# A PARAMETER STUDY FOR IMPROVING THE PERFORMANCE OF THE PRODUCTION TARGET FOR THE MUON g-2 EXPERIMENT*

Diktys Stratakis[†], Fermi National Accelerator Laboratory, Batavia IL, USA

## *Abstract*

The target station of the Muon g-2 Experiment is one of the central pieces for the production of secondary pions which eventually will decay to the desired muons. In this paper, we report adjustments made to optimize its performance. For instance, in the simulation we vary the size of the primary incoming beam and examine its impact on the downstream production. We then compare this with the actual measured beam size upstream of the target. In addition, we examine the sensitivity in performance with the strength of the lithium lens and the distance between lens and target. We compare measured data with simulation results.

## INTRODUCTION

The Muon g-2 Experiment, at Fermilab [1], will measure the muon anomalous magnetic moment, $\alpha_\mu$ to unprecedented precision: 0.14 parts per million. To perform the experiment, a polarized beam of positive muons is injected into a storage ring with a uniform magnetic field in the vertical direction. Since the positron direction from the weak muon decay is correlated with the spin of the muon, the precession frequency is measured by counting the rate of positrons above an energy threshold versus time. The g-2 value is then proportional to the precession frequency divided by the magnetic field of the storage ring.

A sequence of lines that are part of the Fermilab Muon Campus [2] have been designed in order to transport the highest possible quality beam to the Muon g-2 Experiment. Bunches from the Recycler are extracted and guided to a target station. The resulting pions, protons and muons are transported into the Delivery Ring, where they make several revolutions. Finally, the muon beam is injected into a final beamline that terminates at the entrance of the storage ring of the Muon g-2 Experiment. In this paper, we will overview the performance of the production target.

## MUON PRODUCTION TARGET

The production target [3] station consists of five main devices: the pion production target, the lithium lens, a collimator, a pulsed magnet, and a beam dump (not depicted here). A schematic layout is shown in Fig. 1.

The new target design is made of a single cylinder of Inconel, with air blowing through a heat exchanger incorporated into the center shaft. A shell of beryllium provides a cover for the Inconel target, to reduce target oxidation and damage. Inconel was chosen as the best choice of target material because it can withstand higher stresses caused by the rapid beam heating. Immediately downstream of the target module is the Lithium Lens module (see Fig. 2). The lens is designed to focus a portion of the secondaries off of the target, greatly reducing their angular component. The distance between the target and lens, can be adjusted to match the diverging cone of secondary particles to the focal length of the Lithium Lens. For the Muon Campus scenario, the lithium lens acts as a conductor for a 116 kA current, producing a magnetic field gradient of 232 T/m within the lithium and is located 0.3 m downstream the target. The Lithium Lens has the advantage over conventional quadrupoles in that it focuses in both transverse planes and produces an extremely strong magnetic field. The following collimator is used to reduce heating and radiation damage to the Pulsed Magnet (PMAG), which is located immediately downstream of the Collimator. The Collimator is cylindrical in shape and made of copper, with a hole in the middle for the beam to pass through. The PMAG is a 3-degree pulsed dipole that is located downstream of the Collimator. Its purpose is to select 3.1 GeV/c secondaries and bend them into the M2 line. The dipole was designed specifically for the Target Vault and is a single-turn, radiation-hardened, water-cooled, 1.07 m long magnet with an aperture measuring 5.1 cm horizontally by 3.5 cm vertically.

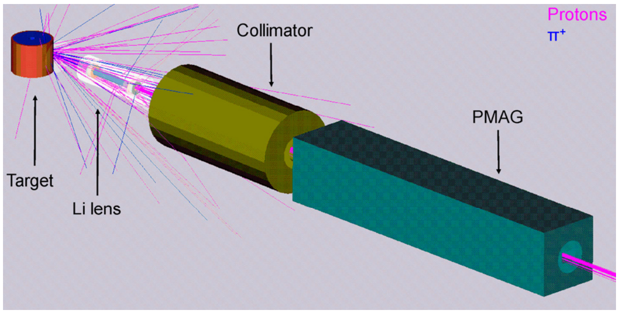

Figure 1: Schematic layout of the target-station that is used to produce muons for the Muon g-2 experiment. Beam dump is not shown.

