Thermal Tests for Mu2e Targets

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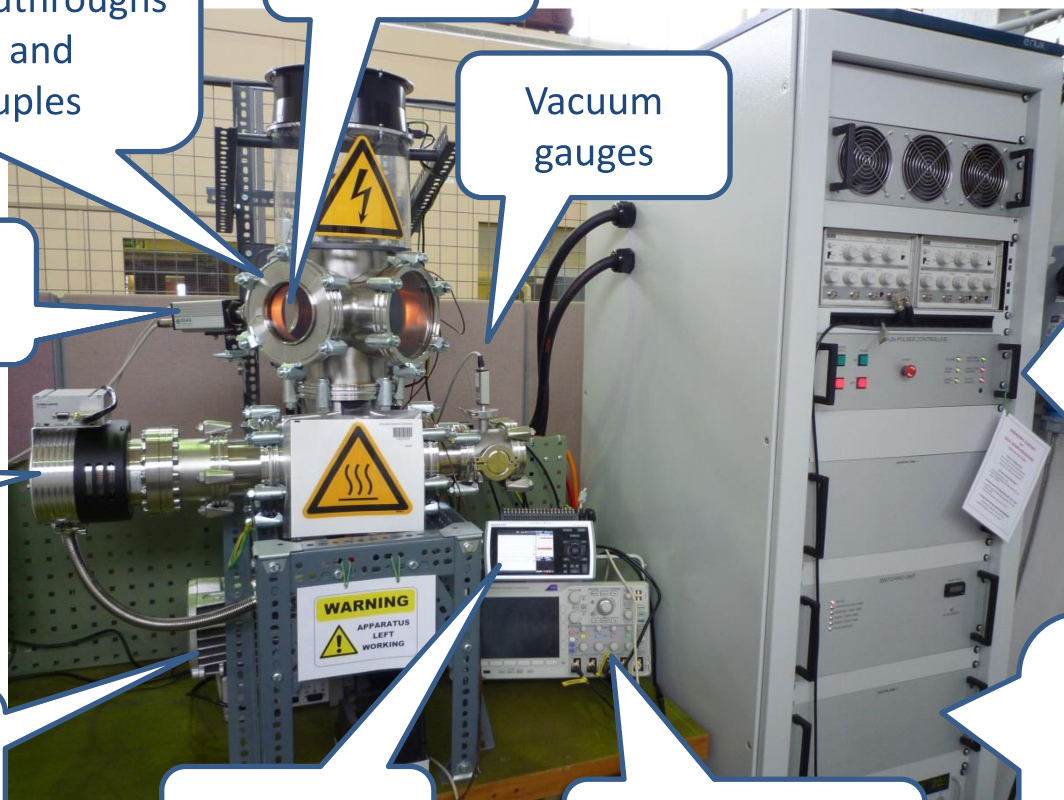
PASI General Meeting
9 September 2014

Target Thermal Test Rig

A new multi-purpose test rig for high temperature target applications



<u>Power supply rack</u>

Pulse mode:
1 msec long half-sine wave pulses
0 - 2.3 kA peak
1 - 50 Hz repetition

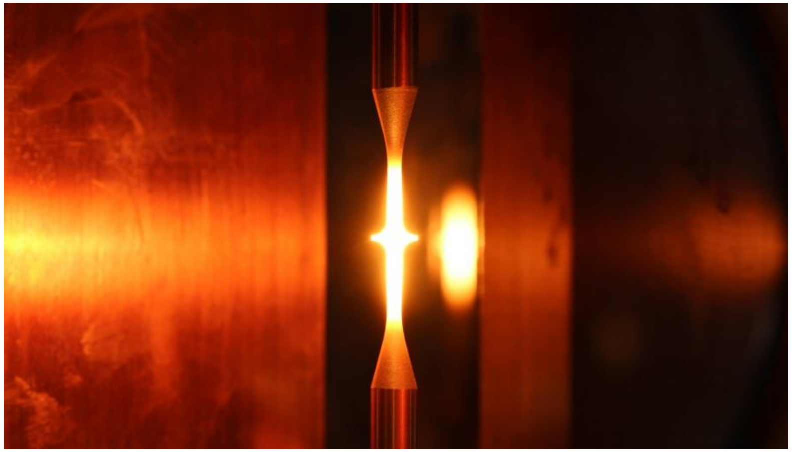
DC mode:
0-250A constant current

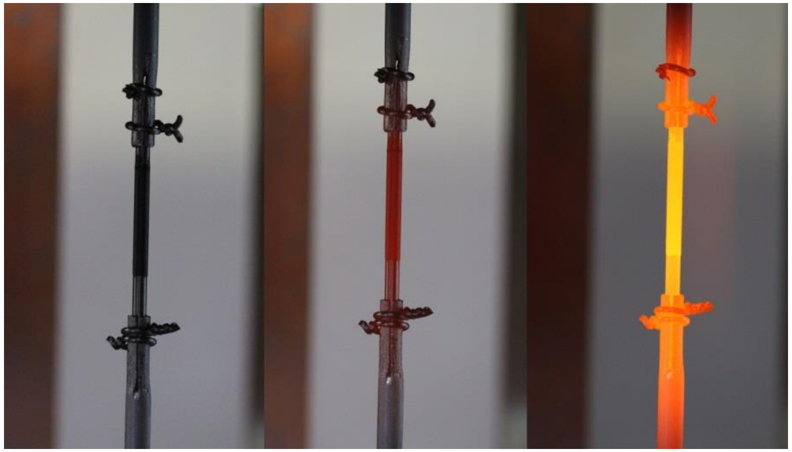
<u>System interlocks</u>
vessel over-temp
coolant flow
sample over-temp
vacuum level

