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INITIAL STUDIES INTO LONGITUDINAL IONIZATION COOLING FOR THE MUON g-2 EXPERIMENT

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Abstract

Fermilab's Muon g-2 experiment aims to measure the anomalous magnetic moment of the muon to an unprecedented precision of 140 ppb. It relies on large numbers of muons surviving many turns in the storage ring without colliding with the sides, at least long enough for the muons to decay. Longitudinal ionization cooling is introduced with respect to Fermilab's Muon g-2 experiment in an attempt to increase storage and through this the statistics and quality of results. The ionization cooling is introduced to the beam through a material wedge, an initial simulation study is made into the positioning, material, and geometrical parameters of this wedge using G4Beamline. Results suggest a significant increase of 20 - 30% in the number of stored muons when the optimal wedge is included in the simulation.

INTRODUCTION

In order to produce the most precise measurement of the anomalous magnetic moment of the muon, the g-2 experiment will transport large number of muons around a (7 meter radius) storage ring and the polarization of their decay products will be observed [1]. In order to obtain the low statistical uncertainty required in this experiment, as many muons as possible must be put into a stable orbit in the ring until they decay. The design of the g-2 storage ring means only particles within about 0.1% of the design momentum will be successfully stored; at present the rms momentum spread is approximately 1%. This paper explores the possibility of using longitudinal ionization cooling from a wedge absorber to increase the number of stored muons.

IONIZATION COOLING

The muons for g-2 are obtained by directing a high energy proton beam from the Linac, Booster and Recycler accelerators through a series of connecting beamlines onto an Inconel target to produce a secondary beam of pions. These pions are transported along the M2/M3 lines which are designed to capture as many muons of the desired momentum as possible; the particles then make 4 turns around the delivery ring such that the protons separate and can be removed from the beam. The muons are then transported along the M4/M5 line which includes the final focus and into the g-2 storage ring [2].

If we consider a region of high dispersion in the beamline we know that the particles are sorted by their momentum, so we can construct an object which has the higher momentum particles traveling through more material. Specifically, in the ideal case of a linear relationship between momentum and position a triangular wedge is suitable. There are two key competing processes to consider when placing an absorber into the beamline; cooling due to ionization of the material, and heating by multiple scattering. The quantitative dependence on material parameters is well known [3].

In order to minimise the heating while maximizing the longitudinal cooling we require the absorber material has a low atomic number (Z) and a high density, and we also require a position in the beamline with high dispersion and low beta functions [3]. In the current beamline for the g-2 experiment the optimal location is one with a dispersion of 0.65 m, and where the beam has horizontal and vertical beta functions of 2.0 m and 6.9 m respectively. A larger dispersion and/or lower beta function would likely significantly increase the effectiveness of the wedge. The choice of material is the first topic explored in this paper.

WEDGE MATERIAL

Wedges were placed in the region shown in Fig. 1.

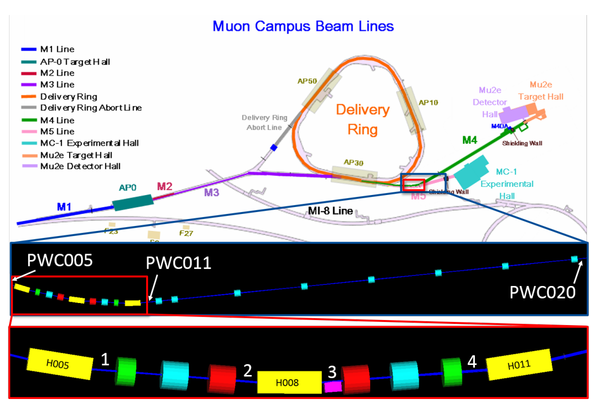

Figure 1: The different positions of the wedge absorber used in this study. The labeled rectangular elements are dipoles, the cylindrical elements are quadrupoles. The white numbers in the bottom frame identify the different positions of the wedge, in this figure the wedge is placed in position 3.

Initial simulations for a wide variety of materials in the same location (labeled 2 in Fig. 1) were carried out with a prepared G4Beamline [4] deck, using a 5000 particle input file produced by end to end simulation from target to PWC005 (also labeled in Fig. 1). PWCs are 'proportional

