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EXTINCTION MEASUREMENT OF J-PARC MR WITH 8 GEV PROTON BEAM FOR THE NEW MUON-TO-ELECTRON CONVERSION SEARCH EXPERIMENT – COMET

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Abstract

At J-PARC, extraction tests of a 8 GeV pulsed proton beam from Main Ring (MR), which is dedicated for the COMET Experiment, have been successfully completed. The COMET Experiment aims to find new physics beyond the Standard Model by searching for the coherent neutrinoless conversion of a muon to an electron in muonic atoms. This requires an extremely clean pulsed beam, and development of this beam plays a key role in the pursuit of the highest level of sensitivity. This successful extraction test is the clearing of a major milestone for the forthcoming experiment.

The number of protons leaking between proton bunches is required to be less than one for every 10^{10} protons in the bunch. Extraction tests in the customized mode were conducted in January and February 2018 and resulted in many successes. In this test, leakage protons between bunches was successfully reduced below the objective of 10^{-10} of the number of protons in a bunch. This is a great success to guarantee the quality of proton beam required by COMET experiment.

In this paper, the result of extinction measurement and future prospect of proton extinction improvement is presented in addition to the detailed description of customized MR operation.

INTRODUCTION

A Lepton Flavour Violation (LFV) among charged leptons, *eg.* $\mu^- N \to e^- N$ process *etc*., which has never been observed while the quark mixing and the neutrino oscillations have been experimentally confirmed, is attracting a great deal of attention, since its observation is highly expected by most of well-motivated theories beyond the Standard Mode [1]. It is predicted that $\mu^- N \to e^- N$ is naturally causable with a branching ratio just below the current experimental upper bound, $10^{-13} \sim 10^{-16}$, by leading theories for physics beyond the standard model, *e.g.* Supersymmetric theories of Grand Unification or Supersymmetric Standard Model with seesaw mechanism (*eg.* see Ref. [2] for a review). The ambitious goal of the **COMET** Experiment (**CO**herent **M**uon to **E**lectron **T**ransition) [3] is searching for a $\mu^- N \to e^- N$ process with an improved sensitivity by at least four orders of magnitude over the last best upper limit on a $\mu^- N \to e^- N$ branching ratio reported by the SINDRUM-II collaboration, 7×10^{-13} [4].

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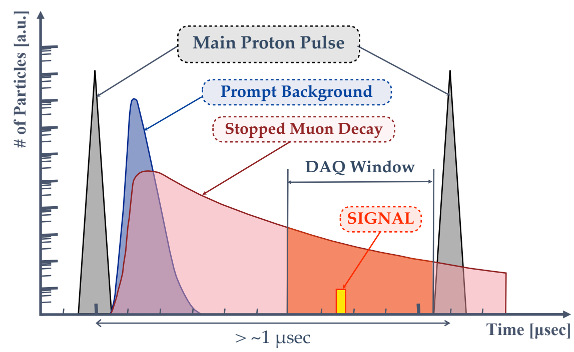

Figure 1: Time structure of the proton beam, background events and DAQ window for the COMET Experiment.

The event signature of $\mu^- N \to e^- N$ in a muonic atom is a monochromatic single electron emitted from the conversion with an energy of $E_{\mu e} = m_\mu - B_\mu - E_{\rm recoil}$, where m_μ is the muon mass, and B_μ is the binding energy of the 1s muonic atom. $E_{\rm recoil}$ is the nuclear recoil energy which is extremely small and can be negligible. Since B_μ depends on nuclei $E_{\mu e}$ varies, *eg.* 104.3 MeV for Ti and 105.1 MeV for Al.

