Mu2e Target Status and Challenges

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HPTW 2023
6-10 November 2023

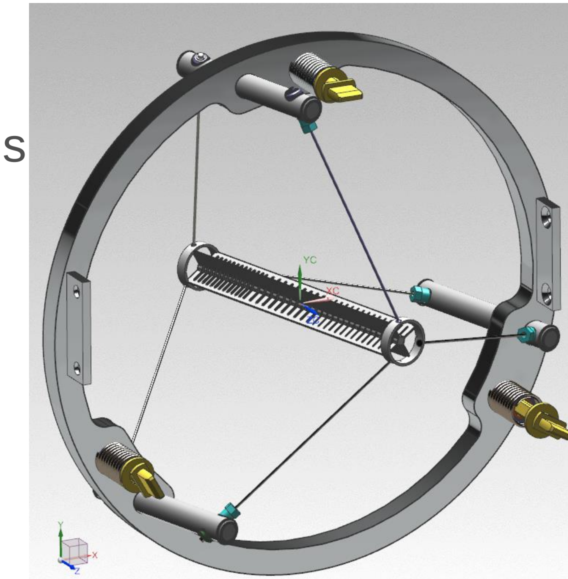
Outline

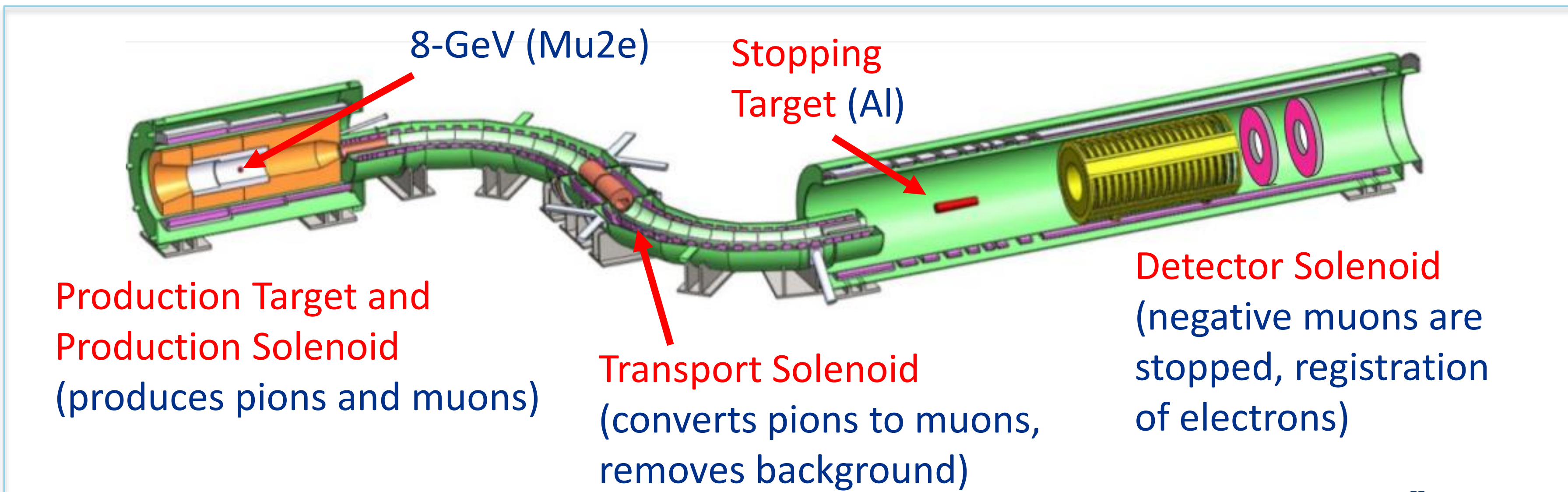
- Status briefing
- Approaches to optimize
- Take-away

Mu2e experiment, target & support

Mu2e radiative cooling tungsten target

- 8 kW beam power at 8 GeV resonant extracted protons
- 1 year operational lifetime (~ 40 weeks/year)
- Designed for replacement with remote handling equipment
- Optimized for stopped muon production
- Operating in FY 2026



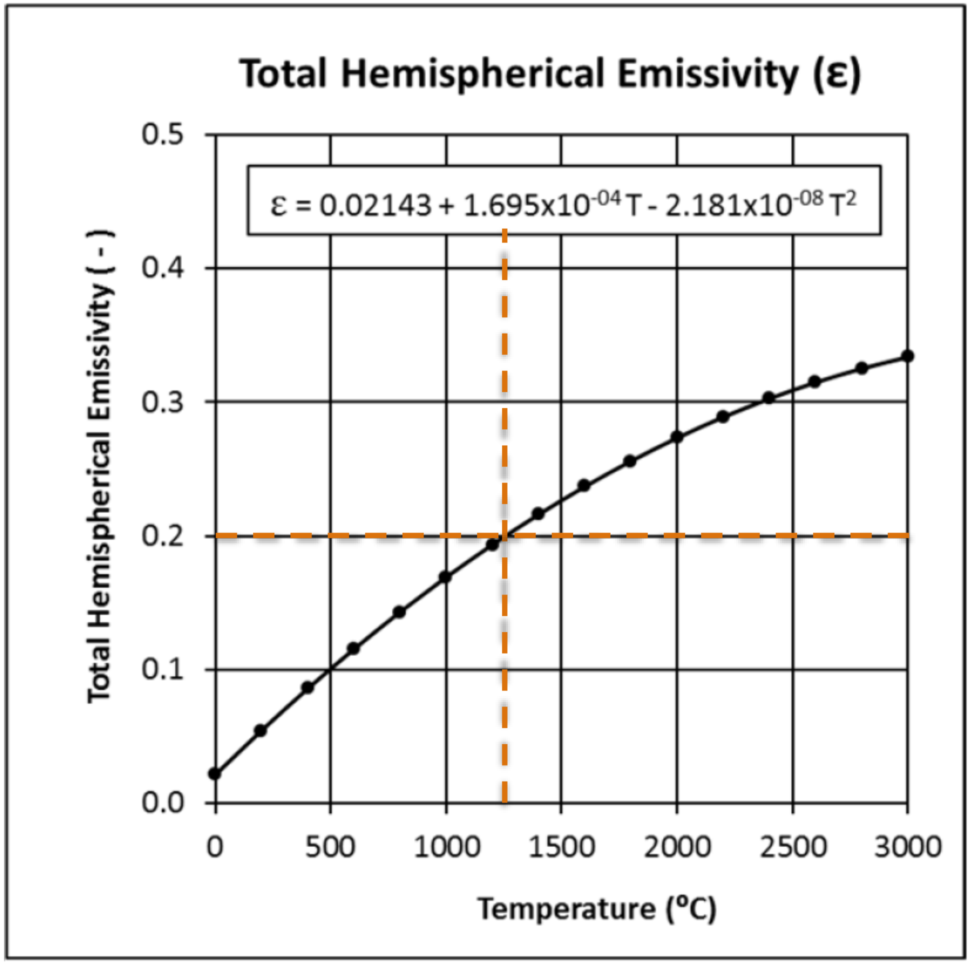


WL10 (W 1% wt. La_2O_3) Target

- Core is wire EDMed from single rod
- Longitudinally segmented cylinder:
  - 6.3 mm diameter
  - 160 + 60 mm length
- Longitudinal fins (4)
  - 1 mm thick
  - 13 mm high (each)
- Spokes
  - 1 mm diameter
- Fabrication challenge
- Expensive

