Beam Delivery for the Fermilab Mu2e Experiment

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For the Mu2e Collaboration

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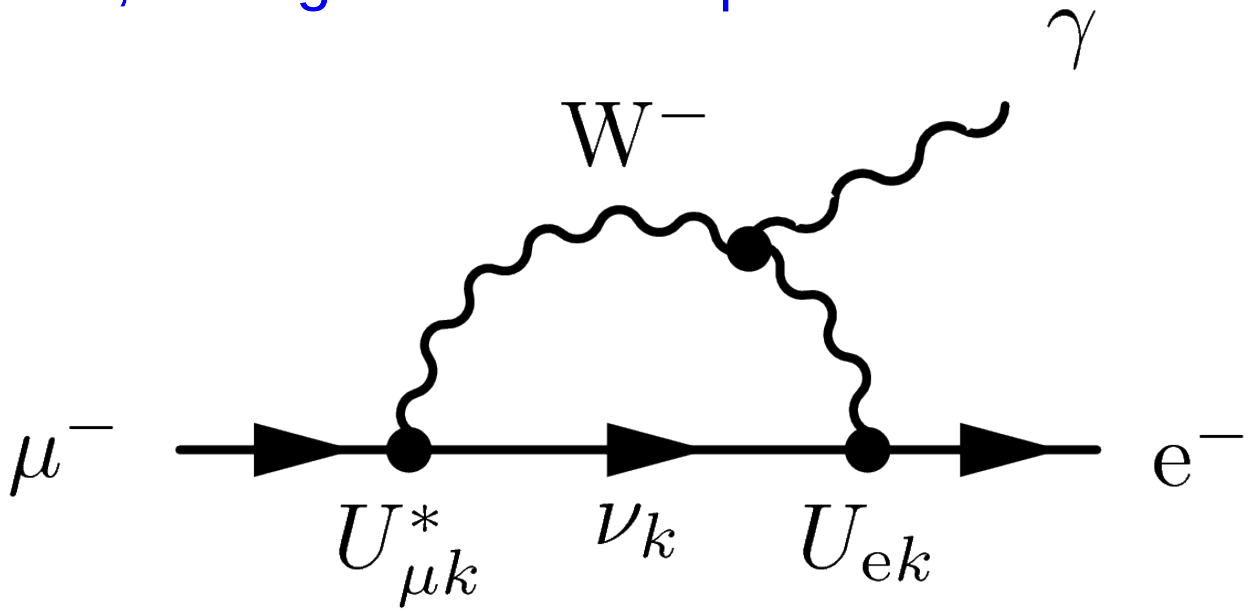
Mu2e is a search for charged lepton flavor violation with *discovery potential*

Although it has never been observed, we know that cLFV **must** occur, *even in the Standard Model*, through neutrino loop effects.



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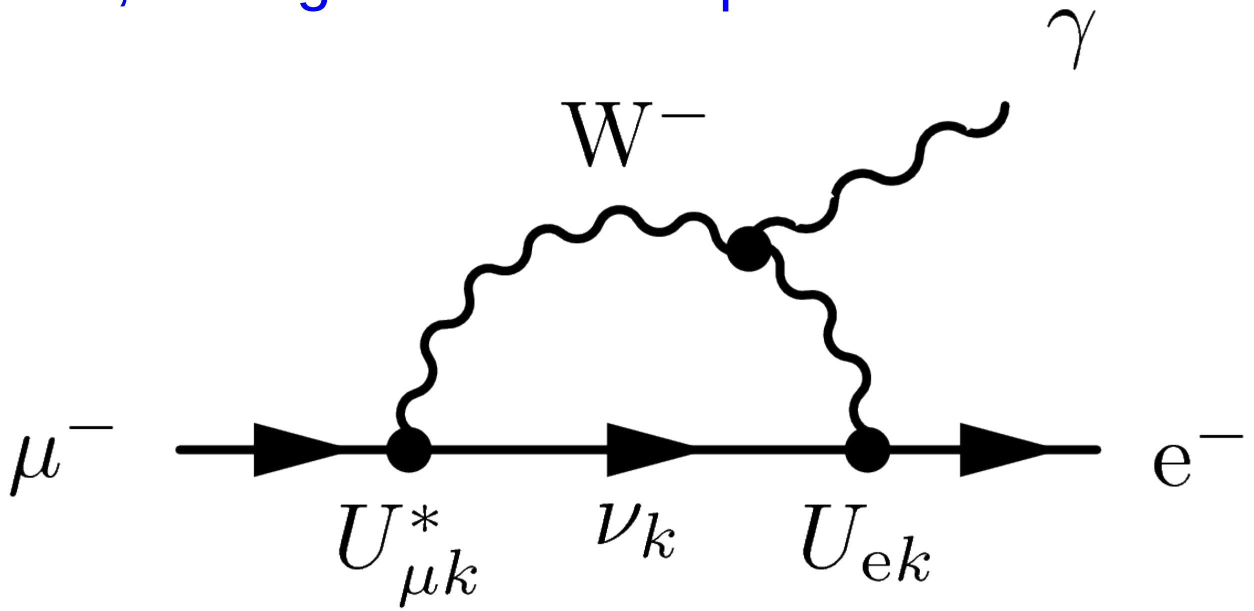

However, the predicted SM rates are unobservably small:

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{k=2,3} U^*_{\mu k} U_{ek} \frac{\Delta m^2_{1k}}{M^2_W}\right|^2 < 10^{-54}$$

This is a good news/bad news story

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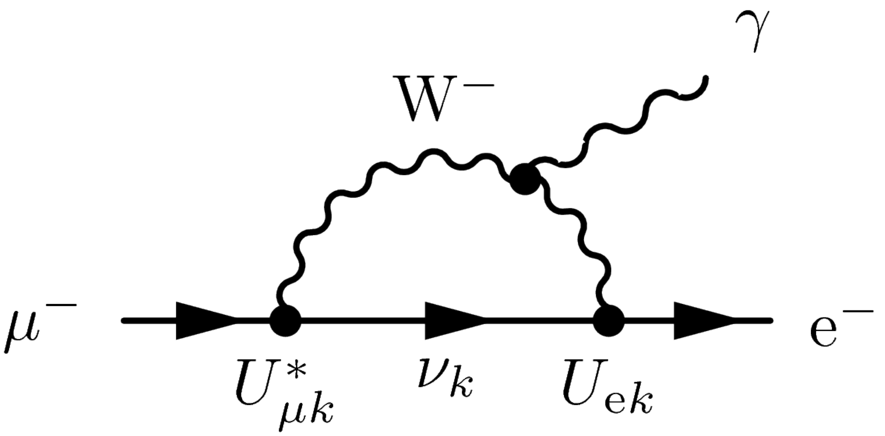
First, the bad news: we'll never observe this!



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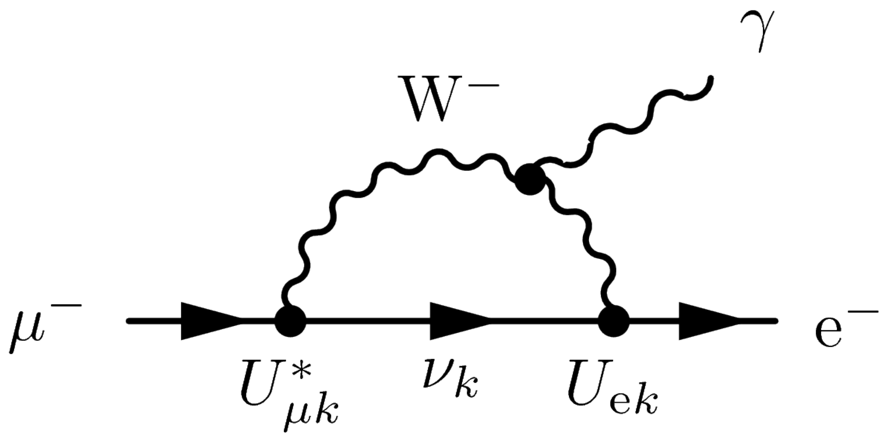

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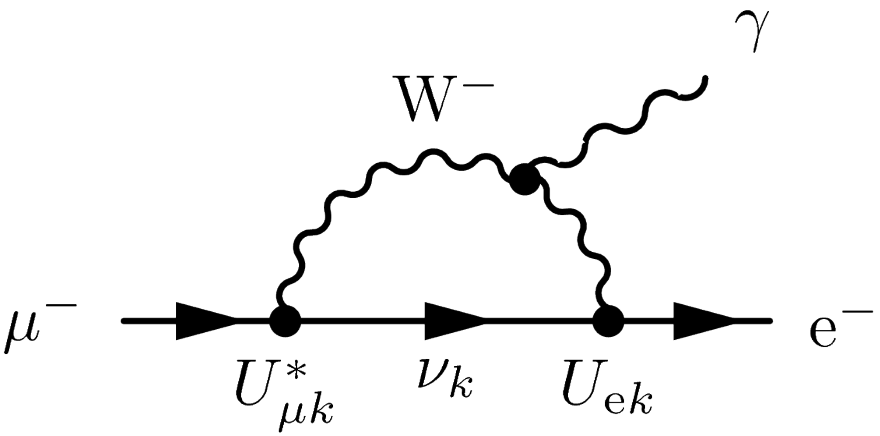


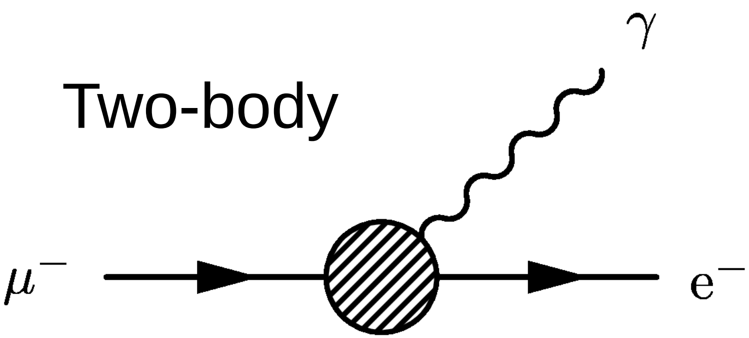
Now, the good news: we'll never observe this!

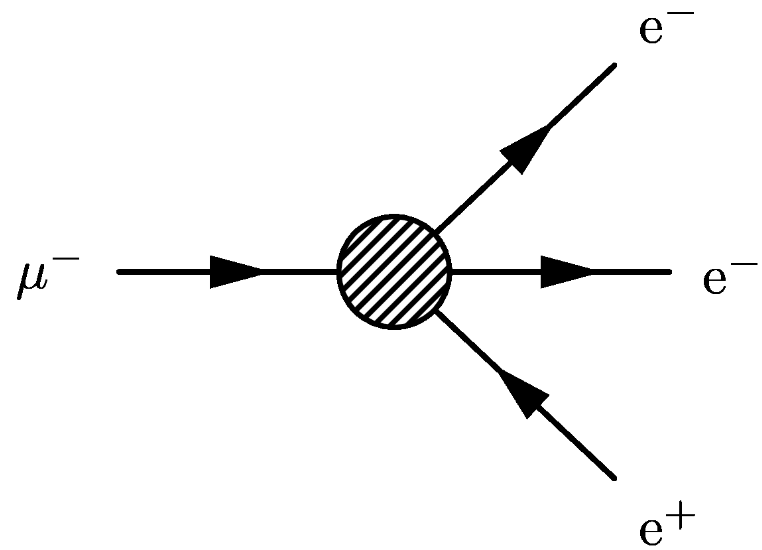
Any signal of CLFV is unambiguous evidence for physics beyond the Standard Model!

There are three powerful signatures of CLFV in the muon sector

$$\mu^+ \to e^+ \gamma$$

Two-body

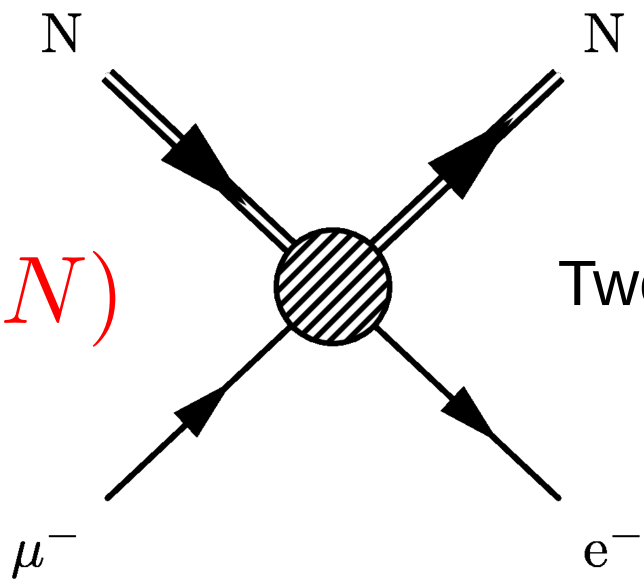




$$\mu^+ \to e^+ e^+ e^-$$

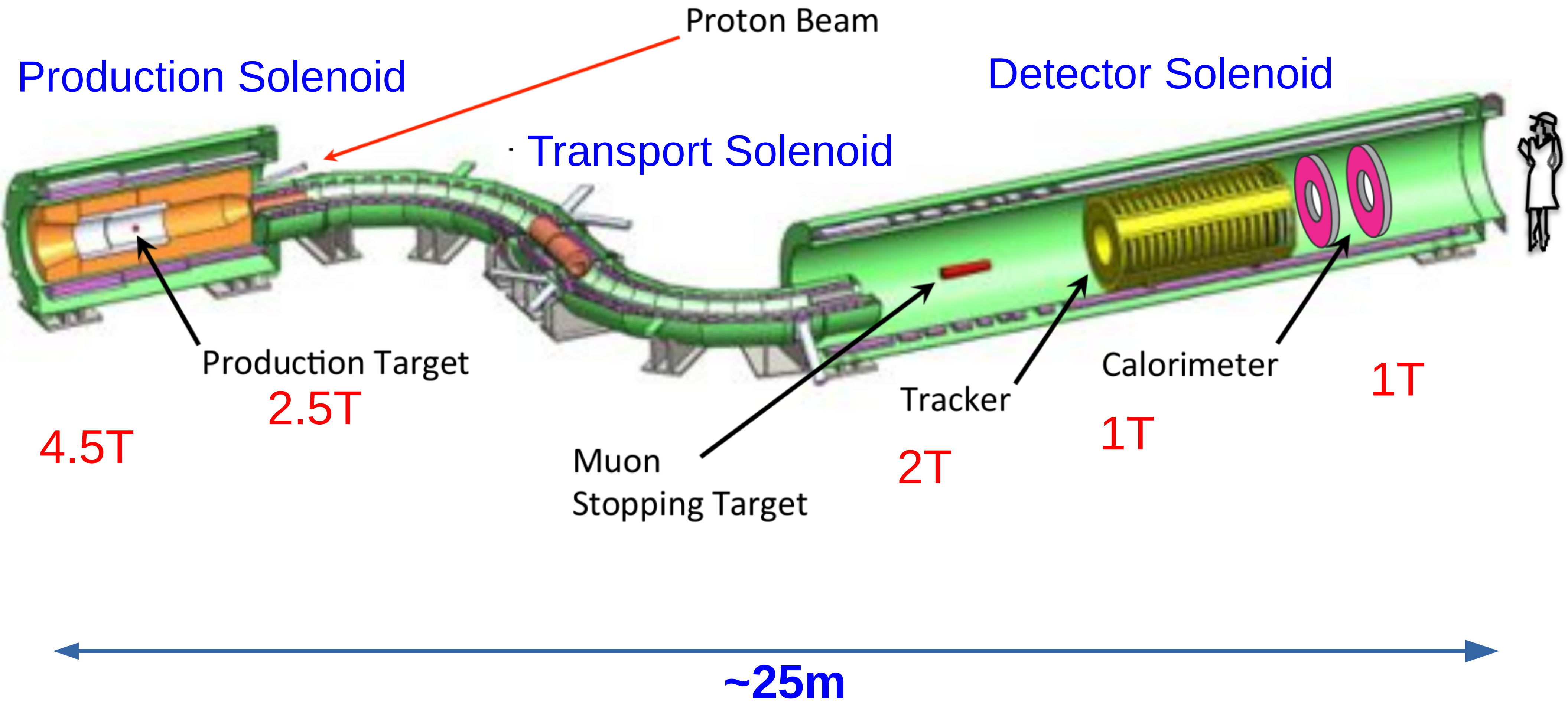
Mu2e and COMET will search
for Coherent Conversion

