Tungsten Status

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Yongjoong Lee (ESS)
19 May 2014

Talk outline

- Review of current knowledge of irradiated tungsten
- PIE possibilities
- (Call for) interested parties and potential collaborators
- ESS Tungsten status report (Yongjoong Lee)

(UK) National Nuclear Laboratory Literature Review

- On The Irradiation Response Of Be, W And Graphite for Proton Accelerator Applications
- R.B. Jones (BazNutec), G. Hall (Manchester), B. Marsden (Manchester) and C. A. English (NNL), November 2013
- Report not publicly available until copyright issues on all materials data resolved

NNL Literature review

Topic	Comments on data reviewed
Information on irradiation induced microstructure	Quantitative TEM information on loops, voids and matrix dislocation density at 600°C and 800°C for low doses ~ 0.15 dpa. *TEM of W and He ion-irradiated W 300°C-800°C up to 10s of dpa [recent additional news from Oxford]*
Void swelling	W is resistant to void swelling (as bcc) Fission neutron data available from 500-1500°C at < 10dpa. Peak swelling is ~1.5% at 800-1000°C.
Gas generation	Greater He and H generation expected for protons cf neutrons H<He for fission neutrons H>He for protons

NNL Literature review (II)

Topic	Comments on data reviewed
Hardening, loss of ductility	For p and n, $Hardening \propto \sqrt{dose}$ up to 20 dpa, 50-300°C. Tensile ductility falls rapidly to zero after < 0.1dpa, test at < 400°C, greater ductility up to 900°C. Very little systematic data on effect of irradiation temperature on hardening.
Ductile to brittle transition temperature (DBTT)	Large upward shifts in the transition temperature after irradiation; for example a shift of ~700°C was observed after 1 dpa at 300°C.
Fracture toughness	No information on the effect of irradiation found *[but see recent STIP results next]*

NNL Literature review (III)

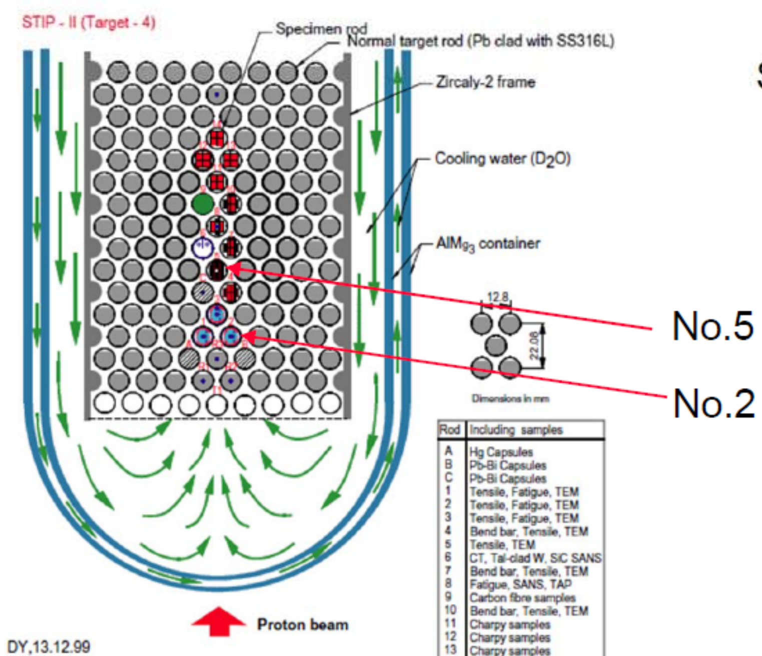
Topic	Comments on data reviewed
Irradiation and thermal creep	One datum on irradiation creep, one on stress relaxation. No general conclusions on irradiation creep sensitivity to applied stress and irradiation parameters could be formulated.
Corrosion	Enhanced corrosion rates in de-ionised water occurred due to radiolysis under the proton beam. Cladding of the W target with Ta has been successfully adopted as a remedy.
Physical properties	No data found on the effect of irradiation on physical properties of W *[KIT reported to have data on effects of neutron irradiation on thermal conductivity]*

Mechanical properties of W alloys and pure Ta irradiated at SINQ target 4

***S. Saito*, D. Hamaguchi**
JAEA
K. Kikuchi,
Ibaraki Univ., Frontier Research Center
K. Suzuki ,S. Endo, H. Obata
JAEA, Dept. of Hot Laboratories and Facilities
H. Kurishita, R. Watanabe
Tohoku Univ.
M. Kawai
KEK
Y. Dai
PSI, Spallation Source Division

2. Experiment -Irradiation condition-

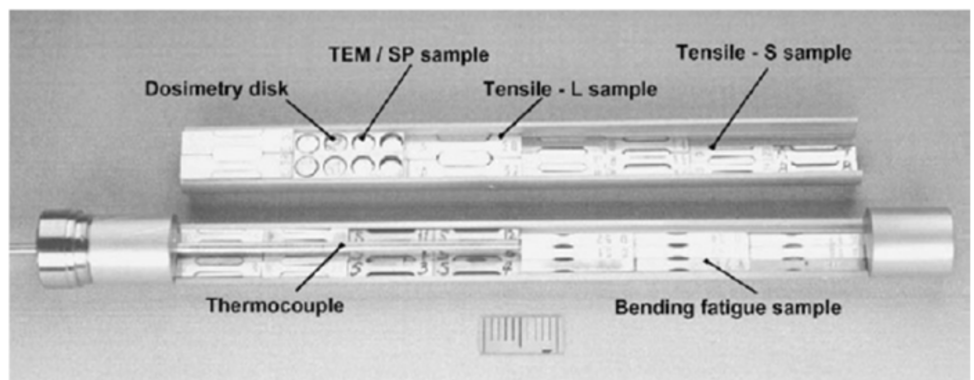
- Irradiation : STIP-II (SINQ target-4)
- Proton energy : 580 MeV
- Irradiation temperature : 132 - 378℃
- dpa (proton+spallation neutron) : 6.5 - 19.5 dpa (in steel)
- Specimen rod :Rod No.2 and 5



Rod	Including samples
A	Hg Capsules
B	Pb-Bi Capsules
C	Pb-Bi Capsules
1	Tensile, Fatigue, TEM
2	Tensile, Fatigue, TEM
3	Tensile, Fatigue, TEM
4	Bend bar, Tensile, TEM
5	Tensile, TEM
6	CT, Tal-clad W, SiC SANS
7	Bend bar, Tensile, TEM
8	Fatigue, SANS, TAP
9	Carbon fibre samples
10	Bend bar, Tensile, TEM
11	Charpy samples
12	Charpy samples
13	Charpy samples
14	Charpy samples

