ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS099

PASSIVE ABSORBERS FOR MAXIMIZING THE PERFORMANCE OF THE Mu2e-II EXPERIMENT*

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Abstract

The Fermilab's Mu2e experiment is designed to search for Charged Lepton Flavour Violation in direct, neutrinoless conversion of a muon into an electron in the presence of a nuclear electromagnetic field. The quantity, which is observed is the ratio between the rate of the above BSM (Beyond Standard Model) conversion reaction and the rate of muon capture on the nucleus. The measurement precision is expected to reach up to 10^{-17} [1]. Mu2e-II is the name for the second phase of the experiment, which is planned to run with the lower energy, higher intensity primary proton beam provided by the PIP-II [2] accelerator, currently under construction. Ionization cooling with a wedge absorber is introduced into Mu2e-II setup to potentially increase the number of low momentum muons reaching the target. A study is made into the position and size of the wedge inside the beamline using G4Beamline simulation framework. Results show an increase up to 12% for muons with momentum P below 30 MeV/c and 7% for muons with P<40 MeV/c when the beam is measured right after the wedge. Further studies are necessary to investigate how this gain can be delivered to the stopping target.

INTRODUCTION

The muons for Mu2e experiment are produced in the process, which starts with the primary proton beam hitting a tungsten target [1]. The backscattered secondary particles produced in the interaction, mostly pions, are subsequently guided through the Transport Solenoid for collimation and selection of the secondary beam and to give the pions enough time for decay. The muons used in the experiment originate from the decay of these pions. As the studies have shown [3], only muons with momentum below 50 MeV/c can be successfully stopped in the target designed for Mu2e experiment. However, the muons produced in the Production Solenoid can have momentum more than 100 MeV. Figure 1 illustrates the problem. This paper investigates the possibility of introducing a wedge absorber into the Mu2e-II beamline to reshape the momentum of the muon beam via ionization energy loss and, in result, increase the number of stopped muons in a single spill.

IONIZATION COOLING

Ionization cooling can be seen as a method to reduce the momentum spread of the beam (in this case a muon beam) by guiding the particles through a dispersive area to separate them by momentum and afterwards pass them through a layer of absorbing material. After the process, in the ideal case, the affected beam should become monoenergetic. The cooling element has to be shaped in the way that higher momentum particles travel through a thicker layer of absorber, so that their momentum is significantly reduced and, at the same time, the muons with momentum less than 50 MeV are not affected at all. The shape of the wedge is determined by the Bethe-Bloch formula with a linear relationship between average muon momentum and the distance from the beamline centre.

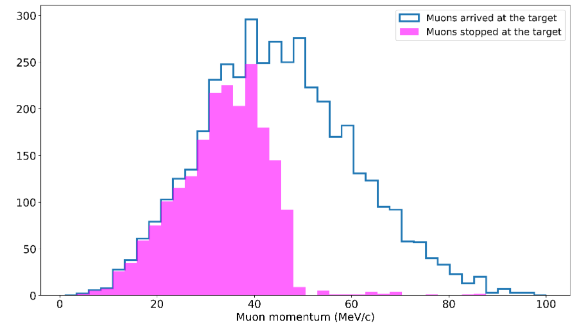

Figure 1: The momentum distribution of muons that arrive at the stopping target and those that are stopped inside the target. The numbers correspond to 200 million protons of initial 800 MeV beam hitting the production target.

WEDGE SIZE OPTIMIZATION

Two different locations of the wedge were tested using G4Beamline. The first one was set in the middle of the Collimator 3 (called C3 wedge in the following sections) and the second at the end of the Collimator 5, just after the Transport Solenoid, close to the stopping target (the C5 wedge). The locations with the layout of the experimental setup are shown in Fig. 2. The beam used in the simulation contained about 3.6 million secondary particles produced by the interaction of the 800 MeV primary proton beam expected for Mu2e-II Tracking for all the performed simulations was starting upstream the Collimator 1.

