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Design and Development of a High Temperature Radiatively Cooled Tungsten Target for Mu2e

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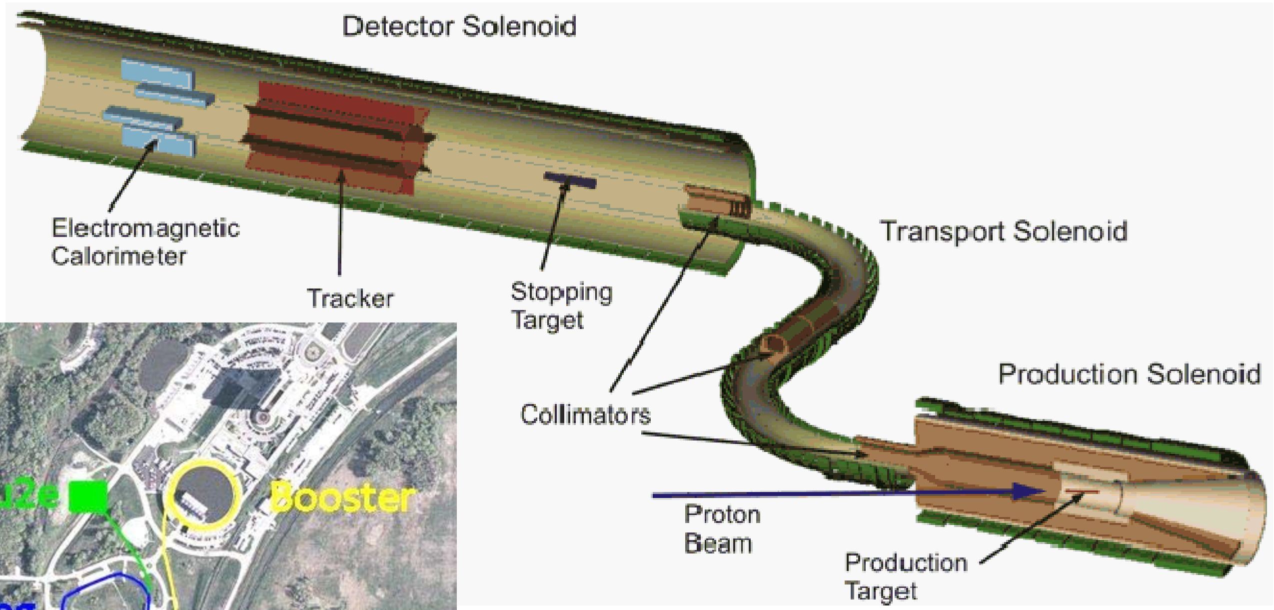
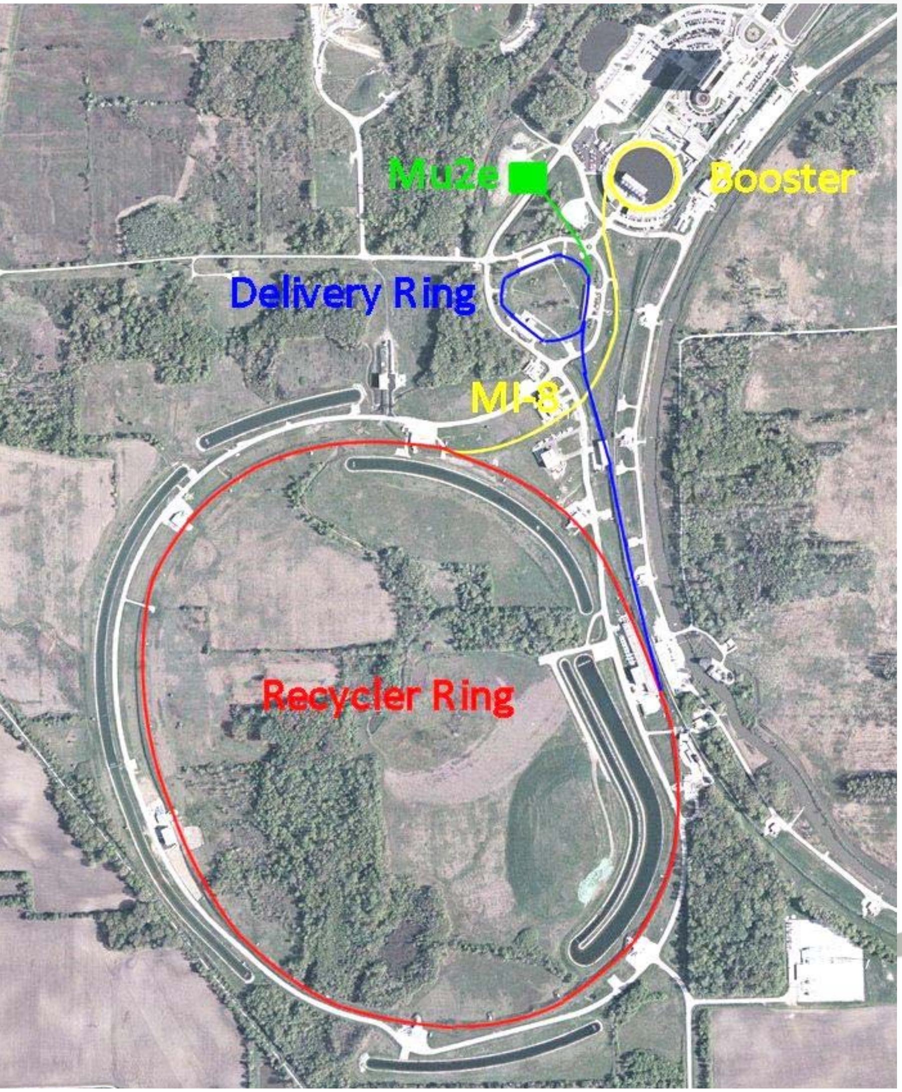
and the Mu2e Collaboration

The Mu2e Experiment





Beam kinetic energy	8 GeV
Beam spot shape	Gaussian
Beam spot size	σx = σy = 1 mm
Main Injector cycle time	1.333 sec
Number of spills per MI cycle	8
Instantaneous spill rate	18.5 Tp/sec
Average spill rate	6 Tp/sec
Duration of Spill	54 msec
Average Beam Power	7.7 kW
Average Power in Production Target	0.6 kW

Why a Radiation Cooled Target?

A tungsten target rod directly radiates the beam induced heat load to its surroundings without the need for an active coolant.

Advantages Over Forced Convection Cooling:

- The cost of an active cooling circuit is avoided
  - no plant room, circulation plant, or maintenance required
- the remote target exchange process is greatly simplified
  - fewer operations = lower risk, smaller assembly
- Disposal of spent targets is simplified
  - e.g. no active water, smaller target assembly/cask
- The potential for coolant leaks in the high-radiation target environment is eliminated

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Target Challenges

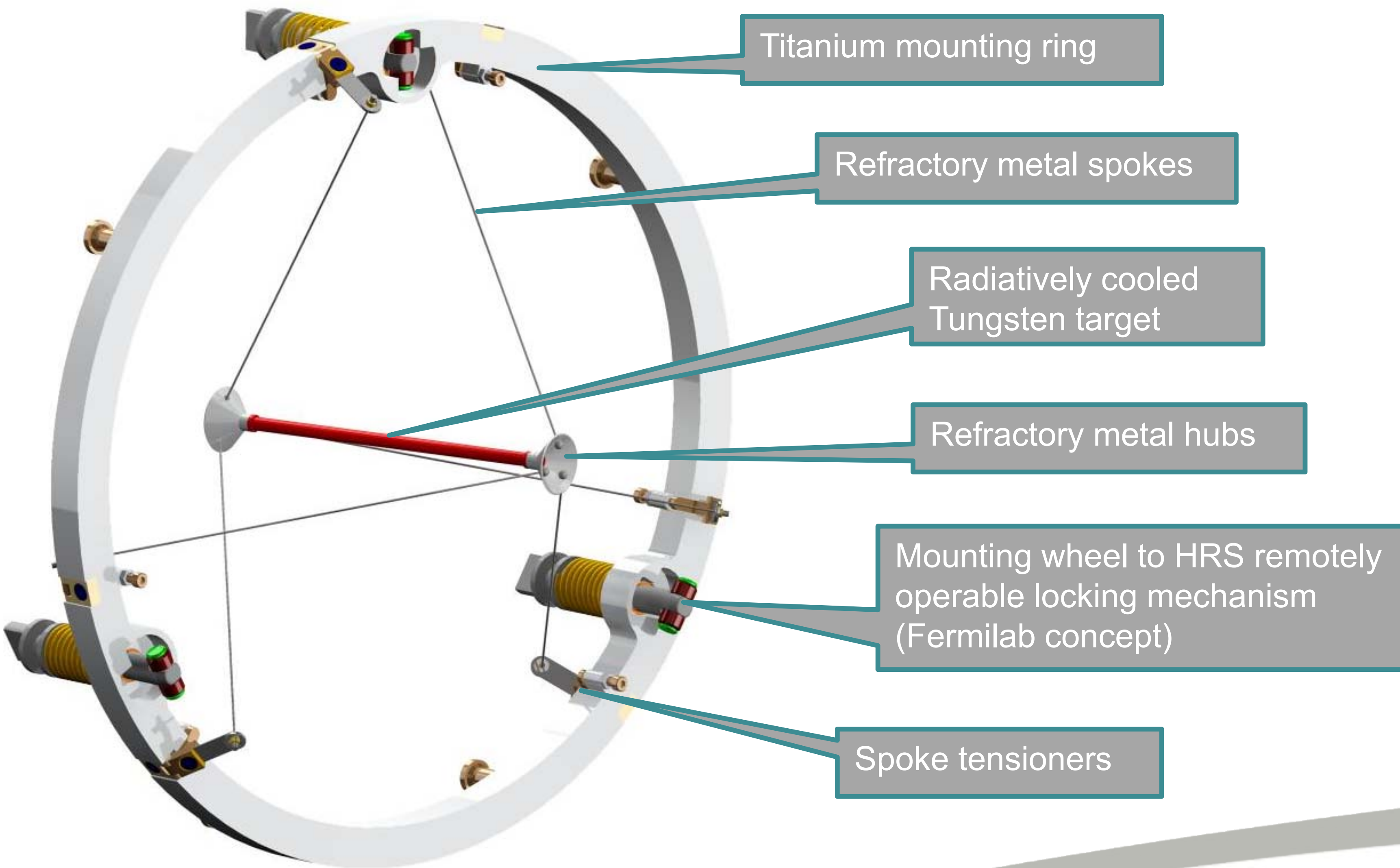
A feasibility study of this radiation cooled target concept was previously carried out in the CD1 phase. Following on directly from that study a programme of design, development and testing was launched in order to address the key technical issues identified:

- High Temperature Operation
  - How hot will the target get?
  - Are its material properties adequate at this temperature?
  - Will it suffer from chemical attack?

- Beam-induced Thermal Cycling
  - Can we rule out failure by fatigue?

- Support Structure
  - Can we design a support structure that is able to cope with the target temperature?
  - What material / manufacturing options are available?

