Hajime NISHIGUCHI, KEK · J-PARC on behalf of the COMET collaboration

StrECAL System for COMET Phase-I & Phase-II

* StrECAL = Straw tracker + Electromagnetic CALorimeter
Contents

- The COMET Experiment
  - Search for a $\mu$-e conversion
  - Experimental overview
- StrECAL System
  - Straw tracker
  - Electromagnetic Calorimeter
- Current Status
- Towards COMET Phase-II
- Conclusions
The COMET Experiment
to
Search for $\mu-N\rightarrow e-N$ (Mu-E Conversion)
Search for Charged Lepton Flavour Violation in $\mu$-processes

- Muon is Best Probe to search for CLFV; *eg.* $\mu^+ \rightarrow e^+\gamma$, $\mu^-N \rightarrow e^-N$, $\mu^+ \rightarrow e^+e^+e^-$

**$\mu$ decay in SM**

- pure leptonic
- only weak interaction
- taking $m_\nu \neq 0$ into account
  
  $BR(\mu \rightarrow e\gamma) < O(10^{-54})$

**$\mu$ LFV in BSM**

- causable via *new particle*
- not suppressed by tiny $m_\nu$
- if BSM assumed...

  $BR(\mu \rightarrow e\gamma) = O(10^{-16}-10^{-13})$

  $\rightarrow$ clear evidence of BSM

- Try to Explore New Physics via *"Charged Lepton Flavour Violation"*

- Among *"Quark"*, *"Neutrino"* = Known as Flavour violated

- *"Charged Lepton Flavour Violation (cLFV)"* = Never Observed so far

- Very sensitive to the TeV-scale new physics beyond Standard Model
  
  $\rightarrow$ Complementary and Competitive to the Energy Frontier (*eg.* LHC)
µ⁻N→e⁻N Search

- “Muon-to-Electron Conversion in Muonic Atom (µ⁻N→e⁻N)”
- Charged LFV, So-called “µ-e Conversion”
- One of the most prominent process of muon LFV

- “Signal”
  - $E_e = m_\mu - B_\mu - E_{recoil}$
  - $\sim 105$ MeV (muonic Al)

- “Background”
  - Beam-related
  - Normal muon decay in Orbit (DIO)
  - Cosmic-ray induced

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“The StrECAL System for COMET”

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The COMET Experiment

Enabled by “Four Features” → Aim to achieve target sensitivity of $O(10^{-17})$

- **Feature(1)** — High Intensity Pulsed Proton Beam by J-PARC

- **Feature(2)** — High Efficiency 5T-Solenoidal Pion Capture System

- **Feature(3)** — Long/Curved Solenoidal pion/muon transport section

- **Feature(4)** — High resolution, vacuum compatible electron spectrometer can select momentum.

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"The StrECAL System for COMET"
Detector Apparatus of the COMET
Detector Apparatus of the COMET

- To stop muons
- Detector Slenoid to detect and identify 100 MeV electrons
- Muon Target Disks
- Beam Blocker
- Beam Collimator
- DIO Blocker
- To eliminate low-energy beam particles and to transport only ~100 MeV electrons

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Dual-Staged Approach

**COMET Phase-I**
- Construct up to first 90° bend and place detector.
- Perform direct beam measurement
  - No backward $\sigma_\pi$ data so far
  - No real BG data so far
- Perform $\mu$-e Search with an intermediate sensitivity ($O(10^{-15})$)

**COMET Phase-II**
- Complete all transport
- Perform $\mu$-e Search with a full sensitivity ($O(10^{-17})$)
Dual-Staged Approach

**COMET Phase-I**
- Construct up to first 90° bend and place detector.
- Perform direct beam measurement
  - No backward $\pi$ data so far
  - No real BG data so far
- Perform $\mu\text{-e}$ Search with an intermediate sensitivity ($O(10^{-15})$)

**COMET Phase-II**
- Complete all transport
- Perform $\mu\text{-e}$ Search with a full sensitivity ($O(10^{-17})$)
Detectors for COMET Phase-I

