Extinction Measurement at J-PARC MR with Slow-Extracted Pulsed Proton Beam for COMET Experiment

The 22nd International Workshop on neutrinos from accelerators (NuFact2021)
6th-11th Sep. 2021 @ THotel, Cagliari, Italy

Muon to Electron Conversion (µ-e conversion)

The µ-e conversion is neutrinoless muon to electron conversion that is **charged lepton flavor violation** (cLFV).

- **Signal**
  - $\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)$
  - Mono-energetic signal electron

- **Bound Negative Muon Decay In Orbit (DIO)**
  - $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
  - Electron energy is lower than and equal to the signal electron energy.

- **Branching Ratio**
  - Standard Model (SM) $< 10^{-54}$ (*)
  - Beyond the SM $\sim 10^{-15}$
    - µ-e conversion is a good probe of new physics.

The COMET (COherent Muon to Electron Transition) experiment [1] searches for µ-e conversion.

- **Background rejection** is important because µ-e conversion is a rare process.

(*) To be precise, it is the SM w/ neutrino mixing.

The COMET Experiment

- The experiment will be carried out in the **hadron experimental facility at J-PARC**.
  - The world's **most intense pulsed proton beam** will be used.

- The experiment will be conducted in two phases.
  - Phase-I / II aims $10^{-15} / 10^{-17}$ sensitivity, respectively.
  - This ultimate sensitivity goal is a factor of about **10,000 better** than the current experimental limit from SINDRUM-II at PSI (Paul Scherrer Institute).

- COMET Phase-I is currently under construction at J-PARC.

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**J-PARC** (Japan Proton Accelerator Research Complex)

- **Main Ring (MR)**
- **Muon Stopping Target (Al)**
- **Muon Transport Solenoid**
- **Cylindrical Detector System**
- **Pion Production Target**
- **Electron Spectrometer**
- **Straw Tube Tracker**
- **Electromagnetic Calorimeter**
- **Phase-I**
- **Phase-II**
- **Hadron Experimental Facility**
The Background of COMET

- One of the most severe source of background is the prompt beam backgrounds produced by protons
  - e.g., in-flight muon decay and pions in a beam
- They are removed by **pulsed proton beam** and performing measurements in a **delayed DAQ window**.

- Inter-bunch residual protons which induce background also must be removed.
- Proton extinction of inter-bunch residual protons is required to be $< 10^{-10}$.

**Proton Extinction** := # of inter-bunch protons / # of in-bunch protons
The COMET Beam Operation

- The COMET experiment needs dedicated beam operation.

- **8 GeV protons** instead of 30 GeV
  - To avoid antiproton-related backgrounds

- **Slow extracted** pulse proton beam
  - To avoid pile-up of detector system

- **1.2 μs bunch separation** instead of 0.6 μs bunch separation
  - To keep bunch separation long enough to accommodate the lifetime of muonic atom in aluminum (τ ~ 864 ns)
  - Each injection batch (K1, K2, K3 and K4) in the COMET operation is structured with proton filled bunch (main bunch) and empty bunch.
Improvement Method of Extinction

- At first, an empty bunch can be made by RF chopper in the Linac.
- But at this stage, the extinction is only $10^{-6}$, which is not sufficient.

**Normal Injection**
- Both front main bunch and residual protons in rear bunch are kicked by injection kicker.
- Residual protons are injected and accelerated.

**Single Bunch Kicking (SBK)**
- The Injection kicker is shifted to kick front main bunch only.
- Not-kicked residual protons are eliminated by collimator.
The Previous 8 GeV Commissioning

- The COMET operation w/ forward SBK was tested, and the extinction was measured in 2018 [2]
- Front buckets were filled with protons of COMET Phase-I intensity (1.6×10^{12} ppp) and injection kicker was shifted 600 ns forward

Measurement setup at K1.8

→ There were residuals after 4th bunch…

- Extinction (requirement < 10^{-10})
  - = 202/(1.7 ×10^{10}) = 1.2×10^{-8}
  - < 1/(1.28×10^{10}) = 7.8×10^{-11}

The Previous 8 GeV Commissioning

- Injection kicker field has a small but a certain trailing component.
- Shift of 600 ns might not be large enough.