Test Rig Applications

Samples subjected to electrical (resistive) heating in a vacuum

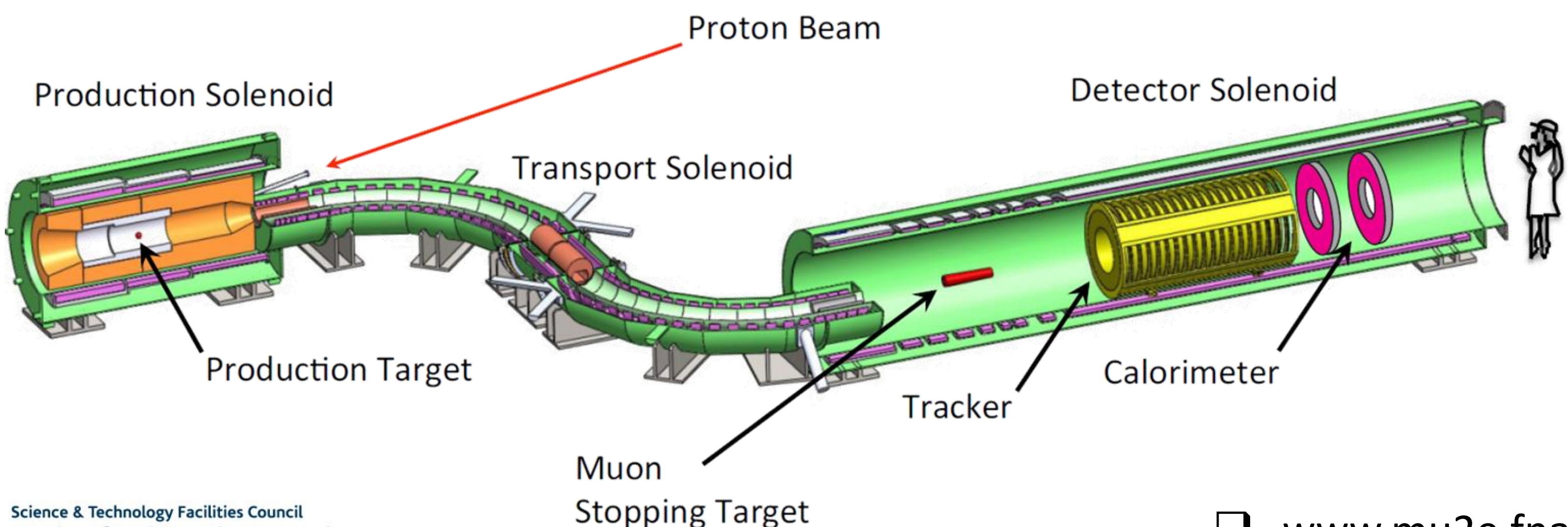
- ❑ Thermal fatigue "lifetime" tests
- ❑ Thermal emissivity (heat transfer) measurements
- ❑ Oxidation studies at various vacuum levels
- ❑ Creep/sag testing
- ❑ Oxidation resistant / high-emissivity coating trials
- ❑ Etc…





Tungsten samples heated to incandescent temperatures

Mu2e – Part of the planned “Muon Campus” at Fermilab



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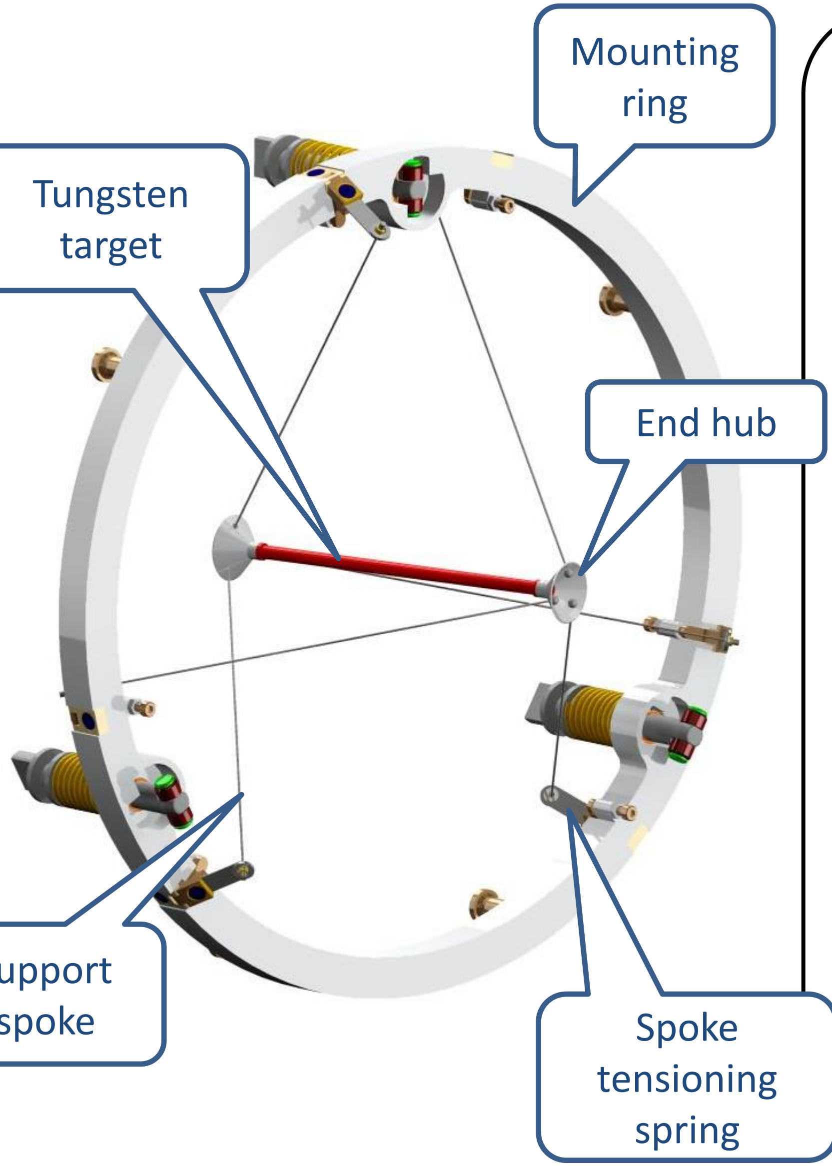
- www.mu2e.fnal.gov

The Mu2e "Bicycle-Wheel" Production Target Concept

Overview:

- Pencil sized tungsten target supported on spring-loaded refractory metal spokes
- Beam heat load (~600W) dissipated radiatively
- Eliminating the need for an active coolant greatly simplifies the remote target exchange process

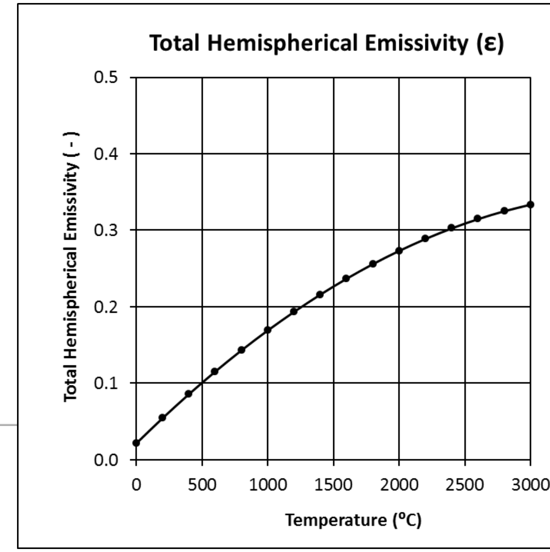


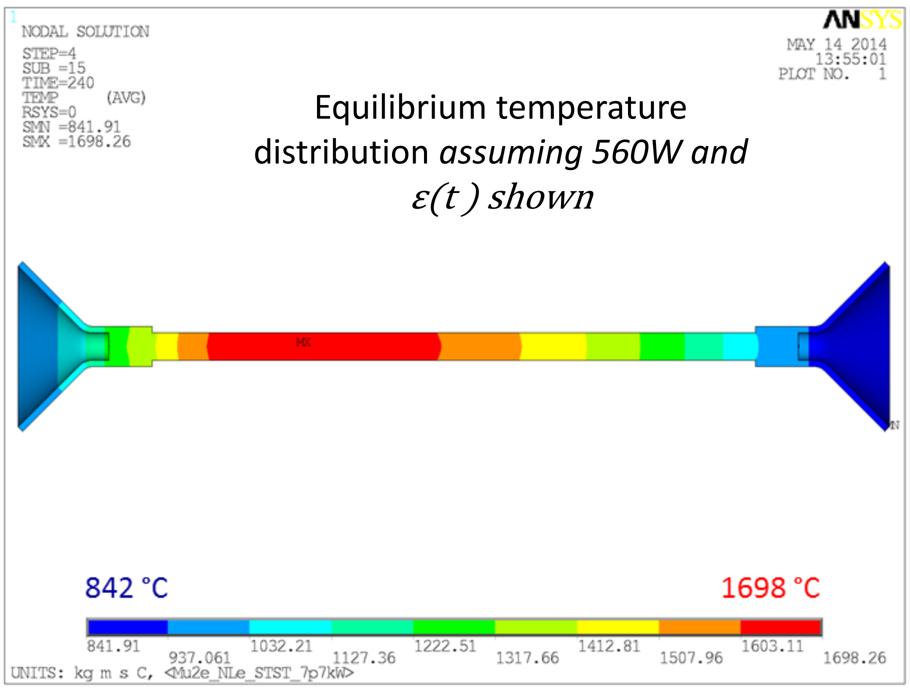
Technical Challenges:

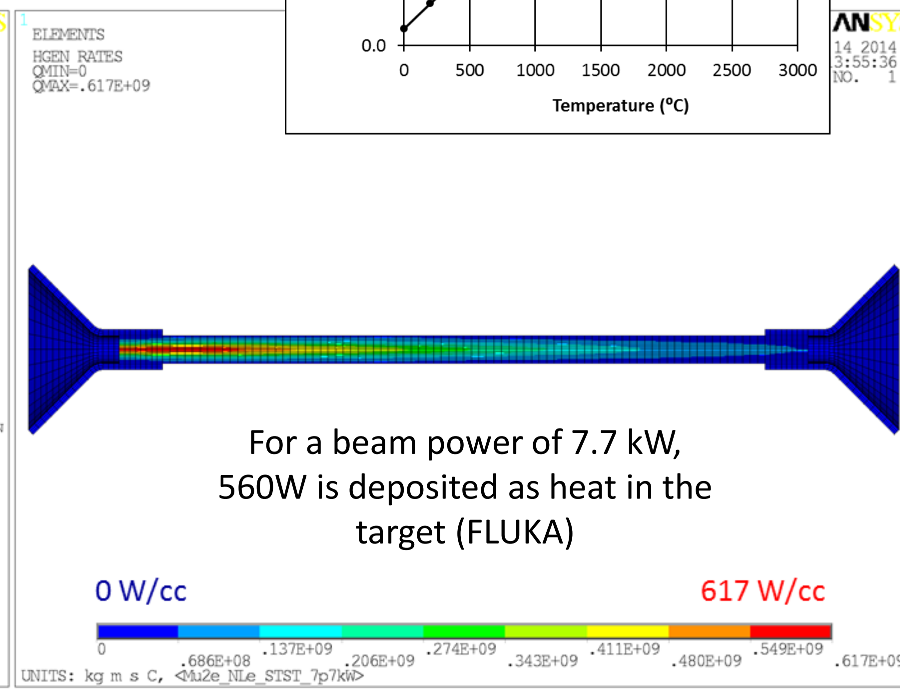
- Harsh radiation environment
- Prolonged operation at high temperature
- Cyclic thermal stresses
- Oxidation / chemical reactions with residual gasses
- Alignment / dimensional stability
- Minimum design life of 1 year (24 million beam cycles)

Target Operating Temperature

- Target heats up until it is able to dissipate the deposited power by thermal radiation
- Equilibrium temperature depends on ***heat load***, ***emissivity*** and ***surface area***.