One of the most severe source of electron background event is beam-related background which is caused by beam particles of muons and other contaminated particles in a secondary muon beam. Since muonic atoms have lifetimes of the order of 1 μsec, a pulsed beam with its width that is enough short compared with these lifetimes would allow one to remove beam-related backgrounds by performing measurements in a delayed DAQ window. The relation between the required time structure of proton beam and the DAQ window for $\mu^- N \to e^- N$ search is schematically shown in Fig. 1. To eliminate prompt beam-related backgrounds, i) a long enough ($\sim 1\mu$sec) interval of proton bunches, and ii) small number of residual protons in between bunches are essential. In particular, ii) is essential and called **EXTINCTION** which is defined as a fraction of the number of residual protons in between bunches and the number of protons filled into bunches. In order to achieve the COMET goal, *i.e.* branching-ratio sensitivity of $O(10^{-16})$, excellent extinction of 10^{-10} is necessary at least.

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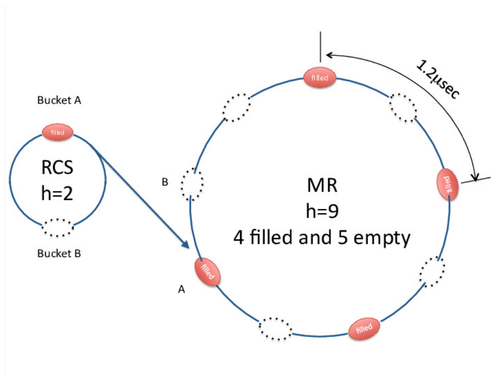

Figure 2: Dedicated beam transfer diagram from RCS to MR to COMET to make the long enough bunch intervals.

CUSTOMIZED OPERATION FOR COMET

In order to realize the specification of proton beam which is required by the COMET experiment, the customized MR operation was proposed.

The J-PARC MR usually accelerates the proton beam (at one bunch per 600 nsec) up to 30 GeV. However, for the COMET, the MR instead accelerates the proton beam (at one bunch per 1.2 μsec) up to 8 GeV. A 1.2 μsec bunch separation of the proton beam at MR can be obtained as followed [5]. The 3 GeV rapid cycle synchrotron (RCS), which is the booster for MR, has harmonics of 2 and accelerates two beam bunches at 25 Hz in normal operation, but one beam bunch for COMET experiment. The empty bucket in RCS is made deflecting the beam by a chopper placed between RFQ (radio frequency quadrupole linac) and DTL (drift tube linac). MR can accelerate 8 bunches with harmonics of 9 (one of them is a gap for the extraction kickers). For COMET experiment, one beam bunch from RCS is injected four times every 40 msec into MR and then accelerated. The beam accelerated at 8 GeV is extracted slowly using the third integer resonance keeping the bunch structure with 1.2 μsec bunch spacing, so-called "*bunched slow extraction*", as schematically shown in Fig. 2. In principle, this scheme can form the required timing structure of proton beam. However the extinction for this scheme is not acceptable for COMET, because a certain amount of protons are still remained in between bunches due to an inefficiency of chopper to make an empty bucket in RCS described above. In order to extinct such residual protons, further customized operation mode was pursued, called "Single Bunch Kicking". The Single Bunch Kicking is realised by shifting the injection kicker excitation timing by 600 nsec such that particles remaining in empty buckets are not injected into the MR.

In January and February 2018, the MR customized operation was tested and a 8 GeV pulsed proton beam have been successfully extracted [6]. In this test, leakage protons between bunches was successfully reduced and measured precisely by a team drawn from the Accelerator Laboratory Group and the COMET Experimental Group.

TEST AND MEASUREMENT

Measurement Methods

Two extinction studies were conducted at two occasions. MR has two extraction ports; one is called FX (Fast Extraction) for the neutrino beam-line and another is called SX (Slow Extraction) for the Hadron Experimental Facility.

Next to the FX port, the abort line is also established. In the abort line, "Abort Monitor" is installed to count the number of leaked proton between bunches [7]. Hence, the first test was conducted at the abort line using this abort monitor with FX proton beam. The abort monitor is usual plastic-scintillator-base so that the counter is not compatible with the continuous irradiation of J-PARC high power proton beam, *i.e.* the test was conducted by the one-shot operation of MR.

