PROCEEDINGS OF SCIENCE

Resonant Extraction and Extinction Measurement for the Mu2e Experiment

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The Mu2e experiment, currently under construction at Fermilab, will search for coherent neutrinoless muon to electron conversion, extending the sensitivity of searches for charged lepton flavour violation by four orders of magnitude in 3-5 years of data-taking. This improved sensitivity is made possible by using a pulsed beam structure that is optimized for reducing prompt backgrounds when muons are stopped on an aluminium target. Producing a high-rate pulsed beam is achieved using resonant extraction of a circulating proton beam, an "AC dipole" with a time-varying field to deflect out-of-time protons, and a system to measure the extinction of out-of-time beam particles incident on the muon production target. These proceedings summarize the systems that have been designed to achieve the required level of extinction and to continuously place limits on the presence of out-of-time beam hitting the production target with a sensitivity of $<10^{-10}$.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

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1. Introduction

Charged lepton flavour violation (CLFV) is a process that is not explicitly forbidden by any known symmetry principles and is, in fact, allowed in the standard model as a consequence of non-zero neutrino masses [1]. In the context of the standard model, however, rates of CLFV processes are extremely small. For example, the process $\mu \to e\gamma$ has a predicted branching fraction of 10^{-54} and consequently, any observation of such a decay would be clear indication of physics beyond the standard model.

Without introducing explicit constraints, many new physics models naturally introduce potentially large CLFV [2], making searches for these processes an important way to constrain extensions to the standard model. Since the discovery of the muon, experiments have placed increasingly strong limits on muon-to-electron conversion processes which may occur via a 4-fermion vertex, or an anomalous $\mu e\gamma$ coupling. Both interactions can lead to a distinctive final state when a μ^- is captured by a heavy nucleus and converts coherently to e^- without the emission of neutrinos. This particular process is one of several final states targeted by the next generation Mu2e [3] and COMET [4] experiments, which will search for CLFV.

2. The Mu2e Experiment

Currently under construction at Fermilab, the Mu2e experiment has been designed to extend the sensitivity of searches for CLFV by four orders of magnitude in 3-5 years of operation. A proton beam will be delivered to a pion production target, and the negatively charged muons from their decays will be transported to a detector where they will stop in a target composed of aluminum foils. Captured muons that undergo normal decays in orbit around the nucleus will produce electrons with a characteristic energy spectrum with an endpoint near 50 MeV [5], but coherent μ to e conversion produces electrons with a characteristic energy of 105 MeV, which the Mu2e tracking detector and calorimeter are optimized to observe.

A potentially limiting source of background for this measurement is from pions produced at the production target that are transported to the stopping target and undergo radiative pion capture with subsequent photon conversion in the stopping target material. This background will be greatly reduced in the Mu2e experiment through the use of a pulsed proton beam with a time structure that is well matched to the lifetime of muons captured on aluminum, which is significantly longer than the pion lifetime. In this way, the search for the emission of 105 MeV electrons will be performed after the decay of any pions that may have been transported to the stopping target.

The reduction in backgrounds from radiative pion capture will rely critically on the quality of the pulsed beam delivered to the pion production target. The beam quality can be characterized by the number of protons-on-target per pulse, but also by the beam extinction, defined as the fraction of protons in the beam that are not in-time with the main beam pulse. The sensitivity of the Mu2e experiment will require the extinction of beam on target to be at most 10^{-10}, but this can be achieved by means of a beam delivery system specifically optimized for the time scales of muons captured on aluminum.

3. Beam Delivery

Protons in the beam delivered to the Mu2e pion production target will be initially accelerated to 400 MeV in the Fermilab Linac, and then to 8 GeV in the Booster ring, after which they will be transferred to the Recycler where their bunch structure is formed. A single batch of 8 GeV protons injected into the Recycler will be divided into 4 bunches which will then be extracted individually and transferred to the Delivery Ring. The Delivery Ring is located in the tunnel originally built for anti-proton production at Fermilab [6], but has a circumference that allows beam to circulate with a period of 1 695 ns. This time structure, shown in Figure 1, is well suited to the Mu2e experimental requirements, as it is much longer than the 26 ns pion lifetime, and approximately twice the 864 ns lifetime of muons captured on aluminum.

