Accelerator R&D for Mu2e-II

Steve Werkema

Mu2e-II Workshop

Northwestern University

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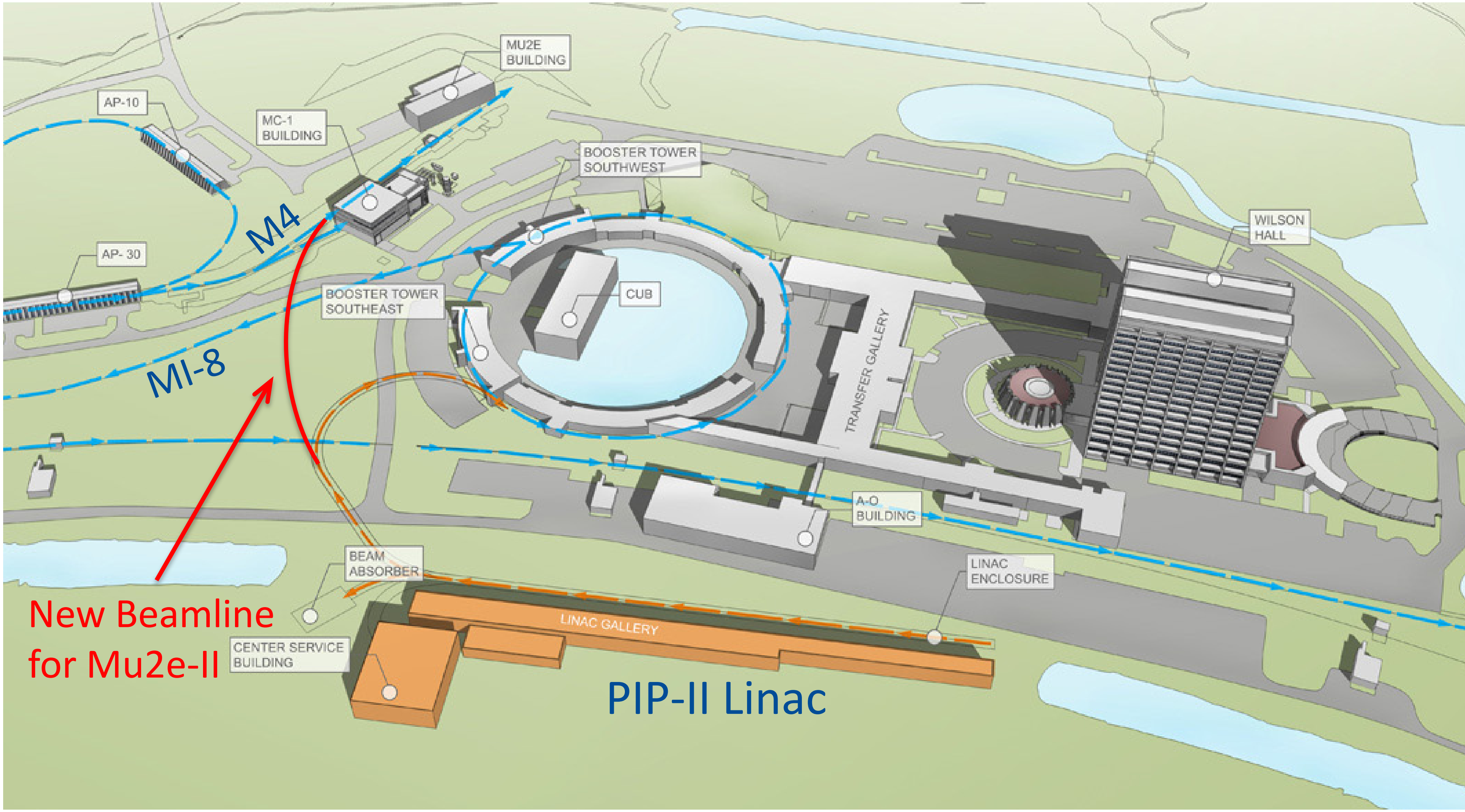
In partnership with:

Outline of Talk

1. Overview of beam delivery to Mu2e-II
2. List of accelerator issues
3. Target Station Taskforce

Mu2e-II Beam Delivery

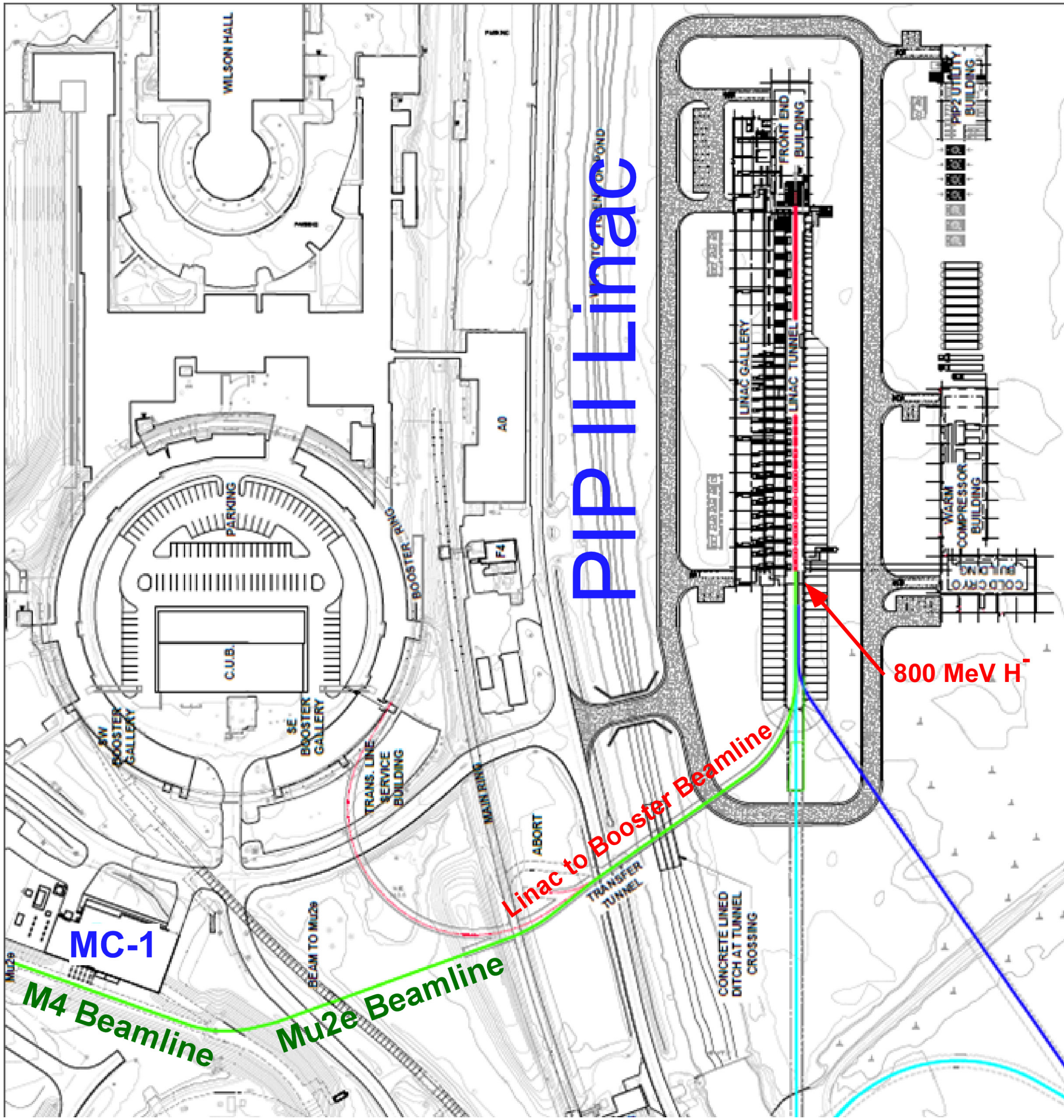
Mu2e II Beam Delivery



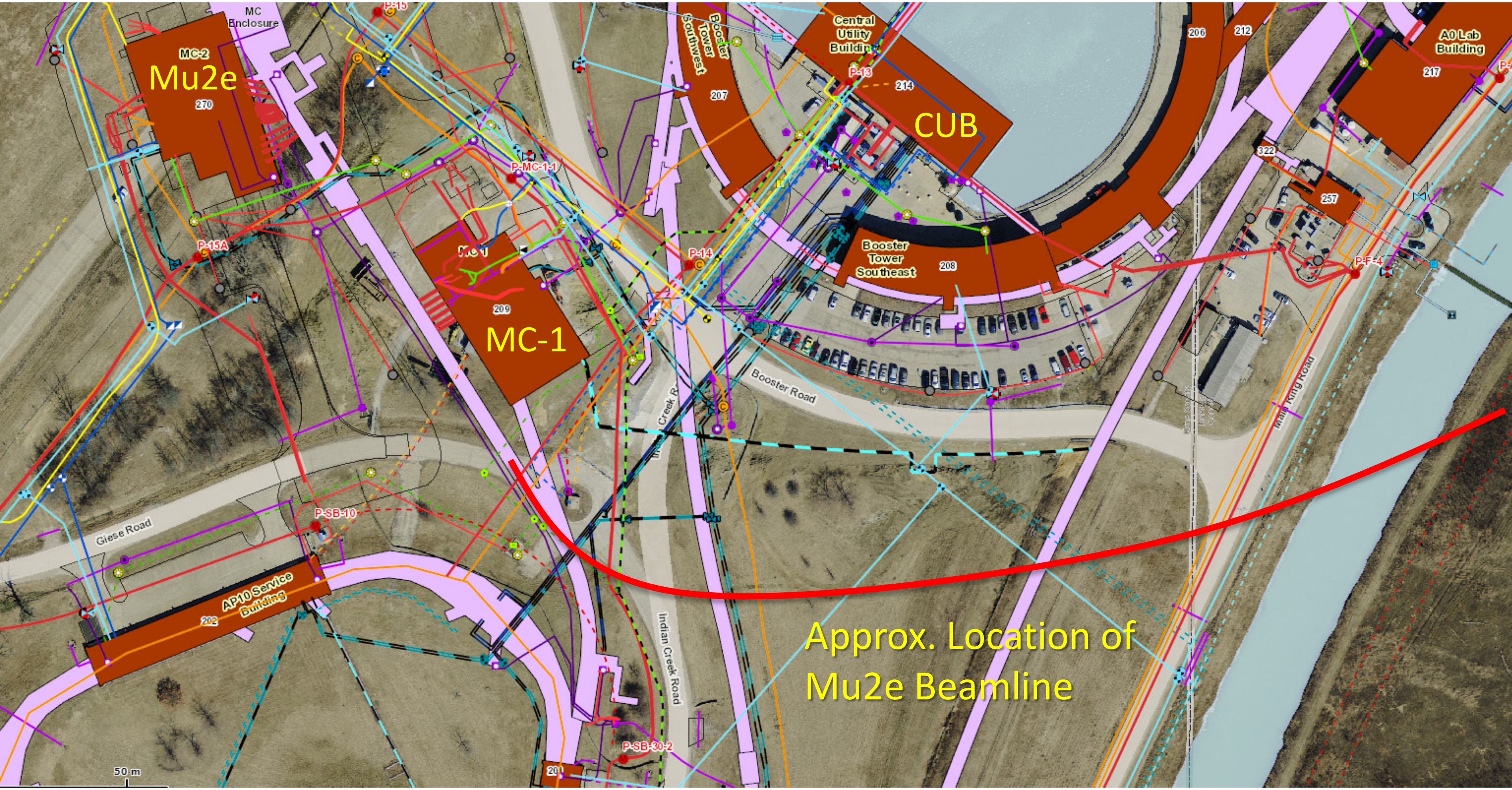
Mu2e-II Beam Delivery

- PIP-II Linac delivers 800 MeV pulsed H$^-$ beam to an extension of the Linac-Booster beamline
- H$^-$ pulse rate can be varied between 0.5 MHz and 1.25 MHz
- H$^-$ pulses are 100 nsec long
- Beam is switched to a dedicated Mu2e beamline

PIP II CDR contains a lattice design for the new Mu2e beamline



Potential Utilities Interference with Mu2e Beamline



Mu2e and Mu2e-II Proton Beam Parameters

Parameter	Mu2e	Mu2e II	Units
Total Protons on Target (3 yr)	4.7×10^{20}	5.2×10^{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}	1.4×10^{9}	protons/pulse
