Beam Delivery and Out of Time Extinction in the Mu2e Experiment at Fermilab

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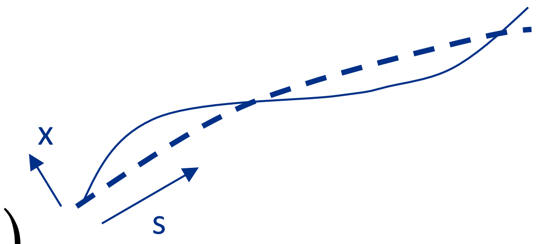
Review: All the Accelerator Physics U Need 2 Know

- We can describe (strongly focused) particle motion in terms of initial conditions and a "beta function" $\beta(s)$, which is only a function of location along the nominal path, and follows the periodicity of the machine.



Lateral deviation in one plane

$\beta(s)$

$$x(s) = A\sqrt{\beta(s)}\cos\left(\psi(s)+\delta\right)$$

Phase advance

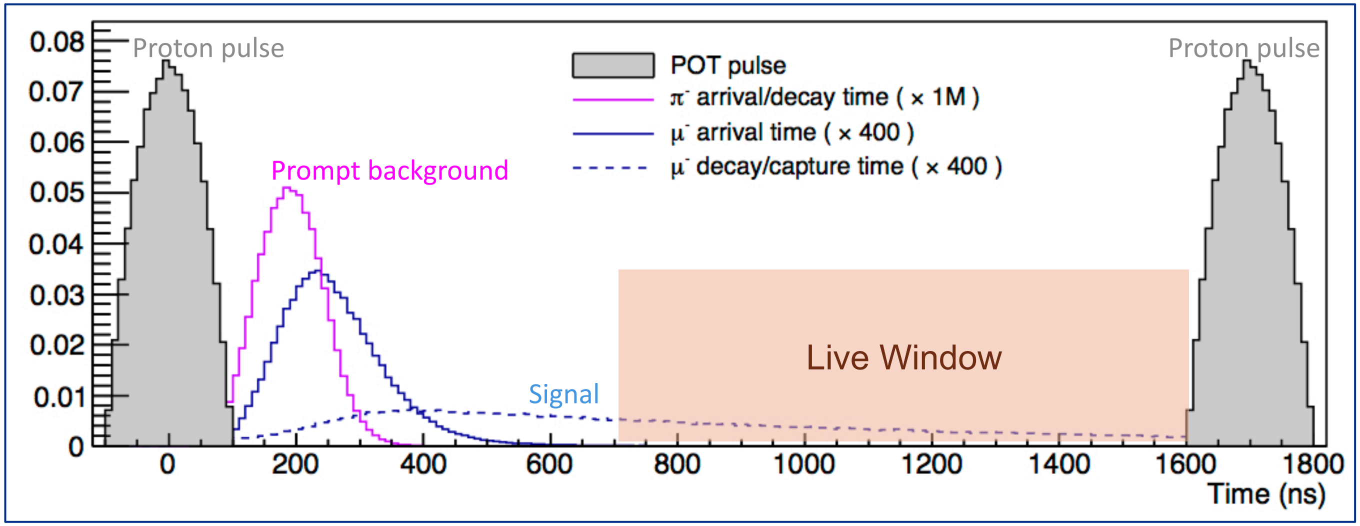
$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

The "betatron function" $\beta(s)$ is effectively the local wavenumber and also defines the beam envelope.

- In other words, particles undergo "pseudo-harmonic" motion about the nominal trajectory, with a variable wavelength and amplitude.
- Note: β has units of [length], so the amplitude has units of $[\text{length}]^{1/2}$

Experimental Technique and Beam Needs

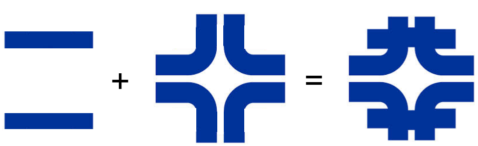
- The general technique is to use protons to make pions, which quickly decay to muons, which are captured on an Aluminum target.
- Previous experiments were rate-limited by the need to gate off after *individual* protons to eliminate prompt backgrounds, which predominantly come from radiative pion capture.
- Mu2e will get around this by using a *bunched* beam of protons, and then waiting for the pions to decay before opening the live window.



- This will allow the experiment to achieve a single event sensitivity that is a *four order of magnitude* improvement of the previous best measurement.

A Brief History of Fermilab

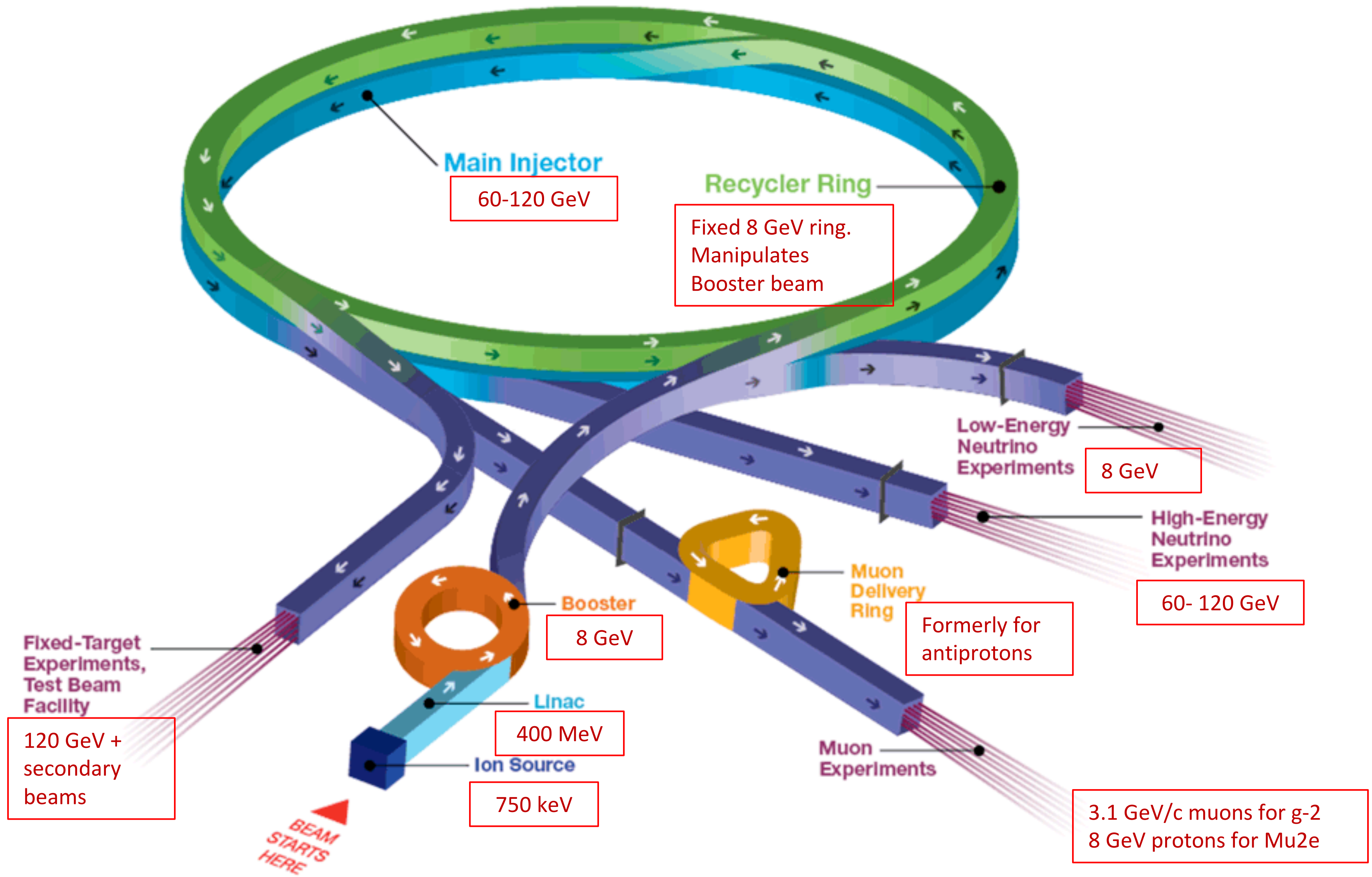
Trivia: original Main Ring was the first "separated function" synchrotron



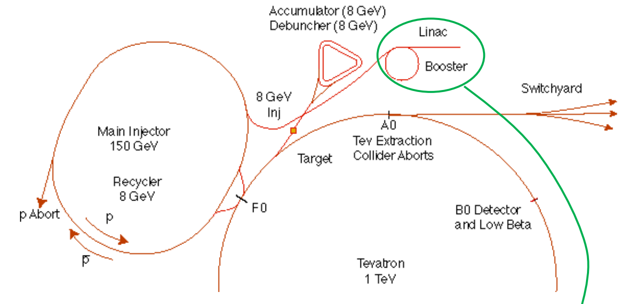
dipole quadrupole Fermilab

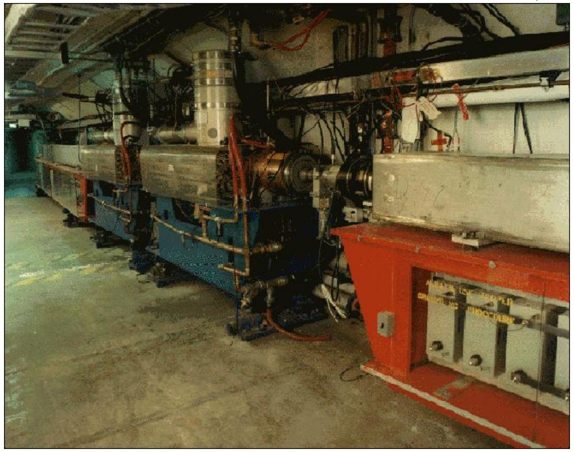
- 1968: construction begins
- 1972: first beams from Main Ring
  - 200→400 GeV proton beams to fixed targets
  - Highest energy lab for next 36 years!
- ~1985:
  - "Tevatron": first superconducting synchrotron shares tunnel with Main Ring
  - 900GeV x 900 GeV p-pBar collisions
  - Highest energy collider for 23 years.
- 1997: Major upgrade
  - Main Injector replaces Main Ring -> more intensity
  - 980 GeV x 980 GeV p-pBar collisions
  - Intense neutrino program
- 2011: Tevatron permanently turned off after the LHC came full online.
- So what is the lab doing now?

