Mu2e → Mu2e-II
Recent Progress on Mu2e-II Proton Beamline Studies

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August 2018

Outline

- PIP-II and mu2e-II
  - Can PIP – II beam be injected into similar mu2e detector?
    - 8 GeV p → 0.8 H^-
    - ~ 8 kW → ~100 kW
- mu2e-II challenges
  - lower energy p-beam injection
  - more beam power on target
- H^- stripping
  - foil heating
- Transport into target through production solenoid
  - requires changes from mu2e baseline
- Extinction options

PIP-II Status and Goals

- **On trajectory toward construction –completion in 2026**
  - CD-1 → CD-2/3a in spring 201
  - The Major Fermilab Accelerator Project

Performance Parameter	Current	PIP-II	
Linac Beam Energy	400	**800**	**MeV**
Linac Beam Current	25	**2**	**mA**
Linac Bunch frequency	201.25	162.5	MHz
Linac Beam Power to Booster	4	17	kW
Linac Upgrade potential		**1.6 MW CW**	
Mu2e Upgrade Potential (800 MeV)		**>100**	**kW**
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	166	kW
Beam Power to 8 GeV Program (max)	32	83	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	**0.7***	**1.0-1.2**	**MW**
LBNF Upgrade Potential @ 60-120 GeV	NA	>2.0-2.4	MW

*NOvA operations at 120 GeV

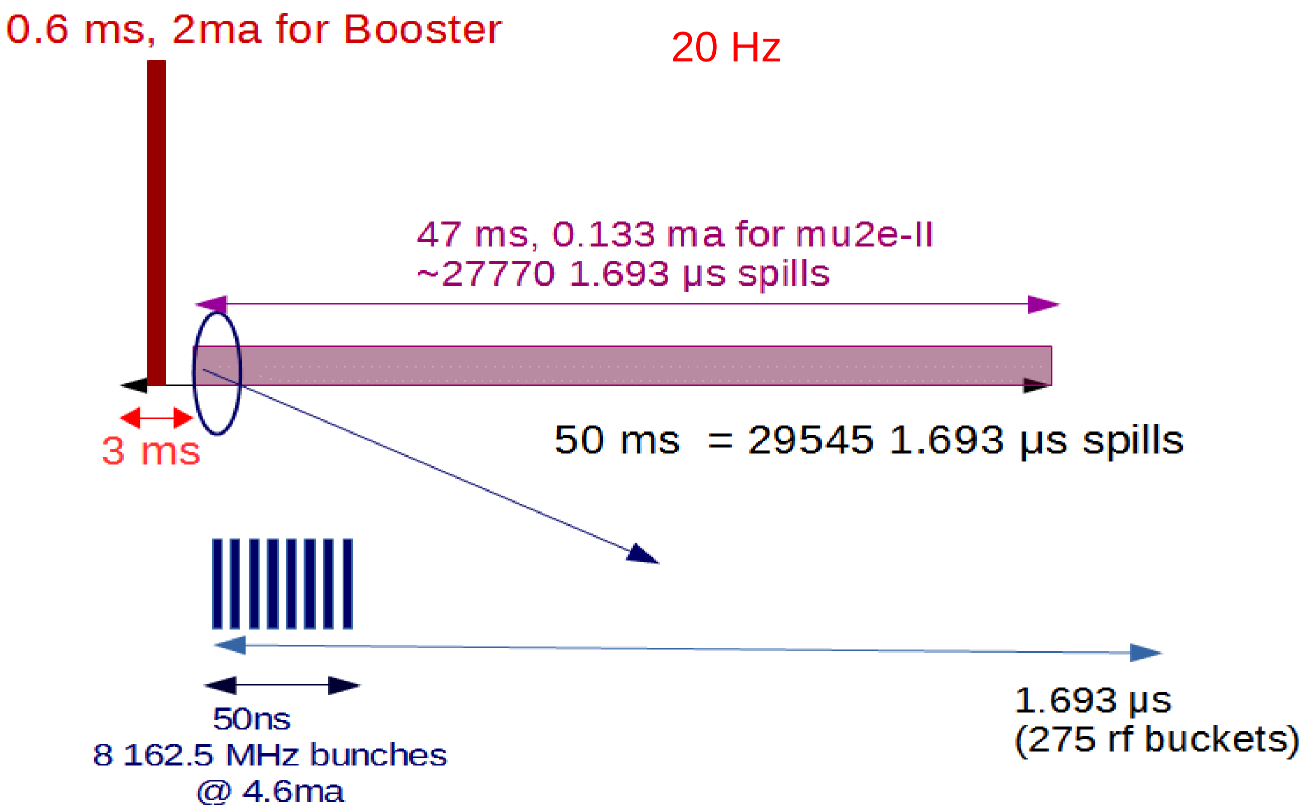
PIP-II and Mu2e-II

- **PIP-II front end can produce arbitrary bunch structures with:**
  - High beam quality !
    - **$\varepsilon_{T,N} \cong$ 0.3 mm-mr; $\varepsilon_{L,N}$ ~1.1 keV-ns** (0.004 ns × 0.275 MeV)
  - Peak current ≤ 5 mA
  - Can deliver **800-MeV protons** to a second generation Mu2e
    - while providing beam to Booster/MI/Dune

- **For Mu2e-II**
  - Use PIP-II (800 MeV) as beam source at up to ~0.1 MW
    - similar beam pattern as used for Mu2e
      - ~100ns beam on / 1.7μs cycle
  - Reuse as much as possible of the baseline Mu2e experiment
    - Follow similar experimental scenario
    - Improve if possible

PIP-II and Mu2e-II beam

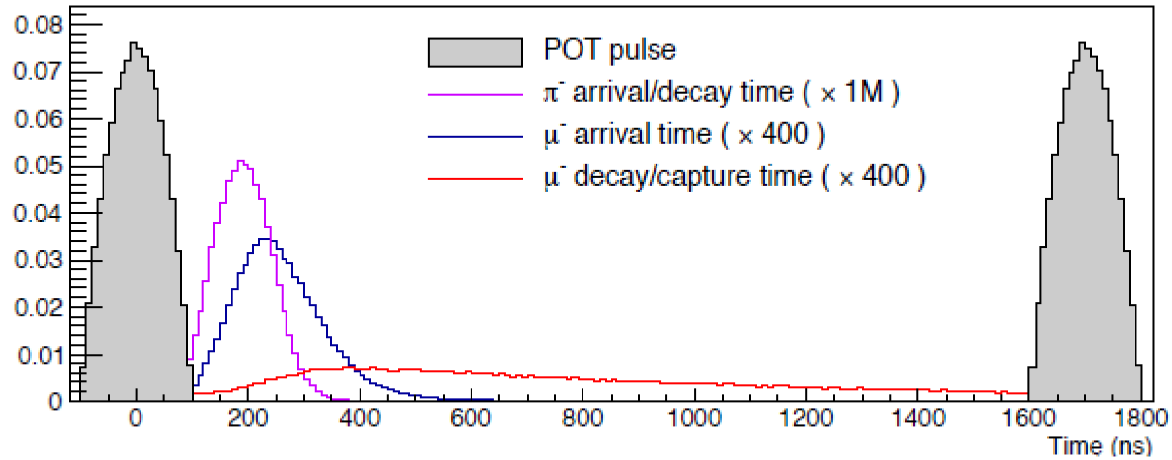
- **Possible beam structure (matched to Mu2e)**
  - 162.5 MHz chopped beam (~1.76 $\times 10^8$ /bunch @ 4.6ma)
  - Beam pulse length: ~50 nsec (8 bunches) 1.4 $\times$10^9 pulse
    - Mu2e cycle: 1.693 μsec
  - Three-year run achieves >~single event sensitivity of **2×10^{-18}**



PIP-II

mu2e→mu2e-II

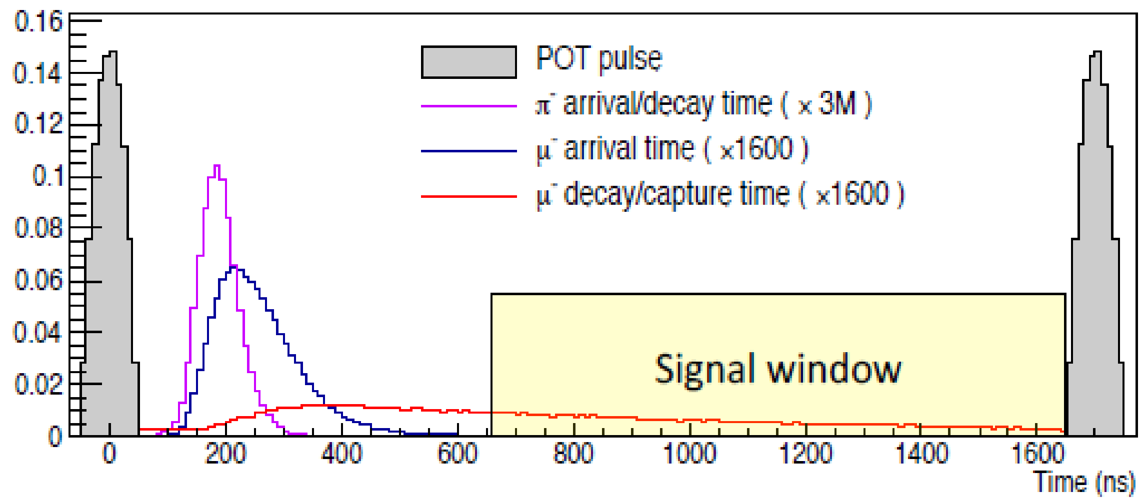
- **mu2e →mu2e-II**
  - shorter pulses
- **timing comparison**
  - K. Knoepfel et al.



