Fermilab
U.S. DEPARTMENT OF ENERGY | Office of Science

Accelerator R&D for Mu2e-II

Steve Werkema

Mu2e-II Workshop

8 December 2017

In partnership with:

Mu2e

Mu2e-II Beam

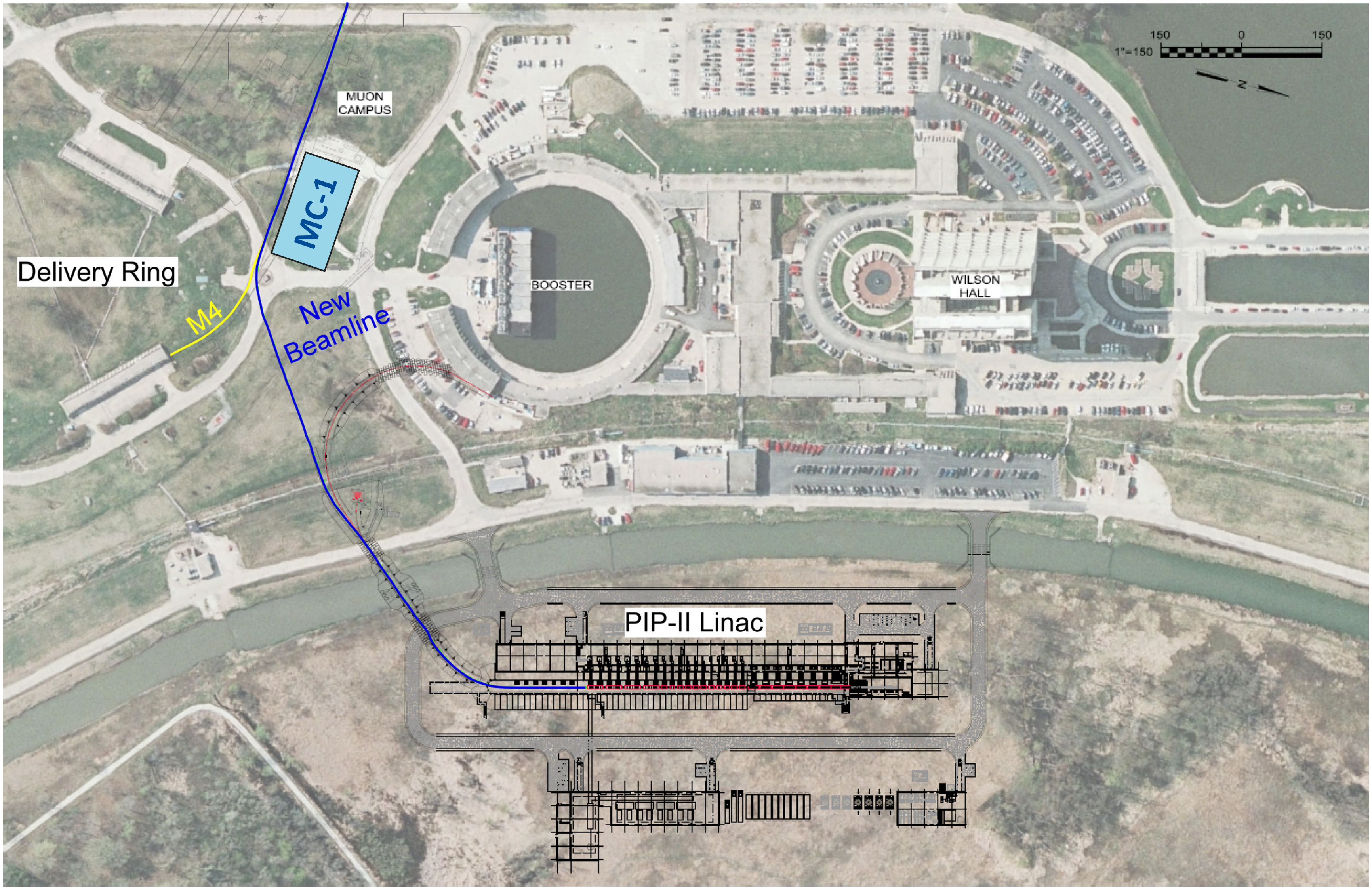
Mu2e and Mu2e-II Proton Beam Parameters

Parameter	Mu2e	Mu2e II	Units
Total Protons on Target (3 yr)	4.7×10^{20}	4.4×10^{22}	protons
Pulse Repetition Rate	590	500 - 1250	kHz
Time Between Pulses	1695	800 - 2000	nsec
Pulse Base Width	250	100	nsec
Extinction Level	10^{-10}	10^{-11}	
Average Intensity per Pulse	3.9×10^{7}	$5.6 – 14 \times10^{8}$	protons
Pulse-to-Pulse Intensity Variation	<50	<10	%
Beam Kinetic Energy	7946	800	MeV
Beam Power	7.3	100	kW
Duty Factor	25	90	%

