Measuring Residual Strain after Hot Isostatic Pressing of ISIS Target Plates

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Overview

- Background
- ISIS target manufacture
- Asymmetric-clad strip method
- Results and analysis
- Future plans
- Implications for target design

Acknowledgements

- Experiment concept – Peter Loveridge
- Sample manufacture – Jeremy Moor, Max Rowland
- Management – Ste Gallimore, David Jenkins

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Background

- ISIS operates two spallation targets; TS1 and TS2
  - Both have tungsten cores clad in tantalum for corrosion resistance
  - Any significant cladding breach means we have to replace the target
    - Causes activation of the cooling plant, which needs hands-on maintenance

- Cladding is attached by Hot Isostatic Press (HIP)
  - Produces a strong bond with good thermal contact
  - High residual stress expected from HIP – more than from beam heating
  - Exact amount of residual stress is a major unknown in current simulations*

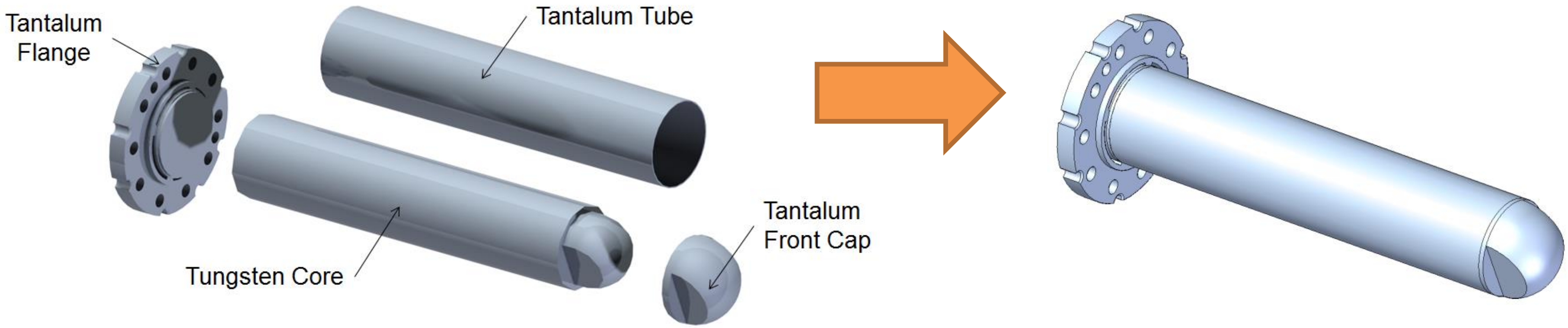
TS1

TS2

*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.

ISIS Target Manufacture

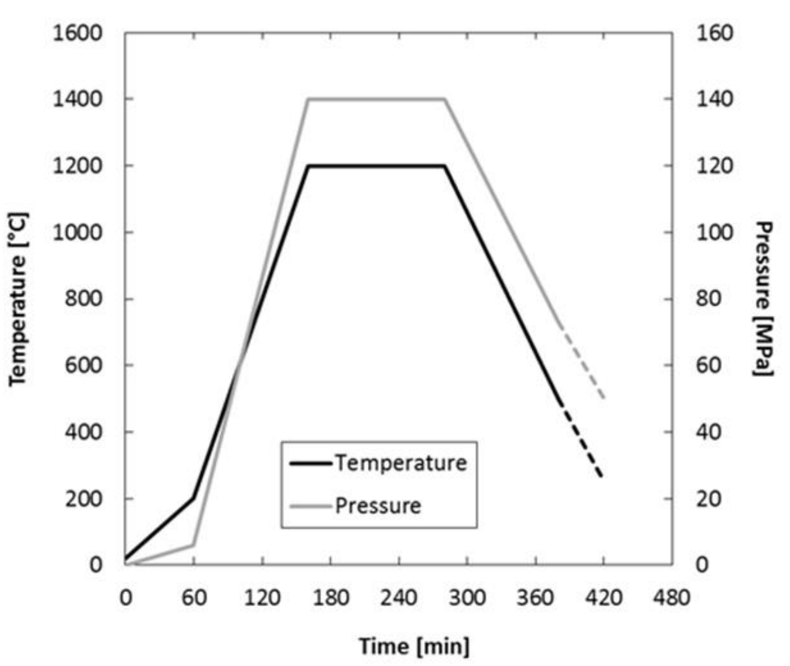
- Tantalum can welded shut with tungsten core inside
- Hot Isostatic Press (HIP) process applies high temperature and pressure, bonding cladding and core
- Final machining to achieve dimensional accuracy
- Plates welded together to form target stack (TS1 Only)



Components of TS2 target HIP assembly

ISIS Target Manufacture

- HIP cycle in detail:
  - Cladding deforms plastically under high pressure (140MPa)
  - Peak temperature is 1200°C, held for 2 hours; this relieves stress, but does not cause grain growth
  - Tantalum and tungsten are bonded together
  - As the clad target cools below the annealing temperature, residual stress builds up due to different coefficients of thermal expansion:
    - Tungsten 4.5E-06/K
    - Tantalum 6.3E-06/K



A typical ISIS HIP cycle

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ISIS Target Manufacture

Simplifying assumptions for calculating residual stress:

- All stress from welding and HIP pressure is relieved during HIPing
- Stress due to final machining and plate welding is small compared to stress from HIPing, and can be ignored
- Stress from HIP cooldown is relieved at first, but below a certain 'lock-in' temperature stress starts to builds up
  - Industry uses a stress relieving temperature of around 850°C
  - Lock-in temperature estimated to be 500°C, but this needs validation

