Mu2e Experiment*

Eric Prebys
For the Mu2e Collaboration

*A Letter of Intent to Search for Charged Lepton Flavor Violation in Nuclear Muon Capture

Goals of Experiment

- Initial Phase (MECO design, No Project X):
  - Exploit NOvA accelerator modifications and post-Run II availability of Accumulator and Debuncher rings to mount a μ->e conversion experiment patterned after MECO
    - 4×10^{20} protons in ~2 years
    - Measure

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- \mathrm{Al} \rightarrow e^- \mathrm{Al}\right)}{\Gamma\left(\mu^- \mathrm{Al} \rightarrow \mathrm{capture}\right)}$$

    - Single event sensitivity of $R_{\mu e}=2\times10^{-17}$
    - 90% C.L. limit of $R_{\mu e}<6\times10^{-17}$
    - ANY signal = Beyond Standard Model physics
- Ultimate goal
  - Exploit Project X and improved muon transport to achieve dramatically increased sensitivity
    - If no signal: set limit $R_{\mu e}<1\times10^{-18}$
    - If signal: measure target dependence, etc

Mu2e Collaboration

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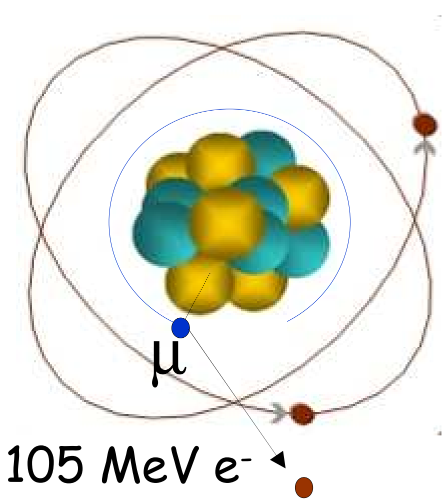
Currently:
50 Scientists
11 Institutions

Search for Charged Lepton Flavor Violation (CLFV)

- The discovery of neutrino oscillations naturally raises the question:
  - What is the rate of charged lepton flavor violation in nature?
- CLFV is a powerful probe of multi-TeV scale dynamics: complementary to direct collider searches
- Among various possible CLFV modes, rare muon processes offer the best combination of new physics reach and experimental sensitivity

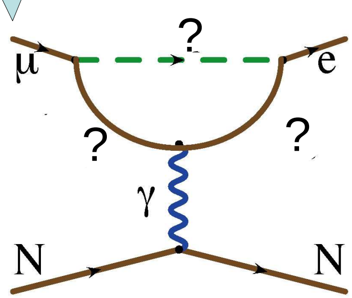
Muon-to-Electron Conversion: $\mu + N \rightarrow e + N$

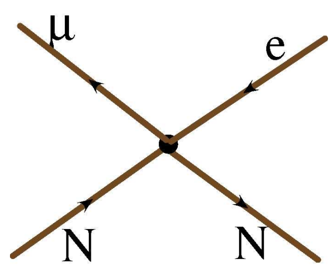


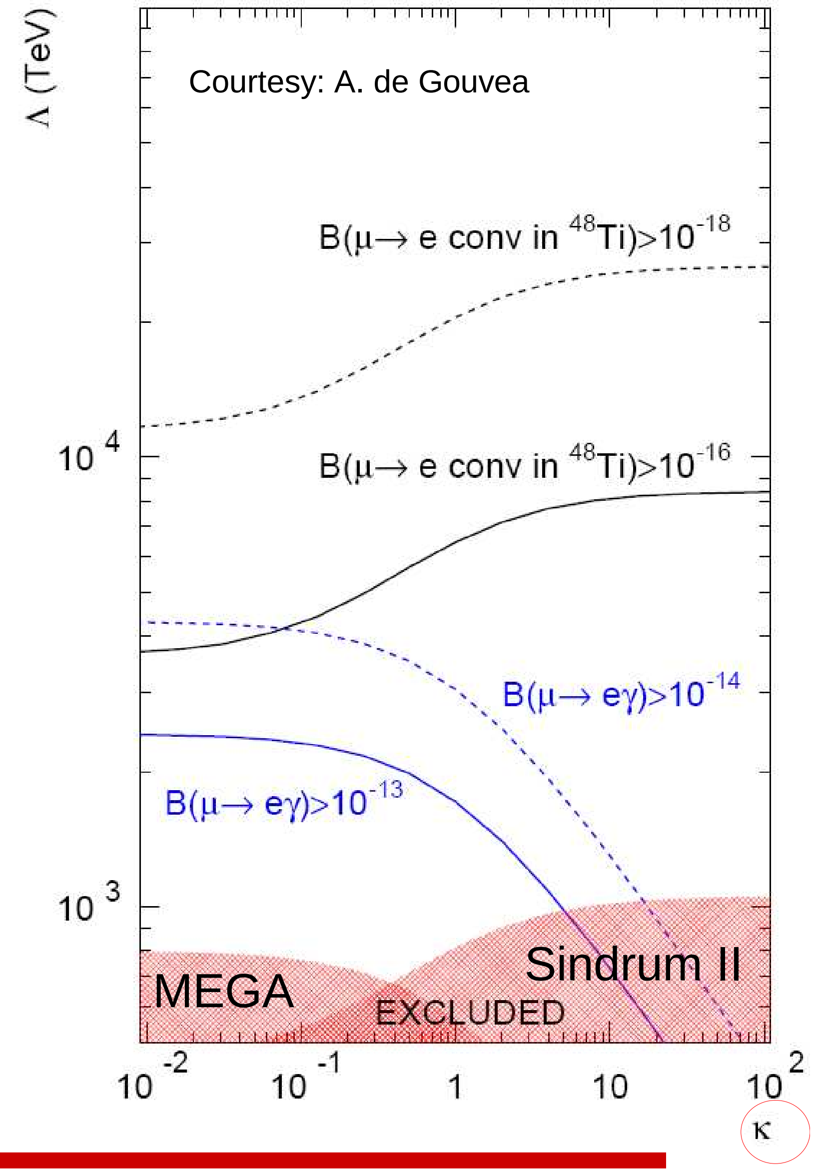
- Standard Model rate via Dirac neutrino mixing is too small to be observed ($\sim 10^{-52}$)
- Very common feature of Beyond Standard Model physics at much larger rates
- Similar to $\mu \rightarrow e\gamma$, with important advantages:
  - No combinatorial background
  - Sensitive to other types of BSM physics
  - Relative rate depends on details of physics

Broadly Sensitive to New High Energy Dynamics

$$\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right).$$



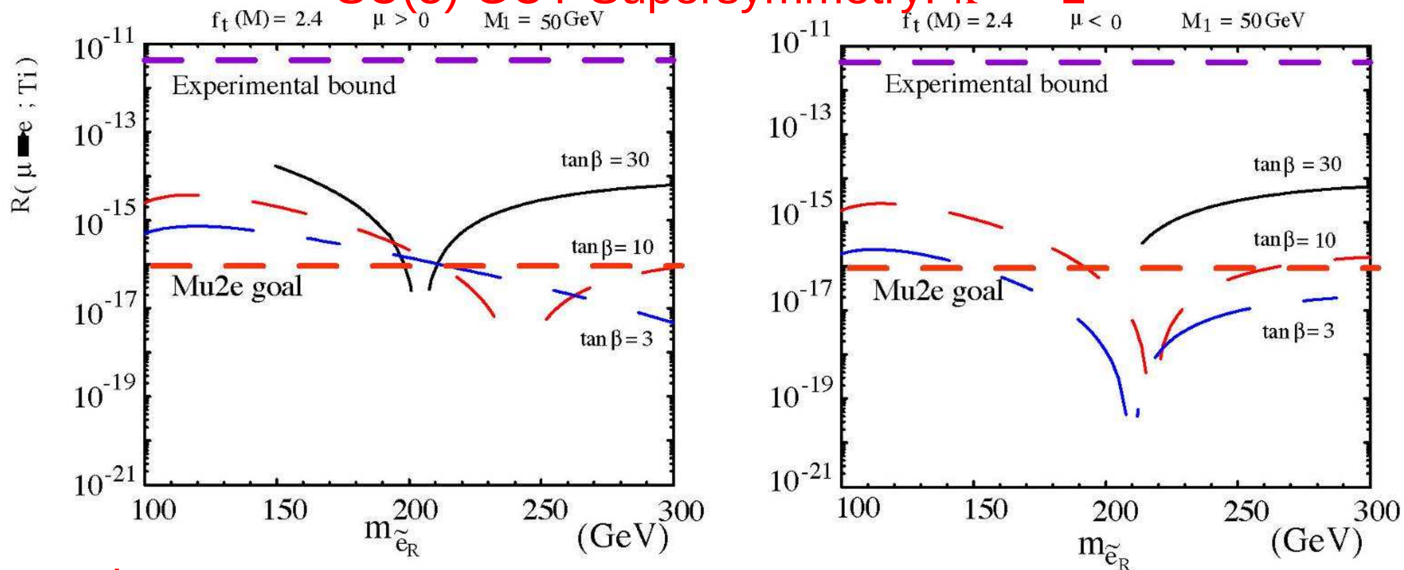




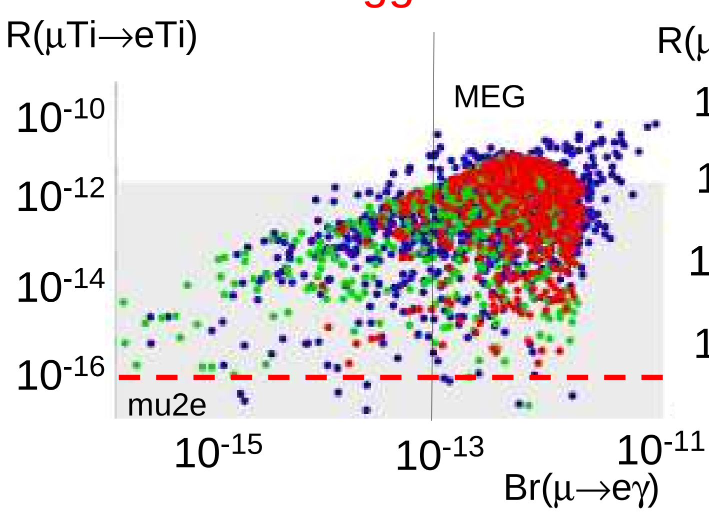
- At $R_{\mu e}$~10^{-16} (first phase, this LOI), the sensitivity is already very compelling, well above the reach of colliders
- At 10^{-18} (potentially, with upgraded apparatus and higher muon flux), energy scales probed would be difficult to access by other means