How the backgrounds change

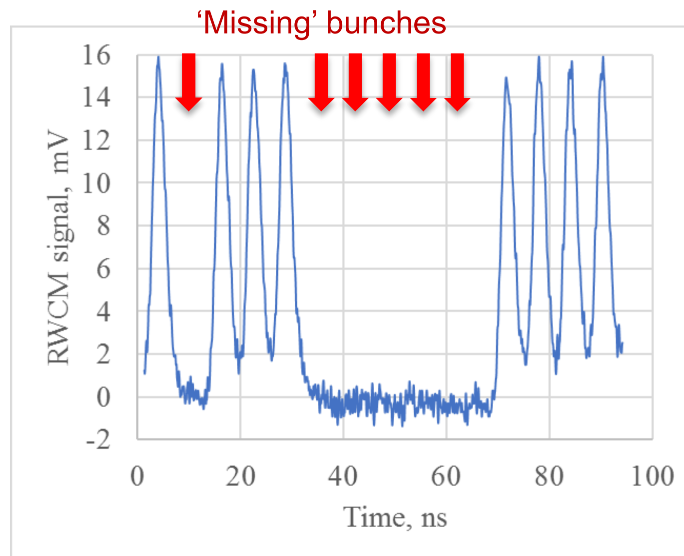
Category	Source	Events Current	Events PX (Al)
Intrinsic	μ decay in orbit	0.22	2.14
	Radiative μ capture	< 0.01	< 0.01
Late-arriving	Radiative π capture	0.03	0.04
	Beam electrons	< 0.01	< 0.01
	μ decay in flight	0.01	0.01
	π decay in flight	< 0.01	< 0.01
Miscellaneous	Antiproton	0.10	—
	Cosmic ray	0.05	0.16
	Pat. Recognition Errors	< 0.01	< 0.01
Total Background		0.41	2.36

Dominant background by far is DIO for PX (Al)

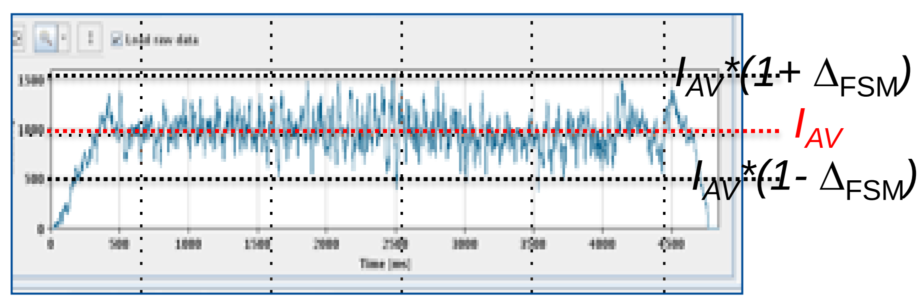


Bunch to Bunch extinction

- **Extinction**
  - kickers designed to deliver beam or no beam
  - > 10^{-4} extinction factor ..
  - need >10^{-11} for mu2e-II
  - need secondary extinction

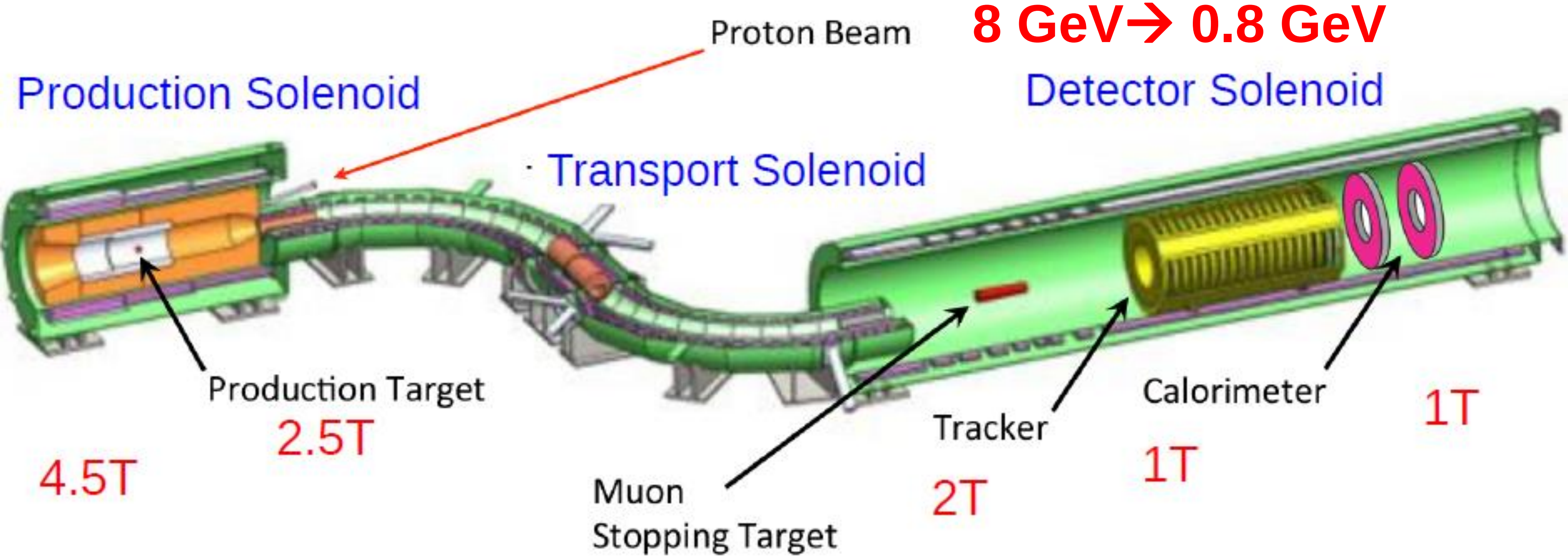


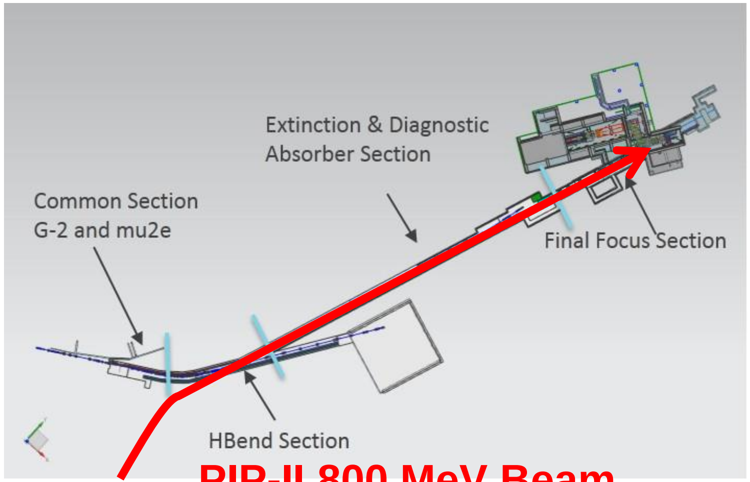
- **spill uniformity**
  - linac pulse-to pulse variation fairly small (few %)
  - variation in mu2e slow extraction is intrinsically large
    - "One should not be expecting beam intensity variations below ±50% in Mu2e" –Nagasleev .



