Mu2e-II : next generation muon conversion experiment

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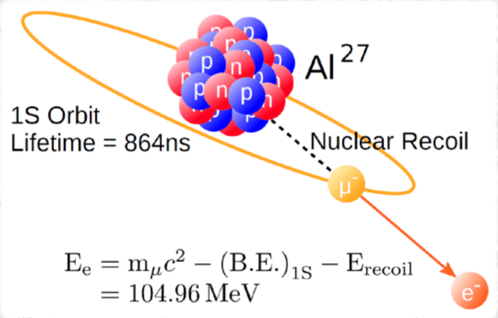
On behalf of the Mu2e-II working group

Mu2e

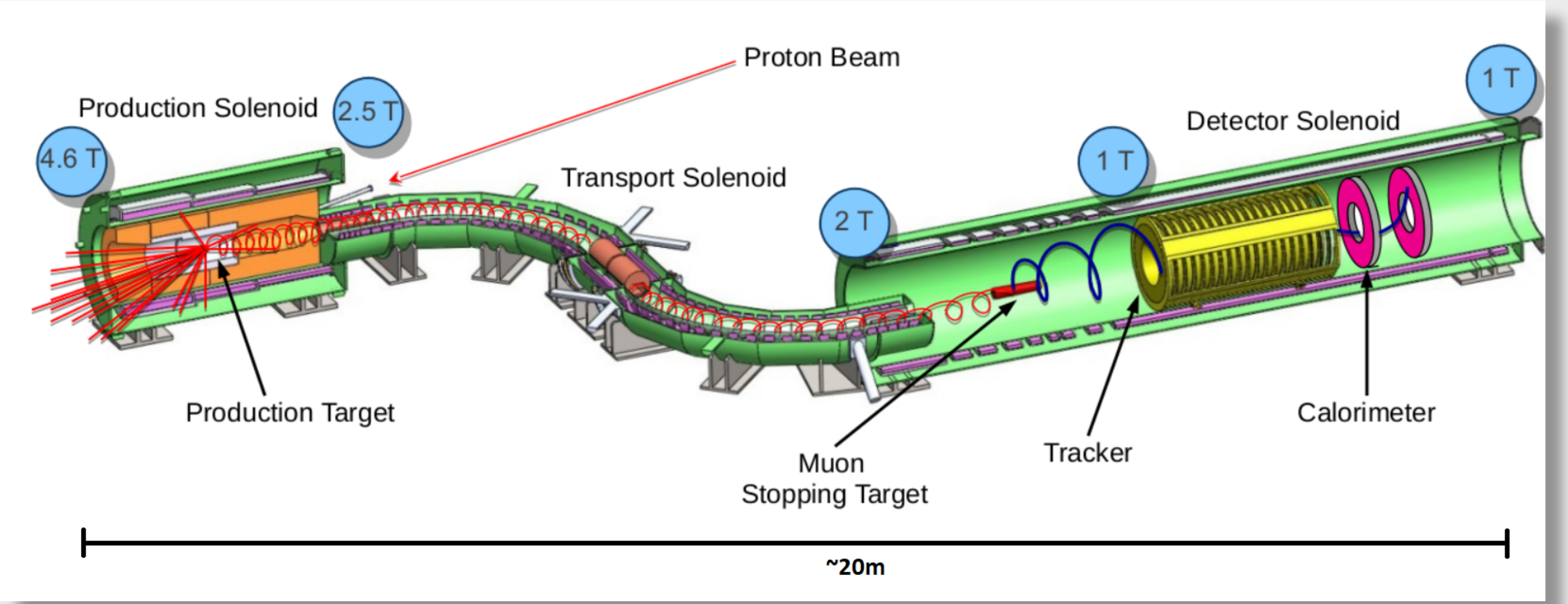
- Mu2e will search for a neutrino-less $\mu^- N \rightarrow e^- N$ conversion on Al
- Improve the current limit on the conversion rate ($R_{\mu e}$) by **four orders** of magnitude:

$$R_{\mu\rightarrow e} = \frac{\Gamma\left(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A)\right)} < 6\times 10^{-17} \text{ (90\% CL)}$$

- Mu2e will produce and stop 7×10^{18} muons on aluminum foils
  - Searching for ~ 105 MeV electrons originating from the stopping target
  - In SM, $\mu^- N \rightarrow e^- N$ is *practically* forbidden ($R_{\mu e} \sim 10^{-54}$)



- **Signal observation at Mu2e is unambiguous sign of New Physics**



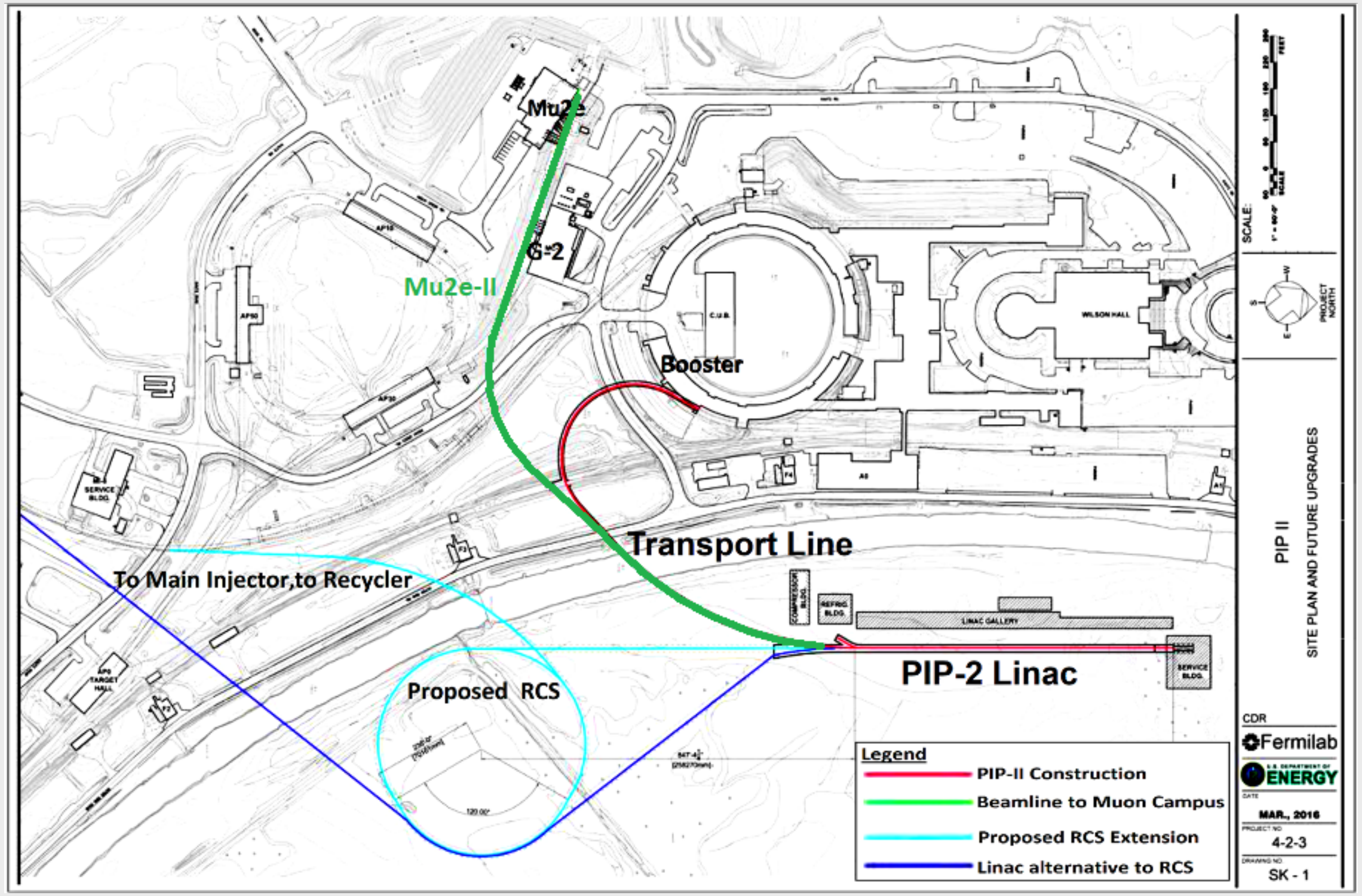
Mu2e-II

- What is Mu2e-II?
  - If approved, Mu2e-II will improve $R_{\mu e}$ sensitivity by $\times 10$ beyond Mu2e limits, extending λ_{NP} reach by $\times 2$
  - Refurbish as much of Mu2e infrastructure as possible
  - Upgrade Mu2e components to handle higher beam intensity
- When?
  - Few years after the end of Mu2e run
  - Expected 5 years of physics run
- Where?
  - Mu2e will utilize 100kW proton beam from Proton Improvement Plan-II (PIP-II) at Fermilab