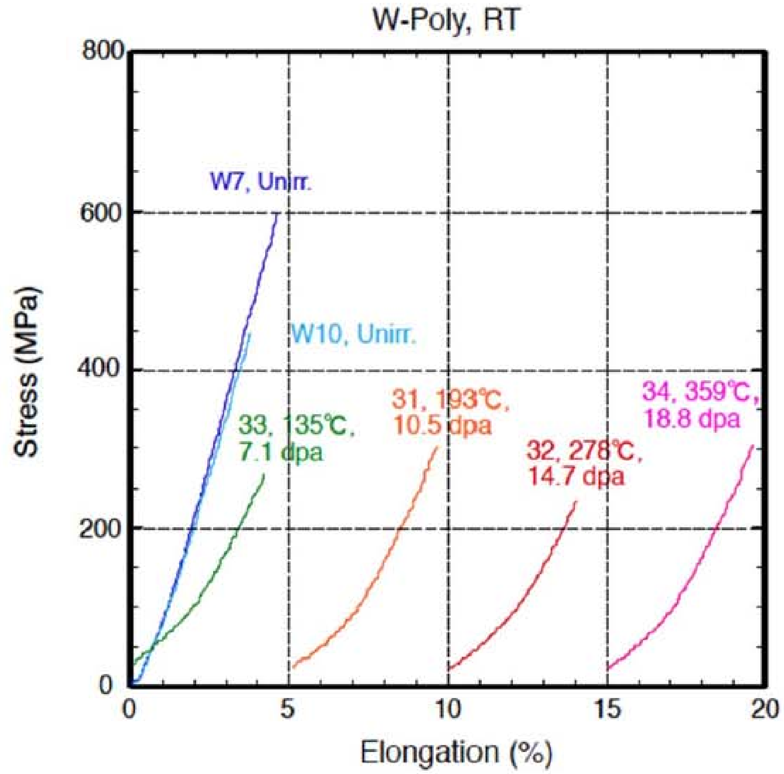
◆ Thermocouple

STIP-II (SINQ target-4)



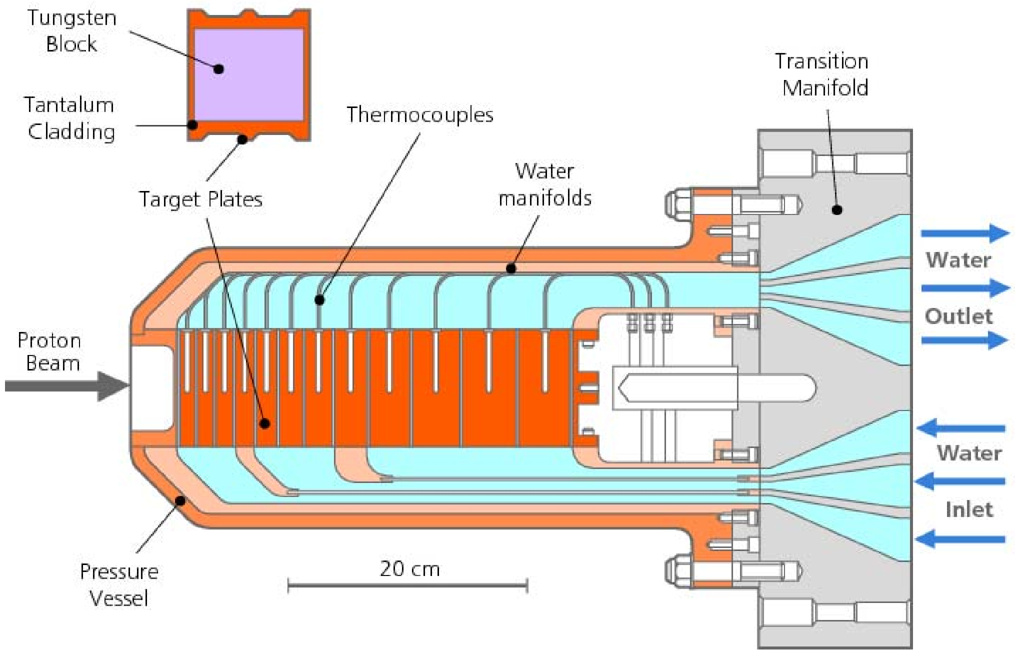
Y. Dai et al. / Journal of Nuclear Materials 343 (2005) 33–44

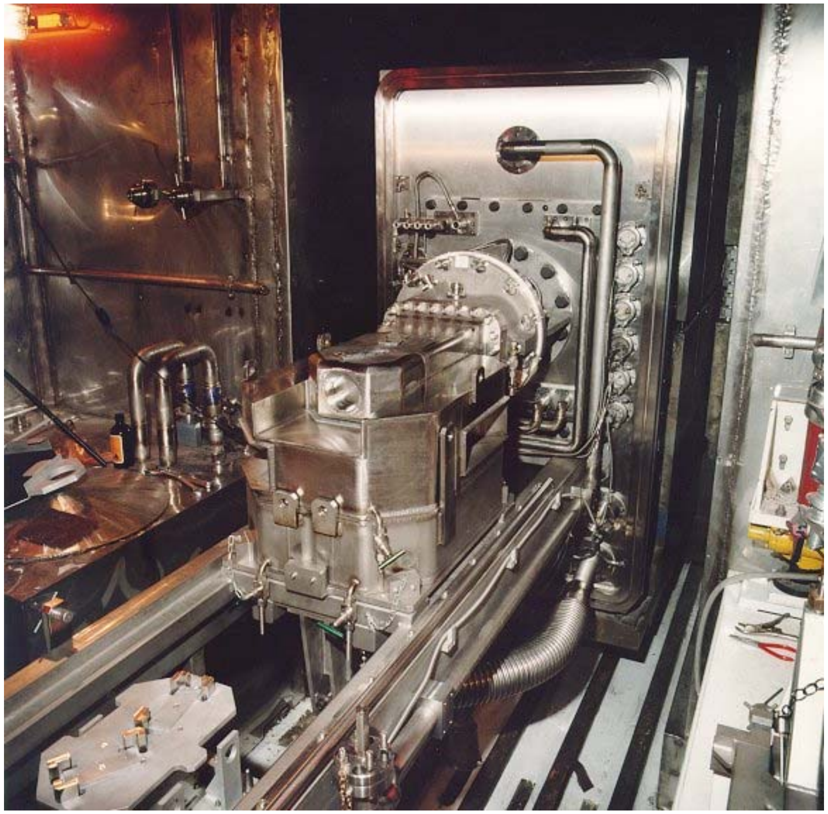
3. Results and discussion (W-Poly)



- Both un-irradiated and irradiated specimens fractured before yield.
- The fracture stress of the irradiated specimens decreased to about half of un-irradiated specimens.
- No dose dependence is clearly seen for the fracture stress of the irradiated specimens.

