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# COMMISSIONING THE SUPERCONDUCTING MAGNETIC INFLECTOR SYSTEM FOR THE MUON g-2 EXPERIMENT*

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*Abstract*

The Fermilab muon $g-2$ experiment aims to measure the muon anomalous magnetic moment with a precision of 140 ppb – a fourfold improvement over the 540 ppb precision obtained in the BNL muon $g-2$ experiment. Both of these high-precision experiments require an extremely uniform magnetic field in the muon storage ring. A superconducting magnetic inflector system is used to inject beam into the storage ring as close as possible to the design orbit while minimizing disturbances to the storage-region magnetic field. The Fermilab experiment is currently in its first data-taking run, where the Fermilab inflector system is the refurbished BNL inflector system. This discussion reviews the Fermilab inflector system refurbishment and commissioning.

## INTRODUCTION

The Fermilab muon $g-2$ experiment (E989) must collect 20 times more data than the previous BNL muon $g-2$ experiment (E821) in order to achieve the nominal goal of 100 ppb statistical uncertainty [1]. Optimizing injection of the muon beam into the storage ring plays a critical role in achieving this goal and completing the experiment in a timely manner. The superconducting magnetic inflector system facilitates injection of the muon beam into the storage ring by canceling the main dipole field of the ring and providing a field-free channel through which the injected muon beam passes, as shown in Fig. 1. The novel truncated-double-cosine-theta geometry of the discrete superconducting currents largely traps the return magnetic flux and a superconducting shield further prevents any remnant fields from disturbing the high-precision dipole magnetic field in the muon storage region [2,3]. In this way, the strict geometrical and field-uniformity constraints are satisfied, and the muon beam is injected as close as possible to the nominal storage-orbit radius, $\rho_0 = 7112$ mm. Several other important physical parameters of the superconducting magnetic inflector system are shown in Table 1.

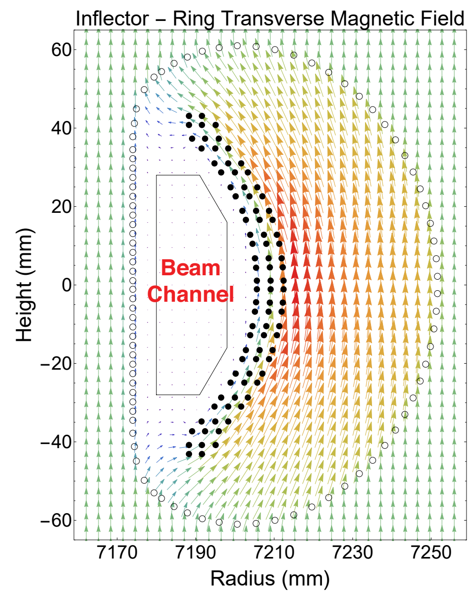


Figure 1: Vector sum of inflector and storage-ring magnetic fields. The superposition creates a field-free region through which the injected beam enters the ring close to the design radius $\rho_0 = 7112$ mm while not disturbing the dipole magnetic field in the muon storage region (toward left).

Table 1: Summary of Physical Parameters

| Parameter | Value |
|---|---|
| Cold mass | 60 kg |
| Magnetic length | 1.7 m |
| Beam channel | 18(W) × 56(H) mm$^2$ |
| Dipole field in beam channel | 1.5 T (@2850 A) |
| Conductor transverse dimensions | 2 × 3 mm$^2$ |
| Number of turns | 88 |
| Conductor volume (NbTi : Cu : Al) | 1 : 0.9 : 3.7 |
| NbTi/Cu composite diameter | 1.6 mm |
| Stored energy | 9 kJ |

## INFLECTOR SYSTEM COMMISSIONING

The inflector system cryogenic lines and superconducting lead splice were cut in order to facilitate the move from BNL to Fermilab. These connections had to be re-established and instrumentation wires reconnected once the storage-ring yoke was in place at Fermilab. A new power supply

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and quench-detection system has also been installed and commissioned. Despite having not been powered in over 15 years, the inflector system reached full operating current without issue. The superconducting shield was also tested using the main field of the storage ring and two Hall probes located inside the inflector. The shielding value is found to be about 0.26 T, which is consistent with $B = \mu_0 J_c d$ where $J_c$ is the current density and $d$ is the shield thickness [3]. Both E821 and E989 have had an issue with one of the Hall probes due to a voltage lead becoming disconnected internally. To salvage this probe E989 reads the voltage from the outgoing current lead, effectively forming a 3-point measurement. The new scaling is calibrated with respect to the other Hall probe and serves as a backup.

Figure 2: Superconducting coil geometry of the 1.7-m long inflector magnet (top, c.f. Fig. 1). Inflector coils and shield being prepared for recommissioning at Fermilab (bottom).

