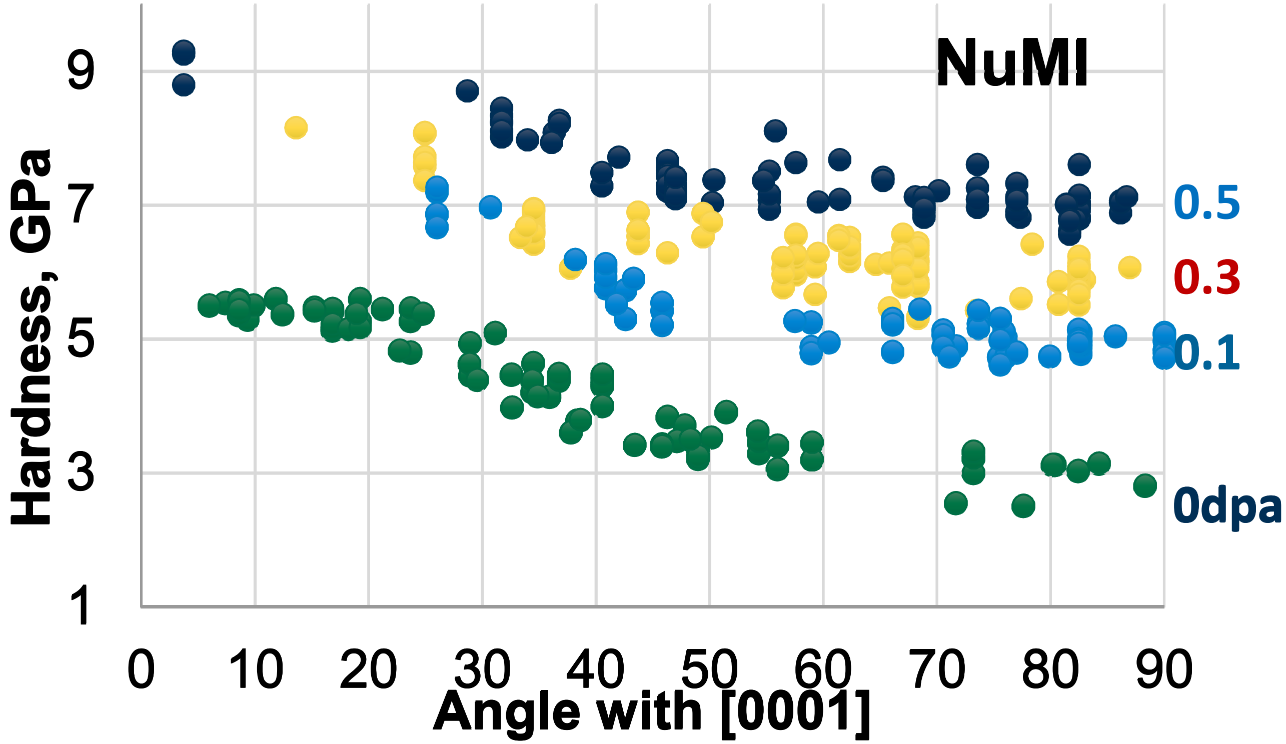
NuMI beam window: radiation induced hardening