Target conceptual design



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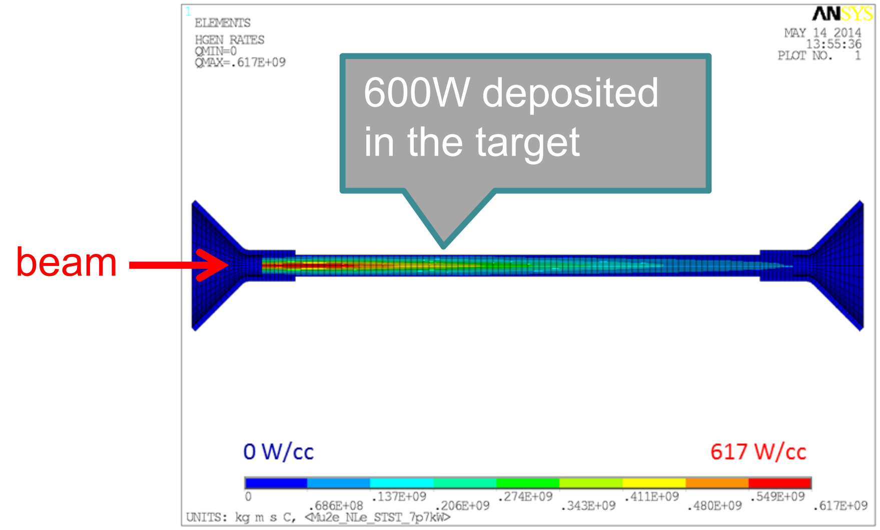
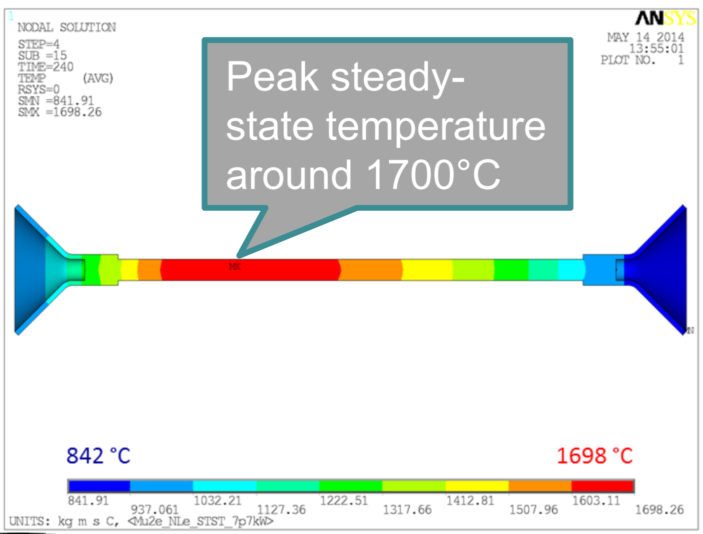
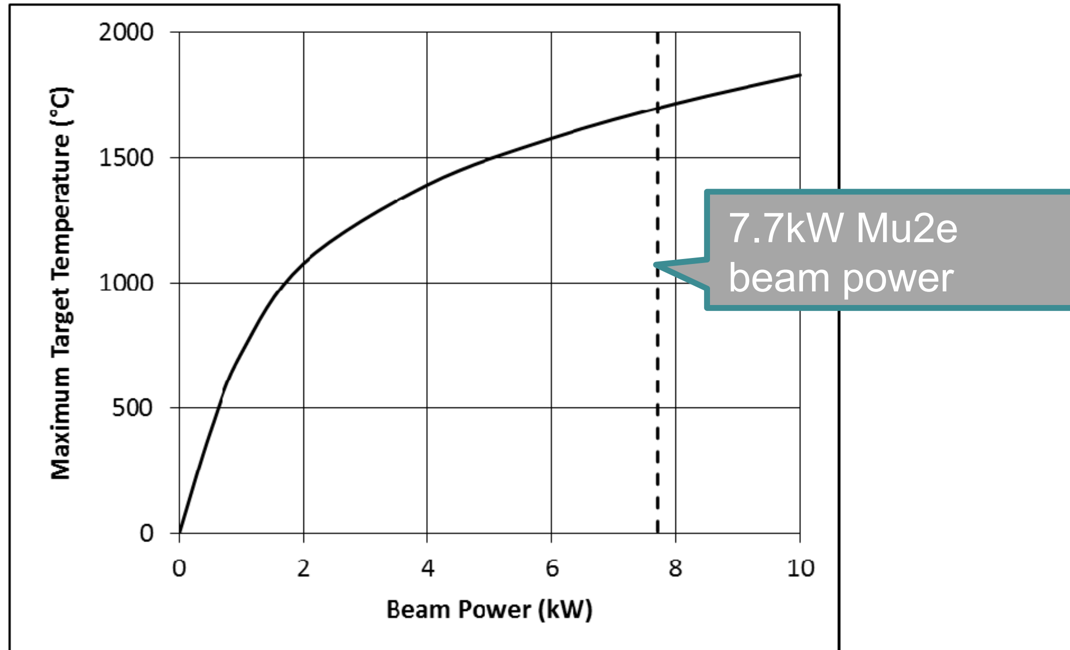
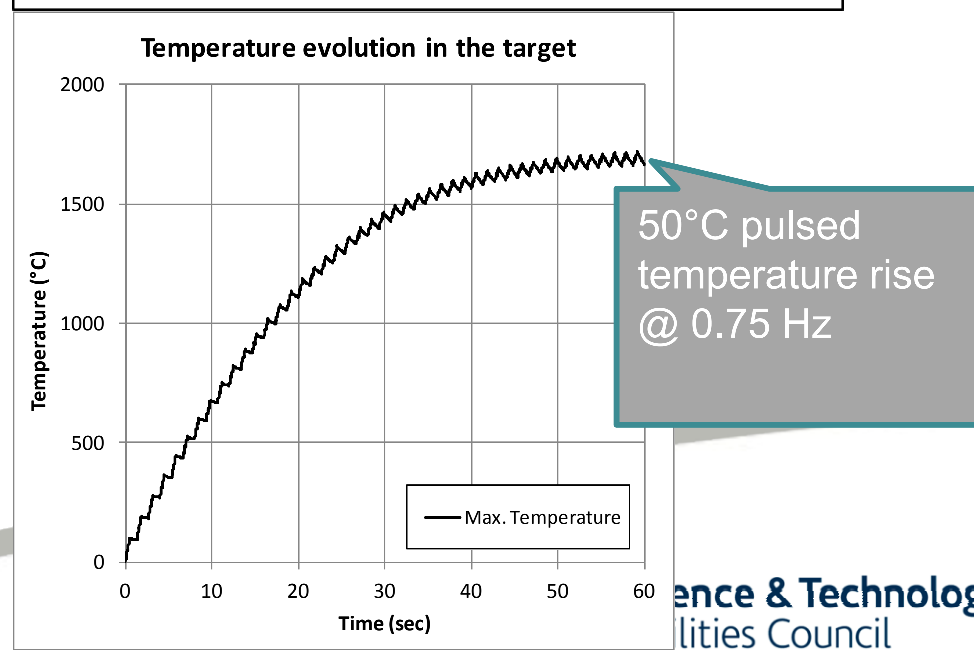
Beam Power Distribution and resultant target heating









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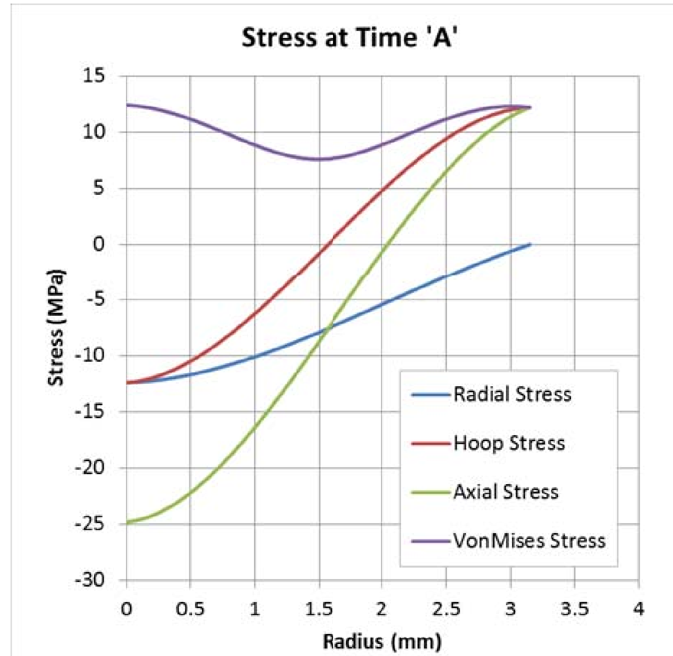
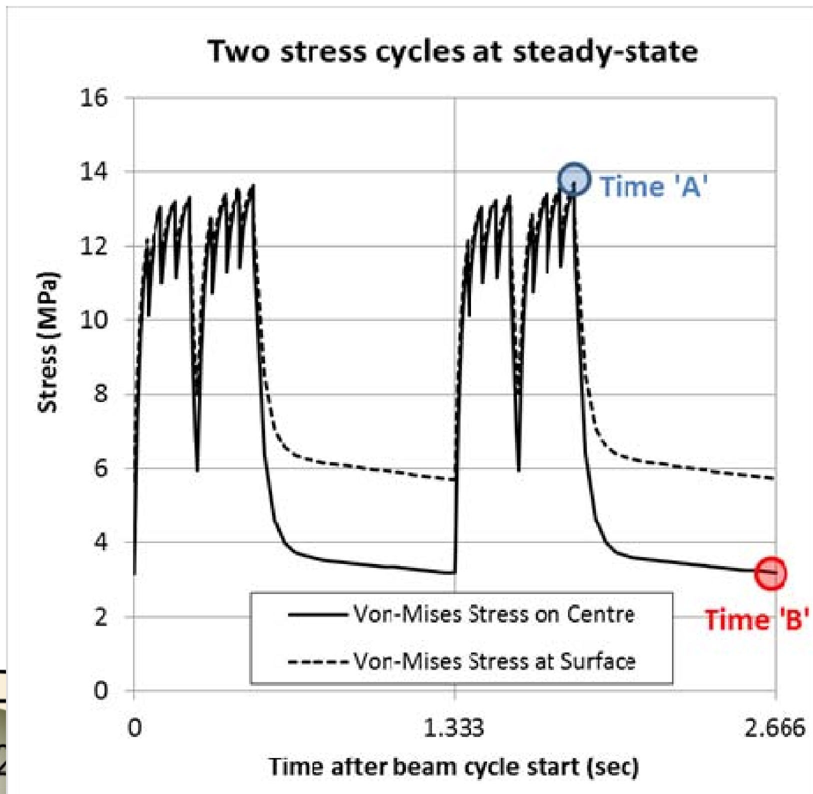
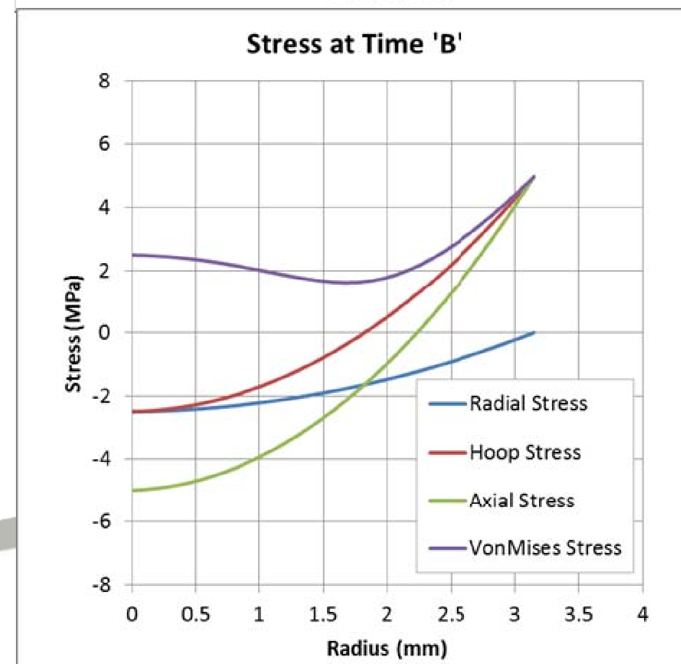
Thermal Stress Cycling in the target