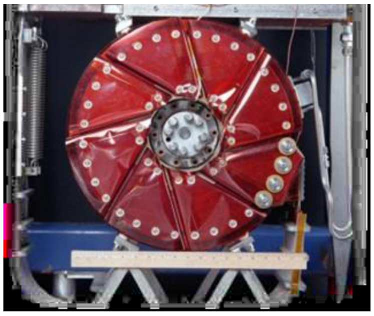

Figure 2: Image of the Lithium lens at the production target station for the Muon g-2 experiment.

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[†] diktys@fnal.gov

## TARGET PERFORMANCE

### *Sensitivity on Beam Spot Size*

Figure 3 displays the measured SEM profile of the incoming primary proton beam just upstream of the target. The histograms are raw data, while the red curves are Gaussian fits to the data. We can see that the beam retains a Gaussian profile with $\sigma_x = 0.22$ mm and $\sigma_y = 0.24$ mm in the horizontal and vertical planes, respectively. This spot size is slightly higher compared to 0.15 mm of the baseline design. To further examine the implications of this, in Fig. 4 we plot the simulated relative pion yield downstream the lithium lens as a function of the primary beam spot size at the target. One can see that if the spot size is reduced from 0.55 mm to 0.15 mm, a 15% increase in pion production can be achieved. As a result, the spot size is a key parameter that governs the final secondary yield in the Muon Campus. In comparison to the baseline design however, we anticipate that the spot size achieved in our experiment should result in no perceptible difference in the downstream secondary beam rates. Quantitatively, both MARS [4] and G4beamline [5], showed that a spot size of 0.20-0.25 mm resulted in a < 3% difference compared to the baseline design performance. Note that the source of a small discrepancy between MARS and G4beamline results is traced back to the lithium lens which in MARS is modeled with more detail.

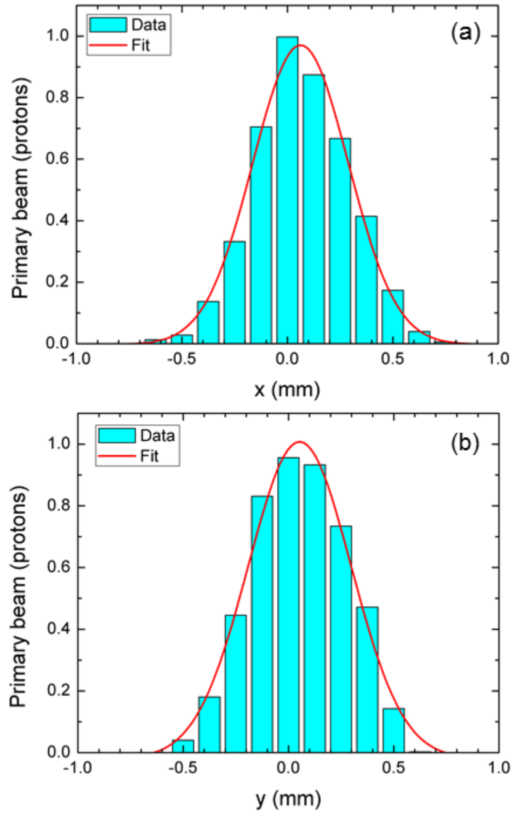

Figure 3: Beam profiles of the primary beam just upstream the production target. The red curves are fit to the data. (a) Profile in the horizontal plan, and (b) profile in the vertical plane.

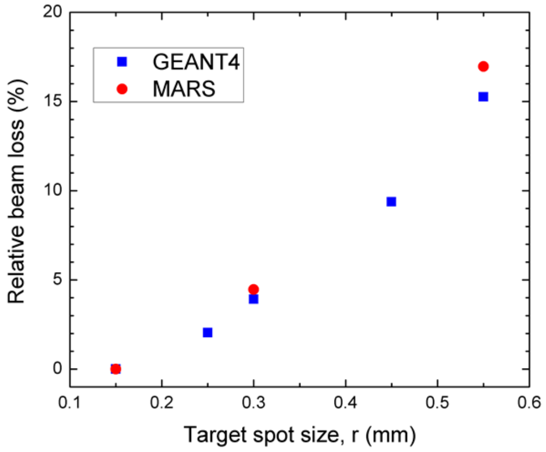

Figure 4: Sensitivity of the downstream pion production vs the size of the incoming primary beam.