mu2e → mu2e-II

8 GeV→ 0.8 GeV

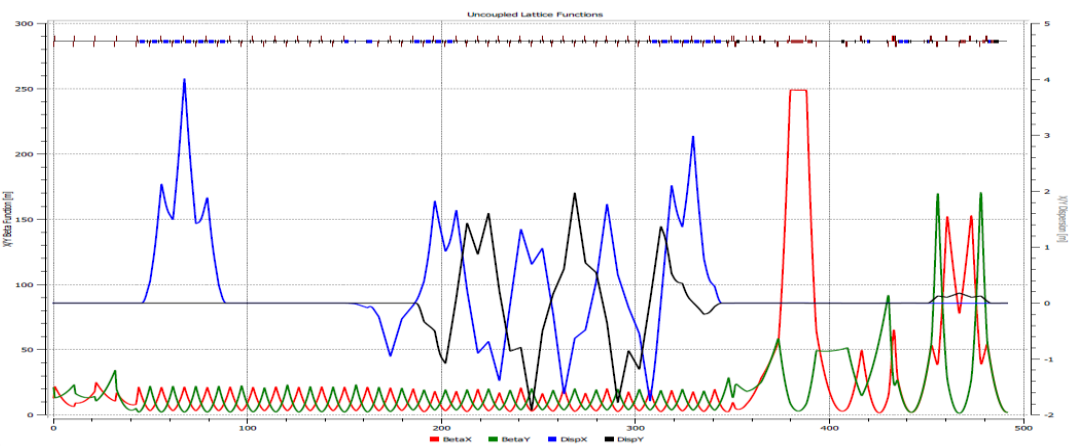


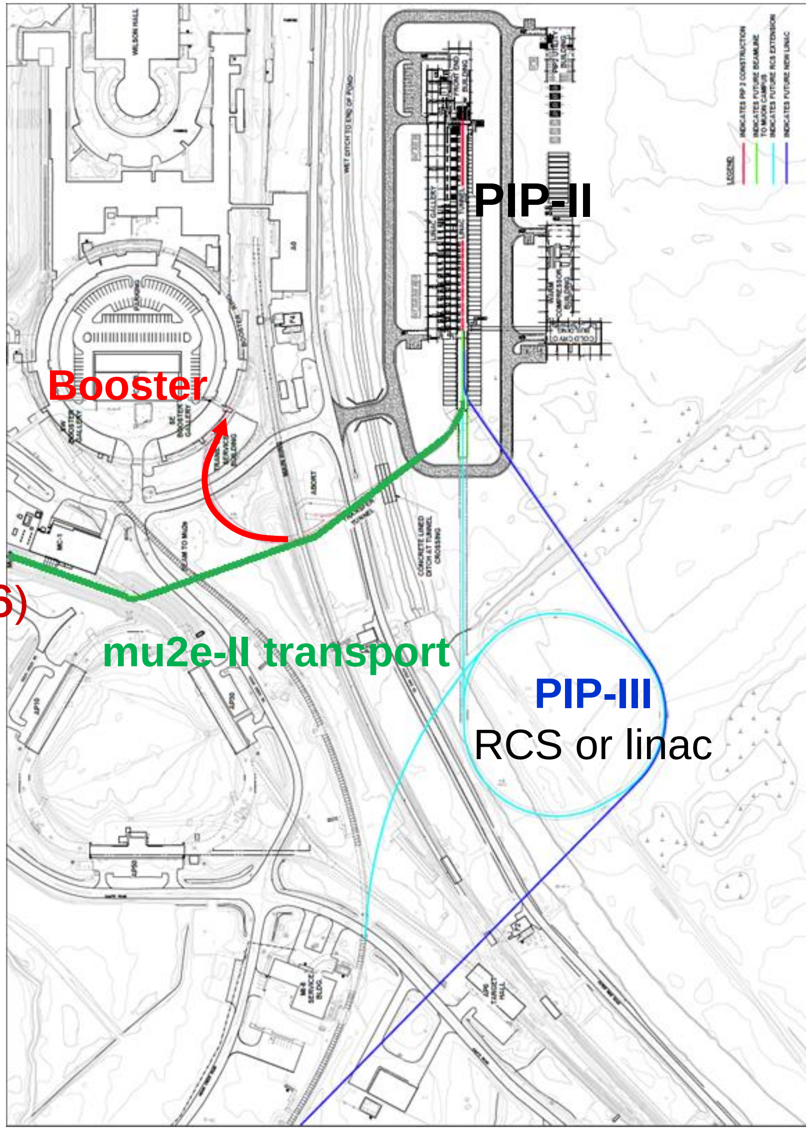


PIP-II 800 MeV Beam

New beamline to Mu2e

- **800 MeV beam line from PIP-II**
  - directly to production target
    - no Recycler, DR, slow extraction
    - 0.3 mm-mrad emittance H^-
  - starts with transport to Booster
    - low-field (B<0.25 T) for H^-
    - switchyard kicker splits (Booster /mu2e)
  - mu2e line continues into M4 line
    - uses same magnets at lower strength (1/6)
      - could use mu2e extinction ...





PIP –II delivery on target

- **PIP-II Linac is H^-**
  - beam enters ~4T field
    - 13° → 0.9 T transverse
    - H^- stripping time (W. Chou)

$$\tau = \frac{3.07 \cdot 10^{-14}}{3.2 P B_t} \exp\left(\frac{44.14}{3.2 P B_t}\right) s$$

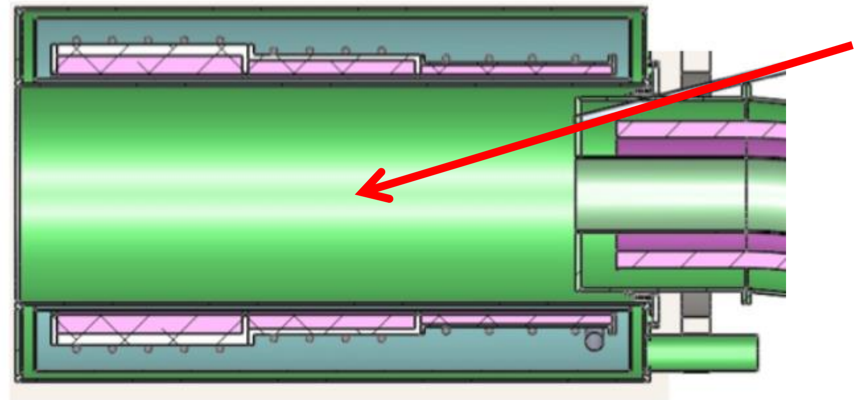
- P=1.463 GeV/c

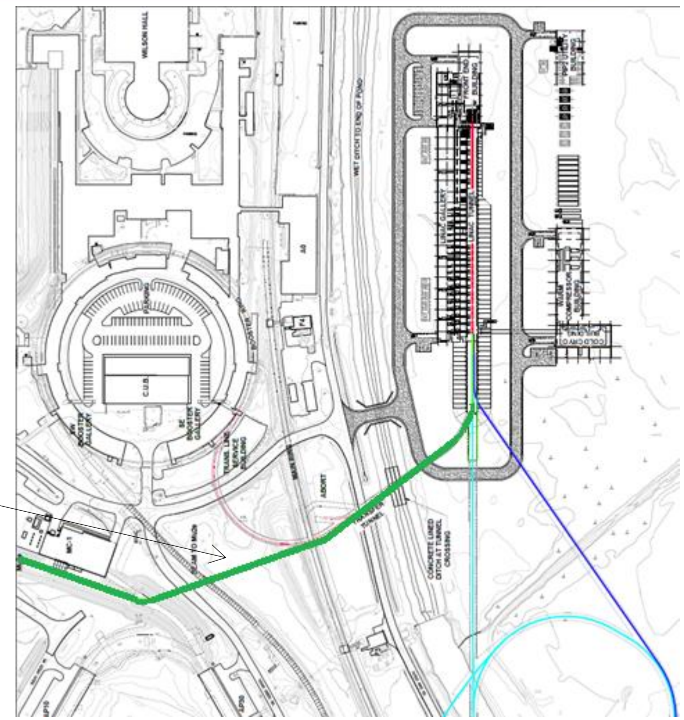
cτ = ~8 cm

(6km at $B_t/2$)

Beam should be stripped upstream

- orbit bump onto stripper foil could add to extinction (Roberts ....)

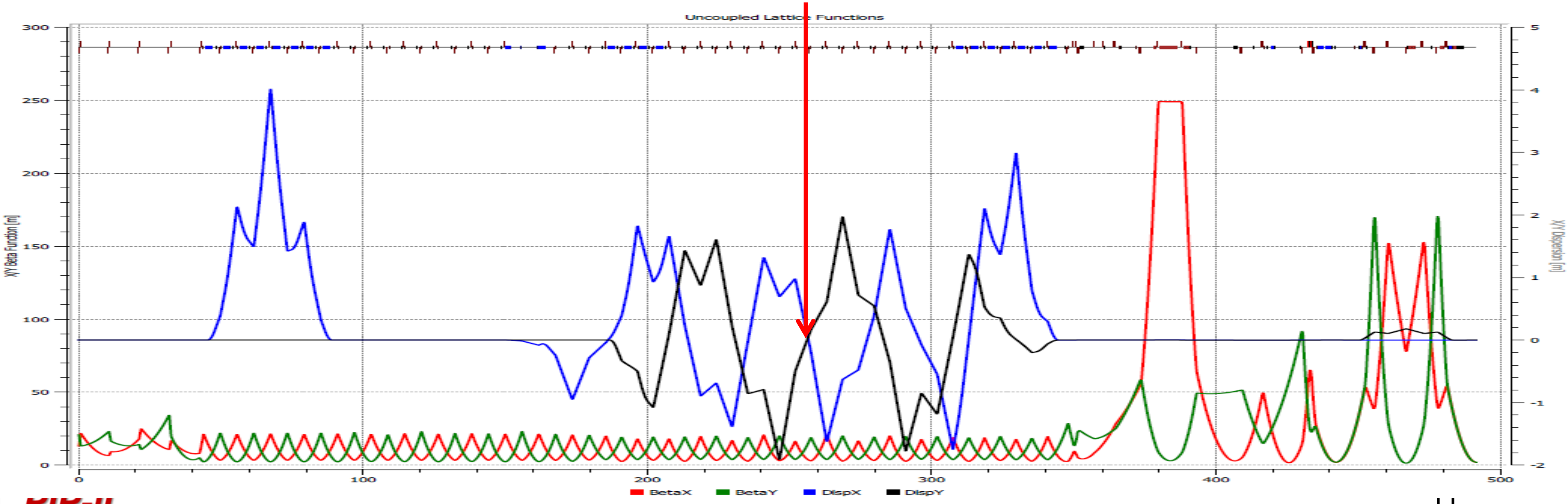




Location in Vivoli lattice

- **Possible foil location is halfway through straight section (at s =257.5)**
  - $\eta_x = 0$, $\eta_y = 0$, $\beta_x = 3.4m$, $\beta_y = 15.2m$
  - Beam spot size is small (1.7 × 0.8 mm), however.
    - more intense spot heating of foil - ~5600 J/gm peak
  - reoptimized lattice with larger beam spot (and collimation to localize foil-induced beam loss) is desirable