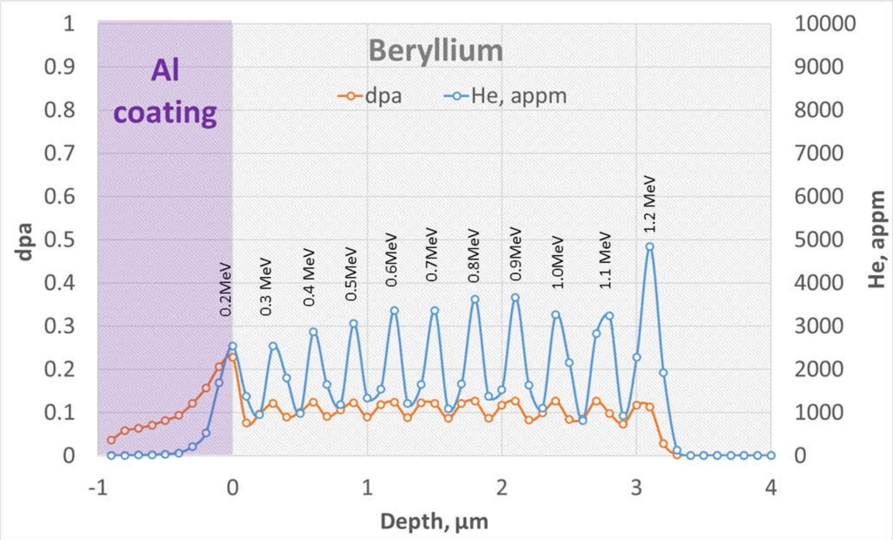
HCP



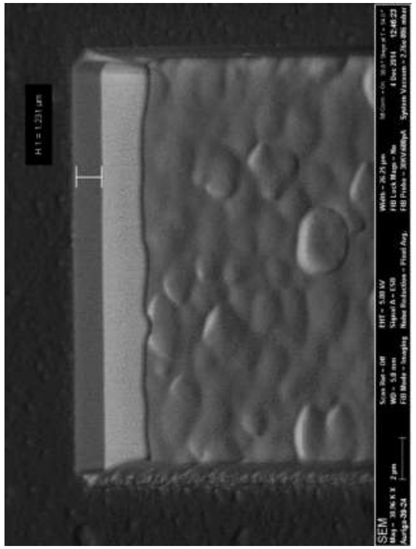


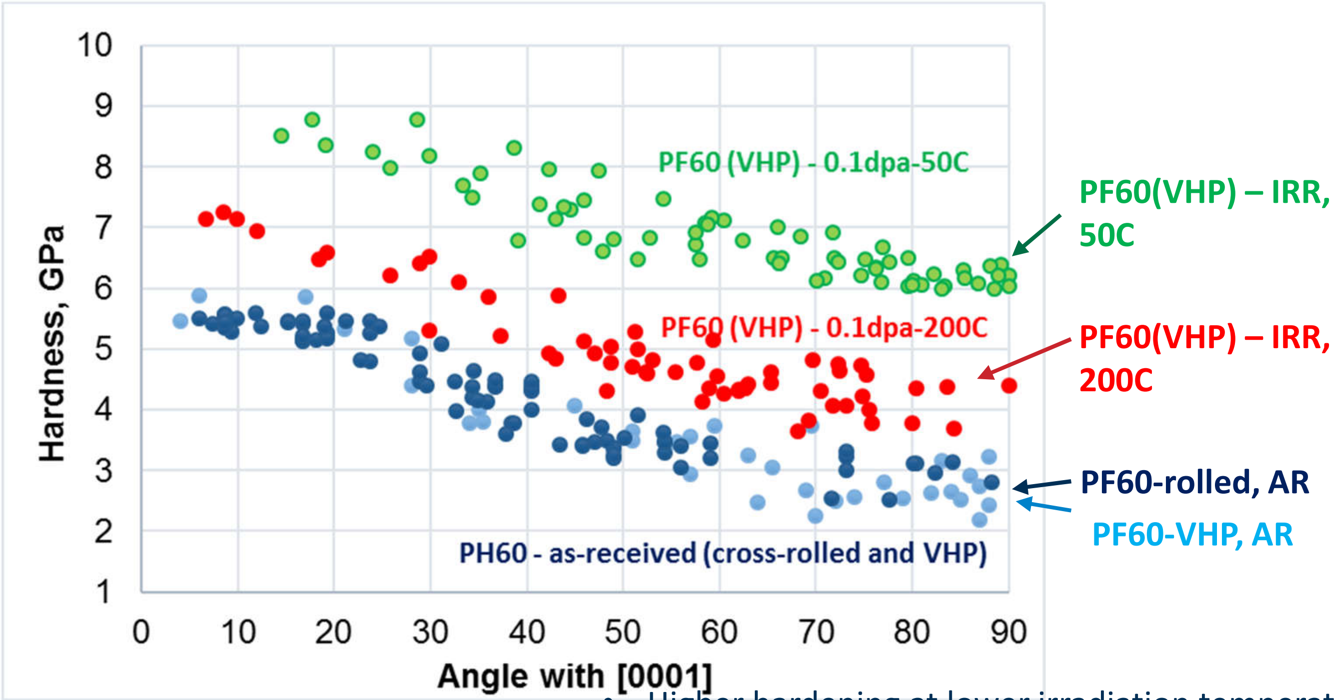


He implantation: temperature effect



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

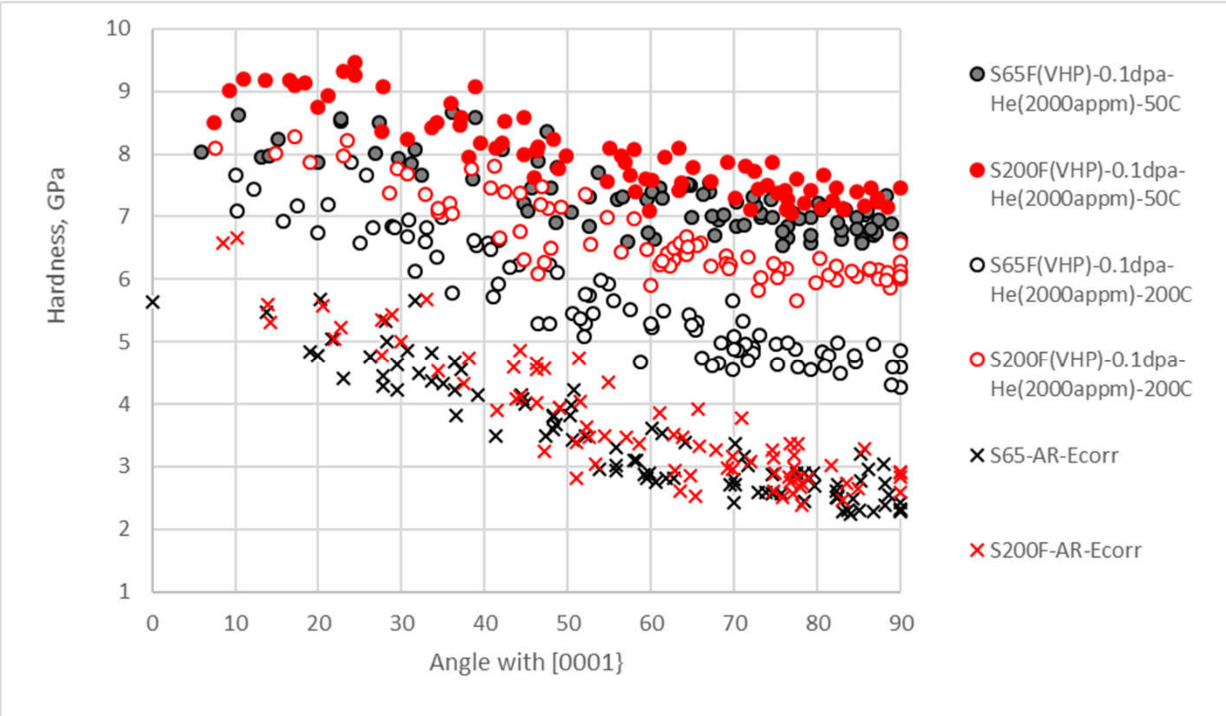




- Higher hardening at lower irradiation temperature

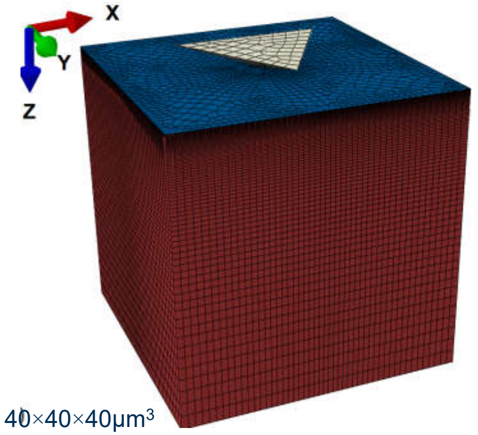
He implantation: composition effect

	S-65	S-200-F
Maximum impurities (O, Fe, Al, Si, Mg, C…)	0.8%	1.5%

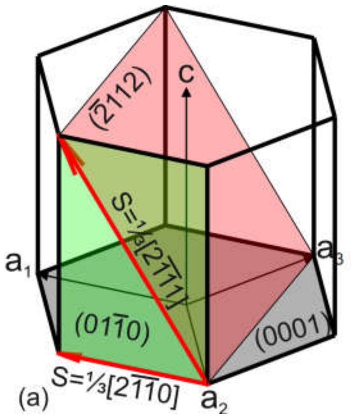


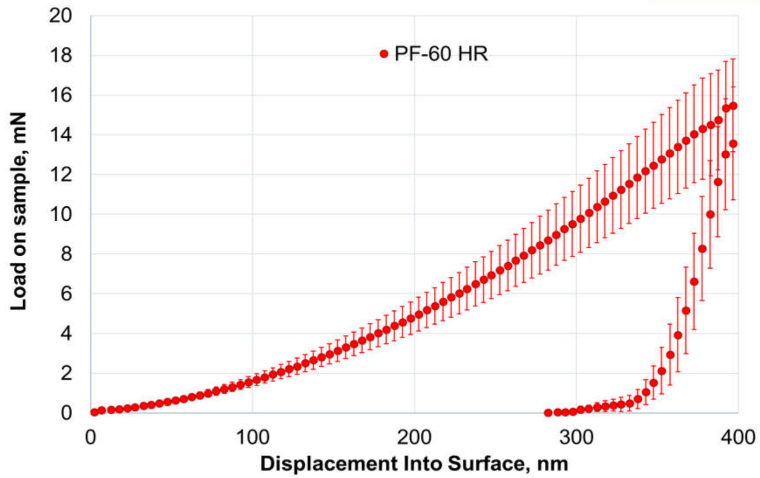
- The average hardness was increased after helium implantation, while anisotropy of hardness was decreased
- Higher hardening in less pure grade after 200°C irradiation

