AC DIPOLE SYSTEM FOR INTER-BUNCH BEAM EXTINCTION IN THE MU2E BEAM LINE*

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Abstract

The Mu2e experiment has been proposed at Fermilab to measure with unprecedented precision the rate for muons to convert to electrons in the field of an atomic nucleus. This experiment uses an 8 GeV primary proton beam consisting of short ($\approx$100 nsec) bunches, separated by 1.7 μsec. It is vital that out-of-bunch beam be suppressed at the level of 10^{-9} or less. Part of the solution to this problem involves a pair of matched dipoles operating resonantly at half the bunch rate. There will be a collimation channel between them such that beam will only be transmitted when the fields are null. The magnets will be separated by an integer multiple of 180° in phase advance, such that their effects cancel for all transmitted beam. Magnet optimization considerations will be discussed, as will optical design of the beam line. Preliminary simulations of the cleaning efficiency will also be presented.

MOTIVATION

The study of rare decays has long been accepted as a powerful tool to probe mass scales that are beyond the reach of conventional searches, particularly those that involve charged lepton flavor violation (CLFV). Among these, rare muon decays offer a unique combination of very low backgrounds and clean experimental signatures.

The Mu2e experiment [1] has been proposed at Fermilab to search for the conversion into an electron of a muon which has been captured by a nucleus ($\mu N \to eN$). The muon would decay through the exchange of virtual particle with the nucleus, thus balancing the momentum of the decay and producing the striking experimental signature of a mono-energetic electron, carrying most of energy associated with the muon's rest mass. This is related to the search for $\mu \to e\gamma$, but is sensitive to a broader range of physics.

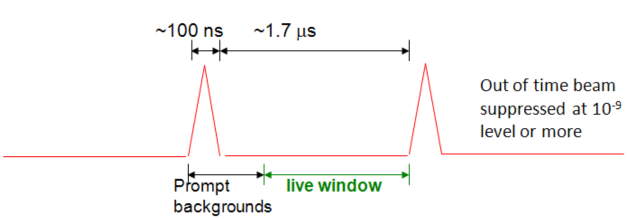

Figure 1: Proton bunch timing required by the Mu2e experiment.

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The Mu2e experimental technique is described elsewhere [2]. A key component of this technique is the proton beam structure, which is illustrated in Figure 1. The beam consists of short ($\approx$100 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 experiment will only search for signal events between these bunches.

Because many backgrounds occur promptly with respect to the muon production, transport, and capture, it's vital that the live interval between the bunches be made as completely free of protons as possible. The experiment is relying on suppression at least 10^{-9} [3]; that is, no more than one out of time proton for every 10^9 protons falling within $\pm$ 100 ns of the bunches.

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 of at least 10^{-6}.

TECHNIQUE

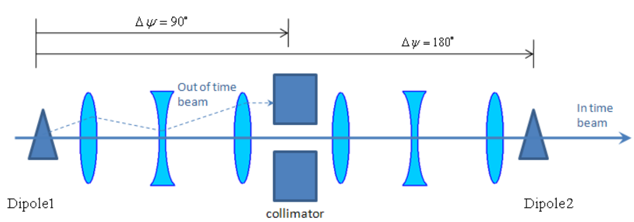

Figure 2: General scheme of the AC dipole extinction channel. Beam is only transmitted at times near the nodes of the AC dipole resonant circuit.

Ideally, one would introduce a pulsed magnet into the beam line which would kick beam into the transport channel at the time of the bunches; however, the high ($\approx$ 600 kHz) bunch rate renders this solution impractical for a beam momentum this high. For this reason, we have designed a system which utilizes a pair of resonant "AC" dipoles.

The basic scheme is shown in Figure 2. Two dipoles are separated by 180° (or an integer multiple of 180°) in phase advance. These are driven by a common sine wave, such that the second dipole cancels any deflection from the

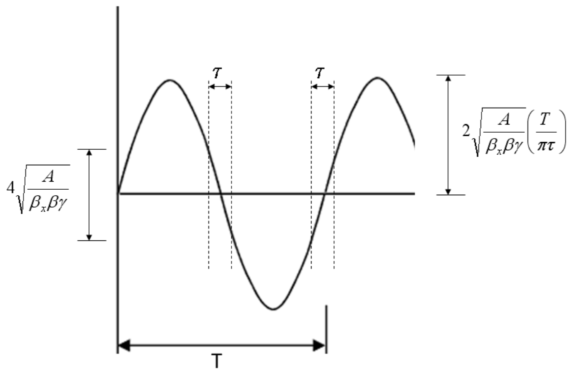

Figure 3: Concept for the AC dipole system. Because beam is transmitted at the node, the system only needs to run at half the bunch frequency. However, producing a short transmission window requires the system to run at a higher amplitude than would otherwise be needed.