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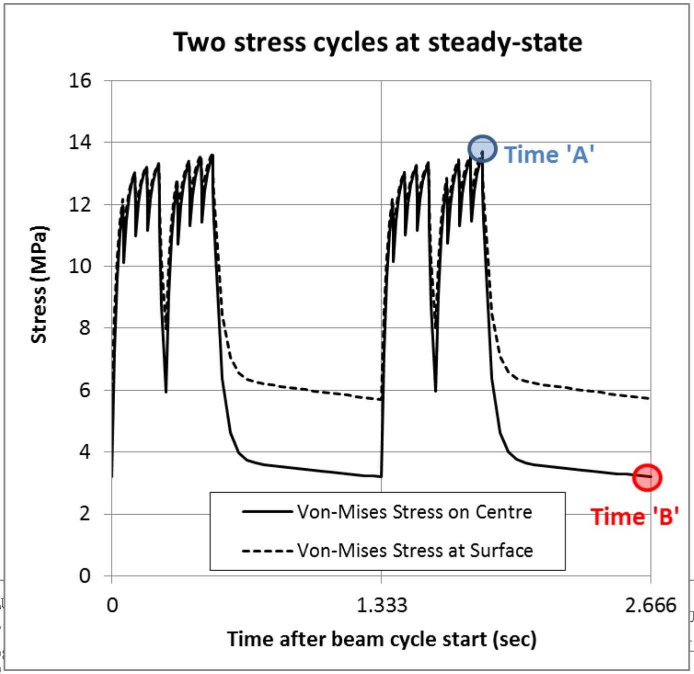
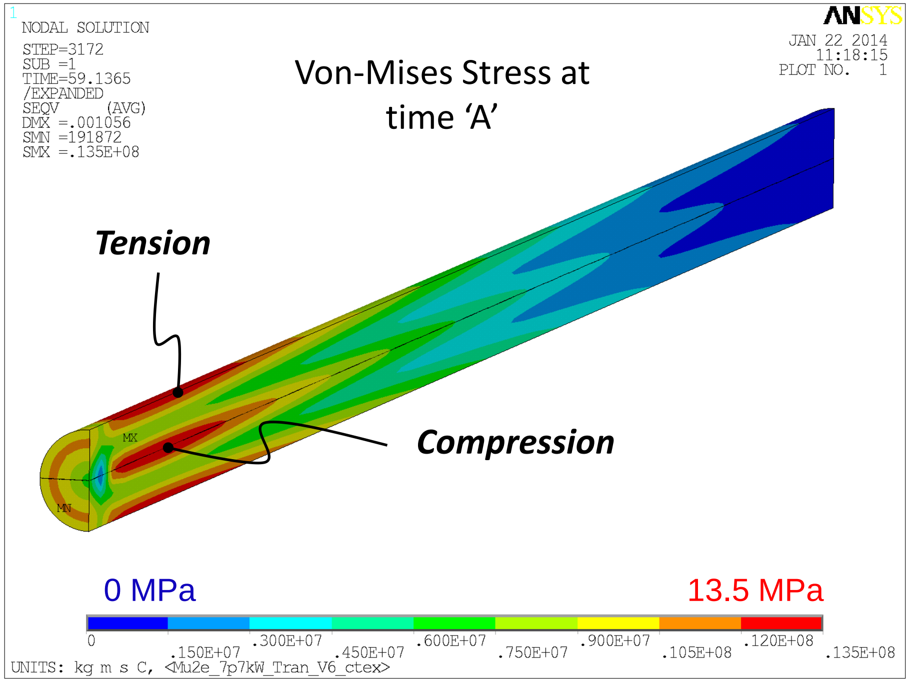
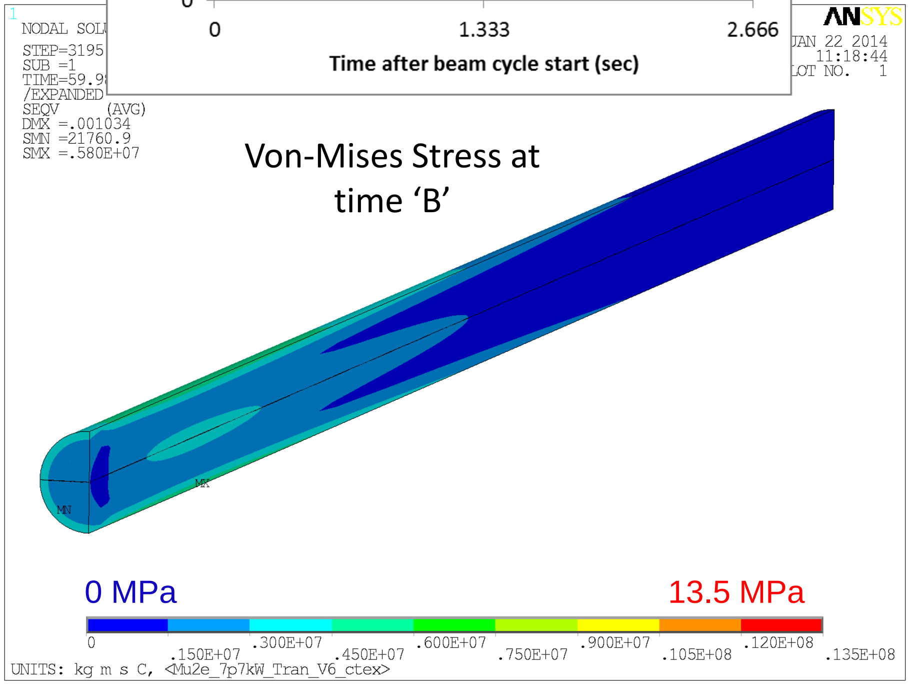
Cyclic Thermal Stress in the Target Rod

- The radial temperature gradient generates a thermal stress in the target
- The thermal stress falls away between pulses as thermal conduction acts to equalise the temperature