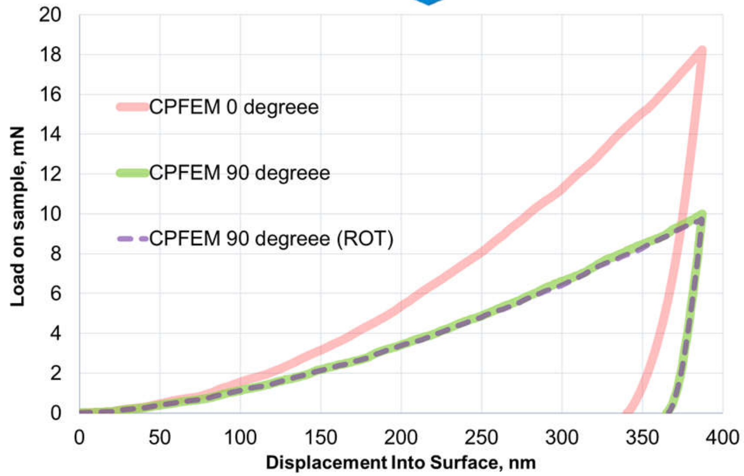
CPFEM (Ed Tarleton)



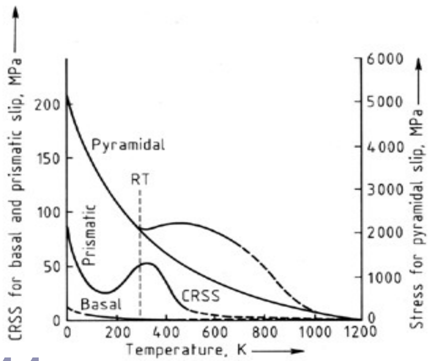
$40 \times 40 \times 40 \mu m^3$







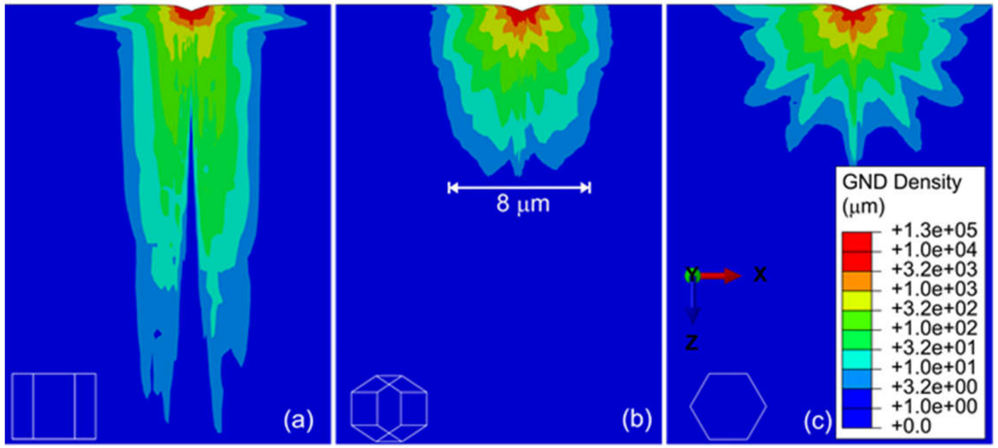
12 slip systems: 3 <a> basal, 3 <a> prismatic and 6 <c+a>



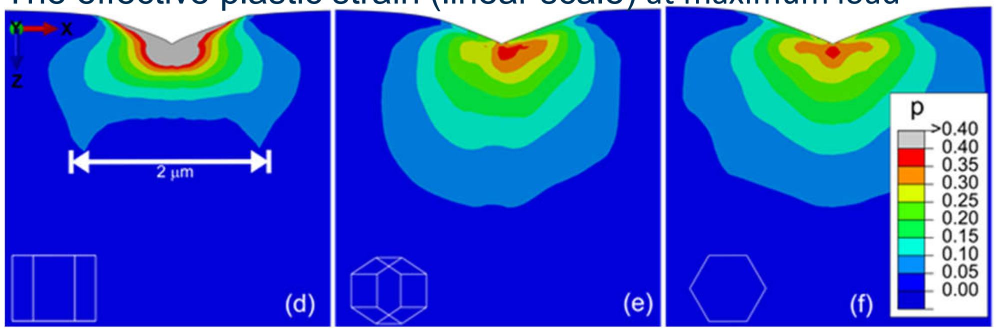
τ_c = 15 MPa the <a> basal
τ_c = 68 MPa for the <a> prismatic systems
τ_c = 2000 MPa for the secondary <c+a> pyramidal systems

Collaboration with Edmund Tarleton (Oxford)

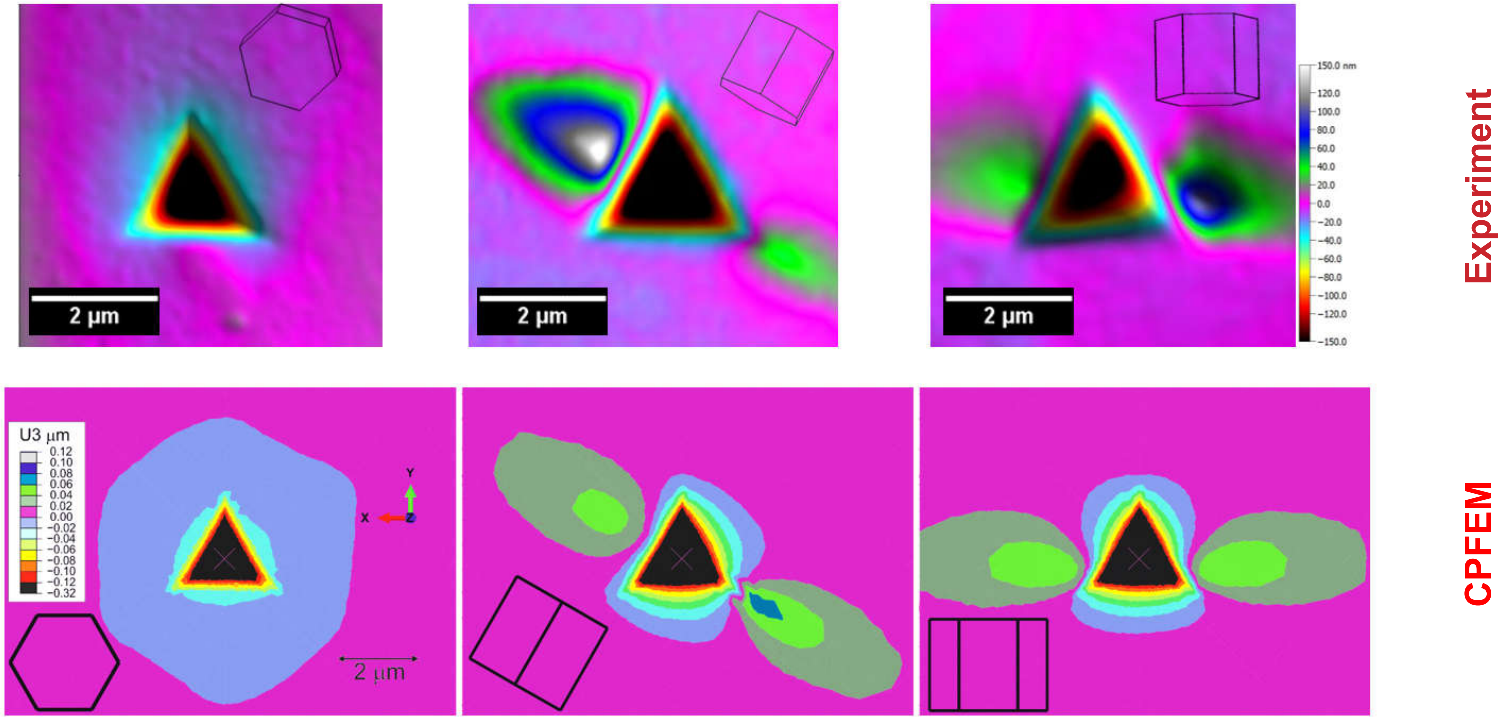
The total GND density (log scale) at maximum load (400 nm deep indentation)



