ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP010

8 GeV SLOW EXTRACTION BEAM TEST FOR MUON TO ELECTRON CONVERSION SEARCH EXPERIMENT AT J-PARC

M. Tomizawa*, Y. Arakaki, Y. Hashimoto, T. Kimura, S. Murasugi,
R. Muto, K. Okamura, E. Yanaoka, ACCL, KEK, Tsukuba, Japan
F. Tamura, JAEA/J-PARC, Tokai-mura, Japan
Y. Fukao, Y. Igarashi, S. Mihara, M. Moritsu, H. Nishiguchi, Y. Shirakabe, K. Ueno,
IPNS, KEK, Tsukuba, Japan
Y. Fujii, Monash University, Clayton, Victoria, Australia

Abstract

A muon to electron conversion search experiment (COMET) planned at J-PARC needs 8 GeV bunched proton beams with a continuous 1 MHz pulse structure. In this experiment, the beam intensity ratio of the background in between to the main pulses, which is expressed as extinction, should be less than levels of 10^{-10}. In the beam test in 2018, we have succeeded in the slow extraction of 8 GeV proton beam with 7.3×10^{12} ppp, equivalent of the COMET phase-I requirement, and the extinction derived from the timing measurement for secondary particles from the target showed a promising result. A mechanism to explain the measured time structure of the extracted beam will be also described in this paper.

INTRODUCTION

COMET (Coherent Muon to Electron Transition) experiment using 8 GeV primary proton beams is planned at J-PARC. The COMET experiment searches a muon to electron conversion process, which is a charged lepton flavor violating (CLFV) process and forbidden in the Standard Model (SM) of the elementary particle physics [1]. The discovery shows a clear signal of the physics beyond the SM. COMET detects a monochromatic 105 MeV electron from $\mu^- + N \rightarrow e^- + N$,where N is a nucleus. The electron is emitted with the time delay due to the lifetime (~ 1μsec.) of the muonic atom. The primary proton beam has a 1 MHz pulsed structure. The time window to detect the conversion electron is set after the background events induced by the pulsed beam. In this experiment, the beam intensity ratio of the background in between to the main pulses, which is expressed as extinction, should be less than levels of 10^{-10}.

A 1 MHz time structure of the 8 GeV beam for COMET experiment can be obtained as followed [2]. The 3 GeV rapid cycle synchrotron (RCS) has harmonics of 2 and accelerates two beam bunches at 25 Hz in normal operation, however 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 from 3 to 8 GeV as shown in Fig. 1. The beam accelerated at 8 GeV is extracted slowly using the third integer resonance keeping the bunch structure with 1 μsec. bunch spacing. On the other hands, the debunched 30 GeV beams are slow-extracted in normal operation. COMET is staged into phase-I and II. The beam powers of phase-I and II are 3.2 and 56 kW, respectively. The residual beam intensity rate in the empty buckets is typically 10^{-6} levels, which are originated by imperfect deflection of the chopper. The residual beam worsens the extinction of the slow extracted beam. To improve the extinction, the MR injection kicker timing is shifted not so as to kick the residual beam as shown in Fig. 2. The residual beam is lost by a large orbit mismatch. A 8 GeV acceleration test and an extinction measurement using a monitor placed the abort beam line [3] were conducted in 2014. In Jan. and Feb. 2018, the first slow extraction test and extinction measurement using the slow-extracted beam have been conducted. The obtained performances will be reported in this paper. The mechanism to generate a behavior unknown in the measured time structure became clear by the beam test in Feb. 2019.

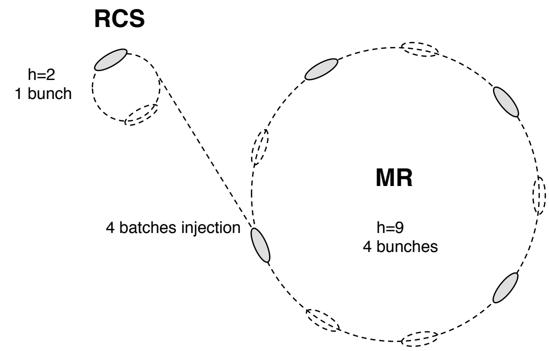

Figure 1: Beam transfer diagram from RCS to MR for COMET.