$$\mu^- A(Z, N) \to e^- A(Z, N)$$

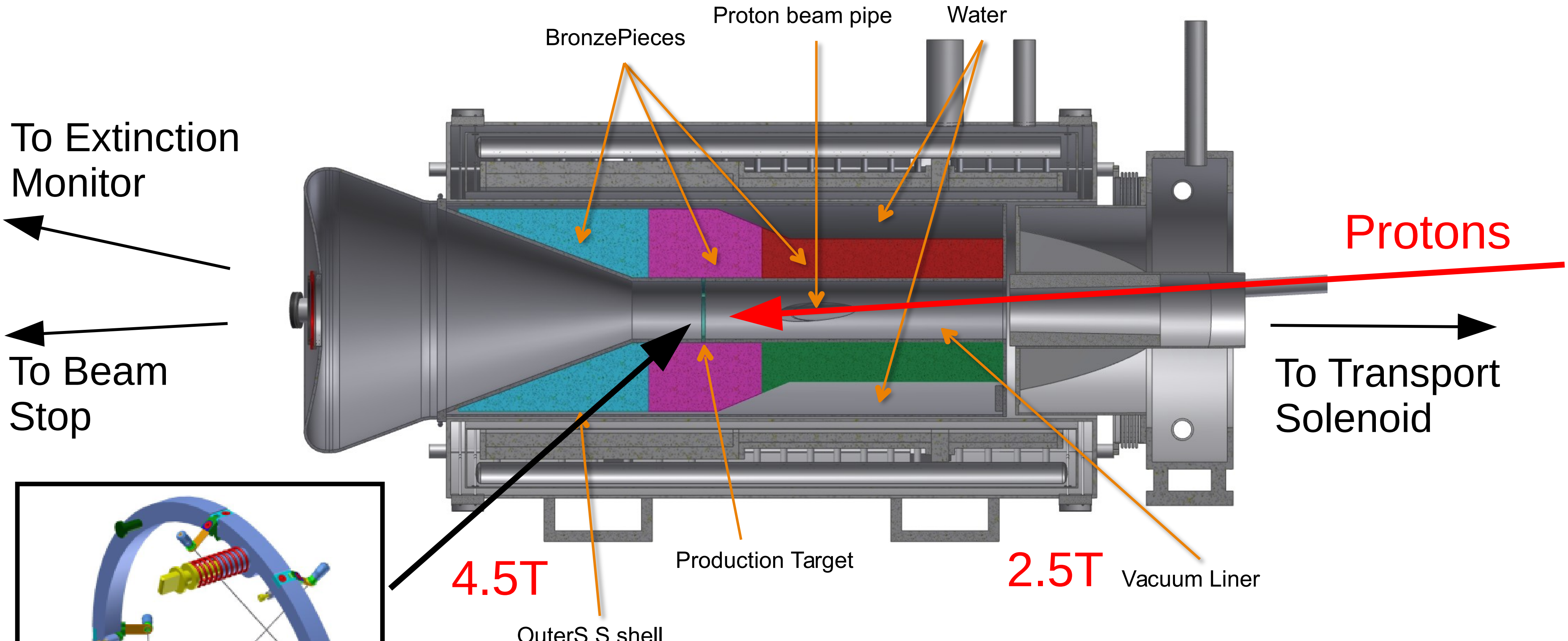


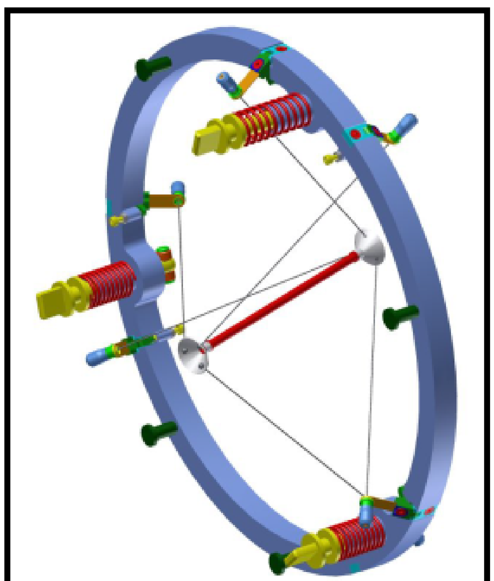
Two-body

The Mu2e apparatus separates the production of muons and our observations of their decays



The production solenoid produces a backward beam to further reduce prompt backgrounds

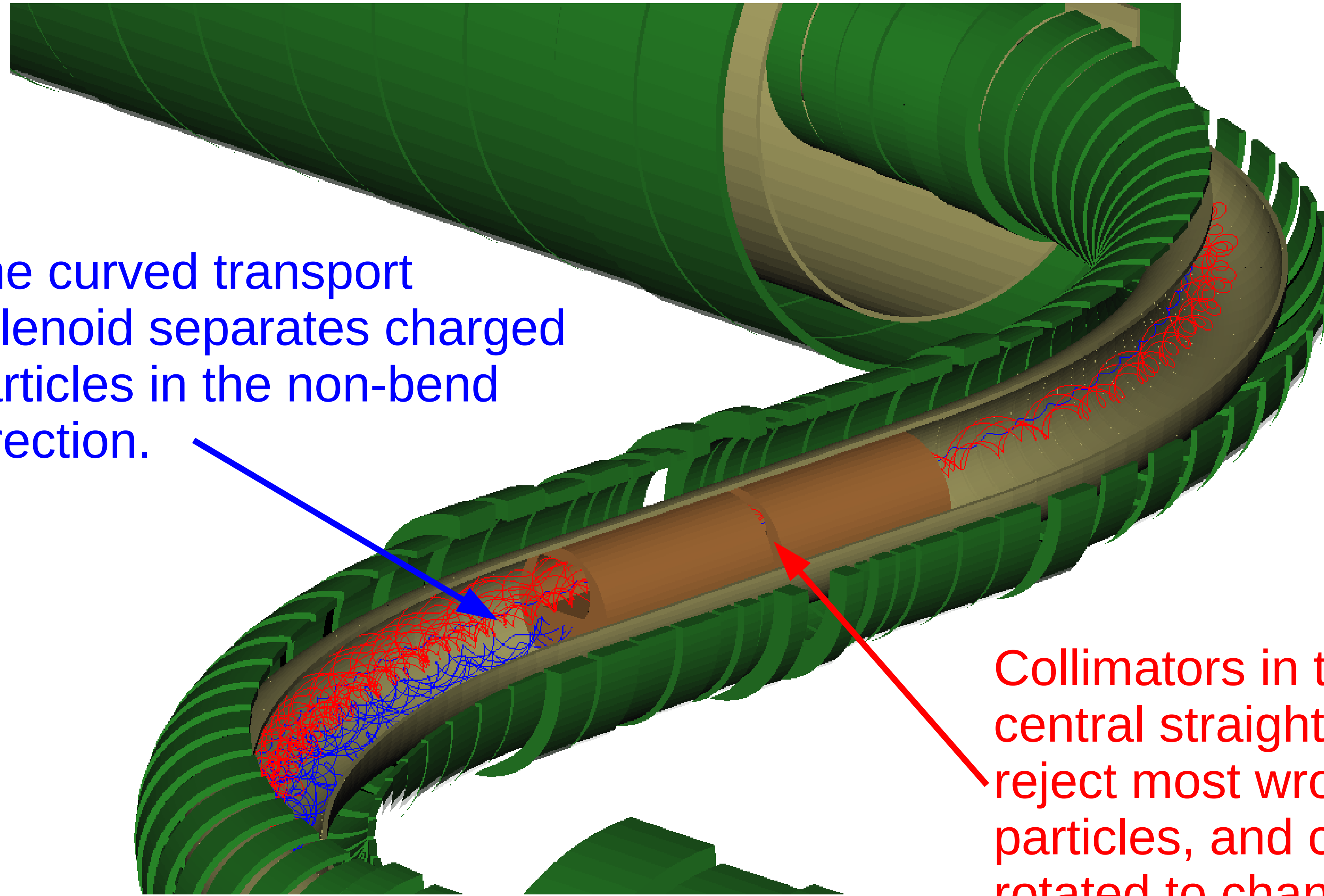




The tungsten production target is about the size of a pencil

The graded field acts as a “mirror” for charged particles, increasing the flux of muons into the TS

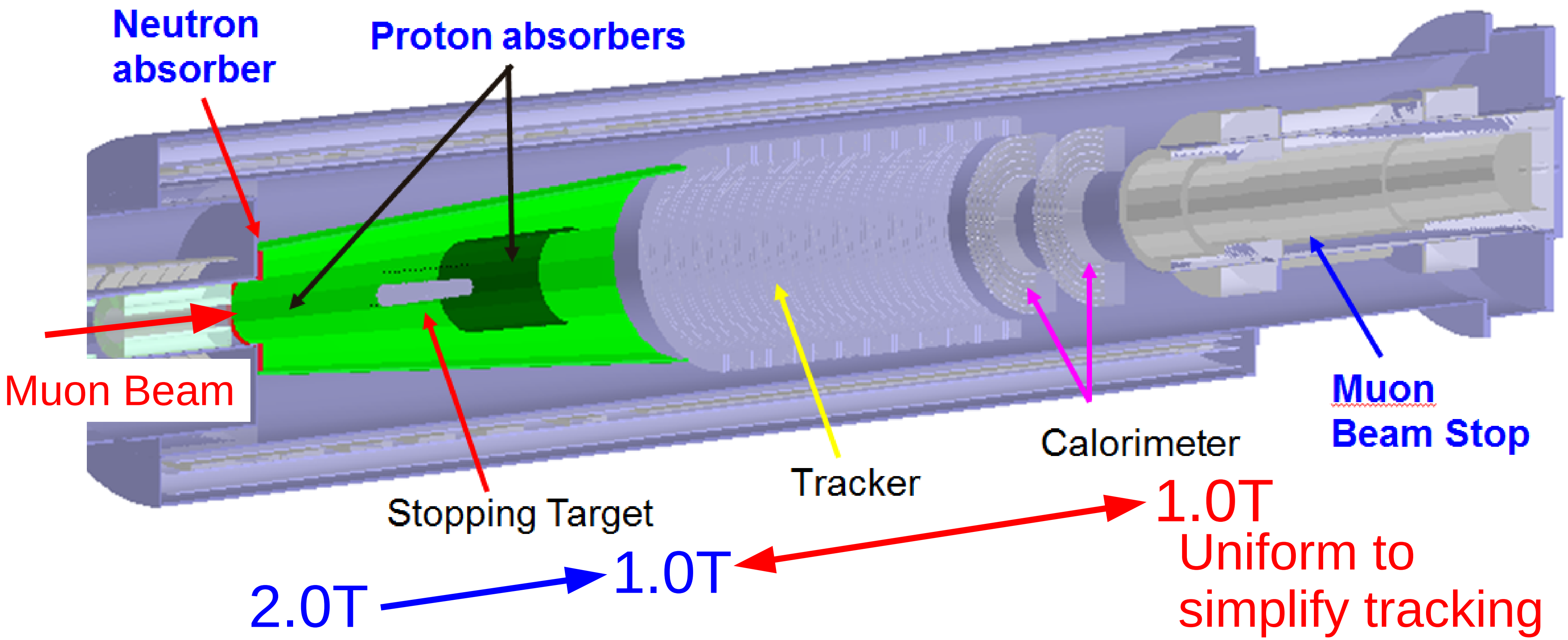
The transport solenoid sign selects charged particles



The curved transport solenoid separates charged particles in the non-bend direction.

Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

The detector solenoid forms the heart of the experiment



Graded to reflect electrons toward the tracker

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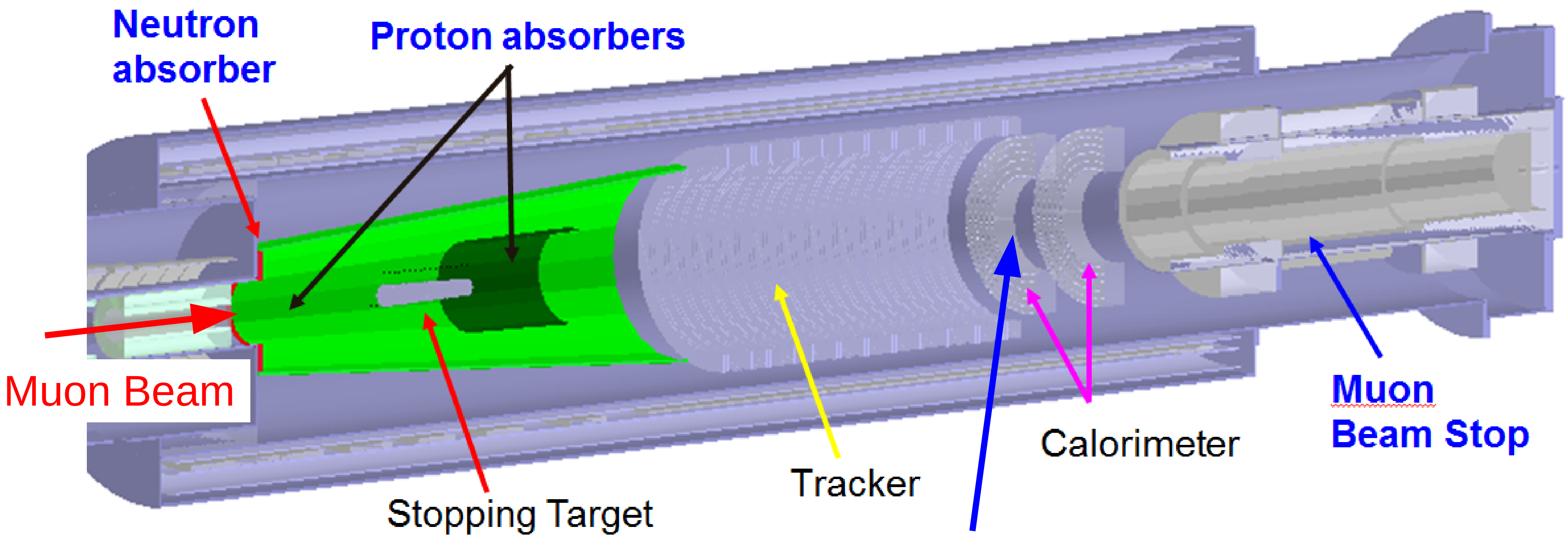
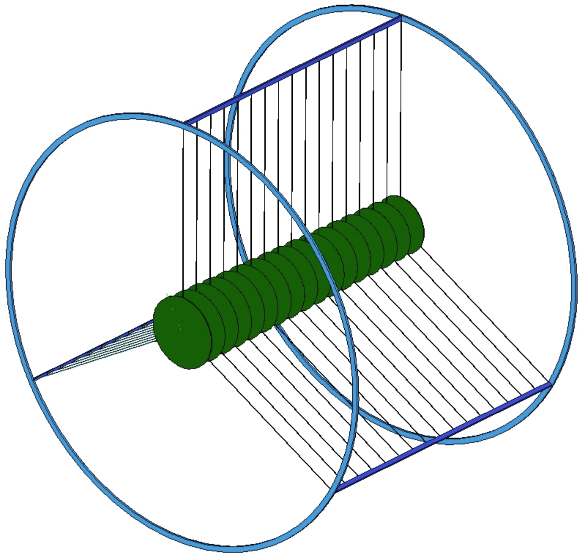


The remnant muon beam and most DIO electrons pass through the central openings, and are caught by a beam stop.



The stopping target is a series of Al foils to intercept and stop the secondary beam.