For µ-e Conversion Search

✦ “CyDet” = Cylindrical Detector System
✦ For Phase-I, centre part of beam is dominated by BG, i.e. Cylindrical Drift Chamber and Cylindrical Trigger Hodoscope is employed to search for µ-e conversion.
✦ He-iC₄H₁₀ gas-mixture to reduce material budget, Hollow cylinder design to have a BG tolerance

For Beam Measurement

✦ “StrECAL” = Straw tracker and ECAL
✦ To measure all delivered beam incl BG, vacuum-compatible tracker and calorimeter is employed
✦ Straw = Planer/Low-mass, LYSO crystal
✦ ECAL = High resolution / High density
✦ Same concept as Phase-II detector
✦ Prototype of Phase-II Final Detector

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“StrECAL System for COMET”

Hajime NISHIGUCHI (KEK)

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The “StrECALE” System

[ Straw Tracker ]
+
[ Electromagnetic CALorimeter ]
**StrECAL : Straw tracker and Electromagnetic Calorimeter**

- For COMET Phase-I, beam detector needs to measure the all delivered beam particle incl. backgrounds;

  - To be light material ➡ Vacuum compatible & Thin wall
  - To have a large acceptance ➡ Planar tracker-based geometry
  - To be capable PID ➡ Long and Heavy enough (TOF & dE/dx)
  - To be operational with bunched beam ➡ Finely segmented

“Straw” + “ECAL” is the BEST
StrECAL: Straw tracker and Electromagnetic Calorimeter

A series of straw tube trackers (StrawTrk)

Electron Calorimeter (ECAL)

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"The StrECAL System for COMET"

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\* Planar wire chamber-based tracker in Vacuum $\rightarrow$ Straw Tracker

\* Five super-layers (station) consist of 4 planes of straw tubes
  \* 2 planes for $x$-coordinate and 2 planes for $y$-coordinate, each layer is staggered by half a cell to solve the left-right ambiguity.

\* All tracker modules are installed in vacuum.

\* Timing (Trigger) is provided by the electromagnetic calorimeter.
**Straw Tracker (2/5), Straw Material**

- Ultra-thin wall and vacuum tight straw is developed within COMET
  - ”20μm-Mylar” + ”70nm-Al coat”, φ9.8mm, enabled by ultrasonic welding

**Ultra thin & gas tight is realized by newly developed method (Thanks to NA62 collaboration)**

<table>
<thead>
<tr>
<th></th>
<th>NA62 straw</th>
<th>COMET straw 20μm</th>
<th>COMET straw 12μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mylar wall thickness</td>
<td>36 μm</td>
<td>20 μm</td>
<td>12 μm</td>
</tr>
<tr>
<td>Tube diameter</td>
<td>9.8 mm</td>
<td>9.8 mm</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>Cathode material</td>
<td>Cu(50nm) + Au(20nm)</td>
<td>Al (70 nm)</td>
<td>Al (70 nm)</td>
</tr>
<tr>
<td>Development status</td>
<td>Currently used in a real experiment</td>
<td>Mass-product Completed, Detector assemble, ongoing</td>
<td>Under R&amp;D</td>
</tr>
</tbody>
</table>
Straw Tracker (3/5), Gas system

* Chamber gas → Also maintain FE electronics temperature in vacuum vessel
* Al(50) : C₂H₆(50), compressed to make a big flow (~1L/sec) and cooled down to -20°C, → FE electronics would be kept as room temp.
Straw Tracker (3/5), Gas system

- GAS system
  - Chamber gas → Also maintain FE electronics temperature in vacuum vessel
  - Al(50) : C\textsubscript{2}H\textsubscript{6}(50), compressed to make a big flow (~1L/sec) and cooled down to -20°C, → FE electronics would be kept as room temp.

