OPTIMIZATION OF AC DIPOLE PARAMETERS FOR THE MU2E EXTINCTION SYSTEM*

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Abstract

The Mu2e experiment is being planned at Fermilab to measure the rate for muons to convert to electrons in the field of an atomic nucleus with unprecedented precision. This experiment uses an 8 GeV primary proton beam consisting of short (≈200 nsec FW) bunches, separated by 1.7 μsec. It is vital that out-of-bunch beam be suppressed at the level of 10^{-10} or less. This poster describes the parametric analysis which was done to determine the optimum harmonics and magnet specifications for this system, as well as the implications for the beam line optics.

MOTIVATION

The goal of the Mu2e experiment [1] is to search for the conversion into an electron of a muon which has been captured by a nucleus ($\mu N \rightarrow eN$). This is related to the search for $\mu \rightarrow e\gamma$, but is sensitive to a broader range of physics.

A key component of the experimental technique is the proton beam structure. The beam consists of short (≈200 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. 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 [2]. 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 factor of at least 10^{-7}.

BACKGROUND

The beam line extinction system will consist of bending magnets and collimators, such that only beam within a nominal time window will be transmitted. A simple pulsed kicker which could accomplish this is beyond the state of the art, so we have focused on "AC dipoles"; that is, dipole magnets or combinations of dipole magnets in resonant circuits.

The early conceptual design has been discussed previously [3]. This initial design involved a complementary pair of AC dipoles, with a collimator in between them, in a more or less typical proton beam line. These dipoles would resonate in a simple sine wave at half the bunch frequency, such that beam would only be transmitted at the nodes. For reasons which will be discussed shortly, this initial scheme had unacceptable transmission efficiency as well as a technically challenging magnet design. These problems drove us to consider designs involving multiple harmonics and to perform a more systematic optimization of the parameters.

Two additional types of waveforms were considered;

- One composed of three harmonics, to approximate a square wave. This was based on a previous design done for MECO [4].
- One which combined the simple 300 kHz wave with a small amplitude high frequency harmonic, to reduce the slewing during the transmission window.

These are illustrated in Fig. 1, along with the simple harmonic waveform. Because both of these new solutions reduce the slewing during the transmission window, a compensating magnet is no longer required.

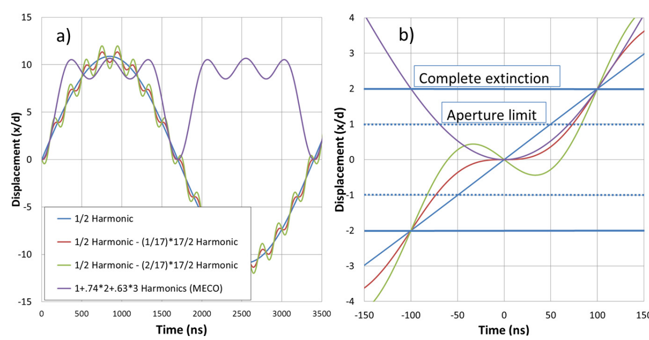

Figure 1: The waveforms considered in this analysis, are shown for (a) two bunch periods and (b) near the transmission window. Two different amplitudes for the high frequency harmonic in the two harmonic scheme are shown.

GENERIC EXTINCTION ANALYSIS

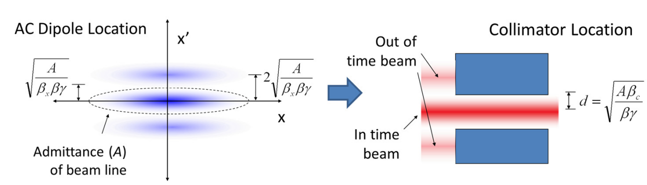

Figure 2: Effect of the AC dipole field in phase space. Beam line admittance A is indicated by the ellipse.

We have developed an analysis which allows us to evaluate the performance of the extinction system independently of the details of the beam optics and beam line design [5]. This relies on the generic behavior of a bending magnet and collimator, which is illustrated in Fig. 2. Relative to

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the nominal beam trajectory, a dipole which bends by an angle θ the x plane causes a shift in phase space along the x' axis. Assuming the collimator is located an odd multiple of $\pi/2$ later in phase advance, this will cause a shift along the x axis at that location of $\pm\theta\sqrt{\beta_x \beta_c}$, where β_x and β_c are the beta functions at the dipole and collimator locations, respectively.