Specific Model Examples

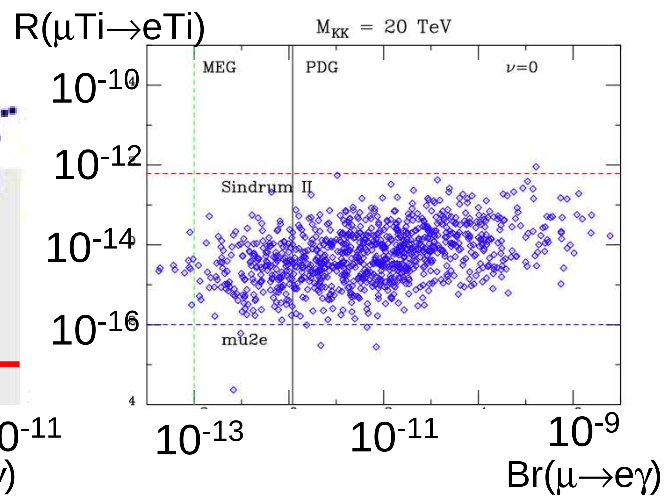
SU(5) GUT Supersymmetry: $\kappa << 1$



Littlest Higgs: $\kappa \approx 1$



Randall-Sundrum: $\kappa \approx 1$



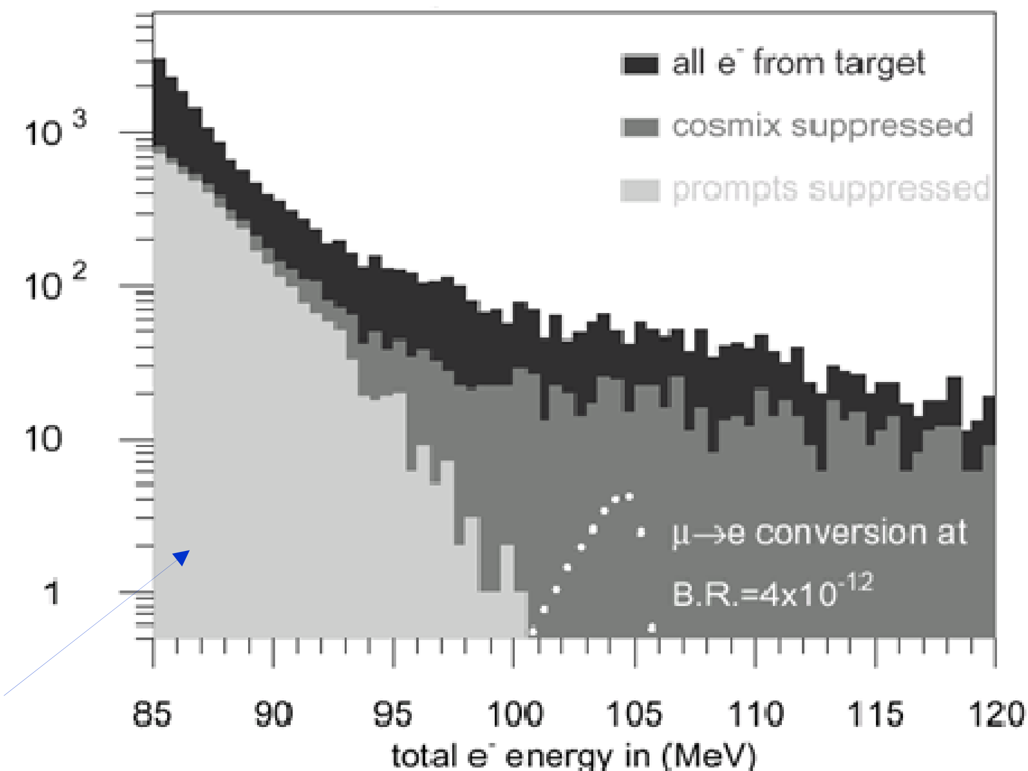
- Examples with $\kappa >> 1$ (no $\mu \to e\gamma$ signal):
  - Leptoquarks
  - Z-prime
  - Compositeness
  - Heavy neutrino

Previous muon decay/conversion limits (90% C.L.)

LFV μ Decay:

$$\Gamma(\mu^- \to e^- \nu_e \overline{\nu_\mu}) < 1.2\times 10^{-2}$$
$$\Gamma(\mu^- \to e^- \gamma) < 1.2\times 10^{-11}$$
$$\Gamma(\mu^- \to e^- e^+ e^-) < 1.0\times 10^{-12}$$
$$\Gamma(\mu^- \to e^- 2\gamma) < 7.2\times 10^{-11}$$

μ–>e Conversion: Sindrum II



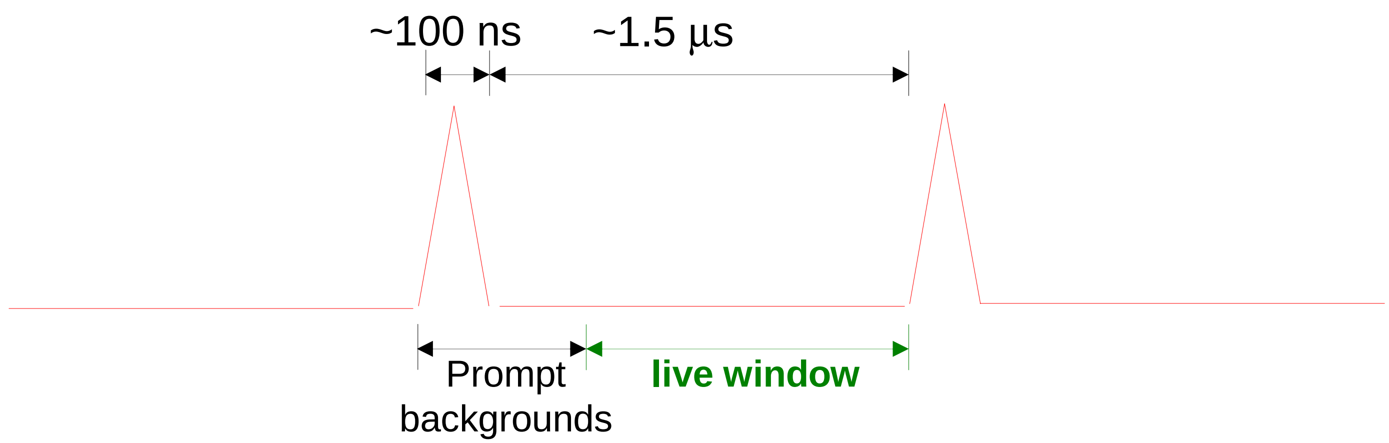
High energy tail of coherent Decay-in-orbit (DIO)

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- Ti \to e^- Ti)}{\Gamma(\mu^- Ti \to \text{capture})} < 4.3\times 10^{-12}$$

- Rate limited by need to veto prompt backgrounds!

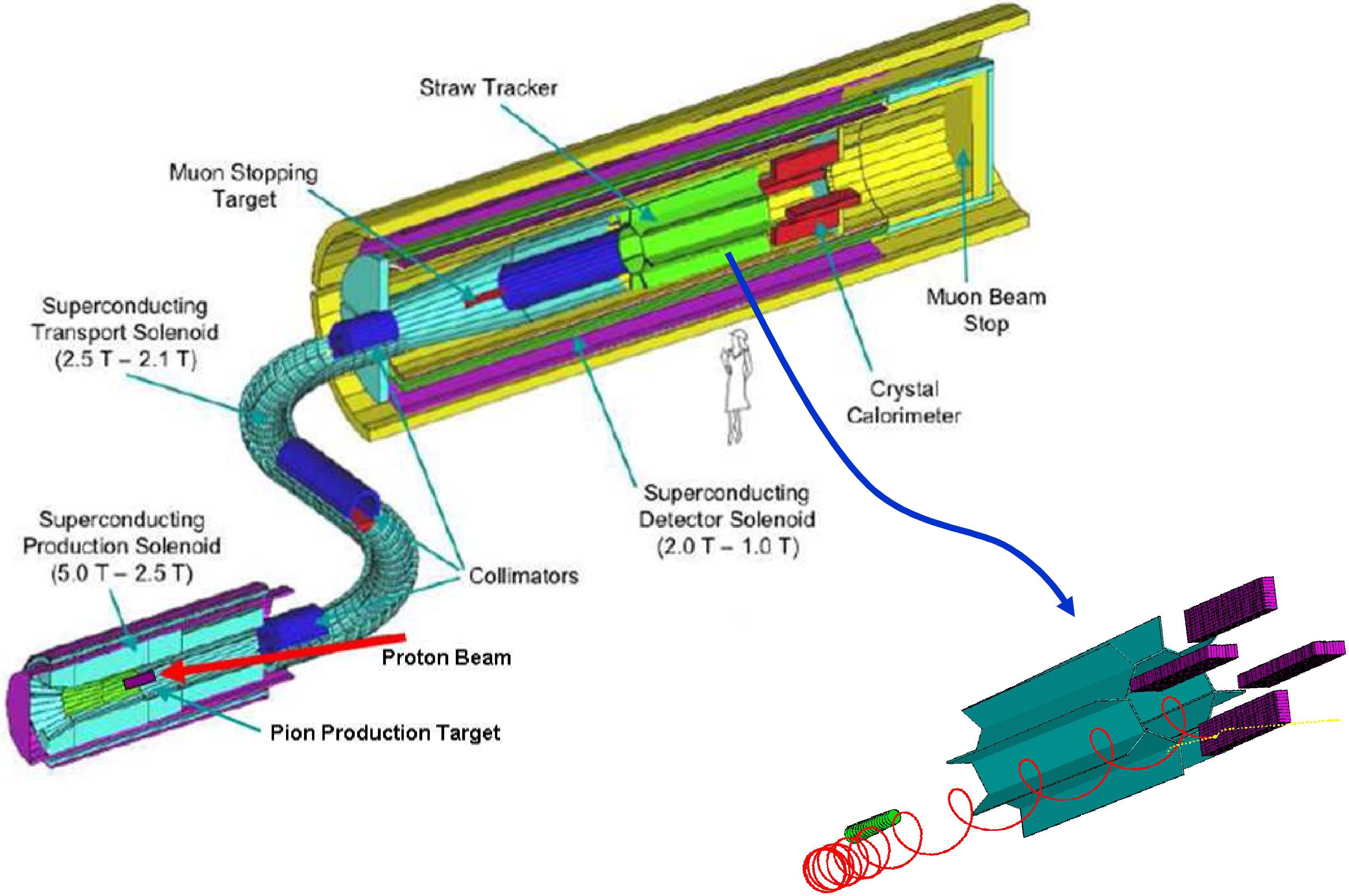
Mu2e (MECO) Philosophy

- Eliminate prompt beam backgrounds by using a primary beam with short proton pulses with separation on the order of a muon life time

