

Update on ISIS Targets: Analysis and Operating Experience

Dan Wilcox, High Power Targets Group,
Rutherford Appleton Laboratory

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13th - 17th April 2026

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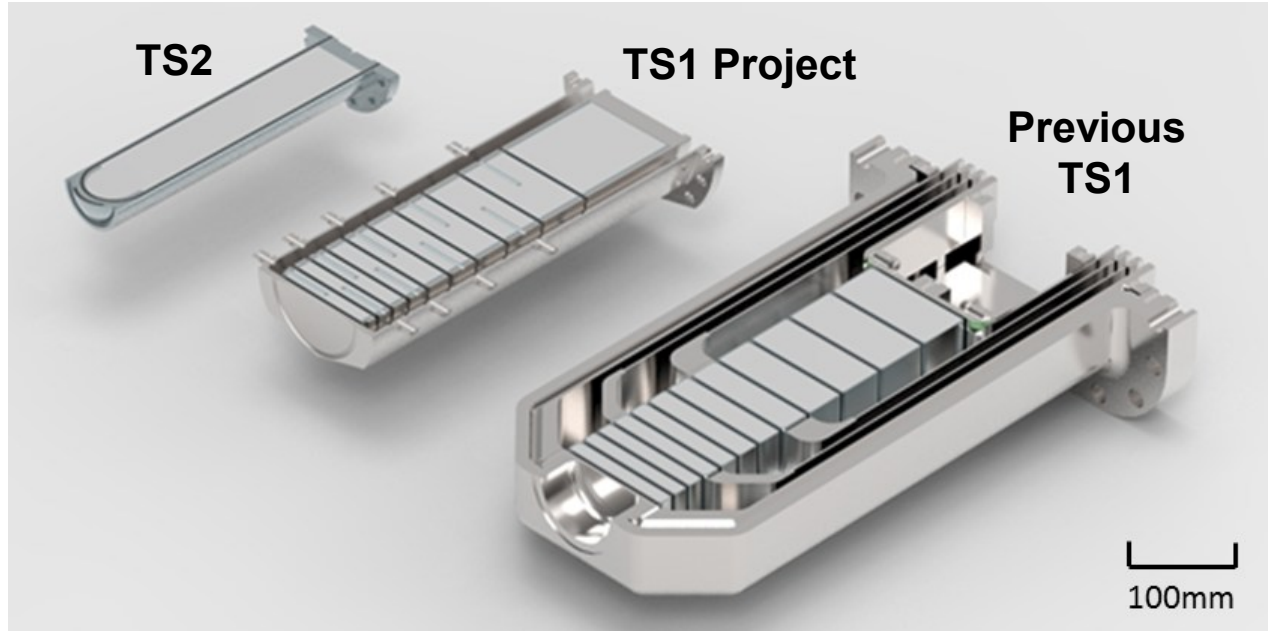


An aerial photograph of the ISIS facility

Current ISIS Targets

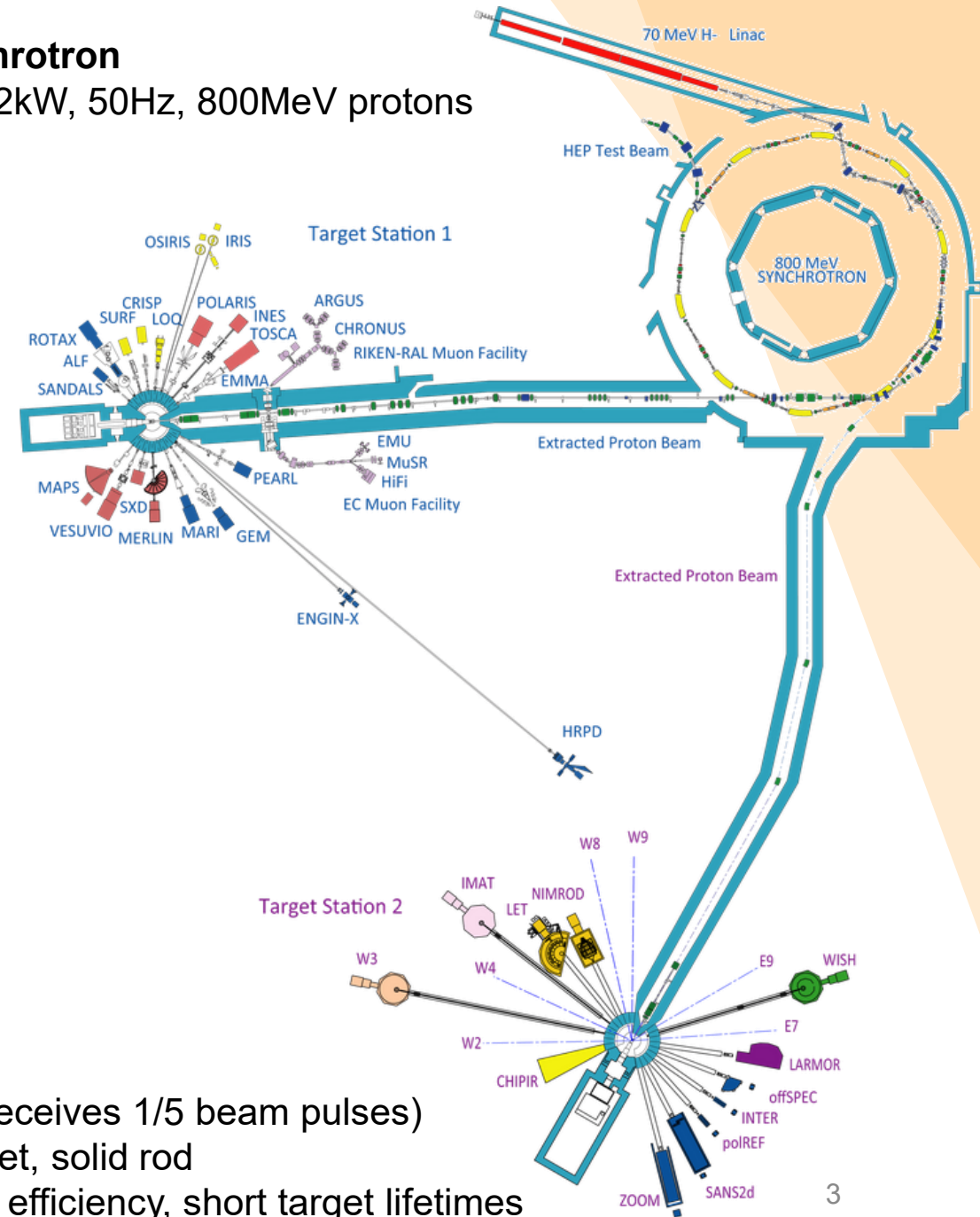
Target Station 1

- 160kW, quasi-50Hz (receives 4/5 beam pulses)
- Ta-clad W target, 10 plates (formerly 12)
- Proven reliability over many years
- New design of target, moderator and reflector installed late 2022, now in operation



Synchrotron

- 192kW, 50Hz, 800MeV protons

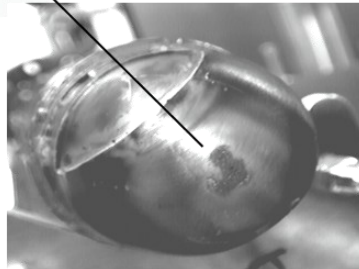
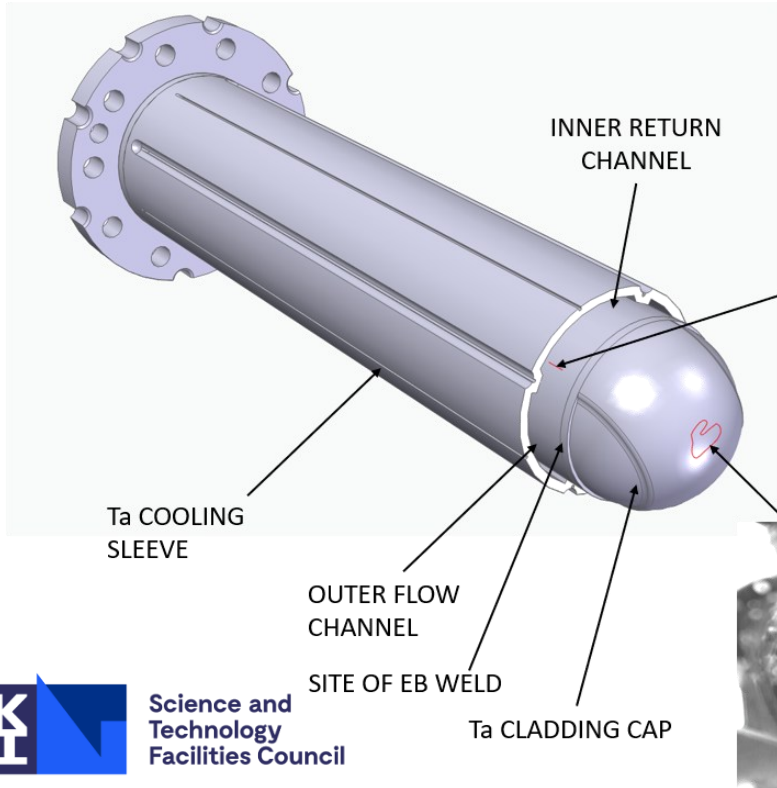


Target Station 2

- 32kW, 10Hz (receives 1/5 beam pulses)
- Ta-clad W target, solid rod
- High neutronic efficiency, short target lifetimes

PIE Evidence – TS2 Target #4

- Visible crack in tantalum cladding – consistent with measurements of tungsten in cooling water
- Surface damage but no visible cracks at target nose
- Videos of end cap removal suggest significant ductility is retained in tantalum



See talk by Stephen Gallimore,
16th April 13:30

Simulating Radiation Damage

Radiation damage is now included in all ISIS target simulations

DPA map calculated from accumulated beam on target then imported from FLUKA/MCNPX

Each material property can be a function of DPA

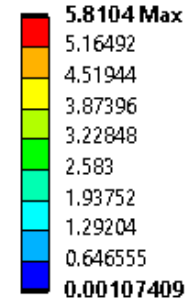
Major changes in irradiated tungsten:

- **UTS: 560 -> 300 MPa** after 1.3 DPA
 - **k: 175 -> 88 W/(m.K)** after ~2 DPA
- } No further change up to 27 DPA