The COMET Experiment is under construction at the Hadron Experimental Facility, and the bunched slow extraction (bunched-SX) beam will be delivered to Hadron. Thus it is essential to conduct the extinction test at Hadron with bunched-SX beam. This test is available by counting the number of all secondary pions in the secondary beam line of the Hadron Experimental Facility. This time, the dedicated test was conducted at one of the secondary beam line, K1.8, with a combination of hodoscope system and beam particle counters. Two extinction studies by two occasions at MR is schematically summarized in Fig. 3.

Extinction at Abort with FX Beam

Abort Monitor recorded four waveforms of PMT outputs simultaneously with different sensitivities viewing the single scintillator, *i.e.* number of residual protons between bunches can be counted by the sensitive PMT while number of filled protons in main bunches can be counted by the insensitive PMT. Using this Abort Monitor with the dedicated "Single Bunch Kicking" operation mode described in the previous section, the extinction factor at Abort with FX beam was studied. It was noticed that the number of residual protons depends on the RF voltage during the flat-top, since these protons are leaked over the potential wall of RF bucket. In order to investigate the mechanism of extinction development, the extinction at FX was measured as a function of RF voltage as shown in Fig. 4. The excellent extinction of $O(10^{-11} \sim 10^{-12})$ was confirmed by employing the Single Bunch Kicking method and keeping the RF voltage during the flat-top.

Extinction at Hadron with Bunched-SX Beam

As described above, the COMET experiment would be stationed at Hadron Experimental Facility and conducted with the bunched-SX beam, *i.e.* the extinction measurement at Hadron with bunched-SX is essential. During the test for customized 8 GeV proton acceleration and extraction in 2018, the extinction measurement at Hadron with bunched-SX beam was also performed. The extinction at Hadron was measured by counting the number of all delivered pions

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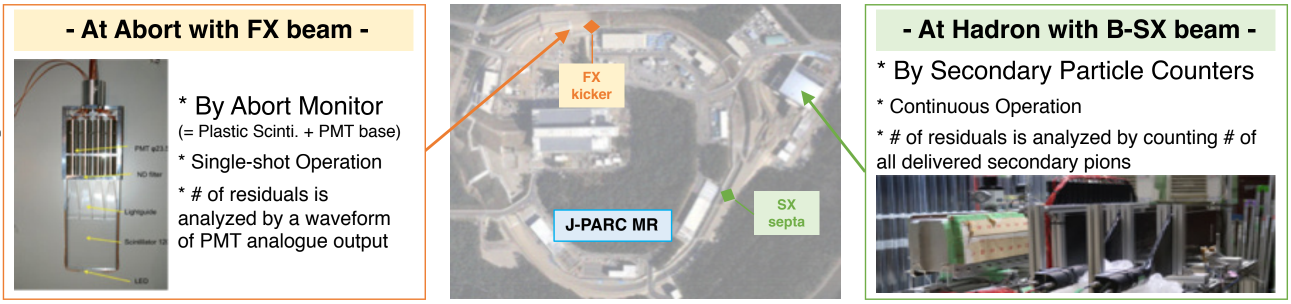

Figure 3: Two measurement schemes at the Abort with FX beam and at the Hadron with Bunched-SX beam.

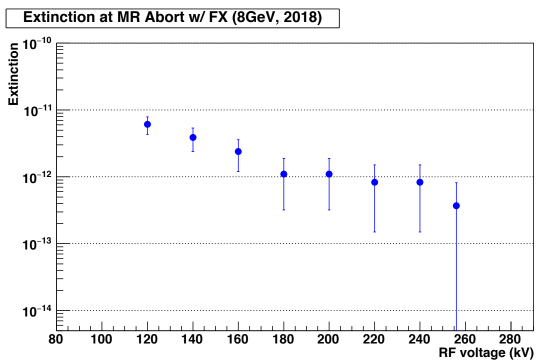

Figure 4: Obtained extinction factor at Abort with FX beam as a function of applied RF voltages.

