Mu2e radiation cooled target R&D

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(Fermilab)

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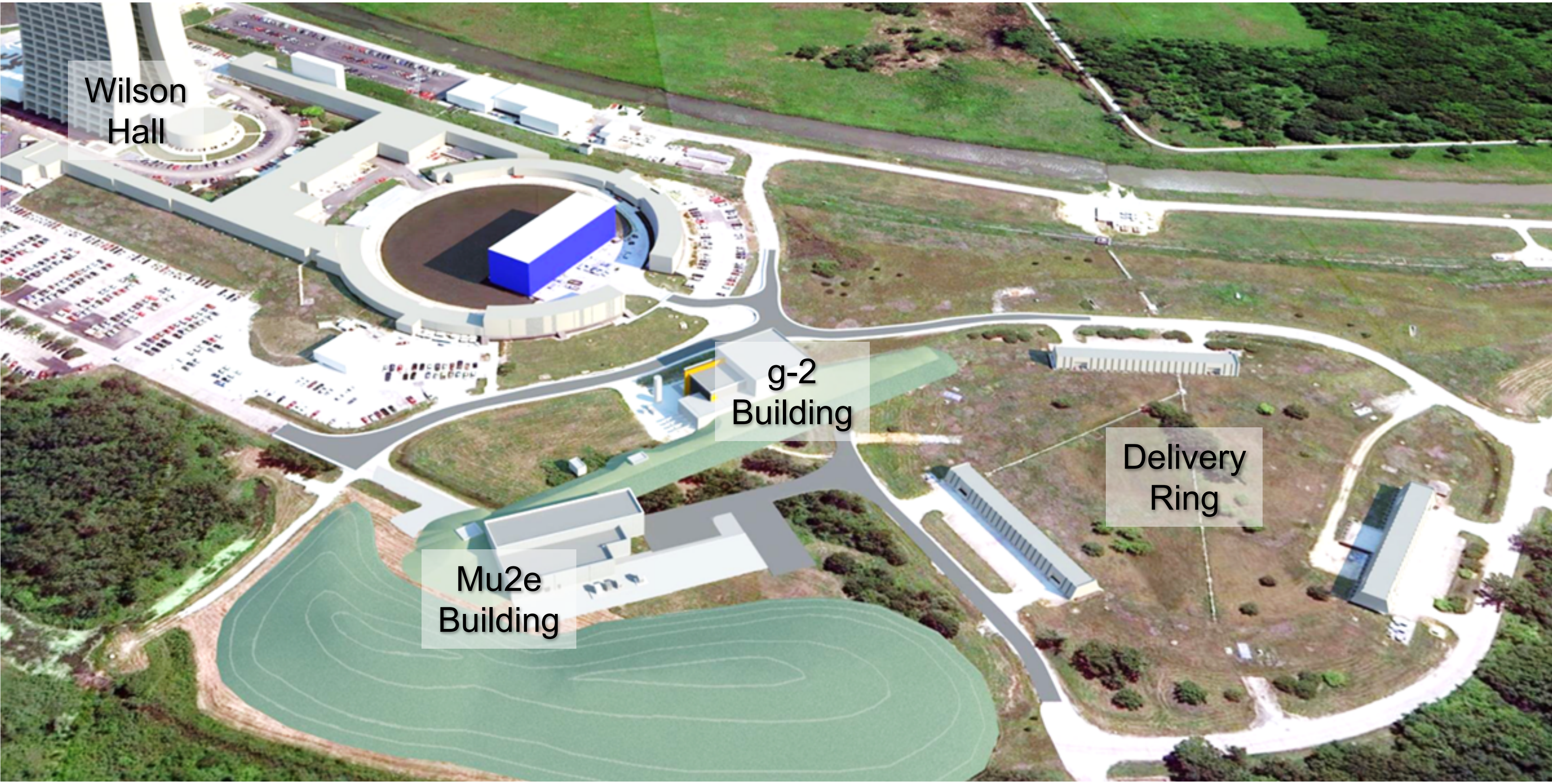
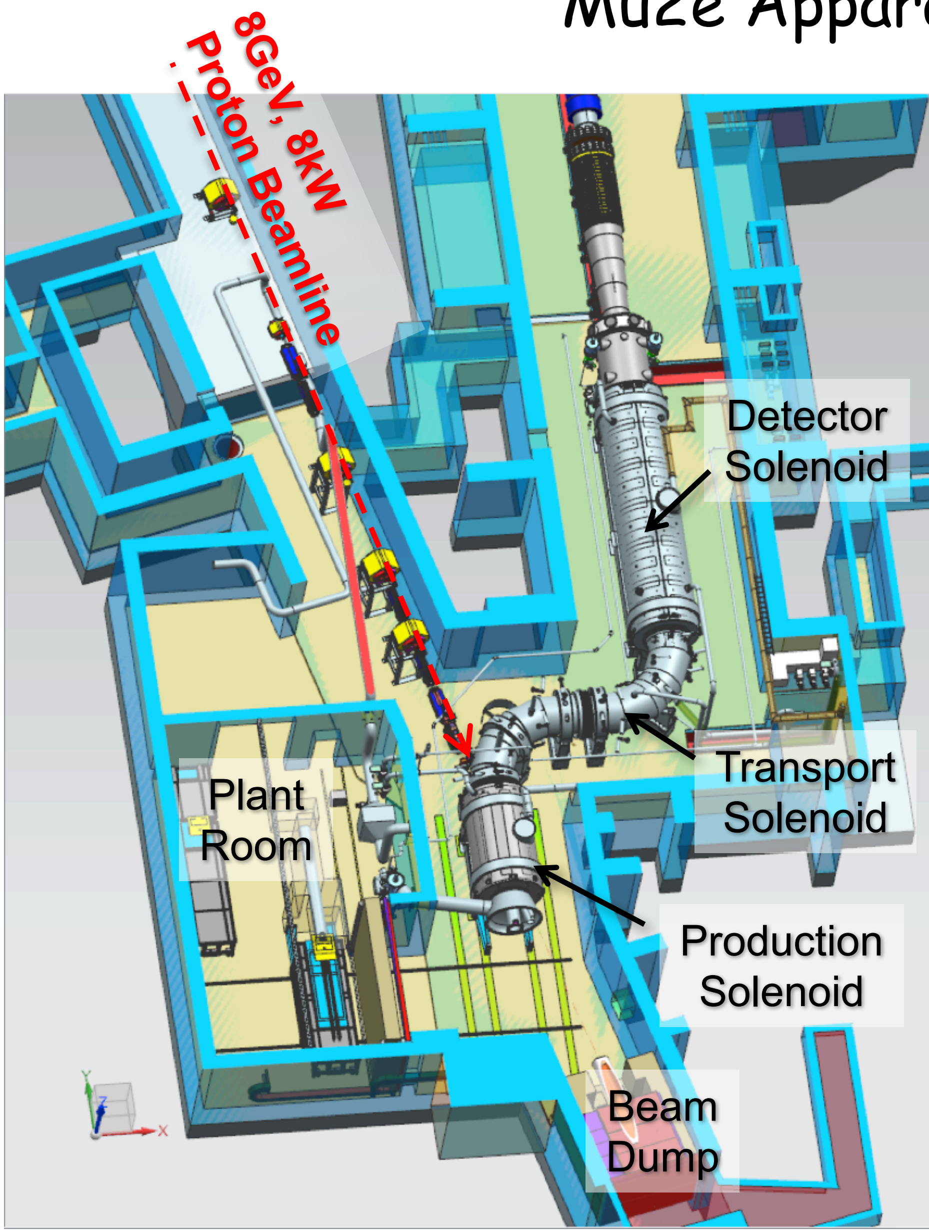
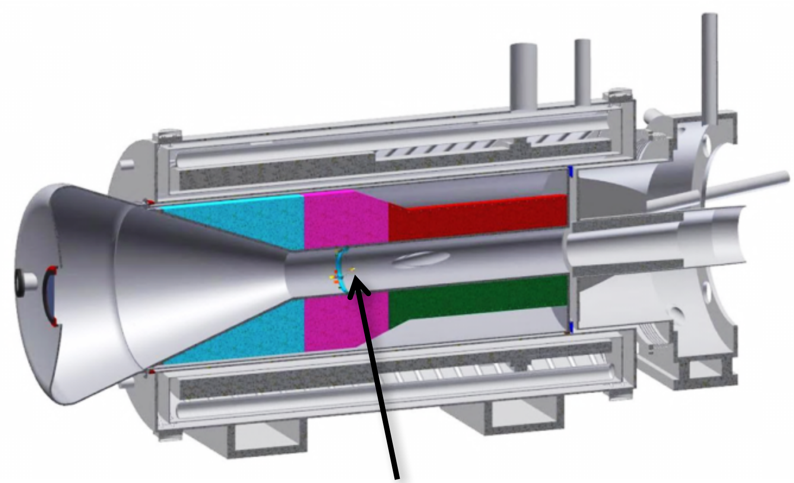
The Muon Campus at Fermilab



Mu2e Apparatus

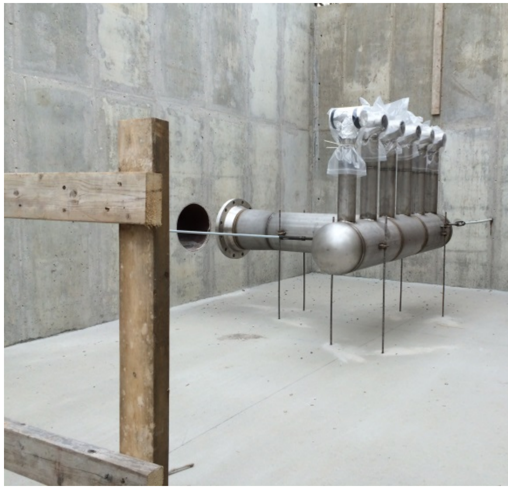


Beam kinetic energy	8 GeV
Main Injector cycle time	1.333 sec
Number of protons per spill	8 Tp
Average Beam Current	1 μA
Average Beam Power	8 kW
Beam spot shape	Gaussian
Beam spot size	$\sigma x = \sigma y = 1$ mm
Target Material	Tungsten



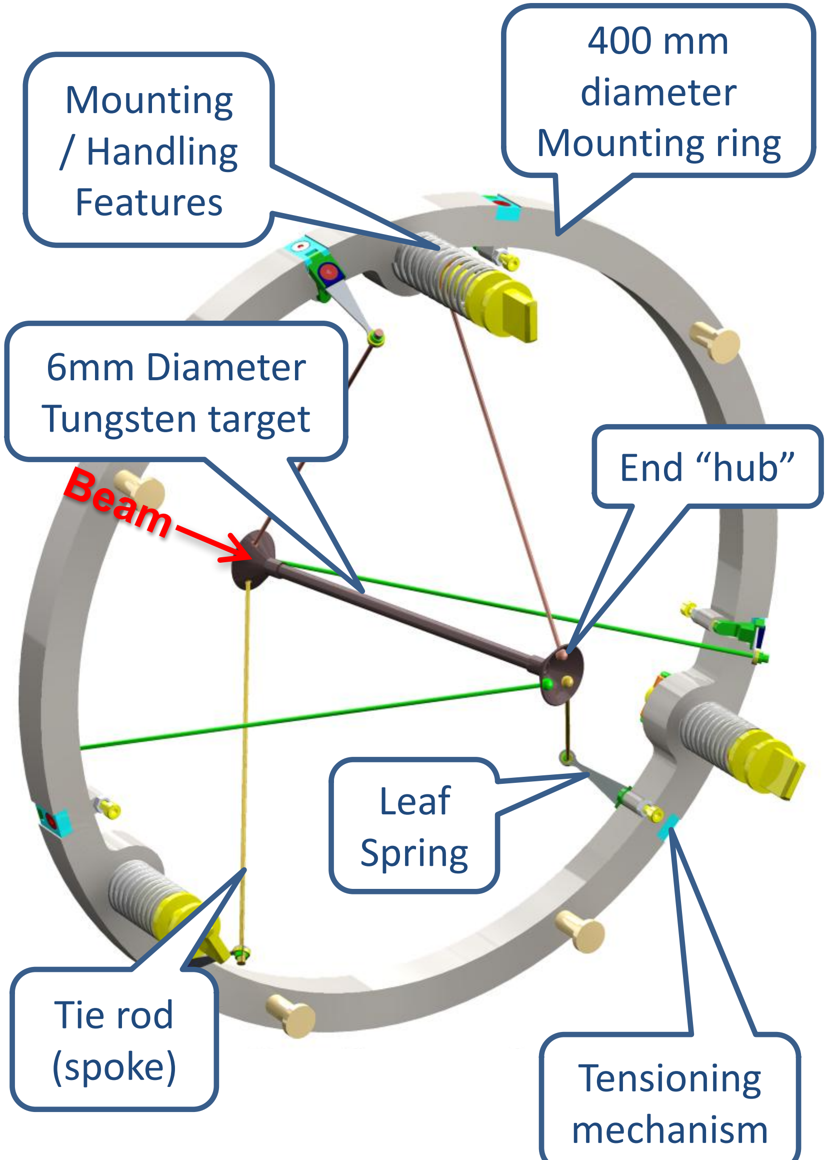
Target lives inside production solenoid here
(c/o Larry Bartozek)

