PROCEEDINGS OF SCIENCE

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

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The COMET experiment aims to search for the neutrinoless conversion of a muon to an electron in a muonic atom. This experiment utilizes a bunched slow-extracted (bunched-SX) proton beam at 8 GeV from the J-PARC main ring synchrotron. To achieve a sensitivity of 10^{-17}, the fraction of inter-bunch stray protons, called extinction, must be less than 10^{-10}. The 8 GeV proton beam commissioning with a bunched-SX beam for the COMET experiment was performed in May 2021. The extinction was measured by counting all secondary pions in the K1.8BR secondary beamline in the J-PARC Hadron Experimental Facility. After the extinction studies tried out several setups, the most extinction achievable setup was performed with $O(10^{10})$ statistics. This paper reports the extinction measurement and the current analysis status.

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1. Introduction

The COMET experiment aims to search for the neutrinoless muon-to-electron conversion (μ-e conversion) in muonic aluminum atoms, which is the lepton flavor violating muon reaction, at J-PARC Hadron Experimental Facility (HD) [1]. It has two phases that are Phase-I and II, and its goal is to search for μ-e conversion with improved sensitivity of 10^{-17}. The COMET Phase-I is currently under construction at the HD.

The COMET needs dedicated beam operation of the J-PARC Main Ring (MR) synchrotron. In contrast to the MR usual acceleration of the protons up to 30 GeV with 0.6 µs bunch separation, the MR instead accelerates the protons up to 8 GeV with 1.2 µs bunch separation [2]. One of the most severe sources of background is the beam-related reaction. A pulsed beam with enough long separation compared with the lifetimes of muonic aluminum atoms (~ 864 ns) would allow the removal of beam-related backgrounds by performing measurements in a delayed DAQ window, shown schematically in Figure 1. The beam is slow-extracted in keeping the bunch structure, which is called "bunched slow extraction (bunched-SX)."

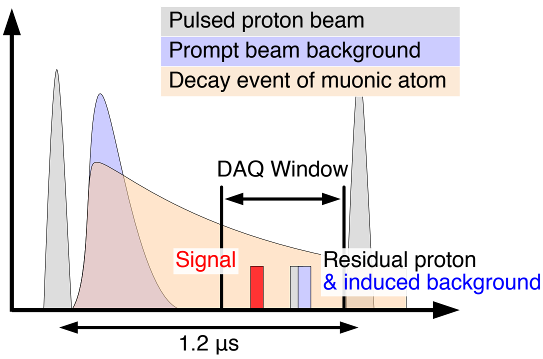
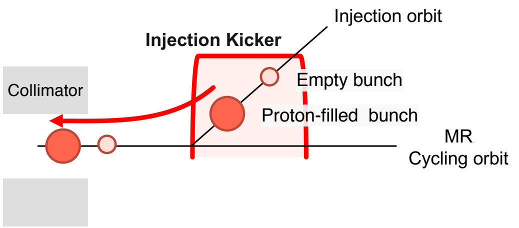
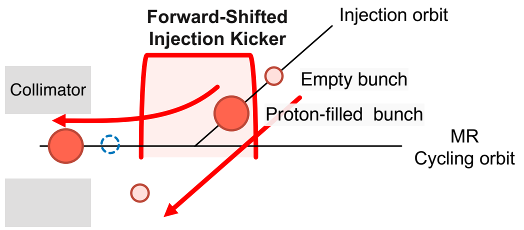


Figure 1: Time structure of measurement for μ-e conversion in the COMET experiment

The most important beam parameter for the pursuit of the highest level of sensitivity is extinction, which is defined as the intensity ratio of inter-bunch stray protons, or so-called residuals, over in-bunch protons. It is required that the extinction must be less than $O(10^{-10})$. A bunch separation of 1.2 µs is realized by sequencing proton-filled and empty buckets alternately. The empty bucket is made by deflecting the beam by a chopper placed J-PARC linear accelerator. Because a certain amount of protons are remained in between bunches due to the inefficiency of the chopper to make an empty bucket, the extinction by this scheme is typically at 10^{-6} levels [3] in the 3 GeV Rapid Cycling Synchrotron (RCS), which is the pre-accelerator of the MR. These bunches are injected four times every 40 ms into the MR. To extinct the residual protons, a customized operation mode was pursued, called “*Single Bunch Kicking* (SBK)”. If the injection kicker was excited the same as normal operation, so-called non-SBK, residual protons would be also injected into the MR as shown in Figure 2a. The SBK is realized by shifting the injection kicker excitation timing such that residual protons are not kicked as shown in Figure 2b. The residual protons are eliminated by collimators installed along with the MR. When the front bunch is proton-filled, so-called front bunch injection, the injection kicker is shifted forward, so-called forward-SBK. In the reverse case, so-called rear bunch injection, it is shifted backward, so-called backward-SBK.