The effective plastic strain (linear scale) at maximum load



- Vast majority of GND-s are localised around the indent
- Indentation far from GB boundaries give quasi-single crystal “plastic response”
- Deeper penetration of GND-s for “hard orientation”

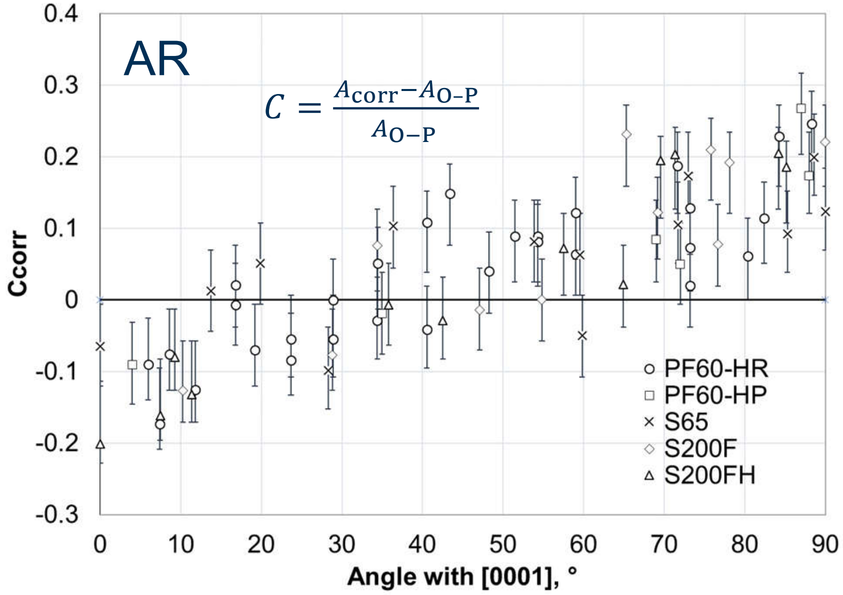


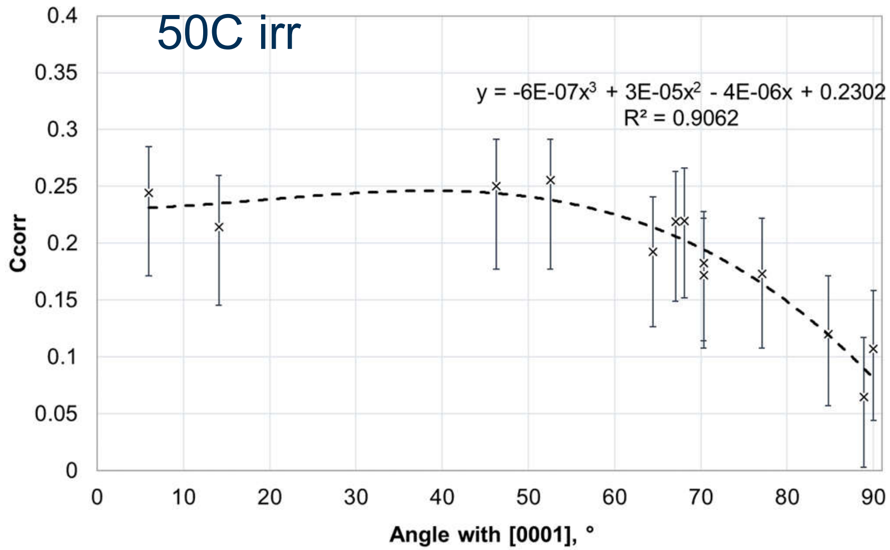
PF-60 HR beryllium. Topography maps scanned with nanoindenter tip. 6°, 82°, 81° with the [0001] axis.

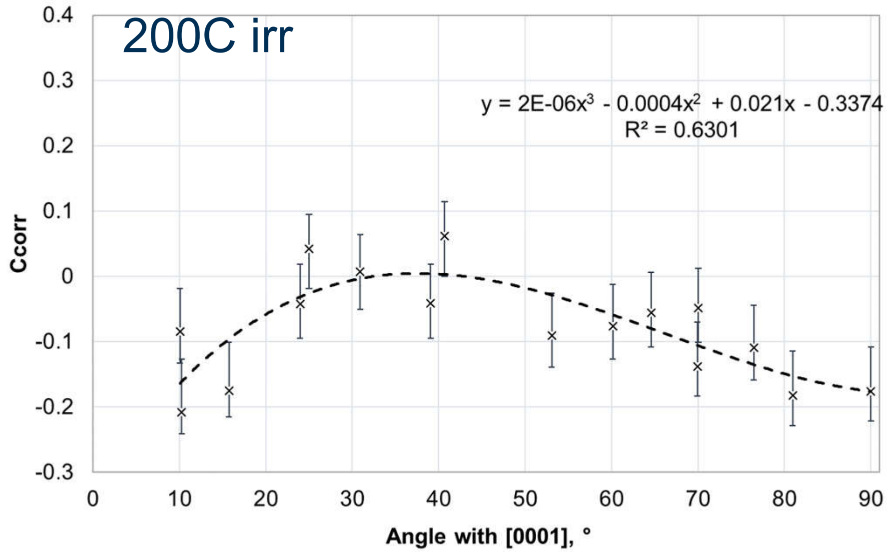
Several factors define pile-up/sink-in patterns:

- Indentation angle with [0001] axis
- Rotation of the tip inside the indentation plane
- Something else? (dislocation density, close proximity of other grains…)