PIP-II status

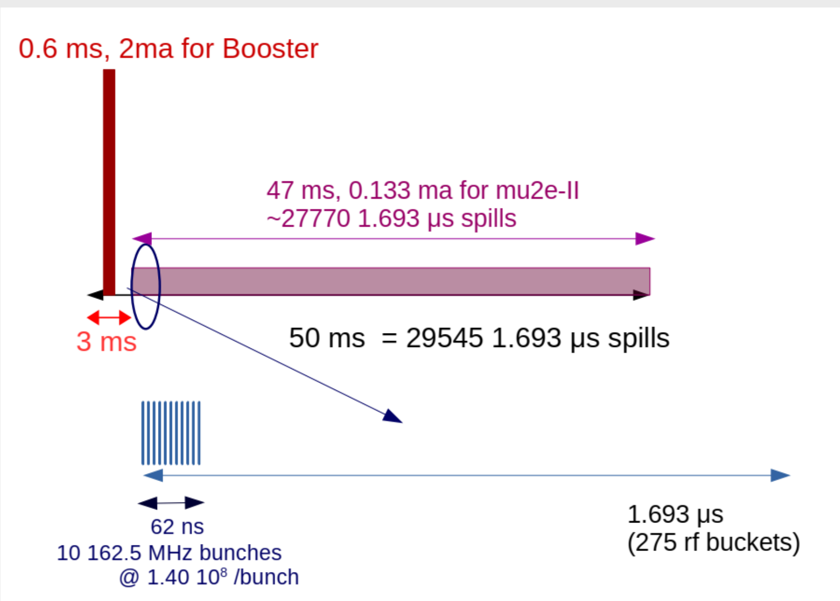
- PIP-II will power DUNE and other experiments like Mu2e-II
- PIP-II project will be complete this decade
- The PIP-II scope enables the accelerator complex to reach design proton power on LBNF target, but
  - **still leaves 98.8% of the beam for other users!**

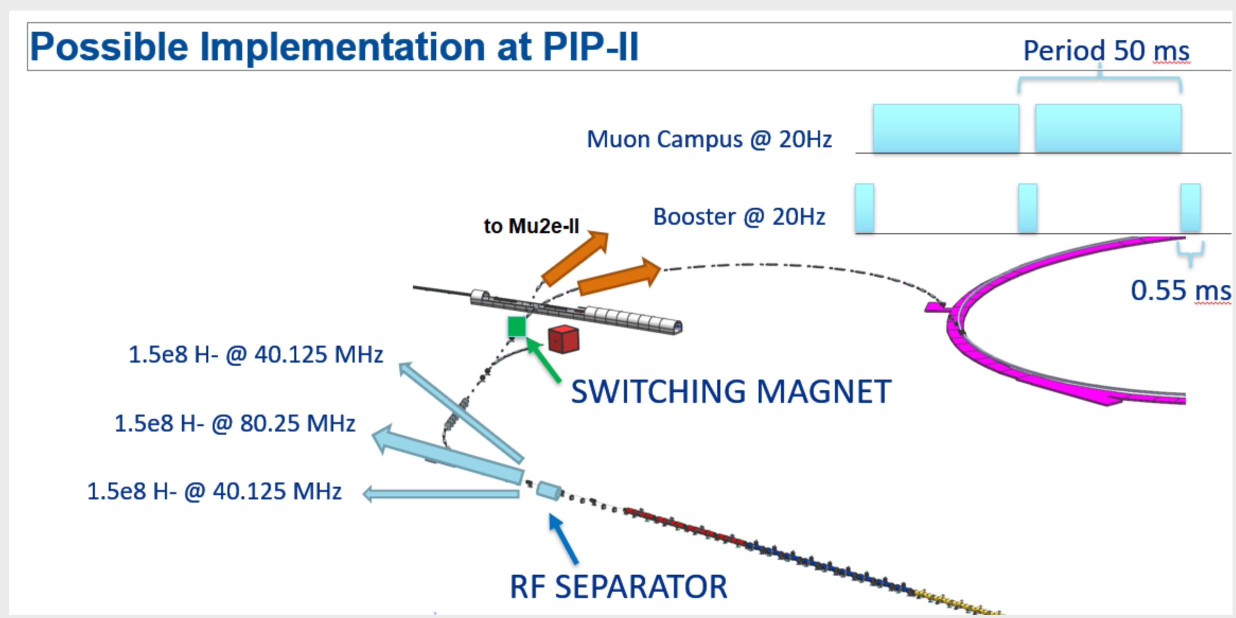
- PIP-II designed to deliver 800 MeV H^- beam to the Booster
  - Chopper system can produce an arbitrary pattern of filled or empty 162.5 MHz buckets
  - The maximum current $\sim 2mA$
- Mu2e-II will get a beam at upstream end of transfer line to Booster
  - Need to build a beamline to deliver beam to Muon Campus



Mu2e-II beam formation

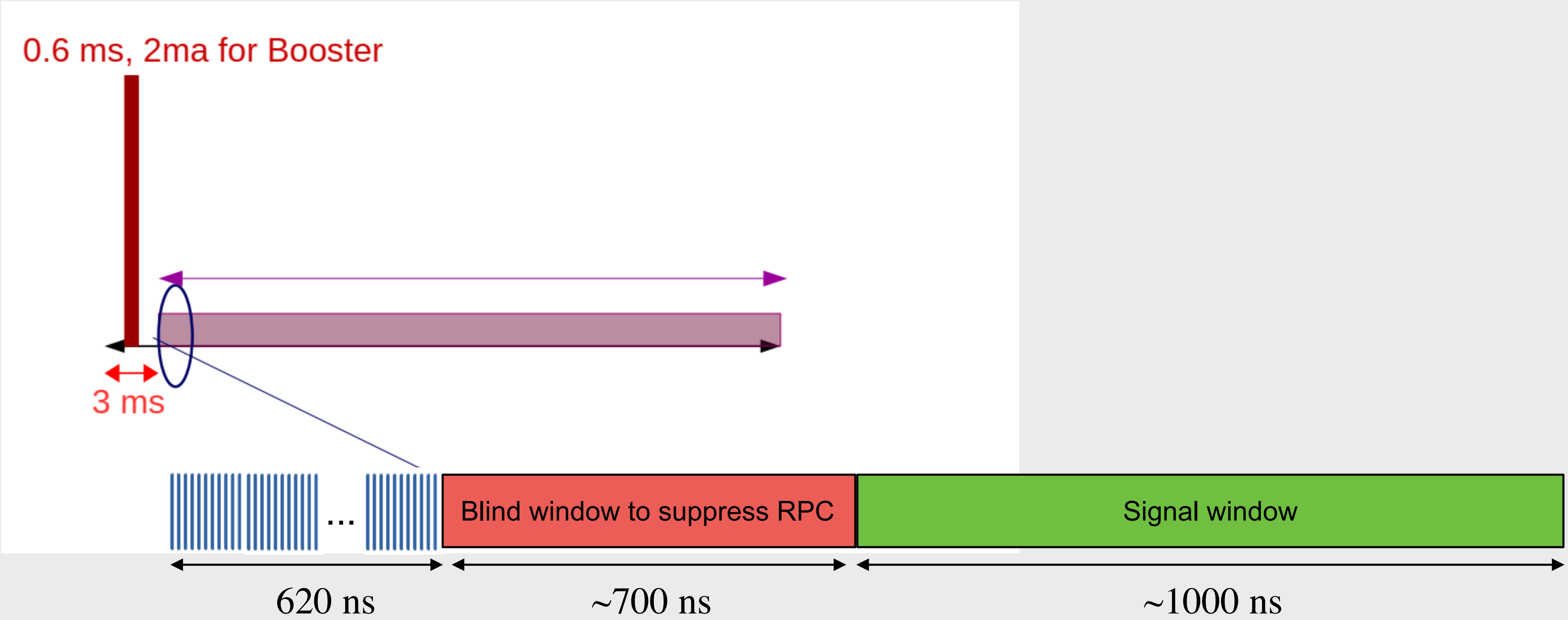
- Beam structure for Mu2e-II $(100\ \mathrm{kW})$:
  - Booster and Mu2e injection the intensity is limited to $1.4 \times 10^8\ H^-$ per bucket
  - Booster requires $\sim 3\ ms$ out of every $50\ ms$. The rest to Muon Campus
  - Mu2e-II needs a short spill followed by a gap to match the muon lifetime in the stopping target
- Mu2e-II needs only 10 buckets in each spill
  - beam pulse width is $\sim 62\ ns$. Much narrower than at Mu2e
- Consider running Mu2e-II at even higher beam intensities