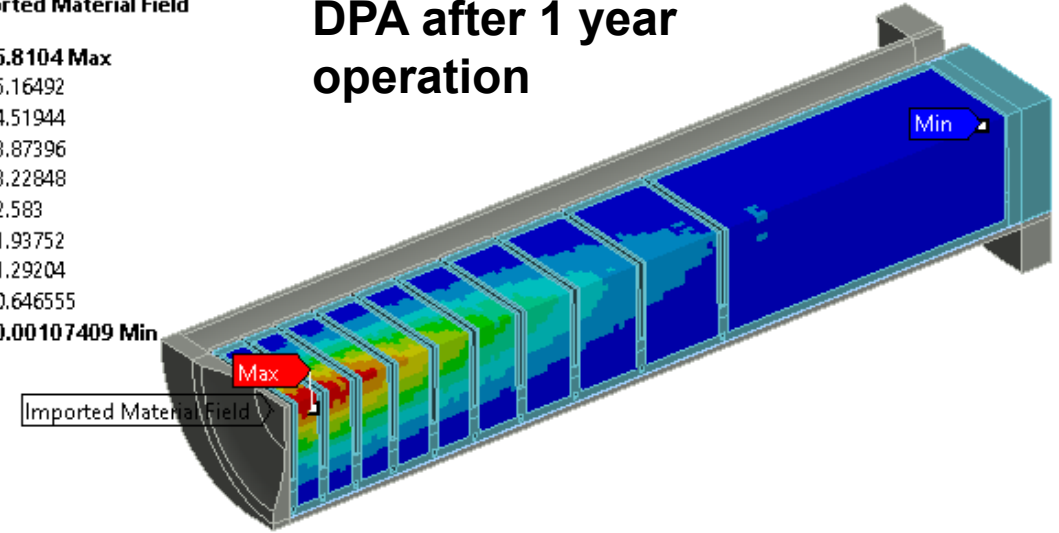
References

J. Habainy et al., "Thermal diffusivity of tungsten irradiated with protons up to 5.8 dpa," *Journal of Nuclear Materials*, vol. 509, pp. 152-157, 2018.
J. Habainy et al., "Mechanical properties of tungsten irradiated with high-energy protons and spallation neutrons," *Journal of Nuclear Materials*, 2019.
Y. Dai, "Thermal diffusivity of tungsten irradiated by protons in spallation environment up to 26.5 dpa", Presentation at HPTW 2023, Thursday Nov 9th 2023
A. Reza et al. (2020). Thermal diffusivity degradation and point defect density in self-ion implanted tungsten. *Acta Materialia*, 193, 270-279.

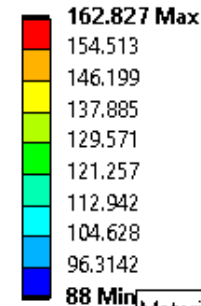
Imported Material Field



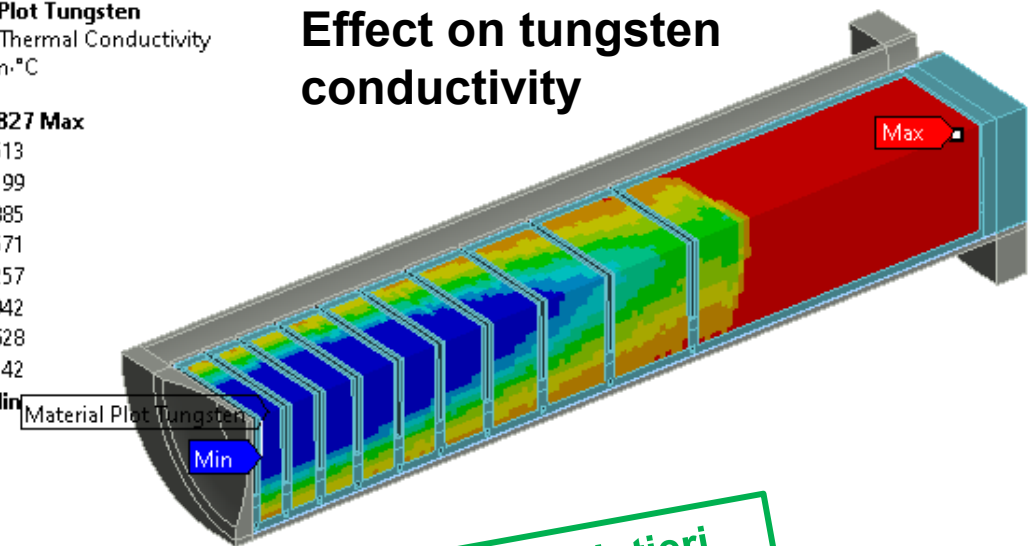
DPA after 1 year operation



Material Plot Tungsten
Isotropic Thermal Conductivity
Unit: W/m.°C



Effect on tungsten conductivity



See talk by Lina Quintieri,
16th April 14:10

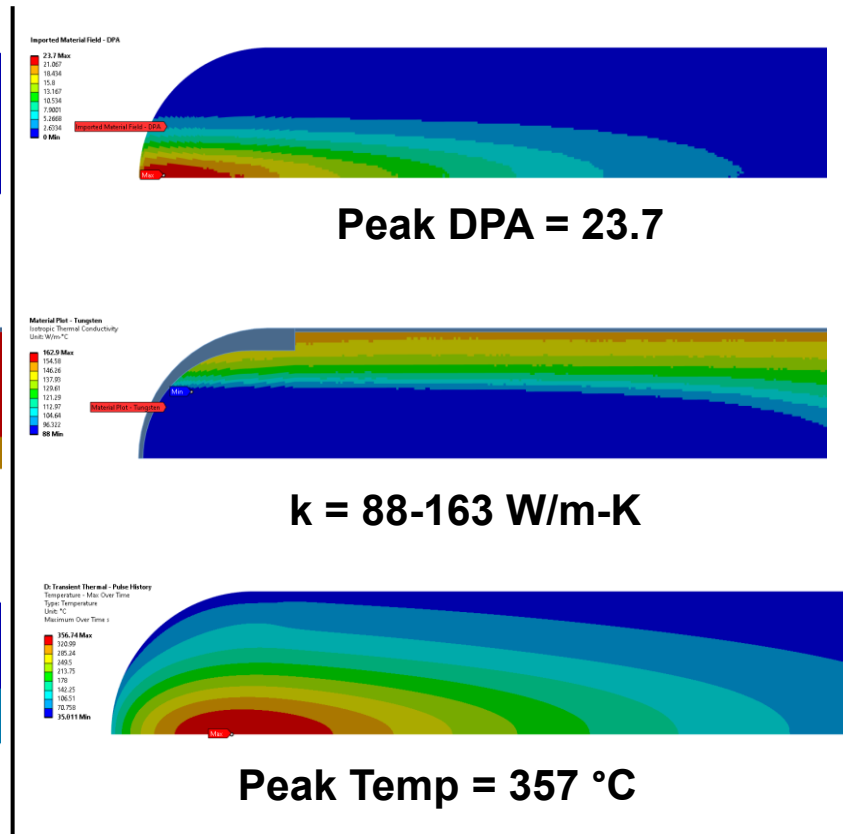
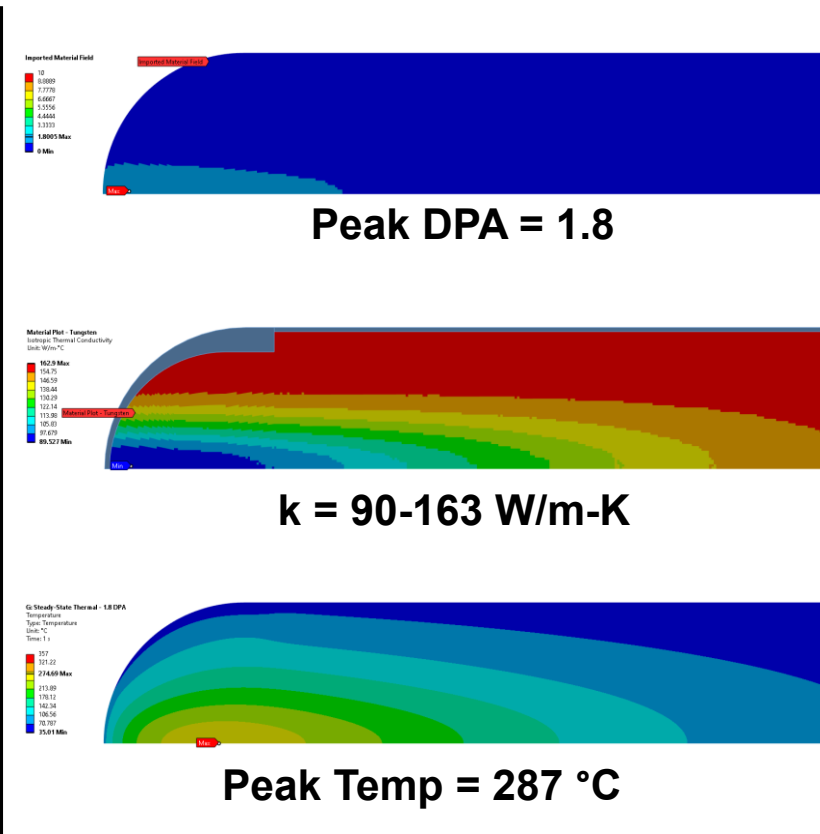
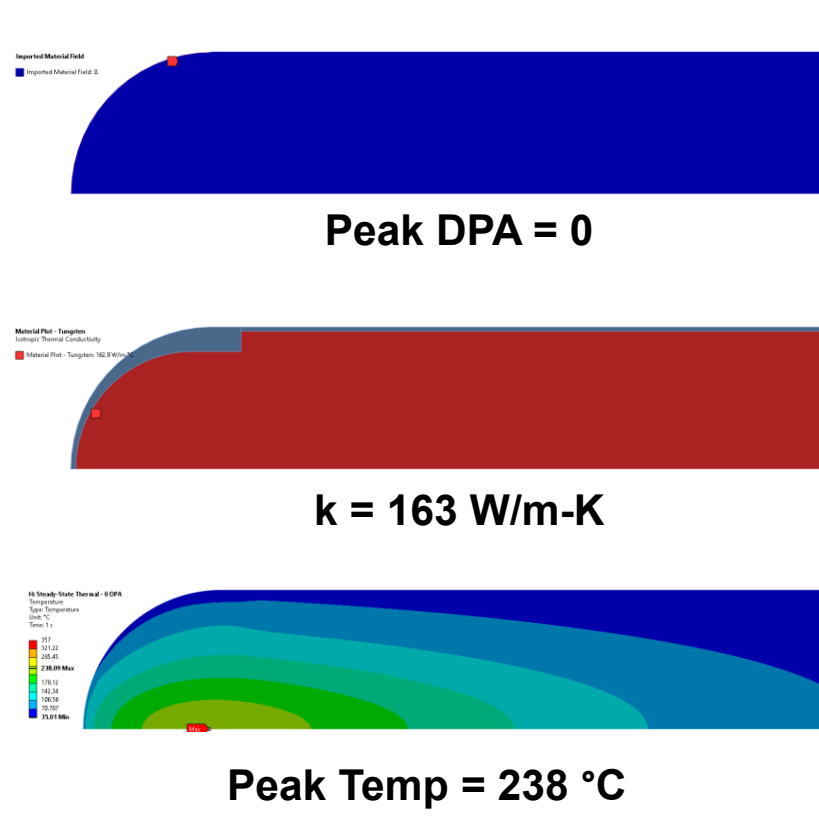
Evolution of Damage in TS2 Target

- Tungsten thermal conductivity degrades as a function of dose, then saturates above 2 DPA

