MEASUREMENT OF PROTON BEAM PROFILE AT 8 GEV ACCELERATION COMMISSIONING FOR THE J-PARC COMET EXPERIMENT

Y. Fukao*, K. Agari, H. Akiyama, K. Aoki, Y. Fujii[A)], E. Hirose, M. Ieiri, Y. Igarashi, Y. Kato, R. Kurasaki, S. Mihara, M. Minakawa, Y. Morino, M. Moritsu, R. Muto, H. Nishiguchi, Y. Sato, S. Sawada, H. Takahashi, K. Tanaka, M. Tomizawa, A. Toyoda, K. Ueno, M. Ukai, H. Watanabe, T. Yamamoto, Y. Yamanoi
KEK, Oho, Tsukuba, 305-0801, Japan
[A)]Monash University, Clayton, VIC 3800, Australia

Abstract

The first commissioning of a bunched slow extraction of a 8 GeV proton beam was performed at J-PARC for the COMET experiment in January and February, 2018. The beam profile of the extracted beam was measured at the primary proton beamline in Hadron Facility and the resulting 2σ emittance was 0.78 π mm mrad and 4.6 π mm mrad in horizontal and vertical direction, respectively. The beam extinction factor of the secondary beam was also measured for the first time at the K1.8 beamline.

INTRODUCTION

The COMET experiment aims at searching the phenomena of the muon-to-electron (μ-e) conversion without neutrino emission [1]. Since such process violates lepton flavor conservation, discovery of the μ-e conversion indicates existence of new physics. The COMET experiment will search for electrons with energy of the muon mass from the muon decay. To avoid background related to the beam, it's preferable for COMET to utilize a bunched beam with the bunch interval of about muon life time. In terms of the beam intensity, the number of beam particles per bunch is limited by the rate capability of the detectors. As the best choice of a source of the muon production, we decided to utilize a proton beam with the bunched-slow extraction method from J-PARC Main Ring (MR) to Hadron Facility (Fig. 1). The beam energy is 8 GeV, which is lower than the normal beam energy of 30 GeV, to suppress background caused by anti-proton production. The extracted beam will be transported via Switch Yard and Hadron Hall to the COMET experimental hall as shown in Fig. 2.

The time structure of the bunched-slow extracted beam for COMET is displayed in Fig. 1. The cycle of the acceleration and extraction of the proton beam at MR is 2.48 s. The beam is extracted for about 500 ms during the flat top. The bunch interval of 1.17 μs or 1.75 μs is achieved by filling the beam to four out of nine MR buckets for MR operation at a harmonic number of nine. The bunch length is estimated to be about 100 ns. In the commissioning in 2018, idle time of about three seconds was added to each cycle to smoothly change accelerator setting between the commissioning and the normal beam operation. Number of protons per bunch in the commissioning was 1.6×10^{7} and was same as that planned in the actual operation at COMET Phase-I.

Two important informations were obtained in the commissioning. One was the measurement of the extracted beam emittance and the other was the measurement of an extinction factor with the secondary beam. The extinction factor is a ratio of the residual beam particles between bunches to those of the main bunch. The extinction factor directly contributes to a prompt beam-related background. The COMET experiment requires the extinction factor of smaller than 10^{-10}. Although the test of the acceleration and extraction for the COMET experiment were partially performed in the past years, the commissioning of the bunched slow extraction of the 8 GeV proton beam was carried out for the first time in this January and February. Most of the beam time was used for the accelerator commissioning and the detector calibration while the last day in February was used for the measurement of the beam emittance and the extinction factor.