Facility design is set (in concrete)



Don't ask about upgrades…

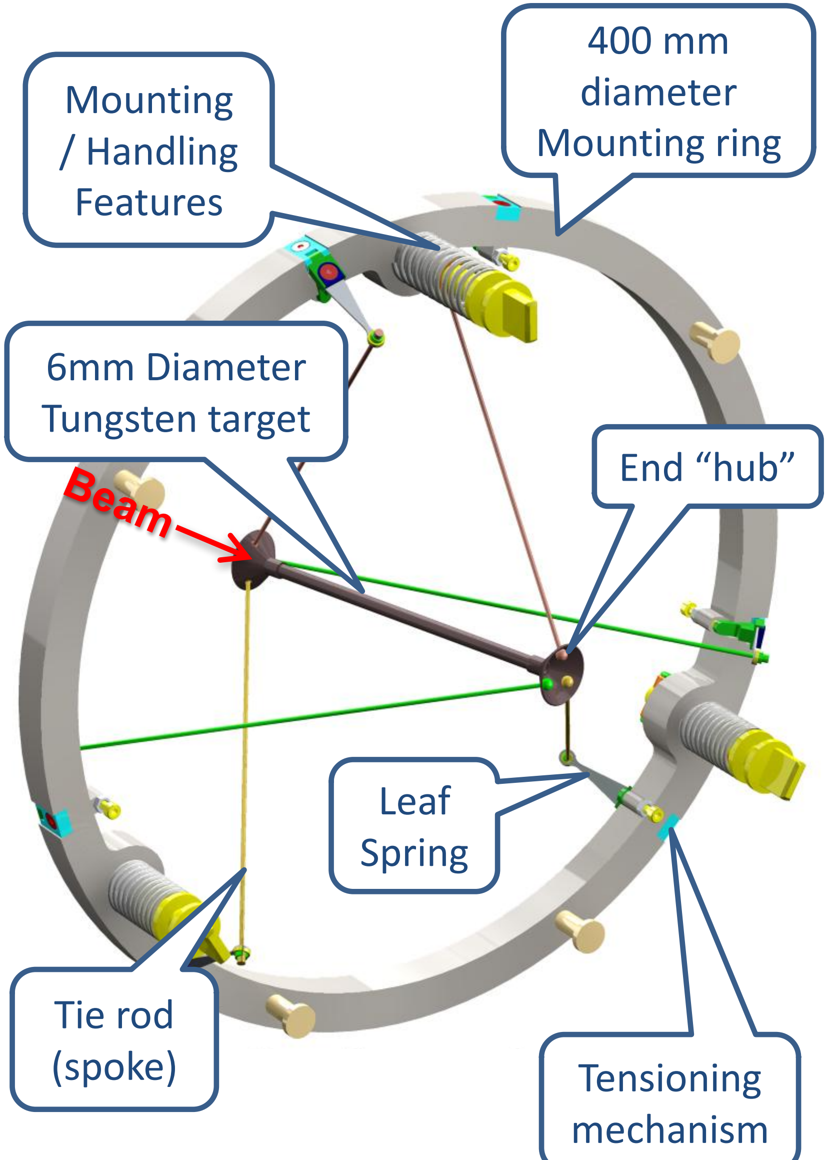
Radiation Cooled Proton Target Concept



Radiation Cooled Proton Target Concept

Drivers:

- ❑ No coolant plant required. Eliminates costs associated with design, hardware, plant room space, maintenance, etc.
- ❑ Eliminating the need for an active coolant greatly simplifies the remote target exchange process.
- ❑ Eliminates the risk of coolant leaks.
- ❑ Minimise material for pion production



Radiation Cooled Proton Target Concept

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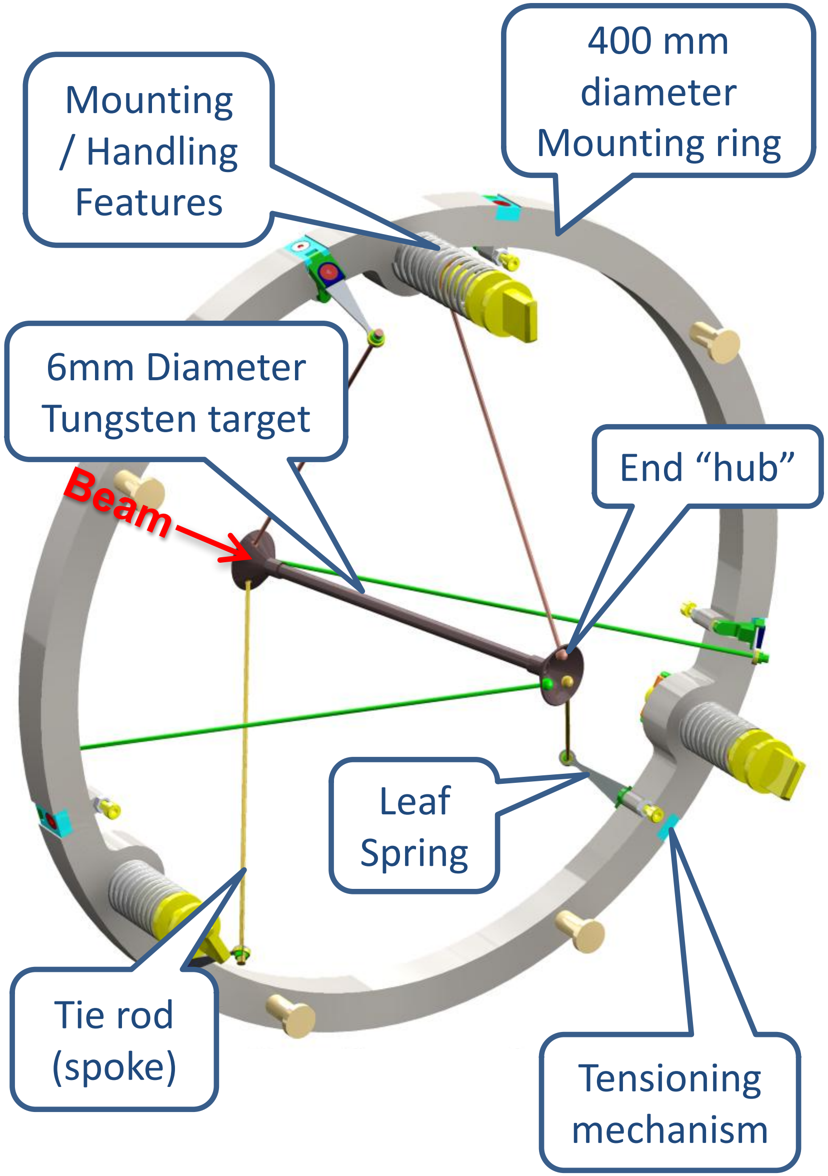

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Technical Challenges:

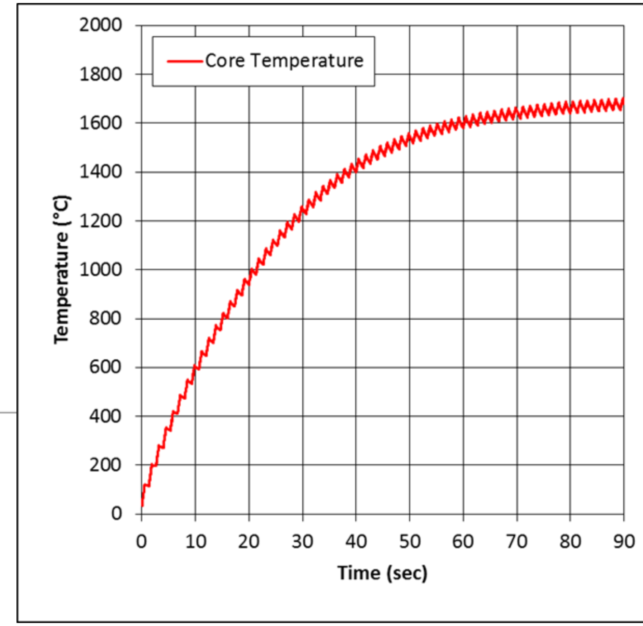
- ❑ Creep/fatigue under continuous thermal cycling at high temperature
- ❑ Oxidation / chemical attack by residual gases in the target environment
- ❑ Dispersion of contamination, particularly during replacement

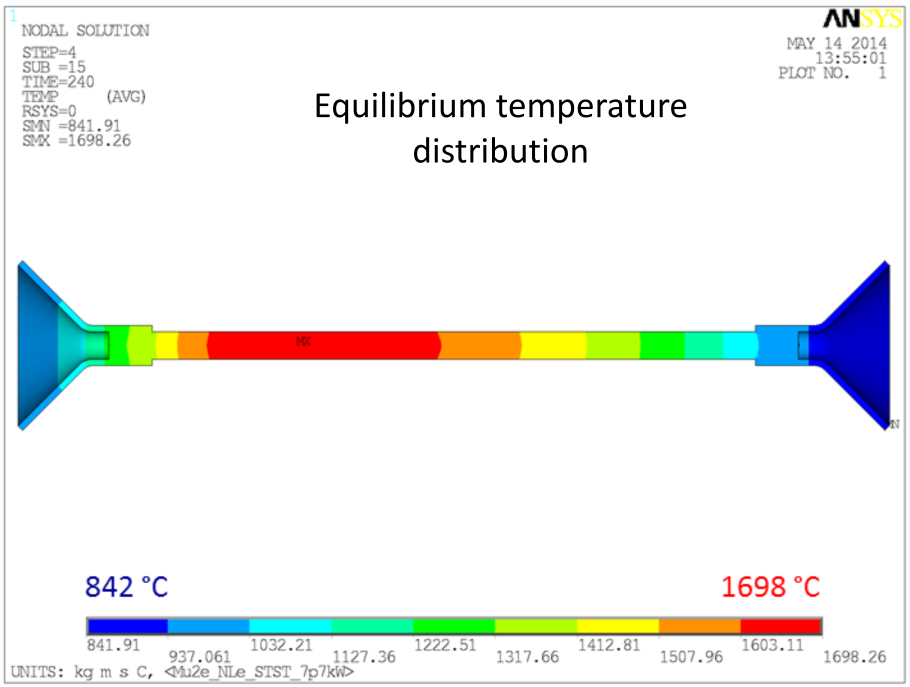
Address via Target Test Programme...

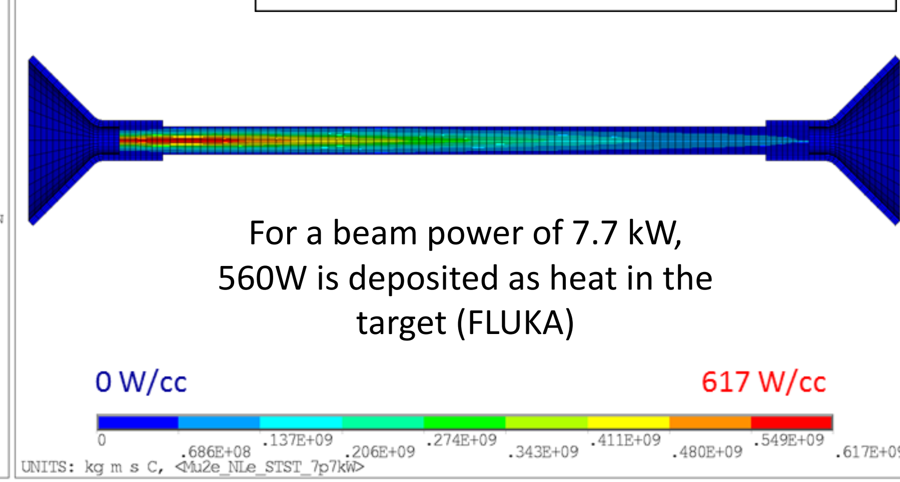
Target Operating Temperature

- ❑ Target heats up until it is able to dissipate the average deposited power by thermal radiation

- ❑ Equilibrium temperature depends on ***heat load***, ***emissivity*** and ***surface area***.