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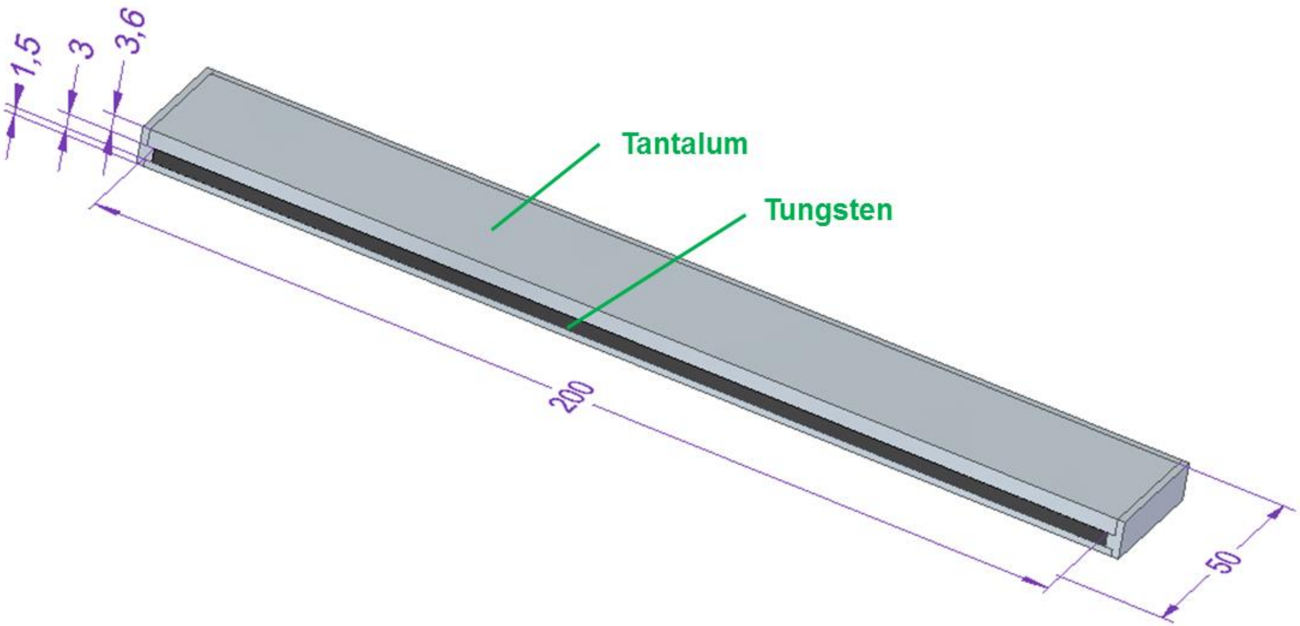
Asymmetric-Clad Strip Method

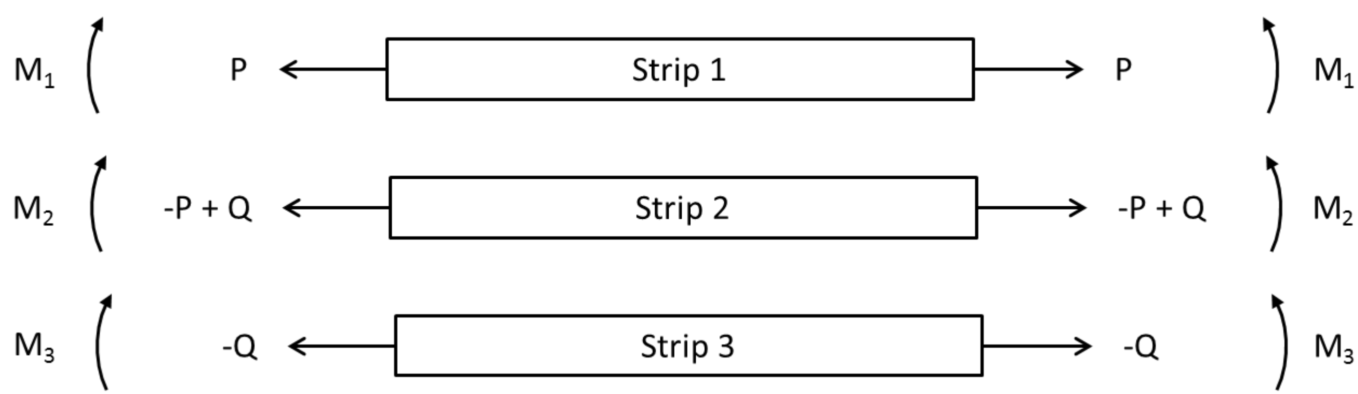
- Provides a simple, mechanical method of measuring residual stress after HIPing
  - HIP a long strip of tungsten with asymmetric tantalum cladding
  - The strip will deflect in proportion to the residual stress
  - A parametric FEA study was used to find the optimum dimensions to produce a measurable deflection without breaking the sample



Nominal dimensions of asymmetric-clad strip

Theory

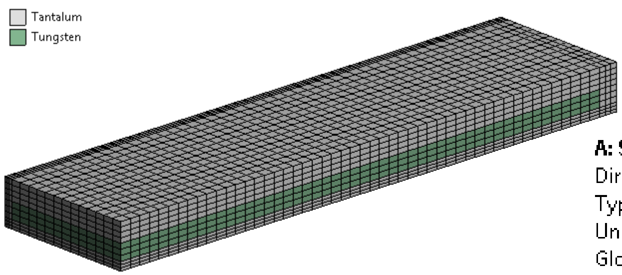
- Behaviour is similar to a bimetallic strip after a temperature change
- We expect stress to be tensile in the cladding and compressive in the core
  - Curvature should be concave on the thick tantalum side
- Should deflect with the same radius of curvature in both directions, forming part of a spherical surface