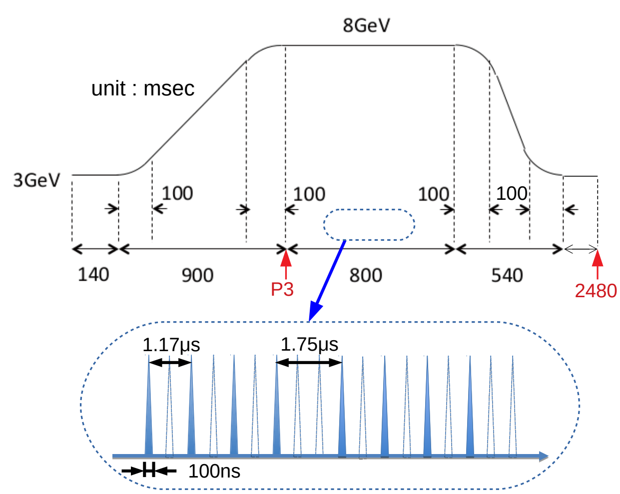

Figure 1: Cycle of the proton beam acceleration at MR and time structure of the bunched-slow extraction beam.

* fukao@post.kek.jp

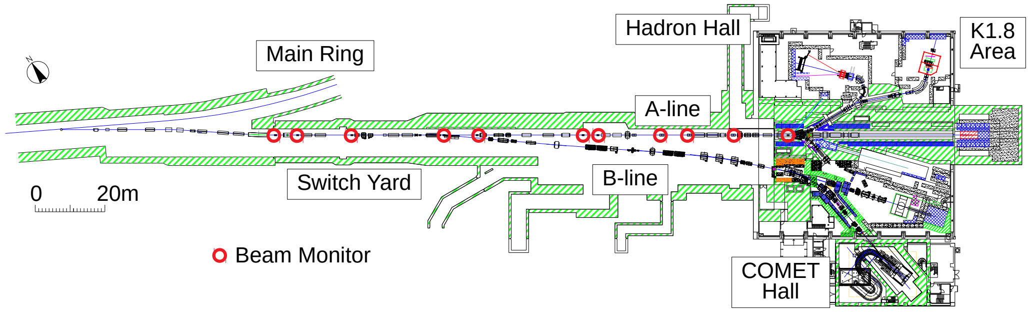

Figure 2: Proton beamline of J-PARC Hadron Facility.

BEAM EMITTANCE

Because the new beamline for the COMET experiment is currently under construction, the extracted proton beam was transported via A-line to an existing primary proton target. To obtain the emittance of the extracted beam, existing beam monitors installed in A-line were used. The beam monitors were Residual Gas Ionization Profile Monitors [2]. Each monitor can measure one-dimensional beam profile and a set of horizontal and vertical monitors was installed at each circle indicated in Fig. 2. Using the PSI TRANSPORT simulation [3], the beam envelope was fitted to the measured beam size to obtain the beam emittance at the point of the extraction from MR to Hadron Facility.

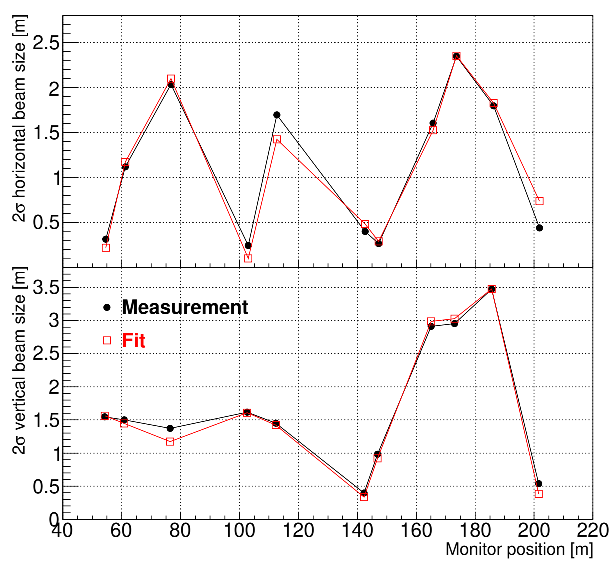

Figure 3: 2σ beam size at the position of the beam monitors. Horizontal axis indicates distance from the beam extraction point.

