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Optimization of Extinction Efficiency in the 8-GeV Mu2e Beam Line*

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Abstract

A muon-to-electron conversion experiment at Fermilab, Mu2e, is being designed to probe for new physics beyond the standard model at mass scales up to 10^4 TeV. For this experiment, the advance in experimental sensitivity will be four orders of magnitude when compared to existing data on charged lepton flavor violation. The muon beam will be produced by delivering a proton beam contained in short 100-ns bunches onto a muon production target, with an inter-bunch separation of about 1700 ns. A critical requirement of the experiment is to ensure a low level of background at the muon detector consistent with the required sensitivity. To meet the sensitivity requirement, protons that reach the target between bunches must be suppressed by an enormous factor, so that an extinction factor, defined as a number of background protons between main bunches per proton in such a bunch, should not exceed 10^{-9}. This paper describes the advanced beam optics and results of numerical modeling with STRUCT and MARS codes for a beam line with a collimation system that allows us to achieve the experimental extinction factor of one per billion.

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OPTIMIZATION OF EXTINCTION EFFICIENCY IN THE 8-GEV MU2E BEAM LINE*

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Abstract

A muon-to-electron conversion experiment at Fermilab, Mu2e, is being designed to probe for new physics beyond the standard model at mass scales up to 10^4 TeV [1]. For this experiment, the advance in experimental sensitivity will be four orders of magnitude when compared to existing data on charged lepton flavor violation. The muon beam will be produced by delivering a proton beam contained in short 100-ns bunches onto a muon production target, with an inter-bunch separation of about 1700 ns. A critical requirement of the experiment is to ensure a low level of background at the muon detector consistent with the required sensitivity. To meet the sensitivity requirement, protons that reach the target between bunches must be suppressed by an enormous factor, so that an extinction factor, defined as a number of background protons between main bunches per proton in such a bunch, should not exceed 10^{-9}. This paper describes the advanced beam optics and results of numerical modeling with STRUCT [2] and MARS [3] codes for a beam line with a collimation system that allows us to achieve the experimental extinction factor of one per billion.

BEAM LINE DESIGN

In order to eliminate backgrounds, inter-bunch or out-of-time protons that would nominally strike the primary target between the 100-ns proton bunches will be swept off the central beam trajectory in the horizontal plane using a 294 kHz sinusoidal waveform AC dipole. The proton bunches are centered on the zero-field crossing point. Three optional solutions are shown in Fig. 1: a first harmonic sinusoidal waveform, a composition of first harmonic and the 17th harmonic (5 MHz) with the amplitude of 1/14 of the main one, and MECO [4] type waveform of the AC dipole. The main bunch length is 6σ = 0.185 rad or 0.1 μsec. Two possible distributions of the DC beam are considered in the simulations: a uniform distribution of background protons and distribution with increased population nearer in time with the main bunches.

Beta-functions in the extinction beam line are presented in Fig. 2. The operational characteristics of the AC dipole are critical to the extinction system. In order to decrease the required strength of the AC dipole for technical reasons, it is placed in a high horizontal and small vertical beta-functions region. Five collimators (CH1-CH5) are located downstream of the AC dipole to intercept swept protons (Fig. 3). The horizontal jaws of first three collimators are aligned with respect to the reference beam trajectory and to optimize collection of swept protons.

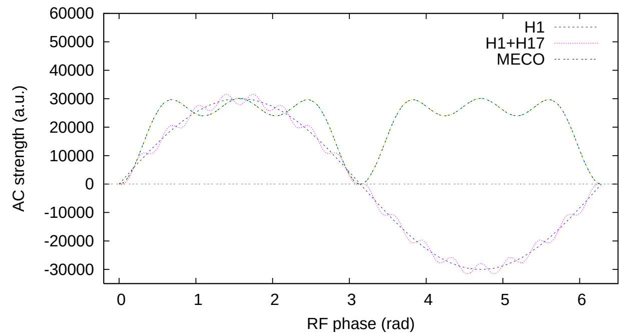

Figure 1: Options of AC dipole waveform: 1st harmonic, 1st and 17th harmonics, and MECO waveform.

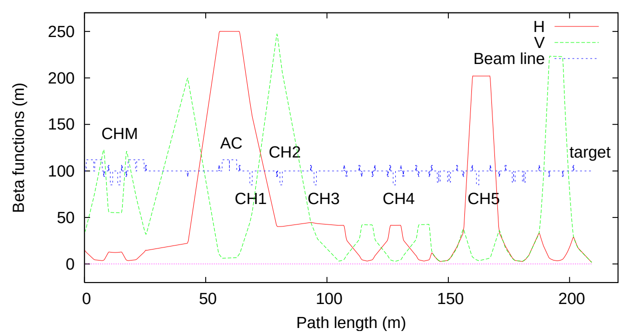

Figure 2: Horizontal and vertical beta functions in the extinction beam line.

