Mu2e radiation cooled target

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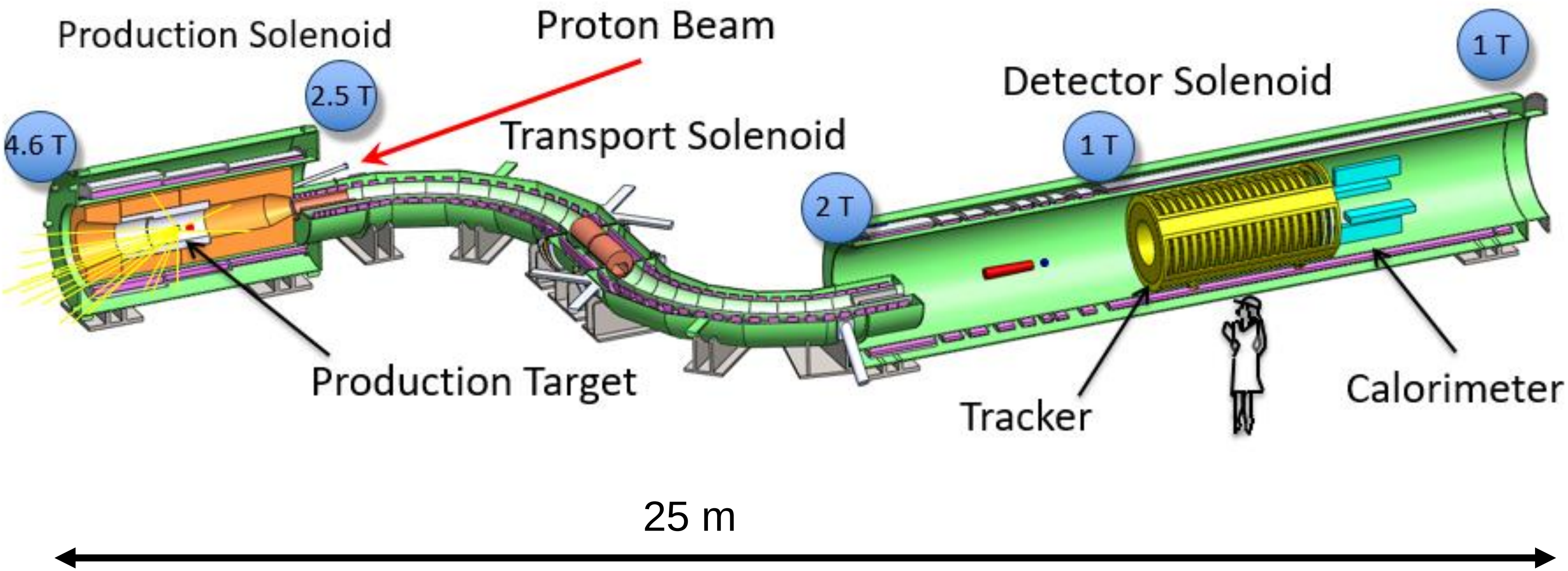
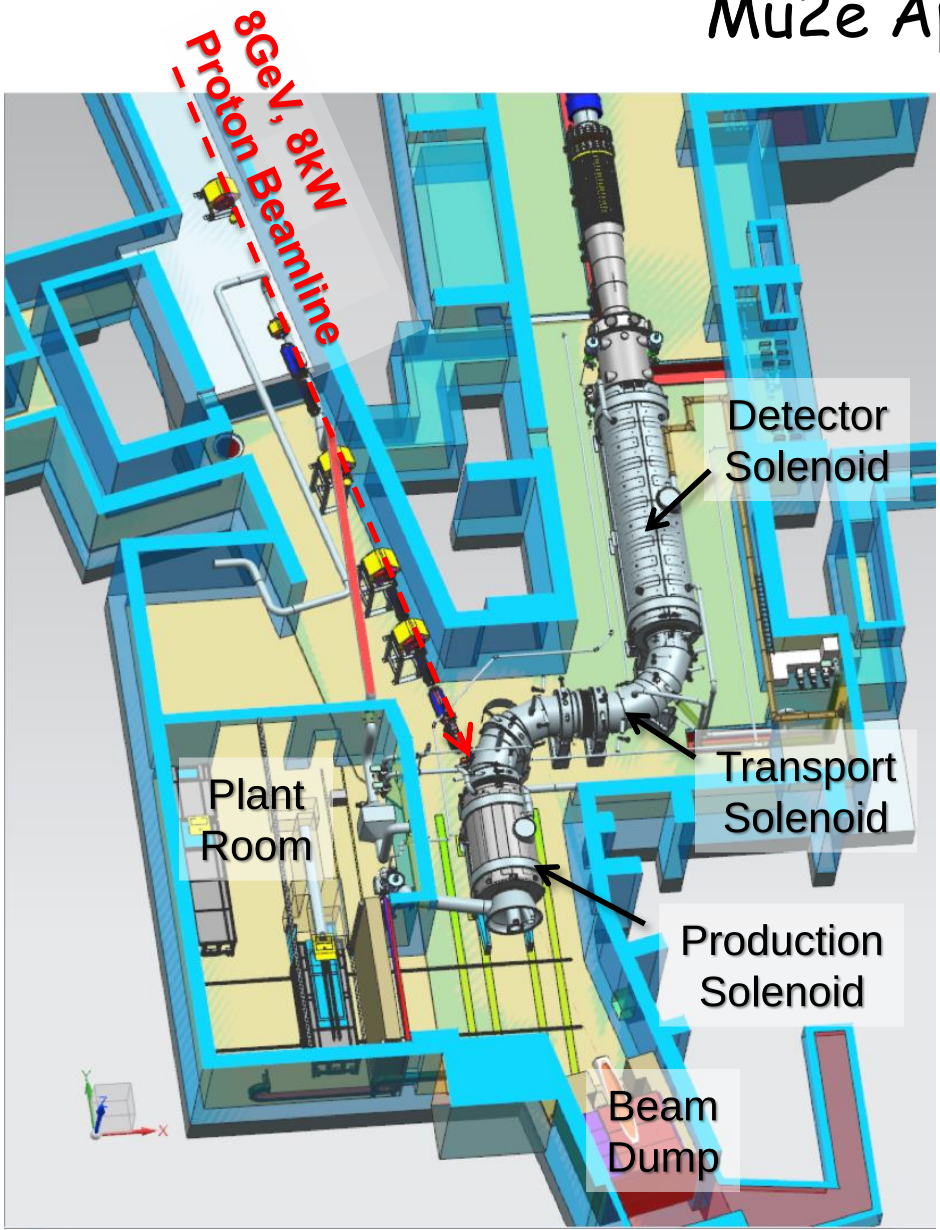
The Muon Campus at Fermilab

Mu2e Apparatus

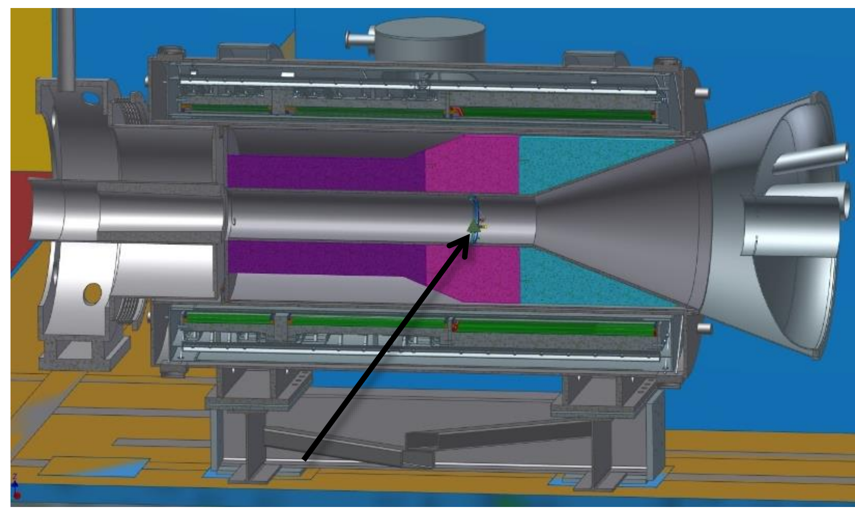


- *Graded field in production solenoid*
- *Acts as a mirror for charged particles*
- *Low momentum pions captured by production solenoid field and transferred to transport solenoid*

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	σx = σy = 1 mm
Target Material	Tungsten



Target lives inside production solenoid here

Production Target Requirements

Maximize the number of stopped muons at the stopping target.

- Composition
  1. High Z and high density
  2. Large Pion production cross-section
  3. High thermal conductivity allowing an acceptable operating temperature
  4. Melting point well above operating temperature

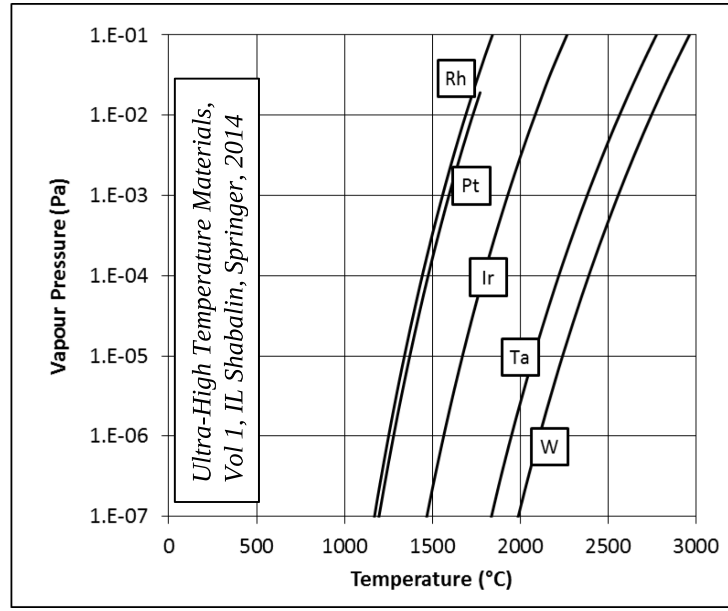
  Tungsten is uniquely qualified

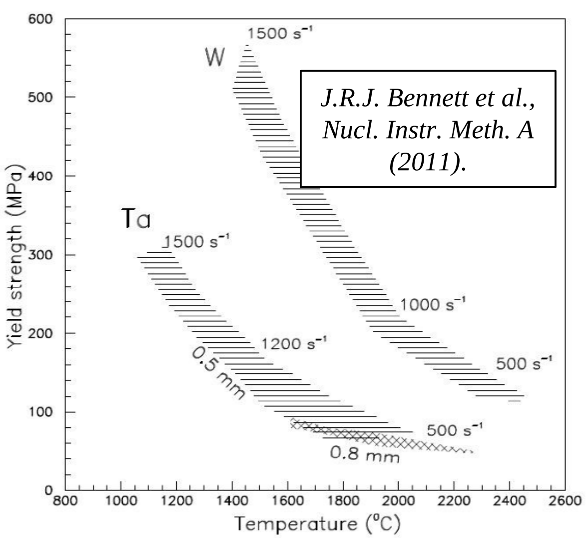
- Geometry
  - Target geometry must minimize pion re-absorption
    - Simple cylinder is optimal
  - Needs to be supported by a low-mass structure

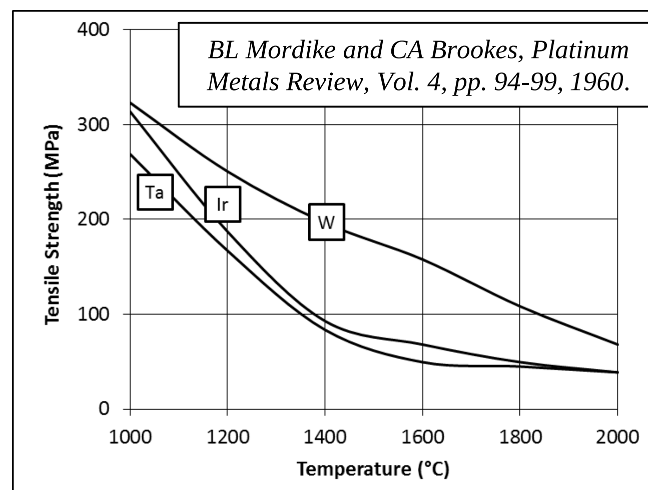
What is good about tungsten?