We assume that the beam line and collimator have the same well-defined normalized admittance A (indicated by the dotted ellipse). Thus, a bend angle of $\theta = \sqrt{\frac{A}{\beta_x \beta\gamma}}$ would move the centroid of the beam to the edge of the collimator, where β and γ have the usual relativistic definitions. If we deflect the beam by twice this amount, then the beam would be completely extinguished, regardless of the transverse distribution. This leads to our definition of the "extinction angle"

$$\theta_e \equiv 2\sqrt{\frac{A}{\beta_x \beta\gamma}} \tag{1}$$

which defines a required integrated field B for the dipole given by

$$BL = (B\rho)\theta_c = 2(B\rho)\sqrt{\frac{A}{\beta_x \beta\gamma}} \tag{2}$$

where L is the length of the dipole and $(B\rho)$ is the beam stiffness. Using this definition, we can compare different waveforms by by first normalizing their amplitudes, such that each will have the field required to fully extinguish the beam at the boundaries of the transmission window. This effectively cancels out the actual values for the lattice functions in the comparison.

Figure 3 shows the efficiency of beam transmission for the various types of AC dipole systems as a function of Gaussian bunch length for two values of the normalized beam emittance, assuming a normalized admittance of 50 π-mm-mr. We see that the original design has very poor transmission efficiency, except for extremely short pulses.

Of the designs considered, the one using the high frequency harmonic has the best performance, provided that it is feasible to build a magnet of such high frequency. We have therefore focused primarily on that scheme in our development.

DESIGN OPTIMIZATION

To first order, magnet cost and complexity depends monotonically on the stored energy

$$U \propto B_0^2 L w g = \frac{(B_0 L)^2}{L} w g \tag{3}$$

$$\propto \frac{1}{\beta_x L} w g \tag{4}$$

where B_0, L, w, and g are the magnet's peak field, length, aperture width (in the bend plane), and pole face gap, respectively, and we have used $B_0 L \propto \beta_x^{-1/2}$ from Eq. 2.

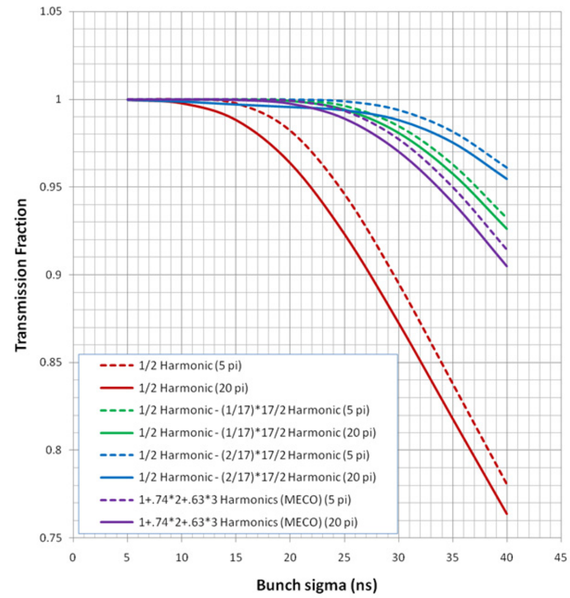

Figure 3: Beam transmission as a function of σ_t for the various extinction dipole waveforms. Dashed and solid lines show the results for ϵ_{95} of 5 and 20 π-mm-mr, respectively.

We assume that we want to make the gap g as small as possible, which is done by putting a waist of $\beta_y^* = L/2$ in the center, giving a value at the ends of $\beta_y = L$. Thus, the smallest possible gap will be $g \propto \beta_y^{1/2} = L^{1/2}$. For the aperture width, we will just have $w \propto \beta_x^{1/2}$. This yields

$$U \propto \frac{1}{\beta_x L} w g \tag{5}$$

$$\propto \frac{1}{\beta_x L}(\beta_x^{1/2})(L^{1/2}) = \frac{1}{\sqrt{\beta_x L}} \tag{6}$$

This somewhat counterintuitive result means that in general, we will simplify the magnet design by going to long, low field magnets located at regions of very high beta in the bend plane. Of course there are practical limits coming from magnet and beam line design considerations. We determined that a beta of 250 m in the bend plane and a total length of 6 m were the largest that could be easily accommodated in the beam line design [6], and we assumed these for all further magnet design. This also shows why our initial design, which have β= 50 m and L = 2 m was so challenging, in that it had roughly a factor of four more stored energy.

