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COMMISSIONING AND FIRST RESULTS OF THE FERMILAB MUON CAMPUS*

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Abstract

In the following years the Fermilab Muon Campus will deliver highly polarized muon beams to the storage ring of the Muon g-2 Experiment. The Muon Campus contains a target section wherein secondaries are produced, the Delivery Ring which separates the muons from the rest of the beam and a straight section that transports them to the storage ring. Here, we report the first experimental results and experience gained from commissioning the Muon Campus, including the interaction of the proton beam with the target, the transport of secondary beam over long sections, the monitoring of muons from the available diagnostics and the development of techniques for measuring the beam optics. We present detailed comparisons between experimental data and simulation and discuss the similarities and differences observed.

INTRODUCTION

The Muon g-2 Experiment, at Fermilab, will measure the muon anomalous magnetic moment, α_μ 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 vertical uniform magnetic field. Details can be found elsewhere [1].

The Muon g-2 Experiment will be running in the new Fermilab Muon Campus [2]. Simulation studies [3] have shown that the Muon Campus has the potential to deliver highly polarized muons with 21 times the statistics of the equivalent Brookhaven experiment [4]. For the Fermilab Muon Campus operations, protons accelerated in the Linac and Booster are adiabatically re-bunched in the Recycler and led to a Inconel target. Secondary beam pions then travel around the Delivery Ring (DR) where the pions decay into muons, and finally the beam continues into the storage ring. The passage through the DR is very beneficial as it will provide enough time for pions to decay into muons and most importantly will increase the gap between the "light" muons and "heavy" protons.

Here report the first experimental results of the Fermilab Muon Campus with emphasis on the experimental milestones that have demonstrated the Muon Campus capability of delivering beam to the Muon g-2 Experiment. These milestones included the interaction of primary proton beam with the target, the generation and transport of muons over long sections, the monitoring of secondaries from the available diagnostics and the development of techniques for measuring the beam optics. We also compare the experimental data with predictions from simulations and show that our model can describe the physics of the experiment within a reasonable level of agreement.

MUON CAMPUS COMMISIONING

Commissioning of the Fermilab Muon Campus begun on April 2017. In the first phase, a 8-GeV proton beam from the Recycler bypassed the target, entered the DR via the M3 line and finally was extracted into the M4 line. The beam intensity was by two orders of magnitudes higher compared to the secondary beam. As a result, this part of the commissioning provided a good testbed from cross-checking the optics and available instrumentation along the Muon Campus. For the second part of commissioning, the primary proton beam was sent to the target with the goal to commission the new-born 3.1-GeV secondary beam. To save experimental time, the secondary beam did not travel around the DR but rather passed straight through, then propagated down the M4/M5 lines, and into the g-2 storage ring. In the last phase, the primary beam was sent to the target and the 3.1 GeV secondary beam was passed through the DR, protons were removed after the fourth turn and the beam was sent in the storage ring via the M4M5 lines. This scenario is illustrated in Fig. 1 and will be the primary focus of this paper.

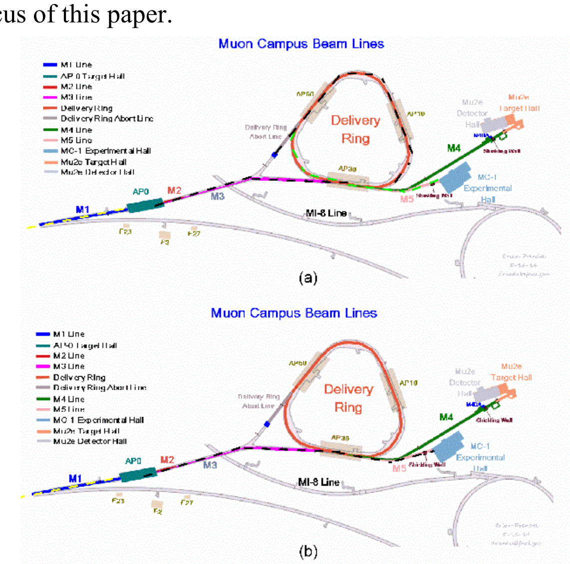

Figure 1: Muon Campus sketch: (a) During operation, and (b) initial commissioning plan. In that case, revolutions of the beam around the DR will be omitted.