- Beam pulses set up transient stresses in the target
- Compressive at core, tensile at surface
- Long spill (54 msec) = quasi-static stress

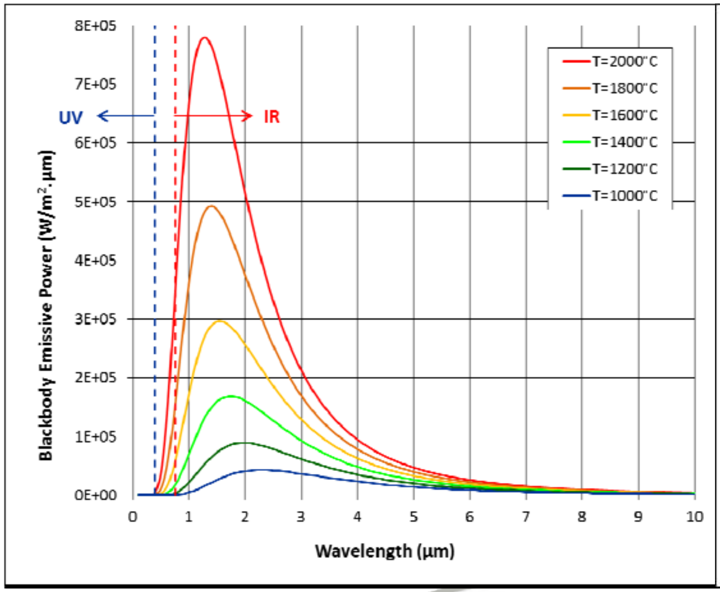


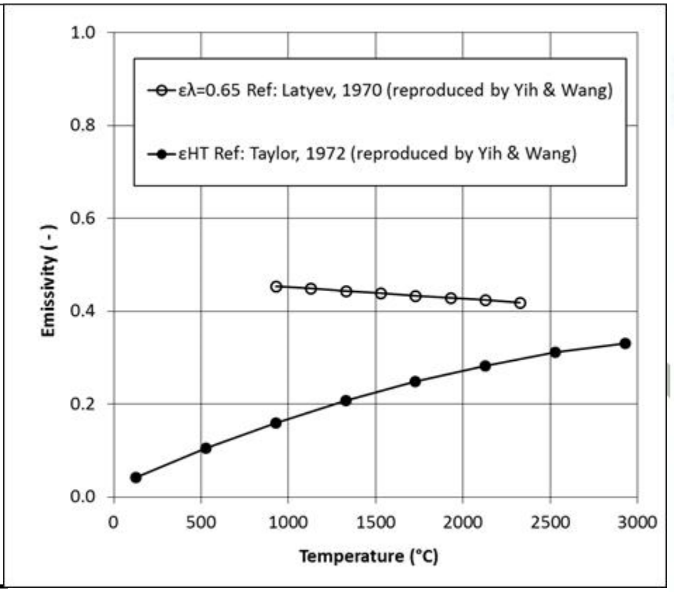


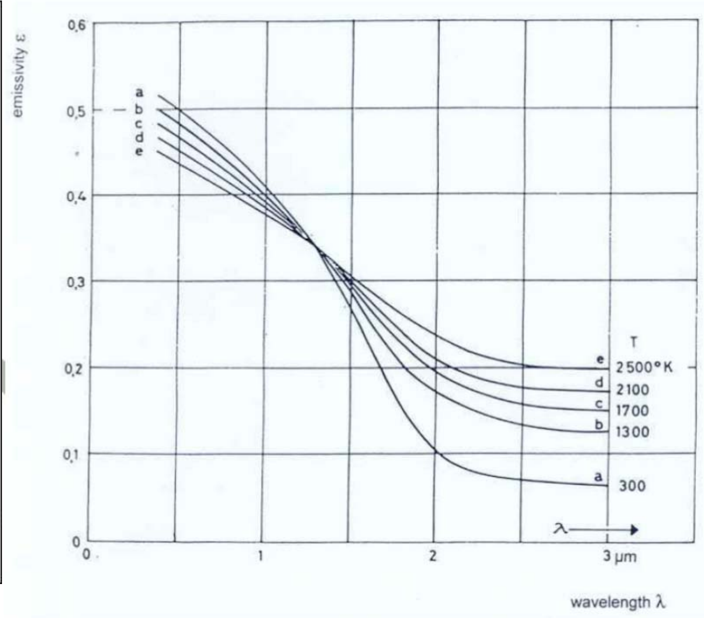


Rationale for Emissivity Measurements

- Target operating temperature depends on heat load, surface area, thermal emissivity
- Literature data for polished (smooth) tungsten surfaces. Are they valid for real engineering surfaces?
- ‘Monochromatic emissivity’ – needed to determine pyrometer temperature corrections
- ‘Total hemispherical emissivity’ – needed to determine radiative heat transfer

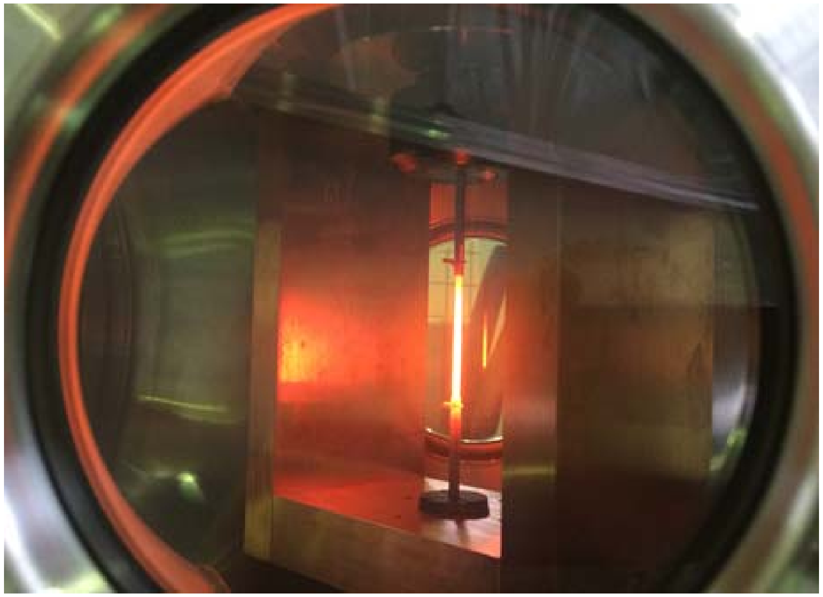




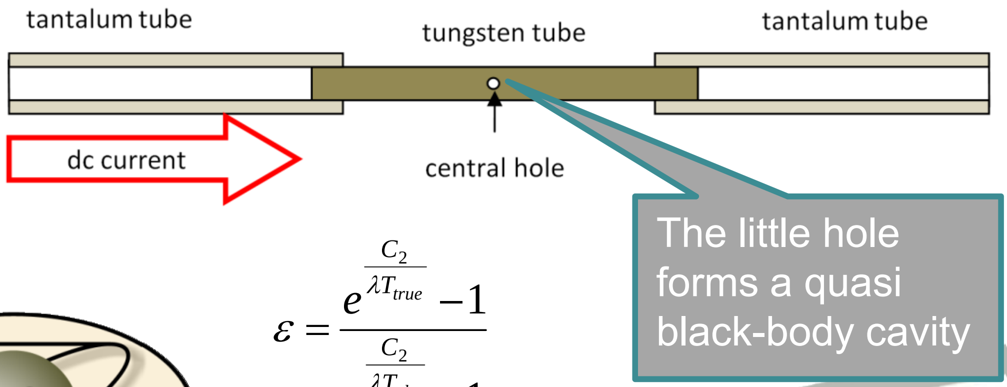


Measuring Monochromatic Emissivity

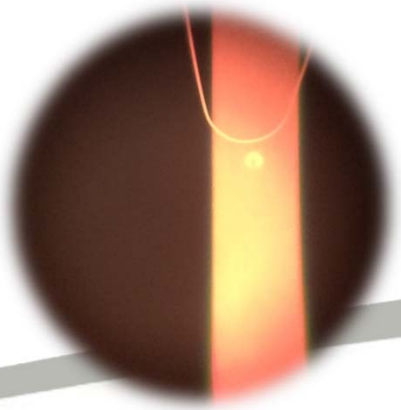
Operating the disappearing filament pyrometer



A tungsten sample under test



$$\varepsilon = \frac{e^{\frac{C_2}{\lambda T_{true}}} - 1}{e^{\frac{C_2}{\lambda T_{obs}}} - 1}$$