Preliminary

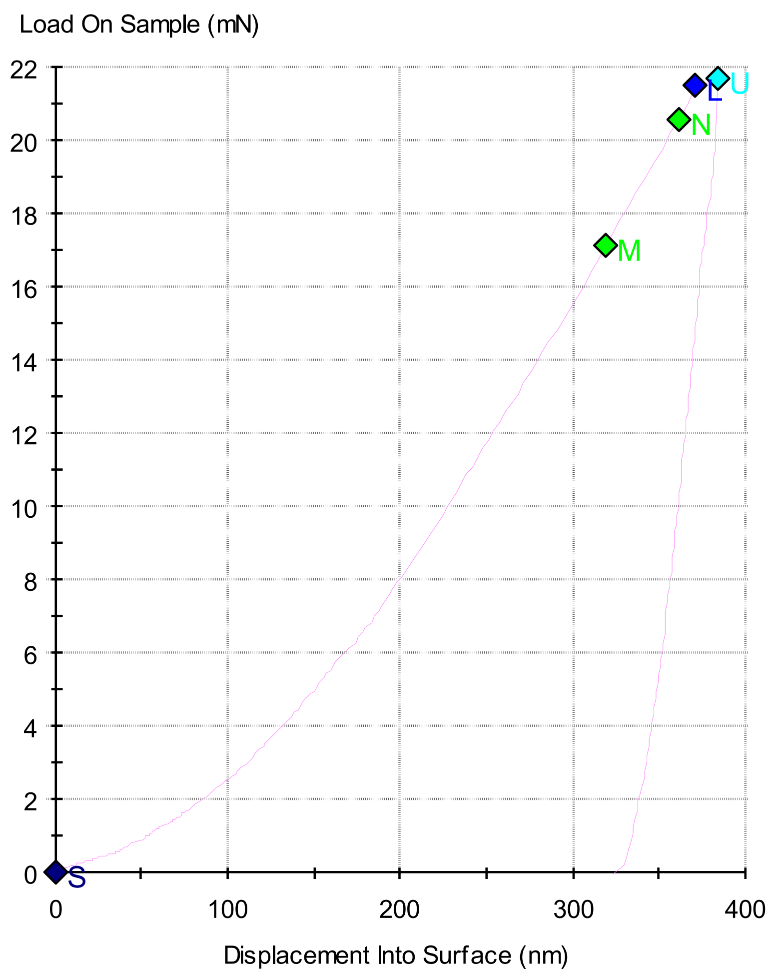


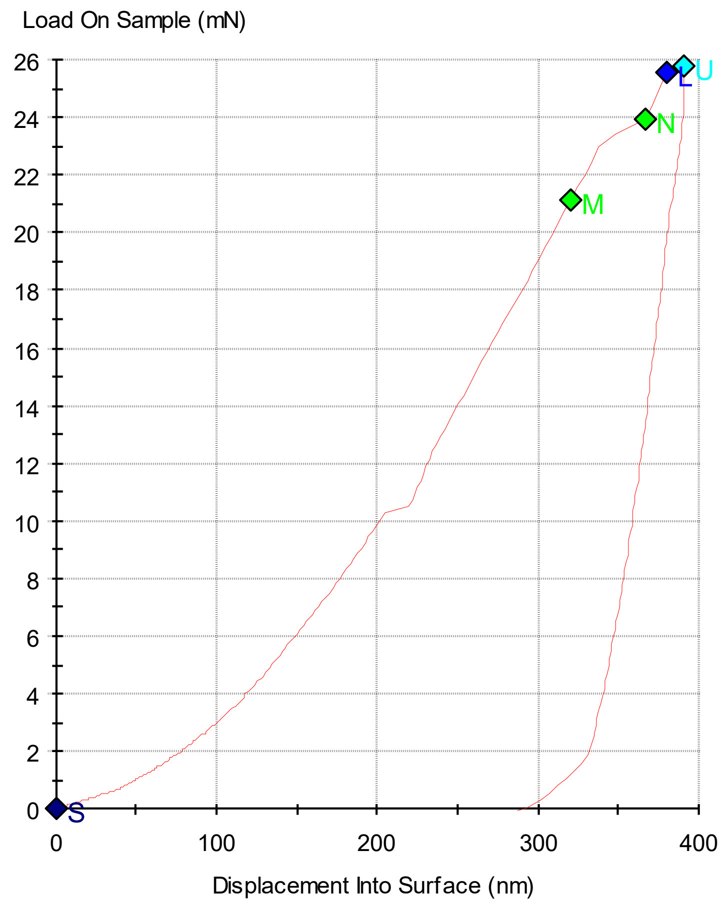




- Both pile-ups and sink-ins are simultaneously present
- Out-of-plain deformation behaviours is highly anisotropic
- Sink-ins dominates for low angles with [0001], pile-ups dominates for high angles with [0001] in as-received

Preliminary





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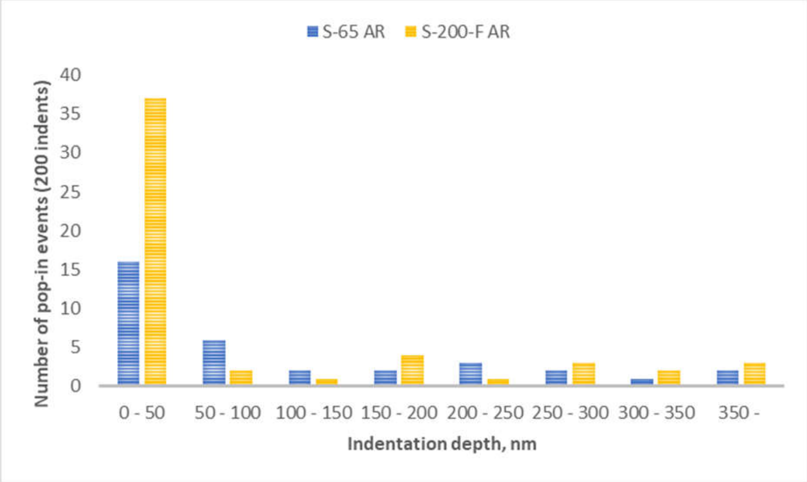

