Mu2e-II
PIP-II Accelerator Beam for Mu2e-II

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Accelerator beam issues

- Topics to include in mu2e-II white paper
- Transport from PIP-II to Mu2e
  - Switchyard
  - H^- stripping
  - Extinction
- Beam-Target transport
  - Trajectories through PS solenoid, beam dump
- Target design
  - V. Pronskikh – LDRD
- Production solenoid
  - Shielding, heat load, radiation, …
  - K. Badgley- PS report
- Compatibility with PIP-III

- **Current draft is relatively minimal**
- **PIP-II must be adapted to enable Mu2e-II**
  - **CW rf** power sources must be installed
  - Beam transport from PIP-II to Mu2e-II must be constructed.

A. Overview of PIP-II capabilities

Construction has begun on the PIP-II accelerator and is expected to be completed by 2028. The PIP-II Linac will provide a 800 MeV proton beam with CW capability, with beam power up to ~1.6 MW (2 ma, 800 MeV beam) available for user experiments [25]. The Mu2e-II experiment would use 100 kW of the PIP-II beam in our initial baseline scenario. This could be increased if the Mu2e-II components can handle more intensity. The Mu2e-II beam will require post-construction upgrades of PIP-II that enable CW operation, which will include installation of CW rf power sources. It will also require construction of the proton beam line to the Mu2e target hall, including beam switching magnets and possibly an rf separator to enable beamlines for other experiments.

Table II presents proton beam parameters for Mu2e-II based on use of the PIP-II linac, with comparison numbers for the Mu2e proton beam, which is based on protons slow extracted from the 8 GeV Delivery Ring (DR). PIP-II can provide very high-quality beam with small emittances and energy spreads. The transverse emittances and energy spreads are smaller than that of the 8 GeV beam, even after considering adiabatic damping. The geometric emittance is a factor of 2 smaller and the relative momentum spread ($\delta p/p$) is a factor of 10 smaller.

Beam parameters

Parameter	Mu2e	Mu2e-II	Comment
Proton source	Slow extraction from DR	PIP-II Linac	
Proton kinetic energy	8 GeV	0.8 GeV	
Beam Power for expt.	8 kW	100 kW	Mu2e-II can be increased
Protons/s	6.25×10^{12}	7.8×10^{14}	
Pulse Cycle Length	1.693 μs	1.693 μs	variable for Mu2e-II
Proton rms emittance	2.7	0.25	mm-mrad, normalized
Proton geometric emittance	0.29	0.16	mm-mrad, unnormalized
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV	
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}	
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}	
Stopped μ per cycle		1.2×10^{5}	

TABLE II. Mu2e and Mu2e-II Proton beam parameters

- **Parameter table**
  - Compares Mu2e and Mu2e-II
  - Proton beam quality from PIP-II Linac much better than PIP-II
    - Smaller beam, smaller $\delta p/p$, many more protons

B. Proton economics and Mu2e-II bunch formation

The PIP-II linac begins with a 162.5 MHz rfq and includes a chopper system that can produce an arbitrary pattern of filled or empty 162.5 MHz buckets. The maximum current per bucket is ∼5 ma (1.93×10^8 particles). For Booster injection the intensity per bucket is limited to $\sim 1.4 \times 10^8$, and concurrent Mu2e-II injection would be constrained by that limit. The PIP-II timeline must reserve time for the pulsed injection into the 20 Hz Booster; this requires ∼3ms out of every 50 ms. The desired Mu2e spill is a relatively short beam spill followed by a gap matched to the muon lifetime in the stopping target. Figure 6 shows a bunch spill pattern for Mu2e-II modelled on the initial Mu2e plan, and designed to provide ∼ 100 kW of beam on target. The time between bunch spills is ∼1.693 μs (similar to the Mu2e period of 1.695 μs). Only 10 buckets are required in each spill; the resulting beam pulse is ∼62 ns. This is much shorter than the ∼250ns of the beam spill / turn for mu2e. This should provide a cleaner separation between primary beam arrival and the later captured μ decay.