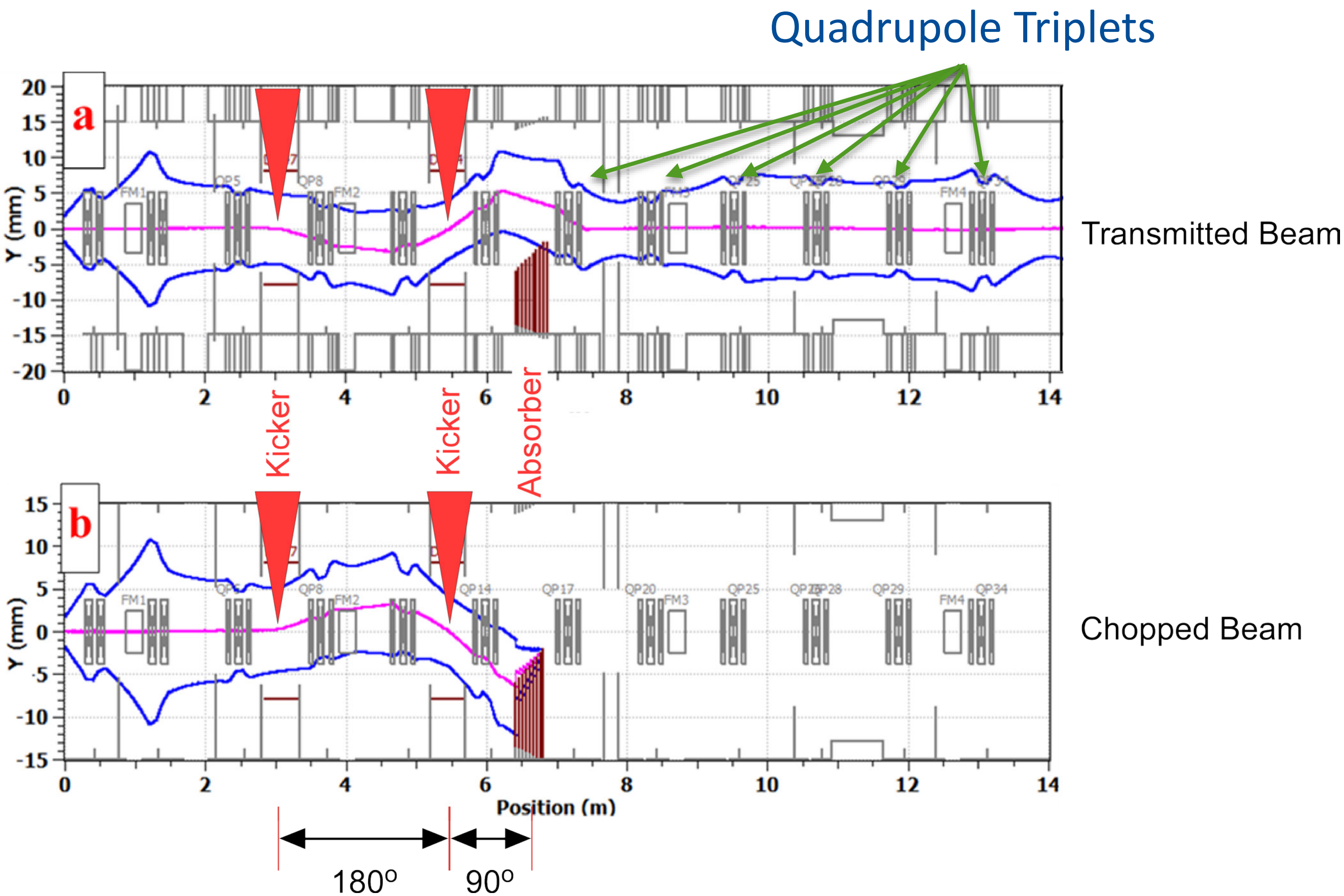
NOTE:

- Blue numbers are calculated from the other parameters.
- Total POT assumes 67% accelerator up-time

Mu2e II Beam Delivery



Pulsed Beam Formation – Beam transport through MEBT



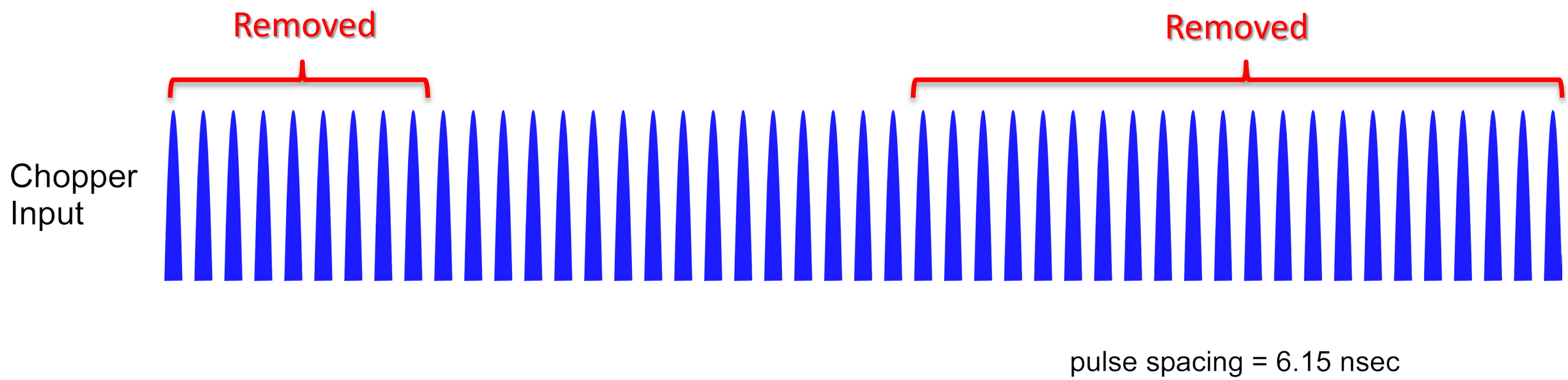
PIP-II Medium Energy Beam Transport (MEBT) section.