Recall Tungsten T_{melt} = 3400°C

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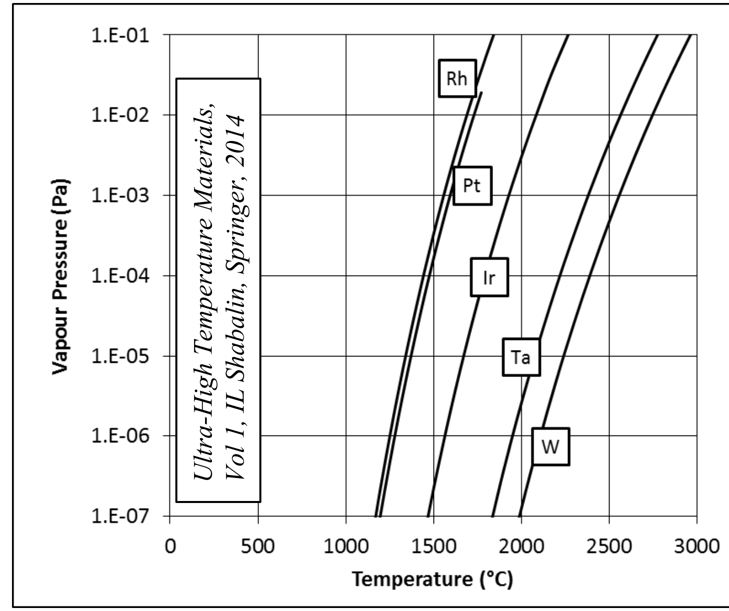
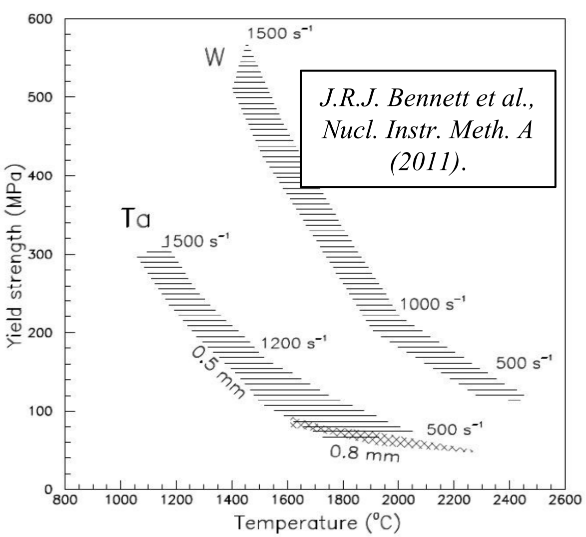
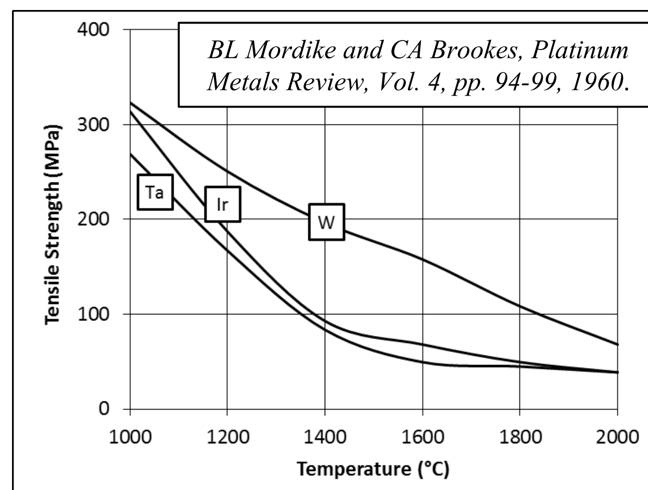
Why Tungsten?

- ❑ Favourable mechanical properties at elevated temperature
  Highest Melting Temperature, lowest Vapour Pressure and lowest CTE of all refractory metals
- ❑ High Z – high pion yield
- ❑ Spallation neutron target material of choice
  Have run tungsten targets at ISIS for many years
- ❑ Excellent lifetime under cyclic thermal loading indicated by High temperature shock wire test programme of Bennett et. al.

W T_{melt} = 3400°C







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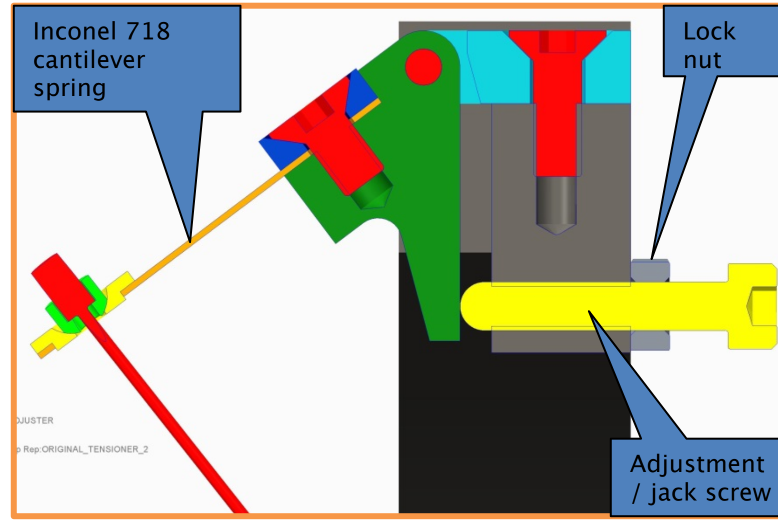
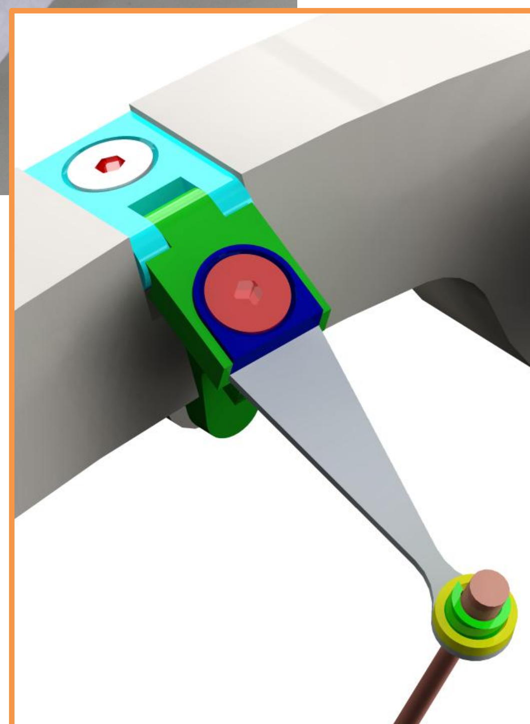
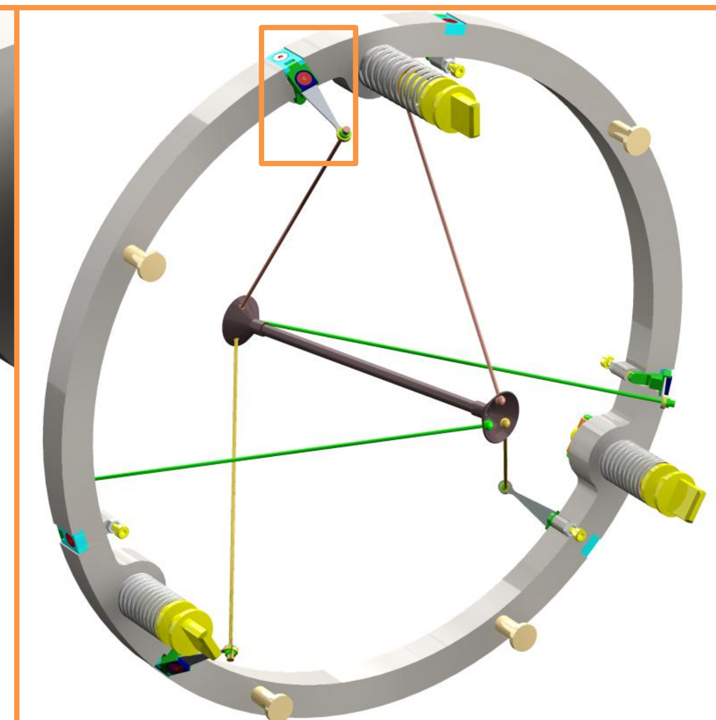
Prototype Cantilever Spring/Tension Mechanism







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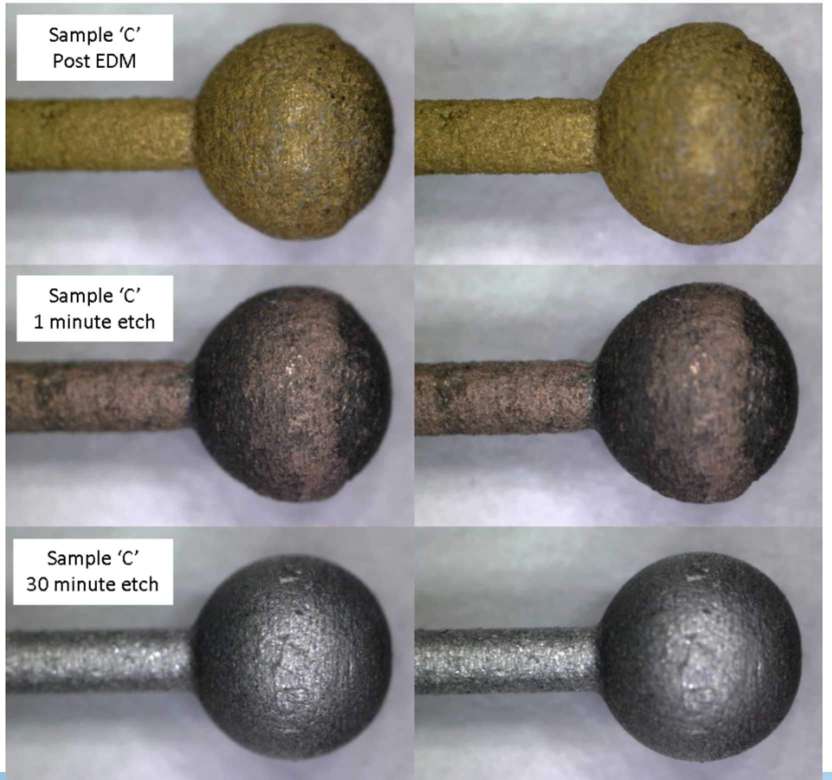
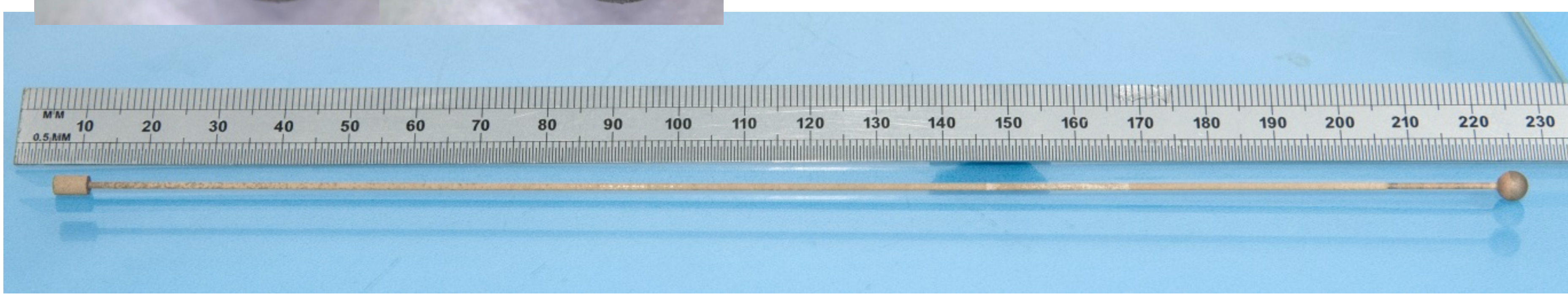
Prototype Refractory Metal Spokes