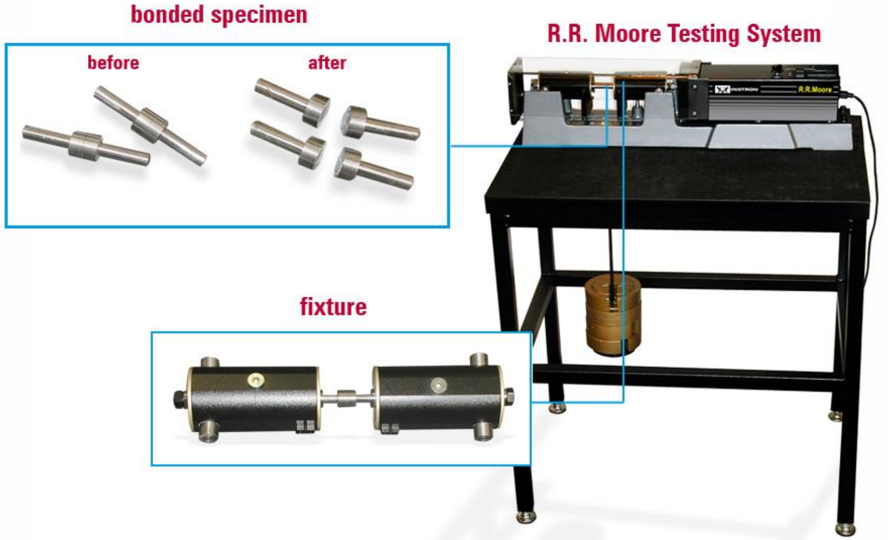




Conventional Fatigue Testing

Little high-temperature fatigue data for tungsten exists in the literature

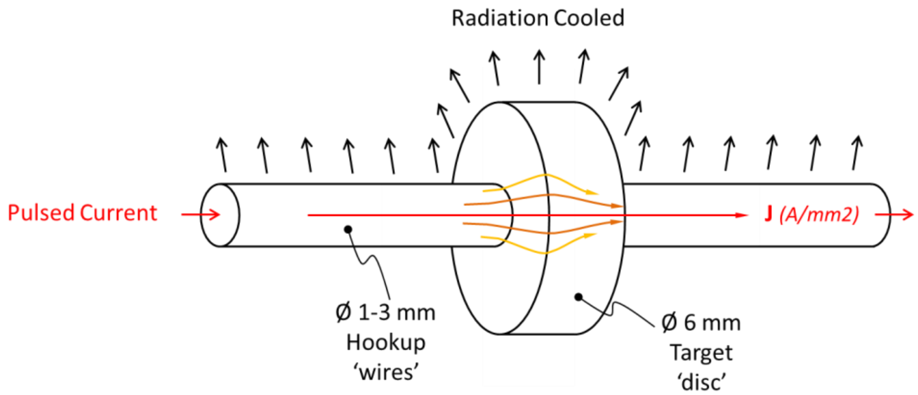
- High cycle fatigue tests are typically performed in either a rotating beam fatigue setup such as the popular 'R.R.Moore' system, or via uni-axial loading according to a force cycle waveform.
- There are commercially available fatigue machines that, using split furnace type heaters, can go up to around 1000°C and there is a standard, BS3987, that specifies dogbone specimens and covers testing up to 1200°C.
- However these conventional systems are not designed to test samples in the ***ultra-high temperature*** range of interest to Mu2e (1000 – 2000°C) or ***in vacuum***.

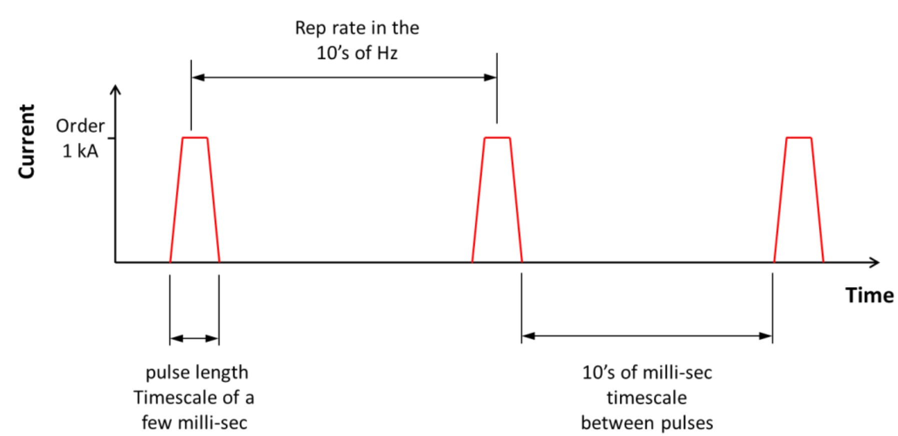


A Novel Thermal Fatigue Test for Mu2e

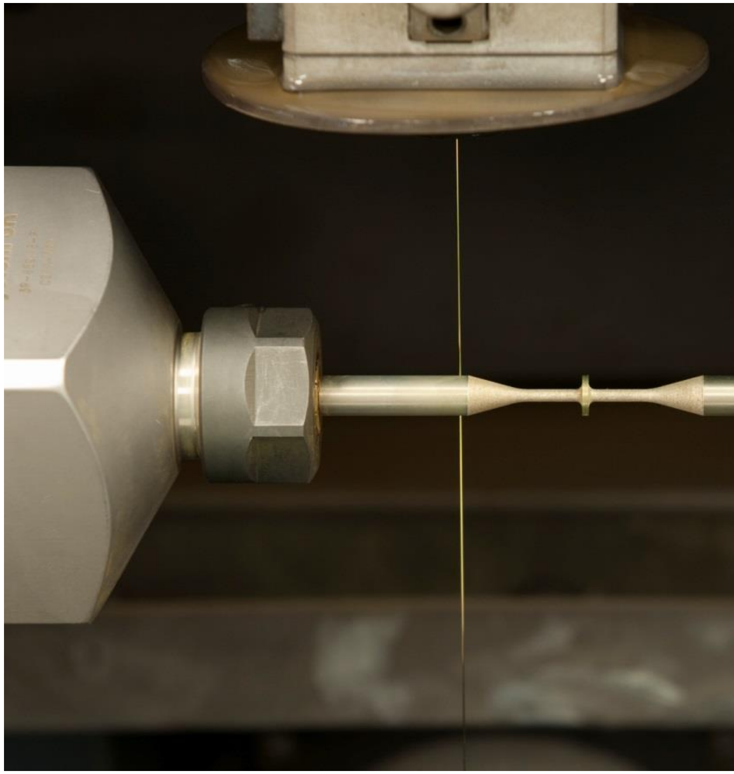
Operating Principle:

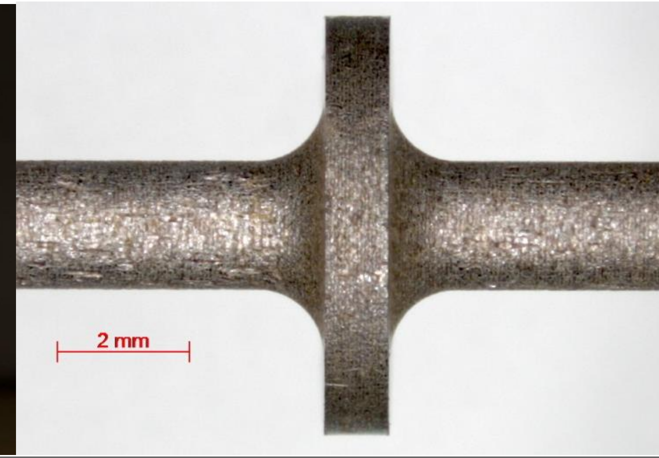
- Use a pulsed power supply to heat specially shaped samples in a vacuum environment
- Control the pulse repetition rate to achieve the desired operating temperature
- This system has the advantage that stresses in the sample are generated by temperature gradients (in much the same way as they are in the real target) and not via mechanical means as is the case in the standard test methods

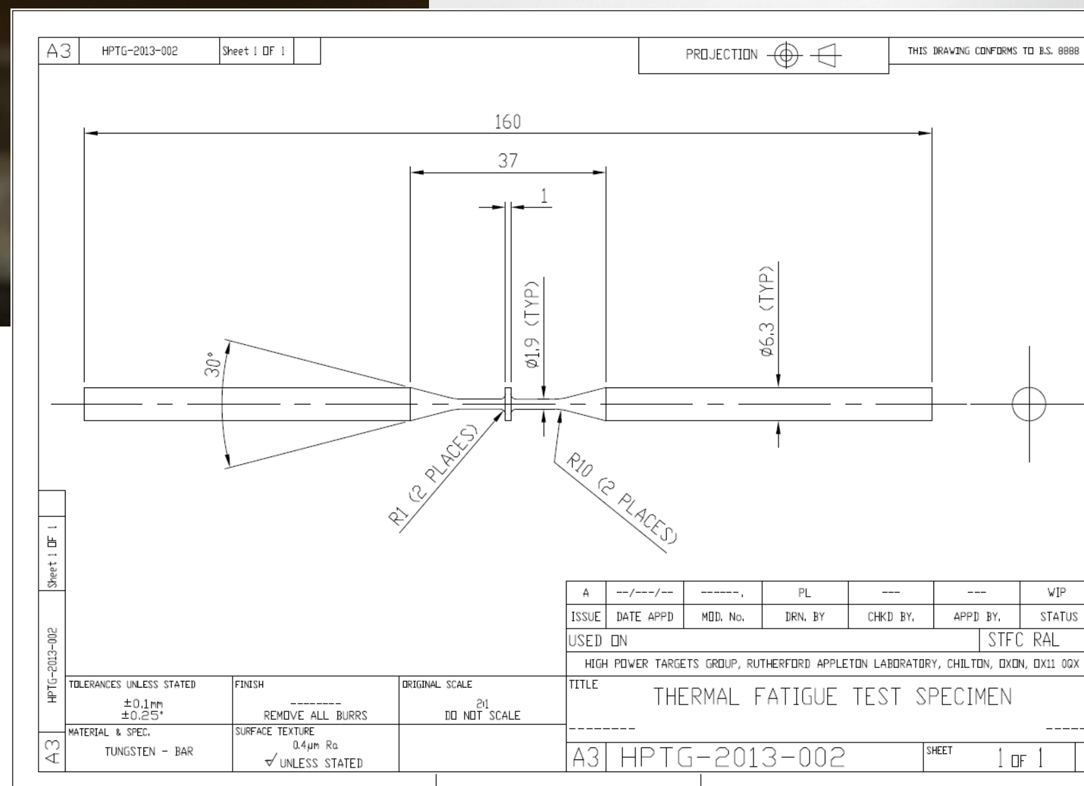




Tungsten Lifetime Test Samples







How to make the samples?