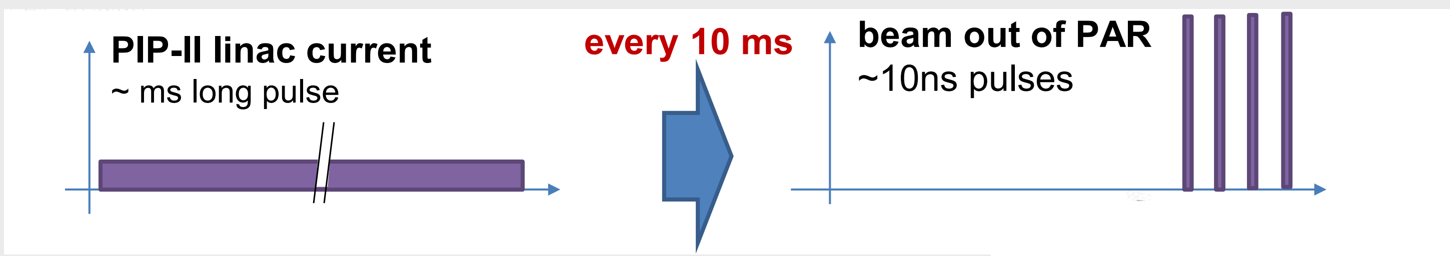
Higher beam power: Option 1

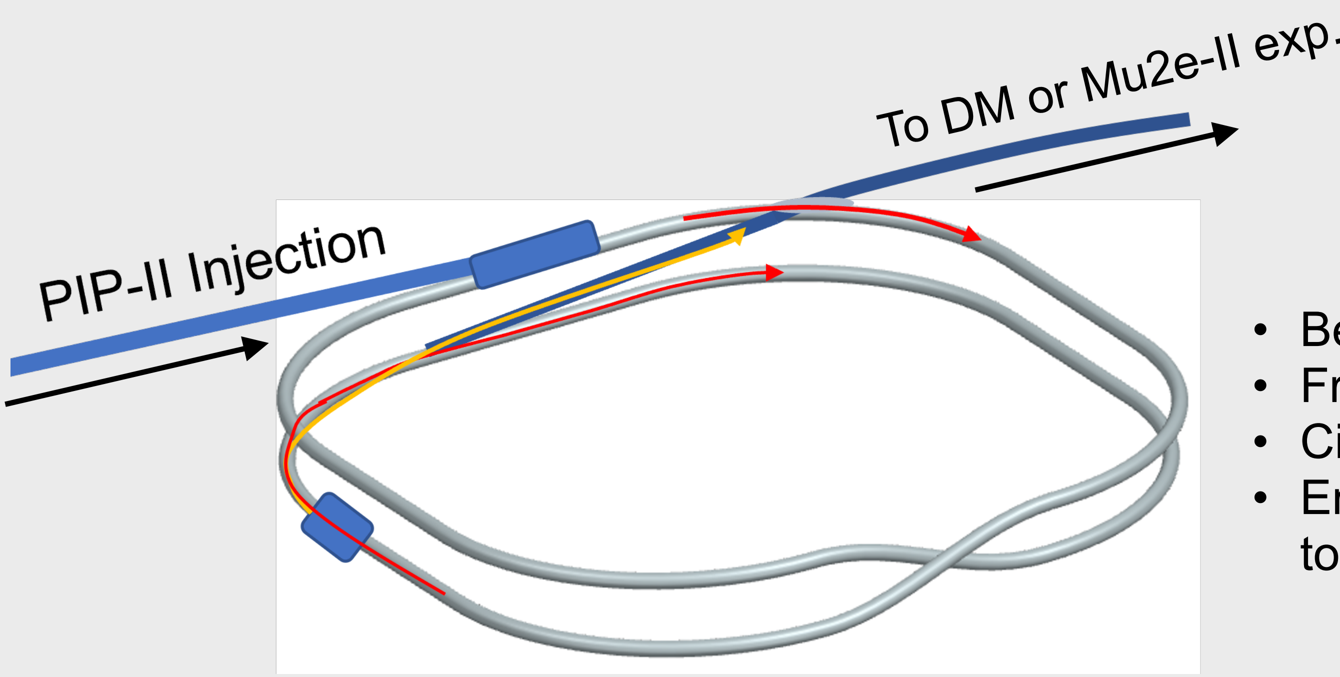
- We can consider Mu2e-II operations at beam power <1MW, assuming:
  - 1MW production target exists
  - Mu2e-II gets the entire 162.5MHz beam from PIP-II
- A beam pulse of 100 bunches results in 620 ns wide 1MW beam
  - Will be followed by 700 ns blind window to suppress RPC background
  - Disadvantage: penalty of 30% muon stops



Higher beam power: Option 2

- PIP-II Accumulator Ring (PAR)
  - Transform a long pulse into few (4) short very intense bunches for one extraction
  - Compact version (C=120 m) would be a better option for Mu2e-II

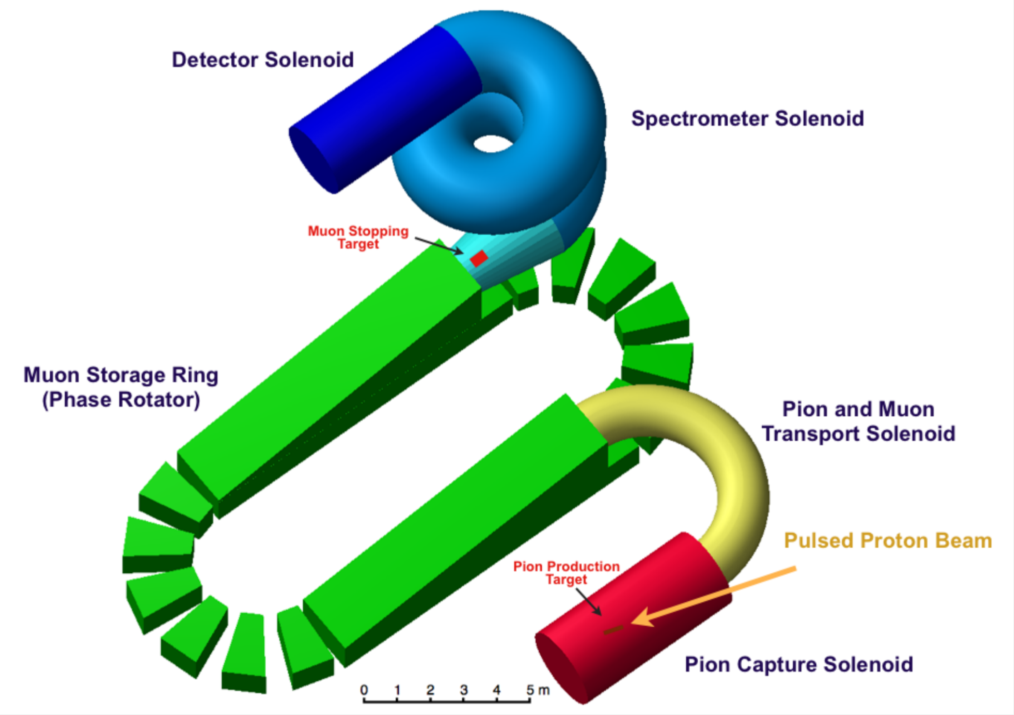


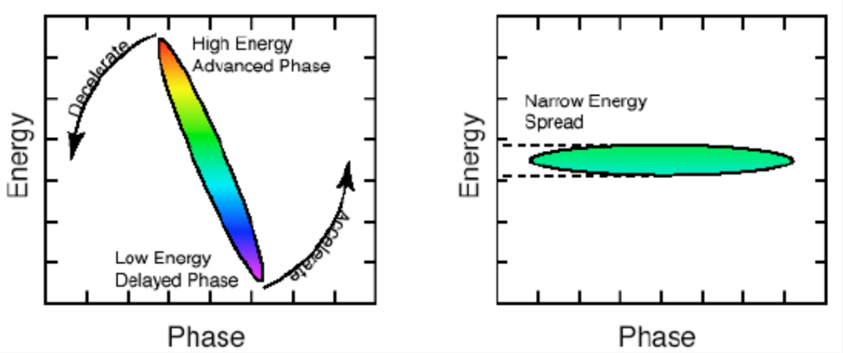


- Beam power: >100 kW
- Frequency: 100Hz
- Circumference: 480 m
- Energy: 0.8 GeV upgradable to 1+ GeV

Higher beam power: Option 3

- A more ambitious option - Fixed Field Alternating gradient (FFA) ring
  - Proposed by Y. Kuno, Y. Mori
- Provides pure muon beam to detector solenoid
  - An opportunity to explore high-Z stopping targets
- Cannot fill this ring directly from PIP-II
  - Needs a “compressor ring” to provide short, intense pulses at 100-1000 Hz.