Fermilab Complex Today



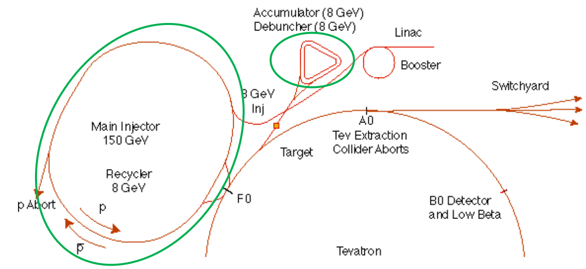
The Challenge of Producing the Mu2e Beam



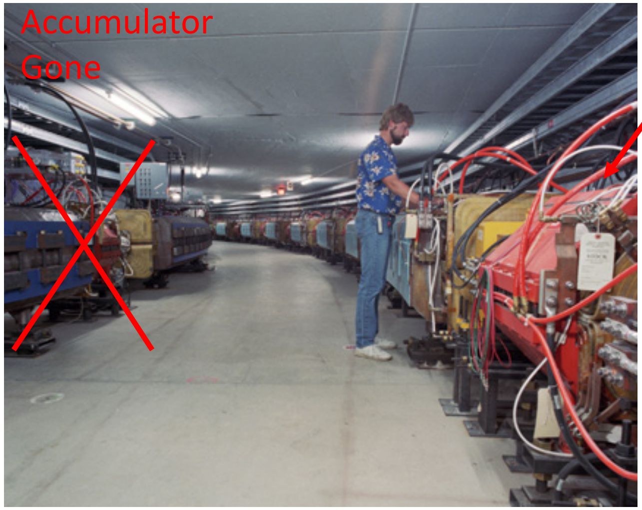


- All protons at Fermilab come from the Linac/Booster system.
  - Only ”original” accelerators at the lab
    - First half of linac
    - Most of Booster
  - The Booster magnets operate in a 15 Hz offset resonant circuit, which
  - Sets a fundamental clock for all all accelerator sequencing
    - 1/15 second = 1 “tick”
  - Sets a fundamental “batch” of protons
    - 1.6 μsec long
    - Up to 5×10^{12} protons
- Because the Booster magnets have no flat top, it cannot produce the beam structure required by the Mu2e Experiment.
  - This is why the experiment (then called MECO) was originally proposed for Brookhaven
- Luckily for us, when the Tevatron shut down in 2011, it freed up some equipment, specifically…

Reduce, Reuse, Recycle...

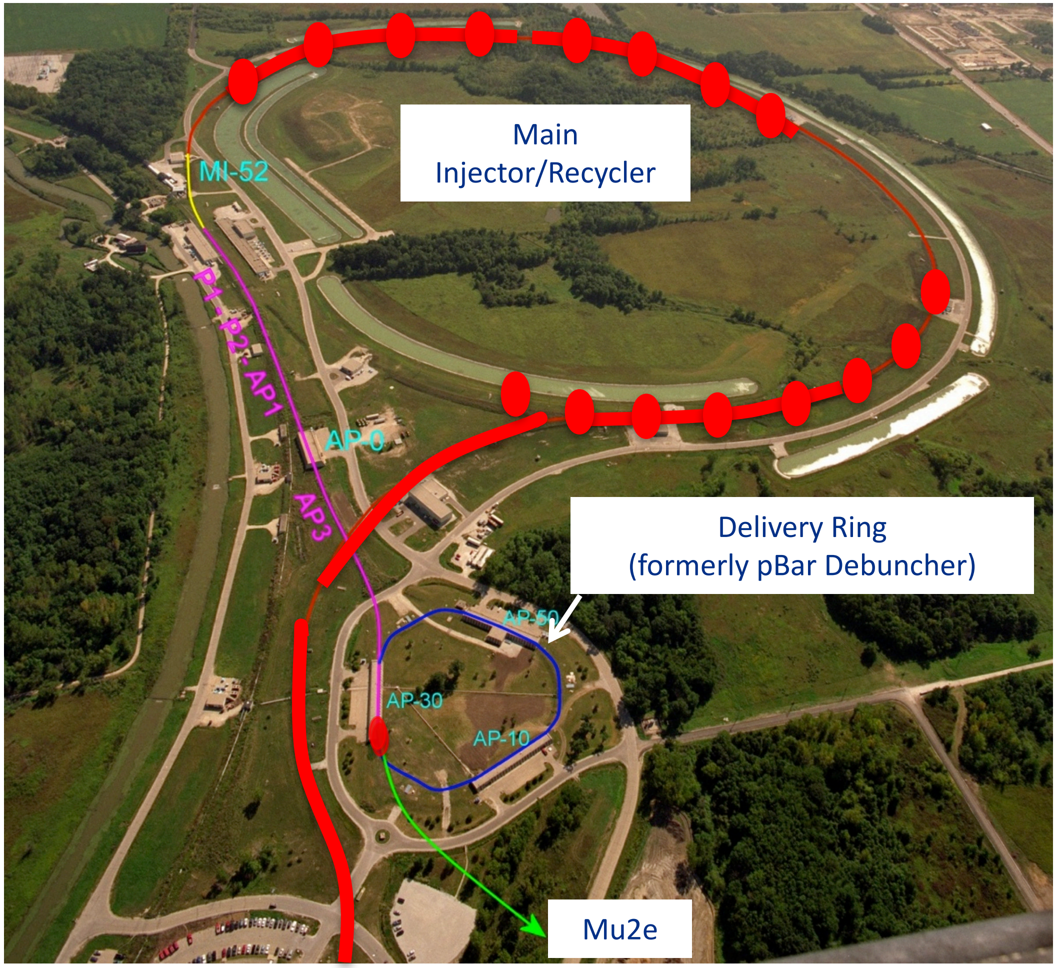


- The Recycler
  - 8 GeV storage ring made of permanent magnets
  - Originally used to store antiprotons for the Tevatron
  - Now used for
    - pre-stacking protons for NuMI beam
    - Bunching each 1.6 μsec booster batches into 4 2.5 MHz bunches with ~1x10^{12} protons each for g-2 and Mu2e



- The Debuncher Ring
  - Together with the Accumulator, it was originally used to collect and store Antiprotons for the Tevatron
  - Now:
    - Used to temporally separate 3.1 GeV/c muons and protons for the g-2 Experiment
  - Future:
    - Used to circulate and slow extract beam for Mu2e