A comparison of the beam size and the simulated beam envelope for a typical shot (one cycle of the beam extraction) is displayed in Fig. 3. The shot-by-shot width of the beam extent and divergence was calculated for about 24 hours to evaluate stability of the beam and the results are shown in

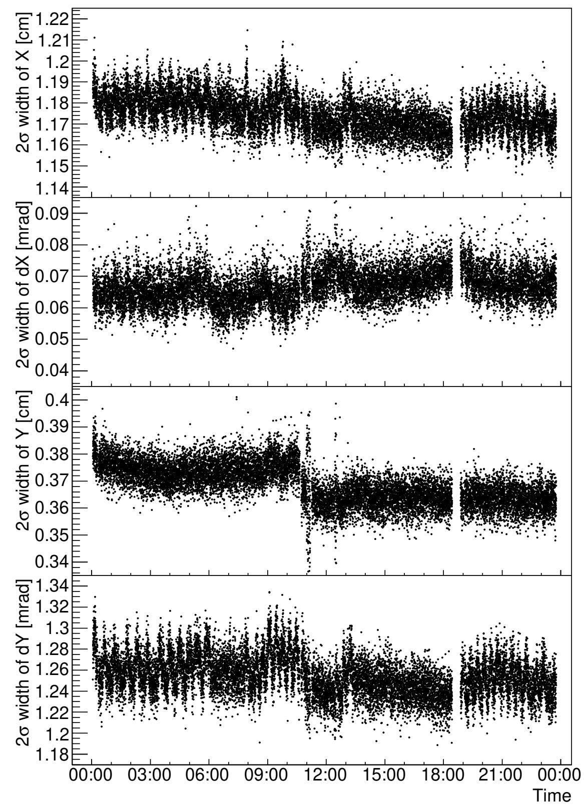

Figure 4: Shot-by-shot beam extent and divergence as a function of time.

Fig. 4. A shift around 11:00 was due to power recycle of a beamline magnet. Frequent deviation with interval of 20 – 30 minutes was caused by instability of a debuncher of the accelerator. Mean values of 2σ width of horizontal extent, its divergence, vertical extent and its divergence were 11.7 (0.09) mm, 0.067 (0.0054) mrad, 3.7 (0.07) mm and 1.25 (0.019) mrad, respectively. Numbers in parenthesis are root-mean-square of each fluctuation. Resulting 2σ horizontal and vertical emittance were 0.78 (0.063) π mm mrad and 4.6 (0.14) π mm mrad, respectively.

Based on the measured beam emittance, the beam optics of the new proton beamline for the COMET experiment was

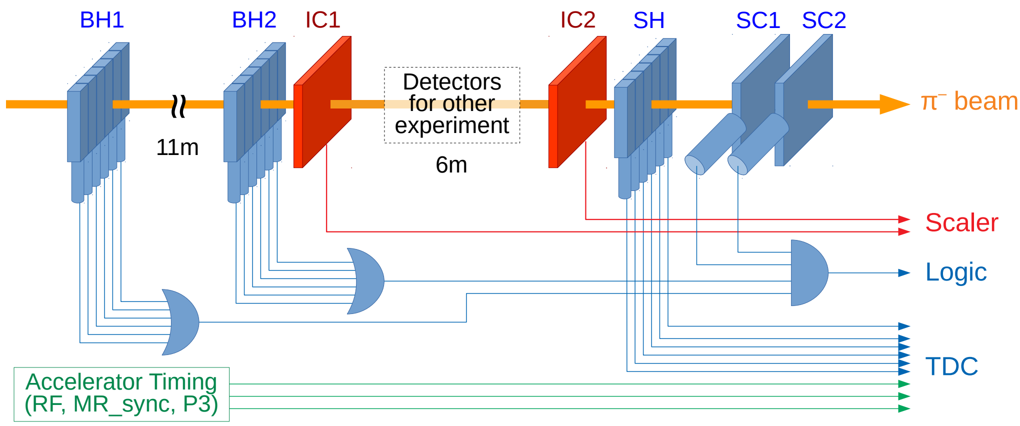

Figure 5: Schematic view of the detector system at K1.8 area.

calculated using the PSI TRANSPORT and TURTLE [3] simulation. The optics was optimized to minimize the beam size at the target of the COMET experiment. The resulting horizontal and vertical beam size at the target was 1.4 mm and 1.0 mm, respectively, in 1σ of Gaussian fit.