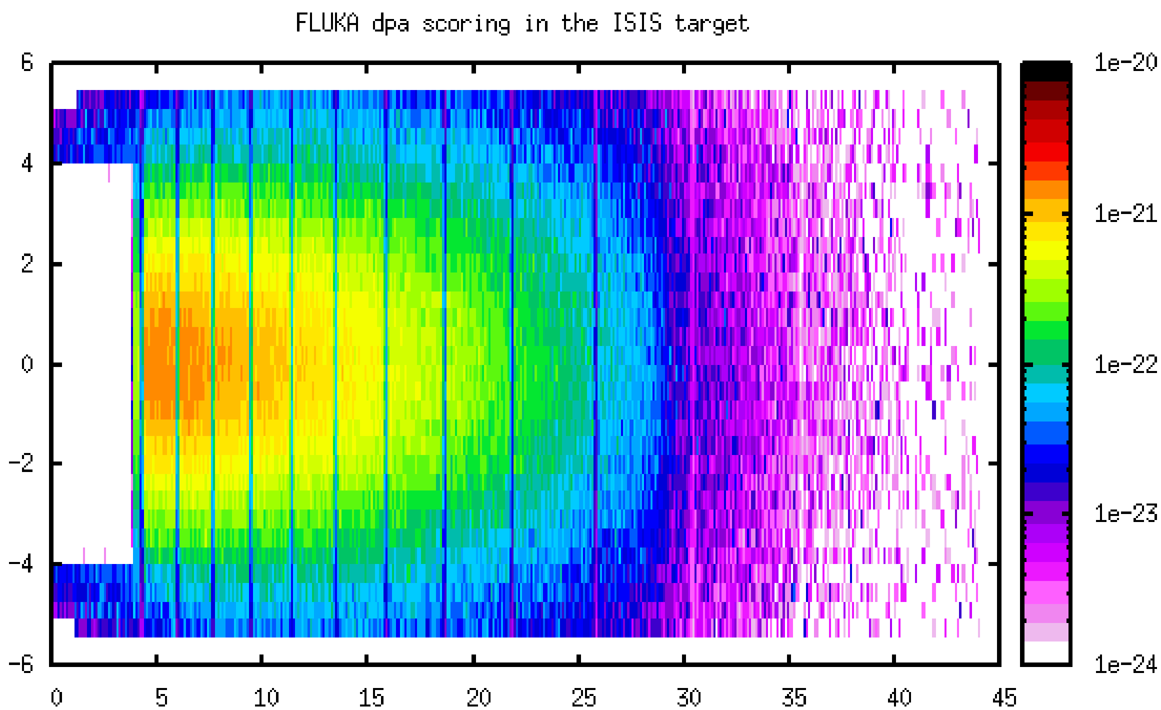
ISIS target (TS1) at RAL



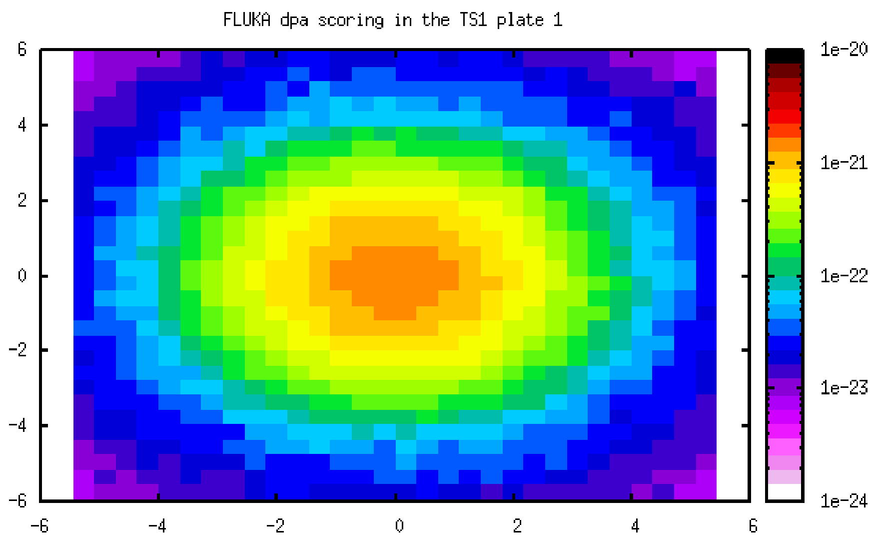


ISIS TS1 summary of FLUKA results (T.Davenne)

Target Plate [800MeV sigx=16.3mm sigy=16.3mm]	max dpa/proton	dpa/s at 210µamps (equivalent to 1.31e15protons/s)	dpa per year 2e7s	Total Power deposited at 210µamps [kW]	Peak energy density at 210µamps [W/m3]	max temp calculated with CFX at 210µamps [°C]
1	1.90E-21	2.49E-06	49.8	11.76	4.79E+08	207
2	1.67E-21	2.19E-06	43.8	12.14	4.64E+08	205
3	1.26E-21	1.65E-06	33.0	12.18	4.11E+08	199
4	1.19E-21	1.56E-06	31.2	11.97	3.67E+08	200
5	9.40E-22	1.23E-06	24.6	11.3	3.21E+08	191
6	7.10E-22	9.30E-07	18.6	10.96	2.46E+08	179
7	5.20E-22	6.81E-07	13.6	9.99	1.86E+08	161
8	4.00E-22	5.24E-07	10.5	9.11	1.32E+08	151
9	3.00E-22	3.93E-07	7.9	8.32	9.01E+07	146
10	1.38E-22	1.81E-07	3.6	5.38	6.34E+07	109
11	2.30E-23	3.01E-08	0.6	0.24	5.15E+06	33
12	1.77E-23	2.32E-08	0.5	0.11	4.18E+06	31



