Proposal for
8 GeV Operation Test and Extinction Measurement

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June 2020

Abstract

We request 6 days of beam time for the COMET experiment to perform **an 8 GeV operation test** of the J-PARC MR and **an extinction measurement** at the abort line of the MR and the secondary beam line of the Hadron Experimental Facility. A beam energy of 8 GeV instead of normal 30 GeV of MR is required by the COMET experiment, and excellent inter-bunch beam extinction is essential in order to achieve the target sensitivity of COMET. The proposed campaign consists of two parts; "an accelerator study" and "an inter-bunch extinction measurement". Both studies were originally carried out in the previous 8 GeV campaign in January and February 2018. Through the present studies, we aim to improve the quality of the 8 GeV proton beam, building on the knowledge obtained in the previous campaign.

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1 Introduction

The COMET Experiment [1], which is currently under construction at the Hadron Experimental Facility (HD) at J-PARC, aims to search for the lepton flavour violating muon reaction, **Muon-to-Electron Conversion in a muonic atom ($\mu^- N \to e^- N$)**, in order to explore new physics beyond the Standard Model. For this experiment, excellent proton beam quality is essential to achieve unprecedented sensitivity of $\mathcal{O}(10^{-17})$ due to the reasons described below. The COMET experiment requires **a pulsed, 8 GeV, slow-extracted proton beam** from the J-PARC Main Ring (MR) synchrotron to HD.

The choice of beam energy is dictated by minimising the production of antiprotons, the production rate of which increases rapidly for proton energies above 10 GeV. One of the most severe sources of background is from beam-related reactions, which are caused by the prompt interactions of particles in the secondary muon beam (including contaminants such as pions). Since muonic atoms, the production of very large numbers of which is the main purpose of the muon beam, have lifetimes of $\sim$1 μsec, a pulsed beam with a pulse that is short enough 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 Figure 1.

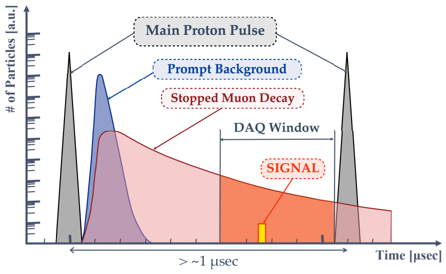


Figure 1: Time structure of the proton beam, background events and DAQ window for the COMET Experiment

In order to realise the specification of proton beam described above, customised operation for the J-PARC MR was proposed [2]. MR usually accelerates the proton beam (at one bunch per 600 nsec) up to 30 GeV. For COMET, however, 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 realised using a customised injection scheme. The 3 GeV rapid cycle synchrotron (RCS), the booster for the MR, has harmonics of 2 and accelerates two beam bunches at 25 Hz in normal operation, but one beam bunch for the COMET experiment. The empty bucket in RCS is made by deflecting the beam using a chopper in the linac. The MR can accelerate 8 bunches with harmonics of 9 [†]. In the customised operation for COMET, one beam bunch from RCS is injected four times every 40 msec into the MR and then accelerated as schematically shown in Figure 2. Finally, the beam accelerated up to 8 GeV is extracted slowly using the third integer resonance,

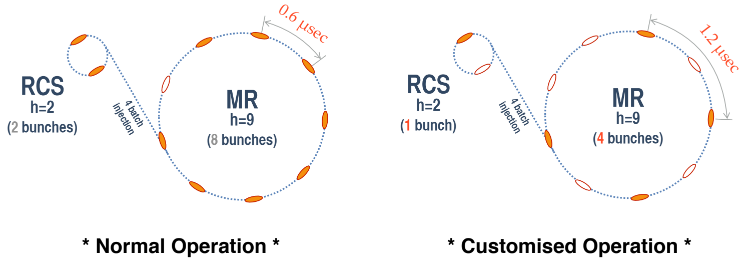


Figure 2: Dedicated beam transfer diagram from RCS to MR for COMET to make the long enough bunch intervals

[†]One of them is dedicated for a gap for the extraction kickers.

maintaining the bunched structure with a 1.2 μsec bunch spacing, the so-called "*bunched slow extraction* (**bunched-SX**)".