## INFLECTOR SYSTEM OPTIMIZATION

### *Inflector Current/Field Optimization*

The inflector current determines the magnetic field in the beam channel, and hence, the extent to which the field cancels the storage ring main magnetic field. Any residual field in the beam channel increases the curvature of the injection trajectory, which in turn increases beam losses due to scraping in the narrow horizontal inflector aperture ($\Delta x = 18$ mm). Residual field in the beam channel also affects the horizontal position and angle $(x, x')$ propagated 90° downstream to the pulsed kicker magnets that place the muon beam on orbit [4], which in turn affects the properties and dynamics of the stored muon beam. The inflector current is therefore an important tunable parameter for optimizing muon injection into the storage ring. Representative inflector-current optimizations measured during commissioning are shown in Fig. 3.

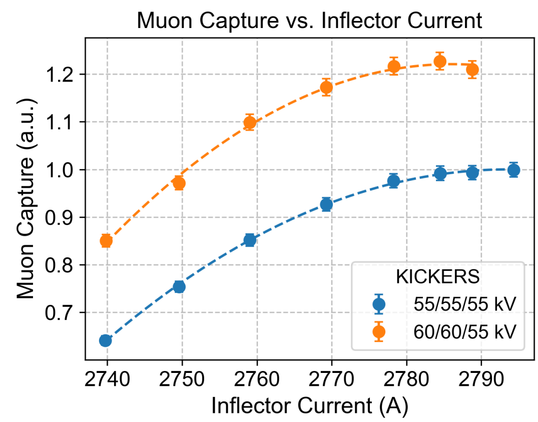


Figure 3: Representative inflector-current optimizations measured during commissioning, where all other parameters are held fixed. Muon capture is measured nondestructively via the decay-positron signal from $\mu^+ \rightarrow \bar{\nu}_\mu \nu_e e^+$ normalized to the amount of injected beam.

### *Optimizing Injection Position and Angle*

The 25-m section of beamline immediately upstream of the muon storage ring plays a critical role in fine-tuning the beam centroid motion and focusing through the narrow inflector aperture into the storage ring [5]. Small dipole corrector magnets (TRIMs) allow the {horizontal, vertical} position and angle of the injected muon beam to be independently adjusted over the ranges $\{\Delta x, \Delta y\} \approx \pm 25$ mm and $\{\Delta x', \Delta y'\} \approx \pm 5$ mrad near the storage-ring entrance. A custom set of Fermilab Accelerator Controls Language (ACL) scripts has been developed to facilitate beam tuning by rapidly scanning over magnet currents and monitoring muon capture in the storage ring. Figure 4 shows muon capture depends very sensitively on the horizontal injection position and angle $(x, x')$ at the storage-ring entrance. The horizontal TRIMs currents investigated in the 2D scan (HT020, HT024) are converted to $(x, x')$ at the storage-ring entrance using two detectors immediately upstream of the inflector and storage ring. The strong correlation and narrow optimal range of $(x, x')$ at the storage-ring entrance are expected since the injected beam must ultimately pass through the narrow 18 mm horizontal aperture of the 1.7-m long inflector. The vertical beam position and angle have also been investigated and optimized with similar success.

### *Optimizing Injection Focusing*

Horizontal and vertical focusing of the injected beam also play a critical role in maximizing muon capture in the storage ring. A conceptual overview of the procedure used to tune and optimize beam focusing is shown in Fig. 5. First,

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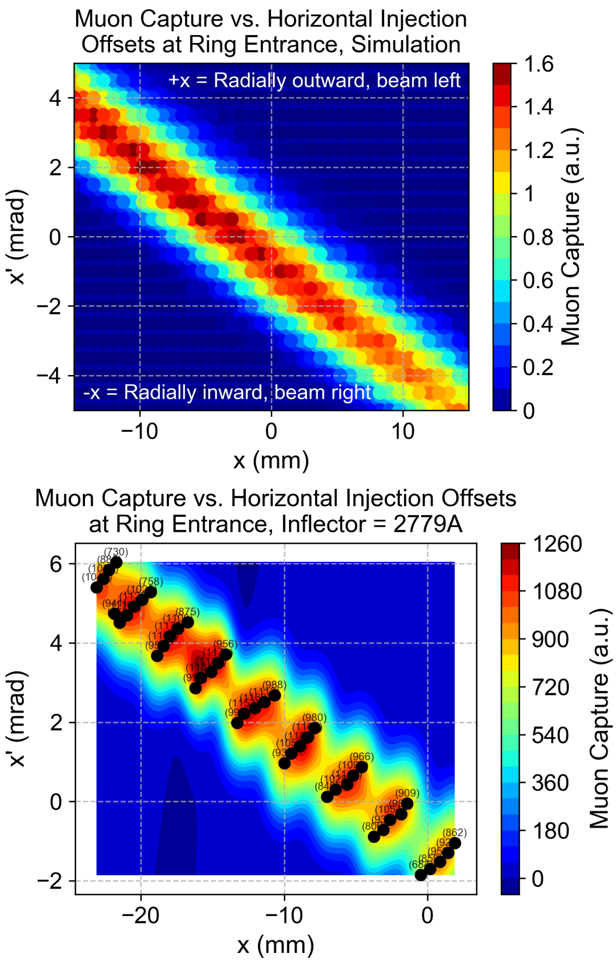