Tungsten spokes machined from solid using wire EDM technique (PDF lab, RAL Space)



A 220mm long 1mm diameter tungsten spoke with integral mounting features at both ends

Mu2e Target Test Bay

Air-cooled vacuum vessel with feedthroughs for power and thermocouples

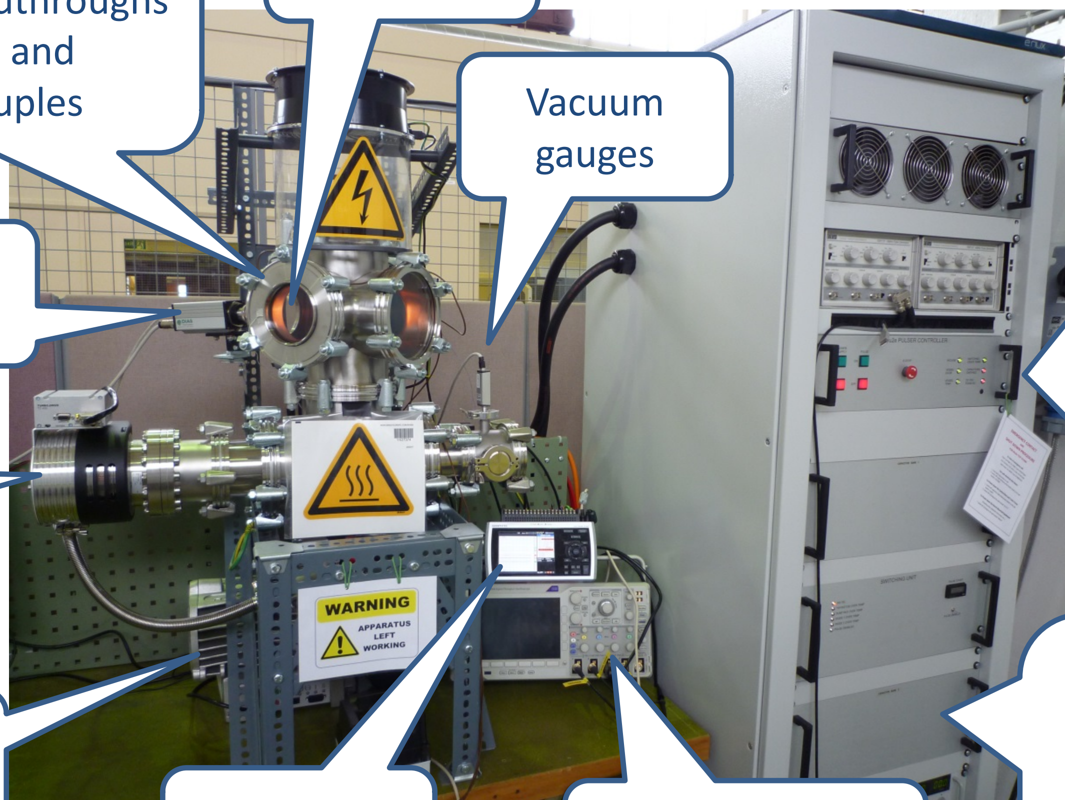
Observation windows

Vacuum gauges

Digital Pyrometer

300 l/s Turbo pump

Backing pump



Data logger

4-channel digital oscilloscope

Power supply rack

Pulse mode:
1 msec long half-sine wave pulses
0 - 2.5 kA peak
1 - 50 Hz repetition

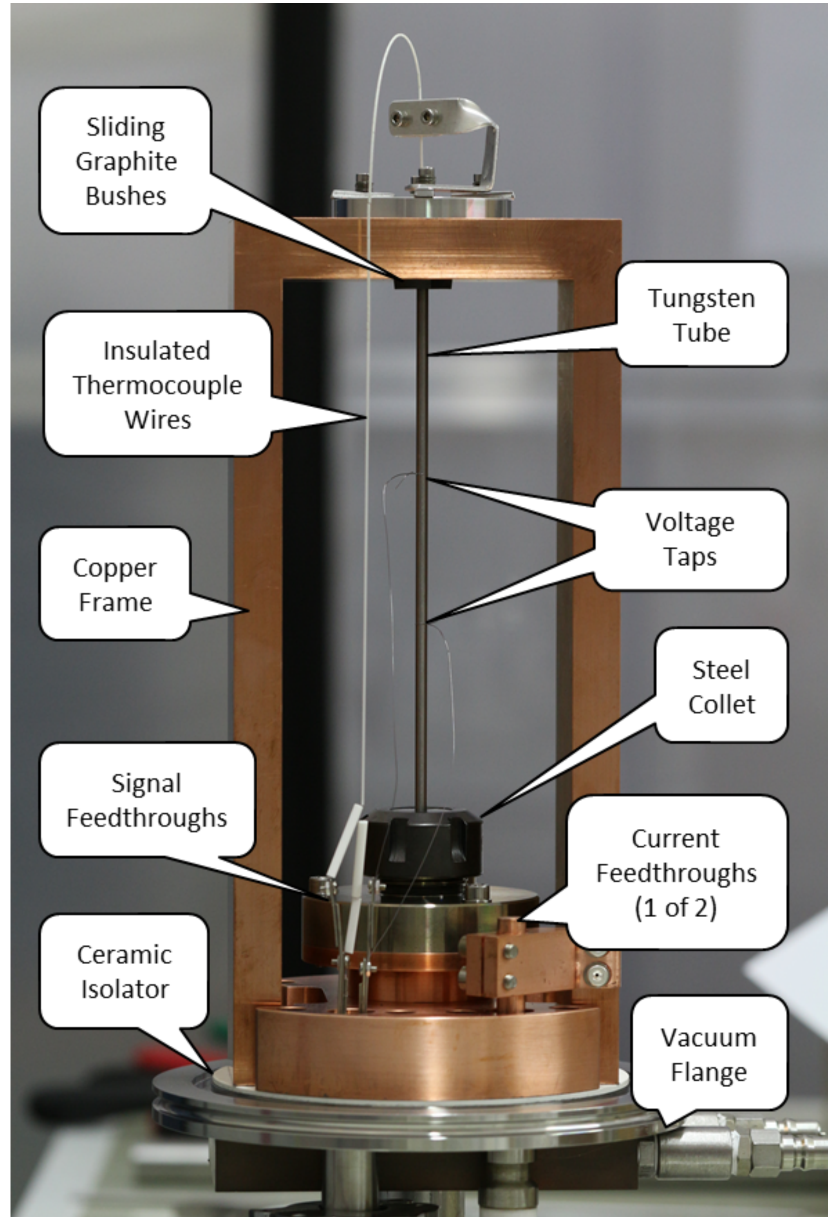
DC mode:
0-300A constant current

System interlocks
vessel over-temp
coolant flow
sample over-temp
vacuum level

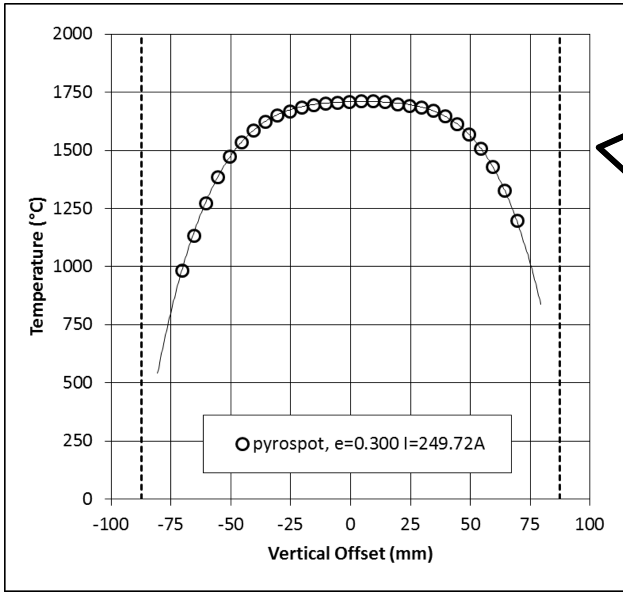
Total Hemispherical Emissivity Measurement Concept

Equilibrium Energy-Balance Method:

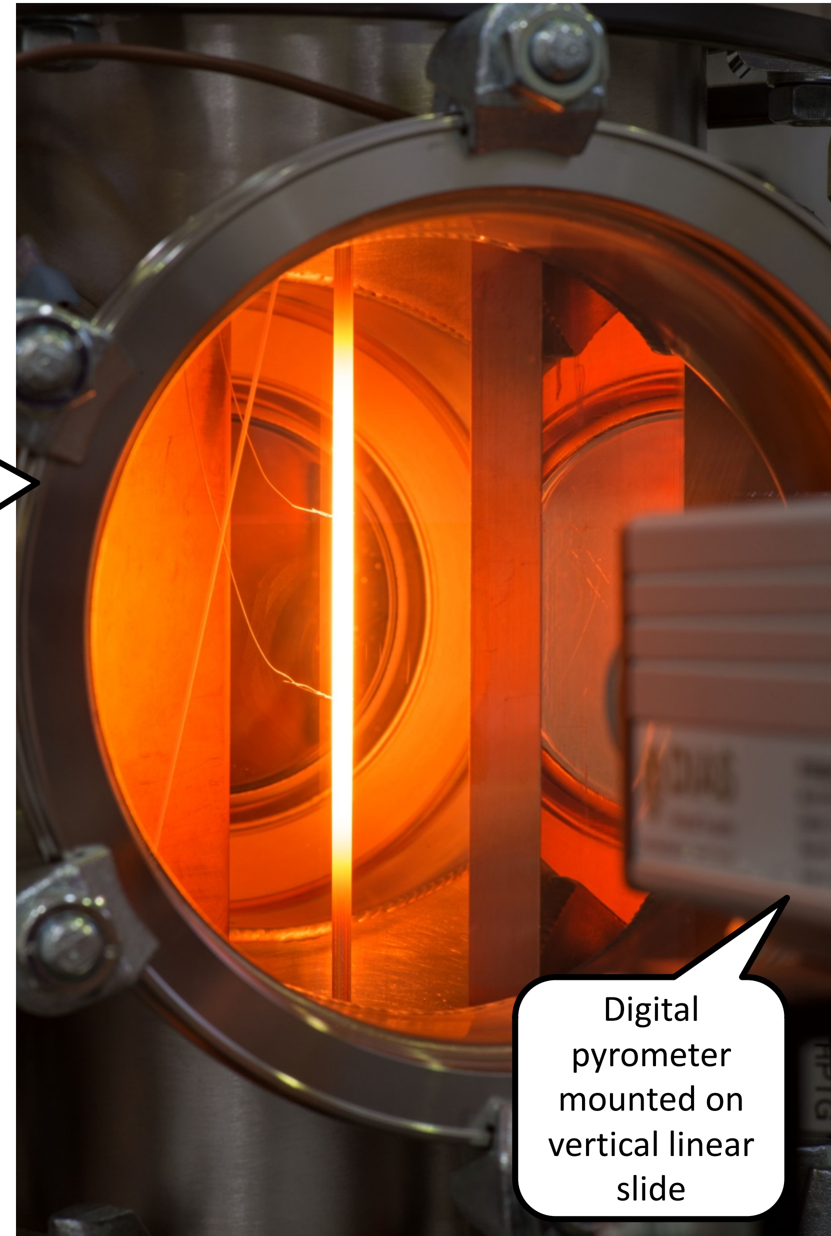
- Long tungsten tube heated by a direct current
- Power deposited between voltage taps found from
  $$Q_{in} = VI$$
- Vacuum prevents convection losses
- Conduction loss calibrated out
  $$Q_{cond} = kA\frac{dT}{dZ}$$
- Radiation heat loss found from
  $$Q_{rad} = Q_{in} - Q_{cond}$$
- Emissivity found from
  $$Q_{rad} = A\varepsilon\sigma({T_s}^4 - {T_e}^4)$$