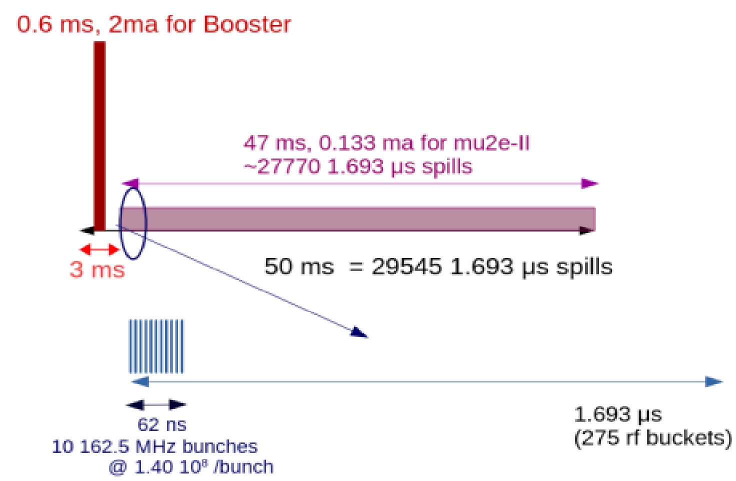


FIG. 6. Schematic view of an example of bunch train formation for Mu2e-II. The beam spill occurs over 47 ms of each 20 Hz cycle of PIP-II, with the first 3 ms reserved for Booster injection. The beam spill is split into 1.693 μs periods, with beam occupying only the first 10 162.5 MHz buckets in each period.

- **Beam sharing with other experiments**
  - **rf separator**
    - For simultaneous beams
    - ~80 MHz
      - 0.7MW to other beams ?
  - **Switching magnet**
    - Separates entire beam to different lines
    - 3ms out of 50 ms to PIP-II

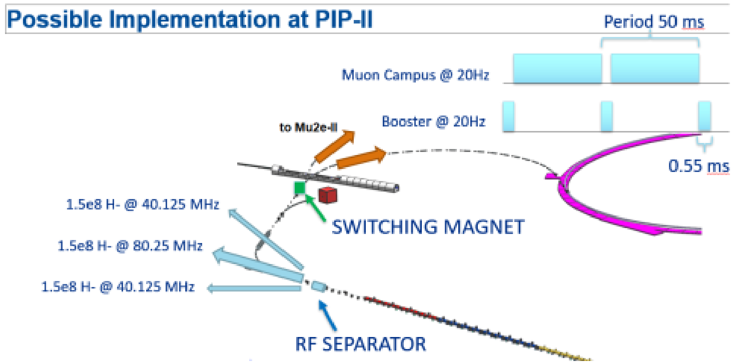


FIG. 7. Layout of a possible implementation of multiple beam delivery at PIP-II. An rf separator is placed at the end of the Linac and a switching magnet separating beam for Mu2e from beam to the booster are shown.

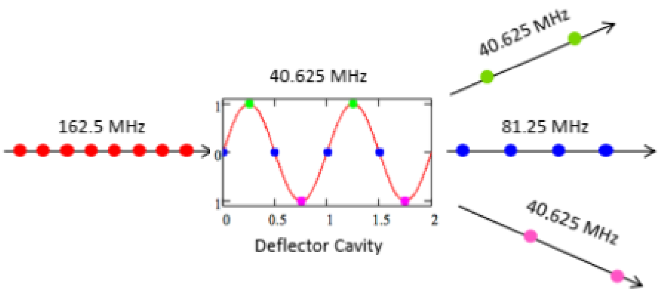


FIG. 8. RF split of a 162.5 MHz beam into 3 beams by a 40.625 MHz deflector cavity. One of these beams would be for Mu2e-II, with the others directed toward other experiments.

Beamline to Mu2e-II

- Mu2e-II beamline from PIP-II must be implemented
  - Initial design in PIP-II Design Report
  - Construction **not** included in PIP-II project
    - Stub for future construction included

Line should include proton stripping ($H^- \rightarrow p$)

D. Beam line design

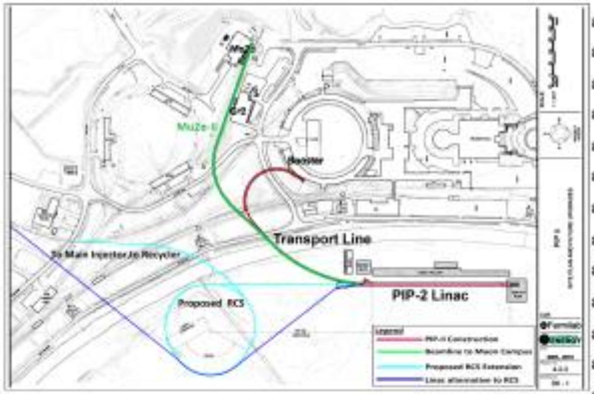
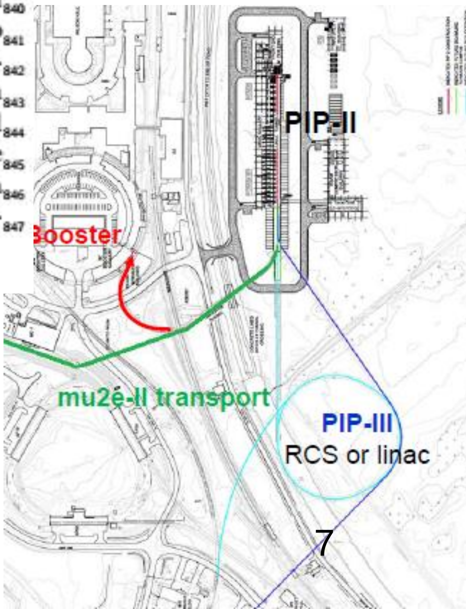