- It can be tested quickly just shift the kicker timing little more
- It was confirmed that the residuals could be removed in fast extraction

Solution Candidates

1. To shift kicker timing forward more
2. To shift kicker timing backward instead (backward SBK)

Test these solutions at J-PARC again!
The 8 GeV proton beam commissioning aimed to optimize the accelerator operation and demonstrate low enough extinction.

The test was performed from 19th to 25th May 2021. Both accelerator study (42h) and extinction study (100h) were completed successfully.

### Beam Status

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Previous Test (2018)</th>
<th>This Test (2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Power</td>
<td>1.8 kW (5.2 s cycle)</td>
<td></td>
</tr>
<tr>
<td># of Bunches</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td># of Protons</td>
<td>7.4×10^{12} ppp</td>
<td></td>
</tr>
<tr>
<td>Extraction Efficiency</td>
<td>97%</td>
<td>99.1% (preliminary)</td>
</tr>
<tr>
<td>Spill Duty Factor</td>
<td>16%</td>
<td>55%</td>
</tr>
<tr>
<td>Spill Length</td>
<td>0.65 s</td>
<td>0.6 s</td>
</tr>
</tbody>
</table>

When the beam cycle is set to 2.4 s, the beam intensity is equivalent to Phase-I (3.2 kW).
The extinction was measured by counting secondary pions at the K1.8BR beamline of Hadron Experimental Facility of J-PARC.

**Experimental Setup**
- For counting, the coincidence was taken with all of six detectors.
- Three independent TDC systems were used in parallel to guarantee measurement reliability.
  - HUL measures TOT also with 1 ns time resolution.
- Both the main detector and all TDC systems were developed to deal with a high hit rate of ~ 10 MHz at the bunch period of ~ 0.5 s.
  - Detailed information was presented by K. Oishi in poster session on 8th Sep.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH1&amp;2</td>
<td>79.2%</td>
</tr>
<tr>
<td>MD</td>
<td>97.8%</td>
</tr>
<tr>
<td>TC1&amp;2</td>
<td>92.8%</td>
</tr>
<tr>
<td>TC3</td>
<td>96.2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>69.2%</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TDC</th>
<th>FCT</th>
<th>KC705</th>
<th>HUL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time resolution</strong></td>
<td>7.5 ns</td>
<td>5 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td><strong>TDC length</strong></td>
<td>24 bits</td>
<td>27 bits</td>
<td>19 bits</td>
</tr>
<tr>
<td><strong># of boards</strong></td>
<td>8</td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>
Run Summary and Analysis Scenario

- **Run Summary**
  - All the planned operation modes were tested.
    - Extinction w/o SBK, extinction w/ forward SBK and backward SBK
    - The extinction was successfully measured.
  - The main measurement of backward SBK was measured with $O(10^{10})$ statistics.

- **Data Analysis**
  - In this commissioning, secondary beam intensity was increased ($\times 3$ previous) to achieve good sensitivity quickly.
    - **Severe problem is an accidental overlap event.**
  - TDC values of each detectors were measured.
  - Software coincidence is performed in the analysis.

- **Following Topics**
  1. Event selection
  2. The confirmation of reproduction from the previous test (2018)
    a. Extinction w/o SBK
    b. Extinction w/ forward SBK
  3. The results of the new approach (backward SBK)
    a. Signal/background discrimination
Event Selection

**Coincidence Logic**

1. A gate with time width of 50 ns is generated from the TDC value of each signal.
   - Signals include Beam passed event, cosmic-ray passed event, after pulse, etc..
2. When gates of all detectors were overlapped, it is judged as an event.
   - Time width of all detectors overlapping is defined as overlap width.
   - Accidental overlap will be discriminated from signal by the overlap width.