Emissivity: Tungsten

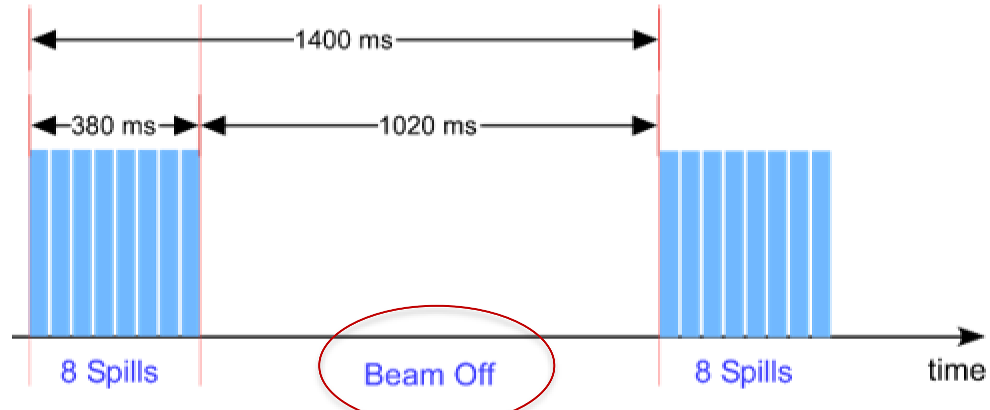
- Mu2e-doc-4305, RAL

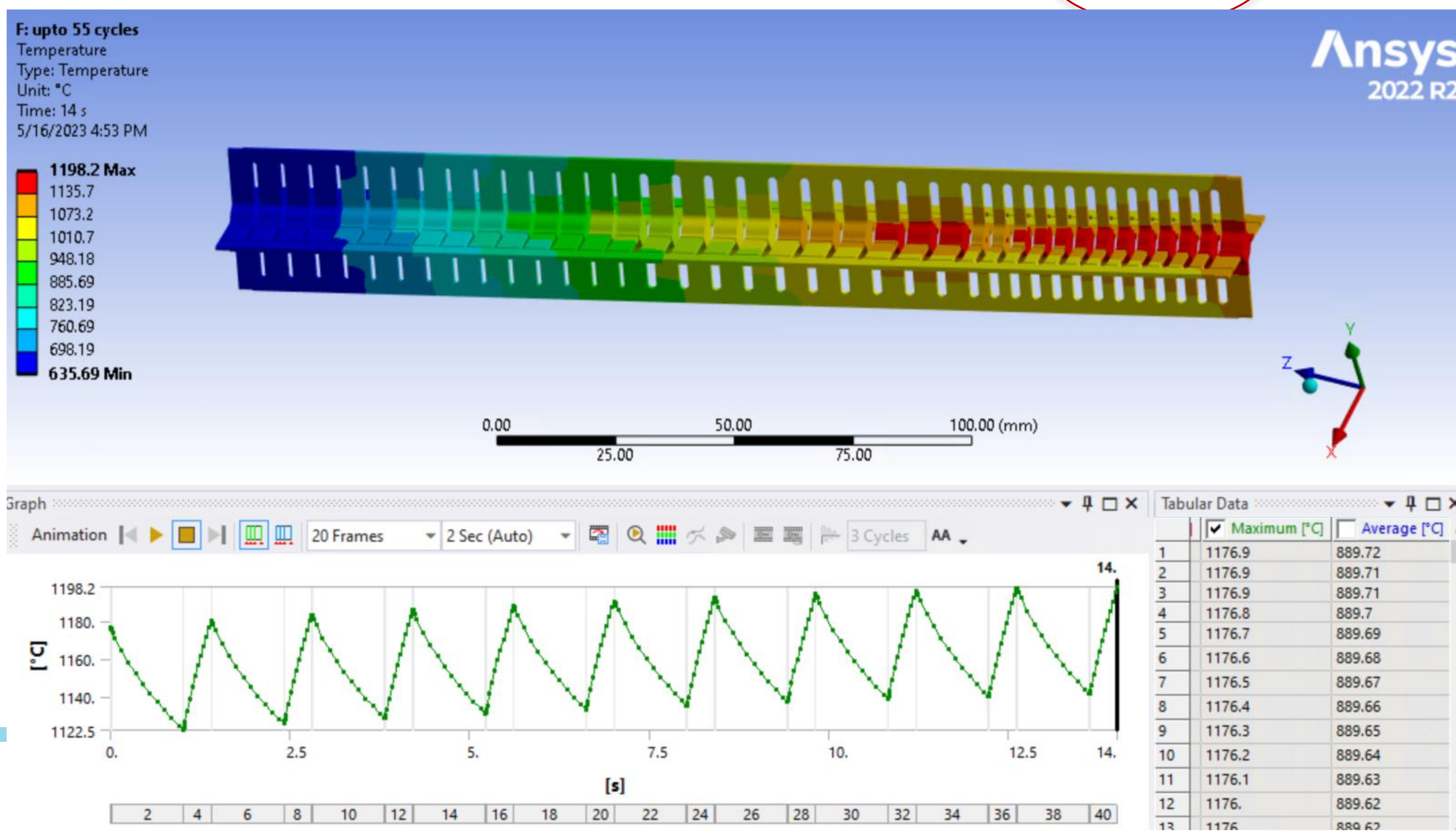


Time Structure & Target Temperature

Pure Tungsten Hayman2 target

- ~ 620 W absorbed power
- 1150 ~ 1200 ˚C



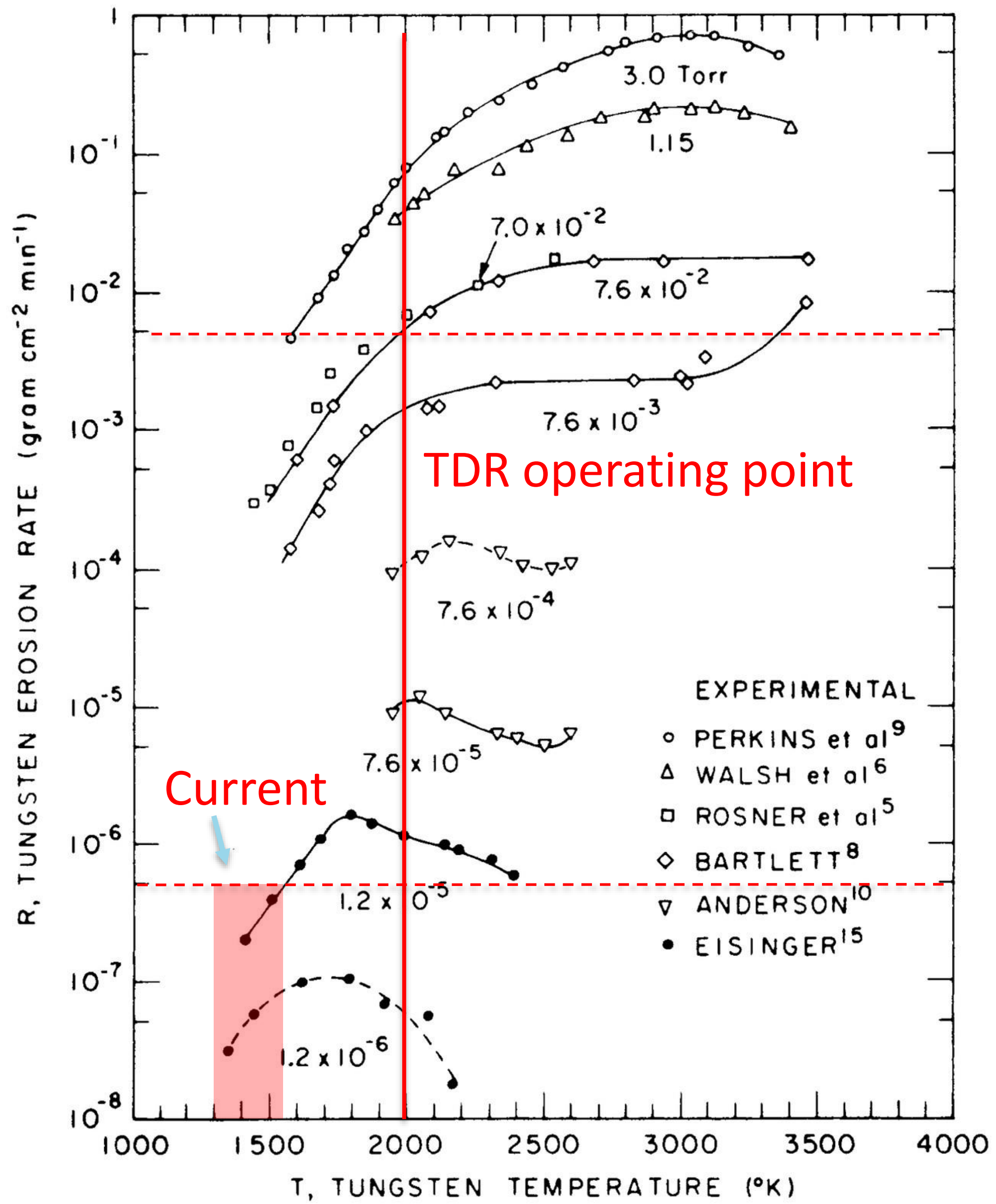


Fermilab

Allowable recession rate of tungsten target

- At low temperature, tungsten is relatively inert
- At high temperatures, it forms highly volatile oxides leading recession of the material.
- Residual water vapor, oxygen, CO_2 and CO are all significant components of the residual gas in the Mu2e vacuum system.
- Allowable 0.1 mm surface recession per operational year (40 weeks)

➔ 4.38e-7 g/cm2/min



Recrystallization Temperature

Material	Temperature °C for 100% recrystallization (annealing time: 1 hour)	
	φ = 90%	φ = 99.99 %
W (pure)	1350	-
WVM	-	2000
WL10	1500	2500
WL15	1550	2600
WRe05	1700	-
WRe26	1750	-

φ = degree of deformation

Source: Plansee, "Tungsten material properties and alloys"

- Recrystallization temperature varies for tungsten by production method, generally 1100~1400˚C
- Thermal cycling may lead randomly oriented small grains merging into directly oriented larger grains
  - Increase ductile to brittle transition temperature
  - Increase susceptibility to radiation damage
  - Increase susceptibility to crack initiation and growth

Approaches for optimization

- Emissivity
  - Coating
  - Material change
- Structure
  - Cooling area
  - Thermal stress
  - Creep
- Fabrication
  - Conventional
  - 3D print

Goverging thermal equation

$$P = \sigma \times \varepsilon \times A \times (T^4 - T_b{}^4)$$

- P = Energy Deposition from the Protons in the Target
  - Absorber Power (P) is between 600 and 700 Watts.
- σ = Stefan-Boltzmann **constant** (5.67x 10^{-8} W/m2* K)
- ϵ = emissivity (temperature dependent)
- A = surface area of the target
- T = temperature of the target
- T_b = temperature of the surroundings (about 305 K , 90 F)

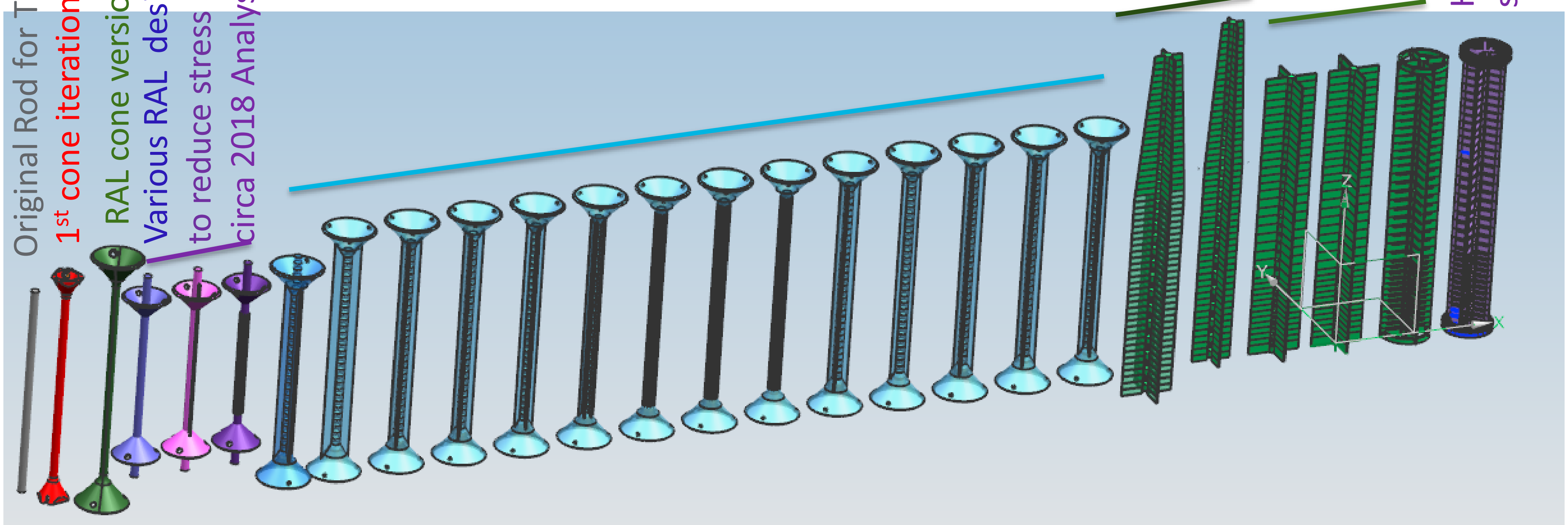
➔

- Takeaway: only two parameters can be adjusted to change the target temperature with constant power input, *ϵ* & *A*.

