AC Dipole Requirements for Beam Extinction for the Fermilab Mu2e Experiment

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Abstract Mu2e experiment is a particle physics experiment which studies the muon-to-electron conversion without producing neutrinos. The experiment has very strict limits on the unwanted proton beam between pulses, so an extinction process to eliminate the unwanted beam is needed. The goal of our study is to simulate an extinction system with AC dipoles and a collimator and verify the 10^{-10} extinction requirement is fulfilled. We also analyze several sources of error to investigate the stability of our system.

Introduction

Mu2e experiment is a particle physics experiment that studies the muon-to electron conversion without producing neutrinos. It's an example of Charged Lepton Flavor Violation process. The conversion starts with a slow muon beam stopped by the targets and captured by the atomic nuclei. The muons then decay in the orbits, and at the final state there are only two bodies, an electron and a recoiling nucleus.

The Mu2e experiment at Fermilab will be operated at the Muon Campus, which is designed to deliver a muon beam with sufficient efficiency. In the experiment, we deliver an 8 GeV proton beam from the Fermilab accelerator complex onto a target placed in a solenoid system. The interaction between the protons and target nuclei produces pions, which then decay to muons. Both pions and muons are captured by the solenoids and the muons are then transported to the target of Mu2e experiment.

The experiment is very sensitive that during the time muons decay, only strictly limited number of protons are allowed. Numerically, we define "extinction" as the ratio of the numbers out-of-time protons on target to the total number of protons on target. The requirement is that our extinction should be at most 10^{-10}. While our beam itself contributes to a 10^{-5} extinction, another at least 10^{-5} needs to be done by an external extinction system.

Our proposed solution is to use periodical magnetic field and collimation system to deflect the out-of-time beam. The goal of this study is to find an appropriate magnetic field, simulate the system and verify its effectiveness.

Proposed Method

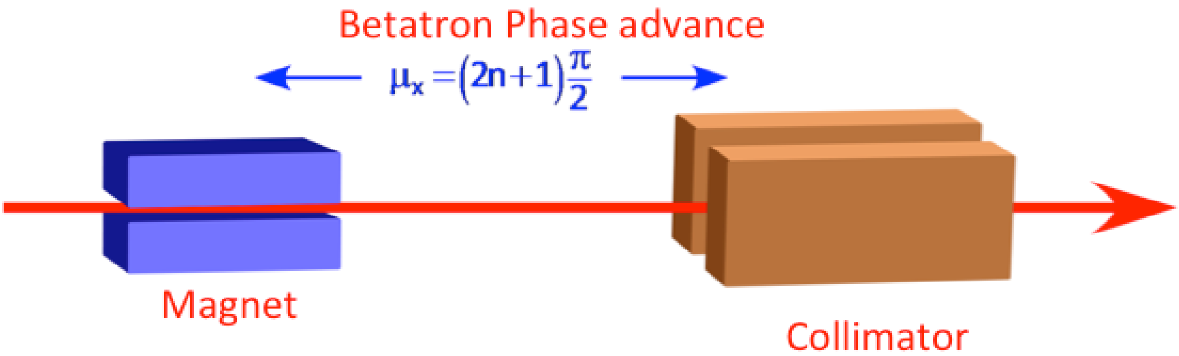

Figure 1: Extinction System

The extinction system consists of a group of AC dipoles and a collimator, such that only the in-time beam will be transmitted to the target. The system will be installed along the M4 line of the Fermilab Muon Campus. We are applying a certain periodical magnetic field so that the out-of-time beam will be deflected into the downstream collimator. The aim of our work is to simulate such a system and verify that we can fulfill the 10^{-10} extinction requirement.

AC Magnetic Field

The requirement of the magnetic field is that it must be near zero to allow the beam pass through during the pulse windows, while large enough outside the windows to deflect the unwanted protons. Ideally, a skewed square wave with certain frequency can perfectly fulfill our requirement. However, under current technology it's impossible to produce such a square wave under required frequency. As a substitution we try a combination of two sinusoidal waves, whose frequencies should satisfy the following requirements: the dominant one has a frequency f_l = 294,990 Hz, corresponding to the 1695 ns pulse period; the other one has a frequency f_2 = 4,424,000 Hz, which is a multiplier of the dominant frequency, and has a period closest to the 250 ns transmission window. The equation of the combined magnetic field is

$$B = B_{0L}\sin(2\pi f_1 t) - B_{oH}\sin(2\pi f_2 t) \qquad 1)$$

B_{0L} and B_{0H} are the magnetic field corresponding to f_l and f_2, respectively.

