Mu2e Project & Delivery Ring RF Overview

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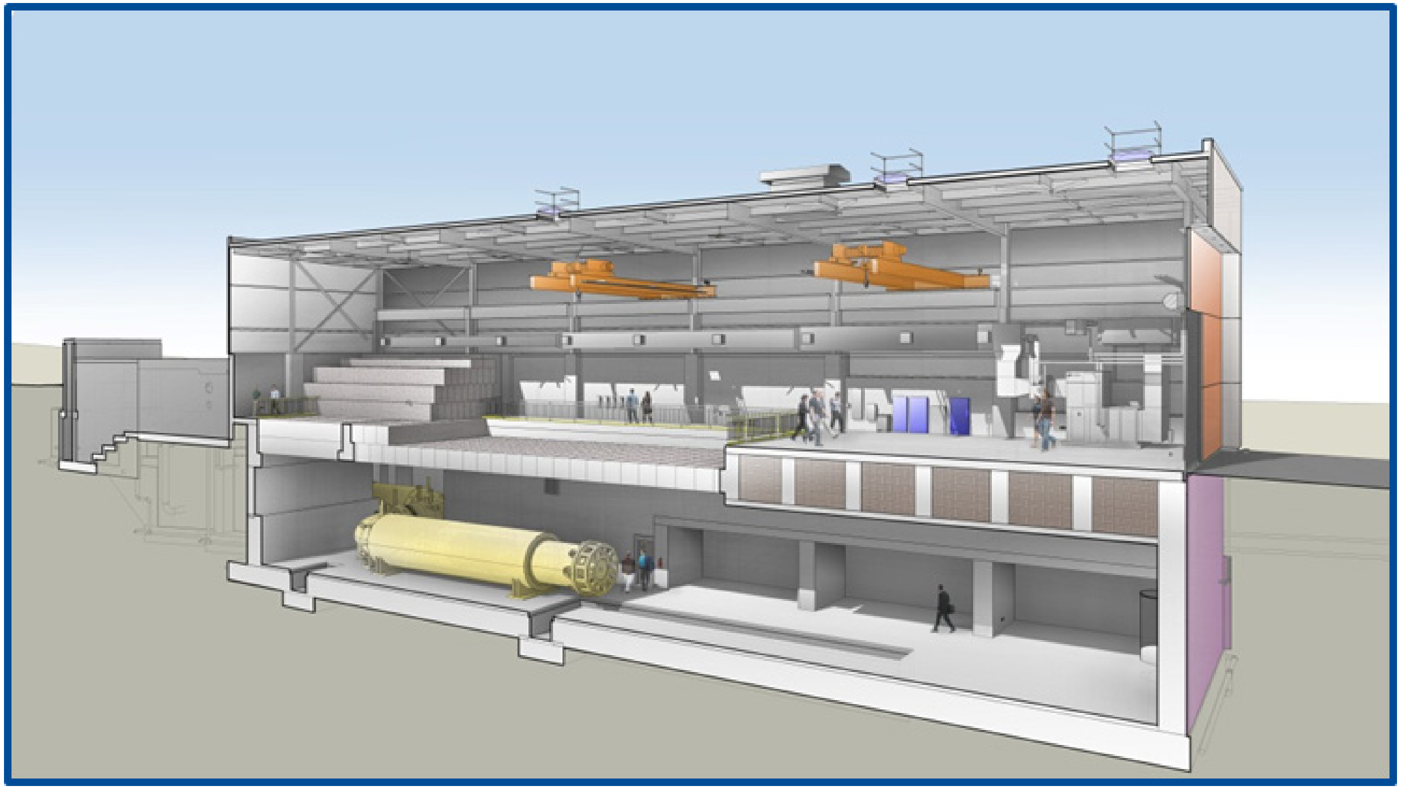
Delivery Ring RF Review

November 19, 2015

Outline

1. The Mu2e Experiment
2. The Muon Campus
3. The Mu2e Project Accelerator Systems
4. Mu2e Longitudinal Phase Space
   - Recycler RF Manipulations
   - Delivery Ring RF
5. Construction Progress
6. Schedule Overview

1. The Mu2e Experiment



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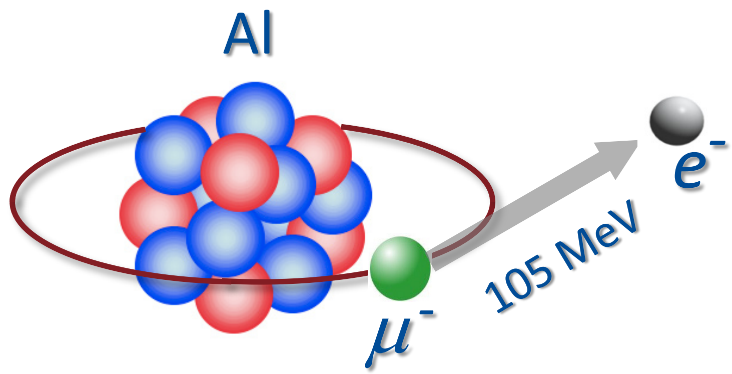
Charged Lepton Flavor Violation

- The Mu2e experiment will attempt to detect Charged Lepton Flavor Violation (CLFV)
- CLFV is a process involving charged leptons ($e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$) that violates the conservation of the number of leptons of each flavor



$$\mu^- N \rightarrow e^- N$$

L_μ:	1	0	$\Delta L_\mu = -1$
L_e:	0	1	$\Delta L_e = 1$

Both L_μ and L_e are not conserved in this process

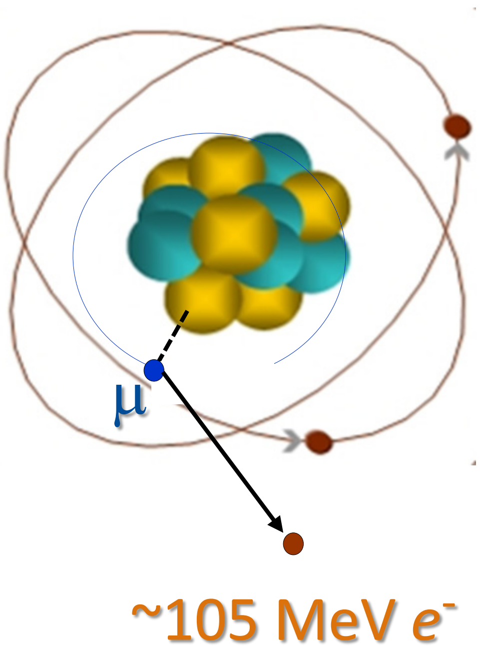
If this is observed, it is evidence physics beyond the Standard Model

Ordinary muon decay is not CLFV

	μ^-	$\rightarrow e^-$	$\bar{\nu}_e$	ν_μ
L_μ:	1	0	0	1
L_e:	0	1	-1	0

Experimental Signature of μ^{-} N $\rightarrow e$ N

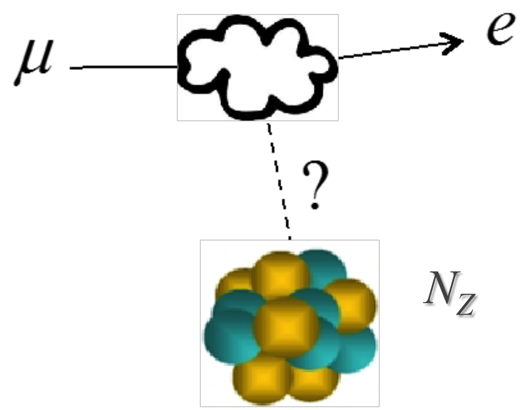
- When captured by a nucleus, a muon will have an enhanced probability of exchanging a virtual particle with the nucleus.
- This reaction recoils against the entire nucleus, producing a *mono-energetic* electron carrying most of the muon rest energy



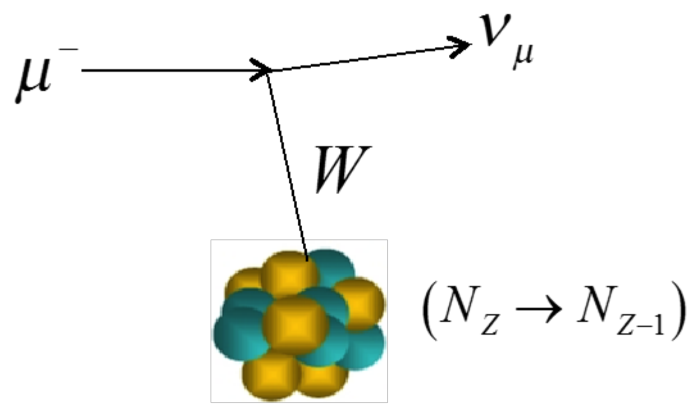
$$E_e = m_\mu c^2 - \frac{\left(m_e c^2\right)^2}{2 m_N c^2}$$

What We (Plan to) Measure

- We will measure the rate of μ to e conversion…



…relative to that of ordinary μ capture



- This is quantified in the ratio $R_{\mu e}$ – which is defined as:

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \rightarrow e^- N(A,Z)\right)}{\Gamma\left(\mu^- N(A,Z) \rightarrow \nu_\mu N'(A,Z-1)\right)}$$

⟵ *Rate of CLFV* $\mu \rightarrow e$ conversion

⟵ μ capture rate

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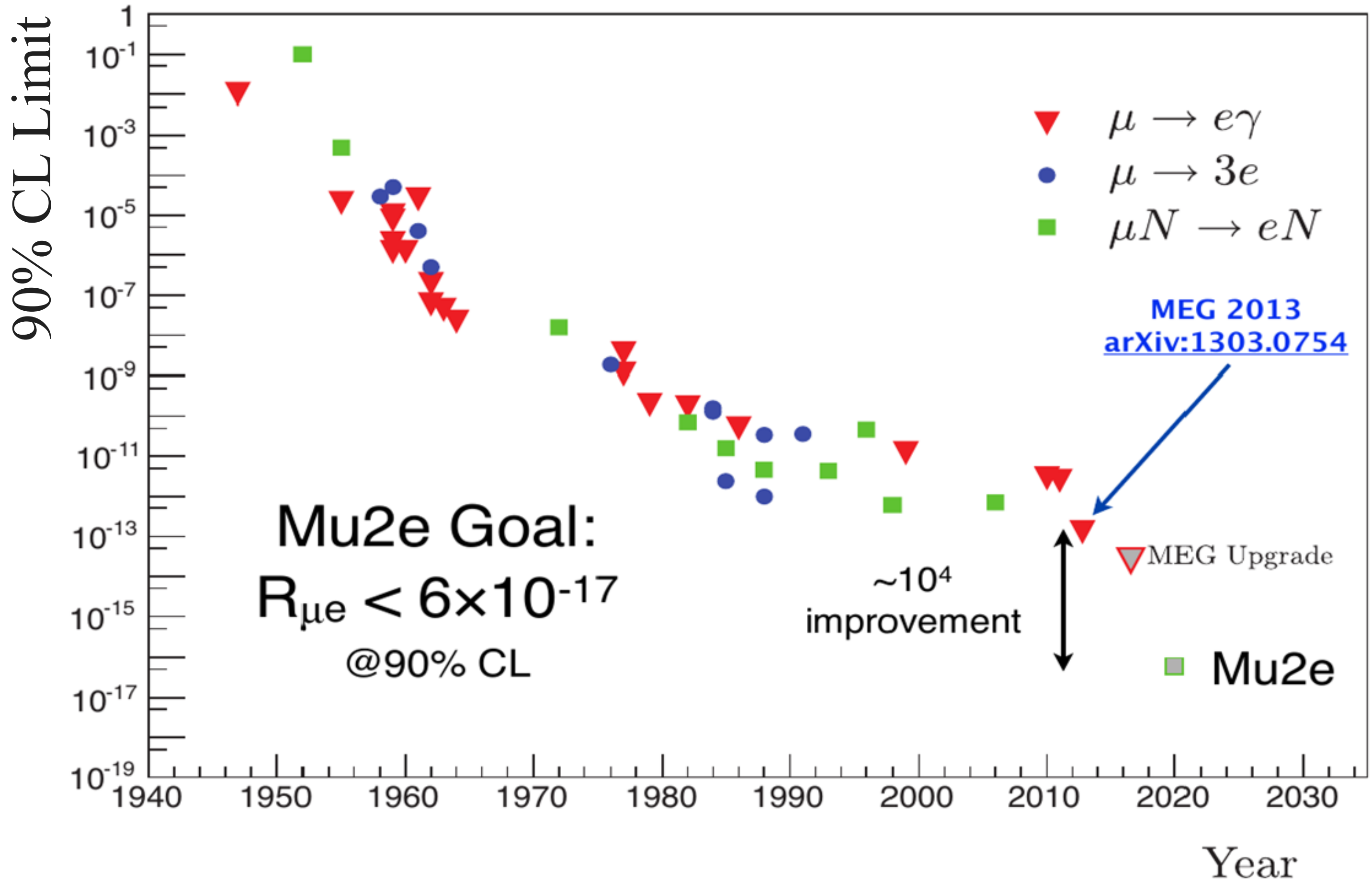
Results of Previous CLFV Searches



Mu2e

- Single event sensitivity = 2.87×10^{-17} (i.e. one observed event yields $R_{\mu e}$ = 2.87×10^{-17})
- 90% CL $R_{\mu e}$ Limit < 6.0×10^{-17}

Mu2e Apparatus

The Mu2e apparatus consists of three superconducting solenoids joined together to make a continuous whole

Production Solenoid

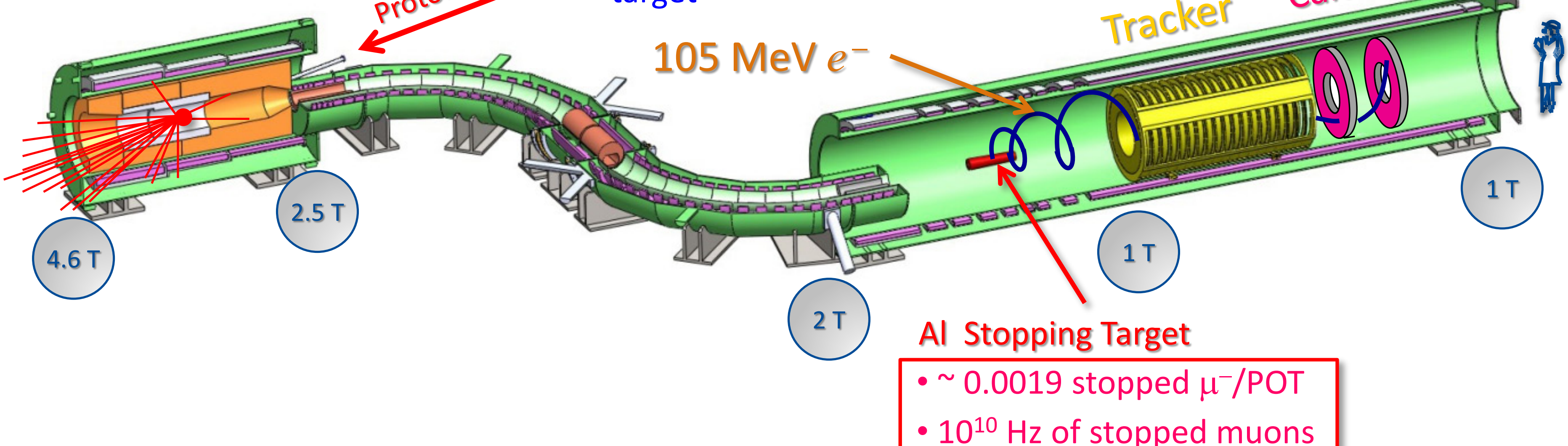
- Contains proton target
- Magnetic mirror – reflects secondaries back toward transport solenoid