(a) Normal Injection



(b) Single Bunch Kicking (SBK)

Figure 2: Scheme of injection into the MR for each injection batch

In January and February 2018, the 8 GeV proton beam commissioning was performed [4]. Although the residuals between bunches were managed to be reduced with forward-SBK with a kicker shift of 600 ns, residuals still existed after the fourth bunch. The residuals were due to the insufficient kicker shifts because its waveform has a slower trailing edge than the rising one. It leads to two solutions to satisfy the requirements for extinction. The first is to shift kicker timing forward more than 600 ns. The second is to perform backward-SBK instead.

2. 8 GeV Proton Beam Commissioning

The commissioning was successfully carried out in May 2021. The commissioning consisted of accelerator and extinction studies. The purpose of the extinction studies was to try out several setups on bunched-SX beam configuration and to demonstrate the removal of residues after the fourth bunch. The goal was to perform extinction measurement with the most extinction achievable setup. The beam parameters are shown in Table 1. When the beam cycle is set to COMET Phase-I of 2.4 s, the beam intensity would be equivalent to COMET Phase-I of 3.2 kW. The extraction efficiency and the spill duty factor were improved from the previous test, respectively.

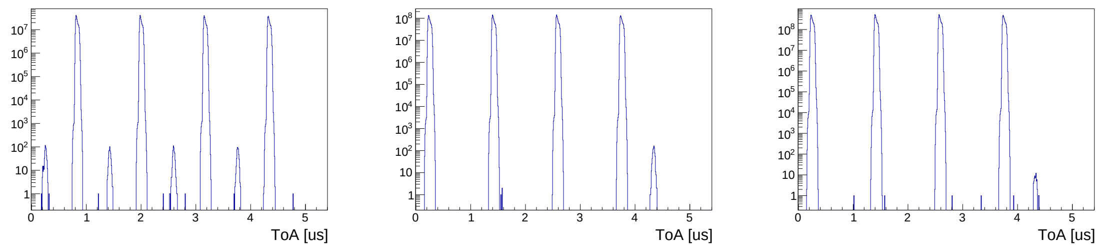
	2018	2021
Beam power	1.8 kW (5.2 s cycle)	
Number of protons	7.4×10^{12} ppp	
Extraction efficiency	97%	99.1%
Spill duty factor	16%	55%
Spill length	0.65 s	0.6 s

Table 1: Summary of the beam parameters for previous and this commissioning

The extinction was measured by counting all secondary pions in the K1.8BR beamline which is a secondary beamline in the HD. All delivered pions coming from both bunched and residual protons were counted by the main hodoscope detector (MD). The detection efficiency of the MD was carefully monitored by an ionization chamber system that is equipped with the same beamline. There are two beamline hodoscopes (BH1 and BH2) upstream of the beamline and three trigger counters (TC1, TC2, and TC3) behind the MD. Irrelevant hits are eliminated by an offline coincidence of these six counters. The overall detection efficiency of the six counters was evaluated at 69.2% by the beam. To guarantee measurement reliability, three independent TDC systems were used in parallel. The TDC systems use the FCT (Fast-Control-and-Timing) board which is developed for the COMET trigger system, the KC705 board which is Xilinx Kintex-7 evaluation kit, and the HUL board which has been developed at HD to be compatible with the Hadron-Universal-Logic system, respectively. The HUL can record with the best time resolution of 1 ns.

The time of arrival (ToA) of a secondary particle from the beginning of extraction for each detector was recorded. The offline coincidence was performed with the gate of 50 ns width which is longer than the signal response time of the MD. The obtained events outside of the bunch period were assigned inter-bunch events. The bunch period was decided for each setup since the timing and the longitudinal width would fluctuate for each setup.