Mu2e-II efforts

- Mu2e-II is a natural extension of Mu2e
- Feasibility studies started a decade ago at last Snowmass
  - Since then, we submitted several study papers and held multiple workshops
- We submitted 12 LOI on Mu2e-II subsystems for Snowmass 21

30 Sep 2013

Feasibility Study for a Next-Generation Mu2e Experiment

https://arxiv.org/abs/1307.1168 **2013**

K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7],

R. Ehrlich[7]

J. Mill

Expression of Interest for Evolution of the Mu2e Experiment[†]

https://arxiv.org/abs/1802.02599 **2018**

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14],

J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12],

F. Cervelli[30], D.

M.A. Cumm

March 17, 2022

Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass

https://arxiv.org/abs/2203.07569 **2022**

K. Byrum,[1] S. Corrodi,[1] Y. Oksuzian,[1] P. Winter,[1] L. Xia,[1] A. W. J. Edmonds,[2] J. P. Miller,[2] J. Mott,[3] W. J. Marciano,[4] R. Szafron,[4] R. Bonventre[b],[5] D. N. Brown[b],[5] Yu. G. Kolomensky[ab],[5] O. Ning[a],[5] V. Singh[a],[5] E. Prebys,[6] L. Borrel,[7] B. Echenard,[7] D. G. Hitlin,[7] C. Hu,[7] D. X. Lin,[7] S. Middleton,[7] F. C. Porter,[7] L. Zhang,[7] R.-Y. Zhu,[7] D. Ambrose,[8] K. Badgley,[8] R. H. Bernstein,[8] S. Boi,[8] B. C. K. Casey,[8] R. Culbertson,[8] A. Gaponenko,[8] H. D. Glass,[8] D. Glenzinski,[8]

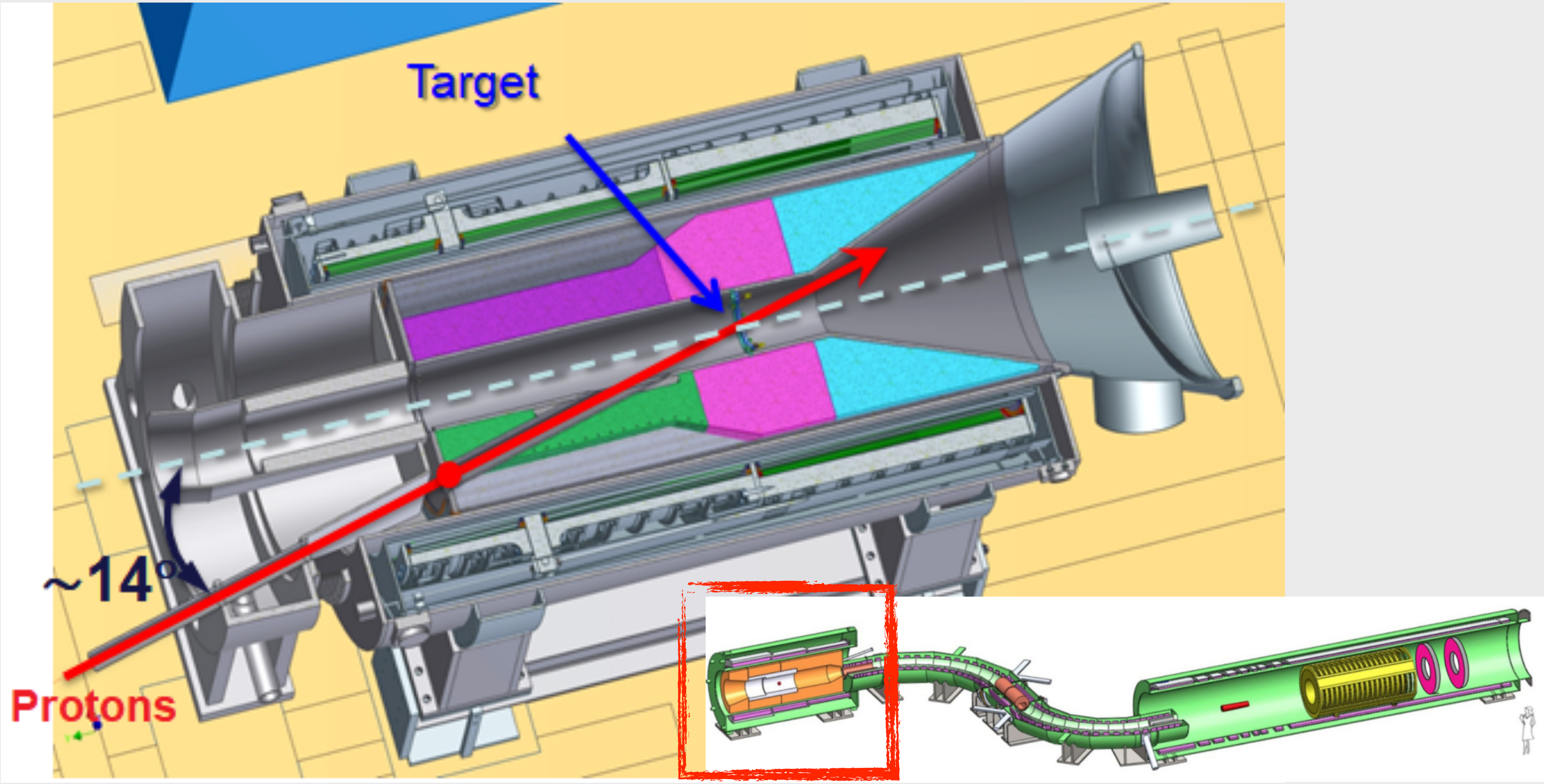
Backgrounds at Mu2e-II

- Mu2e-II assumes 5 years of running and 5.5×10^{19} stopped muons
- The total background needs to be kept <1 event
  - This requires improvements to detector subsystems and beam structure
- Higher beam intensity and detector enhancements will result in an order of magnitude sensitivity improvement

Results	Mu2e	Mu2e-II (5-year)	Required improvement
Backgrounds			
Decay In Orbit	0.144	0.263	Improved tracker resolution
Cosmics	0.209	0.171	Improved veto and enhanced shielding
Radiative Pion Capture	0.025	0.033	Improved extinction $< 10^{-11}$
Radiative Muon Capture	< 0.004	< 0.02	
Antiprotons	0.040	0.000	Beam energy below $\overline{p}$ threshold
Others	< 0.004	< 0.017	
Total	0.41	0.47	
N(muon stops)	6.7×10^{18}	5.5×10^{19}	
SES	3.01×10^{-17}	3.25×10^{-18}	
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}	
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}	