Transport Solenoid

- Collimation
- Momentum and charge selection
- Transport to stopping target

Detector Solenoid

- Contains stopping target
- Tracker (straws)
- Calorimeter (BaF_2 crystals)



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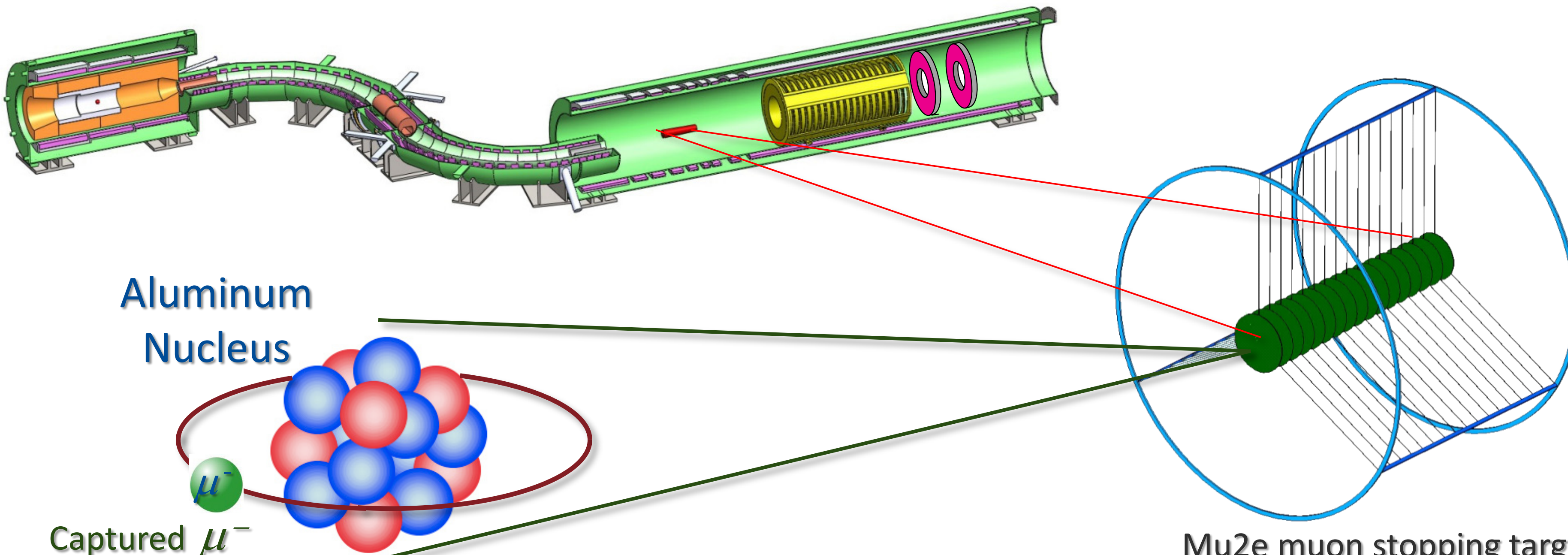
Stopping Muons



M_μ = 105 MeV/c^2

- A muon that is stopped in the Mu2e target is captured into an atomic orbital state of an aluminum nucleus
- The muon quickly ($\lesssim$ psec) transitions to the 1S state where its wave-function overlaps the nucleus *

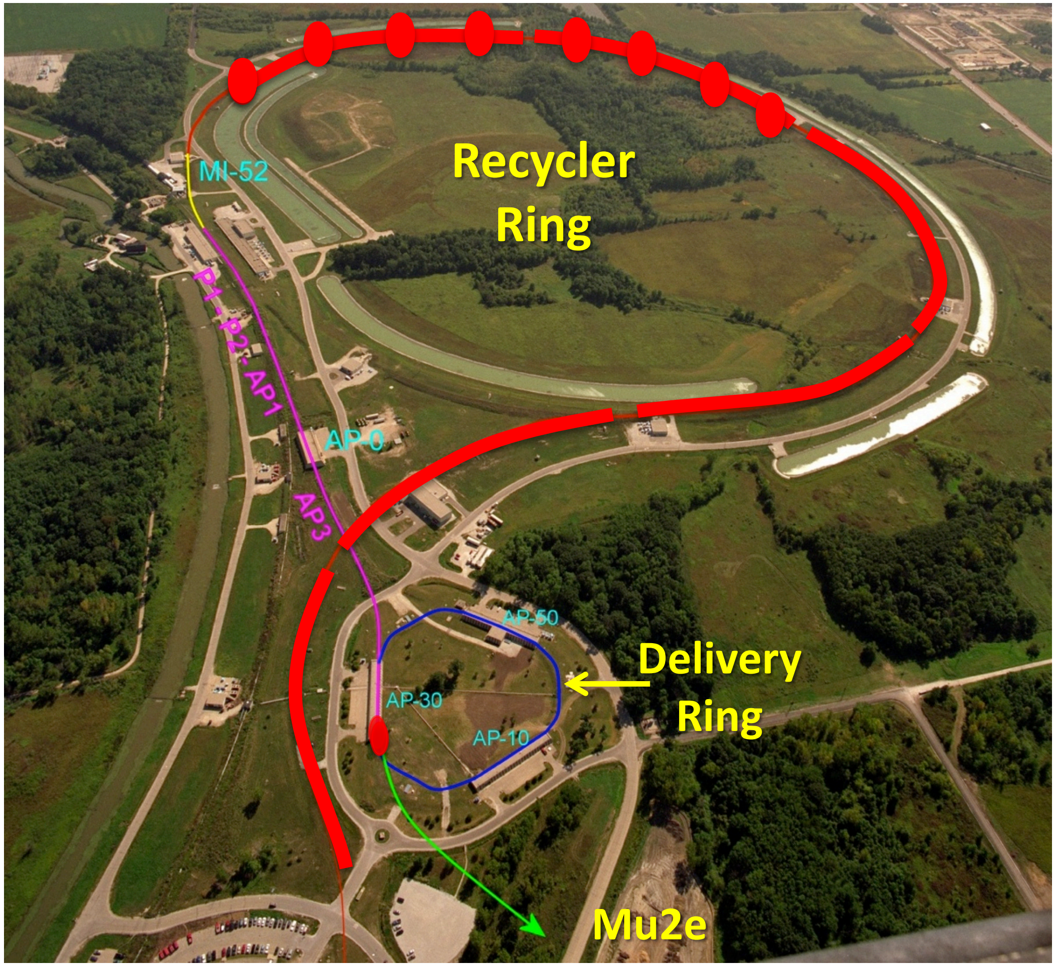
*A stopping target monitor measures detects the photons emitted during these atomic transitions – measuring the denominator of $R_{\mu e}$

Mu2e muon stopping target

- 17 Al foil disks (200 μm thick)
- Disk radii decrease from 83 mm to 65 mm in downstream direction

2. The Muon Campus

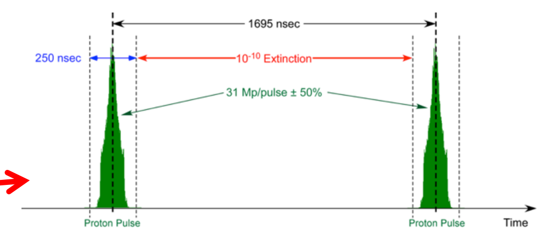
Mu2e Proton Delivery



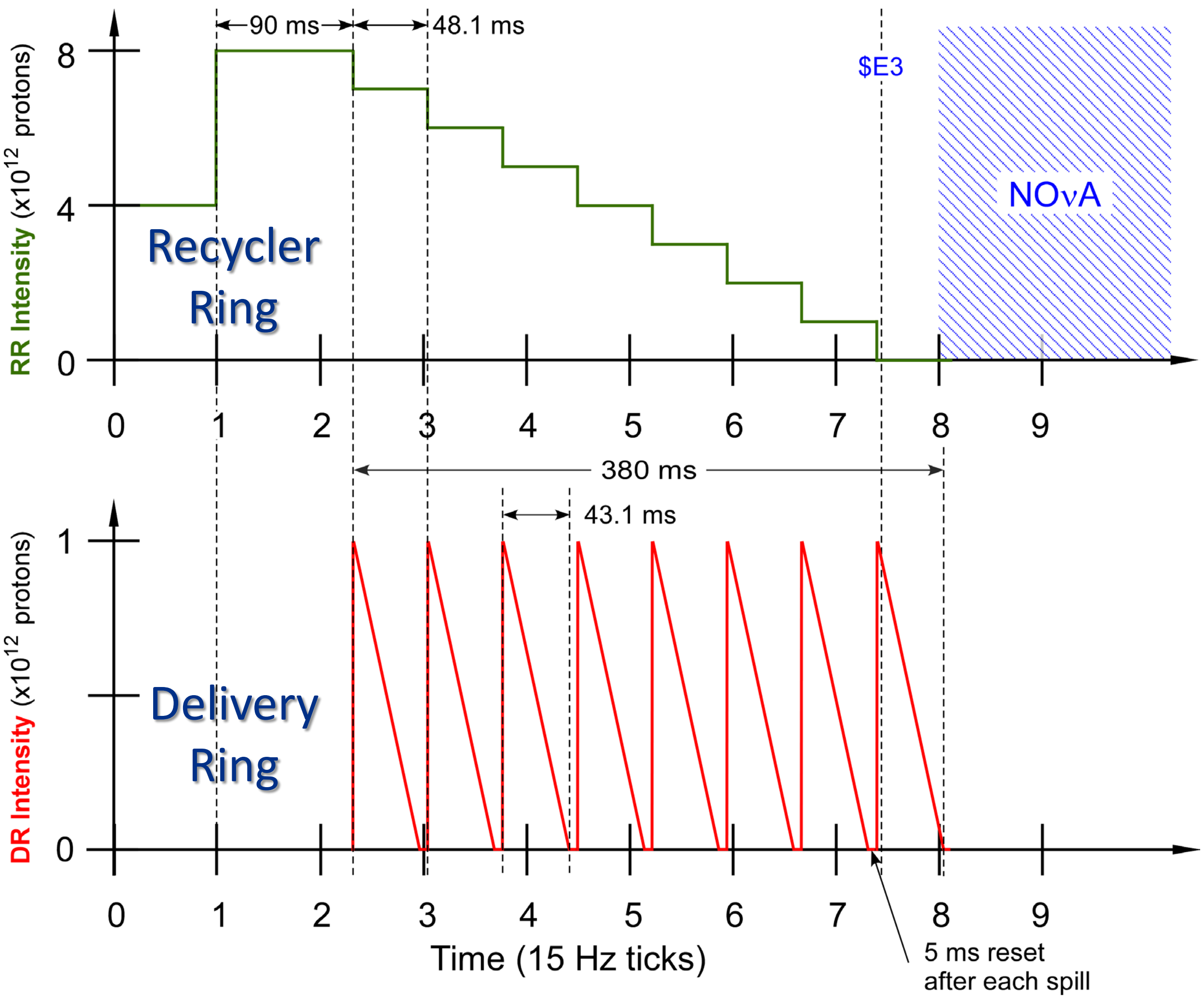
Booster

- Two Booster "batches" are injected into the Recycler (8 GeV storage ring). Each batch is:
  - 4×10^{12} protons
  - Batch Length = 1.7 μsec
- These are re-bunched into 8 bunches of 10^{12} protons each
- The bunches are extracted one at a time to the Delivery Ring
  - DR Period = 1.7 μsec
- As the bunch circulates, it is resonantly extracted to produce the desired beam structure.
  - Pulses of $\sim4\times10^{7}$ protons each
  - Separated by 1.7 μsec

Exactly what we need →



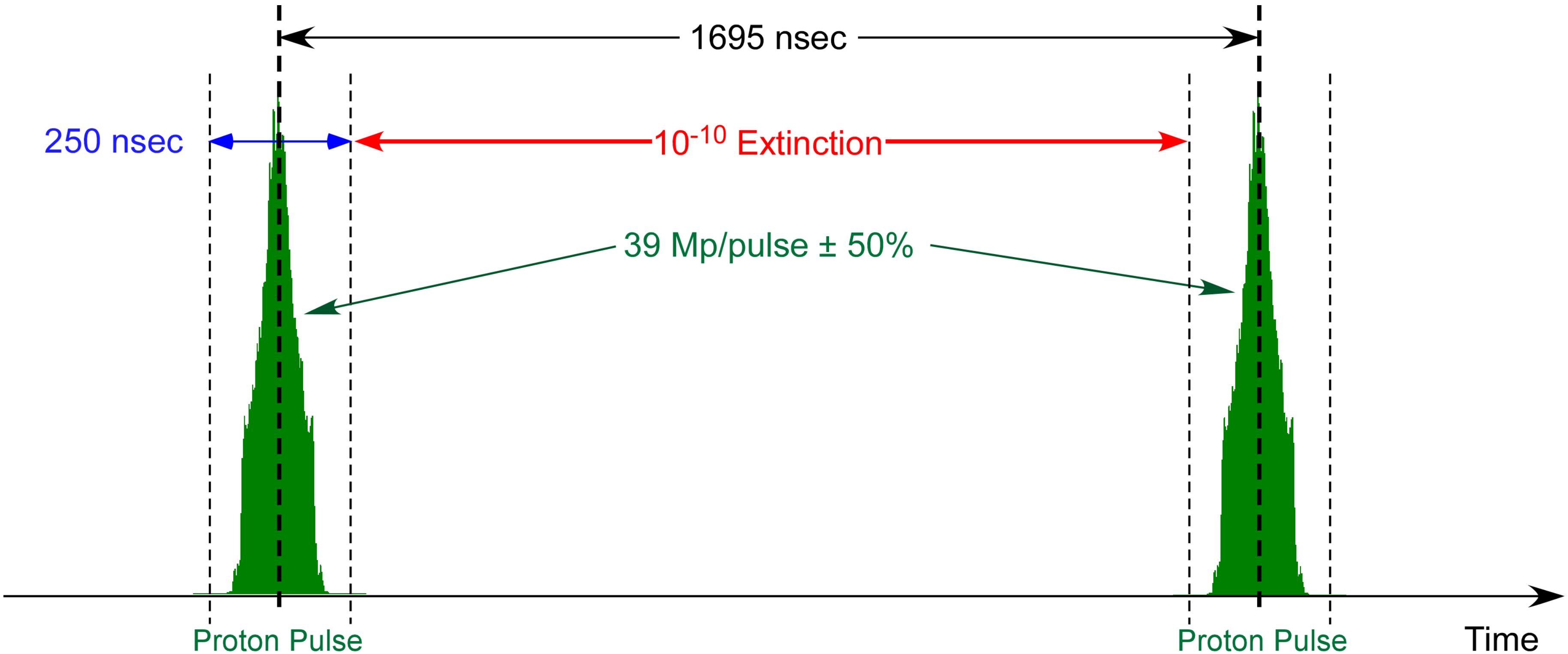
Accelerator Timeline for Mu2e Proton Beam Delivery



Macro Time Structure of the Beam

- Spill duration: 43.1 ms
- Interval between spills 48.1 ms
- Beam on for 380 ms
- Beam off for 953 ms
- Duty Factor: 28%
  (Total Spill Time/Length of Cycle)
- Peak Delivery Ring proton intensity: 1.0×10^{12}

Beam Micro-structure



- The proton beam on target consists of a train of ~25,000 narrow pulses separated by 1.695 μsec
- Extinction = No. of out-of-time protons / No. of in-time protons
- Inter-pulse extinction provides time for prompt backgrounds to decay before the Mu2e detectors go live for events from the current pulse