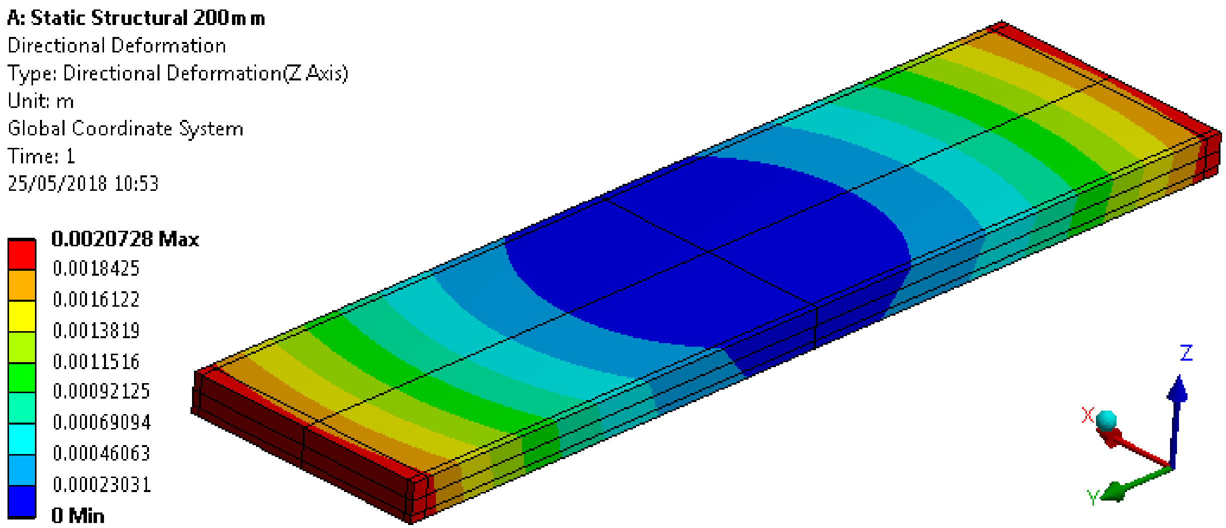


Simulation

- FEA simulation using ANSYS Workbench
  - Includes bilinear model for tantalum plasticity
  - Deflected surface is nearly spherical, as expected