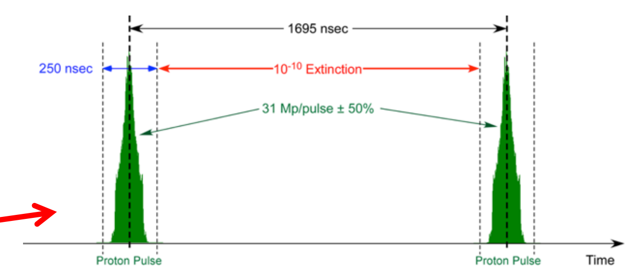
Mu2e Proton Delivery



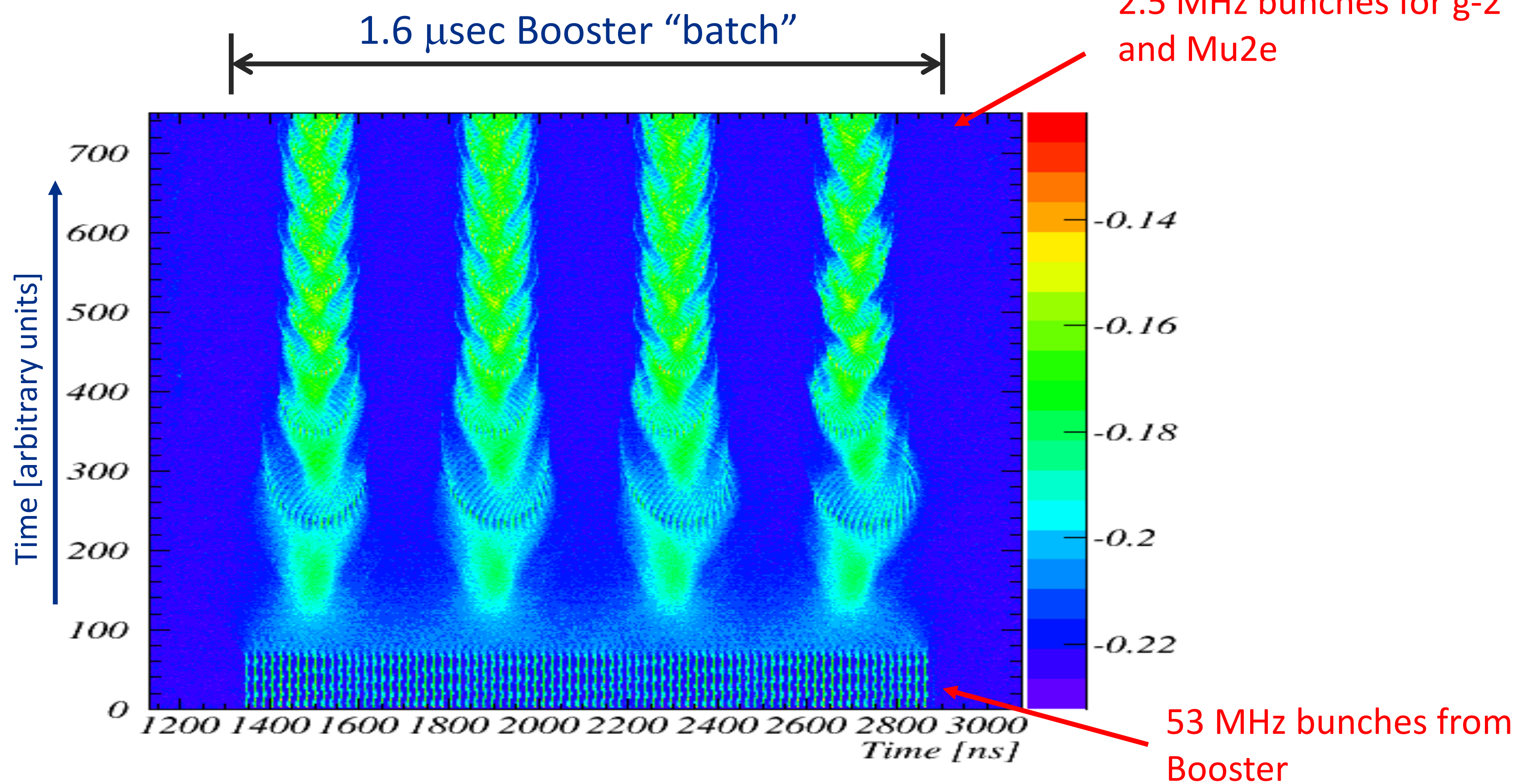
Booster

- Two Booster "batches" are injected into the Recycler (8 GeV storage ring). Each is:
  - 4×10^{12} protons
  - 1.7 μsec long
- These are divided into 8 bunches of 10^{12} each
- The bunches are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As the bunch circulates, it is resonantly extracted to produce the desired beam structure.
  - Bunches of ~3×10^7 protons each
  - Separated by 1.7 μsec

Exactly what we need →

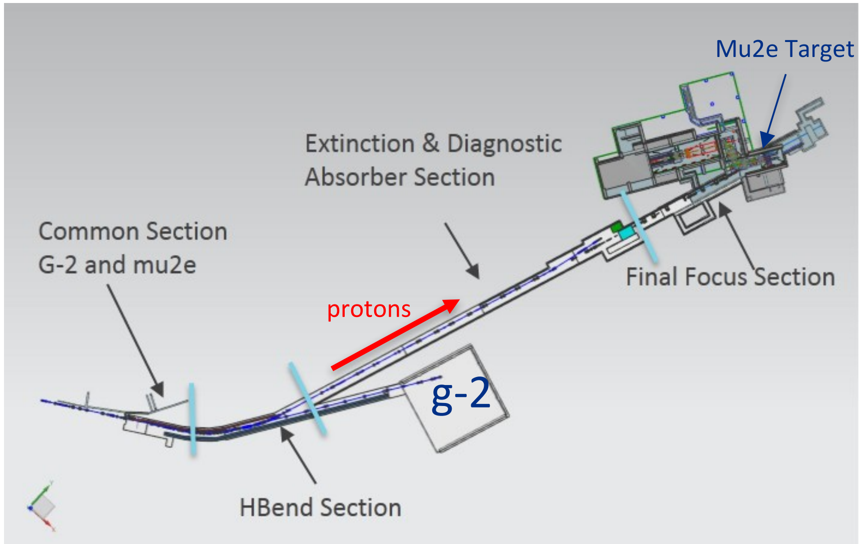


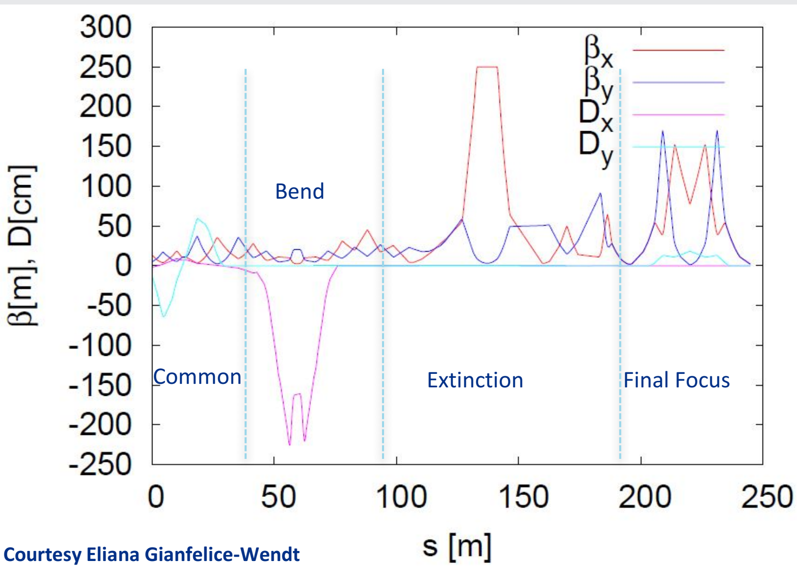
Rebunching in the Recycler*



*Data, presented by I. Kourbanis

M4 Beamline Design Overview*





Courtesy Eliana Gianfelice-Wendt

Common Section:

- g-2 operation
  - Transport 3.1 GeV/c muons from DR to g-2 ring
- Mu2e operation
  - Transport 8 GeV protons to Mu2e

Horizontal Bend Section:

- Left bend section uses 4 SDFW and 2 SDF dipoles to bend beam 41° to the mu2e target.

Extinction Section:

- Out-of-time to in-time particle ratio < 10^{-10}
- At AC dipole location:
  - Large β_x to maximize the kickers effect .
  - Small β_y allow small kicker vertical gap.
- At collimator: 90° of phase between up & down stream collimator & kicker. Small β_x at downstream collimator.

more about this shortly

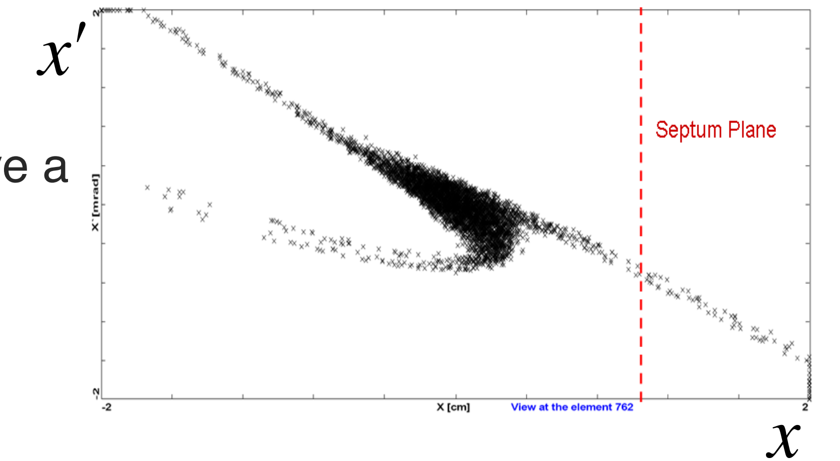
Final Focus Section:

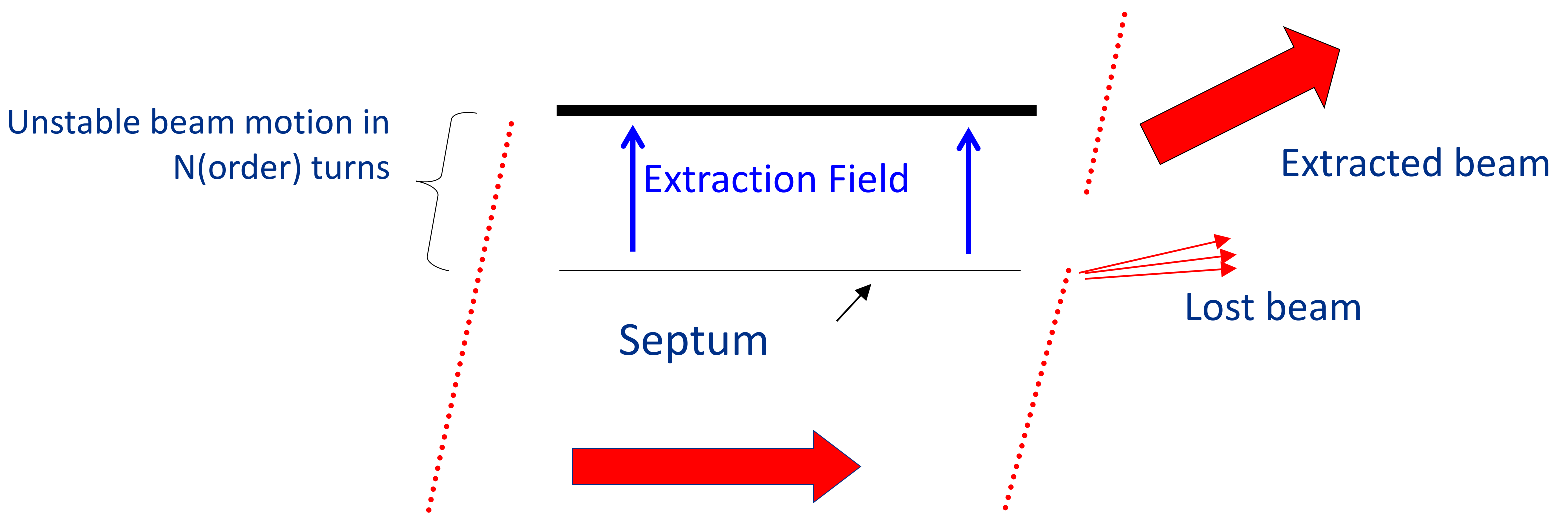
- Brings beam to required spot size at target. (2x2 mm^2)
- 2 Vertical dipoles bend the beam down to the target (2x1.375°)
- FF magnets are installed on a 1.375° vertical slope.

*D. Still

Understanding Resonant Extraction

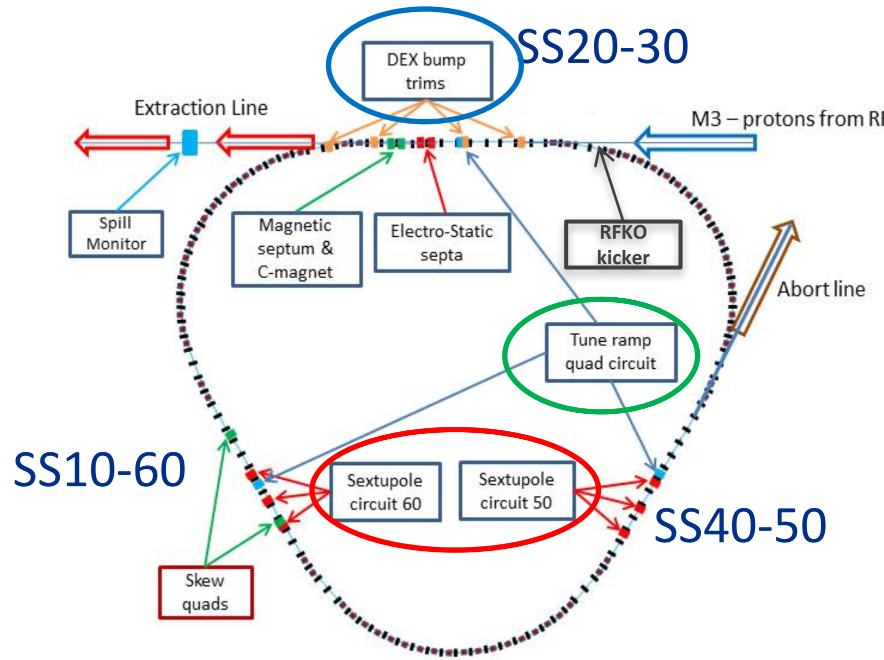
- Extracting all the beam at once is easy, but we want to extract it slowly over ~35 ms (~35,000 revolutions)
- Use nonlinear (sextupole) magnets to drive a harmonic instability
- Extract unstable beam as it propagates outward
  - Standard technique in accelerator physics

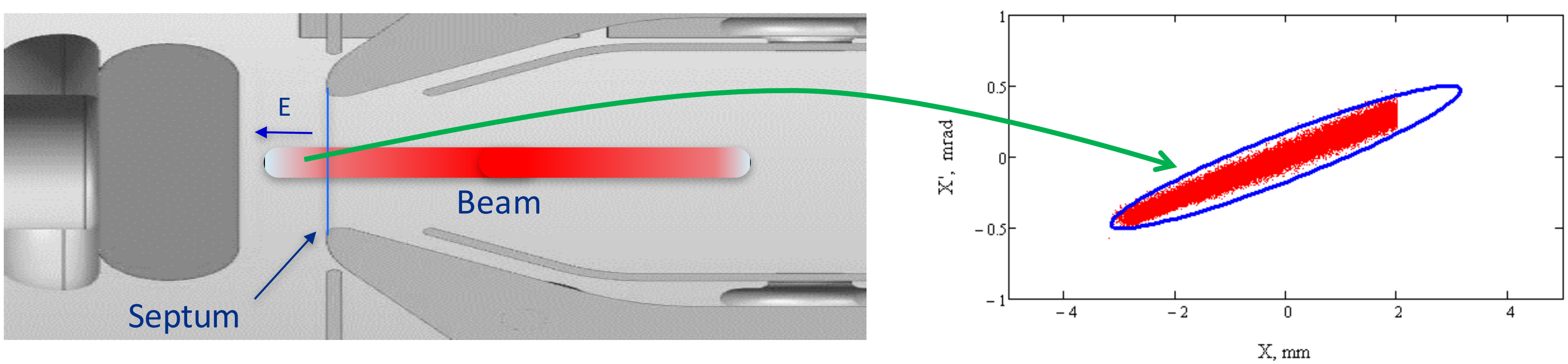




Resonant Extraction in Mu2e*

- Two families of sextupoles control the amplitude and phase of the resonance driving terms.
- Ramped quads control the distance of the tune from the $Q_x=29/3$ resonance.
- Trim dipoles control the position of the beam relative to the electrostatic septum.

