PROCEEDINGS OF SCIENCE

Detector Systems Development for Inter-Bunch Extinction Measurements at the 8 GeV Slow-Extracted Pulsed Proton Beam for the COMET Experiment at J-PARC

Kou Oishi,[a,*] Yuki Fujii,[b] Yoshinori Fukao,[c] Yuya Higuchi,[d] Ryotaro Honda,[c] Youichi Igarashi,[c] Fumihito Ikeda,[e] Yu Nakazawa,[c] Hajime Nishiguchi,[c] Kyohei Noguchi,[f] Masayoshi Shoji,[c] Kazuki Ueno[d] and Hisataka Yoshida[g]

[a]*Department of Physics, Imperial College London,*
Exhibition Road, South Kensington, London SW7 2BX, United Kingdom

[b]*School of Physics and Astronomy, Monash University, VIC 3800, Australia*

[c]*Institute of Particle and Nuclear Studies (IPNS), KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

[d]*Department of Physics, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, Japan*

[e]*International Center for Elementary Particle Physics (ICEPP), University of Tokyo,*
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

[f]*Department of Physics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan*

[g]*Research Center for Nuclear Physics (RCNP), Osaka University,*
10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

E-mail: k.oishi@imperial.ac.uk

The COMET experiment will search for the muon-to-electron conversion process in aluminium with a high single event sensitivity. We use the high-intensity proton beam at 8 GeV slowly extracted from the Main Ring (MR) synchrotron accelerator of the Japan Proton Accelerator Research Complex (J-PARC). The beam must form in a pulsed structure with a distance of 1.2 μsec, and the extinction value, the proton-number ratio outside and inside of the bunch, should be less than 10^{-10}. We measured the extinction by counting proton-induced pions at the K1.8BR secondary beamline at J-PARC, and the analysis is ongoing.

For the measurement, we developed a hodoscope to measure the hit timings with segmented plastic scintillators and its surrounding system, including an amplifier and digitisation electronics and data acquisition (DAQ) software. We prepared three different FPGA-based TDC modules with a time resolution of 1–7.5 nsec and optimised their firmware to have distinct advantages for redundancy. The amplifier boards also discriminate signals and distribute them to all three TDC modules. The DAQ software was designed not to limit the data transfer speed and not be suppressed by disk access. The system worked as expected at a hit rate of roughly 10Mπ/beam spill, the maximally allowed beam intensity.

The detail and performance of the developed detector system will be presented.

**** The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021) ****
**** 6–11 Sep 2021 ****
**** Cagliari, Italy ****

*Speaker

https://pos.sissa.it/

PoS(NuFact2021)216

1. Introduction

The COMET experiment will search for the muon-to-electron (μ-e) conversion in aluminium, a charged Lepton Flavour Violation process, at the Hadron Experimental Facility in J-PARC, Japan [1]. In the first-phase experiment (Phase-I), we aim at a sensitivity of 10^{-15}, which can approach a phase space that several theories beyond the standard model predict its existence. Otherwise, it will improve the upper limit on the branching ratio set by the SINDRUM-II experiment by a magnitude of two orders. We have been developing a high-intensity slow-extracted proton beam dedicated to producing an ample secondary muon beam. Figure 1 illustrates our experimental principle. The beam protons are accelerated up to 8 GeV to suppress antiproton production leading to background electrons and slow-extracted into the COMET facility. They are injected into a graphite target to produce secondary pions, which lead to muons via decay. Once a muon undergoes the conversion process after being captured by a nucleon in the aluminium target, only a signal electron is emitted with a fixed energy of 105 MeV. In order to distinguish it from the beam-induced prompt backgrounds and other electrons via muon capture or decay, we pulse the proton beam and use a timing window for the measurement. However, if part of the beam protons leaks out between the beam bunches, those inter-bunch residual protons bring backgrounds crucially. Our simulation studies figured out the following extinction factor must be suppressed as

$$\text{Extinction factor} = \frac{\text{Number of inter-bunch residual protons}}{\text{Number of in-bunch protons}} < 10^{-10}.$$

We have been optimising the beam equipment and optics and successfully performed beam commissioning in May of 2021. Simultaneously, we carried out an experiment to measure the extinction factor and developed the detector system for it. This paper describes the details of the experimental setup and detector and data-acquisition (DAQ) development.