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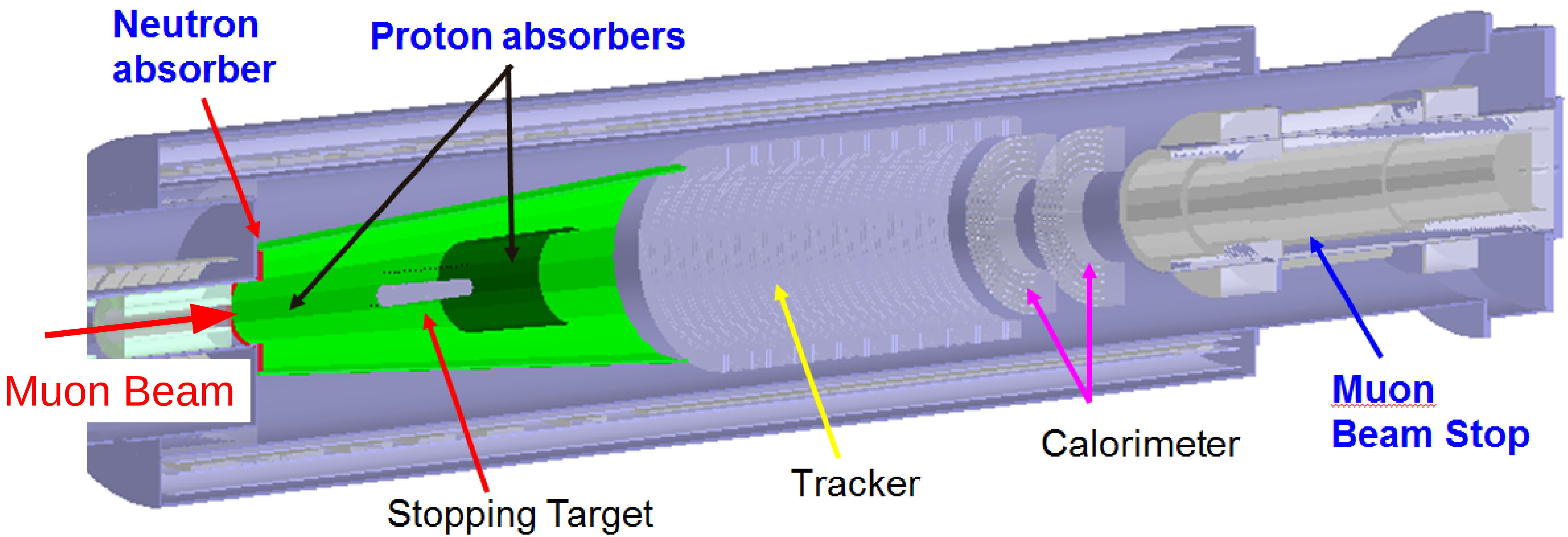

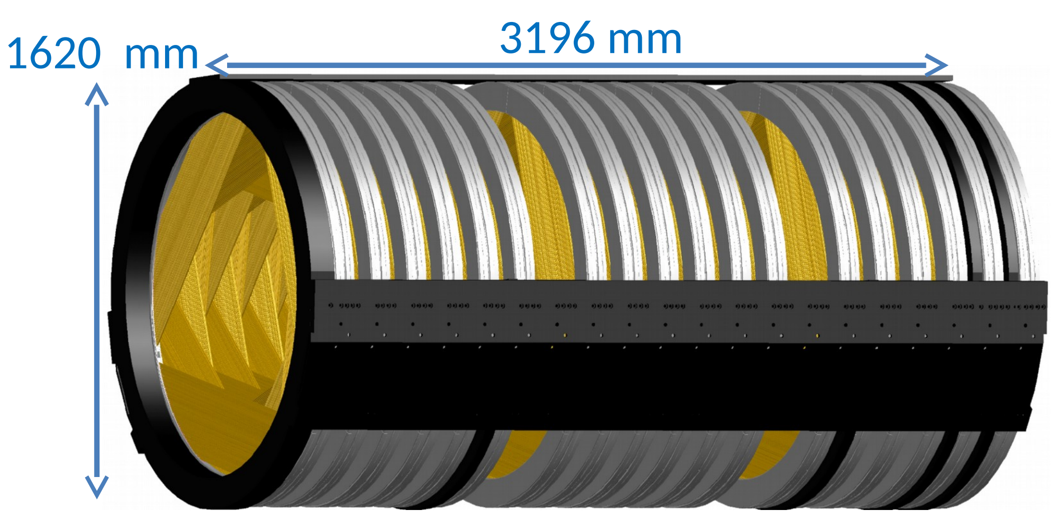

The electron tracker is a low mass straw tube design with 18 planes of tubes transverse to the secondary beam

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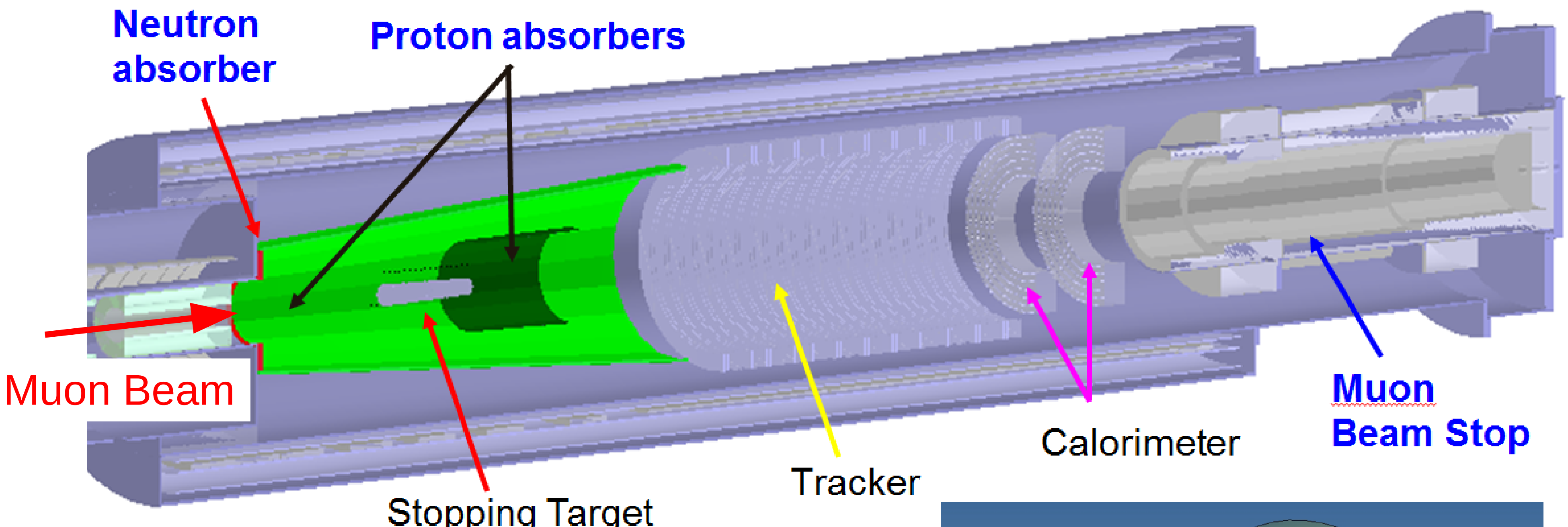
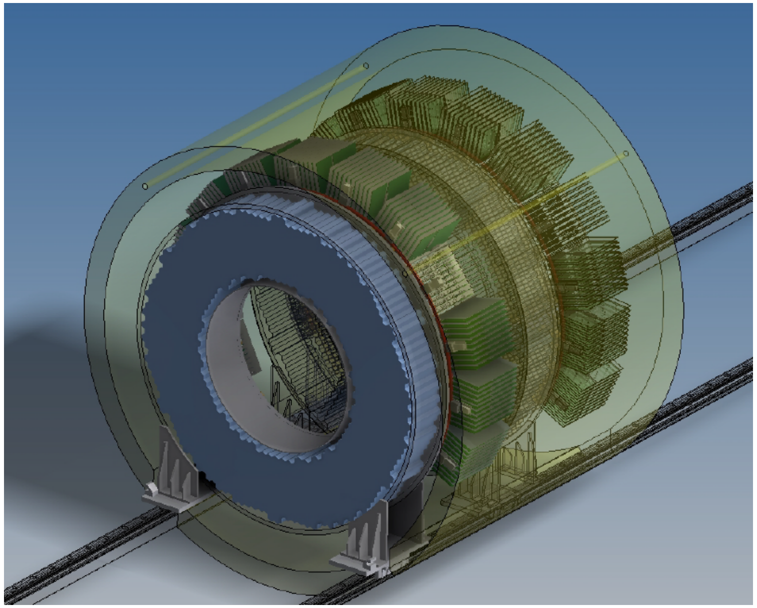


The calorimeter is a two layer, annular crystal calorimeter



If there is new weak scale physics, Mu2e is in an excellent position to observe cLFV

For a 3 year run with 3.6×10^{20} POT, we expect a nearly background free signal:

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

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We'll see a signal of 50 or more events for models that predict conversion at the 10^{-15} level

We’ll need a pulsed beam structure to reduce prompt backgrounds

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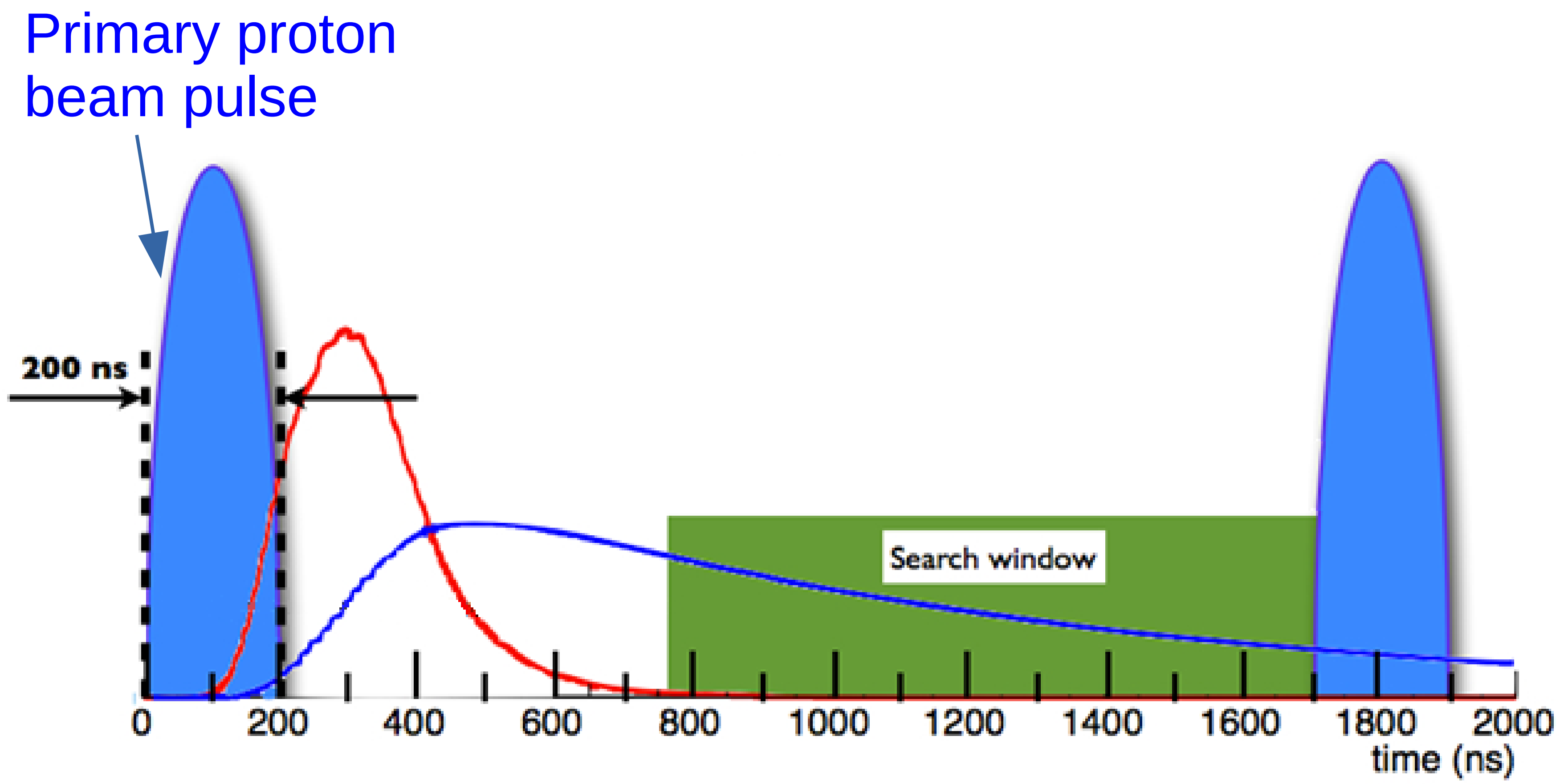

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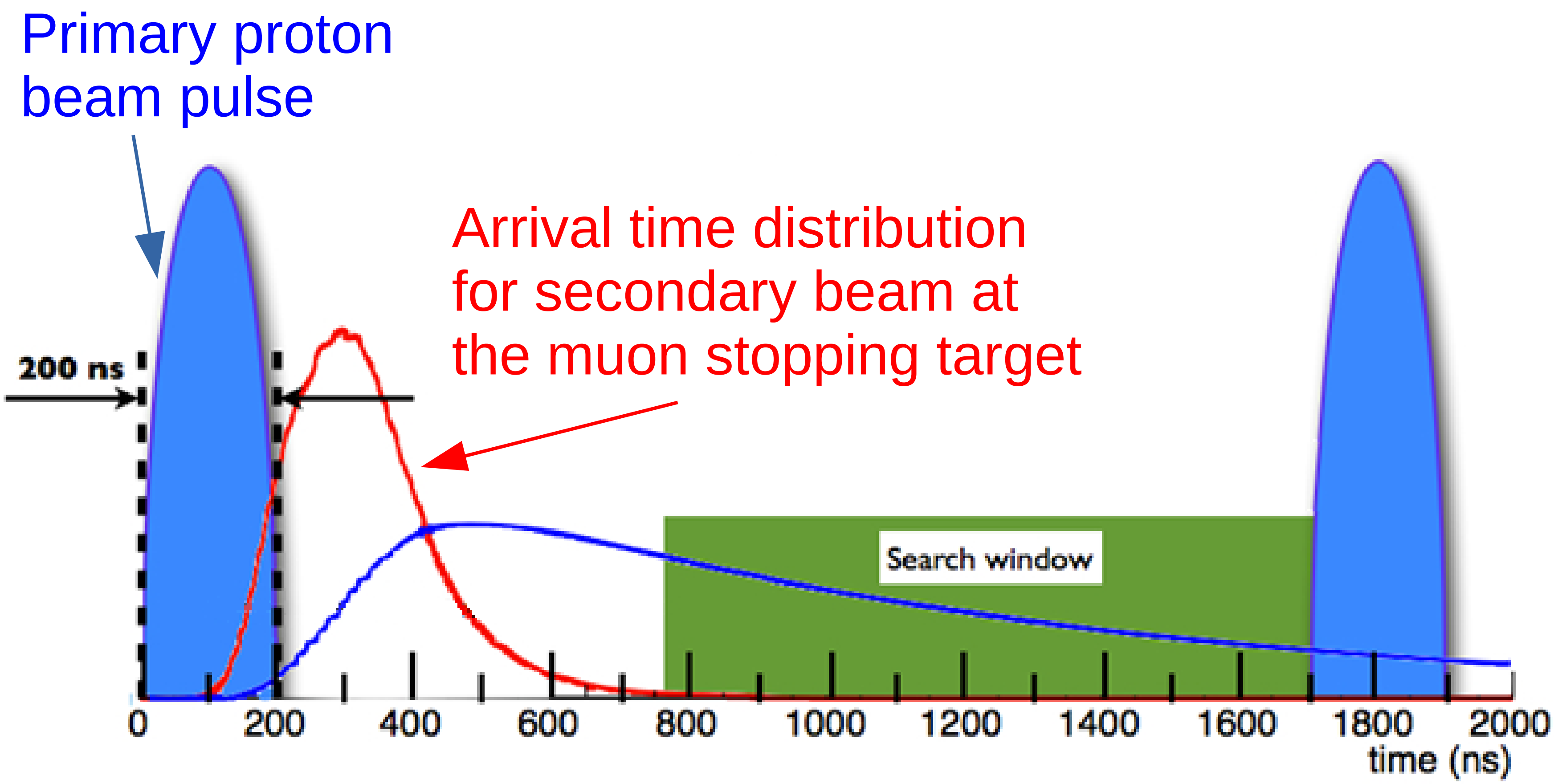