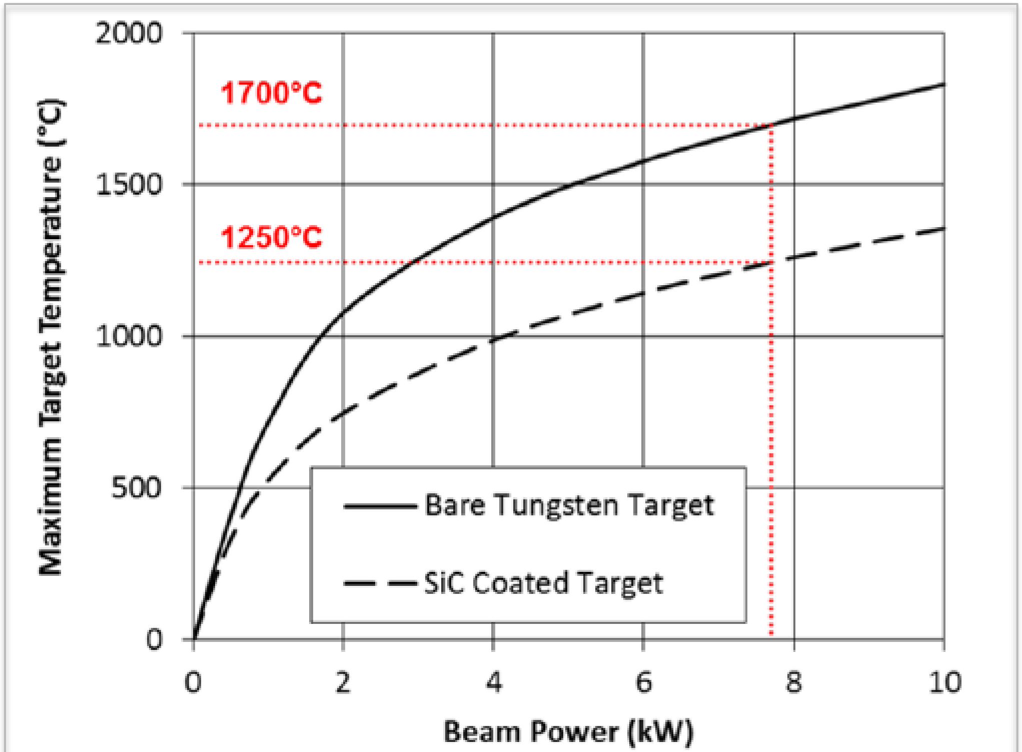
Mu2e Target Evolution

Various FNAL/ RAL iterations with fins (n_{fins} = 3 to 18) to augment cooling with increased surface area during 2018. Includes the T1 Milestone target (CRR in April 2018) (rightmost blue target)

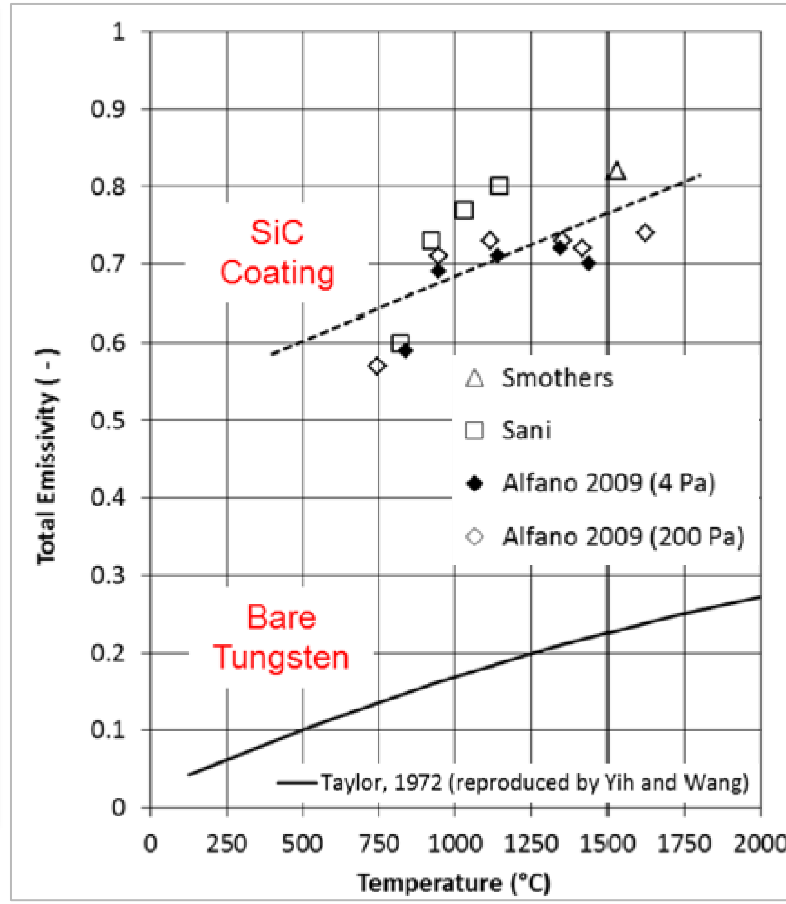
Starting in 2018 Analysis included emissivity as a function of temperature, non-uniform time dependent Energy Deposition (Edep) (380 msec of Edep, 1.02 sec of no heating).



High emissivity coating: SiC



The nominal beam power on rod target is identified by the dashed red line



SiC coating:

When heated in a vacuum at 10-4 Torr, an active oxidation prevails.

➔ A volatile oxide is formed leading to recession of the SiC layer.

Source: Mu2e-doc-8376, “Final Report on the Design of the Mu2e Pion Production Target”, STFC Rutherford Appleton Laboratory, 2017

Texture coating

- CVD coating by Ultramet (CA, USA)
- ε ~ $1/T^4$:

  Tungsten ~ 1200˚C

  WonW RMS50 ~ 1000 ˚C
- W on W coating strong bond

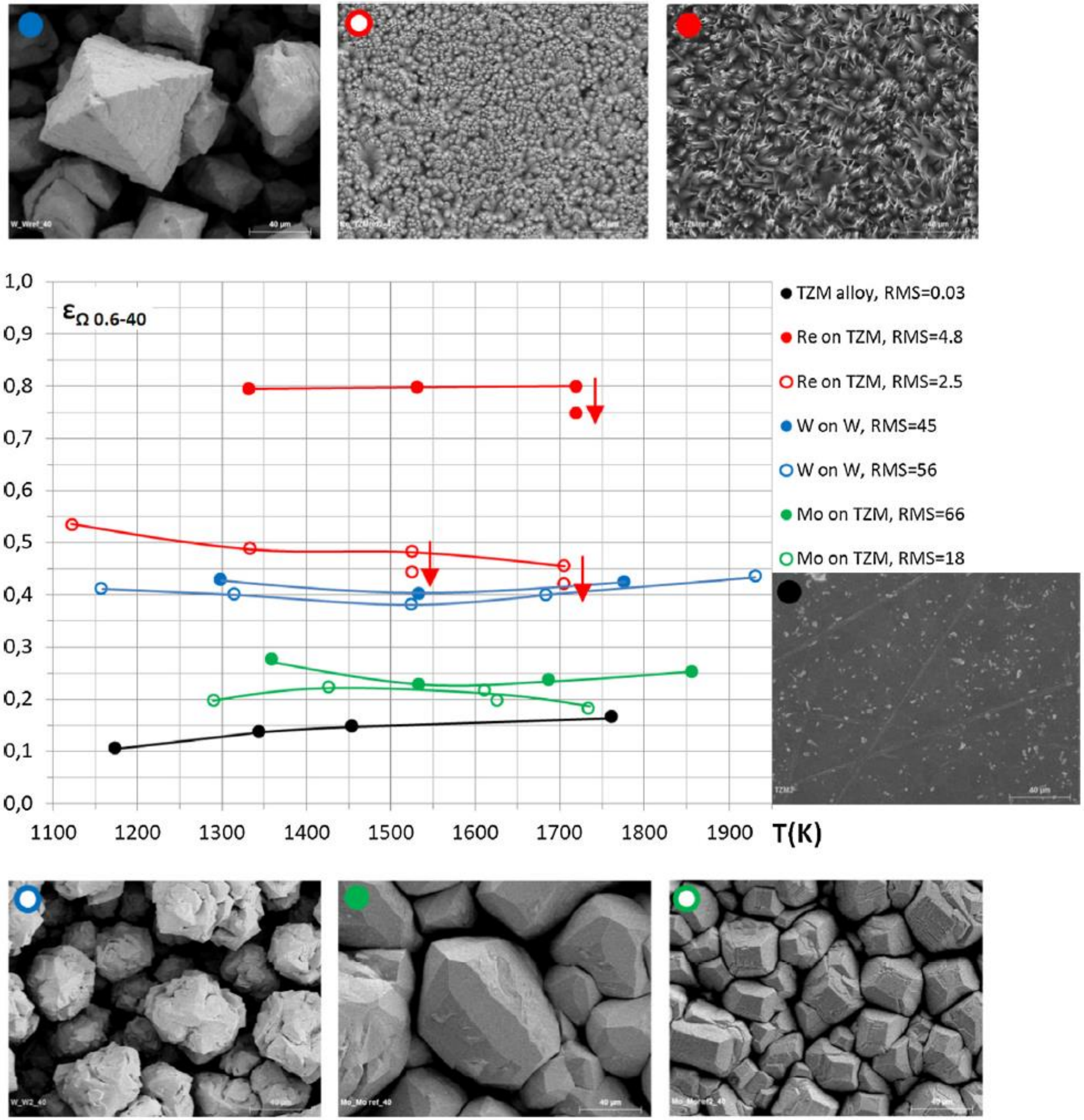
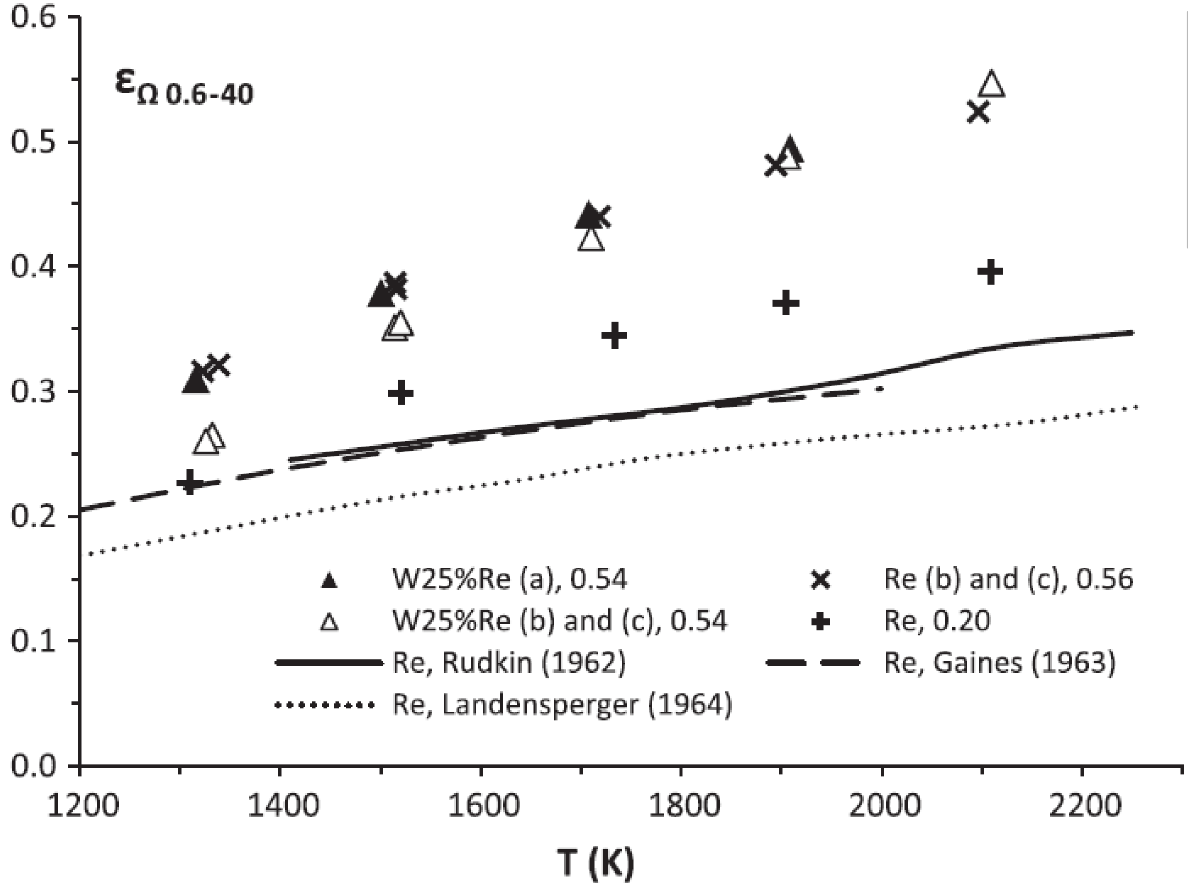


Fig. 17. Comparison of the total hemispherical emissivity of the three coatings, Re on TZM, W on W and Mo on TZM with a polished TZM surface. The red arrows indicate the decrease of emissivity over time measured on the two Re coatings. SEM pictures of the surfaces are provided in order to link each emissivity level to the specific surface structure on which it was measured. The scale bars are all 40 µm. This way one can compare directly the surface structures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

W25%Re: emissivity



- $\varepsilon \sim 1/T^4$:

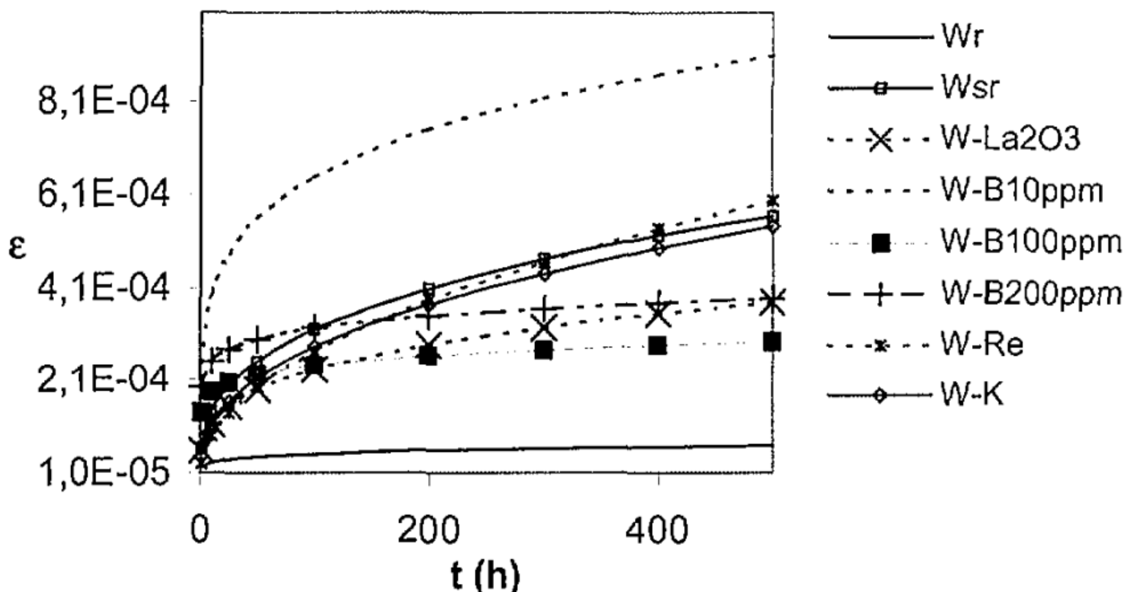
  Tungsten ~ 1200˚C

  W25%Re ~ 1100 ˚C

Comparison of the hemispherical (0.6-40 µm wavelength) emissivity of the pure Re and W-25 wt% Re sample with literature data. The RMS roughness is indicated in the legend and expressed in microns.

– Source: Brodu and et al, “Influence of roughness and composition on the total emissivity of tungsten, rhenium and tungsten–25% rhenium alloy at high temperature”, Journal of Allys and Compounds 585 (2014) 510-517

W25%Re: Creep behavior



Recrystallized tungsten
Stress relieved at 1000 C for 6hrs
1% (wt.) La_2O_3

Boron doped

26% (wt.) Rhenium
Plansee W-VM Potassium

Compared creep curves of tungsten at 975 ˚C and 20 MPa

(Source)

table 6. Norton Creep Law Coefficients for Tungsten and some Alloys

Material	T range (°C)	stress range (MPa)	time (h)	stress exponent n	time exponent m	act. energy Q (kJ/mol)	constant coefficient B
Wr*	900/975	5 / 60	150	1.1	0.2	49	6.2^{e}-5
Wsr	900/975	10 / 30	500	1.0	0.3	134	1.0
W La_2O_3	975/1100	10 / 30	500	0.9	0.3	122	0.4
W B 10ppm	975/1100	10 / 30	500	1.1	0.2	91	4.4^{e}-2
W B 100ppm	975/1100	10 / 30	500	1.0	0.1	83	1.6^{e}-2
W B 200ppm	975/1100	10 / 30	500	1.0	0.1	50	9.3^{e}-4
W Re	975/1050	10 / 30	200	1.0	0.5	109	3.6^{e}-2
W K	975/1050	10 / 30	200	1.0	0.4	126	0.3

* heat treated at 1400°C

AT0100392

D. Gallet et al. RM 40a 277

15th International Plansee Seminar, Eds. G. Kneringer, P. Rödhammer and H. Wildner, Plansee Holding AG, Reutte (2001), Vol. 1

$$\varepsilon = B \exp\left(-\frac{Q}{RT}\right)\sigma^{n} t^{m}$$

CREEP LAWS FOR REFRACTORY TUNGSTEN ALLOYS BETWEEN 900 AND 1100°C UNDER LOW STRESS

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BP111, 26702 Pierrelatte, France
** Plansee Aktiengesellschaft

W25%Re: other properties

	W-25Re	W	WL10
Density	19700 kg/m3	19250 kg/m3	19250 kg/m3
Ultimate Tensile Strength at RT	2100 MPa	980 MPa	~980 MPa
Poison’s Ratio	0.29	0.284	~0.284
Young’s Modulus of Elasticity at RT	400 GPa	390 GPa	~390 GPa
Brinell Hardness at RT	500 BHN	2750 BHN	~2750 BHN
Melting Point	3027 °C	3410 °C	~3410 °C
Thermal Conductivity at RT	70 W/mK	167 W/mK	~167 W/mK
Heat Capacity at RT	140 J/kg K	134 J/kg K	~134 J/kg K
Recrystallization Temperature	1750 K	1350 K	1500 K

- Tungsten is alloyed with rhenium to obtain greater ductility and a lower brittle-to-ductile transition temperature. In addition, tungsten-rhenium also has a higher recrystallization temperature and better creep resistance.