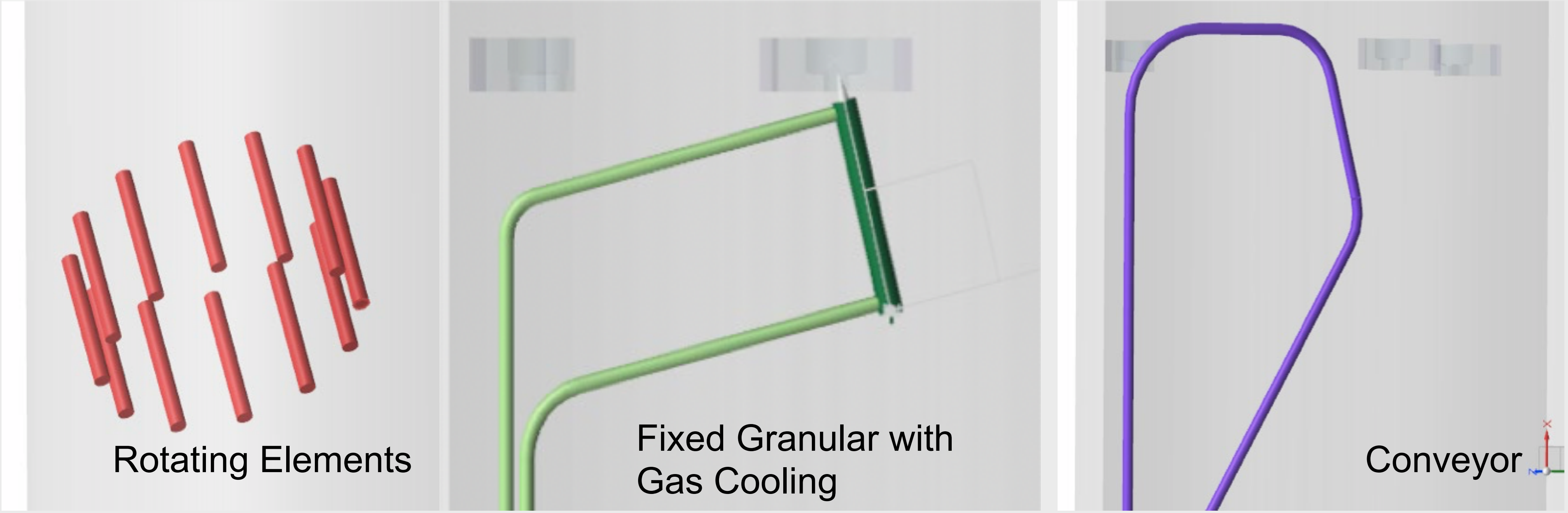
Beam production and transport

- Mu2e-II needs to tolerate x10 more beam power
- Mu2e target and super-conducting coils will not survive the beam power
  - Actively investigating alternative target station designs
  - Tungsten Heat Radiation Shield looks promising in reducing the rad damage on super-conducting coils

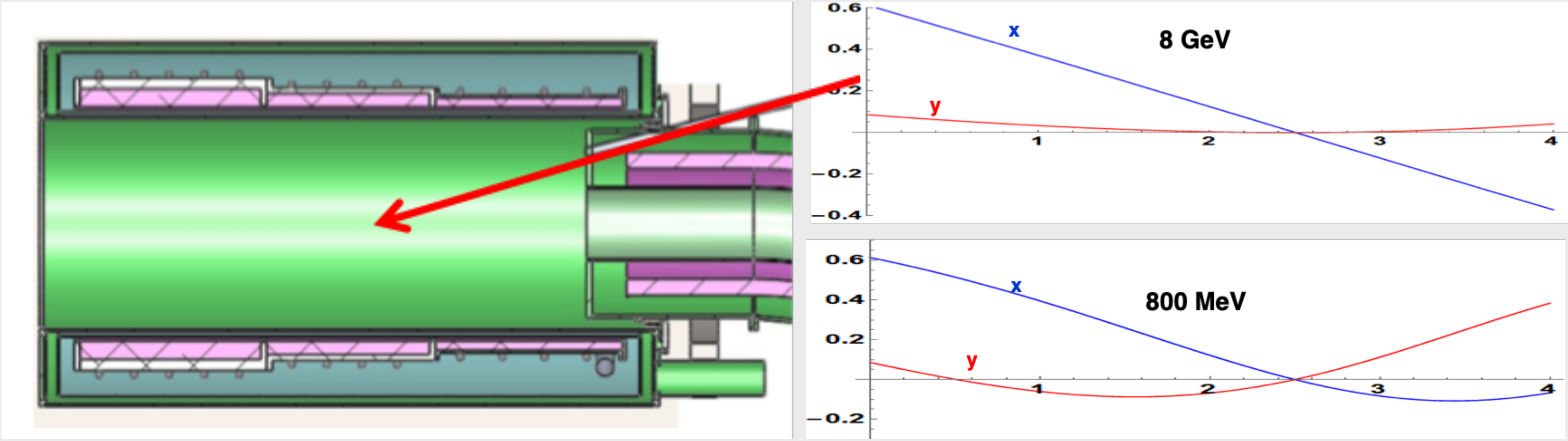


Production target

- Fermilab's LDRD project investigates production targets that survive Mu2e-II beam intensities: rotating, granular, conveyor concepts
- Simulation of: muon yield, thermal stress, radiation damage, residual activation, radiation loads
- In out Mu2e-II sensitivity study, we have considered conveyor type production target with carbon spheres
    - Early prototype has been fabricated

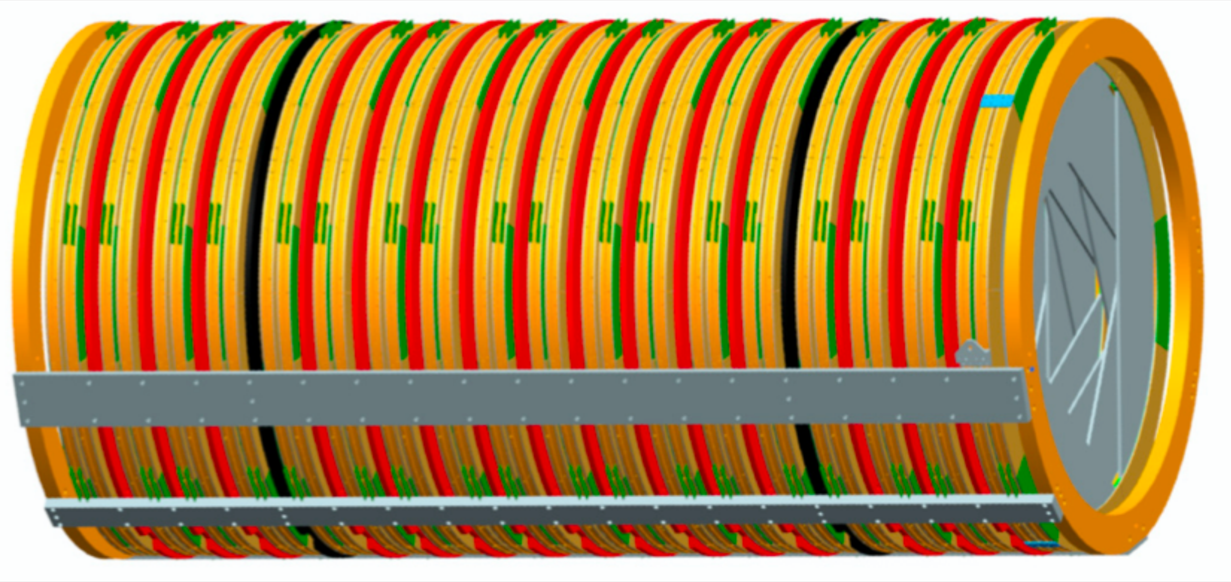


- Aiming the beam on target: 0.8 GeV (Mu2e-II) vs 8 GeV (Mu2e)
  - It also impacts the position of beam dump and extinction monitor position
- To hit the target Mu2e-II will optimize the following parameters
  - Vertical and horizontal incoming angles
  - Production target location
  - Production Solenoid magnetic field