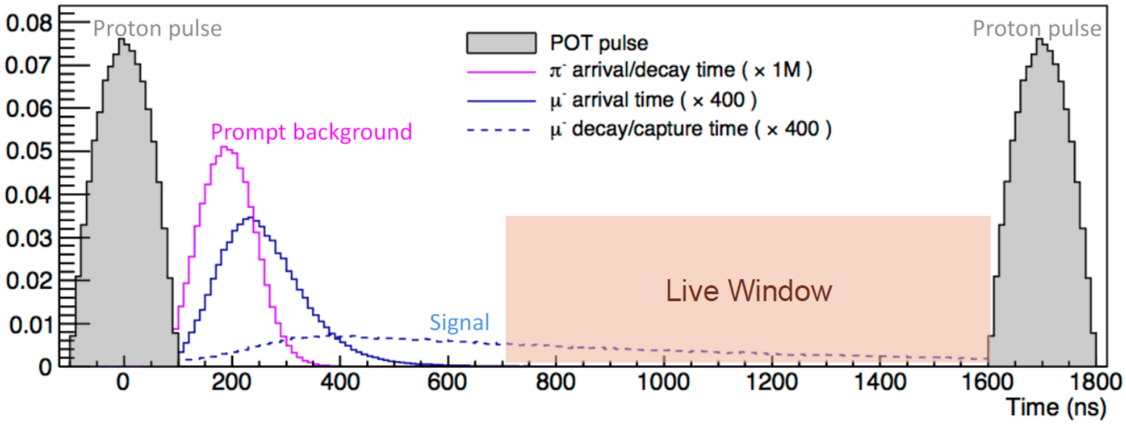

Figure 1: Time structure of the beam pulses delivered to the pion production target, muons delivered to the stopping target, prompt backgrounds and muon decays.

The pulsed beam will be obtained by forming a circulating bunch within the Delivery Ring with a longitudinal time structure that is less than 250 ns in width, and extracting a portion of the circulating beam on each orbit. A key requirement of the extraction system is to deliver pulses with approximately equal intensity, nominally 4×10^7 protons-on-target, throughout the extraction process until the circulating beam is exhausted.

3.1 Resonant Extraction

A circulating bunch in the Delivery Ring will initially contain 10^{12} protons in a stable orbit. The extraction of much lower intensity pulses will be performed by allowing the circulating beam to gradually migrate to an unstable orbit, by operating close to a resonant tune with significant sextupole field strength [7]. Beam on the unstable orbit will pass through an electrostatic septum, which will place it in a region of high electric field, while protons on the stable orbit will pass through a field free region, separated by a conducting metal foil. Both beams will then pass through a quadrupole which will not deflect beam on the central orbit, but which will increase the separation between the stable and unstable beam trajectories. These will then pass through a second electrostatic septum and quadrupole magnet, before entering a Lambertson magnetic septum that will eject the extracted protons into a beam line that leads to the pion production target.

3.2 AC Dipole

The bunch structure of the circulating beam is expected to have a natural extinction of 3.2×10^{-5} which is much larger than the 10^{-10} requirement needed to reach the desired experimental sensitivity. To further improve the beam extinction, the extracted beam pulses will pass through a series of three 1 meter dipole magnets that are excited with an AC current source. The in-time beam pulse will pass through this system during the zero-crossing of a superposition of 300 kHz and 4.5 MHz harmonics, while out-of-time beam will be kicked at an angle and removed by a downstream collimator. This system has been designed to transmit in-time beam with an efficiency of 99.5% but has a total transmission of less than 5×10^{-8} for beam outside a 250 ns transmission window. In this way, the extinction of beam on target will be less than 1.6×10^{-12}, sufficient to satisfy experimental requirements.

