

BEAM EXTINCTION MONITORING IN THE Mu2e EXPERIMENT*

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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 of 250 ns FW, separated by 1.7 μ sec, with no out-of-time protons at the 10^{-10} fractional level. The verification of this level of extinction is very challenging. The proposed technique uses a special purpose spectrometer that will observe particles scattered from the production target of the experiment. The acceptance will be limited such that there will be no saturation effects from the in-time beam. The precise level and profile of the out-of-time beam can then be built up statistically, by integrating over many bunches.

INTRODUCTION AND REQUIREMENTS

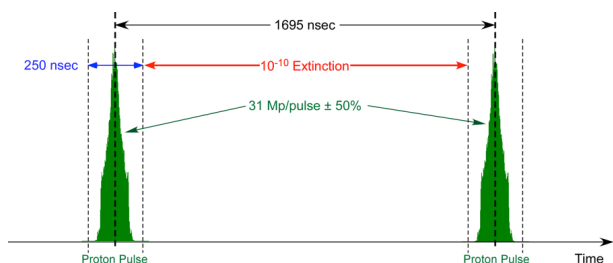


Figure 1: The proton bunch structure required by the Mu2e experiment.

The goal of the Mu2e experiment [1] is to search for the conversion into an electron of a muon that has been captured by a nucleus ($\mu N \rightarrow e N$). This manifestly violates the conservation of charged lepton flavor number, and its observation would therefore be an unambiguous indicator of physics beyond the Standard Model.

A key component of the experimental technique is the proton beam structure, 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 μ sec, which are used to produce pions, which subsequently decay to 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. The technique used to achieve this level of extinction is described elsewhere [2]. It is achieved in two parts. The formation of the bunches in Fermilab Recycler and Delivery ring is expected to have extinction on the order of 10^{-5} . The remaining extinction will be accomplished in the primary

beam line with a system of resonant dipoles and collimation, configured to allow only the in-time beam to be transmitted.

It is of course vital to verify that this level of extinction has been achieved, so the experiment has specified that a level of extinction of 10^{-10} or lower can be measured within a few hours of running at the nominal intensity.

TECHNIQUE

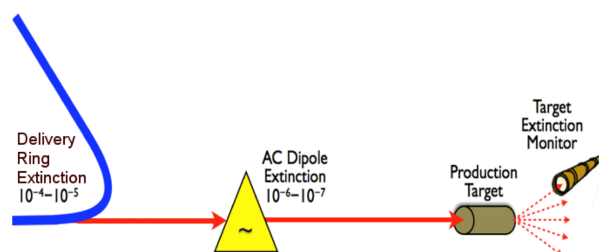


Figure 2: Concept for the statistical extinction monitoring technique.

Each bunch in the Mu2e experiment has roughly 3×10^7 protons, so our desired extinction level corresponds to less than one out-of-time proton every 300 bunches. Unfortunately, measuring single protons in the presence of such large bunches would require a dynamic range that is beyond state of the art for current beam instrumentation. We choose instead to focus on a statistical technique, as illustrated in Figure 2. The pion production target will be monitored by a dedicated spectrometer, the acceptance of which has been designed such that it will not be saturated by the particles observed from the in-time bunch. The spectrometer will then detect a small fraction of out-of-time particles, so that over many bunches, an accurate time profile can be integrated for both the in- and out-of-time protons. Over time, a measurement of the out-of-time beam can be made with increasing sensitivity, limited ultimately by the rate of fake background tracks.

It must be stressed that our aim is not to veto individual events occurring near out-of-time protons, but rather to verify that the total rate of such protons is below that which we have determined to be acceptable.

This technique is conceptually very similar to techniques that have been used for precision measurement of transverse beam halo [3].

DESIGN

The layout of the Mu2e pion production target is shown in Figure 3. Primary protons are incident on a Tungsten target that is within a superconducting solenoidal magnet. The experiment itself uses low momentum, backscattered

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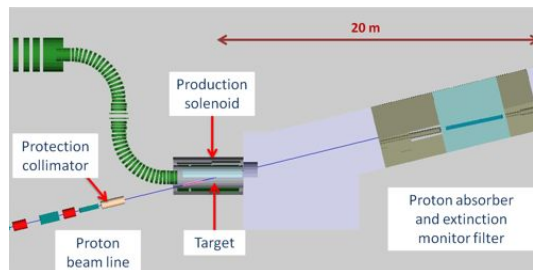


Figure 3: Orientation of the Extinction Monitor within the Mu2e experiment.