Pulse-to-Pulse Intensity Variation	<50	<10	%
Beam Kinetic Energy	7946	800	MeV
Beam Power	7.3	100	kW
Duty Factor	25	90	%

NOTEs:

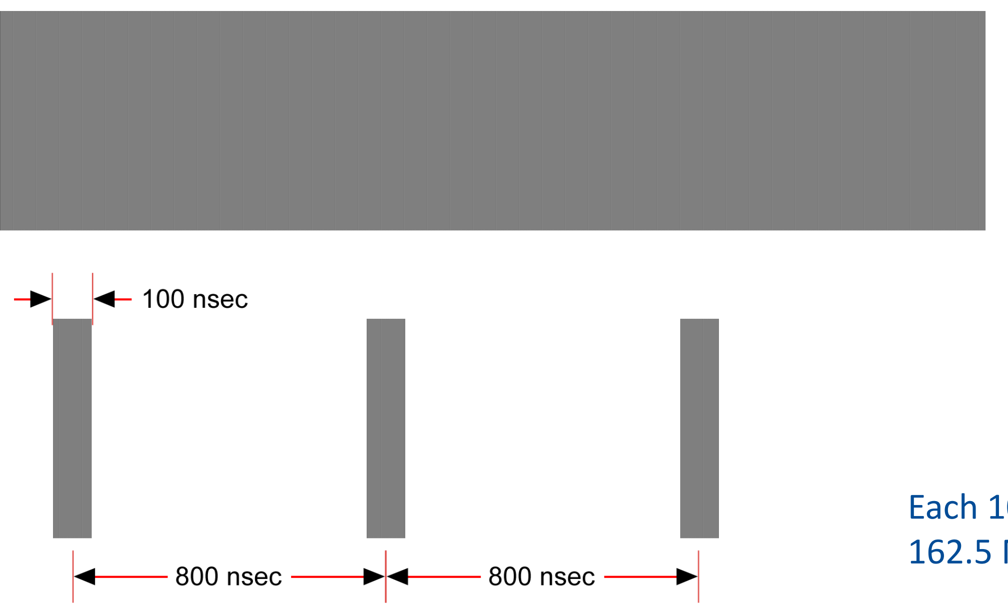
- Blue numbers are calculated from the other parameters.
- Total POT assumes 63% accelerator up-time (2×10^{7} sec/yr)

Pulse Formation for Mu2e-II

- Most of the pulse formation for Mu2e will occur in the Medium Energy Beam Transport (MEBT) section of the PIP-II Linac. MEBT is the final stage of the warm front end of the linac.
- The input to MEBT is a 162.5 MHz pulse train of 2.1 MeV H^- ions.
- The chopper system in the MEBT forms 100 nsec pulses for Mu2e by the removing unwanted beam between pulses.

MEBT input
(CW Mode)