Quarter symmetry model and mesh

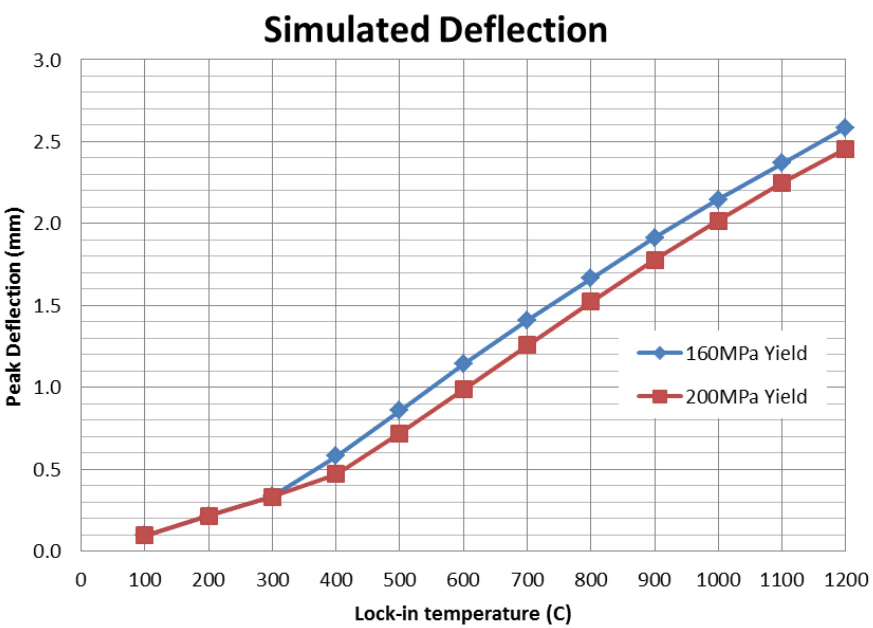


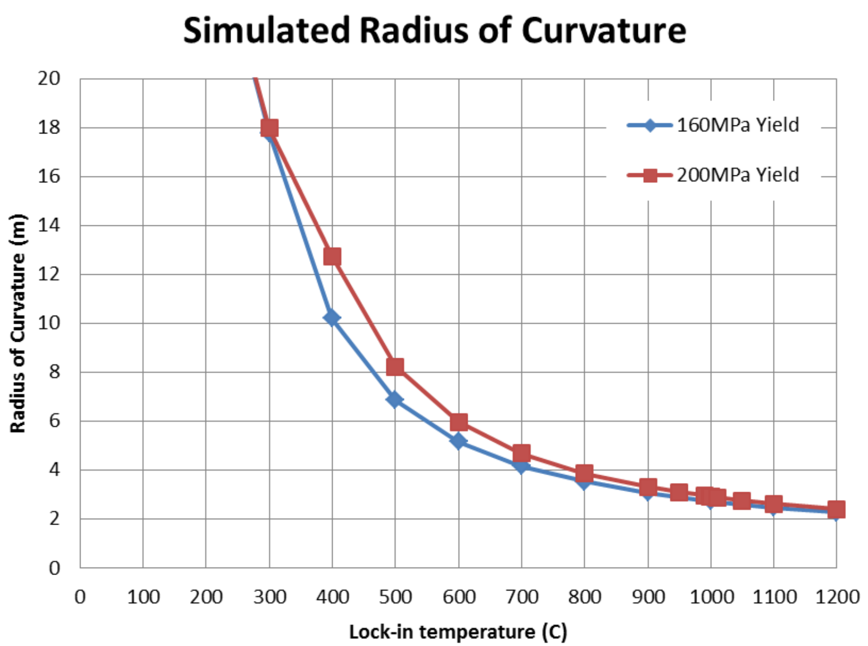


Out of plane deformation result for 200MPa yield, 500°C lock-in

Simulation

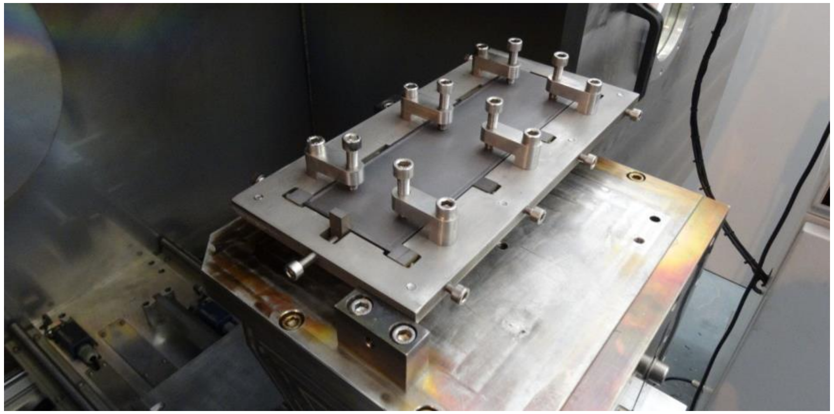
- The deflection result depends on two unknowns: lock-in temperature and tantalum yield strength
  - Deflection is roughly proportional to lock-in temperature, with a change in gradient when yielding occurs

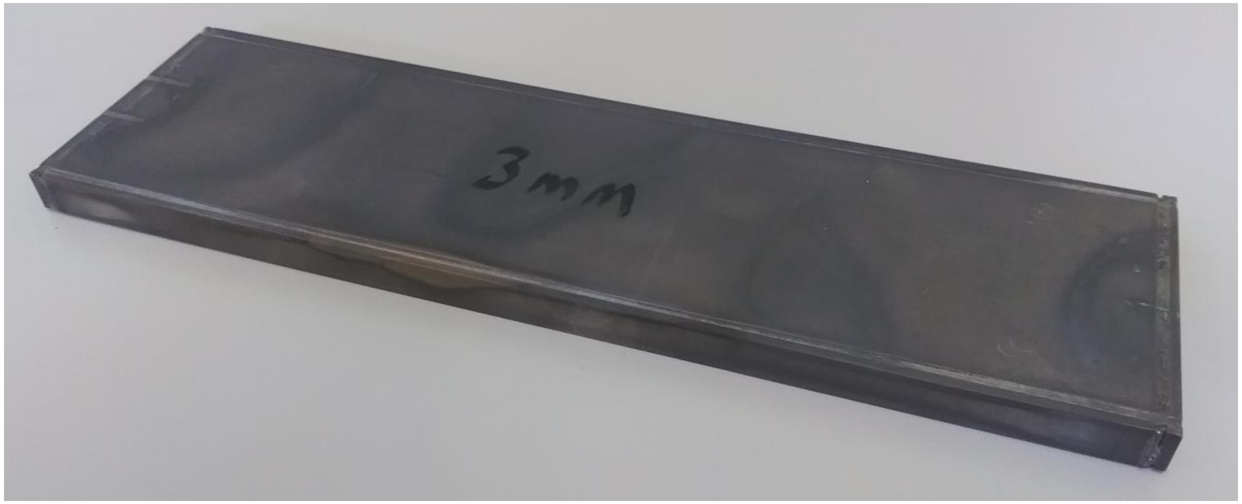




Manufacture

- Manufactured by Jeremy Moor and his team using the same materials and methods as ISIS targets



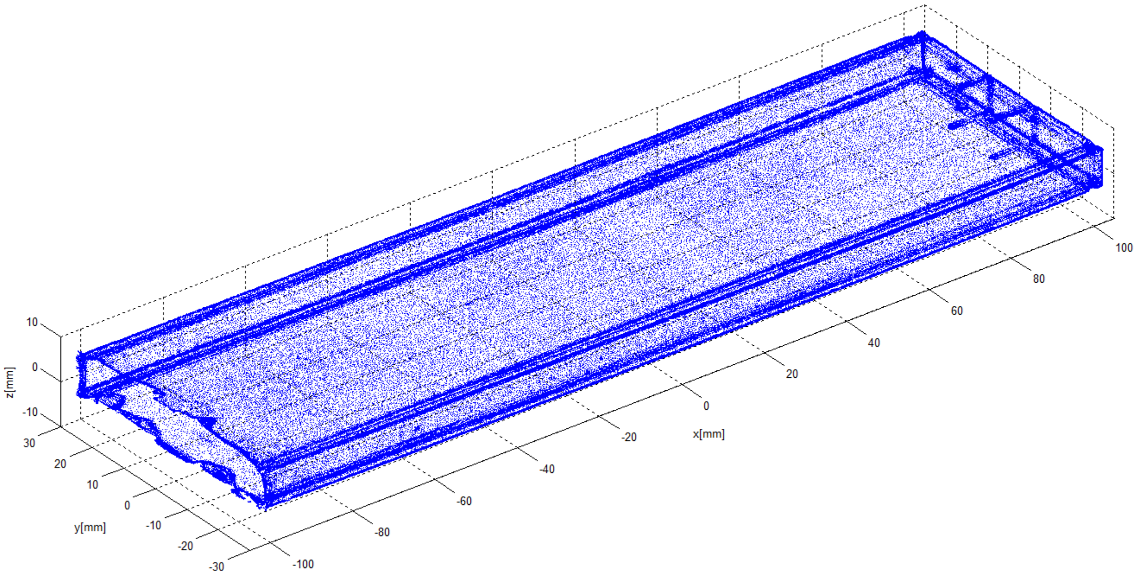


Photos: Jeremy Moor

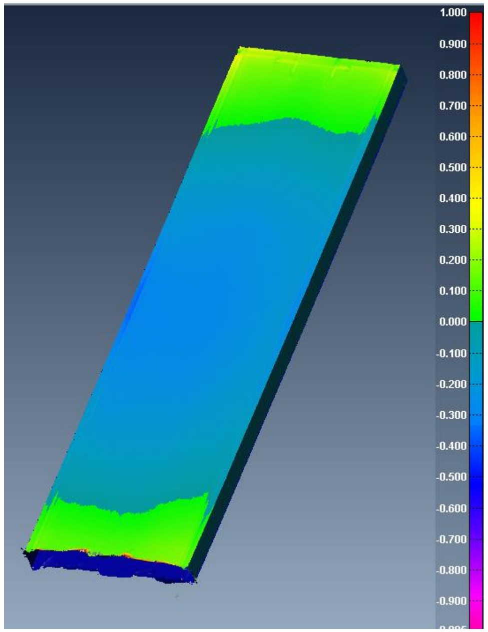
Measurement

- Sample was measured before and after HIP using a Faro Edge arm (laser scanner coordinate measuring machine)
  - Concave on upper (thick tantalum) side as expected