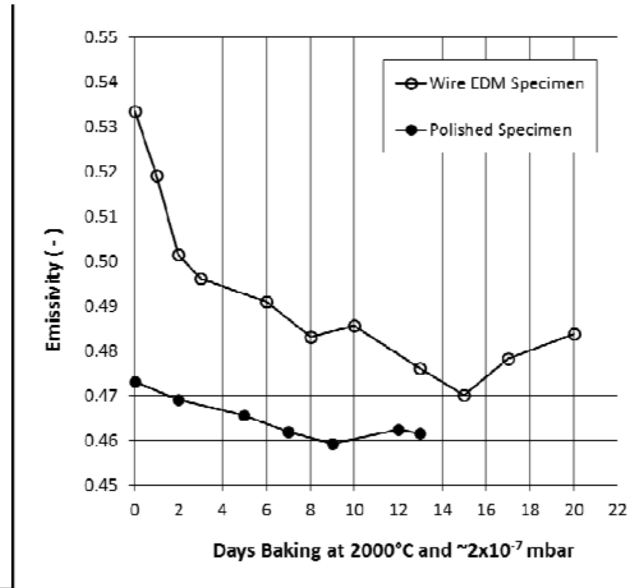


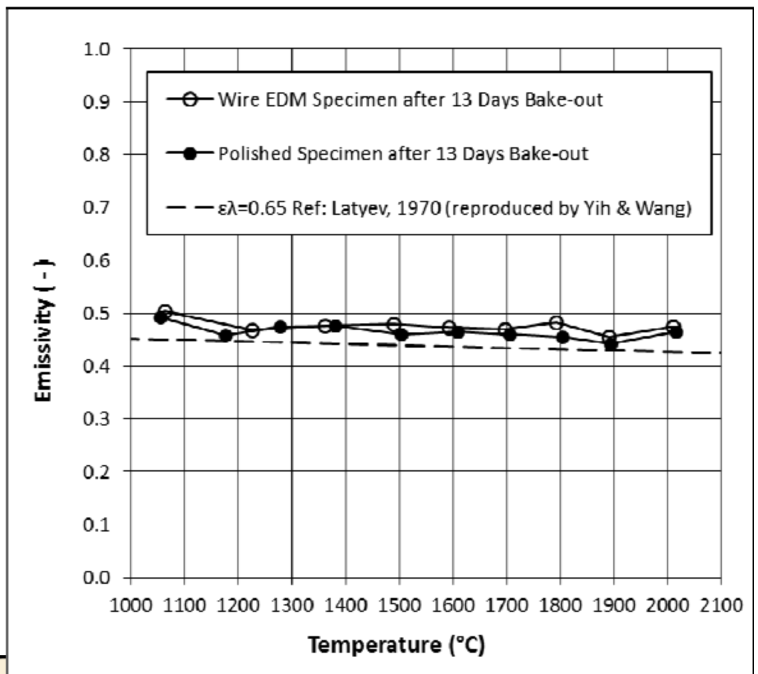
View down the pyrometer telescope

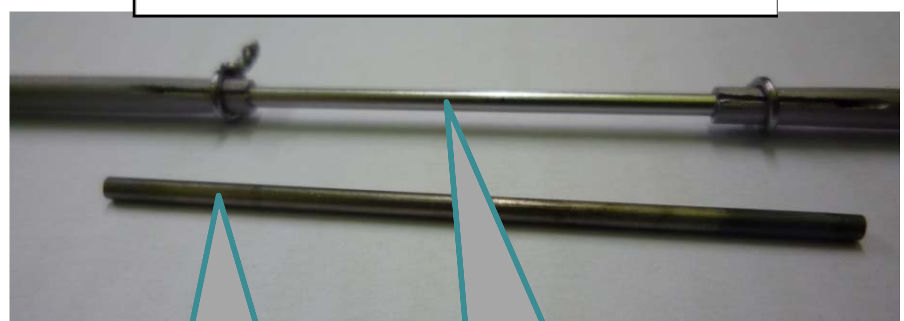
Monochromatic Emissivity Measurement Results

Little difference observed in emissivity between rough (EDM machined) and smooth (polished) surfaces.

Indicates that we can apply literature data on polished material to designs using real engineering surfaces.







Ground tungsten Samples were dull/grey in appearance before testing

They became shiny in appearance after the test

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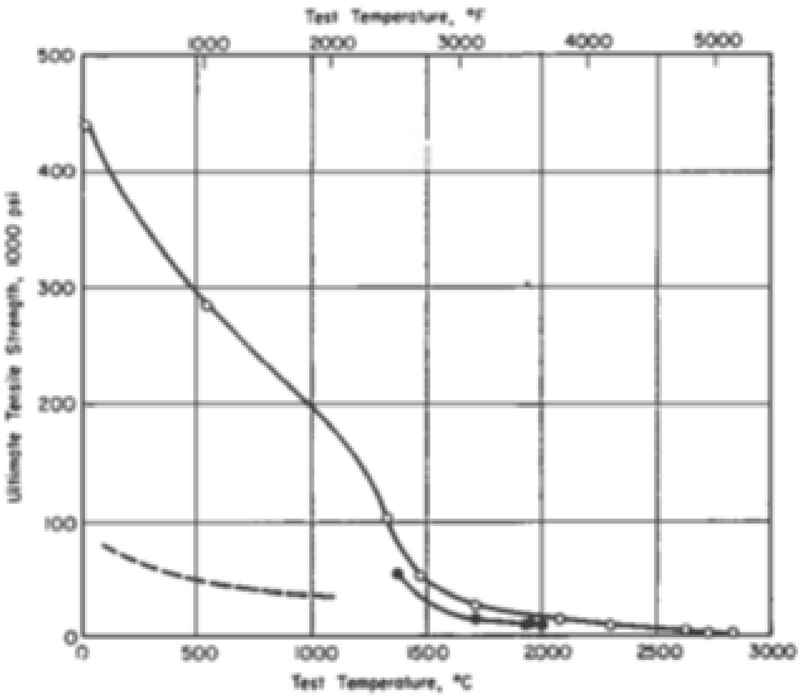
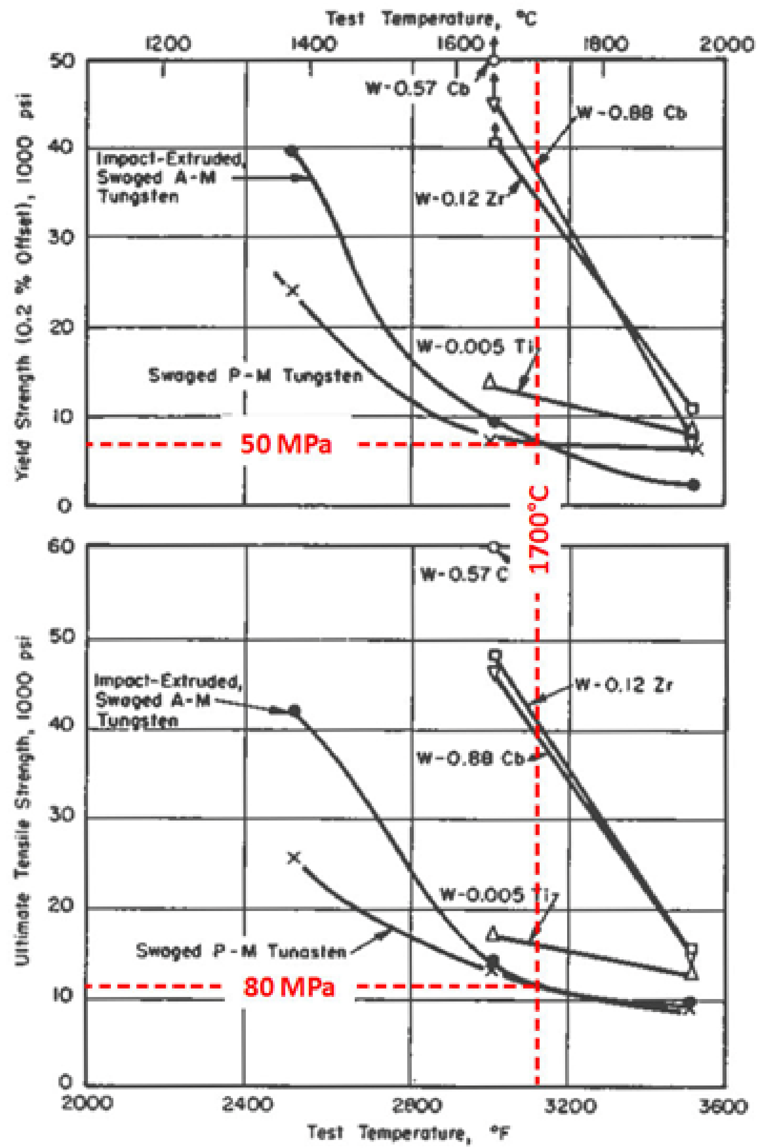
High Temperature Tensile Properties of Tungsten



Tensile strength of wrought tungsten for test temperatures up to 2830 °C (5100 °F).

Symbol	*Test Material*	*Reference*
—○—	Wrought 0.003-in. wire	Tajime
—●—	Wrought 0.500-in. rod	Hall and Sikora
— — —	Recrystallized rod	Pugh



Rationale for Thermal Fatigue Measurements

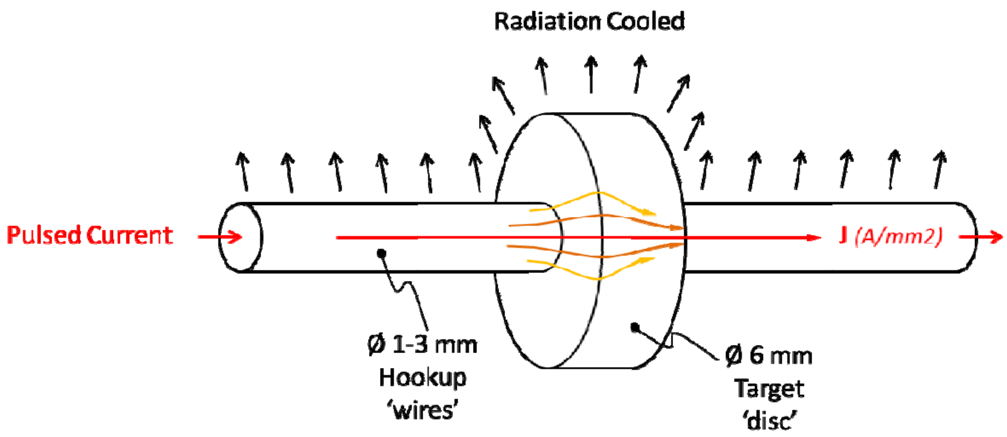
There is a scarcity of data available in the literature to predict the fatigue life of tungsten at the relevant temperature (~2000K) , and number of cycles to failure (10^7 - 10^8)

- Conventional fatigue machines typically operate at room temperature. There are commercially available fatigue machines that can go up to 1000°C using split furnace heaters. Need higher temperature.
- High strain-rate lifetime measurements have been made by Skoro and Bennett at temperatures up to 2000°C. But the long beam spill at Mu2e will generate **low strain rate** effects.
- The target is a critical component. Testing the proposed target material under representative load conditions is necessary to quantify the expected lifetime.

