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Simulating Performance of Tantalum-Clad Tungsten Targets

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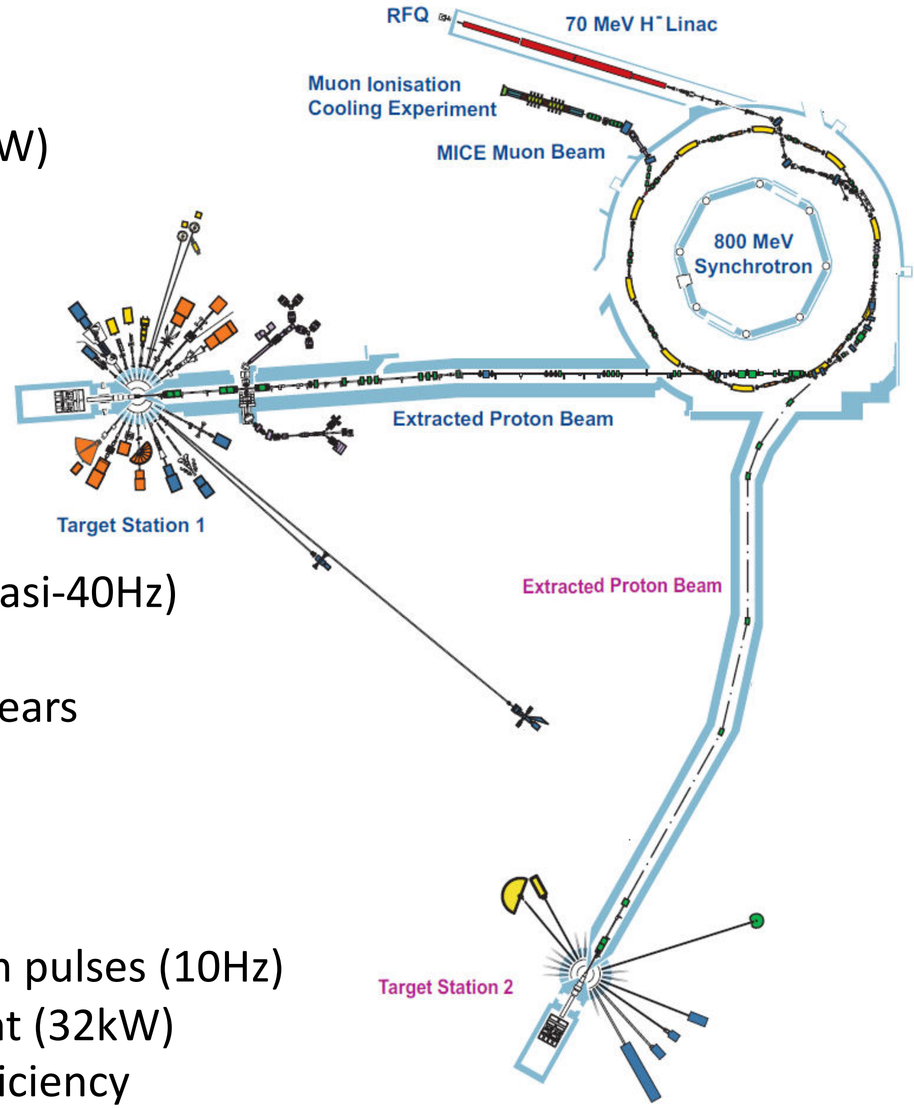
Overview

- Background
- Stress in ISIS targets – manufacturing and beam induced
- Review of fatigue and irradiation data
- Implications for current and future ISIS targets
- Conclusions

Background – ISIS Facility



Synchrotron

- 800MeV proton energy
- Up to 240uA beam current (192kW)
- Pulsed at 50Hz

Target Station 1

- Opened in 1984
- Receives 4/5 beam pulses (quasi-40Hz)
- 200uA beam current (160kW)
- Proven reliability over many years

Target Station 2

- Opened in 2007
- Receives 1/5 beam pulses (10Hz)
- 40uA beam current (32kW)
- High neutronic efficiency