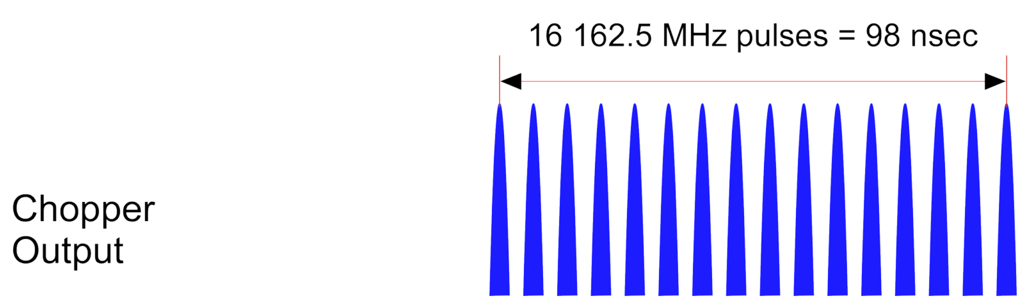
- Pulse formation is accomplished by a fast bunch-by-bunch chopper.
- Chopper consists of two fast vertical kicker magnets and a beam absorber
- Kickers are excited during transmission and chopping

Input: Bunch train of 2.1 MeV H^- ions @162.5 MHz (6 nsec bunch-bunch)
Transmitted bunch: Upstream kicker defects down, downstream kicker deflects up, bunch clears absorber
Chopped bunch: Upstream kicker defects up, downstream kicker deflects down, bunch hits absorber

This system can produce 100 nsec pulsed beam with 800 – 2000 nsec bunch spacing.

MEBT Chopper Operation for Mu2e-II





This is the longitudinal profile seen by the production target

Notes:

- LEBT chopper will eliminate most leading and trailing bunches upstream of MEBT
- Upstream collimation will remove transverse tails

Beam Related Issues

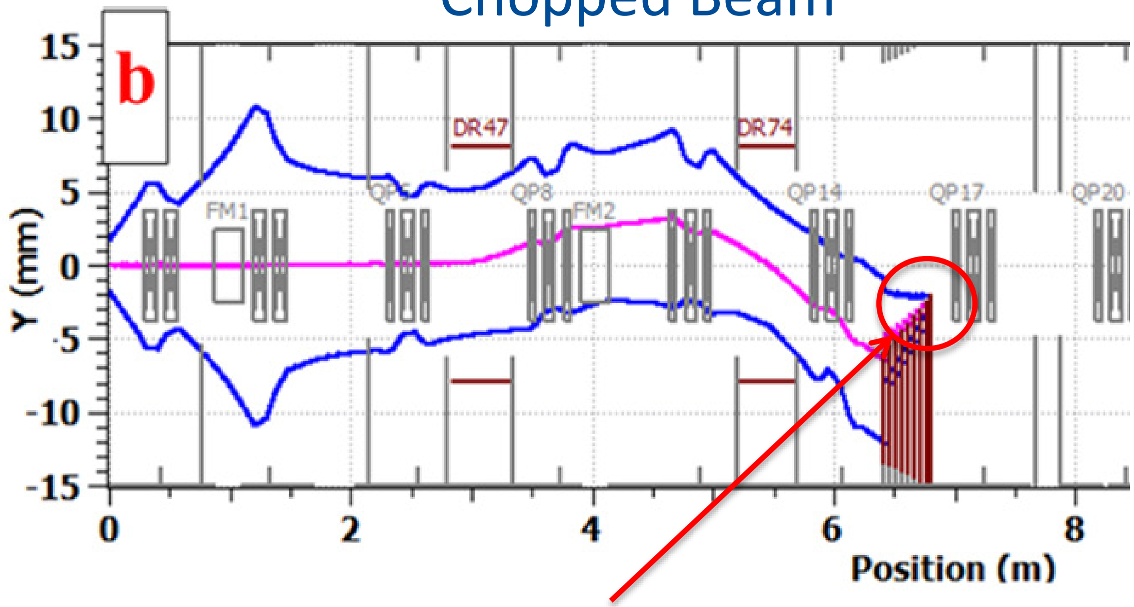
List of Major Issues

1. Extinction depends on MEBT chopper system – can this system achieve the required 10^{-11} extinction factor?
2. Where to strip H^- to *p*. Can we transport and target H^- ?
3. Beam enclosure and Mu2e building radiation shielding. Present facilities designed for 8 kW. Can shielding be augmented to accommodate 100 kW?
4. Primary beam transport into and through the PS – can we still hit the target and dump? What are the implications for the extinction monitor?
5. Target and target handling upgrades required for 100 kW beam.
6. HRS upgrades to provide the additional PS and TS thermal and radiation shielding required for 100 kW beam.