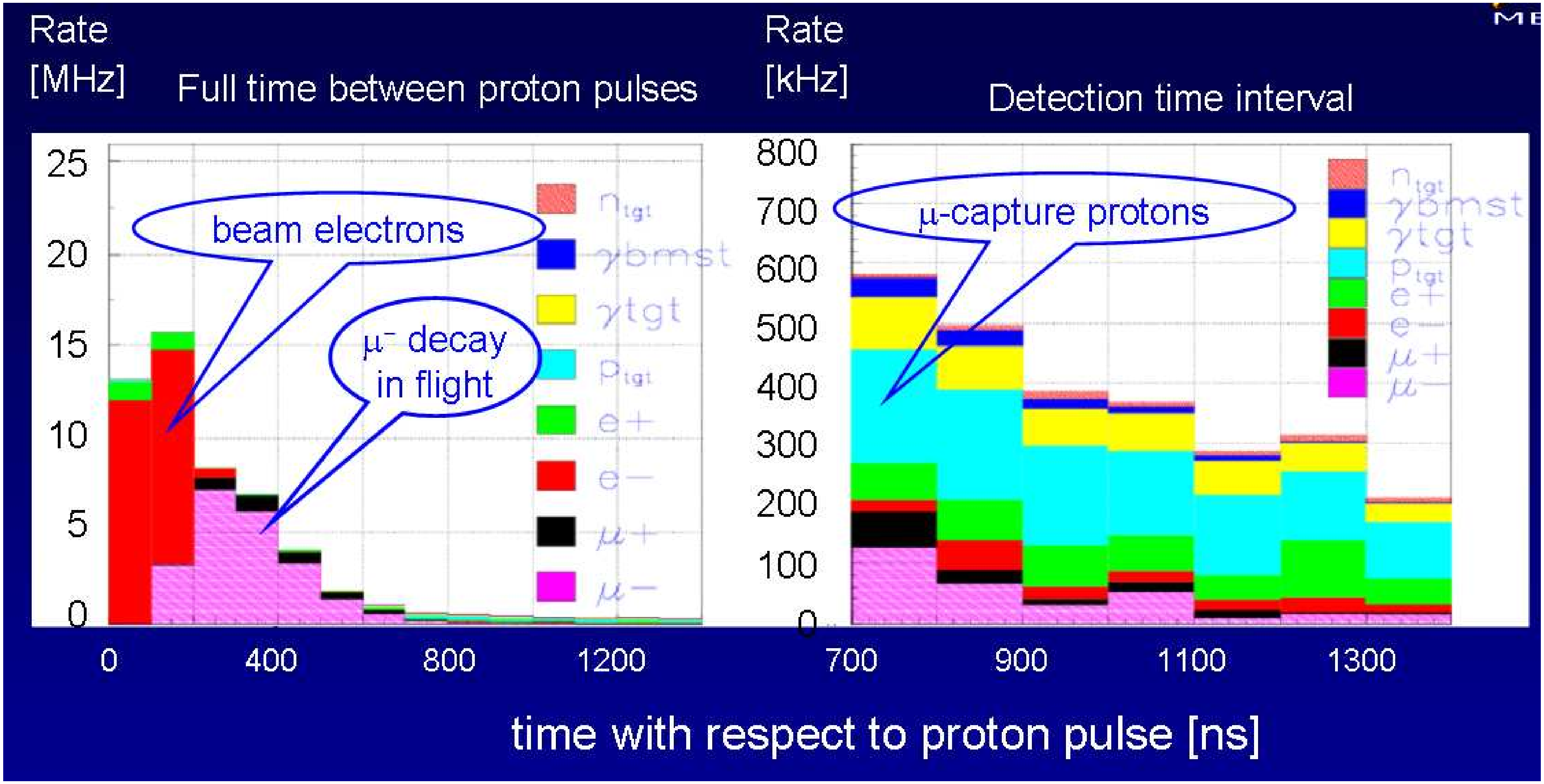


- Design a transport channel to optimize the transport of right-sign, low momentum muons from the production target to the muon capture target.
- Design a detector to *strongly* suppress electrons from ordinary muon decays

Detector Layout

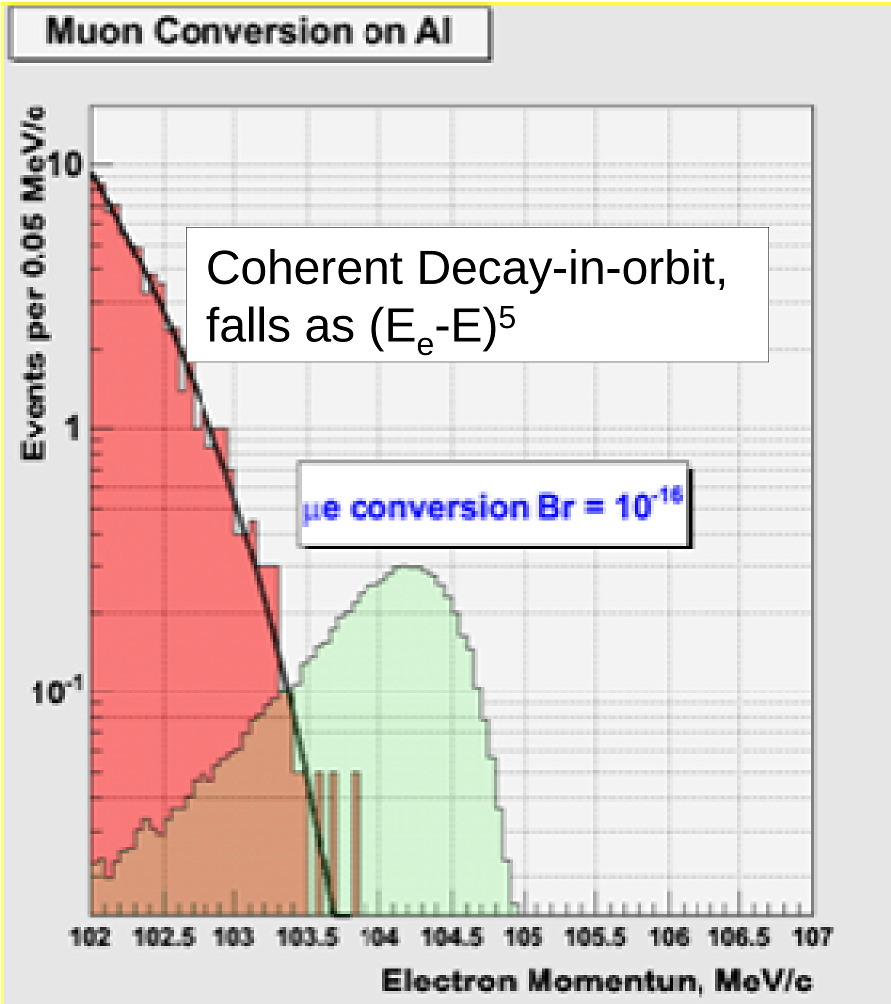


Beam Related Rates



- Cut ~700 ns after pulse to eliminate most serious prompt backgrounds.

Sensitivity



- $R_{\mu e} = 10^{-16}$ gives 5 events for $4\text{x}10^{20}$ protons on target
- 0.4 events background, half from out of time beam, assuming 10^{-9} extinction
  - Half from tail of coherent decay in orbit
  - Half from prompt