- 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

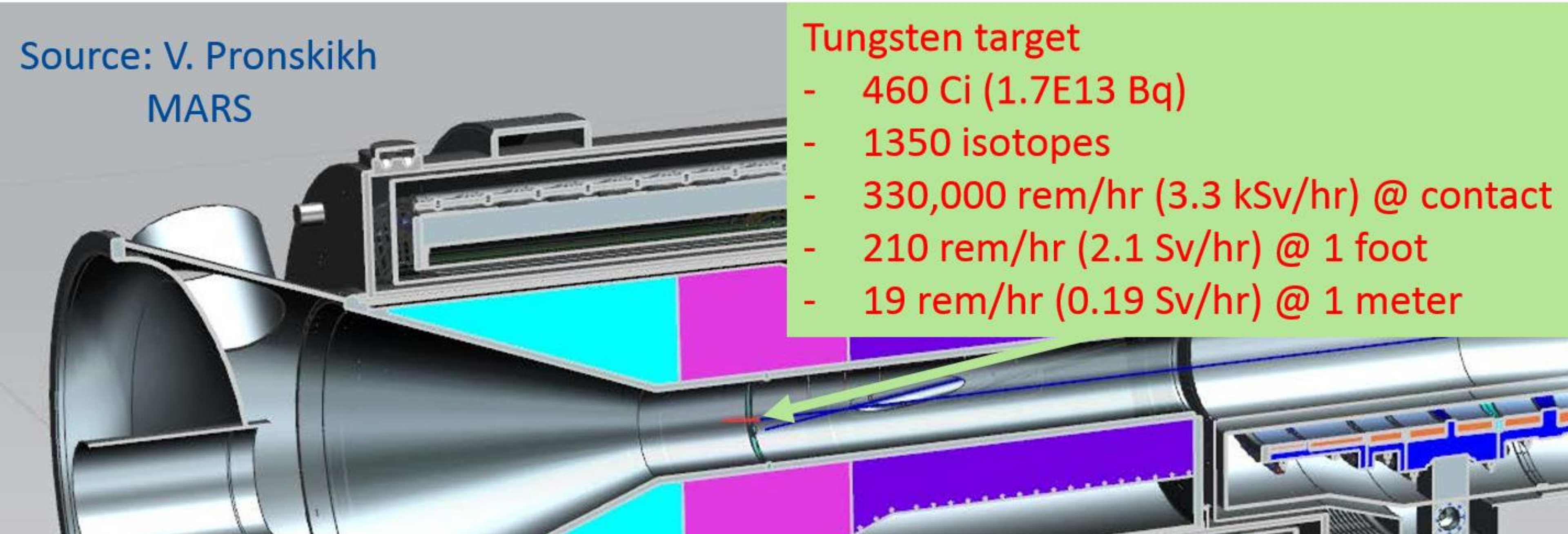






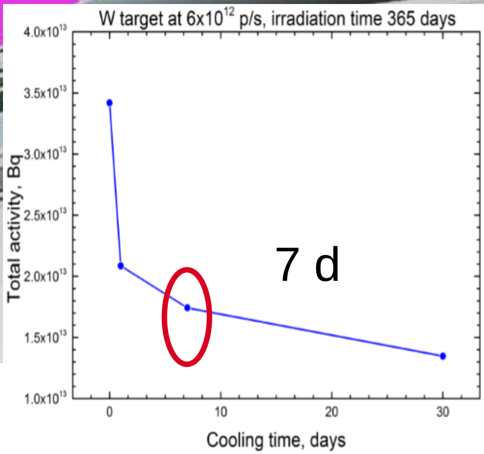
What is bad about tungsten? Radiological issues!

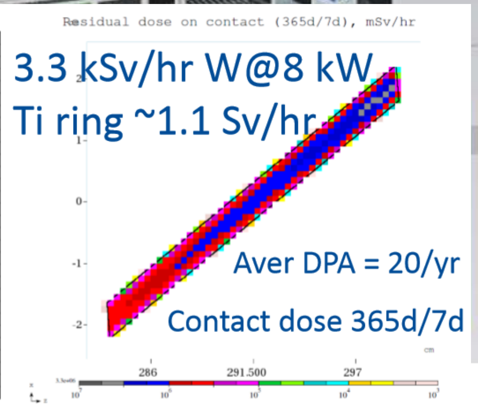
- Calculation for 365 days running, 7 days cooling



Tungsten target

- 460 Ci (1.7E13 Bq)
- 1350 isotopes
- 330,000 rem/hr (3.3 kSv/hr) @ contact
- 210 rem/hr (2.1 Sv/hr) @ 1 foot
- 19 rem/hr (0.19 Sv/hr) @ 1 meter





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Target Cooling Options – 'traffic lights'

	Radiation Cooled	Water Cooled	Helium Cooled
Material	Hot Tungsten	Cold Tantalum clad Tungsten or gold	Cold Tungsten
Physics Performance	No pion absorbing containment shell	c. 5% pion loss	c. 1% pion loss
Chemistry	High temperature /poor vacuum	Some chemistry (W/H_2O)	No Chemistry
Operating Temperature	High	Low	Low
Ease of Remote Handling	No service connections	Water connections	Helium Connections
Plant Issues	No plant	Known technology	Complexity, cost
Diagnostics	Rely on muon yield and beam absorber diagnostics?	ΔT, activity	ΔT, activity
Contamination	No local containment shell	Water activation Issues with leaks	Low activation Low leak concerns
Experience/Data	Little radiation damage data on high temperature W	Data on Ta clad W	Data on pure W
Upgradeability	No	Yes	Yes

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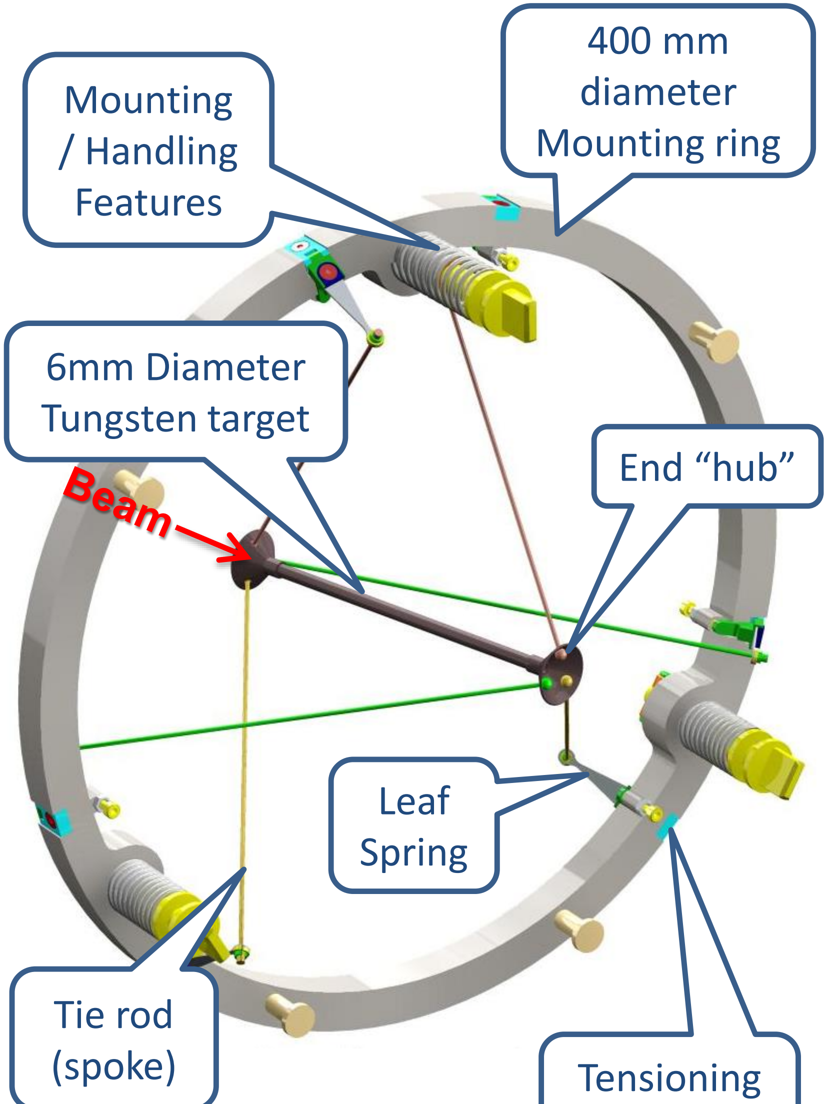
Radiation Cooled Proton Target Preliminary Design



Radiation Cooled Proton Target Preliminary Design

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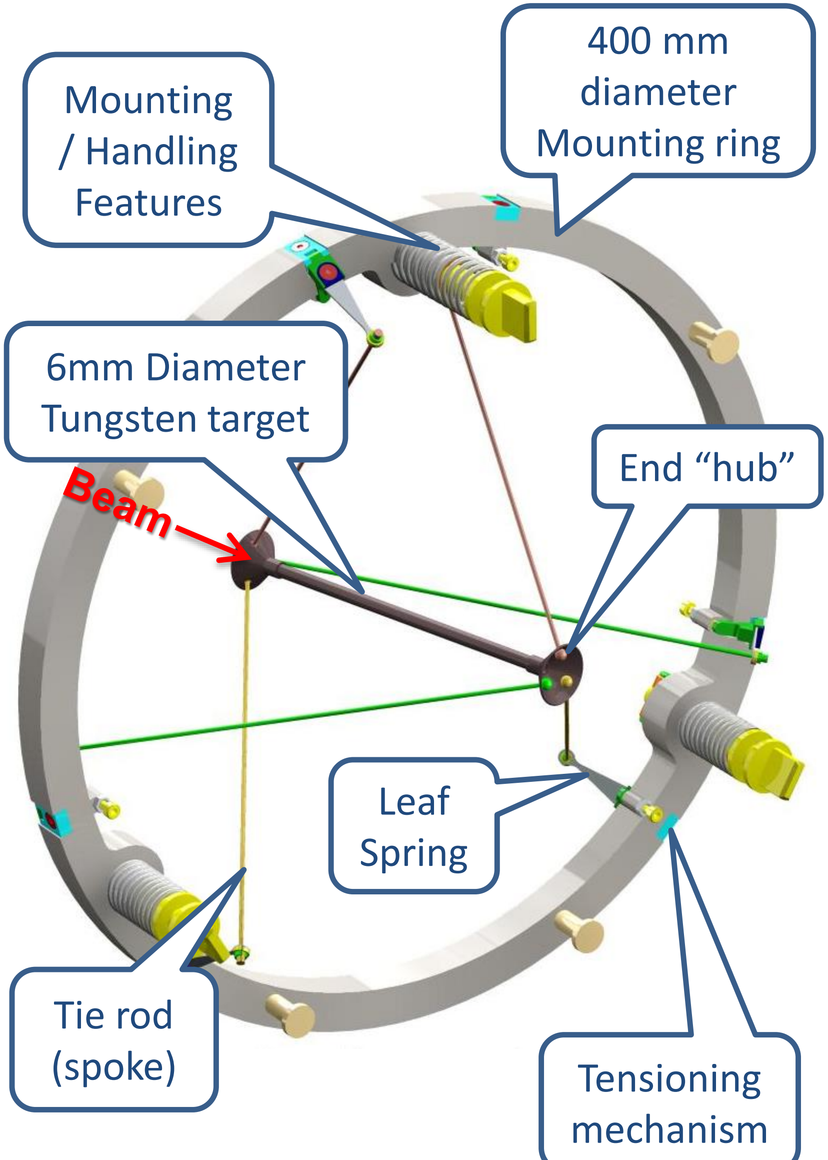
Drivers:

- No coolant or container - minimises pion absorption
- No cooling plant required
- Simplifies the remote target exchange requirements
- Eliminates the risk of coolant leaks.