In addition, excellent inter-bunch beam **extinction**[‡] is essential for COMET. As shown in Figure 1, the signal electron from the $\mu^- N \rightarrow e^- N$ process would appear after a delay on the order of the lifetime of muonic atoms, τ_{Mu}, *e.g.* τ_{Mu} = 864 nsec if aluminium is employed as the muonic atom production target, hence DAQ timing window of several hundred nsec can be opened after the pulse has passed and closed just before the next primary proton bunch timing. Such a delayed DAQ scheme allows one to achieve an excellent sensitivity because the muon yield can be improved by increasing the proton beam intensity as high as possible. However, if some protons leak from the main bunches into the inter-bunch periods, where the DAQ timing window lies, they could represent a severe source of background events. In order to achieve the COMET target sensitivity, proton-beam extinction should be better than 10^{-10} at least.

In principle, customised MR operation described above realise the required bunch separation of 1.2 μsec. However extinction whith this scheme is not good enough for COMET, because a certain amount of protons will still remain in between bunches due to an inefficiencies of the chopper when making empty buckets. In order to extinguish such residual protons, further customised operation mode was pursued, called " **Single Bunch Kicking (SBK)** ". In normal

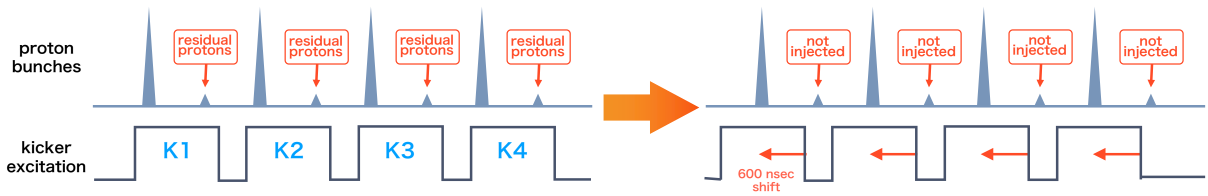


Figure 3: Scheme of the Single Bunch Kicking Mode (SBK)

operation, the injection kicker is fired once for each of the four injection batches, called K1, K2, K3 and K4 batch, sequentially. In the SBK mode, the injection kicker timing is shifted by 600 nsec so that particles remaining in empty buckets are not injected into the MR, as schematically shown in Figure 3.

2 Results from the Previous 8 GeV Campaign

In January and February 2018, the customised operation mode of MR was tested, and a 8 GeV pulsed proton beam has been successfully extracted to HD. In this series of accelerator tests, **the 8 GeV campaign**, all configuration parameters for the J-PARC accelerators, linac, RCS and MR, were adjusted to carry out the 8 GeV acceleration and extraction. In addition, proton leakage between filled 4 RF buckets was successfully controlled using SBK described in the previous section, and measured precisely by a team drawn from the Accelerator Laboratory Group and the COMET Experimental Group [3].

In the 8 GeV campaign in 2018, three main studies were carried out; **i) Accelerator Operation Test, ii) Extinction Study at the abort line of MR with FX beam**, and **iii) Extinction Study at the Secondary Beam-line of HD with bunched-SX beam**.

[‡]The ratio between the number of inter-bunch protons and those in the main bunches.

2.1 Accelerator operation test

This was the first test to extract 8 GeV proton beam to HD § in order to establish bunched-SX running that is stable and efficient enough for COMET, *i.e.* the optimisation of the configuration parameters for all relevant accelerator components was indispensable.

In the MR, electrostatic septa (ESS1 and ESS2) and magnetic septa (SMS1, 2 and 3), bump magnets and a slow collimator are placed in a long straight section to perform the standard slow extraction (SX) for the HD. ESS1 is placed in two adjacent focusing quadrupole magnets with the largest β_x function. The separatrix for the resonance at ESS1 is made of the beam momentum by setting the horizontal chromaticity to zero. The dynamic bump scheme applied under these conditions can drastically reduce the beam loss [4].