Calculated losses along the beam line from the DC background beam are shown in Fig. 4. The intensity of DC beam has been set equal to 0.1% of 6 Booster batches of 4×10^{12} particles per 1.33 second (the Main Injector cycle time) or 1.8×10^{10} particles per second for the purposes of simulation. Collimator jaws are located at 3σ of a $\varepsilon_{95\%}$=20πmm-mrad beam.

Optimization of AC dipole parameters

The 17th harmonic of the AC dipole waveform produces a flattop in the waveform (Fig. 5) that allows a decrease in the impact kick of the AC dipole on the bunched beam. As shown in Fig. 6, there is no intensity loss of the bunched beam for a relative strength of this harmonic within the range of 0.06-0.08. The corresponding intensity loss with a MECO-type AC dipole is, however, 2.69%.

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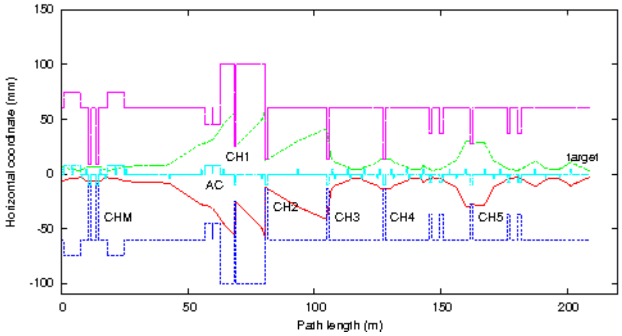

Figure 3: Horizontal aperture (blue and pink) and DC beam size (red and green) at extinction.

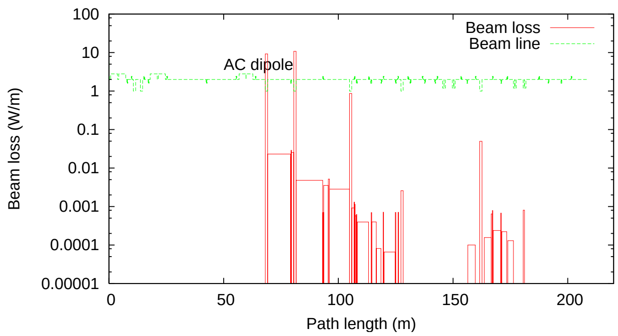

Figure 4: DC beam particle loss along the Mu2e 8-GeV beam line.

COLLIMATION STUDIES

Optimization of the collimation system is performed in two stages.

First, the distribution of beam loss generated by the AC dipole is calculated with the STRUCT code for given positions of the collimators. The extinction factor at the target is obtained at this stage with detailed modeling of proton interaction with material of the collimators, but without

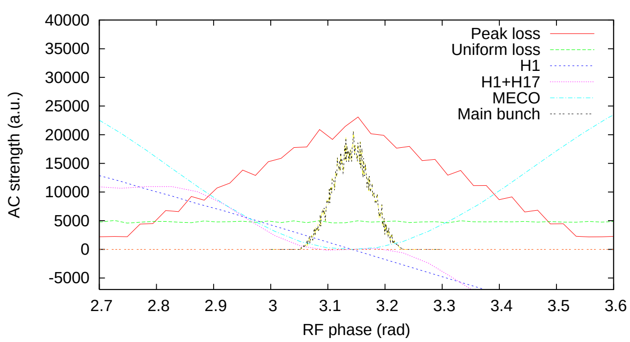

Figure 5: Effect of AC dipole waveform to DC beam and main bunch for three AC dipole waveforms: (i) 1st harmonic; (ii) 1st and 17th harmonics; (iii) MECO waveform. Beam loss and main bunch are presented to only show their behavior relative to RF phase equal to π.

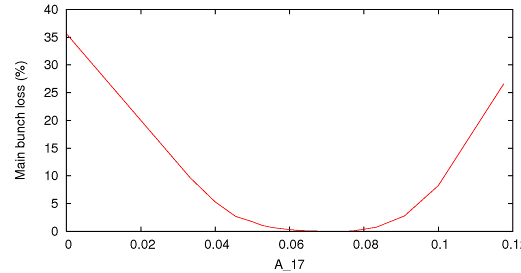

Figure 6: Effect of relative strength of the 17th harmonic to the main bunch intensity loss.

possible interaction of protons, scattered off the collimators, with aperture of beam line elements downstream. In this study, particles that strike the apertures are assumed to be lost.

Second, using the primary beam loss distributions on the collimators as a source term, Monte Carlo simulations are performed with the MARS code with detailed modeling of proton interaction with material of all elements of the beam line. This allows us to predict a more accurate distribution of the background proton flux *vs* time-of-flight at the production target location.

Several iterations were necessary in order to optimize the collimator positions and alignment to enhance the extinction efficiency.

Calculation of Extinction Factor with STRUCT

The calculated distributions of background protons and their number at the target, normalized to the main beam intensity, are shown in Fig. 7 as a function of proton time-of-flight for tungsten jaws with (top) and without (bottom) alignment with respect to trajectories of swept protons. The distribution in time of the 100-ns bunches is also shown for comparison, but not to scale. Particles from the DC background close to the proton bunches are not affected by the AC dipole kick, and therefore pass the system without interaction with the collimators and strike the target.