The reproducibility checks were performed. The extinction with non-SBK was measured first. There were 1915 inter-bunch events for 1.46×10^9 in-bunch events as shown in Figure 3a. The extinction of $O(10^{-6})$ is consistent with the previous test. The forward-SBK with a kicker shift of 600 ns was performed to reproduce residuals after the fourth bunch. Although the residuals were reproduced successfully as shown in Figure 3b, the extinction of $O(10^{-7})$ is not exactly equal to the previous test since the accelerator condition fluctuates each launch. The injection kicker was shifted forward into the available maximum shift of 700 ns. Although the residuals decreased with the extinction of $O(10^{-9})$ as shown in Figure 3c, the extinction did not meet the requirement.



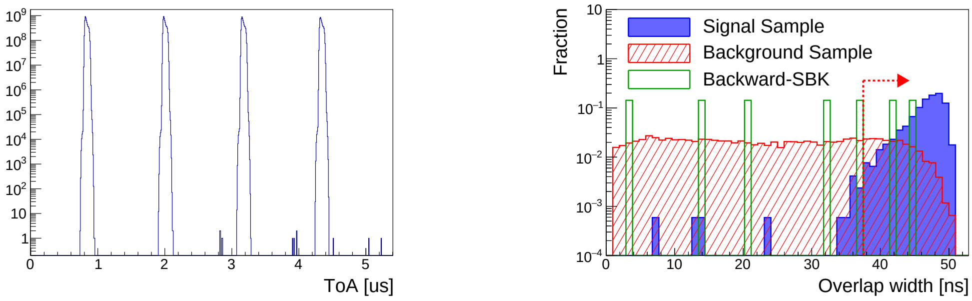
(a) Non-SBK **(b)** Forward-SBK (600 ns) **(c)** Forward-SBK (700 ns)

Figure 3: Event distribution for each setup. The numbers in parentheses indicate the amount of kicker shift.

The most extinction achievable setup of backward-SBK with a kicker shift of 600 ns was performed with $O(10^{10})$ statistics. Although there is no obvious peak of residuals like the forward-SBK, there were seven inter-bunch events as shown in Figure 4a. These events were confirmed by all TDC systems. The coincidence overlap widths of these events are shown in Figure 4b with ones of non-SBK which are expected to be dominated by residuals, not by accidental overlap. There are backward-SBK events with smaller overlap width compared to non-SBK events. It implies that most of them are like accidental overlap events.

The dominant source of background is estimated to be beam-induced delayed events. A particle in the secondary pion beam stops on components along the beamline. After its lifetime, the daughter particle could fly and pass into downstream detectors (MD and TC1–3) apart from in-bunch timing. The beam-induced delayed events were confirmed by the coincidence of downstream detectors in backward-SBK data. The background sample was generated by the combination of measured data from downstream detectors and randomly generated data from upstream detectors (BH1 and BH2). The overlap width distribution of the background sample is also shown in Figure 4b.

The cut-base analysis using overlap width was performed. The events with longer overlap width than a certain threshold were classified into signals. The preliminary operating point of a threshold of 38 ns was selected at the point, where signal efficiency is 99% evaluated with inter-bunch events of non-SBK. The background rejection efficiency is 80%, evaluated with background samples described above. After overlap-cut with the threshold, two inter-bunch events remained.



(a) **(b)**

Figure 4: (a) Event distribution of backward-SBK with a kicker shift of 600 ns. (b) Overlap width distribution of inter-bunch events with backward-SBK, signal sample (non-SBK), and background sample. The events to the right of the red line are classified as signal-like.

The extinction of 9.3×10^{-11} was calculated using the signal efficiency and the overall detection efficiency, which achieved the requirement. To conservatively estimate, the extinction of 1.4×10^{-10} including an event aside from the threshold was also calculated. Although it is slightly more than the requirement of 10^{-10}, COMET Phase-I allows such a level of excess.

3. Conclusion

The COMET experiment plans to search for μ-e conversion at J-PARC HD. The experiment requires a dedicated 8 GeV pulsed proton beam operation. Proton extinction required to be less than 10^{-10} of inter-bunch residual protons is critical to eliminate beam-related backgrounds. The 8 GeV proton beam commissioning for COMET was completed successfully. The extinction measurement was performed at the K1.8BR beamline of J-PARC HD with $O(10^{10})$ statistics. The extinction requirement was achieved with backward-SBK with a kicker shift of 600 ns by preliminary cut-based analysis. Both the background estimation and analysis update are ongoing.

References

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