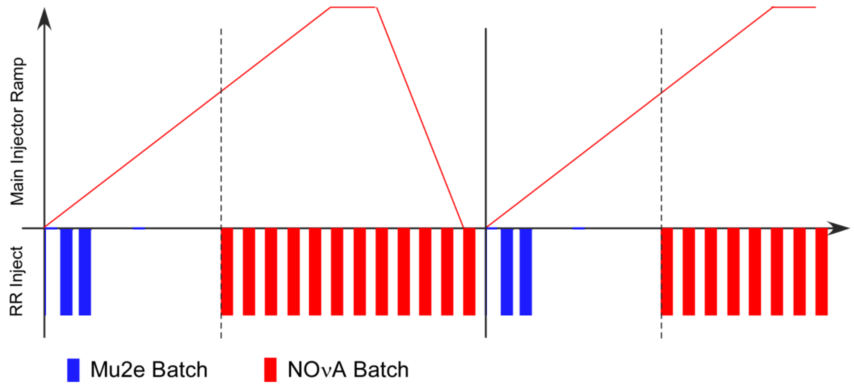




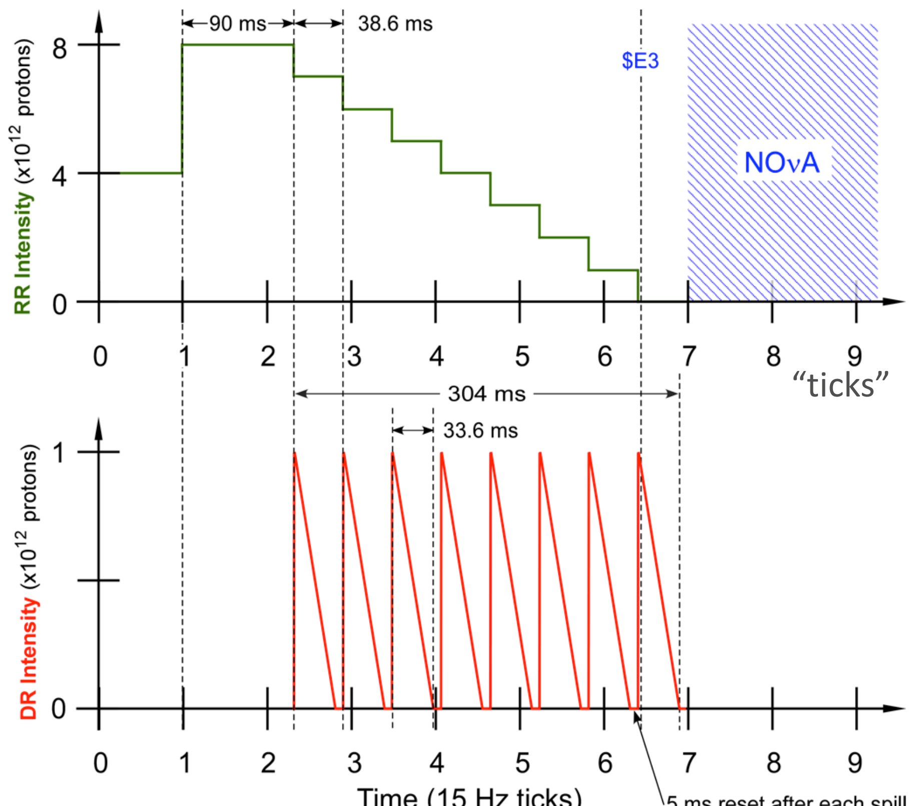
*V. Nagaslaev

Mu2e Spill Structure

1.33 sec Main Injector cycle

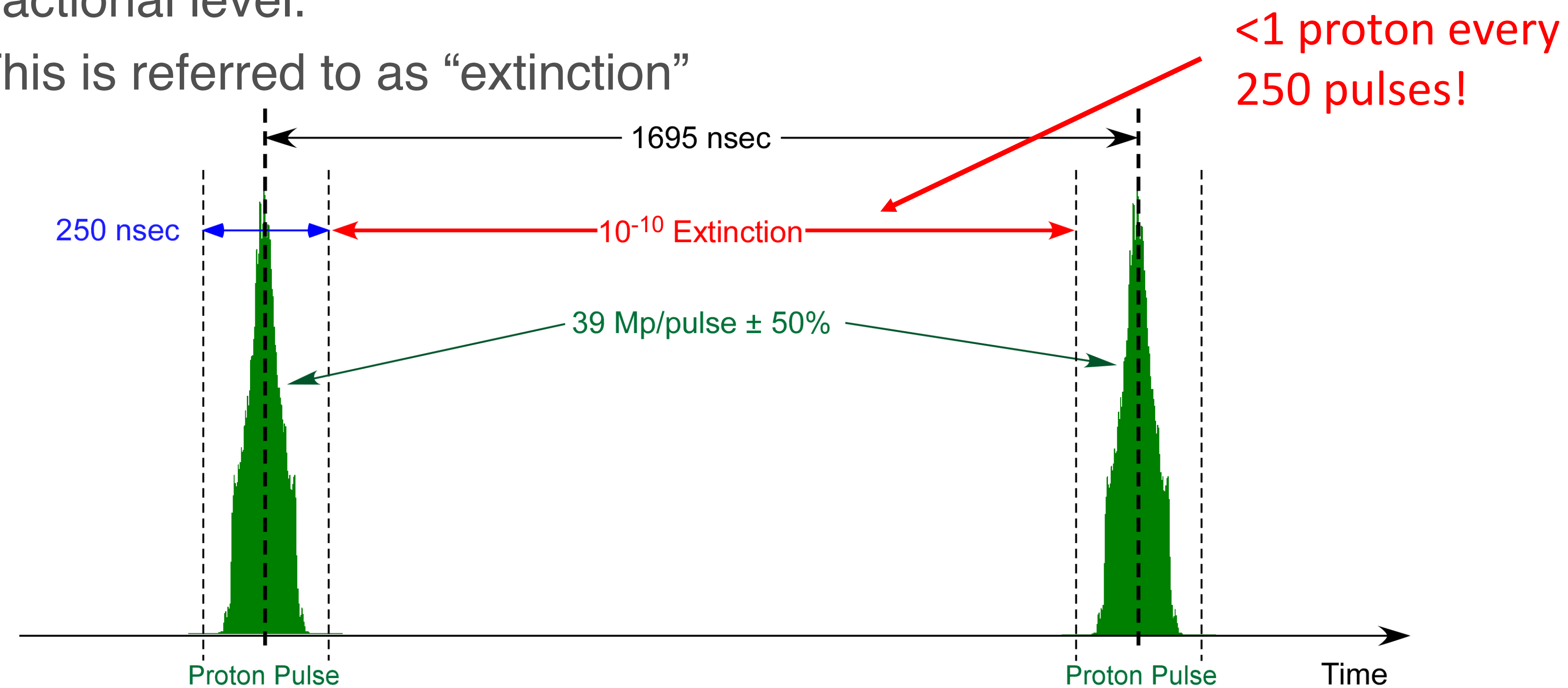


- Detail:
  - 3×10^7 p/bunch
  - 1.7 μsec bunch spacing
  - ~30% duty factor
  - ~1.2×10^{20} protons year



Extinction

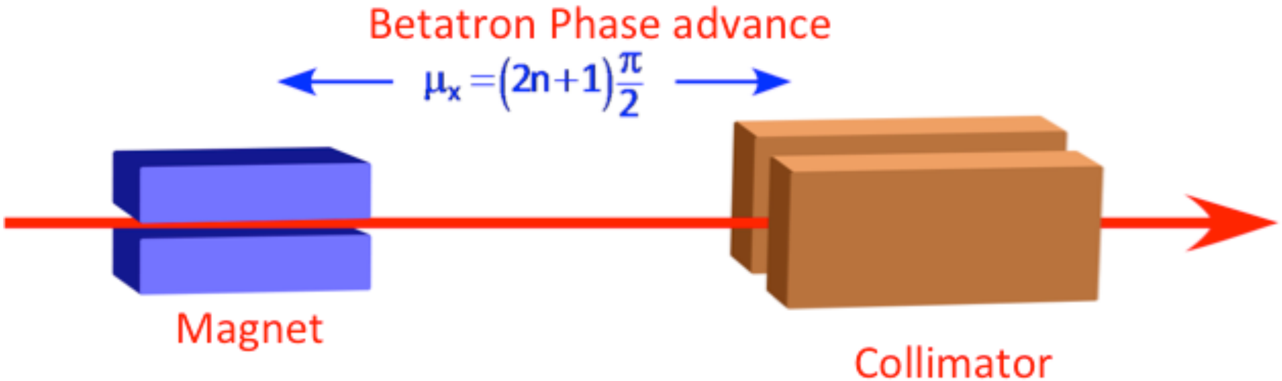
- Because out-of-time protons could produce prompt backgrounds, it is critical that there be nothing between the proton bunches at the 10^{-10} fractional level.
- This is referred to as “extinction”



- In addition to the challenge of achieving this level of extinction will be the challenge of verifying that we have achieved it (“Extinction Monitoring”)

Principle of Beam Line Extinction

- A magnet is used to deflect out-of-time beam into a downstream collimator



Think miniature golf

- Ideally, we would use a square pulse to kick out-of-time beam out of (or in-time beam into) the transmission channel, but the 600 kHz bunch rate makes this impossible with present technology.
- We will therefore focus on a system of resonant magnets or "AC Dipoles".
  - Even this isn't trivial

Design Considerations

- The cost and complexity of magnets scale roughly with the stored energy
- Clearly, we want to minimize *g* (waist in the non-bend plane)
- The bend plane is a little less obvious. A detailed analysis shows that to achieve the required bend

$$U \propto B^2 L w g$$

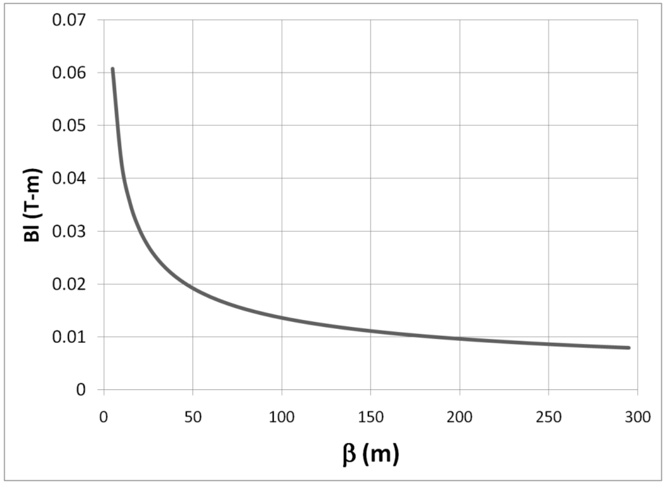
Magnet length

Bend plane aperture

Non-bend plane gap

$$U \propto \frac{1}{\sqrt{\beta_D L}}$$

betatron function at dipole



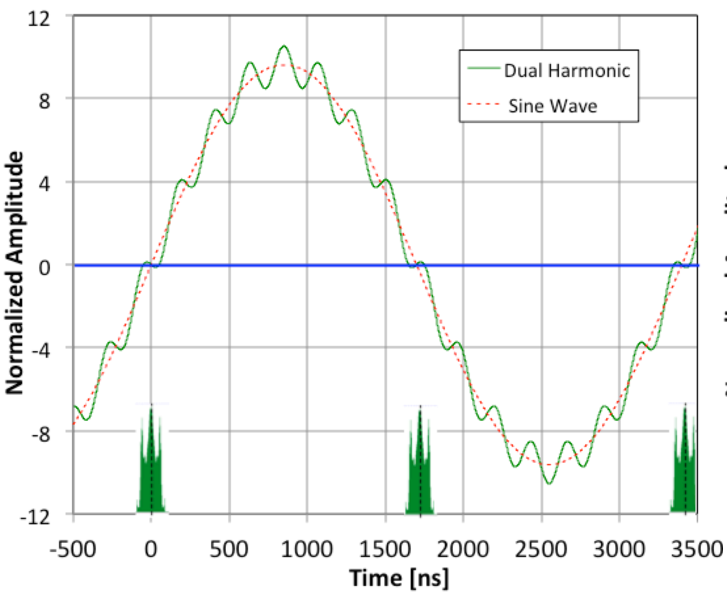
➔ Large β_D, long weak magnets

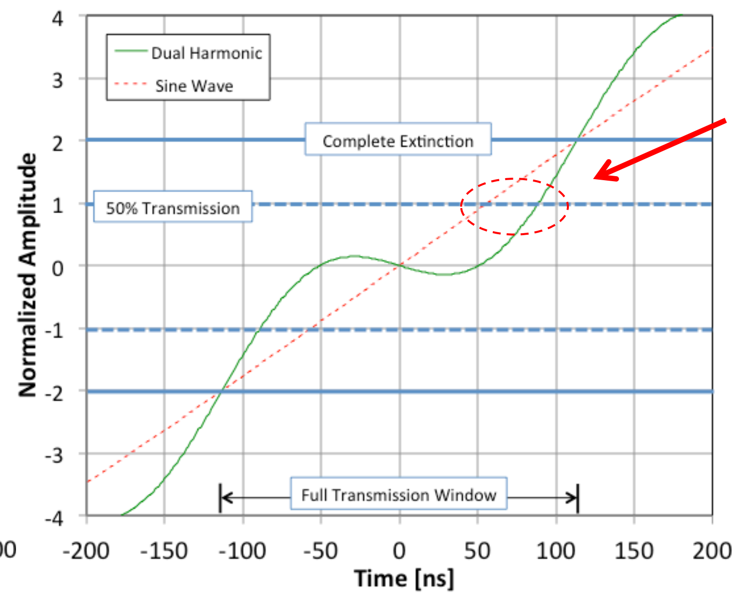
- Assume β_D=250m, L=6m
- Factor of 4 better than "typical" values of β_D=50m, L=2m

Driving consideration in beam line design!

