Mu2e Target

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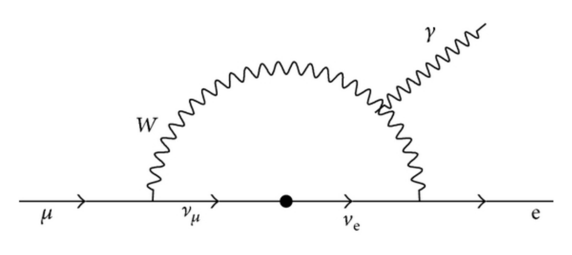
Charged Lepton Flavor Violation

Charged leptons are only fermions without observation of flavor violation

- Quarks mix (CKM)
- Neutrinos oscillate

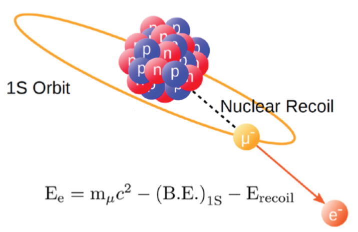
CLFV is **required** in νSM, but ludicrously suppressed



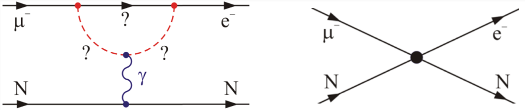
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U^*_{\mu k} U_{ek} \left(\frac{\Delta m^2_{1k}}{M^2_W}\right)^2 \right|^2 < 10^{-54}$$

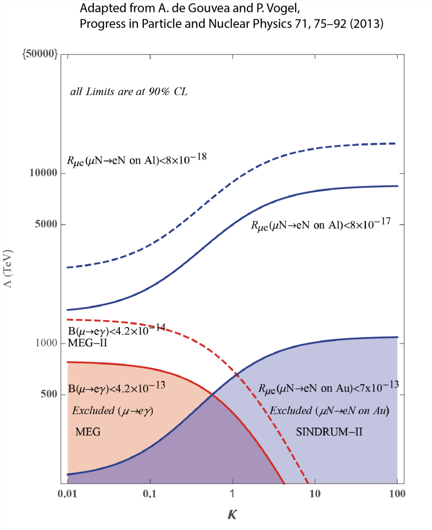
Any experimental observation would unambiguously indicate New Physics

CLFV: $\mu \to e$ conversion



- Monoenergetic ~105 MeV/c conversion-electron (CE)
- Sensitive to Λ-scales $\mathcal{O}(10^3)$ TeV





$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Challenge 1: μ^- beam from FNAL protons