- Measured points were imported into MATLAB for surface fitting



Cloud of points for MATLAB

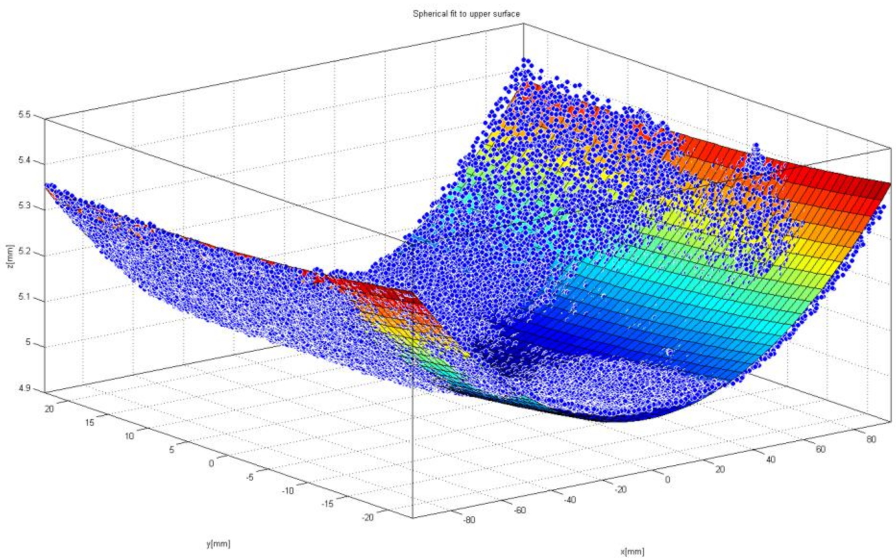


Deflection of upper surface

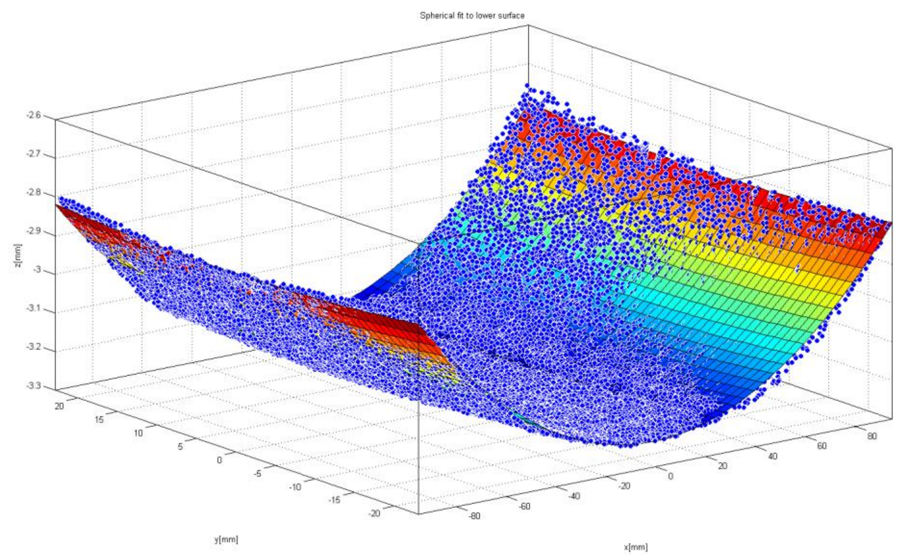
Curve fitting

- Ignore tantalum sides and outer 5mm tungsten (edge effects)

- Spherical fit to upper surface (thick Ta) and lower surface (thin Ta)
  - Good fit ($R^2 = 0.990$)
  - Fit radius of curvature = 11.4m upper, 10.4m lower