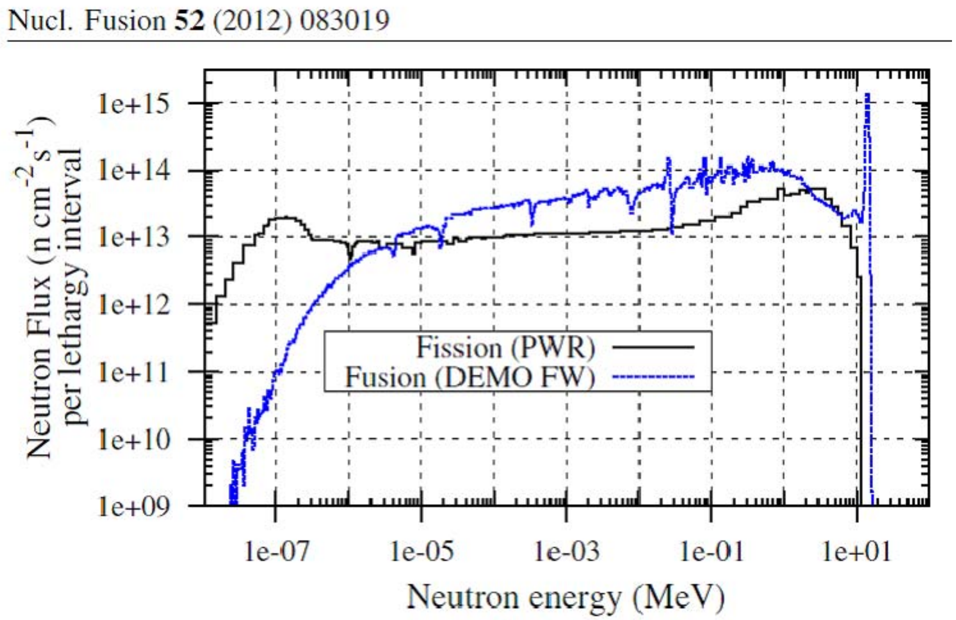
Variation of dpa through out target



Variation of dpa across a target plate

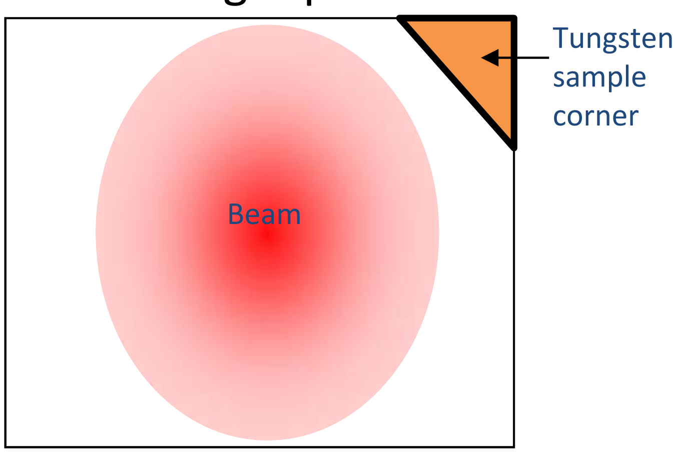
Applicability to fusion materials research? (T.Davenne)