Tracker

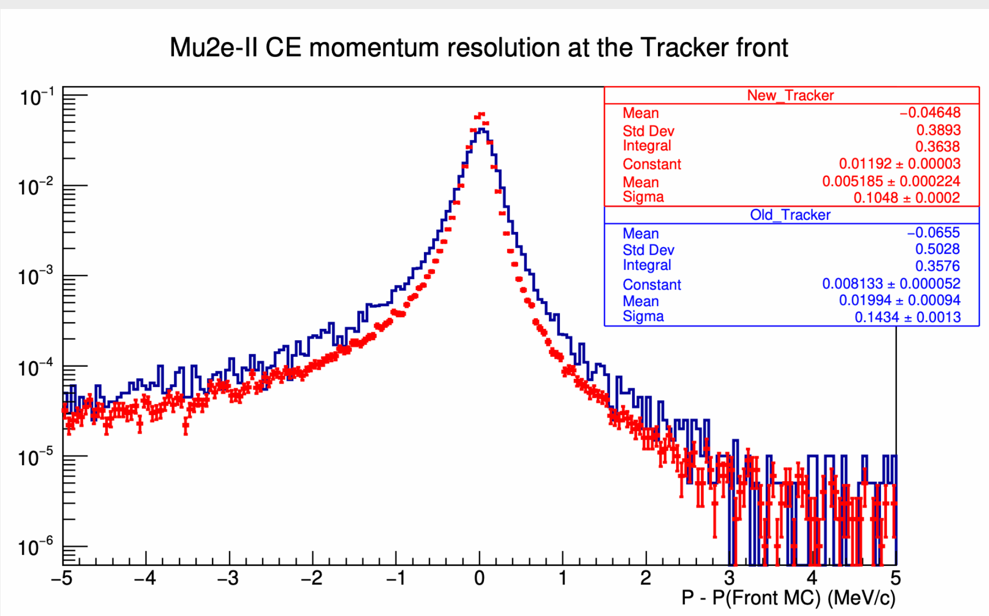
- Conversion electron momentum at Mu2e is reconstructed using straw tracker
- Expected Decay In Orbit (DIO) background at Mu2e: 0.144 events
  - DIO background would increase 10x at Mu2e-II, linear to the number of stopped muons
- Improve momentum resolution to suppress DIO by reducing straws thickness: $15\ \mu m \rightarrow 8\ \mu m$
  - In this study, we also reduced the momentum window $1.05\ MeV \rightarrow 0.85 MeV$ to further suppress DIO

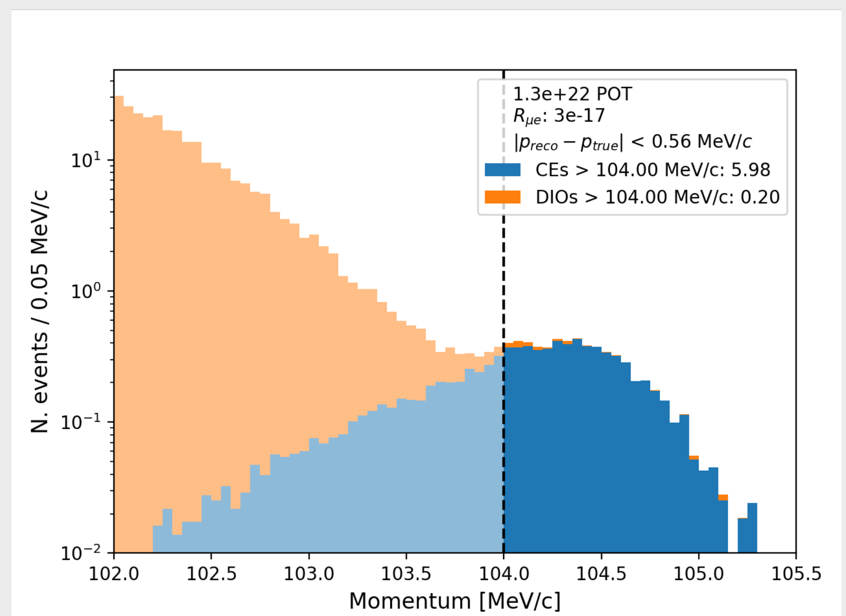


	Mu2e	Mu2e-II
Wall thickness (μm)	18.1	8.2
Al thickness (μm)	0.1	0.2
Au thickness (μm)	0.02	0.0
Linear Density (g/m)	0.35	0.15
Pressure limits (atm)	0–5	0–3
Elastic Limit (gf)	1600	500

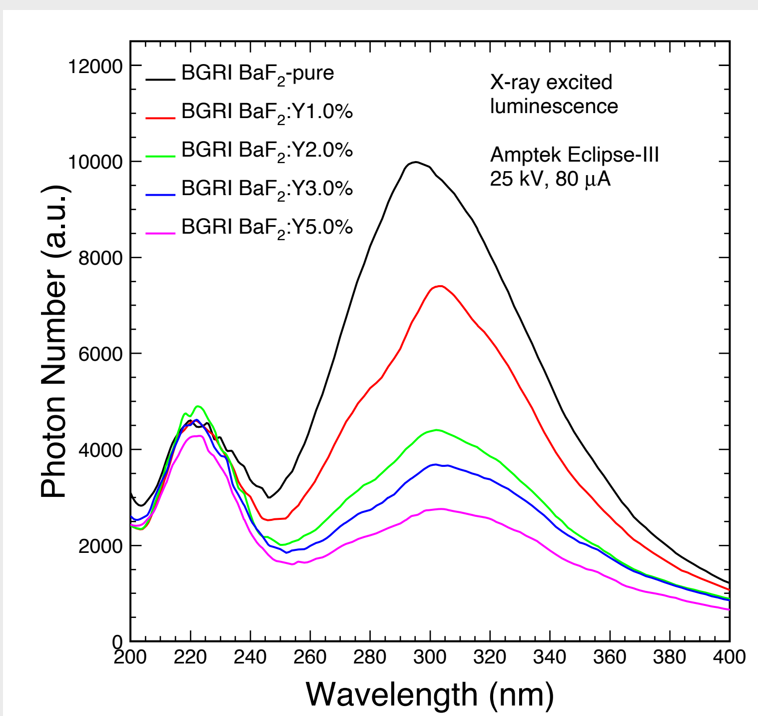
Tracker

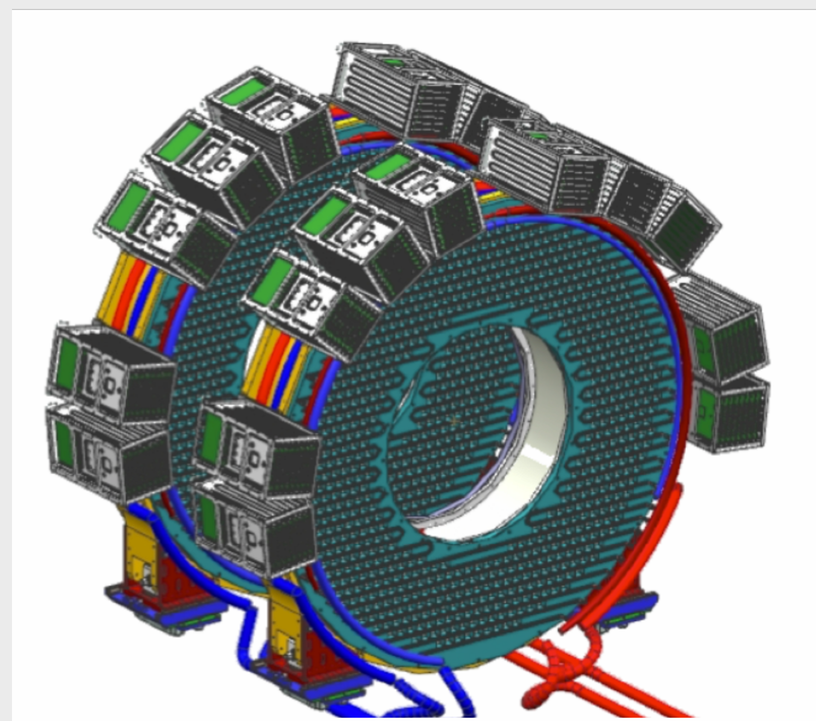
- The momentum resolution is improved with thinner straws: $140 \rightarrow 100\ keV$
- Fermilab's LDRD has been investigating challenges with: vacuum tightness, long term stability and large scale production
- Radiation levels (3 Mrad) exceeds the safety factor for electronics
  - Consider using application-specific integrated circuit electronics to handle the rad levels
- Investigate other detector alternatives:
  - Light gas vessel to ease straw leakage requirements
  - All wires construction and remove the straws
  - Wires separated by mylar walls