- Turn and Burn wire EDM process at RAL precision development facility

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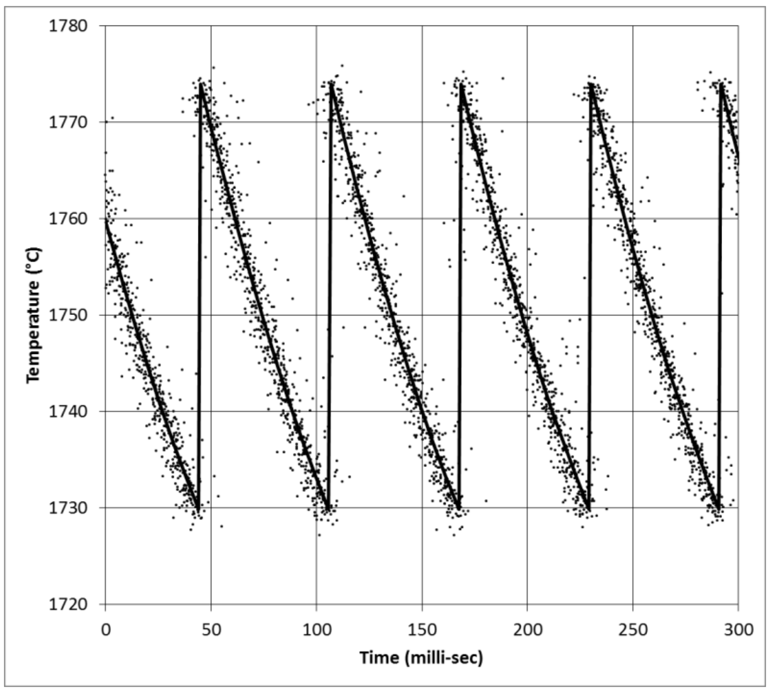
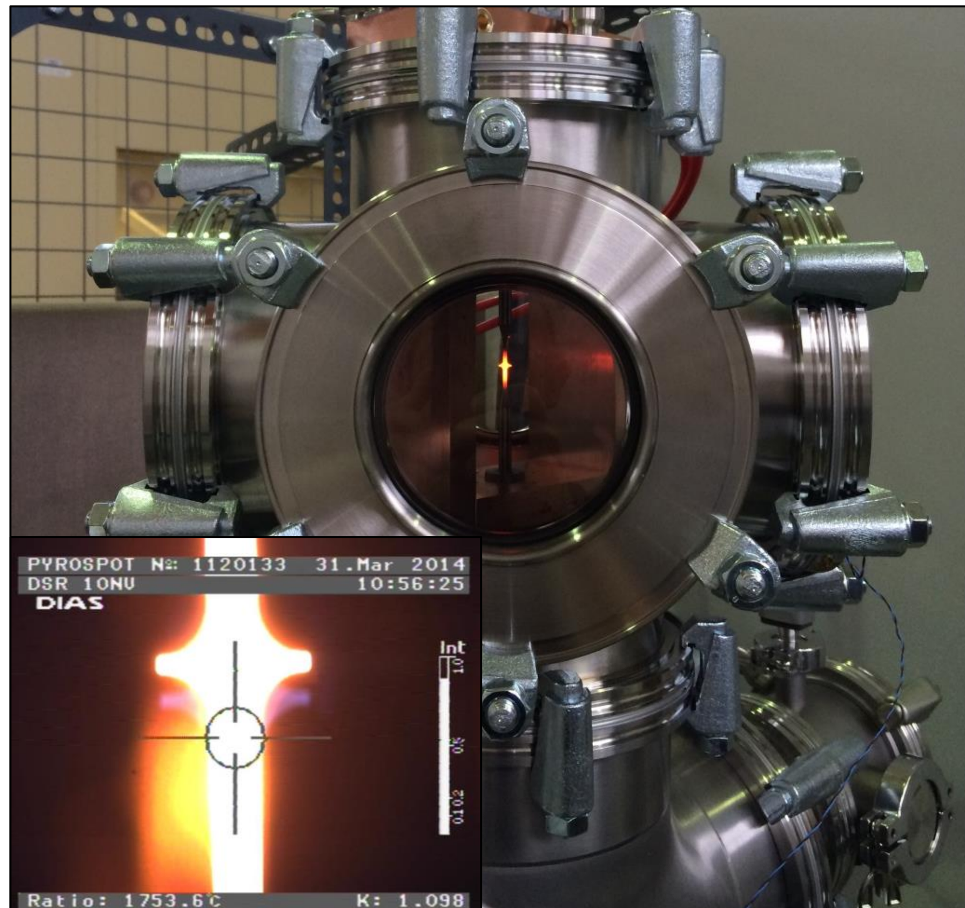
Test Parameters

Test designed to mimic the target operating conditions

Peak Current (A)	Repetition Frequency (Hz)	'mean' operating temperature	ΔT at surface (°C)	Number of Cycles Run	Failure?
1900	16.2	1750°C	44	100 Million	No



Above: data from the digital pyrometer
Right: a fatigue sample inside the vessel
Inset: pyrometer software



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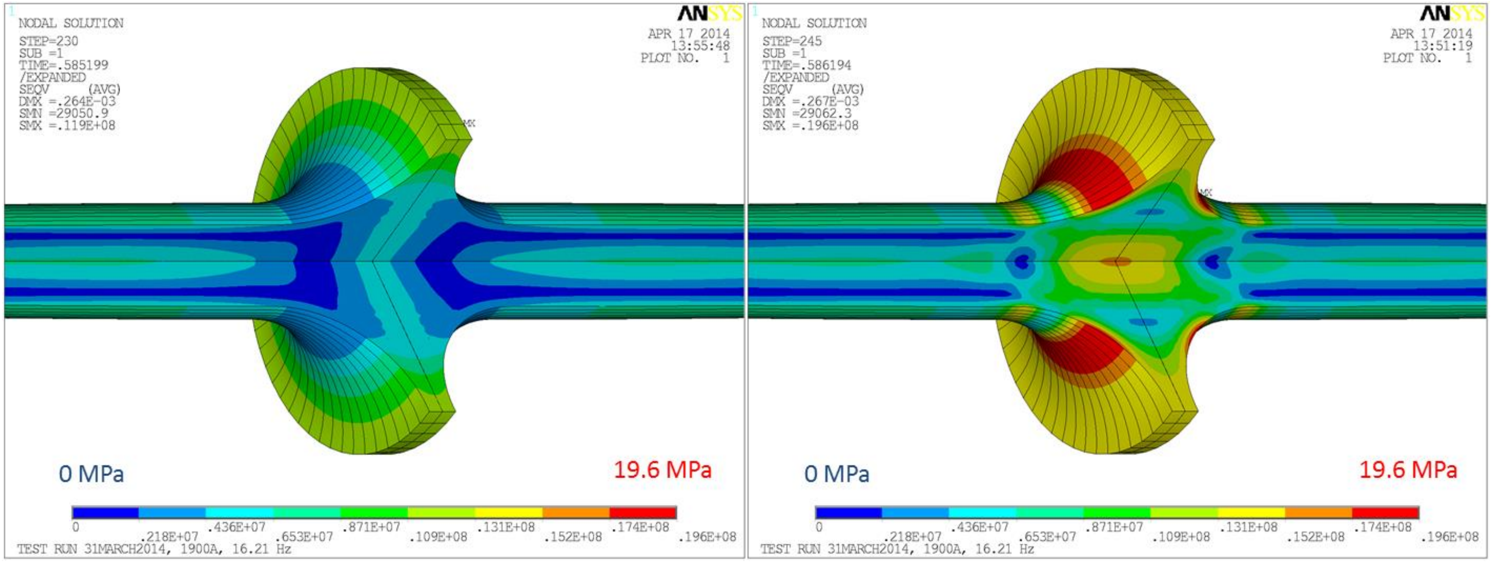
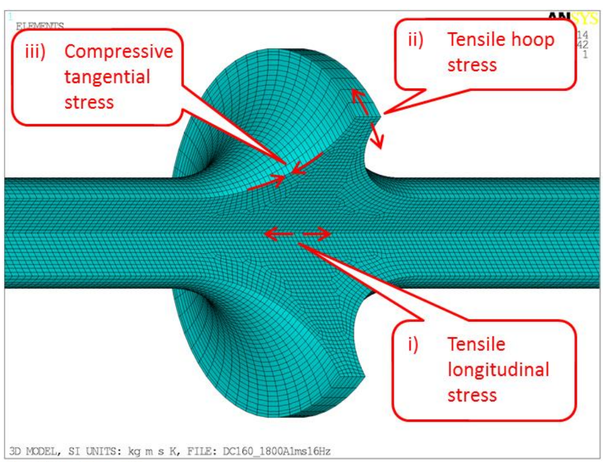
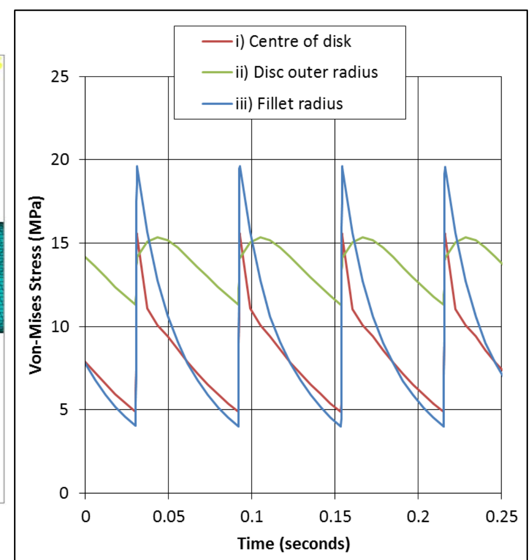
Calculated Stresses in the Sample