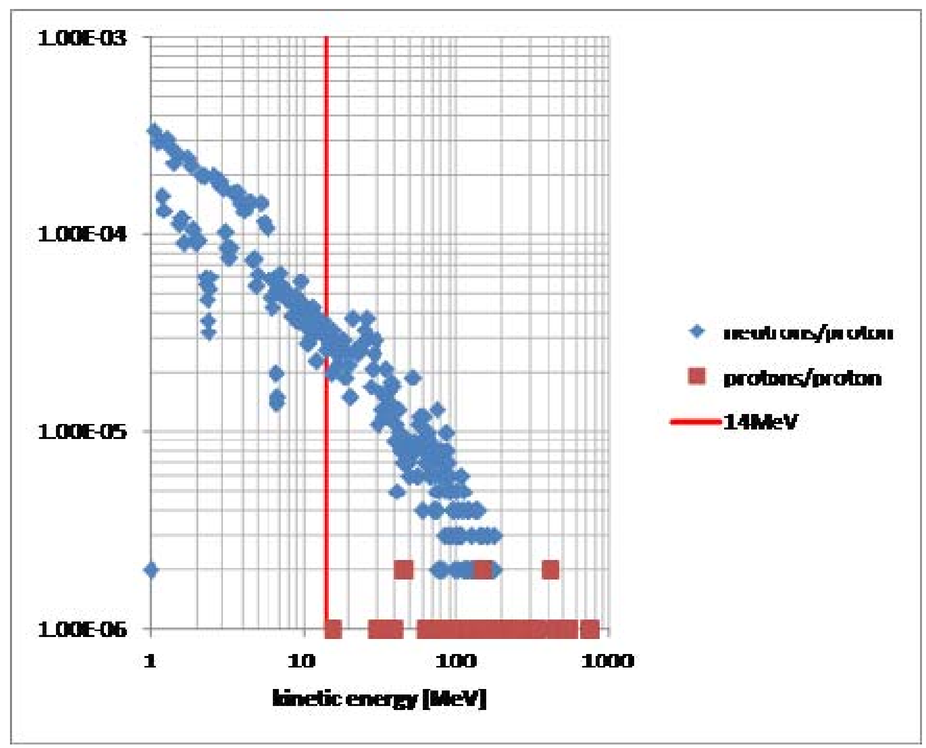
Typical fusion neutron spectrum



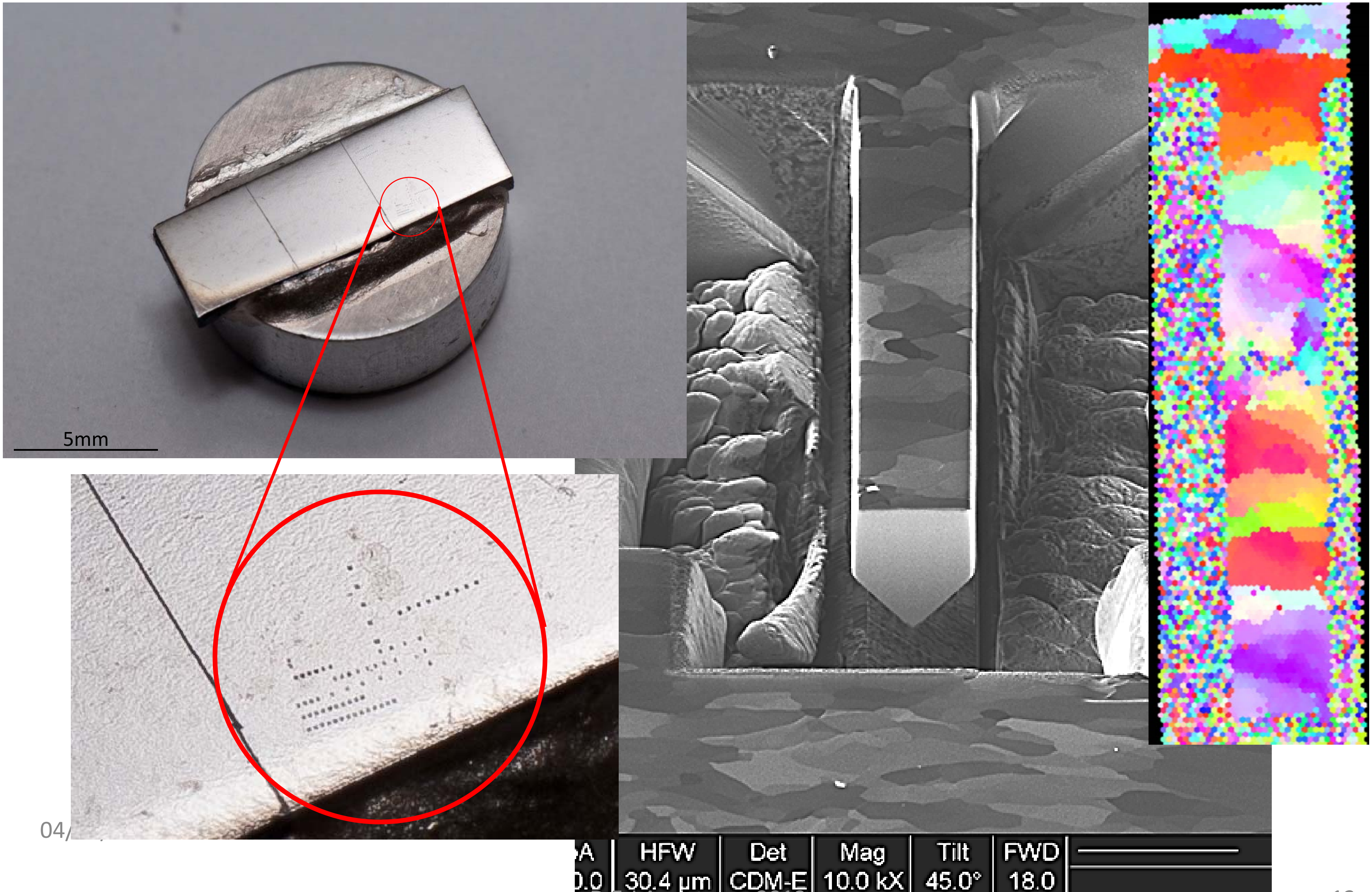
Fluka calculation indicates ≈1dpa per fpy in sample corner and the following neutron and proton flux

Consider a sample corner of a TS1 target plate

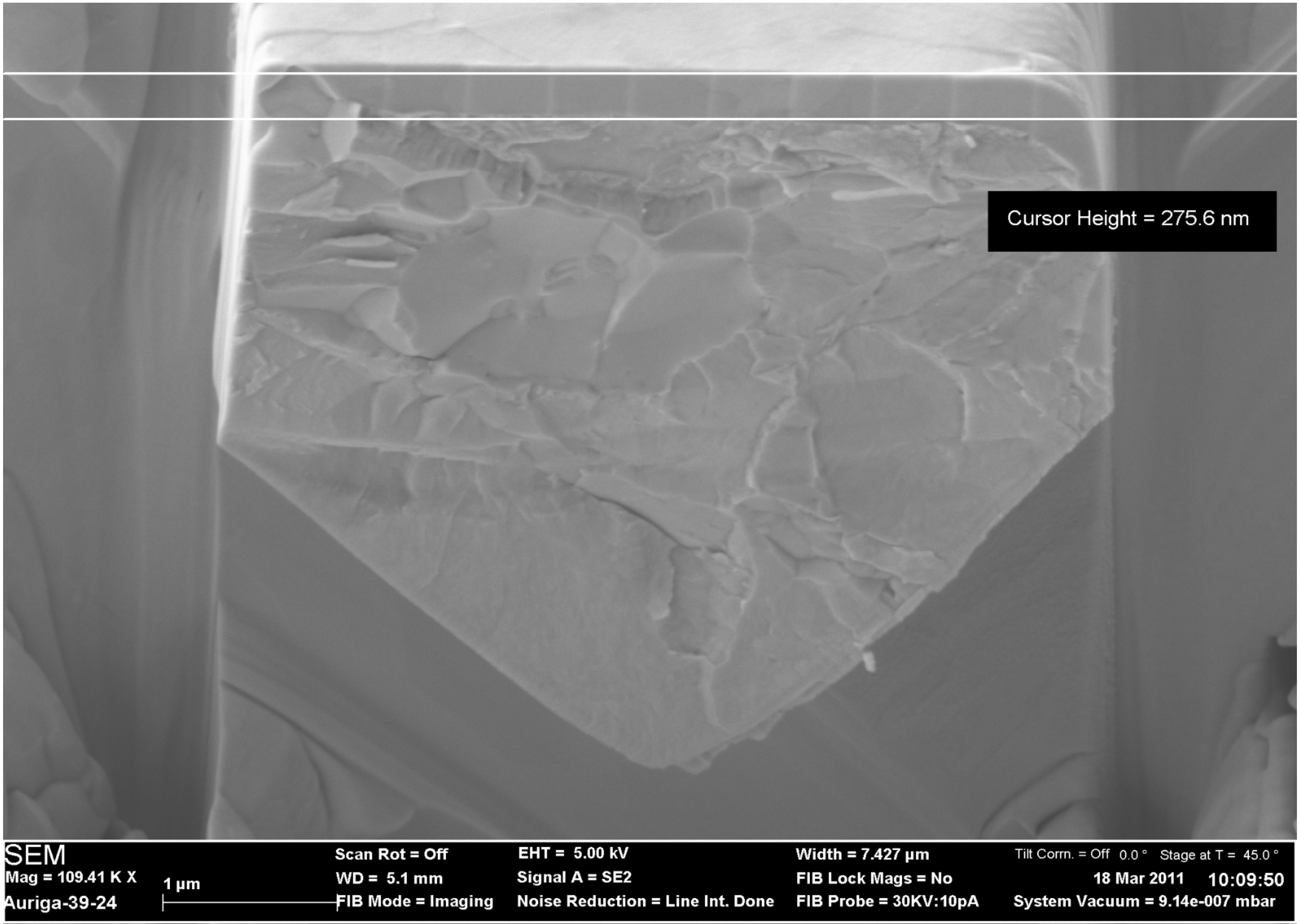




W5Ta micro-cantilever sample (D. Armstrong)