MEBT output



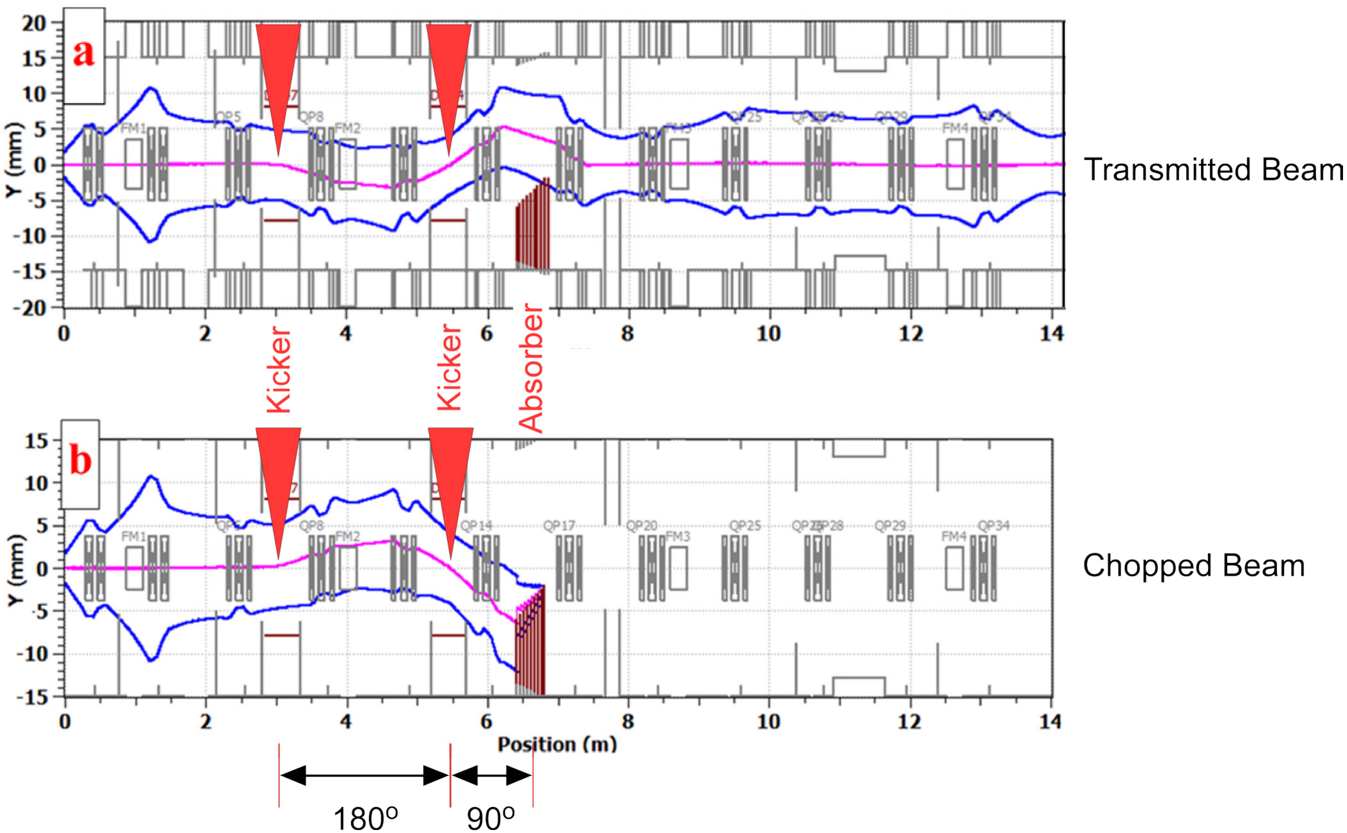
Continuous train of
162.5 MHz (6.15 nsec) pulses

(162.5 MHz bunches too small to see on this scale)

1.25 MHz (800 nsec) train of
100 nsec pulses for Mu2e

Each 100 nsec pulse contains 16 162.5 MHz pulses

Pulsed Beam Formation – Beam transport through MEBT



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

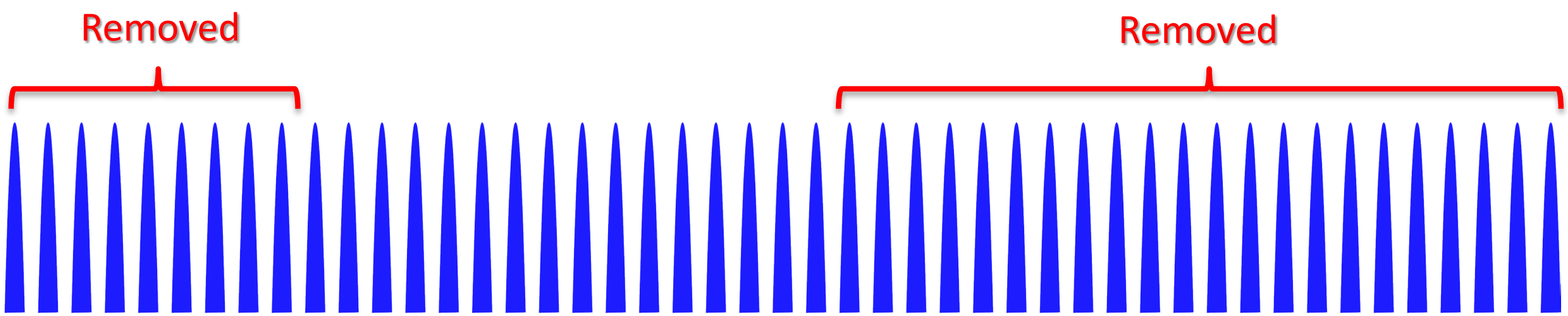
- Pulse formation is accomplished by a fast bunch-by-bunch chopper.
- Chopper consists of two fast vertical kicker magnets and a beam absorber
- Kickers are excited during transmission and chopping

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 variable 800 – 2000 nsec bunch spacing.

