The Commissioning Run Update of The Muon g-2 Experiment at Fermilab

Ran Hong
(Muon g-2 collaboration)
Argonne National Laboratory
Outline

› Introduction

› Experiment Construction and Commissioning Status

› Experiment Progress

› Summary
Introduction: Muon g-2 and BSM Physics

- **Issues in modern particle physics:**
  - Naturalness of Higgs mass
  - What is the dark matter made of?
  - Baryon asymmetry
  - Unification of fundamental interactions

- **The measured muon anomalous magnetic moment disagrees with the SM prediction**

- **What can the new muon g-2 experiment tell us?**
  - Whether the hint of new physics is true?
    - If true: energy scale/interaction strength of new interactions
    - If not true: limits of energy or interaction strength of new interactions

---

Keshavarzi, Nomura, Teubner arXiv: 1902.02995

Diagrams of supersymmetrical particle exchanging
Introduction: Brief description of the New Measurement

\[ \vec{\mu} = g \frac{q}{2m} \vec{s} \]

\[ a_\mu = \frac{g_\mu - 2}{2} \]

\[ a_\mu (\text{Exp}) = -\frac{m\omega_a}{eB} \]
**Introduction: Brief description of the New Measurement**

\[ \vec{\mu} = g \frac{q}{2m} \vec{s} \]

\[ a_\mu = \frac{g_\mu - 2}{2} \]

\[ a_\mu (\text{Exp}) = -\frac{m \omega_a}{eB} \]

- Measure muon anomalous precession frequency:
  - Asymmetry in positron emission angular distribution
  - Positron energy oscillation in lab frame
  - Measure oscillation frequency ($\omega_a$) of the counting rate of positrons above an energy threshold

- **Measure magnetic field:**
  - Using NMR probes
  - Measure proton spin precession frequency ($\omega_p$)
  - Average the measured field over the muon distribution

**Improvement:**
- $\omega_a$: 180 ppb -> 70 ppb
- $\omega_p$: 170 ppb -> 70 ppb
Experiment Construction and Commissioning Status

- Muon beam line
- Muon storage ring
- Detectors
- Field sensors
Muon Beam

- Ion source
  - Linac
    - 400 MeV proton
  - Booster
    - 8 GeV proton

- Delivery ring
  - kick out protons
  - let pions decay

- Target
  - Create pions

- Recycler
  - Bunching

MC1
- Experiment Hall

16 Shots / 1.4 s
Muon Storage Ring: Magnet

Key:
- Transportation: 2015
- Construction: 2015-2016
- Shimming: 2015-2016

E821 (BNL)  E989 (FNAL)
Muon Storage Ring: Vacuum Chamber

Deformation of the chamber under vacuum

Commissioning:
- Modifying and cleaning: 2016
- Alignment: 2016
- Installation: 2016-2017
Muon Storage Ring: Inflector

Need to cancel the fringe field before the muons reach the storage region

Commissioning:
- Installation: Oct 2016
- Cooled down: Dec 2016
Muon Storage Ring: Kicker Magnet

Kicker Magnet

~5000A through the sheets

Ideal kicker pulse

Beam pulses

Measured kicker pulse shapes

Commissioning:
- Installation: Nov 2016 - June 2017
- Conditioning: Summer 2017
- Optimization: 2018
  1. Timing optimization
  2. Increasing strength

1. Timing optimization
2. Increasing strength
Muon Storage Ring: Electric Quads

Thin mylar for the outer electrode

Quadrupole electrodes for beam focusing

1: Quad plates, 2: Stand-offs, 3: Trolley rails, 4: Radial adjustment screws

Commissioning:
- Alignment: 2016
- Installation: Early 2017
- Conditioning: June 2017

Field Map (Opera3D)
Detectors: Calorimeters (x24)

**Upgrades:**
- Pile-up separation: saving digitized waveform and template fitting
- Position sensitivity: read out each crystal
- Gain stability control: Laser calibration system
- Data processing: GPU accelerated pulse finder

**Commissioning:**
- Fabrication and testing: 2014-2016
- Installation: 2016-2017

Digitized wave forms for all crystals, template fitting
Detectors: Straw Trackers (x2)