Initial condition

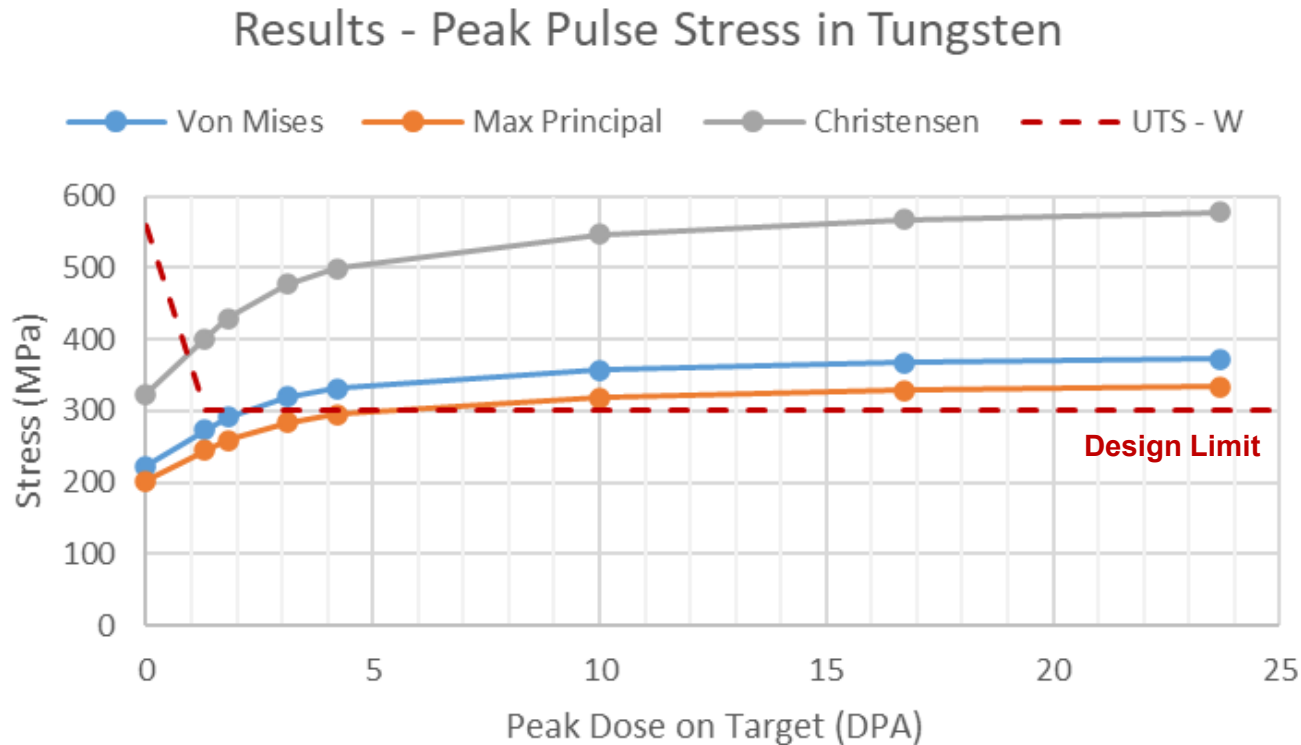
After ~2 months operation

TS2 W#10 target at end-of-life



Evolution of Damage in TS2 Target

- Tungsten safety factor is initially large but drops rapidly.
- Tantalum may slightly exceed yield stress but remains below UTS. Limited data at high DPA.
- Measured water activation begins some time after safety factors exceeded



Activity started to rise from around 150mAh (12.3 DPA) on TS2 W#10 target.

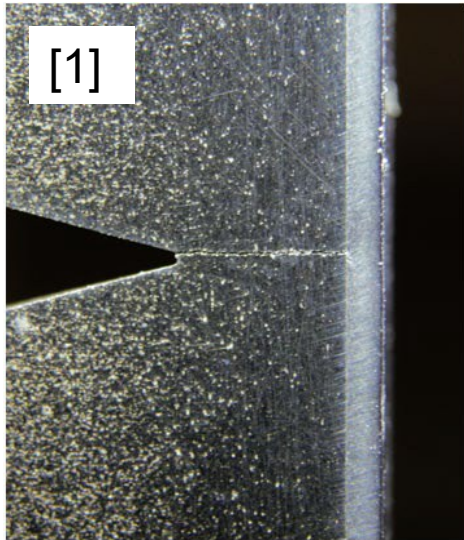
Very rapid rise from 250mAh (20.5 DPA).

Ultimately replaced at 290mAh (23.7 DPA)

Crack Propagation at Ta/W Interface

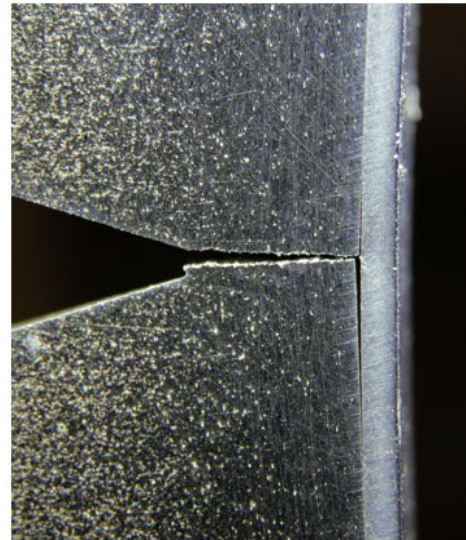
Simulations show possible cracking in tungsten core – what happens next?

- Testing by SNS Second Target Station team [1] found that: *“Tungsten cracks caused delamination damage then cladding failed in fatigue”*
- Charpy impact tests on ISIS clad samples [2] also showed that the HIPed interface debonds rather than propagates through Ta

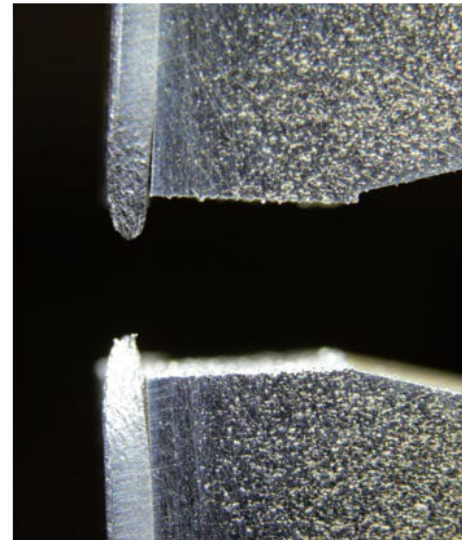


[1]

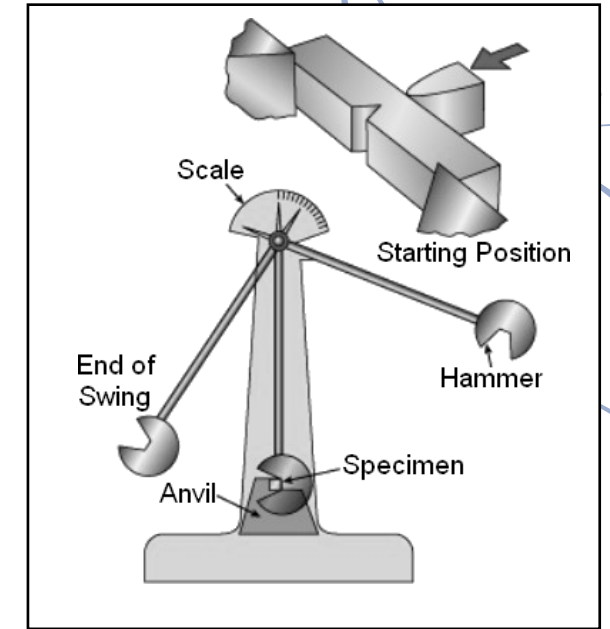
Start of stage 3 test



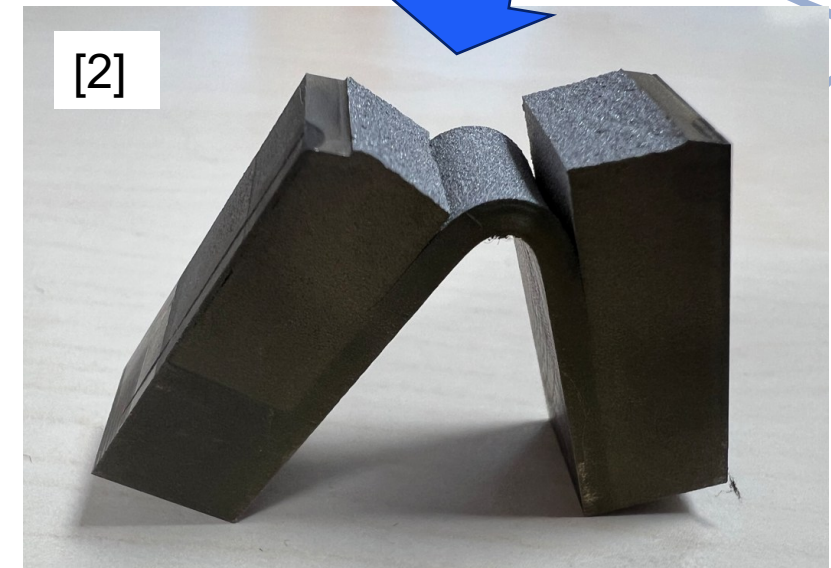
Specimen failed (right side)



Specimen failed (left side)



Charpy Impact Test Setup



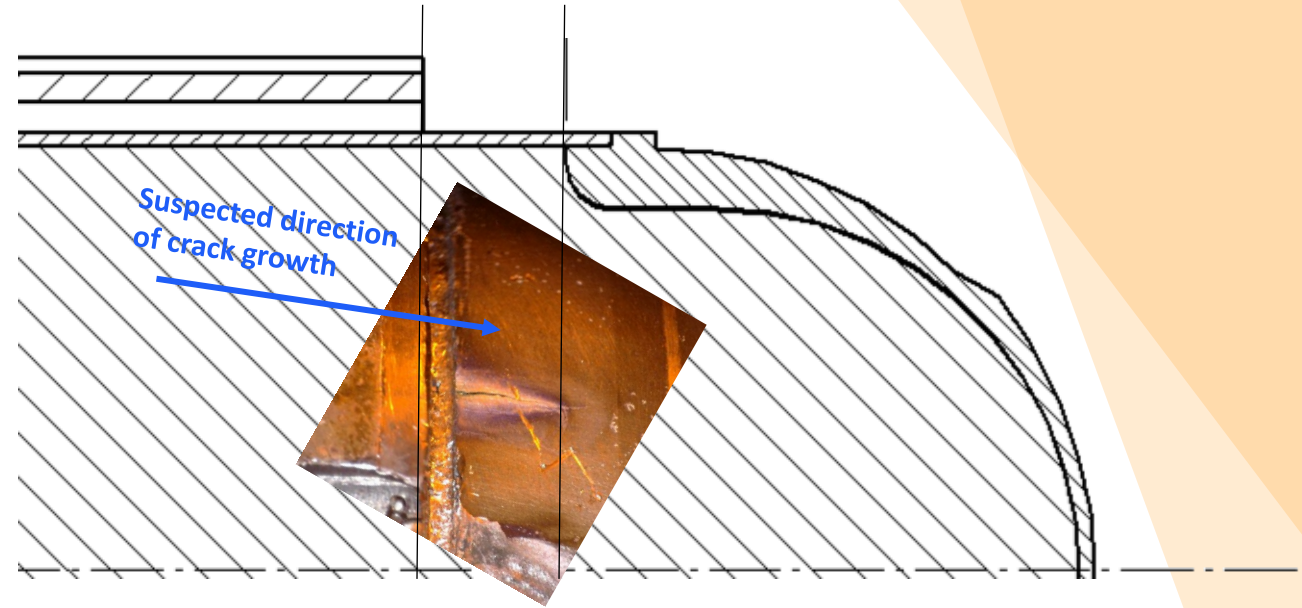
[2]