first. A collimator is placed at a point 90° advanced from the first dipole, which will intercept any beam significantly far away from the nodes of the driving sine wave. Because beam is transmitted on the nodes, the system only has to run at half the pulse rate, or roughly 300 kHz, as illustrated in Figure 3. The fact that the circuit runs resonantly will significantly reduce the demands on the power supply.

MAGNET OPTIMIZATION

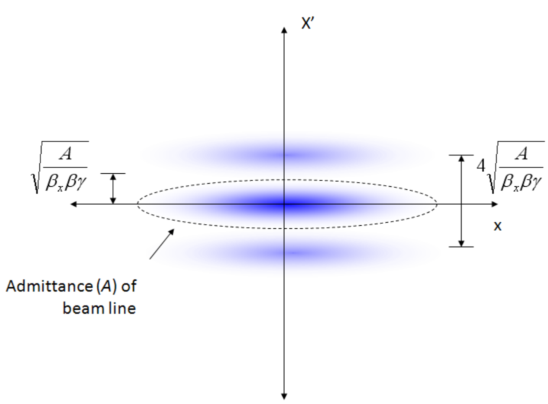

Figure 4: Effect of the AC dipole field in phase space. Beam line admittance A is indicated by the ellipse.

The optimization of the magnet design is discussed in detail elsewhere [4]. The effect of the AC dipole field can be generically treated as a shift in phase space, as shown in Figure 4. If we assume that the beam admittance A is well defined elsewhere in the beam line and is equal to the admittance of the collimator, then beam will be completely extinguished by an angular kick corresponding to twice the full angular amplitude corresponding to the admittance, or

$$\Delta\theta = 2\sqrt{\frac{A}{\beta_x\beta\gamma}}$$

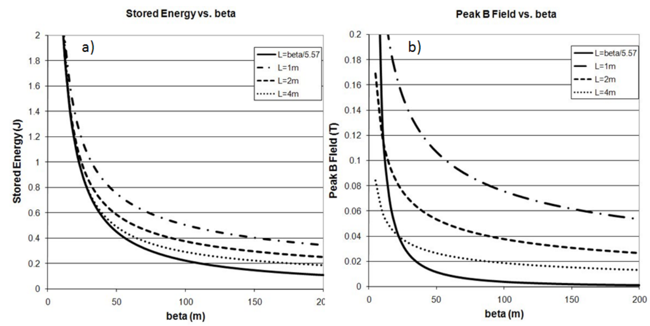

Figure 5: The dependence of peak stored energy (a) and peak magnetic field on β_x at the location of the AC dipole. Note that a length of $L = \beta_x/5.57$ corresponds to the optimum length for a particular β_x, in terms of minimizing the total stored energy.

where β_x is the betatron function in the bend plane and β and γ have their usual definitions. Referring again to Figure 3, we see that the need for a narrow transmission window also drives the peak field requirement. The required peak magnetic field and aperture can be explicitly calculated as a function of admittance A, betatron function β_x, and full width transmission time τ (fixed at 200 ns for our purposes). In general, we would like a magnet with as low field and as low stored energy as possible; however, as illustrated in Figure 5, these things continue to fall with increasing β_x and magnet length, so eventually practical considerations of magnet and beam line design must be considered. Initial magnet and beam line specifications for the nominal Mu2e parameters are shown in Table 1. These specifications have been used for the preliminary design of the magnet [5].

Table 1: Preliminary beam line and AC dipole specifications for the Mu2e experiment.

