COMET Phase-α Experiment: to Investigate COMET's Novel Muon Beamline at J-PARC

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Outline

• COMET and Its Novel Muon Beamline
• Muon Beam Detectors
• Run Summary
• Proton Beam Commissioning
• Muon Beam Measurement
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The COMET experiment

- Utilizing the proton beam from the J-PARC main ring, COMET searches for the muon to electron conversion process, which violates charged lepton flavor conservation, with an unprecedented sensitivity.
- The experiment comes in a phased approach.

**COMET Phase-I**
- 8 GeV, 3.2 kW, graphite target
- Search for $\mu - e$ conversion with $\mathcal{O}(10^{-15})$ sensitivity (factor of 100 improvement)
- Directly measure the muon beam.
- TDR published in 2020 (*)

**COMET Phase-II**
- 8 GeV, 56 kW, tungsten target
- Search for $\mu - e$ conversion with full sensitivity $\mathcal{O}(10^{-17})$ or better: > factor of 10,000 improvement

* COMET Phase-I Technical Design Report, DOI:10.1093/ptep/ptz125
COMET’s Novel Muon Beamline

- The success of COMET is relying on its novel muon beamline
  - The pion production target and the pion capture solenoid: to get enough muons
  - The transport solenoid: to reject beam-induced background, and to control the hit rate in detectors.

8 GeV Proton Beamline

- Pion production target with ~ 1 hadron interaction length. Pion capture solenoid with 5 T field.
- A 3 T curved solenoid with a vertical field and a collimator system to select particle by its momentum and charge
COMET’s Novel Muon Beamline

• Current status of the COMET muon beamline:
  ✓ Proton beamline (C-Line) ready.
  ✓ Muon transport solenoid ready.
  • Pion capture solenoid still under preparation.
COMET’s Novel Muon Beamline

Complete the muon beamline with a thin graphite target and some vacuum ducts: COMET Phase-α

• Commissioning for both the proton beamline and the transport solenoid
• Study pion production process by 8 GeV protons on a graphite target.
• Study the performance of the transport solenoid.

Thin target system
• 2×2 cm², 1.1 mm thick C/C composite pion production target
• Beam-loss measuring stainless target for beam profile measurement

* Due to the concern with the force by Eddy current, extra support rods need to be mounted to operate at 3 T.
Beam-Masking System

- To better study the performance of the transport solenoid, a beam-masking system was introduced in front of its entrance.
- The beam-masking system has two movable slits (horizontal and vertical).
  - By scanning the position of slits, the transportation matrix can be reconstructed.
Proton Beam Monitor

Polycrystalline TiO2 was developed to monitor the proton beam pulse by pulse.

• Very thin (0.3 μm) and much lower cost (handmade) than diamond detectors.

• Good performance was observed in lab as well as in the main ring dump.

• Eight modules were attached around the vacuum windows at the entrance and end of the COMET beam room.

Design of the Proton Beam Monitor

doi.org/10.1109/JSEN.2022.3224809
The Construction of the Moun Beamline

The movable slits in the beam-masking system.

Vacuum ducts mounted with 3-D printed vacuum windows.

2×2 cm², 1.1 mm thick C/C composite pion production target put inside the vacuum chamber.

Target monitor: 3 plastic scintillator with photo multipliers.
The Construction of the Moun Beamline

The movable slits in the beam-masking system.

Vacuum ducts mounted with 3-D printed vacuum windows.

Covered with shielding blocks

2×2 cm², 1.1 mm thick C/C composite pion production target put inside the vacuum chamber.

Target monitor: 3 plastic scintillator with photo multipliers

Proton Beam Monitor

4 @ Pre-target

4 @ Post-target

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Muon Beam Detectors

- Muon Beam Monitor
  - Position measurement
- Straw Tube Tracker
  - Position & direction measurement
- Range Counter
  - For momentum reconstruction and muon identification
  - Also generates trigger signals
- DAQ
  - Based on the MIDAS DAQ framework, officially adopted by COMET.
Muon Beam Monitor

• Scintillator fiber hodoscope
  - 1 mm² plastic scintillating fibers, readout by SiPMs.
  - 30×30 cm² area holds 2D-aligned 128+128 fibers.

• A multi-channel input electronics was developed.
  - ~3 nsec time resolution.
  - Good hit rate tolerance and capability for the experiment.
Straw Tube Tracker

A single station of Phase-I straw tube tracker was assembled for Phase-α.