MUON CAPTURE AND TRANSPORT

The spot size of the primary beam impacting the production target is a key parameter that governs the final pion

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and muon yields in the Muon Campus. While a 0.15 mm spot size was initially desired, we measured 0.22 mm and 0.24 mm in the horizontal and vertical planes, respectively. Based on simulation, we anticipate that the spot size achieved should result in no perceptible difference in the delivered muon rates. The purpose of the M2-M3 lines that are following the target is to capture magic-momentum muons from pion decays and then direct them towards the DR. They have a high quadrupole density so that to maximize the capture efficiency of the secondary beam and a narrow momentum acceptance, i.e. $\Delta p/p=\pm 2\%$, to ensure that most muons are born from forward decayed pions, providing so the foreground of a highly polarized muon beam. 71% of the pions is expected to decay to muons therefore making this part of the channel, the location wherein most pions decay to muons. The total simulated beam intensity as function of distance along the M2-M3 lines is shown in Fig. 2. The main species leaving the target are protons, pions, muons, and positrons. There is a small fraction of Deuterons traveling as well but their rates are much smaller compared to positrons. There is a substantial drop in intensity as the beam travels downstream the target. This fact is not surprising since only protons near 3.1 GeV/c are selected and as the beam travels further downstream pions decay into muons, where only the daughter muon near 3.1 GeV/c is getting accepted. The additional drop near 160 m is from collimation [3]. The black square corresponds to the measured intensity at the ion chamber at the end of the line and it agrees well with our simulations. This demonstrates that the target and the following beamlines can produce, capture and deliver the desired secondary beam parameters.

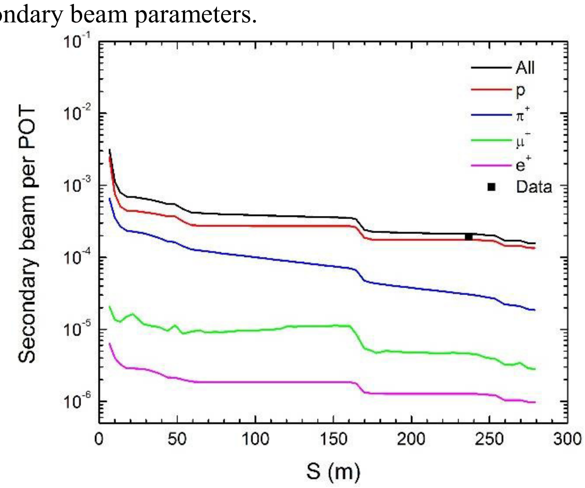

Figure 2: Simulated performance of the transmission of secondary particles. Plots for different acceptances are shown.

MUON SEPARATION

As noted earlier under normal operations for the Muon g-2 Experiment only four turns in the DR are required. Since this is not enough to evaluate the behavior of muons, we deliberately increase the number of turns to 100 with the goal to measure the muon rate for each revolution. The experiment was carried out as follows: First, protons were removed during the fourth turn using the abort kicker. Then, the number of revolutions was progressively increased. For a discrete set of turns, two intensity measurements were taken. One at IC025 which is placed just upstream of the entrance of the Muon g-2 Experiment storage ring and one inside the storage ring using its electromagnetic calorimeters [1].