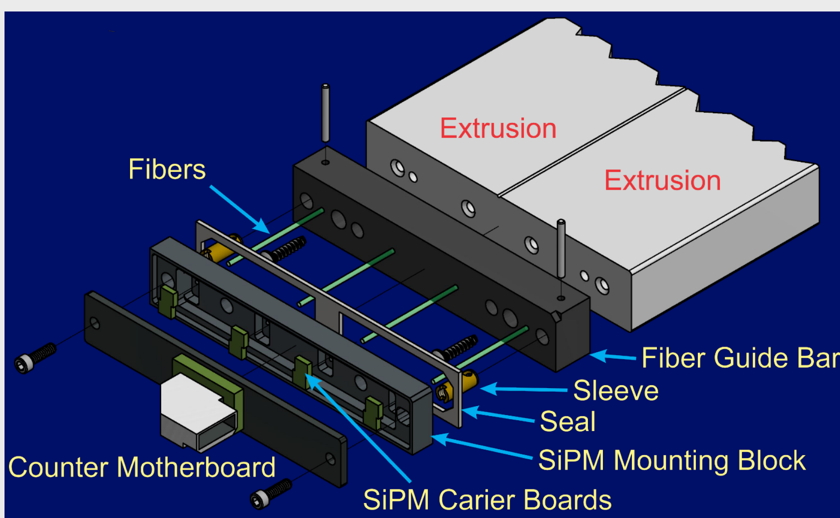
- Mu2e uses CsI calorimeter for PID, seed tracking and provide a fast trigger
- Requirements: $\sigma_E/E < 10\,\%\,@\,100MeV$ and $\sigma_t < 500\ ps\,@\,100MeV$
- CsI can't handle rad doses and crystals occupancy at Mu2e-II
  - $< Mrad,\ 10^{13}\ n_{1MeV-eq}/cm^2$
- BaF_2 is an excellent candidate: rad hard (< 100 Mrad) and has a fast UV component
  - Challenge: slow component can cause pileup
  - Suppress the slow scintillation component by doping BaF_2 with (Y)ttrium, (La)nthanum and (Ce)rium
  - Develop solar-blind photosensor: SiPMs with an external filter or UV-sensitive photocathodes
- This R&D is currently unfunded

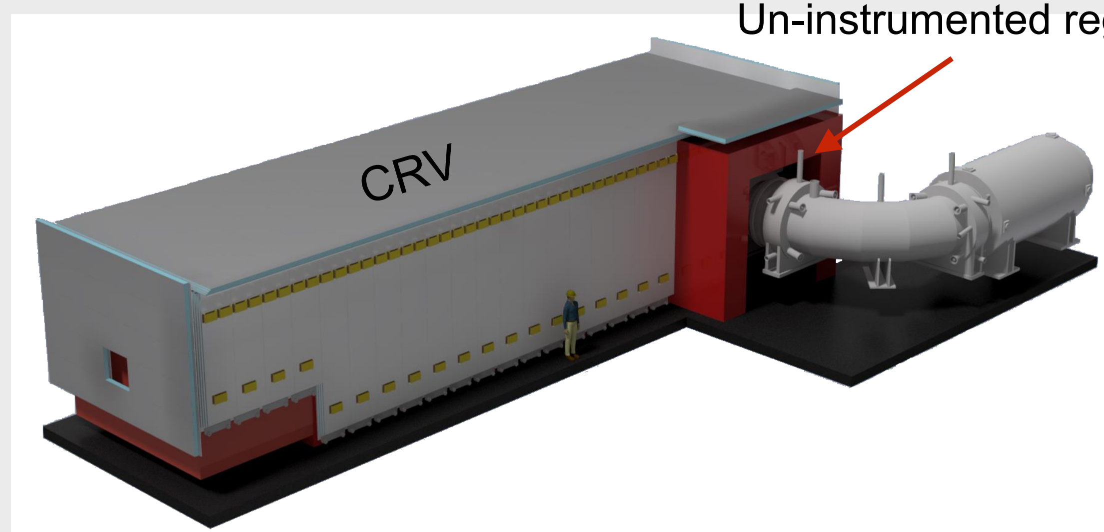




Cosmic Ray Veto (CRV)

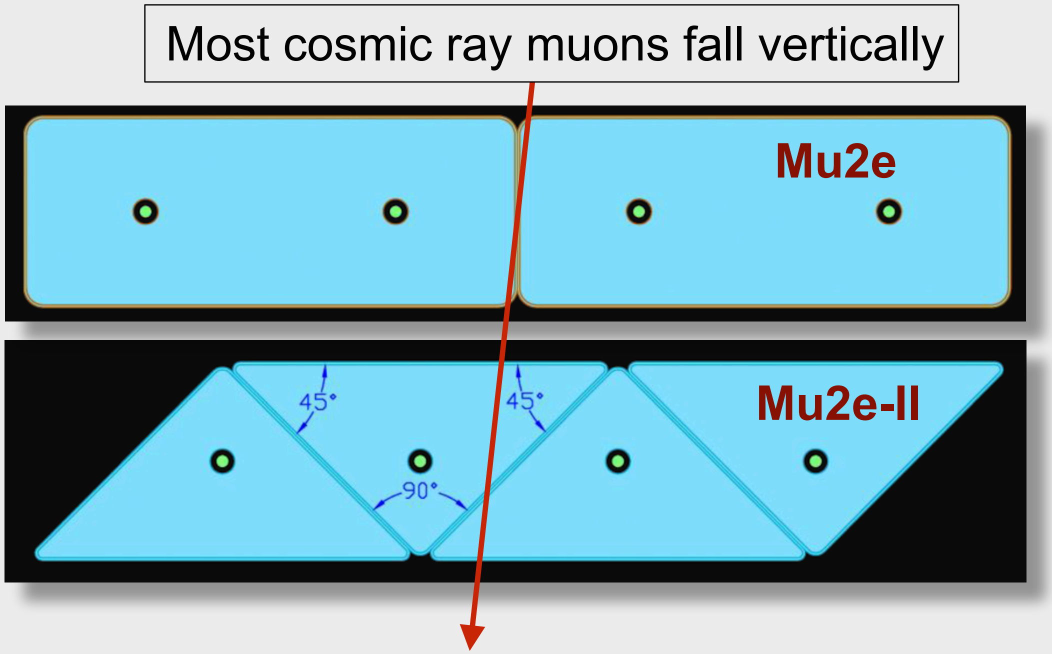
- CRV identifies cosmic ray muons that produce conversion-like backgrounds
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors
- Expected live-time and hence cosmic ray background is >3x higher at Mu2e-II
  - Use alternative CRV design to enhance the detection efficiency
- Higher (>x3) rad doses: higher DAQ rates, dead-time, rad damage
  - Promising results with enhanced shielding: tungsten PS and boron doped heavy concrete
- Cosmic ray background sources undetectable by CRV:
  - Cosmic ray neutrons is a significant (~0.6) source, if not addressed with enhanced shielding
  - Muons entering through un-instrumented CRV region is small (<0.1), but challenging to suppress contribution

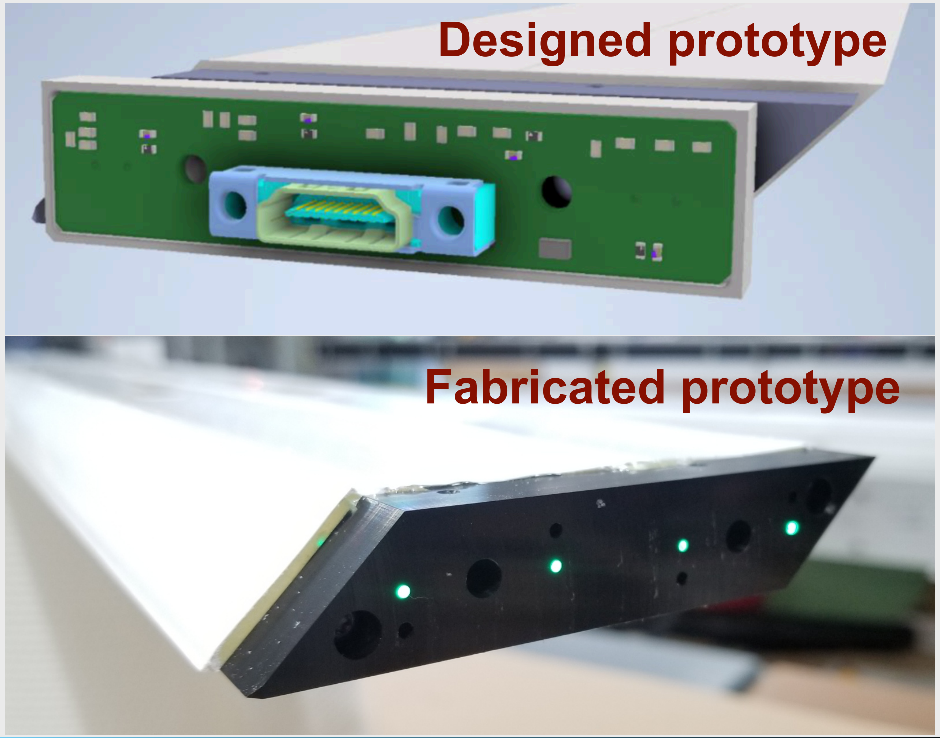




CRV design@Mu2e-II

- Enhanced CRV design using triangular-shaped counters
  - Improved efficiency due to reduced gaps
  - Better (1 mm) positional resolution reduces fake cosmic id, and hence dead-time
  - Lower DAQ rate from beam-induced detector noise
- CRV will be replaced due to aging
  - Enhance the light yield with thicker fiber, improved PDE SiPMs and potting fiber
- A prototype has been designed, fabricated and studies show promising results
- This R&D is currently unfunded