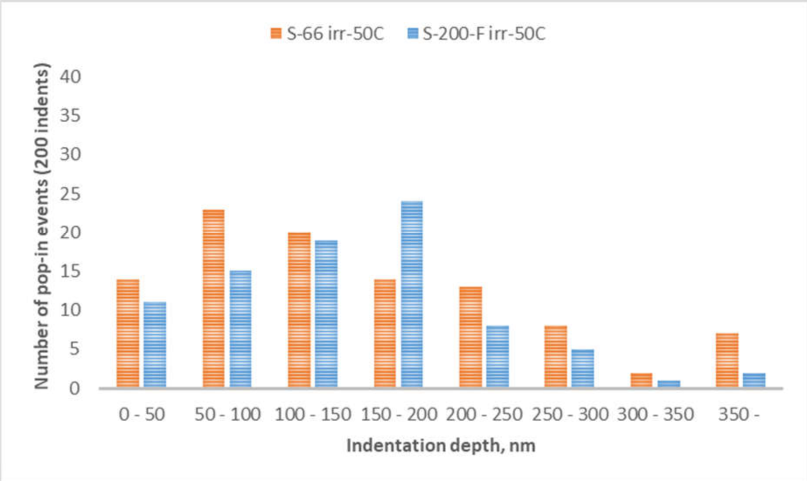

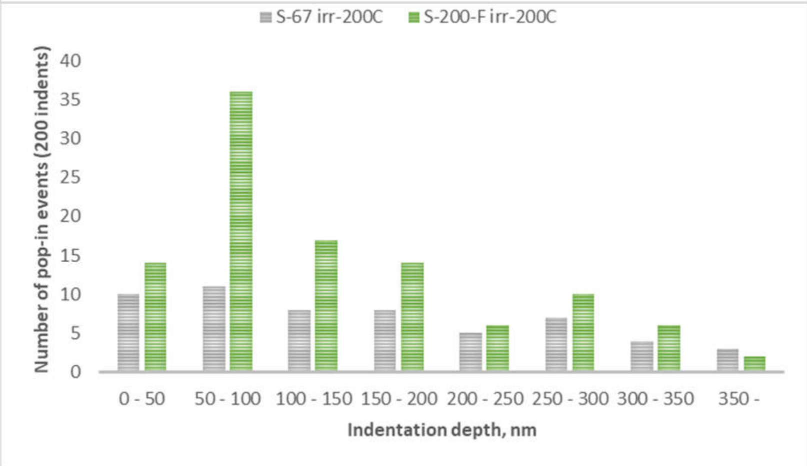

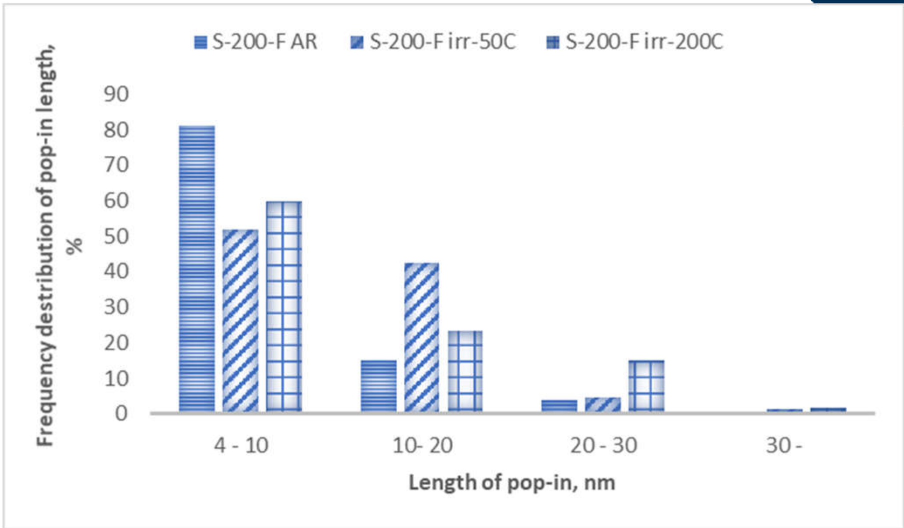

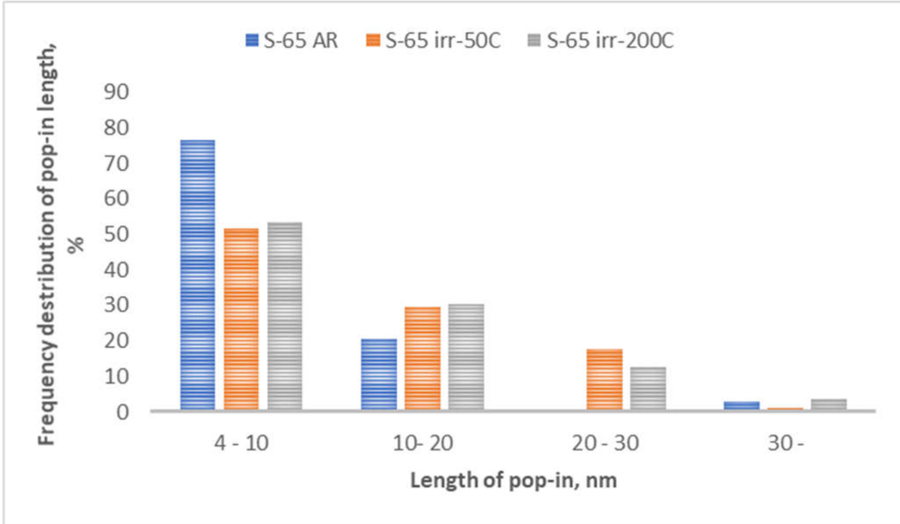

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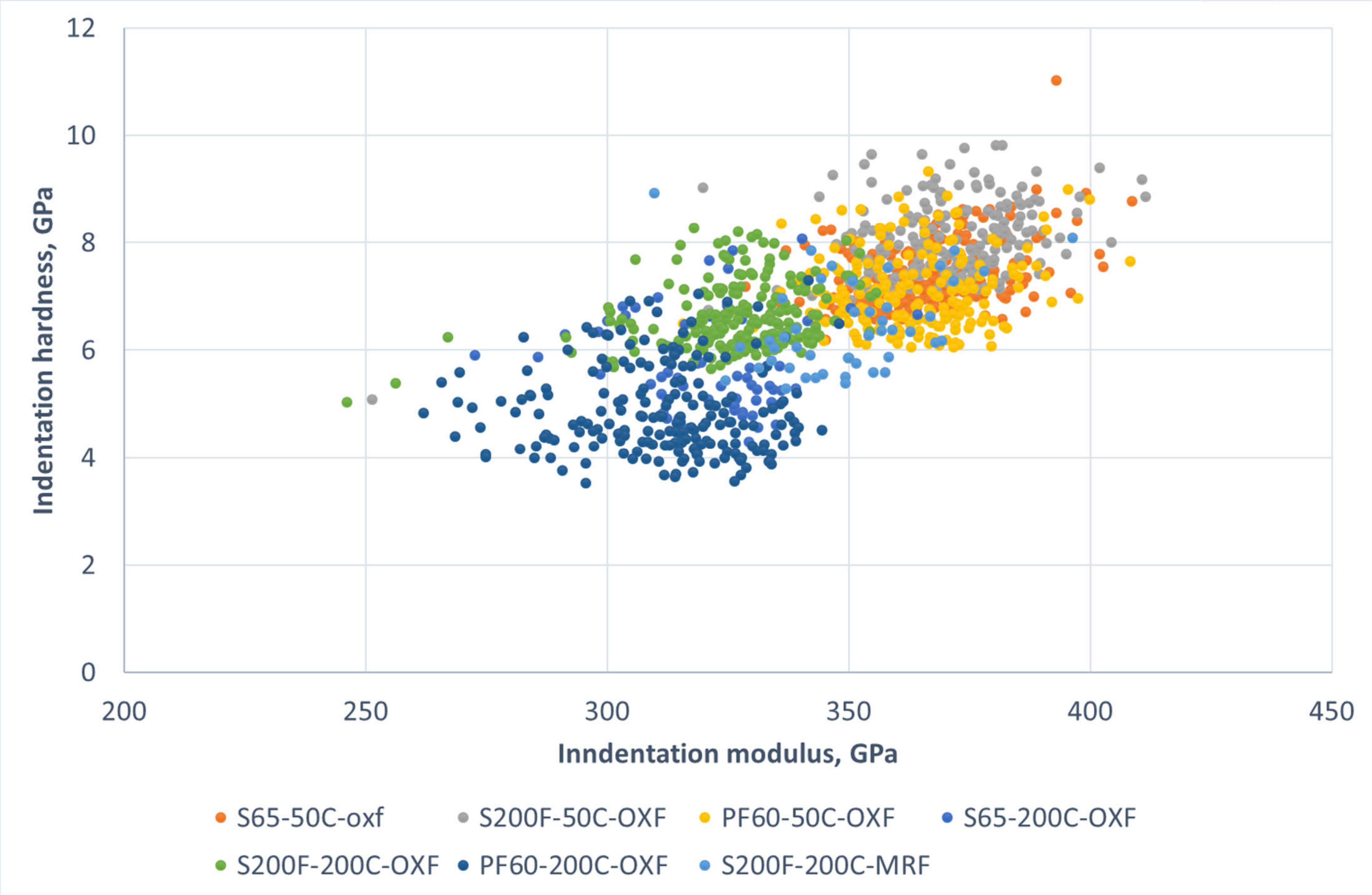
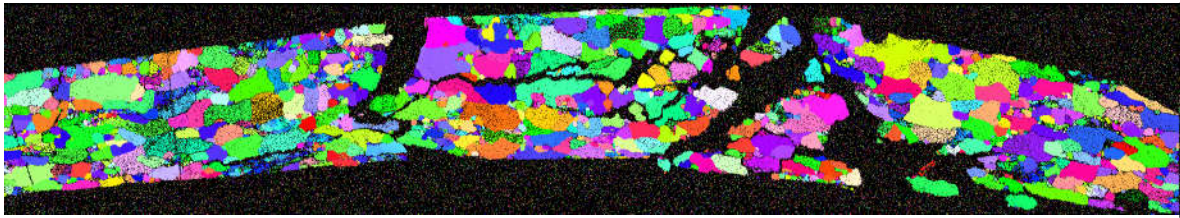
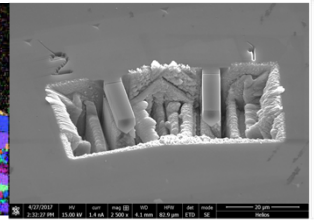
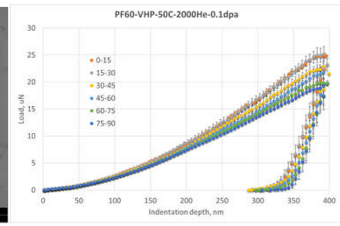


Conclusions

1. Radiation induces significant hardening and fracture mechanism change of beryllium even at 0.1 dpa
2. Irradiation at 200C leads to much lower hardening
3. Less pure grade has more hardening at 200C irradiation
4. Pop-in, pile-ups and contact stiffness are affected by He implantation

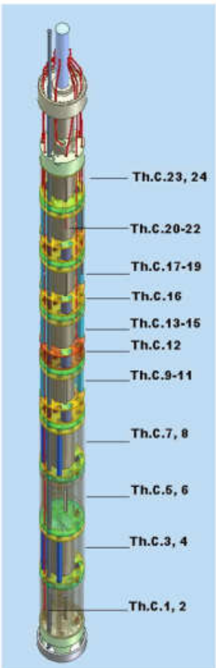






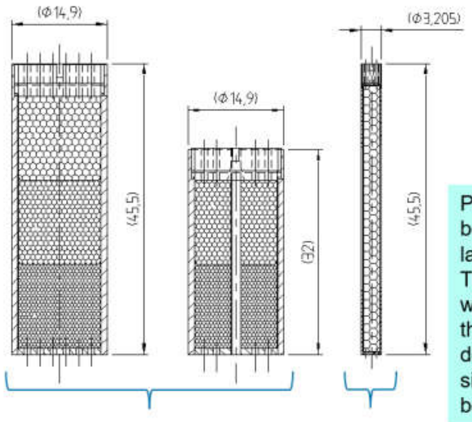
Microstructural and micromechanical investigation of beryllium pebbles from HIDOBE-02 experiment
Collaboration with KIT (Vladimirov, Chakin and the team)