A Novel Lifetime Pulsed Heating Test

Operating Principle:

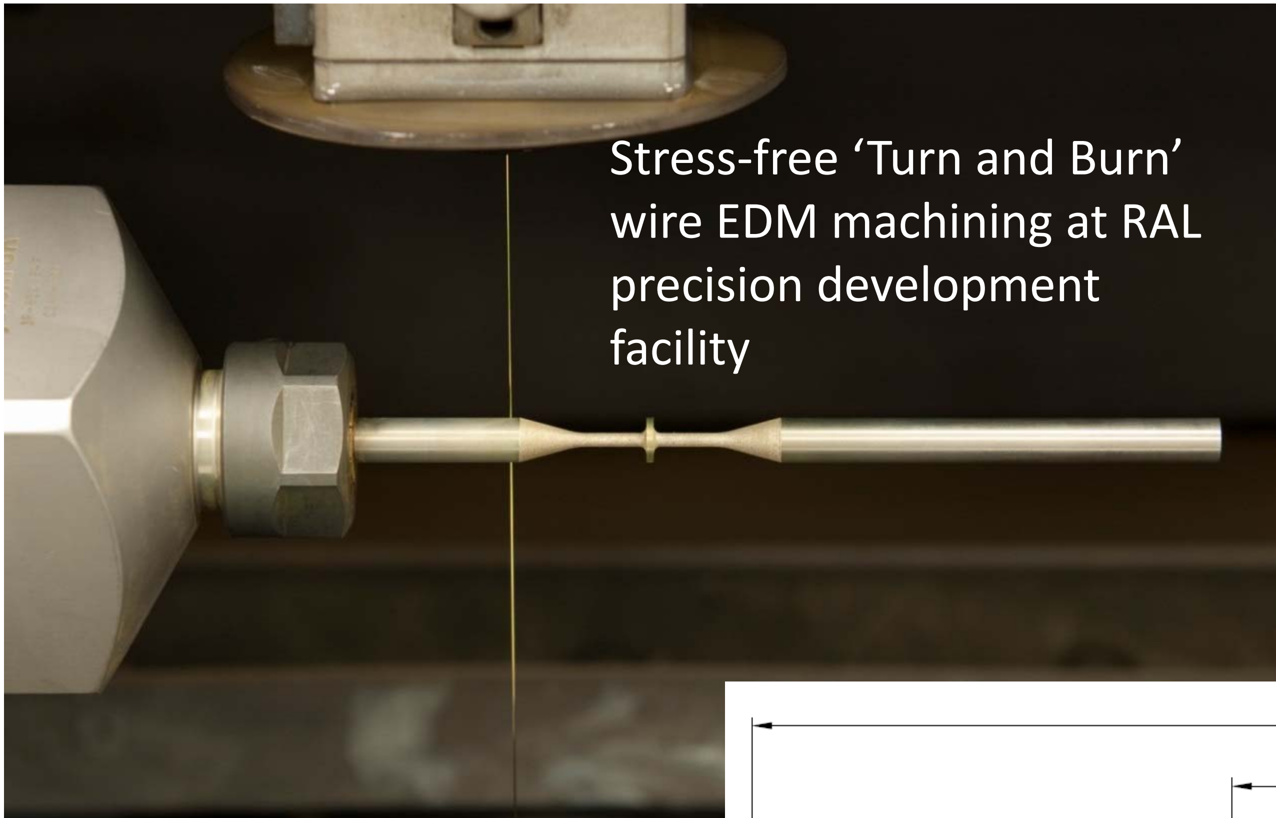
- ❑ Use resistive (Joule) heating from an electric current pulse to preferentially heat the centre of a disk
- ❑ Pulse length long enough to give 'static' stress field
  (do not want inertial stresses)
- ❑ Inter pulse gap long enough for transient stress component to decay
  (on the timescale of thermal conduction)
- ❑ Rep rate of 10's of Hz
  (to allow accelerated testing of target lifetime cycles)
- ❑ RMS current tuned to achieve desired operating temperature

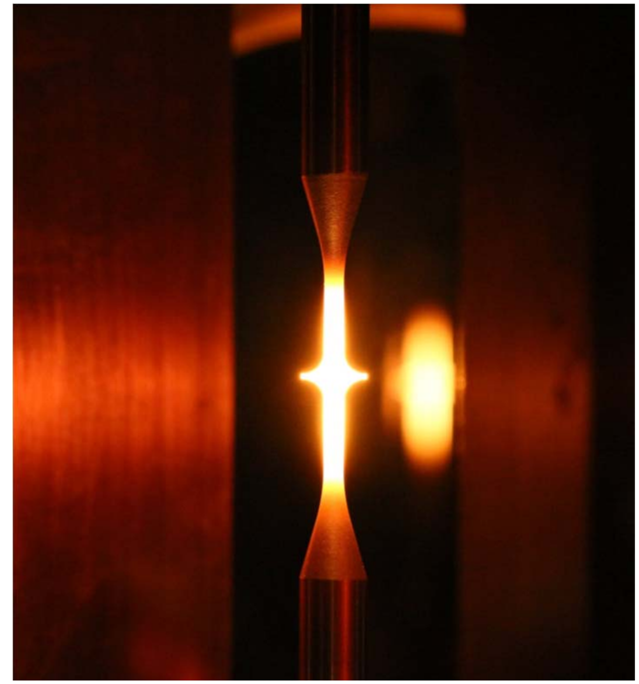


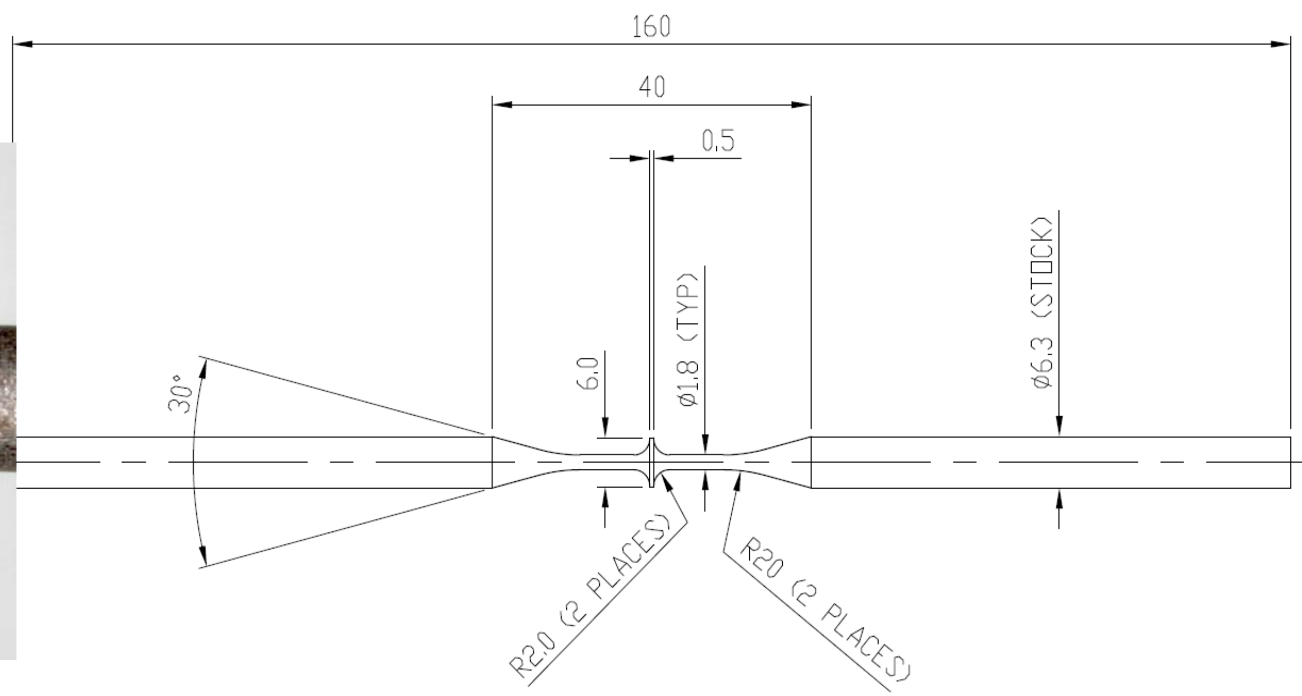
Reproducing the target conditions

- Samples cut from representative stock material
- Realistic engineering surface finish
- Correct elevated temperature regime
- Similar temperature jump
- Correct strain-rate regime
- Correct pressure (vacuum) regime
- Thermally induced stress
- Possibility to superimpose target self weight bending load

Tungsten Lifetime Test Samples



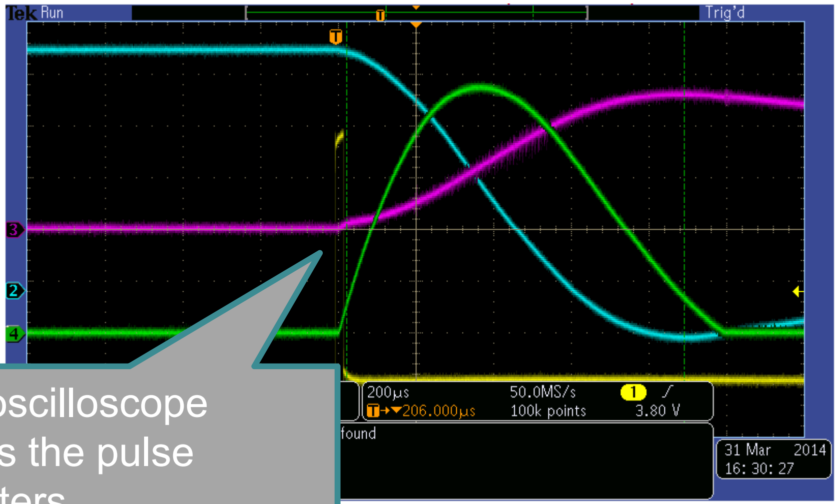




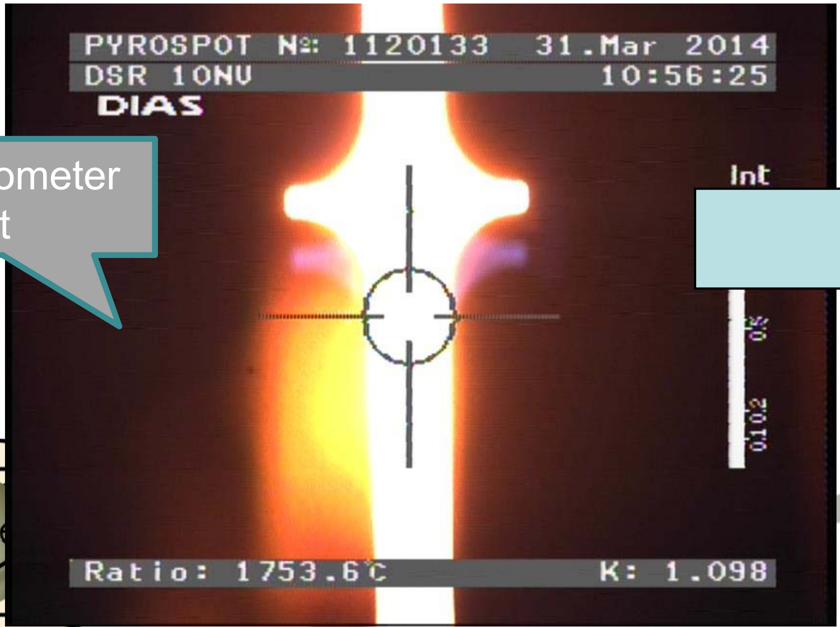
Diagnostics

Measurement Strategy

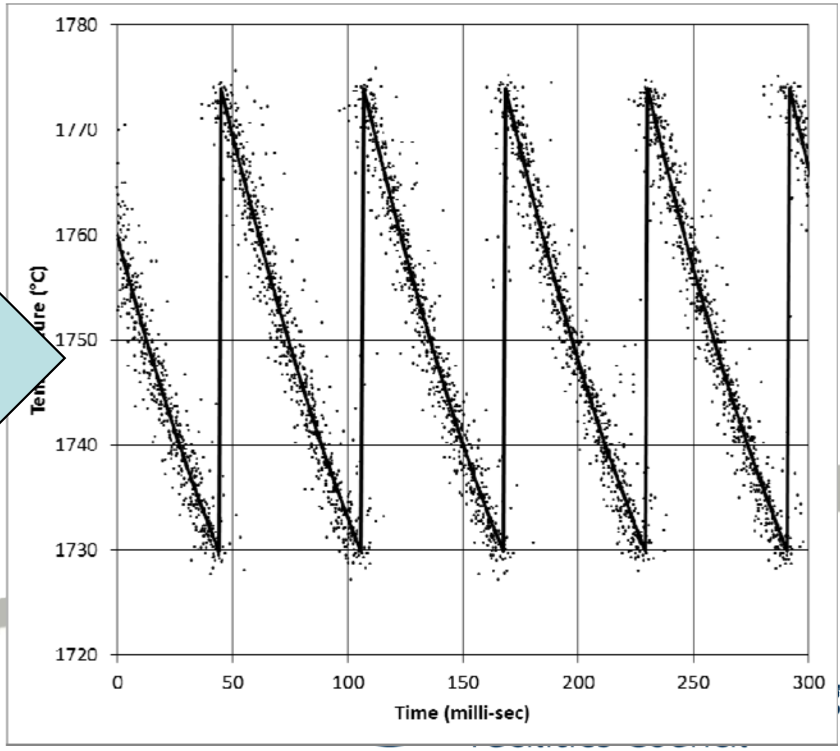
- Cannot measure stress directly…
- Simulate the test using multiphysics Finite Element Analyses
- Current pulse shape measured and used in the simulations
- Stress calculated from the predicted temperature distribution
- Verify by measuring pulsed temperature rise in the test