**Track reconstruction**
- Hits at 154μs in 50ns window

**Beam distribution**

**Upgrades:**
- In vacuum tracking: better beam position retrieval
- Minimize scattering: Thin straw walls

**Commissioning:**
- Fabrication and testing: ~2016
- Installation
  1. Tracker 1: May 2017
  2. Tracker 2: Dec 2017
Field Sensors: Field Scanning Trolley

**Upgrades:**
- Automated mechanical motion control
- New probes and electronics: recording fully digitized waveform

**Commissioning:**
- Design and construction: 2016
- Installation: March 2017
- Resolving interference: March 2017 - March 2018
- Operation and optimization: More automated motion control
Field Sensors: Fixed-Probe Drift Monitors and fluxgates

Field stabilization

Fixed Probe Signals → Online analysis → Average field

B-field perturbation → Current in the coils → Power supply feedback

378 fixed probes

Upgrades:
- New probes: petroleum jelly (no leak)
- GPU accelerated online analysis: 1.67s per measurement

Commissioning:
- Building probes: 2015
- Constructing electronics: 2016-2017
- Installation: 2016-2017
**Field Sensors: Calibration Probes**

**“Plunging” Probe**
- Align with each trolley probe in vacuum
- Correct for systematic shifts

**$^3$He Probe**
- Plunging probe assembled and installed: 2018
- Calibration: on-going
- Helium probe and spherical water probe: testing

**Spherical Water Probe**

Commissioning:
- Plunging probe assembled and installed: 2018
- Calibration: on-going
- Helium probe and spherical water probe: testing
Experiment Progress

- Review of the progress (2015 ~ 2018)
- Current status
- Upcoming events
- Short-term improvements
Review of the Progress (2015~2018)

- 2015.11: Magnet construction
- 2015.11: Magnet Shimming
- 2016.10: Vacuum chamber installation
- 2016.10: NMR probe installation
- 2017.1: Vacuum chamber alignment
Review of the Progress (2015~2018)

- 2015.11: Magnet construction
- 2016.10: Magnet Shimming
  Vacuum chamber alignment
  Vacuum chamber installation
  NMR probe installation
- 2017.1: Detectors/trolley installation
  DAQ installation
- 2017.5: Commissioning Run I
  - First beam
  - First muon decay
  - First field scan
- 2017.7:
Review of the Progress (2015~2018)

- **2015.11**
  - Magnet construction

- **2016.10**
  - Vacuum chamber installation
  - NMR probe installation

- **2017.1**
  - Commissioning Run 1
    - First beam
    - First muon decay
    - First field scan

- **2017.5**
  - Detectors/trolley installation
  - DAQ installation

- **2017.7**
  - Repairing and Upgrading
    - Trolley motion
    - Quad and kicker
    - etc.

- **2017.10**
  - Magnet Shimming
  - Vacuum chamber alignment
Review of the Progress (2015~2018)

- 2015.11: Magnet construction
- 2016.10: Vacuum chamber installation, NMR probe installation
- 2017.1: Commissioning Run 1
  - First beam
  - First muon decay
  - First field scan
- 2017.5: Detectors/trolley installation, DAQ installation
- 2017.7: Commissioning Run 2
  - Improving stored muons
  - Improving detectors
  - Improving field
- 2017.10: Repairing and Upgrading
  - Trolley motion
  - Quad and kicker
  - etc.
- 2018.3.17

Argonne National Laboratory
Review of the Progress (2015~2018)

- Magnet construction
- Vacuum chamber installation
- NMR probe installation
- Commissioning Run 1
  - First beam
  - First muon decay
  - First field scan
- Vacuum chamber installation
- DAQ installation
- Repairing and Upgrading
  - Trolley motion
  - Quad and kicker
  - etc.
- Improving detectors
- Improving field
- Improving stored muons
- Production Run 1
  - Clock Blinded
  - Stable runs
- Production Run 2
  - Improving detectors
  - Improving field