### *Sensitivity in Lithium Lens Strength*

In the experiment we varied both the strength of the lens and the distance between lens and target (focal length). Then, we looked at the overall intensities at three different locations. One was near the end of the M3 line (IC740), the other one was at the end of the M5 (IC025) line which is at the entrance of the storage ring and the last one was inside the storage ring. With our G4beamline model, we tried to compare the experiment data with simulation. More details on the beamlines can be found elsewhere [2].

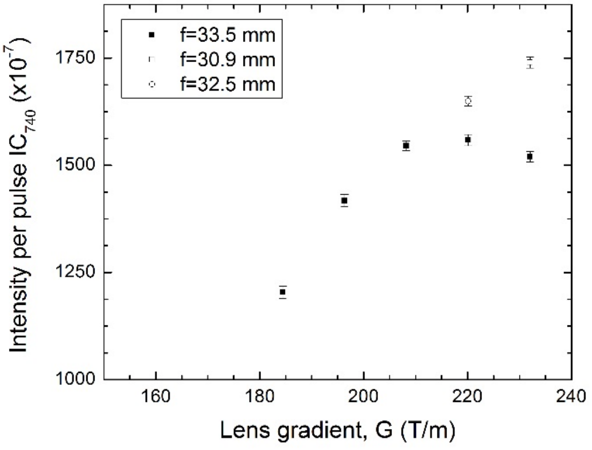

Figure 5: Performance at IC740 vs different magnet strengths of the lithium lens. For some points we had to adjust the distance between target and lens. Unfortunately, we couldn't increase the distance beyond 33.5 mm.

Figure 5 displays the measurement at IC740. In that part of the line, the beam contains a mixture of muons, pions, positrons and deuterons. However, protons overpass all other species by two orders of magnitude. Figure 6 shows the predictions from simulations at the same location. Note that in order to speed-up the simulation time, we track only pions and muons. As a result, the scale in the vertical plane between Figs. 5 and 6 is not comparable. It's important to emphasize that the simulation assume 2x$10^9$ protons on target (POT). While this result is enough to derive some scaling laws, a more detailed study will require higher statistics. The simulation, in agreement with the data, shows an increase in performance when the lens gradient is increased if the focal length remains 33.5 mm. This trend continues until 220 T/m. At 232 T/m, which is the maximum lens gradient we can operate, both simulation and data show an enhancement when the focal length is reduced to 30.9 mm. While the data suggest an improvement at 220 T/m if the focal length is reduced, the simulation disagrees.

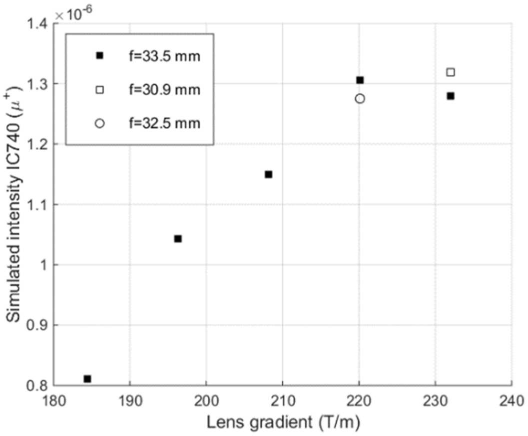

Figure 6: Same as Fig. 5 but this time the predictions from our simulations are shown. Only muon intensity is counted.

Figure 7 displays the same measurement at IC025 while Fig. 8 shows the prediction from the simulation. Note that in the simulation we count only muons while in the data the beam is a mixture of 60% muons and 40% positrons. As a result, the simulated muon beam intensity at the end of M5 exceeds by ~1/3 the measured value, in agreement to the findings of an earlier study [6]. Note that the scaling between performance and lens gradient of both plots is the same as in Figs. 5 and 6. It's unclear why there is a discrepancy between simulation and data at 220 T/m for the two different focal lengths. A possible reason could be the simplified approach the simulation models the lithium lens.