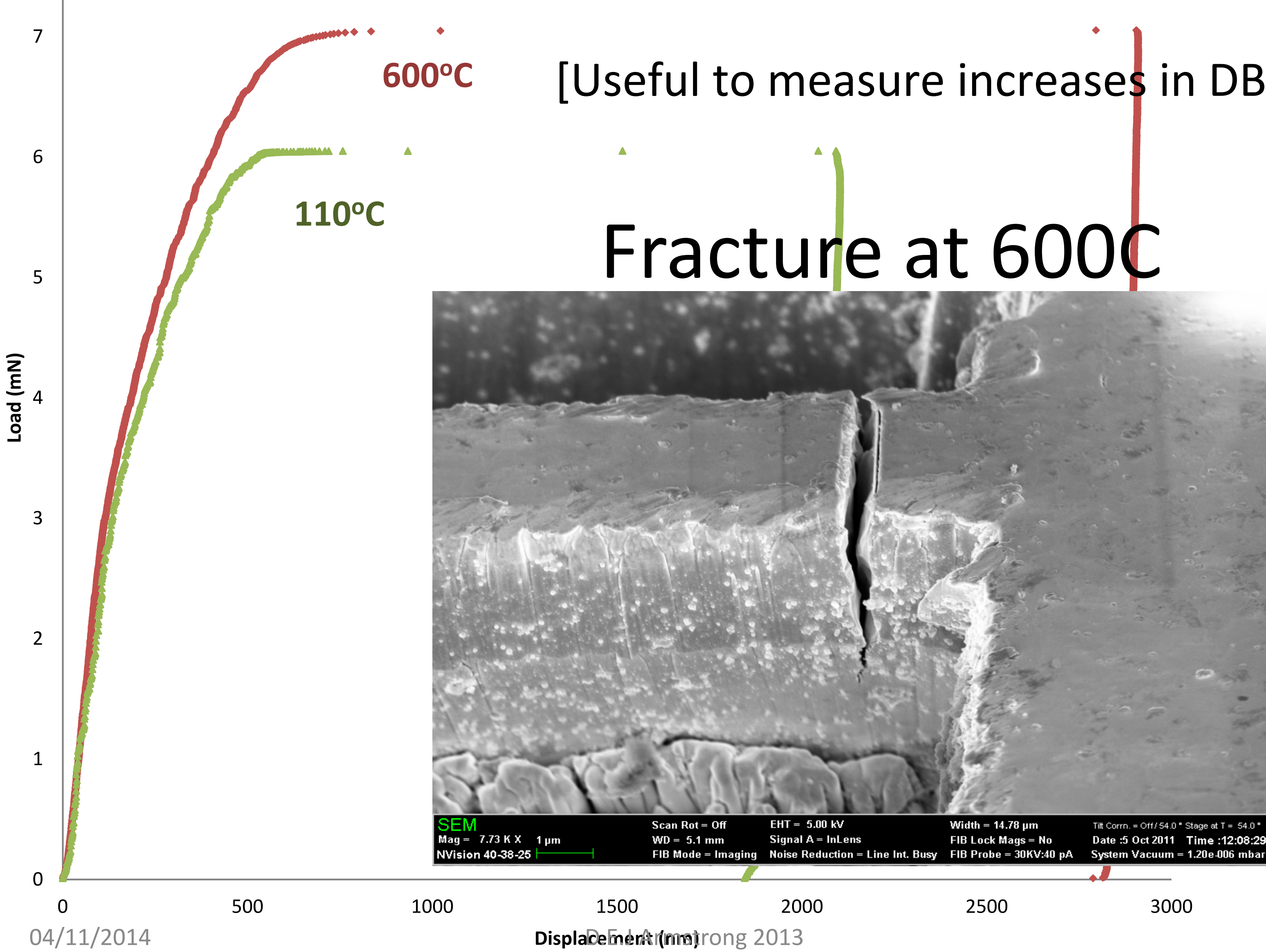
Tested micro-cantilever (D. Armstrong)



Elevated Temperature Results (D. Armstrong)

[Useful to measure increases in DBTT]

Fracture at 600C



Updated RaDIATE table of proton irradiated tungsten

Physical Description			Beam Parameters			Irradiation Parameters							Status		Comments
Name	*Quantity*	*Size and Form*	*Energy (GeV)*	*Spot Size (sigma - mm)*	*Pulse Structure*	*Average Temp (˚C)*	*Peak Temp (˚C)*	*Environment*	*Peak Proton Fluence (p/cm^2)*	*Peak Damage (DPA)*	*Gas Production (appm/DPA)* He	*Gas Production (appm/DPA)* H	*Current Location*	*Activity (Bq)*	
ISIS TS1	12 plates	80 mm height, 105 mm width	0.8	16	0.1 µs pulse of 2.5e13 at 50 Hz, 27 years operation	Min: 30, Max: 250	ΔT/pulse : 10	water (D_2O) around tantalum clad	4.96E+22	~250 dpa			RAL	~10^{13}	5 years operation, 5 years cooling
ISIS TS2	1	56 mm diameter, 300 mm length	0.8	6	0.1 µs pulse of 2.5e13 at 50 Hz, 4 years operation	Min: 36, Max: 400	ΔT/pulse : 39	water (H_2O) around tantalum clad	5.23E+22				RAL		~ 1 year target lifetime
BLIP CTE Sample	5		0.2	σx = 9.4, σy = 6.4	525 µs pulse of 7.5e13 at 7.5 Hz	900	---	water	2e13 $p/cm^2.s$	2			BLIP-BNL		lost mass due to water
BLIP Tensile Sample	7		0.2	σx = 9.4, σy = 6.4	525 µs pulse of 7.5e13 at 7.5 Hz	900	---	water	2e13 $p/cm^2.s$	2			BLIP-BNL		lost mass due to water
STIP (SINQ)	2	rods	0.58			Min: 132, Max: 378	---			6.5 - 19.5			PSI		PIE carried out on: W-Poly (Tokyo tungsten, 99.99% purity), W-Sin (Tokyo tungsten), W-TiC (Tohoku Univ., W(4N) + TiC(3N), TiC : 0.25 wt.%),W-SUS (Tohoku Univ., W : 93 wt.%, 304L : 7 wt.%)