To optimize the size of the wedge at a given position, an average momentum versus Y coordinate (axis perpendicular to the beamline facing upper part of the solenoid) dependence must be determined for muons inside the beam. The distance from the beamline centre (Y coordinate) was divided into bins, inside which the muon average momentum was calculated. A linear relationship can be seen in Fig. 3(a).

* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.
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10th Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia JACoW Publishing
ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS099

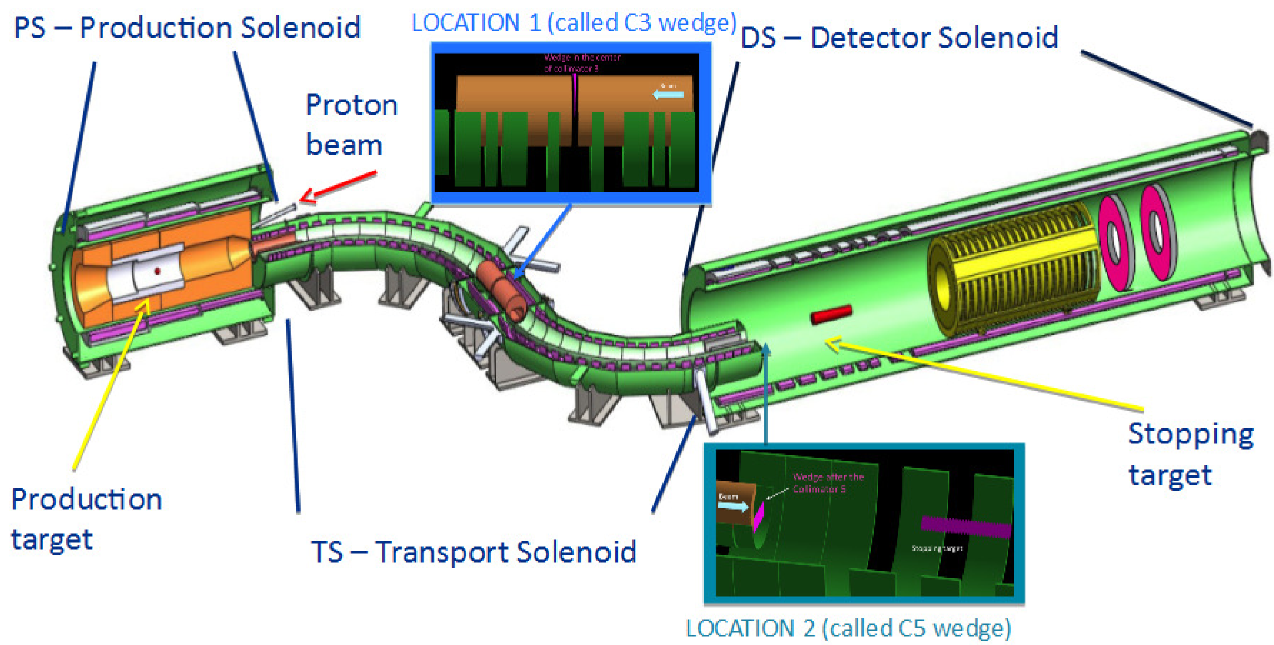
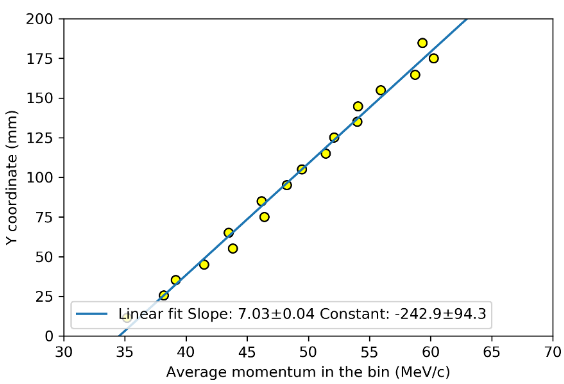
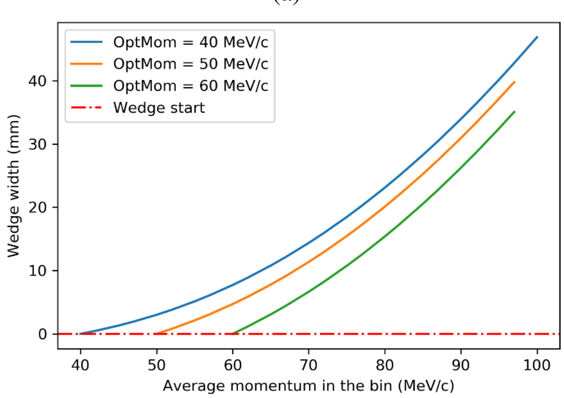