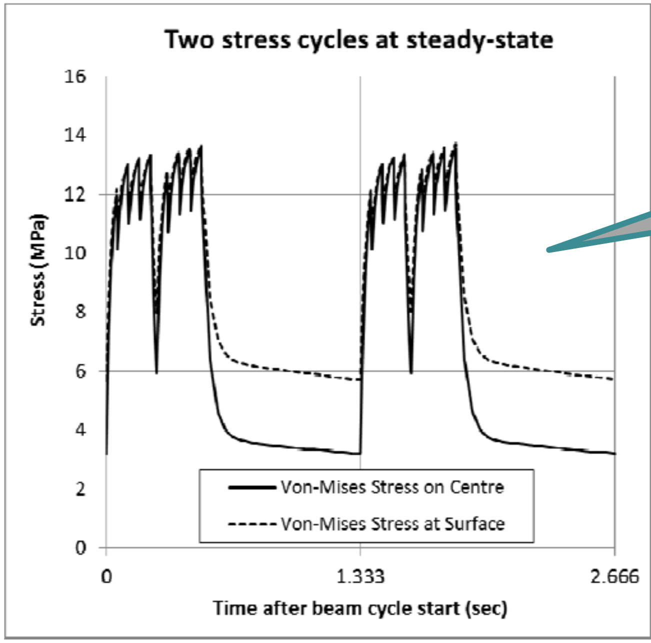
Digital oscilloscope monitors the pulse parameters



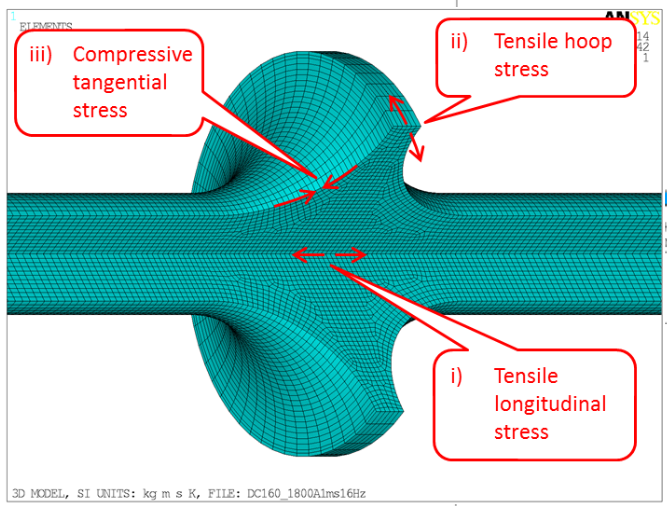
Digital pyrometer screen plot



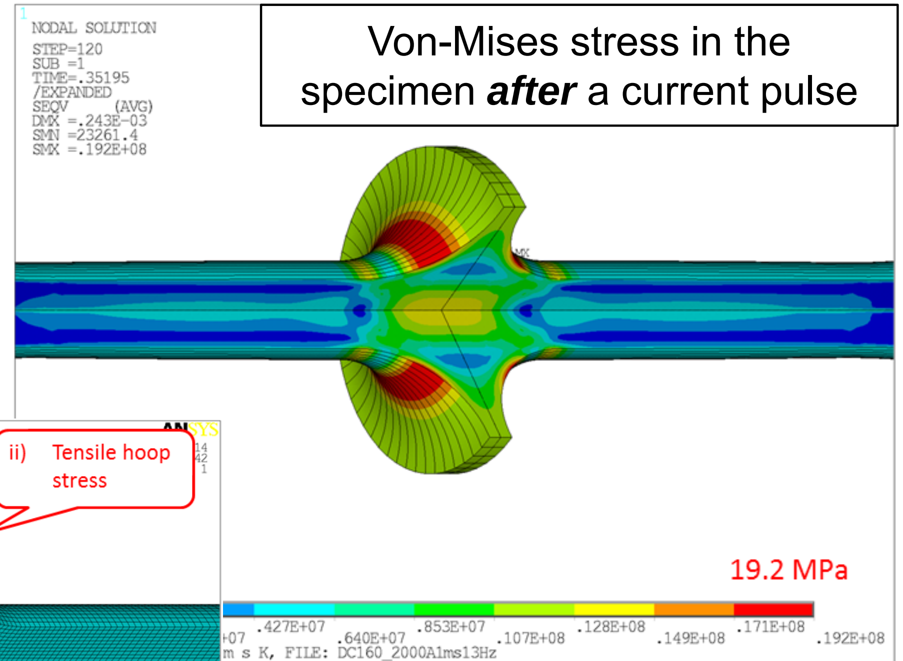
Replicating the Target Thermal Stress Cycle

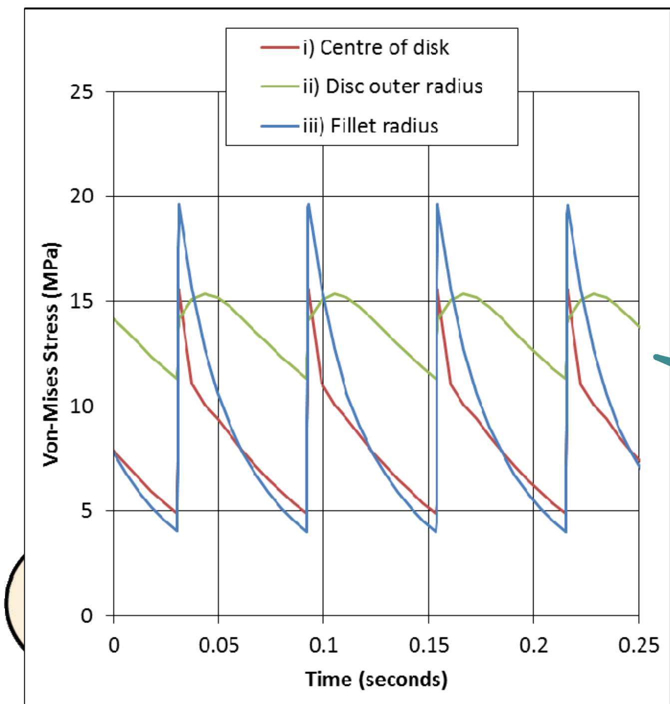


Mu2e Target Stress Cycle



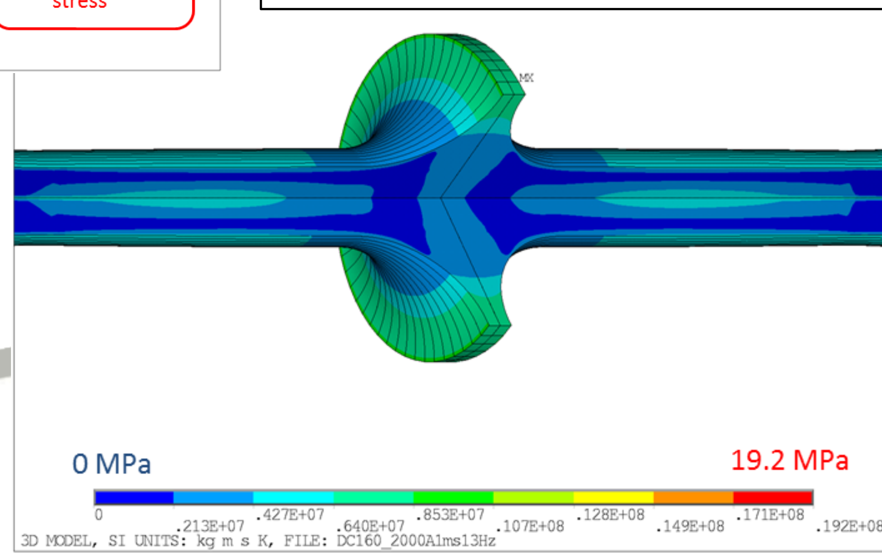
Von-Mises stress in the specimen ***after*** a current pulse