FIG. 9. PIP-II linac with transport lines to Booster (red) and mu2e-II (green) indicated.

The mu2e-II experiment will require a new beam transport from the end of the PIP-II Linac into the M4 beamline that continues into the mu2e experimental hall. An initial design of that beam line was included in the PIP-II design report, and its trajectory is shown in figure 9. The beam line may be modified to include H^- stripping and a beam switchyard for beam sharing with other experiments.

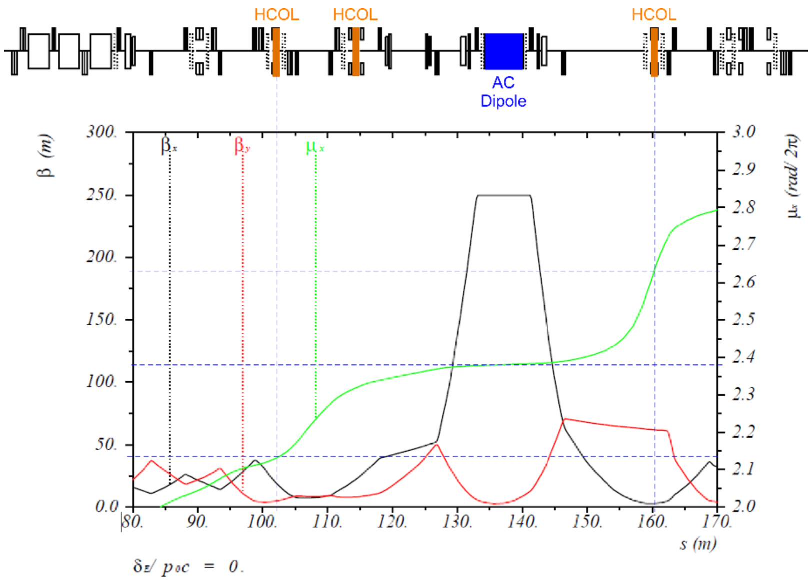
E. Proton stripping

The beam from the PIP-II linac is an 800 MeV H^- beam. The 800 MeV H^- beam would be magnetically stripped to hydrogen atoms in the production solenoid, complicating the beam delivery. Foil stripping to obtain 800 MeV protons should be incorporated into the transport line toward Mu2e



Extinction

- **Last part of transport to Mu2e-II is the M4 line**
  - Includes extinction line for Mu2e
  - Parameters can be modified to provide extinction for Mu2e-II
    - Better for Mu2e-II because of superior beam quality