The Muon Campus

DOE Projects, AIPs, GPPs

Building the Muon Campus requires the following projects:

1. DOE Projects
   - Muon g-2
   - Mu2e
2. AIPs (Accelerator Improvement Projects)
   - Recycler RF
   - Beam Transport
   - MC Cryo Plant
   - Delivery Ring
3. GPPs (General Plant Projects)
   - MC-1 Building
   - Beamline Enclosure
   - MC Infrastructure Upgrade

Muon Campus Upgrades Required for the Mu2e Experiment but not on the Mu2e Project

Accelerator Upgrade	Project
MI-8 beamline to Recycler Ring Injection	NOvA Project
Recycler Ring 2.5 MHz RF system	Recycler RF AIP
Delivery Ring 2.4 MHz RF Cavities and HL Amps & Cooling	Recycler RF AIP
Single bunch extraction from Recycler Ring	Beam Transport AIP
Beamline aperture upgrades	Beam Transport AIP
AP1, AP2, AP3 to M1, M2, M3 conversion & upgrade	Beam Transport AIP
Beam transport instrumentation & infrastructure	Beam Transport AIP
Beam transport controls	Delivery Ring AIP
Delivery Ring Injection	Delivery Ring AIP
Delivery Ring Abort	Delivery Ring AIP
Delivery Ring infrastructure	Delivery Ring AIP
Delivery Ring Controls and Instrumentation	Delivery Ring AIP
D30 straight section reconfiguration	g-2 Project
Delivery Ring Extraction (except ESS)	g-2 Project
Extraction line (M4) to M5 split	g-2 Project
M4 beamline enclosure	MC Beamline Enclosure GPP

3. The Mu2e Project Accelerator Systems

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Mu2e Accelerator Systems Scope Overview

475.02.08.03 Extinction Monitor

475.02.09 Target Station

475.02.07 External (M4) Beamline

475.02.08.02 Extinction

475.02.03 Instrumentation & Controls

475.02.04 Radiation Safety

Everywhere

475.02.05 Resonant Extraction

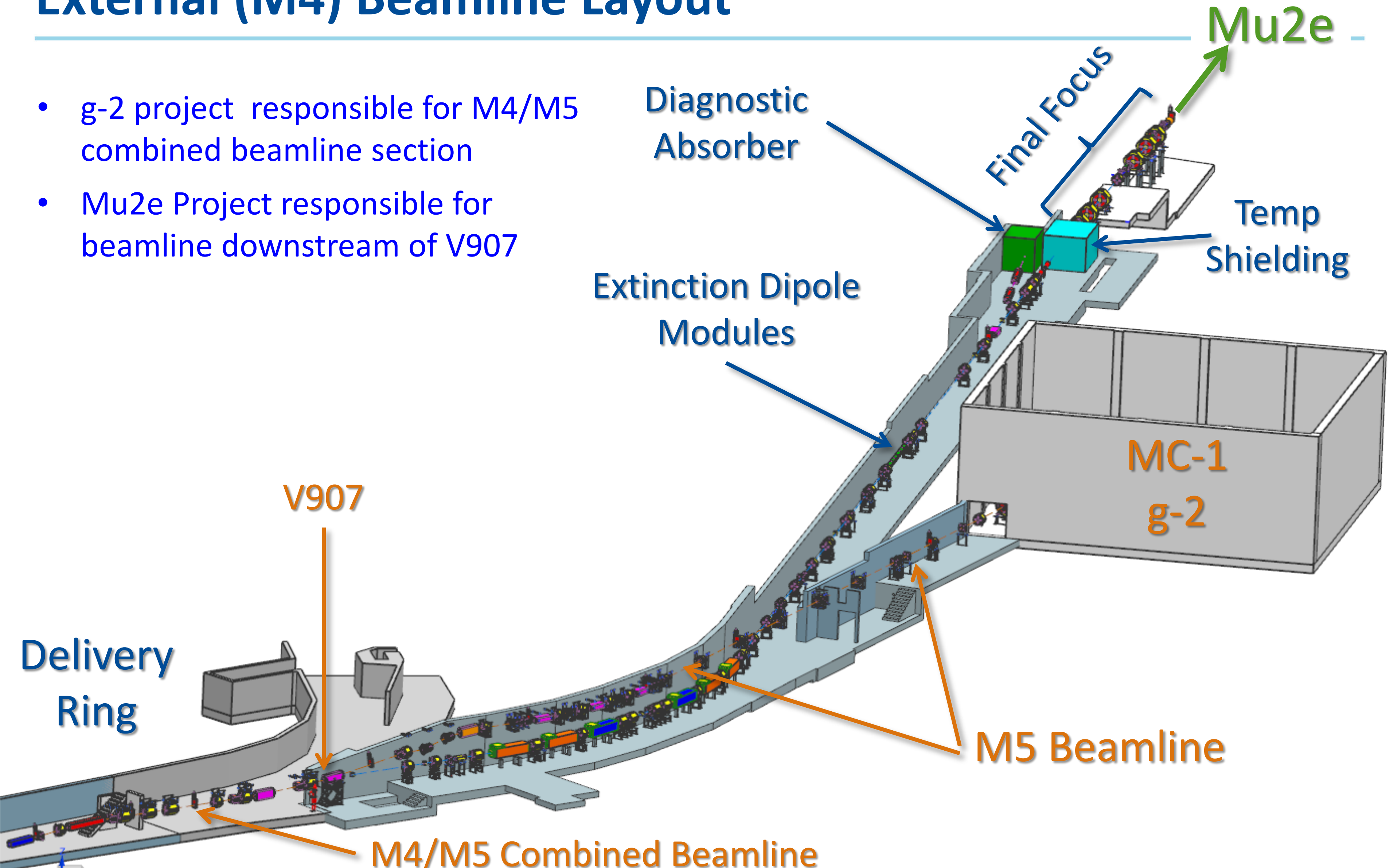
475.02.06 Delivery Ring RF

Mu2e Proton Beam Requirements

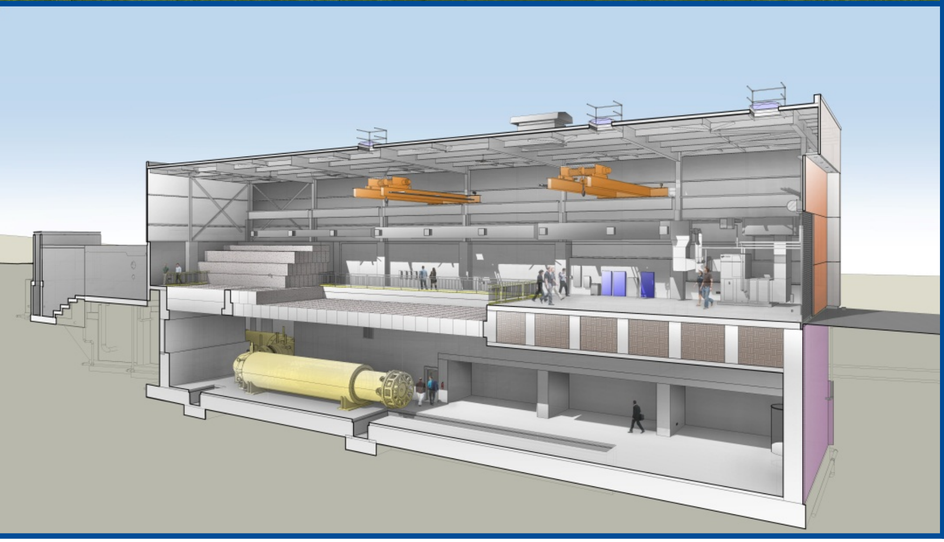
	Parameter	Design Value	Requirement	Unit
3-4 year run	Total protons on target	3.6×10^{20}	3.6×10^{20}	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
	Maximum variation in pulse separation	< 1	10	nsec
	Spill duration	43	> 20	msec
	Beamline Transmission Window	230	250	nsec
	Transmission Window Jitter (rms)	5	<10	nsec
	Out-of-time extinction factor	10^{-10}	$\leq 10^{-10}$	
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

External (M4) Beamline Layout

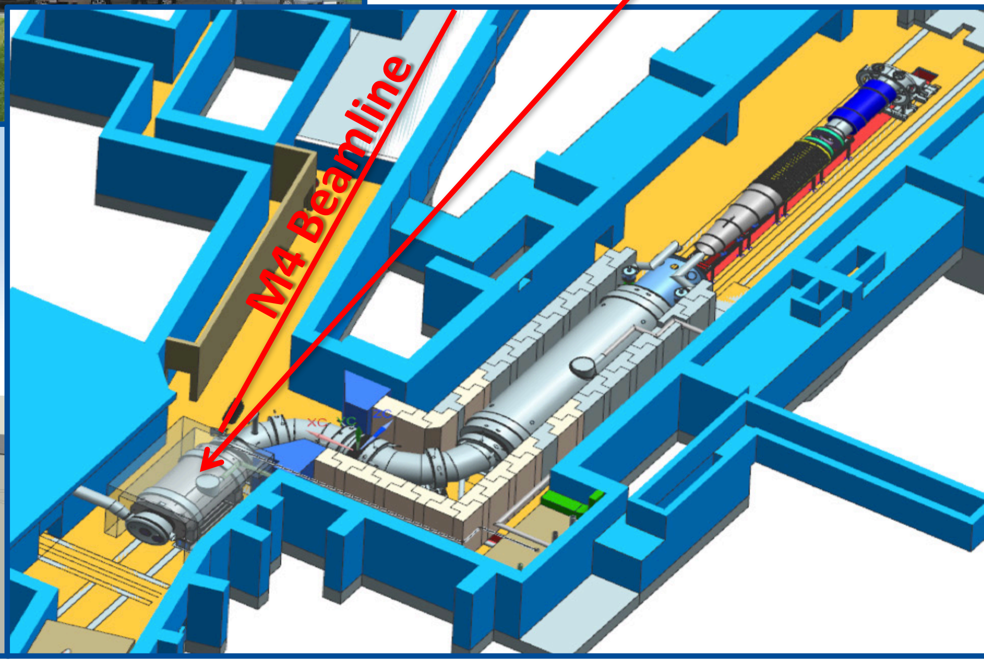
- g-2 project responsible for M4/M5 combined beamline section
- Mu2e Project responsible for beamline downstream of V907



The Mu2e Building



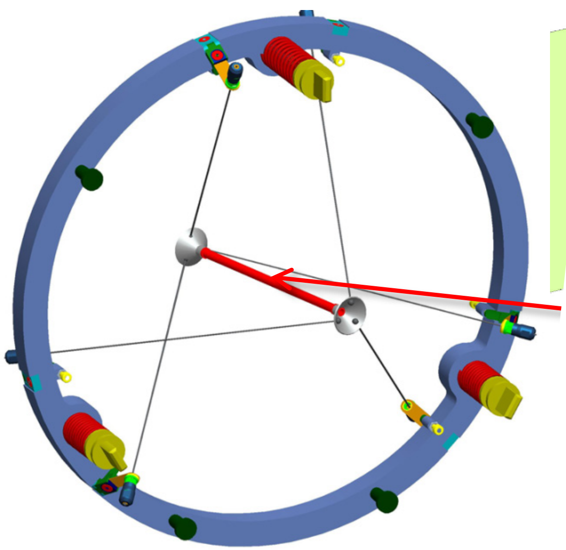
Proton Target lives here

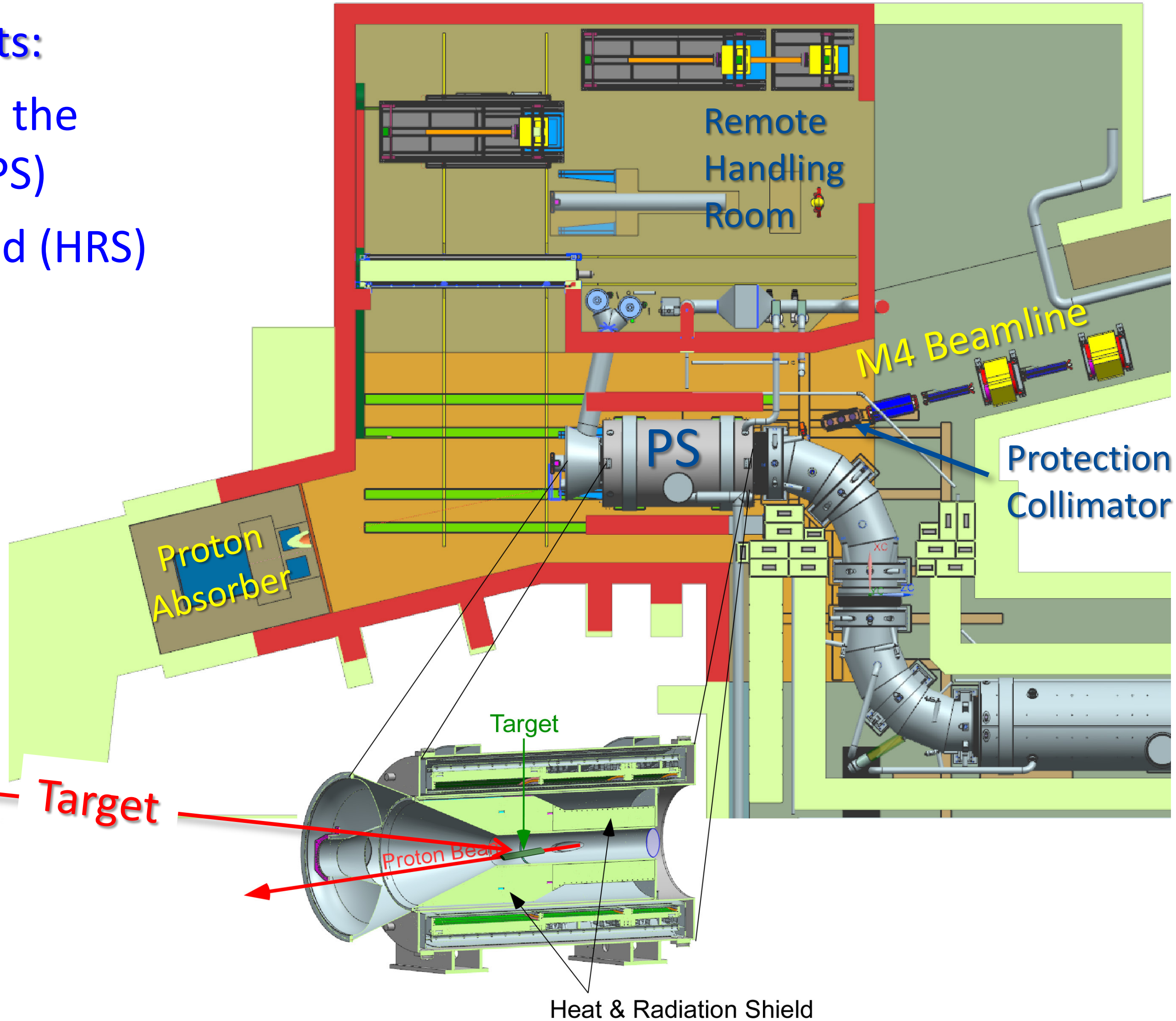


Mu2e Proton Target Station

Target Station Components:

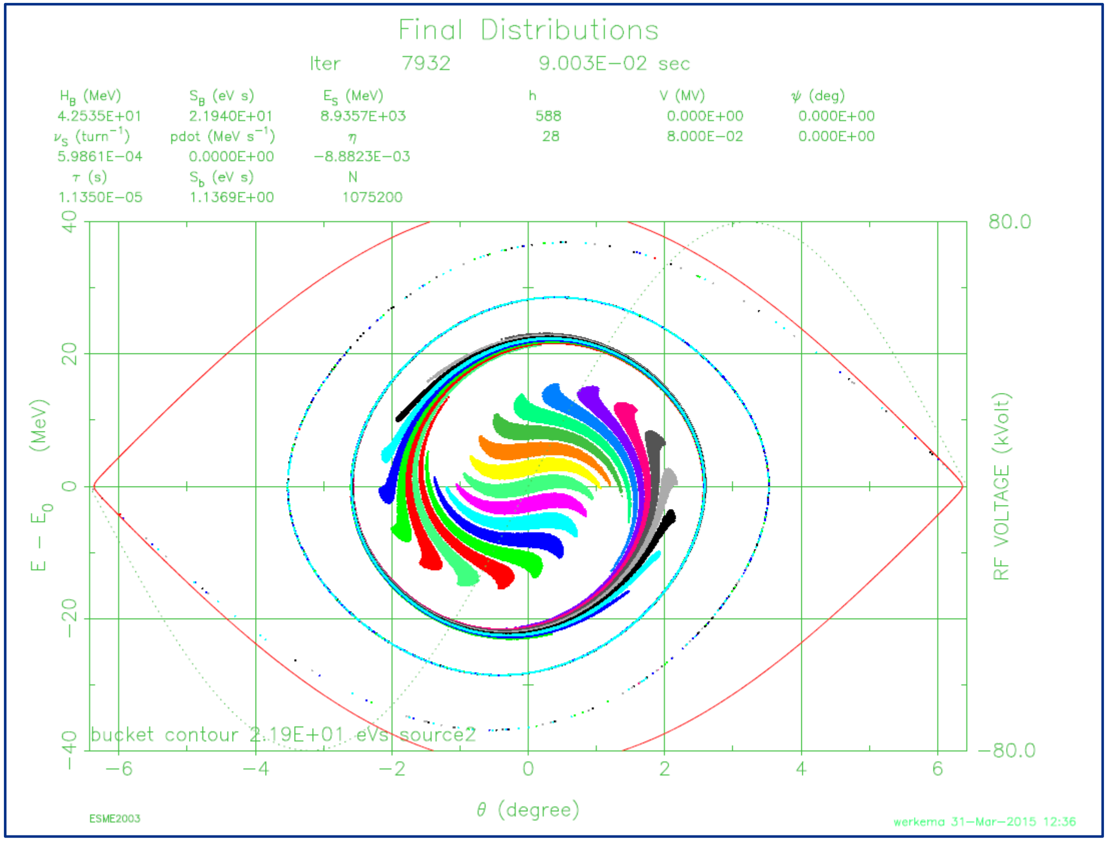
- Target – located inside the Production Solenoid (PS)
- Heat & Radiation Shield (HRS)
- Target Handling
- Proton Absorber
- Protection Collimator





4. Mu2e Longitudinal Phase Space

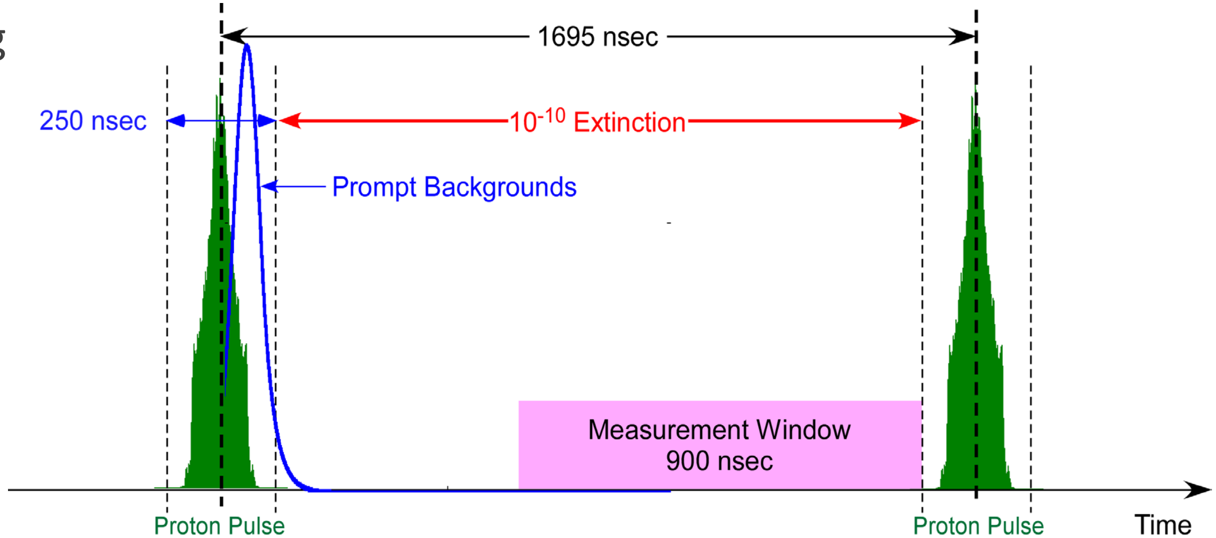
- Recycler RF Manipulations
- Delivery Ring RF



Proton Beam Requirements (Revisited)

The 2.5 MHz RF manipulations in the Recycler and Delivery Ring achieve two goals:

1. FW bunch length $\leq$ 250 ns
2. Extinction of beam extracted from DR < 10^{-4}
   (beamline extinction insert provides additional factor of 10^{-7})



The bunch length requirement is primarily accomplished by the Recycler 2.5 MHz RF system.

The function of the Delivery Ring 2.4 MHz RF system is to preserve the narrow bunch width received from the Recycler.

The g-2 experiment uses the same Recycler 2.5 MHz system for their bunch formation.

Since the g-2 requirements are more severe than those of Mu2e, the system will meet the needs of Mu2e.

FW Bunch Length Requirements	
Mu2e	g-2
250 nsec	149 nsec

Recycler and Delivery Ring RF Parameters

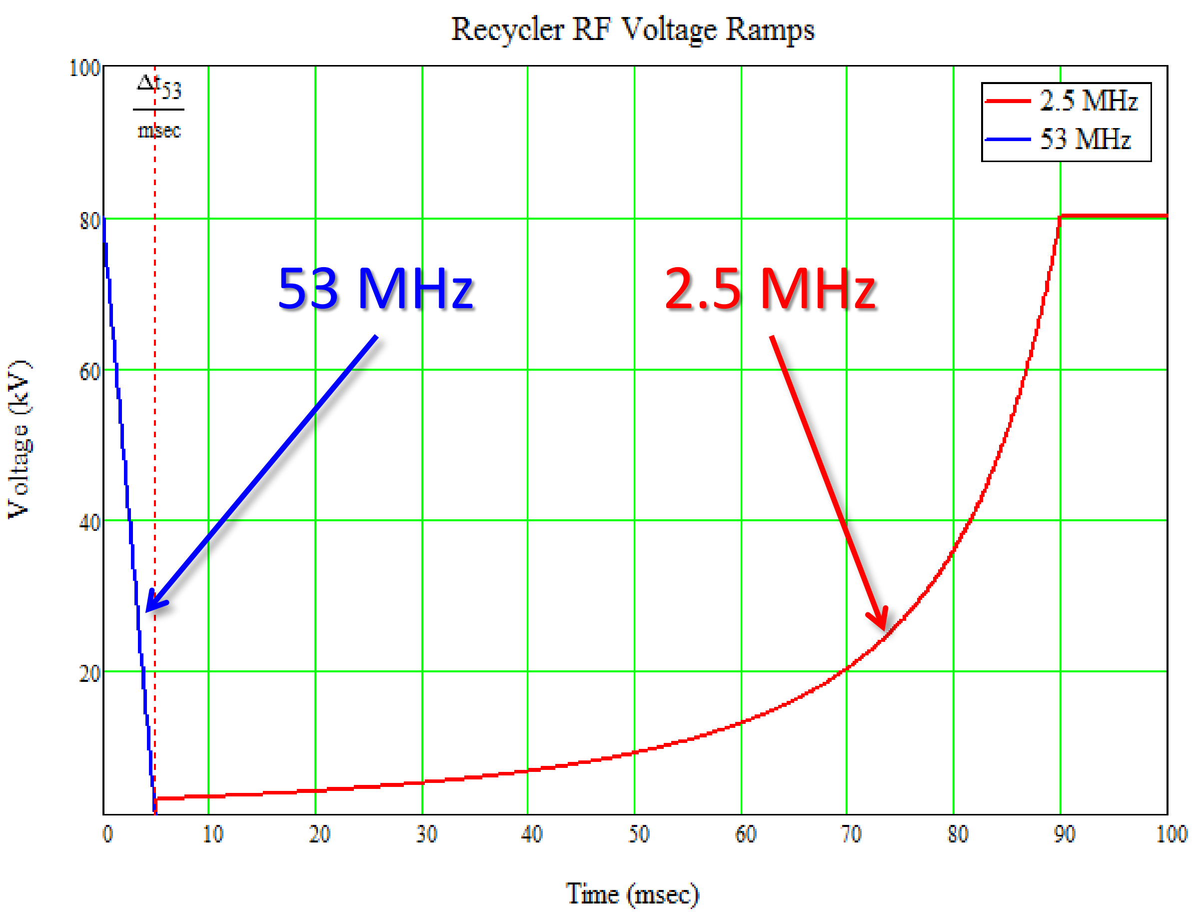
Parameter	Value	Units
Recycler Ring 2.5 MHz Bunch Formation RF System		
Harmonic Number	28	
Frequency	2.515	MHz
Peak Total Voltage	80	kV
Number of Cavities	6	
Duty Factor	33	%
Bunch Formation time	90	msec
Delivery Ring 2.4 MHz RF System		
Harmonic Number	4	
Frequency	2.360	MHz
Peak Total Voltage	10	kV
Number of Cavities	1	
Duty Factor	27	%
Both Systems		
R/Q	400	Ω
Q	125	
Beam loading Comp. feedback gain	4	

Note: the 2.5 MHz Cavities for the Recycler and Delivery Ring are identical

Two Stage ESME Model

1. Recycler Ring Model
    - 10,752,000 protons generated in twenty one (21) 53 MHz buckets. This is done in ten separate runs of 1,752,000 proton each.
    - Initial longitudinal emittance of each bunch is 0.10 eV-sec
    - Tracked using ESME through Recycler RF manipulations until time of extraction
    - Final phase coordinate of each proton is converted to Delivery Ring phase
    - Resulting energy and phase of each proton written to disk for use as input to the Delivery Ring Model
2. Delivery Ring Model
    - Input = Energy/phase output from Recycler model
    - Cavity impedance and space charge effects simulated
    - Beam loading compensation simulated by reducing cavity shunt impedance and Q by the beam loading compensation feedback gain (4) and applying an accelerating phase to compensate for energy lost
    - Beam is tracked using ESME to various spill times

Recycler RF Voltage Ramps



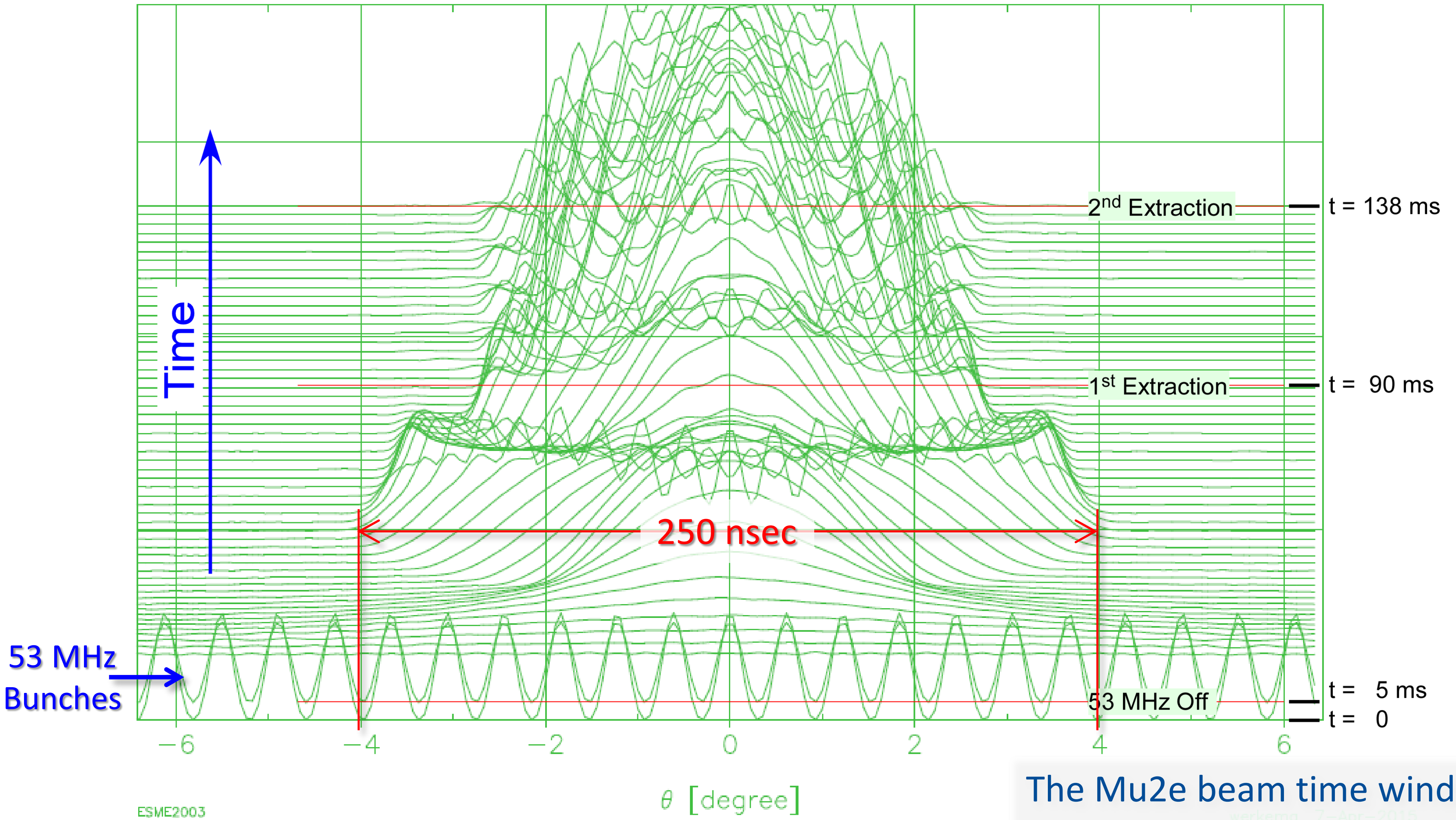
- Synchronous transfer from Booster to Recycler into 53 MHz RF buckets at t = 0
- 53 MHz RF voltage linearly ramped to zero in 5 msec
- When 53 MHz is off, the 2.5 MHz voltage is adiabatically ramped to 80 kV in 85 msec

➢ The purpose of the 2.5 MHz re-bunching is to produce narrow (FW < 250 nsec) bunches

➢ Note: Muon g-2 uses this system before Mu2e and requires FW < 150 nsec

Each 2.5 MHz bunch is synchronously transferred to the Delivery Ring into a stationary 2.4 MHz bucket

