ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF121

OUT-OF-TIME BEAM EXTINCTION IN THE MU2E EXPERIMENT*

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

Abstract

The Mu2e Experiment at Fermilab will search for the conversion of a muon to an electron in the field of an atomic nucleus with unprecedented sensitivity. The experiment requires a beam consisting of proton bunches 250 ns FW long, separated by 1.7 μ sec, with no out-of-time protons at the 10^{-10} fractional level. Satisfying this "extinction" requirement is very challenging. The formation of the bunches is expected to result in an extinction on the order of 10^{-5}. The remaining extinction will be accomplished by a system of resonant magnets and collimators, configured such that only in-time beam is delivered to the experiment. Our simulations show that the total extinction achievable by the system is on the order of 10^{-12}, with an efficiency for transmitting in-time beam of 99.6%.

INTRODUCTION AND REQUIREMENTS

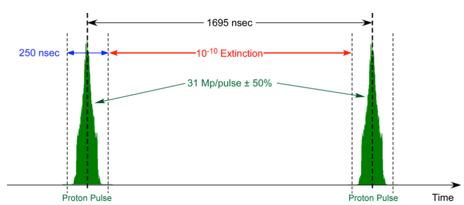

Figure 1: The proton bunch structure required by the Mu2e experiment.

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 manifestly violates the conservation of charged lepton flavor number, and therefore its observation would be an unambiguous indicator of physics beyond the Standard Model.

A key component of the experimental technique is the proton beam structure [2], which is illustrated in Figure 1. The primary beam consists of short (250 ns FW) proton bunches with 8 GeV kinetic energy, separated by approximately 1.7 μs, which are used to produce muons. To suppress backgrounds, 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 [3]. This will be achieved in two steps. The first step will be in the formation of the bunches, which - as we will show - we expect to achieve an extinction on the order of 10^{-5}. The remaining extinction will be provided by a system of resonant magnets and collimators in beam line, configured such that only the in-time beam is transmitted to the target. This system is designed to provide an additional extinction factor of below 10^{-7}. There is thus a safety margin of two orders of magnitude, which we feel is appropriately conservative, given the importance of the issue.

In the interest of minimizing radiation damage and secondary activation, we have also imposed the specification that less that 1% of the in-time beam be lost on the collimator.

BUNCH FORMATION

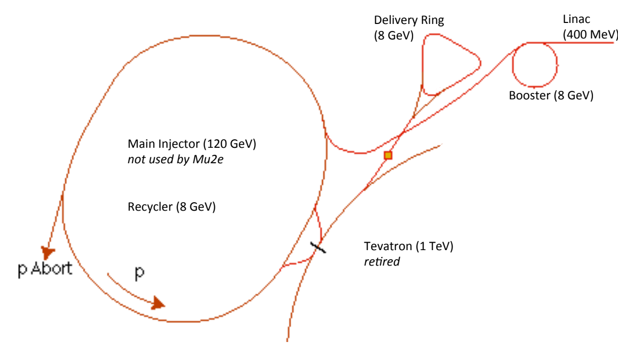

Figure 2: The parts of the Fermilab Accelerator Complex used for the Mu2e Experiment. The “Delivery Ring" was formerly the Antiproton Debuncher

The parts of the Fermilab accelerator complex which are required are shown in Figure 2.

Protons with 8 GeV of kinetic energy will be transferred from the Booster to the Recycler, an 8 GeV permanent magnet storage ring developed for the Tevatron program. In the Recycler, beam will be re-bunched into 2.5 MHz bunches. These will be transfered one at a time to the 8 GeV “Delivery Ring" (formerly the Antiproton Debucher"). Beam will then be resonantly extracted from this ring, which has a period of 1.7 μs, thus producing the bunch structure needed by the experiment.