Extinction

- What level of out-of-time extinction can we expect from the MEBT chopper system
- Some simulations have been done. MEBT Chopper estimated extinction factor is 10^{-9}.
- Additional beamline extinction system required – Mu2e AC Dipole system (with modifications) still required.
- Extinction testing at PIP2IT (PIXIE) cancelled to reduce costs ⇒ this test program <u>must</u> be restored.

Chopped Beam



3σ beam envelope at edge of absorber

- Is 0.135% of gaussian beam transmitted?
- <u>Answer</u>: NO
  - Tails beyond 3σ removed by upstream collimation and LEBT chopper
  - Does this get us to an extinction factor of 10^{-11}?

H^- Stripping

- Presently there is no provision for stripping the electrons in the PIP-II Linac
- H^- has two electrons: one tightly bound (13.6 eV), the other is not so tightly bound (0.75 eV).
- Two Options:
  1. Transport H^- to Mu2e production target
     - Is this option available for consideration?
     - Need to keep the H^- intact all the way to the target
     - In each beamline magnet the electrons see a rest frame electric field given by: $\vec{E} = \gamma c\vec{\beta} \times \vec{B}$ $\Rightarrow$ *relatively easy to neutralize* H^- *to* H. PS field could be a problem. What will the extinction dipole do to out-of-time H^-?
     - Target station geometry designed for positively charged beam.
     - Does this option require better beamline vacuum?
  2. Strip the electrons:
     - Where? (225 μA e^- has to go somewhere)
     - Radiological issues?
     - Inefficiencies
     - Should be a solvable problem

Radiological Issues

- Mu2e-II removes from consideration two very serious radiological liabilities
  - Resonant Extraction (very lossy)
  - Poor shielding of the Delivery Ring enclosure
- However, the increased beam power on target greatly aggravates the radiological hazard in the Mu2e building.
  - Radiological conditions for 8 kW primary beam:
    - Radiation does rates on berm above PS hall: 3 – 5 mRem/hr (steel shielding required to achieve these rates)
    - Sky shine does rate at Wilson Hall $\lesssim$ 0.1 mRem/yr
    - West wall concrete augmented to prevent surface and ground water activation
  - Mu2e-II beam 14× greater beam power, 14 – 22× greater intensity per pulse, 3.5× greater duty factor give:
    - increased dose rates on berm at the Mu2e building
    - increased sky shine dose rates in remote locations (i.e. Wilson Hall, Site Boundary)
    - much greater target and beam dump activation
- Greater neutron and charged particle fluence toward Mu2e detectors
- Very little space available to augment shielding

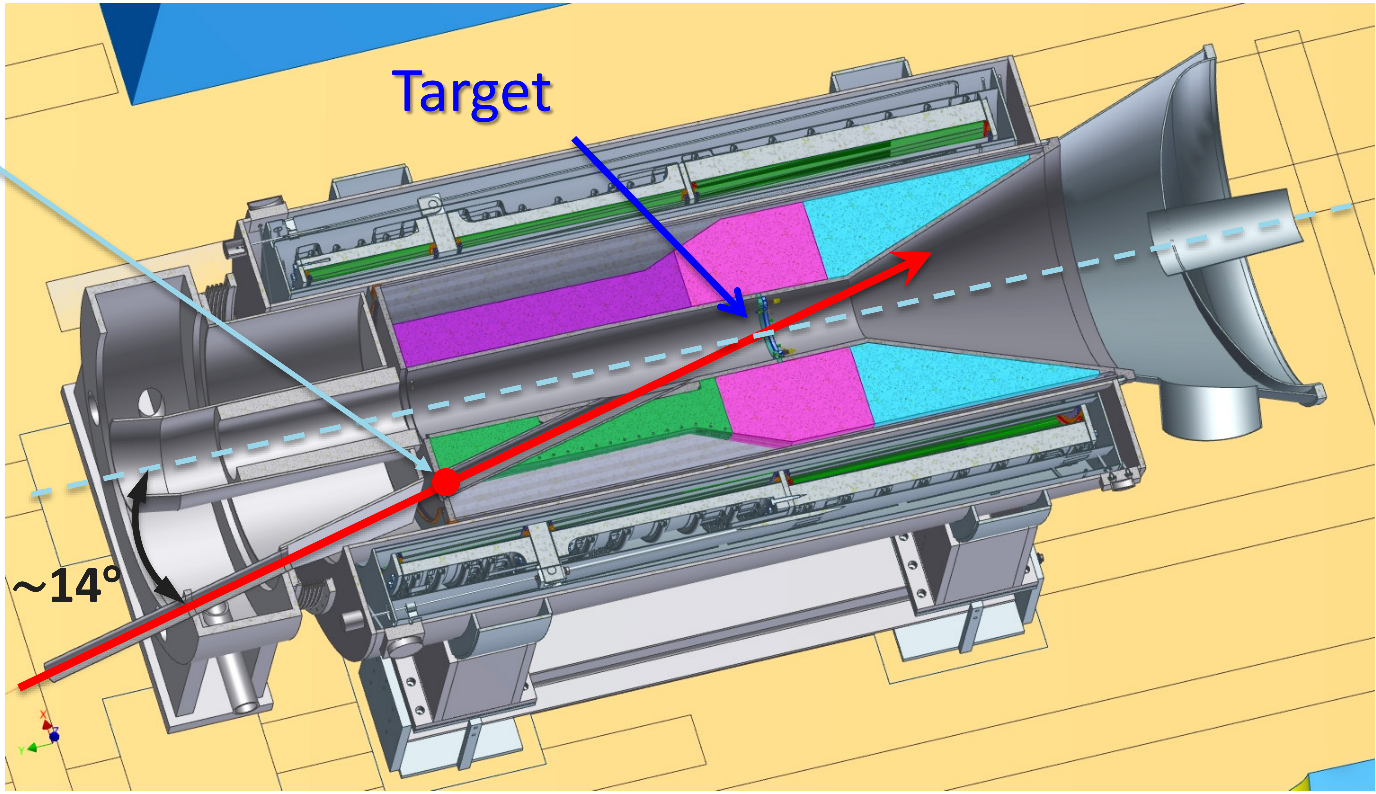
Primary Beam Transport through the Solenoids: 8 GeV Proton Beam Trajectory