Parameter	**Value**
(Mu2e beam parameters)	
Kinetic Energy	8 GeV
Admittance	50 π-mm-mr
Bunch Rate	600 kHz
Transmission Window (τ)	200 ns
(AC Dipole specifications)	
β_x	50 m
Length	2 m
Full Aperture in Bend Plane	5 cm
Full Aperture in Non-bend Plane	1 cm
Peak Magnetic Field	600 Gauss
Peak Stored Energy	1.43 J

BEAM LINE MODELING

An extinction channel of this form has been incorporated into the design for the Mu2e proton delivery beam line,

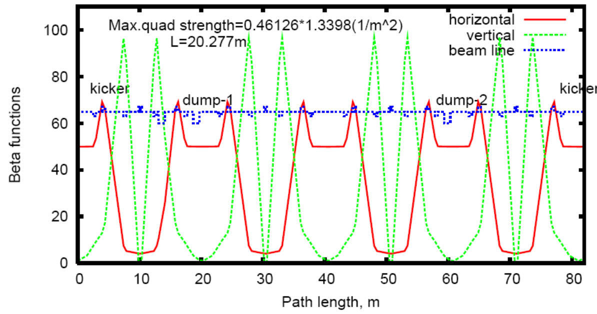

Figure 6: Optical design of Mu2e extinction channel. AC dipoles are indicated as "kickers" and the collimators as "dumps".

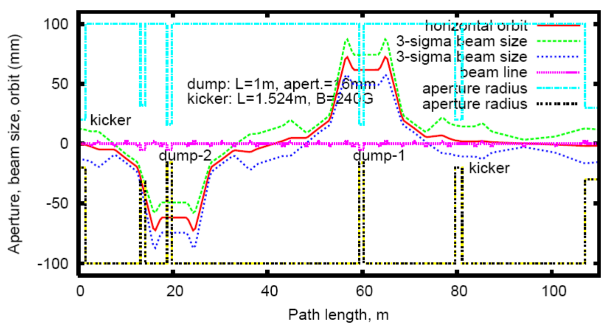

Figure 7: Trajectory of beam deflected by the first AC dipole, such that beam is fully extinguished. Three sigma envelope for a 20π-mm-mr (95%) beam is shown.

as illustrated in Figure 6. In this case, the compensating dipole has been moved to 360° from the first, to allow for a secondary collimator at 180°.

Preliminary simulations of the beam line have been performed using STRUCT [6], and are described in more detail in [7]. Figure 7 shows the trajectory of a fully extinguished portion of the beam. To calculate extinction efficiency, a beam is generated with flat time distribution is generated and transported through the system, with the AC dipoles operating at the nominal frequency and strength. For the purposes of calculation, the beam is divided into 70 pseudo-bunches for each cycle of the AC dipoles. This makes the bunch spacing approximately 50 ns.

Figure 8 shows the time distribution of the surviving beam when starting with a flat time distribution. Note that the beam in the bunch 50 ns away is already showing significant loss. This is somewhat worrisome, as the Mu2e bunches will have a sigma of about 38 ns. However, we see that as expected, beam that is more that 100 ns from the central peak is completely extinguished.

Initial MARS15 [8] simulations have shown that a single steel collimator $20 \times 20 \times 100$ cm with a Tungsten liner of inner aperture 12×36 mm provides a suppression of about 10^5 [9]. We expect that a two-collimator system will substantially improve the system efficiency.

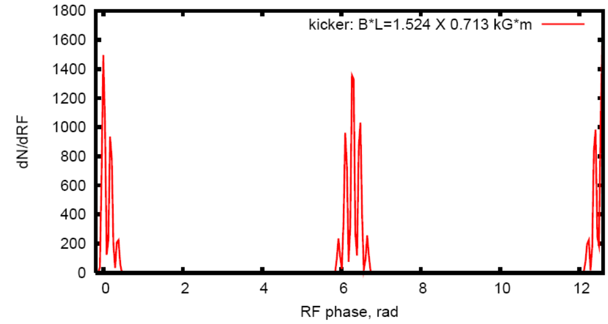

Figure 8: Time distribution of surviving beam, plotted as a function of the phase corresponding to the bunch frequency (twice the AC dipole phase). Pseudo-bunch separation is approximately 50 ns.

STATUS AND PLANS

The Mu2e experiment has been granted Stage 1 approval at Fermilab [10], and the collaboration is working to refine and optimize the experimental design, including the extinction technique. It's become clear that the preliminary magnet specifications present challenges in terms of the peak field required, so we will explore larger, lower field alternatives, based on the relationships shown in Figure 5.

The loss of beam within the longitudinal bunch envelope is undesirable, so we are investigating the addition of higher harmonics in order to reduce the beam slewing within the transmission window.

In addition, preliminary investigations show that the efficiency can be increased dramatically by introducing a secondary collimator at 90° of phase advance past the first one. The beam line has been designed to allow for this. We are in the process of performing full MARS simulations of the two collimator system.

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