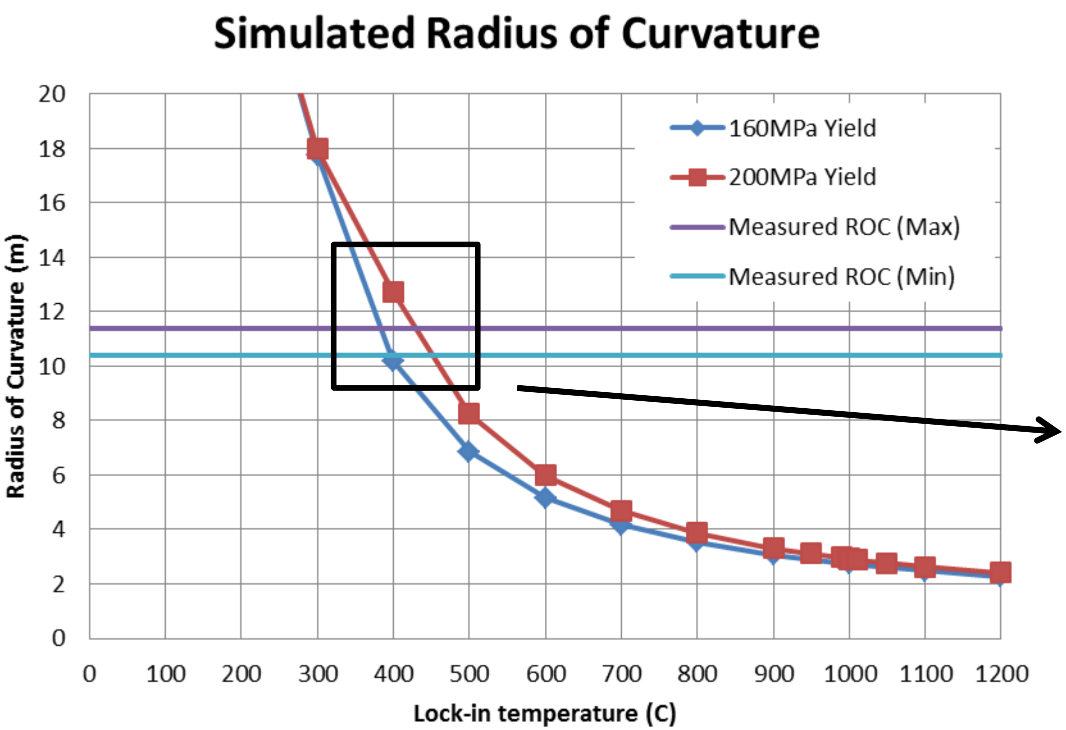
Upper surface

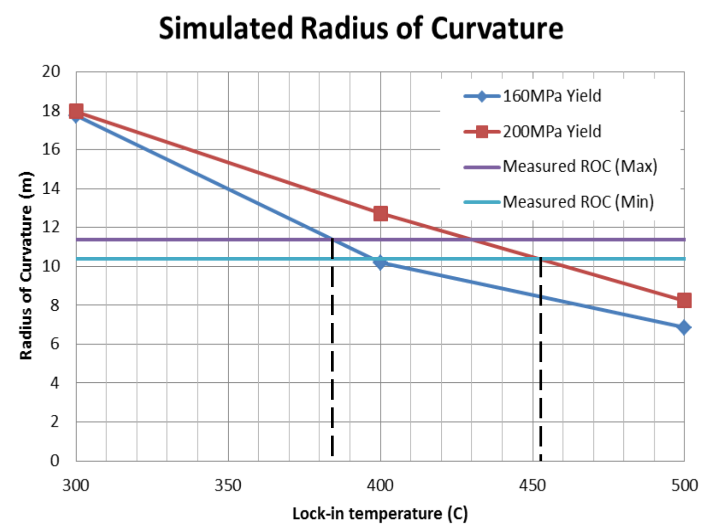


Lower surface

Comparison with Theory

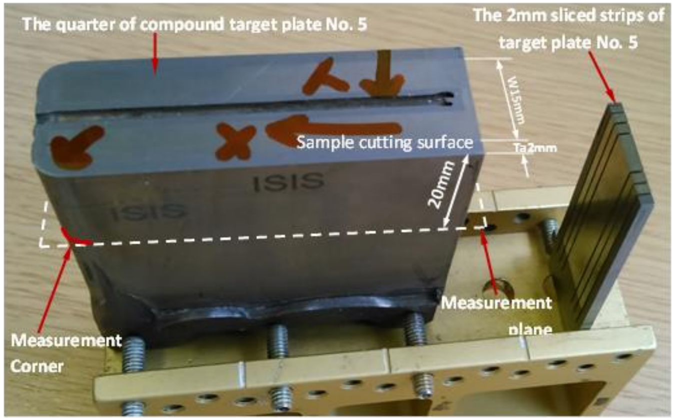
- Compare fit and simulated radii of curvature
  - Estimates lock-in temperature at 385-450°C
  - To produce the measured deflection the tantalum must have yielded

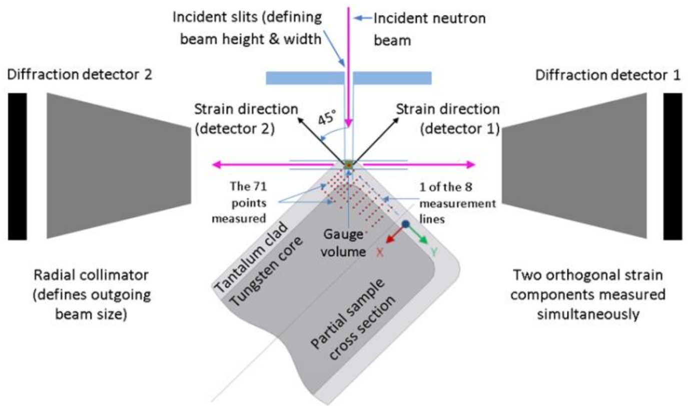




Future Work

- Neutron diffraction experiment on ISIS Engin-X instrument
  - Builds on previous work by Yanling Ma et al. on a TS1 plate*
    - Previous results suggest tantalum has yielded, but not enough data to confirm
    - Demonstrated that neutrons will be able to pass though our sample
- Re-measure deflection in a few years to see if stress has relieved
  - Strip manufactured last year, no stress relieving observed so far
  - However cyclic stress relieving may occur in beam?





**Yanling Ma, et al., "An Experiment Using Neutron Diffraction to Investigate Residual Strain Distribution in a Hot Isostatic Pressed (HIPPED) Target Plate," in Joint 3rd UK-China Steel Research Forum & 15th CMA-UK Conference on Materials Science and Engineering, 2014.*

Implications for ISIS Targets

- Appears to confirm our assumption that HIPing produces a residual stress large enough to yield the tantalum, i.e. HIPing rather than applied beam is the largest source of stress

- High tensile stress will reduce fatigue life of the cladding, although we currently have a large safety factor even with this included
  - Limited data on radiation damage and fatigue effects in tantalum
  - If tantalum ductility is lost this may present a problem

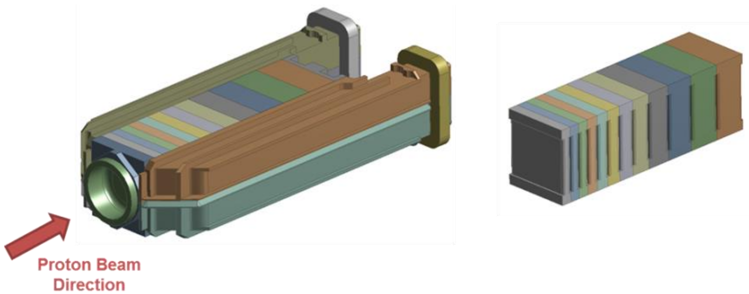
- Continuing to develop our understanding of failure modes will enable more optimised targets and higher beam powers in future