Radiation Cooled Proton Target Preliminary Design

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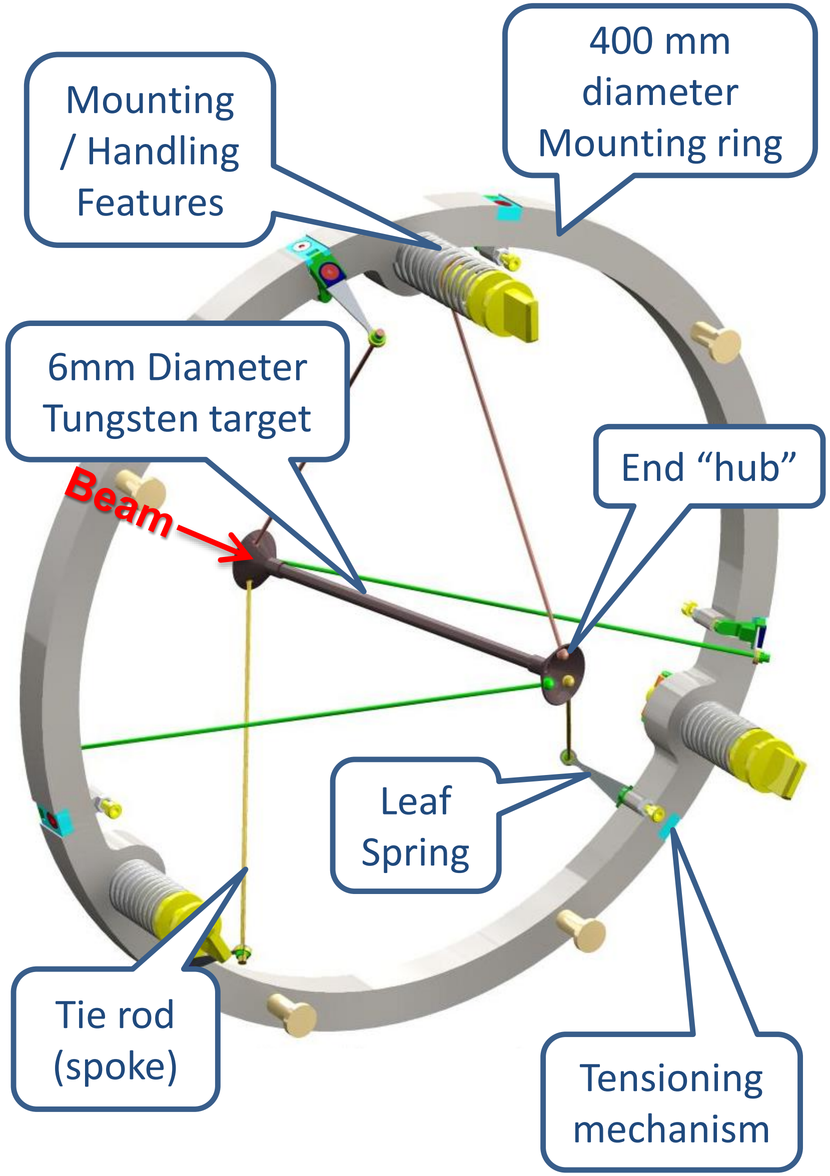

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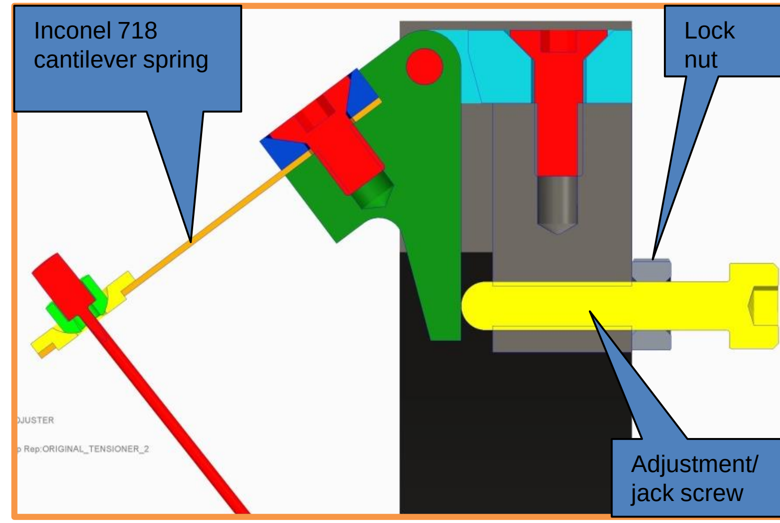
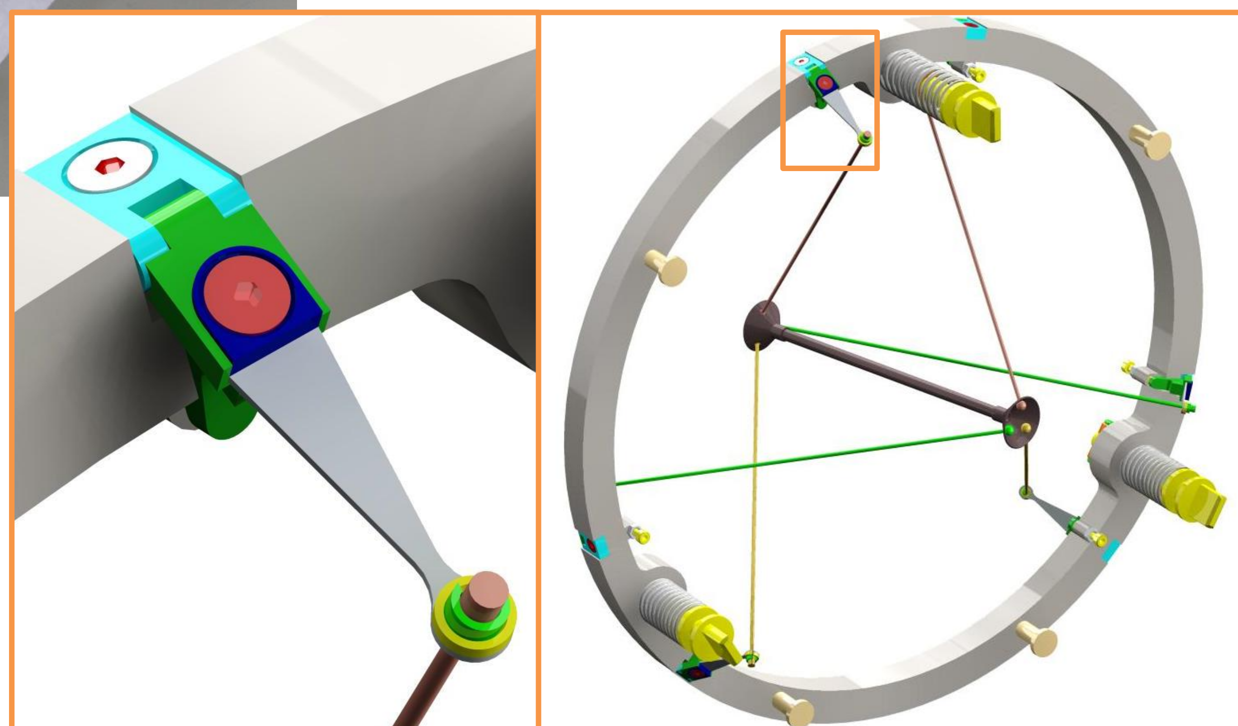
Technical Challenges:

- 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…

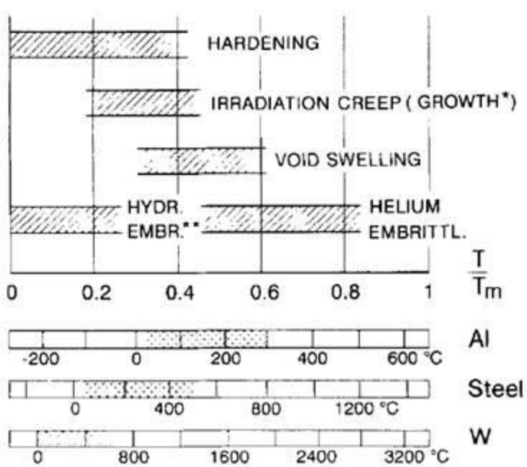
Prototype Cantilever Spring/Tension Mechanism





Radiation Damage Considerations for tungsten

- $T_{operating}$>> $T_{recrystallization}$ (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 (μA/cm²)	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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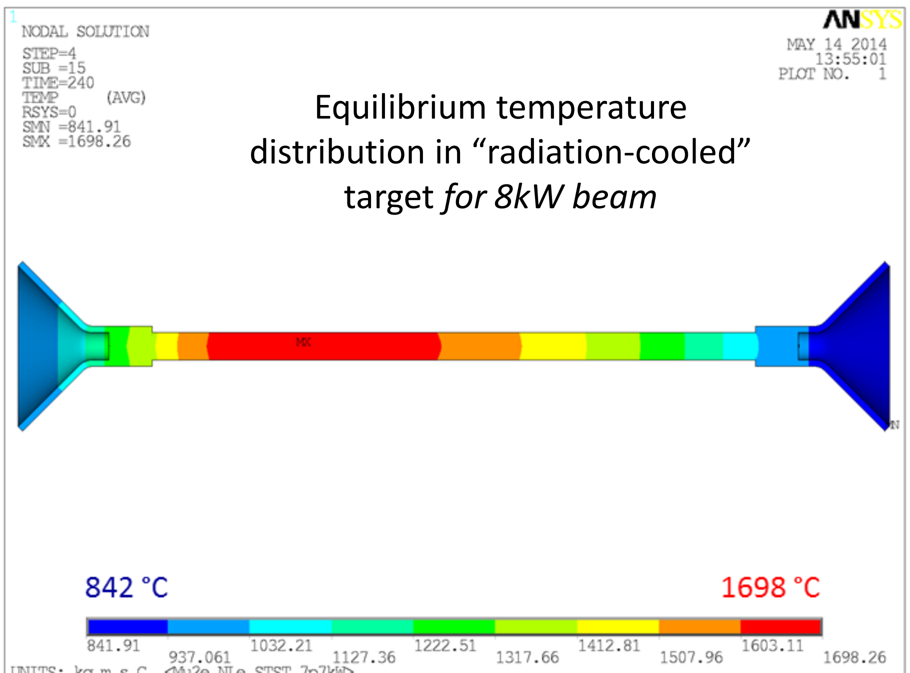
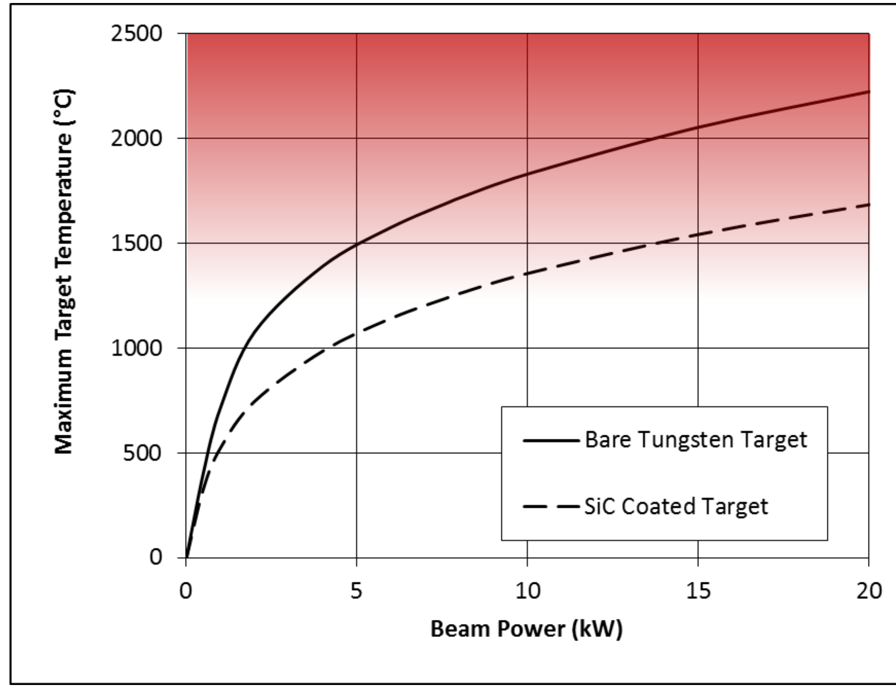
Beam Power Limit for Radiation Cooling

- Heat transfer dominated by thermal radiation
  $Q = A\, \varepsilon(T)\, \sigma\, (T_{hot}^4 - T_{cold}^4)$
- When beam is on target heats up until it is able to dissipate the deposited power
- That "equilibrium temperature" depends on ***heat load***, ***emissivity*** and ***surface area***.