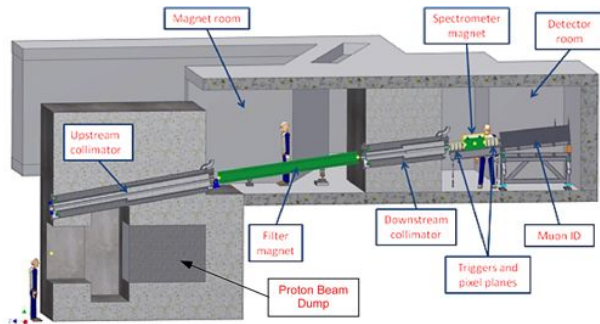


Figure 4: Details of the Extinction Monitor. A selection channel limits the acceptance of the spectrometer. Tracking is done with pixel planes before and after a permanent magnet, which is used to select momentum. An absorption calorimeter can be used to measure the muon content of the particles.

pions, most of which decay to muons. Forward particles and non-interacting protons strike the dump, shown at the right of the figure. The Extinction monitor is located above the dump, and is integrated into its shielding.

The design has been optimized to detect scattered particles of 4-5 GeV/c momentum, which will be primarily scattered protons. Relatively high momentum particles were chosen both to achieve the desired rate and because we have more confidence on the models in that range.

An important component of the detector is the “selection channel”, which consists of a momentum selection magnet and two collimators. The first collimator is integrated into the shielding, as shown in Figure 5. This is a collimator with a 50 mm circular aperture. Except for this aperture, there must be no gaps in the shielding. To meet this requirement,

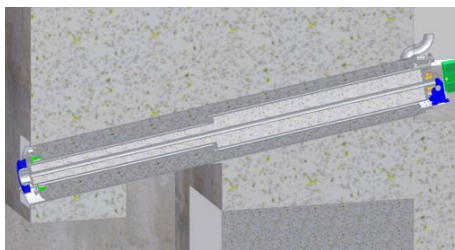


Figure 5: The acceptance collimator, which is integrated into the dump shielding.

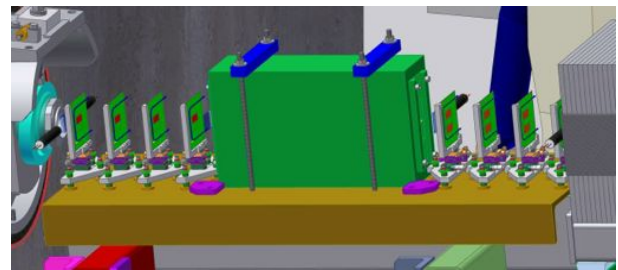


Figure 6: The tracking spectrometer of the Mu2e experiment, consisting of eight planes of pixel detectors and a permanent magnet spectrometer.

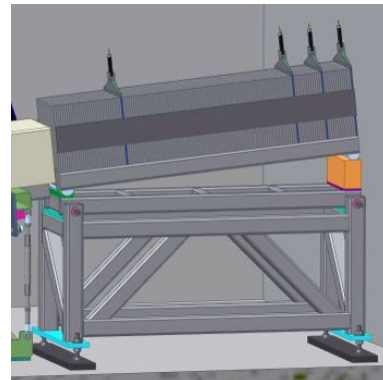


Figure 7: Muon range stack, consisting of steel absorber plates and scintillator.

the collimator consists of a central channel segment, placed inside slightly larger channel, which is rough aligned when the shielding concrete is poured. Adjustment hardware at the upstream and downstream ends allows for precise alignment of the channel. Once it is aligned, the space between the inner and outer channel will be filled with steel shot, to complete the shielding.

The tracker consists of eight detector planes, four upstream and four downstream of a spectrometer magnet, as shown in Figure 6. The detector is based on the ATLAS planar pixel modules developed for the insertable B-layer upgrade [4, 5]. A module consists of a silicon sensor bump bonded to two FE-I4 chips. Each chip reads out 26,880 pixels arranged into 80 columns on a 250 μm pitch by 336 rows on a 50 μm pitch. The upstream planes have two sensors each, while the downstream planes have 3 each.

The spectrometer magnet is a repurposed prototype permanent dipole from the Fermilab Recycler Ring. Its Mu2e purpose is to bend out low energy electrons generated from muons stopping in the upstream silicon and decaying out of time. It was chosen because it was the shortest (0.5 m) available permanent dipole. Its 0.14 T-m integrated field provides enough bend to permit a $\sim 10\%$ momentum measurement, although that is not its primary purpose.

Particles from target interactions will have a very small muon content. If significant out-of-time tracks are observed, the muon content can be used to determine if they are from genuine out-of-time beam particles striking the target, or are

instead due to some other source of background. For this reason, the detector includes a muon range stack, consisting of a steel block, 40 cm square and 180 cm in depth, as shown in Figure 7. To facilitate construction, the steel will consist of a series of plates, 40 cm square and 1.2 cm in thick. The range stack will include four scintillating planes. Three scintillator counters will be placed as close to 145 cm, 162 cm and 180 cm as practical, subject to engineering considerations.