Possible Foil location



Stripper Foil calculations

- **Passing through foil, H^- beam strips, to H^0, H^+**

$$f_{H^-}(t,\beta) = Exp[-(0.479+0.0085)\cdot 0.05t/\beta^2]$$

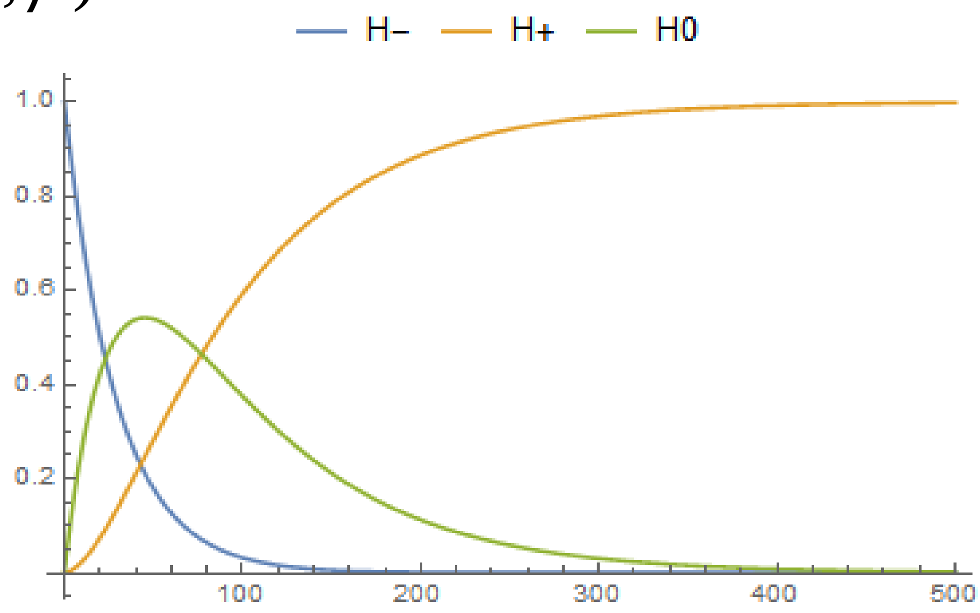
$$f_{H^0}(t,\beta) = \frac{0.479}{(0.479+0.0085-0.187)}\left(Exp[-(0.187)\cdot 0.05t/\beta^2] - Exp[-(0.479)\cdot 0.05t/\beta^2]\right)$$

$$f_{H^+}(t,\beta) = 1 - f_{H^0}(t,\beta) - f_{H^-}(t,\beta)$$

Use ~400 μgm/cm²

- 99.2% stripped to H^+
- requires ~2μ graphite or 1.2μ diamond

- ~1% beam loss from stripping
  - 1 kW beam loss



Stripper thickness in μgm/cm²
For Graphite 0.1mm=200 μgm/cm²

Stripper foil effects

- **Multiple Scattering and Energy loss effects are fairly small**
  - **for** β_t=10m, $\Delta\varepsilon_N$= 0.011 mm-mrad
    - $\varepsilon_N \cong$0.3mm-mrad from linac
  - The energy loss is ~ 1.0 keV (~ 10^{-6}),
    - energy spread increase is less
  - Optics should be almost unchanged, provided magnet polarities are all switched downstream of the foil.

$$\Delta\varepsilon_N \cong \frac{\beta_T (13.6)^2 t}{2\beta^2 P_{beam} m_{beam} X_0}$$

PIP-II

Stripper Foil heating

- **Energy loss of $H^- \rightarrow p$ heats foil:**

$$\rho V C_h \frac{dT}{dt} \cong \frac{dE_{H^- \to p}}{ds} t \frac{I}{e} - 2A\varepsilon\sigma_B (T^4 - T_0^4)$$

  - heating due to beam E loss, minus black body radiation
    - (Liaow et al.

- **Equilibrium temperature is given by:**

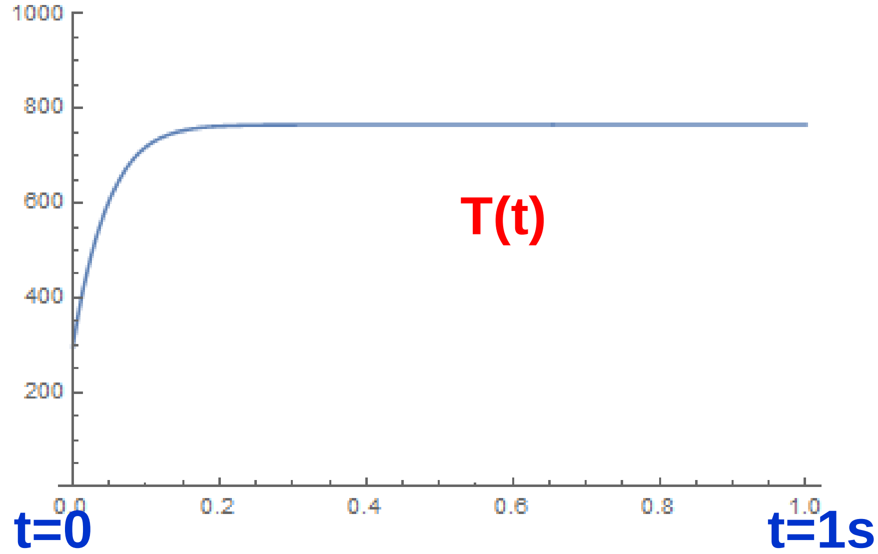
$$(T_{eq}^4 - T_0^4) = \frac{dE_{H^- \to p}}{ds} t \frac{I}{\sigma_B 2\pi\varepsilon\sigma_x\sigma_y e}$$

  - for nominal focus, $T_{eq} \cong 760°$ K
    - a slightly larger focus ($\beta^* = 30$m) would reduce this to 540° K

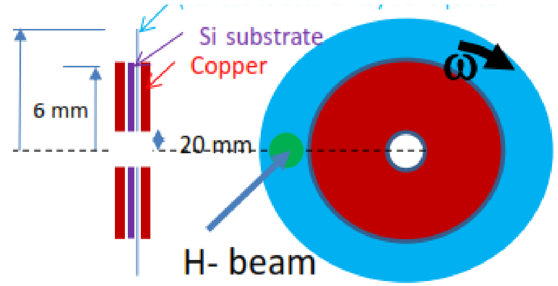
- **Heating is moderated by cw operation, and only one pass of beam through foil**
  - foils in SNS, Booster peak at up to 1800° (T_{eq}~1000 °)

Foil heating:

- Numerical solution of heating equation:
  - T_{eq}= 760° K **(0.8×1.7 mm)**
    - **larger spot:**
    - T_{eq}= 540° **K (2.5mm)**

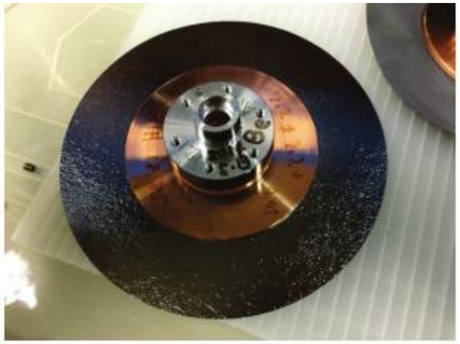


- Can spread out heating by moving beam across target
  - or moving target – rotating

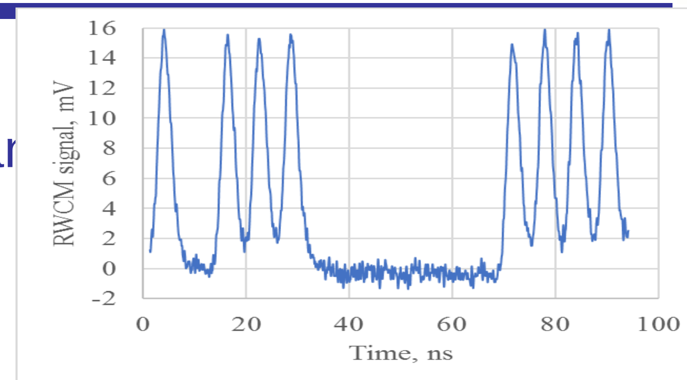


Johnson & Tang

- Foil heating is relatively modest and manageable
  - at 100kW
  - but at 1MW
    - T → 1350 °K – 940 °K

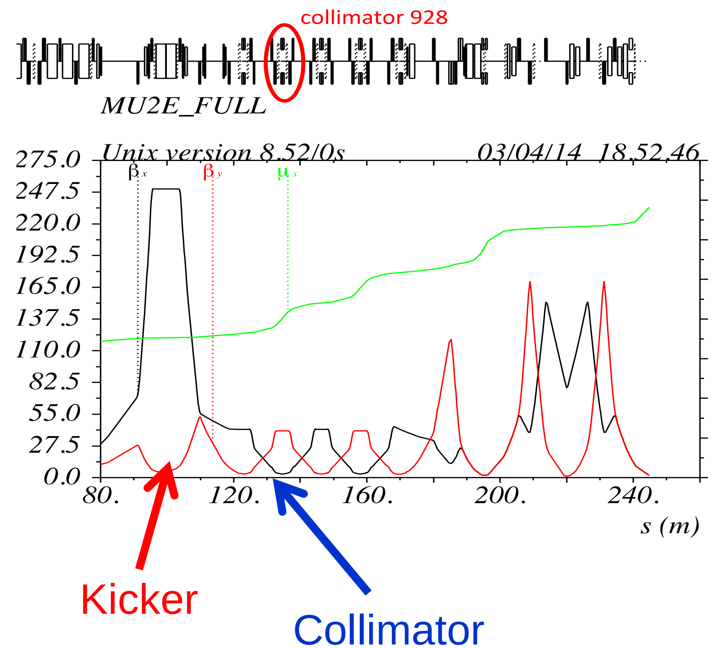


Extinction Considerations



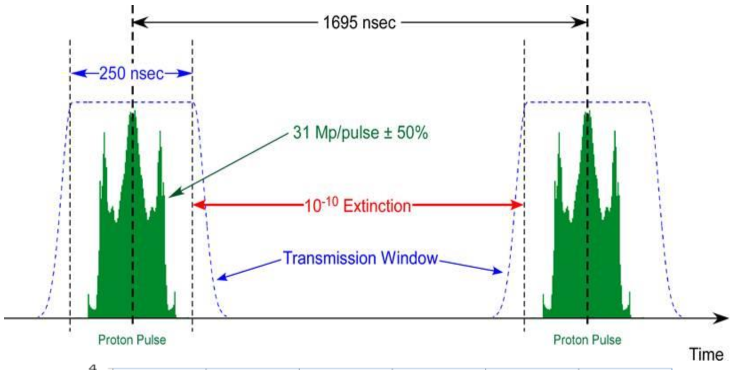
- **Need ~10^{-11} extinction**
  - Extinction from linac should be better than from Delivery Ring
    - $< 10^{-4}$
  - measure in PIP2IT?