High-level proton beam parameters

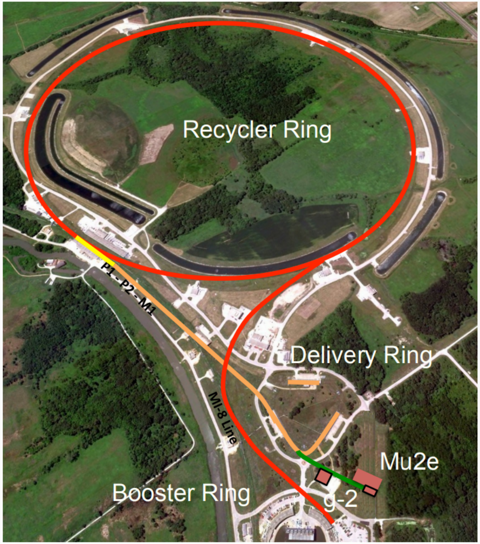
Linac: 400 MeV

Booster: 8 GeV

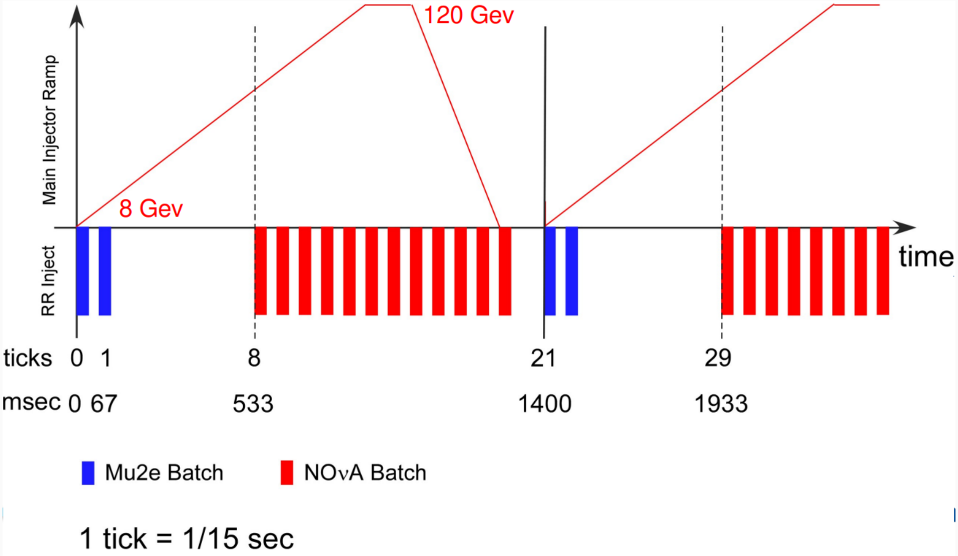
Recycler rebunches

Slow-extraction in Delivery Ring

Beam to Mu2e



FNAL neutrino needs drive the 8 GeV proton beam

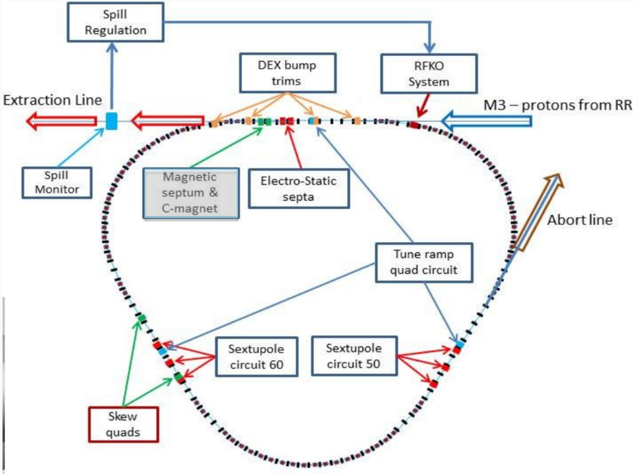


Resonant extraction in Delivery Ring

Take-home: Inject instability, "scrape" off small piece of spill every revolution

Mu2e target will see:

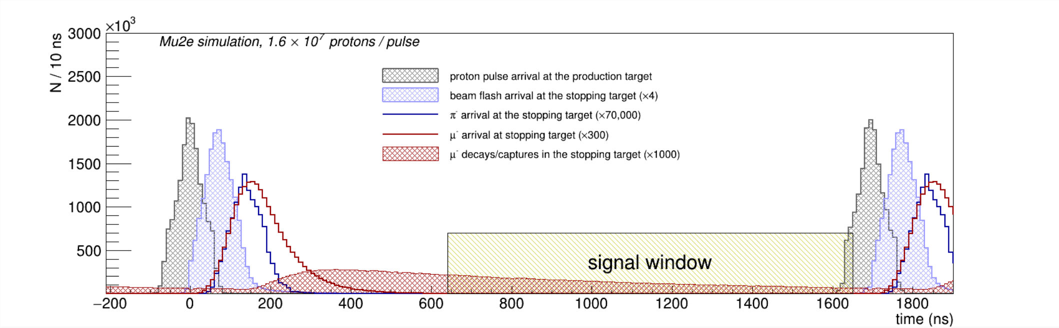
- $\sim 4 \times 10^7$ protons @ 8 GeV
- $\sim$ 1 mm gaussian beam radius
- 250 ns pulses
- 1.7 μs pulse period
- At 2.5 MHz



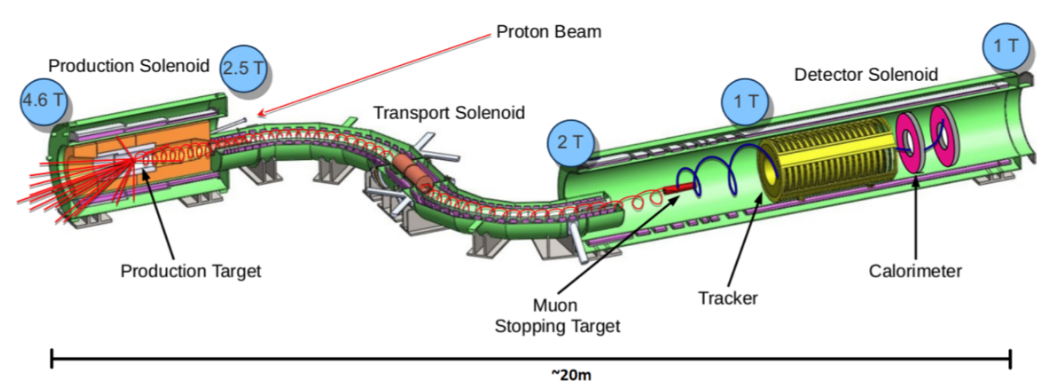
Challenge 2: Ideal Mu2e conditions

Mu2e needs:

- High yield of *stoppable* muons ⇒ low momentum μ^- beam
- Minimal beam-induced backgrounds (i.e. radiative pion capture)
- Low radiation environment



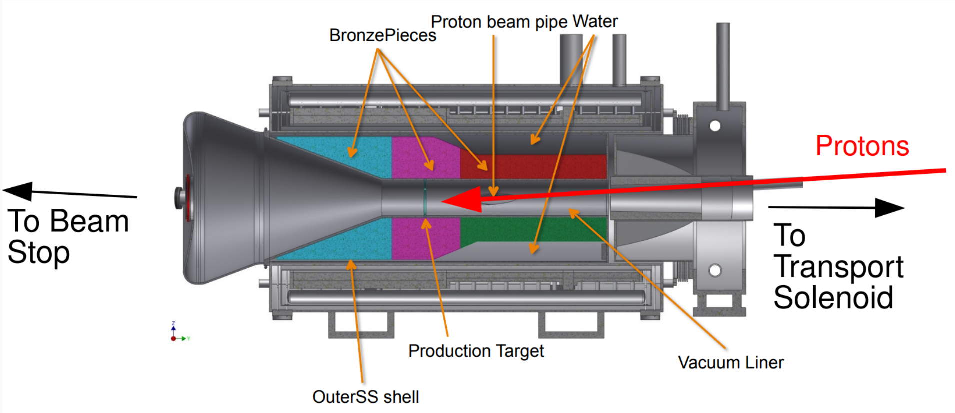
Mu2e



Discovery potential of $R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A))} > 2 \times 10^{-16}$ (5σ)

- $R_{\mu e} < 8 \times 10^{-17}$ (90% CL)
- $\mathcal{O}(10^4)$ improvement of previous result (SINDRUM-II)

Production Solenoid (PS)



Compact, high-Z pion-production target in high B-field with backwards extraction

Production Target

LaO_2-doped Tungsten, core EDMed from single rod

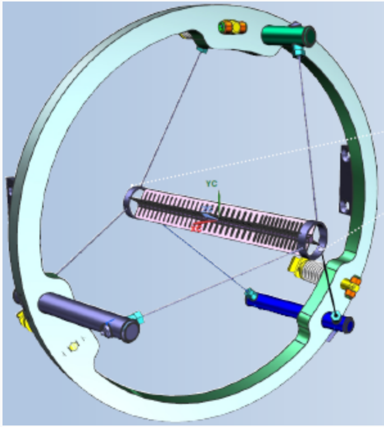
Longitudinally segmented cylinder
⇒ stress management