Mu2e History

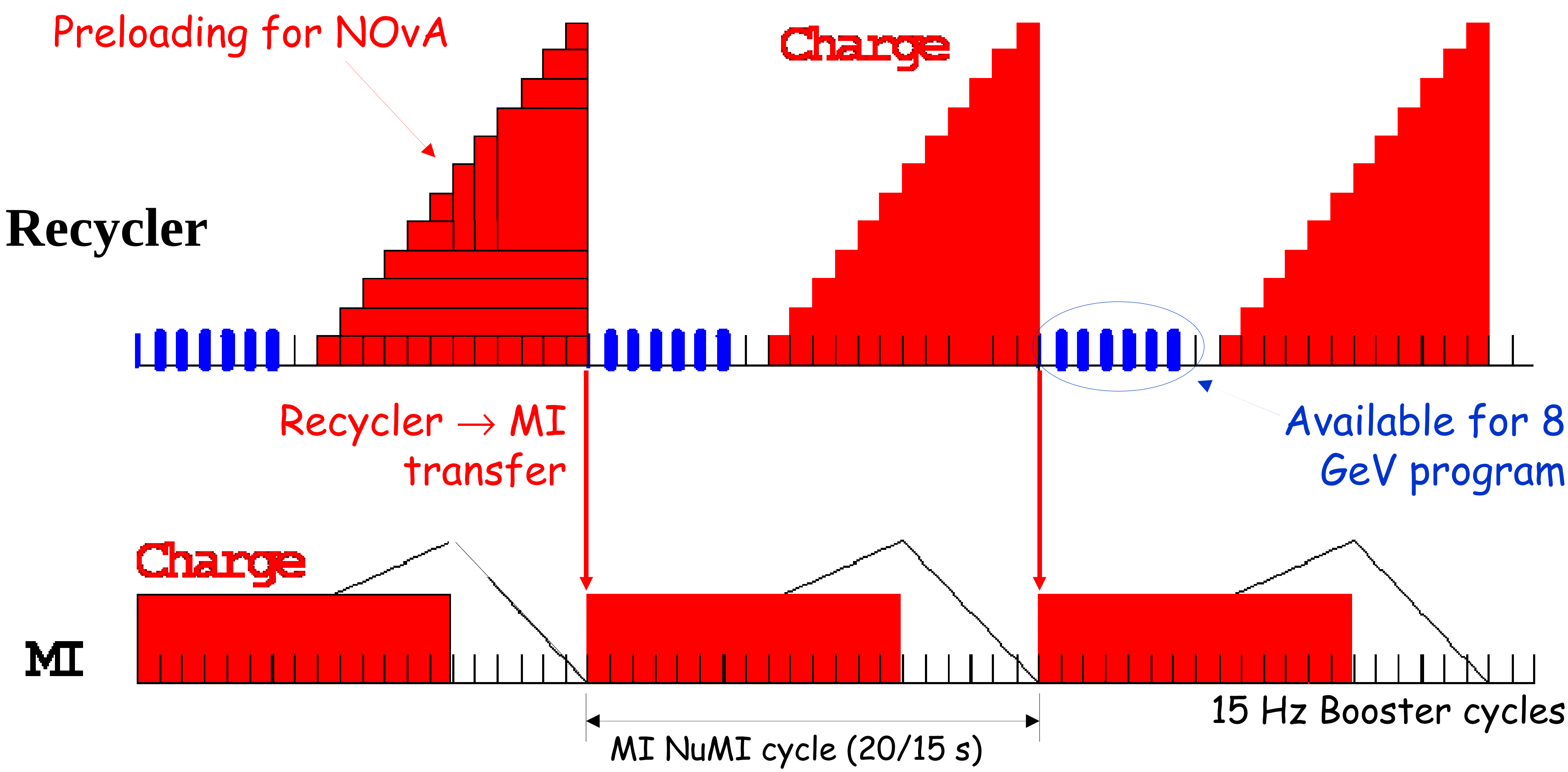
- 1997
  - MECO proposed for the AGS at Brookhaven
  - Approved, along with KOPIO, as part of RSVP program
- 1998-2005
  - Design refined
  - Frequent favorable reviews
- 2005
  - June: final reviews, very positive
    - Physics goals: HEPAP RSVP Subpanel
    - Cost and schedule: "Wojcicki Panel"
  - July: RSVP cancelled for financial reasons
    - MECO and KOPIO "charged" for entire cost of continued AGS operation.
- 2006
  - January: First informal meeting at BNL
  - September: First meeting at Fermilab
- 2007
  - June: Mu2e expression of interest submitted to Fermilab Directorate
  - August: First Mu2e collaboration meeting
  - October: Letter of Intent submitted to Directorate

Mu2e at Fermilab

- If the current suite of proton source upgrades is effective, there should be at least enough excess 8 GeV protons during the NOvA era to do an experiment with similar sensitivity to MECO in a reasonable amount of time.
  - The resonant operation of the 8 GeV Booster makes it impossible to directly generate the desired time structure.
  - There is a scheme to generate this time structure using the antiproton Accumulator and Debuncher rings, which will become available after the termination of the collider program.
  - This scheme requires only modest modifications beyond those planned for NOvA, *with which it is fully compatible.*

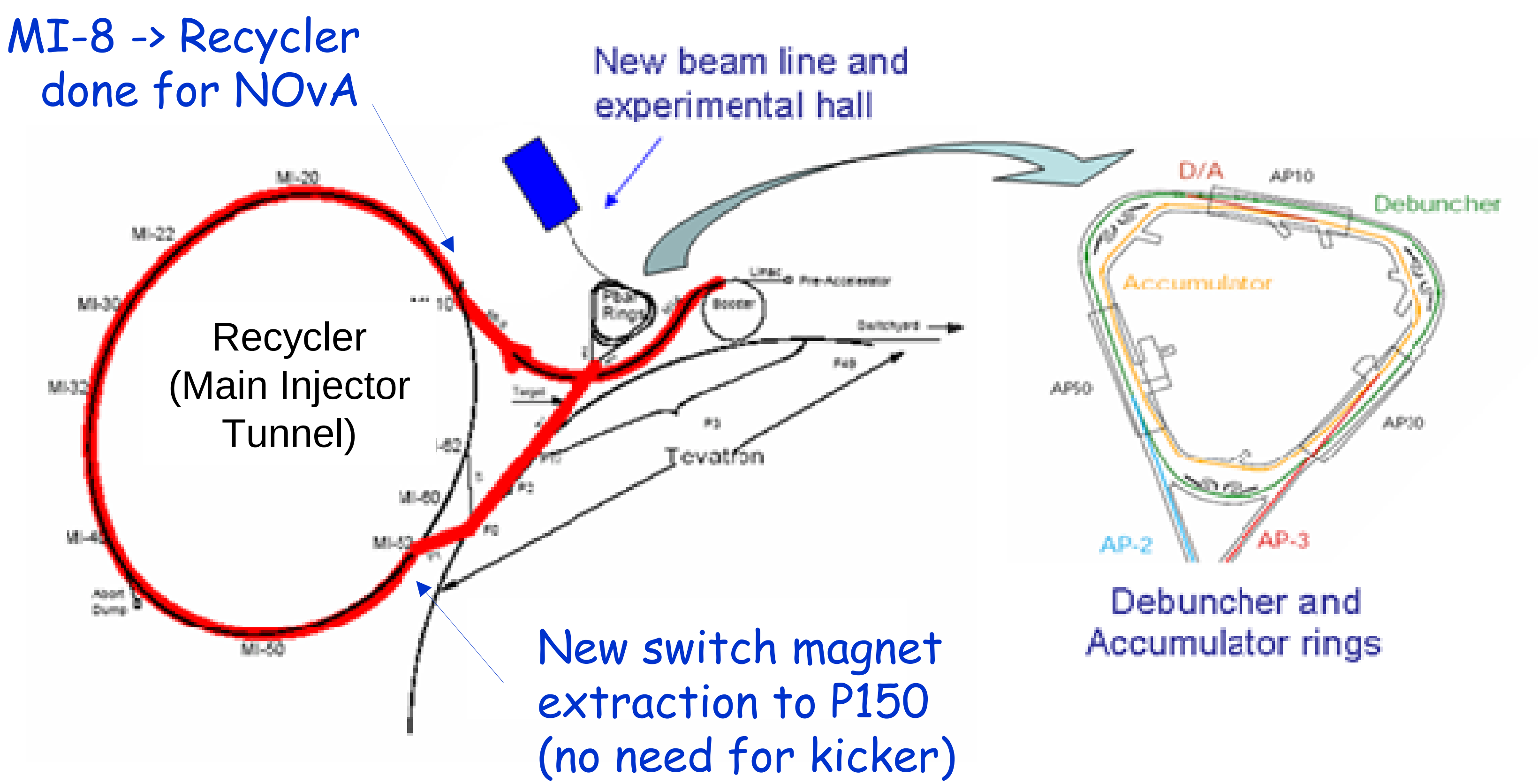
Available Protons: NOvA Timeline

MI uses 12 of 20 available Booster Batches per 1.33 second cycle



Roughly 6*(4x10^{12} batch)/(1.33 s)*(2x10^{7} s/year)=3.6x10^{20} protons per year available

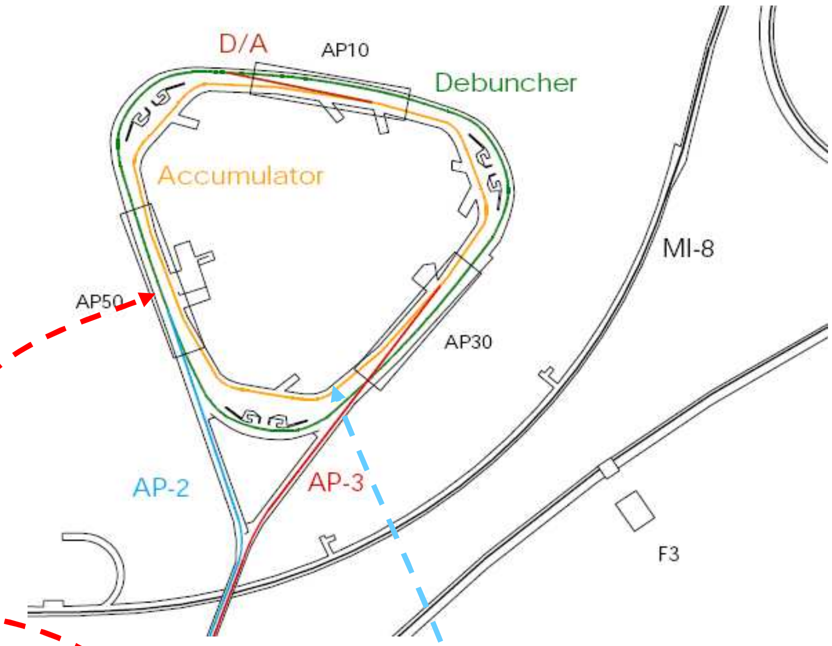
Delivering Protons: "Boomerang" Scheme

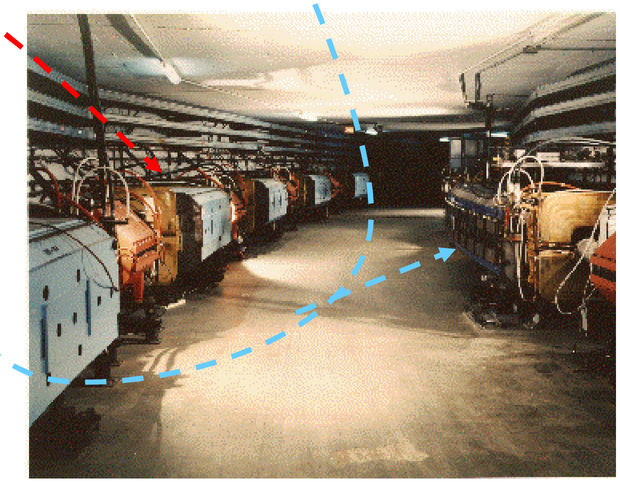


- Deliver beam to Accumulator/Debuncher enclosure with minimal beam line modifications and *no civil construction*.