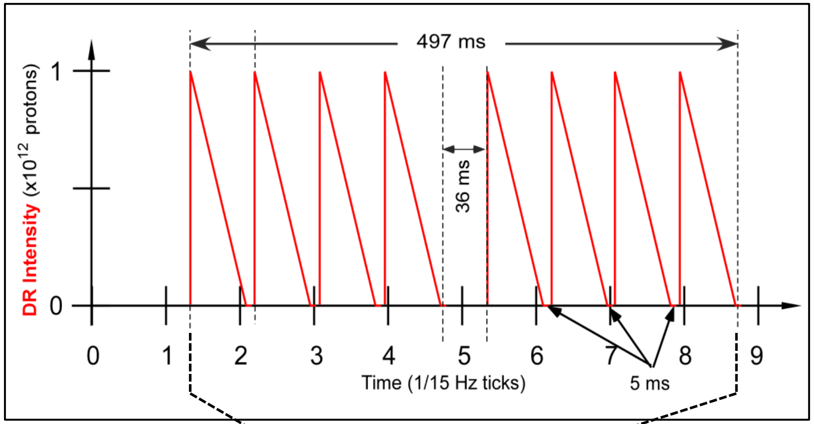
Equilibrium temperature distribution in "radiation-cooled" target *for 8kW beam*

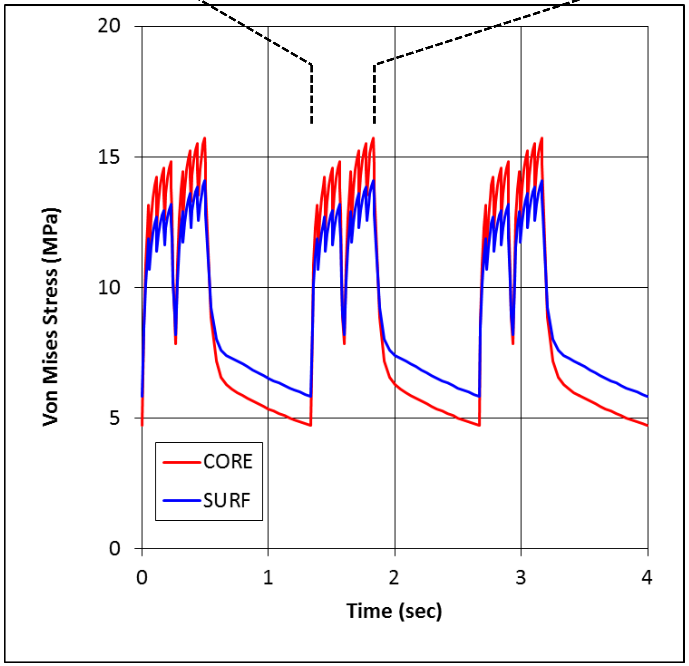


- Above 1500°C even tungsten begins to approach its useful limit
  - Reduction in strength
  - Chemical "erosion"
  - Creep/Sag
- High emissivity surface treatments can potentially help up to a point

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

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Mu2e Target Test Bay

Air-cooled vacuum vessel with feedthroughs for power and thermocouples

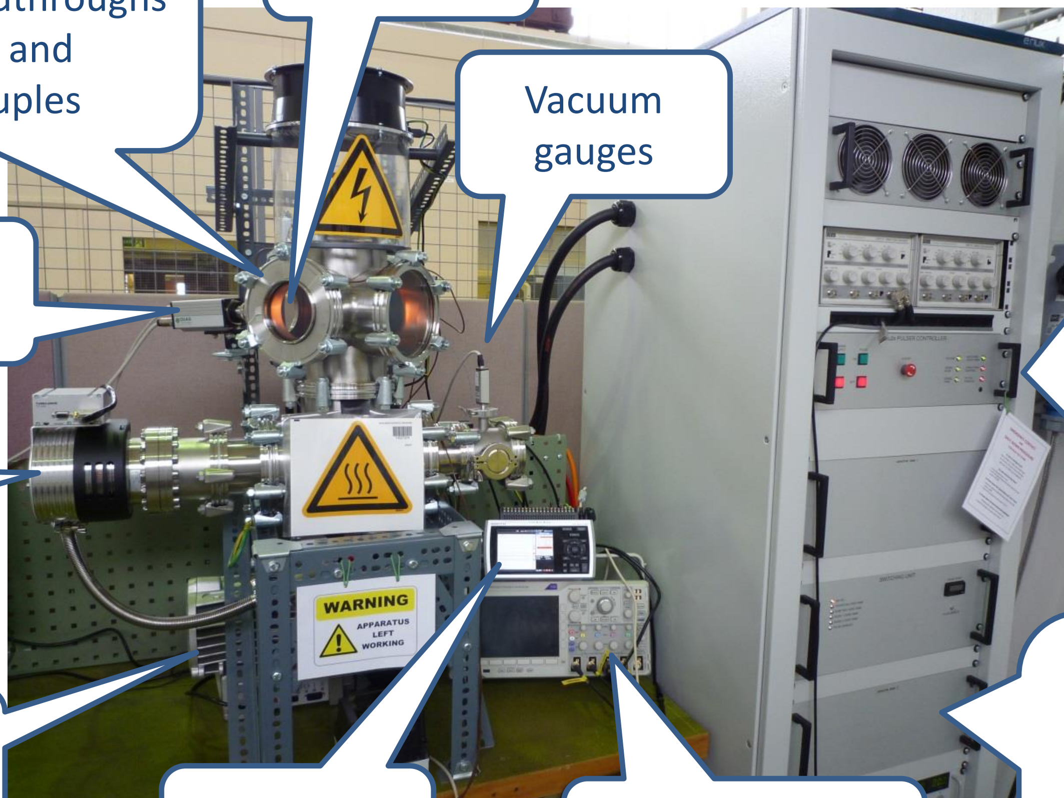
Observation windows

Vacuum gauges

Digital Pyrometer

300 l/s Turbo pump

Backing pump



Data logger

4-channel digital oscilloscope

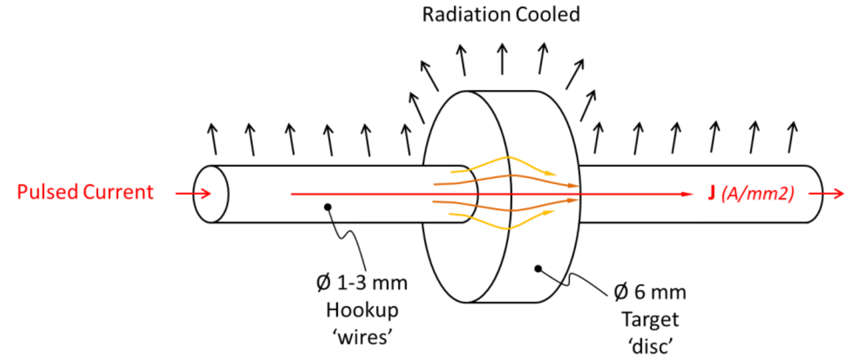
<u>Power supply rack</u>

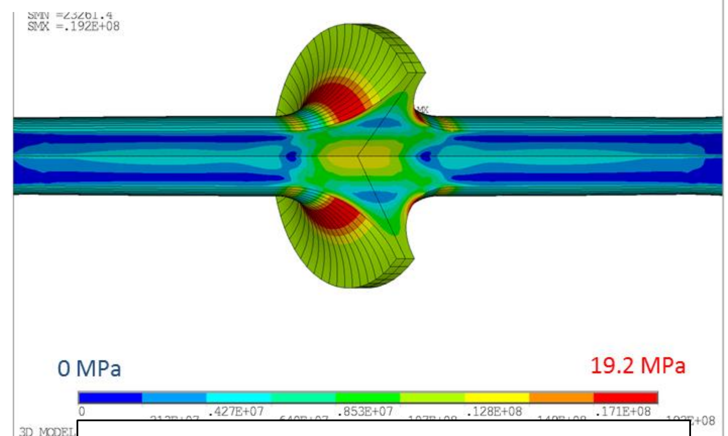
Pulse mode:
1 msec long half-sine wave pulses
0 - 2.5 kA peak
1 - 50 Hz repetition

DC mode:
0-300A constant current

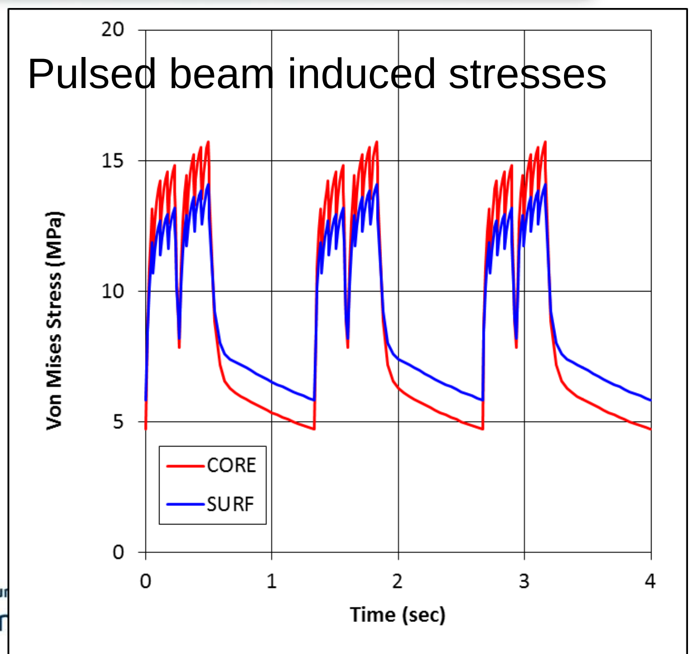
<u>System interlocks</u>
vessel over-temp
coolant flow
sample over-temp
vacuum level

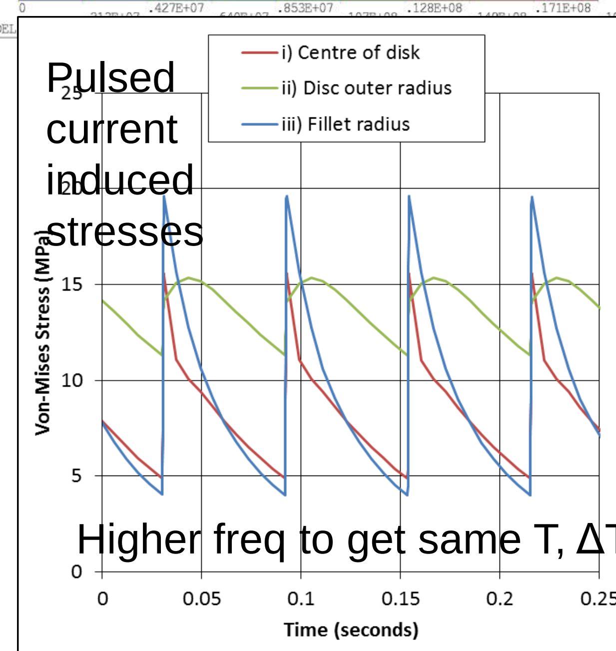
Pulsed-current high temperature tungsten fatigue experiments – to reproduce pulsed beam effects





10^8 pulses at 1750°C (followed by $4x10^7$ pulses at 2000°C) [Failure probably by electro-migration]