Longitudinal fins
⇒ thermal and structural management

1mm tungsten spokes

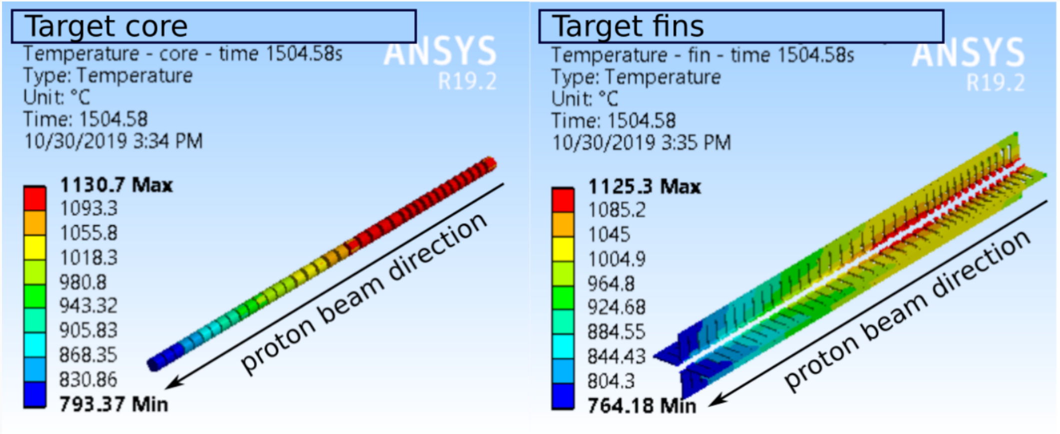
∼700 W power absorbtion ⇒ ∼1500 K

- Radiatively cooled

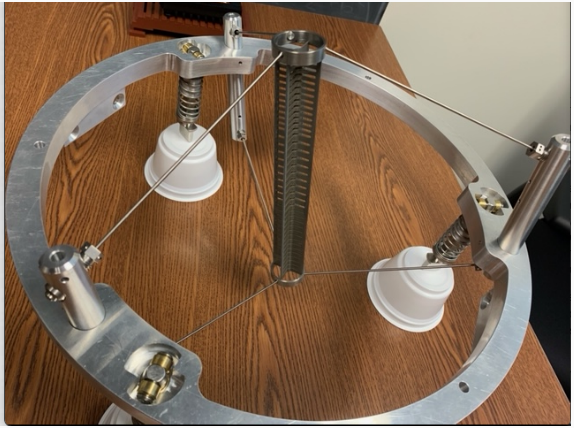


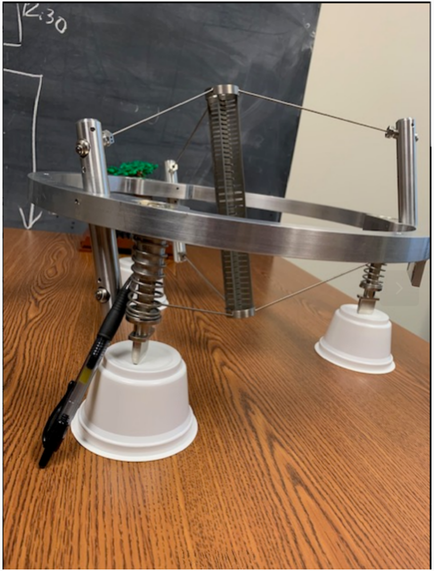
Expect target lifetime of ∼1 year: ⇒ replace during summer shutdowns

Simulation driven design



Production Target





Possible failure modes

Temperature

- W melts at 3500 K, but can undergo *creep* (softening) at lower temps
- Want to keep deformation from creep less than 0.5 mm

Oxidation

- Driven by residual O_2 and water
- Expect sufficient vacuum at 10^{-5} torr

Recrystallization & Radiation damage

- Not major failure modes, but we do want to avoid large material changes affecting muon production

Simulations suggest suitable performance

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- But how do we know...?

Target testing

Without testing, we are flying blind

Idea: place target at Fermilab "AP0"

- 8 GeV protons
- Skeleton test plan somewhat outlined already, needs work in implementation
  - Expose target to beam, steady-state temp, take measurements, validate sims

Complications:

- No resonant extraction (more severe thermal shock than Mu2e)
- Spot sizes (beam sigma) slightly different
- Facility available, but still needs plenty of work before starting

No showstoppers, but need to start soon

Future work and remaining questions

Mu2e "Hayman" production target is in-hand

- Mu2e Run 1 scheduled for ~2026 ($\leq$ 1 year long, ~0.5x beam intensity)

First-of-its-kind target: fully simulation-driven optimization and stress analysis

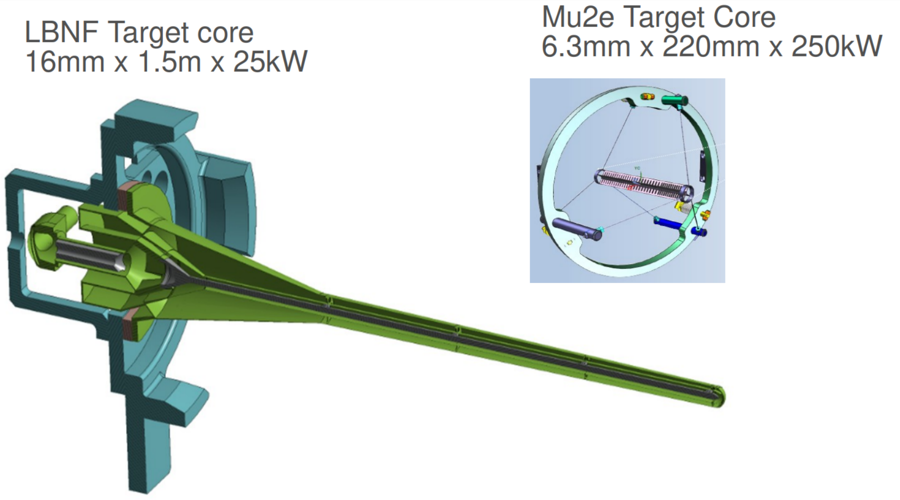
- Designed with nominal beam intensity @ 1 year: $\Rightarrow$ Run 1 should not be a concern
- Target failure and replacement outside of shutdown window would hurt experiment

Can we get testing facility setup at AP0 after g-2 finishes?