Recycler RF Model – Time Distribution Waterfall during 2.5 MHz Bunch Formation

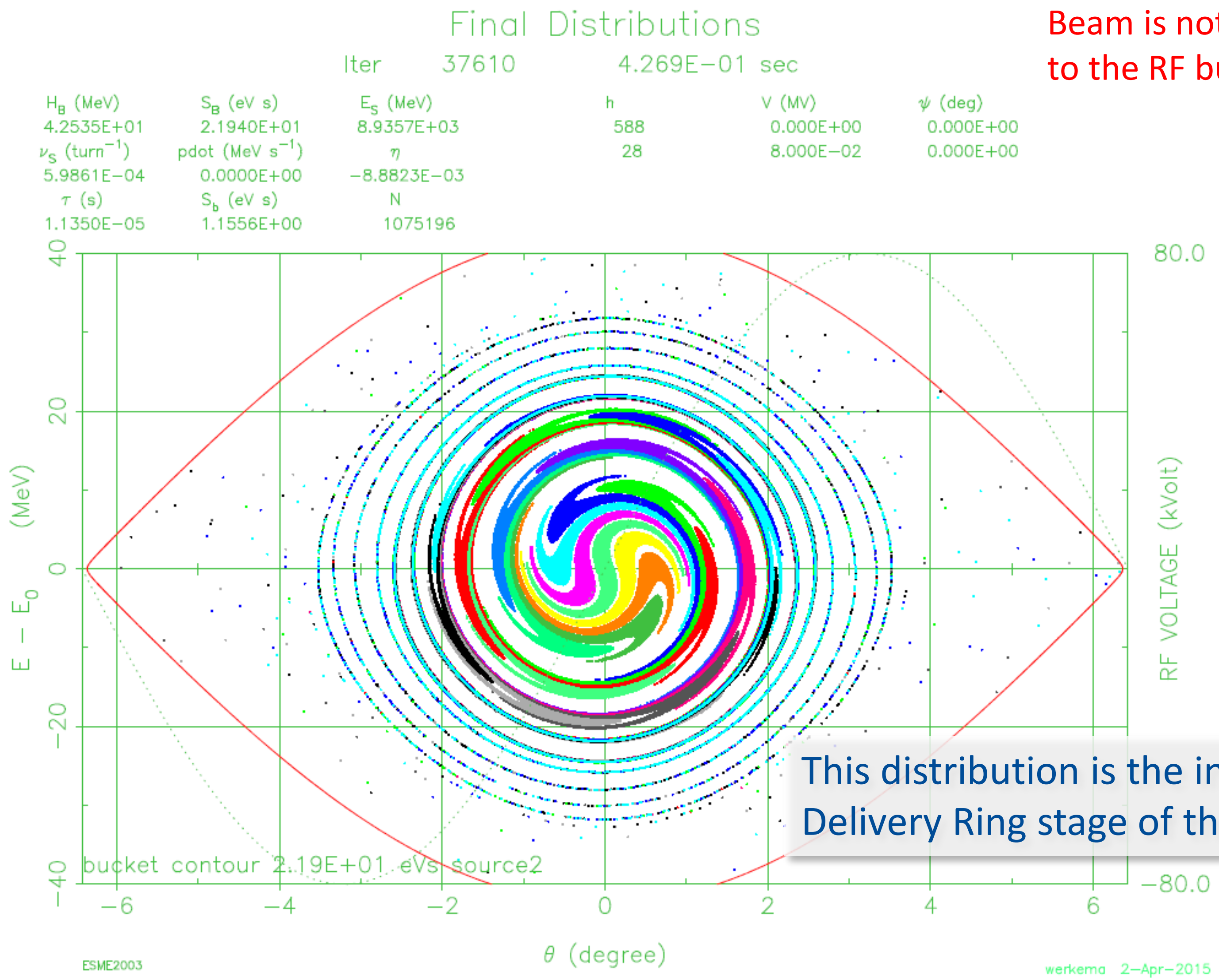


Recycler intensity vs. θ from injection to the time of extraction of the 2nd bunch.
Trace separation: 207 turns = 2.30 msec.
$\theta = 2\pi f_{rev}\Delta t$, 1° = 31 nsec

The Mu2e beam time window is defined to be the center of the RF bucket ±125 nsec

Recycler Longitudinal Phase Space at Extraction Time for Bunch 2

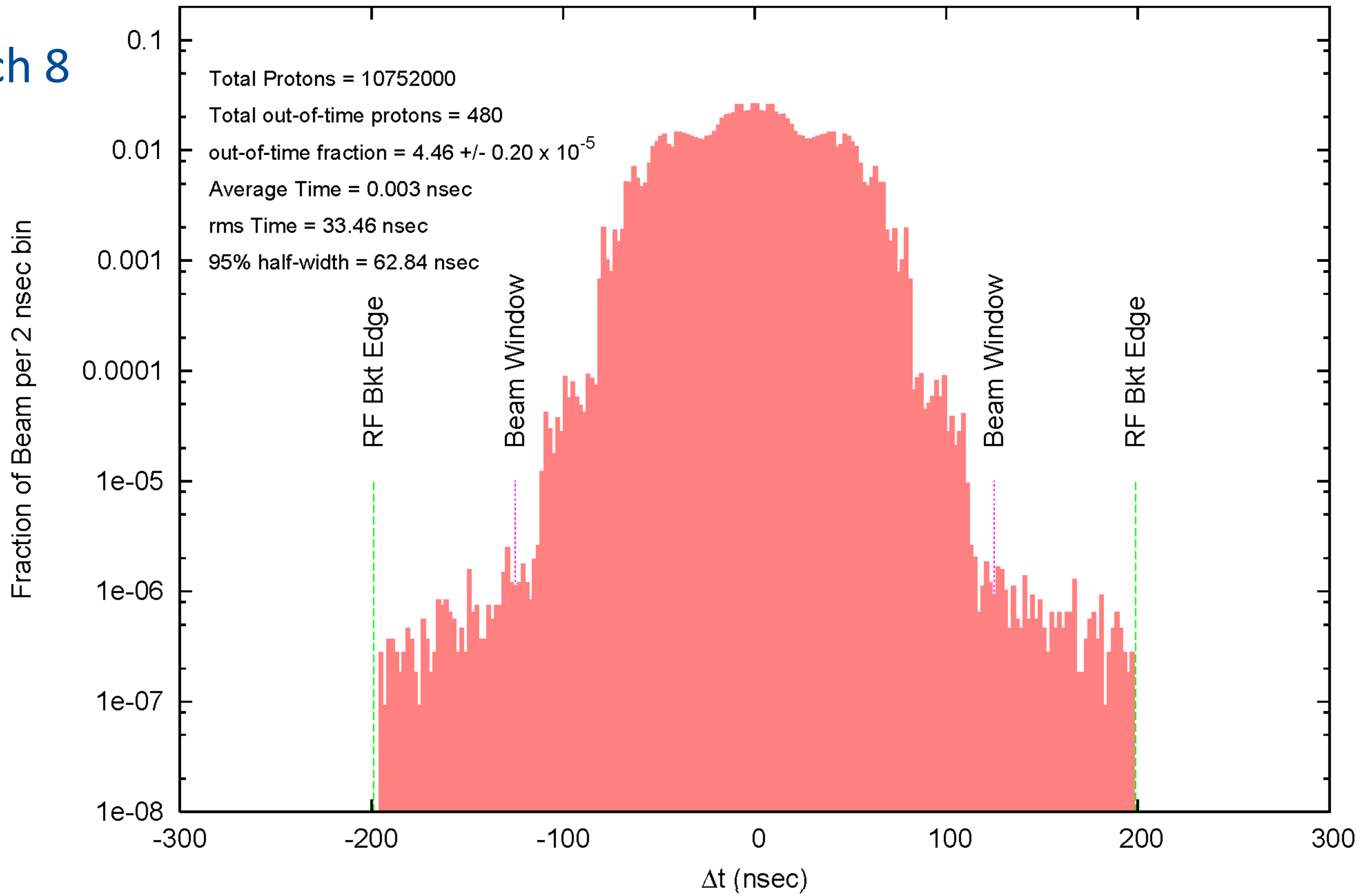
Beam is not matched to the RF bucket.



This distribution is the input to the Delivery Ring stage of the model

Recycler Proton Time Distributions at Extraction Time

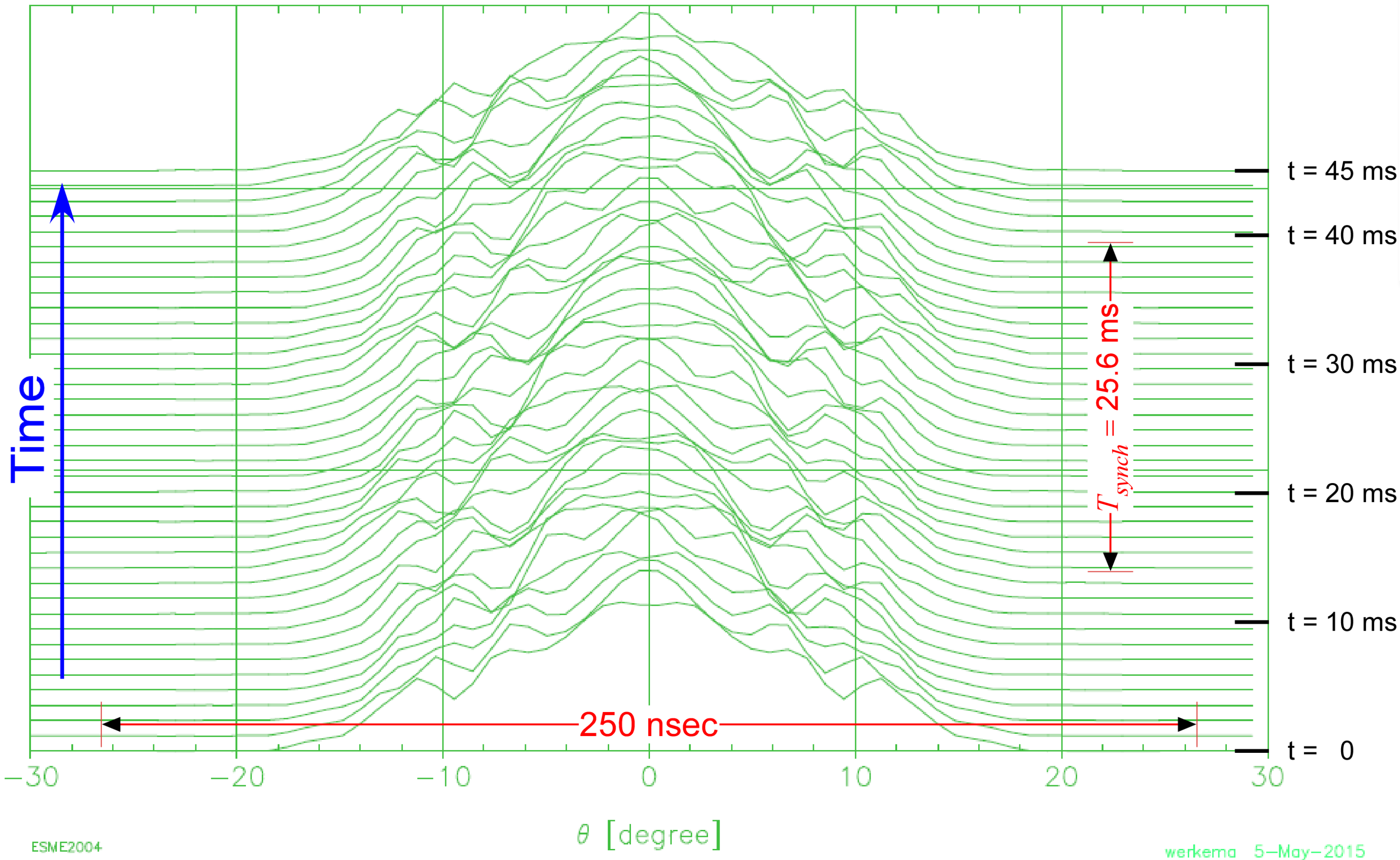
Bunch 8



Recycler to Delivery Ring Synchronous Transfers

- A bunch containing 1×10^{12} protons is transferred from the Recycler to the Delivery Ring every 48.1 msec
- The circumferences of the Delivery Ring and the Recycler are not harmonically related. $\frac{f_{DR}}{f_{RR}} = \frac{590.0\text{ kHz}}{89.8\text{ kHz}} = 6.57 \neq \text{integer}$
- Recycler 2.5 MHz RF operates at h = 28 (f_{RF} = 2.515 MHz)
- Delivery Ring RF system operates at h = 4 (f_{RF} = 2.360 MHz)
- Synchronous transfer is accomplished by a phase re-synchronization in the digitally synchronized Low Level RF system that ensures exact phase alignment at Delivery Ring injection time
- The Delivery Ring RF system maintains a 10 kV stationary bucket throughout the spill