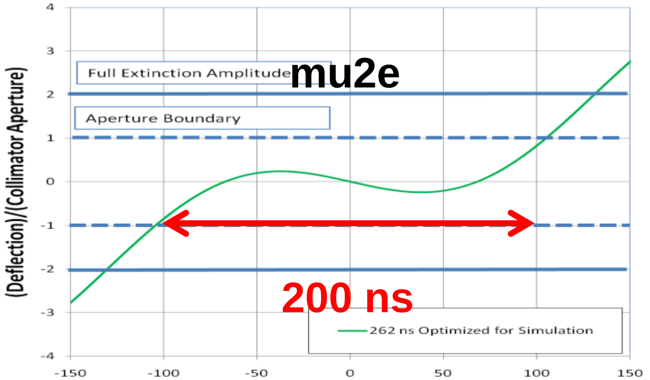
- **Need additional extinction**
  - **can use Mu2e AC dipole** extinction
    - Kick ~ $\mathrm{Sin}(\pi x/t_o)$-f $\mathrm{Sin}(\pi \mathbf{h} x/t_o)$
  - **Geometric** emittances of PIP-II and mu2e P-beam are similar
  - $\varepsilon_{N,Rms}$: 2.5 (8 GeV) → 0.3 (0.8 GeV) mm-mr
  - $\varepsilon_{geo,RMS}$: **0.26** (8 GeV) → **0.19** (0.8 GeV) mm-mr
  - ~same apertures in same lattice
    - Bρ: 29.84 → 4.91 T-m
  - Use magnets and fields at **1/6 strength**

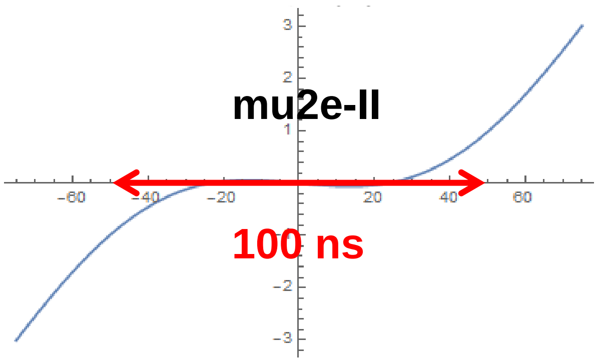


Extinction comments

- **Mu2e extinction is designed to accept ±125ns**
  - Kick ~ Sin(πx/t_o)-f Sin(π**h**x/t_o)
  - **h** – harmonic (15), f =0.084
- **Mu2e-II bunch length could be ~2× shorter.**
  - can reduce window a factor of 2 by changing h, f, and Kick strength
    - K=2.5, h=21, f=0.055
- **should work at least as well as for Mu2e**







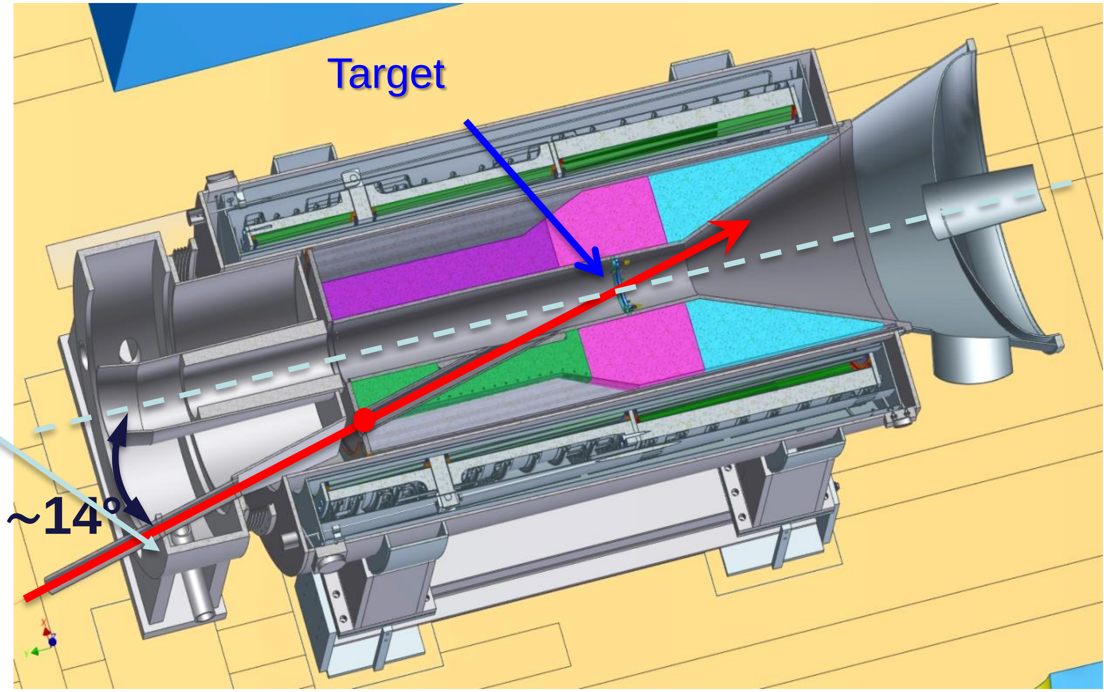
Primary Beam Transport through the Solenoid:

8 GeV proton beam enters PS:

- **0.6 m off-axis**
- **vertical pitch =~ -3°**
- **horizontal bearing = ~13.6 °**
- **For 8 GeV beam, the proton trajectory is well approximated by a straight line.**

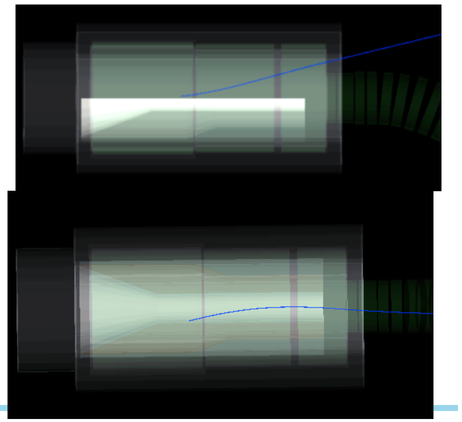
This is not the case at 800 MeV

- S. Werkema



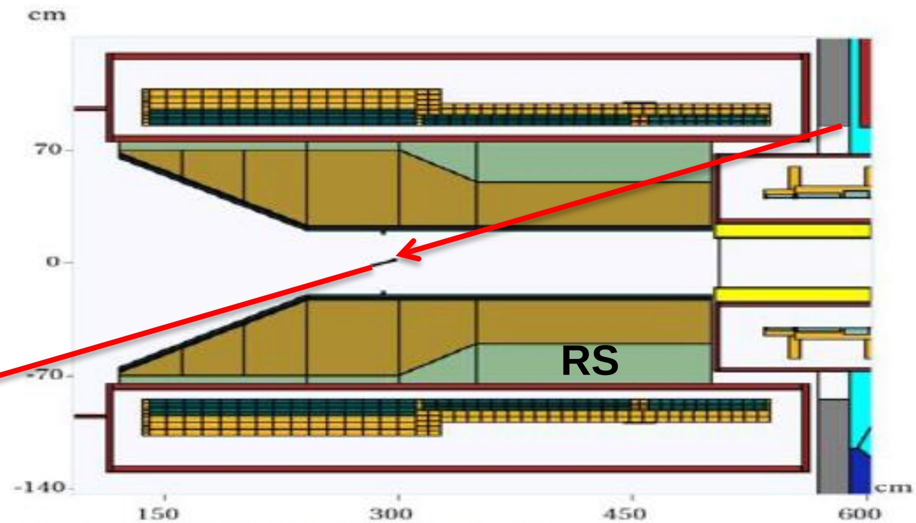
800 MeV p would not follow 8 GeV path

- miss target and hit shielding
  - T. Roberts
- Can we modify motion to ~fit mu2e ?

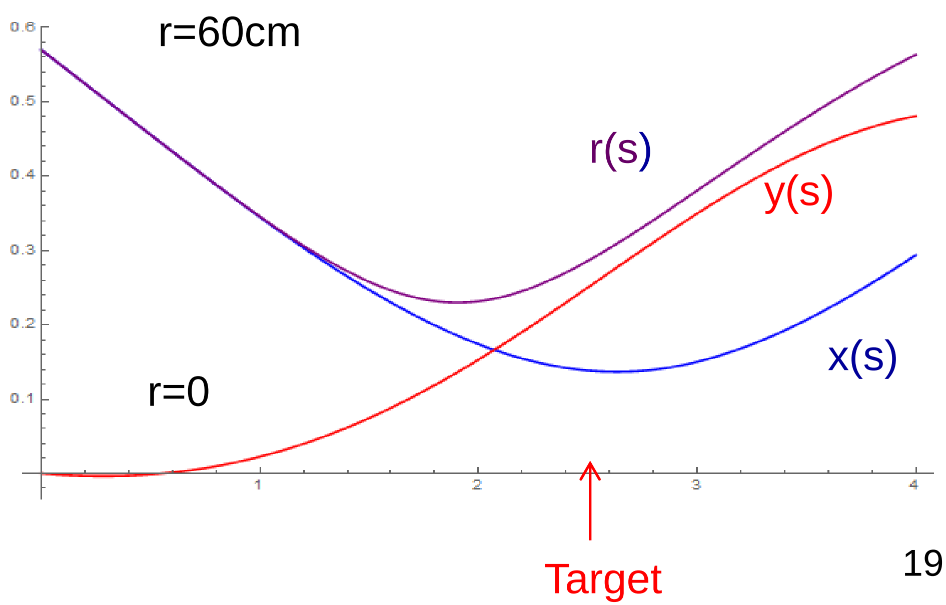


8GeV beam → 0.8 GeV

- **Unlike 8 GeV beam, 800 MeV beam is significantly deflected by B-field**
  - 8.89 → 1.46 GeV/c
- **If sent along same direction, would miss target by ~30cm**
  - hit HRS shielding



gure 6.26. MARS15 model of the PS magnet and the HRS.