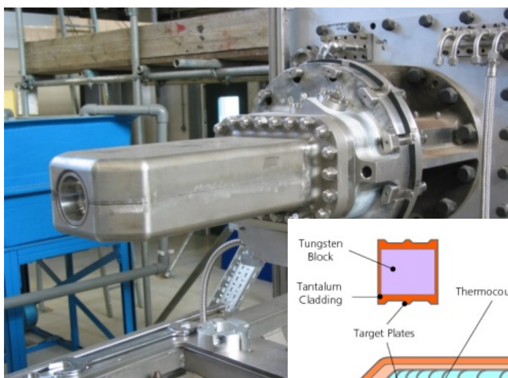
Background – ISIS Targets

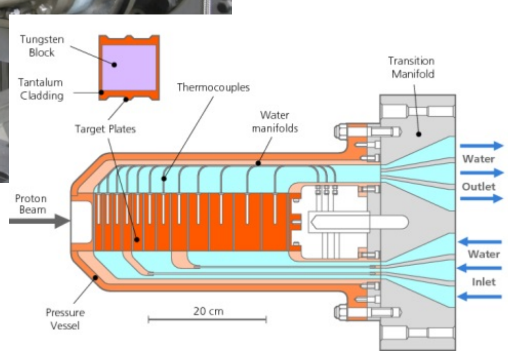
Target Station 1

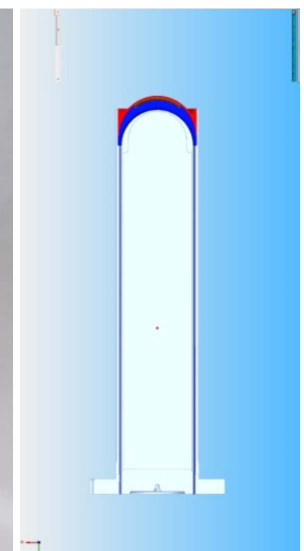
- 160kW
- Ta clad W target, 12 plates
- Lifetime 4-5 years, limited only by thermocouple failure

Target Station 2

- 32kW
- Ta clad W target, solid rod
- Lifetime about 1.5 years, limited by release of activated tungsten into water circuit – weld failure suspected







Background

- Ongoing work to understand the performance of ISIS targets
  - Design a more optimised upgrade target for TS1 without compromising reliability
  - Have hopefully resolved weld issues on TS2 targets – what is the new lifetime limiting factor?

- Modern FEA software allows highly optimised targets to be designed, assuming appropriate limits are set on temperature, stress, etc.
  - Better understanding of failure modes enables more optimised target designs
  - Important to meet the demand for ever higher beam powers

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ISIS Target Manufacture

- Tantalum can welded shut with tungsten core inside
- Hot Isostatic Press (HIP) process applies high temperature and pressure, pressing cladding onto core
  - Tantalum and tungsten are bonded together, ensuring good thermal contact
  - Cladding deforms plastically under high pressure (140MPa)
  - Peak temperature is 1200°C, held for 2 hours – relieves stress, but does not cause grain growth
  - As the clad target cools below the annealing temperature, residual stress builds up due to different coefficients of thermal expansion
- Final machining to achieve dimensional accuracy
- Plates welded together to form target stack (TS1 Only)

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

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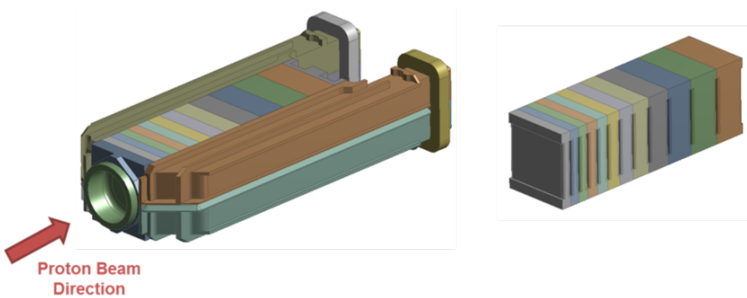
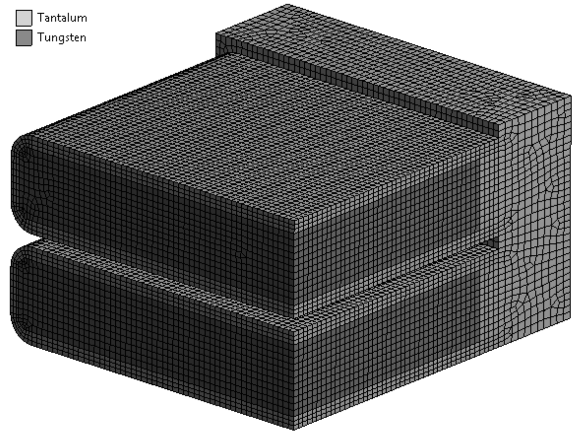
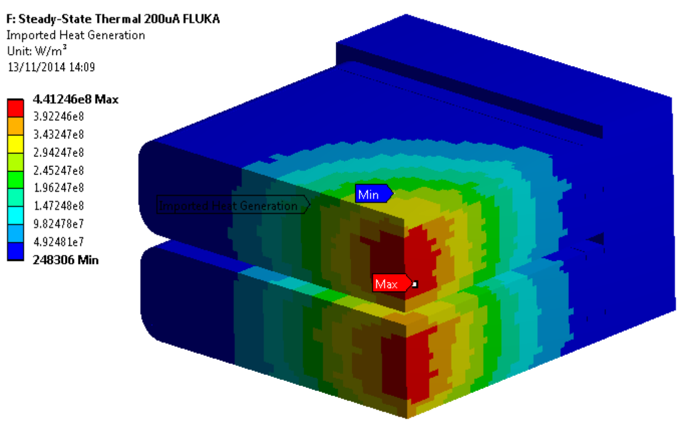
TS1 FEA Simulation – Setup