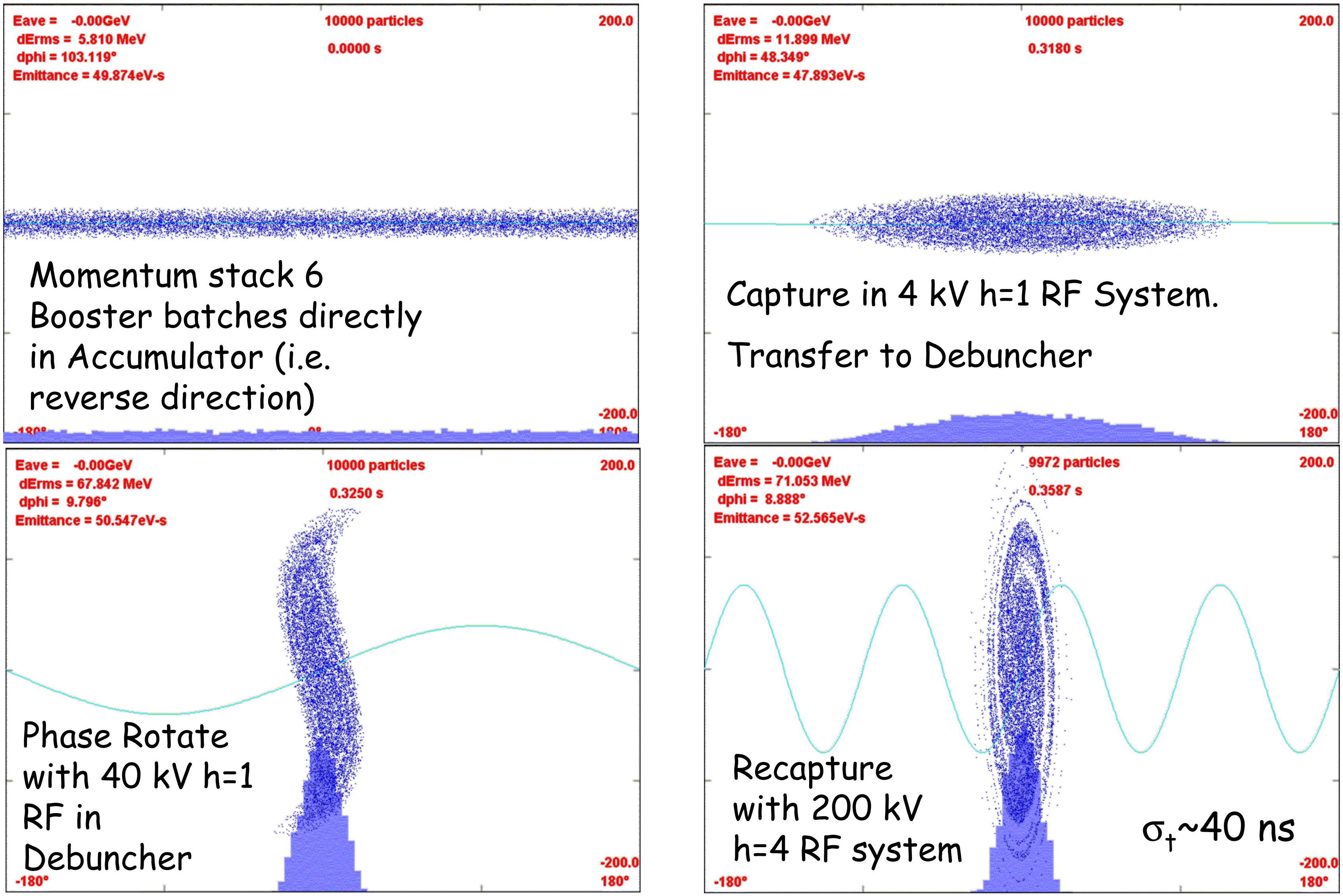
Present Operation of Debuncher/Accumulator

- Protons are accelerated to 120 GeV in Main Injector and extracted to pBar target
- pBars are collected and phase rotated in the "Debuncher"
- Transferred to the "Accumulator", where they are cooled and stacked
- Not used for NOvA

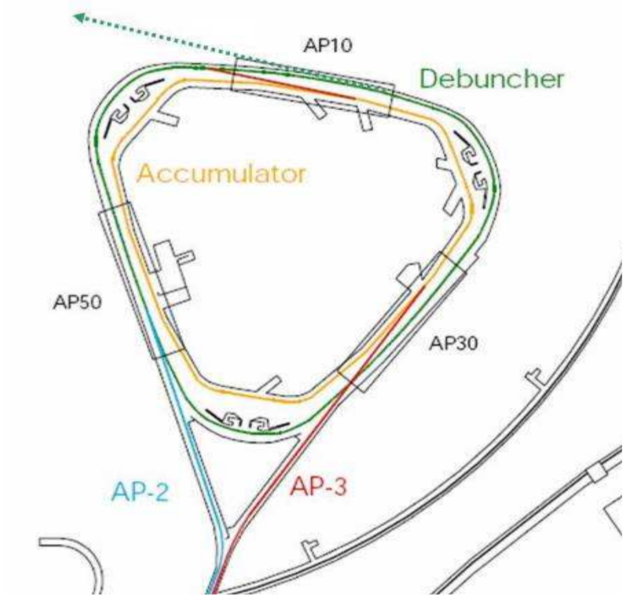




Rebunching in Accumulator/Debuncher

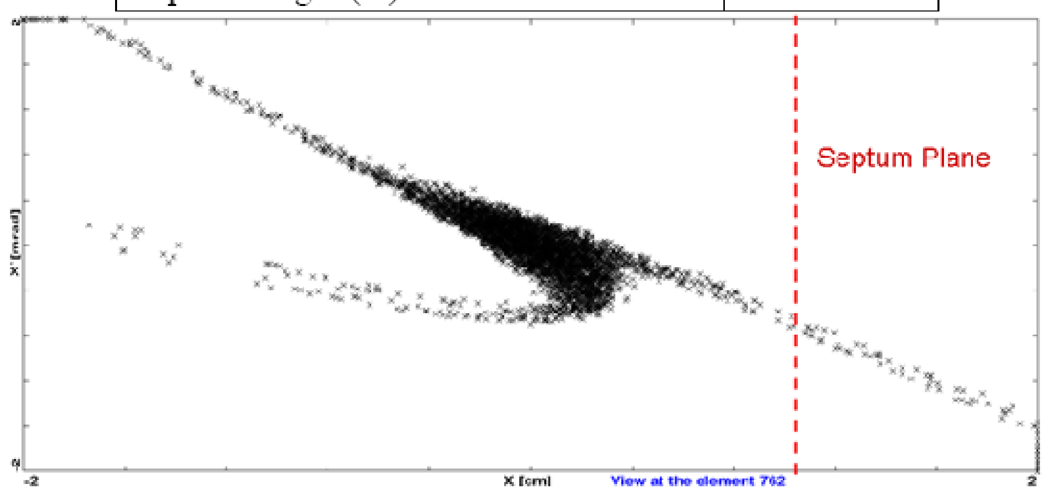


Resonant Extraction



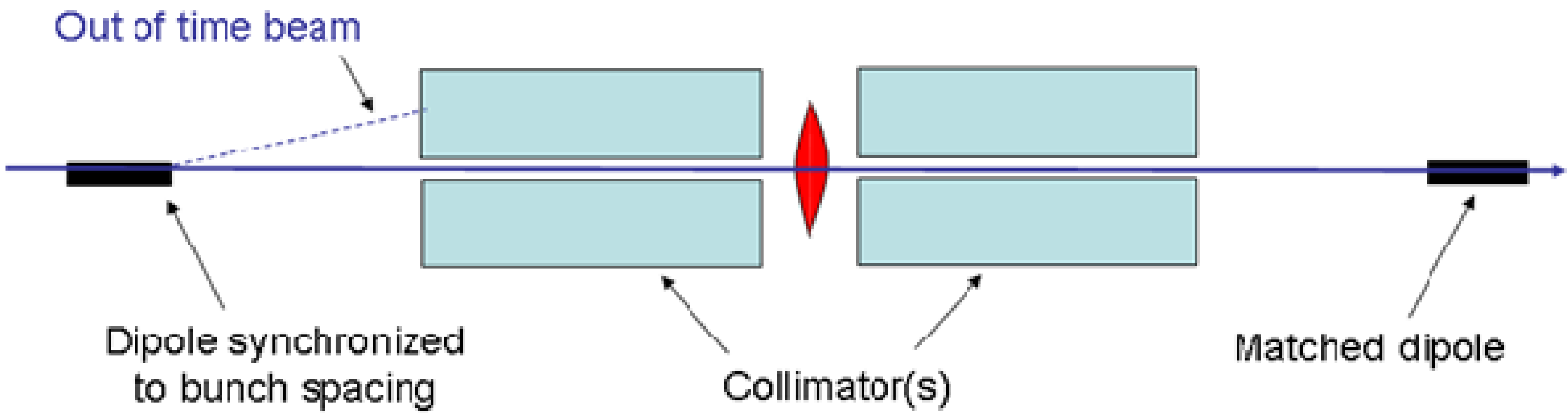
Resonant Extraction Parameters	
Kinetic Energy (GeV)	8
Working tune (ν_x/ν_y)	9.769/9.783
Resonance (ν_x)	29/3
Normalized acceptance (x/y πmm-mr)	285/240
Normalized beam emittance (πmm-mr)	20
β at electrostatic septum (m)	15
β at Lambertson (m)	22
β at harmonic quads (m)	14
Septum Position (mm/σ)	11/4.8
Septum gap/step size (mm)	10
Sextupole Drive Strength (T-m/m^2)	473
Initial Tuneshift	.048
Septum field (MV/m)	8
Septum length (m)	3

- Exploit 29/3 resonance
- Extraction septum and Lambertson similar to Main Injector
  - Septum: 80 kV/1cm x 3m
  - Lambertson+C magnet ~.8T x 3m