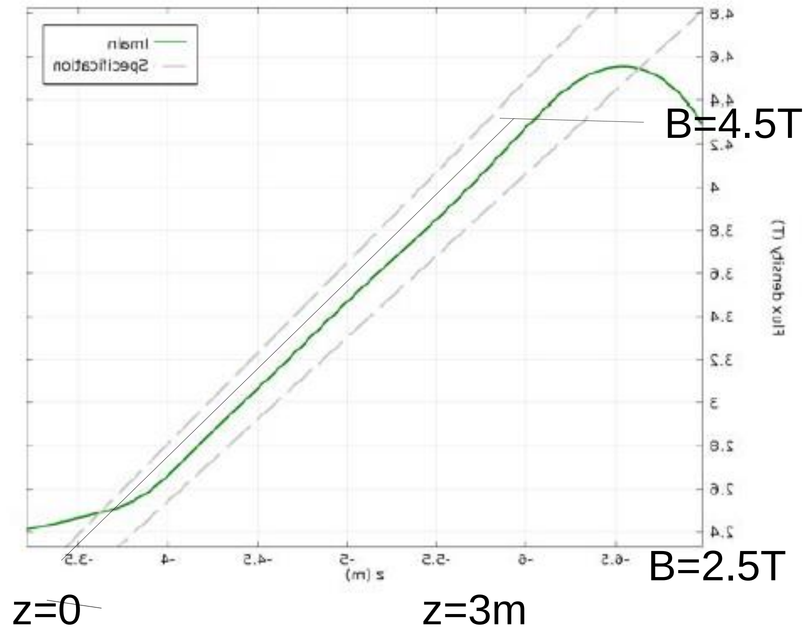


Injection beam dynamics

- **Variation for mu2e-II**
  - Require beam to go through entry point and target (G4BL Mu2e modell
    - (x=0.6, y=, at z=0) and (x=y=0 at z=2.5m)
  - Use linearized magnetic field

$$x'' = \frac{B}{B\rho} y' + \frac{B'}{2B\rho} y$$

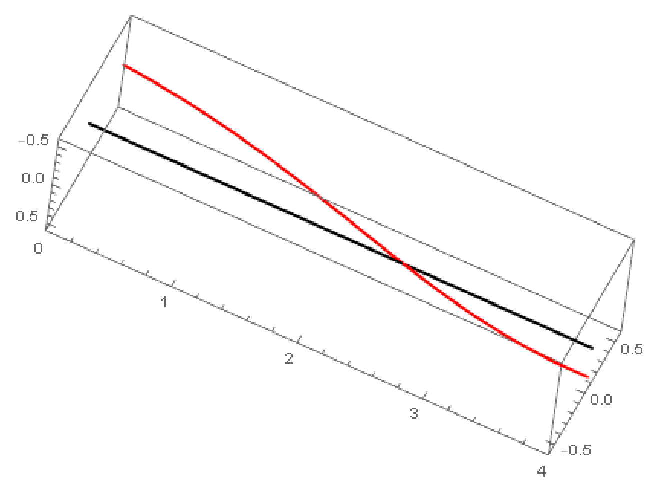
$$y'' = -\frac{B}{B\rho} x' - \frac{B'}{2B\rho} x$$



  - Solve using mathematica
    - for 800 MeV, 8 GeV
    - Third order terms:

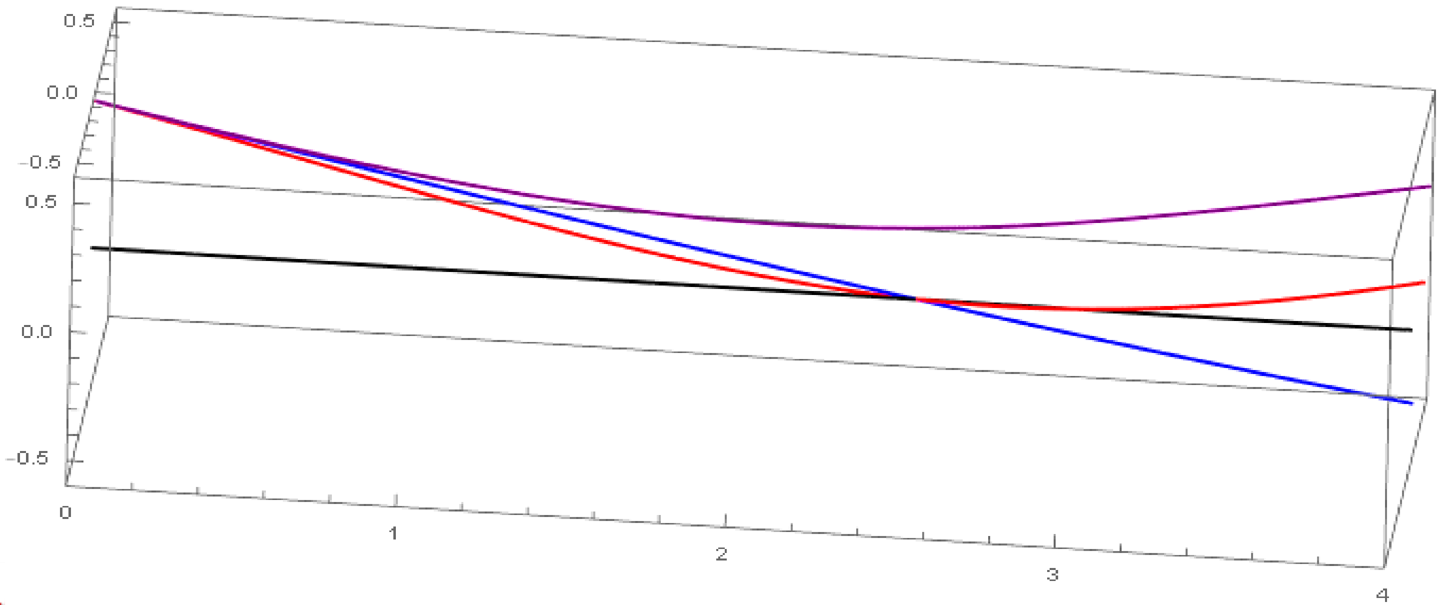
$$x'' = +Sy' + \tfrac{1}{2} S'y + \tfrac{1}{4}\left(2x'^2 y'S + x'^2 yS' + 2y'^3 S + y\, y'^2 S'\right)$$

$$y'' = -Sx' - \tfrac{1}{2} S'x - \tfrac{1}{4}\left(2x'y'^2 S + x\, y'^2 S' + 2x'^3 S + x\, x'^2 S'\right)$$



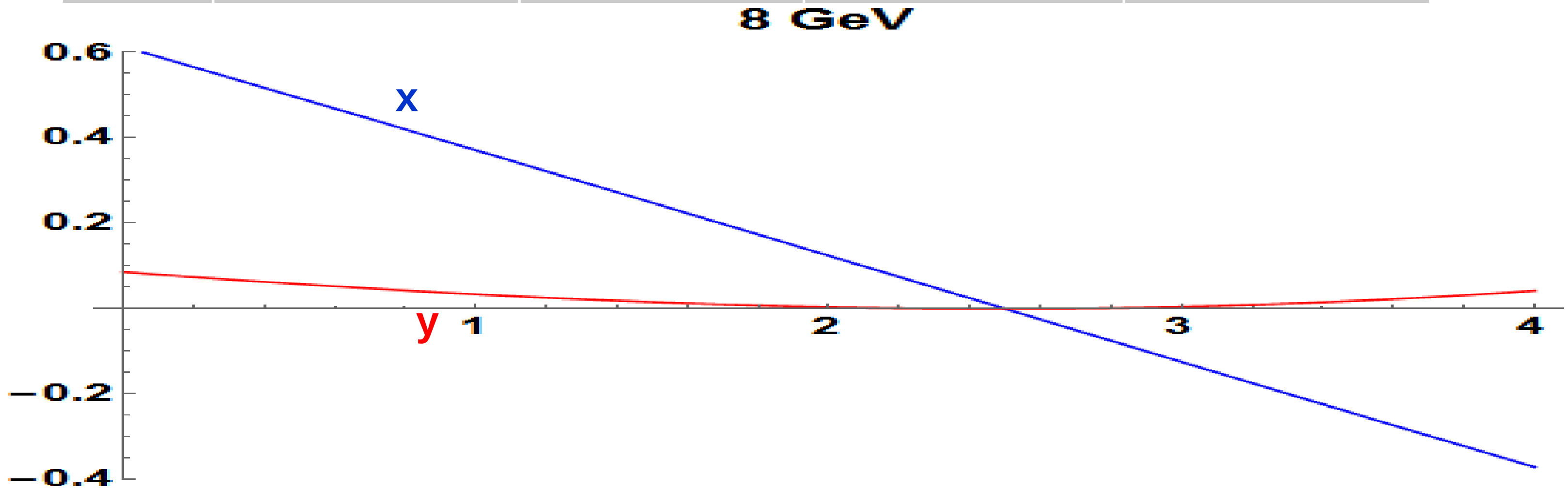
Solution exists!