**Inter-Bunch Event Selection**

- The events immediately around the main bunch were assigned in-bunch events.
- The rest of the events were assigned inter-bunch events.
Setup: **Rear main bunch + Normal injection** (no kicker shift)

**Extinction Calculation**

- **1915** inter-bunch events
- The total number of particles $1.46 \times 10^9$ was corrected by the ion chamber from the number of hits obtained by the main detector.
  - The results of intensity scan by ion chamber were used to correct efficiency and saturation of the main detector.

→ Extinction of $O(10^{-6})$ is consistent with previous test (2018).
Reproduction – SBK 600 ns and 700 ns

- **Setup:** *Front main bunch + Forward SBK*
- Residual particles were observed at K4 rear as well as previous test

![Graph showing Hit time [μs] for Forward SBK 600 ns and 700 ns](image)

- SBK 600 ns has the extinction of $O(10^{-7})$.
- The extinction of $O(10^{-9})$ in SBK 700 ns was improved from SBK 600 ns.
- Perfect extinction was not achieved in forward SBK.
New Setup – Backward SBK 600 ns

- Setup: Rear main bunch + Backward SBK w/ 600 ns injection kicker shift
- It was expected to be no inter-bunch event.

- There were 7 inter-bunch events.
  - These events are confirmed in all TDC systems.
- Most of them are accidental like events in comparing overlap width with data of extinction w/o SBK.
  - They were evaluated using a signal sample and generated background sample.
Accidental Overlap (Background) Sample

- **Background candidate:** Beam-induced delayed events
  - They were identified with the coincidence of downstream detectors: the main detector and three trigger counters.

- The most probable background events are estimated accidental overlaps of beam-induced delayed events and two beamline hodoscopes.

- The background sample was generated from data-driven beam-induced delayed event data and randomly generated beamline hodoscopes data.
Event discrimination using with overlap width was evaluated.
  - Signal Sample
    - Inter-bunch events in data of extinction w/o SBK
  - Background Sample
    - Generated background sample

The threshold for overlap width of 38 ns was selected at the point where $\varepsilon_{\text{signal}}$ is 99%.

Two inter-bunch events remained

→ The extinction is $9.3 \times 10^{-11}$

Backward SBK w/ 600 ns shift achieved the extinction requirement of the COMET.

### Parameters

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td># of inter-bunch particles $N_{\text{out}}$</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Detection efficiency $\varepsilon_{\text{det}}$</td>
<td>0.692</td>
<td></td>
</tr>
<tr>
<td>Cut efficiency $\varepsilon_{\text{cut}}$</td>
<td>0.990</td>
<td>0.992</td>
</tr>
<tr>
<td># of residual particles $N_{\text{res}} = N_{\text{out}}/\varepsilon_{\text{det}}\varepsilon_{\text{cut}}$</td>
<td>2.92</td>
<td>4.37</td>
</tr>
<tr>
<td># of in-bunch particles $N_{\text{tot}}$</td>
<td>$3.14 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Extinction $R_{\text{Extinction}} = N_{\text{res}}/N_{\text{tot}}$</td>
<td>$9.3 \times 10^{-11}$</td>
<td>$1.4 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
The COMET experiment plans to search for $\mu$-e conversion at J-PARC. The experiment requires a dedicated 8 GeV pulsed proton beam operation. Proton extinction of inter-bunch residual protons is critical to eliminate beam-related backgrounds. The extinction is required to be $< 10^{-10}$.

The 8 GeV proton beam commissioning for COMET was completed successfully. The extinction measurement was performed at the K1.8BR beamline of the hadron experimental facility of J-PARC with $O(10^{10})$ statistics.

The extinction requirement was achieved with a 600 ns backward SBK (preliminary). Phase-I requirement is satisfied.

Both background estimation and analysis are ongoing. Online extinction monitor is under development.