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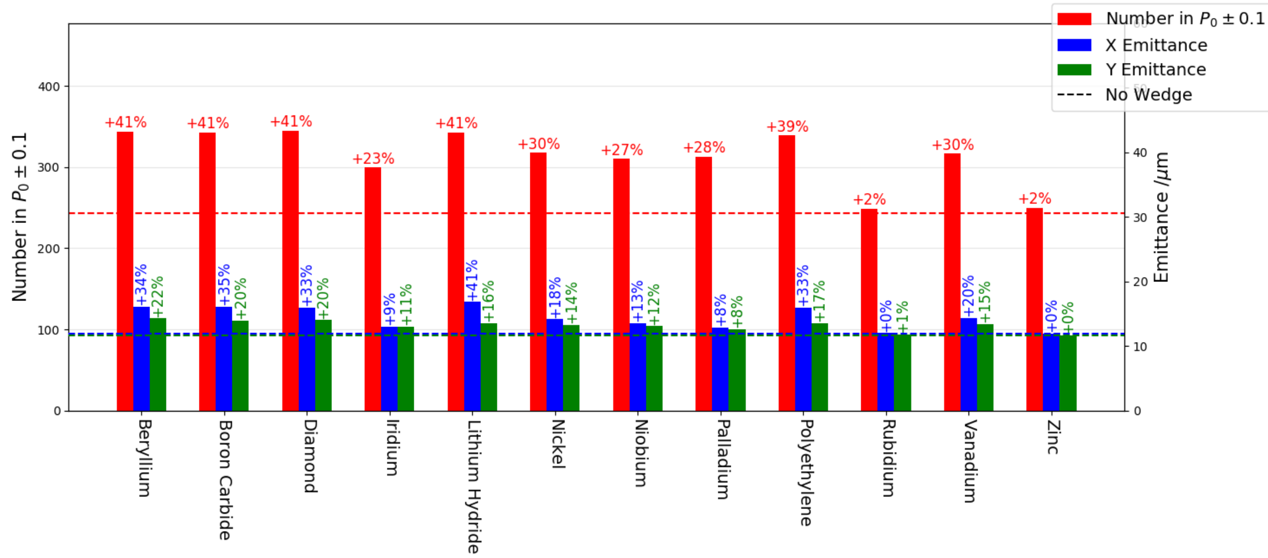

Figure 2: Comparison of materials for the wedge absorber using data obtained at PWC020, several meters downstream of the absorber and after a FODO lattice. The dashed lines show the values with no wedge.

wire chambers' used to measure beam profiles. The simulation began at PWC005 and continued to the point of injection into the storage ring, with particle distributions produced at PWC011 and PWC020 (See Fig. 1). The simulation was run repeatedly for a range of transverse beam offsets and half angles in intervals of 1 mm and 1 degree respectively, with the maximum absorber length parallel to the beam set to the the largest value which could fit between quadrupoles. This is larger than is practical to install but acceptable for initial simulations. In all cases, there was no adjustment of the beamline from the design specifications. Figure 2 shows the results at PWC020. Note that the number of particles within 0.1% of the mean is stated rather than the distribution width, this takes into account losses due to the wedge.

The ideal absorber will show a large increase in the number of particles within 0.1% of the mean momentum and a low emittance increase, and at PWC011 a variety of results are seen, but as the beam propagates to PWC020 they generally become more level. This is likely due to the scattered particles responsible for the higher emittance being lost in the FODO lattice, and optimization of the beamline may further increase the gain at PWC020 but this is beyond the scope of this initial investigation. Typically, it was observed that very dense materials like Rubidium and Zinc required wedges that were too thin to have any large effect on the beam, and Lithium Hydride (the material used in the MICE experiment [5]) led to the greatest increase in muons within the target momentum range.

WEDGE POSITION AND LENGTH OPTIMIZATION

The same type of simulation as discussed in the previous section was run with one or more polyethylene absorber(s) in varying positions in the region (Fig. 1). It was seen that over this small region the increase in muons within 0.1% of the mean momentum due to a single wedge varied between 29% and 53%. The introduction of a second wedge increased transverse emittance gain from 25% to 37% for only a (maximum) increase in particles of 2% (from a 53% gain to 56% gain on the no wedge case); a second wedge typically decreased transmission.The key insight produced by this stage of the investigation is that having multiple wedges is generally no more effective than having a single wedge under these conditions, and that even over a small region of beamline there is a significant dependence on wedge position. As well as the simulations shown in Fig. 2, runs were carried out with wedges of different materials in different positions (eg. Vanadium in position 1, polyethylene in position 3) to attempt to combine benefits of each (such as low emittance gain from vanadium and high increase in acceptance of polyethylene) however these generally performed worse than the two polyethylene wedges.

To improve the accuracy of the results, a higher statistics run with the largest end-to-end distribution available (70,000 particles) was then used to repeat the simulations for a few select cases using NERSC's Edison system. Each of these was optimized again for the higher number of particles with slightly different parameters giving optimal results. A single LiH wedge in position 3 was shown to increase the number of muons within the acceptance range by 30% with the cost of a 38% increase in transverse emittance; polyethylene and vanadium wedges in position 3 increased the number of muons within $P_{mean} \pm 0.1\%$ by 26% and 5% respectively, with a corresponding 39% and 27% increase in emittance. In this high statistics run, the trends of above still stand however the net effect is decreased. Finally, a high statistics run was carried out for two 150 mm long polyethylene wedges in positions 2 and 3, these wedges could feasibly be installed between existing components with no modification required

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to other active components. In this case, the wedges were optimized independently, firstly the front wedge (with the other absent) and then with the front wedge in the optimal position the rear wedge was optimized for the maximum number of muons in the target momentum range. After this small ranges were covered around this optimal positioning to verify that independent optimization was reasonable. These short wedges resulted in a 28 % increase in the number of muons in the target range, with a 41 % increase in transverse emittance.