The center of the beam bunches in Fig. 7 are shown at T=500, 2200, and 3900 nsec. Background at a target location, calculated from T=1250 ns to T=2150 ns, is shown in Fig. 8.

Calculation of Extinction Factor with MARS

The calculated distribution of the background proton flux at the target location is shown in Fig. 9. Initially stainless steel was considered as collimator material. The calculated energy spectrum of incoming protons for the target shown in Fig. 10 reveals that the momentum acceptance of the collimation section is small. In other words, protons that experience small-angle elastic scattering or ionization energy loss in collimator walls and lose only a small fraction of their energy can contribute significantly to the background at the target location. Therefore, in order to reduce the background, one has to provide conditions for a larger

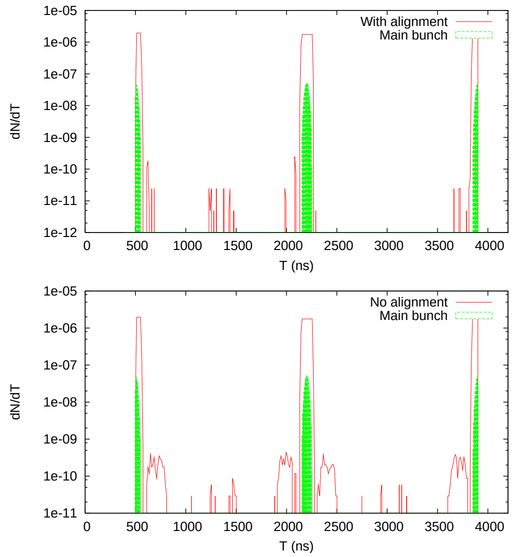

Figure 7: The calculated distributions of background proton flux at the target location.

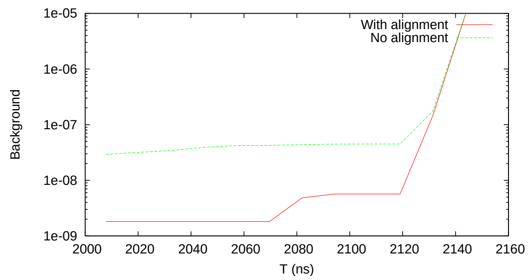

Figure 8: Number of background protons at the target location calculated between bunches centered at 500 and 2200 ns.

energy loss in the collimator walls. When considering conventional collimator materials, ionization energy loss, dE/dx, of 8-GeV protons in tungsten—24.4 MeV/cm—is approximately twice as high as that in iron or copper. Thus, if one uses collimators made of tungsten the amount of protons that reach the target is reduced significantly, when compared to steel collimators, due to increased energy loss in collimator walls (see Fig. 10).

Temporal distributions of proton flux at the target location, calculated for steel and tungsten, are shown in Fig. 9. The integrated number of background protons on the target between two main bunches (and normalized per proton to the bunch intensity) is 3.8×10^{-9} and 5.6×10^{-10} for steel and tungsten, respectively. One should note, however, that the main contribution (about 60%) is from the time bins nearest to a bunch. As a consequence, the most straightforward approach to improve the extinction efficiency is to select a more narrow time interval when the detector is on, regardless of the material used for the collimators. Also, only thin layers of tungsten on the inner surfaces of the collimators are required. Currently, a study is underway to determine the optimal dimensions of such layers. The optimized design will allow us to achieve the design goal.

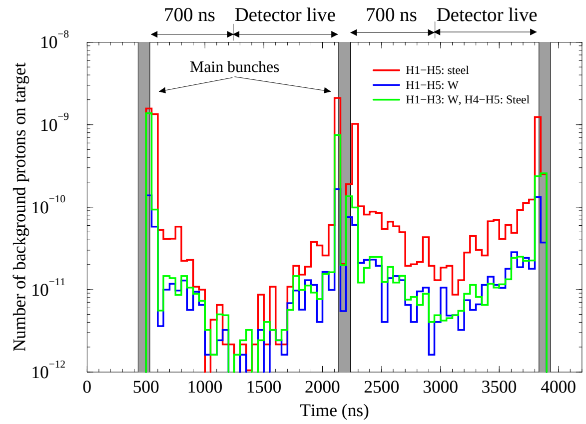

Figure 9: The calculated distributions of proton background *vs* time-of-flight at the target location. Normalization is per proton in main bunch. It is assumed that 10^{-3} protons in uniform beam loss (*i.e.* background) are generated per proton in main bunch.

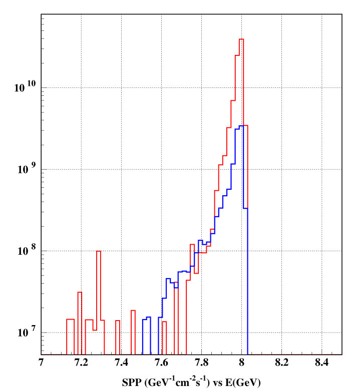

Figure 10: Proton energy spectra at the target location for collimators made of steel (red) and tungsten (blue). Normalization is arbitrary.

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