[1] *“Current Status of the STS Target Segment Manufacturing Development & Evaluation”*, Justin Mach, IWSMT-15, March 2023

Simulation of TS2 Target #4

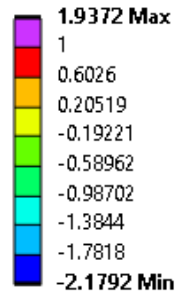
Simulated at the actual end-of-life dose on TS2 W#4 target: Peak DPA = 19.2

Crack is not at the first location we would expect from simulations (nose), but is at the second location (shoulder)



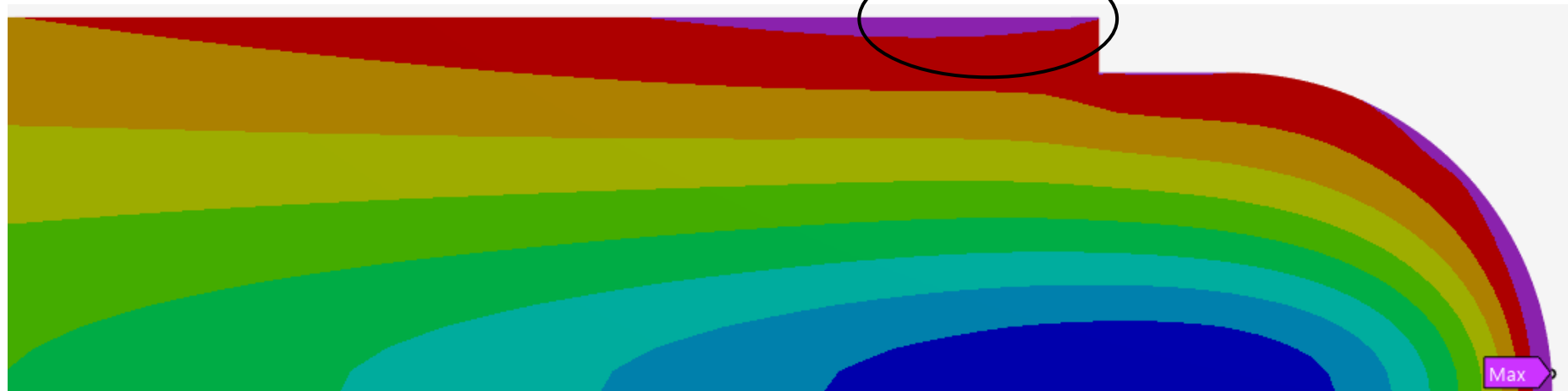
I: Transient Structural - Pulse History

Chr, UTS=300MPa, UCS=2120MPa, Tungsten - Max over time
Expression: $(1/300-1/2120)*(S1+S2+S3)+1/(300*2120^2)*((S1-S2)^2+(S2-S3)^2+(S3-S1)^2)$
Maximum Over Time s



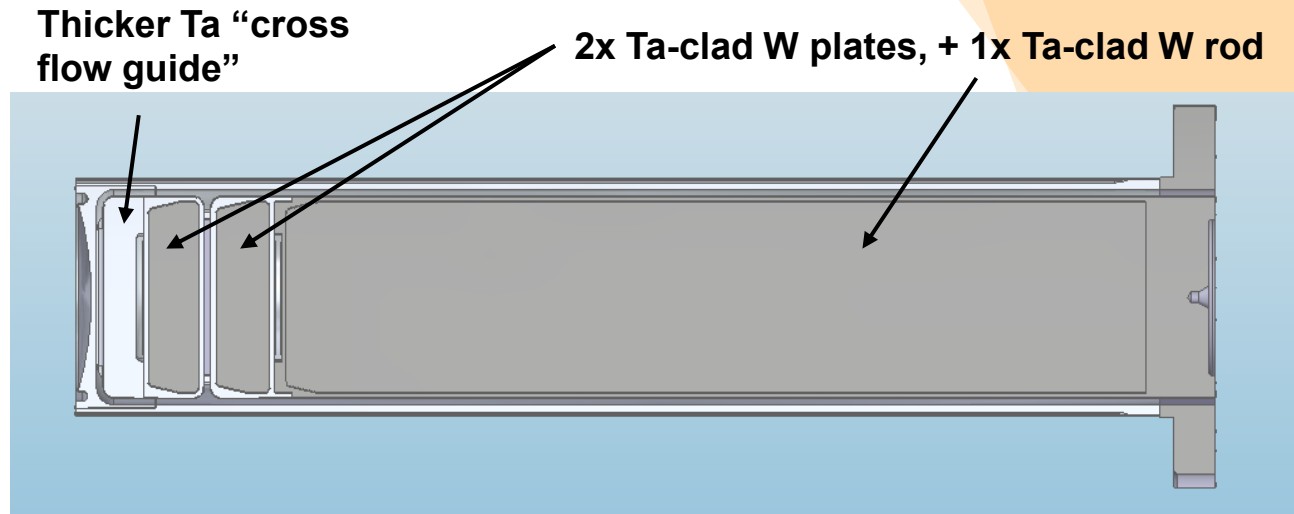
Location of observed crack:

Purple = Christensen failure criterion exceeded



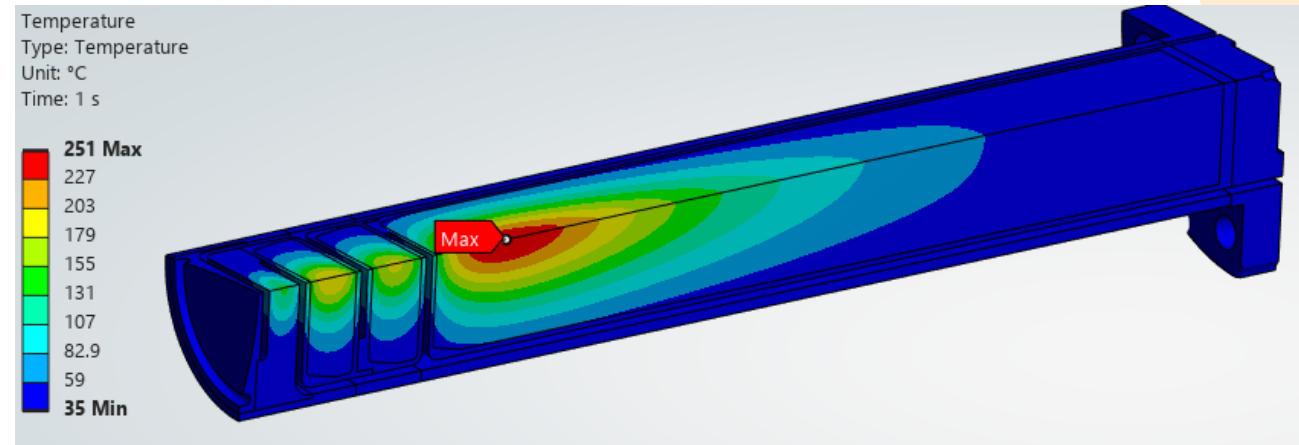
Multiplate TS2 Variant – Mk5 Proposal

- Split monolithic target rod to improve cooling
- Plate thicknesses optimised based on irradiated material properties
- Brings operating conditions more in line with TS1 targets
- Design review expected mid-2026