ISIS target PIE: Potential collaborators

- ISIS/RAL
  - MD Fletcher, DM Jenkins, JRJ Bennett, TR Edgecock
  - CJ Densham, T Davenne, O Caretta, P Loveridge
- UK National Nuclear Users Facility (NNUF)
  - M O'Brien, C Hardie (Culham Centre for Fusion Energy)
  - Sellafield to cut up (£££ quote expected)
  - Culham to test (ready Sept 2015)
- Oxford (Materials for Fission & Fusion Power)
  - SG Roberts, D Armstrong, J Gibson (Micro-fracture tests)
- SCK-CEN, Belgium
  - I. Uytdenhouwen
- JAEA?
- KIT?
- PNNL?
- ESS
  - Yongjoong Lee

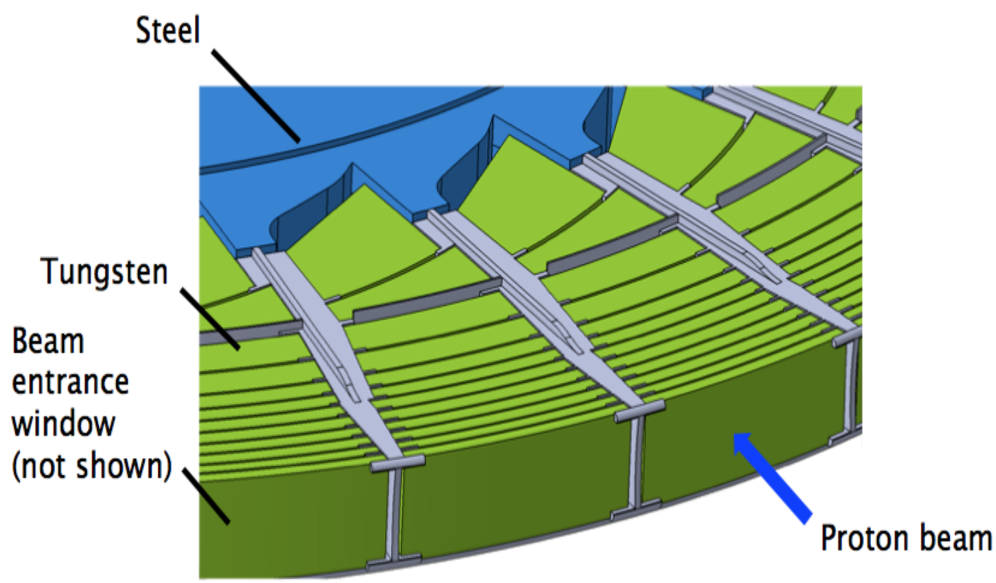
Tungsten Status Report: ESS

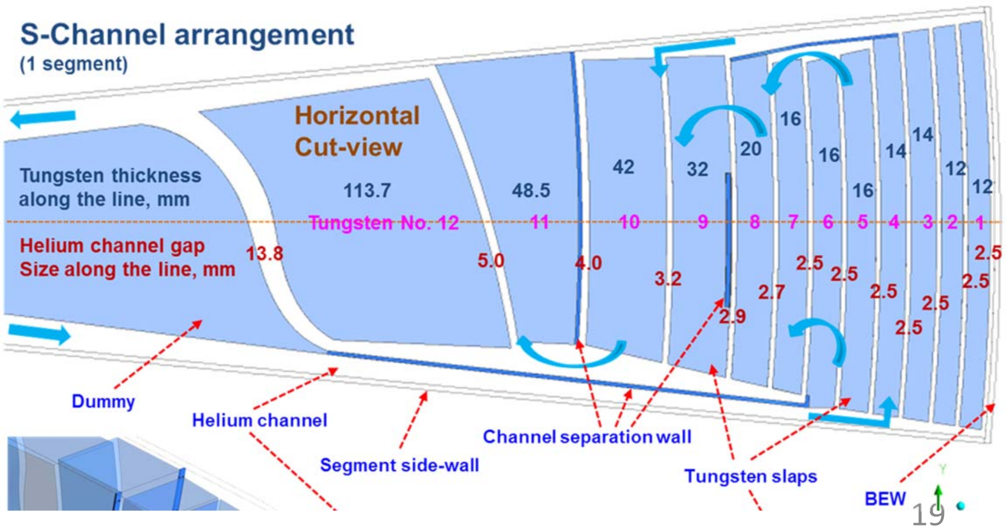
Yongjoong Lee
Materials, Target Division

RaDIATE Collaboration Meeting
May 19, 2014

Tungsten at ESS

- 5 MW spallation source
  - 5 MW (2.0 GeV/2.5 mA) proton beam
  - 2.86 ms long beam pulse with 14 Hz repetition rate
- Rotating tungsten target:
  - Helium cooled target with water cooled backup
- Structural integrity of tungsten is important for reliable target operation





Target Material Study Plan

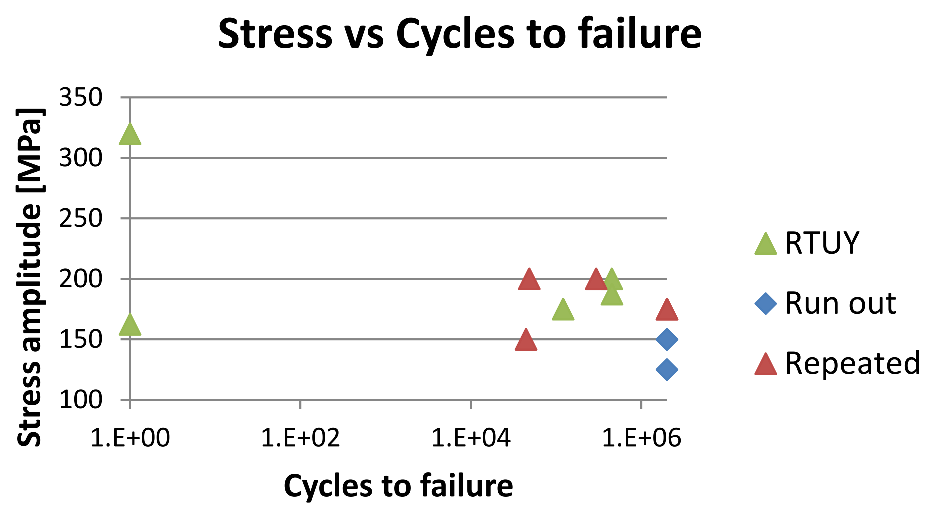
- Tungsten
  - Non-Irradiated
    - Oxidation in inert gas
    - Mechanical properties
      - DBTT
      - Tensile strength
      - Fatigue endurance
    - Tungsten with coating/cladding
  - Irradiated
    - Mechanical Properties
      - DBTT
      - Tensile strength
      - Microstructure
    - Thermal properties