Figure 2: Mu2e apparatus with highlighted tested locations of the wedge absorber.



(a)



(b)

Figure 3: (a) Relationship between the average momentum and the Y coordinate of muons inside the beam in the middle of Collimator 3. (b) Wedge shapes for different optimization momentum valeus.

For each average momentum there is a certain wedge width that would be needed to reduce the muon momentum to the desired value, which is called the optimization momentum. The width is determined by the Bethe-Bloch formula for muons $\frac{\mathrm{d}E}{\mathrm{d}x}(p)$ [3] by the following expression:

$$\int_{P_{opt}}^{P_{avg}} \left(\frac{\mathrm{d}E}{\mathrm{d}x}(p)\right)^{-1} dp = \text{wedge width}, \qquad (1)$$

where P_{opt} is the optimization momentum, P_{avg} is the average muon momentum corresponding to a certain distance from the beamline centre (Y coordinate). An example resulting from using Eq. (1) is shown in Fig. 3 (b). A higher optimization momentum means a smaller wedge in terms of both dimensions - width and length. A whole spectrum of optimization momentum values was tested since the actual muon momentum in each bin is a gaussian-like distribution with a certain width, and the optimum energy loss for stopping muons is unknown. The values tested for the optimization momentum were between 40 and 70 MeV/c.

RESULTS

As was mentioned above, two locations of the wedge were investigated. Moreover, scenarios with and without external collimators were also considered since some collimation is expected due to the wedge itself. Two criteria were chosen to evaluate the wedge performance - gain in the number of muons with momentum below 30 MeV/c and gain in those with momentum below 40 MeV/c, both measured right after the wedge. It was found that the wedge absorber performs better in increasing the number of muons with momentum below 30 MeV/c than below 40 MeV/c.

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C3 Wedge

Figure 4 shows how the number of muons below 30 MeV/c changes right after the C3 wedge with respect to different optimization momentum used for its creation. The trend observed in the plot is expected - first the absorber is so thick that it stops a large number of the good muons, then some optimal wedge size can be determined for the observed maximum and finally the wedge becomes so small that it doesn't affect the beam at all. On the other hand, the result indicates that the collimator shapes that were prepared for Mu2e may need to be redesigned for Mu2e-II. The wedge gives much better results without Collimator 3. The best performance can be seen in Fig. 5, which presents the momentum distribution of the muons in the beams after crossing the wedge placed in the middle of Collimator 3. It was obtained for P_{opt} = 59 MeV/c. Unfortunately, no gain in the number of final stopped muons was detected at the stopping target. The attenuated muons were either not able to reach the target or distributed too far from the beamline centre (the radius of the stopping target is smaller than the one of the Transport Solenoid pipe). The background of unstopped muons was reduced.

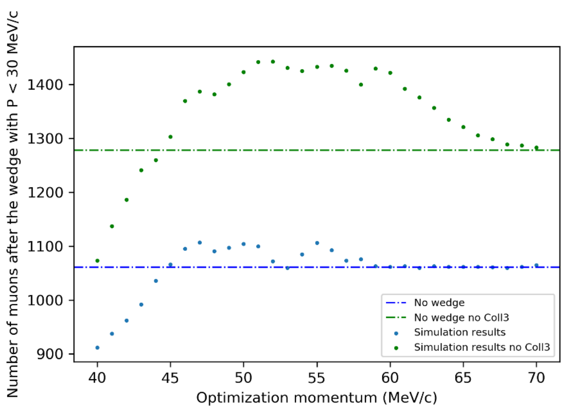

Figure 4: Performance of the C3 wedge with and without the Collimator 3 in obtaining muons with momentum less than 30 MeV/c.