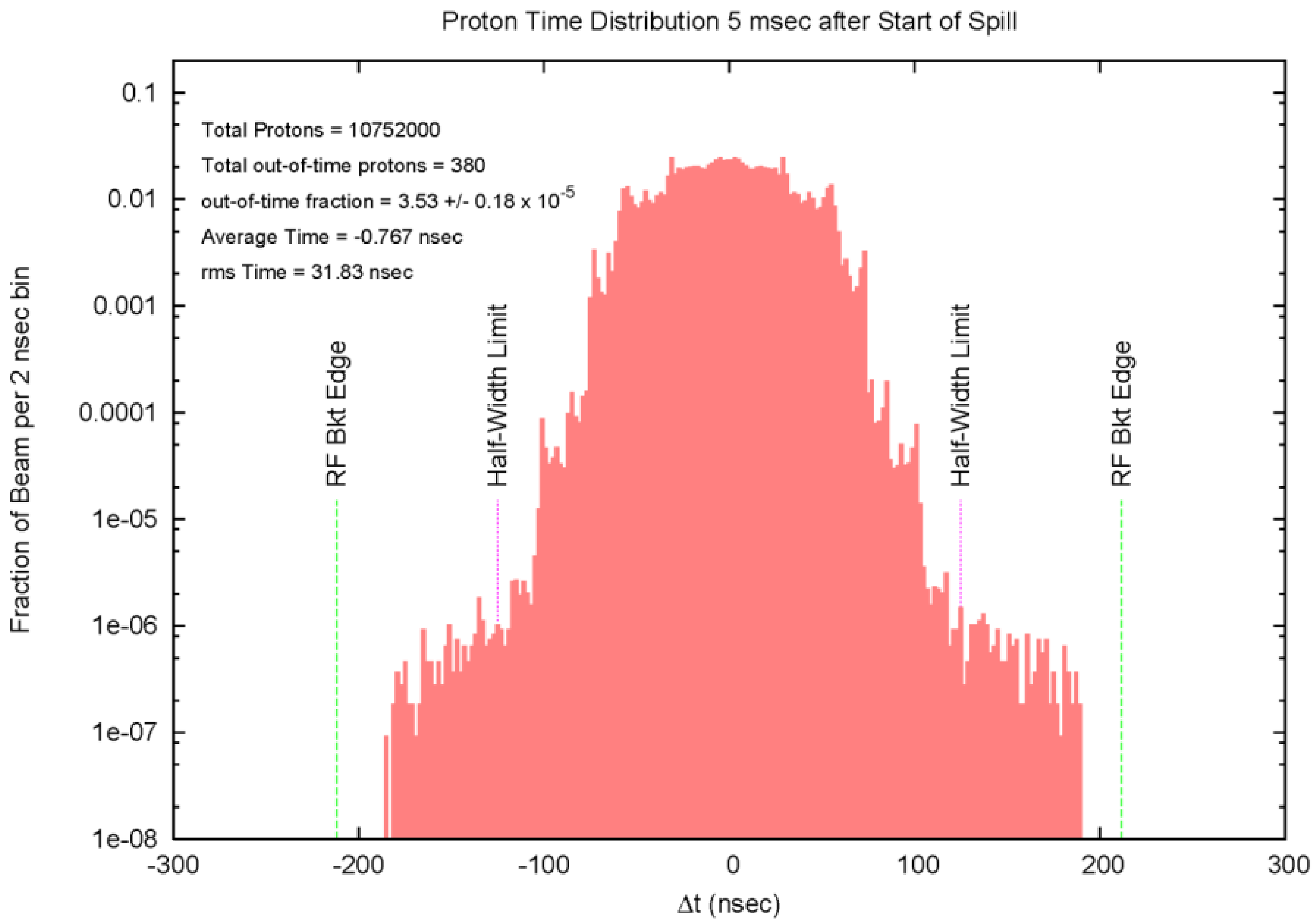
Delivery Ring RF



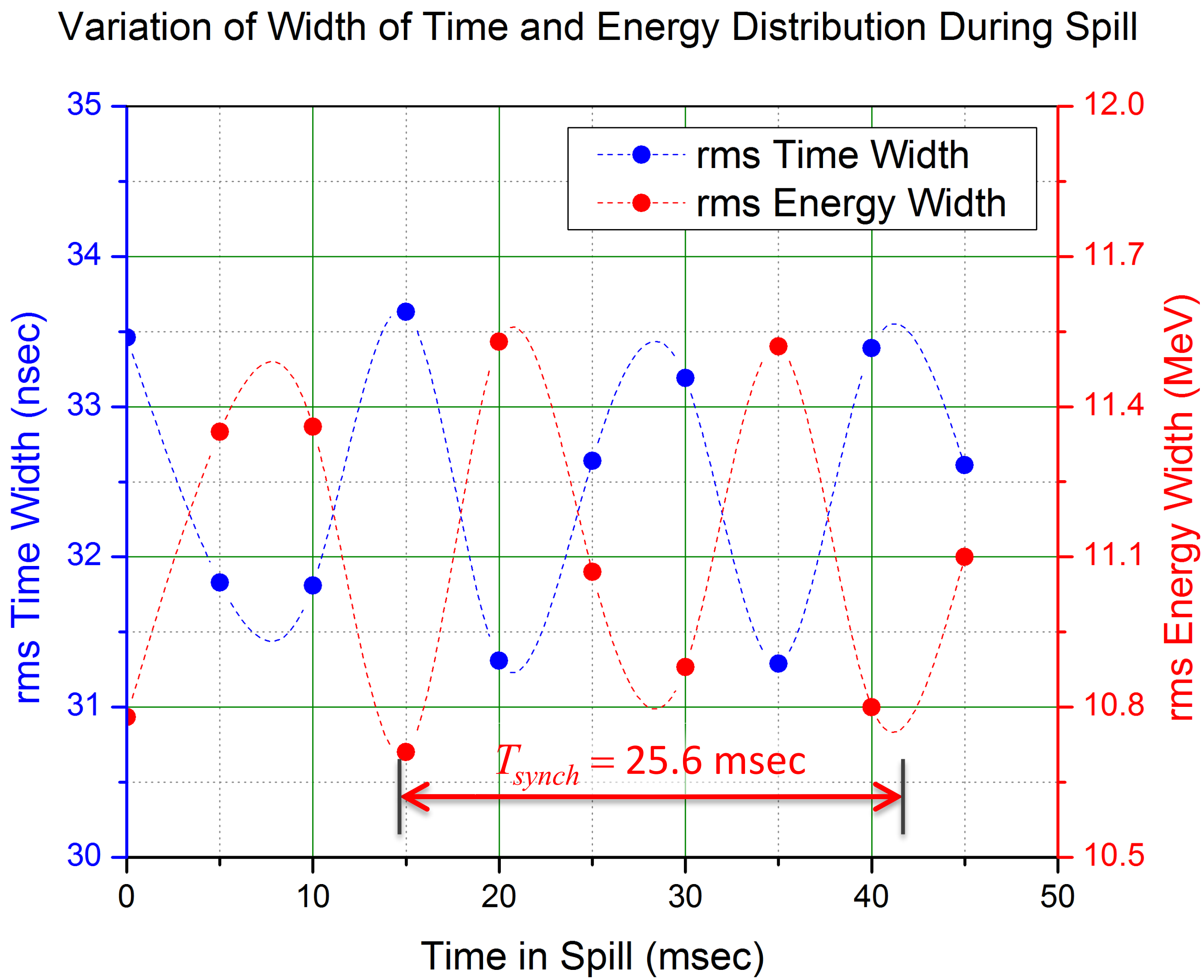
Delivery Ring RF maintains a stationary 10 kV bucket for the duration of the spill

Delivery Ring longitudinal distribution vs. θ for 45 msec of spill time.
Trace separation: 664 turns = 1.125 msec.
$\theta = 2\pi f_{rev}\Delta t$, 1° = 4.71 nsec

Delivery Ring Proton Time Distribution During Spill Animation



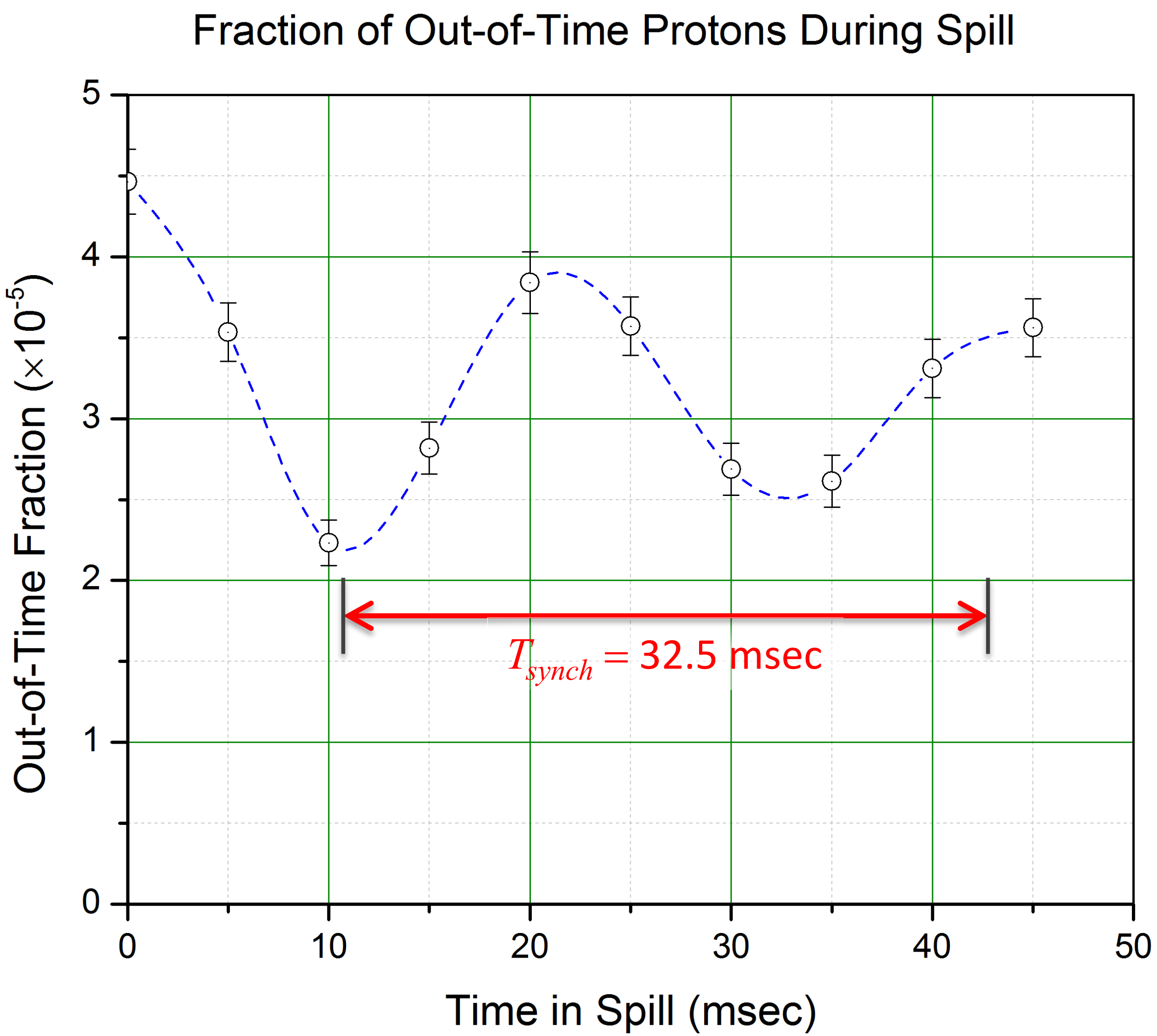
Variation of RMS Energy and Time Width



RMS widths oscillate at twice the synchrotron frequency as expected.

Note: the T_{synch} given here is the small amplitude synchrotron frequency.

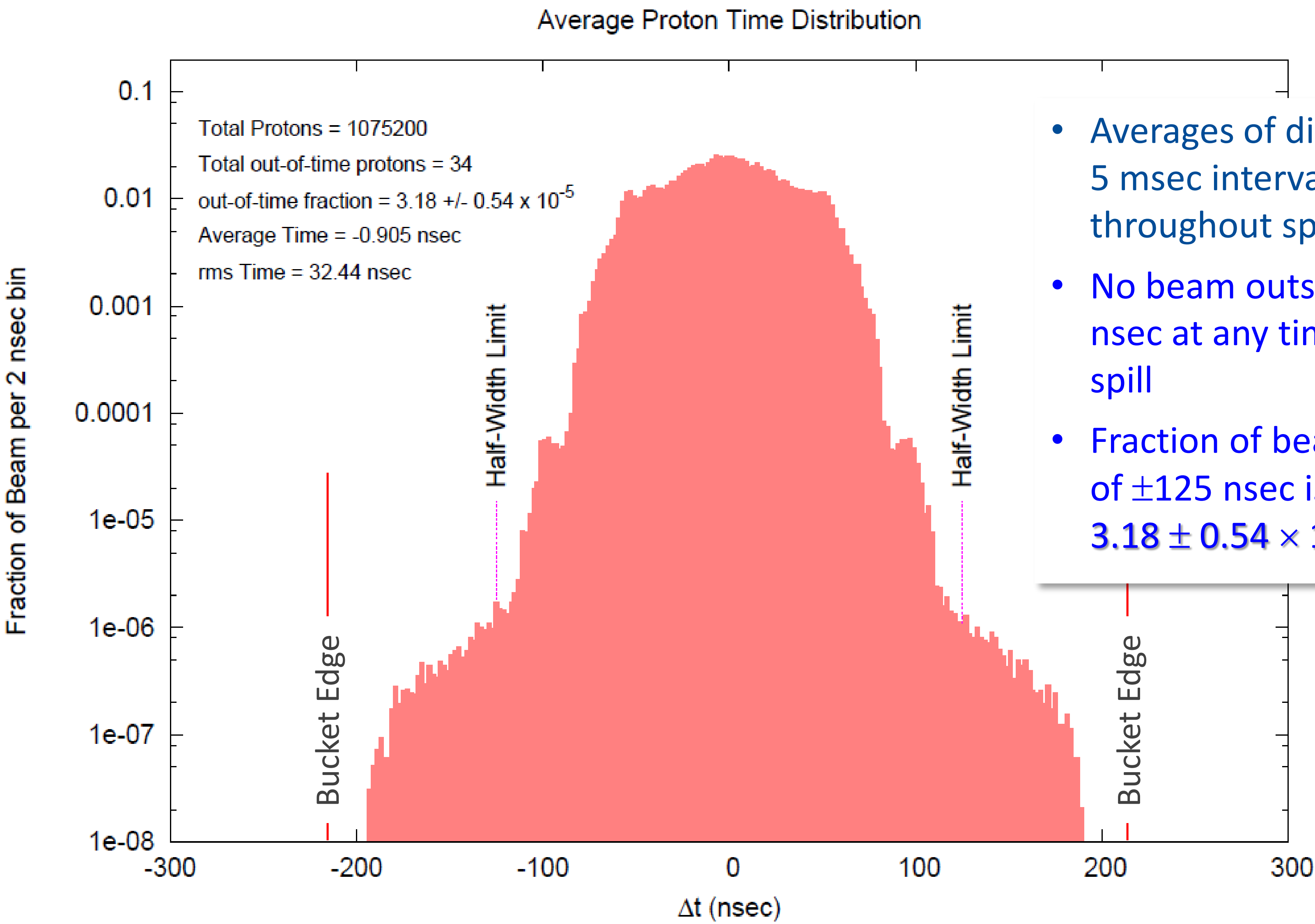
Variation of the Out-of-Time Fraction Over a 45 msec Spill



Not particularly well correlated with synchrotron period.

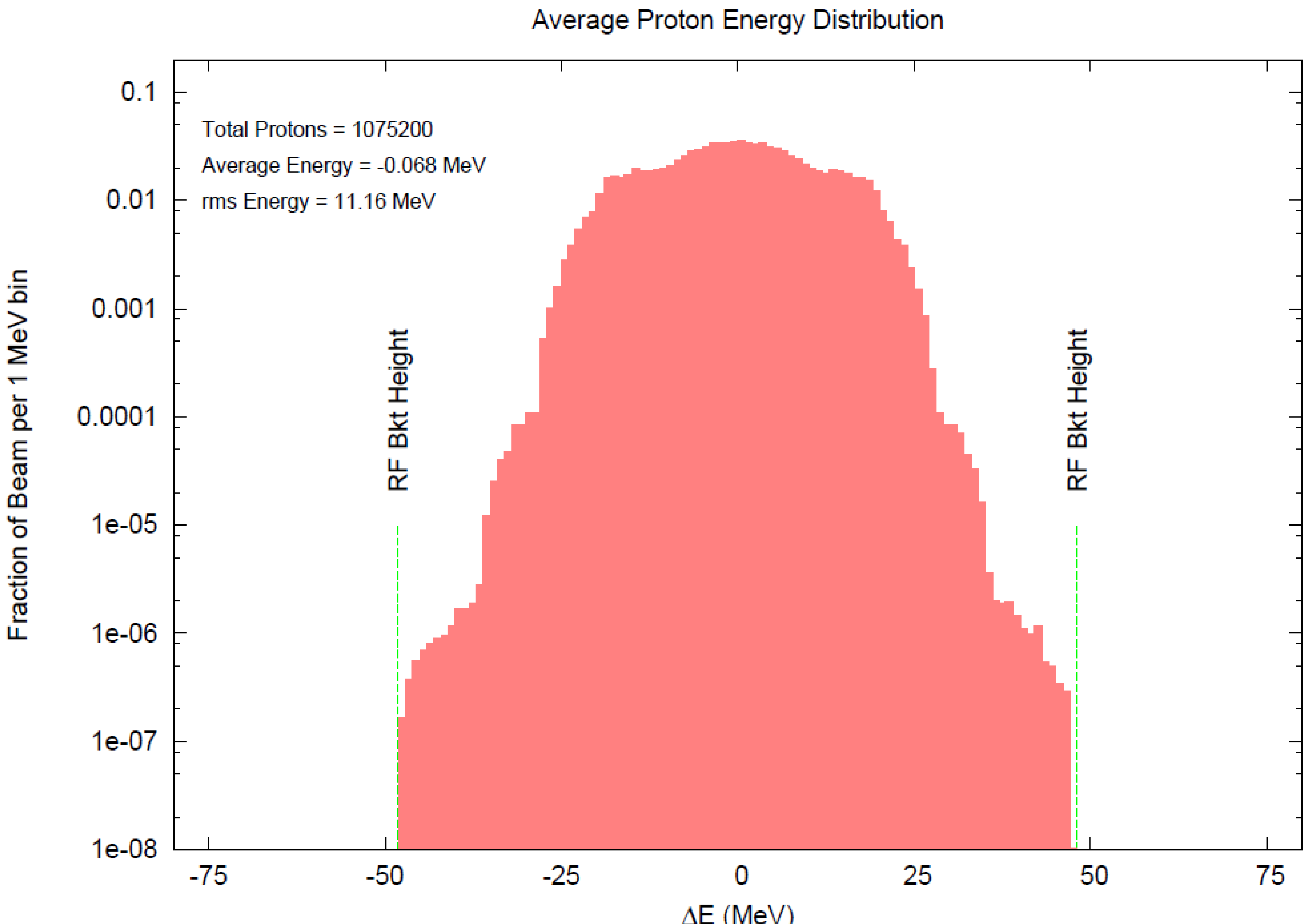
Note: the T_{synch} shown here is that of a proton 125 nsec from the center of the RF bucket. This is larger than the small amplitude synchrotron period.