Magnet Shimming
Vacuum chamber
alignment

- Detectors/trolley installation
- DAQ installation

- Commissioning Run 1
- First beam
- First muon decay
- First field scan

- Commissioning Run 2
- Improving stored muons
- Improving detectors
- Improving field

Argonne National Laboratory
R. Hong, rhong@anl.gov
CIPANP 2018, Palm Springs, CA
Current Status

Experiment Progress

**Beam Performance:**
- Quads and kickers experienced several major repairs, but are improved significantly in 2018

**Field Performance:**
- >30 successful trolley runs (field scans)
- 100% DAQ UP time since 3/17/2018
- Field monitors are ON for all field-up time
- Magnet uptime > 95%

**DAQ/Detector Performance:**
- DAQ live time ~90%
- Calorimeters and trackers: stable
- Beam Monitors: stable
Current Status

Commissioning Run 1, 2017

Positron-count oscillation Plot

Field Map (6/15/2017)

Transverse

Azimuthal

FNAL Muon g-2
Run 702 - 706
Jun 10-11, 2017

T-method wiggle plot chi2 minimization fit

Entries: 10203
$\chi^2$/ndf: 366.3/329
Prob: 0.07673

N: 30.79 ± 1.16
T$_w$: 66.54 ± 2.60
T$_r$: 4.369 ± 0.006

B [ppm]

Y [cm]

X [cm]

B [ppm]

Phi [deg]
Current Status

Production Run 1, 2018

Positron-count oscillation Plot

Field Map (5/16/2018)

-3  -2   -1    0    1    2     3
X [cm]

-3  -2   -1    0    1    2     3
Y [cm]

-1   -0.5    0    0.5    1   1.5

0    50   100   150   200  250  300  350

B [ppm]

-40    -20      0      20     40
Phi [deg]

B [ppm]
Upcoming Events

› End of Run 1: July 7th 2018
› Analysis
› Full analysis of Run 1: Summer-2019
› Start of Run 2: October 2018
Short-term Improvements

- **Kicker**
  - Improve kicker strength, shape and width: more stored muons and less beam oscillation

- **Inflector**
  - Install new inflector with open ends to improve stored muons by 30%

- **Quads**
  - Ramp up to higher voltages: improve storage and reduce beam oscillation

- **Vacuum**
  - Activate cryogenic pumps for better quad performance

- **Field**
  - Install thermal insulation to improve field stability
  - Calibrations: cross-calibrating plunging probe, spherical probe and the helium probe
  - External trigger for fixed-probe readouts: read when muon comes
Short-term Improvements

- **Kicker**
  - Improve kicker strength, shape and width: more stored muons and less beam oscillation

- **Inflector**
  - Install new inflector with open ends to improve stored muons by 30%

- **Quads**
  - Ramp up to higher voltages: improve storage and reduce beam oscillation

- **Vacuum**
  - Activate cryogenic pumps for better quad performance

- **Field**
  - Install thermal insulation to improve field stability
  - **Calibrations**: cross-calibrating plunging probe, spherical probe and the helium probe
  - **External trigger for fixed-probe readouts**: read when muon comes
Short-term Improvements

‣ Kicker
  • **Improve kicker strength, shape and width**: more stored muons and less beam oscillation

‣ Inflector
  • **Install new inflector with open ends** to improve stored muons by 30%

‣ Quads
  • **Ramp up to higher voltages**: improve storage and reduce beam oscillation

‣ Vacuum
  • **Activate cryogenic pumps** for better quad performance

‣ Field
  • **Install thermal insulation** to improve field stability
  • **Calibrations**: cross-calibrating plunging probe, spherical probe and the helium probe
  • **External trigger for fixed-probe readouts**: read when muon comes

---

**Field drift differences across the ring**

- **1.2 ppm**
- **-2.1 ppm**

11:00 - 13:00 May 28th 2018
Summary

‣ The Muon g-2 experiment is commissioned!
‣ Number of decay e⁺ detected: $1.08 \times 10^{10}$
‣ More improvement in summer 2018
‣ Run 2 will start in October
‣ Expect the run 1 result in 2019
Thanks for your attention!