8 GEV SLOW EXTRACTION TEST

The 1567.5 m long MR has a three-fold symmetry with 3 arc and 3 long straight sections [4]. Electrostatic septa (ESS1 and ESS2) and magnetic septa (SMS1,2 and 3), bump magnets and a slow collimator are placed in a dispersion free long straight section for the slow extraction. ESS1 is placed in adjacent two focusing quadrupole magnets with a largest β_x function. The separatrix for the resonance at ESS1 is independent of the beam momentum by setting the horizontal

* masahito.tomizawa@kek.jp

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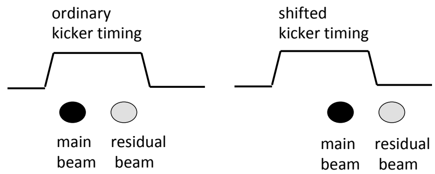

Figure 2: MR injection kicker timing and beam bunches.

chromaticity at zero. The dynamic bump scheme applied under these conditions can drastically reduce the beam loss [5]. Typical slow extraction efficiency has achieved 99.5% for the 50 kW beam power operation at 30 GeV [6]. In Jan. and Feb. 2018, the first 8 GeV slow extraction test has been conducted to establish the slow extraction at 8 GeV and know the extinction performance for the slow-extracted beam. The MR cycle time was conventionally set to 5.2 sec., which was same as that of the 30 GeV operations held before and after the test. The 8 GeV acceleration pattern was swept in 2.38 sec., which is supposed for the COMET phase-I. The proton number is 7.3×10^{12}, corresponding to the design beam power of 3.2 kW at the cycle time same as the sweeping time. The bending and quadrupole patterns at 8 GeV were tuned to obtain the target tunes and to reduce the beam loss by the betatron resonances. The chromaticity sextupoles were tuned to obtain suitable chromaticiies. The bump orbit sets of x' at ESS1 necessary for the dynamic bump were derived by using MICAD [7] implemented in SAD code [8]. Skew Quadrupoles were used to correct the strong coupling resonance of $Q_x + Q_y = 43$. The slow extraction efficiency was achieved to 97% by the beam-based alignment of ESS1 and SMS1 and by tuning the ESS2 voltage. The beam loss rate was 6 times larger than that of the 30 GeV operation at 50 kW, however the absolute loss beam power is acceptable and less than that of the 30 GeV operation. The extraction efficiency can be improved by the fine tuning of further alignments of ESSs and SMSs in future beam test. The extracted beam time structure was regulated by the feedback quadrupoles to obtain an uniform spill. The transverse rf (TRF) system applied to the circulating beam to improve the spill time structure in a high frequency region [6] was not used in this beam test. The obtained spill duty factor was 16%, which would be improved near 50% achieved in the 30 GeV oeration by using the TRF system.

EXTINCTION MEASUREMENTS

The time structure of the slow-extracted beam has been derived by a hodoscope system to detect secondary particles produced from the primary gold target [9]. Figure 3 shows the time spectrum of the detected secondary particles. 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 early and late 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 shifted to early timing by 600 nsec. corresponding to the time distance between two bunches. As seen in Fig. 3 top, no signal events was observed in the rear buckets from K1 through K3. This gives the extinction less than 6×10^{-11}. However 202 events were observed for the K4 rear timing. The slow extraction process can not produce such a fine time structure. We can mention the K4 rear events were produced by other process. We can conclude the contribution to the extinction by the slow extraction process is less than 6×10^{-11}. This is a very important result derived in this beam test.

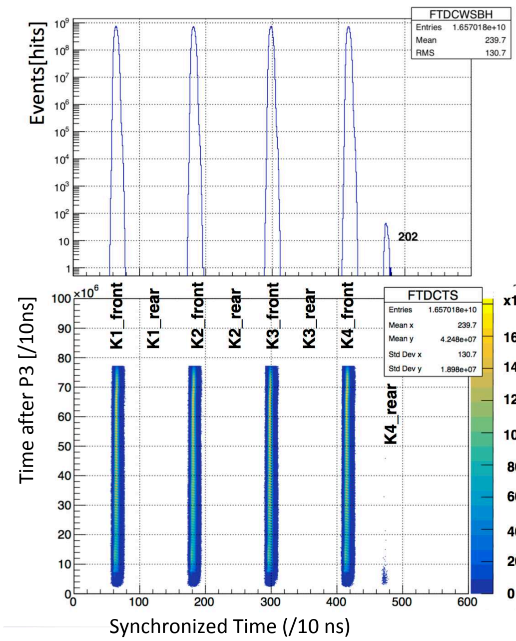

Figure 3: Time spectrum (top) and progress (bottom) of secondary particles.

INVESTIGATION ON OBSERVED RARE EVENTS

Figure 3 bottom shows the time progress of the secondary particles in each bucket. The events in the K4 rear were distributed just at the start of extraction. The separatrix size in the phase space shrinks during the slow extraction. Therefore the beam in the K4 rear bucket has a large horizontal betatron amplitude. Figure 4 shows schematic relationships between the beam bunches injected into MR, the kicker timings and the MR rf buckets. The residual rate of 10^{-6} can be in the rear buckets by the imperfect deflection by the chopper as mentioned in introduction. Even if the beams at the rear buckets timing from K1 to K3 could be injected and circulated, these beams are lost by the kicker field excited at the following injection (K2,K3 or K4, respectively) as shown in Fig. 4. However, the beam in the K4 rear is

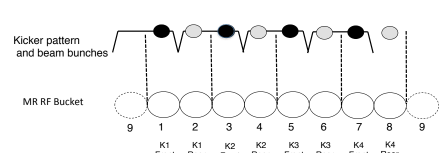

Figure 4: Relationships between beam bunches, kicker fields and rf buckets.