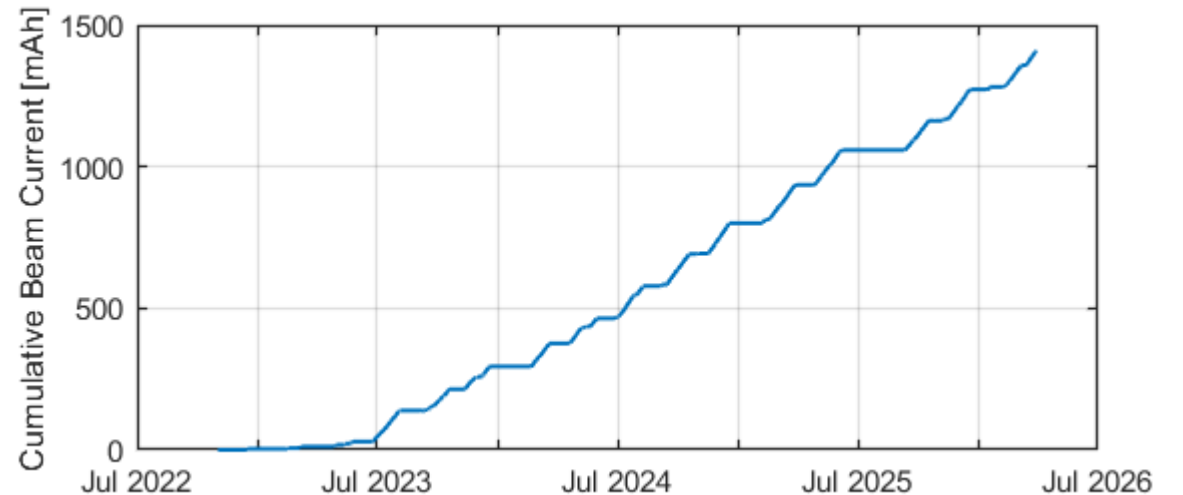
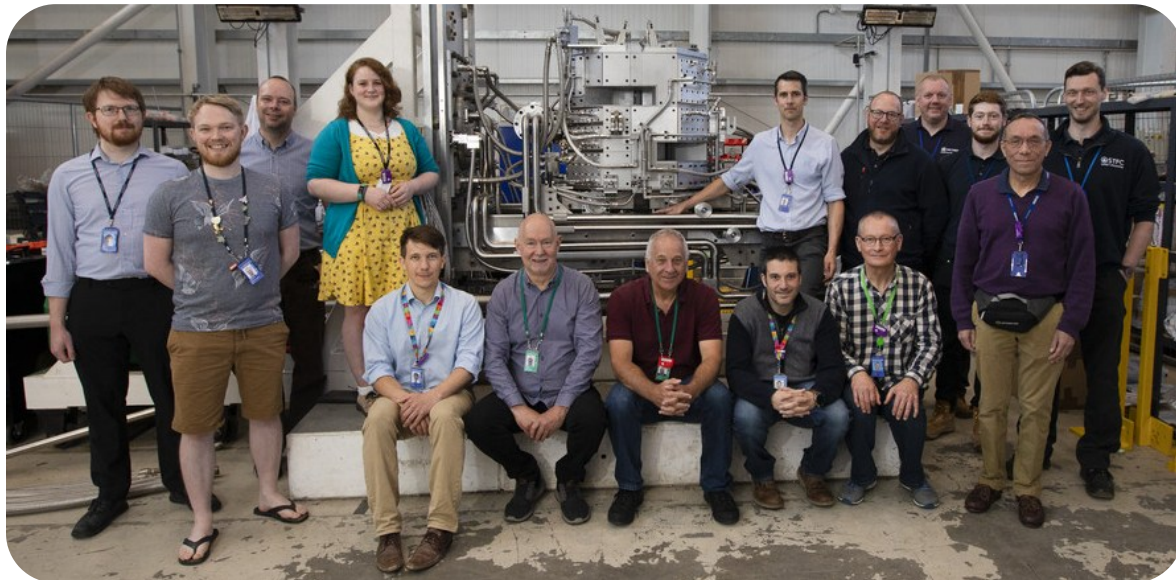
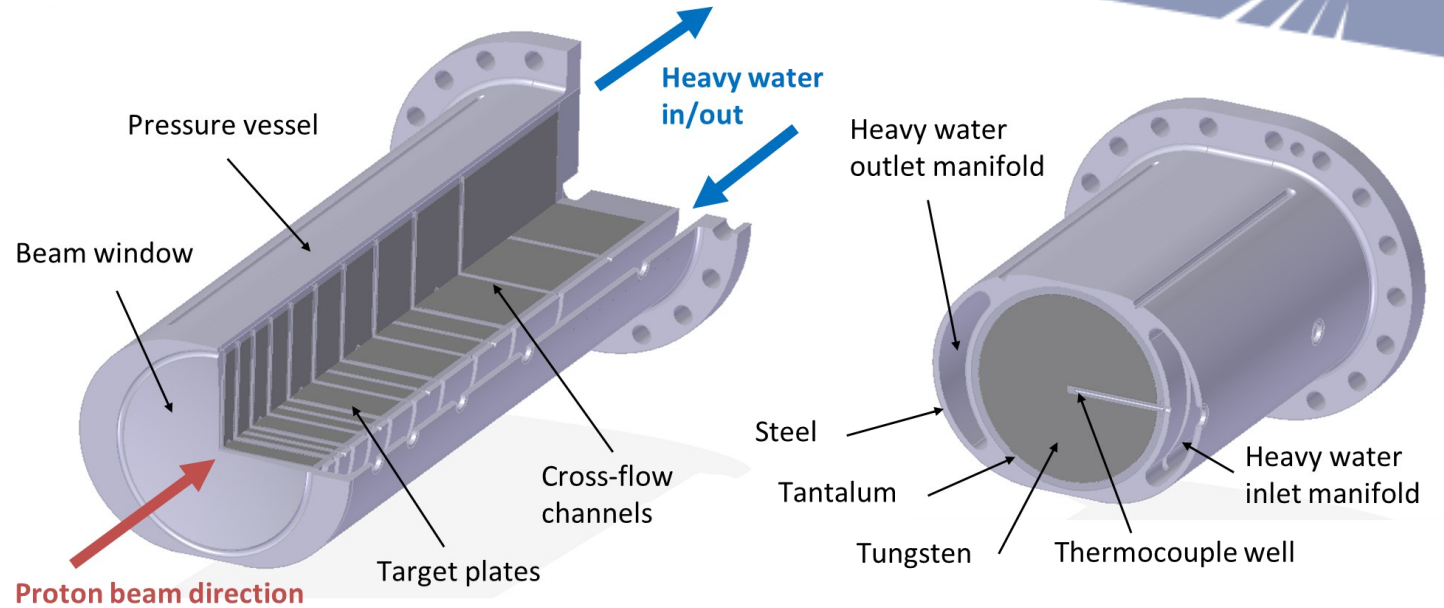
Results summary with irradiated tungsten properties:

Geometry	Temperature (°C)	Heat Flux (MW/m ²)	Von Mises Stress Ta (MPa)	Christensen Criterion W ()
TS1 Project	253	2.3	106	0.68
TS2 Mk2	377	2.6	241	1.70
TS2 Mk5	273	2.4	110	0.85
Limit	N/A	3	160	1



TS1 Project Target Experience

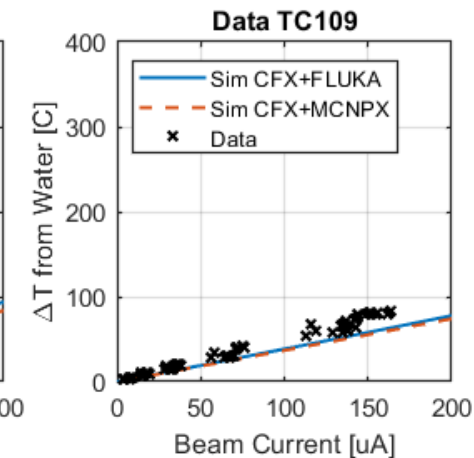
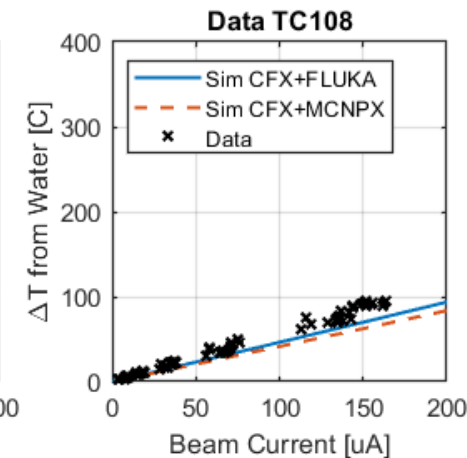
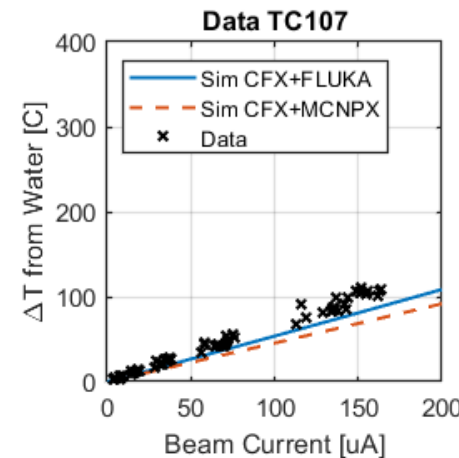
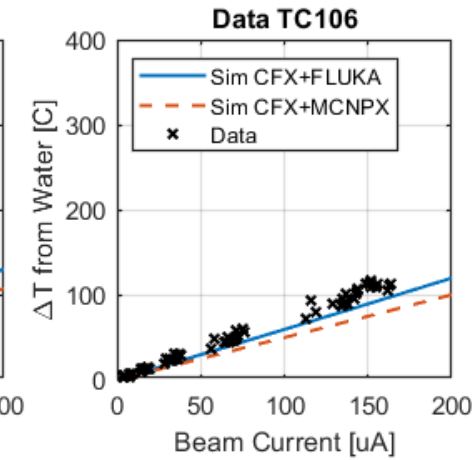
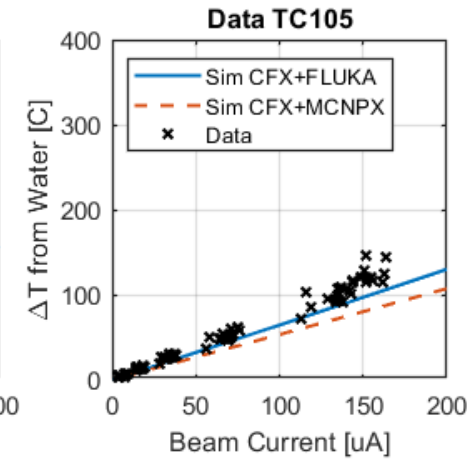
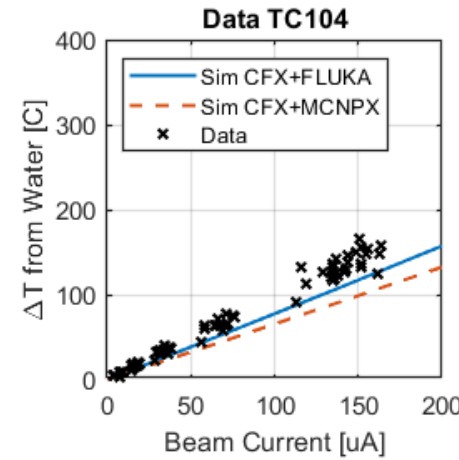
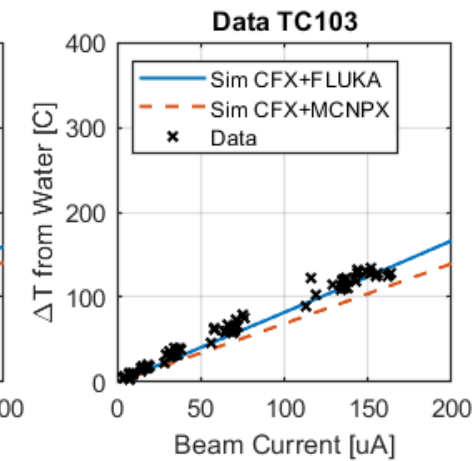
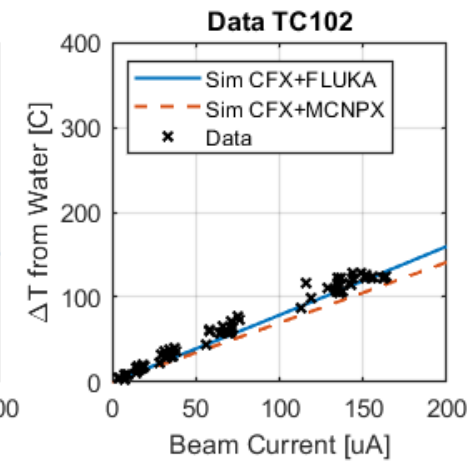
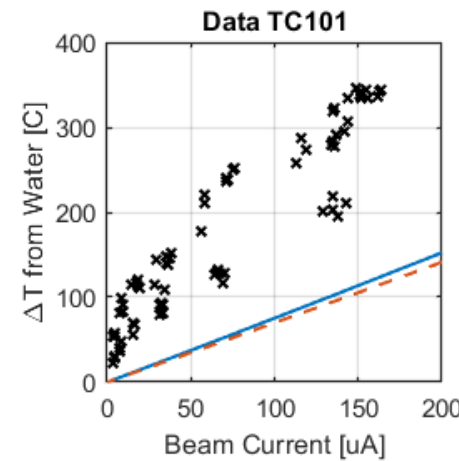
- First beam in November 2022
- Now operating at up to 164 μA
- Accumulated mAh = 1409 so far
- Thermocouples in each plate, and cooling water inlet and outlet



Cumulative beam current on first TS1 Project target
Note: Previous TS1 targets have lasted 2000-4000 mAh