- Test whether expected performance degradations (e.g. thermal stresses, oxidation, creep) within tolerances

Backup
(mostly quoting work from others)

Target comparisons



Tungsten thermal stresses

- Melting, Tungsten melting temperature ~ 3500 K
- But, long before it melts, it softens and low mechanical stresses result in plastic deformations.
  - think of a stick of butter on a warm summer day.
  - Usually called Creep which is a function of Temperature, Stress, and Time. Strain, ϵ, Described by Norton Creep Law:
    - 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.

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

- Thermal Stresses.
  - Parts that heat up are constrained by those that heat up less, resulting in thermal stresses.

Tungsten oxidation

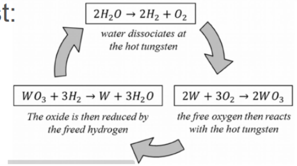
Oxidation driven by residual Oxygen and Water Vapor in the vacuum.

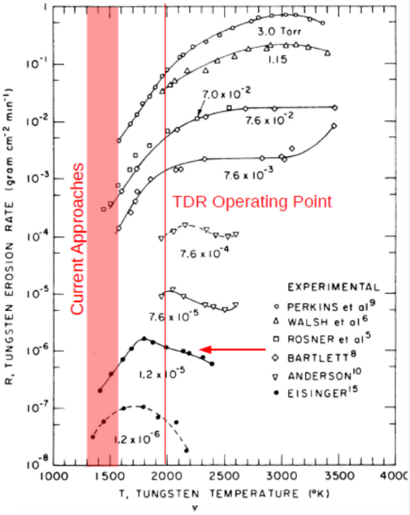
- Depends on the concentrations of O2 and H2O and on the temperature. Negligible if the temperature is sufficiently low.
- Oxygen Cycle:

$$W_{(s)} + O_{2\,(g)} \rightarrow WO_{2\,(g)}$$

$$2W_{(s)} + 3O_{2\,(g)} \rightarrow 2WO_{3\,(g)}$$

- Water Catalyst:





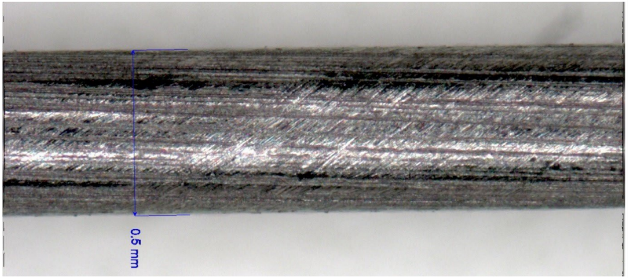
Tungsten oxidation

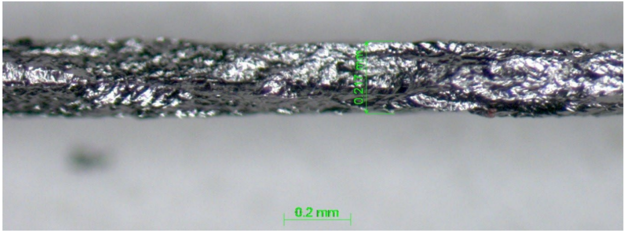
Before (top) and after (bottom) of oxidation tests at RAL with vacuum leak

Vacuum lowers O_2 and H_2O, minimizing effect

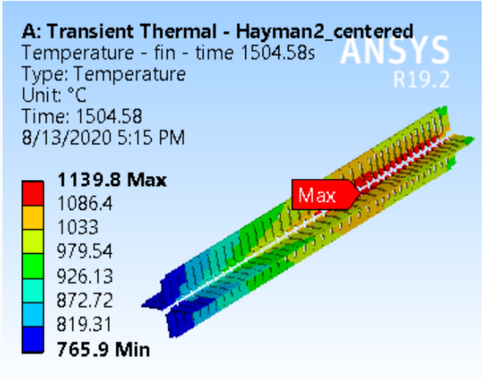
Expect 10^{-5} torr vacuum

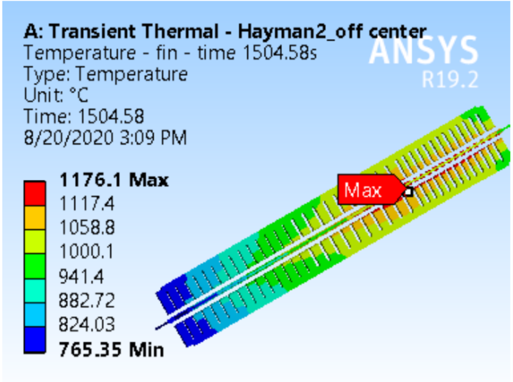
Vacuum limited by conductance of high vacuum line





Beam-target alignment





AP0 test

Existing Target and Shielding Module Removed.

Test target and Module inserted in place of target used for g-2

Instrumentation and vacuum utilities connected to top of module.