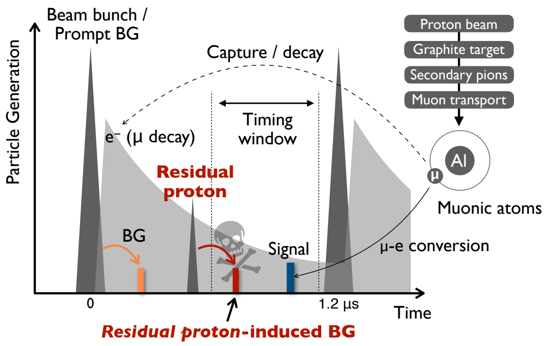


Figure 1: Experimental principle for the μ-e conversion measurement in the COMET experiment

2. T78 Experiment – 8 GeV Extinction Measurement at J-PARC

The T78 experiment [2] was conducted from 20th to 25th May of 2021 at the K1.8BR beamline at the Hadron Experimental Facility of J-PARC, which is shown in Figure 2. The 8-GeV proton beam, operated in several pulsed slow-extraction modes for COMET, was injected into a fixed gold target of T1. The secondary-produced pions are transported into the K1.8BR beamline. The requirements for the measurement were (1) a timing resolution < 10 nsec that allows counting the pions properly, (2) a dynamic time range > 0.5 sec, which is the beam-spill period, and (3) a high rate capability for up to about 10M pions/beam spill, which was expected to be the in-bunch pion rate. We designed the experimental setup and developed detectors and software to meet them.

The right side of Figure 2 illustrates the equipment we installed from the beginning of the K1.8BR beamline. The Beamline Hodoscopes (BH) with plastic scintillators, Spectrometer Magnets, and Ion Chamber (IC) had already been there, and we made the Trigger Counters (TC) with simple plastic scintillators read out by photomultiplier tubes (PMT). In particular, we developed the Extinction Detector (ED) and its electronics, whose design and details are described in the next section. Both BH and TC were used to trigger DAQ by coincidence with the ED. The extinction factor was calculated by counting the in-bunch and inter-bunch pions. Since the in-bunch pions were supposed to pile up in the solid detectors due to their high rate, the IC hit data were used to correct its counting.

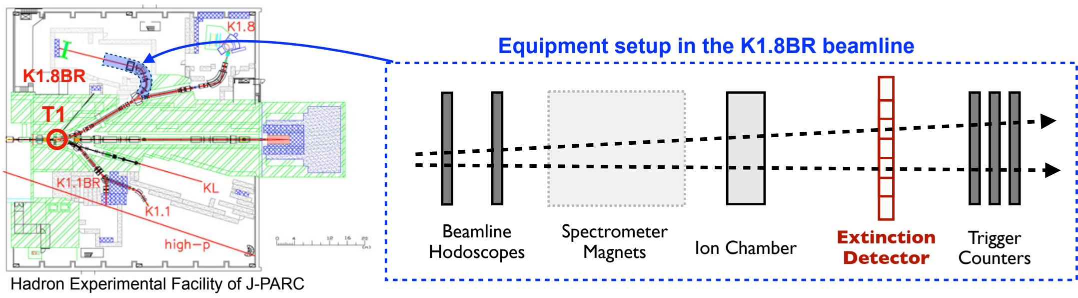
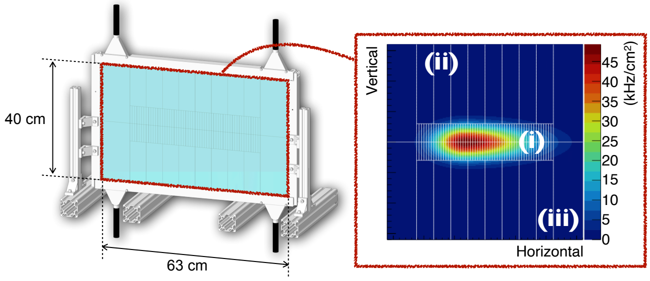