Steady State Temperatures

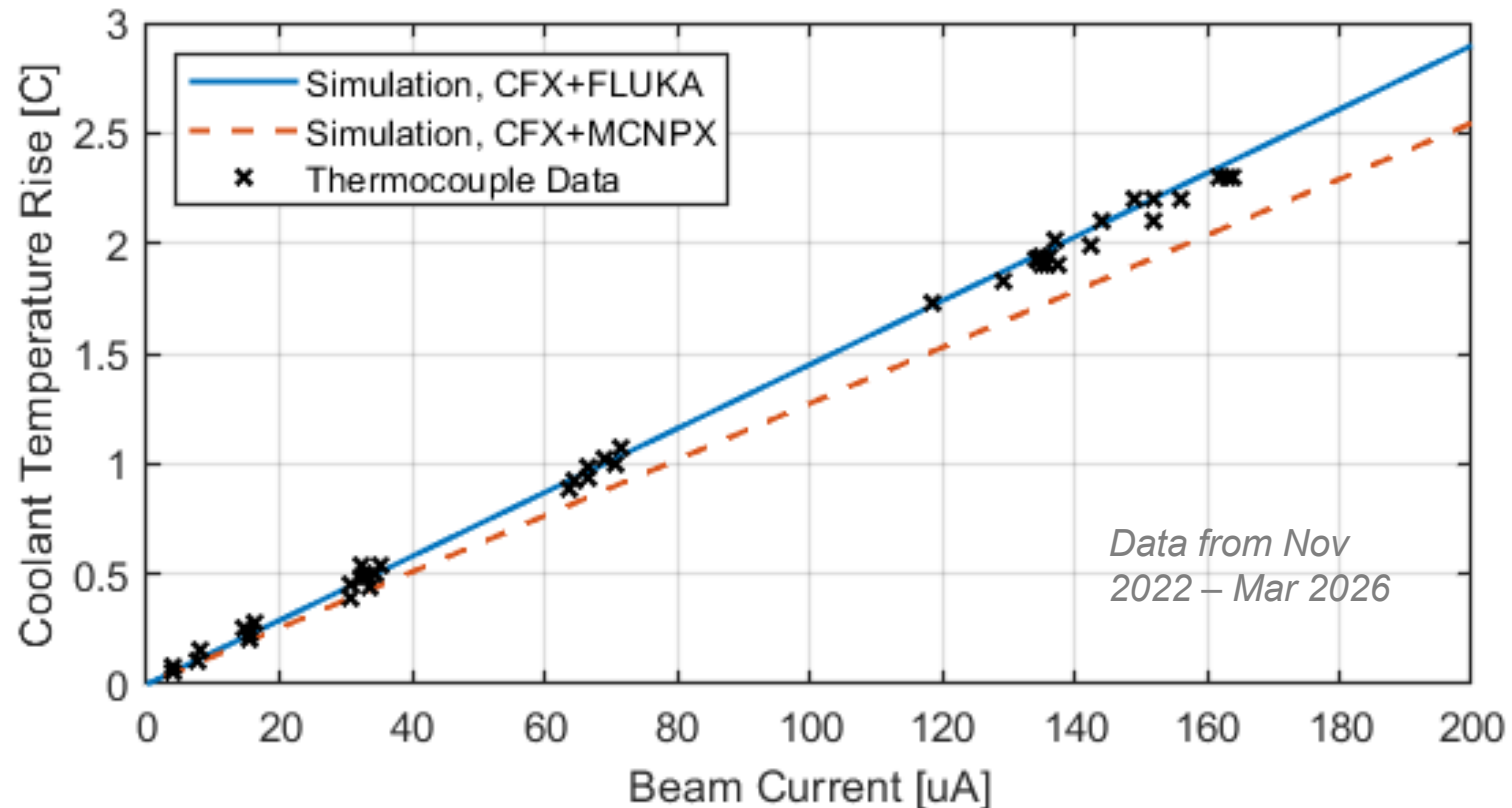
- Temperature simulations close but consistently slightly high
 - Possible effect of beam focus
- Plate 1 temperature clearly anomalous
 - Thought to be due to poor thermal contact around thermocouple
 - For more details see: *D. Wilcox et al., "Simulated and measured performance of the ISIS TS-1 Project target", Journal of Neutron Research, vol. 26, pp. 47–58, 2024.*



Power Deposition in Target

Calculated from temperature rise in cooling water: $Q = \dot{M} C_p \Delta T$

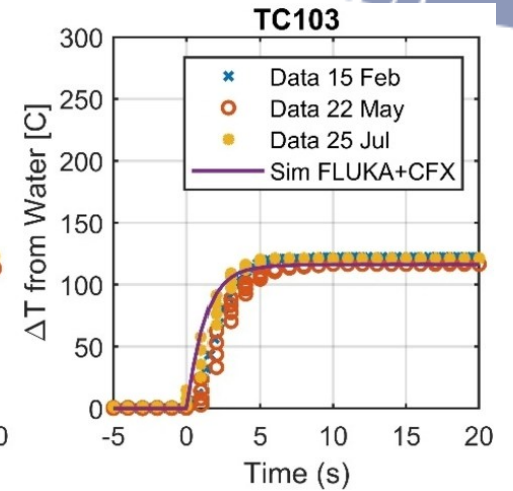
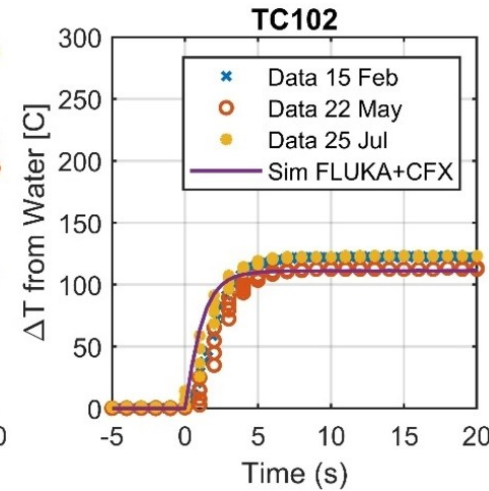
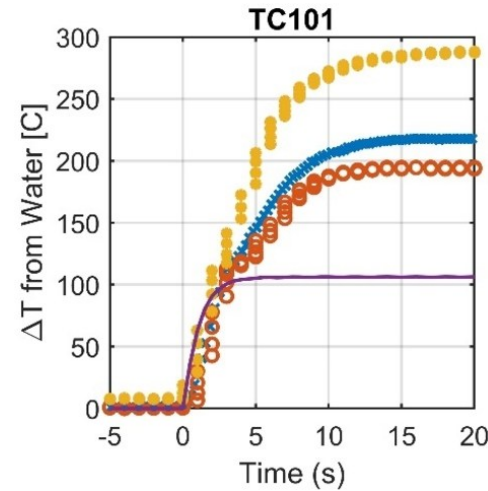
Water circuit ΔT is small, but appears to be as expected – validating Monte Carlo estimate of heat deposition



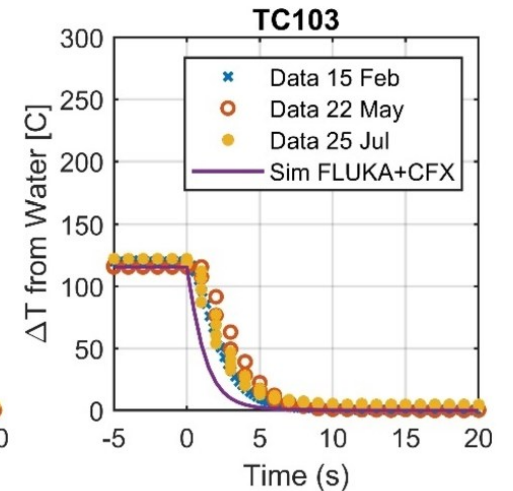
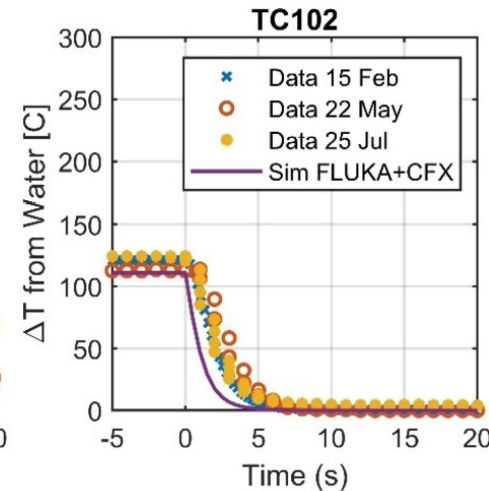
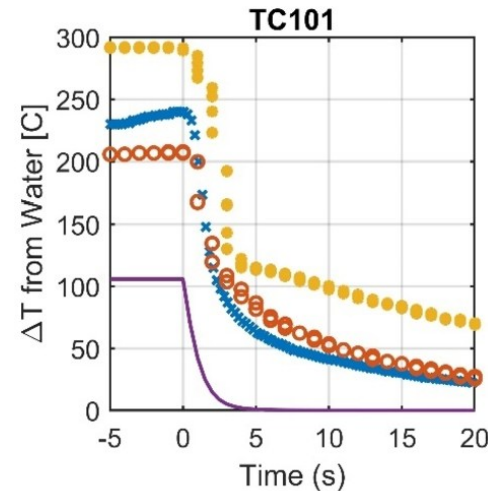
Transient Temperatures

- Very low cooling rate on plate 1 at low temperatures
- Broadly good agreement apart from plate 1 (anomalous sensor)
- Initial heating rate gives an independent validation of heat deposition
- Rapid cooling rate indicates water system is functioning as expected


Heating Rates:



Cooling Rates:

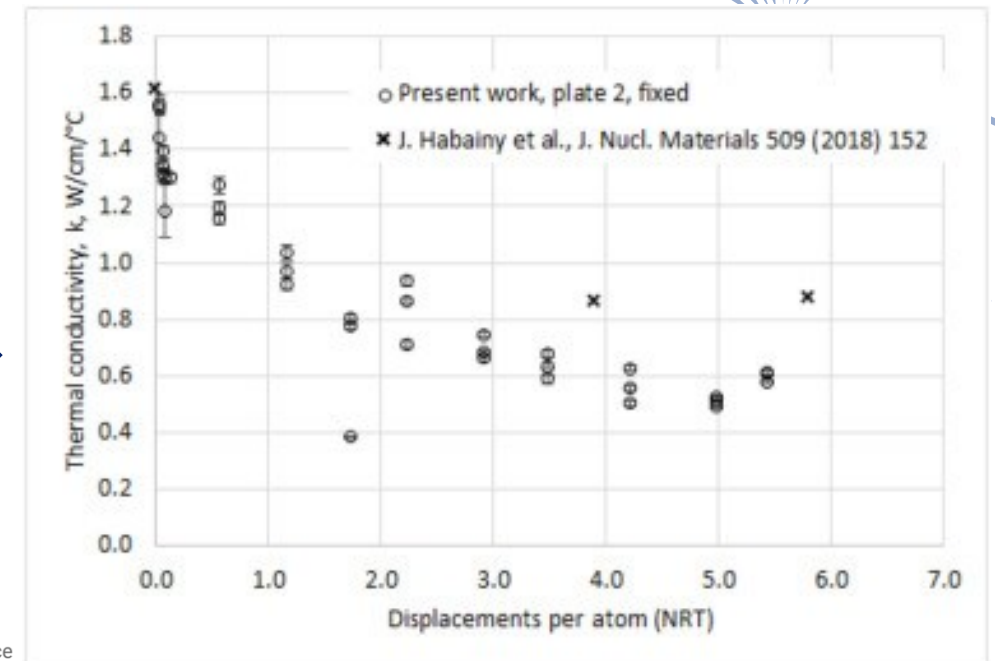


In-Situ Measurement of Conductivity Loss

- Expected effects of thermal conductivity loss in tungsten:
 1. Increase in steady-state plate temperatures
 2. Decrease in cooling rate after beam off
- TS1 plates are thin, effect of conductivity is relatively small ($\sim 40^\circ\text{C}$)
- Beam profile and focus effects are potentially larger, particularly for 1). Beam profile monitor currently not working.
- See recent publication by David Findlay et al. for an investigation of 2):
 - <https://doi.org/10.1016/j.nima.2026.171555> 
 - “Measurements of decreasing tungsten thermal conductivity in an operating spallation neutron target”

Potential factors affecting thermocouple temperature:

Cause	Possible Effect (%)
Beam focus (spot size)	50
Beam profile (gaussian or parabolic centre?)	40
Tungsten radiation damage	30
Monte Carlo code used (MCNPX vs FLUKA)	15
Beam centre position	15
D2O Flowrate variation within trip range	10



Summary

- Continually updating our simulation approach, and can now include radiation damage to materials in detail
- We are improving our understanding of TS2 failure modes via new irradiated material data, better simulations, and ongoing PIE
- TS2 Mk5 targets redesign will hopefully bring thermomechanical performance more in line with TS1 targets
- Continuing to monitoring TS1 Project target performance. Validation of simulations against real data is generally as expected

Thank you for your
attention.
Any questions?