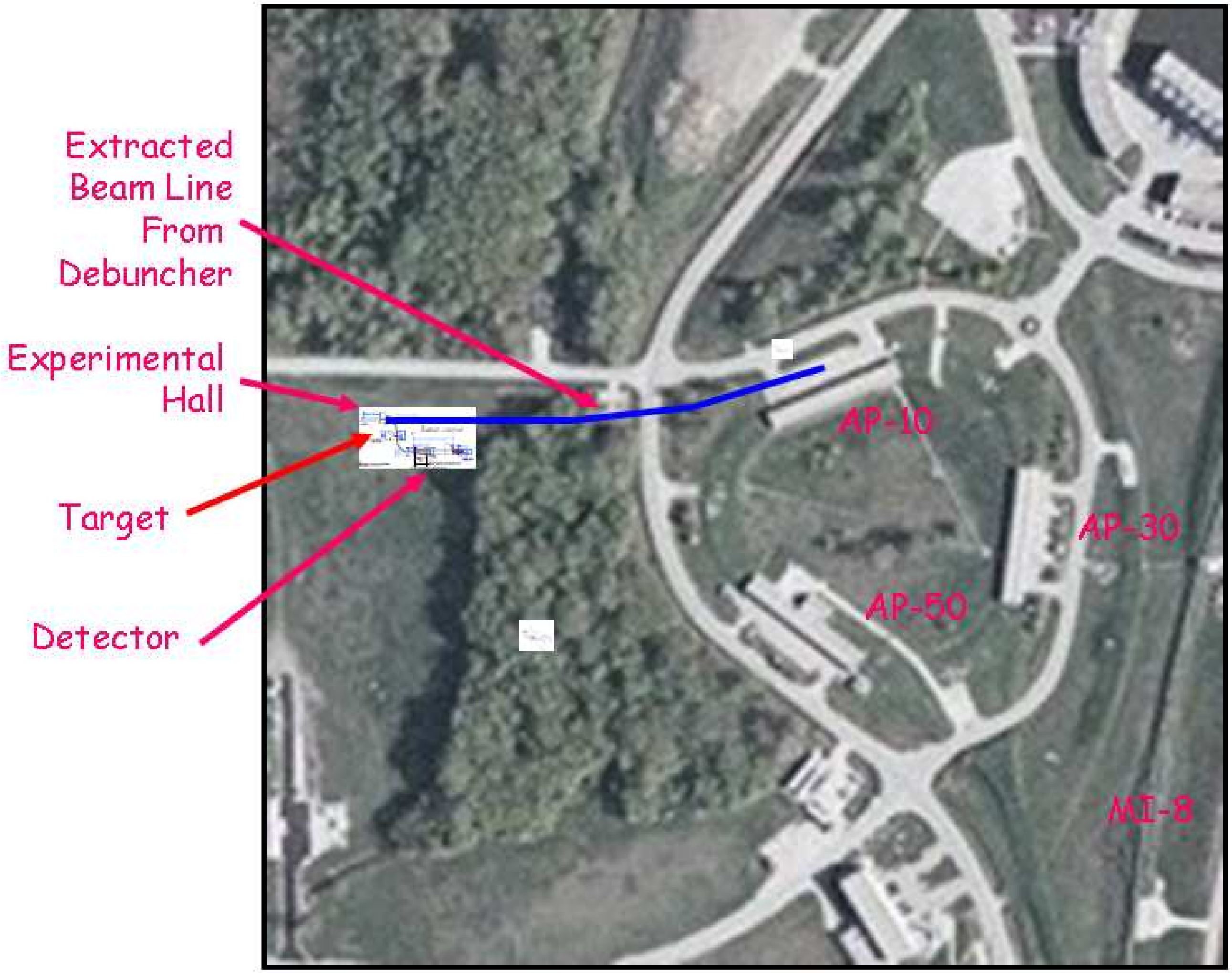
Beam Extinction

- Need 10^{-9}
- Get at least $\sim 10^{-3}$ from beam bunching
- Remainder from AC Dipole in beam line



- Working with Osaka (FNAL+US-Japan funds) to develop AC dipole design, as well as explore measurement options

Proposed Location



- Requires new building.
- Minimal wetland issues.
- Can tie into facilities at MiniBooNE target hall.

Cost and Time Scale

- A detailed cost estimate of the MECO experiment had been done just before it was cancelled*
  - Solenoids and cryogenics: $58M
  - Remainder of experimental apparatus: $27M
- Additional Fermilab costs have not been worked out in detail, but are expected to be on the order of $10M.
- Hope to begin Accelerator work along with NOvA upgrades
  - ~2010 (or 2011 if Run II extended)
- Based on the original MECO proposal, we believe the experiment could be operational within five years from the start of significant funding
  - Driven by magnet construction.
  - ~2014
- With the proposed beam delivery system, the experiment could collect the nominal 4×10^{20} protons on target in about one to two years, *with no impact on NOvA*
  - NOvA rate limited by Main Injector

*Costs in 2005 dollars, including contingency

Mu2e and Project X

- We have described the initial phase of mu2e, which is based on the proposed data sample of 4×10^{20} protons.
  - 90% C.L. limit of $R_{\mu e}<6\times10^{-17}$ (improvement over existing limit of more than 4 orders of magnitude).
- The Project X linac would provide roughly a *factor of ten* increase in flux.
- Slow extraction directly from Recycler ruled out by Project X Working Group
  - Will need to load beam from Recycler to Accumulator as we are planning to do for Phase I
- A preliminary scheme to exploit this additional flux will be included in our proposal.

Mu2e and Muon Collider/Neutrino Factory

- There are a number of synergies between this project and muon cooling efforts
  - The Debuncher beam could be extracted in a single turn to produce the short, intense bunch needed by muon production experiments
  - Muon cooling studies have increased the understanding of solenoidal transport.
  - It is possible that a "helical cooling channel", of the sort envisioned for muon cooling, could generate a significantly higher muon yield for this experiment.
- We will investigate these in more detail for the proposal.

A combination of increased flux from Project X and a more efficient muon transport line could potentially result in a sensitivity as low as 10^{-18}

Experimental Challenges for Increased Flux

- Achieve sufficient extinction of proton beam.
  - Current extinction goal directly driven by total protons
- Upgrade target and capture solenoid to handle higher proton rate
- Improve momentum resolution for the ~100 MeV electrons to reject high energy tails from ordinary DIO electrons.
- Operate with higher background levels.
- Manage high trigger rates
  - All of these efforts will benefit immensely from the knowledge and experience gained during the initial phase of the experiment.
- If we see a signal a lower flux, can use increased flux to study in detail
  - Precise measurement of $R_{\mu e}$
  - Target dependence
  - Comparison with $\mu \rightarrow e\gamma$ rate

Required Resources for Proposal

- ~$100K of FESS time
  - for a preliminary cost estimate of the experimental facility and beam line civil construction
- ~1/2 FTE beam line design expert
  - to produce a preliminary design of the primary proton line, including extinction channel
- ~1/2 FTE of ES&H radiation safety expert
  - to help us produce a plan to deal with the increased flux in the pBar enclosure (VERY important!)
- ~1/2 FTE of a TD magnet expert
  - to evaluate the MECO magnet design, and advise of possible improvements.
- A dedicated postdoc and guest scientist position
  - Focus on Monte Carlo work.
  - Could also be supplemented with PPD resources

Conclusions

- The mu2e experiment is an opportunity for Fermilab to make an important measurement
  - ➢ In the initial phase (without project X) we would either
    - Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e}<6\times10^{-17}$ @ 90% C.L.)

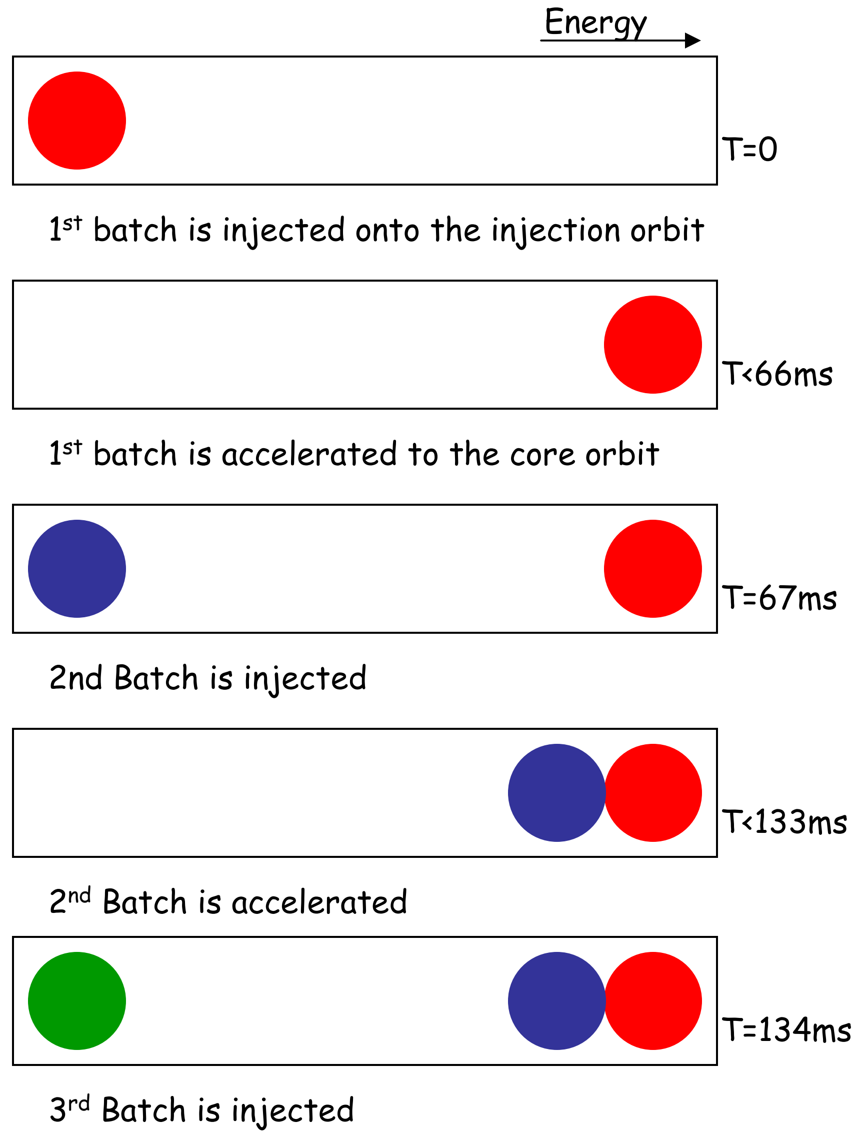
      OR
    - Discover unambiguous proof of Beyond Standard Model physics
- This experiment benefits greatly from both the voluminous work done for the MECO proposal and by fortuitous configuration and availability of Fermilab accelerator components.
- With a combination of Project X and/or improved muon transport, we could either
  - ➢ Extend the limit by up to two orders of magnitude