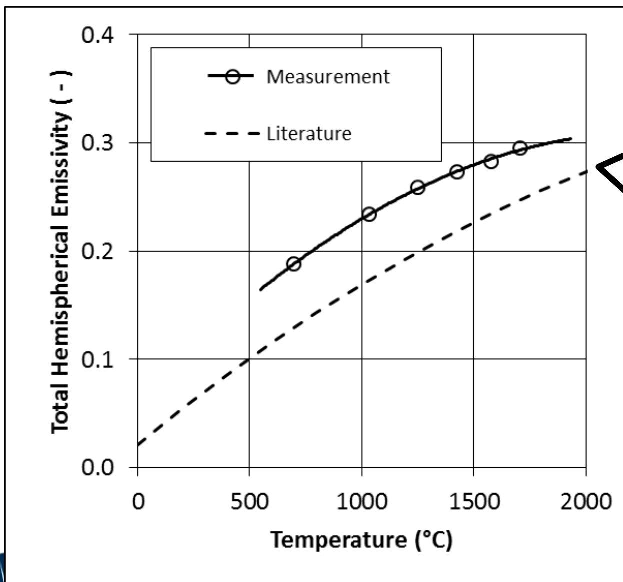
Typical Measurements



Temperature distribution along the tungsten tube



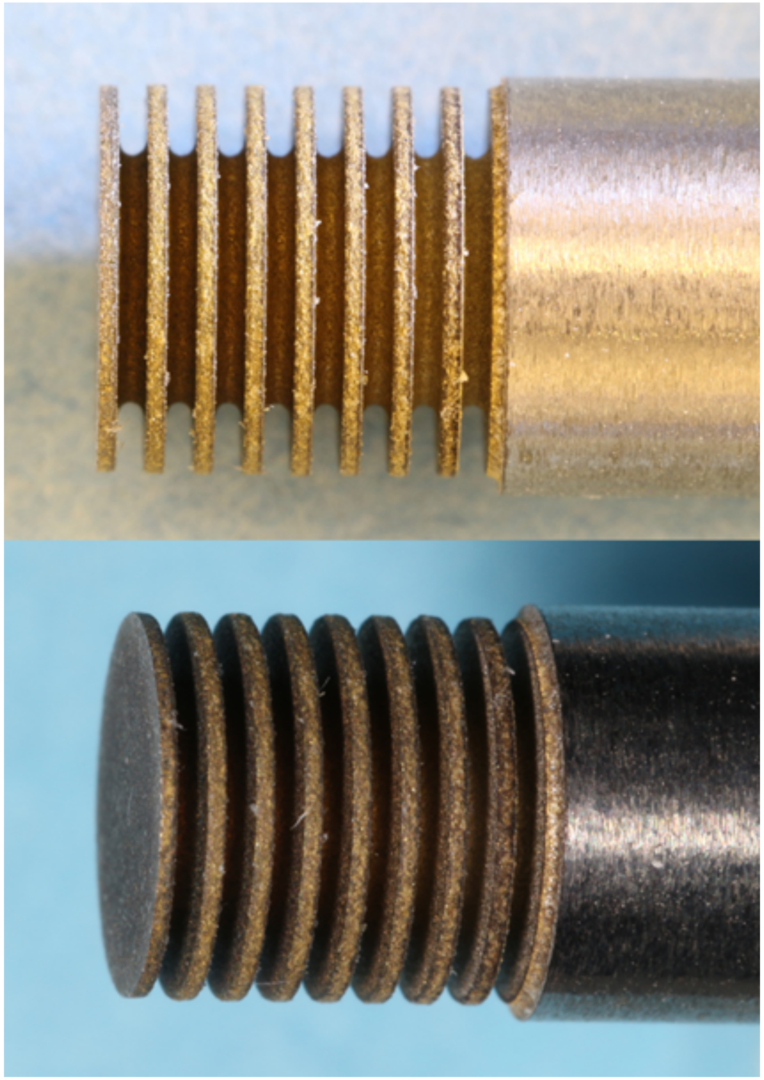
View through the optical window



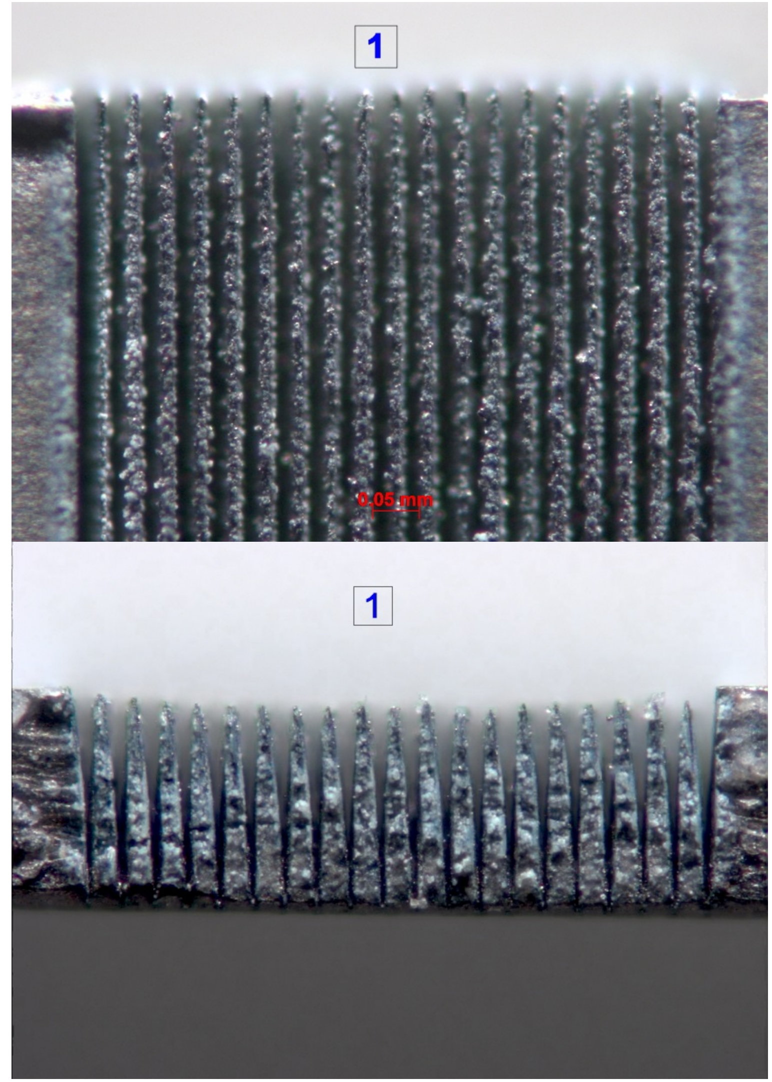
Temperature dependent emissivity deduced

Digital pyrometer mounted on vertical linear slide

Possible Finned Surface to Enhance Emissivity?



0.7mm pitch Wire EDM fins
(PDF lab, RAL Space)



35 micron pitch laser-machined fins
(Micronanics Laser Solutions Centre)

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But need to consider fatigue lifetime

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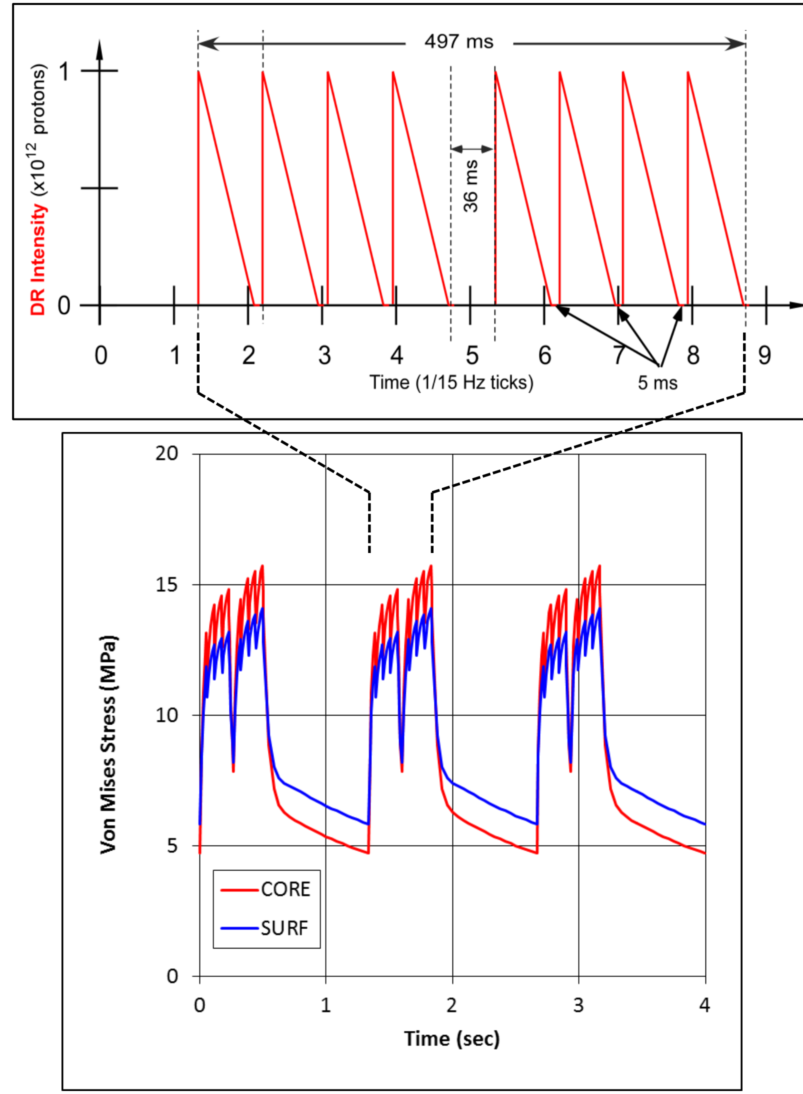
Thermal Fatigue in the Target

- The beam cycle causes transient thermal stresses in the target rod
- Thermal stress generated by radial temperature gradients in the rod
- When beam is “on” radial temperature gradient and thermal stress increase because heat deposition is biased towards the centre of the rod
- When beam is off the heat spreads by thermal conduction and the thermal stress decreases
- Tensile stress at the surface, compressive stress in the core
- ~24 Million cycles per year of continuous running on a 1.333 sec cycle time
- 1 year target life requirement



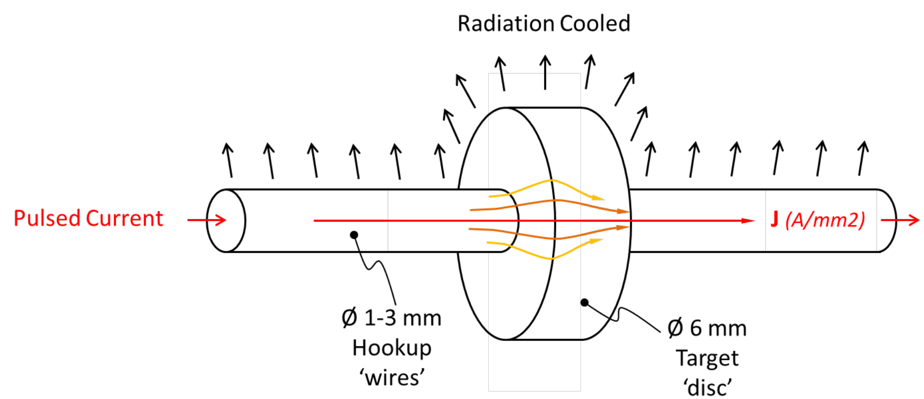
Above: The Delivery Ring beam intensity as a function of time