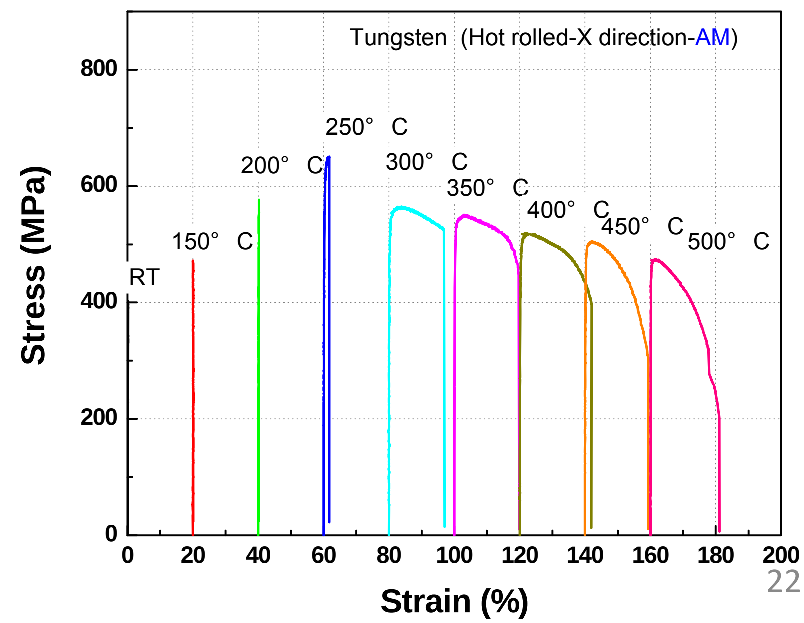
Target Material Study Partners

- Partners
  - Yongjoong Lee (ESS)
  - Jemila Habainy (ESS, LTH)
  - Srinivasan Iyengar (LTH)
  - Yong Dai (PSI)

Status Report: Mechanical Strength

- Tensile and fatigue properties of tungsten at different temperatures are being examined (Lund University)
  - Three different vendors were chosen for the tests.
  - The mechanical properties of hot rolled and hot forged tungsten specimen are being studied, for different surface smoothness and grain orientations.
- Mechanical strength of tungsten at different temperatures are being studied with mini-samples (PSI)
  - Small punch test, three point bending tests and tensile tests are being performed.
  - The DBTT for the tested specimen are being identified.





Status Report: Tungsten Oxidation

- Tungsten oxidation at different temperatures are being examined (Lund University)
  - The tests are being performed in inert gas (Ar, He) with different O2 or H2O impurities
  - ”Pure” is not pure enough – Tiny impurity of oxygen ≤ $5\cdot10^{-6}$ atm led to oxidation at 500°C.
  - Oxidation was observed from 400°C.
- Using WO3 specimen, the threshold temperature for WO3 evaporation in air is being investigated (Lund University)

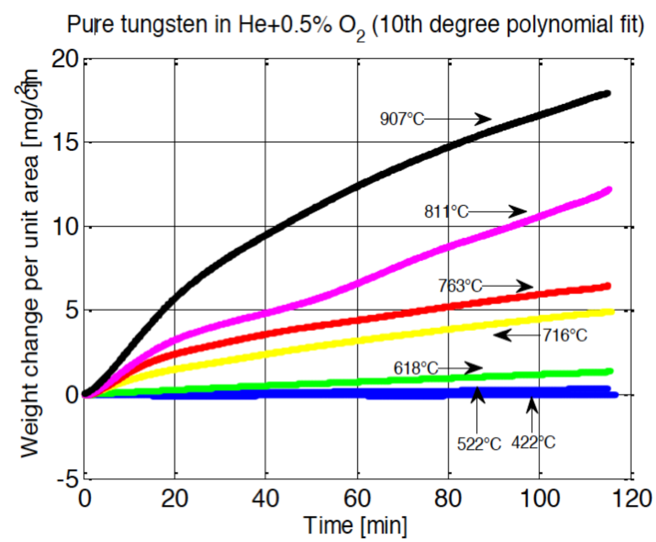


Figure 5.8 Tenth degree polynomial fit to the results in the TGA with helium and 0.5% oxygen

Status Report: Tungsten PIE at PSI

STIP	Tungsten Type	Dimension	Qty	Irradiation Condition
STIP-V (2007-2008)	HR-W for CSNS	60 x 8 x 1 [mm3]	2	5-28 dpa at 100-800 C
STIP-VI (2011-2012)	HR-W from Goodfellow	27 x 5(6) x 0.5 [mm3]	52	5-25 dpa at 100-600 C
STIP-VII (2013-2014)	HR-W from a Chinese vendor	Bend bar	10	5-35 dpa at 100-600 C
STIP-VII (2013-2014)	HR-W from a Chinese vendor	Rods with HIP'ed Ta cladding/canning	11	5-35 dpa at 100-600 C
STIP-VII (2013-2014)	HIP'ed PIM-W from KIT	Bend bar	5	5-35 dpa at 100-600 C
STIP-VIII (2015-2018)	TBD	TBD	TBD	TBD

PIE Plan for STIP-V Tungsten Specimen

PIE	Anticipated Results
Bend tests at high temperatures	Flexure and yield strength
Small punch tests	Tensile strength and ductility
Hardness tests at RT	Irradiation hardening
Thermal diffusion tests at different temperatures	Thermal conductivity and specific heat capacity at different temperatures
Scanning electron microscopy (SEM)	Fracture mode at different doses and temperatures
Transmission electron microscopy (TEM)	Microstructure change at different doses and temperatures
Thermal desorption spectroscopy (TDS)	H, D, T retention

Time Plan: STIP-V Tungsten Specimen

	Start	Finish
Project Preparation	2014.01.01	2014.03.31
Mechanical tests with cold samples	2014.04.01	2014.09.30
Transport of STIP-V rods to PSI-East	2014.04.01	2014.06.30
Sample preparation for PIE	2014.07.01	2014.09.30
Mechanical and thermal tests	2014.10.01	2015.03.31
Microstructure analyses	2015.04.01	2015.06.30
Thermal desorption spectroscopy	2015.07.01	2015.09.30
Synthesis analysis and report	2015.07.01	2015.09.30
Data analyses and publication of the results	2015.07.01	2015.12.31

PIE of STIP-VI/VII Tungsten Specimen

- PIE of each STIP specimen set roughly costs 0.5 MEUR.
- STIP-VI are for general material properties of tungsten after irradiation
- STIP-VII specimen are for investigating the properties of cladding and canning.
- STIP-VIII will include a number of chosen tungsten specimen.
- Collaboration can be set up for STIP-VI/VII tungsten PIE.