8 GeV proton beam enters PS:

- 0.57 m off-axis
- vertical pitch = -3.1°
- horizontal bearing = 13.6° relative to the PS axis

For 8 GeV beam, the horizontal projection of the proton trajectory is well approximated by a straight line.

This is not the case at 800 MeV.



Horizontal section of production solenoid.
PS axis is parallel to the magnetic field.

Primary Beam Transport through the Solenoids

8 GeV proton beam

- Proton beam enters PS 0.57 m off-axis with vertical pitch of -3.1° on a horizontal bearing of 13.6° relative to the PS axis
- Beam hits target on PS axis (approx.) with zero pitch and 14° relative bearing
- Non-interacting beam is centered in the target dump
- Extinction monitor properly aimed and outfitted to see 4 GeV secondaries

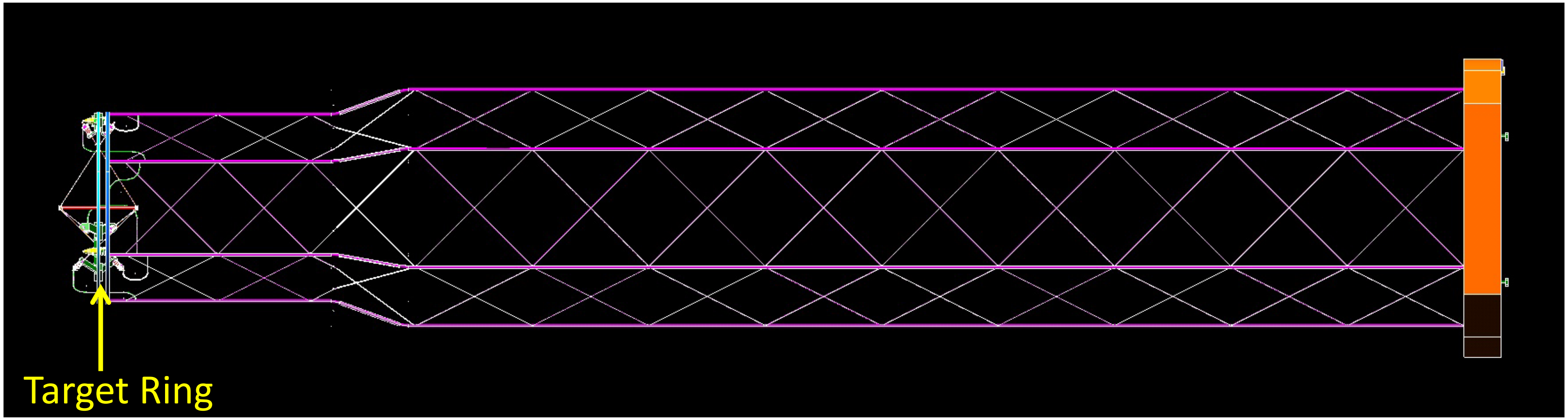
800 MeV beam

- Would not hit the target if constrained to enter PS along 8 GeV trajectory (H^- more problematic than *p*) $\Longrightarrow$ *must steer primary beam parallel to and close to the PS axis.*
- Bringing beam in closer to PS axis requires a beam pipe that goes through TSu coils (problematic if the TS is to be retained)
- Beam injected into the PS along its axis will no longer be centered in the dump
- Extinction Monitor concept must be re-thought
  (**Note also:** Extinction Monitor sensitivity must be increased to measure 10^{-11} extinction factor)

