PROTON BEAM INTER-BUNCH EXTINCTION AND EXTINCTION MONITORING FOR THE MU2E EXPERIMENT*

E.J. Prebys, Fermilab, Batavia, IL 60510, USA

Abstract

The goal of the Mu2e experiment at Fermilab is the search for the conversion of a muon into an electron in the field of a nucleus, with a precision roughly four orders of magnitude better than the current limit. The experiment requires a beam consisting of short (≈200 ns FW) bunches of protons separated by roughly 1.7 μsec. Because the most significant backgrounds are prompt with respect to the arrival of the protons, out of time beam must be suppressed at a level of at least 10^{-10} relative to in time beam. The removal of out of time beam is known as "extinction". We will discuss the likely sources of out of time beam and the steps we plan to take to remove it. In addition, two possible techniques for monitoring extinction will be presented.

MOTIVATION

The goal of the Mu2e experiment [1] is to search for the conversion into an electron of a muon which has been captured by a nucleus ($\mu N \rightarrow eN$). This is related to the search for $\mu \rightarrow e\gamma$, but is sensitive to a broader range of physics.

A key component of the experimental technique is the proton beam structure. The beam consists of short (≈200 ns FW) proton bunches with 8 GeV kinetic energy. These strike a production target, producing muons which are in turn transported and captured on a secondary target. The pulses are separated by approximately 1.7 μs, during which time the captured muons either decay normally or *potentially* convert into electrons. The most important background comes from the radiative capture of pions, which are prompt with respect to the primary proton. To suppress this background, it's vital that the interval between the bunches be free of protons at a level of at least 10^{-10} relative to the beam in the bunches [2]. Some of this suppression will come from the method used for generating the bunches, but active suppression in the transport line should be designed for an additional suppression factor of at least 10^{-7}.

BEAM DELIVERY SCHEME

The details of the beam delivery scheme are described elsewhere [3], and Fig. 1 shows the relavent components of the Fermilab accelerator complex. A "batch" of approximately 4×10^{12} protons is accelerated to 8 GeV kinetic energy in the Fermilab Booster and injected into the Recycler permanent magnet storage ring. There, a 2.5 MHz RF system splits the batch into four bunches of 10^{12} protons each. These are transferred one at a time to the Delivery Ring (formerly the Antiproton Accumulator Ring). Each bunch is resonantly extracted, forming a chain of 3×10^7 proton bunches, separated by the 1.7 μsec period of the Delivery Ring.

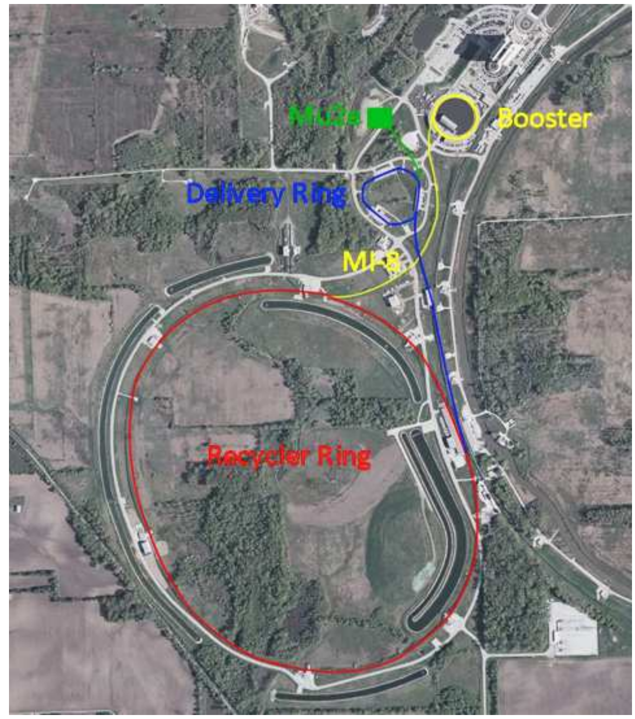

Figure 1: The elements of the Fermilab complex used for the Mu2e experiment. Beam is transported from the Booster to the Recycler to the Delivery Ring (formerly the Antiproton Accumulator). The experiment itself will be built in a new detector hall.

The average beam intensity will be 8 kW or 2×10^{16} protons/hour. At that rate, it will take approximately three years to collect 3.6×10^{20} protons on target, the nominal data set for the experiment.

IN RING EXTINCTION

Our goal is to maintain an extinction level of 10^{-5} or better for the beam which is extracted from the Delivery Ring. The transfer scheme described above insures that bunches going into the Delivery Ring will have at least this level of extinction, and the concern is that beam will leak out of time during the slow extraction process. The mechanism for protons to drift out of time involves changes in energy that cause particles to migrate to the boundaries of the bucket, or to leak out of the bucket entirely.