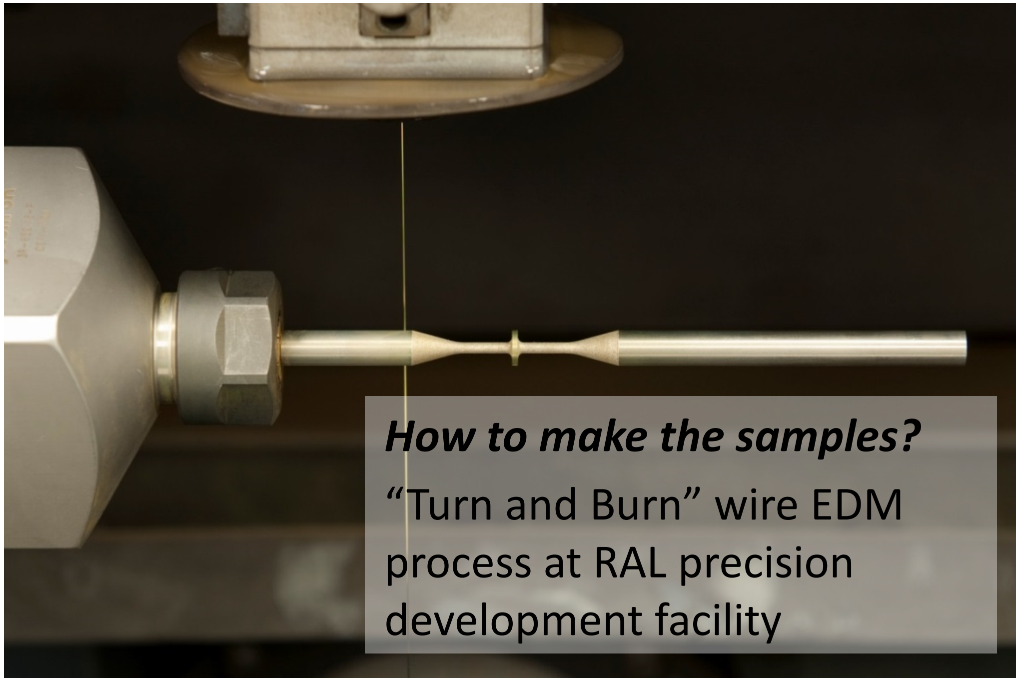
Below: Von-Mises Stress at a Z slice in the target rod near to the shower-max

A Novel Thermal Fatigue Test for Mu2e

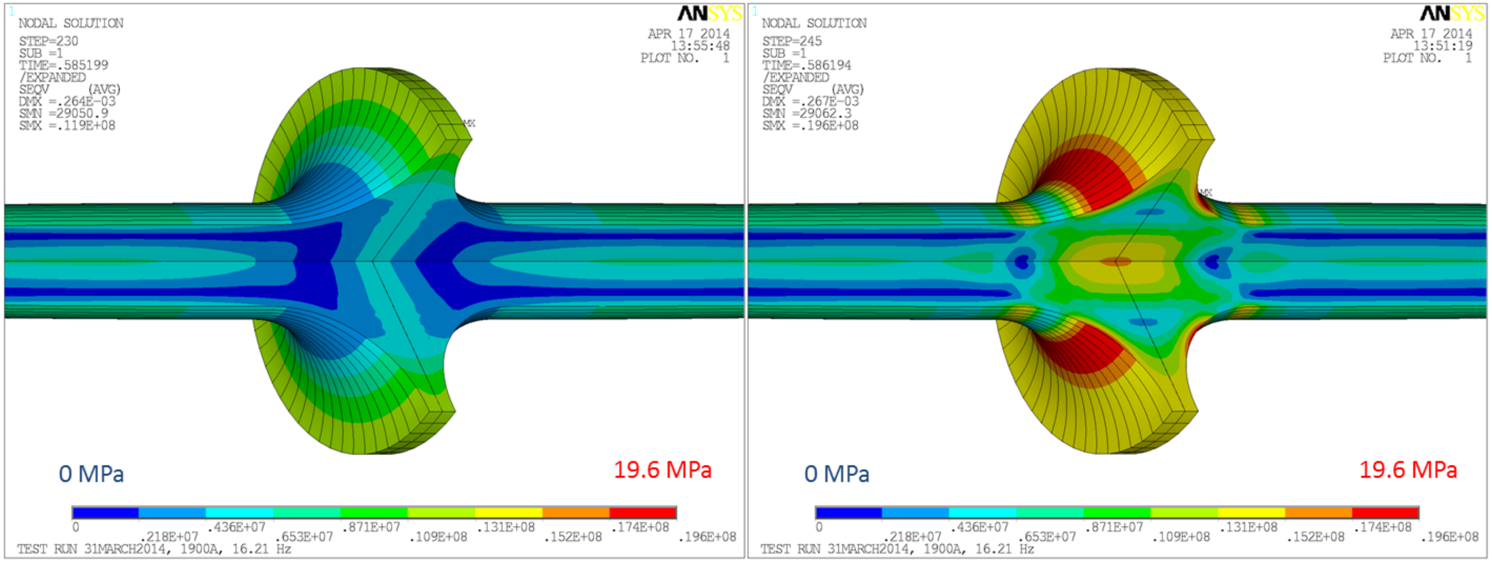
How to mimic beam induced thermal stresses without using a proton beam?

- Use a pulsed power supply to heat specially shaped tungsten samples in a vacuum environment
- Mimic the transient thermal gradients in the target
- Control current pulse intensity and repetition rate
- Closely match the target dimension, operating temperature, pulse temperature rise and thermal stress cycle in an accelerated lifetime test

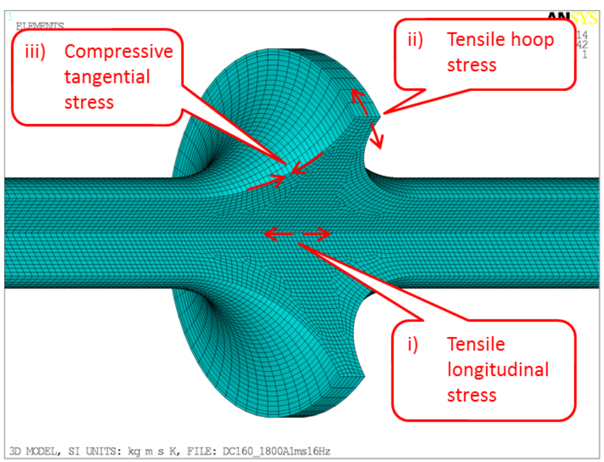


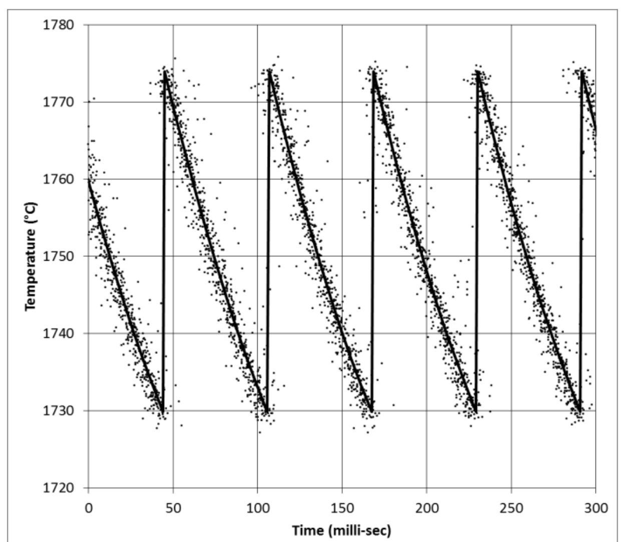


Calculated Stresses in the Sample

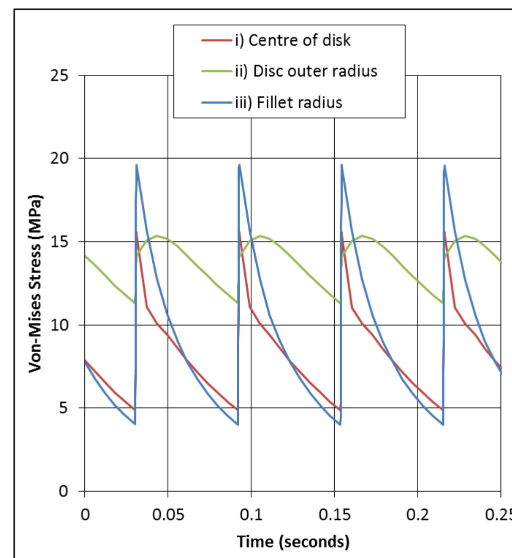


Von-Mises stress distribution before (left) and after (right) a current pulse





Sample temperature recorded using digital pyrometer



Sample stresses back calculated using ANSYS

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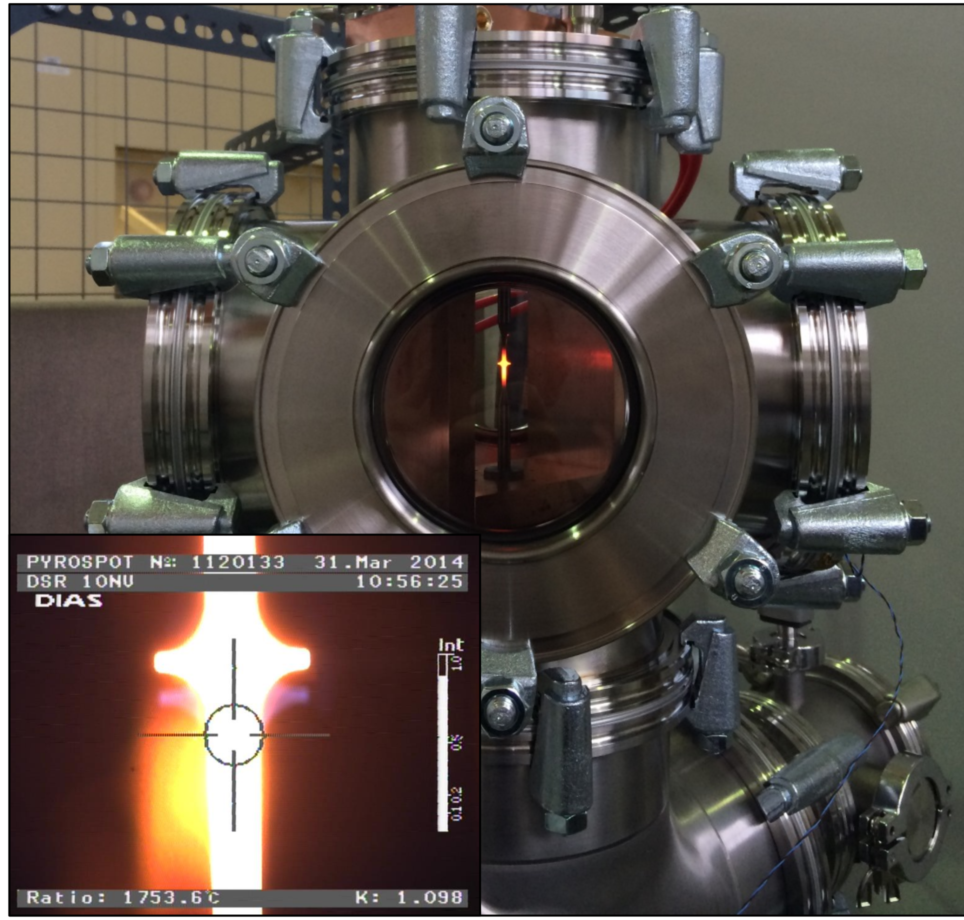
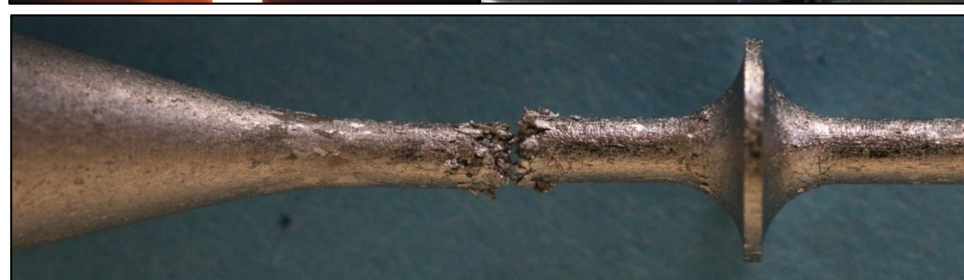
Lifetime Test

	Mimic Mu2e target operation	**PSU “flat out”**
Peak Current	1900 A	2300 A
Repetition Frequency	16 Hz	11.5 Hz
‘mean’ operating temperature	1750 °C	2000 °C
Measured ΔT at surface	44 °C	73 °C
Cumulative Number of cycles	100 million	137 million
Failure?	No	Yes



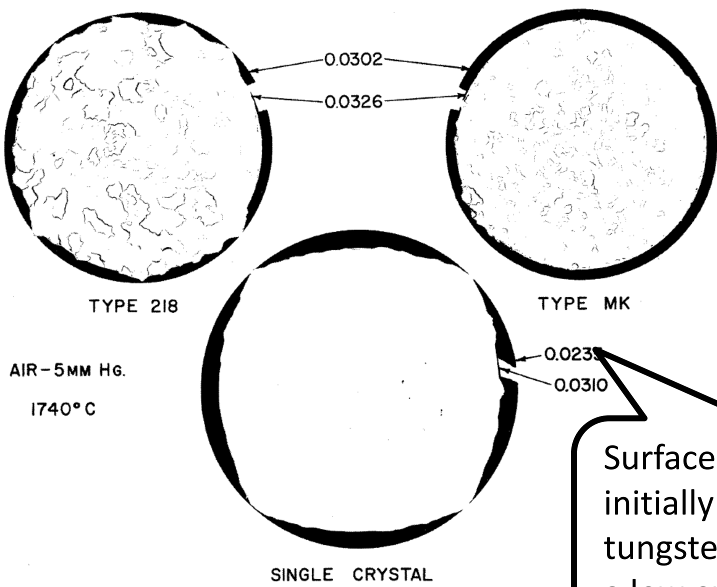
The sample survived 100 million cycles under conditions designed to mimic Mu2e Target operation. Equivalent to 4 years continuous operation.