The Average Beam Pulse at Extraction from the Delivery Ring – Time

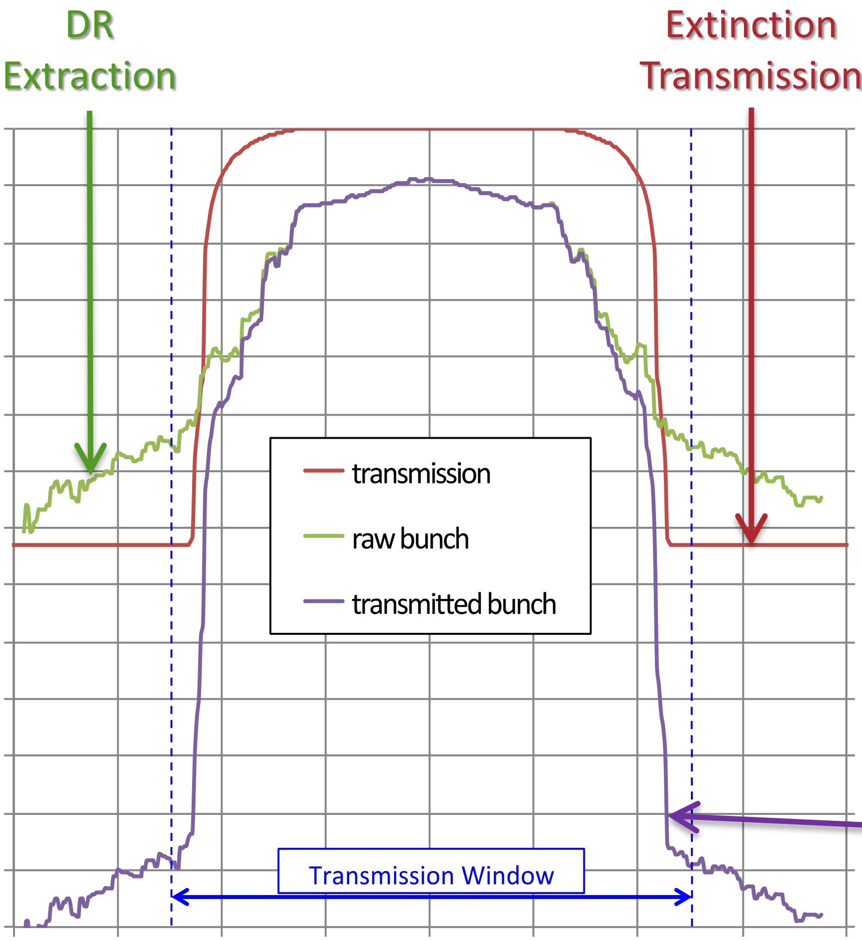


- Averages of distributions at 5 msec intervals throughout spill
- No beam outside of ±200 nsec at any time during spill
- Fraction of beam outside of ±125 nsec is: $3.18 \pm 0.54 \times 10^{-5}$

The Average Beam Pulse at Extraction from the Delivery Ring – Energy



Extinction Performance



Fraction of extracted beam outside of ±125 ns:	3.2×10^{-5}
In-time beam transmission:	99.5%
Beam line extinction:	$<5\times10^{-8}$
Total extinction:	$<1.6\times10^{-12}$
Extinction Requirement:	$<1.0\times10^{-10}$

Two order of magnitude margin

Beam on Target

Fermilab

5. Construction Progress

Pouring Mu2e building floor slab

- Looking east toward g-2 Building

Framing the walls in the proton target station area of the Mu2e building

Concrete floor complete

Framing and pouring the walls

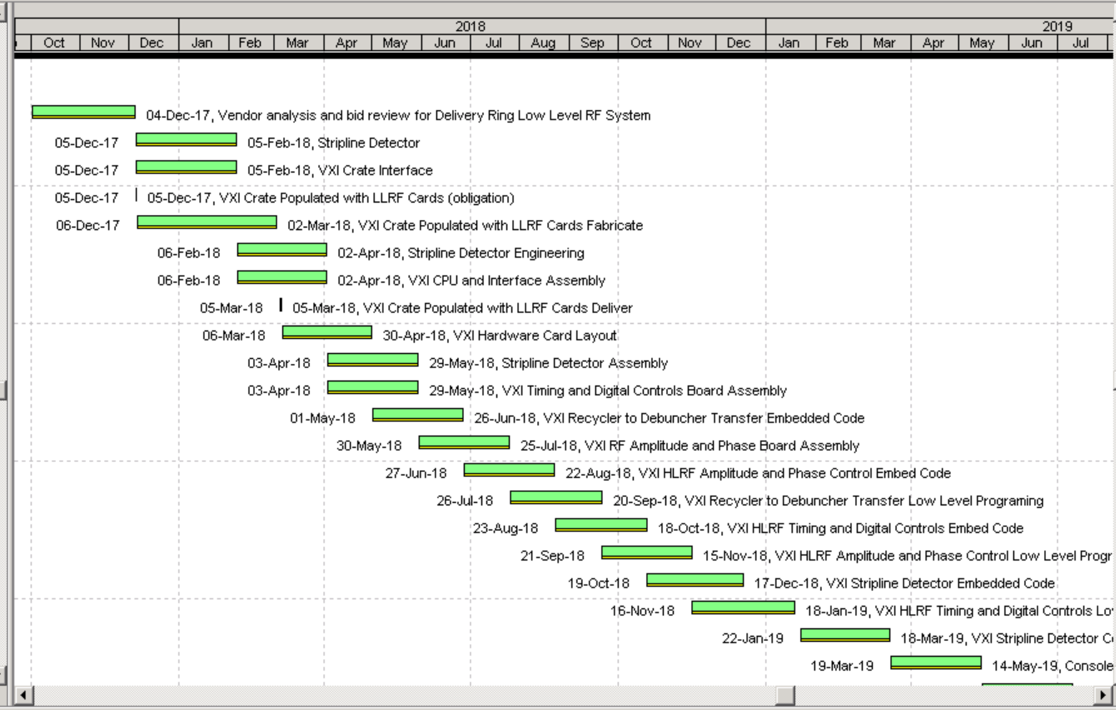
Target Proton Beam Absorber Air Manifold

Saturday, 17 October 2015

Why Start Building Construction before Design is Complete?

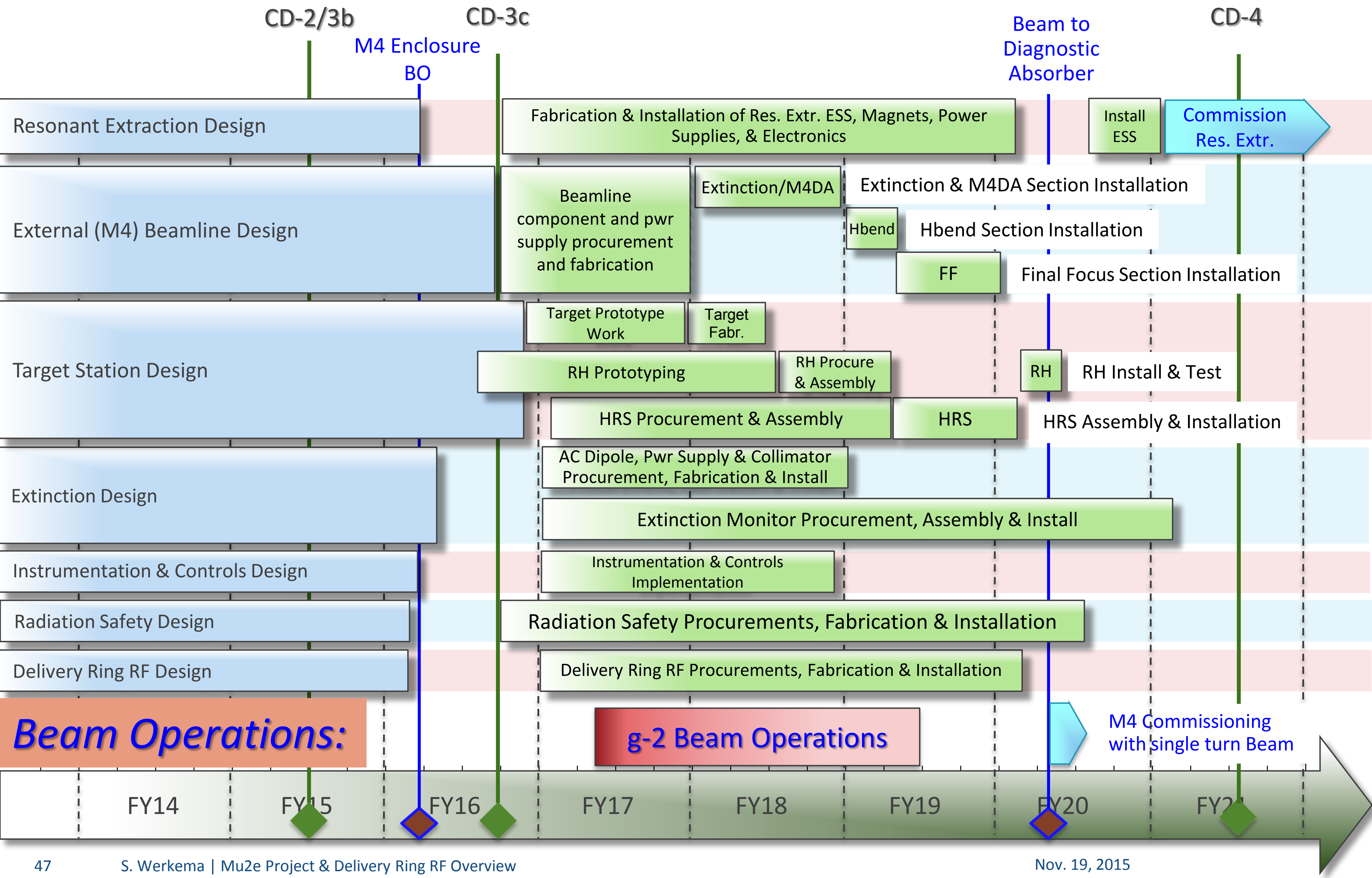
- Generally, this is a very bad thing to do
  - Removes the flexibility to accommodate unforeseen design issues that might be alleviated by building changes
  - Once an A&E firm is retained, building design changes are expensive. Once a construction contract is awarded changes become even more costly
  - The building becomes a design constraint as soon as concrete is poured
- The Muon Campus and Mu2e projects did this because:
  - Allows early start on projects necessary for g-2 – early g-2 running simplifies accelerator commissioning for Mu2e
  - Construction costs were relatively low and projected to trend up when this decision was made

Activity ID	Activity Name	Start	Finish
475.02S.06.01	Low Level RF System	03-Oct-16	05-Sep-19
47502.06.01.000500	T5 - Start Low Level RF System Procurements	03-Oct-16	
47502.06.01.001000	Vendor analysis and bid review for Delivery Ring Low Level RF Sys	02-Oct-17	04-Dec-17
47502.06.01.001160	Stripline Detector	05-Dec-17	05-Feb-18
47502.06.01.001080	VXI Crate Interface	05-Dec-17	05-Feb-18
47502.06.01.001020	VXI Crate Populated with LLRF Cards (obligation)	05-Dec-17	05-Dec-17
47502.06.01.001009	VXI Crate Populated with LLRF Cards Fabricate	06-Dec-17	02-Mar-18
47502.06.01.001170	Stripline Detector Engineering	06-Feb-18	02-Apr-18
47502.06.01.001090	VXI CPU and Interface Assembly	06-Feb-18	02-Apr-18
47502.06.01.001010	VXI Crate Populated with LLRF Cards Deliver	05-Mar-18	05-Mar-18
47502.06.01.001030	VXI Hardware Card Layout	06-Mar-18	30-Apr-18
47502.06.01.001180	Stripline Detector Assembly	03-Apr-18	29-May-18
47502.06.01.001100	VXI Timing and Digital Controls Board Assembly	03-Apr-18	29-May-18
47502.06.01.001040	VXI Recycler to Debuncher Transfer Embedded Code	01-May-18	26-Jun-18
47502.06.01.001110	VXI RF Amplitude and Phase Board Assembly	30-May-18	25-Jul-18
47502.06.01.001050	VXI HLRF Amplitude and Phase Control Embed Code	27-Jun-18	22-Aug-18
47502.06.01.001120	VXI Recycler to Debuncher Transfer Low Level Programing	26-Jul-18	20-Sep-18
47502.06.01.001060	VXI HLRF Timing and Digital Controls Embed Code	23-Aug-18	18-Oct-18
47502.06.01.001130	VXI HLRF Amplitude and Phase Control Low Level Programing	21-Sep-18	15-Nov-18
47502.06.01.001070	VXI Stripline Detector Embedded Code	19-Oct-18	17-Dec-18
47502.06.01.001140	VXI HLRF Timing and Digital Controls Low Level Programing	16-Nov-18	18-Jan-19
47502.06.01.001150	VXI Stripline Detector Code Low Level Programming	22-Jan-19	18-Mar-19
47502.06.01.001190	Console Application Programming	19-Mar-19	14-May-19



6. Schedule

Mu2e Accelerator Schedule



Significant Milestones

Milestone	Date
Diagnostic Absorber Installation Complete	March 2015
M4 Beamline Enclosure Beneficial Occupancy	Nov 2015
DOE CD-3c Approval	July 2016
2.5 MHz RF Cavity Installed in Delivery Ring	Sep 2016
Start of Muon g-2 Run	May 2017
Delivery Ring RF System Complete	Dec 2019
Ready to run beam to diagnostic absorber	June 2020
DOE CD-4 Approval	May 2021

Muon Campus Program Cost

Project	Total Project Cost ($M)	Accelerator Costs ($M)
Muon g-2 Project	46.4	22.2
Mu2e Project	271.0	50.2
Recycler RF AIP	9.7	9.7
Beam Transport AIP	6.2	6.2
Delivery Ring AIP	9.3	9.3
Cryo AIP	9.7	9.7
MC-1 Building GPP	9.0	
Beam Enclosure GPP	9.7	
MC Infrastructure GPP	1.0	1.0
Total	372.0	108.3

Delivery Ring RF total cost: ~$2.2M

- ~4% of Mu2e Accelerator

All costs are base cost + estimate uncertainty (contingency)
(These costs compiled November 2014)