At the previous 8 GeV test, the number of protons was set to 6.4×10^{12} ppp (protons-per-pulse) which corresponds to 1.6×10^{12} ppb (protons-per-bunch) since only half the RF buckets need to be filled with protons in the customised MR operation for COMET as described in Section 1. This proton beam corresponds to a beam power of 1.4 kW, but this is equivalent to 3.4 kW in fact for the planned MR cycle for COMET Phase-I ¶, *i.e.* this test was successful under conditions that were identical to the planned COMET Phase-I operation.

Several examples of accelerator optimisation are given here from the many that were successfully completed in this first 8 GeV operation test. For the injection, the 1-σ emittance was measured at the beam transport from the RCS to the MR, and it was 0.66 and 0.85 πmm·mrad in the horizontal and vertical directions, respectively, which is within the expected emittance for the COMET beam intensity ||. The magnet patterns for the dipoles and quadrupoles needed to be optimised, because the frequency pattern of RF was out of the acceptable range when the pattern of main magnets were simply scaled down from normal 30 GeV operations. In addition, the horizontal betatron tune needed to be finely adjusted, because the beam loss just after the injection was too big when the tune was set to the same as 30 GeV normal operation. To reduce the beam loss more, the chromaticity at injection and skew-Q magnet were also adjusted. After the injection optimisation, studies on the bunched-SX were carried out. For normal 30 GeV SX, the dynamic bump scheme [4] is employed to correct the closed orbit distortion (COD) which is caused through tune variation. For the 8 GeV operation, bump orbit set was not derived by simply scaling from 30 GeV, and hence, it has been simulated by using MICAD [5] as implemented in SAD code [6] beforehand. By using these predetermined parameters, bump orbit was formed

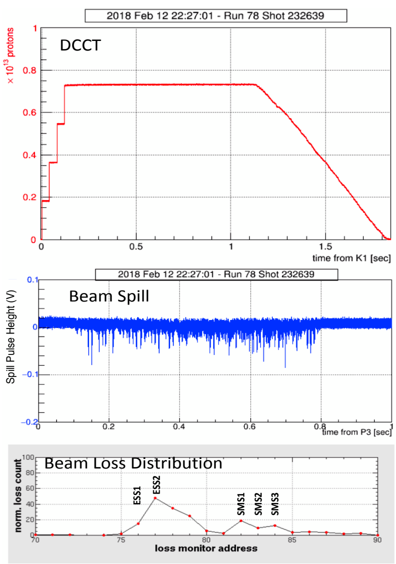


Figure 4: Measured beam current, beam spill, beam-loss distribution for 8 GeV bunched-SX

§A pilot test to accelerate protons up to 8 GeV was conducted at the MR in 2014. At that test, accelerated protons were dumped via the abort line of MR, and thus not extracted to HD.

¶MR cycle for the previous 8 GeV campaign was 5.52 sec, but it will be 2.48 sec for the COMET Phase-I operation. In order to demonstrate the accelerator operation as it is planned for the final COMET condition, the acceleration pattern was configured to be same as the MR cycle of 2.48 sec.

||To realise a 3.4 kW beam power for 8 GeV acceleration, linac parameters were also optimised; pulse width = 50 μsec, chop width = 280 nsec, and thinning = 26/32 (for a peak current of 40 mA).

and the bunched-SX for 8 GeV was successful even for the first test. After the first extraction, fine tuning for dynamic bump, alignment of ESS1,2 and SMS1, and a voltage adjustment on ESS2 were performed. With the optimisations in place as described above, a final extraction efficiency of 97% was achieved. A duty factor of about 16% was obtained during each spill. The extracted beam current, as measured using a current transformer (DCCT), beam spill time profile, and the beam loss around the SX area are shown in Figure 4. The beam emittance immediately after the extraction to the HD was measured by the Hadron Beam-line Group of J-PARC [7], and confirmed to be within the extraction acceptance.