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Effects that can cause these energy changes are:

- RF Noise
- Intrabeam scattering
- Beam loading
- Beam-gas interaction
- Scattering off of extraction septum

Simulations are still ongoing, but the preliminary conclusion is that the 10^{-5} goal should be achievable.

BEAM LINE EXTINCTION

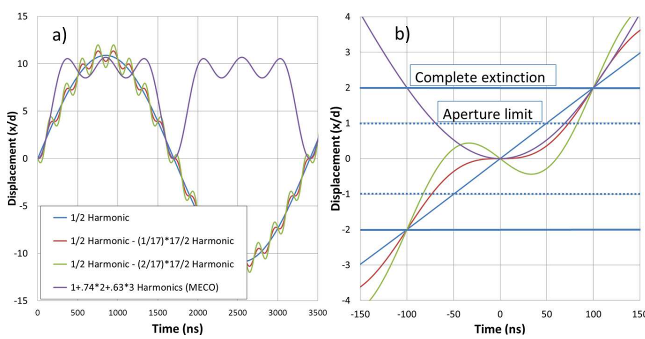

Figure 2: The waveforms considered in this analysis are shown for (a) two bunch periods and (b) near the transmission window. Two different amplitudes for the high frequency harmonic in the two harmonic scheme are shown.

Conceptually, the beam line extinction system consists of a deflecting magnet and a collimation system, timed such that only the in time beam makes it through the collimators. The most straightforward approach would be a pulsed kicker, which deflected the in time beam into the transmission channel; however, such a kicker of sufficient amplitude and repetition rate is well beyond the state of the art. The solution will therefore have to involve some sort of resonant system, and we have focused on combinations of resonant dipoles, or "AC dipoles".

The optimization of the magnet design is discussed elsewhere [4]. A generic analysis of the behavior of a magnet and collimator system shows that the stored energy in the magnet scales approximately as

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

where β_x is the beam line beta function in the bend plane and L is the length of the magnet. Assuming that the complexity of the magnet and power supply scale monotonically with the stored energy, one reaches the somewhat counterintuitive conclusion that it's best to build long, low field magnets at regions of high β_x. This places severe constraints on the beam line design, and it was determined that a β_x of 250 m and and length of 6 m were the largest that could be practically accommodated [6].

We have considered three classes of wave forms for the AC dipole system, illustrated in Fig. 2:

- A single harmonic, running at half the bunch frequency (300 kHz), such that beam is transmitted at the nodes.
- One which combines the 300 kHz wave with a small amplitude high frequency harmonic, to reduce the slewing during the transmission window.
- One composed of three harmonics, to approximate a square wave. This is based on a previous design done for MECO [5].

It was determined that two harmonic magnet provided the best transmission efficiency. Further optimization, using a more realistic bunch shape, showed that $> 99\%$ transmission efficiency could be achieved by using the 13^{th} harmonic, with the amplitudes shown in Tab. 1. The resulting wave form is shown in Fig. 3 and the trasmission window is shown in Fig. 4

Table 1: Magnet Parameters for the Two Harmonic Components of the Optimized AC Dipole System

Frequency	Length	Peak Field
300 kHz	3 m	108 Gauss
3.8 MHz	3 m	13 Gauss

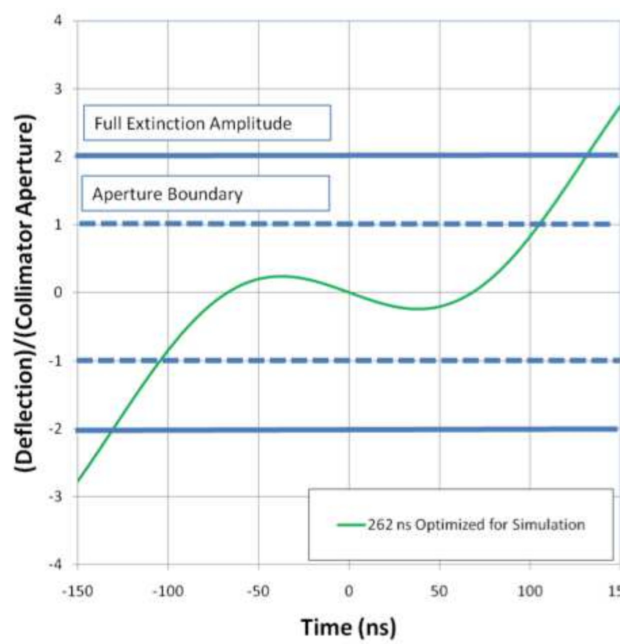

Figure 3: The motion of the beam at the collimator for the final, optimized waveform.

A .5 m prototype, illustrated in Fig. 5, has been constructed and successfully tested at both low and high frequency. The base line plan is to build the final magnet systems out of six identical 1 m magnets of design similar to this.