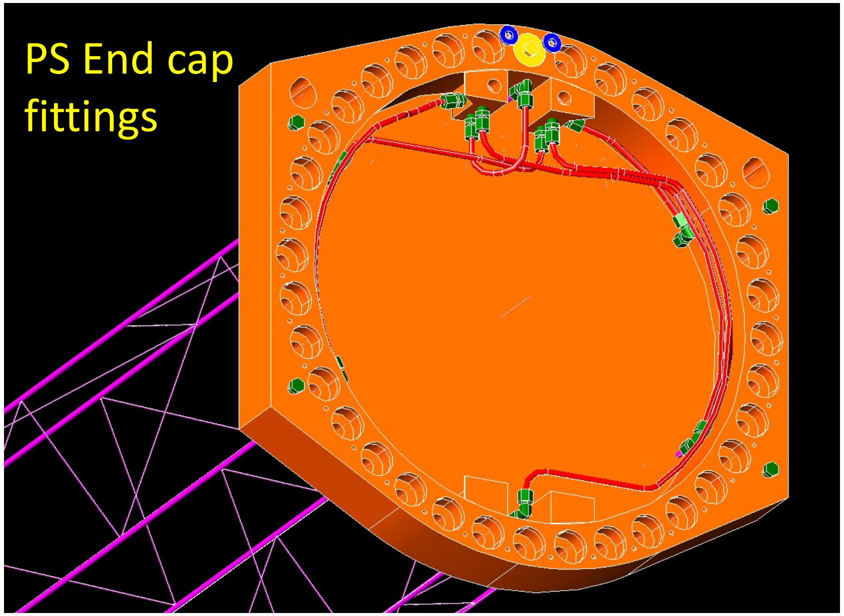
Target Station Issues

- Present target is radiatively cooled – designed to survive one year of 8 kW beam
  - One year target lifetime at 100 kW will require forced cooling of the target.
  - A conceptual design of a target cooling system exits (next slide)
- At 100 kW, radiation damage to the target will be an issue – may be the principle factor determining target lifetime $\Longrightarrow$ *R&D Required*
- The present target beam dump is air cooled
  - Target dump for 100 kW primary beam will require water cooling
  - Requires disassembly of a highly radioactive component (i.e. the present dump after 3+ years of exposure)
- Target handling system will require upgrade to accommodate a more radioactive target and the cooling system plumbing.

Target Cooling Scheme – Mike Campbell (Mu2e-doc-4146)