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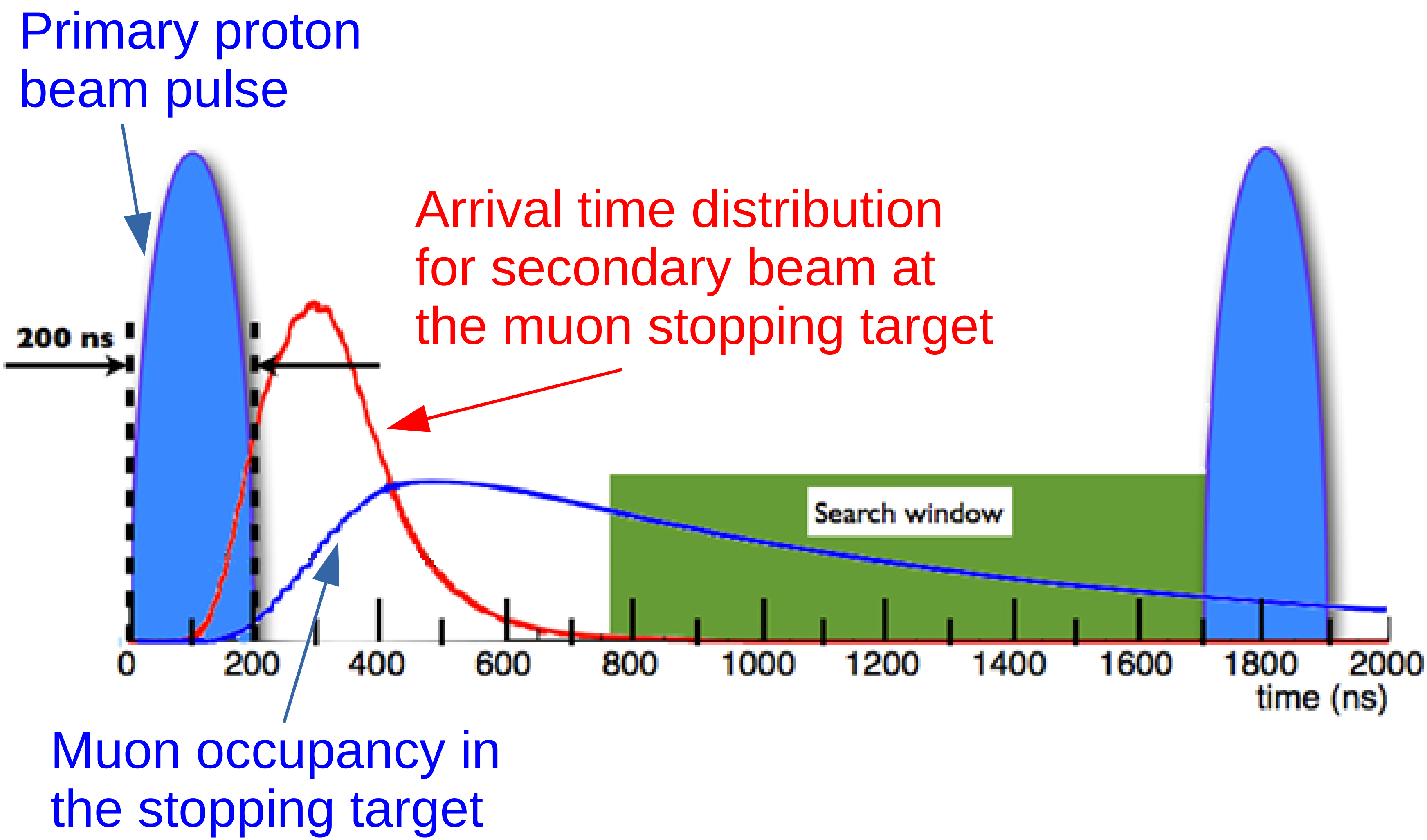
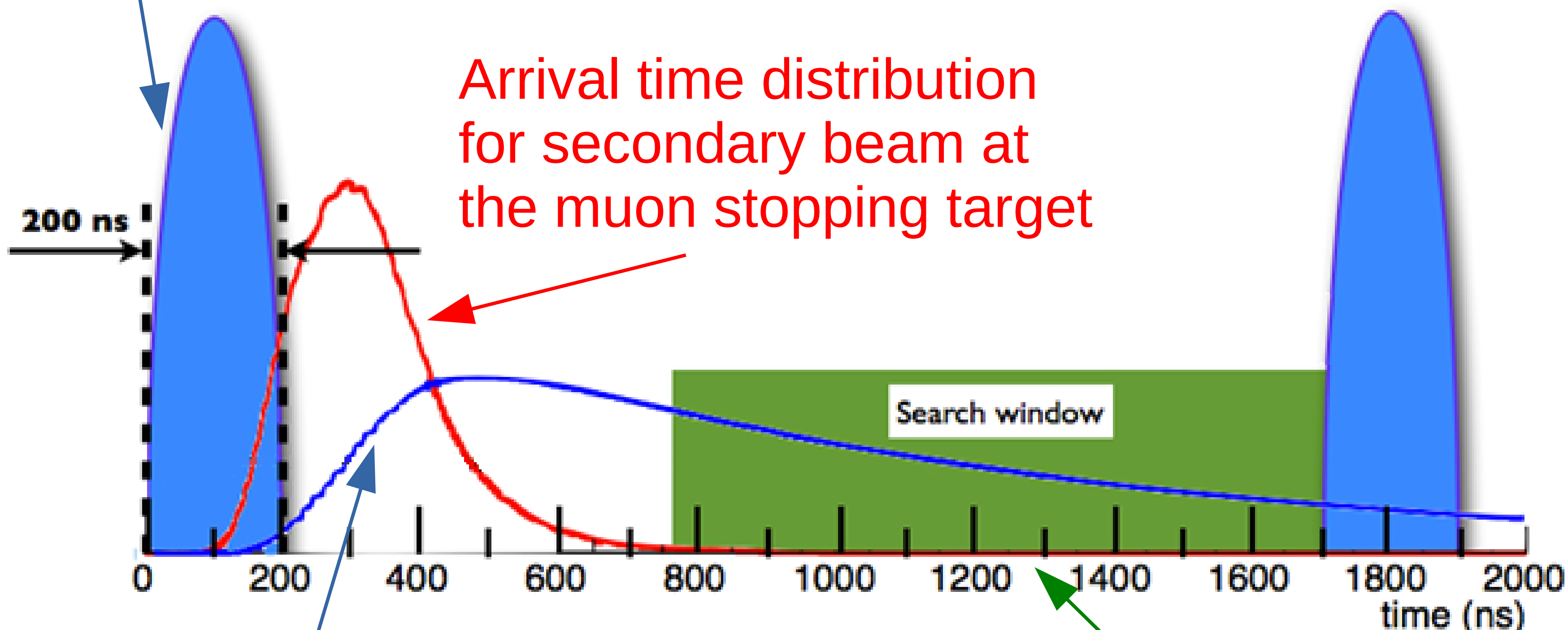


We’ll need a pulsed beam structure to reduce prompt backgrounds

Primary proton
beam pulse

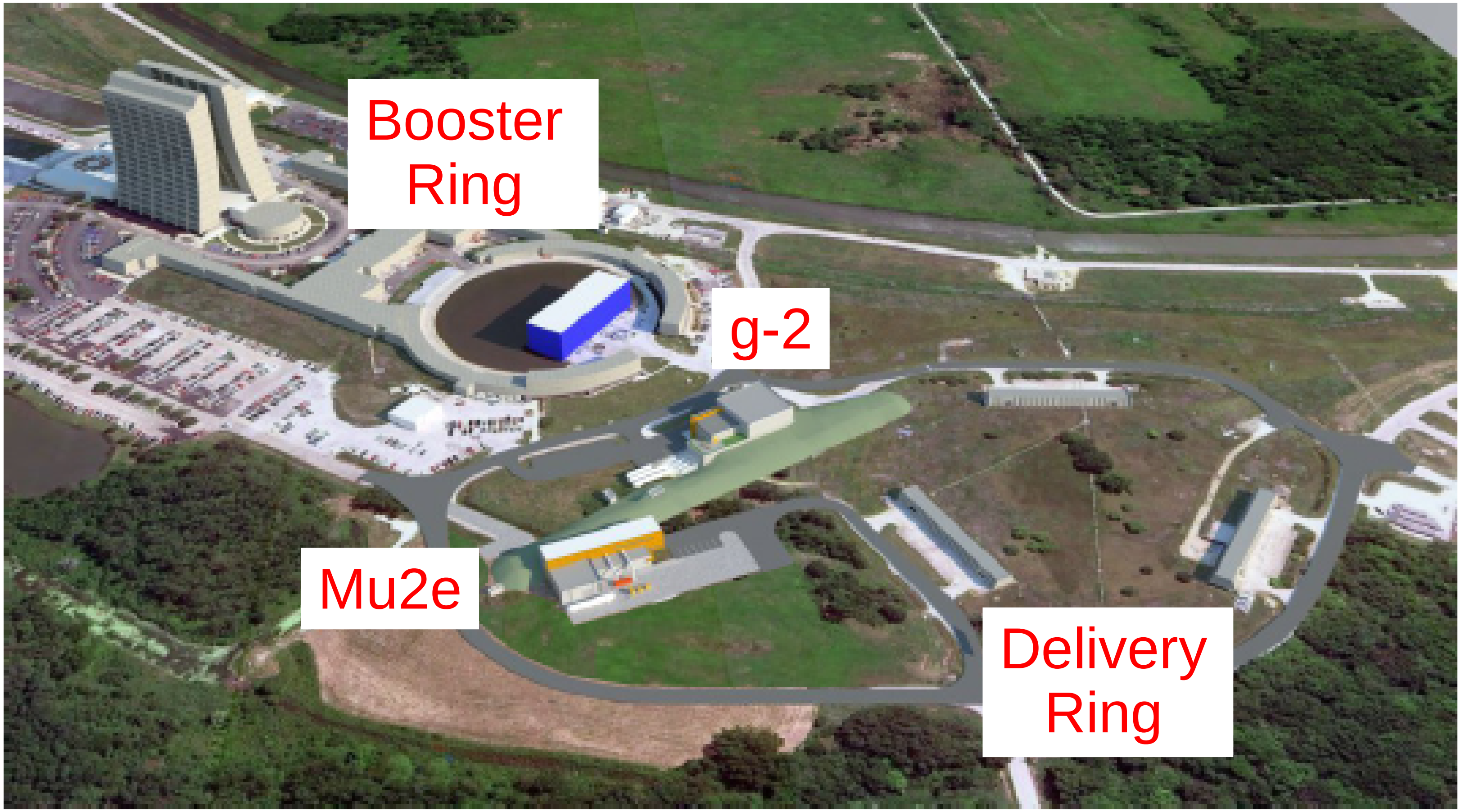
Arrival time distribution
for secondary beam at
the muon stopping target



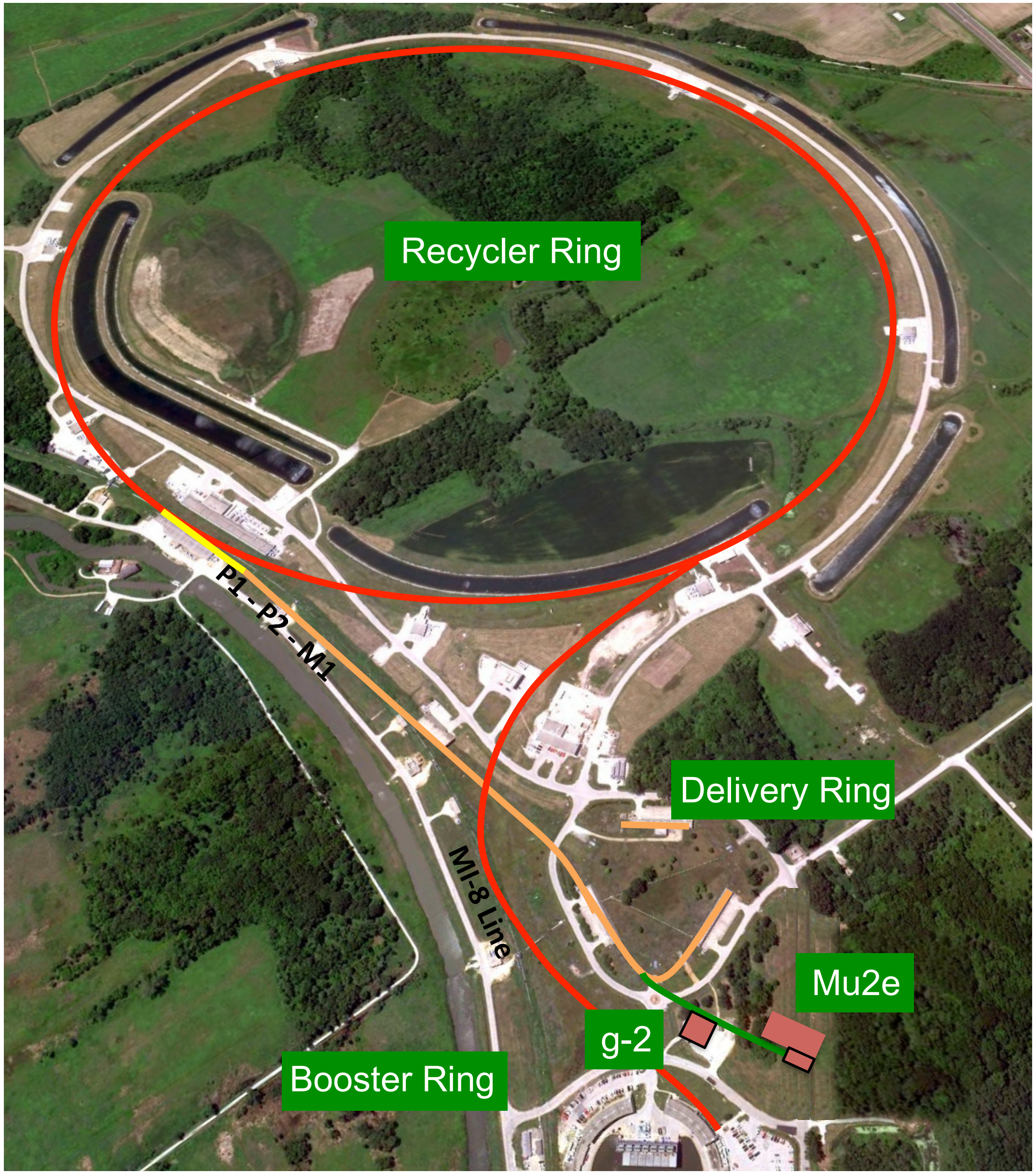
Muon occupancy in
the stopping target

Adjust the live window to “wait out” the prompt backgrounds from pions and beam particles

The Fermilab complex simultaneously drives both the Neutrino and Muon Campus programs



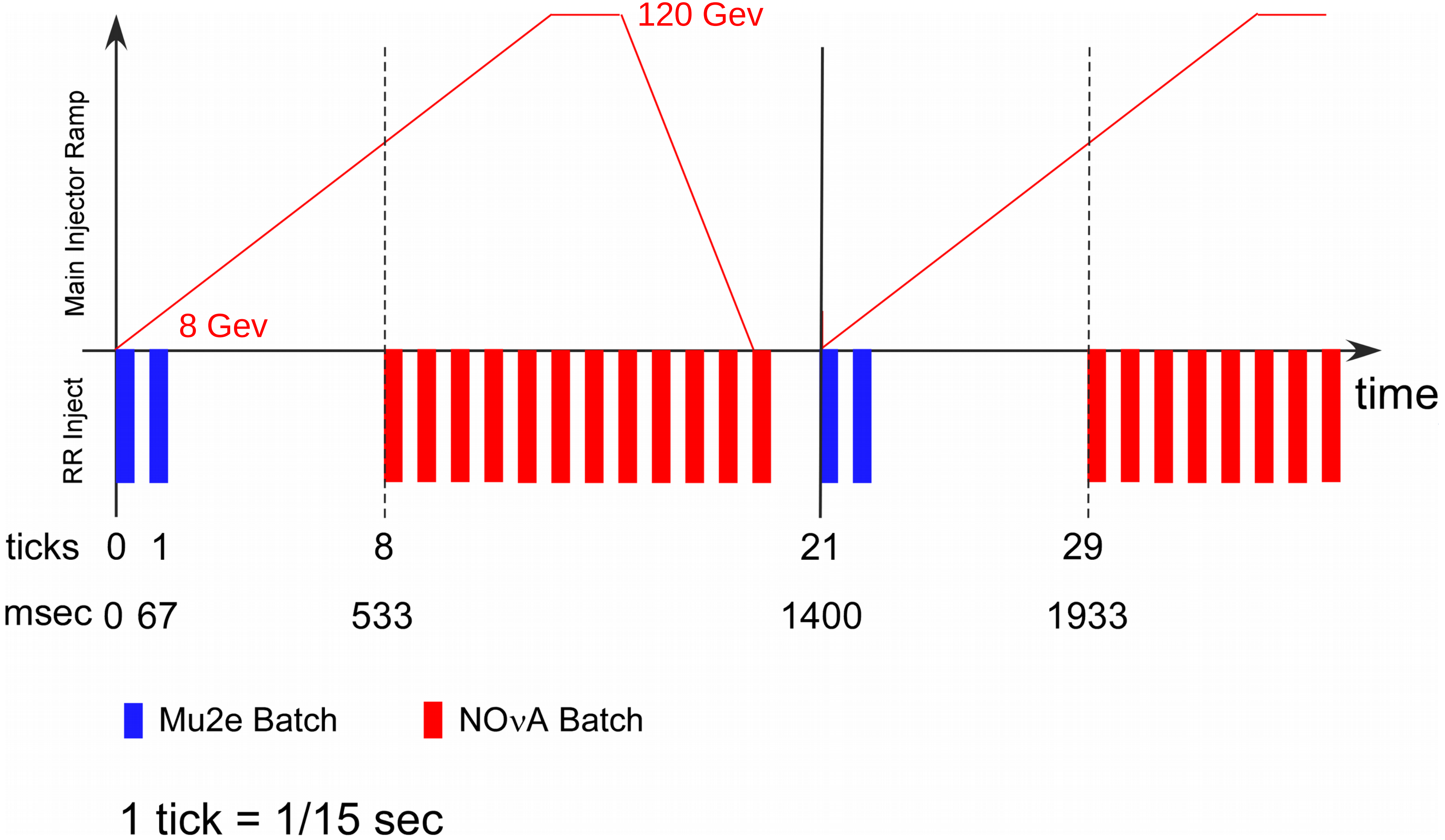
The Muon Campus program is run with 8 GeV protons



Proton beam requirements

	Parameter	Design Value	Requirement	Unit
	Total protons on target	4.7×10^{20}	$\geq 4.7\times10^{20}$	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
	Maximum variation in pulse separation	< 1	10	nsec
	Spill duration	43.1	> 20	msec
	Beamline Transmission Window	230	< 250	nsec
	Transmission Window Jitter (rms)	< 5	<10	nsec
	Out-of-time extinction factor	1.6×10^{-12}	$\leq 10^{-10}$	
Intensity	Average proton intensity per pulse	3.9×10^{7}	$< 5.0\times10^{7}$	protons/ pulse
	Maximum Pulse to Pulse intensity variation	50	50	%
Beam Size	Target rms spot size	1	0.5 – 1.5	mm
	Target rms beam divergence	0.5	< 4.0	mrad