Conclusions

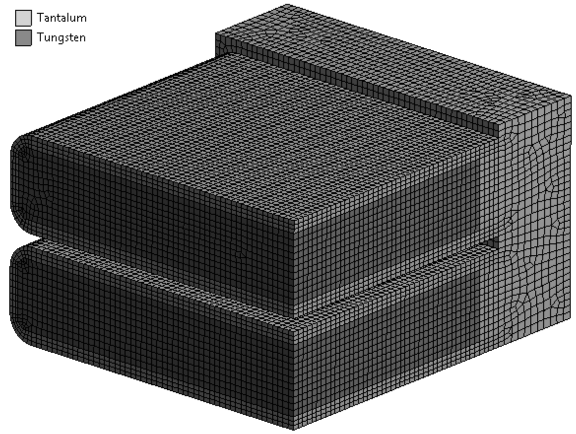
- Residual stress due to HIP process has been measured by a simple, mechanical method
- This will be followed up with neutron diffraction measurements on the same sample
- Measured residual stress is very high, therefore it is important to include this in any Ta-clad W target analysis
- We were able to accurately simulate the deflection of an asymmetric-clad strip by assuming a lock-in temperature of 385-450°C

Back-up slides

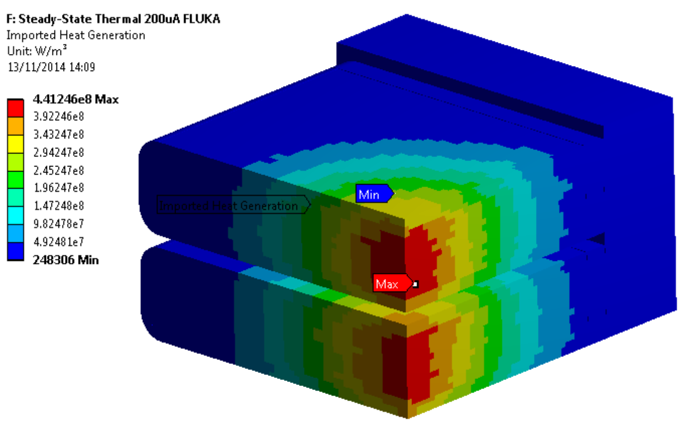
TS1 FEA Simulation – Setup



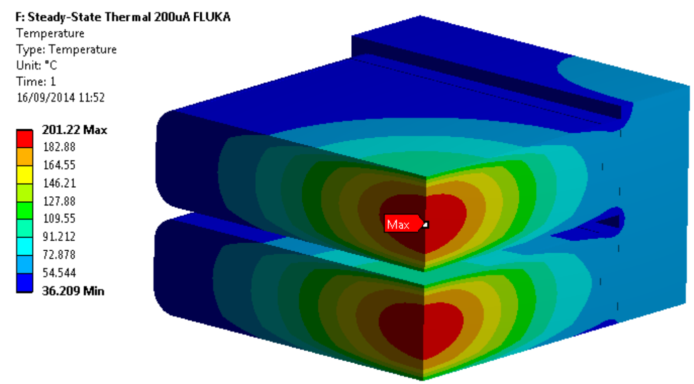
TS1 Target CAD Model



FEA mesh for plates 1 and 2 (quarter model)



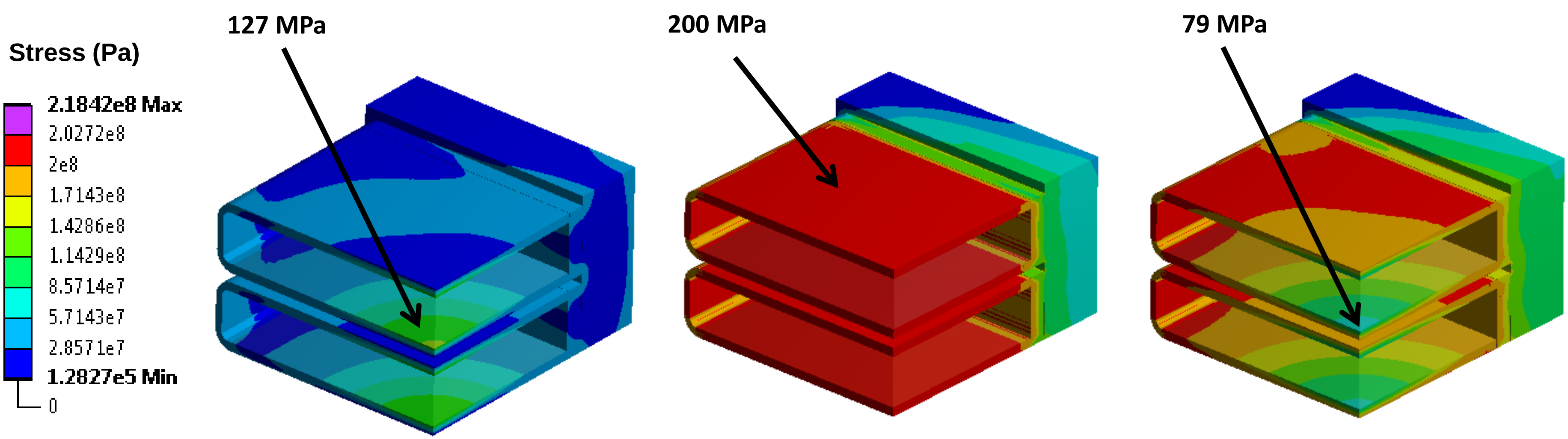
FLUKA heat deposition data



Thermal result (200°C max)