    OR
  - ➢ Study the details of new physics

Backup Slides

Momentum Stacking

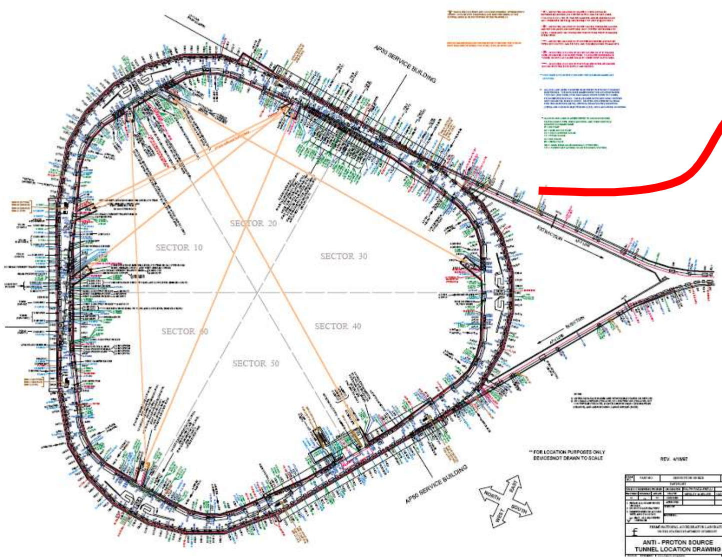
- Inject a newly accelerated Booster batch every 67 mS onto the low momentum orbit of the Accumulator
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-6 Booster batches

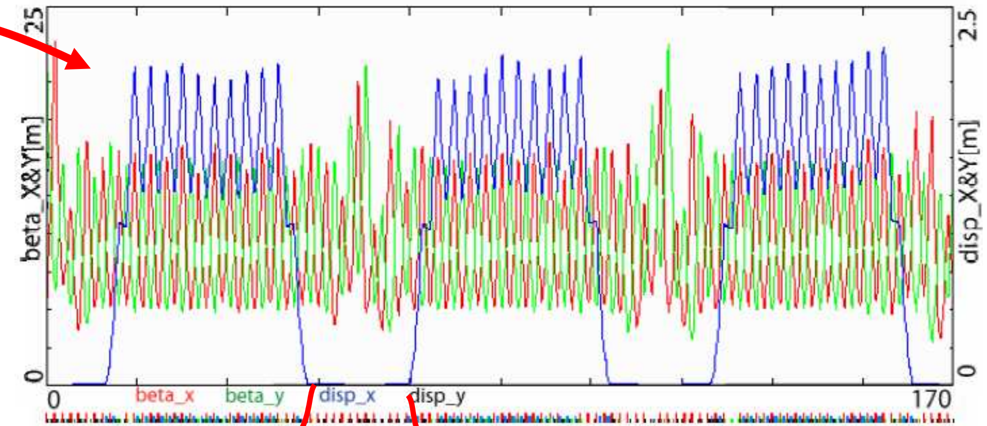


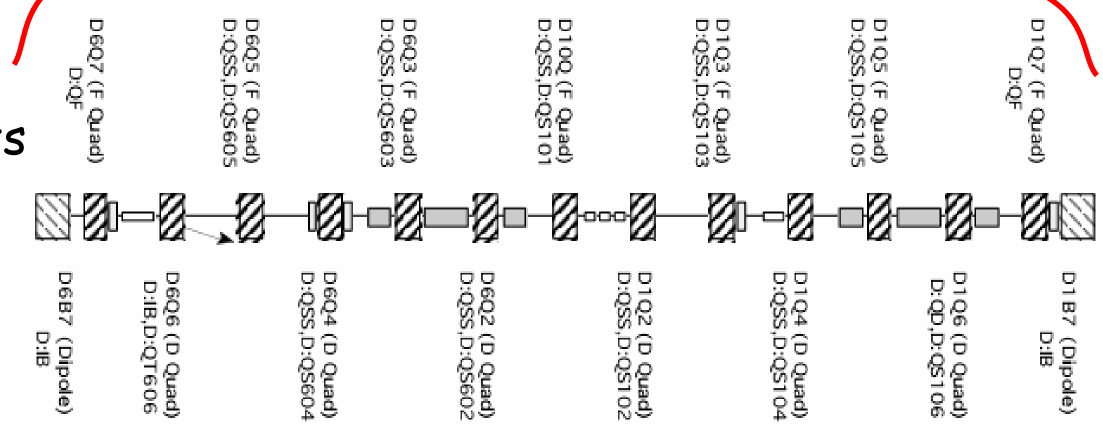
Rebunching Scheme

- **Accumulator**
  - Momentum stack 1 to 6 booster batches
  - Adiabatically bunch at h=1- **4kV**
    - 500ns gap for kicker
    - Some beam/halo cleaning in Acc and transfer
    - Adiabatic easier at γ_T=5.5
  - Transfer to Debuncher
- **Debuncher**
  - h=1 90-degree phase rotation at fixed voltage
    - **40kV** - 0.007s
  - Capture and store at h=4
    - ~**200** to 250 kV ~0.02s; σ_τ = 42ns
    - Beam halo cleaning also ....

Attractive Features of Debuncher



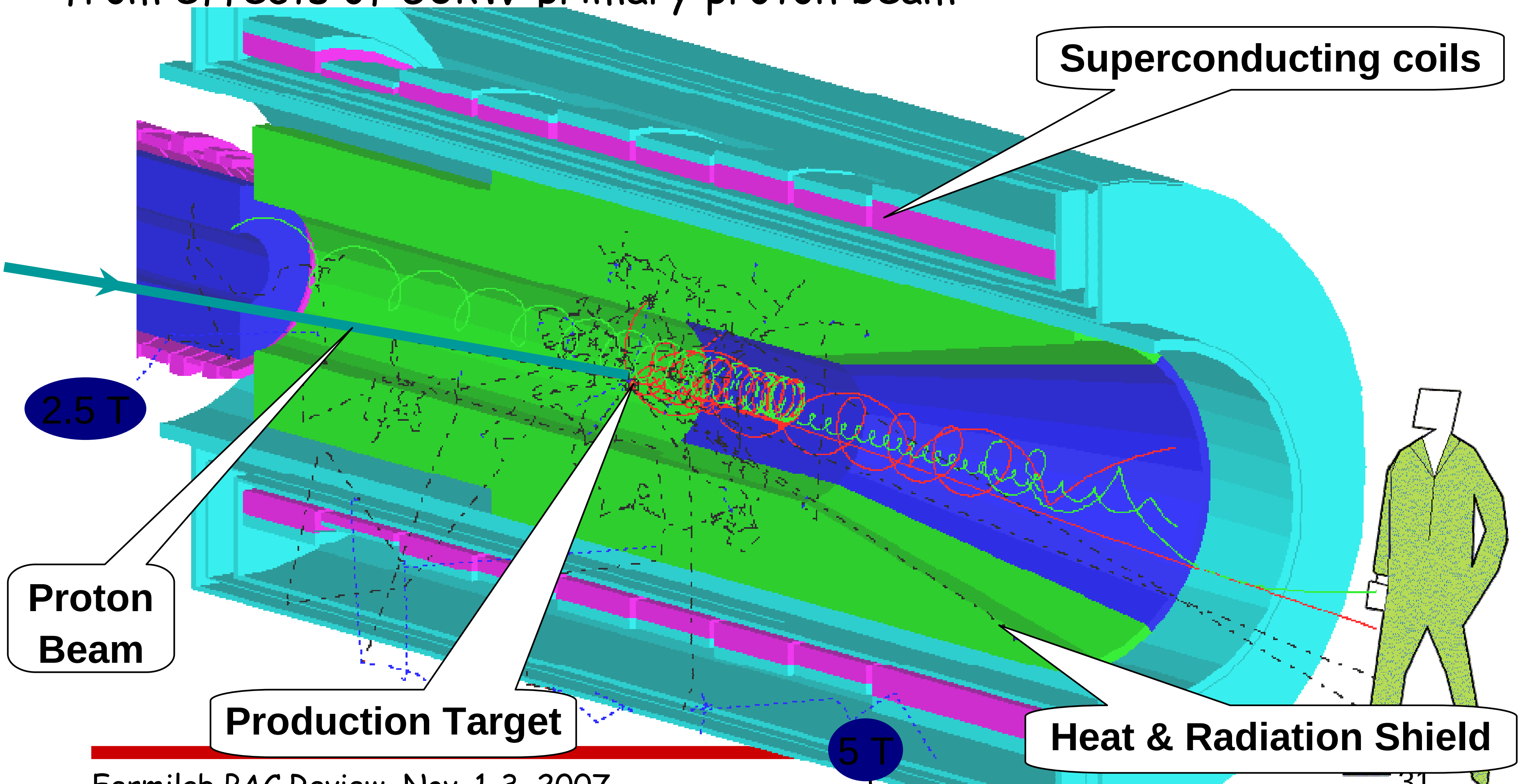




- Large Acceptance
- Low chromaticity
- Long, dispersion-free segments
- Lots of open straight sections after cooling hardware removed
- Problem:
  - Getting protons there