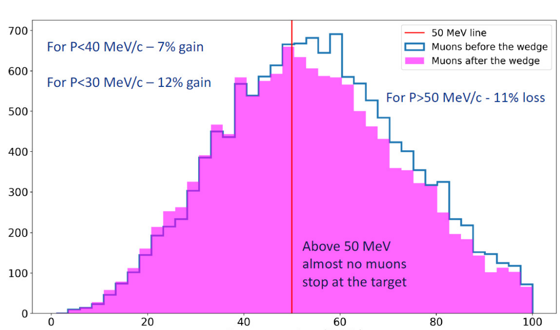

Figure 5: Momentum distributions of muons before and after the wedge. The numbers correspond to 59 MeV/c optimization momentum for the wedge creation and beamline without Collimator 3.

C5 Wedge

A plot with the C5 wedge performance is shown in Fig. 6. Again, the wedge performed better without the collimator. The C5 wedge was placed much closer to the stopping target, so in this case a small increase in the number of stopped muons was actually observed.

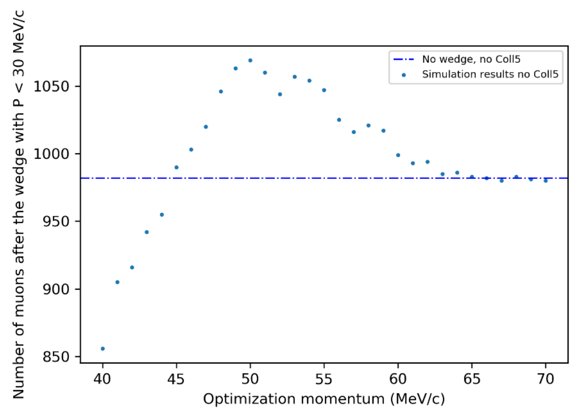

Figure 6: Performance of the C5 wedge without Collimator 5 in obtaining muons with momentum less than 30 MeV/c.

CONCLUSIONS

A wedge inserted in the Mu2e-II beamline can increase the number of muons with momentum less than 40 MeV/c, which would be stopped in a matched stopping target. The improvement is even more significant for muons with P<30 MeV/c. The main benefit from the increased number of low momentum muons is a possibility of shortening the target to match the desired stopping momentum. A shorter stopping target will result in a smaller number of scattered electrons originating from the desired reaction. At the same time, the wedge also reduces the number of background muons with P>50 MeV/c. Using the wedge could therefore highly benefit the Mu2e-II experiment, with a modest investment.

The obtained results also give some clues for potentially beneficial directions in future studies. Reshaping the collimators designed for Mu2e will be necessary for the optimum performance with the wedge inserted. Extending the target radius should also be considered after identifying the spatial distribution of the muons gained with the wedge. The sensitivity in performance to the field of the detector solenoid can be investigated to find out if the muons can be transported more efficiently to the stopping target. An interesting scenario, which was not yet tested is to use 2 wedges at the same time. Also, shaped wedges could provide superior collimation. The material of the absorber could also be varied. For this study only beryllium was tested as a wedge material. For example, preliminary calculations showed that the higher density boron carbide has a potential for the same performance within a shorter length.

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REFERENCES

[1] L. Bartozek *et al.*, “Mu2e Technical Design Report”, arXiv:1501.06241, (2014)

[2] PIPII, https://pip2.fnal.gov/

[3] D. V. Neuffer, J. Bradley, D. Stratakis, in *Proceedings of C00L17*, (Bonn, Germany, 2017), p. 32