BEAM LINE EXTINCTION

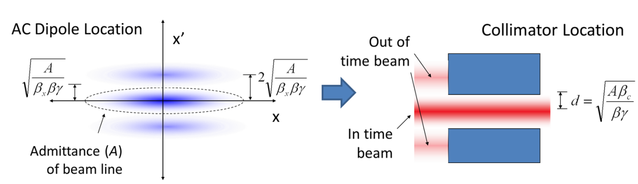

Figure 3: Effect of the AC dipole field in phase space. Beam line admittance A is indicated by the ellipse.

The AC dipole/collimator system and it's optimization has been described in detail elsewhere [4]. The principle is shown in Figure 3. A bending dipole deflects out-of-time beam, such that it will be absorbed by a collimator located 90° downstream in betatron phase advance. If the

* Work supported by the United States Department of Energy under Contract No. DE-AC02-07CH11359

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF121

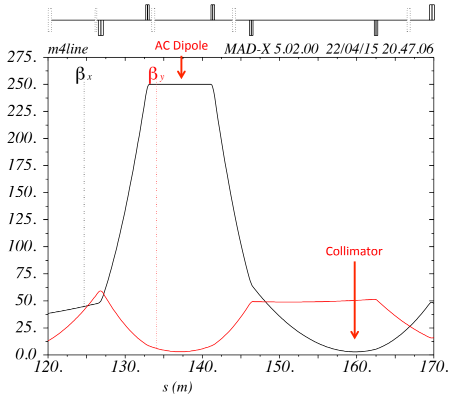

Figure 4: Beam optics in the region of the AC dipole and collimator. The AC dipole is centered at s = 137 m.

normalized admittance of the collimator, A, is matched to to the bounding emittance of the beam, then one can define a normalized bend angle

$$\delta \equiv \sqrt{\frac{A}{\beta_x \beta\gamma}}$$

where β_x is the betatron function in the bend (X) plane at the location of the AC dipole, and β and γ have their usual relativistic definitions. With this definition, $\delta = 1$ will put the center of the beam at the edge of the collimator, and $\delta = 2$ will cause all the beam within the bounding emittance to hit the collimator. We therefore refer to $\delta = 2$ as the "extinction angle".

A simple pulsed kicker which could accomplish this is beyond the state of the art, so we have focused on "AC dipoles"; that is, dipole magnets or combinations of dipole magnets in resonant circuits. We have found [5] that to minimize the cost and complexity of the magnet, it is desirable to build longest possible magnets, with a waist in the non-bend (Y) plane and the largest feasible betatron function in the bend plane. For our beam line, the largest practical values for the length and betatron function are 6 m and 250 m, respectively [6]. The resulting optics are shown in Figure 4. The beta function at the location of the collimator is β_C=3.15 m. Designing for a normalized admittance of A=50 π-mm-mrad gives a collimator half gap of 4.08 mm.

Table 1: Harmonic Specifications for AC Dipole System

Freq. [MHz]	Length [m]	Amplitude [Gauss]
.3	3.0	138
4.5	3.0	12

Two frequency components will be used to excite the AC dipole: a 300 kHz sine wave (half the bunch frequency) will serve to quickly sweep the out of time beam out of the transmission channel, while a 4.5 MHz sine wave (15th harmonic) will reduce the slewing near the nodes of the first harmonic to maximize the transmission of in time beam. The AC

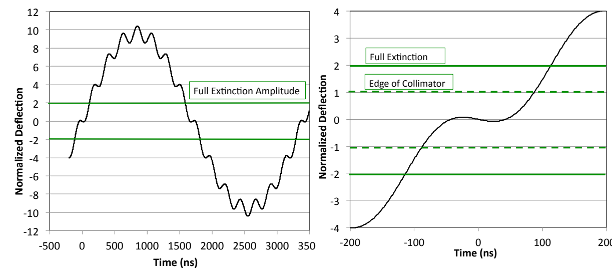

Figure 5: The two harmonic waveform used to excite the AC dipole. The full waveform is shown in the left plot, while the right plot shows a closeup near the time of the in-time beam passage. The normalized angle is defined such that δ=1 corresponds to the center of the beam hitting the edge of the collimator and δ=2 corresponds to all of the beam hitting the collimator.

dipole system consists of six identical 1m segments, with three allocated for each frequency component. The amplitudes of these harmonics have been optimized to maximize transmission of in-time beam while maintaining maximum extinction outside of ±125 ns. The harmonics and amplitudes are shown in Table 1 and the resulting wave form is shown in Figure 5.