2.2 Extinction study at MR/Abort with FX beam

It is useful to perform the extinction study "within MR" and "after extraction" to pursue the source of proton leakage. At the abort line of the MR, Extinction Monitor (XM) is installed to measure the extinction factor within the MR. XM can count the number of protons extracted to the MR Abort. Its dynamic range has to be sufficiently high enough to measure the numbers of protons in both filled and empty buckets – which should differ by more the 10 orders of magnitude. To allow this, XM consists of a plastic scintillator that is viewed by 4 PMTs. Each PMT is connected to a plastic scintillator via light guides with different light attenuation filters so that each PMT has a different sensitivity to count protons, *e.g.* one PMT is sensitive enough to count the protons one-by-one to count the leaked protons, and another PMT is designed to count the huge number of protons in bunch.

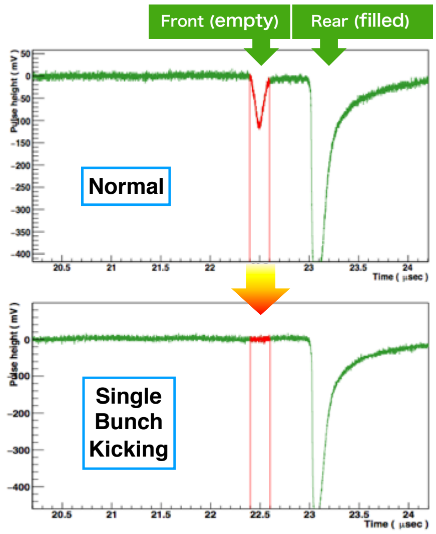


Figure 5: Demonstration of SBK

By using this XM, SBK mode-running was shown to be successful. At first, one RF bucket (rear) out of two buckets in RCS was filled with protons and the other bucket (front) was kept empty for customised COMET operation, as shown in the upper plot of Figure 5. The small pulse that appears in the front bucket position is caused by protons that have leaked in because of chopper inefficiencies, and it is estimated to correspond to an extinction factor of $\mathcal{O}(10^{-6})$, *i.e.* an improvement of four orders of magnitude is necessary to achieve the COMET goal: extinction $<10^{-10}$. Then, the injection kicker timing was shifted backwards by 600 nsec to run with SBK. As shown in the lower plot of Figure 5, residual protons in the front bucket disappeared successfully.

The pilot test for SBK running described above was performed with a reduced beam intensity. With the full proton intensity for COMET, *i.e.* 1.6×10^{12} ppb, even when SBK is used, a small number of protons leaked from the filled bucket as shown in the left plot of Figure 6. As shown in this plot, the leakage was distributed uniformly while the residual protons from chopper inefficiencies were distributed in the front bucket as shown in the upper plot of Figure 5, *i.e.* the former may have escaped over the potential wall of the RF bucket then distributed themselves uniformly. To confirm this assumption, the RF voltage was increased up to 200 kV, compared to 100 kV for the first demonstration. This eliminated proton leakage was extinct as shown in the right plot of Figure 6. In order to investigate the behaviour of proton leakage, the

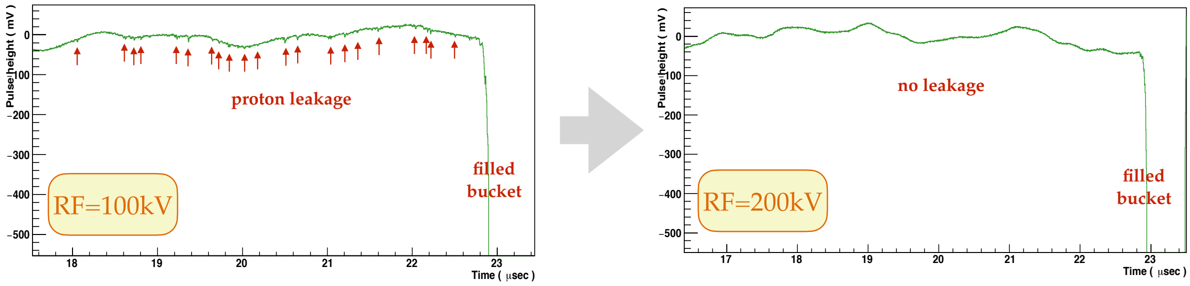


Figure 6: Proton leakage suppression by potential wall of RF

extinction factor was measured by changing the RF voltage during the accelerator flat-top as shown in Figure 7. From this test, excellent extinction of $\mathcal{O}(10^{-12} \sim 10^{-11})$ was demonstrated which is good enough to fulfil the requirement for COMET.