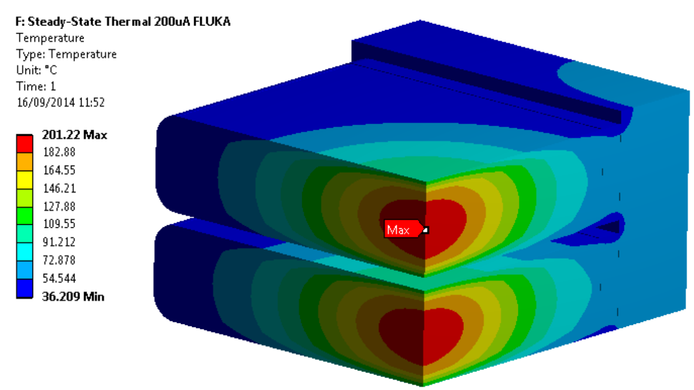
TS1 Target CAD Model



FEA mesh for plates 1 and 2 (quarter model)



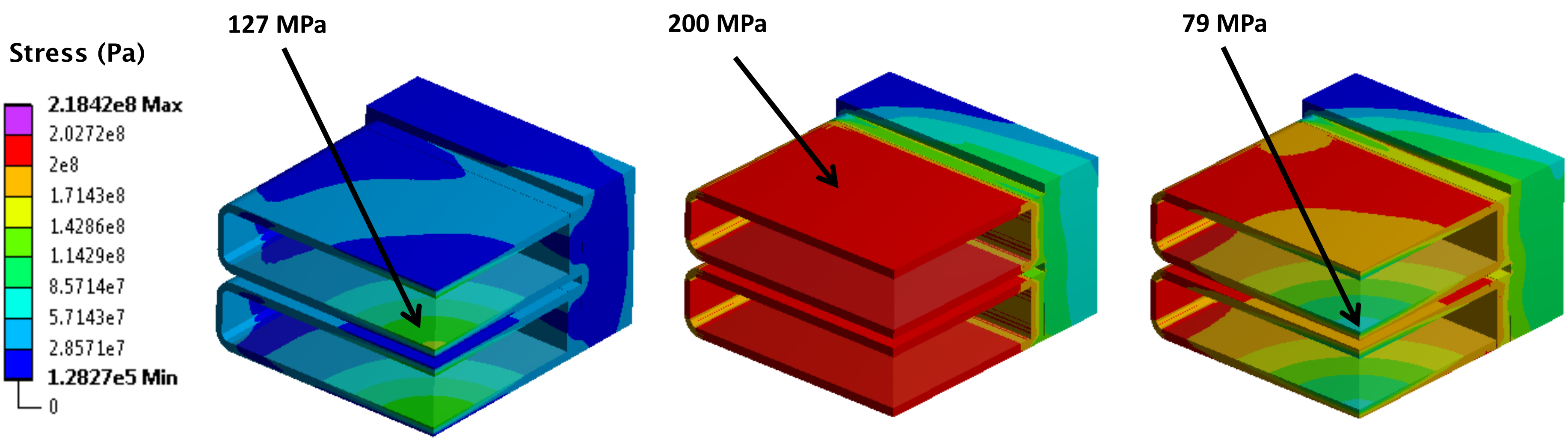
FLUKA heat deposition data



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%

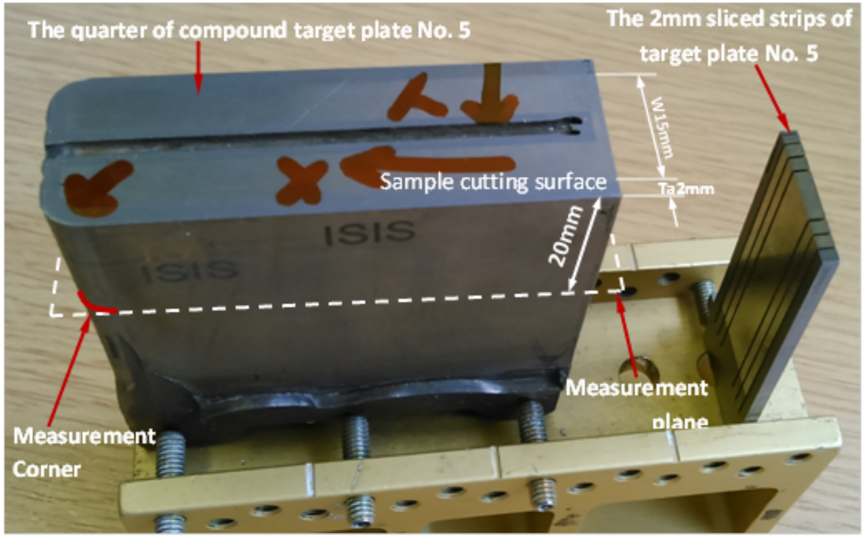
**200MPa is the yield stress of tantalum*

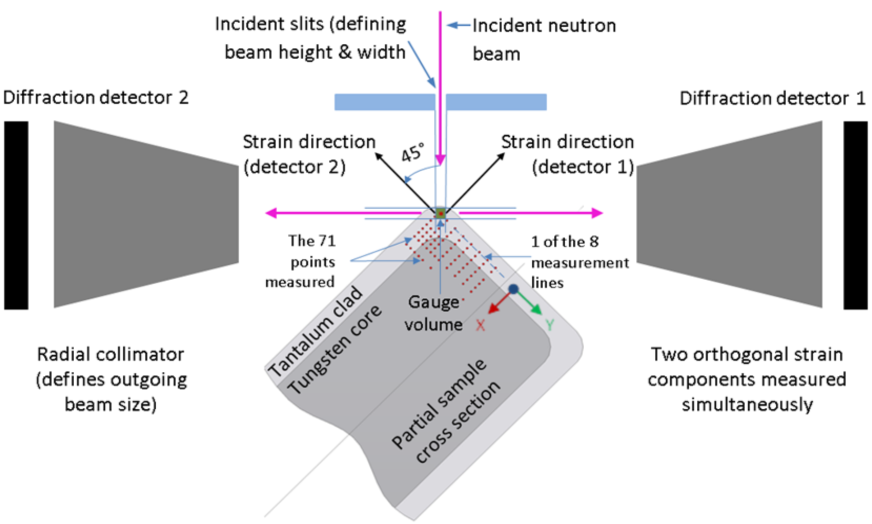
- No failure of the tungsten core is expected – the main concern is to ensure integrity of the cladding

