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DESIGN OF A PIP-II ERA Mu2e EXPERIMENT

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Abstract

We present an alternative Mu2e-II production scheme for the Fermilab PIP-II era based on production schemes we devised for muon-collider and neutrino-factory front ends. Bright muon beams generated from sources designed for muon collider and neutrino factory facilities have been shown to generate two orders of magnitude more muons per proton than the current Mu2e production target and solenoid. In contrast to the current Mu2e, the muon collider design has forward-production of muons from the target. Forward production from 8 GeV protons would include high energy antiprotons, pions and muons, which would provide too much background for the Mu2e system. In contrast, the 800 MeV PIP-II beam does not have sufficient energy to produce antiprotons, and other secondaries will be at a low enough energy that they can be ranged out with an affordable shield of ~ 2 meters of concrete.

INTRODUCTION

The Mu2e experiment at Fermilab will search for evidence of charged lepton flavor violation by searching for the conversion of a negative muon into an electron in the Coulomb field of a nucleus, without emission of neutrinos. The current Mu2e experimental production setup will be capable of producing $\sim 2 \cdot 10^{17}$ negative muons per year. Regardless of the Mu2e outcome, a next generation experiment, Mu2e-II, with a sensitivity extended another factor of 10 or more, has a compelling physics case. This upgrade will require a complete re-design of the muon production and transport, which is the subject of this proposal.

The current Mu2e design is optimized for 8 kW of protons at 8 GeV. The proposed PIP-II upgrade project is a 250-meter-long CW linac capable of accelerating a 2 mA proton beam to a kinetic energy of 800 MeV (total power 1.6 MW). This would significantly improve the Fermilab proton source to enable next-generation intensity frontier experiments. Much of the beam will be utilized for the Fermilab Short Baseline Neutrino and Long Baseline Neutrino Facility neutrino programs, but more than 1 MW of 800 MeV protons will be available for additional experiments. It is expected that Mu2e-II will require about 100 kW.

PREVIOUS WORK ON MU2E

In 2015 Muons, Inc. had a subcontract from Fermilab's Mu2e Project to perform an initial study of how PIP-II would affect the Mu2e experiment, in particular the impact of using 800 MeV protons. This was specifically in the context of the current Mu2e design, with the intent of evaluating minimal changes required to use 800 MeV protons at ~ 10 times the power, to obtain 10 times the rate of stopping muons. We have used the Muons, Inc. software package G4Beamline [1] in these studies. Figure 1 shows a G4Beamline simulation of the current Mu2e experiment.

Muons, Inc. did initial studies of Mu2e in the PIP-II era, looking at three scenarios. The first scenario attempted to put 800 MeV protons onto the Mu2e production target, using the same hole in the HRS as the 8 GeV beam. We found that while it is possible to hit the target, it is not possible for the beam to miss the HRS. The HRS (obviously) cannot handle the full 100 kW beam. The production solenoid field was varied from 3 T to 5 T (baseline, 4.5 T), but it is not possible to use 800 MeV protons with the current HRS, production solenoid, and target.

The second scenario considered drilling a new beam hole into the HRS and moving the beamline ahead of the HRS to match. By moving the incoming proton beam closer to the production solenoid axis, it is possible to hit the target and miss the HRS. But this was found unacceptable for three reasons: 1) One or more transport solenoid coils were always in the way. 2) The brass HRS was found to be inadequate to protect the production solenoid coils from 100 kW of beam. 3) It is unlikely that holes could be drilled, as the HRS will be highly radioactive after Mu2e operation.

The third scenario introduced a modest change, removing one TS coil, so two of the gaps between coils would be combined into one gap about 20 cm wide. By putting the proton beam right down the production solenoid axis, it is possible to hit the target and miss the HRS. This would require a re-design of the HRS and target, plus the change to the TS, and the beam absorber must be moved (Fig. 2).

So the "modest change" approach would require:

- Removing one TS coil and drilling a hole for the beam in its cryostat.
- Replace the HRS with one made of tungsten.
- Move the beamline ~100 mm closer to the TS, slight angle.
- Move the target, add active cooling.
- Move the beam dump.