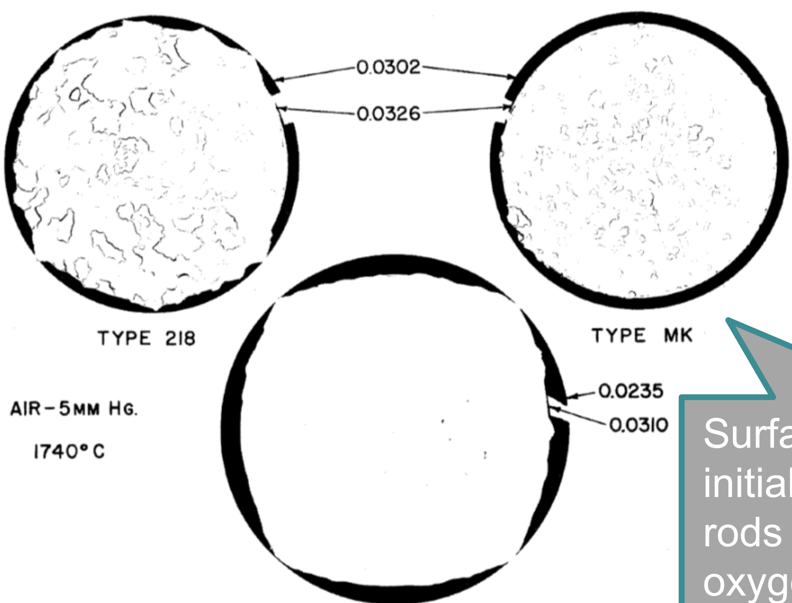
Test Specimen Stress Cycle

Von-Mises stress in the specimen ***before*** a current pulse

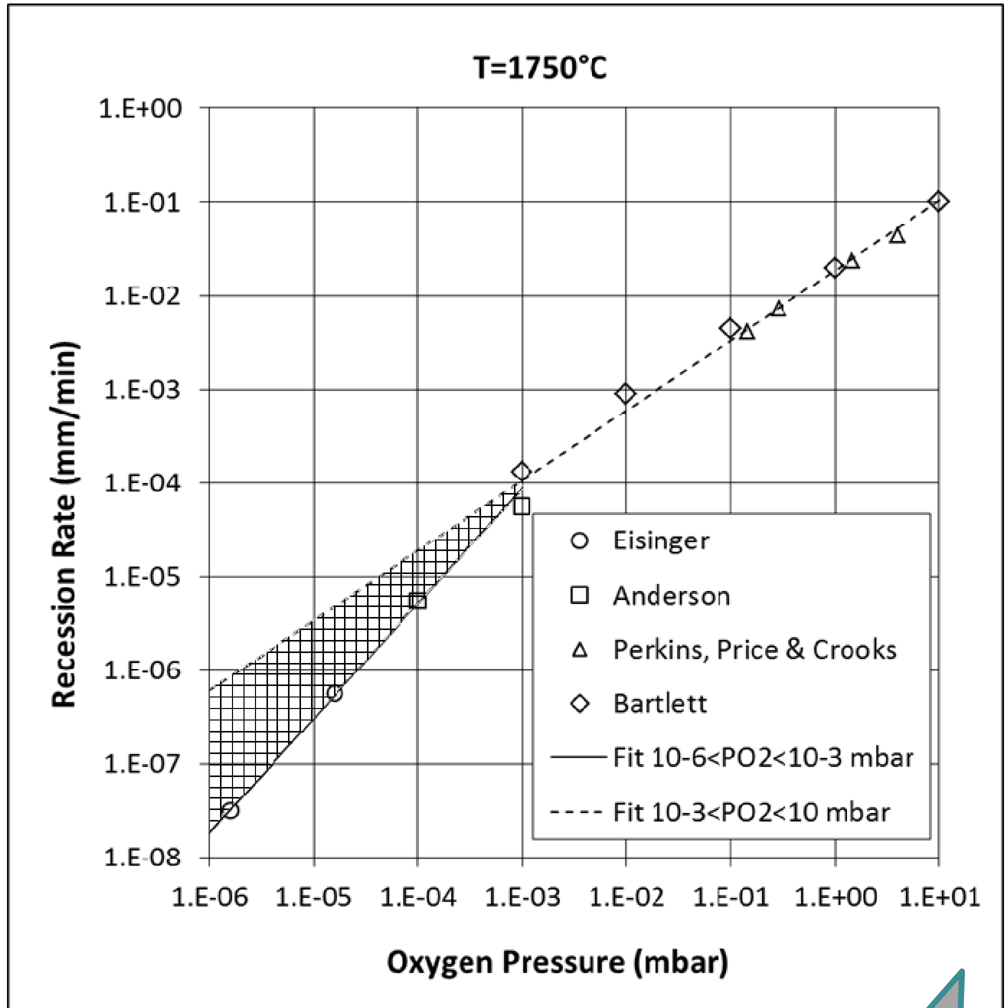


Rationale for Chemical Erosion Tests

At temperatures exceeding ~1300°C in vacuum, tungsten oxide will evaporate faster than it is formed. In this regime oxidation is realised as a surface recession, the rate of which depends strongly on temperature and oxygen pressure.



Surface recession of initially cylindrical tungsten rods heated in a low oxygen pressure

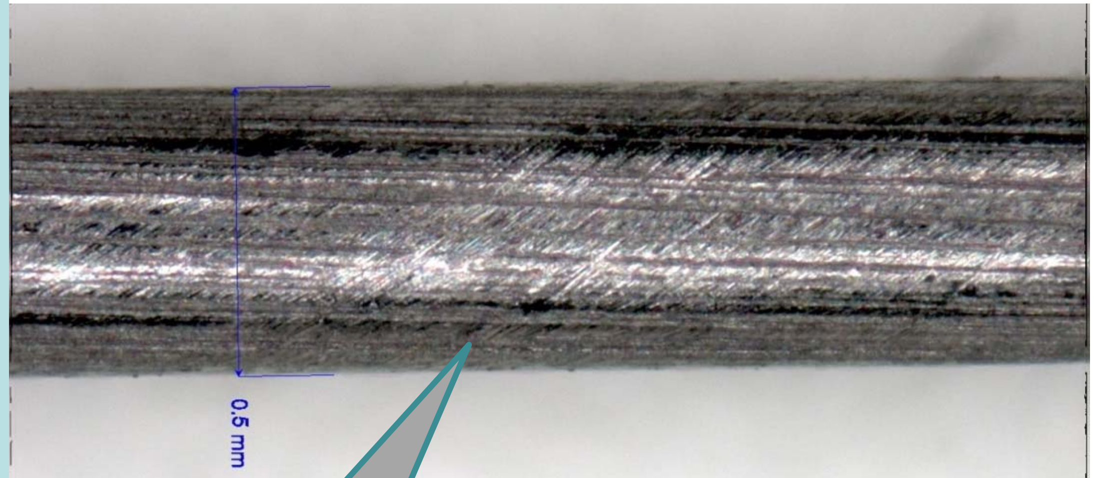


Literature data on recession rate as a function of oxygen pressure

Chemical Erosion Study

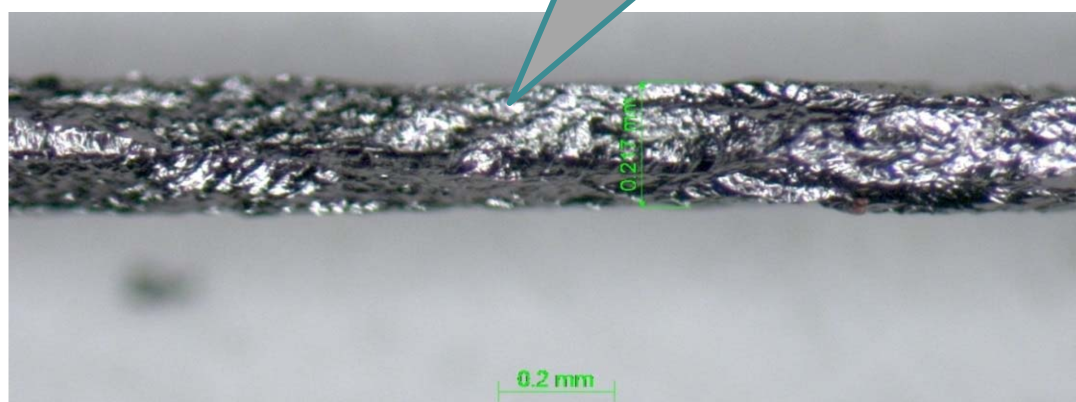
Polythene Outgassing Test

- Mu2e target environment will not be Ultra High Vacuum
- A 0.5 mm diameter tungsten wire was heated in a vacuum of a few Torr
- The ultimate pressure was limited by outgassing from a large surface area of polythene inside the vessel
- The temperature varied between 1500 and 2300°C
- The average surface recession rate was 0.13 mm/day



The wire before the test

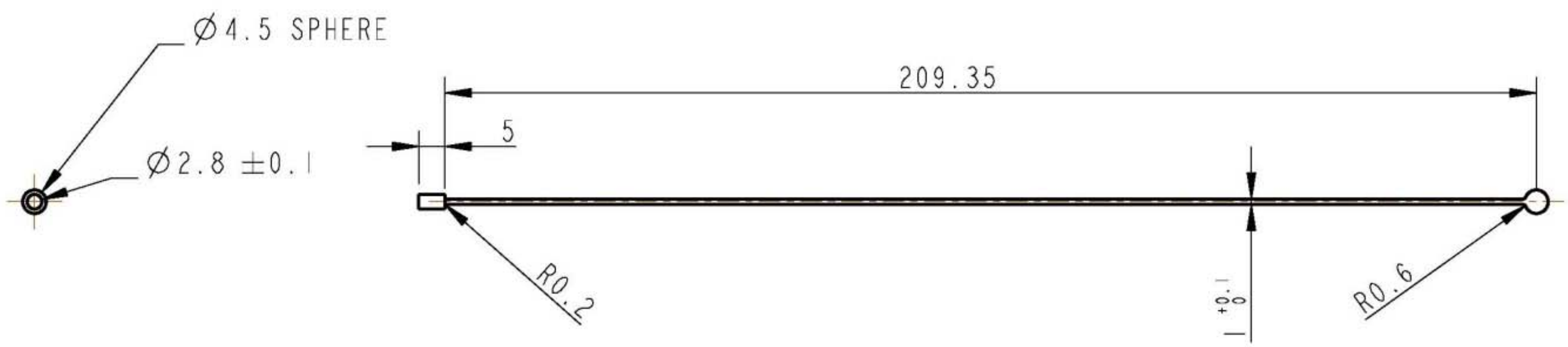
The wire after the test



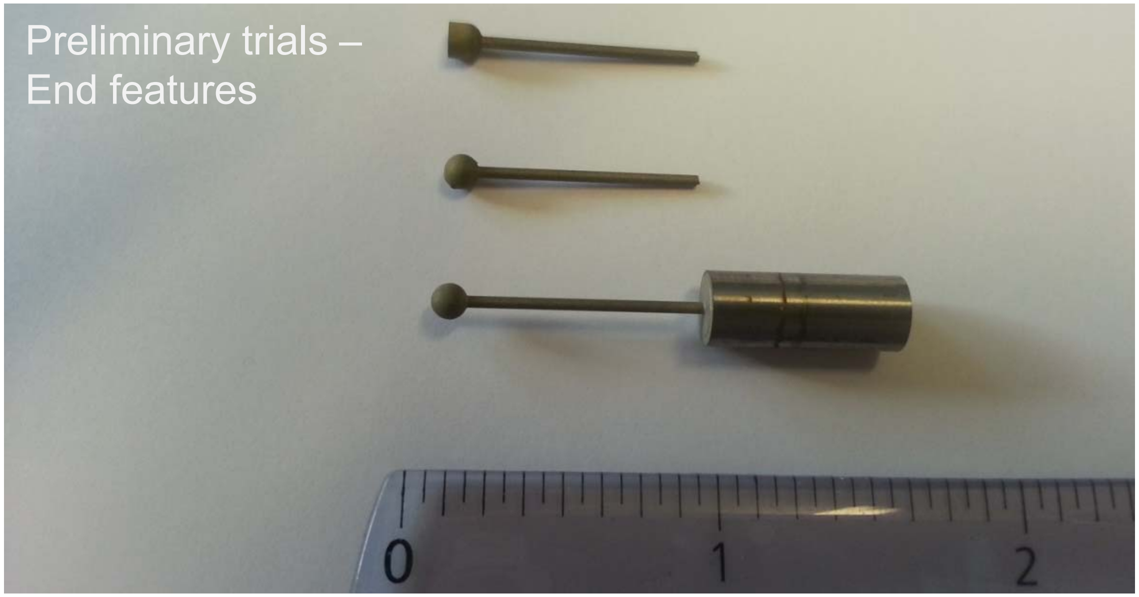
The apparatus post test. Note the thinning of the wire in the hottest (central) region

Spoke Manufacturing Challenges

- Tungsten Material
  - Difficult to process by conventional machining methods
  - Not malleable enough to use wire with stamped/formed end features
- Application
  - Too high temperature for most brazes, and high temperature brazes can alter Tungsten chemistry around the joint
  - Too weight/strength critical to use diffusion bonding with axial compression force, and geometry not suitable for radial compression joint
- Geometry
  - Difficult to achieve by grinding from solid