EXTINCTION FACTOR MEASUREMENT AT K1.8 AREA IN HADRON HALL

Several measurements of the extinction factor were performed at J-PARC in the past years. However those early tests were done with the beam energy of 30 GeV and/or at the MR abort line without extraction. The measurement with 8 GeV and bunched slow extraction was performed for the first time in 2018. The measurement was carried out at the K1.8 experimental area in Hadron Hall (Fig. 2). The extracted proton beam was injected to the primary target and produced secondary particles were transported to the K1.8 area. The secondary beamline was adjusted to transport 1.32 GeV/c negative pions with typical beam intensity of 1.5×10^6 per shot. The pion beam was used for the extinction factor measurement. The bunch structure of the secondary pions is inherited from the primary proton beam and its intensity is proportional to the proton intensity.

The schematic view of the detectors for the measurement is displayed in Fig. 5. Coincidence of five layers of the scintillation counters or hodoscopes was employed to identify the beam pions. The most upstream beam hodoscope (BH1) was installed in the middle of the secondary beamline. The second hodoscope (BH2) was located near the focal point. Signal OR of slabs of each hodoscope of BH1 and BH2 was used in the measurement. Another hodoscope (SH) and two counters (SC1 and SC2) were installed at the most downstream region. Their photo was shown in Fig. 6. SH was the main detector to count beam pions. SH consists of 16 scintillation counters read out by photomultiplier tubes. The size of each scintillator was 40 mm wide, 250 mm high and 20 mm thick. The signal of each slab was recorded separately to avoid signal pileup because about four pions per bunch were injected on average in the measurement. Two ion chambers

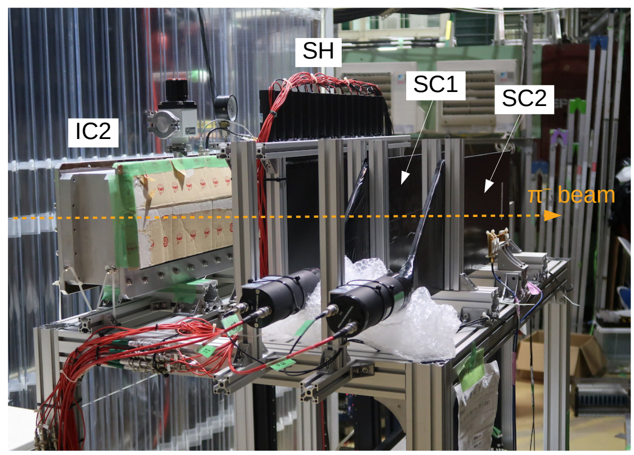

Figure 6: Photo of the downstream part of the detectors.

(IC1 and IC2) were used to supplement shot-by-shot beam intensity.

The signals from counters were recorded by three different TDCs (Time-to-Digital Converter) for redundancy. One is a commercial TDC (Acqiris TC890) with high time resolution of 50 ps but the number of input channels is limited to six. Signals from SH were additionally merged only for this TDC. Another is TDC based on Xilinx Kintex-7 FPGA evaluation board with 16 input channels. The third is FPGA-based TDC with 64 input channels and was developed for general purpose used at Hadron Facility. Signals from SH were recorded without coincidence with BH1, BH2, SC1 and SC2 for this TDC and the coincidence was performed in offline analysis. We finally obtained consistent results between these TDCs.

In addition to the signals from the detectors, three timing signals from the accelerator were used in the measurement. One is a synchrotron RF which is synchronized with beam bunches. Another is MR_sync which is a timing of the first bucket out of nine in MR. MR_sync is used as a time zero of

TDC. The third is P3 which is a timing of the beam extraction as displayed in Fig. 1.