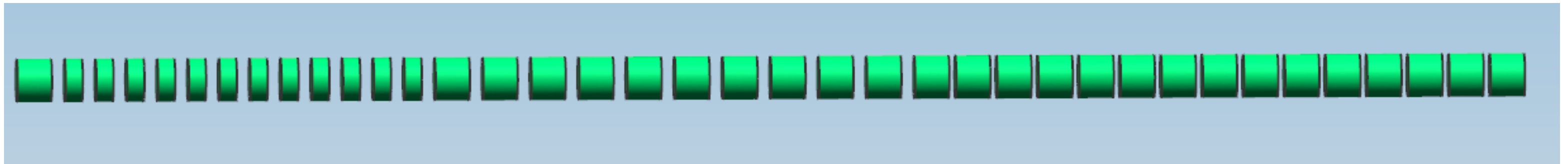
- Tungsten is dopped with lanthanum oxide, WL10, to improve its creep resistance and increase the recrystallization temperature.

Reduce Thermal Stress

- Melting, Tungsten melting temperature ~ 3500 K
- Before melting, it creeps -- soften leading to plastic deformations and low mechanical stresses.
  - Creep is a function of Temperature, Stress, and Time. Strain, ϵ, described by Norton Creep Law:

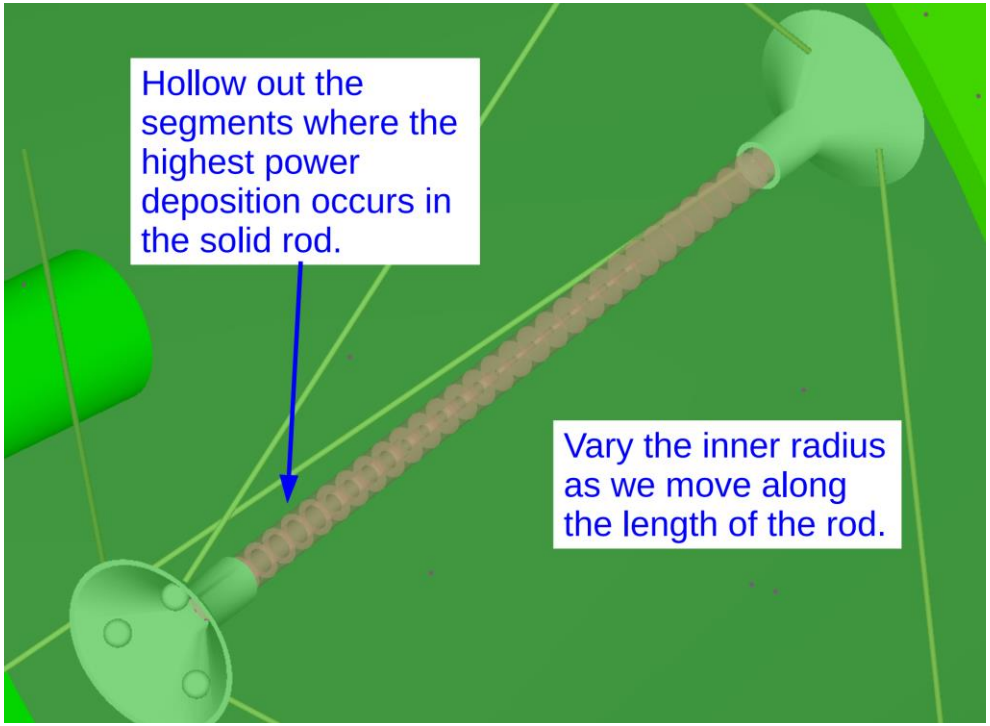
$$\varepsilon = B \exp\left(-\frac{Q}{RT}\right)\sigma^{n} t^{m}$$

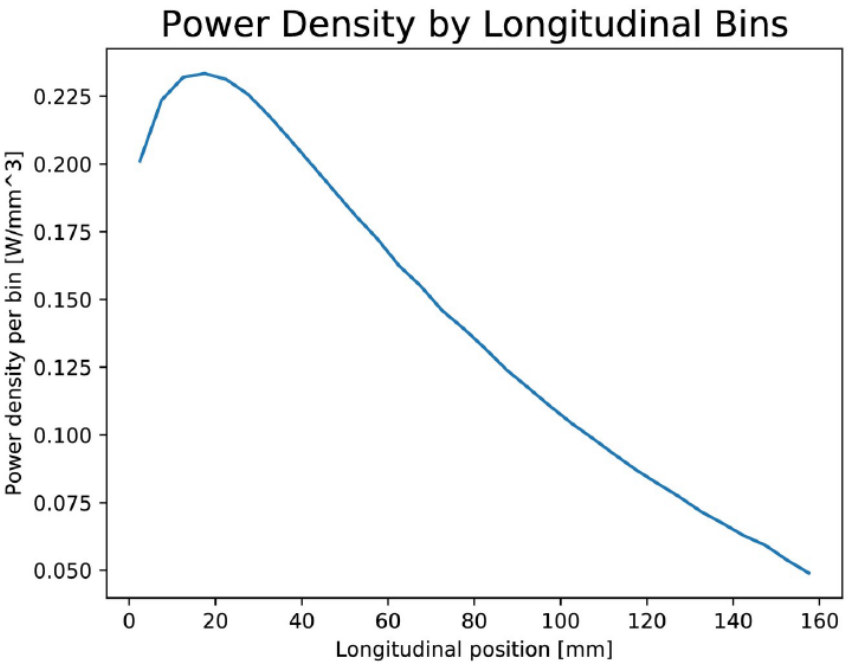
    - Stress to the 0.9 power
    - Time to the 0.3 power
    - Constant B = 0.4, Q = 122 kJ/mol for 1% La_2O_3 doped W.
    - Conclude: Support target to minimize mechanical stress.
- Thermal Stresses.
  - Parts that heat up are constrained by those that heat up less, resulting in thermal stresses.
  - Thermal Stress can be reduced by separating the core elements and giving the hot part room to expand:



Reduce Thermal Stress (cont.)

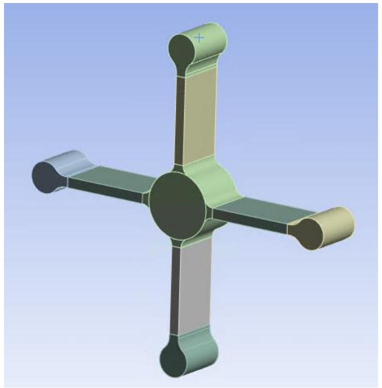
- Thermal Stresses.
  - Parts that heat up are constrained by those that heat up less, resulting in thermal stresses.
  - Thermal Stress can also be reduced by distributing heat load in such a way to decreasing thermal gradient: Mu2e-DocDB-19126
- Fabrication -- Challenge





Fabrication

- Fabrication
  - Hayman 2 (Expensive & not fail-to-safe)
  - Optimization proposal
    - Segments can be made individually and assembled as a unit. Failure of individual segment won't affect performance of other segments.
      - Assembly and support to be detailed
    - Core of segments may be hollowed with various diameter to evenly distributed thermal load.
    - 3D printing is possible



Take-away

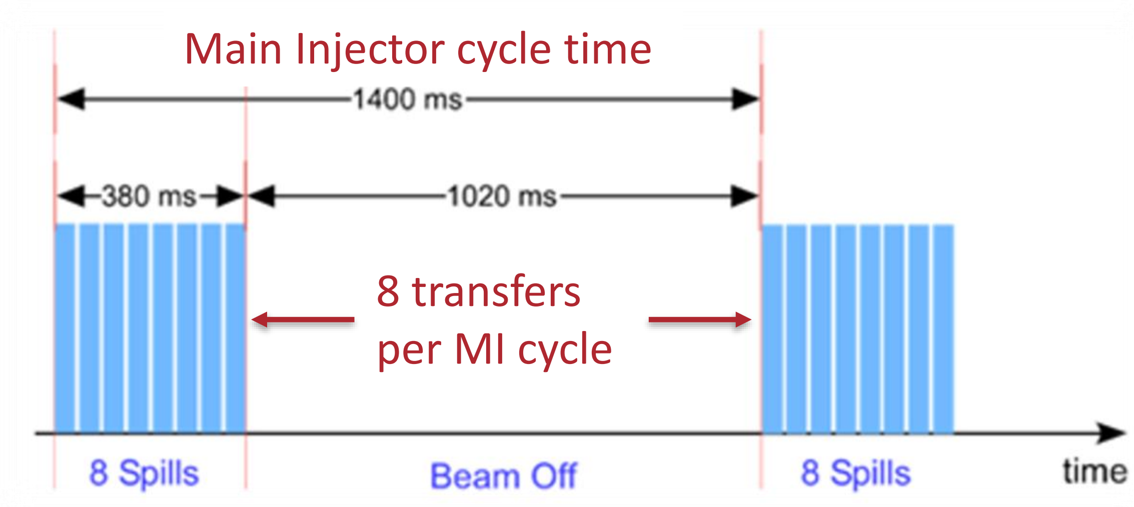
- The current design of the Mu2e target should work as predicted
- There are rooms to optimize it:
  - Coating: W on W RMS-50
  - Material change: W 26% Re
  - Structure-wise: Assembly of individual segments
    - Various thickness, or
    - Various hollow diameter
  - Fabrication
    - Conventional EDM with less cost, or
    - 3D printing

Thanks!