Dual Harmonic Waveform

- AC Dipole driven by two harmonics
  - 300 kHz (half bunch frequency) to sweep out of time beam into collimators
  - 4.5 MHz (15th harmonic) to maximize transmission of in-time beam
  - Beam transmitted at nodes!





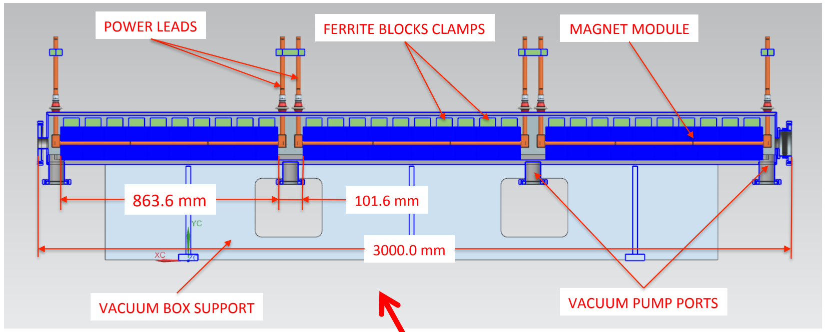
Single harmonic would hit collimator too soon

Normalized deflection
- δ=1 center of beam at edge of collimator
- δ=2 all beam hitting collimator

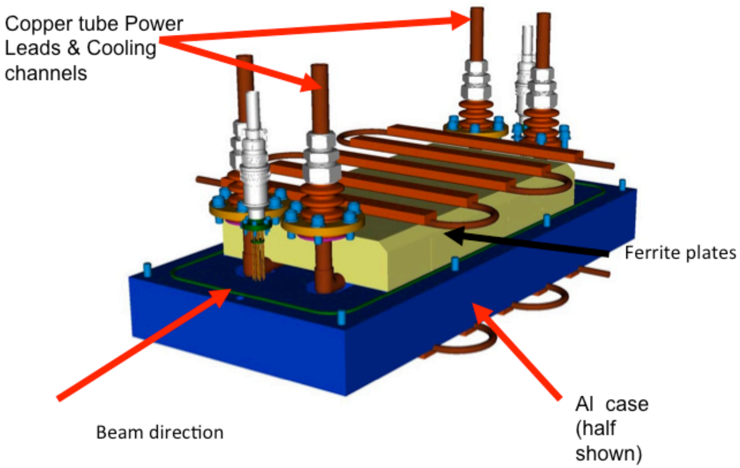
- Higher harmonic optimized for maximum transmission: 99.5%

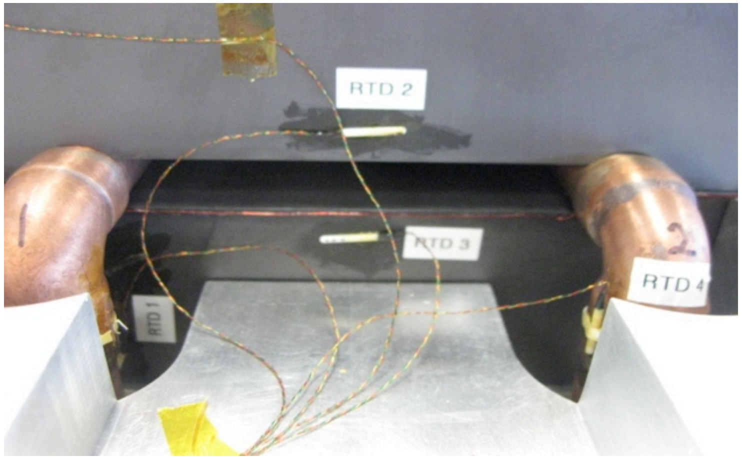
AC Dipole Design and Prototype

- AC dipole system consists of 6 identical one meter elements, arranged in two 3-meter vacuum vessels.
- Extensive tests done with half-meter prototype
  – meets all specifications



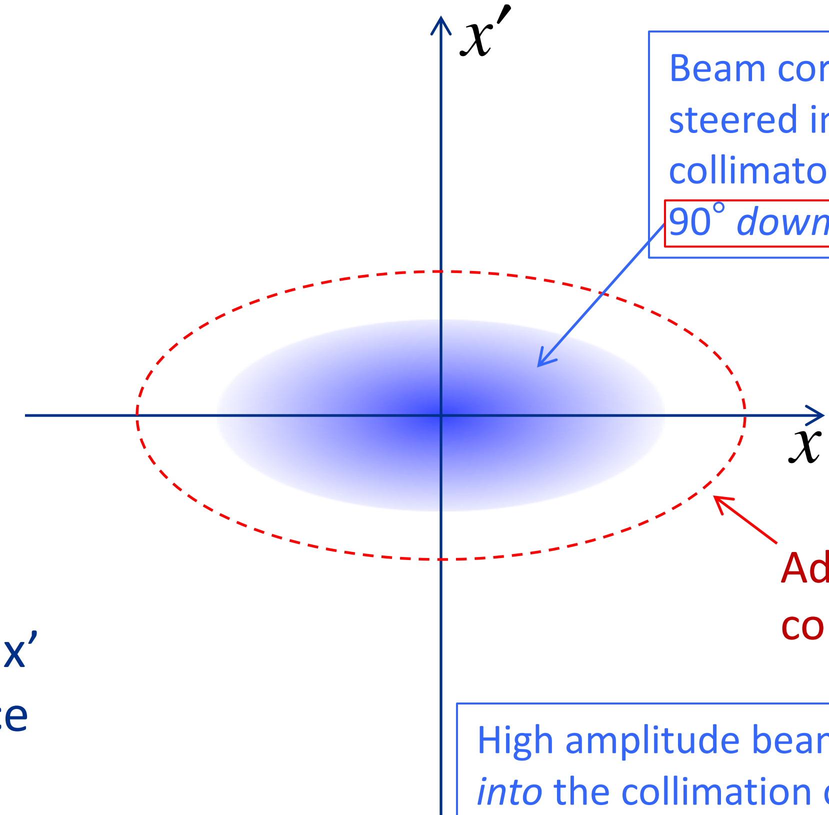
Elements individually powered



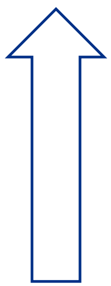


Extinction Collimation: Two Separate Collimation Issues

Phase space distribution of out of time beam at location of AC dipole



Beam core: out of time beam will be steered into the collimator or collimators
90° *downstream* of the AC dipole



AC dipole shifts distribution along x' axis in phase space

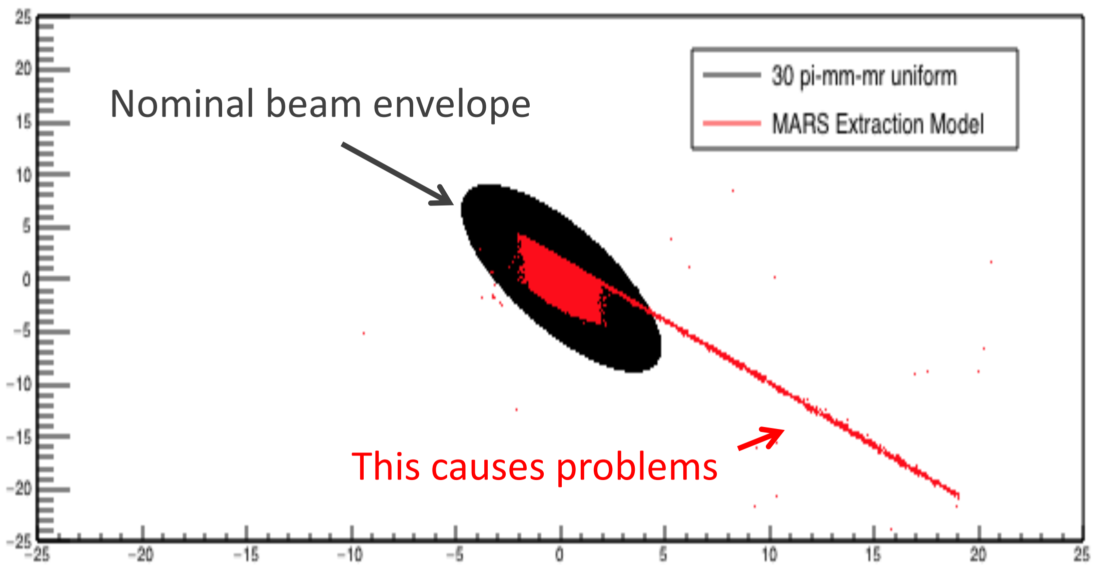
Admittance of downstream collimation system