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*





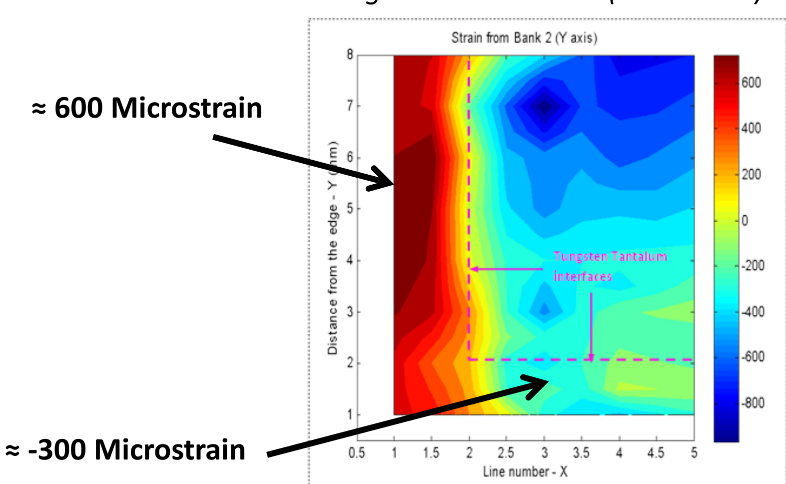
Yanling Ma, et al., "An Experiment Using Neutron Diffraction to Investigate Residual Strain Distribution in a Hot Isostatic Pressed (HIPPED) Target Plate," in Joint 3rd UK-China Steel Research Forum & 15th CMA-UK Conference on Materials Science and Engineering, 2014.