Stopping target

- We have considered stopping target designs alternative to Mu2e
  - However, we found that the current design with 34 Al foils is close to optimal
- If the signal is observed, will change stopping target to probe underlying New Physics operator
  - Titanium (Vanadium) and even Lithium stopping targets will be investigated
- Will adjust the micro-bunch length period to accommodate the muon lifetime of 329 ns on Ti vs 864 ns on Al

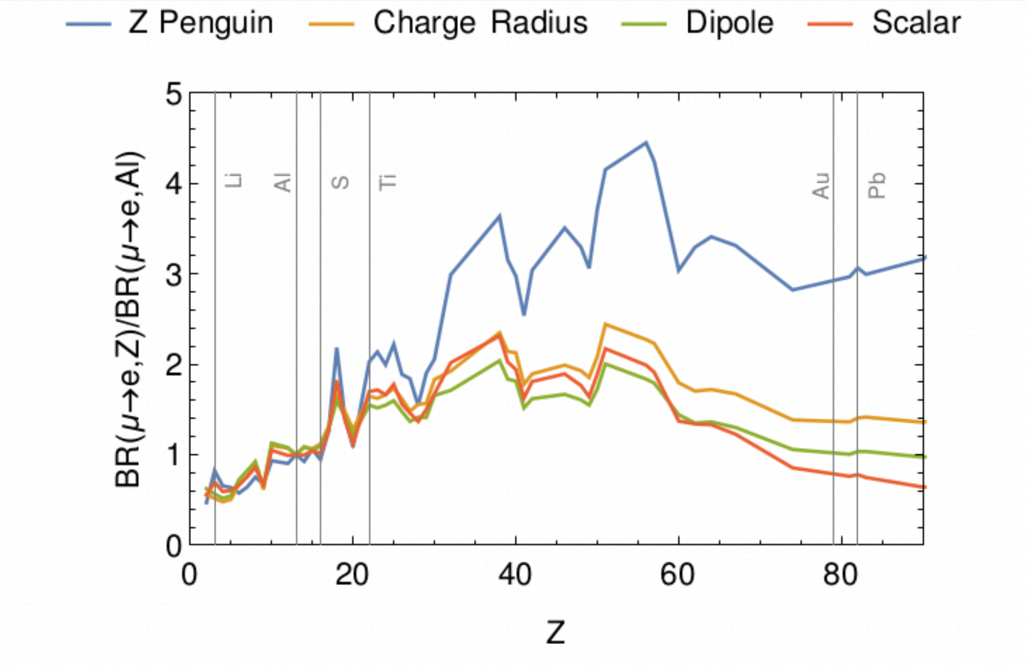


FIG. 1: Z dependence of $\mu \to e$ conversion rates for some example scenarios

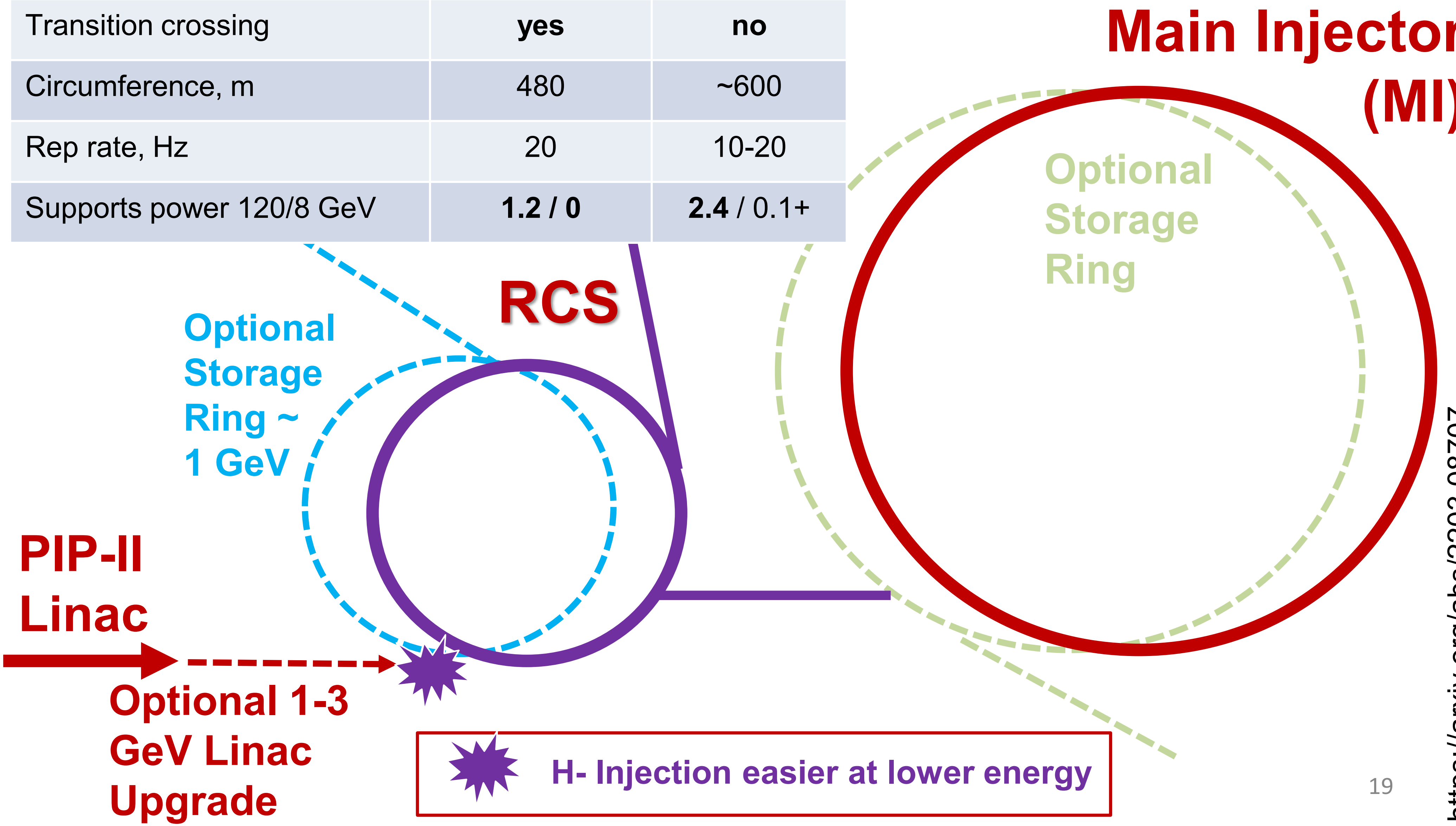
Summary

- Mu2e-II will advance CLFV search in $\mu^- N \rightarrow e^- N$ channel
  - Order of magnitude improvement in $R_{\mu e}$
- Physics case of Mu2e-II is compelling, regardless of Mu2e's findings
  - If Mu2e sees signal, Mu2e-II will study underlying physics
  - If Mu2e doesn't see a signal, Mu2e-II will extend the sensitivity reach
- Mu2e-II has a support from muon physics community and Fermilab's PAC
- Broad R&D program has been identified
- If approved, Mu2e-II expects to start data taking in 2030 decade

Backup slides

2.4 MW: Rapid-Cycling Synchrotron (RCS) Option

	8 GeV Booster	8 GeV RCS
Injection energy, GeV	**0.8**	**1-3**
Transition crossing	**yes**	**no**
Circumference, m	480	~600
Rep rate, Hz	20	10-20
Supports power 120/8 GeV	**1.2 / 0**	**2.4** / 0.1+



https://arxiv.org/abs/2203.08707