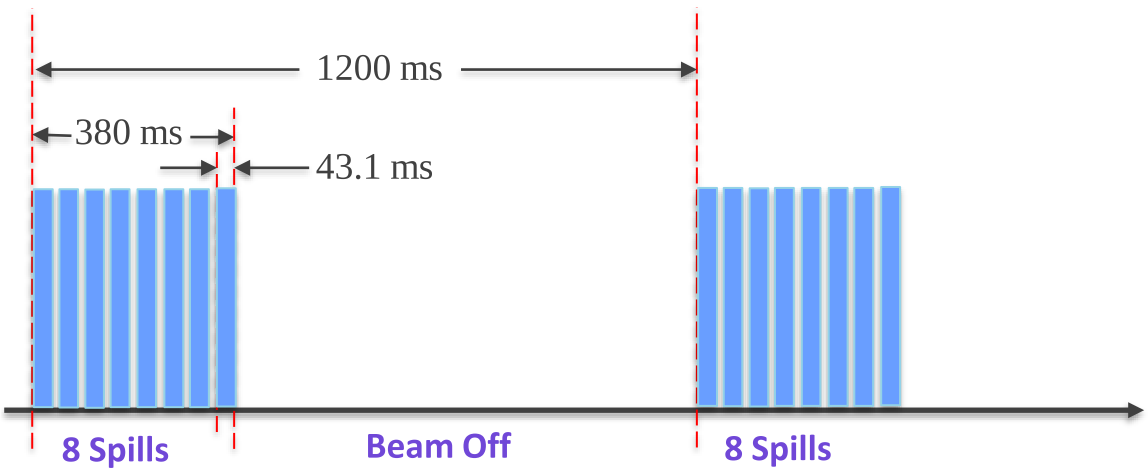
- Appreciate input from Kevin Lynch & Steve Werkema