High amplitude beam tails will be steered *into* the collimation channel, so they must be cleaned up
90° *upstream* of the AC dipole

Additional Problem: Slow Extraction Tails

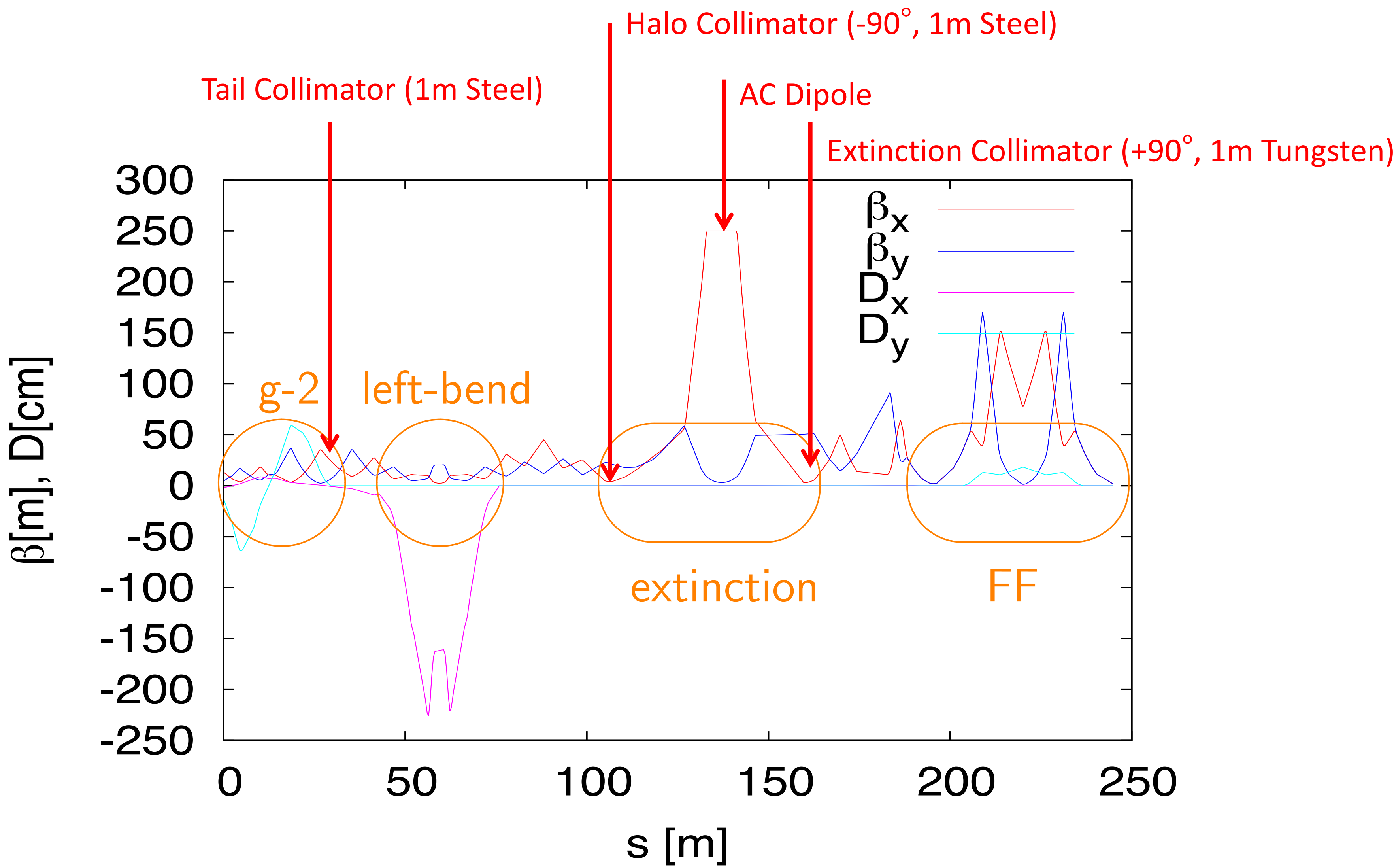
- Beam that strikes the electrostatic septum during slow extraction results in a large tail in phase space, which can result in beam being scattered into the transmission channel.

X Phase space at exit from Delivery Ring



- Requires an additional collimator

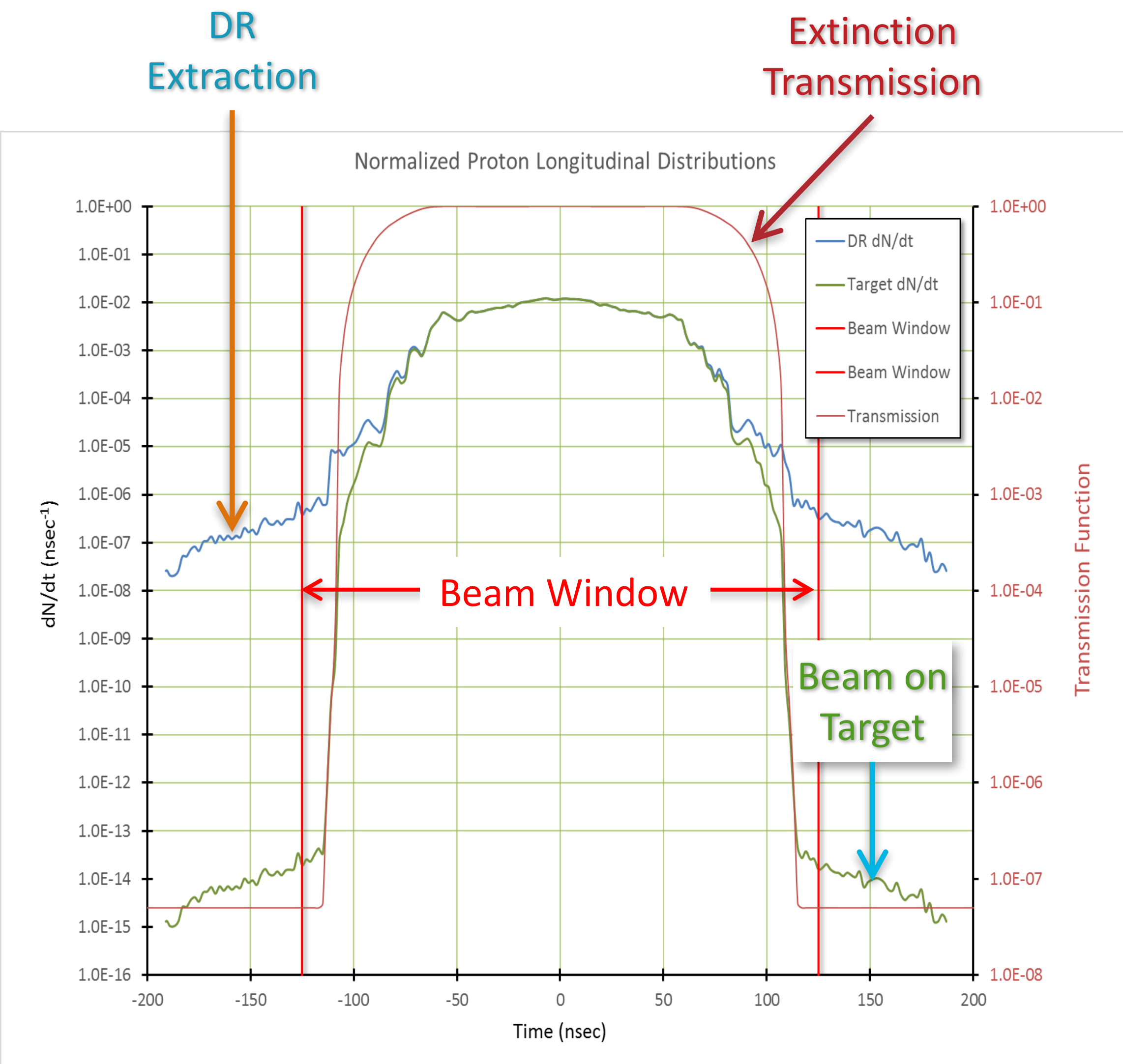
Summary: Collimator Needs and Locations



Simulation Procedure

- Longitudinal development in Recycler and Delivery Ring simulated by numerical integration model (I. Kourbanis, S. Werkema)
- Beam propagation and evolution of third-order resonance in Delivery Ring simulated by Synergia (V. Nagaslaev)
- Extraction interaction with electrostatic septum simulated by MARS (V. Nagaslaev)
- Beam line propagation and interaction with collimators simulated with G4Beamline as a function of AC dipole deflection angle to produce transmission tables (E. Prebys)
- Transmission tables convoluted with longitudinal distributions to optimize harmonic content of AC dipole magnets transmission of in-time beam and extinction of out-of-time beam (E. Prebys)