FORWARD PRODUCTION MU2E PIP-II

The conclusion of this earlier work was that for Mu2e in the PIP-II era, using the 800 MeV beam requires a redesign of the beamline, target, shielding, production solenoid, and beam absorber at minimum. In this case a whole new configuration of the front end should be considered. We proposed that our **forward production** schemes for muon colliders and neutrino factories be considered as an alternative.

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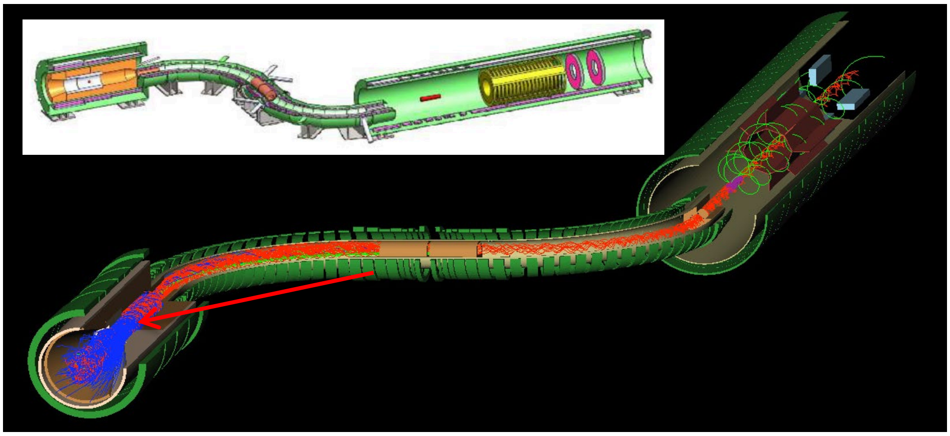

Figure 1: Simulation of the Mu2e beam channel and detector as an example of use of the G4beamline interface to Geant4 which can accommodate simulations of complex magnet channels, acceleration fields and tracking of particles through these field. The arrow shows the direction of the proton beam into the production solenoid "backward production".

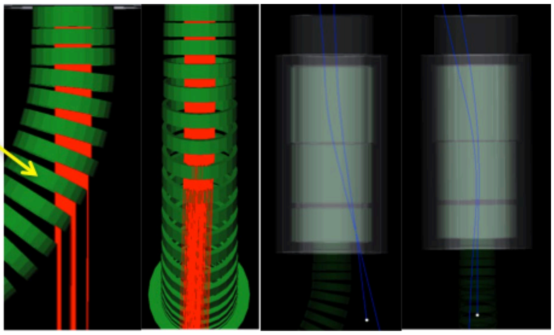

Figure 2: Side and top views of coils in the transport sole-noid, with 800 MeV protons from the target tracked *back-wards* (headed downward) to show where they intersect the transport solenoid. The yellow arrow points to the TS coil that would be removed (left). This moves the beam in the production solenoid (right).

Muon-collider front ends generate significantly more muons per proton than Mu2e's target and production solenoid. (.06 m/p vs .0016 m/p). Mu2e rejected such forward production due to the muon background it generates, but for 800 MeV muons 2 meters of concrete can range out 800 MeV muons. Furthermore, Mu2e-II 800 MeV beam will not produce anti-protons. A small amount of longitudinal cooling can significantly increase the fraction of muons that stop. The absorber used for cooling can significantly clean up the hadron flash. This might permit a shorter dead time and allow the use of higher-Z stopping targets.

In previous grants Muons, Inc. applied the Helical Cooling Channel (HCC) concept [2] for muons colliders, improved capture techniques, and simulation tools to develop designs for low-energy beam lines to stop many muons in small volumes. We had two previous studies that can be adapted for the PIP-II era Mu2e experiment upgrade, described below.