The neutrino program drives proton economics for the 8GeV program



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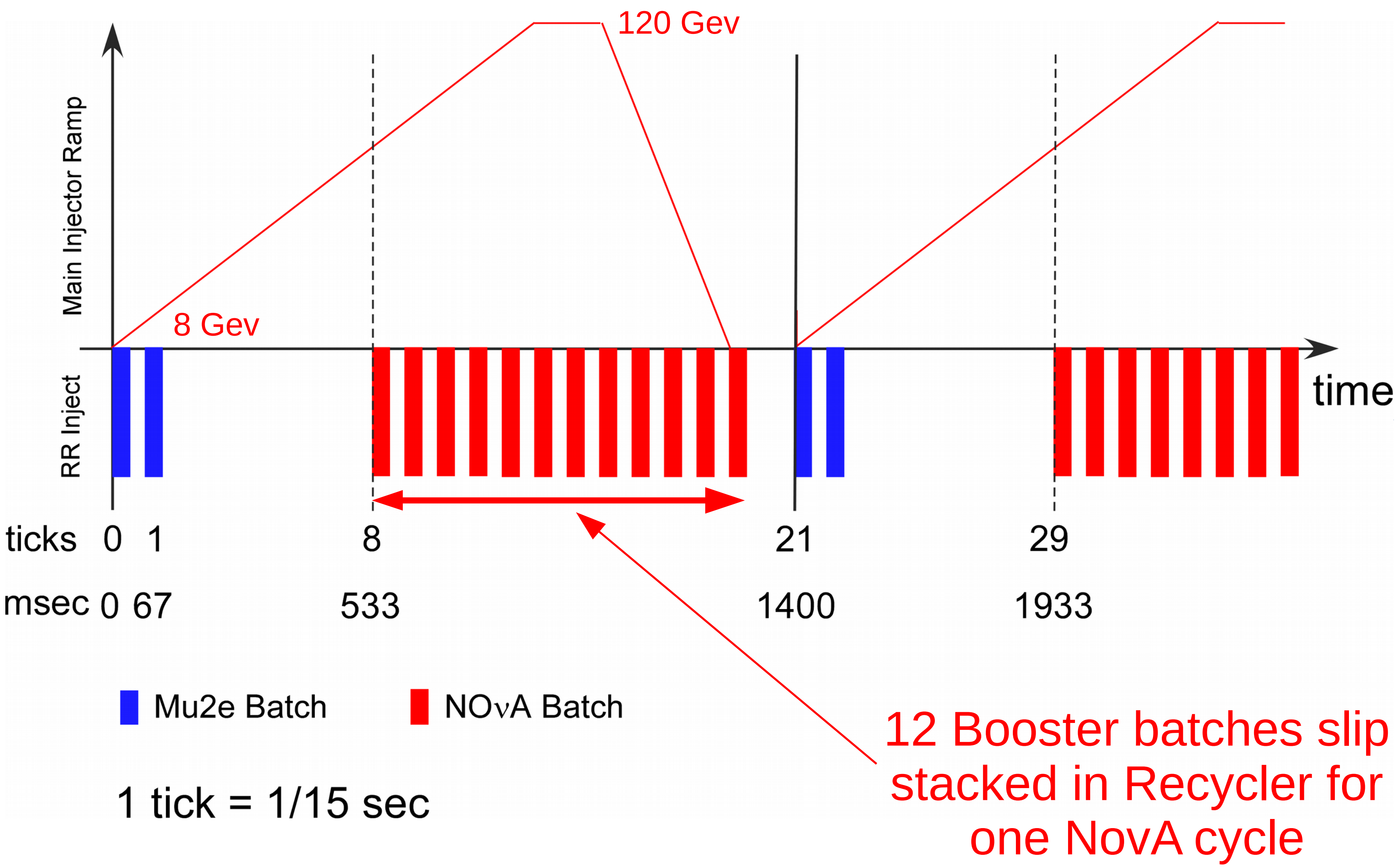

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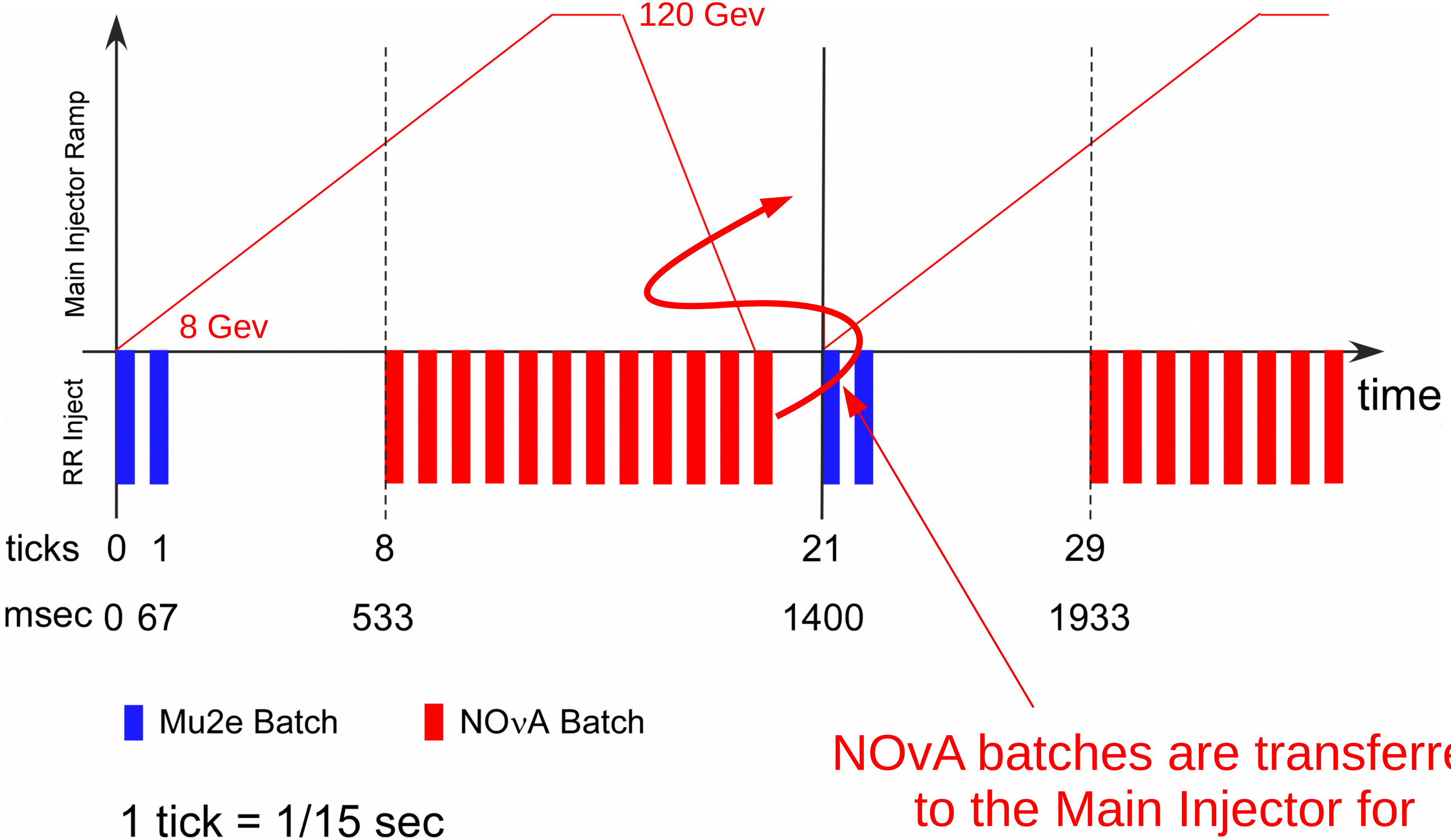
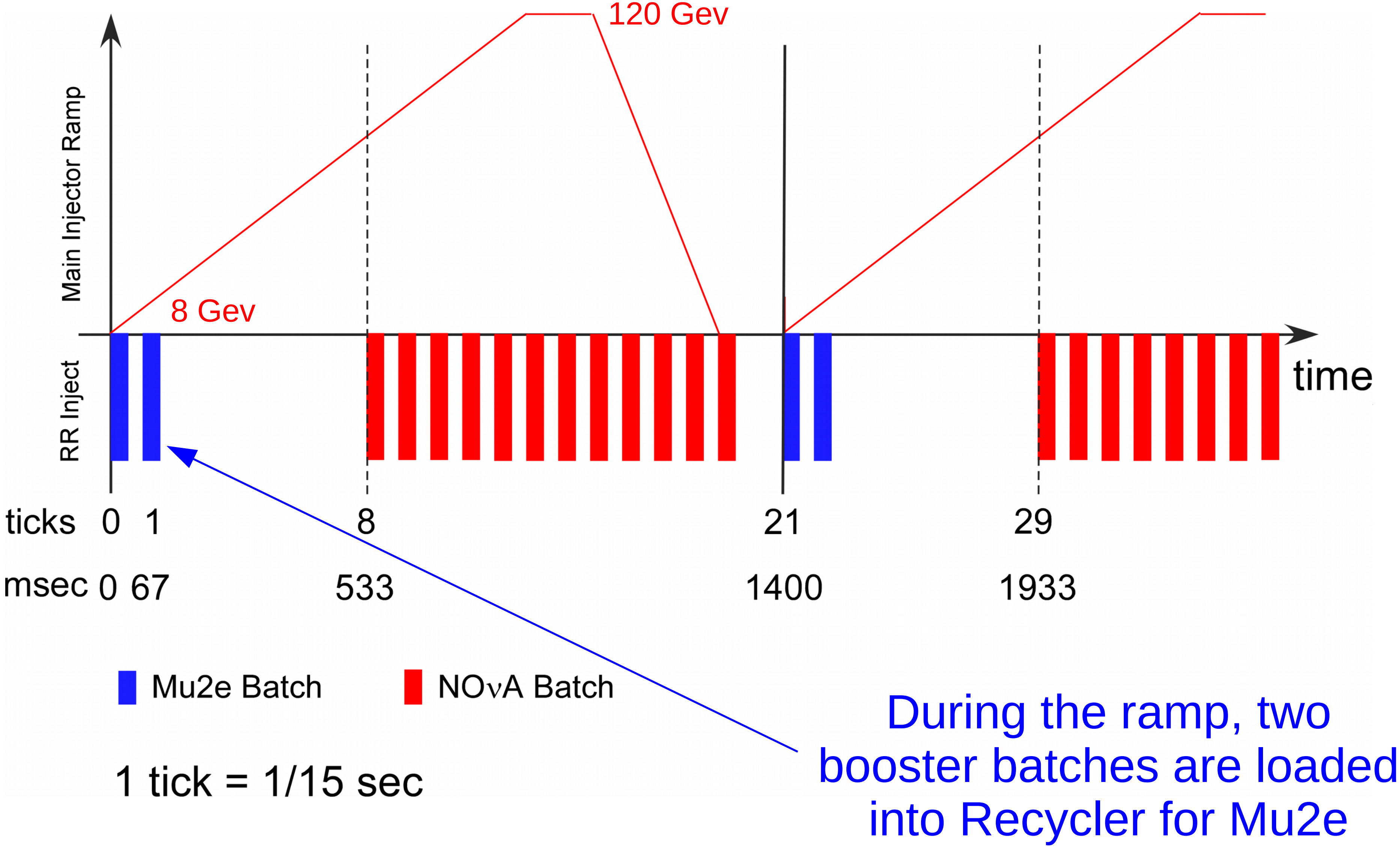
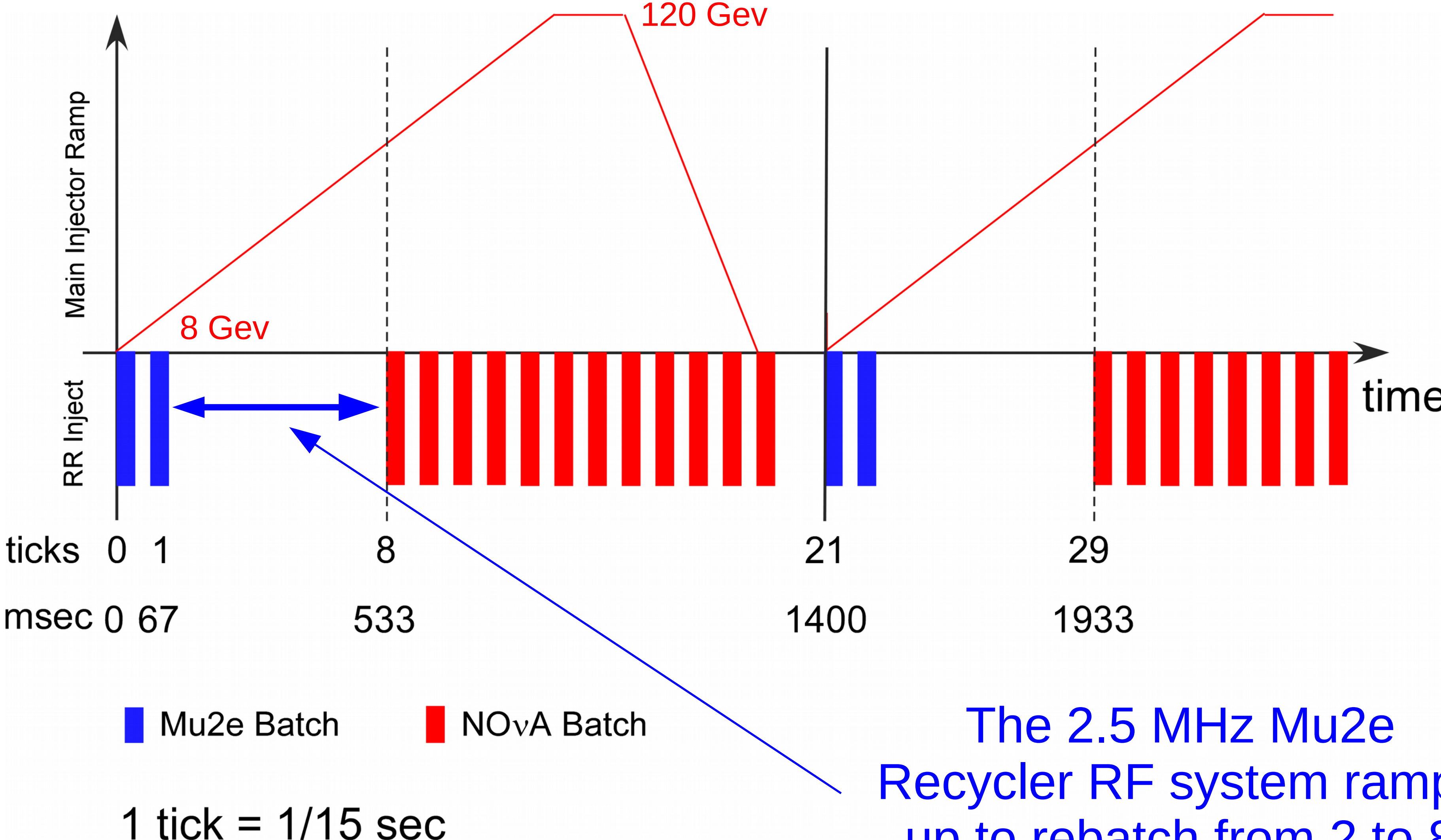


NOνA batches are transferred to the Main Injector for acceleration to 120 GeV

The neutrino program drives proton economics for the 8GeV program

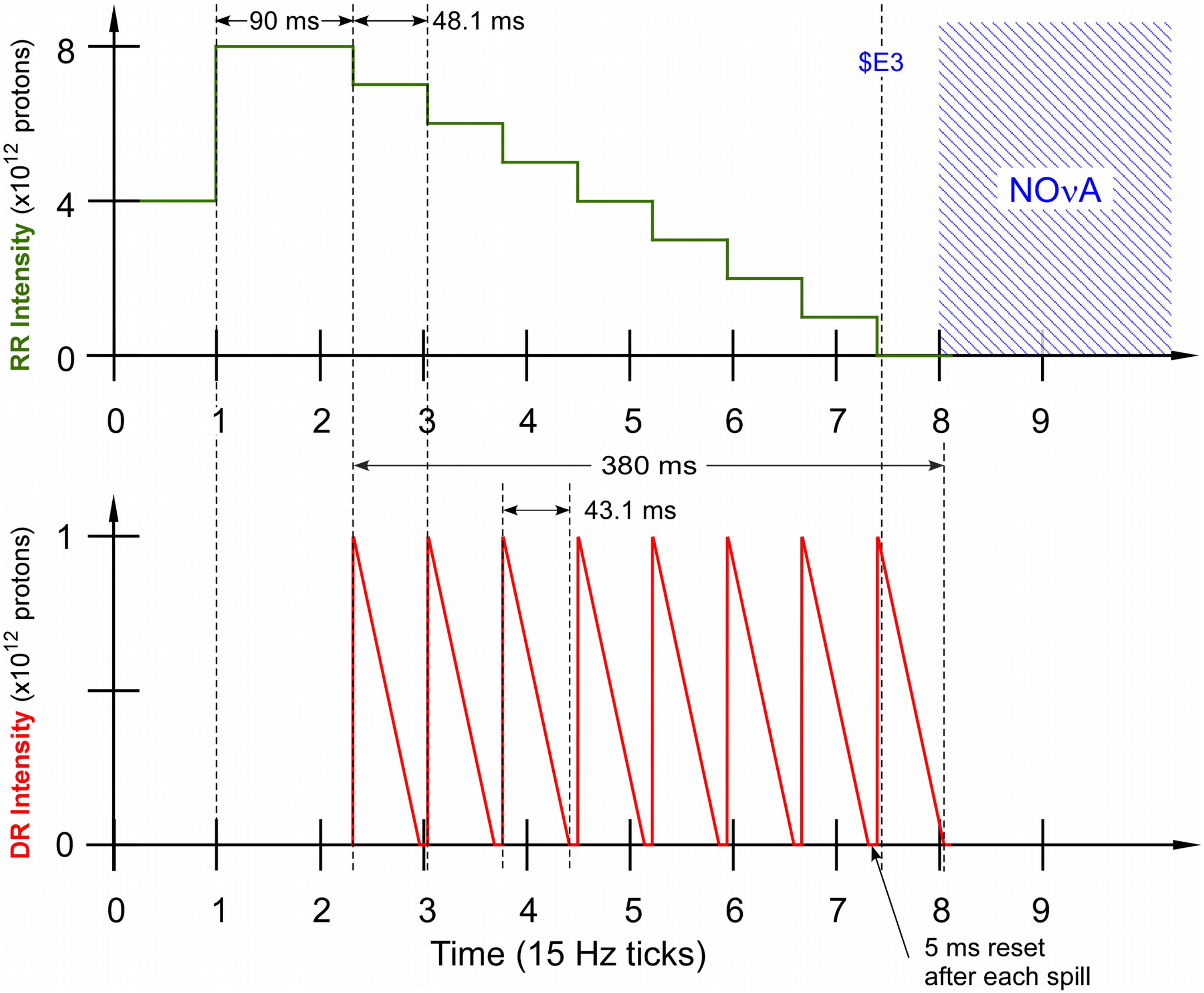


The neutrino program drives proton economics for the 8GeV program



The 2.5 MHz Mu2e Recycler RF system ramps up to rebatch from 2 to 8 bunches...