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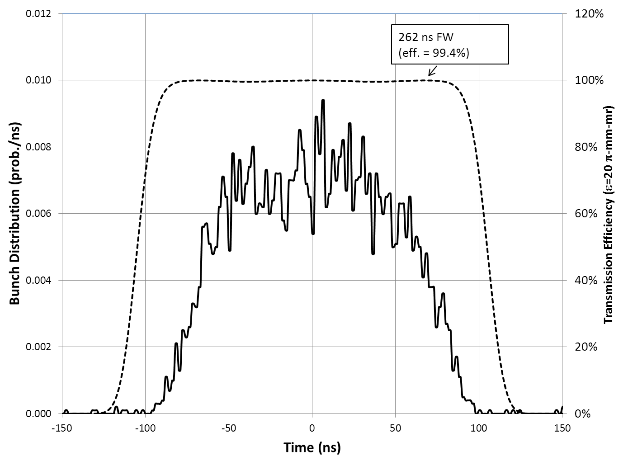

Figure 4: Transmission window for optimized waveform. The solid line is the simulated bunch shape and the dotted line is the transmission probability as a function of time for a beam with a normalized transverse 95% emittance of 20 π-mm-mr.

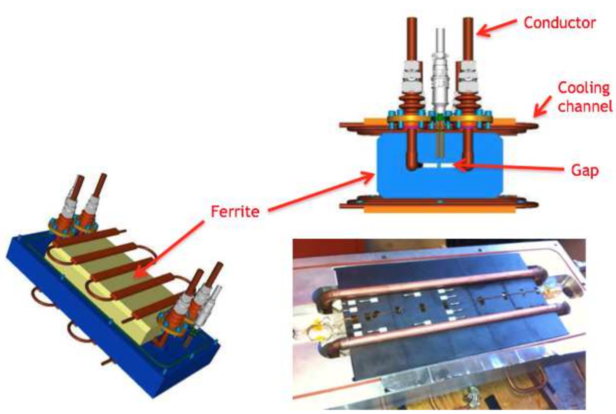

Figure 5: Prototype for AC dipole magnet.

BEAM LINE AND BEAM LINE SIMULATION

The beam line optics are dominated by the requirements of the AC dipole insertion, as shown in Fig. 6. The location of the AC dipoles themselves has a high β region in the bend plane and a waist in the non-bend plane. The subsequent beam line includes multiple collimators and dispersion regions for secondary momentum collimation.

A simulation was carried out using STRUCT and MARS [7]. In addition to the AC dipole, a system of 5 collimators was simulated, in order to maximize the overall cleaning efficiency for particles which struck the first collimator. STRUCT was used to track the particles and MARS was used to simulate the interaction of particles with the collimators. The results are shown in Fig. 7. We see that we can achieve better than the required 10^{-7} extinction over most of the inter-bunch region and better than 5×10^{-8} over much of it.

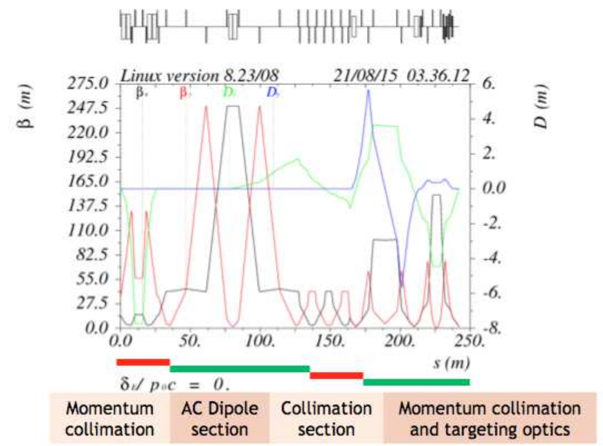

Figure 6: Beam line optics for the Mu2e experiment.

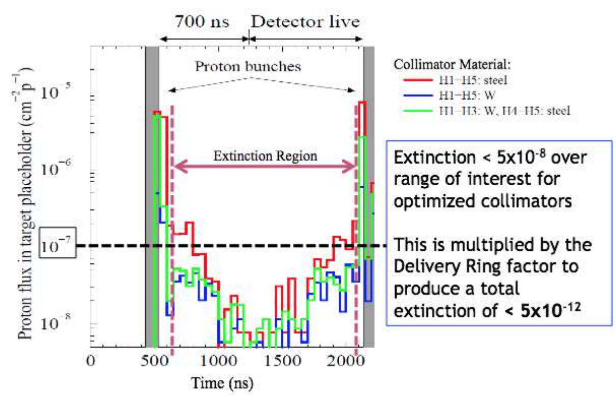

Figure 7: Simulation results for the AC dipole and collimation system.

We consider the magnet and collimation system to be adequate for our needs.