HCC ELEMENTS FOR MUON BEAMS

In HCC beamlines, higher-momentum particles lose more energy because they have longer path lengths in a continuous gaseous absorber, thereby reducing the beam energy spread and hence the longitudinal emittance. The HCC can be used without absorber as a decay channel as in Fig. 3, and a succession of HCC segments in Fig. 4.

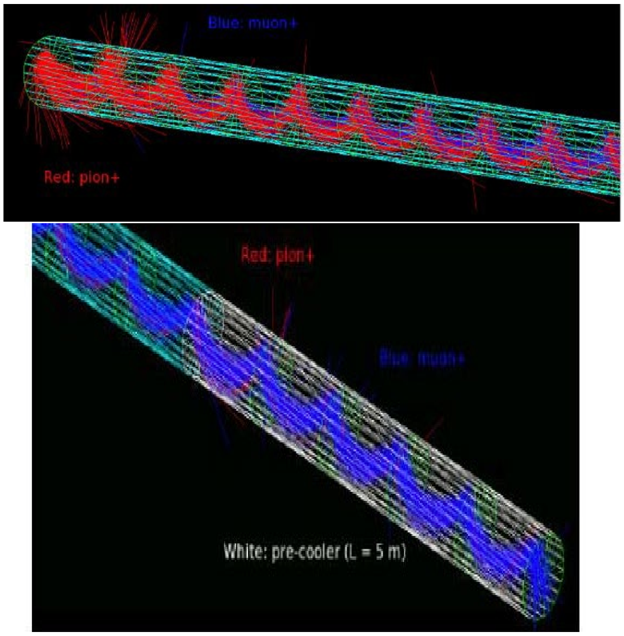

Figure 3: G4Beamline simulation of muon (blue) and pion (red) orbits in a HCC-type magnet that is adapted as a decay channel.

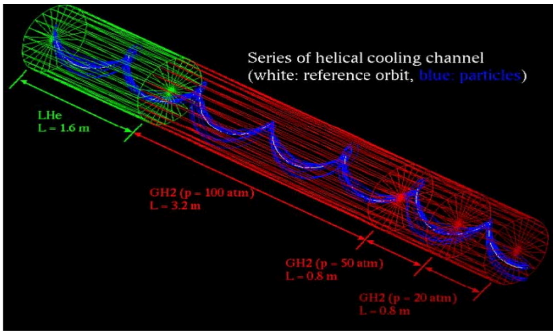

Figure 4: An HCC channel – the red area is absorber filled for cooling.

INTENSE STOPPING MUON BEAMS

The Muons, Inc. Stopping Muons Beams [3] study looked at a forward production model based on an 8 GeV proton source. The conceptual innovation developed by Muons, Inc. used an HCC segment that received pions that decayed into muons, produced off a target in front of a dipole. The combination of dispersion from the magnet and a wedge absorber narrowed the momentum distribution, which is fed into an HCC segment. Figure 5 shows the schematic for this channel. Muons with a narrow time and momentum spreads will enable the use of higher Z target, and maintain the necessary "extinction" factor. Figure 6 shows the evolution of the muon energy spread through simulations.

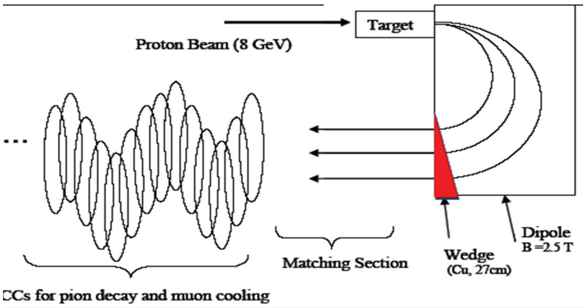

Figure 5: Dipole and Wedge into an HCC.