Beam manipulations



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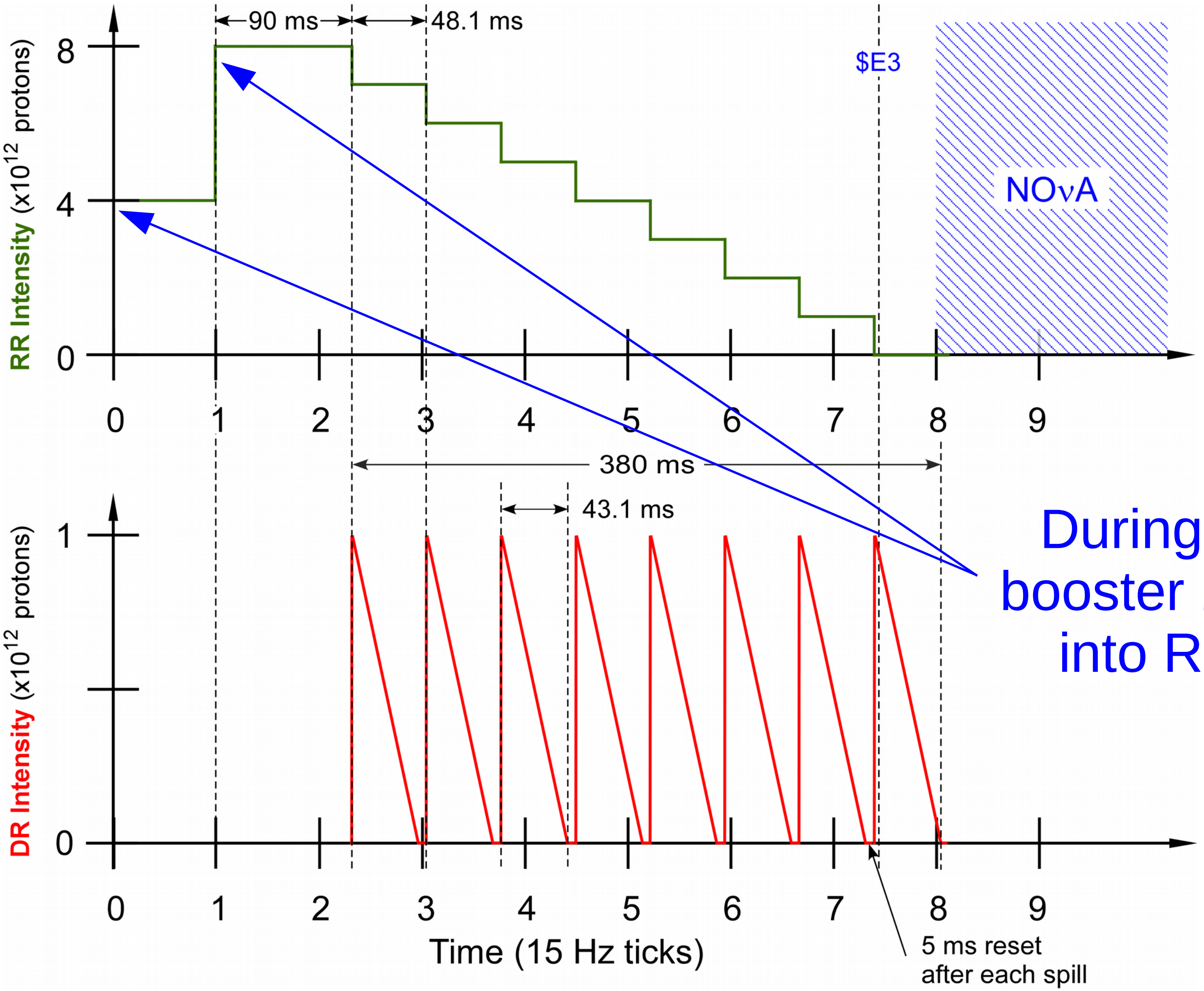
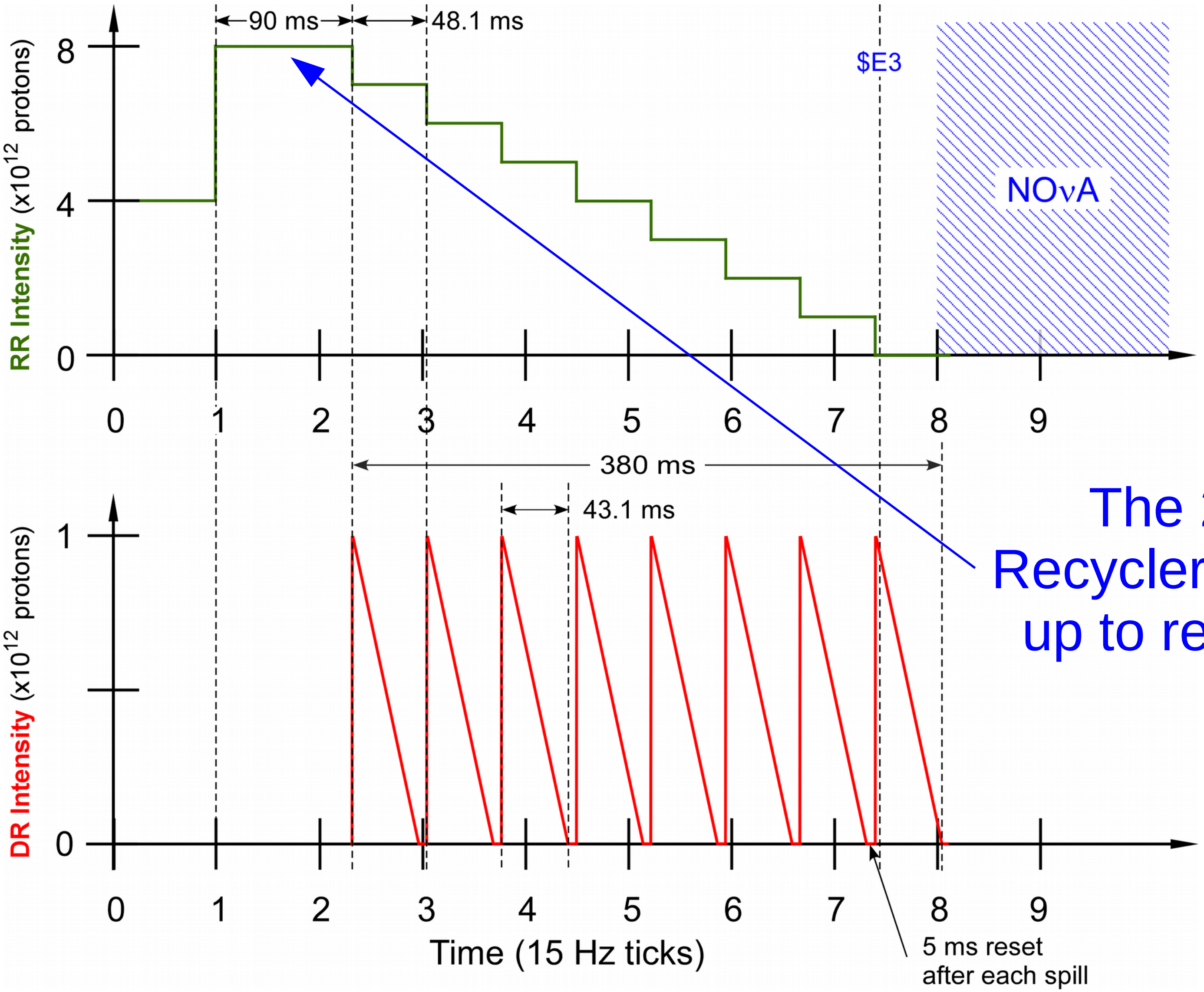


During the MI ramp, two booster batches are loaded into Recycler for Mu2e

Beam manipulations



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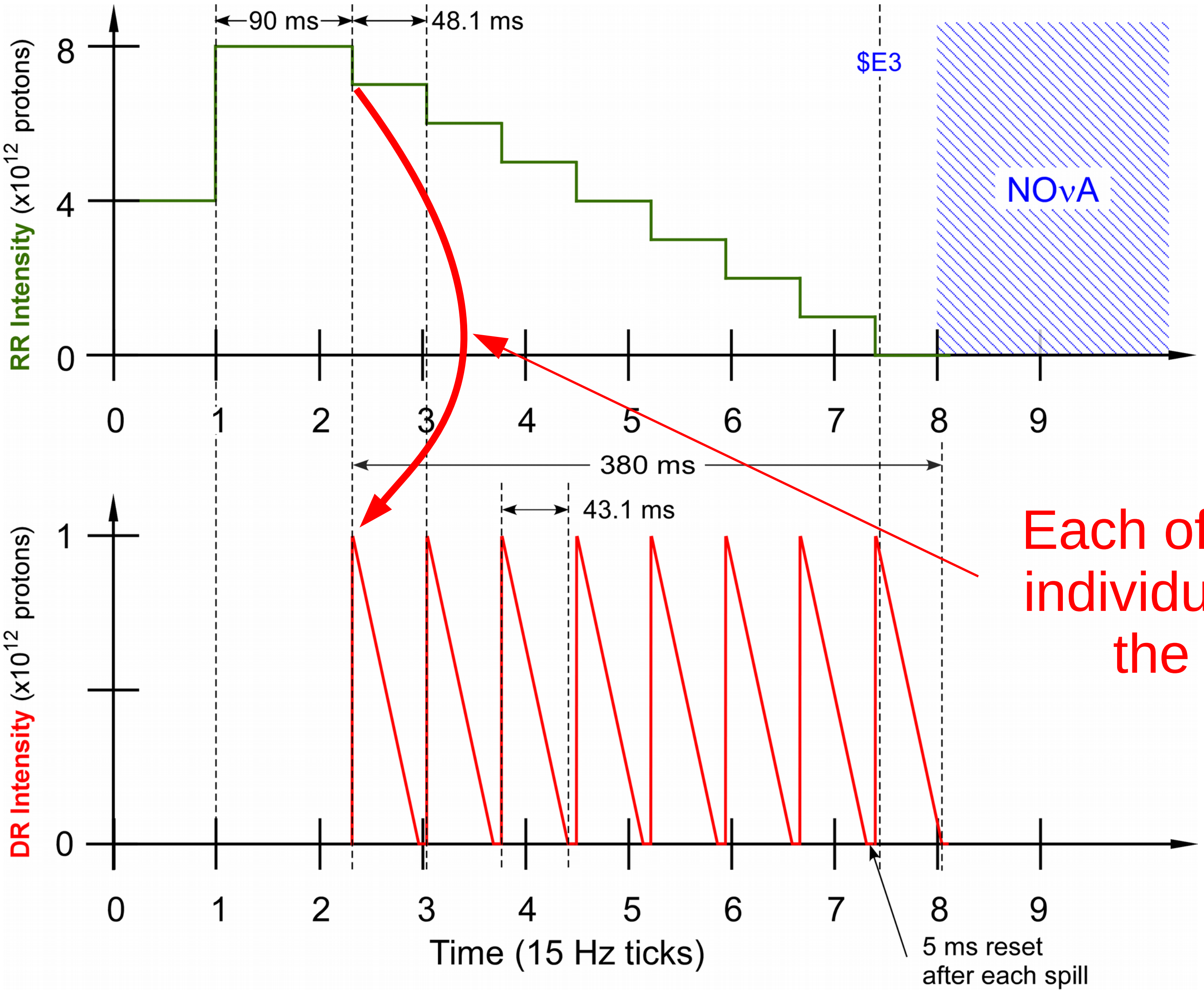
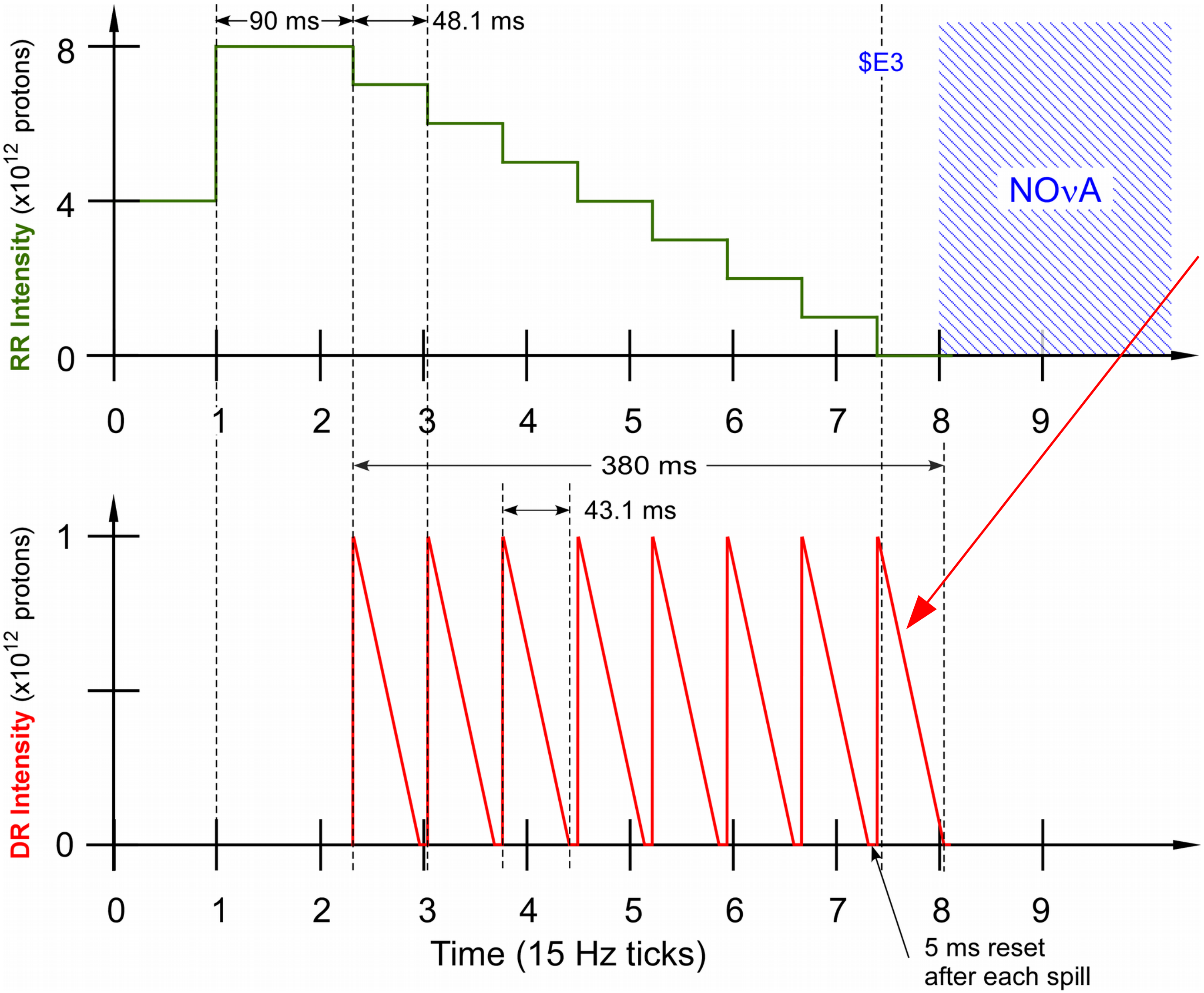