HIDOBE-02 experiment at HFR, Petten



European programme (EFDA) and F4E in collaboration JP:

- Irradiation behaviour of beryllium under DEMO blanket relevant helium/tritium productions and temperatures
- Study microstructure evolution and tritium release/retention
- Study thermo-mechanical behaviour under irradiation
- **Achieve 30% of DEMO End-Of-Life Helium production**



Deformation parameters for pebble beds

Type	Diameter of pebble, mm	Height of PB, mm	Decrease of PB height, %
PB	0.5	~13	1.24
	0.5		1.03
	1		0.41
	1		0.97

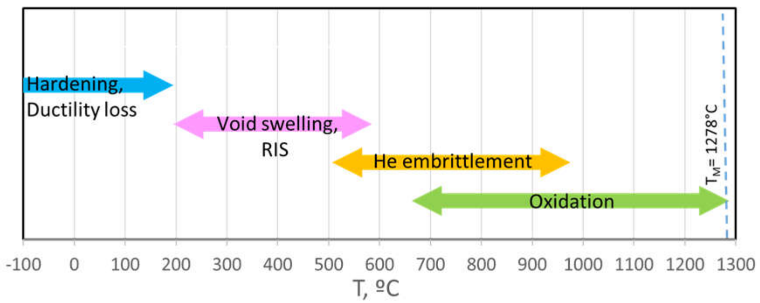
Pre-deformation allows to simulate the behavior of pebbles at high doses, when large swelling will be achieved.
The pebble swelling will be limited by the walls of the pebble bed. The response of the walls from the pebble swelling at high doses will deform the structure. This is the situation of constrained Be pebble bed before irradiation.