A failure was then induced by running the PSU “flat out” for a further 37 million cycles.

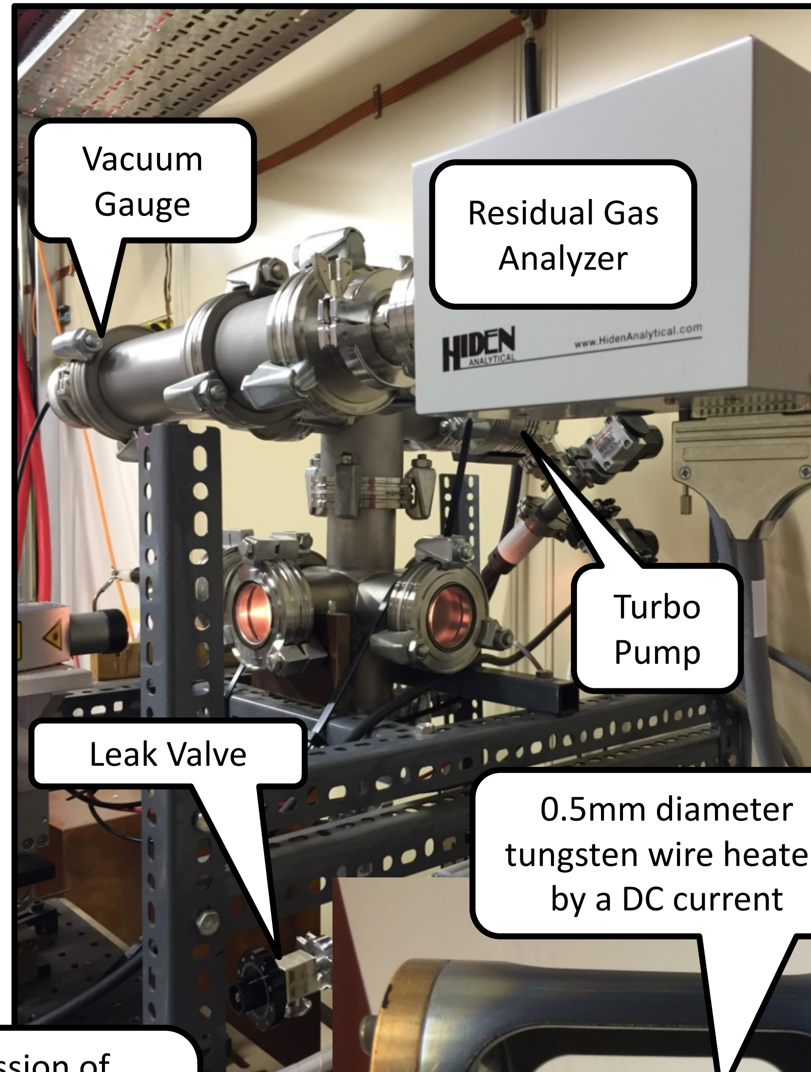


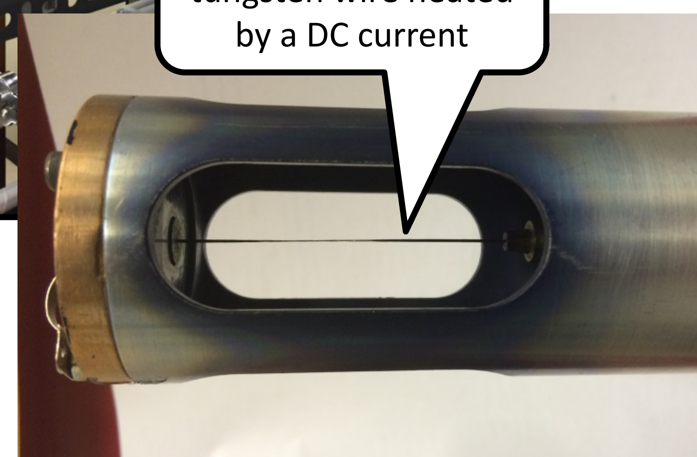
Effect of oxygen contamination in vacuum

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.

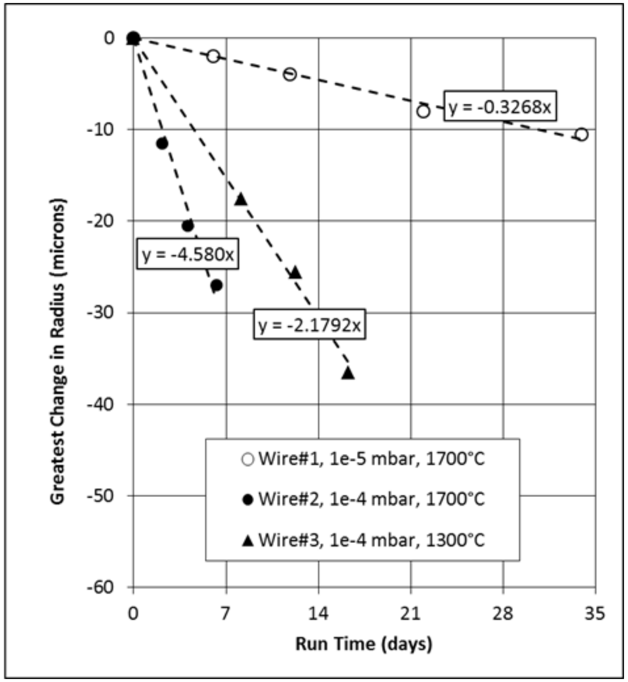


Surface recession of initially cylindrical tungsten rods heated in a low oxygen pressure

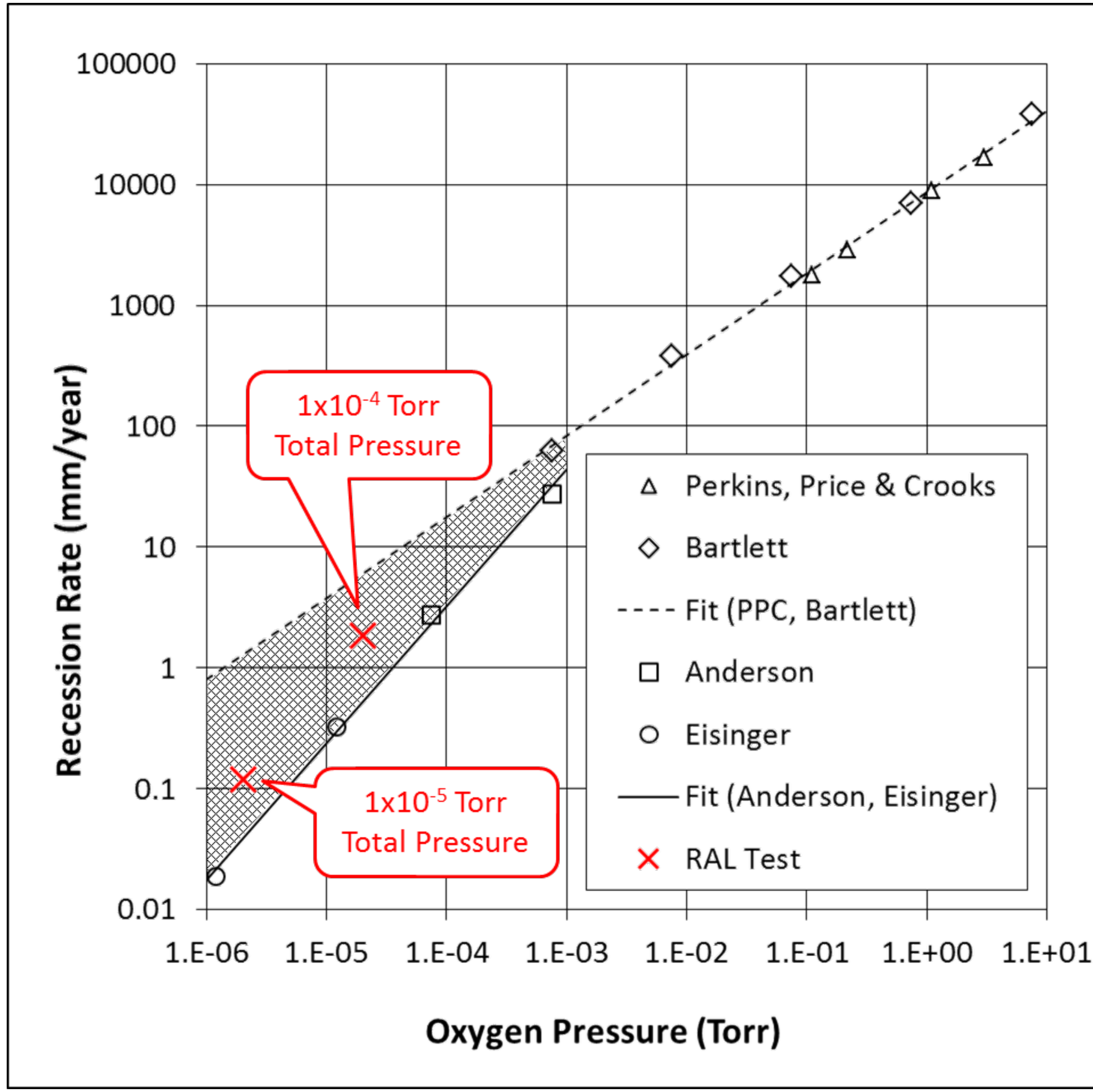




Vacuum/Leak Test Results



Total Pressure *(Torr)*	Recession Rate *(mm/year)*
1×10^{-6}	Few Microns
1×10^{-5}	0.12
1×10^{-4}	1.8



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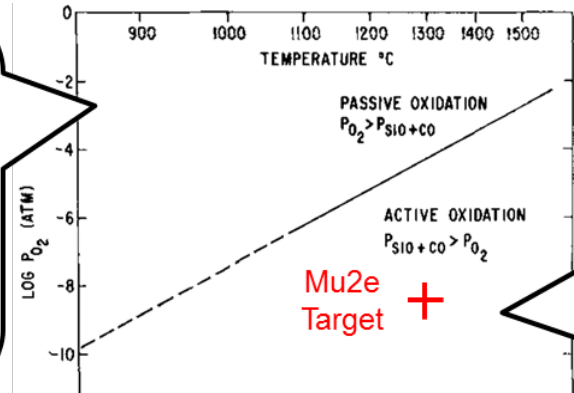
Attempts with oxidation resistant coating – e.g. SiC