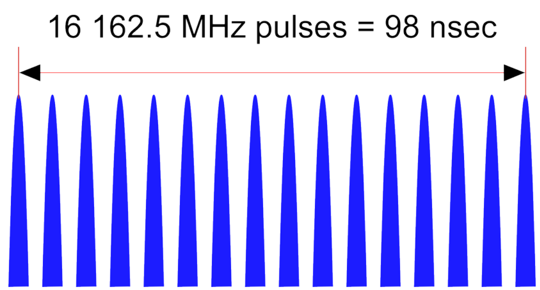
MEBT Chopper Operation for 100 nsec pulse formation

Chopper Input



pulse spacing = 6.15 nsec

Chopper Output

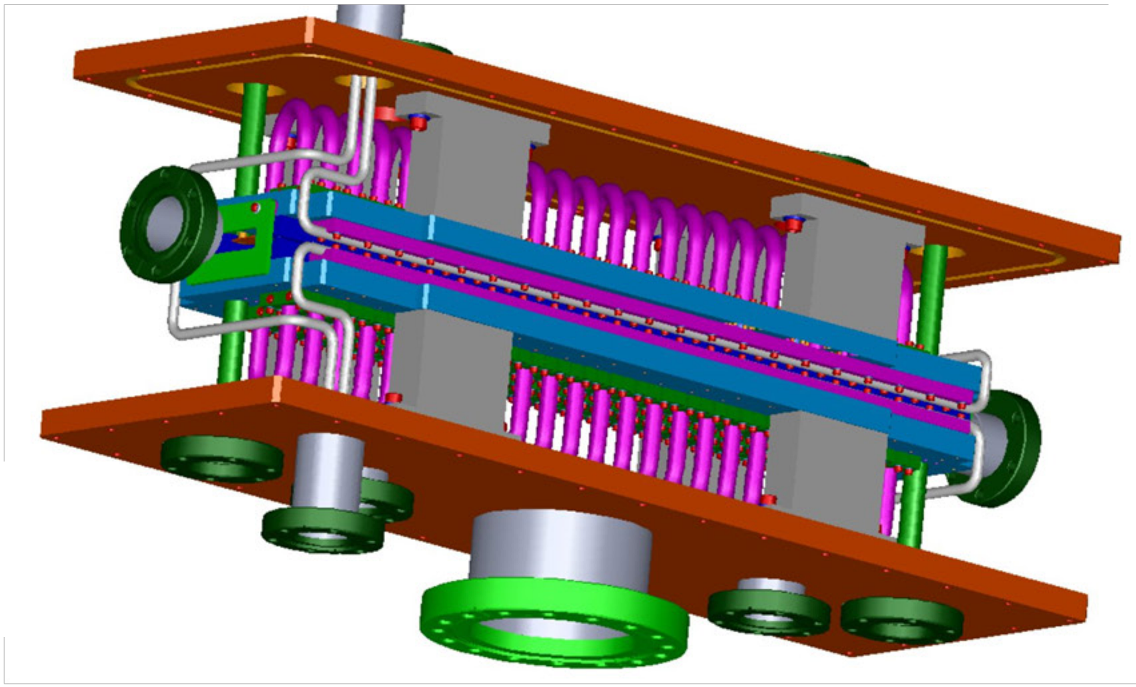


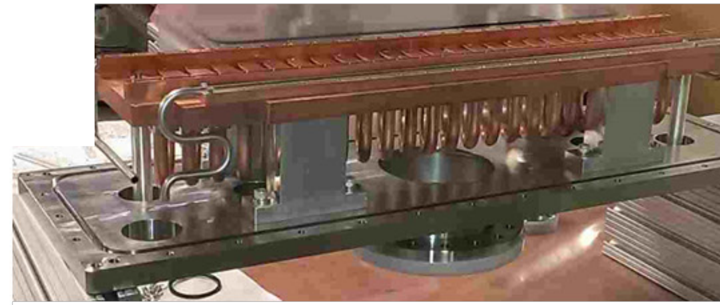
This is the longitudinal profile seen by the production target

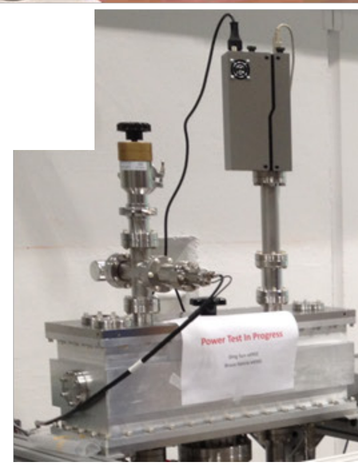
Notes:

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

Fast Kicker for MEBT chopper







This is one of two prototype kickers built for testing in PIP2IT

Accelerator Issues

List of Major Issues

1. Extinction depends on the MEBT chopper system – can this system in combination with the M4 AC dipoles achieve the required 10^{-11} extinction factor? What modifications to the M4 AC dipoles and power supplies are required to accommodate 0.5 to 1.25 MHz variable pulse repetition rates?
   Relatively Easy

2. Where do we strip the electrons in the H^{-} beam?
   Worrisome

3. What upgrades to the radiation shielding of the M4 Beamline enclosure and Mu2e building are required? Present facilities designed for 8 GeV / 8 kW protons. Can the existing shielding be augmented to accommodate 100 kW? At what cost?
   Difficult/Expensive

4. Primary beam transport through the TS and PS – can we still hit the target and the proton absorber? What are the implications for the extinction monitor?
   Difficult/Expensive

5. Target station and target handling upgrades required for 100 kW beam.
   Difficult/Expensive

6. HRS upgrades to provide the additional PS and TS thermal and radiation shielding required for 100 kW beam.
   Worrisome/Expensive

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: $\vec{E} = \gamma c\vec{\beta} \times \vec{B}$ ⇒ *relatively easy to neutralize* H^- *to* H. PS field could be a problem. What will the extinction dipole do to out-of-time H^-?
     - 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 from the Delivery Ring (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: 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

