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First measurement of traverse beam optics for the Fermilab Muon Campus using a magnet scanning technique

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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 transmission fraction of the storage ring has been shown to depend strongly on the transverse optics of the injected beam. Unfortunately, the current diagnostics in the Muon Campus allow only measurement of the beam configuration space which limits how well propagation can be predicted. This paper demonstrates an experimental technique based on a conventional magnet scan to obtain the Twiss parameters at a point, using only beam profiles such that installation of new equipment is not required. A proof-of-principle experiment is presented which shows that this new method is applicable to the Muon Campus, offering a viable approach to optimization of injection in the Muon g-2 Experiment.

1. Introduction

Over the next few years the Fermilab Muon Campus [1] will deliver highly polarized muon beams to the storage ring of the Muon g-2 Experiment [2,3] with 21 times the statistics of the equivalent Brookhaven experiment [4]. For Fermilab Muon Campus operations, protons accelerated in the upgraded Linac and Booster are adiabatically re-bunched in the Recycler and led to an Inconel target [5,6]. Pions of the appropriate energy are then directed into a Delivery Ring (DR) [7] around which they travel 4 times. The passage through the DR is very beneficial as it will provide enough time for pions to decay into muons and will increase the gap between the "light" muons and "heavy" protons so that the latter can be properly removed with a kicker. The remaining muon beam then travels through a sequence of beamlines which end with a set of 5 magnets known as the final focus, then through an inflector and into the storage ring of the Muon g-2 Experiment.

The aim of Fermilab's Muon g-2 experiment is to achieve an unprecedented 140 ppb precision measurement of the anomalous magnetic moment of the muon, to do so it will observe the polarization of muon decays in a precisely designed storage ring [8]. This can be accomplished with the considerable challenge of generating, transporting, and focusing large numbers of muons confined to a narrow region of phase space, without significant particle losses or deterioration of beam quality. Unfortunately, the current diagnostics in the Muon Campus beamlines allow only measurement of beam profiles which limits how well propagation can be predicted. Moreover, several numerical studies [9,10] have shown that the number of stored muons for the Muon g-2 Experiment is largely dependent on the injection parameters, specifically the Twiss parameters. Thus, it is of great importance to develop techniques for measuring the transverse beam optics with a high level of accuracy. This becomes even more challenging for secondary beams (such as pions and muons) since they have low intensity and contain particles with limited lifetimes.

The main goal of this paper is to demonstrate an experimental method based on a conventional quadrupole scan [11] to measure the Twiss parameters of a muon beam offering so a viable approach to optimizing injection into the storage ring of the Muon g-2 Experiment. It is important to emphasize that to the best of the authors' knowledge this is the first time wherein such a measurement is applied to muon beams. It is also shown that the technique is capable of detecting variations in the design parameters. As an example, it is used to quantize the effect of scattering that is introduced from other diagnostic devices that are located upstream of the scan area. The outline of the paper is as follows. Section 2 gives an overview of the Muon Campus beamlines and its available instrumentation. The magnet scan technique is introduced in Section 3 and in Section 4 the proof-of-principle experiment for the Muon campus is presented. Conclusions are presented in Section 5.

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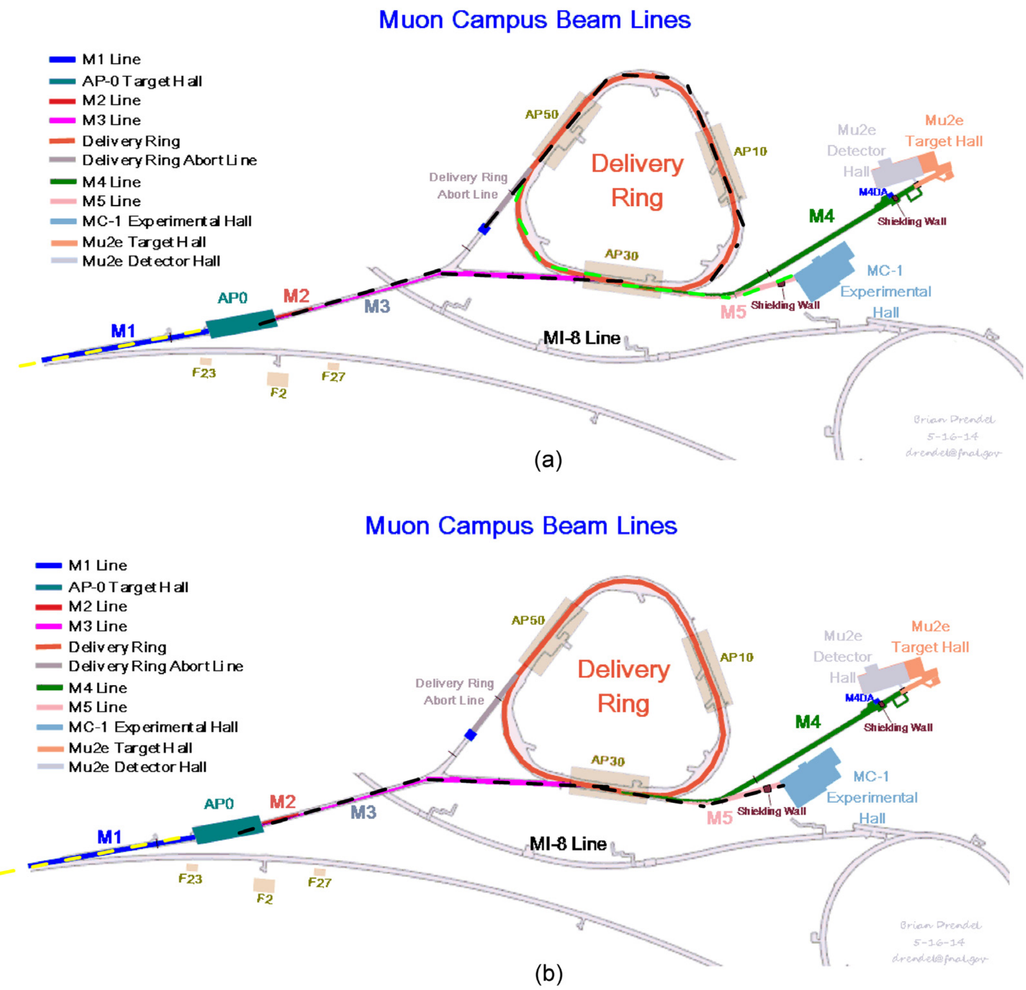