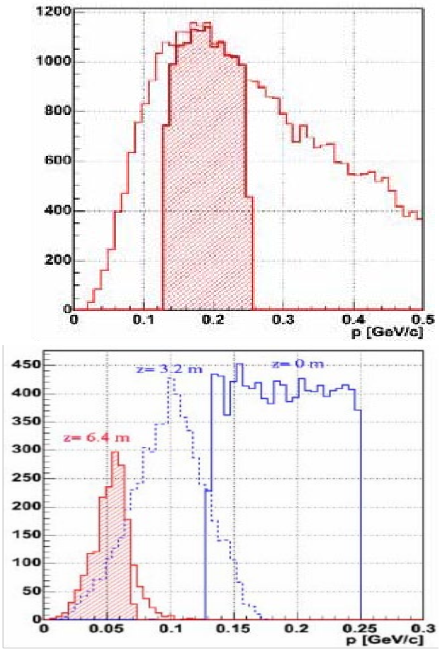

Figure 6: (top) A plot of the muon flux from the target pro-duced by an 8 GeV proton beam and the subset (hatched area) that enters the first HCC segment. (bottom) A plot of the evolution of the muon momentum spread from the start of the cooling channel (z=0) through a series of HCC seg-ments with reduced hydrogen absorber density to the stop-ping target at z=6.4 m.

QUASI-ISOCHRONOUS HCC

A related idea conceived for the collection and cooling of muon beams, namely, a Quasi-Isochronous Helical Channel (QIHC) [4] to facilitate capture of muons into RF buckets, has been developed further. The resulting distribution could be cooled quickly and coalesced into a single bunch to optimize the luminosity of a muon collider. It also can be optimized for Mu2e. The QIHC concept takes advantage of the larger RF buckets for particles traveling in nearly isochronous orbits. Critical components of a QIHC system include the following: (1) a helical magnetic field that creates helical particle trajectories near a reference orbit of a selected muon momentum, (2) RF cavities that capture particles in stable buckets, and (3) an absorber that reduces the energy of particles that would otherwise be too energetic to be captured, shown in Fig. 7. Figure 8 shows the beam evo-lution and longitudinal compression.

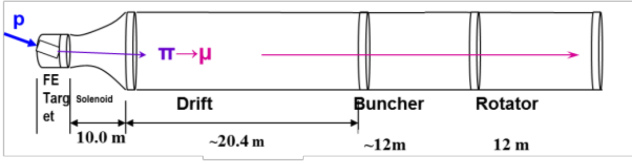

Figure 7: Conceptual Layout of Front End for low energy μ capture.

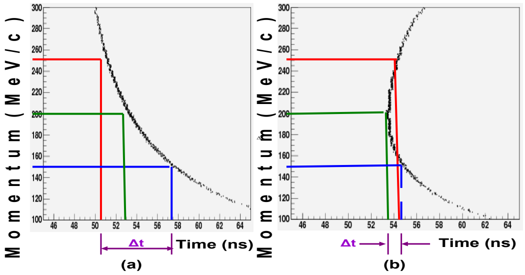

Figure 8: Isochronous evolution in a QIHC.

LOW ENERGY PRODUCTION

The Muons, Inc. inventions were based on 8 GeV proton sources. For an 800 MeV proton source, the same cooling sections may not be as efficient, and other or additional schemes will be examined. Neuffer et al [5] have looked into wedge concept to narrow the energy spread as the beam is decelerated. They also considered RF deceleration. The simplest decelerator is a constant frequency RF system matched to the bunch spacing at the end of the rotator (~208.7MHz), with phase matched to reduce the energy at ~5 MV/m. A first attempt is relatively efficient in reducing the beam momentum to < 70MeV/c (21MeV), as may be needed for a rare decay experiment. Roughly half of the trapped μ's can be decelerated into the low energy region by this simplified system, obtaining beam for rare decays at ~0.04 μ/p. For comparison, that is about two orders of magnitude larger than the μ/p ratio of the current Mu2e beam. The layout is shown in Fig. 9.

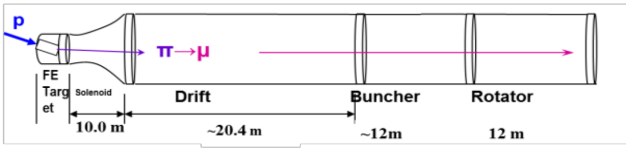

Figure 9: Conceptual Layout of Front End for low energy μ capture.

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