SIMULATIONS

Bunch Formation

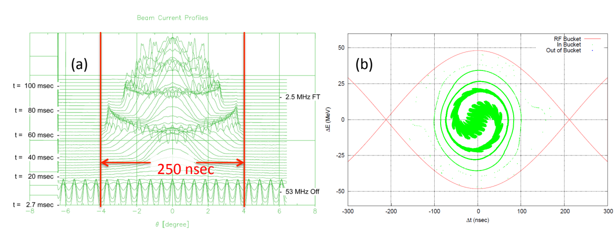

Figure 6: Bunch formation is shown (a) in the Recycler, beginning with the 53 MHz bunches from the Booster, and (b) in the Debuncher.

Bunch formation was simulated using ESME [7], beginning with 8 GeV, 53 MHz Booster bunches after injection into the Recycler. The 53 MHz RF system was then turned off, and the beam was adiabatically rebunched with a 2.5 MHz RF system. Once it was rebunched, a bucket-to bucket transfer was done to the 2.4 MHz RF system in the Delivery Ring, where the longitudinal structure was allowed to evolve. The ESME model in the Delivery Ring included space charge and cavity impedance.

Figure 6 shows bunch simulations in the Recycler and in the Delivery Ring. At the time of extraction, the fraction of beam found outside the ±125 ns transmission window is 2.1×10^{-5}.

Beam Line Extinction

The beam line transmission was simulated using G4Beamline [8], a scripting tool for the GEANT4 monte

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF121

carlo program. The model included bend magnets, quadrupoles, the beam pipe, and the collimator. The collimator was simulated with two Tungsten jaws, each 5 cm(W)x 10 cm(H) x 100 cm(L), set at the 4.08 mm half gap described above. The simulation was performed in two parts. In the first, the core of the beam transverse distribution was tracked from the AC dipole to the muon production target and transmission was measured as a function of normalized deflection angle. This simulation used particle distributions based on simulations of resonant beam extraction: a uniform distribution of 30 π-mm-mrad full normalized emittance in the horizontal AC dipole bend (extraction) plane, and a Gaussian distribution with 15 π-mm-mrad 95% normalized emittance in the non-bend plane.

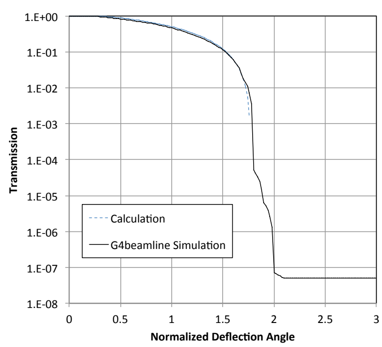

Figure 7: The transmission is shown as a function of deflection angle in, along with a naive calculation assuming perfect collimator performance.

A particle was determined to be transmitted if it fell withing 5 mm of the target (the actual target radius is 3 mm). Small deflection angles had a large transmission, so only a relatively small number of particles were required. As transmission decreased, the number of initial particles was increased, up to a maximum of 10^8 per setting, which is the number that was used for all normalized deflections beyond $\delta = 1.8$. The transmission was defined as the number of transmitted particles divided by the inital particles, down to a minimum of 5×10^{-8}.

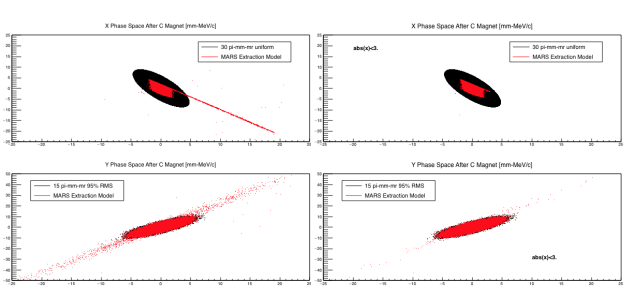

Figure 8: Phase space used for the simulations. The MARS extraction model is shown in red, while the core model emittance distributions are shown in black. The left and right show the distributions with and without X collimation, respectively.