Performance of the counters was evaluated during the commissioning period as well as beam time with normal slow extraction. Overall efficiency of the detectors was 92% for single pion injection. The inefficiency mainly came from acceptance of BH1 and BH2 because pion beam size was larger than usual experiment at K1.8 area. Count loss of SH due to signal pileup was evaluated by hit multiplicity of SH as well as comparison between SH and ion chambers and was estimated to be 10%. A fake signal due to accidental coincidence of the detectors was evaluated based on single count rate of each detector and was obtained to be 4×10^{-13} Hz. It corresponds to 10^{-8} hits or less during the measurement time.

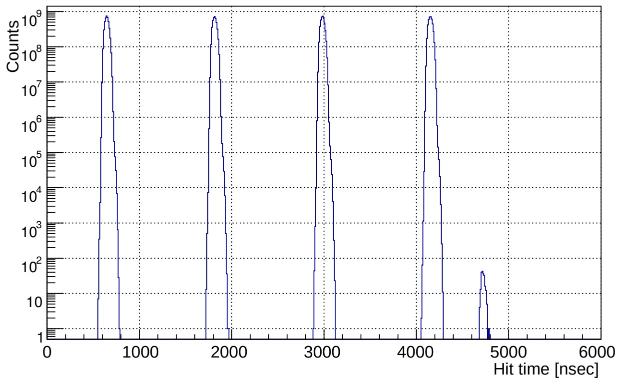

Figure 7: Hit time distribution. Time zero was determined by MR_sync with arbitrary offset. Four large peaks correspond to the filled bunches.

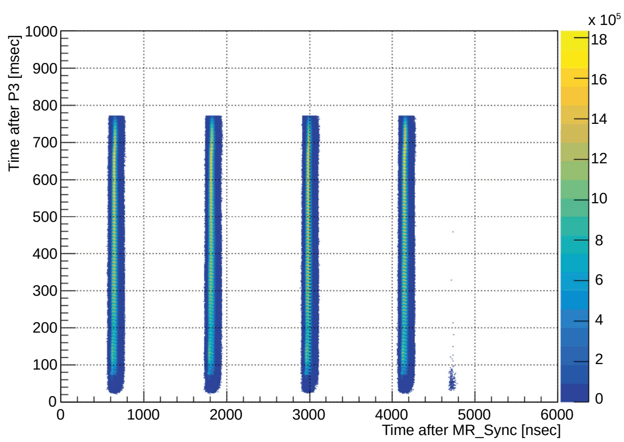

Figure 8: Time evolution of the hit time distribution.

The obtained hit time distribution is displayed in Fig. 7. Four large peaks correspond to filled bunches. The number of the accumulated pions was 1.7×10^{10}. No particles between bunches were observed before the 4th bunch while 202 counts of residual beam pions were detected after the 4th bunch. The resulting extinction factor was the order of 10^{-8} and is unacceptable for the COMET experiment. By masking the 4th bunch, we achieve acceptable level of 6×10^{-11} but signal yield decreases to 75%. Correlation with P3 timing is displayed in Fig. 8. The undesirable hits concentrate near the beginning of the beam extraction. Note that the extinction factor was also measured at MR abort line directly using proton beam to be better than 10^{-11}. However the region after the 4th bunch was invisible due to its measurement method.

SUMMARY AND PROSPECTS

Commissioning of the bunched slow extraction of 8 GeV proton beam was performed at J-PARC for the first time. The emittance of the extracted beam and the extinction factor were measured during the commissioning. Based on the measurements, it becomes possible to evaluate a design of the new beamline for the COMET experiment. More realistic simulation of the COMET experiment is also ongoing to evaluate signal yield and sensitivity. We achieved the extinction factor of 6×10^{-11} or less while the significant beam leakage was observed after the 4th bunch. The leakage shows characteristic time structure and it would help to solve the source of the leakage.

REFERENCES

[1] http://comet.kek.jp/

[2] Y. Sato *et al.*, “Residual gas ionization profile monitors in J-PARC slow-extraction beam line”, Proceedings of IBIC2012, Tsukuba, Japan, pp. 267-270, 2013.

[3] PSI Graphic Transport and Turtle Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version by K.L. Brown *et al.*; http://aea.web.psi.ch/Urs_Rohrer/MyWeb/