The radiological issues will be very difficult to solve

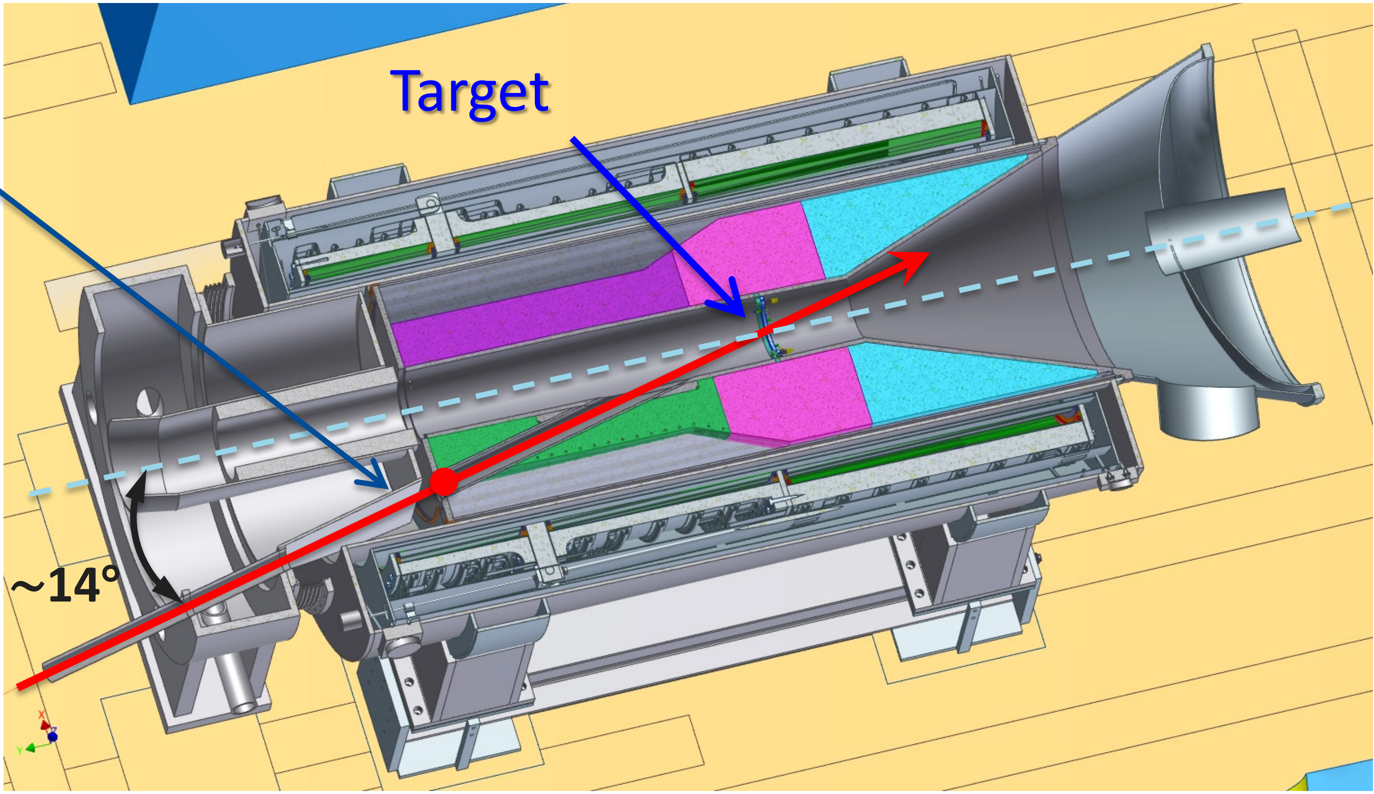
Primary Beam Transport through the Solenoids: 8 GeV Proton Beam Trajectory

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.