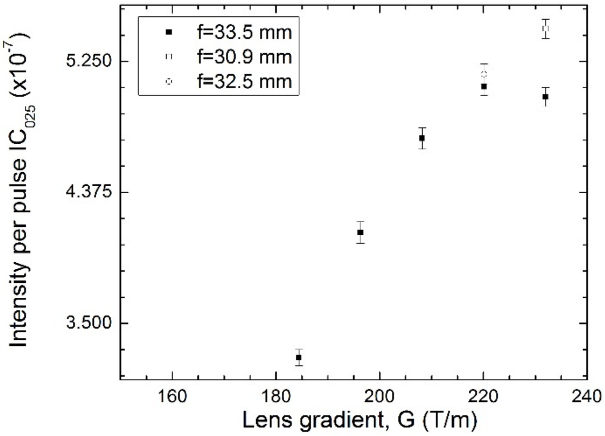

Figure 7: Performance at IC025 for different magnet strengths of the lithium lens. For some points we had to adjust the distance between target and lens in order to optimize performance.

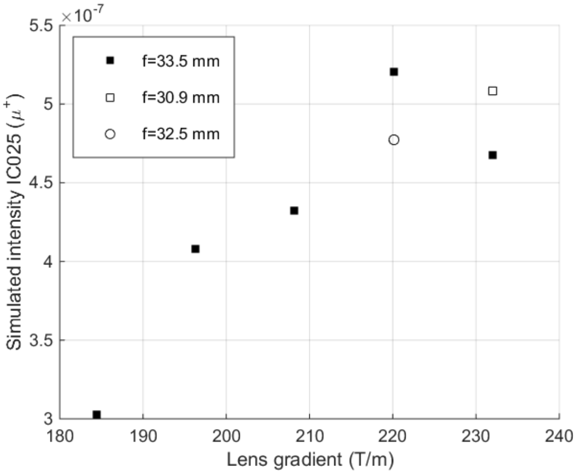

Figure 8: Same as Fig. 7 but this time predictions from simulations are shown. Only muon intensity is counted.

Finally, Fig. 9 displays the number of stored muons inside the g-2 storage ring as a function of the lithium lens gradient. The trend is very similar to one seen in the previous locations. One can see that the stored muons can shrink considerably if the lens cannot operate at its maximum strength. Some adjustments can always be made by varying the focal length. Unfortunately, this is not always practical because there are space limitations in the beamline set up.

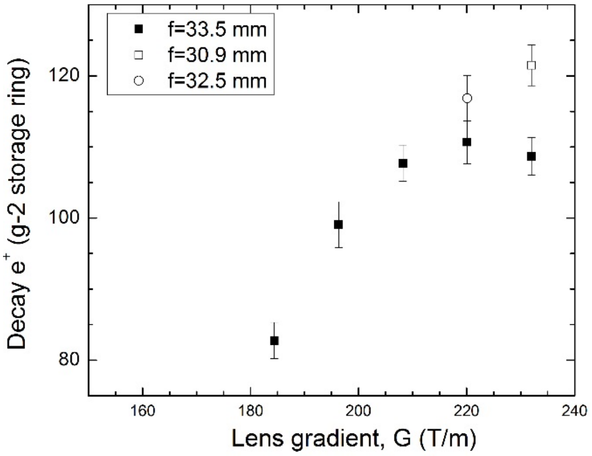

Figure 9: Dependence of the number of muons inside the storage ring of the Muon g-2 experiment with the gradient of the lithium lens and the focal length.

For a future study the modelling of the lithium lens should be improved. Currently, in the simulation we assume the lens to be an infinite rod and therefore the magnetic field inside the lens is simply given by

$$B = \frac{\mu I r}{2\pi R^2}, \tag{1}$$

where $\mu$ is the permeability of Lithium, $I$ is the current, $R$ is the radius of the lens ($R = 10$ mm) and $r$ is the radial distance from the lens axis. In reality, the field needs to include nonlinear terms as well [7]. It is likely, that some of the discrepancies observed are related to this simplified linear approximation although more studies are needed to verify this argument.

## REFERENCES

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