Measuring the Residual Stress

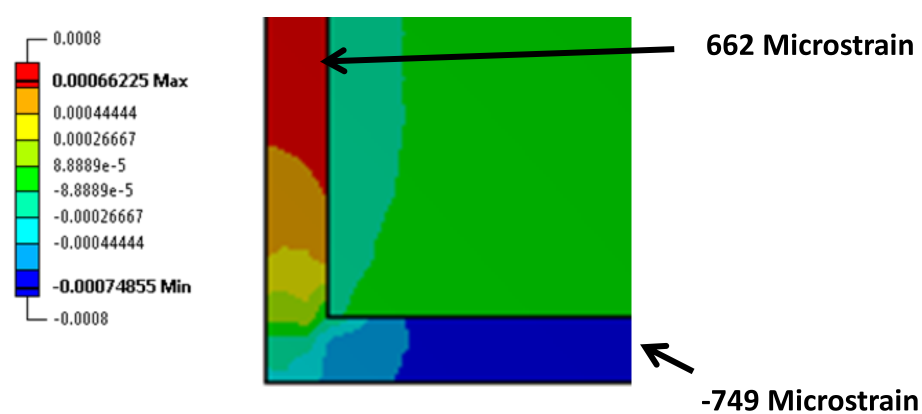
- Neutron diffraction measures spacing between atoms and uses this to determine elastic strain
  - Cannot measure plastic strain by neutron diffraction

- 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)



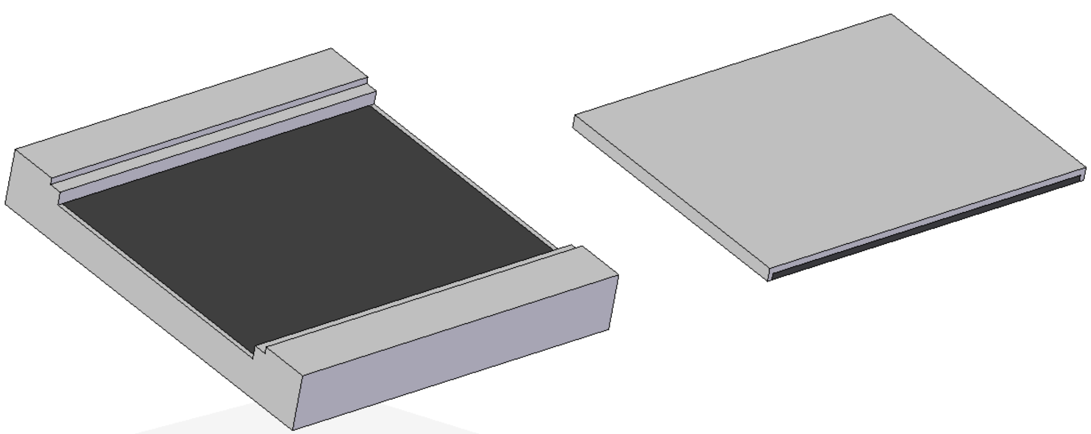
ANSYS Simulation of Engin-X Sample



Measuring the Residual Stress

- A second Engin-X run is being planned to investigate further
  - Can use furnace to heat/cool sample during strain measurement

- Physical measurements of residual stress are also under consideration
  - Cut plate surface to produce a bimetallic strip; its deflection depends on residual stress
  - A trimetal strip with thick tantalum on one side and thin tantalum on the other will allow residual stress measurement without cutting the sample



Transient and Fatigue Analysis

- Two types of cycle: beam pulses and beam trips
  - If the accelerator trips, the target will cool to room temperature causing a larger thermal cycle

- FEA simulations output the Goodman equivalent stress amplitude in each case
  - Shows the combined effect of stress change and average stress
  - Tensile residual stress makes fatigue loading in the cladding more severe

Case	Frequency (Hz)	No. per year*	No. per 5 year target lifetime	Equiv. Stress Amplitude in Ta (Mpa)
Pulse TS1	40	5.37E+08	2.69E+09	4.2
Pulse TS2	10	1.34E+08	6.72E+08	17.5
Trip TS1	1.66E-04	2.23E+03	1.12E+04	113
Trip TS2	1.66E-04	2.23E+03	1.12E+04	98