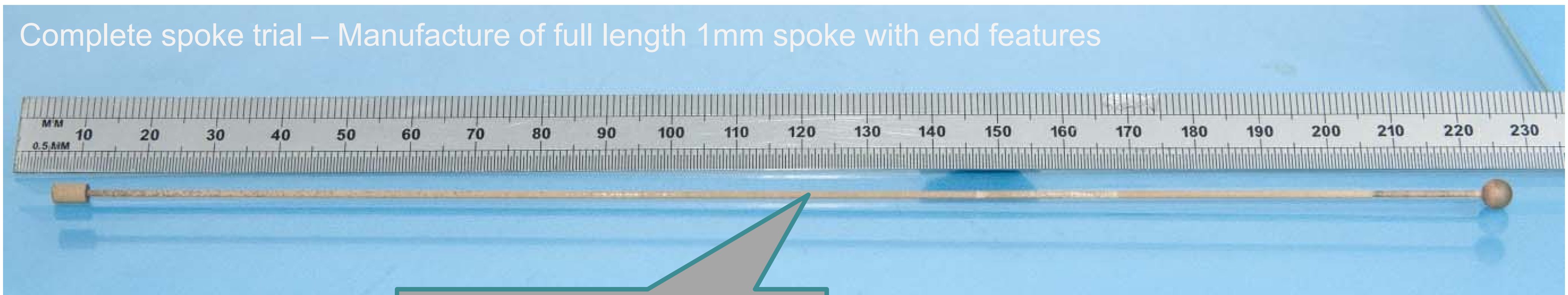


EDM Manufacturing trials



Preliminary trials – End features

Intermediate trial – short 1mm spoke and end feature



Complete spoke trial – Manufacture of full length 1mm spoke with end features

A 220 mm long (full length) prototype tungsten spoke

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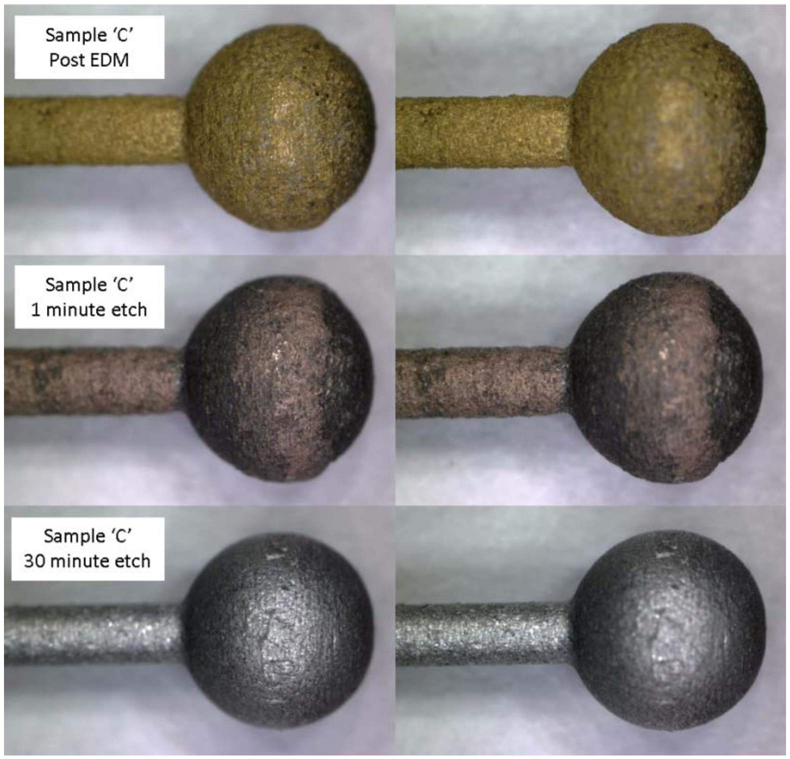
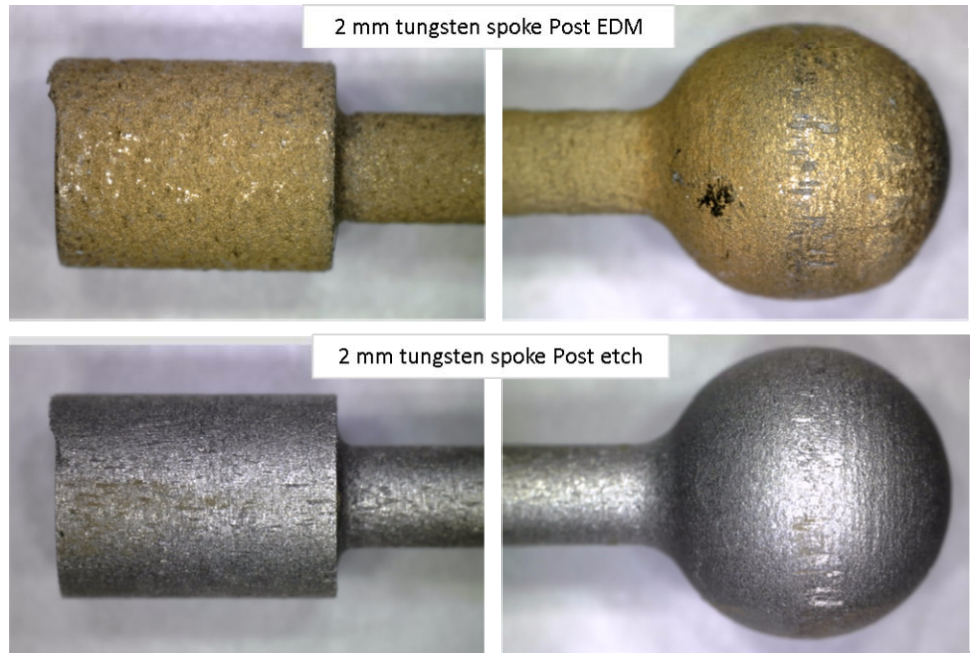
Post EDM surface treatments

EDM machined components from manufacturing tests exhibited a brassy scale. Due to the brittle nature of tungsten, mechanical means of abrading or polishing have been avoided. Instead a chemical etch has been successfully trialled.





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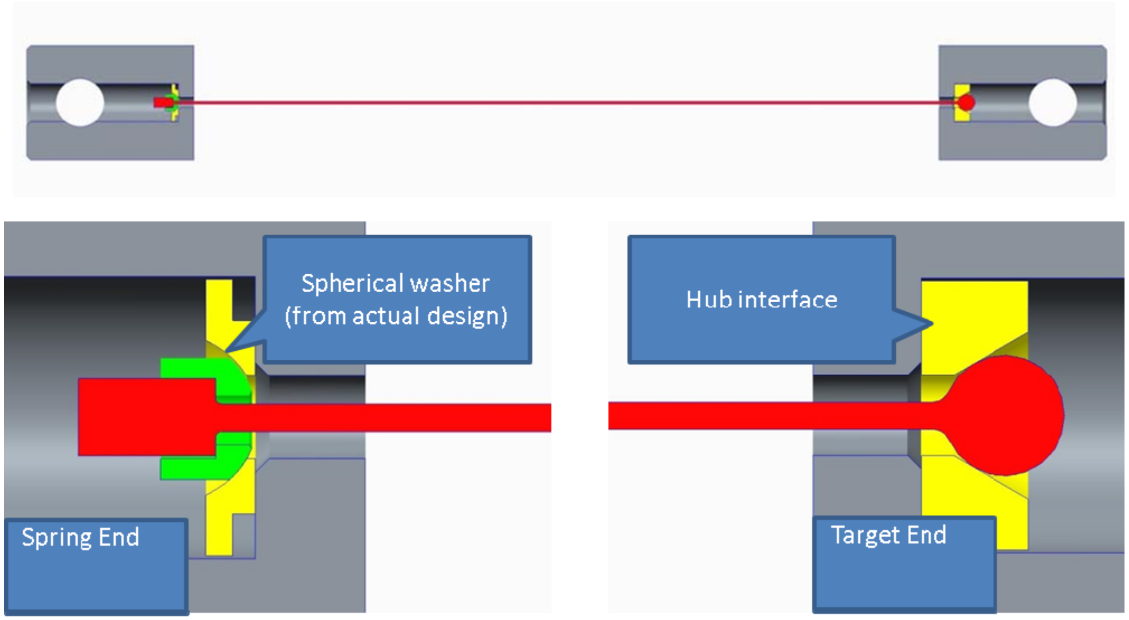
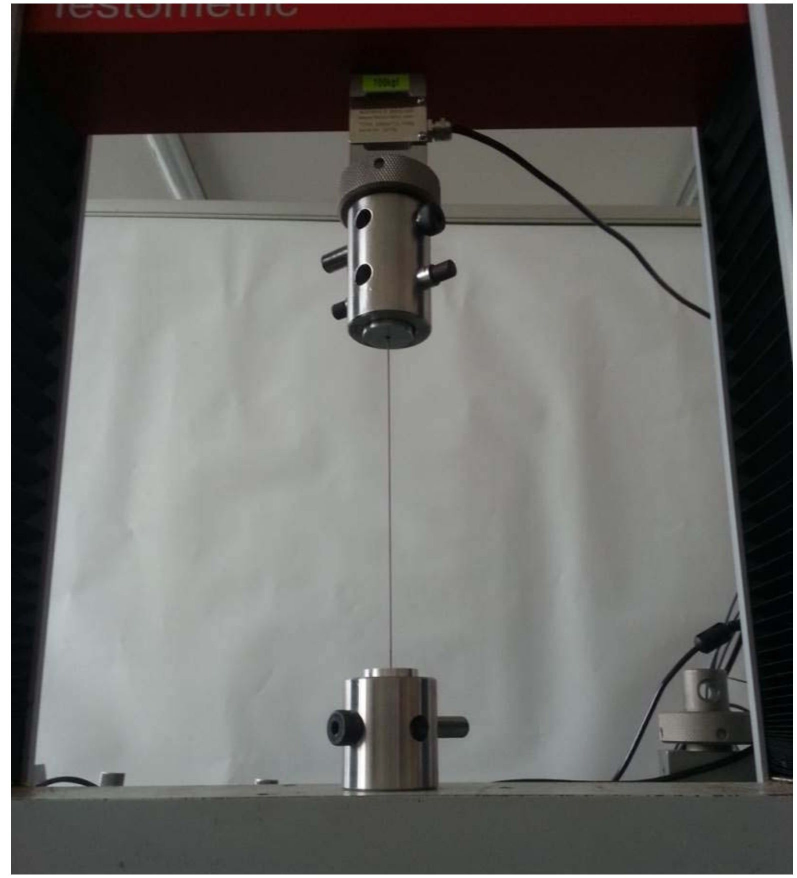
Spoke pull testing





- The 1mm spoke broke at a tension of 392N, at which the stress in the spoke was ~550MPa
- This is approximately forty times greater than the expected working tension of the spoke

Summary

- Radiation cooled target for Mu2e at 7.7 kW beam power appears realistic
- ~5 x 10^7 representative fatigue cycles on first test piece so far, equivalent to few years running
- Spoke support system demonstrated
- Jury still out on lifetime in expected vacuum quality
- Continuation of test program planned
  - total hemispherical emissivity
  - coatings and micro-finned surface tests
  - reduced vacuum quality tests
  - bending + thermal fatigue tests
  - prototyping