- **Extinction Monitor**
  - Must be replaced

Beam trajectory to target

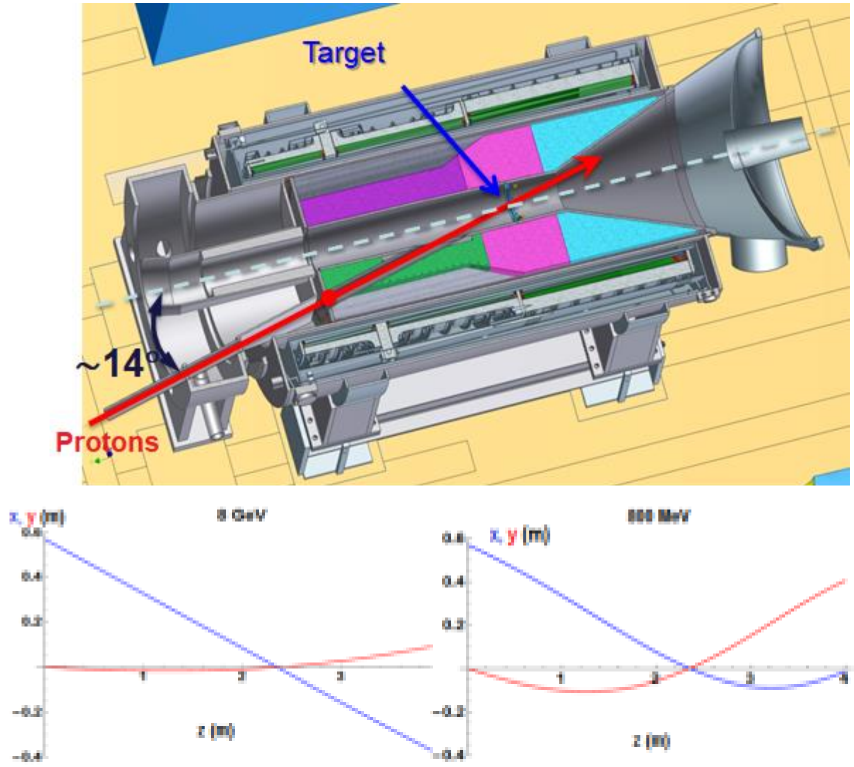


FIG. 14. Figure: Horizontal (x, blue) and vertical trajectories (y, red) of protons passing through the PS at 8 GeV (left) and 800 MeV (right) The target is at z =2.35 m. 8 Gev protons are relatively undeflected while 800 MeV beam is deflected by 10cm vertically on its tractory toward the target, which would intersect the mu2e HRS. 800 MeV beam would also be deflected away from the mu2e beam dump when exiting the PS (z > 4 m). [99]

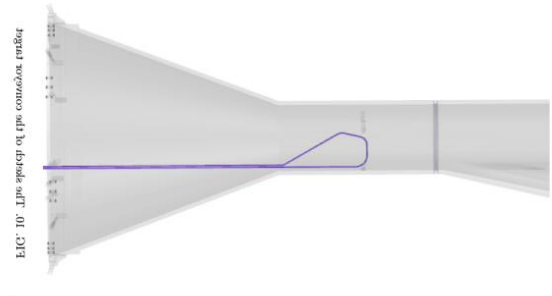
G. Beam trajectory to target

The proton beam is injected into the production solenoid (PS), which has high solenoidal fields. 8 GeV protons are relatively undeflected by the fields, but 800 MeV protons are significantly deflected [96]. Calculations have shown that 800 MeV protons entering along the same trajectory as the 8 GeV Mu2e beam would be deflected into the HRS (heat and radiation shield) and not reach the production target. The Mu2e-II beam must be redirected, and the HRS must be modified, possibly by increasing the diameter of the beam port through the HRS.

Target design

H. Target design

The Mu2e experiment will use a radiatively cooled tungsten target which is limited to 8 kW of 8 GeV beam. The larger proton beam current associated with 100 kW of 800 MeV beam will require an actively cooled target.



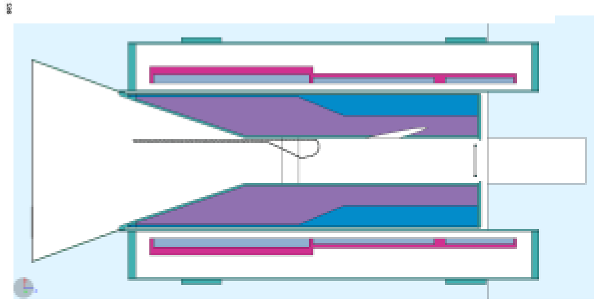


FIG. 11. FLUKA geometrical model of the tungsten target design inside the HRS and PS sturctures.

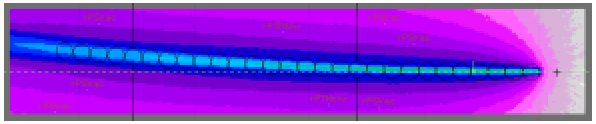


FIG. 13. Proton fluence obtained with FLUKA for 800 MeV proton beam hitting the carbon target.

Solenoid Design

IV. SOLENOIDS

The Mu2e-II muon beamline is very similar to the Mu2e muon beamline, with a production solenoid(PS), a transport solenoid(TS), and a detector solenoids(DS) as the principal components. Mu2e-II will reuse as much as possible of this beamline from Mu2e in order to save on cost and time.