4. Extinction Measurement

In order to claim the required experimental sensitivity, it is necessary to measure the fraction of non-extinct beam arriving at the pion production target. This will be achieved by observing particles produced at the production target, or scattered by the target material, and which intersect a small region of phase space selected by a system of two collimators with a permanent dipole magnet between them. This arrangement will select a collimated beam of protons and pions originating from the production target with a median momentum of approximately 4 GeV. These particles will pass through 8 planes of silicon pixel sensors, constructed using an ATLAS sensor design [8] and FE-I4b readout chips [9], which can be triggered by means of plastic scintillators, located upstream and downstream of the pixel planes. A permanent dipole magnet between the four upstream and the four downstream planes removes low-energy secondary particles from the beam and provides a way to discriminate between out-of-time particles emerging from the collimator, and electrons produced from the decays of low-energy muons that have stopped in the detector.

4.1 Pixel Telescope

The pixel system is read out using a system of custom electronics for control, monitoring, and logic-level translation, which interface with FPGA's on modules in a MicroTCA form factor. Scintillators in the system are read out using 12 bit waveform digitizers operating at 1 GSPS and the trigger logic is implemented in the design of the firmware. Pixel hit data is read out over a 10 Gbps Ethernet link and will be analyzed in a multi-core server to identify patterns of hits that correspond to tracks passing through the pixel telescope.

The choice of pixel readout allows for high efficiency track identification with low fake rates, and excellent linearity with beam intensity. Any track passing through the scintillators that is not in-time with the expected beam pulse will trigger the readout of the pixel system, while in the absence of any such track, a pre-scaled trigger will be generated to sample the hits from tracks that are in-time with the beam pulse. Calculations performed using G4Beamline [10] indicate that at nominal pulse intensity, approximately 40 charged particles are expected to pass through the fiducial acceptance of the pixel telescope. In the absence of any out-of-time event, this rate will allow a limit on the extinction better than 10^{-10} to be measured on a time scale of a few hours.

4.2 Slow Extraction Feedback

The electronics that interfaces with the pixel system also digitizes the signal from a larger scintillator (40 cm x 40 cm) which is coupled to a photomultiplier tube by means of embedded wavelength shifting fibers. The resulting waveform is digitized to provide an estimate of the light yield on a pulse-by-pulse basis. Pulses of nominal intensity are expected to result in an average of 200 minimum ionizing particles passing through this scintillator, corresponding to a 7% pulse intensity measurement.

The digitized pulse-by-pulse intensity is to be transmitted back to the Delivery Ring via optical fiber and provides information with which to modulate the amplitude of an RF noise source which forces circulating beam to migrate towards the unstable orbit. In this way, the intensity of the extracted beam will be regulated to reduce fluctuations in extracted pulse intensity over timescales of milliseconds.

5. Status and Future Outlook

At this time, beam is planned to be first delivered to the pion production in 2023 and the extinction monitor will be an integral tool with which to study the time structure and intensity of the delivered beam pulses. The components of the extinction monitor have already been assembled and will be moved into the experimental area after installation of the system of collimators and the Mu2e detector system in 2022.

The beam delivery system for the Mu2e experiment is optimal for the time scales involved in the capture of muons on aluminum, given existing constraints of the Fermilab accelerator complex. Should a conversion electron signal be observed, it will be necessary to determine the nature of the new physics couplings responsible for this process. Fortunately, additional information can be obtained by measuring conversion rates on elements other than aluminum [3], but the lifetimes of muons captured on these nuclei is typically much shorter than 1 695 ns.

In the future, high intensity muon beams with suitable time structure will be provided at Fermilab by the PIP-II superconducting linear accelerator [11] which is planned to deliver an 800 MeV proton beam to a broad range of particle physics experiments. In addition to the greater flexibility in generating required beam time structures, the energy is below the anti-proton production threshold, eliminating another source of potential background in future CLFV experiments. It appears, however, that the next generation pixel readout chips, currently under development for experiments operating at the High-Luminosity LHC, will be well suited for extinction measurements using the principles employed in the Mu2e experiment.

Acknowledgments

We are grateful for the vital contributions of the Fermilab staff and the technical staff of the participating institutions. This work was supported by the US Department of Energy; the Italian Istituto Nazionale di Fisica Nucleare; the Science and Technology Facilities Council, UK; the Ministry of Education and Science of the Russian Federation; the US National Science Foundation; the Thousand Talents Plan of China; the Helmholtz Association of Germany; and the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement No. 690835. This document was prepared by members of the Mu2e Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

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