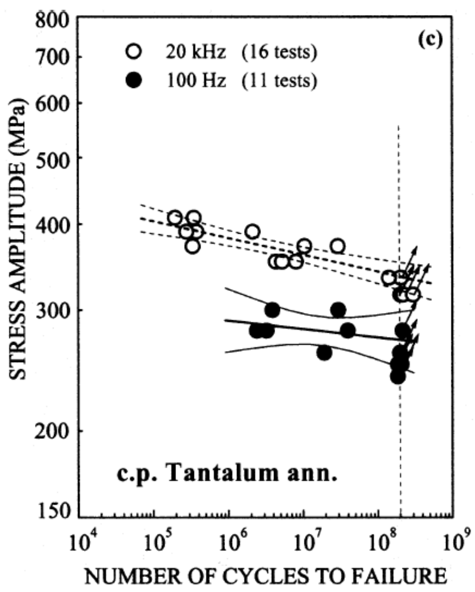
**Assuming ≈45% facility uptime*

Review of Fatigue Data

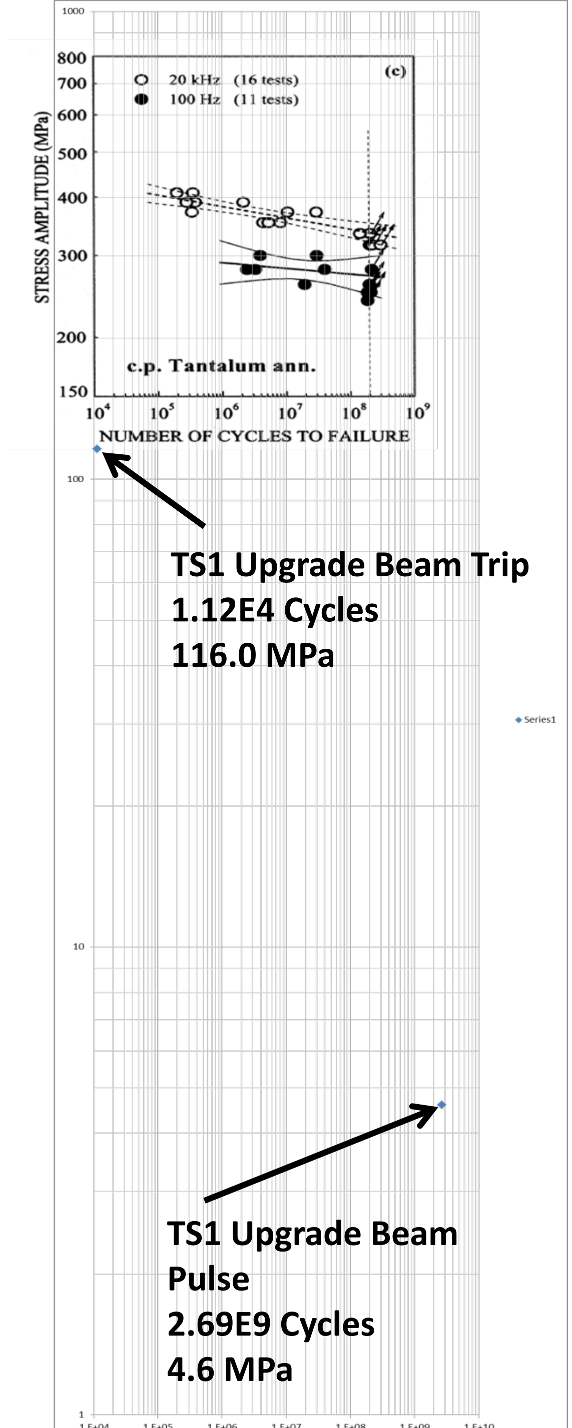
- To determine target lifetime, we need to know the number of cycles to failure in tantalum
  - Tungsten is under compressive residual stress and has a large factor of safety on yield stress, so it is unlikely to fail by fatigue
- Limited data, but reported endurance limits for tantalum are very high (in many cases higher than the yield strength)
  - Due in part to significant cyclic hardening
- ISIS targets see low stress amplitudes, but many more cycles than have ever been tested.
- Radiation damage will also have an important (but difficult to model) effect

Review of Fatigue Data

Authors	Year	Test Details	Test Frequency	Number of Cycles	Endurance Limit (MPa)
Papakyriacou et al.	2001	Rotating bend, annealed tantalum	100Hz	2E8	270 ± 30
		Ultrasonic, annealed tantalum	20kHz	2E8	335 ± 15
		Rotating bend, cold worked tantalum	100Hz	2E8	290 ± 35
		Ultrasonic, cold worked tantalum	20kHz	2E8	365 ± 10
Bornemann and Gela	1953	Universal fatigue machine	Unknown	2E7	240
		Rotating beam fatigue machine	Unknown	2E7	≈440
Helebrant and Stevens	1971	Constant stress amplitude	20Hz	5E6	≈200