Von-Mises stress distribution before (left) and after (right) a current pulse





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Results

- After 100 Million cycles (equivalent to 4 years operation at Mu2e) under temperature and stress conditions closely representing Mu2e target operation the sample had not failed.

- The test conditions were then made more severe to see if we could induce a failure.

  I_{peak} 1900 A → 2300 A
  ΔT_{surf} 44 °C → 73 °C
  T_{mean} 1750 °C → 2000 °C

- The sample survived a further 37 million cycles before the failure (pictured) was observed.

Observations

At various times the sample was cooled down and the following observations made:

- The sample was initially ‘dull/grey’ in appearance
  (manufacturing surface impurities)

- After a few hours operation at ~1750°C it had become ‘bright/shiny’
  (surface impurities ‘burned-off’)

- After many days operation at ~1750°C a patchwork of grains covered the surface
  (recrystallization)

- Following many days operation at the more severe setting a failure occurred with material ejected laterally from the sample

Discussion: Failure Mechanism

Could electro-migration be a contributing factor?

- When an electric field is applied to a metal, in addition to the transport of electrons, a relatively small transport of the metal ions also occurs
- This process of mass transport of metal ions is referred to as ***electro-migration*** or ***electro-diffusion***
- Rate of mass transport depends on ***temperature*** and ***current-density***
- Can be the lifetime limiting factor in DC tungsten filament lamps

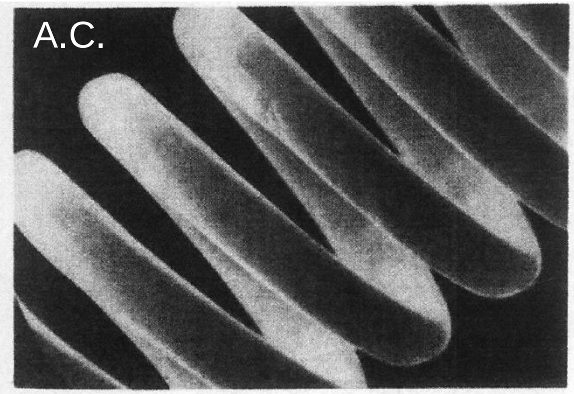

FIG. 2. Tungsten coils heated to 1900°K with alternating current. Electromigration of tungsten ion is random resulting in a smooth surface appearance. Electron microscan photo taken at 1000 times, shown here at ×500.

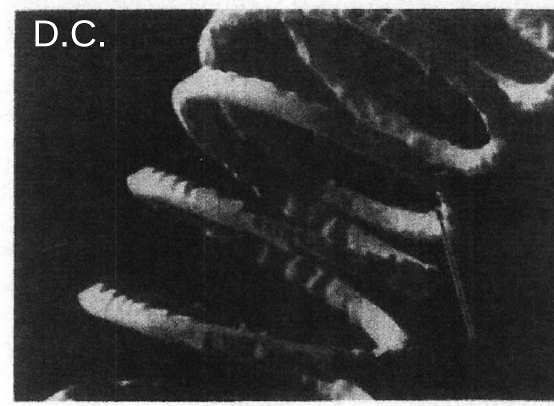

FIG. 4. Electron microscan photo of a tungsten filament heated with direct current. Photo shows surface structure developed due to electromigration of tungsten ions toward the cathode. Original magnification 400 times, shown here at ×200.

Figures reproduced from: J. Appl. Phys., Vol. 36 No. 9, 1965

Summary

A multi-purpose thermal test rig for high temperature target applications has been constructed and commissioned with funding contributions from PASI

- ❑ Vacuum vessel
- ❑ Pumping rig
- ❑ Pulsed and DC power supplies
- ❑ Diagnostics

A programme of thermal tests using this apparatus is underway as part of the Mu2e production target design and development