Figure 2: Schematics of the Hadron Experimental Facility and the equipment setup in the K1.8BR beamline

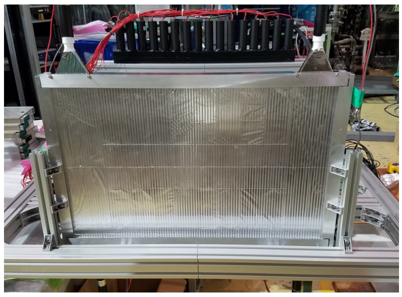
3. Extinction Detector and Electronics

The ED is a hodoscope with 132-channel segmented plastic scintillator pads with a thickness of 20 mm in order to separate as much as possible the large number of particles that overlap at the bunch injection. Figure 3 shows its 3D model and segmentation layout and a picture of the constructed ED. We divided the sensitive area into three regions (i–iii), depending on the beam fluence estimated with a Geant4-based simulation study, which is displayed on the layout; the pad sizes are (i) 8×60, (ii) 54×120, and (iii) 100×200 mm^2. The (i) and (ii) pads are read out by Multi-Pixel Photon Counters (MPPCs), Hamamatsu S13360-1350PE and S13360-3050PE, and the (iii) pads are read out by PMTs, Hamamatsu H3167, via light guides. We evaluated the overall detection efficiency to be 98% in the experiment.

The purpose of the readout system focused on counting the hits as a function of hit timing. Figure 4 shows the electronics for the ED readout. The Amplifier, Discriminator, and Repeater (ADR) board was designed from scratch to convert the MPPC signals into differential digital signals and distribute them into back-end TDC modules. The thresholds can be adjusted for every 16 channels, and we set them up to show the same detection efficiency as far as possible. The PMT signals have the same output as the ADR boards using NIM-standard discriminators and level converters. We prepared three types of TDC modules for redundancy because of fear of missing



(a) 3D model and simulated beam profile



(b) Constructed detector

Figure 3: Extinction Detector

the inter-bunch pions. We prepared several products with an FPGA chip: the Xilinx KC705 FPGA evaluation board, the FCT COMET trigger board, and the Hadron Universal Logic (HUL). We developed FPGA firmware for each, which meets the requirements but has different time resolution per clock, dynamic time range, and the number of channels that a board handles. As differentiating features, the KC705 can count multiple hits in a clock, the FTC has the most compact data size per board to minimise the data bandwidth, and the HUL has the best time resolution and measures time-over-threshold. Every firmware uses the SiTCP technology [3], which realises 1 Gbps TCP/IP communication with DAQ machines.

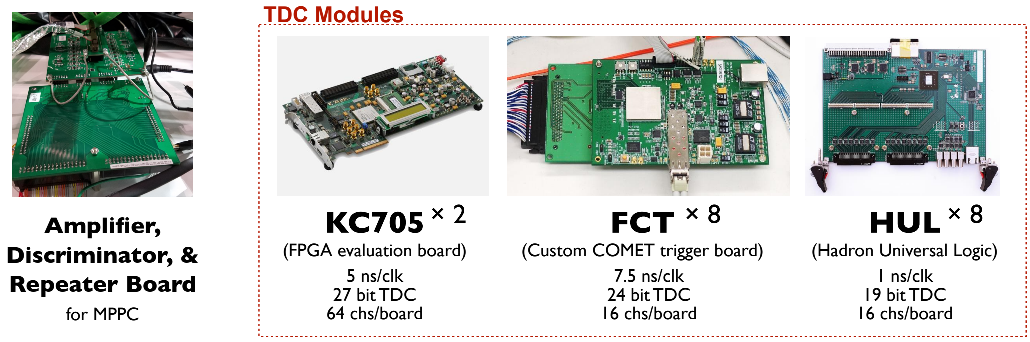
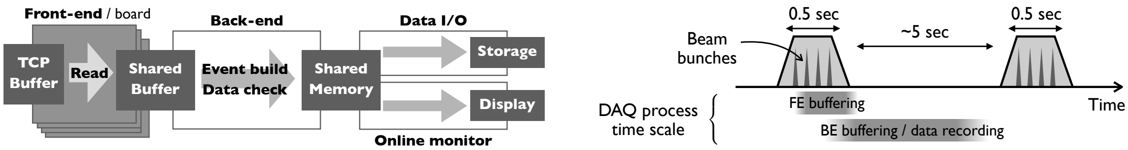