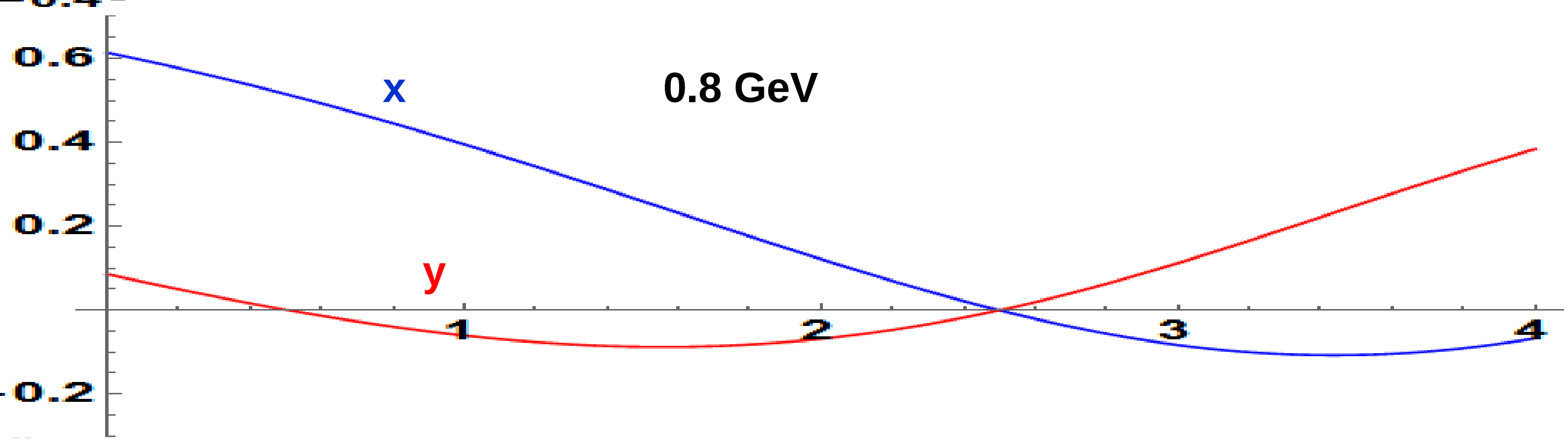
- **Requires change in direction of injection**
- **A path compatible with the Production solenoid is possible**
  - need initial vertical angle (~10.5º), and reduced horizontal angle (~10º)
  - beam wobbles away from straight line (by ~10cm before target)
    - (Mu2e entry beam pipe is too narrow)
  - emerges after target in different location and angle
    - (horizontal→vertical)



Compare x, y for 8, 0.8 GeV

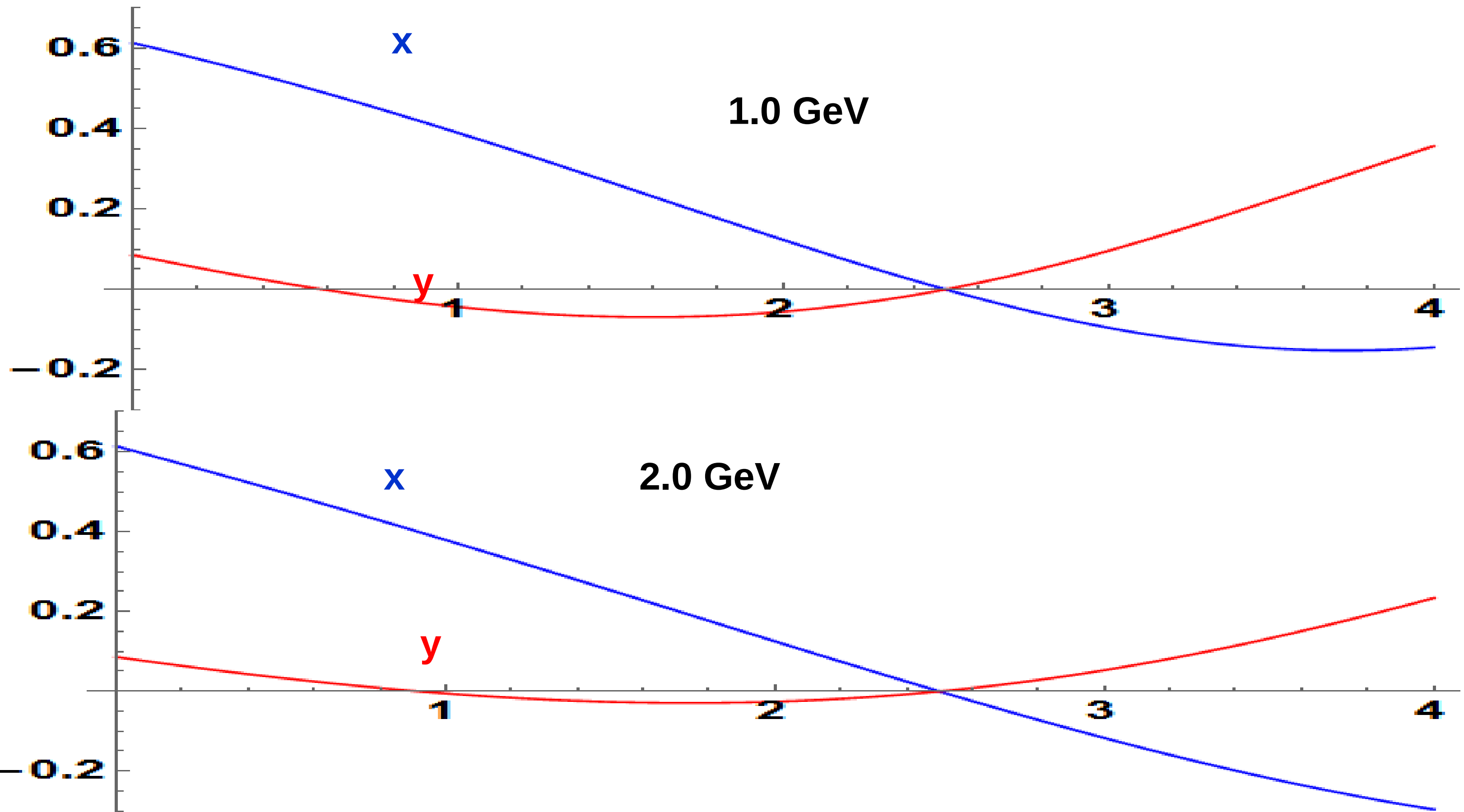
	x,y (8)	x',y' (8)	x,y (0.8)	x' , y ' (0.8)
0	0.614, 0.086	-13.5°, -3.4°	0.614, 0.086	-9.9°, -10.5°
2.5	0, 0	-14.0°, 0°	0, 0	-12.0°, 10.5°
4	-0.37, 0.042	-13.6°, 3.2°	-0.067, 0.384	7.95°, 13.75°





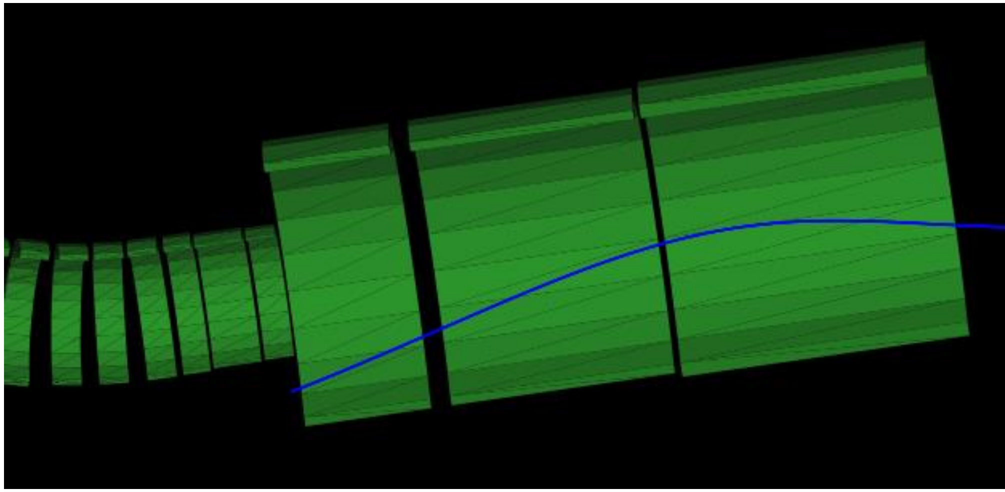
Compare x, y for 1, 2 GeV

	x, y (1)	x', y' (1)	x, y (2.0)	x', y ' (2.0)
0	0.614, 0.086	-10.8°, -9.4°	0.614, 0.086	-12.78°, -5.86°
2.5	0, 0	-12.7°, 8.7°	0, 0	-13.87°, 3.435°
4	-0.144, 0.357	3.29°, 14.9°	-0.321, 0.194	-9.56, 10.78°