EXTINCTION MONITORING

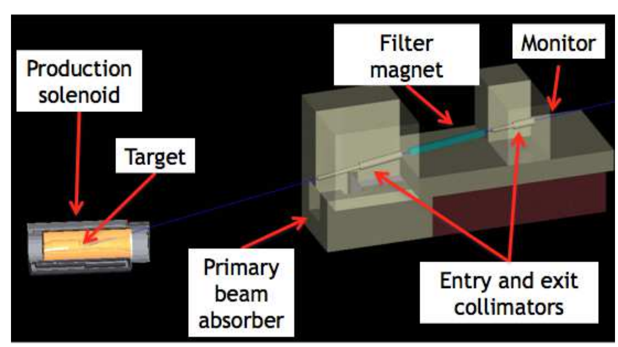

Figure 8: Pixel based extinction monitor.

It is vital that we be able to monitor the extinction level in the experiment, and measuring extinction to this precision is extremely challenging. An extinction of 10^{-10} corresponds to roughly one out of time proton every 300

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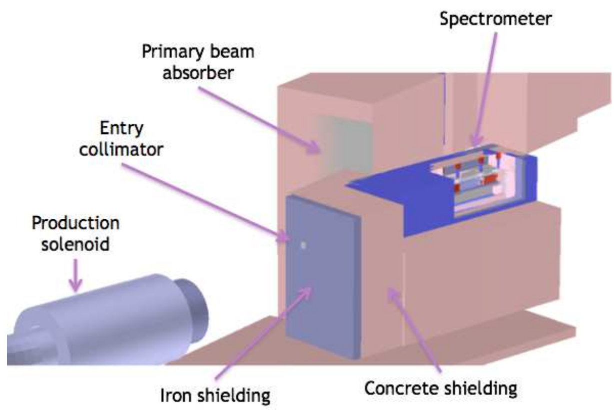

Figure 9: Spectrometer based extinction monitor.

bunches. We have not been able to identify an instrumentation solution which is sensitive to single particles yet blind to the protons in the bunches, so we are instead focusing on a statistical monitor of the target itself. This has the added advantage that it measures exactly what we are interested in; namely, the out of time particles hitting the target. In contrast, a measure of out of time particles in the beam line might might overestimate the out of time component by measuring particles which ultimately miss the target, given that out of time particles might have a different transverse distribution than in time particles.

We intend to pursue a "filter and detector" strategy, comprised of two parts:

- **Filter**: a channel to select a small sample of secondaries from the production target, on the order of a "few" per incident bunch.
- **Detector**: measure the precise time of the secondaries which pass through the filter and build up a statistical measure of "in time" and "out of time" particles.

The efficiency of the filter will be determined by the maximum rate of the detector for in time particles and by the required rate for the desired measurement accuracy. It's important for the efficiency of the in time and out of time rates to be the same, or at least well known. The requirements for the beam line monitor [8] specify a 10^{-10} measurement at the 90% confidence level within one hour. The nominal proton rate for Mu2e is 2×10^{16} protons/hour, so the required extinction would be less than 2×10^{6} out of time protons in that time. Assuming a very low background, a measurement at the 90% confidence level would be 2.3 events, or a required filter efficiency of 1.2×10^{-6} [9].

Two solutions have been proposed. The first one, shown in Fig. 8, is being designed at Fermilab. It has the filter channel integrated into the shielding steel of the proton dump. It is optimized to select positively charged secondaries in the momentum range of 3-4 GeV/c, and uses the same time of pixel detectors used in the vertex detector of the ATLAS experiment at the LHC.

The second proposal is being developed at UC Irvine and is shown in Fig. 9. It is designed to select positive secondaries of approximately 1 GeV/c momentum. The detector employs a magnetic spectrometer and four scintillator stations to measure dE/dx, time-of-flight, and momentum.

At the moment, both solutions appear capable of satisfying the monitor requirements. A committee has been formed to evaluate both proposals and recommend which option the collaboration should pursue. Their report is expected in early November of this year.

NEXT STEPS

The most pressing need of the experiment is to continue simulations of the beam in the Delivery Ring to determine the out-of-time leakage rate and develop a mitigation strategy if this rate is too high.

The AC dipole design appears fundamentally sound, and further development can proceed when the funding profile of the experiment allows it. We will continue to optimize the collimation system to improve cleaning efficiency, and it appears we will be able to achieve the desired level of extinction.

We have two viable solutions for the extinction monitor system, and a base line choice is expected in November of this year.

The Mu2e Collaboration is currently working on the Preliminary Design Report, scheduled to be completed in early 2014, with full scale construction beginning in mid 2015. Data taking is currently scheduled for late 2019 or early 2020, but at the recommendation of the latest review committee, we are investigating ways to accelerate the overall schedule.

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