A. Requirements for Mu2e-II

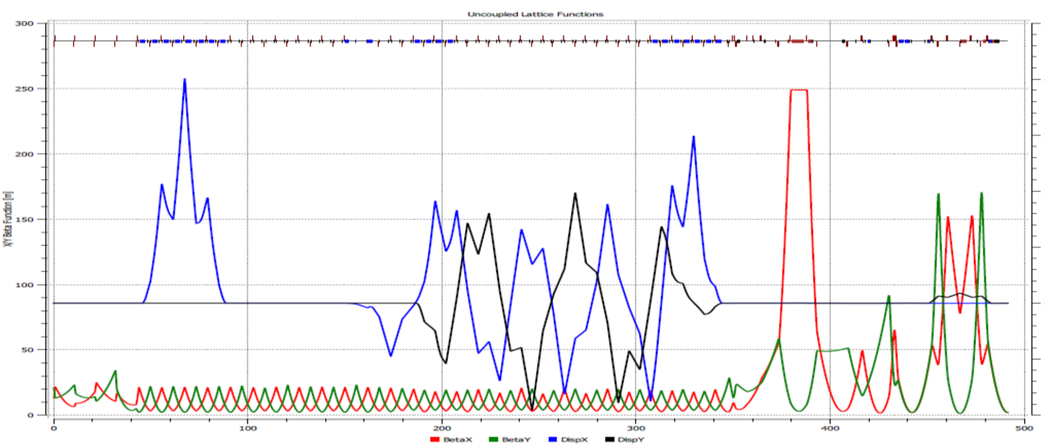
- **B. PS Solenoid options**
  - Reuse Mu2e Solenoid
  - Replacement PS
- **C. Transport Solenoid**
  - Reuse
    - No changes
  - Modify transport solenoid to enable more on-axis injection into PS ??
    - Could then reuse PS ?
- **D. Decay Solenoid**
  - Reuse. No changes

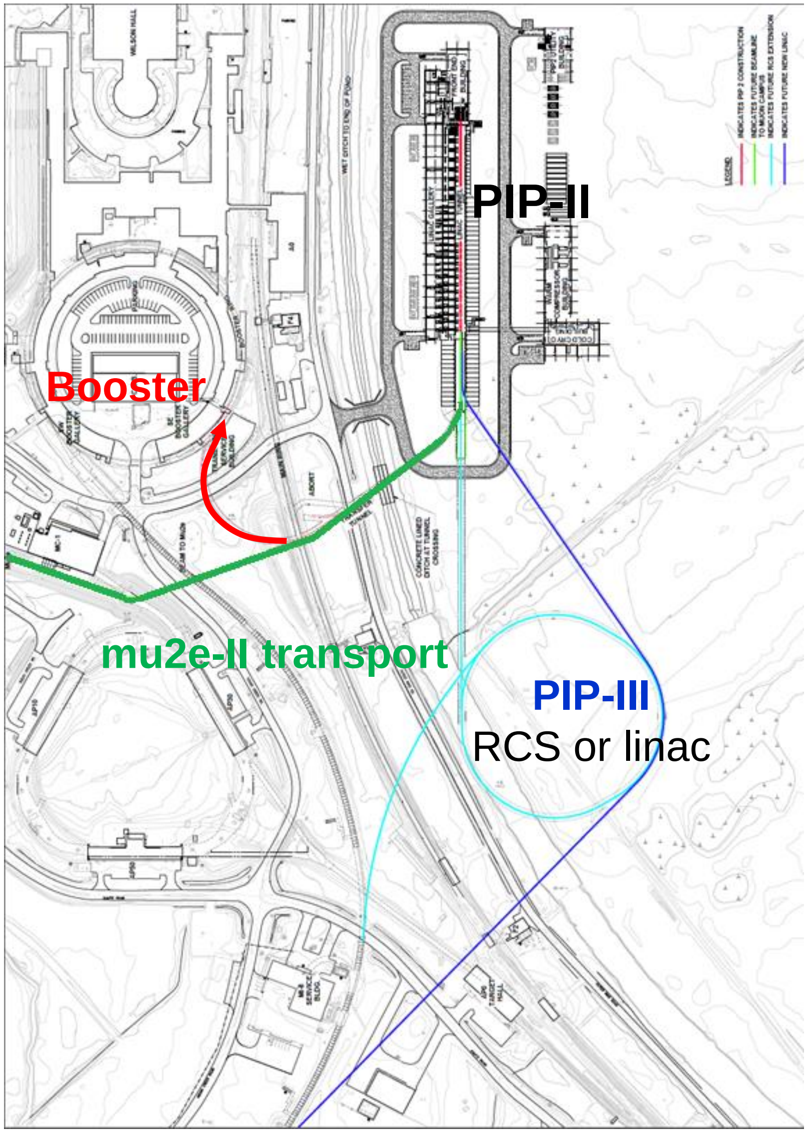
Discussion

- **Thanks for your attention**

Beamline to mu2e-II experiment

- **800 MeV beam line from PIP-II**
  - Switchyard – new mu2e-II transport
- **Switch yard location ?**
  - Other experiments ??
- **Identify other experiments for facility proposal**





A. Vivoli

PIP-II