Once the basic design choice was made, more detailed simulations were done to optimize the details of the magnets. More realistic simulations of bunch distributions made it clear that the transmission window would need to be widened, meaning lower harmonics had to be considered for the high frequency magnet.

For each harmonic which was considered, the full transmission window was defined as the time between the nodes before and after the nominal bunch time; that is, one full period of the high harmonic. The amplitude of the funda-

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Figure 4: Required amplitude of the fundamental harmonic as a function of the transmission window, assuming a normalized admittance of 50 π-mm-mr.

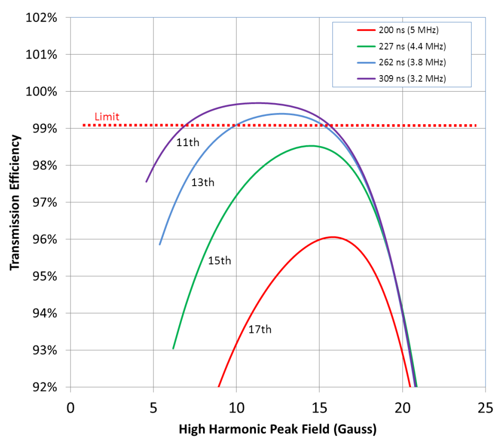

Figure 5: The transmission efficiency for various choices of high harmonic as a function of the peak magnetic field in that magnet. The harmonic number is indicated next to each curve. This analysis uses the simulated longitudinal distribution and assumes a normalized 95% transverse emittance of 20 π-mm-mr.

mental harmonic is then set to provide full extinction at this time, as defined by Eq. 2, as illustrated in Fig. 1b In calculating the field strength, we have assumed that the total 6 m length is divided equally between the two harmonics, so each component is 3 m. This means that as the transmission window gets wider, the required field for the low frequency component gets lower, as shown in Fig. 4.

We then studied the transmission efficiency as a function of the amplitude of the higher harmonic. For this study, we assumed a transverse normalized 95% emittance of 20 π-mm-mr and the simulated longitudinal distribution [7]. Results are shown in Fig. 5, for several values of the higher harmonic number as a function of peak magnetic field at that harmonic.

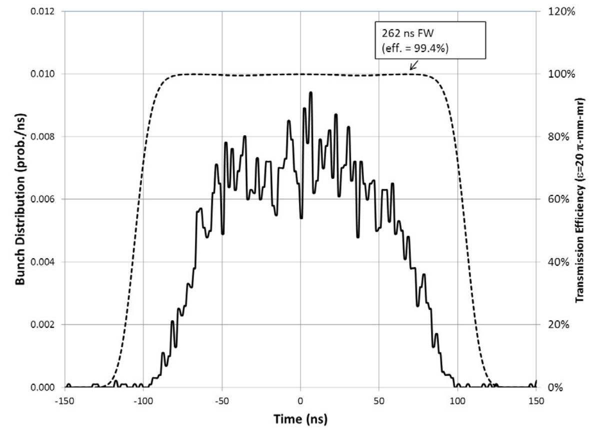

Figure 6: This transmission window shows the fraction of the beam which will be transmitted through the extinction collimator as a function of time. Superimposed is the longitudinal time distribution used the analysis.

RESULTS AND CONCLUSIONS

We have set a goal of having at most 1% beam loss at the collimator, and we see that this can't be achieved with the 17th harmonic of the original design. We must go at least to the 13th harmonic, giving a full width transmission window of 262 ns. With this harmonic, we get approximately 99.4% transmission efficiency for a peak fields in the low and high frequency magnets of 108 and 13 Gauss, respectively.

This performance will meet the extinction specifications of the experiment, so we will pursue this as our baseline design.

RELATED CONTRIBUTIONS

Other papers related to the Mu2e extinction system concern beam line modeling (MOPPD084) and prototype tests (THPPD017).

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