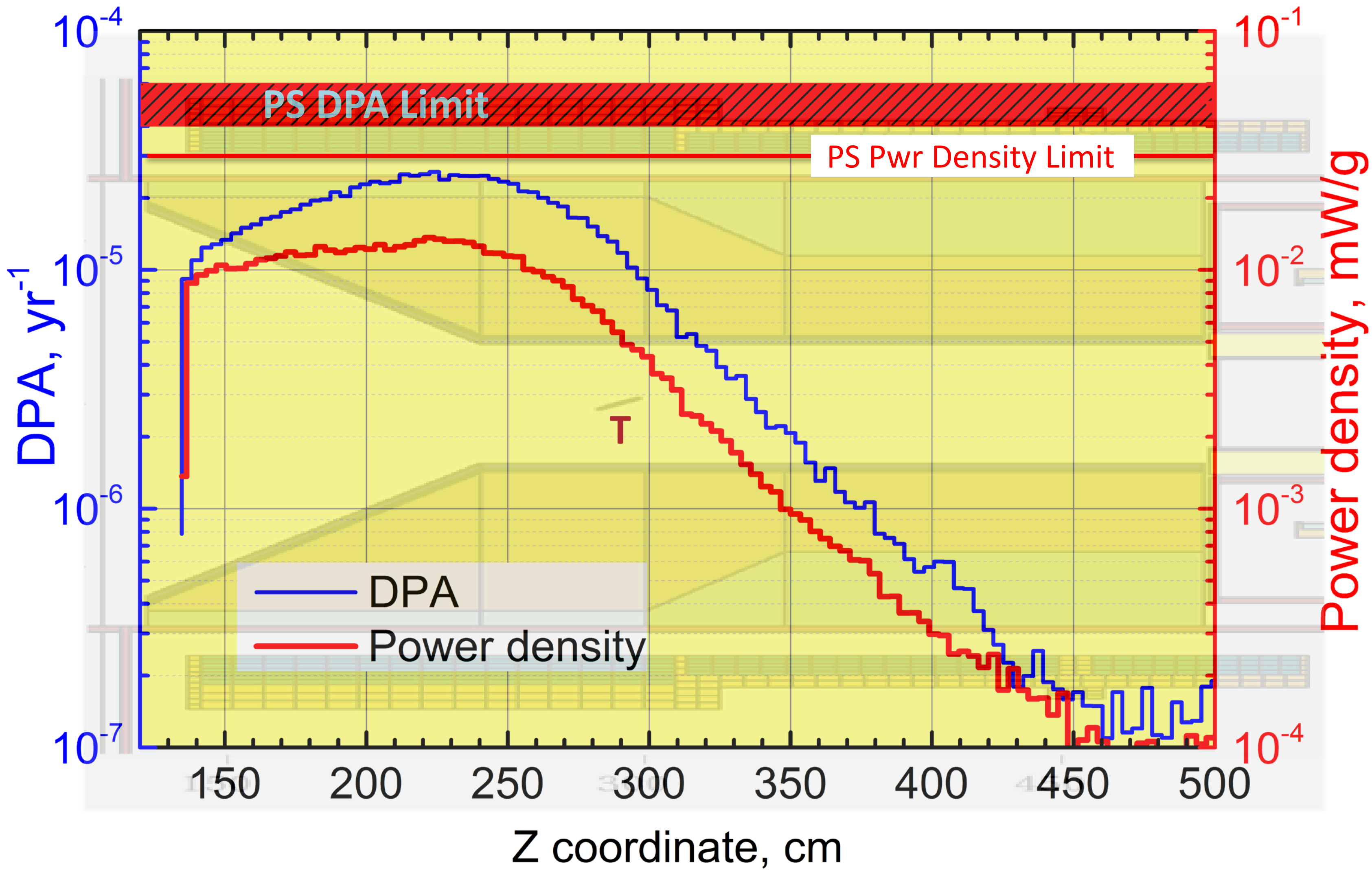


- Concept for a plumbing scheme for a cooled target has been developed
- Very low mass – minimal impact on muon yield
- Target would be enclosed in a Titanium jacket
- Target change-out includes plumbing replacement



Simulated 8 GeV HRS Performance

MARS Simulations
Vitaly Pronskikh



HRS Upgrades

- At 8 GeV, HRS radiation damage and energy deposition margins are small
  - no room to increase beam power
  - do not want to warm up for annealing more than once per year

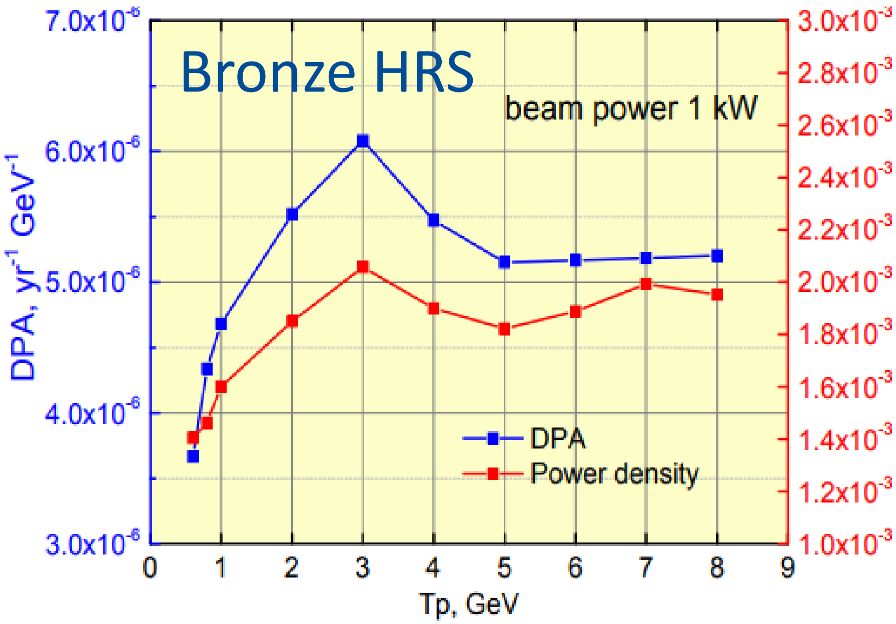
  ⇒ HRS must be replaced

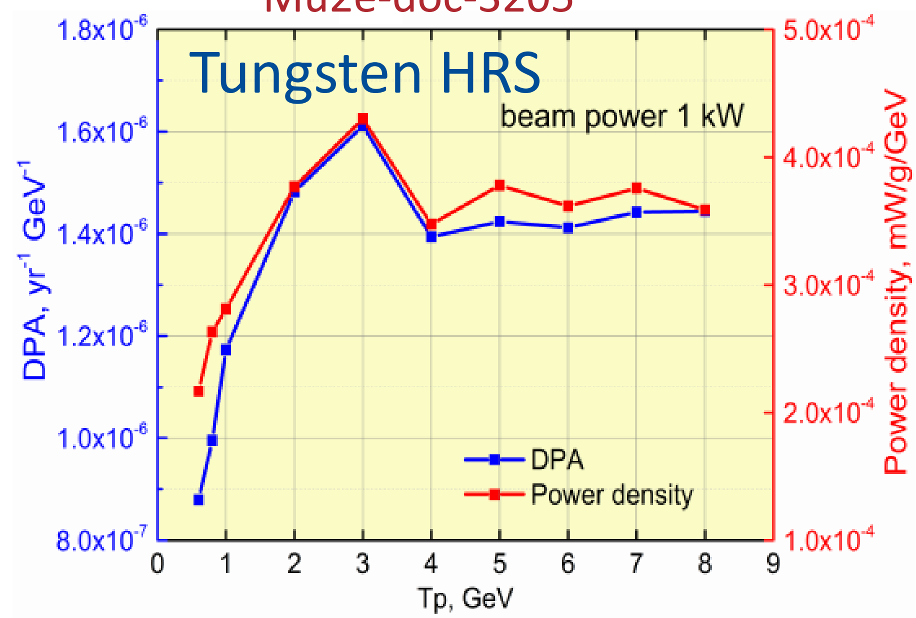
- HRS removal will be difficult
  - HRS is welded to the PS cryostat
  - HRS will be extremely radioactive after Mu2e run
  - Must consider removing both HRS and PS together

- Options for improving heat and radiation shielding:
  - Change material (tungsten instead of bronze) – very expensive
  - Increase HRS thickness – lost muon yield