With the frequencies of the magnetic field fixed, our work is then to find the magnitude of the field that best satisfies the following requirements. First, the field should be almost zero during most of the transmission window, and second, the minimum field required for full extinction at ±125 ns is ±33 Gauss. Different combinations of B_{0L} and B_{0H} are shown in table 1, while figure 2 and figure 3 are the waveforms of the magnetic fields.

$Ratio$	$B_{0L}(G)$	$B_{0H}(G)$
14.0	131.5	9.4
11.6	129.1	11.1
9.0	125.1	13.9
8.0	123.0	15.4
7.0	120.4	17.2
6.0	117.1	19.5

Table 1: Different Ratio and Corresponding Magnetic Field

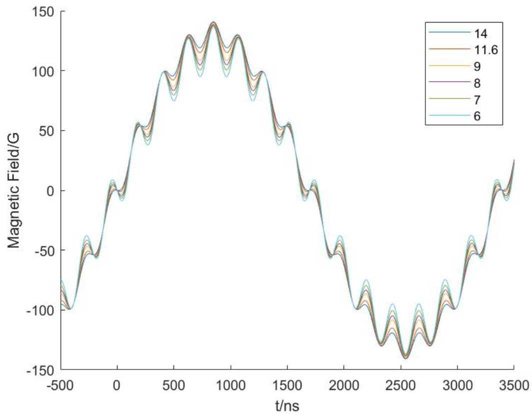

Figure 2: Magnetic Field under Different Ratio

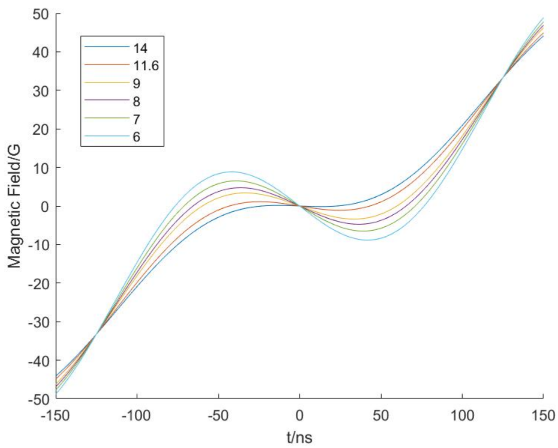

Figure 3: Details Waveform at Transmission Window

Transmission Studies

We use G4beamline to simulate our extinction system. G4beamline is a beam simulation tool where we can set up the beam line and investigate the motions, decays and interactions of the particles. The simulation model we use is shown as figure 4.

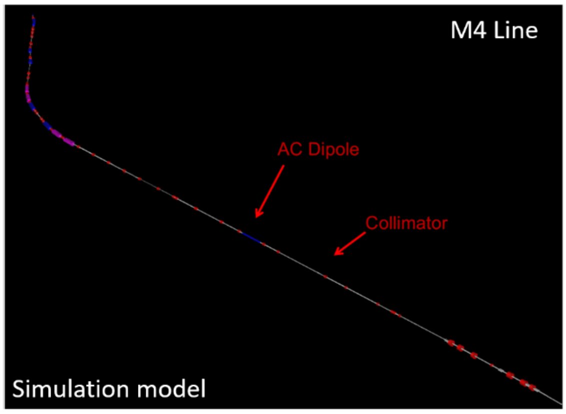

Figure 4: Simulation Model

We set the field in the AC dipoles as the field at a certain peak-field ratio and certain time of the field stated above. The beam we use for all the simulation here has 100,000 protons in total, a 30 μm full normalized emittance in bend plane and a 15 μm 95% normalized Gaussian emittance in the non-bend plane. The transmission window is 250 ns and the pulse period is 1695 ns, as shown in figure 5.