DATA ACQUISITION

The detector includes six scintillator paddles used for triggering. Online signal processing, trigger generation, and data formatting for readout are performed using FPGAs that receive data from the front-end electronics by means of FPGA Mezzanine Cards (FMCs). The FMC provides a well-defined interface between the front-end electronics and the DAQ system that largely decouples the design of the front-end electronics from specific choices of hardware platforms.

We expect several tracks during every in-time bunch, so in-time triggers will be prescaled by a factor on the order of 10.

PERFORMANCE

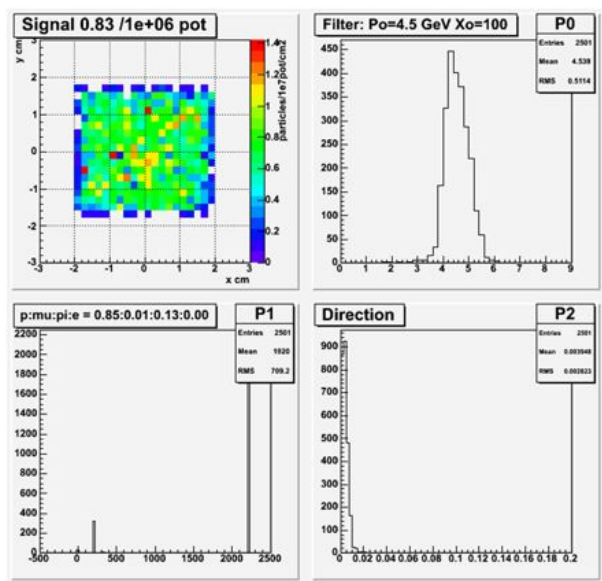


Figure 8: Results of a signal rate simulation for the target extinction monitor. The top left panel shows the expected distribution of signal tracks at the first pixel plane. The top right shows their momentum distribution. The bottom left shows the distribution of GEANT4 particle IDs and the bottom right shows the angle in radians between their direction of travel and the filter axis.

The target station, beam dump, shielding, and Extinction Monitor detector were simulated using G4Beamline [6], and the resulting distributions are shown in Figure 8. It was found that 8.3×10^{-7} tracks were detected for each proton

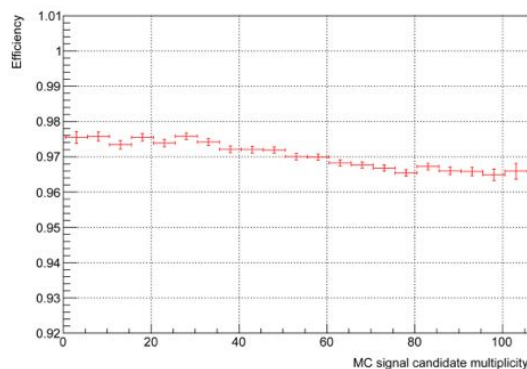


Figure 9: Efficiency of the tracking system as a function of track multiplicity.

on target, for an average of 25 tracks per 3×10^7 proton bunch. A GEANT4 based simulation that included detailed sensor and chip response effects, followed by a simple track finding and reconstruction code, showed that the detector has a good track reconstruction efficiency up to over 100 track per microbunch, as shown in Figure 9. As expected, the tracks are primarily protons, with momentum between 4 and 5 GeV/c. Assuming we need roughly 10 tracks to establish a signal at 10^{-10} , this would mean correspond to $(10)/(10^{-10})/(8.3 \times 10^{-7}) = 1.2 \times 10^{17}$ protons on target, which takes about six hours at the nominal beam intensity for the experiment.

Cosmic ray backgrounds were estimated using a GEANT4 [7] simulation, and were found to be less than 0.03 tracks per hour, corresponding to $.2 \times 10^{-10}$. The background induced by late arriving particles from proton beam interactions was estimated using a high statistics, multi-stage simulation. The simulation used MARS [8] to simulate proton interactions in the production target and the beam dump, and propagation of shower particles through the shielding. Particles entering the detector room volume were passed to the GEANT4 simulation. In addition, noise hits from electronics and radiation were added. The number of resulting fake tracks were found to be negligible compared to the cosmic rate.

CONCLUSION

Analysis has shown that the proposed extinction monitor will be able to measure extinction levels at the 10^{-10} level or lower in the Mu2e experiment, as required by the physics goals of the experiment.

RELATED CONTRIBUTIONS

“Out of Time Beam Extinction in the Mu2e Experiment” (THPF121) describes the technique and projected performance of the Mu2e extinction system.

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