Replacement HRS

Plots: Vitaly Pronskikh
Mu2e-doc-3205





Estimated Mu2e-II DPA and Pwr Density @100 kW with Tungsten HRS:

Mu2e-II	Value	Limit
DPA (DPA/yr)	16×10^{-5}	4×10^{-5}
Power Density (mW/g)	4.2×10^{-2}	3.0×10^{-2}

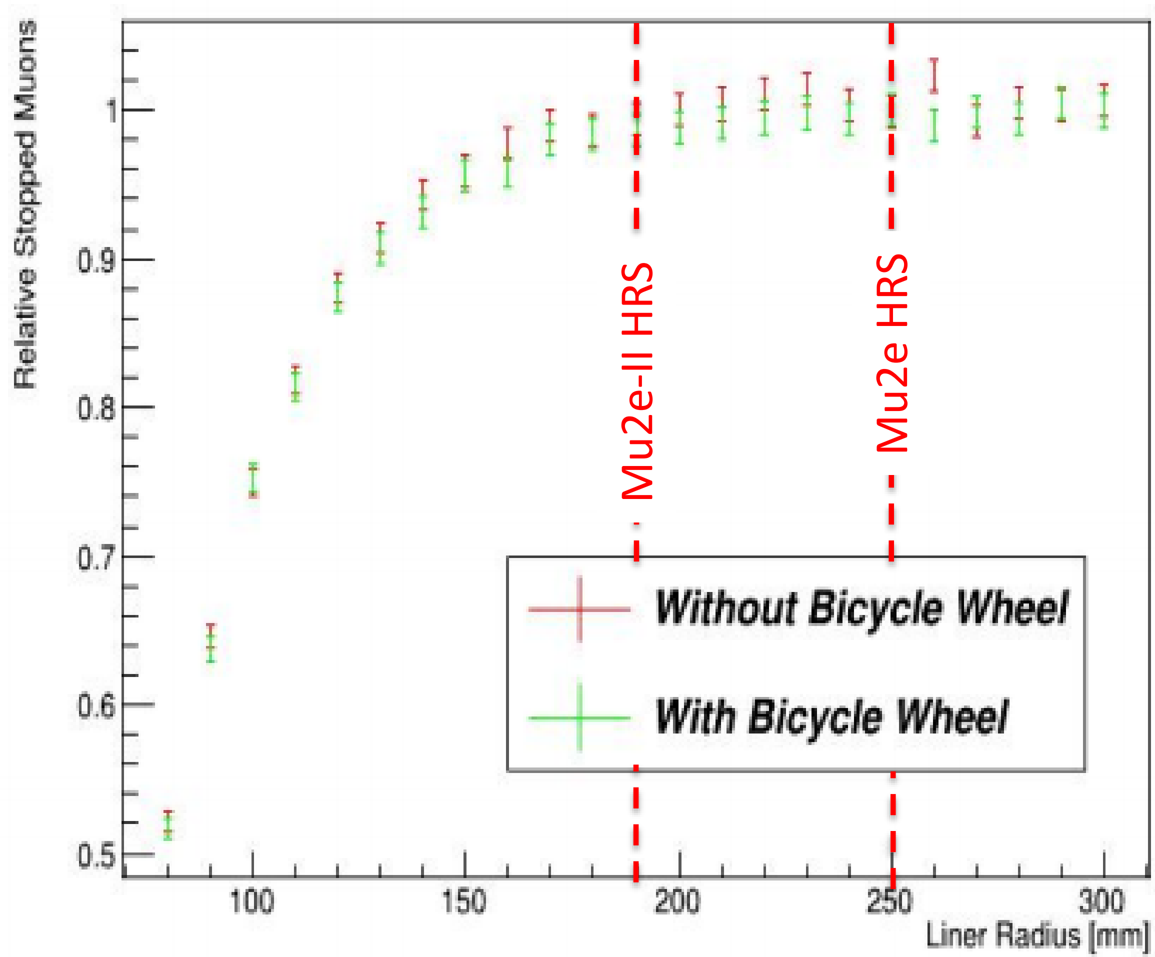
Conclusion:

Changing material to Tungsten not sufficient

HRS Options

1. Build Tungsten HRS and do nothing else – warm up 2 to 3 times per year to anneal PS coils
2. Build Tungsten HRS with increased thickness (smaller bore)
   - From Vitaly: 9 cm decrease in HRS radius lowers DPA 4×
   - We require 2.5× reduction (25 cm → 19 cm)
   - *Muon yield decreases by less than 5%*

HOWEVER, all of the plumbing to cool the target takes up space inside the HRS bore decreasing the effective radius.



J. Popp & K. Lynch
Mu2e-doc-3165

Accelerator Issues Approximately Ordered by Difficulty

1. Primary beam transport into and through the PS – How do we hit the target, dump, and extinction monitor?
2. Radiological issues – Can shielding be augmented to accommodate 100 kW?
3. Target and target handling upgrades required for 100 kW beam.
4. HRS upgrades
5. Extinction – Can MEBT chopper + beamline extinction system achieve the required 10^{-11} extinction?
6. Where to strip H^- to *p* – Can we transport and target H^- ?