Fig. 1. (Color online): A schematic representation of the Muon Campus accelerator complex that is used by the Muon g-2 Experiment. Secondaries are produced on a target then travel through the M2-and M3-line, which is designed to capture as many 3.1 GeV/c muons from pion decays as possible. The beam is injected into the DR wherein a kicker is used to remove the protons, the resulting muon beam is then extracted into the M4-line, and the muon beam is eventually transferred to the new M5-line that leads to the muon storage ring. The combined M2-and M3-line and M4-and M5-line lengths are 280 m and 130 m respectively, and the DR that has a circumference of 505 m. (a) The full operation scenario wherein the beam is doing four turns in the DR before extraction into the M4, and (b) The commissioning scenario described in this study, wherein the beam is not doing any DR turns but is rather passing through a straight section of the DR. Note that the storage ring of the Muon g-2 Experiment is enclosed in the MC-1 building.

2. Overview of the fermilab muon campus

Fig. 1(a) shows a schematic layout of the Fermilab Muon Campus. While a more detailed description of all Muon Campus beamlines can be found elsewhere [9], their main features are reviewed here. Protons with 8 GeV kinetic energy are transported via the M1 beamline to the target station at AP0 and produce a beam of secondary particles that is a mixture of different species but consists mainly of protons and pions. The target station consists of four main devices: a production target to generate secondaries, a lithium lens to focus secondaries, a pulsed magnet for energy selection, and a beam dump to remove unwanted particles. The target is made out of Inconel 600 (a nickel–iron alloy) cylinder with its center bored out for pressurized air to pass for internal cooling. A Beryllium outer shell keeps the target from spattering Inconel into the Lens. The target assembly is positioned relative to the proton beam such that the beam subtends a chord of the cylinder. Transverse motion of the cylinder axis perpendicular to the beam allows the effective length of the target to be changed so that the target efficiency can be optimized. During full operation, 16 pulses of 10^{12} protons each within a 1.4 s cycle length are arriving at the target. The secondaries are focused by a lithium lens and then momentum-selected via a downstream pulsed dipole magnet (PMAG). The PMAG selects 3.1 GeV/c positive particles and bends them 3° into the M2-line channel. The M2-line is 50 m long and consist of series of 120° phase-advance FODO cells. Further downstream, a second dipole magnet provides another 3° bend to align the beam with the M3-line trajectory. The M3-line continues with a sequence of 90° phase-advance FODO cells for nearly 100 m, wherein a horizontal right bend, provided by a specialized insertion created from two 9.25° dipole bends, aligns the beam to the injection leg of the Delivery Ring (at $S = 160$ m). This line continues with another sequence of 72° phase-advance FODO cells for about 120 m, wherein the beam is injected vertically into the DR. The mixed secondary beam enters the DR (circumference 505 m) and circulates several turns to achieve a longitudinal separation between the protons and muons, due to the velocity difference between the different species. On the fourth turn, the longitudinal separation is sufficient for a fast kicker to cleanly remove the trailing proton beam.

Injection from the M3-line and extraction to the M4-line takes place in the same straight section (AP30) with the latter happening in the downstream half. Two kicker magnets are first used to kick the beam out of the closed orbit, then with the aid of a Lambertson magnet and a pair of two vertical bending magnets, the beam is extracted upward out of the DR. After traveling 30 m in the M4-line, the beam bends again upward into the M5-line and continues towards the storage ring