Figure 4: Muon capture vs. horizontal position offset and angle $(x, x')$ near the storage-ring entrance: Simulation (top) and commissioning data (bottom).

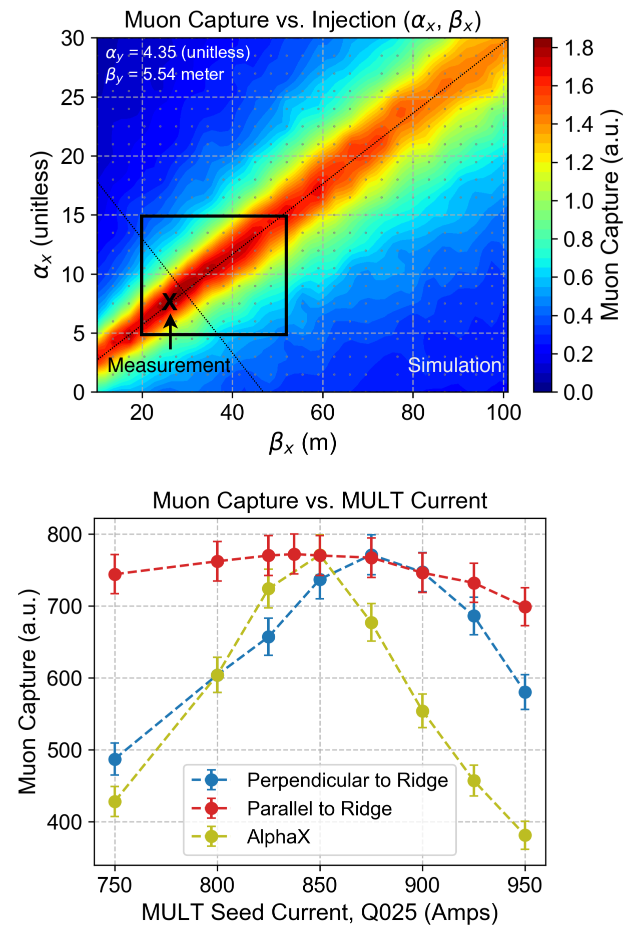


Figure 5: Muon capture vs. horizontal injection beam parameters $(\beta_x, \alpha_x)$ according to simulation (top) and observation (bottom). The narrow, highly correlated ridge of optimal $(\beta_x, \alpha_x)$ is shown in red in both plots.

horizontal and vertical beam parameters are measured using the quadrupole-scan technique [6, 7] at a detector located about 20 m upstream of the ring. Next, the measured beam parameters are propagated downstream to the ring entrance in order to connect with simulations (Fig. 5, top). Finally, simulation results are used to determine where in the landscape of optimal injection parameters the measured beam parameters lie, and to formulate an effective tuning strategy from that point forward. Simulations indicate a highly correlated "ridge" of optimal injection Twiss parameters $(\beta, \alpha)$ in both transverse directions, which reflects the need to focus the beam horizontally and vertically through the narrow transverse aperture of the 1.7-m long inflector. The final six magnetic quadrupoles immediately upstream of the ring are then adjusted simultaneously using current ratios chosen that target specific features of the landscape. Simultaneously adjusting several beamline elements is known as "MULT" at Fermilab; 8 quadrupole MULTs are constructed in total, viz. 4 to target each of the canonical directions $\{\hat{\beta}_x, \hat{\alpha}_x, \hat{\beta}_y, \hat{\alpha}_y\}$ and another 4 to step "parallel" or "perpendicular" to the ridge of optimality shown in the landscape of Fig. 5 (top). In this way, the abstract space of injection beam parameters is quickly and effectively explored, and beam focusing for injection into the storage ring is rapidly optimized (Fig. 5, bottom). The observed variation of muon capture vs. injection beam parameters is found to agree very well with simulation.

## CONCLUSION

The E821 superconducting magnetic inflector system has been refurbished for use as the E989 inflector system, where it has been successfully commissioned for the Fermilab experiment. A custom set of beam-tuning scripts have been developed to facilitate the rapid and effective optimization of injection position, angle, and focusing through the inflector into the muon storage ring. The inflector current has been optimized, and the Fermilab experiment is now collecting physics-quality data.

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