Backup slides

Beam Timing Structure

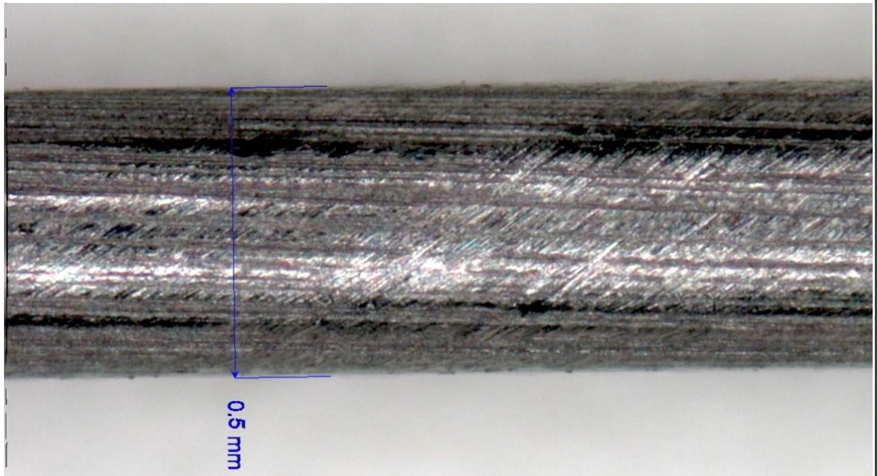


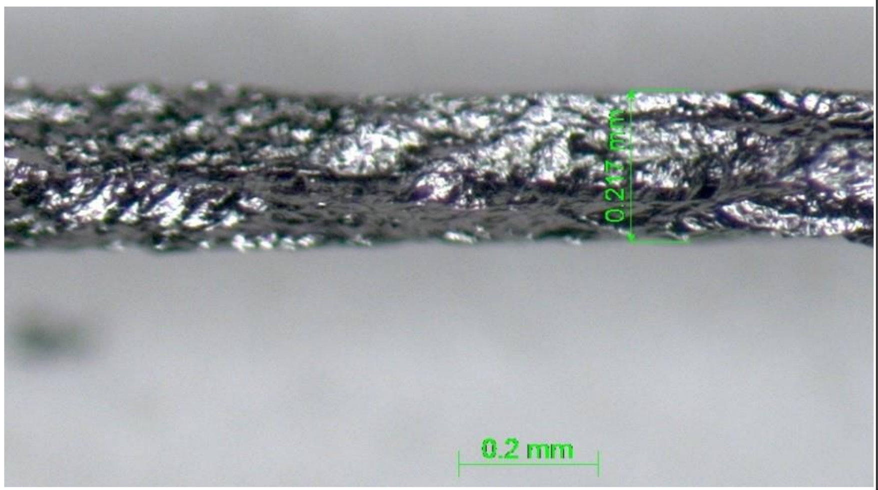
Booster cycle rate
15 Hz

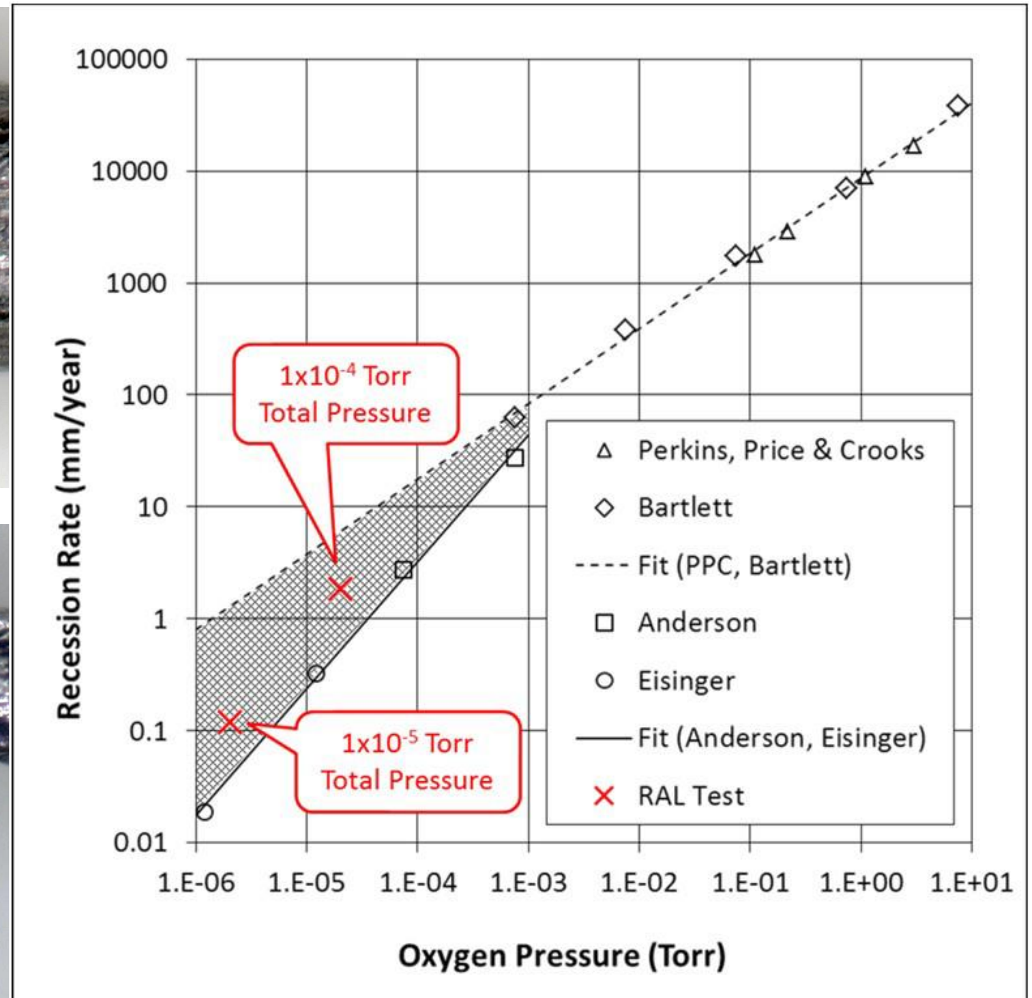


Booster cycle rate
20 Hz

Target lifetime requirements drive a higher vacuum







Mu2e beam

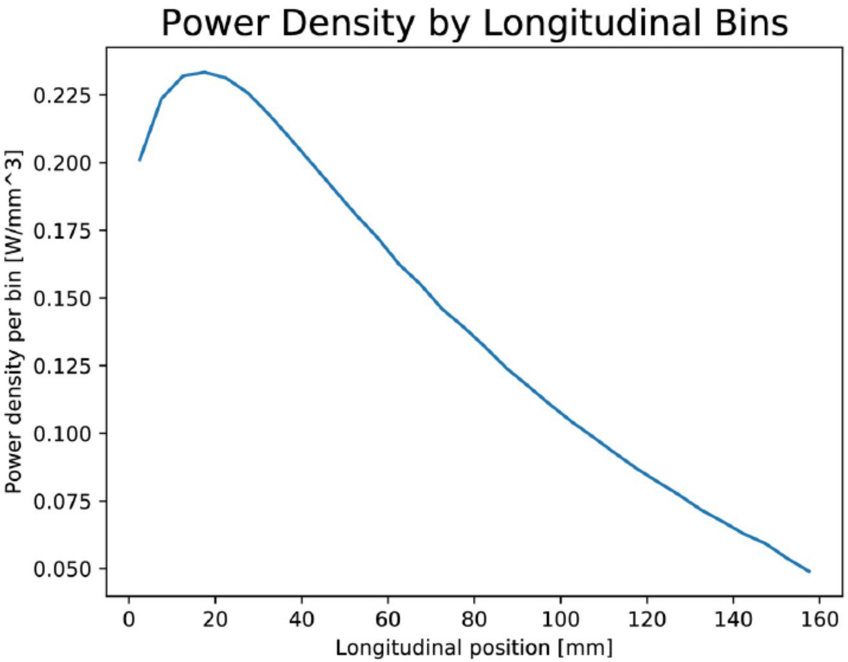
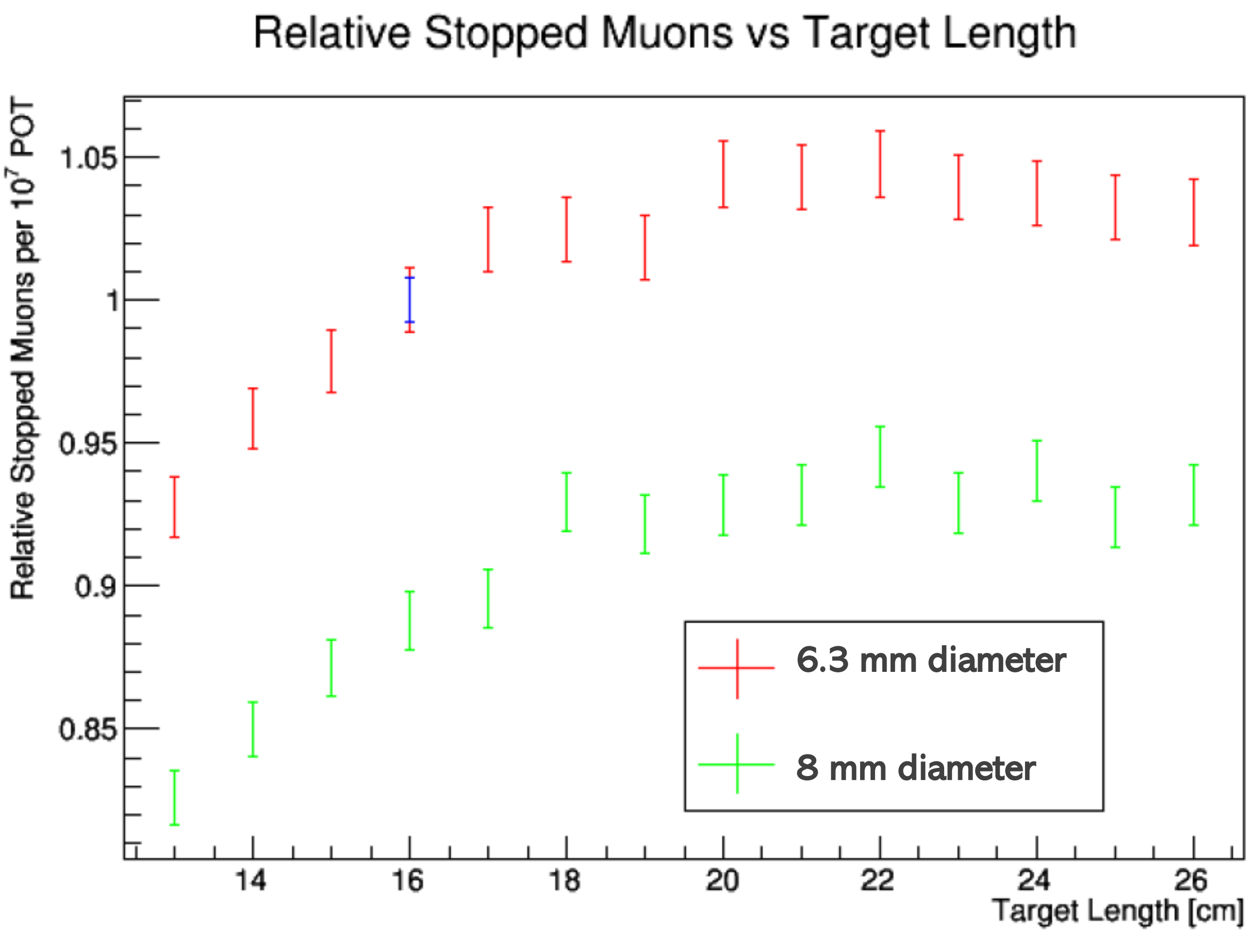


Table 15, Mu2e Beam Parameters

Beam kinetic energy	8 GeV
Beam spot shape	Gaussian
Beam spot size	$\sigma x = \sigma y = 1$ mm
Main Injector cycle time	1.333 sec
Number of spills per MI cycle	8
Duration of Spill	54 msec
Number of protons per spill	1 Tp
Duty Factor	32 %
Average Beam Power	7.7 kW
Average Beam Current	1 μA

Optimized target for muon yield at the stopping target

- Target diameter
- Target length
- Target position
- Target angle
- Beam profile
- Etc.



Radiation Damage

	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/cm^2)	12.4	15.3
Peak DPA / year *	27	260
Helium Gas Production (appm/DPA) *	10	20
Typical Target life (years)	5+	1

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

Source: Mu2e-doc-25791

Fermilab

Radiation Damage

- Radiation Damage:
  - Very large DPA (Displacement Per Atom).
  - Production of Hydrogen and Helium within the Tungsten Material.
  - No test prior to operation

	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
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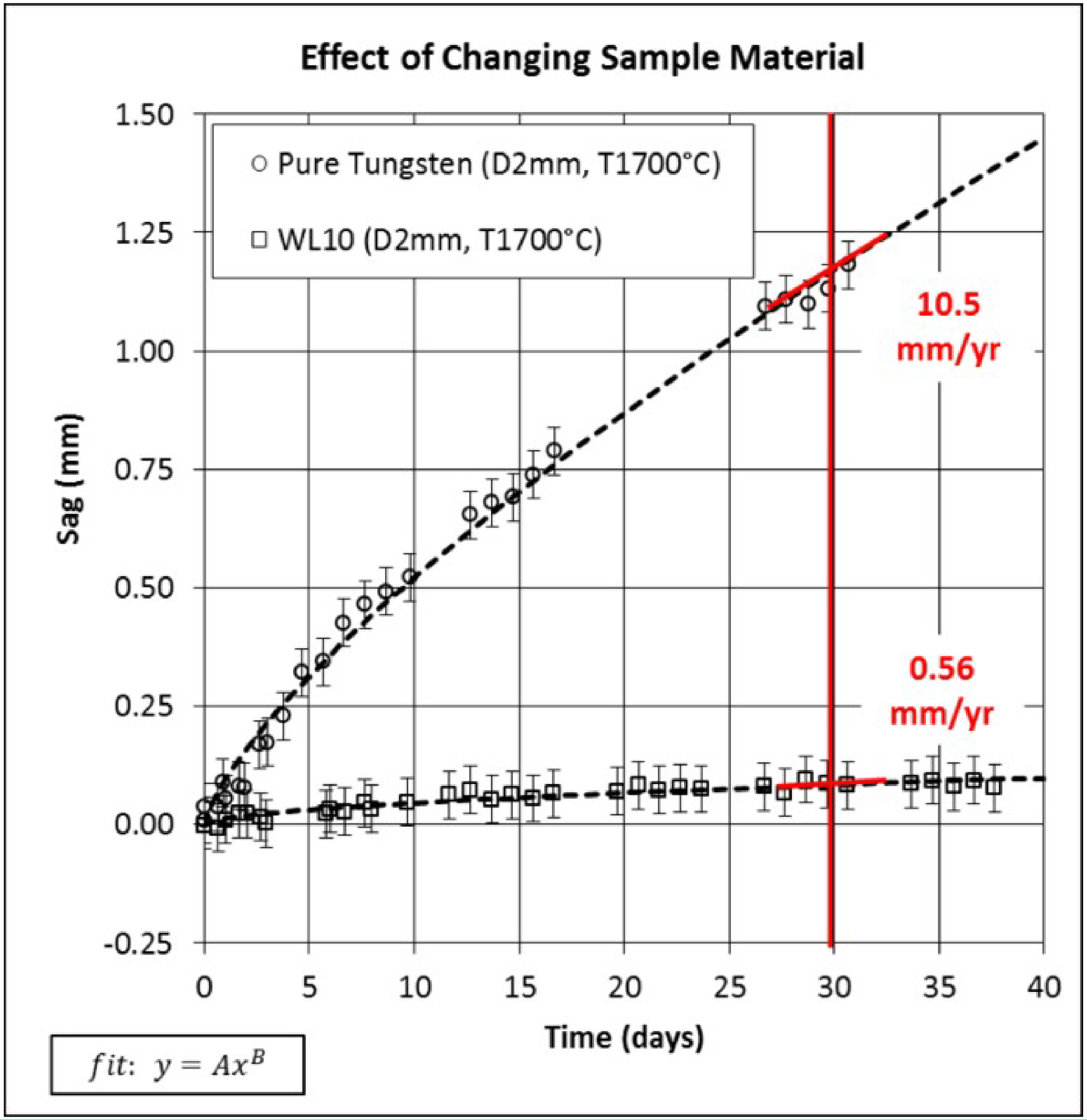
(Source: Mu2e-doc-25791)