Each of these bunches is individually transferred to the Delivery Ring

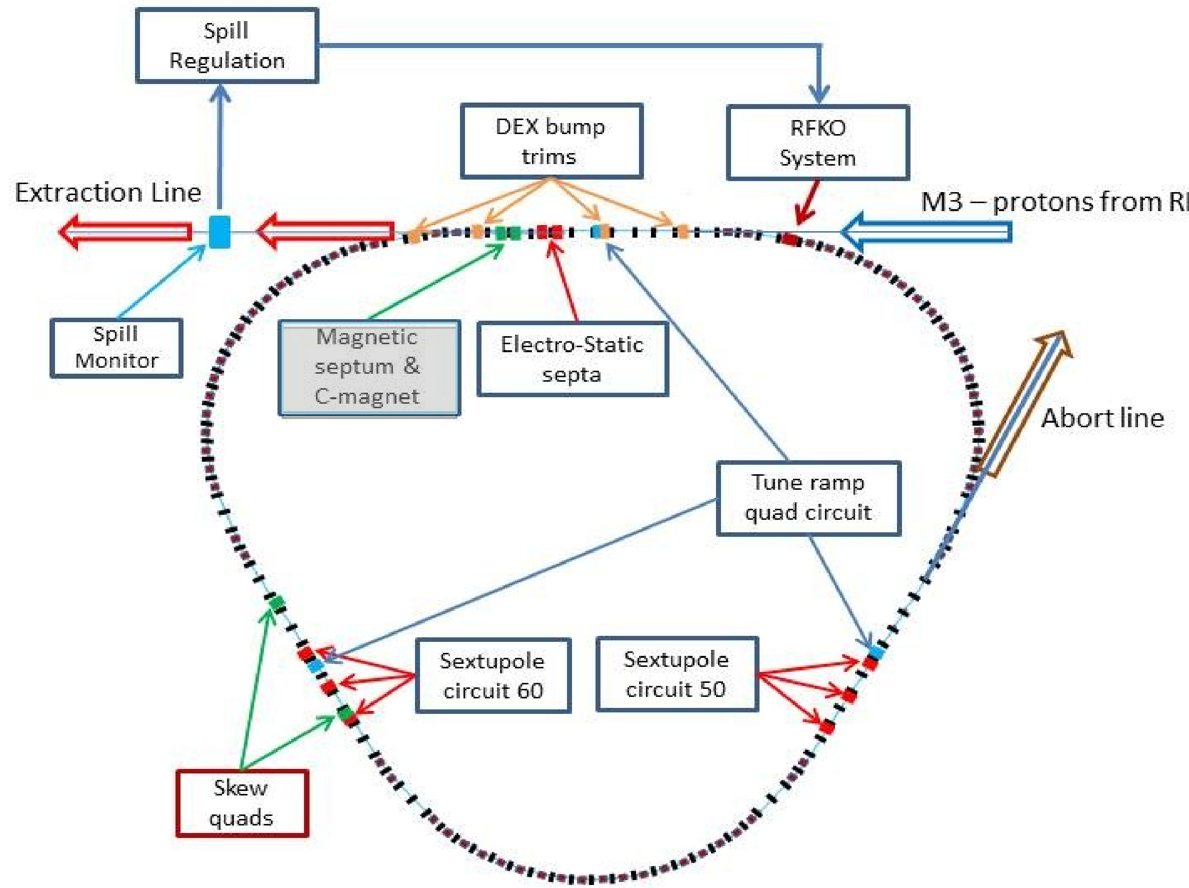
Beam manipulations

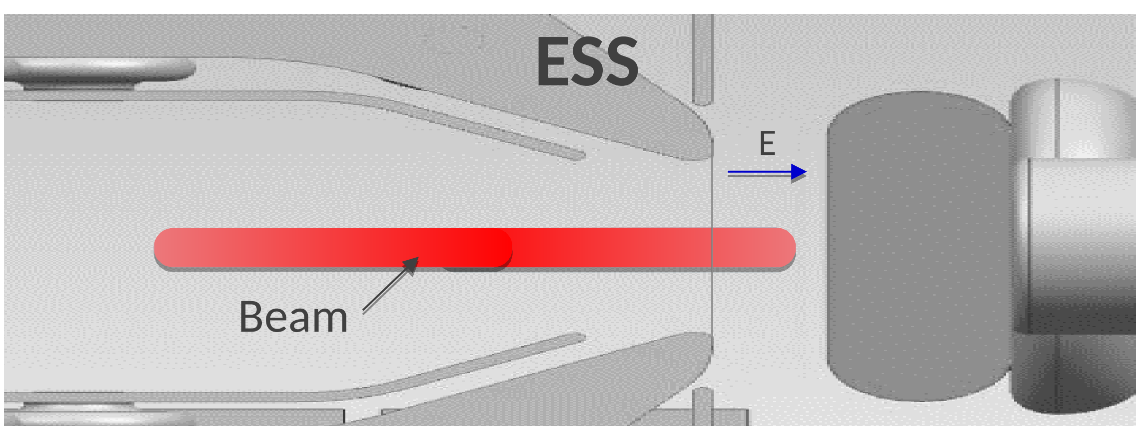


Resonant extraction slow spills protons from the DR and sends them to the Mu2e Production Target

Delivery Ring manipulations

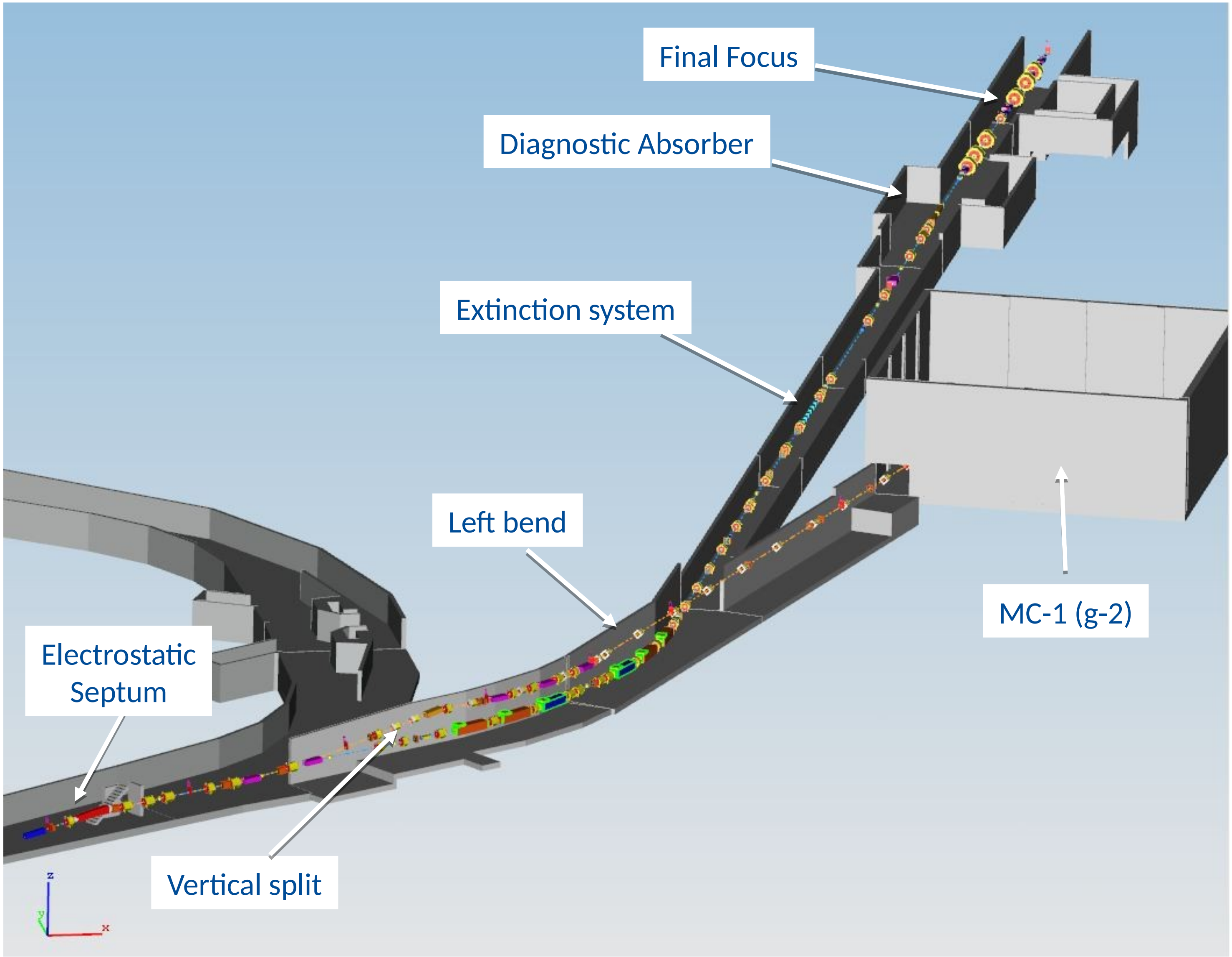
1) Quadrupoles drive a 1/3 integer resonance (29/3) in the horizontal tune
2) Sextupoles induce a controlled beam instability
3) Septum peels off a microbunch on each turn
4) Dynamic spill regulation control via an RFKO system
5) Full extraction over ~32,000 turns





Delivery Ring orbital period (1695 ns) is nearly an ideal match for muon lifetime in Al

Extracted beam exits the DR in a tunnel shared by Mu2e and g-2

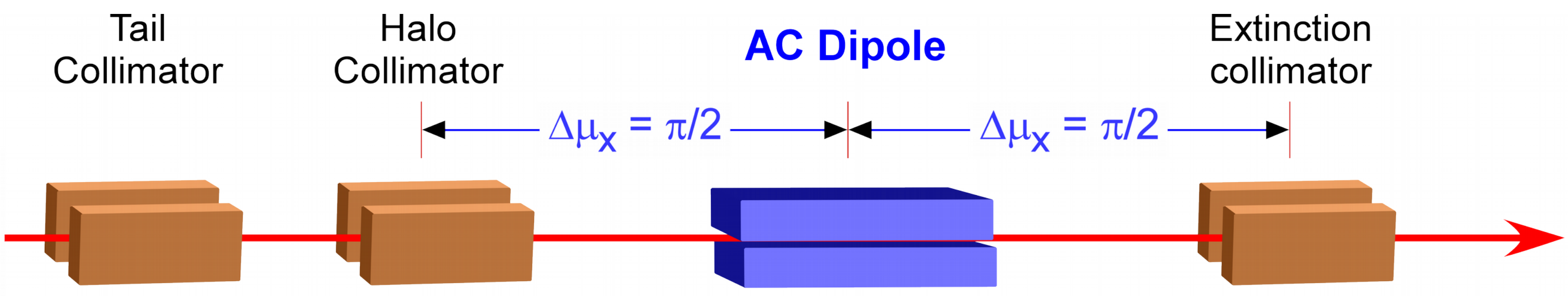


Extracted beam exits the DR in a tunnel shared by Mu2e and g-2

M4 (lower) and M5 (upper) beamlines as the exit the Delivery Ring enclosure.

An AC Dipole extinction system significantly reduces out-of-time beam

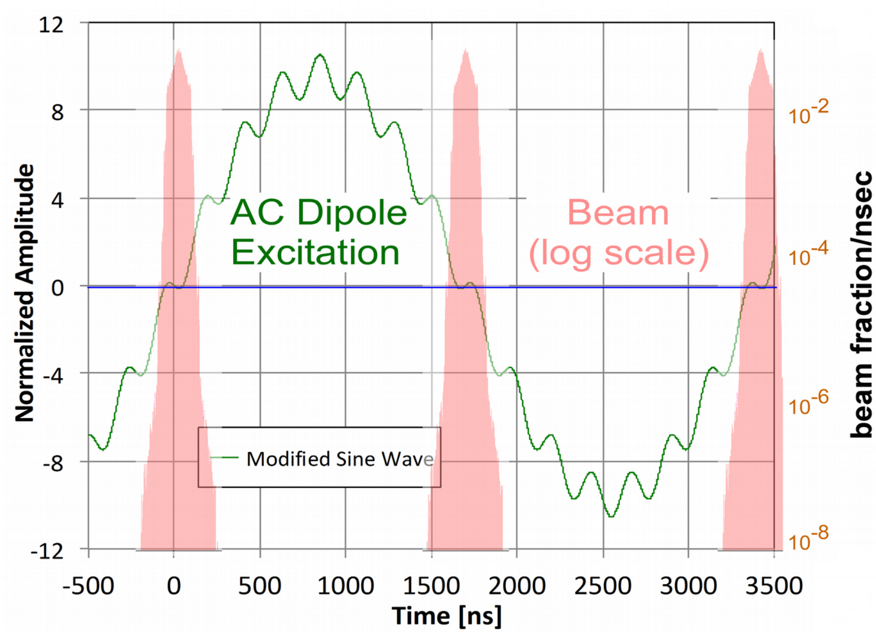
External Beamline Extinction Components



	Extracted from DR		At Proton Target
Extinction Level:	2×10^{-5}	← Factor of 5×10^{-8} →	1.1×10^{-12}

AC Dipole Excitation

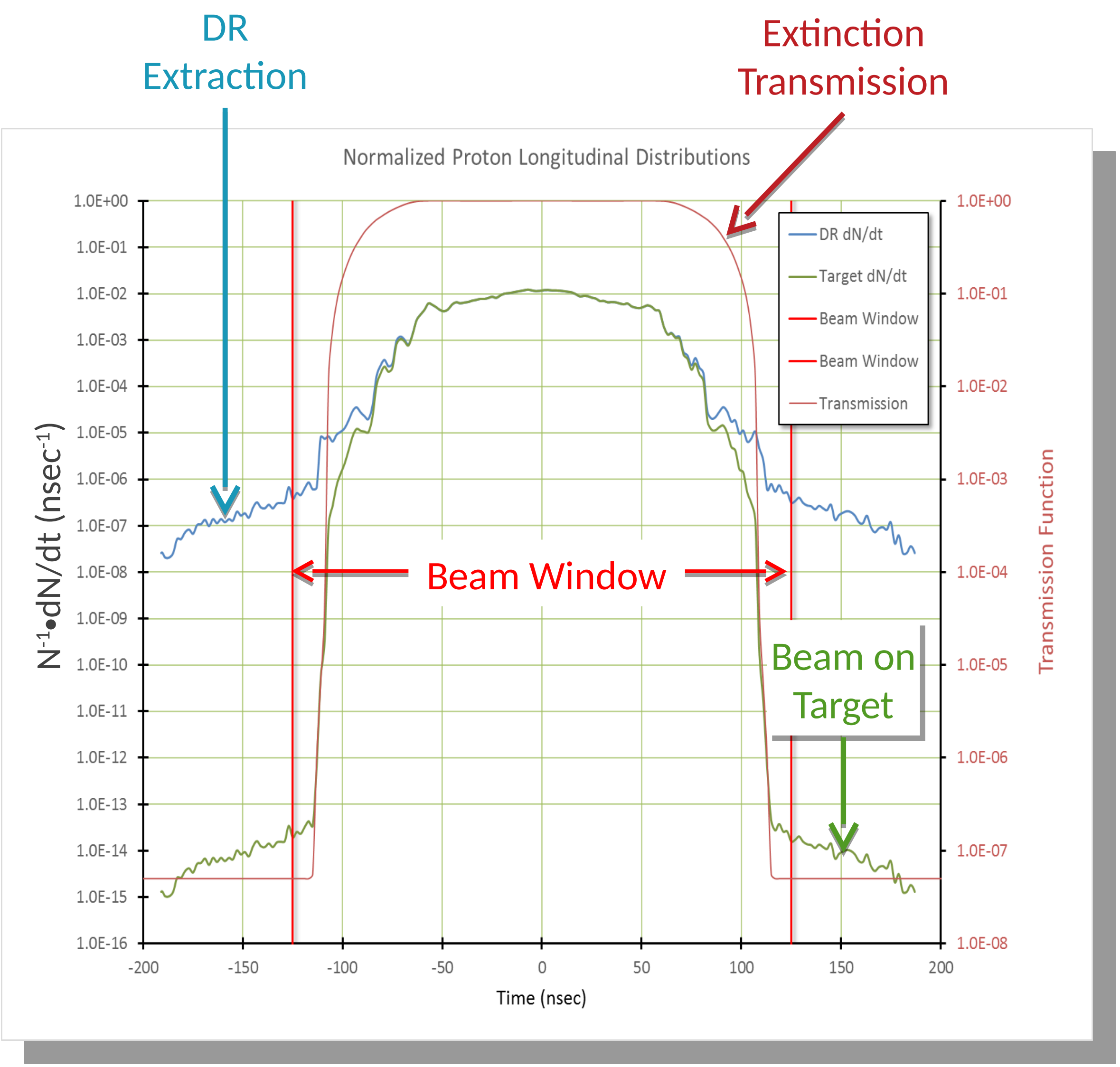
The AC Dipole excitation is a superposition of two harmonics: 300 kHz and 4.5 MHz.