• 480 straw tubes (narrow drift chambers) aligned on the X and Y planes.
  • Ar & C2H6 (50:50) gas mixture
• Phase-α was the first opportunity for commissioning a Phase-I detector!
  • Full readout chain was tested.

“ROESTI”, front-end electronics for COMET Phase-I/II

Straws for Phase-I
  • 1 cm diameter
  • 20 um thick
Range Counter

Multi-layered plastic scintillating counters measuring muon decay time

• Change the momentum range to measure with different thicknesses of a graphite degrader.

• Reconstruct the number of muons stopped in a copper muon stopper.
  • Negative muon's life time in copper is about 160 nsec compared to about 2 μsec in lighter materials.

• Generated trigger signals when a particle hits BDC & T0 with no simultaneous hits in T1 / T2.
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COMET Phase-α Run Summary

Commissioning Run (10th – 14th February)
✦ First proton beam commissioning succeeded.
✦ Tested the detectors, checked signal timings, and checked trigger logics.

Measurement Run (~ a week in 3rd – 15th March)
✦ 3rd – 4th: Principal check of beam muons
  ★ Checked if the muon's copper-induced short lifetime disappears w/o the copper absorber.
✦ 9th – 13th: Muon momentum spectrum measurement
  ★ Changed the Range Counter's configuration.
    ❖ Degrader thicknesses to change the momentum range to measure
    ❖ Range Counter's position to see the beam profile wider.
✦ 13th – 15th: Positive-charged beam measurement
  ★ Inverted the dipole magnet's polarity
  ★ Took data for beam kinematics studies using positive pions and the beam-masking system.

Muon beam in the COMET experimental hall for the first time!
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Proton Beam Commissioning

- Slow extraction with the COMET proton beamline (C-Line) was commissioned for the first time!
  - Same bunch filling structure as COMET Phase-I, but longer accelerator cycle
  - Lower beam power: 260 W (3.2 kW in Phase-I)
Proton Beam Commissioning

Sweeping bending magnet and measuring target monitor counts, center of the target was determined.
Proton Beam Commissioning

Sweeping bending magnet and measuring target monitor counts, profile at the target was measured.

Measured beam dimensions:
- Horizontal $\sigma(\text{tgt}) = 2.14 \text{mm}$
- Vertical $\sigma(\text{tgt}) = 3.88 \text{mm}$
Proton Beam Commissioning

8 TiO₂ sensors used to measure the proton beam
- 4 on the pre-target station, 4 on the post-target station.

Hits observed on one of the TiO₂ sensor.
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Muon Beam Measurement

Muon decay spectrum
• The signal ‘short’ muon decay component was observed.
  • Negative muons transported via the 90°-curved Transport Solenoid!

Muon momentum spectrum
• Reconstructed the number of negative muons stopped in the muon stopper from the fitted value.
  • Only statistical uncertainties plotted.
• The spectrum shape is close to our expectation from the design.

Comparison with simulation
• These measurements contribute to our hadron production model studies.
  • The model reproducing the data will be chosen for simulation studies for Phase-I & -II.
Muon Beam Measurement

Muon beam 2D profile

- Moved the Range Counter two-dimensionally by 25 cm step.
- Muons with a momentum of around 40 MeV/c were measured.
- Muons in this momentum range are expected to concentrate around the center in the vertical direction.
COMET Phase-α in simulation

- The full geometry of Phase-α, including the shielding blocks, is implemented in the Geant4 based simulation framework developed for COMET Phase-I and Phase-II.
  - 3D field map from calculation, including the fringe field, is implemented in the simulation.
- To study the hadron production physics in the pion production target, multiple physics models are being tested, with the comparison to the muon beam measurements.
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• The COMET’s muon beamline was constructed
  • Without the pion capture solenoid. With a thin target.

• COMET Phase-α carried out in February and March
  • Proton beam was successfully extracted into the COMET beam hall.
  • Achieved the first observation of beam particles (muons) successfully transported via a 90°-curved Muon Transport Solenoid.
  • Expected muon momentum spectrum and beam profile were observed.

• In the future
  • More analysis to research the muon transport optics, too, by combining all detector data.
  • Measure the backward π/μ production cross-section.
  • The COMET simulation software (hadron production model) will be validated.
  • Further Phase-α data-taking requested.
  • Operate the muon transport solenoid with 3 T.
  • Move towards the Phase-I experiment!
Thank you for listening!