The irradiation parameters are very high for neutron irradiation test with beryllium:

- Duration 2005-2011 (48 reactor cycles, 1247 Full Power Days)
- Average temperature 370-650 ºC
- Damage dose 21-37 dpa
- Helium accumulation 3632-5925 appm
- Tritium accumulation 367-644 appm

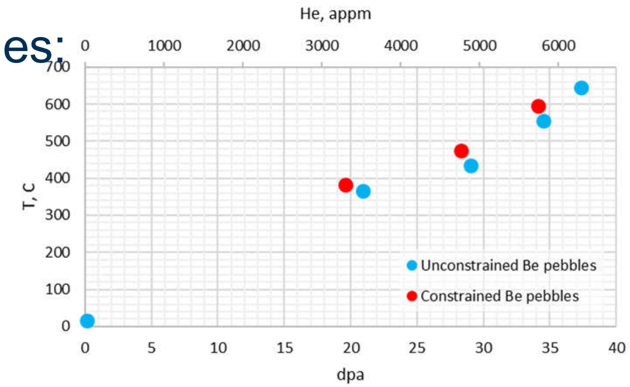
From Chakin et al. BeWS-13, Narita, CHIBA, Japan, 21-22 September, 2017

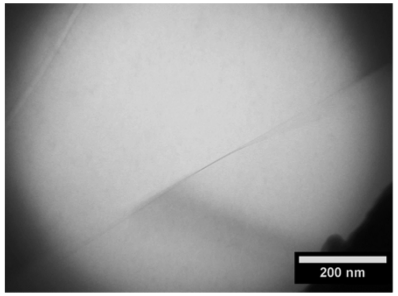
Beryllium: radiation induced effects

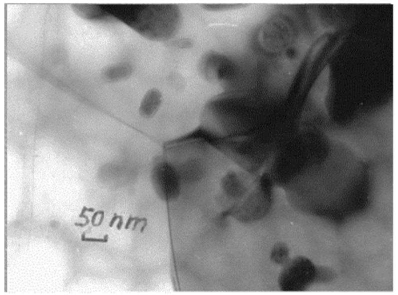


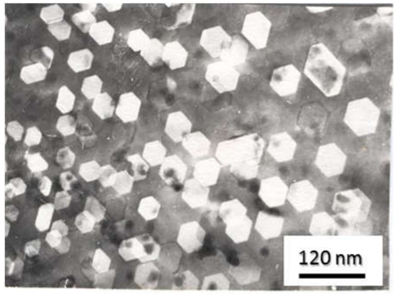
After Zinkle & Busby. Mater. Today (2009)

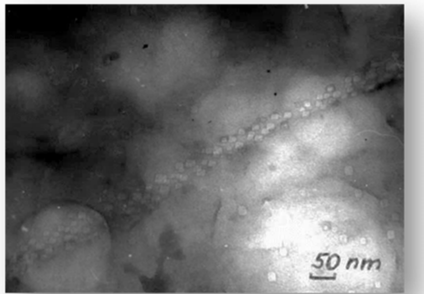
KIT samples:











T_{irr} = 50°C
NuMI beryllium.
0.5 dpa, 2000 appm of He

T_{irr} = 130–180°C SM reactor.
1.8-2,7 dpa, 600-1100 appm of He. (*B. Kupriyanov et al. F Eng. D.,* 2000)

T_{irr} = 400°C, BOR-60.
93 dpa, 34300 appm ^{4}He (Chakin, HPTW, Oxford, 2016)

T_{irr} = 650–700°C SM reactor.
2-3 dpa, 680-1140 appm of He. (*B. Kupriyanov et al. F Eng. D.,* 2000)

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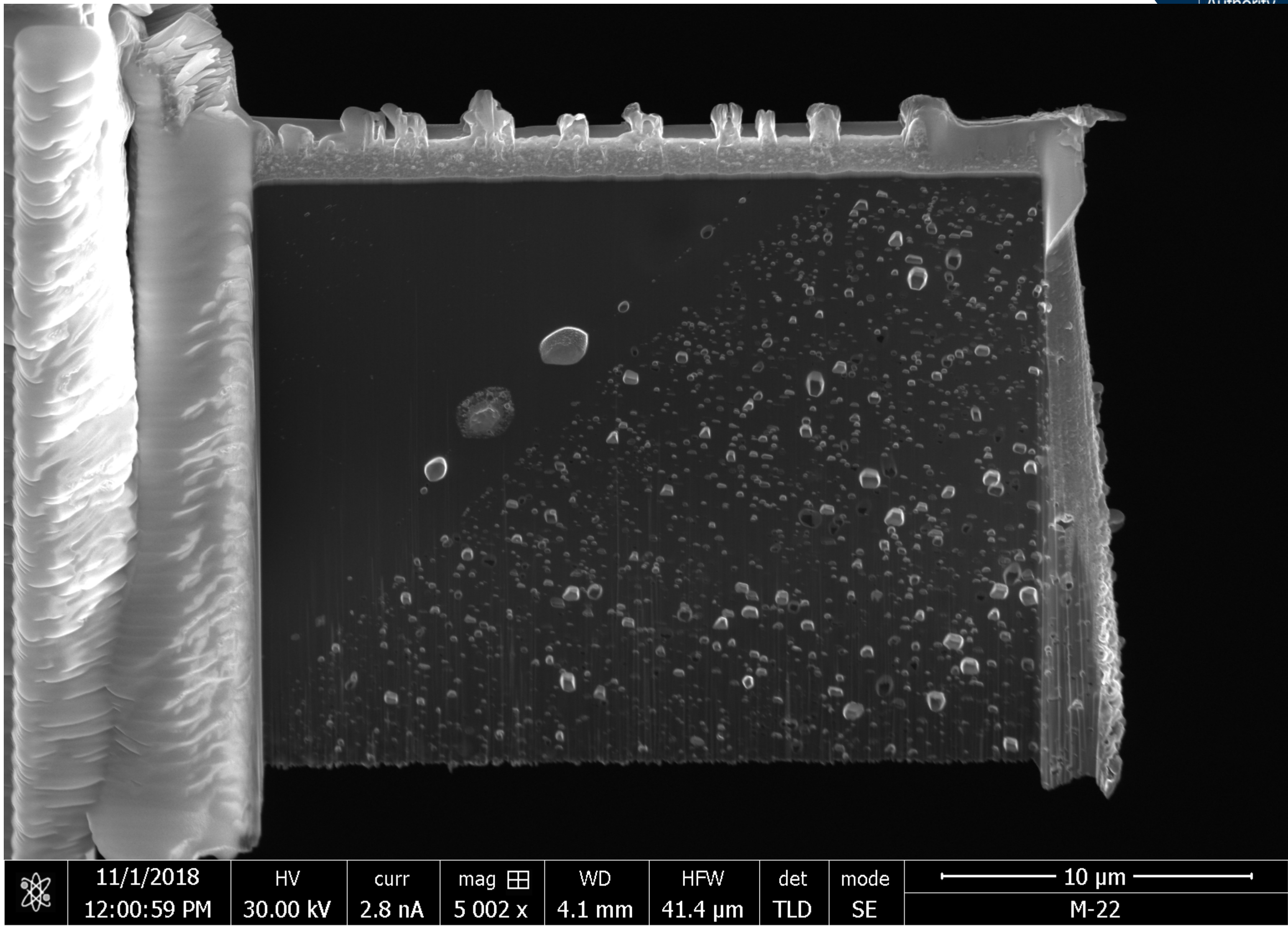

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Thank you!