Figure 4: Electronics for the Extinction Detector

4. Data-Acquisition (DAQ) System

We also created a DAQ system for this measurement. It was required to read the input packet data, perform event building, save the data into storage, and show online monitors. In terms of the requirement (3) described in Section 2, there was a risk of missing inter-bunch pions due to data overflow on the DAQ side. SiTCP does not have a large buffer, so data is lost while the TCP buffer at the packet receiver is full up by in-bunch pions' data that come before inter-bunch pions' data. It led us to separate all the required functionalities into different software and utilise the time structure of the beam, as illustrated in Figure 5. Every software runs asynchronously. The first front-end software exclusively focuses on transmitting packet data from each TDC module board to a shared buffer. The back-end software collects data from the buffers for all the boards with a simple data-consistency check, combines them into data packages for each event, and distributes them to further two software. The data-I/O part finally stores the data into the hard disk storage, and the online monitor part displays a summary of the events.

The front-end part must keep an available space in the TCP buffer. The processes later than the front-end software require more computation and time, which means the front-end's shared buffer and the TCP buffer will eventually be filled with the maximum data input rate of 1 Gbps. However, the beam-spill structure solves this issue with its spill distance of 5 sec. The front-end's shared buffer is larger than the TCP buffer and enough to keep all the data during a beam spill of 0.5 sec. We took the time between the spills to perform the data processing from the back-end software, and then all the buffers could get ready for a new spill data. We confirmed that the developed system achieved a DAQ efficiency of $> 99.9\%$ for dummy testing signals input to the TDC modules at the realistic maximum hit rate.



(a) Structure of the DAQ software

(b) Time structure of the data processing

Figure 5: Structure of the DAQ system and its data processing associated with the beam-spill structure.

5. Summary

The COMET experiment will search for the μ-e conversion at J-PARC, Japan, in which the extinction factor of the proton beam must be less than 10^{-10}. We carried out the T78 experiment at the K1.8BR beamline in J-PARC in May of 2021 to directly measure the extinction factor with several beam configurations. We prepared a series of detectors and developed the Extinction Detector and three TDC modules. They have different features for redundancy not to miss a few inter-bunch proton-induced hits. The DAQ system was also designed and made for it by utilising the beam-spill structure. Overall, the detector and DAQ system showed satisfactory performance without any critical problems in the experiment. The data analysis is currently being finalised, and it shows values of the extinction factor that meet the requirement.

References

[1] The COMET Collaboration et al., *COMET Phase-I technical design report*, Progress of Theoretical and Experimental Physics, Volume 2020, Issue 3, March 2020, 033C01.

[2] Y. Fukao, *et al.*, *Proposal for 8 GeV Operation Test and Extinction Measurement*, 2020, https://j-parc.jp/researcher/Hadron/en/pac_2007/pdf/P78_2020-06.pdf.

[3] T. Uchida, *Hardware-based TCP processor for Gigabit Ethernet*, IEEE Transactions on Nuclear Science, Volume 55, Issue 3, June 2008.