at K1.8 secondary beam line with the hodoscope system[1]. According to the extinction test at Abort with FX beam, the RF voltage of 180 kV during the flat-top was employed to guarantee the good enough extinction within MR, and the Single Bunch Kicking method was employed again to demonstrate the good enough extinction. Figure 5 shows the result of obtained timing structure of delivered pions. The MR RF bucket is assigned as front or rear one for each injection batch named as K1,K2,K3 or K4, sequentially. The front and rear buckets mean the ones injected at forward and backward timing for each batch, respectively. In this measurement, the main proton beam was injected into the front bucket for each injection batch. The injection kickers were then shifted by 600 nsec forward corresponding to the time distance between two bunches. As shown in Fig. 5 top, no any entry was recorded in the rear buckets from K1 through K3. This is corresponding to the proton extinction of 1×10^{-10} which is just same value as the requirement. Tiny amount of residuals, however, were observed in the K4 rear timing only as indicated with a circle in Fig. 5 top. By investigating the timing of leaked pions with respect to the timing of injection and extraction, it was also noticed that the leakage of pion in K4 rear was occurred only within 100 msec of start of bunched-SX. The slow extraction process

[1] All delivered pions coming from bunched and leaked protons both were counted by the hodoscope system, and irrelevant hits were eliminated by vetoing by beam-line counters. Detection efficiency of the hodoscope was carefully monitored by an ionization chamber system which is equipped into the same beam line.

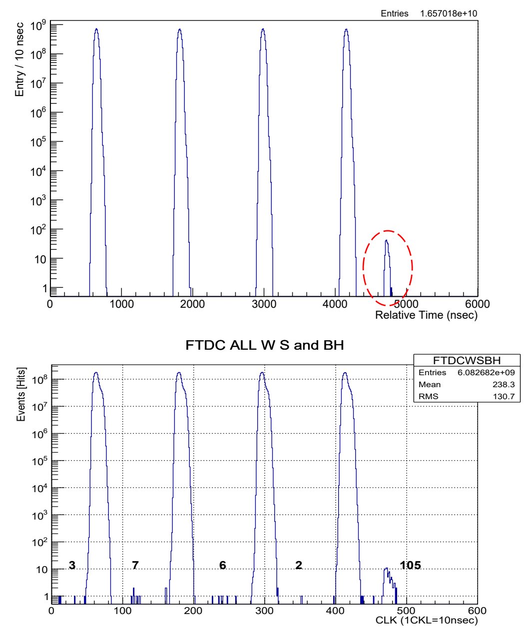

Figure 5: Obtained timing spectra of delivered pions; (*top*) Number of hit entries of hodoscope as a function of relative timing with respect to the injection-batches timing, (*bottom*) Timing spectra with lower RF voltage of 30 kV.

can not produce such a fine time structure. In order to pursue the cause of this leak, RF voltage during flat-top was reduced down to 30 kV as shown in Fig. 5 bottom. Due to the lower RF bucket height, some pions were spilled over from the filled buckets of K1-K3 front. Concurrently, it is observed that the distribution of leaked pions in K4 rear was run out wider than normal. This can be explained due to the lower RF voltage, thus the leakage should be occurred within the MR, *i.e.* before the extraction.

In consequence, by this measurement, it is possible to figure out four *scenarios* as summarized in Table 1. As de-

Table 1: Possible Three *Scenarios* Based on This Result

Scenario	Description	Extinction
Scenario-A	Mask beginning events	6×10^{-10}
Scenario-B	Use only K1, K2 and K3	1×10^{-10}
Scenario-C	Solve K4-rear mystery	$<6 \times 10^{-11}$