TS1 FEA Simulation – Results

- Model of ISIS TS1 target plates 1 and 2
  - HIP residual stress assuming 500°C lock-in temperature
  - Thermal stress due to steady-state proton beam
  - Simulated tantalum plasticity assuming 200MPa yield strength



200uA Beam **HIP Residual Stress** **HIP + 200uA Beam**

TS1 FEA Simulation – Results

- Beam heating partially relieves the residual HIP stress, as the unstressed state for the target is now uniformly at 500°C

- Results are similar for other ISIS targets
  - Tungsten yield stress is 550MPa
  - Tantalum strain-to-failure is around 30-40%

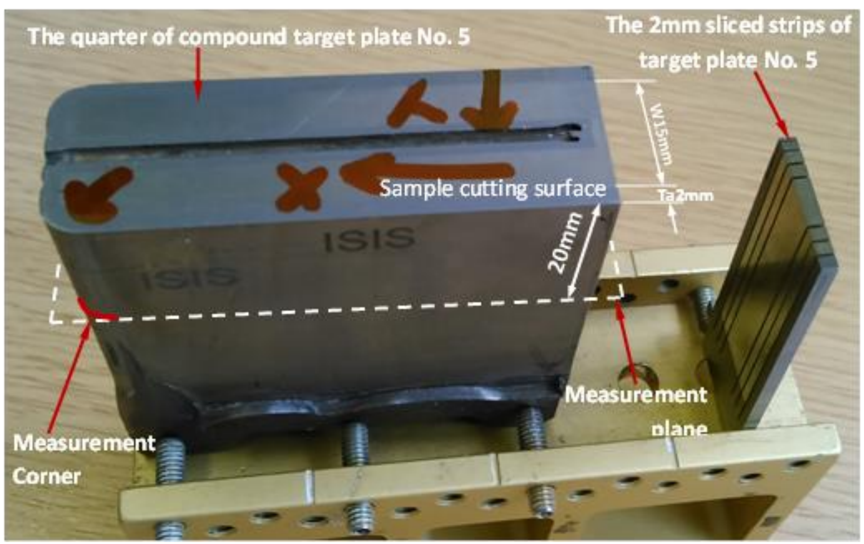
	TS1	TS2	TS1 Upgrade
Tungsten Stress [HIP+Beam] (MPa)	207	191	165
Tantalum Stress [HIP+Beam] (MPa)	200*	200*	200*
Tantalum Total Strain (/)	0.40%	0.38%	0.42%

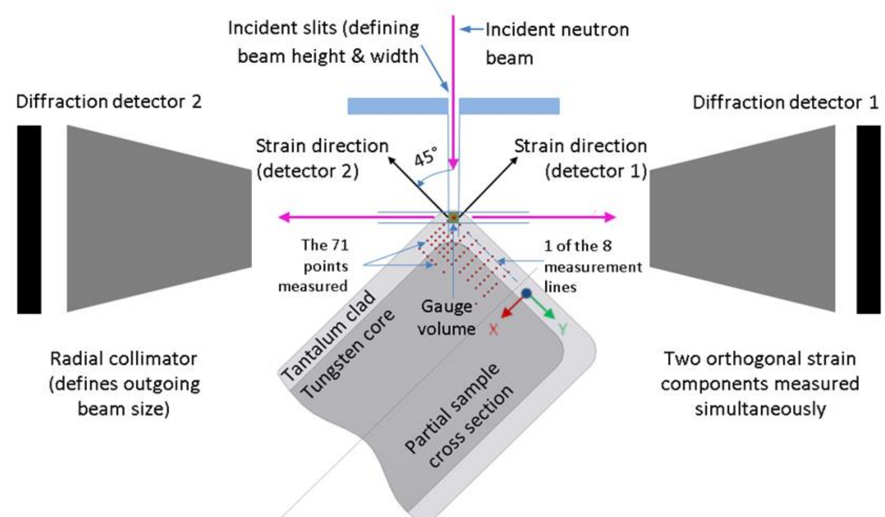
**200MPa is the yield stress of tantalum*

- No failure of the tungsten core is expected – the main concern is to ensure integrity of the cladding

Measuring the Residual Stress

- This analysis depends entirely on the assumed value of lock-in temperature, which cannot be measured directly
- The Engin-X instrument at ISIS used neutron diffraction to make preliminary measurements of residual stress in a clad ISIS plate*





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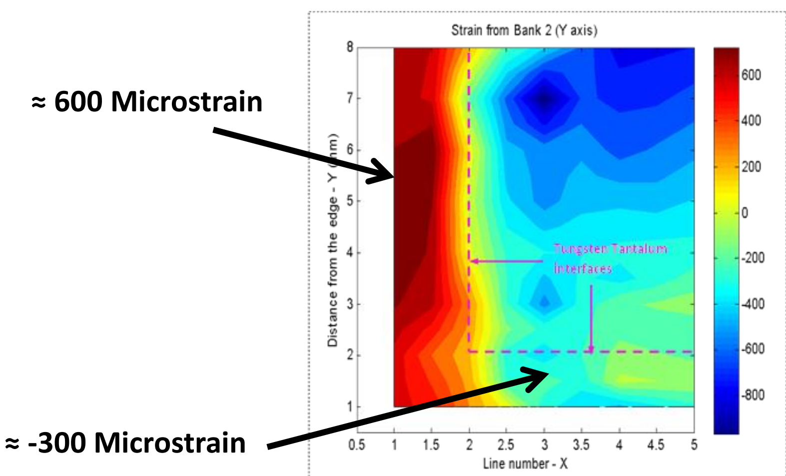
Measuring the Residual Stress

- Neutron diffraction measures spacing between atoms and uses this to determine elastic strain
  - Cannot measure plastic strain by neutron diffraction

- Measured elastic strains are broadly consistent with the cladding being at the yield stress as predicted – however the experiment did not measure all three directions so this cannot be confirmed

Engin-X Strain Result (Y direction)



ANSYS Simulation of Engin-X Sample