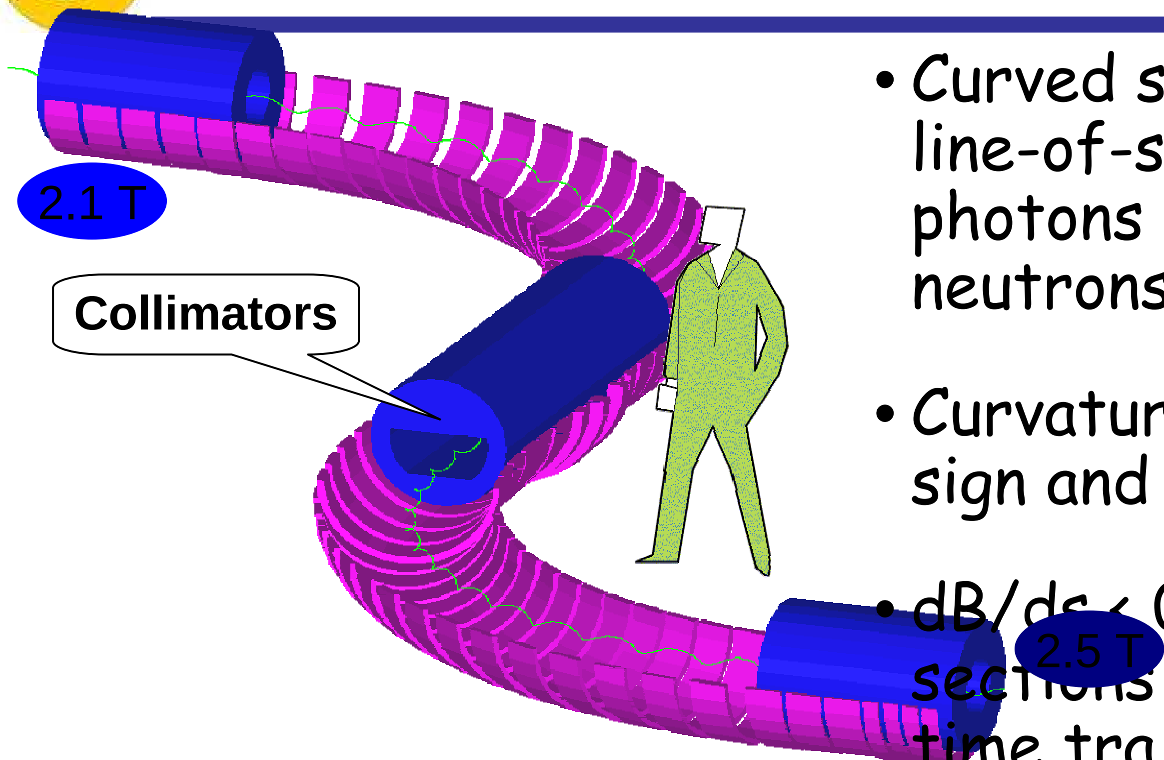
Production Region

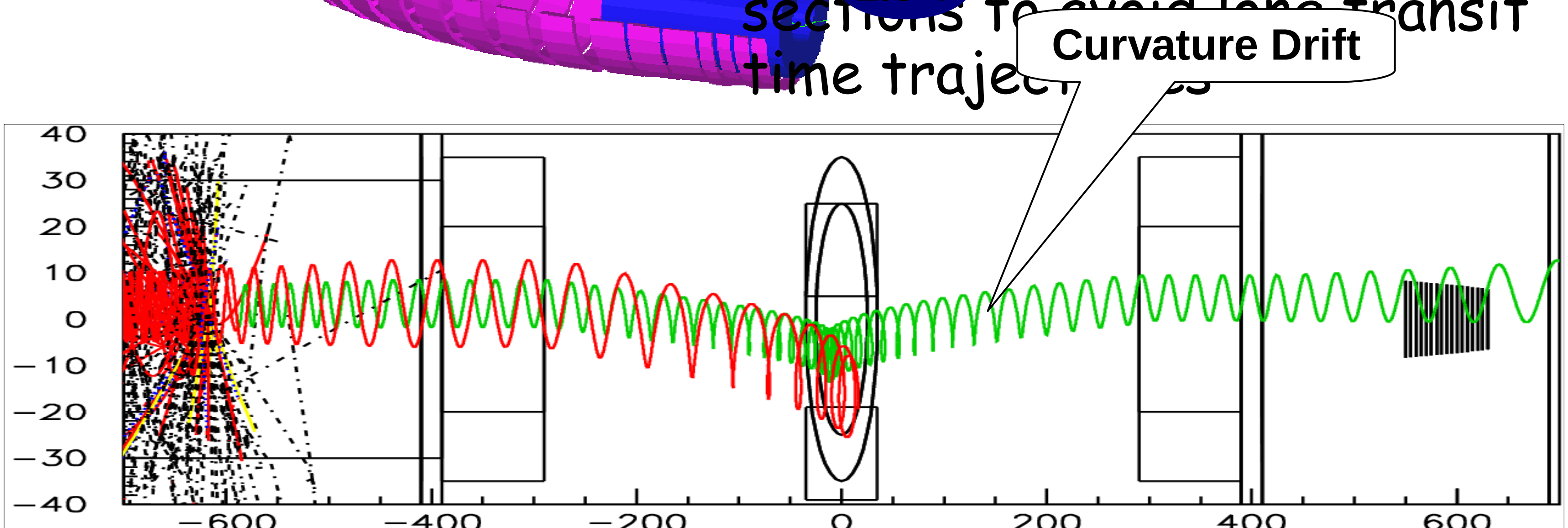
- Axially graded 5 T solenoid captures pions and muons, transporting them toward the stopping target
- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam



Transport Solenoid

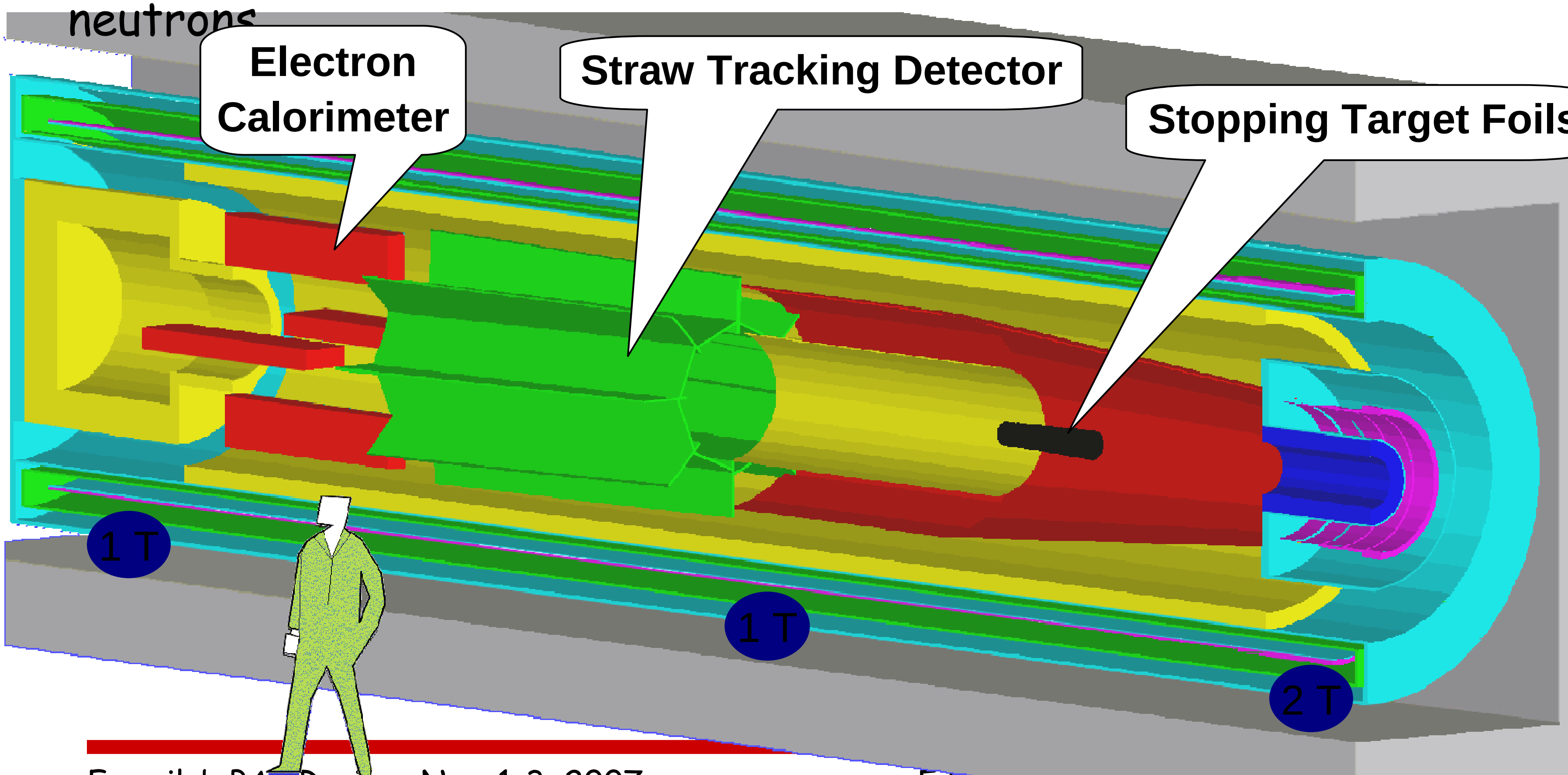
- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam
- dB/ds < 0 in the straight sections to avoid long transit time trajectories





Detector Region

- Axially-graded field near stopping target to increase acceptance and reduce cosmic ray background
- Uniform field in spectrometer region to simplify momentum analysis
- Electron detectors downstream of target to reduce rates from γ and neutrons



Expected Sensitivity of the MECO Experiment

We expect ~ 5 signal events for 10^7 s (2800 hours) running if $R_{\mu e} = 10^{-16}$

Contributions to the Signal Rate	Factor
Running time (s)	10^7
Proton flux (Hz) (50% duty factor, 740 kHz micropulse)	4×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ stopping probability	0.58
μ capture probability	0.60
Fraction of μ capture in detection time window	0.49
Electron trigger efficiency	0.90
Fitting and selection criteria efficiency	0.19
Detected events for $R_{\mu e} = 10^{-16}$	5.0

Expected Background in MECO Experiment

We expect ~ 0.45 background events for 10^7 s running with sensitivity of ~ 5 signal events for $R_{\mu e} = 10^{-16}$

Source	Events	Comments
μ decay in orbit	0.25	S/N = 20 for $R_{\mu e} = 10^{-16}$
Tracking errors	< 0.006	
Radiative μ decay	< 0.005	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	Without scattering in stopping target
μ decay in flight	0.04	With scattering in stopping target
π decay in flight	< 0.001	
Radiative π capture	0.07	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	Assuming 10^{-4} CR veto inefficiency
Total Background	0.45	Assuming 10^{-9} inter-bunch extinction