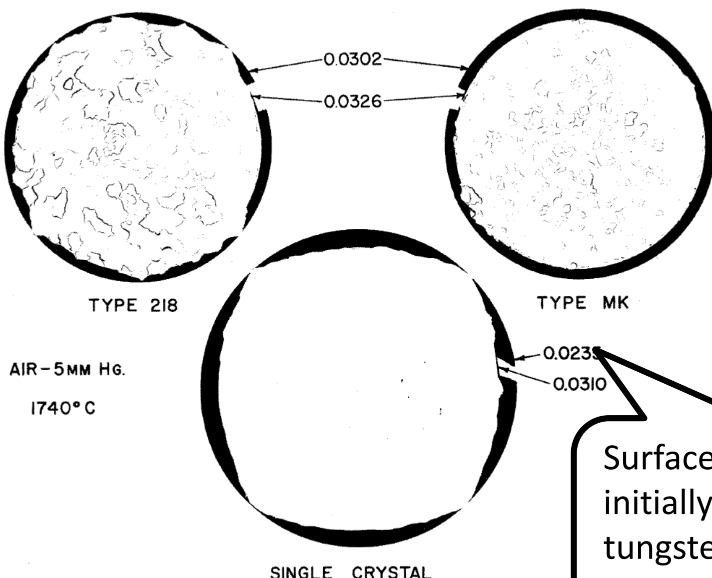


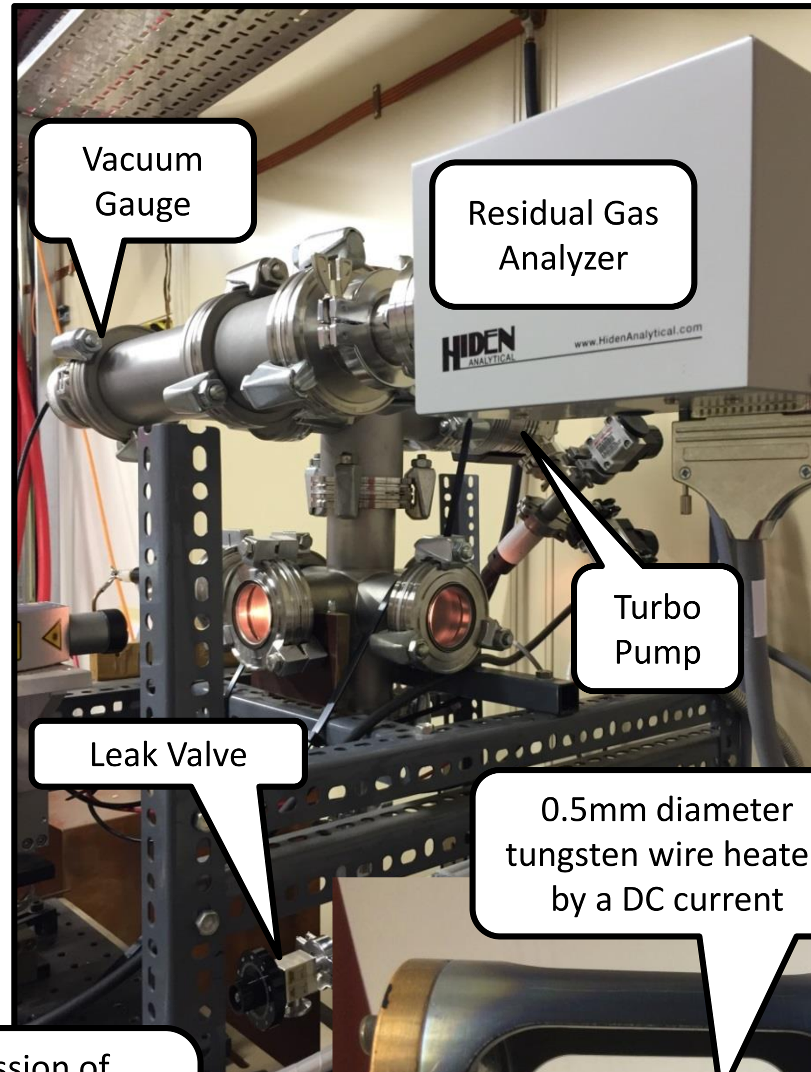


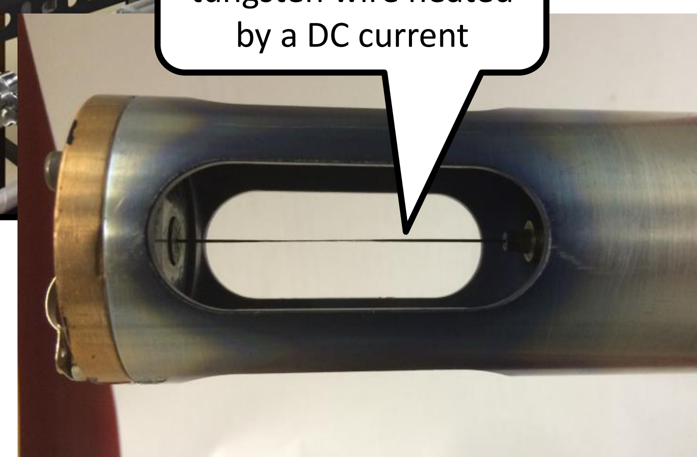
c/o P. Loveridge

Effect of oxygen contamination in vacuum

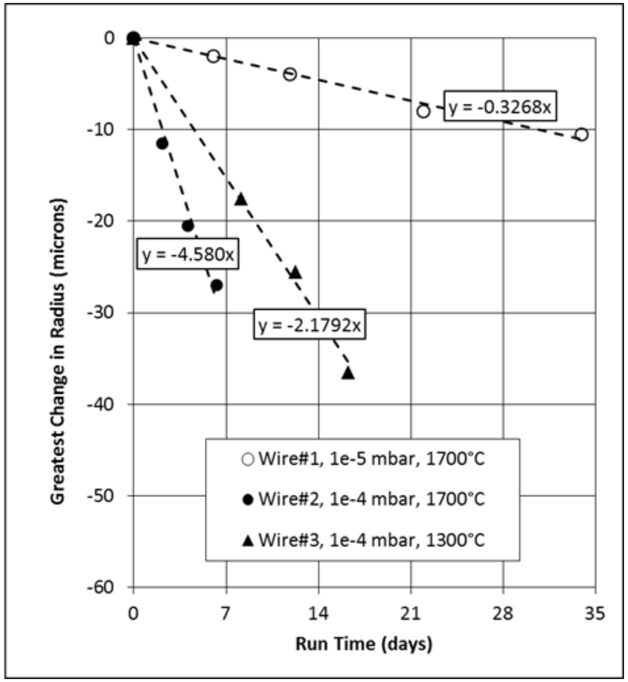
At temperatures exceeding ~1300°C in vacuum, tungsten oxide will evaporate faster than it is formed. In this regime oxidation is realised as a surface recession, the rate of which depends strongly on temperature and oxygen pressure.



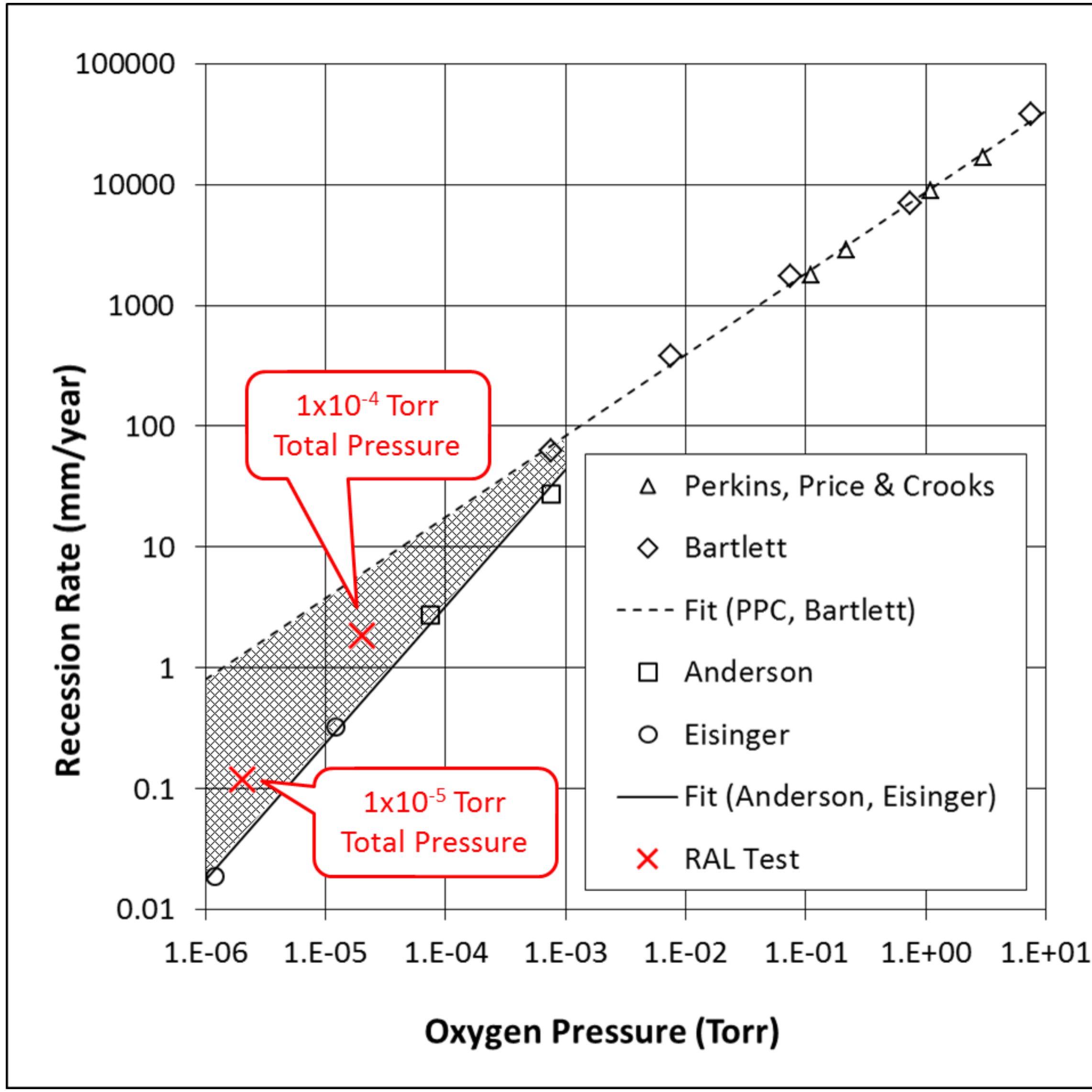




Vacuum/Leak Test Results



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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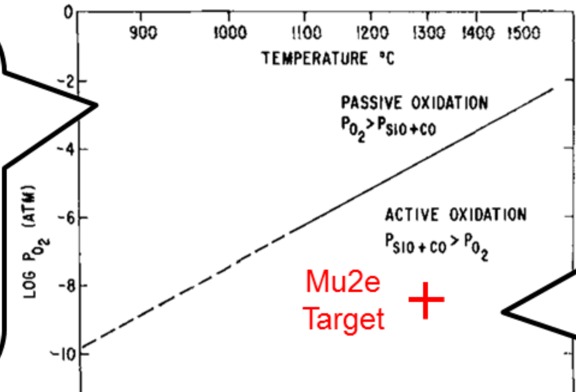
Experiments with SiC oxidation resistant coating

High pressure and low temperature
⇨ ***<u>Passive</u> Oxidation***

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

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

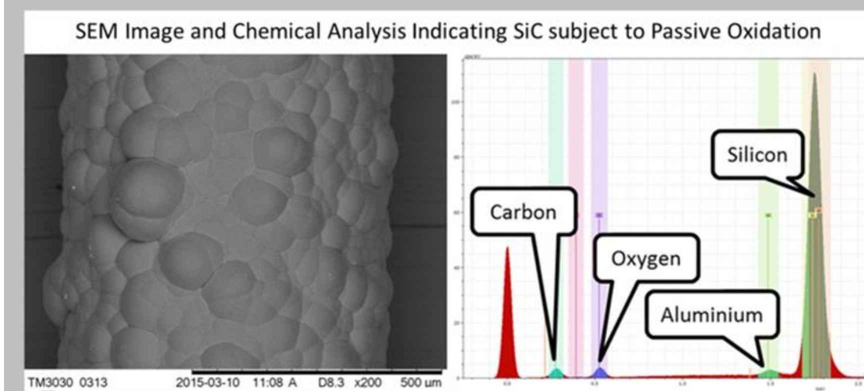


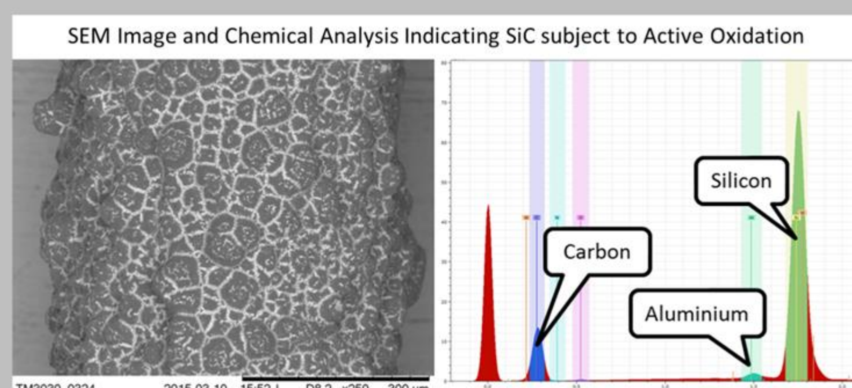
Low pressure and high temperature
⇨ ***<u>Active</u> Oxidation***

Forms a volatile oxide which leads to recession of the SiC

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

- High emissivity coating
- Excellent performance with vacuum pressure < 10^{-6} torr
- Good performance in very poor vacuum (passive oxidation)
- Poor performance (active oxidation) in c. 10^{-4} torr expected in Mu2e