- Pilot test w/o detector satisfies the required specifications

Calculation (FEM/\textsc{Ansys}) meets all requirements.
Straw Tracker (4/5), Prototyping

- **Prototyping strategy**: 1) 1-straw prototype → 2) Full-scale prototype
  - 1) for assembly technique R&D, 2) for performance validation

- Basic assemble technique was established, *e.g.*, pre-tension, feedthrough, gas tightness, *etc.*
- Vacuum compatibility was also confirmed, *e.g.*, outgas, leak, pressure maintenance, *etc.*

**Full-Scale Prototype**
- All parameters, *e.g.*, size, electronics, gas, *etc.*, are same as final detector, but only # of straw is small → Only 32 straws (16 for x-axis, 16 for y-axis) are installed.

- Detector performances, *e.g.*, efficiency, resolution, stability, vacuum compatibility, *etc.*, are investigated with a 105 MeV/c electron beam and final experimental conditions.
Straw Tracker (5/5), Detector Performance

- Test-beam w/ 105 MeV/c electron was conducted at Tohoku university.
- Vacuum tightness has been proven down to 0.1 Pa
- Spatial resolution better than 150 μm has been confirmed
  - Good enough to realize a required momentum resolution of <200 keV/c with a 1T magnetic field)
- Detector design has been fixed based on these studies by Full-scale prototype
  ➙ Green signal to start construction of Phase-I straw tracker

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ECAL (1/4), Electromagnetic CALorimeter

- **Purposes;**
  1) Measure electron energy with a good resolution
  2) Provide hit position with electron trajectory at the ECAL position
  3) Provide the trigger and the timing information

- **Requirements;**
  - Energy resolution;
    - $\sigma_E < 5\%$ @ 105 MeV
  - Cluster position resolution;
    - $\sigma_x < 1$ cm
  - Fast timing response
    - $f_t < 100$ nsec
  - Operational in B-field (1T)

- **Solutions;**
  - Highly segmented scintillating crystals with high light yield and fast response
    - LYSO
  - Silicon-based photodiode & low-noise preamplifier
    - APD (Avalanche photodiode)
ECAL (2/4), LYSO Crystal

- R&D in the collaboration
  - Choice of the candidate crystals
    - GSO: 20×20×150mm³ (10.9X₀)
    - LYSO: 20×20×120mm² (10.5X₀)

- Performance-cost evaluation
  - Test-beam experiment has been carried out to decide the choice
    - With 5×5mm² APDs, 1st prototype preamp, and 105 MeV/c electron
  - Our decision from the results is LYSO

<table>
<thead>
<tr>
<th>Crystal</th>
<th>GSO(Ce)</th>
<th>LYSO</th>
<th>PWO</th>
<th>CsI(pure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>6.71</td>
<td>7.40</td>
<td>8.3</td>
<td>4.51</td>
</tr>
<tr>
<td>Radiation length (cm)</td>
<td>1.38</td>
<td>1.14</td>
<td>0.89</td>
<td>1.86</td>
</tr>
<tr>
<td>Moliere radius (cm)</td>
<td>2.23</td>
<td>2.07</td>
<td>2.00</td>
<td>3.57</td>
</tr>
<tr>
<td>Decay constant (ns)</td>
<td>600⁺, 56⁻</td>
<td>40</td>
<td>30⁺, 10⁻</td>
<td>35⁺, 6⁻</td>
</tr>
<tr>
<td>Wave length (nm)</td>
<td>430</td>
<td>420</td>
<td>425⁺, 420⁻</td>
<td>420⁺, 310⁻</td>
</tr>
<tr>
<td>Refractive index at peak emission</td>
<td>1.85</td>
<td>1.82</td>
<td>2.20</td>
<td>1.95</td>
</tr>
<tr>
<td>Light yield (NaI(Tl)=100)</td>
<td>3⁺, 30⁻</td>
<td>83</td>
<td>0.083⁺, 0.29⁻</td>
<td>3.6⁺, 1.1⁻</td>
</tr>
</tbody>
</table>

Waveform

Energy Resolution

Position Resolution
ECAL (3/4), Assembly

- Module-base assembly is employed
- Basic unit = 2x2 crystal matrix module
- × 480 modules to cover the full cross-section of detector fiducial

(a) 1 crystal

(b) 2x2 module
4 crystals

(c) 4x4 super-module
16 modules = 64 crystals

A Single Completed Module

Front view w/o APD

Back view

2x2 APD board
ECAL (4/4), Prototype

- Last prototype (with the final matrix configuration but only 16 modules, LYSO size, APD, FE-electronics, signal feedthrough) was constructed.
- Test-beam experiment with 105 MeV/c electron was conducted.