Modify target material to improve creep resistance

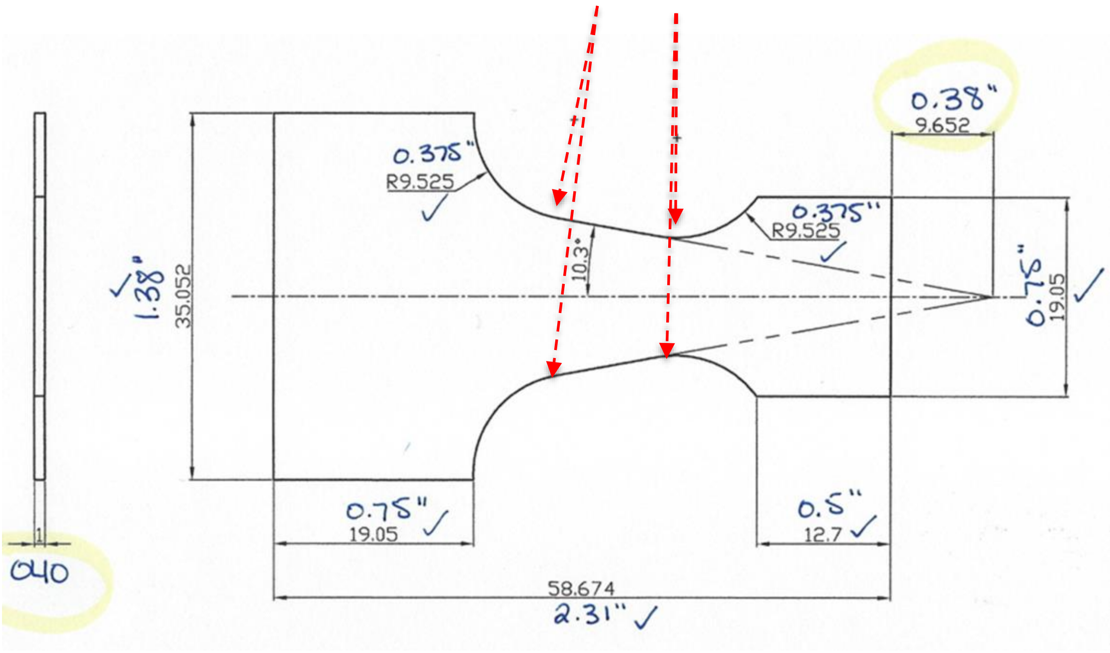


Pure tungsten

WL10 (Tungsten doped with 1% wt. La_2O_3

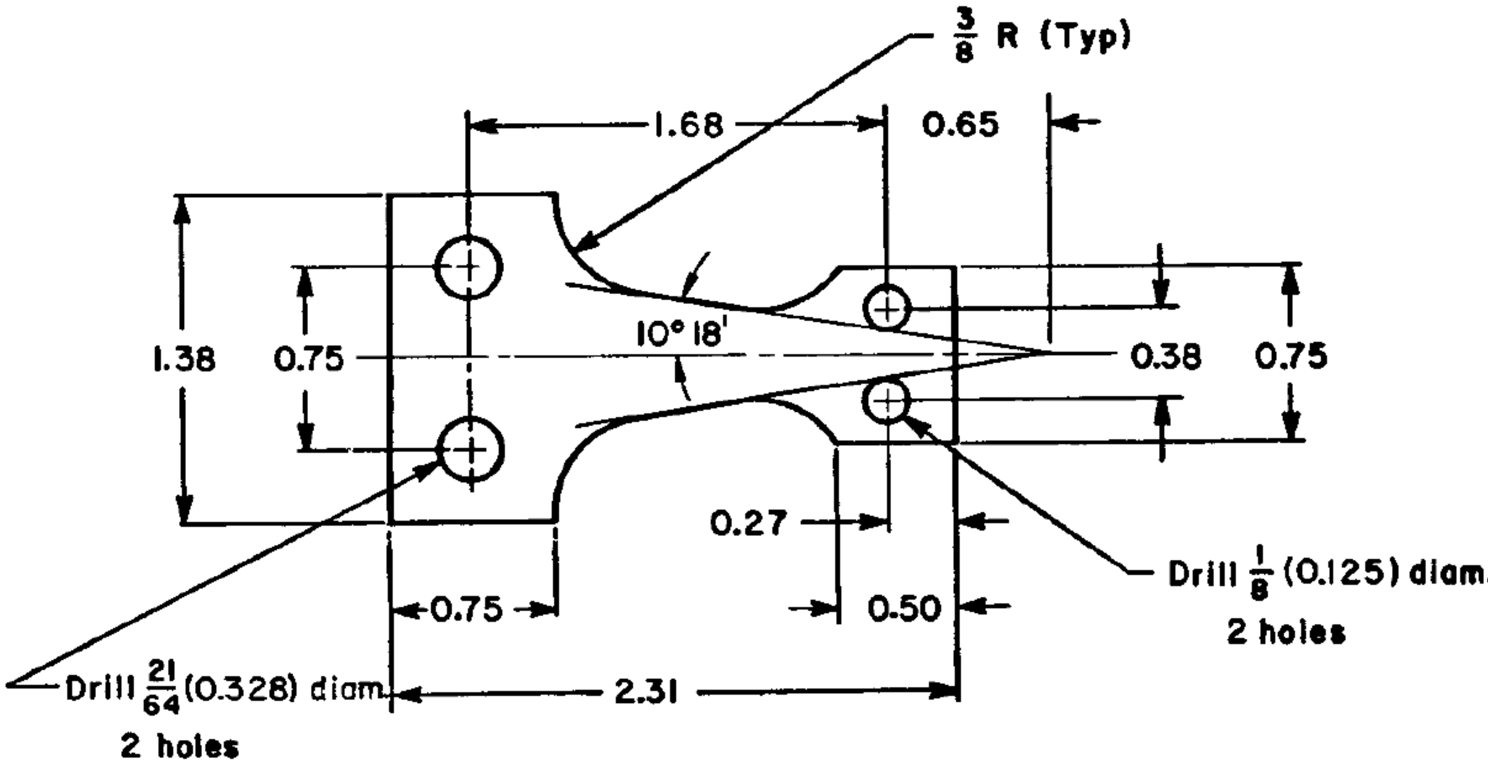
Specimen for ML10 mechanical properties

Note:
1. Make sure these fillet radius are tangent to the lines drawn at 10.3 degrees.
2. The angle 10.3 degree is acceptable, and it could be down to 10.18 degree.



Ref: ASME B593 [Standard Test Method for Bending Fatigue ...]

Krouse Type Specimen



(c) Sheet or Strip Fatigue Test Specimen (Krouse Type) for Thickness Ranging from 0.008 to 0.031 in. (0.203 to 0.787 mm)

(Gage length is increased for thicker material.)

NOTE 1—All dimensions are in inches: in. × 25.4 = mm.

FIG. 2 Sheet or Strip Fatigue Test Specimens

Ref: ASME B593 [Standard Test Method for Bending Fatigue ...]

High emissivity coating: SiC

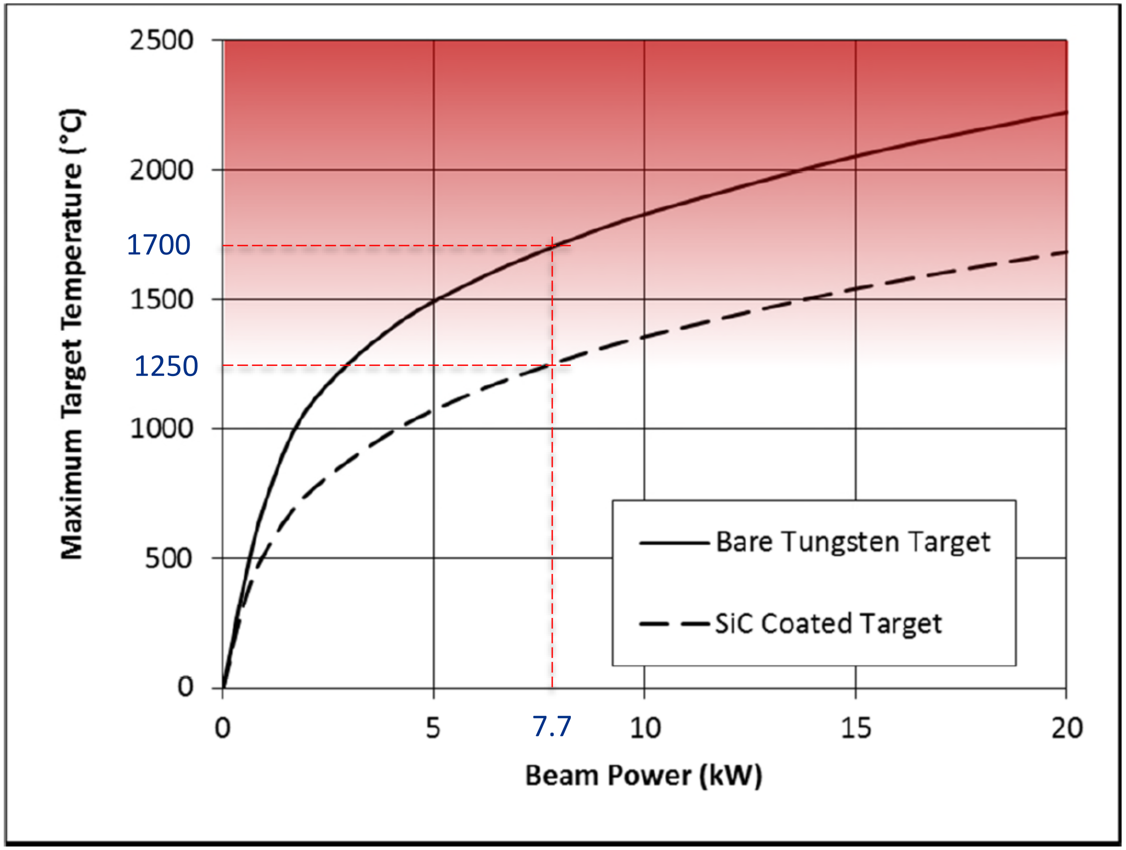
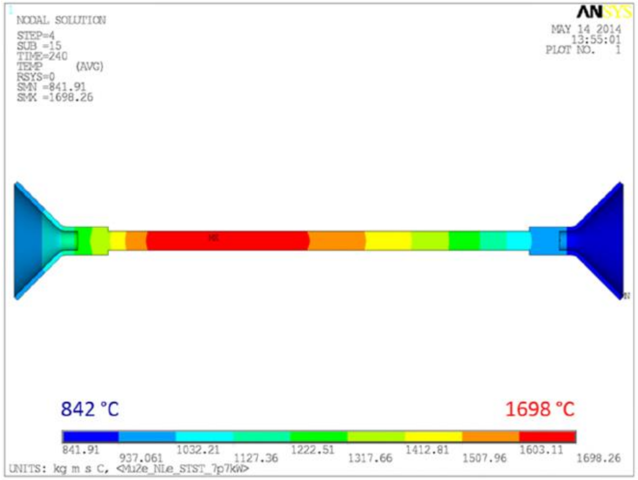


Figure 94, Target equilibrium temperature as a function of beam power

SiC coating:
When heated in a vacuum at 10-4 Torr, an active oxidation prevails.
➔ A volatile oxide is formed leading to recession of the SiC layer



Source: Mu2e-doc-8376, "Final Report on the Design of the Mu2e Pion Production Target", STFC Rutherford Appleton Laboratory, 2017