- Iridium coating also attempted but unsuccessful

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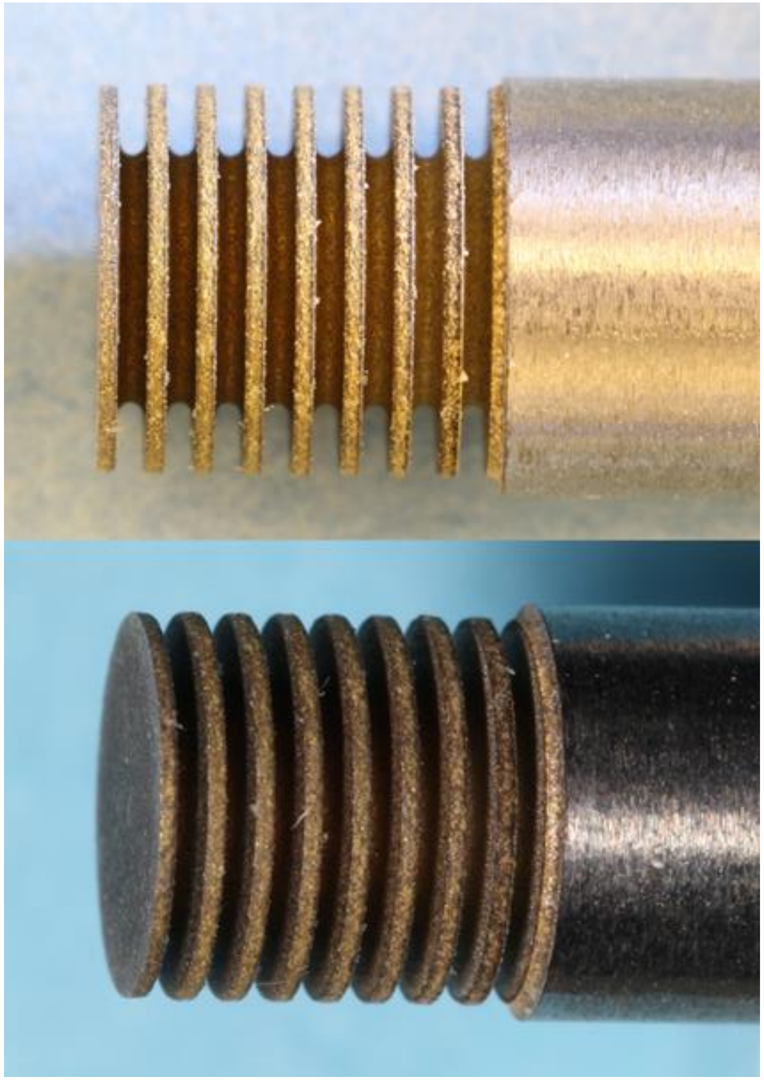
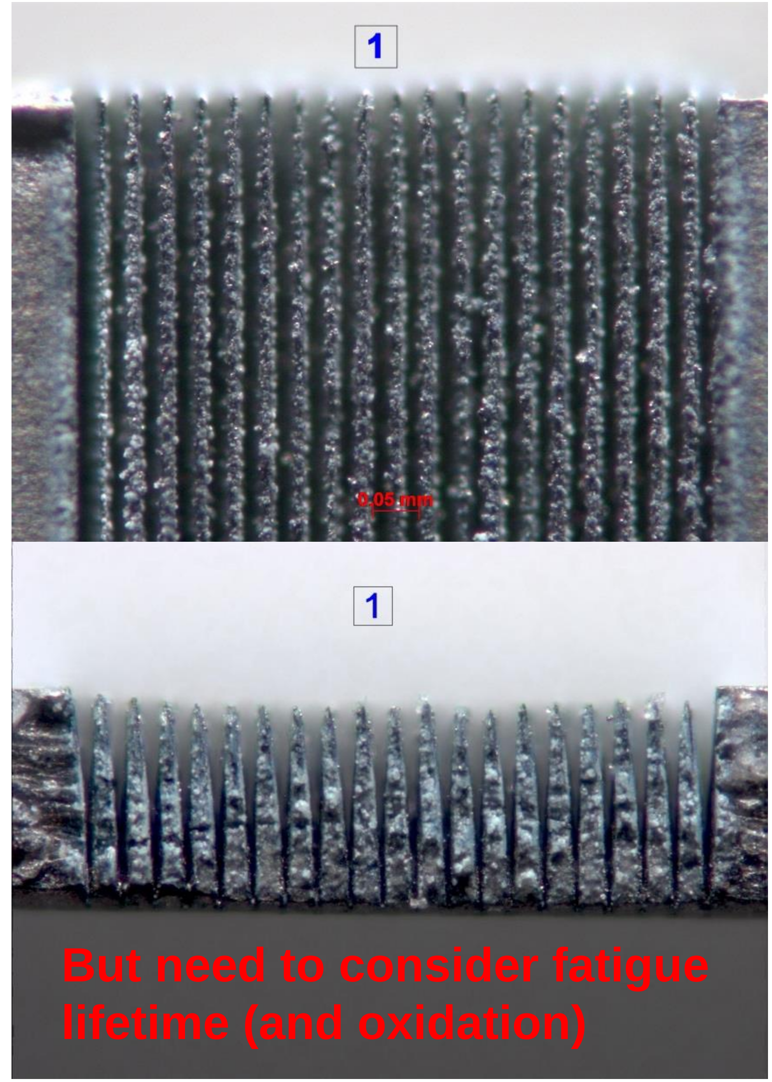
Possible Finned Surface to Enhance Emissivity?



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



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

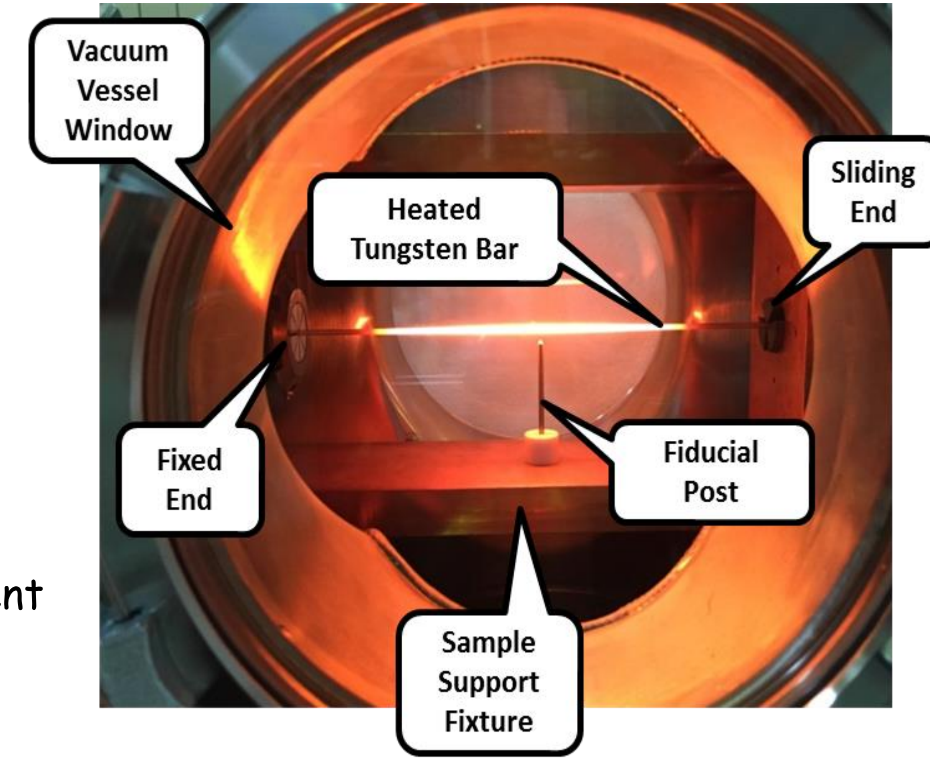
Testing creep under “Mu2e-like” conditions

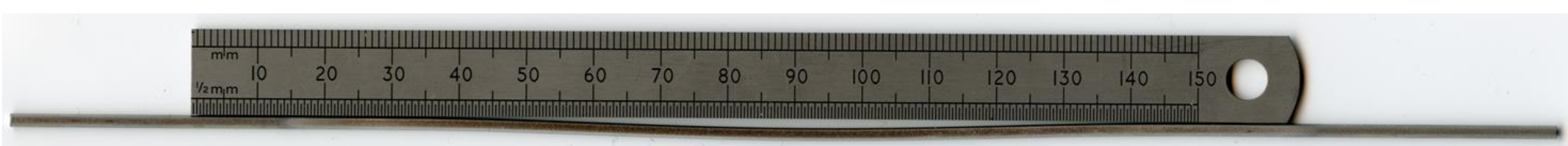
Issue:

- 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:

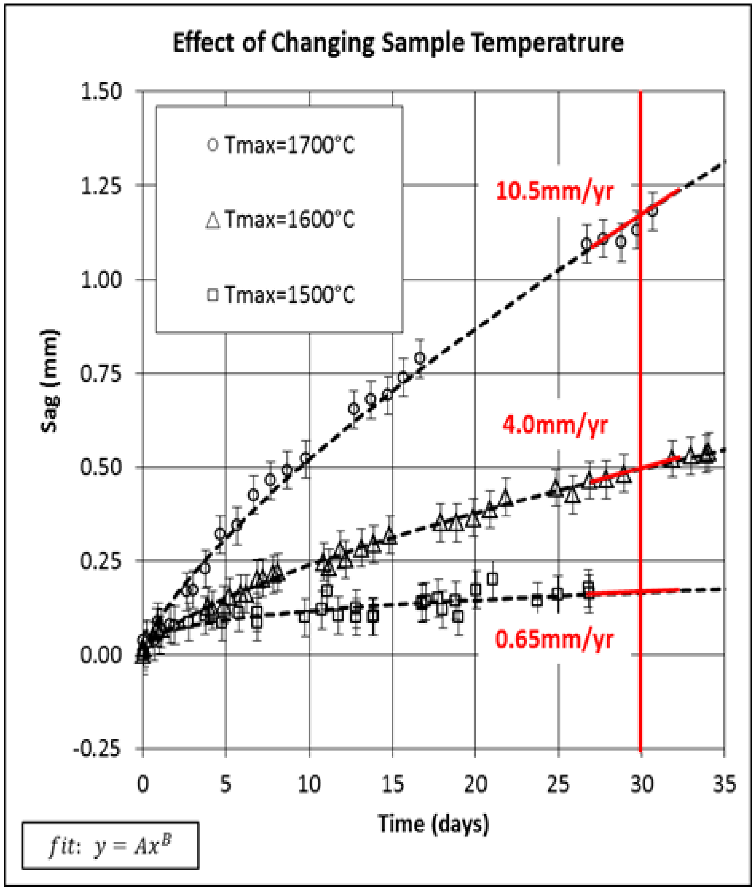
- Tungsten bar mounted in a horizontal configuration and heated by a direct current in vacuum
- Creep rate depends on ***operating temperature*** and ***self-weight bending stress***