A high statistics investigation was also carried out into the dependence of the wedge effects on length. This was done by running the full 70,000 particle distribution through the deck using the ideal absorber with different maximum lengths. Figure 3 shows how the effectiveness of a single polyethylene

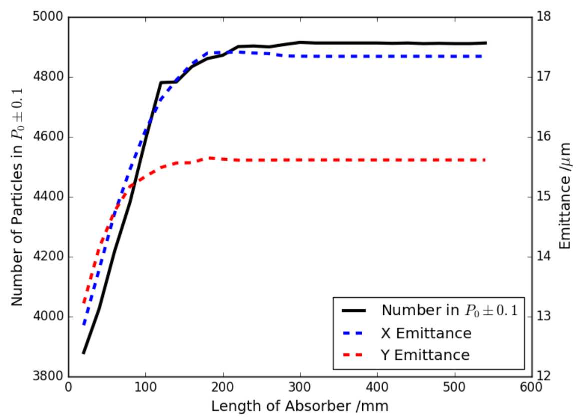

Figure 3: Effect of length on beam momentum and emittance (Full 70,000 particle distribution) on effectiveness of a single polyethylene wedge.

wedge varies with length, it can be seen that there is a sharp increase in effectiveness with length up to approximately 100 mm, this then smooths off such that the effectiveness is independent of length above approximately 200 mm. This is likely as the majority of surviving particles will be near the centre of the beamline so only effected by the region of wedge nearest the tip, which will be unaffected when increasing length beyond some threshold which depends on wedge angle and beam width.

STORAGE SIMULATIONS

In order to determine whether this is indeed a positive effect, a distribution can be produced with the same momentum spread and run through the inflector and storage ring model which have already been produced in BMAD [6]. To avoid reoptimizing the final focus, this momentum distribution was scaled to the magic momentum (achievable experimentally by adjusting the early dipoles in the beamline to select an initial momentum higher than that required) and transferred onto the distribution from the case with no wedge. This means that the twiss parameters match those already in use, however emittance growth is not accounted for and this is left for a future study. Note that this also assumes particle loss between PWC020 and the inflector is negligible - this seems a reasonable assumption to at least first order. The results are shown in Fig. 4.

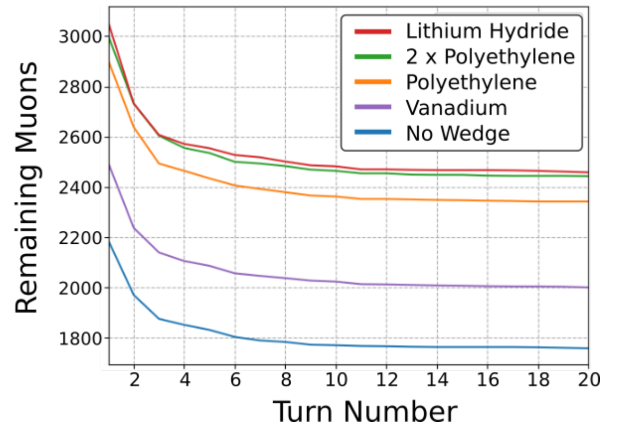

Figure 4: Simulated transmission through the ring for the high statistics runs, with the momentum distribution transferred onto the nominal particle distribution.

Interestingly, the number of stored muons increases significantly more than the number within $P_0 \pm 0.1\%$, this is likely partially due to neglected losses between PWC020 and the inflector however there is also the possibility that the acceptance range is slightly wider than the expected 0.1%. Key improvements to be made are reoptimization of the FODO lattice between PWC011 and PWC020, as well as the final focus, and investigation of other potential positions of the wedges (eg. the delivery ring).

CONCLUSION

Initial simulations have been carried out into the potential placement of a material wedge into the beamline of the muon g-2 experiment, with the goal of increasing the number of stored muons by decreasing momentum spread. Wedges of a variety of materials have been simulated and compared to reveal several promising candidates for such a wedge, in particular polyethylene is effective, cheap, and reasonably practical in this situation, and it has been further shown that two such polyethylene wedges could be implemented without any significant changes to the current beamline (other than reoptimization of voltages). An increase of up to 40 % in the number of stored muons is possible in the configurations tested, and a conservative estimate of 20 - 30% is made when considering emittance growth. Studies are now being carried out into alternate positions for the wedge where dispersion is increased, which could potentially yield even larger increases. Other work will also be carried out into modelling the effect of emittance growth, and reoptimization of the beamline downstream of the wedge(s) is not a trivial task. In short, the work presented here is a very early stage of the investigation, however the results yielded appear extremely promising.

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