High pressure and low temperature
⇨ ***Passive* Oxidation**

Forms a protective (white) oxide film which limits further attack of the SiC

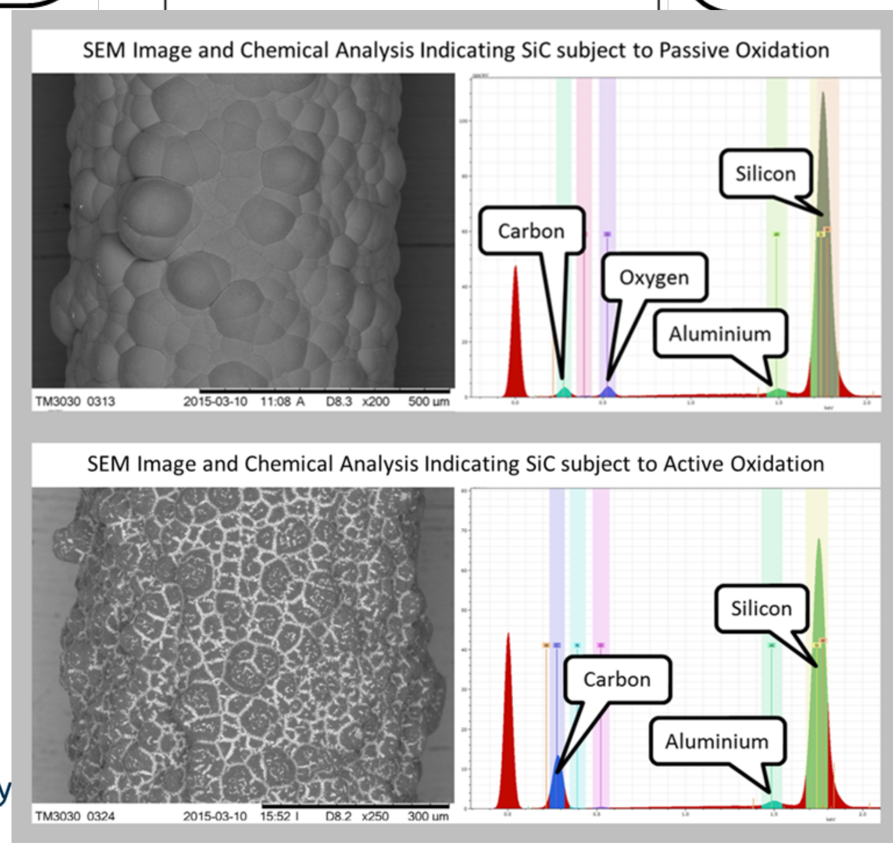
$SiC(s) + 2O_2(g) \longrightarrow SiO_2(s) + CO_2(g)$



Low pressure and high temperature
⇨ ***Active* Oxidation**

Forms a volatile oxide which leads to recession of the SiC

$SiC(s) + O_2(g) \longrightarrow SiO(g) + CO(g)$



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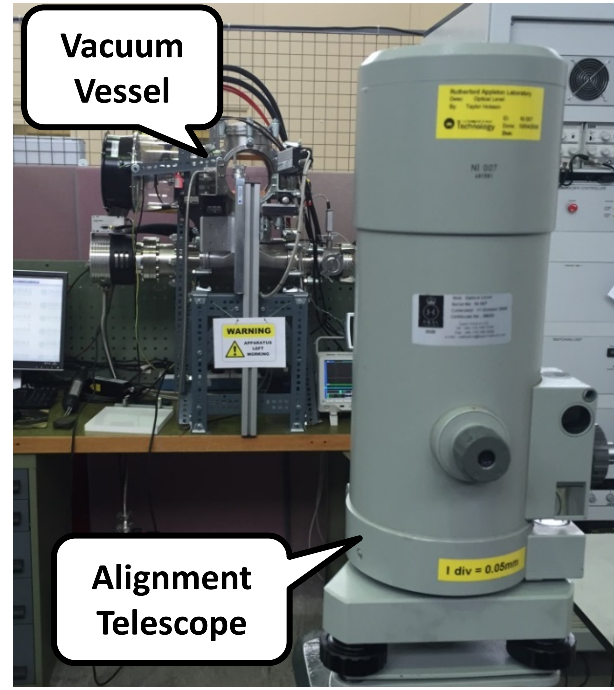
Testing creep under "Mu2e-like" conditions

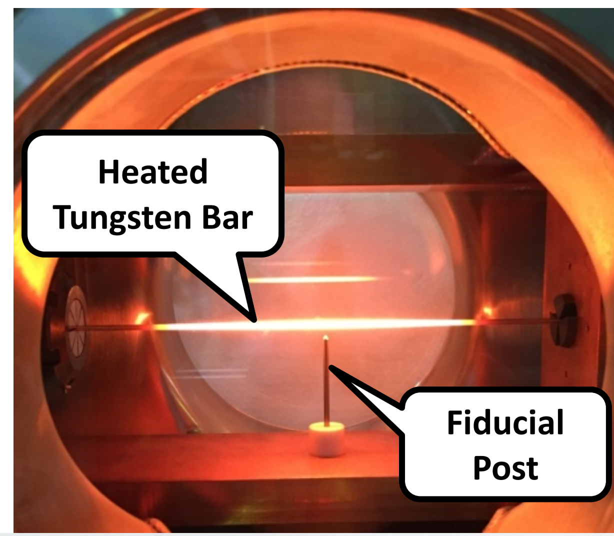
Issue:

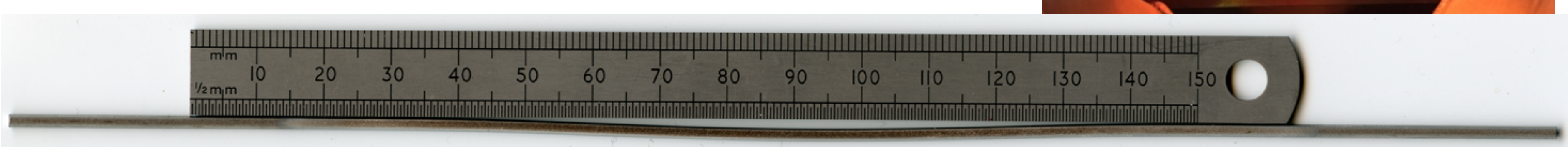
- As a rule-of-thumb creep tends to become significant at temperatures beyond $T_{melt}/2$, ~1840K in tungsten. Recall Mu2e target expected operating temperature ~2000K.
- Self-weight could result in an unwanted permanent "sag" in the target rod

Test:

- Tungsten bar mounted in a horizontal configuration and heated by a direct current in vacuum
- Monitor the vertical gap between sample and a fiducial post using an alignment telescope
- Creep rate depends on ***operating temperature*** and ***self-weight bending stress***

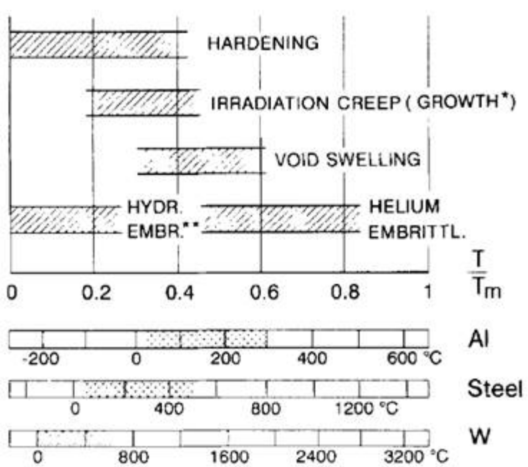






Radiation Damage Considerations – 8kW Beam

- T>> $T_{recrystallization}$ (considered a design limit for the plasma facing components in fusion applications), traverse of DBTT every beam trip
- Dpa rate and integrated dose that are typically 2 orders of magnitude greater than that for which data exists in the literature, and at higher temperatures.
- Issues of concern include: helium embrittlement, elevated DBTT, hardening, radiation enhanced corrosion … reductions in thermal conductivity, fracture toughness etc etc



H Ullmaier and F Carsughi, Nucl. Inst. And Meth. In Phys. Res. B, Vol. 101, pp. 406-421, 1995.

	ISIS	Mu2e
Beam kinetic energy (GeV)	0.8	8
Average Beam Current (μA)	200	1
Average Beam Power (kW)	160	8
Beam shape	Gaussian	Gaussian
Beam sigma (mm)	16	1
Peak Flux on target front face ($\mu A/cm^2$)	12.4	15.3
Peak DPA / year *	27	260
Helium Gas Production (appm/DPA) *	10	20
Required life (years)	5+	1+

* Brian Hartsell mars calculation for the RADIATE collaboration, www.radiate.fnal.gov

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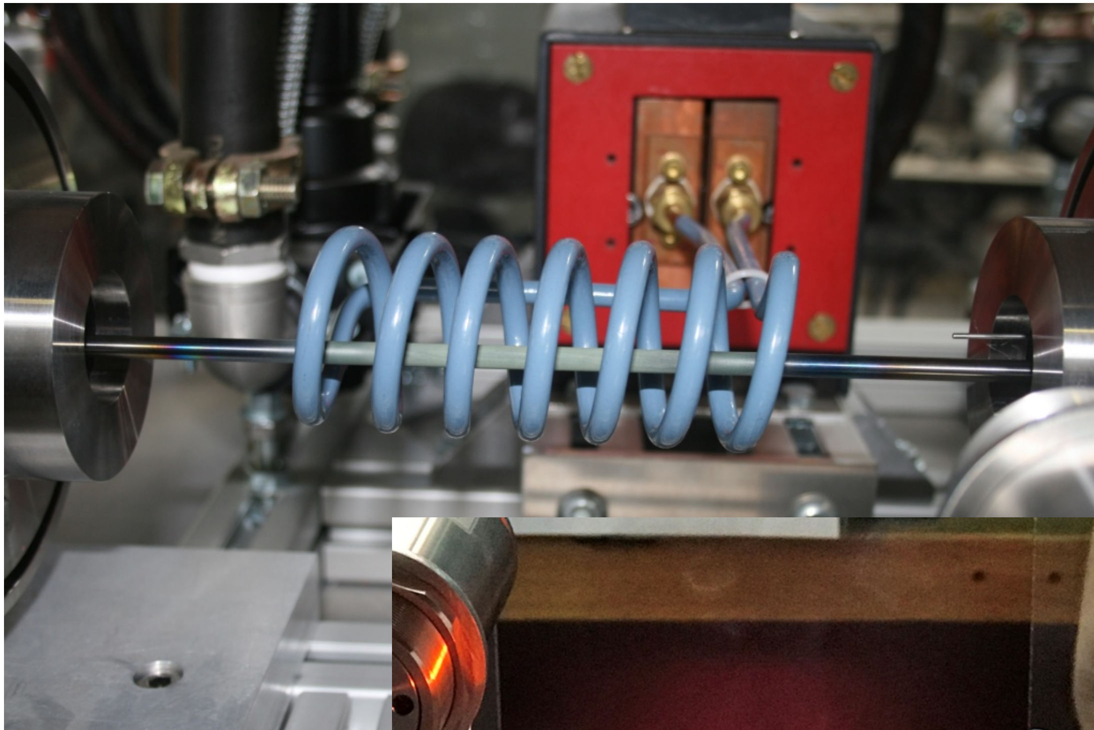
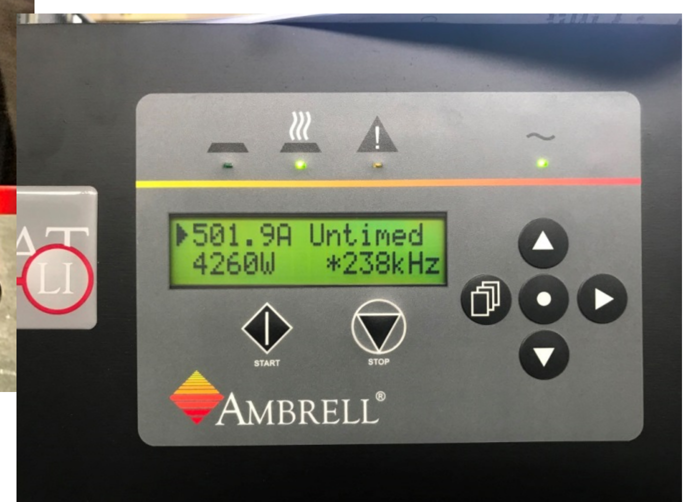
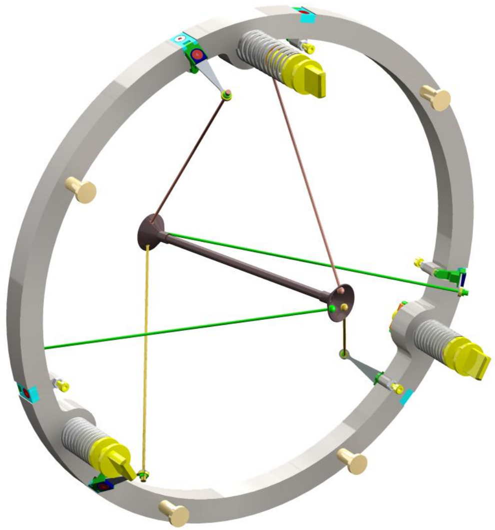
Initial induction furnace tests (last Friday)





Summary and Next Steps



- The baseline technology choice for the Mu2e production target is a radiation cooled tungsten rod mounted in a support structure that resembles a spoked wheel.
- Target test programme underway
- Manufacturing route for critical components demonstrated
- Full scale prototype and heating test to follow
- Issues of concern include radiation damage and material erosion/evaporation