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scribed above, the K4-rear leakage was occurred only within 100 msec of SX start. Thus *Scenario-A* is realized by masking the beginning events of extraction for < 100 msec. By this *scenario*, feasible extinction is 6×10^{-10} which is not matched with the requirement by COMET. The next one, *Scenario-B* is enabled by using only K1, K2 and K3 batches to avoid K4 rear leakage. By this *scenario*, feasible extinction is 1×10^{-10} which is just matched with the requirement by COMET. The last one, *Scenario-C* is desired by solving "K4-rear Mystery". If we can understand the mechanism of leakage on K4 rear and suppress that, feasible extinction is better than 6×10^{-11}. This is the upper limit on extinction, and it is limited by the statistics obtained this time, *i.e.* the actual extinction can be better than this as long as no leakage would be appeared.

FUTURE PROSPECTS

As described in the previous section, in order to achieve a better extinction which can lead the COMET to successful conclusion, it is necessary to understand the mechanism of K4-rear Mystery. Why only K4 shows a small amount of leakage at only the beginning of SX while K1, K2 and K3 realized a perfect extinction ? This is most likely related to the trailing component of injection kicker. Such stray field can inject a part of residual protons into MR, but not actually injected for K1, K2 and K3, because they are suppressed by the following kicker excitation. However, the last injection batch, K4, does not have the following kicker excitation so that only K4 rear has a residual protons.

This assumption was quickly proved by the accelerator test during the regular accelerator tuning period in February 2019. In this quick test, several test shots were delivered to the abort line with FX mode with 4-bunch filling as required by the COMET. The kicker timing was shifted sequentially with 50 nsec steps, and K4-rear Mystery was successfully demonstrated even with FX mode as shown in Fig. 6 top. Normally, to employ the Single Bunch Kicking method, kicker timing was shifted with 600 nsec which is corresponding to the half period of single injection batch. By this test, it was found to be not long enough to suppress the effect by trailing component of kicker field in particular for the K4 batch. In order to suppress such an effect, kicker timing was further shifted, and it was noticed that the kicker shift of 750 nsec is long enough as shown in Fig. 6 bottom.

In consequence, the K4-rear Mystery was understood and solved, at least for FX operation. As the next step, and also the final step, this should be demonstrated at Hadron Experimental Facility with bunched-SX in the next occasion.

CONCLUSION

At J-PARC, extraction tests of a 8 GeV pulsed proton beam from MR have been successfully completed. Extraction tests in the customized mode were conducted in January and February 2018 and resulted in many successes. In this test, leakage protons between bunches was successfully reduced below the objective of 10^{-10} of the number of protons in a bunch. This is a great success to guarantee the quality of

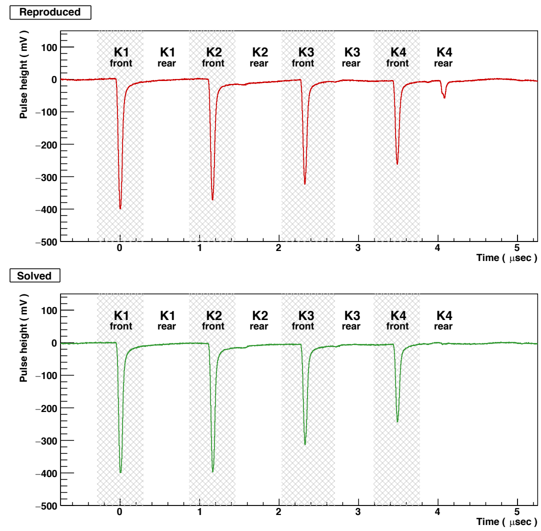

Figure 6: Quick test with different kicker timings; (*top*) Reproduced K4-rear Mystery with 600 nsec kicker shift, (*bottom*) Suppressed K4 leakage with 750 nsec kicker shift.

proton beam required by COMET experiment. In addition, the time development of proton leakage was also precisely studied with several RF settings which enables us to further improve the extinction. By the recent quick test on MR, the key to improve the obtained extinction was realised. Now the best scenario is promising such can achieve an excellent extinction of $<6 \times 10^{-11}$.

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