We plot in Fig. 3 (squares) the decay positrons which are measured at the calorimeter as a function of the revolution number in the DR. For simplicity and since we are interested in relative rates and not actual values, we shall assume that the count of decay positrons equals the muon count. In reality, the measured positrons are only about 10.0% of the storable muons. Next to support our measurements we compare our results to the exponential decay expression. Note that the values in vertical axis are the measured decay positrons (scaled) and therefore can be seen as a indication of the remaining stored muons. One can see that the muon rate is strongly correlated to the number of turns in the DR which becomes more noticeable within the first 40 turns. The measured muon decay rate is found to follow the exponential decay law, suggesting that the primary reason of muon loss is muon decays from nature.

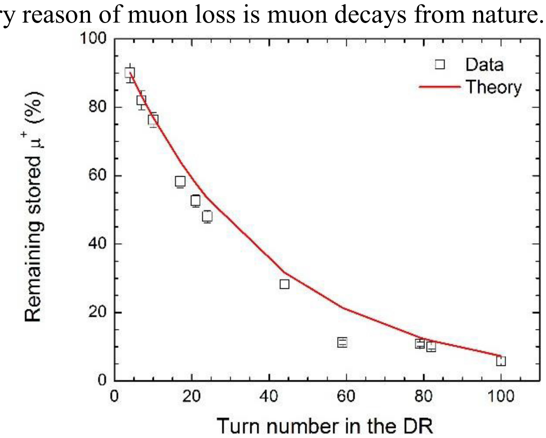

Figure 3: Percentage of stored muons in the g-2 ring versus the DR turns. Red curve is the exponential decay law.

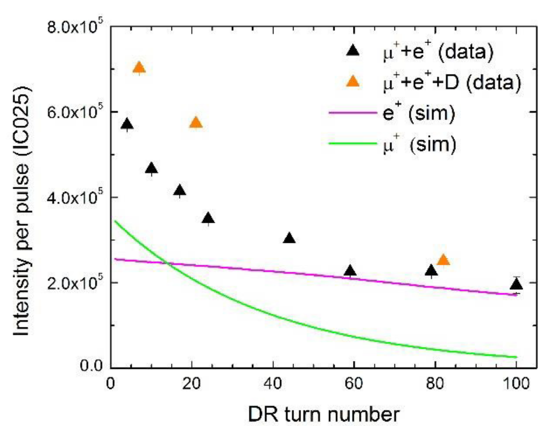

Figure 4: Total beam intensity just upstream of the entrance to the g-2 storage ring. After the fourth turn the beam in the DR contains a mixture of muons, positrons and deuterons. The green and magenta solid curves, illustrate the expected rates of muons and positrons rates, respectively.

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The total intensity measured in the IC025 is illustrated in Fig. 4. While the results in Fig. 3 show that the muon intensity is accompanied by a consistent muon loss on every turn, a salient feature of the data in Fig. 4 is that for some discrete number of turns there is an increase in the total intensity. This can be understood as follows: After proton extraction, the three remaining species are muons, e+ and deuterons. While both e+ and muons nearly overlap for most of the turns, deuterons will not. This is a direct consequence of their lower relativistic factor γ and as a result, they will remain behind. However, for some discrete number of turns they will overlap with the rest of the beam and will be extracted to the M4 line as well. This is the reason behind the increase in intensity for turns 7, 24, and 82.

Next, we estimate the number of muons and positrons in the bunch using the data in Fig. 4. More specifically, after 4 revolutions the combined measured intensity of muons and positrons is 5.69×10^5 per proton pulse. After 100 revolutions the beam intensity has been reduced to 1.94×10^5. If we assume a 7 % muon survival over 100 turns as confirmed by our aforementioned measurements and theoretical predictions, the only unknown is the transmission of positrons. With aid of tracking, we find that ~31% of muons are lost after 100 turns, primarily due synchrotron radiation. Using the above information, we estimate that the number of muons at the end of the M5 beamline is 57% and the number of positrons is 43%. With this numbers in mind the following points are noteworthy: First, a test using a Pb block with variable thicknesses along the beam path at the end of M5 revealed also a ratio of 57/43 [5]. Moreover, the simulation found a ratio of 60/40 between positron and muons which is very close to our experimental findings.