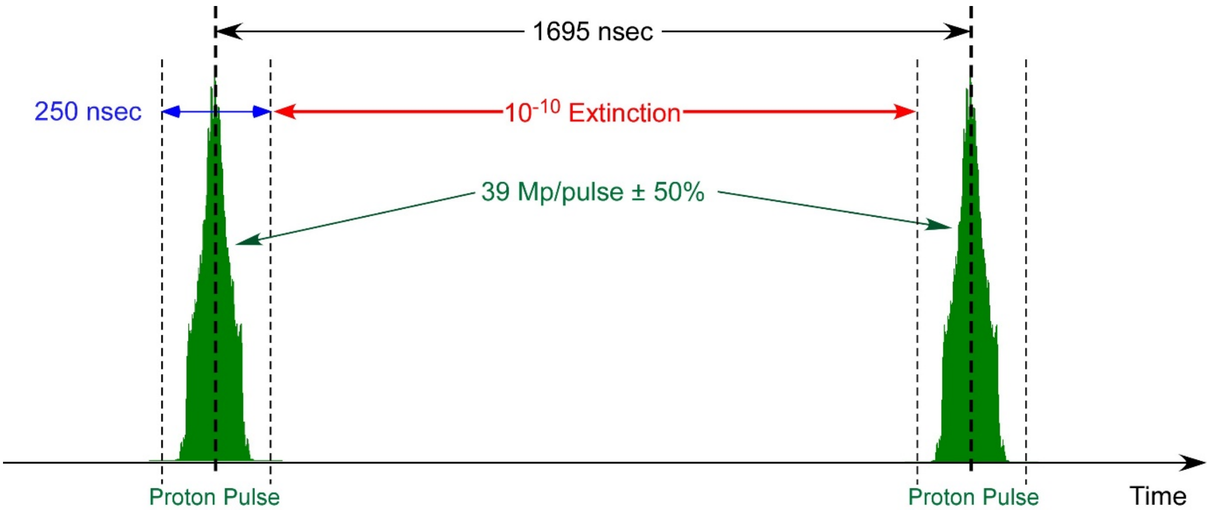

Figure 5: beam distribution

To keep the run time of our simulation under an acceptable range, we start our simulation exactly in front of the AC dipoles. Then we track the protons pass through the collimator and record the number of protons that reach the target. Due to the size limit of the target, our record includes the total number of protons at the target, as well as the number of protons within a radius of 5 mm and 3 mm. However, our result shows that all the protons reach the target are within the 3 mm radius. Then we repeat this process with different ratio and time and plot the transmission rate versus time plot for each ratio as in figure 6.

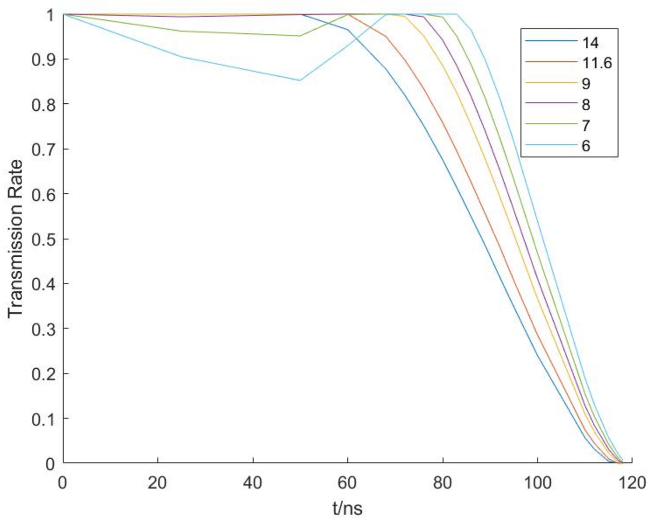

Figure 6: Transmission Rate under Different Peak-field Ratio

From the plot we can see that, as the ratio decreases, we are losing beam later. On the other side, starting from the ratio 8, we are losing beam near the center of the beam window. As our beam pulse will be concentrated to the center of the window, we should avoid those loss. Combining these two factors, we select the ratio 9 as the best.

With that conclusion, we then repeat the simulation for the ratio 9 at the edge of full extinction with 10,000,000 protons to get a more accurate and higher extinction rate. Then we multiply this "uniform" transmission rate to the actual beam distribution, which results in the actual transmission rate, as shown in figure 7.