Backup Slides



ISIS Target Lifetime History

Table and DPA estimates courtesy of David Findlay, ISIS

TS-1 target	Irradiated	Milliamp-hours	Number of protons
W#1	May 2001 – July 2005	2677	6.02E+22
W#2	Sep 2005 – Mar 2009	1947	4.38E+22
W#3	May 2009 – Aug 2014	2949	6.63E+22
W#4	Mar 2015 – Jun 2021	3966	8.91E+22
TS-2 target	Irradiated	Milliamp-hours	Number of protons
W#1	Sep 2008 – Dec 2009	118	2.65E+21
W#2	Feb 2010 – May 2010	38	8.54E+20
W#3	Mar 2011 – Nov 2012	218	4.90E+21
W#4	Nov 2012 – Jun 2014	235	5.28E+21
W#6	Jul 2014 – Jul 2015	109	2.45E+21
W#7	Sep 2015 – Jun 2017	302	6.79E+21
W#8	Sep 2017 – Mar 2019	249	5.60E+21
W#9	Jun 2019 – Jun 2021	262	5.89E+21
W#10	Mar 2022 – Mar 2024	290	6.52E+21

Table 3. Total integrated beam current delivered to target during lifetimes of targets, and corresponding numbers of protons delivered to target (TS-2 target W#5 was never installed). Numbers for milliamp-hours were taken from a compilation of cumulative day-by-day milliamp-hours kept at \\isis\shares\isis_source_ops\milliamp-hours-by-day.

Used for first TS2 target PIE

TS-1 Target	Lifetime (mAh)	Peak DPA	Cause of Replacement
W#1	2677	24.7	Thermocouples reached end of life
W#2	1947	18.0	
W#3	2949	27.2	
W#4	3966	36.6	
Project #1	1409 so far		In Operation

TS-2 Target	Lifetime (mAh)	Peak DPA	Cause of Replacement
W#1 Mk1	118	9.7	Oxidation of front face Ta
W#2 Mk1	38	3.1	
W#3 Mk2	218	17.8	Cooling water activation
W#4 Mk2A	235	19.2	
W#6 Mk2A	109	8.9	
W#7 Mk2A	302	24.7	
W#8 Mk2B	249	20.4	Isotope analysis indicates tungsten
W#9 Mk2B	262	21.5	
W#10 Mk3	290	23.7	
W#11 Mk3A	271 so far		In Operation

Target Simulation Approach

Ta cladding attached to W core via Hot Isostatic Press (HIP). Residual stress simulated with 500°C “lock-in” temperature [1] [2]:

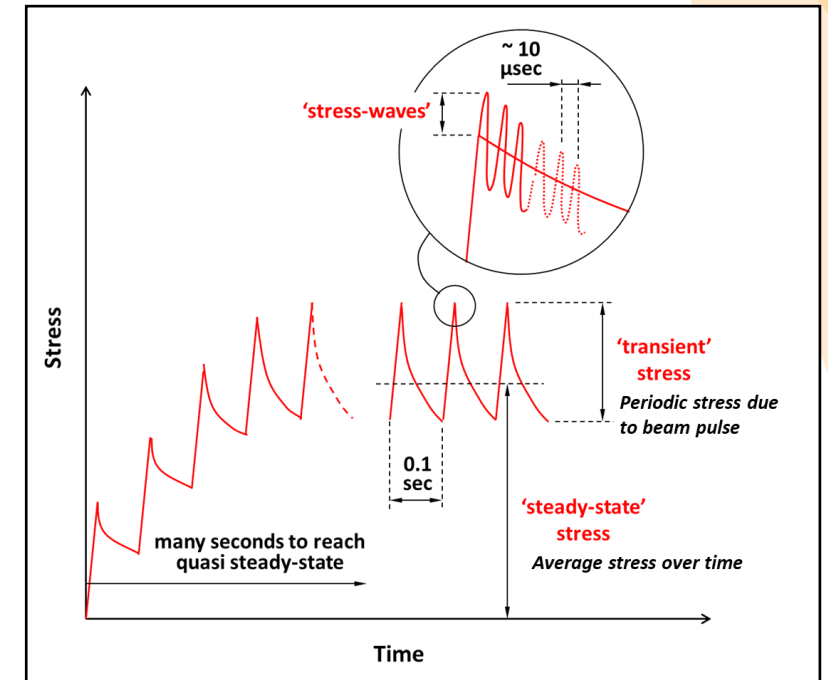
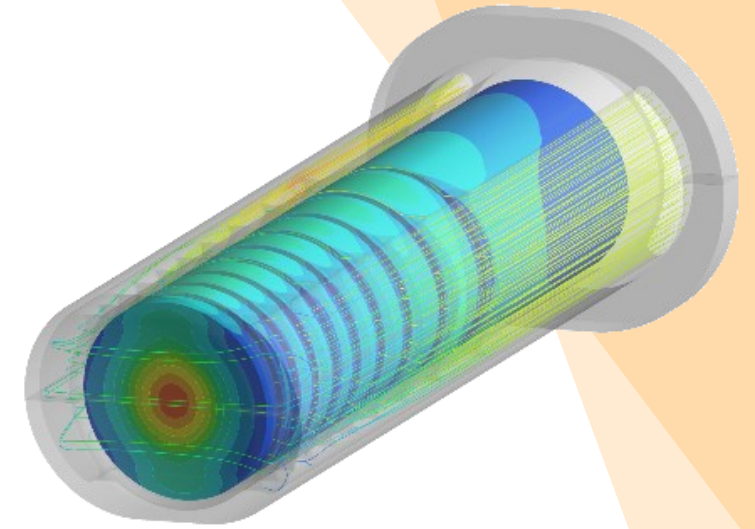
- Tensile in Ta, induces yielding but not failure. Detrimental to fatigue life.
- Compressive in W – initially beneficial for fatigue life
 - Does radiation damage act to relieve this residual stress? Currently unproven.

Proton beam heating adds thermal stress, which is higher in TS2

Short pulse facility (~400ns), so stress waves are inevitable

- Much worse in TS2 due to smaller beam spot

Fatigue due to beam pulses (many, small stress) and beam trips (few, large stress)



References

- [1] D. Wilcox, P. Loveridge, T. Davenne, L. Jones and D. Jenkins, "Stress levels and failure modes of tantalum-clad tungsten targets at ISIS," *Journal of Nuclear Materials*, vol. 506, pp. 76-82, 2018.
- [2] D. Wilcox, P. Loveridge, S. Kabra, T. L. Lee, J. Moor and D. Jenkins, "Measurement of residual strain in tantalum-clad tungsten after hot isostatic pressing," *Journal of Neutron Research*, vol. 22, no. 2-3, pp. 287-297, 2020.

Summary of Irradiated Material Properties

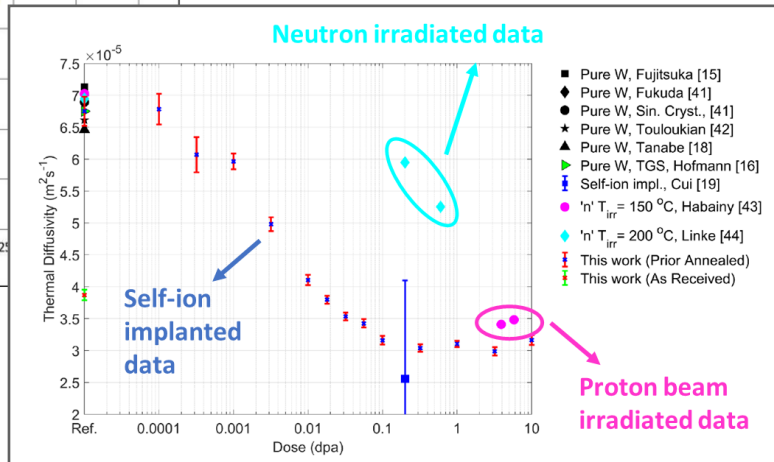
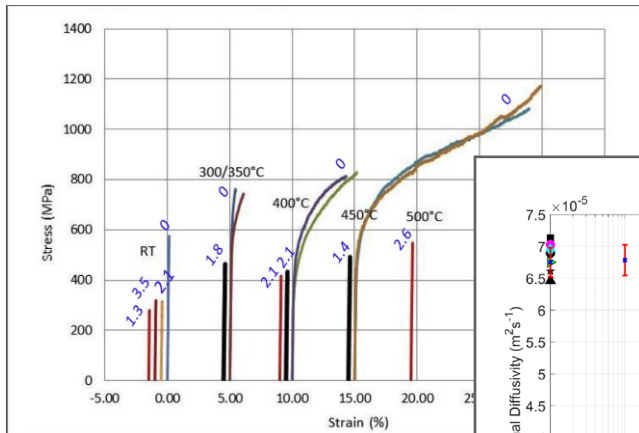
Tungsten

Brittle at room temp. even before irradiation

UTS: 560 → 300 MPa after 1.3 DPA
 k: 175 → 88 W/(m.K) after ~2 DPA } No further change up to 27 DPA

UCS: 1170 → 2120 after 23.3 DPA, no saturation

UCS/UTS: 2.1 → 7.1 (brittle → very brittle)



References

J. Habainy et al., "Thermal diffusivity of tungsten irradiated with protons up to 5.8 dpa," *Journal of Nuclear Materials*, vol. 509, pp. 152-157, 2018.
 J. Habainy et al., "Mechanical properties of tungsten irradiated with high-energy protons and spallation neutrons," *Journal of Nuclear Materials*, 2019.
 Y. Dai, "Recent spallation materials researches performed at PSI", Presentation at HPTW 2023, Monday Nov 6th 2023
 Y. Dai, "Thermal diffusivity of tungsten irradiated by protons in spallation environment up to 26.5 dpa", Presentation at HPTW 2023, Thursday Nov 9th 2023
 A. Reza et al. (2020). Thermal diffusivity degradation and point defect density in self-ion implanted tungsten. *Acta Materialia*, 193, 270-279.