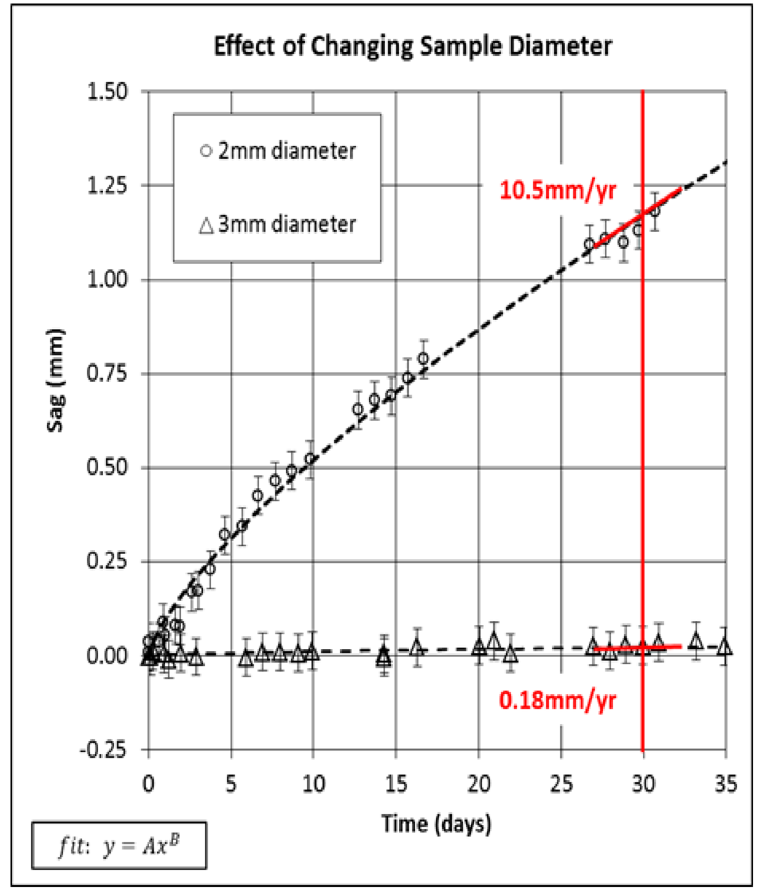




Creep results for pure tungsten

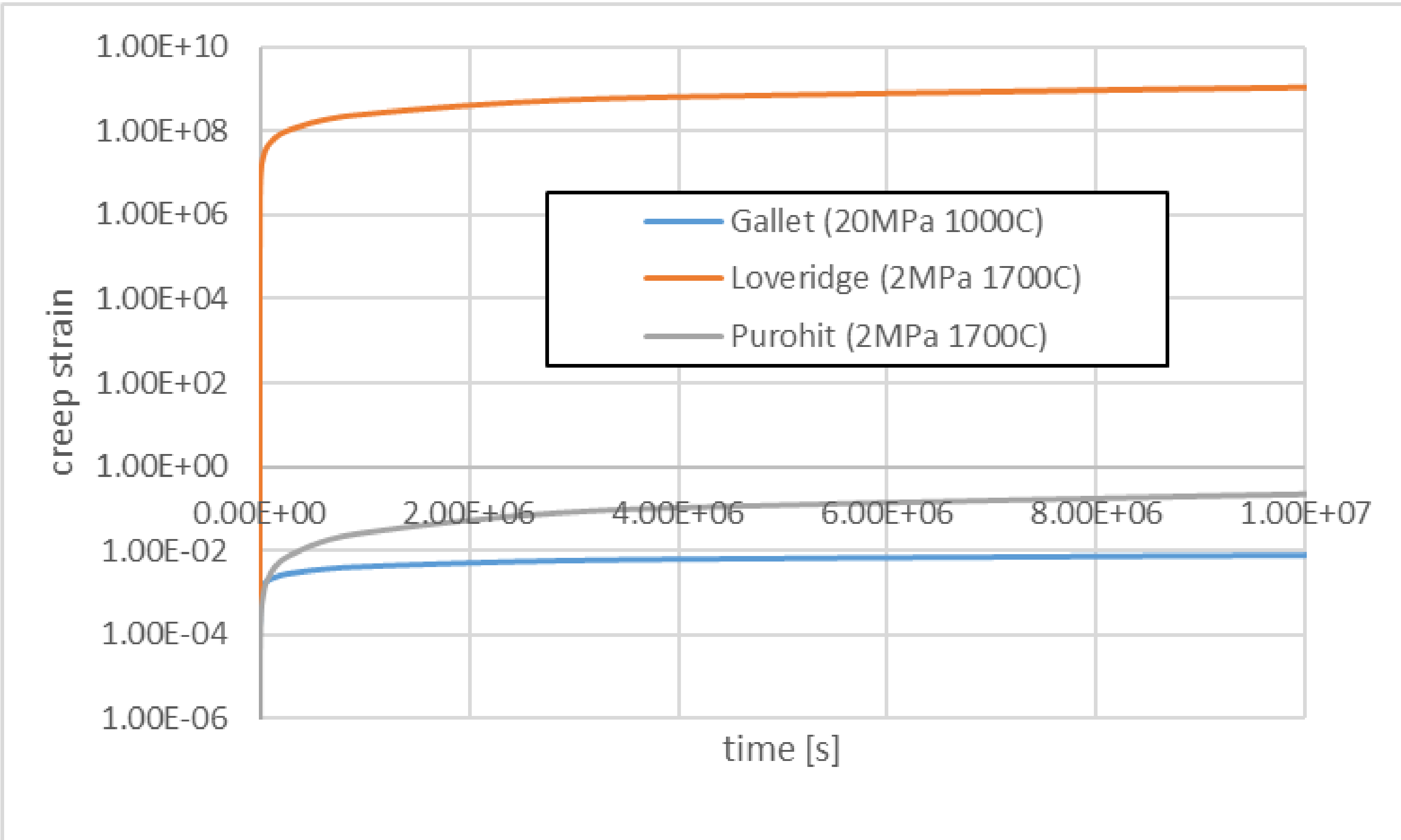
- When spoke tension is fully accounted for, preliminary Mu2e target design is slightly **worse** than the worst case tested (2 mm diameter rods)
- Some mitigation with low creep LaO doped tungsten





Comparison with literature

- Much, much worse than expected…



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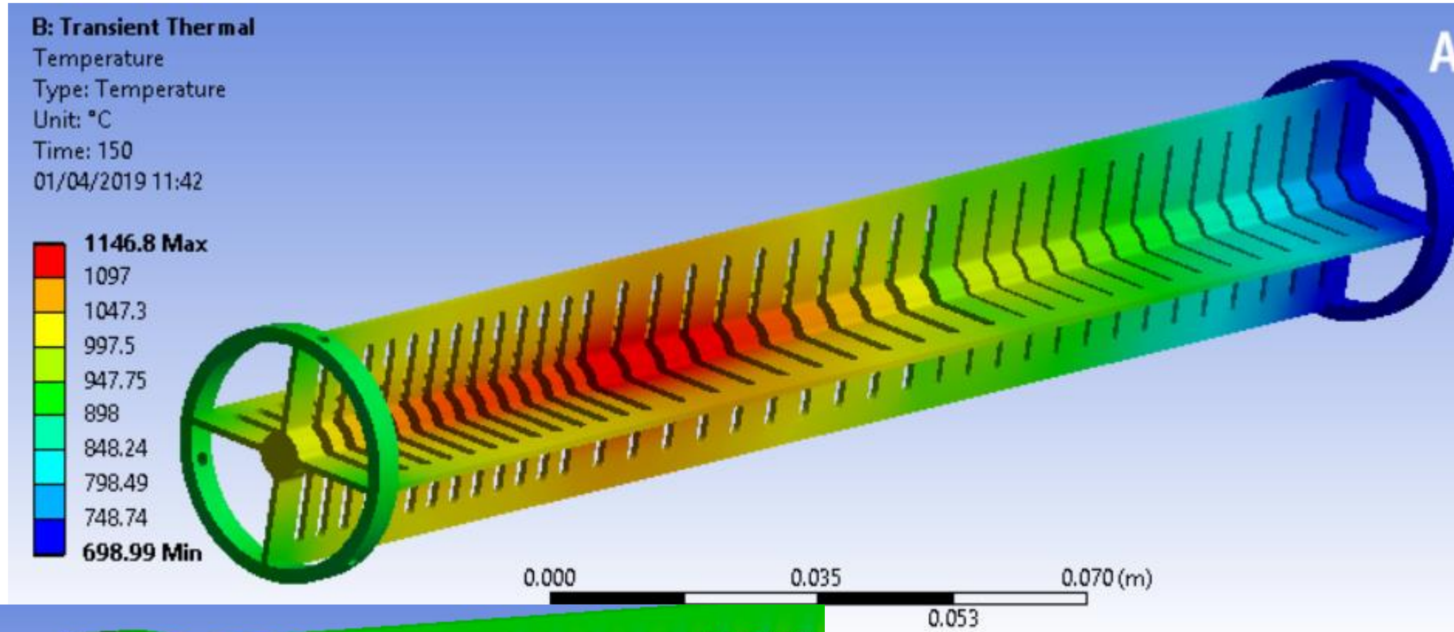
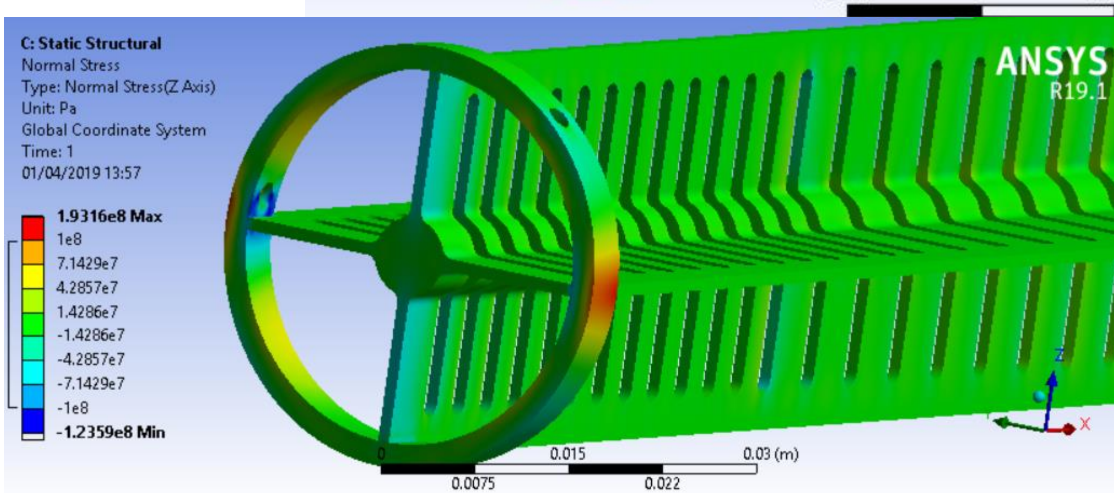
A new target specification

- Research programme identified many challenges with a simply supported radiation cooled tungsten rod, e.g.
  - Creep
  - Oxidation
- Although low creep alloys and high emissivity coatings and surface treatments should help, effectiveness is limited by anticipated vacuum quality in Mu2e apparatus
- 1 year lifetime for target considered challenging
- Reducing operating temperature highly desirable
- **Decided to sacrifice some (theoretical) physics performance to improve engineering performance** (and so improve **actual** physics performance)
  - Tolerance to loss in stopped muon production increased from <2% to **c.20%**
  - Many more target design options can be considered

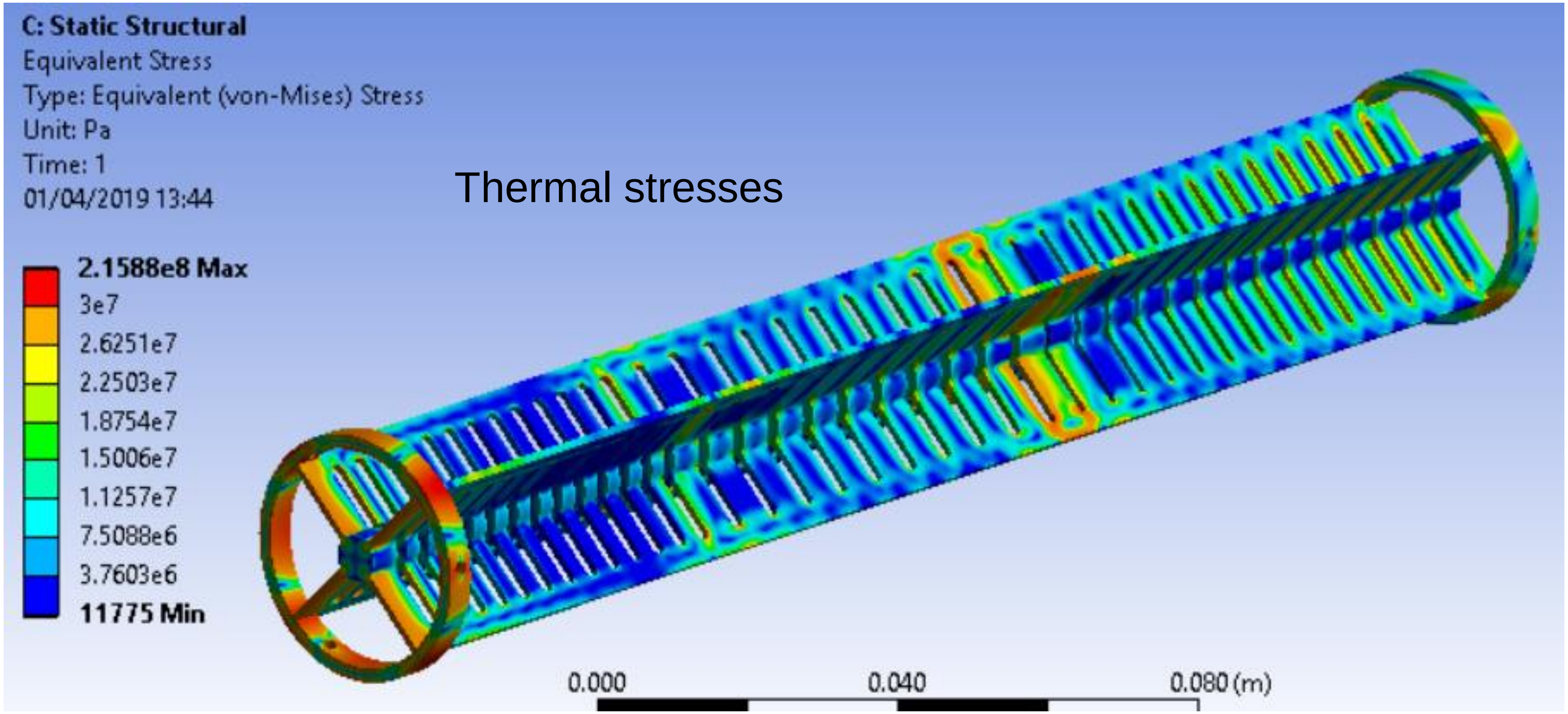
One proposal: the 'hayman'