Proton beam pulses shown in pink.

AC Dipole waveform shown in **blue**

Extinction performance should exceed requirements

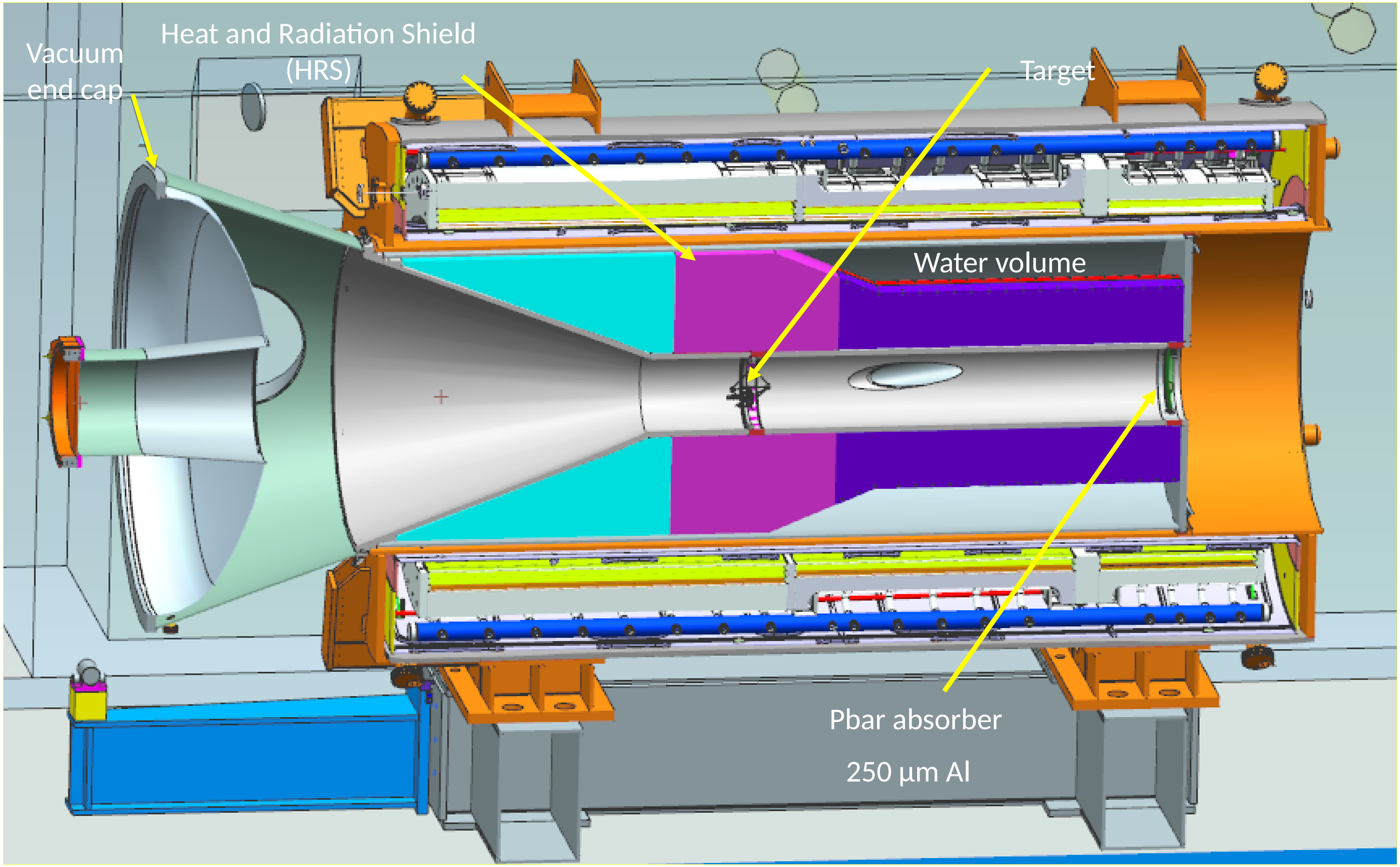


Simulation Results

Fraction of DR extracted beam outside of ±125 ns:	2.1×10^{-5}
In-time beam transmission:	99.5%
Beam line extinction:	$<5\times10^{-8}$
Total extinction:	1.1×10^{-12}
Extinction Requirement:	$<1.0\times10^{-10}$

Our margin should be greater than 2 orders of magnitude

The pion production target is a radiatively cooled tungsten rod



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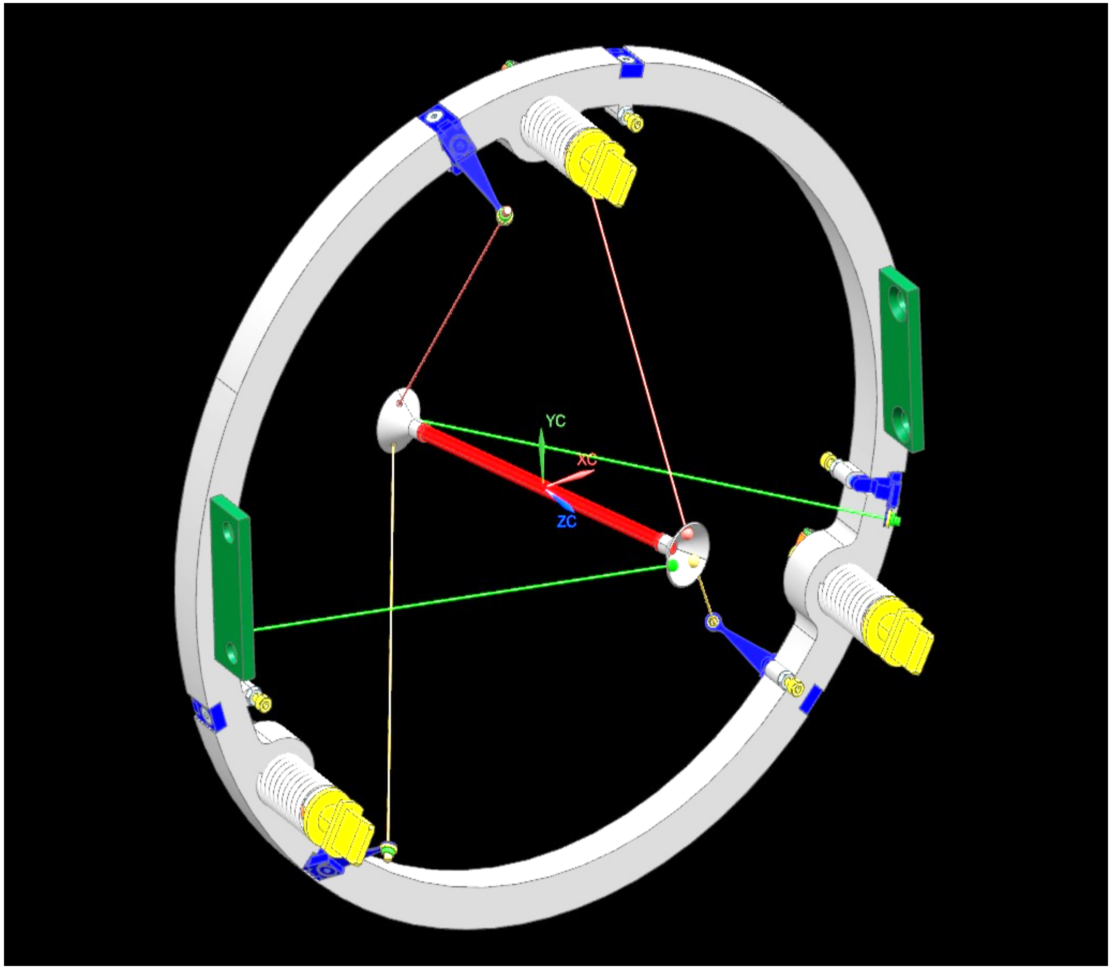
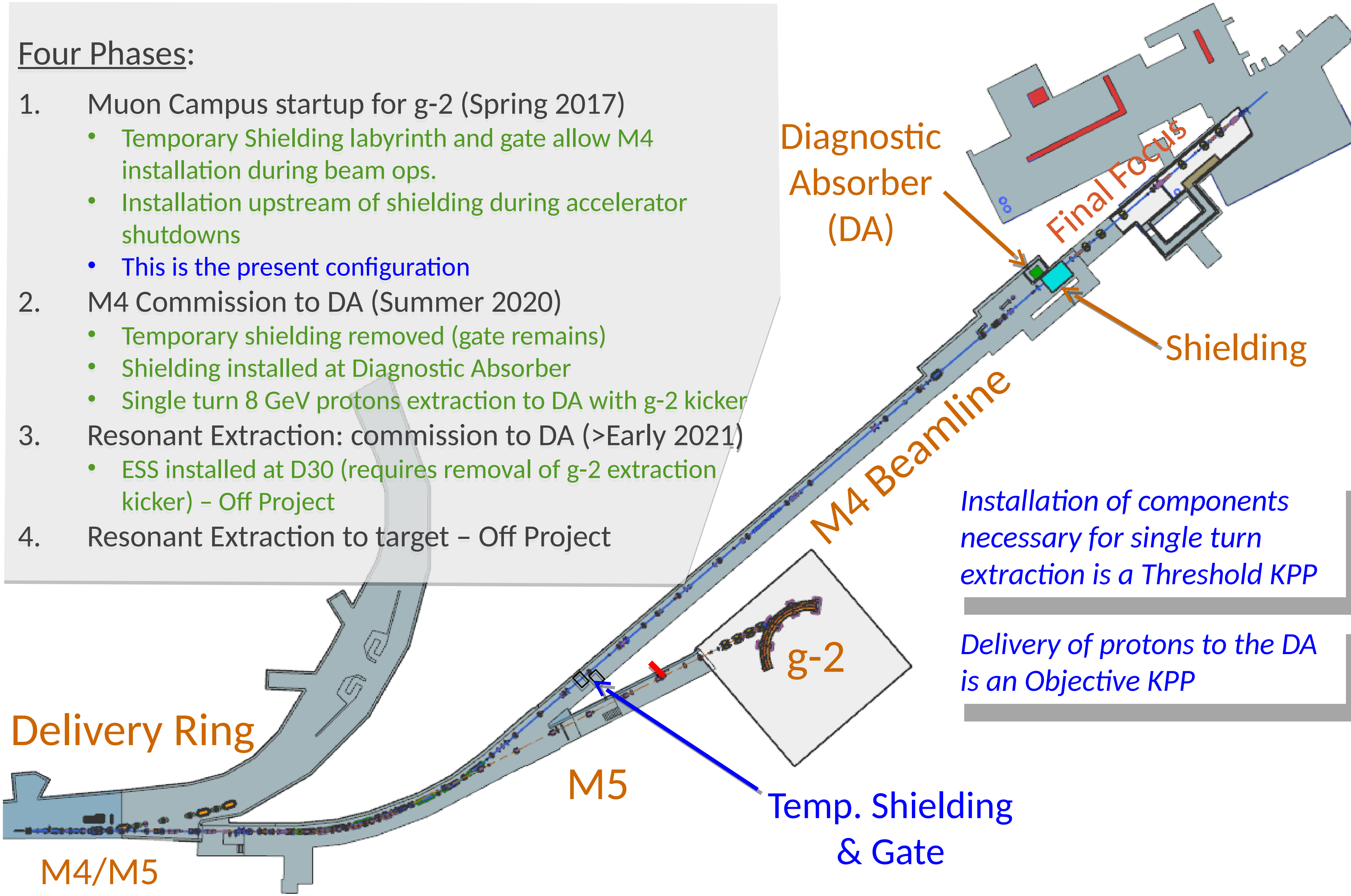


- 16 cm x 6.3 mm tungsten cylinder
- 1700 C surface temperature
- Oxidative erosion is a significant aging concern
- Primary design, prototyping, validation, and production being done at RAL
- There is a signficant remote handling system being designed at FNAL

Accelerator Status and Schedule

Four Phases:

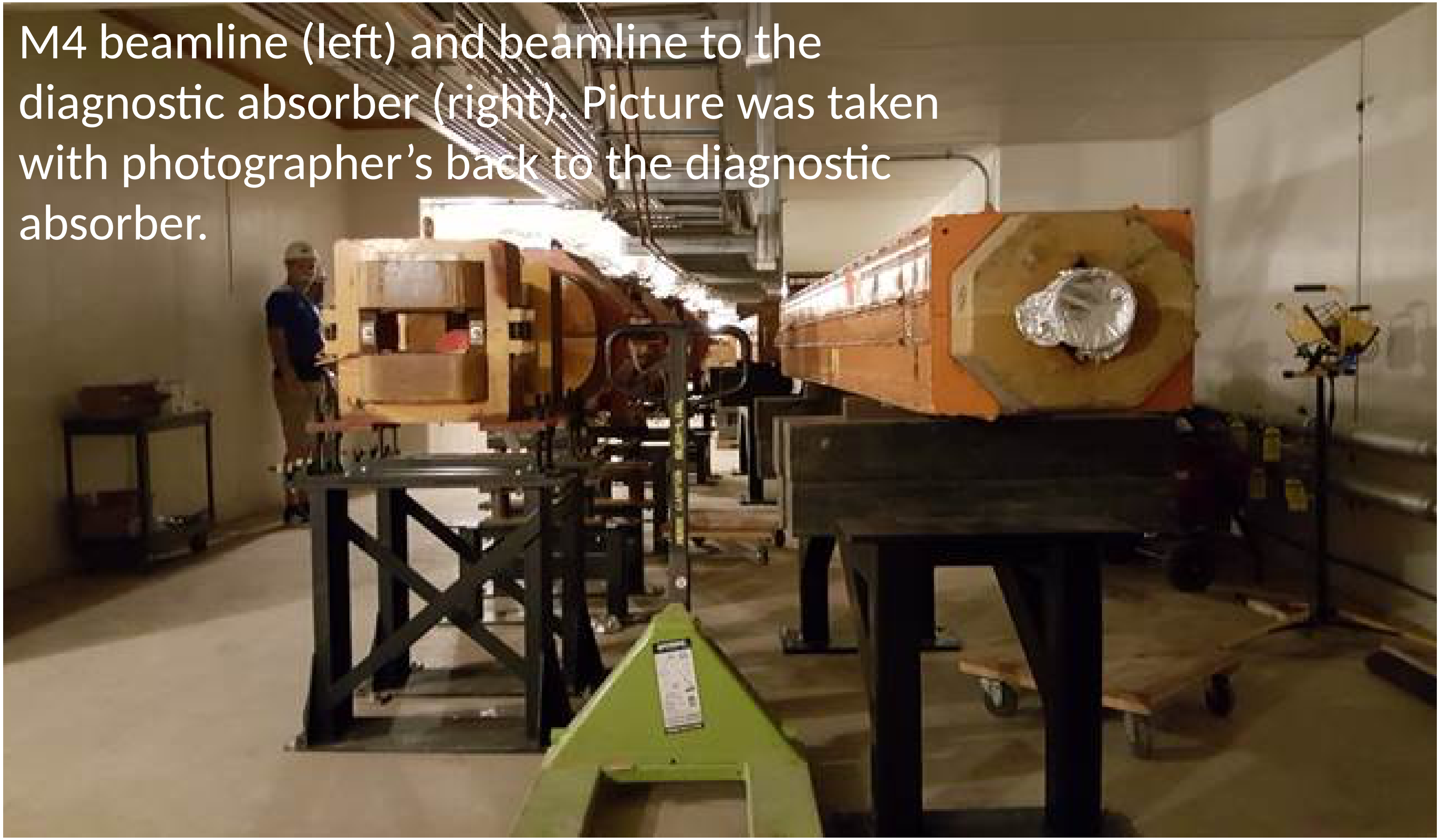
1. Muon Campus startup for g-2 (Spring 2017)
   - Temporary Shielding labyrinth and gate allow M4 installation during beam ops.
   - Installation upstream of shielding during accelerator shutdowns
   - This is the present configuration
2. M4 Commission to DA (Summer 2020)
   - Temporary shielding removed (gate remains)
   - Shielding installed at Diagnostic Absorber
   - Single turn 8 GeV protons extraction to DA with g-2 kicker
3. Resonant Extraction: commission to DA (>Early 2021)
   - ESS installed at D30 (requires removal of g-2 extraction kicker) – Off Project
4. Resonant Extraction to target – Off Project



Installation of components necessary for single turn extraction is a Threshold KPP

Delivery of protons to the DA is an Objective KPP

Some very recent progress has included mounting magnets in the M4 line ...



M4 beamline (left) and beamline to the diagnostic absorber (right). Picture was taken with photographer's back to the diagnostic absorber.

… and prototyping of various components

Prototype AC Dipole being pumped down

In summary

Mu2e is on track to either unambiguously discover CLFV or push the limit on muon conversion by four orders of magnitude in the next decade.

For more information

- Mu2e Homepage: http://mu2e.fnal.gov
- Technical Design Report: http://arxiv.org/abs/1501.05241

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or
Jim Miller, *miller@bu.edu*.