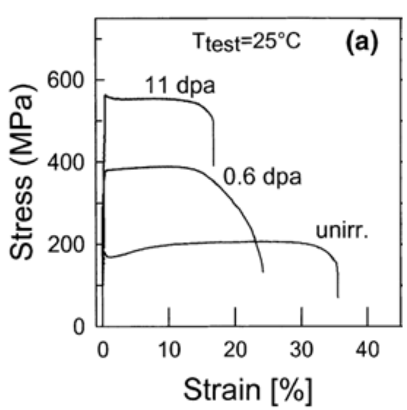
S-N curve from:
Papakyriacou, et al. (2001). Influence of loading frequency on high cycle fatigue properties of b.c.c. and h.c.p. metals. Materials Science and Engineering: A, 308(12), 143-152



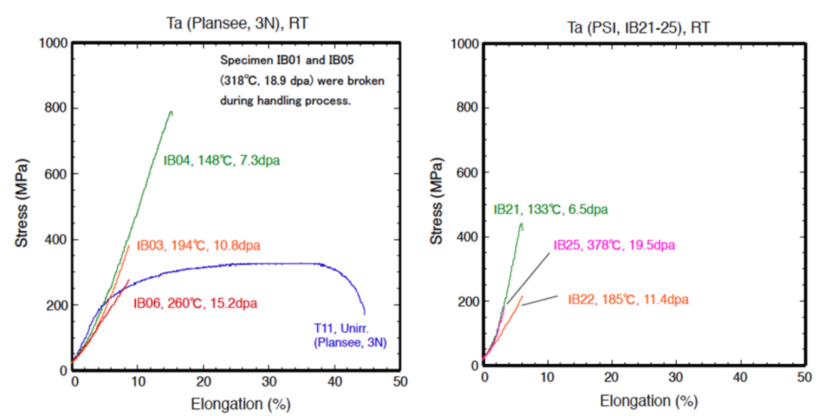
STRESS AMPLITUDE (MPa)
20 kHz (16 tests)
100 Hz (11 tests)
(c)
c.p. Tantalum ann.
NUMBER OF CYCLES TO FAILURE
TS1 Upgrade Beam Trip
1.12E4 Cycles
116.0 MPa
Series1
TS1 Upgrade Beam
Pulse
2.69E9 Cycles
4.6 MPa

Review of Irradiation Data

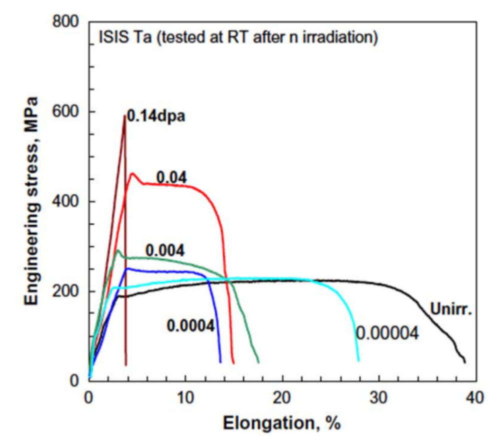
- ISIS Target cut up at FZ-Juelich (published 2003)
  - 800MeV proton irradiation up to 11dpa, tantalum remained very ductile
- Specimens from STIP-II programme at SINQ (presented 2012)
  - 580MeV proton irradiation up to 19.5dpa, less ductility was retained
- Reactor neutron irradiation at HFIR (published 2008)
  - > 0.1MeV fast neutron irradiation up to 0.14dpa, tantalum had lost most of its ductility by 0.14dpa



ISIS target at FZ-Juelich



STIP-II Specimens



HFIR Specimens

Review of Irradiation Data

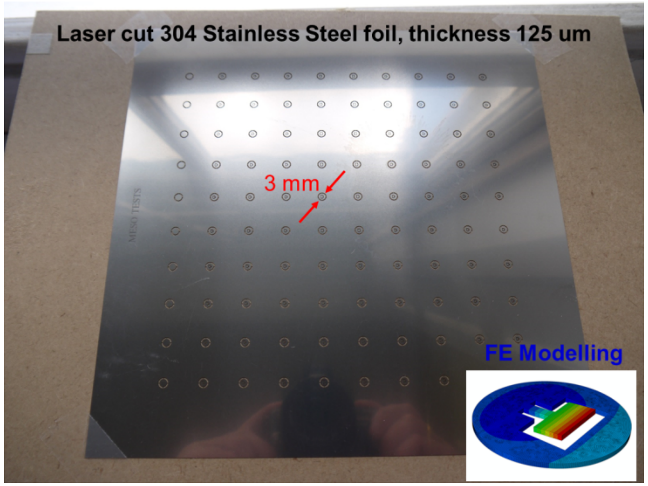
- Limited data
- Ductility after irradiation varies significantly between tests
  - Literature suggests it is quite sensitive to impurities, particularly oxygen and hydrogen