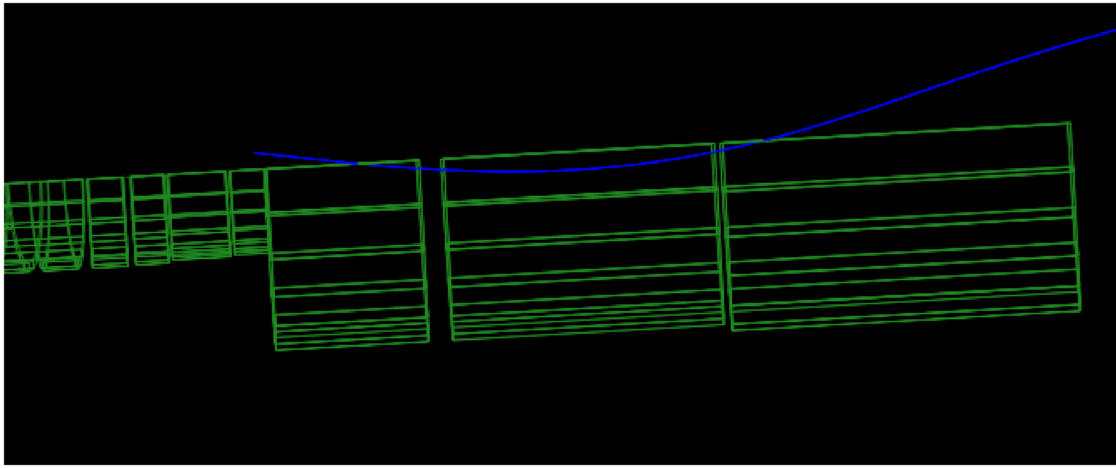


Verified in G4Beamline Mu2e Model

- **Direct copy misses target by 1-2cm**
  - tweak initial momentum to match
- **Requires minor tweaks from Mathematica model**
  - $P_y \rightarrow (260 \rightarrow 230$ MeV/c)
    - ~1° correction



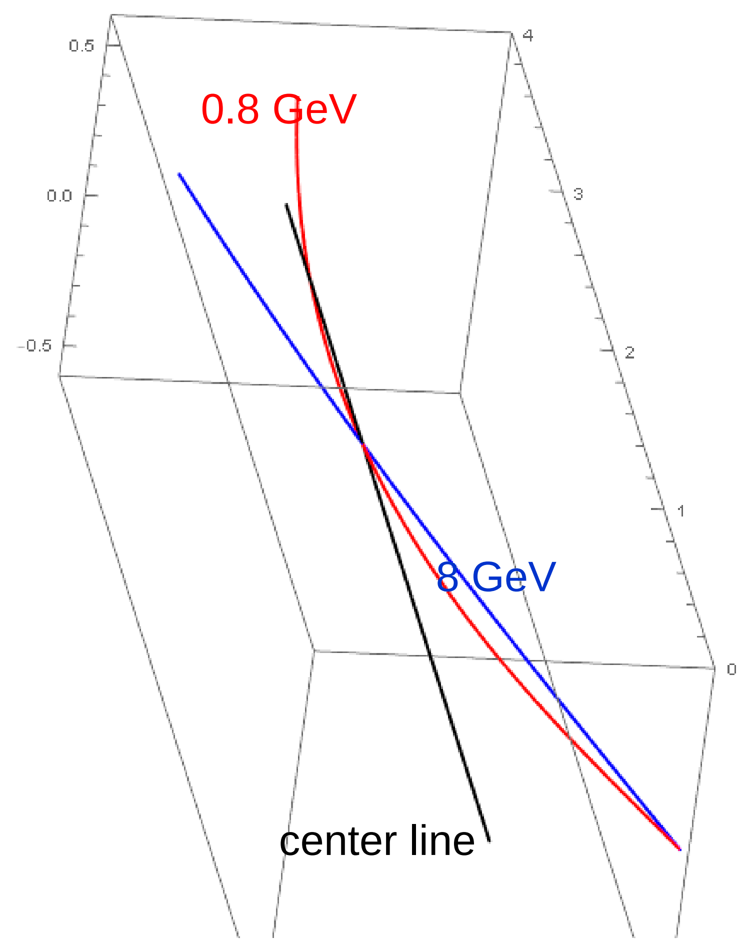
x projection



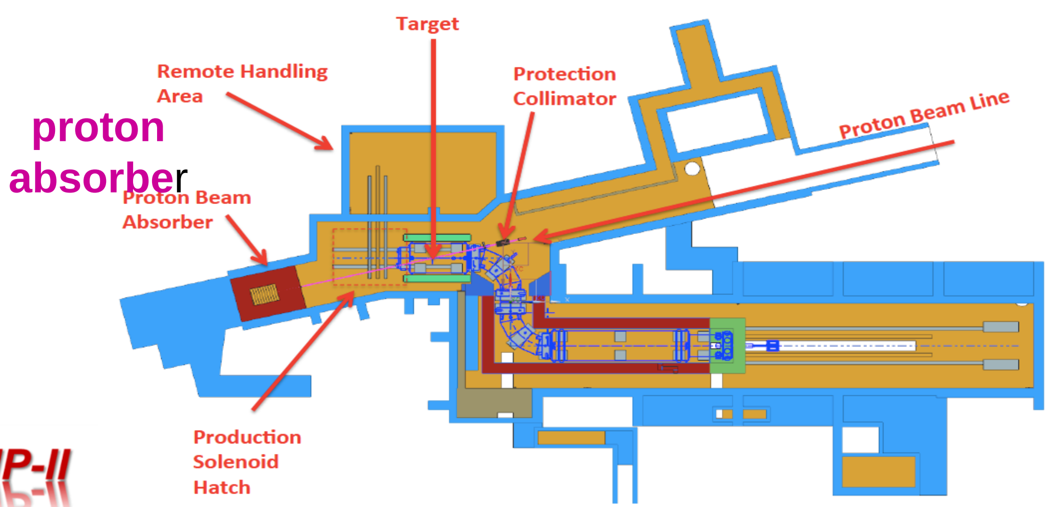
y projection

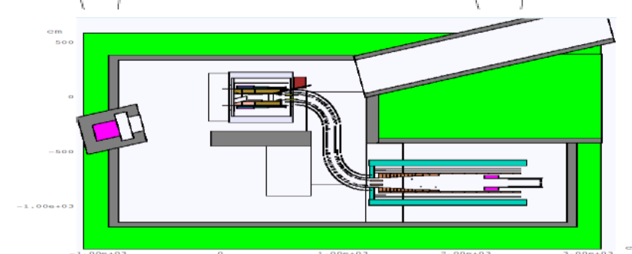
3-D projection of trajectories..

- **0.8 GeV beam would not meet proton absorber**
  - unless steered toward it …
    - ~0.3 T-m bend ..
  - **Or inject ~vertically**
    - **exiting beam would be horizontal**



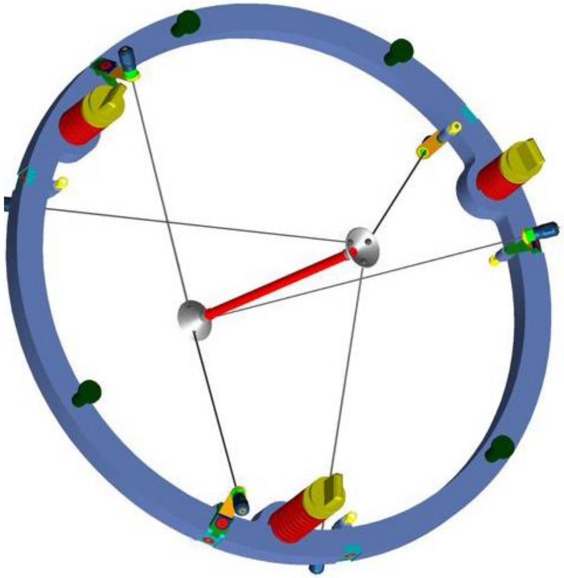
- **proton absorber changes?**
  - multiple scattering in target is six times larger angle ($\theta_o \rightarrow 3.6^o$ at 16cm W)





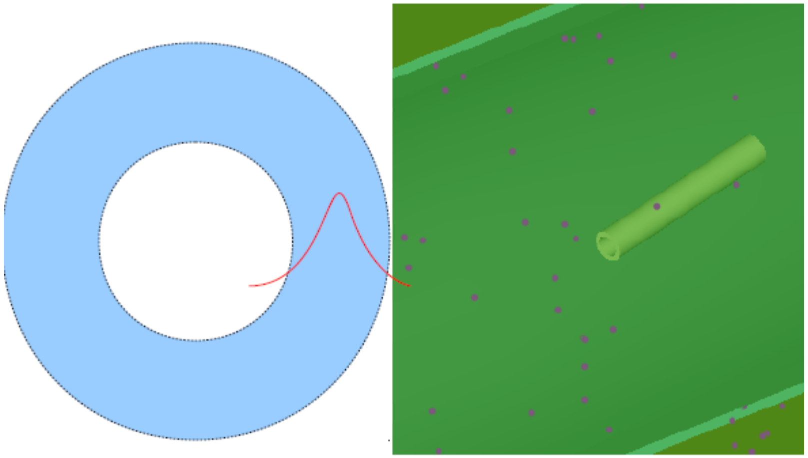
Target considerations

- **Mu2e**
  - 8 GeV, 8 kW (0.7 kW in target)
  - passively cooled freestanding W target
  - 3mm radius, 16cm long



- **Mu2e-II**
  - 800 MeV, 100kW (22.5 kW in target)
  - Target DPA >> 1 → (rad damage)

- **Update requires**
  - active cooling (?)
  - rastering on target
  - could lose ~1/3 of μ's from target reabsorbtion



Summary

- **A Mu2e-II scenario using PIP-II 800 MeV H^- beam could follow the mu2e baseline**
- **Minimal changes needed:**
  - PIP-II to mu2e beam transport
  - need $H^- \rightarrow p$ stripping
  - beam must enter production solenoid at different angle
    - and possibly location?
    - production solenoid shielding modified …
  - Proton Absorber (after target) must be changed
    - ~10× more irradiation in production solenoid/target vault
  - target for 10× power (and 800 MeV)
  - could reuse AC Dipole extinction system

Comments

- **More extensive variations from mu2e should be considered and compared by mu2e-II task force**
  - Higher power ?
    - 100 kW → MW
  - changes in timing pattern 1.69 μs →?
    - Ti or Au target
  - change collimation
    - no p-bar, K, etc.
  - Change extinction
    - use stripping foil
  - Include other experiments using PIP-II beam
    - μ → e γ using ~cw PIP-II source ??
  - Use forward muons ?