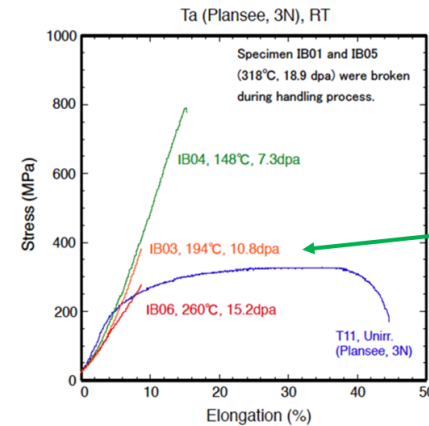
Tantalum

Initially: High ductility, very high fatigue endurance limit

Large variation in reported ductility after 10 DPA

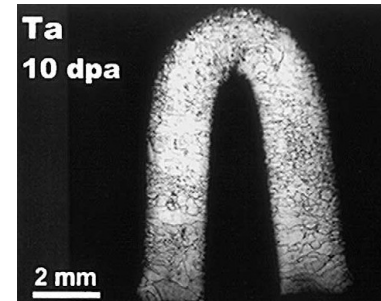
Less irradiated data overall

STIP-II specimens were brittle by 7.3 dpa

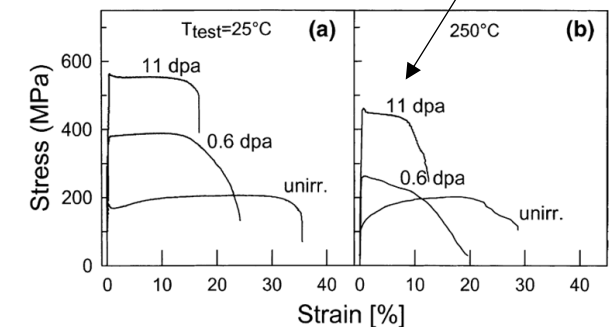


STIP-II tantalum specimens may have been contaminated by extra hydrogen released by other specimens in the same container

UTS after 10.8 DPA is no worse than unirradiated UTS in either case



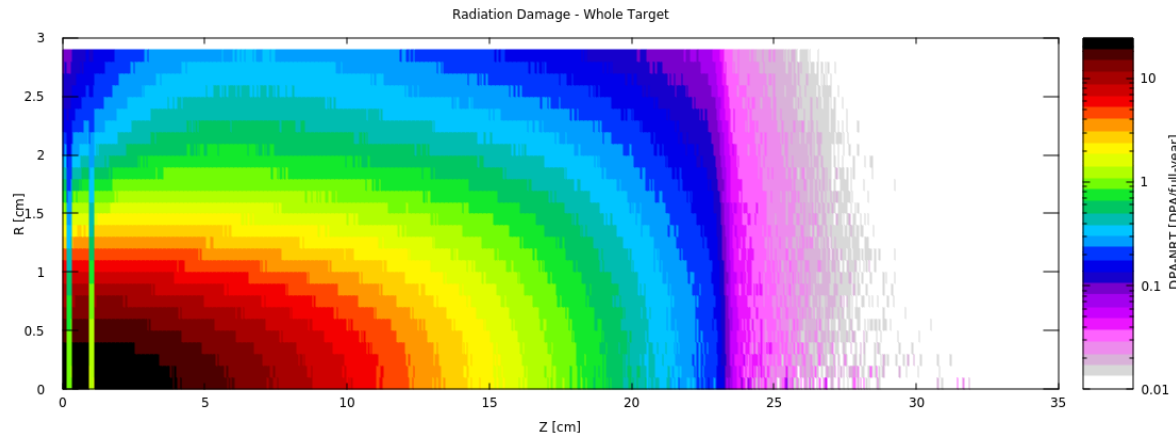
ISIS target cut up at FZ-Juelich remained ductile at 11 dpa



Simulation of TS2 Target #4 – Received Dose

- What was the condition of TS2 target #4 when PIE was carried out?
- ~16 DPA at centreline (survived), 0.18 DPA at crack location in Ta

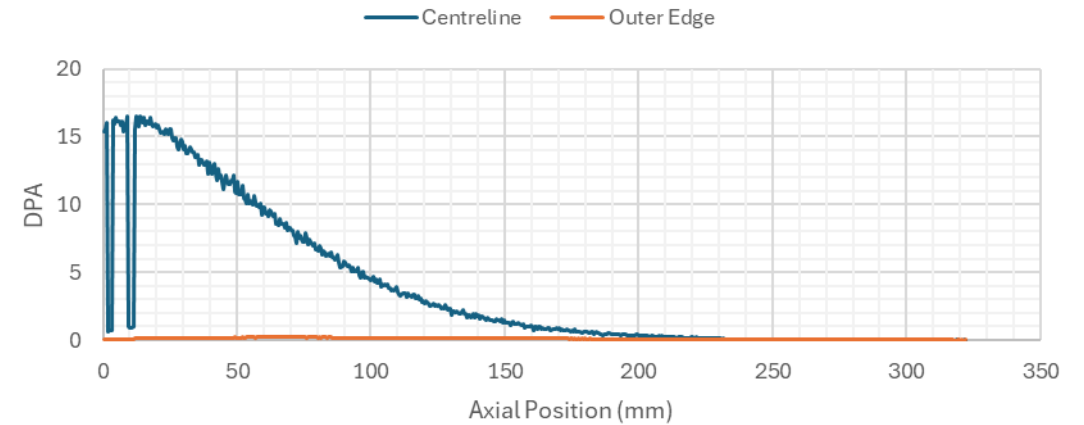
DPA-NRT after 1 full year of 40uA operation:



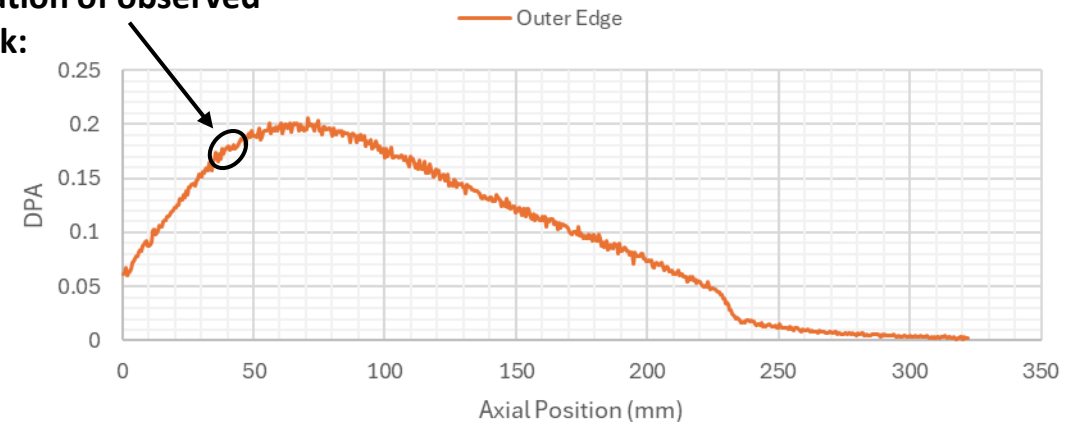
Scale to accumulated mAh on real target



TS2 #4 Target at end-of-life condition (235 mAh)



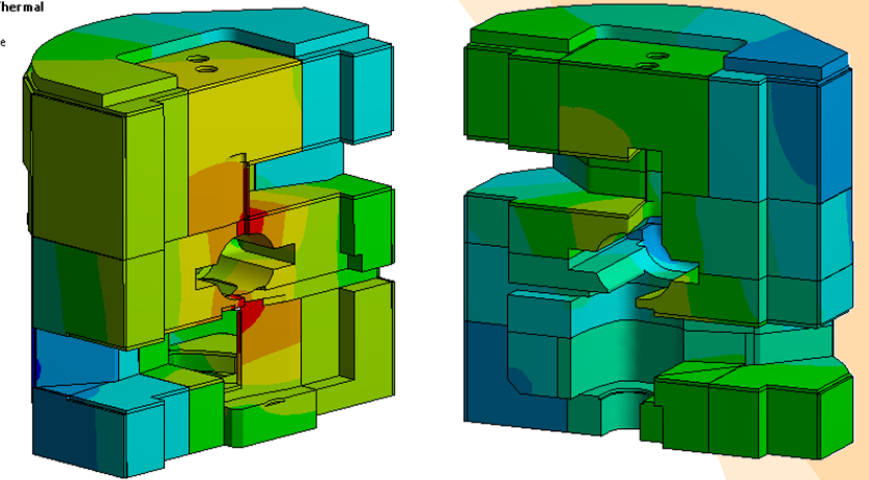
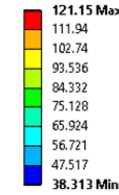
Location of observed crack:



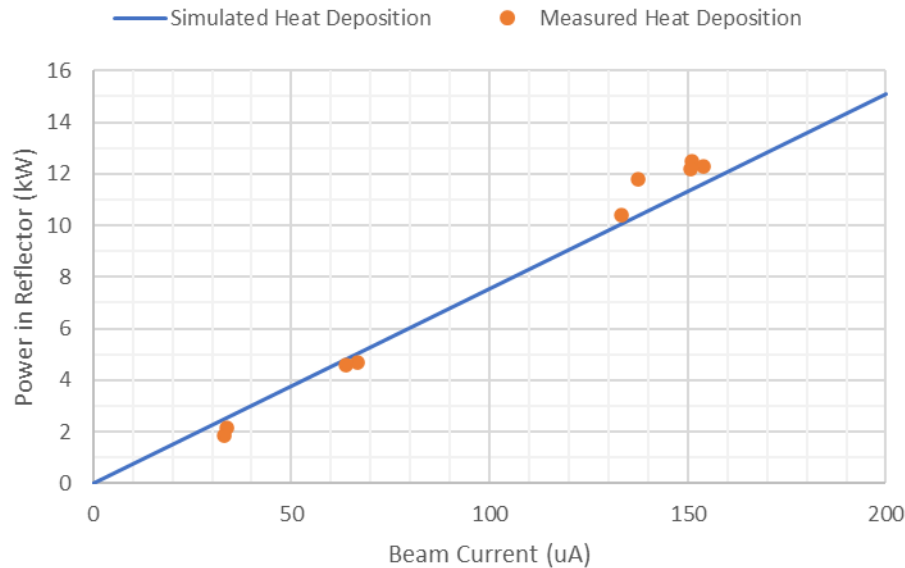
TS1 Project Reflector – Measured Data

- Total heat deposition estimated from coolant ΔT
- Four thermocouples are directly in contact with Be
- Peak temperature estimated from simulation only

C: Steady-State Thermal
 Temperature
 Type: Temperature
 Unit: °C
 Time: 1



Total Heat Deposited in Reflector



Steady State Data Normalised to 25C Inlet