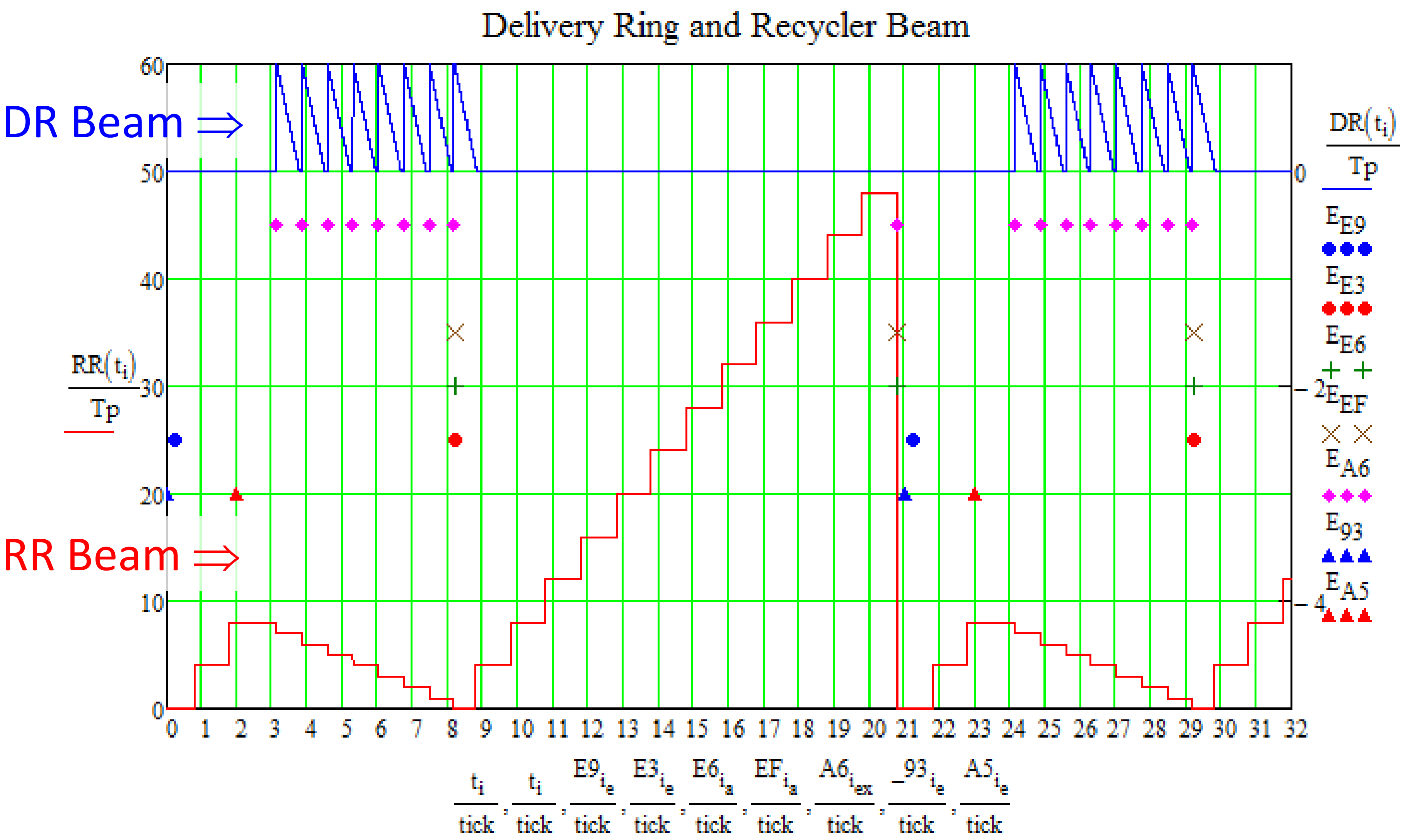
6. Conclusions

Conclusion

- Thank you for your helping us by participating in this review
- The Mu2e project is in the final stages of completing its final design
  - We expect to begin our CD-3c reviews in ~March of next year
- We would very much appreciate your advice on how we should best focus our attention in preparation for these reviews

Backup Slides

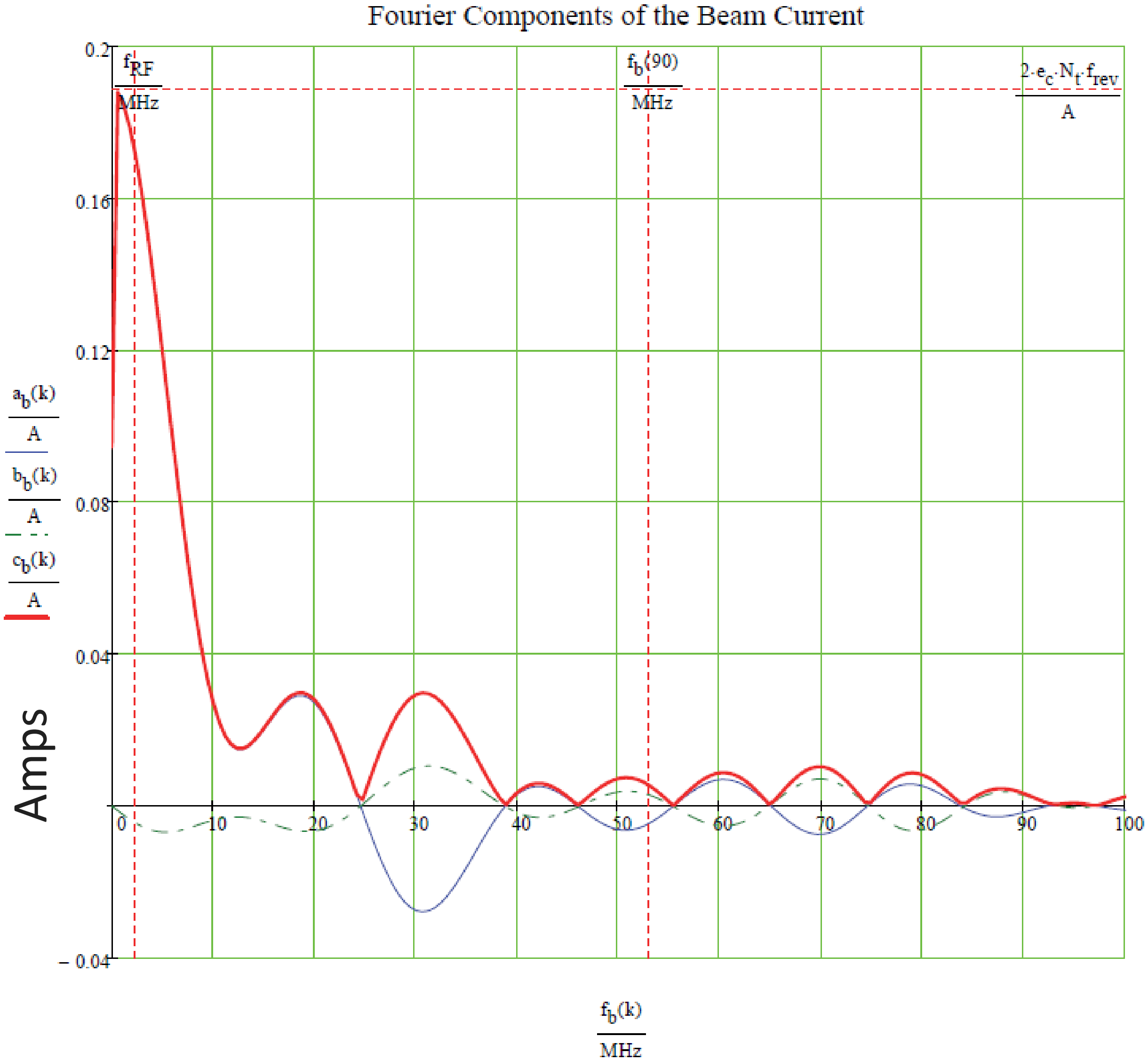
Mu2e / NOvA Accelerator Timeline Model



Fourier Components of Delivery Ring Beam at Injection

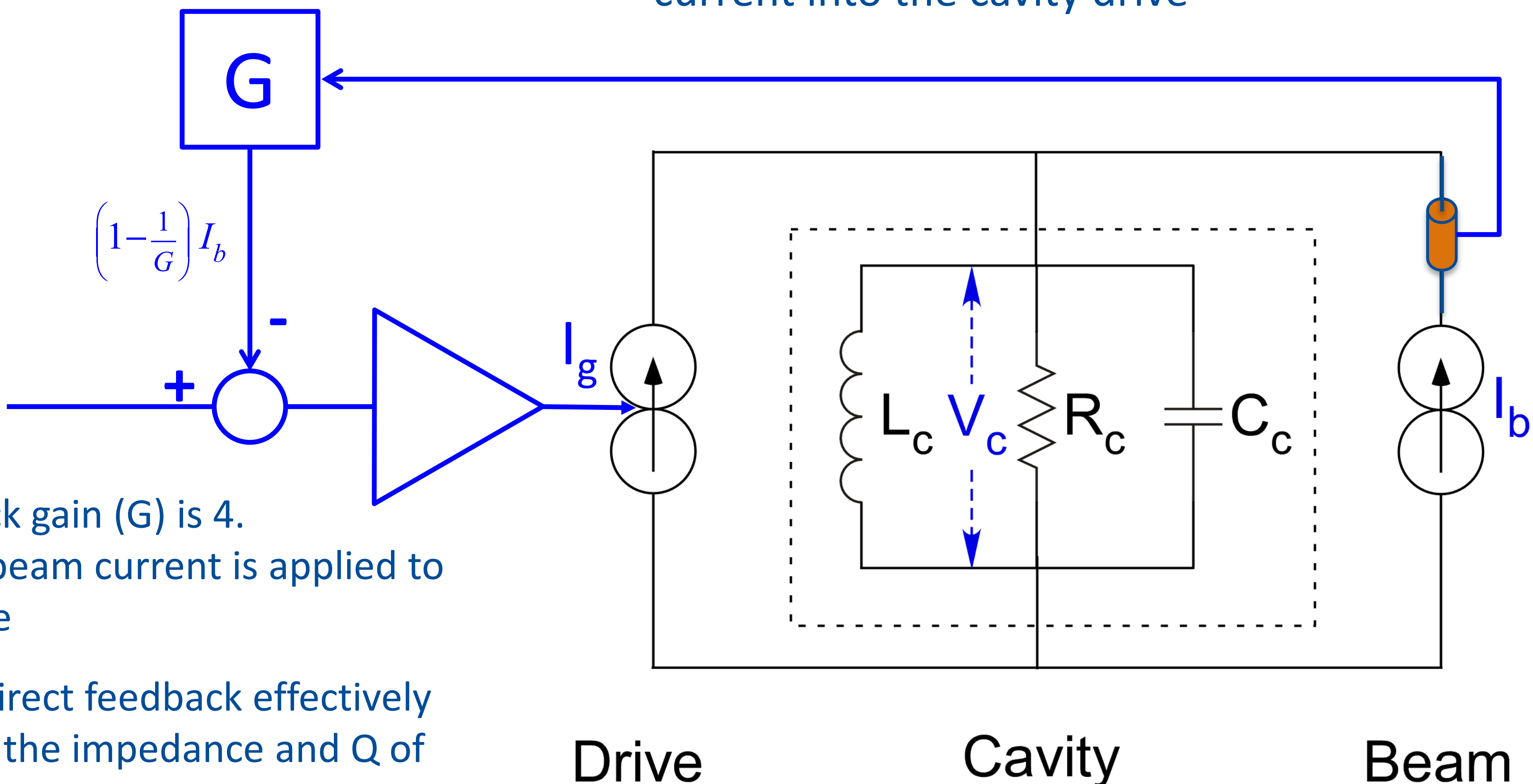
1×10^{12} protons
Single Bunch
ESME Simulation

$a_b(k)$ = cosine amplitudes
$b_b(k)$ = sine amplitudes
$c_b(k)$ = overall magnitude



Beam Loading Compensation

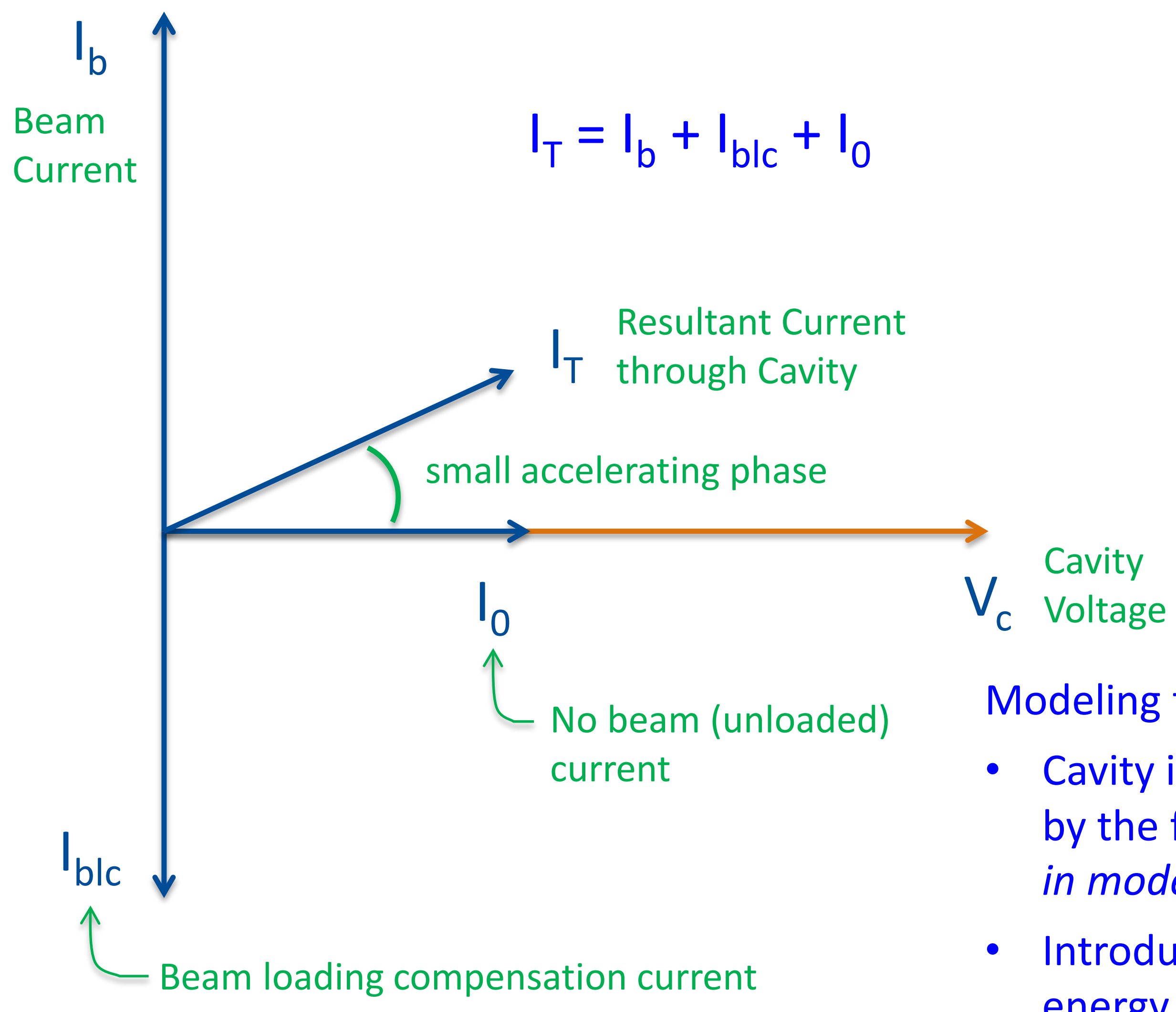
Detect and feed back the beam current into the cavity drive



Feedback gain (G) is 4.
75% of beam current is applied to the drive

NOTE: direct feedback effectively reduces the impedance and Q of the cavity by a factor of G.

Application of Beam Loading Compensation



Result is:

- The required voltage (10 kV) is applied to the cavity
- There is a small accelerating phase (which is compensated in the actual RF system by phase feedback)

Modeling this is done by the following:

- Cavity impedance and Q is reduced by the feedback gain (4×) – (*already in model*)
- Introduce a phase ramp to keep the energy constant

Delivery Ring Synchrotron Period as a Function of Δt