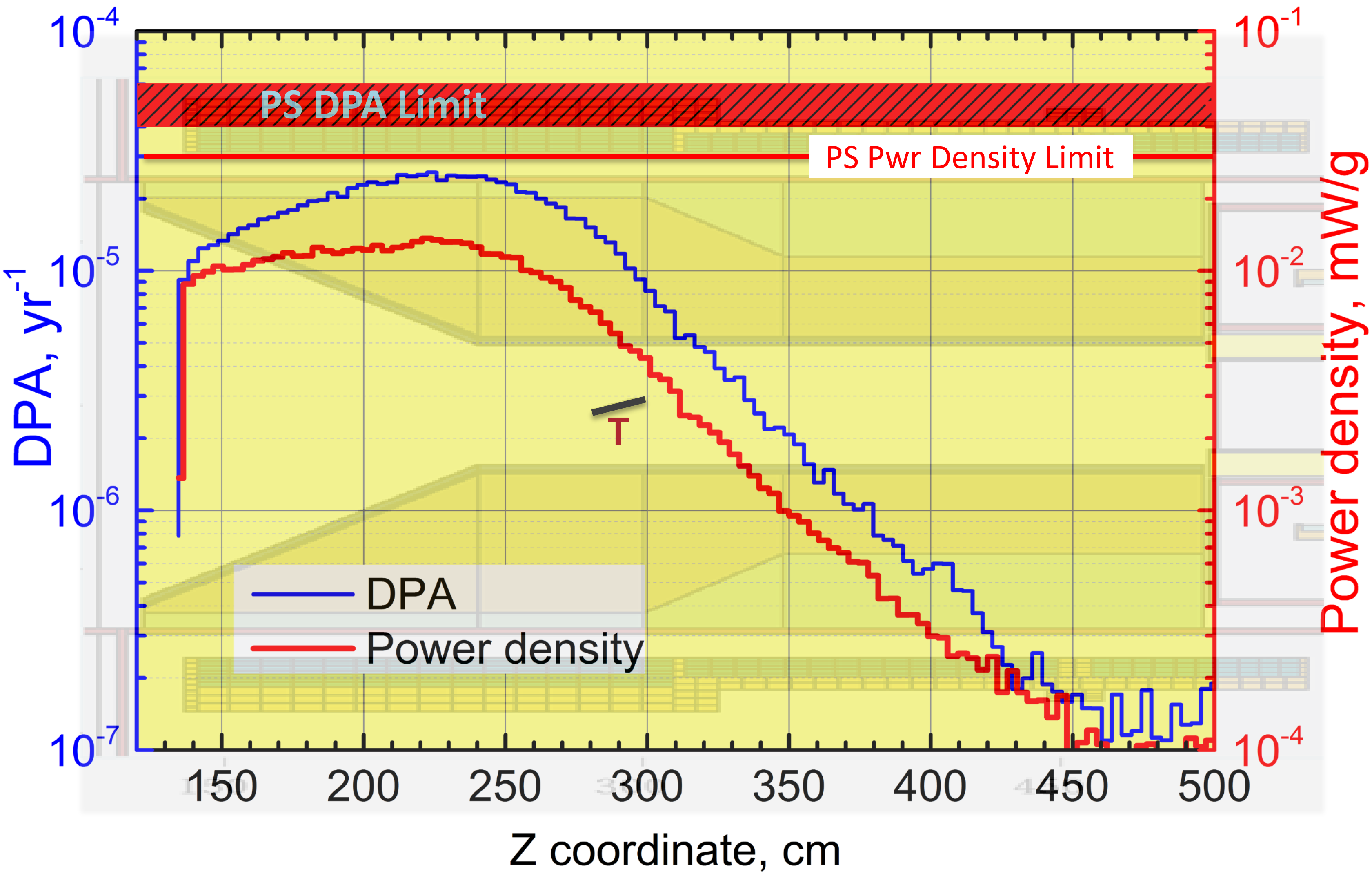
Horizontal section of production solenoid.
PS axis is parallel to the magnetic field.

See talk by David Neuffer at this workshop

This is a difficult problem – smart people are working on it. See:
Tom Roberts, Mu2e-doc-6810, and
David Neuffer, Mu2e-doc-16328

Simulated 8 GeV Bronze 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
  - Very likely we will remove the 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

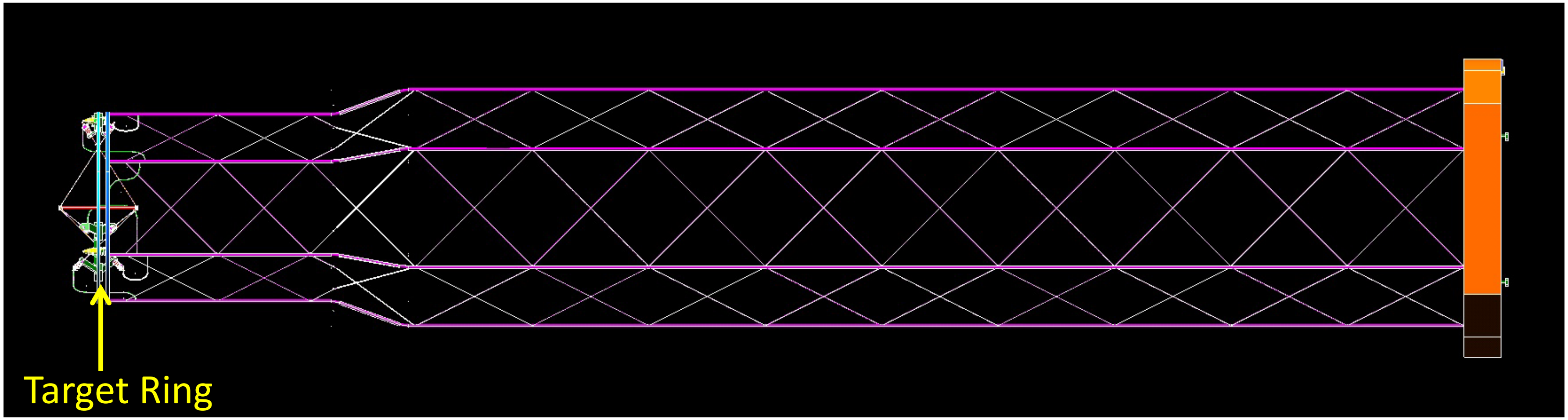
See talk by Vitally Pronskikh at this workshop