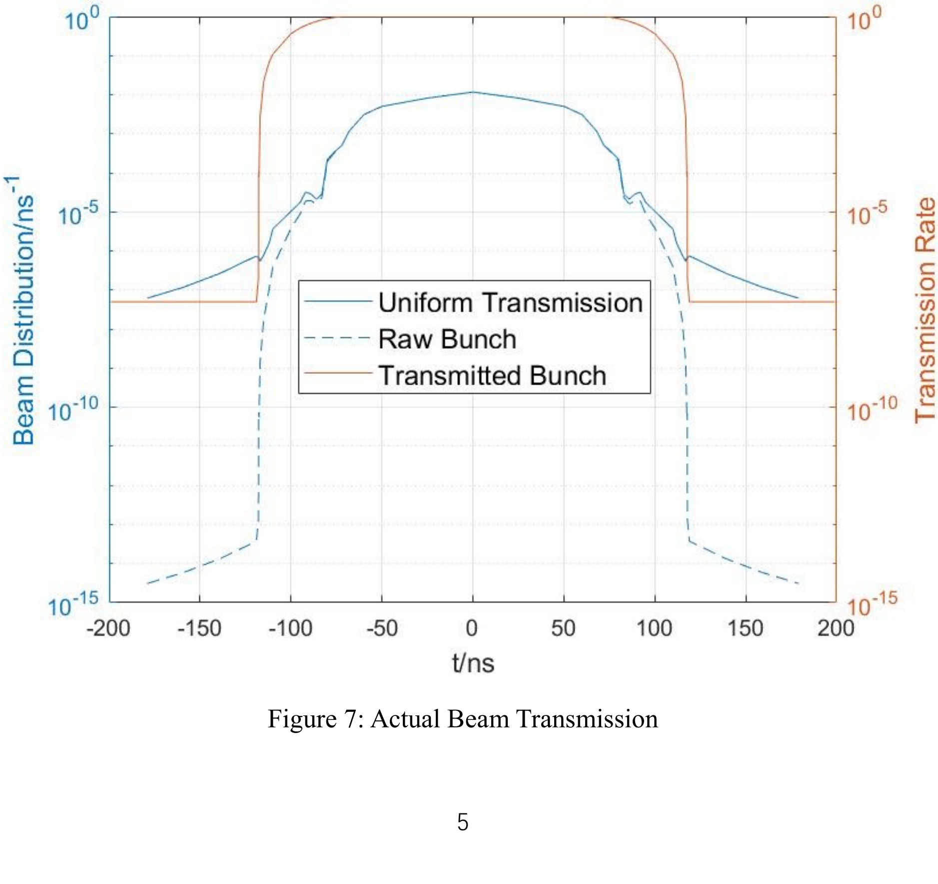

Figure 7: Actual Beam Transmission

In the raw bunch the fraction of beam outside of ±125 ns is $3.2*10^{-5}$, while the extinction rate provided by the extinction system is $5*10^{-8}$. The total extinction we have is therefore $1.6*10^{-12}$, which is much better than the minimum requirement of 10^{-10}. The total transmission (the number of protons transmitted in the window as a ratio of the total number) is 99.66%, which is a good result.

Error Analysis

For ratio 9, we analyzed the sensitivity of our extinction system under collimator alignment error by varying the gap size of the collimator. The ideal gap size is about 3.9 mm, while our simulation shows that even if we are having an alignment error as large as 0.7 mm, we can still reach full extinction in the required time, as shown in figure 8.

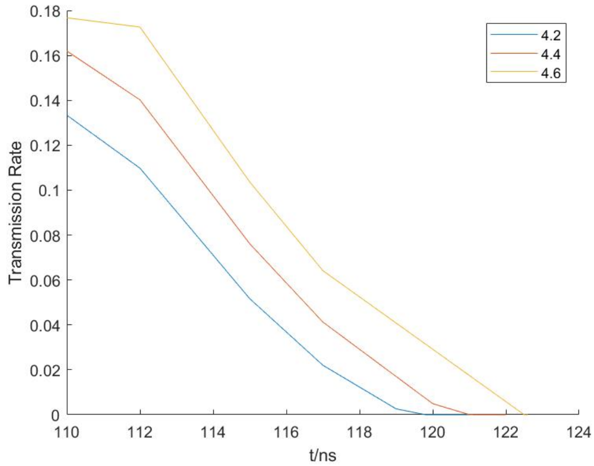

Figure 8: Transmission Rate under Collimator Alignment Error

For ratio 9 we've also examined the sensitivity to the initial beam emittance by using a beam with 40 μm full normalized emittance in bend plane and a 15 μm 95% normalized Gaussian emittance in the non-bend plane. The performance of the extinction system is worse when emittance increased, but still acceptable. In figure 9 we can see that there is a small beam loss near the center of the transmission window, while the full extinction is reached later.