Performance



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:	$<1.0\times10^{-10}$

Almost two order of magnitude margin

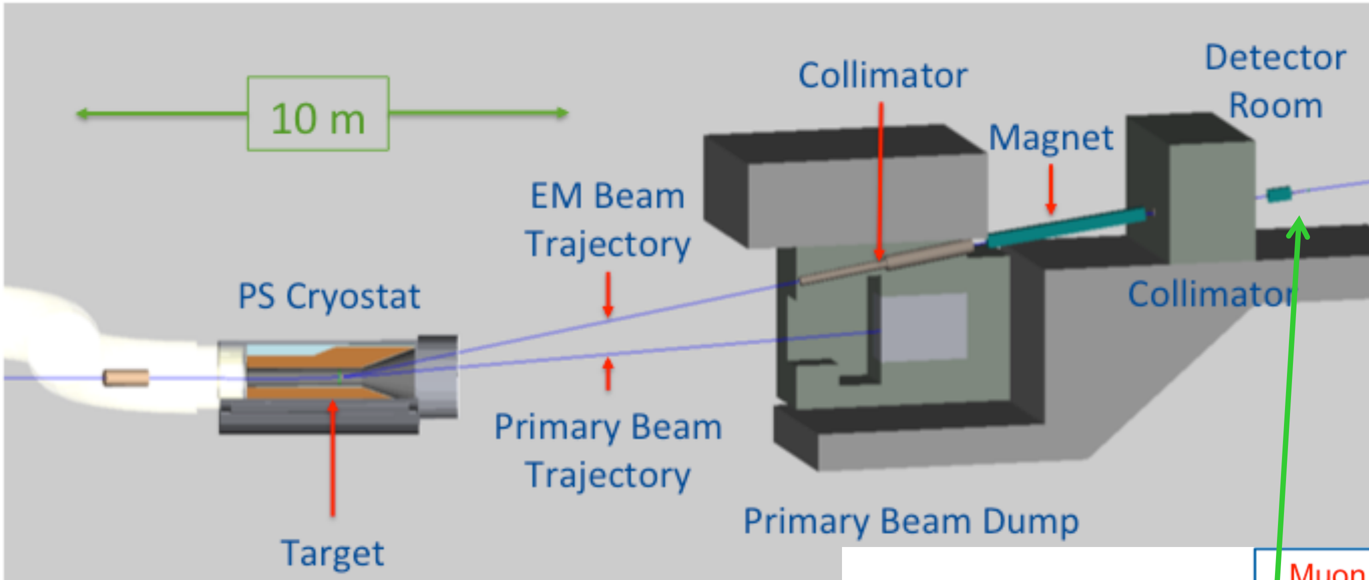
Extinction Monitor*

- No confidence in extinction unless we can verify it!
- Must measure extinction to 10^{-10} precision
  - Roughly 1 proton every 250 bunches!
- Required ~10^{8} dynamic range precludes direct measurement
  - Particles in bunches would blind detector to out of time particles
- Focus on statistical technique
  - Designed a monitor to detect a *small fraction* of scattered particles from target
    - 10 - 50 per in-time bunch
  - Statistically build up precision profile for in time and out of time beam.
- Requirement: 90% C.L. for 10^{-10} extinction after 6×10^{16} p.o.t.
  - Signal rate per p.o.t. must be > $2.3 / 6 \times 10^{6} = 0.4 \times 10^{-6}$
  - i.e. 16 for a 4×10^{7} bunch

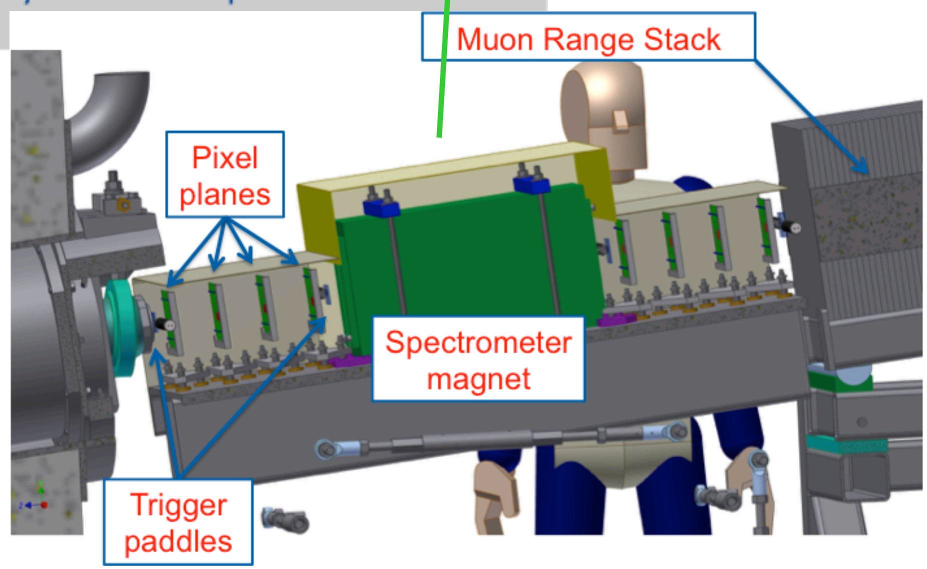
*P. Kasper

Fermilab

Extinction Monitor Design*



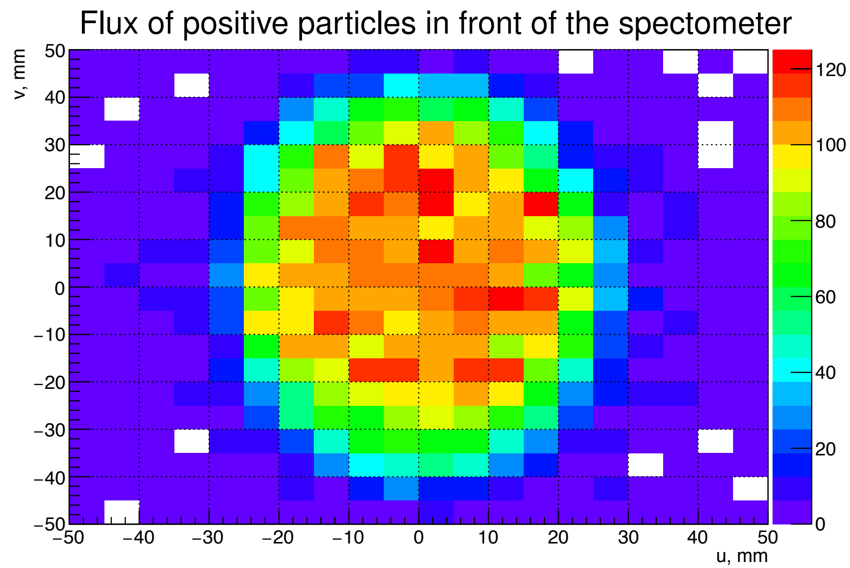
Selection channel built into target dump channel



- Spectrometer based on 8 planes of ATLAS pixels
- Optimized for few GeV/c particles
- ~ 1 track per 10^6 on target

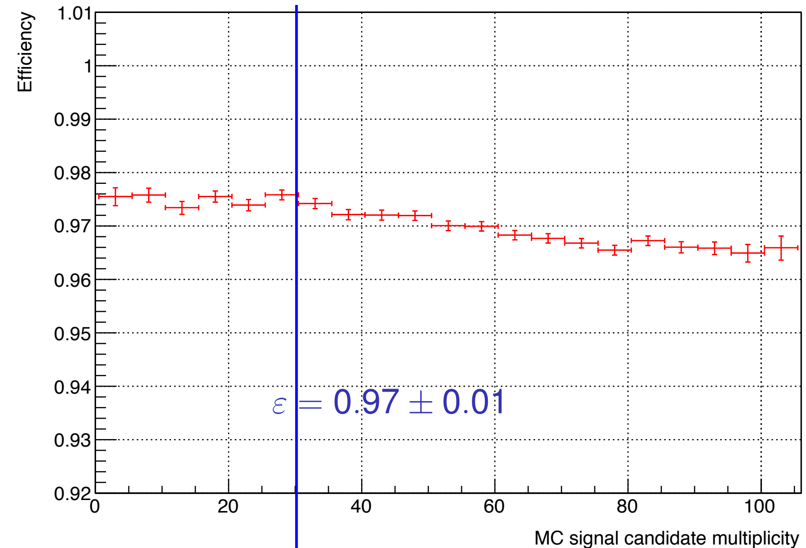
P. Kasper, L. Bartoszek, M. Jones, A Gaponenko

Extinction Monitor Performance*



Reconstructed 4528 tracks/5.1 × 10^9^ POT = 0.89 × 10^−6^ yield

Test: simulate "microbunches" of 1 to 100 tracks through the spectrometer



Expect ~30/bunch

Backgrounds considered

- Accidental combination
- Cosmic rays
- Off-target interactions

➔ Negligible at 10^{-10} level

*A. Gaponenko

Summary

- Mu2e had developed innovative techniques to deliver the beam structure required by the experiment, including the stringent limits on out-of-time beam (“extinction”)
- We have a robust technique for verifying that we have achieved the required level of extinction.
- A projects are well on track to meet the schedule of the experiment as a whole.