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

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The Search for $\mu+N \rightarrow e+N$

- 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.
- Very clean experimental signature!
- The virtual particle could be
  - a photon, in which case, $\mu \rightarrow e\gamma$ searches will also see a signal
  - A neutral, heavy boson, in which case they will not!
- Can only occur in the Standard Model through virtual neutrino mixing – but at a rate *38 orders of magnitude* below anything we could detect.
- Virtually *all* models beyond the Standard Model predict this will happen, most at a rate we could detect (already rules out or constrains many).
- *Any signal will be unambiguous proof of new physics!* 

$\sim 105$ MeV $e^-$
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.
• All protons at Fermilab come from the Linac/Booster system.

• The Booster magnets operate in a 15 Hz offset resonant circuit, which
  – Sets a fundamental clock for all accelerator sequencing
    • 1/15 second = 1 “tick”
  – Sets a fundamental “batch” of protons
    • 1.6 \( \mu \)sec long
    • Up to \( 5 \times 10^{12} \) 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 \( \sim 1 \times 10^{12} \) 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
Two Booster “batches” are injected into the Recycler (8 GeV storage ring). Each is:

- $4 \times 10^{12}$ 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 $\sim 3 \times 10^7$ protons each
- Separated by 1.7 μsec

Exactly what we need
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
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”)

<1 proton every 250 pulses!
Principle of Beam Line Extinction

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

- 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
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 (15\textsuperscript{th} harmonic) to maximize transmission of in-time beam
  - Beam transmitted at nodes!

- Higher harmonic optimized for maximum transmission: 99.5%

Single harmonic would hit collimator too soon
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.

- Requires an additional collimator
Summary: Collimator Needs and Locations

- Tail Collimator (1m Steel)
- Halo Collimator (-90°, 1m Steel)
- AC Dipole
- Extinction Collimator (+90°, 1m Tungsten)

Diagram showing 
- $\beta_x$, $\beta_y$, $D_x$, $D_y$
- s [m]
- $\beta$ [m], D[cm]
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: <5×10⁻⁸
Total extinction: 1.1×10⁻¹²
Extinction Requirement: <1.0×10⁻¹⁰

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 $\sim 10^8$ 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 $6 \times 10^{16}$ 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 $4 \times 10^7$ bunch

*P. Kasper
Extinction Monitor Design*

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

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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.