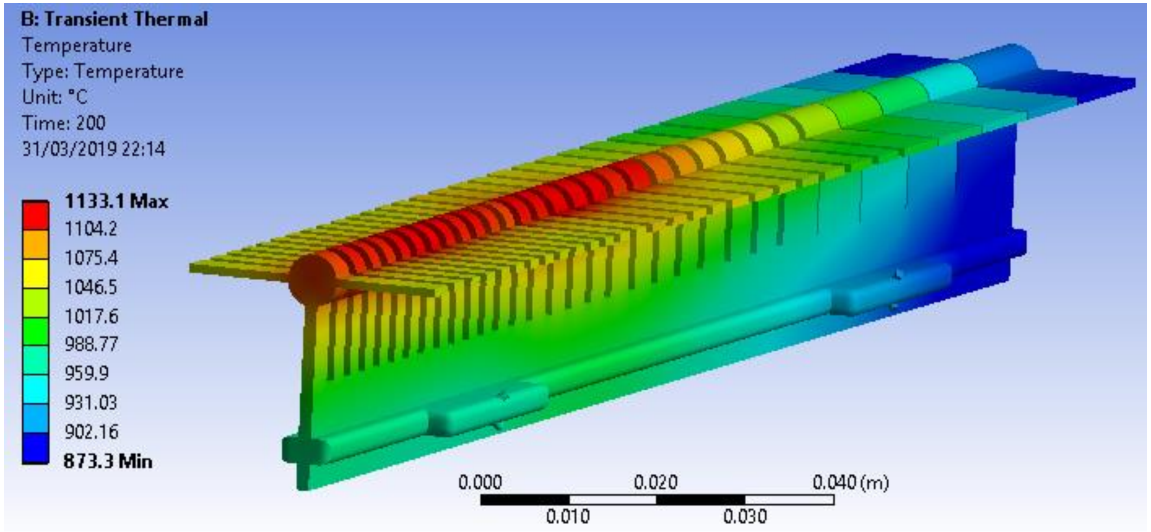
- Target material segmented along length
- Longitudinal radiative fins reduce maximum temperature from c.1700 °C to <1200°C
- Stopped muon loss >20% but deemed acceptable

Some issues with the 'hayman'



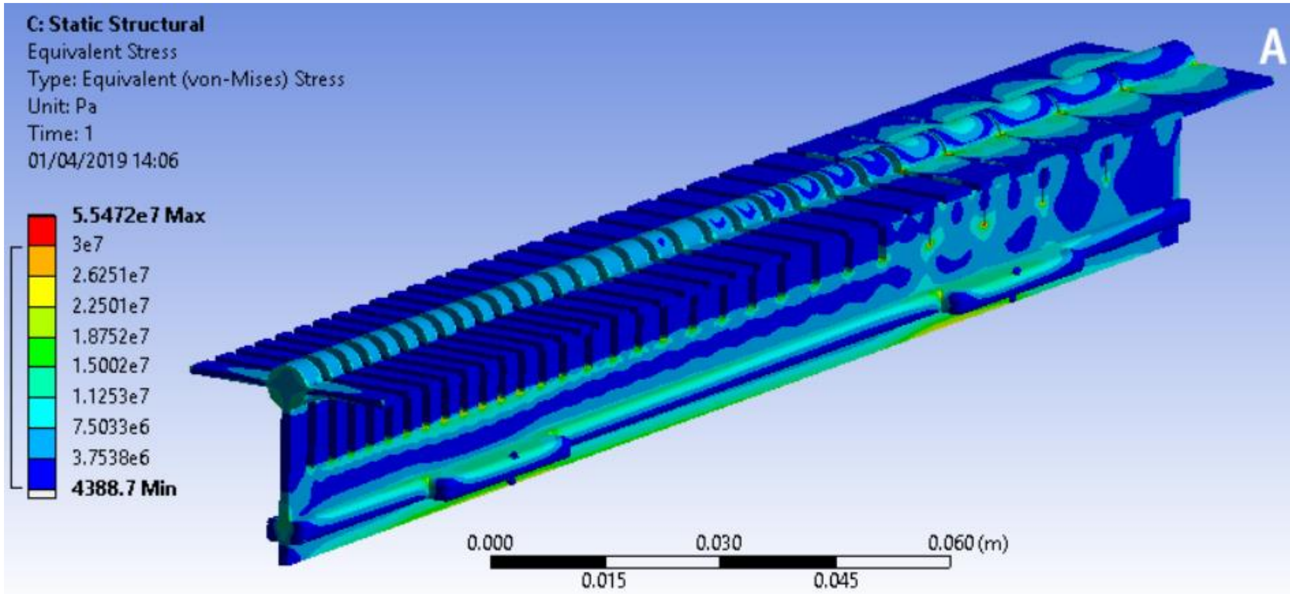
- High thermal stress levels (even considering lower operating temperature)
- How to mount the spoke supports?
- Low natural frequency of complete mounted target?

Another idea: the 'bunnyman'



- Same stopped muon production as hayman proposal
- Same operating temperature as hayman

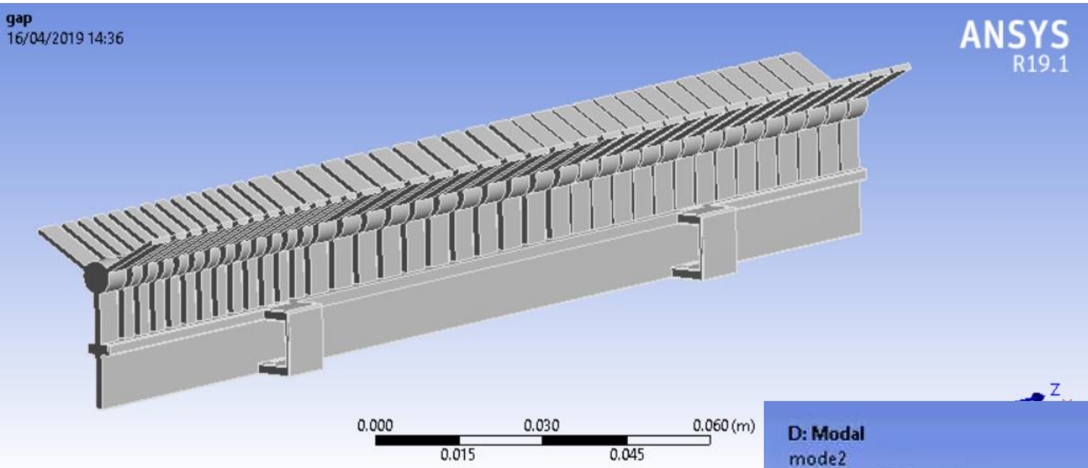
- Considerably lower stresses c.f. hayman
- Scope for fin optimisation
- Can realistically be tested off-line using induction furnace

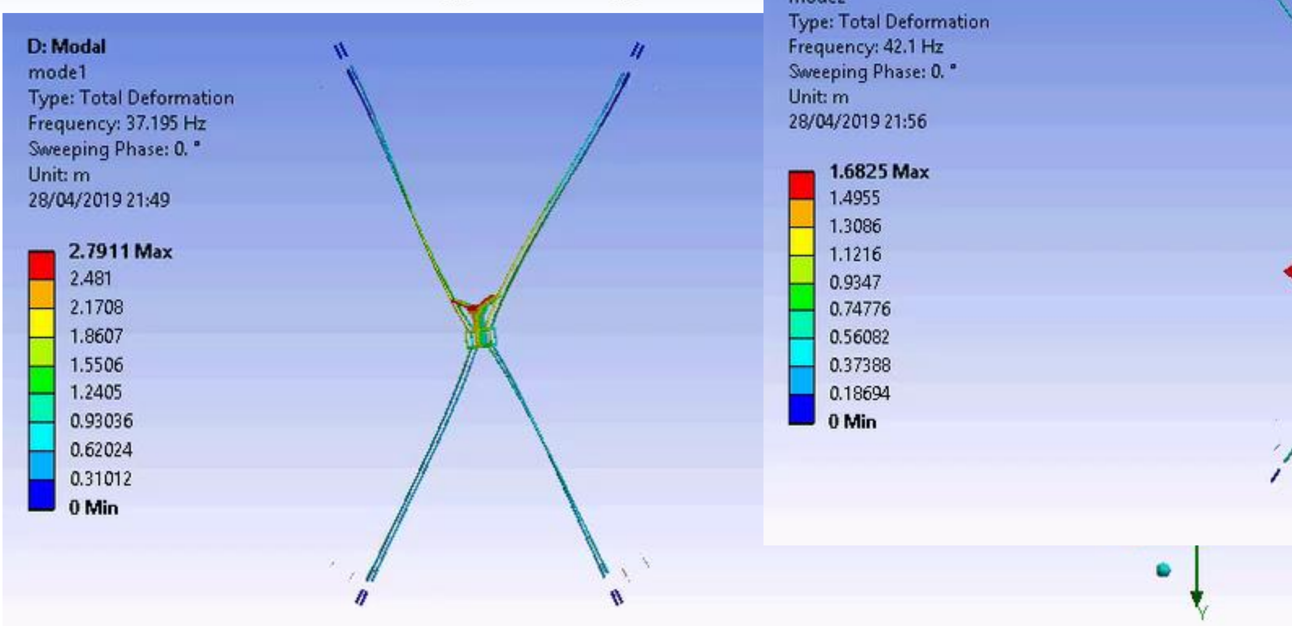


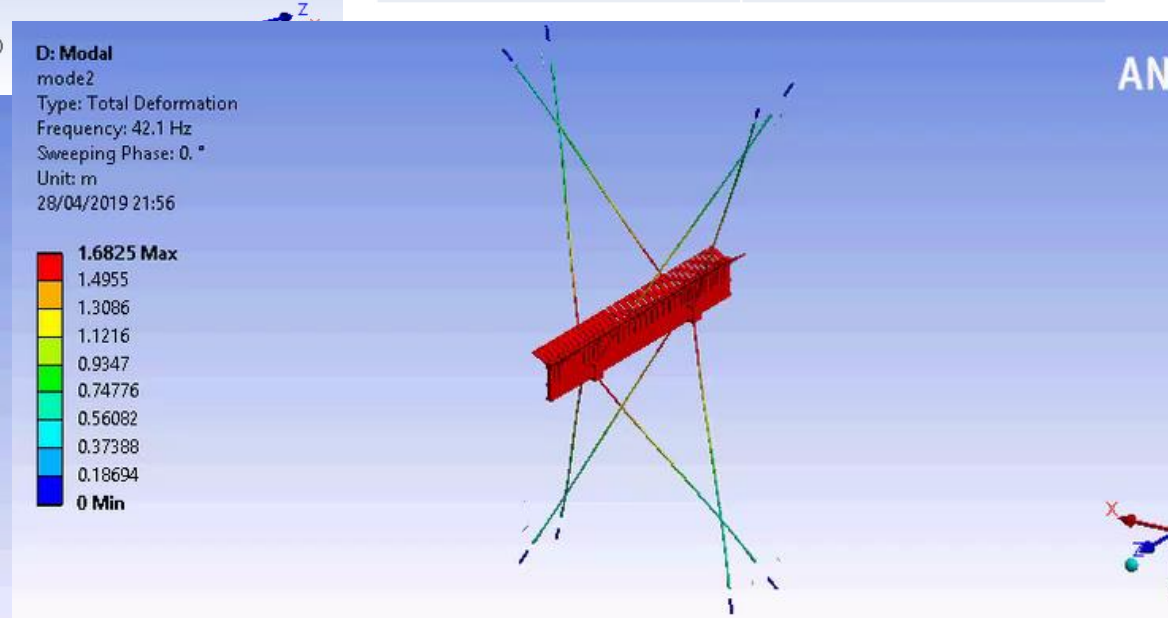
Design development of 'bunnyman' – dynamic response

NB 8 spills from recycler at 20.8 Hz – need to avoid resonance

Mode	Frequency (Hz)
1	37.2
2	42.1
3	43.3
4	79.8
5	86.1
6	91.5







Summary

- Mu2e experiment is committed to a radiation cooled muon production target
- 'Optimal' physics geometry of a simple spoke supported radiation cooled tungsten rod cannot realistically achieve a 1 year lifetime
- Compromise solution appears realistic by use of radiative fins to reduce operating temperature so creep and oxidation not a problem in Mu2e conditions
  - Stopped muon yield will be reduced by c.20% but a solution looks realistic
- Ideally a prototype target design will be tested off-line e.g. using an anduction furnace
- Effects of radiation damage still an open question