Target Station Issues

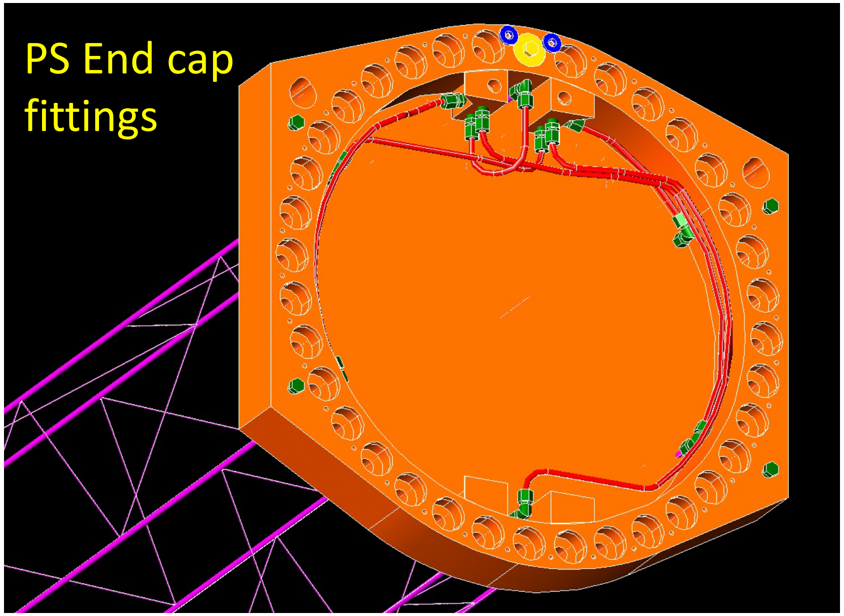
- Present Mu2e target is radiatively cooled – designed to survive one year of 8 kW beam
  - One year target lifetime at 100 kW will require forced cooling of the target.
    - Plumbing for cooling system kills muon yield
    - Need real-estate for cooling plant
  - A conceptual design of a target cooling system exits (next slide)
- At 100 kW, radiation damage to the target will be an important issue – may be the principle factor determining target lifetime $\Longrightarrow$ *R&D Required*
- The present location of the target dump is optimized for 8 GeV beam, not 800 MeV
- 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.

These could be the most difficult issues to be solved for Mu2e-II

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



- Concept for a plumbing scheme for a cooled target has been developed
- Very low mass to minimize impact on muon yield
- Target would be enclosed in a Titanium jacket
- Target change-out includes plumbing replacement (more expensive)



Target Station Task Force

Target Station Task force

- In June, a task force was formed to study the target station issues of Mu2e II.
- The task force participants (so far) are:

Bob Zwaska	FNAL AD	co-chair
Steve Werkema	FNAL AD	co-chair
Kevin Lynch	York College	
Jim Popp	York College	
Eliana Gianfelice-Wendt	FNAL APC	
Vadim Kashikhin	FNAL TD	
Dave Neuffer	FNAL APC	
Giorgio Ambrosio	FNAL TD	

- The task force has had one meeting (yesterday)

Charge for Mu2e-II Target Station Task Force (1)

22 June 2018

The Task Force will develop conceptual design options for a production target capable of handling sufficient beam power to enable the Mu2e-II experiment. Mu2e-II is an upgrade that aims to improve the sensitivity to the flavor-violating process, $\mu N \rightarrow eN$, by another order of magnitude relative to the Mu2e experiment. The production target will be located inside the Mu2e Production Solenoid and shall be designed to meet the following physics requirements:

- will utilize a pulsed beam of 800 MeV protons from PIP-II
- will tolerate a total number of protons on target large enough to produce at least 7 x 10^{18} stopped muons (i.e. about x10 more than the current Mu2e) over a total running time of 6 x10^{7} seconds (i.e. full intensity running for 3y at 2 x10^{7} seconds per year, the same as the current Mu2e)[†]

The pulsed proton beam is expected to have these characteristics:

- the proton pulses will have a full width of no more than 100 ns
- the proton pulses will be spaced about 1700 ns apart
- the pulse-to-pulse intensity variation will be no larger than +/-20% of the nominal intensity
- the ratio of out-of-pulse beam to in-pulse beam (ie. extinction) is no more than 1 x 10^{-11}
- the Mu2e pulses will be delivered uninterrupted for >900 ms of every second (on average) $\Rightarrow$ Duty Factor $\geq$ 90%

Very similar to parameters given earlier

Owing to the increased radiation and heat loads necessary for Mu2e-II, the Mu2e Production Solenoid (PS) will have to be replaced. Since the upgraded production target will be located inside the upgraded PS, the conceptual design of the two should be developed together. The new PS should:

- fit within the existing Mu2e PS hall
- match the TS field
- house the production target and the associated supports and services
- house an upgraded Heat and Radiation Shield.

We expect to raise the beam power

† Assuming the same stopped-μ/POT ratio as the current Mu2e, this would correspond to an average beam power of about 80 kW. **Any reduction in the stopped-μ yield, owing, for example, to significant changes to the geometry of the production target or its associated supports and services, should be compensated by an increase in beam power in order to meet this requirement.**

Charge for Mu2e-II Target Station Task Force (2)

Provide a prioritized list of target and solenoid R&D items that must be investigated to further develop the production target and PS designs for the Mu2e-II experiment. This list should be annotated with specific questions that must be answered to begin estimating the cost for the upgrades necessary for Mu2e-II.

Issue preliminary report by **01-November-2018**, and final report by **31-January-2019**.

Note: it has not escaped our notice that we haven't (yet) been asked to solve any problems

Target Station Task Force – Likely Beam Power Adjustments

- Target will require convective cooling (Mu2e target is radiatively cooled). The plumbing required to bring the cooling media to the target will absorb secondaries.
- Convectively cooled target will require a cooling jacket giving the target a larger footprint inside the PS bore.
- Target material may need to be changed. A lower Z target would reduce the yield.
- The curvature of the primary beam trajectory in the PS is greater causing some reduction in the overlap of the beam transverse distribution and the target.
- HRS thickness may need to be increased, reducing the aperture for transport of secondaries. This also moves the target cooling pipes closer to the target where the secondary flux is greater.

Accelerator Issues Approximately Ordered by Difficulty

1. Delivery of beam to Mu2e-II will be a challenging and expensive undertaking.

2. Work has begun on some of the most important issues as you'll hear in the next few talks.

3. The Target Station Task Force is up and running