Another consideration is that large amplitude halo upstream of the AC dipole could be scattered *into* the out of time transmission channel. To simulate this effect, a MARS [9] based simulation of beam transport and scattering in the Delivery Ring extraction channel was performed [10]. Figure 8 shows this distribution compared to the idealized distribution used for the core simulation. The large tail seen in the X plane is caused by scatters from the electrostatic extraction septum in the Delivery Ring. This scattering is also responsible for the large amplitude halo particles in the Y plane. For our simulation, an X collimator was added to remove it. For this simulation, a full G4Beamline model of the beam line was used; however, because the behavior of the core particles had already been simulated, only particles with a normalized emittance amplitude of >40 π-mm-mrad in at least one of the planes were simulated, greatly reducing the computing time required. For deflection angles of ≥ 2, at most one to two particles were observed to be transmitted out of 10^8 initial particles, which does not significantly add to the transmission observed for the core beam.

The final results of the transmission simulation simulation are shown in Figure 7. We see that that the specification that the beam line extinction be less than 10^{-7} outside of the nominal ± 125 ns transmission window has been satisfied. The total bunch transmission is 99.6%, satisfying the <1% beam loss requirement.

RESULTS AND CONCLUSIONS

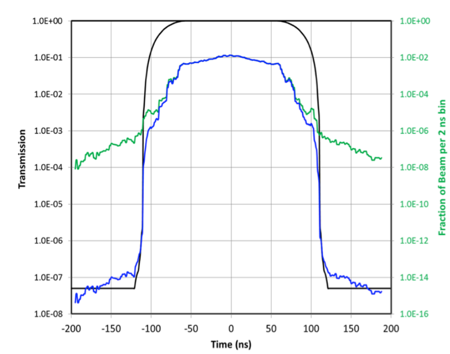

Figure 9: The total beam transmission is shown, combining the effects of the bunch formation and beam line extinction.

Figure 9 shows the final results of the simulations. The transmission curve is the convolution of the simulated transmission and the optimized AC dipole waveform. The simulated bunch distribution is shown both superimposed and convoluted with the transmission curve. The final fraction of beam outside of ± 125 ns is $\approx 10^{-12}$, which comfortably exceeds the 10^{-10} requirement. The total beam transmission is 99.6%.

RELATED CONTRIBUTIONS

“Beam Extinction Monitoring in the Mu2e Experiment" (MOPWI017) describes the monitoring of the beam extinction.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF121

REFERENCES

[1] Mu2e Collaboration, "Mu2e Technical Design Report", arXiv:1501.05241,http://arxiv.org/abs/1501.05241 (2015)

[2] *Ibid.*, Chapter 4

[3] J. Miller, "Beam Extinction Requirement for Mu2e", http://mu2e-docdb.fnal.gov, Mu2e-doc-1175

[4] E. Prebys *et al*, "Optimization of AC Dipole Parameters for the Mu2e Extinction System", Proceedings of the 2012 International Particle Accelerator Conference, WEPPD081 (2012)

[5] E. Prebys, "Parametric Analysis of Beam Transmission in the Mu2e Extinction Channel", http://mu2e-docdb.fnal.gov, Mu2-doc-550

[6] C. Johnstone, FNAL, *private communication*

[7] S. Stahl, J. MacLachlan, "User's Guide to ESME v7.1", FNAL-TM-1650 (1990)

[8] "G4beamline", http://www.muonsinternal.com/muons3/G4beamline

[9] "MARS Code System", http://www-ap.fnal.gov/MARS/

[10] V. Nagaslaev, *et al.*, "MARS Tracking Simulations for the Mu2e Slow Extracted Proton Beam", *this conference*, THPF125, (2015).