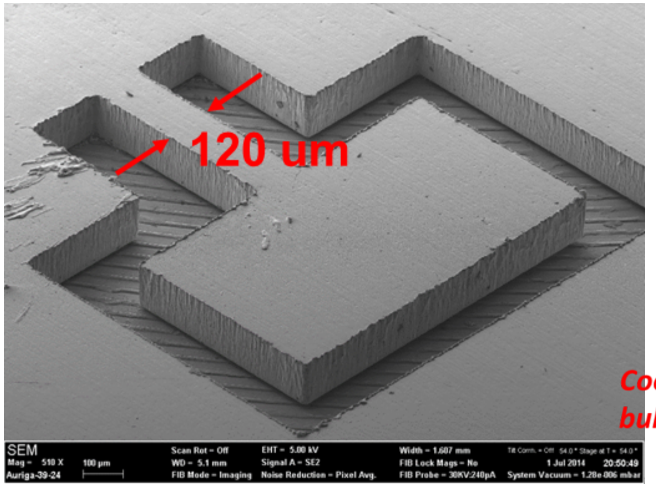
Tantalum Sample	Total Impurities (ppm)	Oxygen Content (ppm)
ISIS target at Juelich	66	8
STIP-II specimens	1050	100
HFIR specimen (ISIS Ta)	585	496

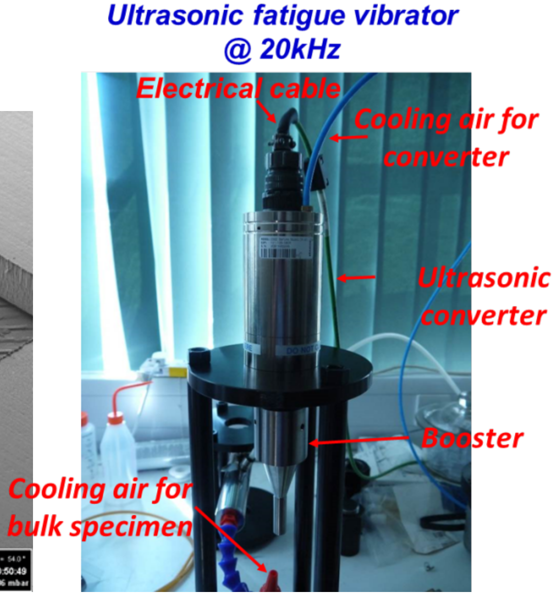
- Recent estimates of dpa in ISIS targets have varied from ≈10 to 100
- We have spent ISIS targets in storage, but not the budget or facilities to do PIE on them

Future Fatigue/Irradiation Measurements

- Oxford University have a new technique for fatigue testing thin foils
- Laser cut cantilevers from thin foil and vibrate at high frequency
- Laser measurement of cantilever deflection
- Many grains through cantilever thickness
- Well suited to irradiated materials – plans to install a fatigue vibrator in a hot cell at Culham Centre for Fusion Energy







Credit: Jicheng Gong & Angus J Wilkinson, Micromechanics Group, Oxford University

Implications for ISIS Targets

- ISIS target lifetimes are currently limited by thermocouples (TS1) and weld quality (TS2)
- TS1 upgrade target will experience fatigue and radiation damage at a similar rate to current TS1 target, so should achieve similar reliability
- If weld/thermocouple issues were fixed – what is the next failure mode?
  - Intergranular corrosion at the welds?
  - Water leak from pressure vessel welds?
  - Next issues are probably also manufacturing/materials related

Implications for ISIS Targets

- Will eventually see radiation embrittlement + fatigue failure of the cladding
  - May be able to establish this limit directly by micro fatigue testing
- How much beam power can we put on a Ta-clad W target?
  - Decay heat in the tantalum becomes hard to manage
  - Can use thicker tungsten plates to reduce decay heat, but this will increase internal stress in the tungsten
  - Optimising plate and cladding dimensions will be important to push the power limits of stationary tantalum-clad tungsten targets

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Conclusions

- ISIS target lifetimes are currently limited by thermocouples (TS1) and weld quality (TS2); we have not yet reached the limits of the material

- Large HIP residual stress is expected in the cladding, experiments to measure this are ongoing

- Fatigue and irradiation data for tantalum is limited, but endurance limit and ductility after irradiation look promising

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

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