BEAM TRANSPORT TO THE G-2 RING

The purpose of these beamlines is to transport the secondary beam to the g-2 storage ring. At either end, the lines contain two detectors for measuring the beam intensity. In Fig. 5 we plot the muon and positron rates as a function of distance along the M4-M5 lines.

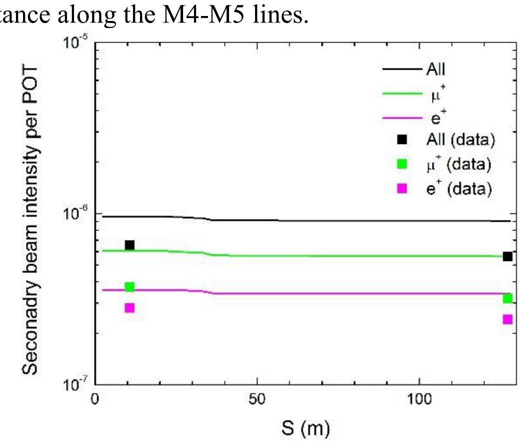

Figure 5: Simulated performance along the M4 and M5 lines. The squares indicate the measured intensity at the entrance and exit of the lines for the different species.

The black squares depict the measured rates from the two aforementioned detectors. The measured transmission along the M4-M5 lines is 90% which agrees well to the simulated values. One can see that the discrepancy between measurement and simulation is near 1/3 with the latter predicting a higher transmission. While the precise geometry of all magnetic apertures has to be accounted on the simulation in order to obtain a quantitative comparison, it is likely that a fraction of the beam is getting lost during injection to the DR. To further shed light on the behaviour of the M4-M5, we measure the beam optics at various locations along the lines. To achieve this, we implement a conventional quadrupole scan technique [6,7]. In our case the quadrupole scan method is implemented along four different locations along the M5 lines. Those locations were strategically chosen so that to cover a broad spectrum of the M5 line. The measured unormalized rms emittance with their corresponding uncertainty is illustrated in Fig. 6. The measured uncertainty was less than 10%, which was a fortunate finding given the simplicity of the technique. Notice the good agreement between measured and simulated emittance. The horizontal emittance is preserved along the M5 line, suggesting minor, if any, mismatch, positioning or field errors which are typically associated with substantial emittance growth. This finding aligns well to the agreement in transmission from the results in Fig. 5.

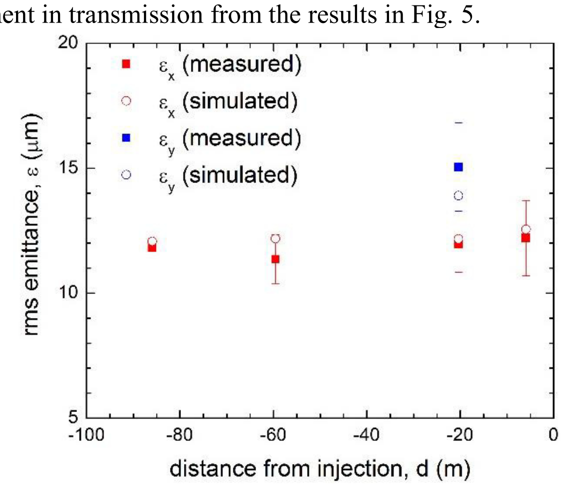

Figure 6: Emittance along the final stretch of the M5 line. Note that d=0 denotes the entrance of the storage ring.

CONCLUSION

In this paper we have reported the first experimental results and experience gained from commissioning the Fermilab Muon Campus. We provided emphasis on milestones that have demonstrated the Muon Campus capability for delivering beam to the Muon g-2 Experiment which included the interaction of primary proton beam with the target, the generation and transport of muons over long sections, the monitoring of secondaries from the available diagnostics, the development of techniques for measuring the beam optics and the creation of computational models for tracking our secondary beams..

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