Prototype was successfully operated in vacuum

- Excellent performances that satisfies requirements for COMET Phase-I & II
  - $\sigma_E/E = 4\%$, $\sigma_x < 6\text{mm}$, $\sigma_t = 0.5 \text{nsec}$ @ 105 MeV electron beam
  - Scalable to the actual detector ➔ Final design for Phase-I has been fixed.

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Current Status
Straw Tracker Assembly for Phase-I

Straw assembly with a support structure (pressure vessel) performed (Station #1)

Started in 2020, All steps; 1) glueing with end-plug of straw, 2) fixing the straw-positioning jig, 3) straw insertion, 4) applying the tension on all straws (1.3 kgf), and 5) glueing all ends of straws, are finished.

All straws for Station #1 (4 planes, 480 tubes in total) installation, completed !!
Completed Straw Station #1
ECAL Construction for Phase-I

- Final detector design for Phase-I is fixed.
  - 1024 crystals in total
    - 256 modules
    - approx 1/2 the final ECAL (Phase-II)
- Crystal support structure, pressure vessel, end-flange, are completed.
  🔄 Crystal installation will start soon!!
Prospects towards COMET Phase-I

- At the J-PARC Hadron-Experimental-Facility, C-Line (primary proton beam line dedicated for COMET) is under construction, expected to be completed by the end of JFY2021.

- In JFY2022, low intensity beam commissioning (COMET Phase-α, 200W = 1/16 of Phase-I) is planned. StrECAL might be partially tested.

- In JFY2023, StrECAL for Phase-I will be completed, and ready for beam measurement at COMET Phase-I.
Towards COMET Phase-II
Final detector for Phase-II would be basically same as Phase-I.
What will be different from Phase-I?

Final detector for Phase-II would be basically same as Phase-I.

Need to be optimized by the result from Phase-I beam measurement.
What will be different from Phase-I?

Final detector for Phase-II would be basically same as Phase-I.

Need to be optimized by the result from Phase-I beam measurement.

Expected to be almost same as Phase-I, but some upgrades will be made.
Detector Upgrades

- Straw will be upgraded with a thinner/smaller straw tube
  - 12 μm/φ4.8mm straw was recently developed by JINR COMET group
  - Collaborating with CERN NA62 group to utilize this as an actual tracker

- ECAL upgrades; Naturally, # of LYSO crystal will be increased for Phase-II as designed. (Need to be doubled at least)
  - FE-electronics might be upgraded by experiences at Phase-I.
    - In particular, radiation tolerance might be an issue.
    - Output for trigger might be optimized reflecting the Phase-I results.
  - LYSO crystal?
Conclusions

COMET experiment aims to search for a μ-e conversion with an excellent sensitivity of $10^{-17}$ to explore the new physics beyond Standard Model.

To realize the experiment efficiently, dual-staged approach is employed.

StrECAL system (= “straw” tracker + “Electromagnetic CALorimeter”) was originally designed for the “full” COMET (=Phase-II).

In Phase-I, two experiments will be conducted; “beam measurement” and “μ-e conversion search”

Beam measurement will be carried out by StrECAL

StrECAL for Phase-I is real prototype for Phase-II StrECAL

StrECAL construction

Design for Straw tracker and ECAL is finally fixed by R&D with test-beam.

Straw assembly → Station #1 completed. Station #2 starts soon.

ECAL assembly → Support structure completed. Crystal installation starts soon.

Aim to be ready in 2023 for Phase-I beam measurement.

Towards Phase-II

In parallel to Phase-I construction, upgrade R&D is ongoing.