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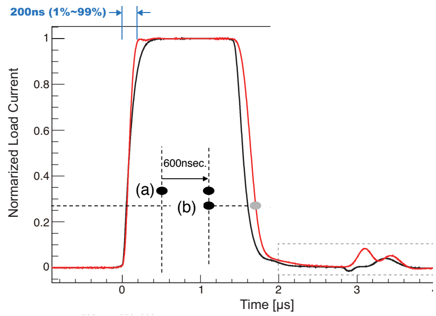

Figure 5: Kicker field and beam bunches.

not lost, since there is no more following kicker excitation. The red line in Fig. 5 shows the field pattern used for the present kicker operation. (a) shows the beam bunches in the normal injection case without the kicker timing shift and (b) with the kicker timing shift by 600 nsec. to early direction. The fall time of the kicker field is slower than the rise time. Then the rear beam can feel roughly 27 % of the flat top field. When the main beam is injected into the rear bucket and the kicker timing is shifted to late direction, it can be improved. However the circulating beams in the K1 and K2 rear buckets are affected by the reflection field seen in Fig. 5 at the K3 and K4 injection timings, respectively.

Figure 6 shows horizontal phase space plots of ellipses; (a) is of the ring acceptance of 54 π mm·mrad determined by the collimators placed downstream of the injection area. (b) is of the circulating beam with the emittance same as the acceptance kicked by the following kicker excitation. The kicked circulating beam is lost since the ellipse is outside of the acceptance ellipse. (c) is of the beam injected without kicker field and (d) of the beam feeling 27% of the nominal field. The both areas are assumed to 140 π mm·mrad, which is similar to the acceptance of the beam line from RCS to MR. The beam in area (d) overlapping with (a) can be circulated and has a large horizontal betatron amplitude in the ring. The beam can be accelerated and extracted at the start of the extraction.

The mechanism assumed above has been qualitatively confirmed by the beam test in Feb. 2019. The beam accelerated at 30 GeV was extracted to the abort beam line by the

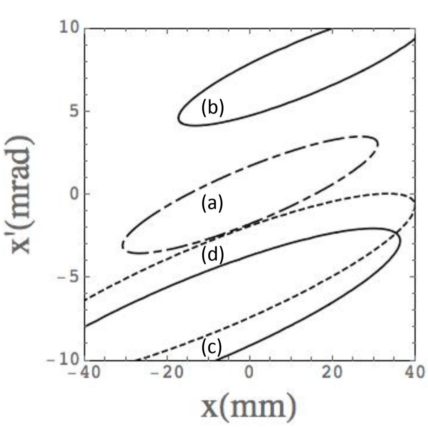

Figure 6: Phase space ellipses at the kicker exit.

fast extraction. An extinction monitor consisting of a photomultiplier and scintillator measured the extracted beam time structure. Avoiding the signal saturation, the chopper was turned on for all buckets timings to reduce the beam intensity. The injection kicker timing was shifted to early direction. At first the beam was injected at the K1 timing without the following K2 kicker excitation by a special timing setting. The kicker shift was set to 600 nsec. in early direction. This case, a small amount of the beam was observed at the K1 rear timing. On the other hands, no beam were observed for the normal setting so as to excite the following K2 kicker. Next, the beams from the K1 through K4 timings were injected and the kicker shift was set to 600 nsec. Then the beam signals were observed in the K4 rear timing as obtained in 8 GeV slow extraction test (Figure 7 (1)). When the kicker shift was changed to 750 nsec., the beam signals in the K4 rear timing was not observed (Figure 7 (2)). These results show the assumed mechanism mentioned is correct.

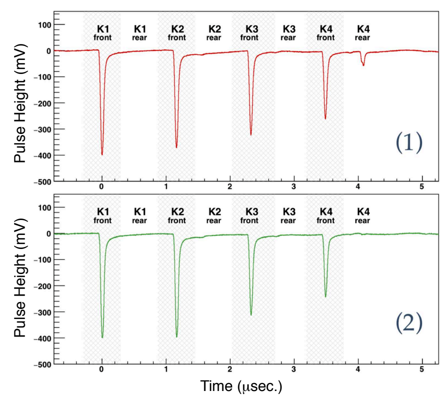

Figure 7: Time structures of beams extracted to the abort beam line.

CONCLUSION

COMET (Coherent Muon to Electron Transition) experiment using 8 GeV primary proton beams is planned at J-PARC. The 8 GeV proton beam has been successfully slow-extracted from the main ring in the first slow extraction beam test. The contribution to extinction of the slow extraction process turned out to be less than 6×10^{-11}, which is enough acceptable for the COMET requirement. We have found the rare beam events seen just in the K4 rear timing is caused by the fall field of the injection kicker. The kicker timing shift by 600 nsec. is not enough to kill enough mount of beam in the rear timing. This can be improved by shifting the kicker timing by 750 nsec. or more. We will confirm it in the next 8 GeV slow extraction test.

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