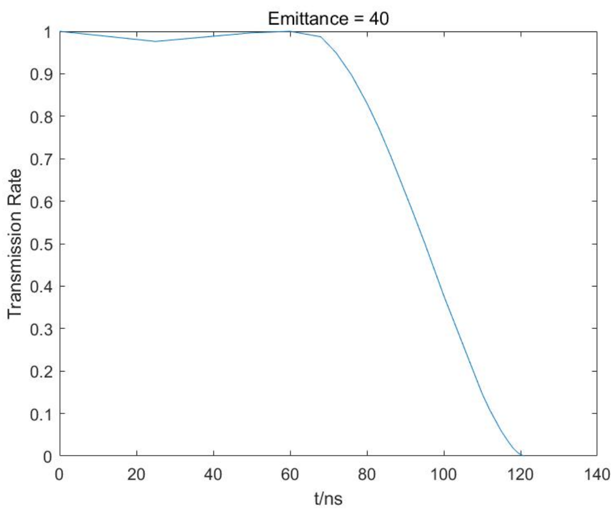

Figure 9: Transmission Rate under Higher Emittance

Beam Displacement Study

As a supplement and verification of our study, we also record and analyze the beam displacement just before it enters the collimator. We track the beam under the ratio 9 for an entire pulse period. The standard deviation of the beam in either x or y direction and the mean position in y direction are mostly unchanged. The mean position in x direction (figure 10) follows the same trend of the AC dipole field, which verifies the effect of our extinction system.

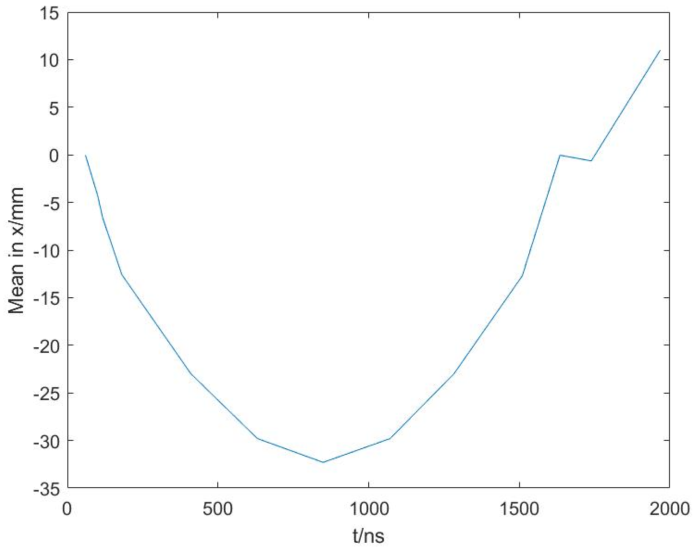

Figure 10: Mean Position in x Direction

Conclusion

The Mu2e Experiment will search for the conversion of a muon to an electron in the field of an atomic nucleus with unprecedented sensitivity. This experiment uses an 8 GeV primary proton beam consisting of ~250 ns bunches, separated by 1.7 μs. In order to improve the quality of the measurement, the out-of-time beam must be suppressed of at least 10^{-10} relative to the incoming bunch. In this study, we examined a magnet-collimator system that was appropriately configured so that only in-time beam is delivered to the Mu2e Experiment. First, using the tracking code G4beamline, we simulated the performance of such system. We found that a magnetic field in the form of

$$B = B_{0L}\sin(2\pi f_1 t) - B_{oH}\sin(2\pi f_2 t) \quad 2)$$

would appropriate for extinction however the extinction rate was sensitive to the ratio between the peak fields of the low and high frequencies We found a ratio of 9 to provide the optimum transmission. Our simulation results verified that our system can reach a 10^{-12} extinction, which surpasses the minimum requirement. We also analyzed several possible sources of error like collimator alignment error or beam emittance error. Our findings showed that the system is stable, and extinction still happens as expected even with collimator alignment errors of the order of 10%.

Acknowledgement

Figures 1, 4 and 5 are from Eric Prebys' slides on Mu2e Weekly Meeting on September 8, 2016.

References

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