The extinction study within the MR described above was based on "one-shot" operation, *i.e.* not continuous beam operation. Thus the plastic-scintillator-based extinction monitor could measure the extinction with no problems from radiation damage. However, it is necessary to develop an extinction monitor which is robust enough against continuous irradiation by the beam at full intensity. Diamond detector technology is a candidate for such proton beam monitors. In the previous 8 GeV campaign, a prototype diamond detector was tested at the MR Abort line in parallel to the extinction study, and the potential of the detector to distinguish the small amount of proton leakage from the proton bunch was successfully confirmed [8].

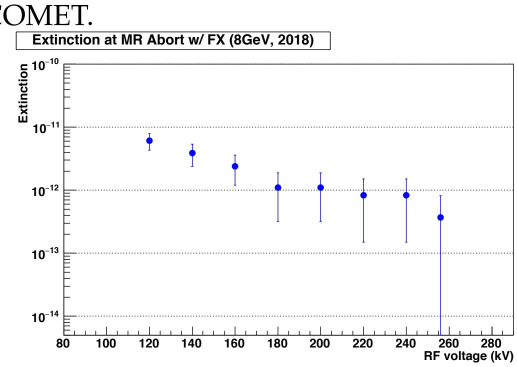
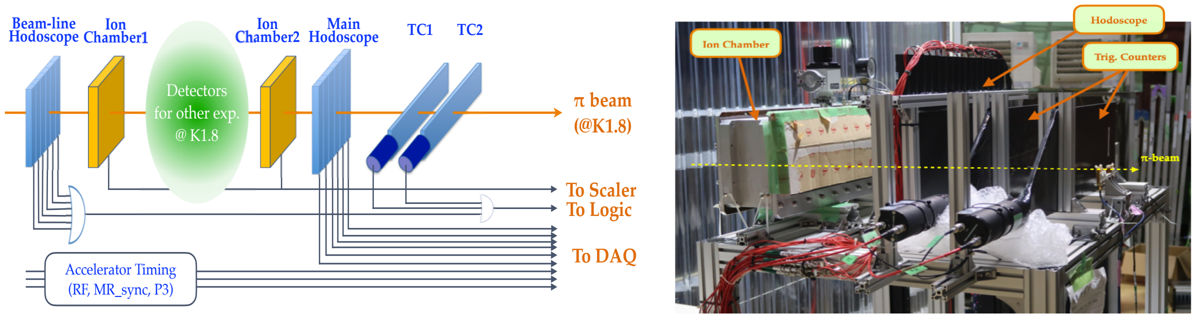


Figure 7: Proton extinction at MR/Abort as a function of RF voltage

2.3 Extinction study at Secondary Beam-line of HD with bunched-SX beam

Adequate inter-bunch beam extinction for COMET was achieved through a combination of SBK and keeping the RF voltage high during the flat-top. This was confirmed at the MR Abort Line, *i.e.* it is necessary to repeat this recipe with bunched-SX at HD. Because some beam-line components for SX scrape the proton beam directly, there is concern over the deterioration of proton extinction. Thus, it is critical that we demonstrate and confirm good enough extinction at HD with bunched-SX. However, unfortunately, there is no any occasion to measure the proton extinction at the primary proton beam line between the MR and HD. Therefore, an extinction measurement using the secondary beam at HD has been proposed in 2008, Test Experiment T25 [9]. In that proposal, proton-beam extinction was supposed to be extracted by counting the number of secondary particle (pion) with bunched-SX operation. This test experiment was finally realised by the 8 GeV campaign 2018.

In order to count the number of secondary particles at the HD with a bunched beam-timing structure, the rate capability of the detectors and DAQ is an issue. To overcome the severe



(a) (b)

Figure 8: Setup for the extinction measurement at secondary beam line of HD; (a) Logic diagram, (b) Photograph of setup.

pile-ups due to the bunched beam timing structure, a hodoscope-based measurement setup was developed as schematically shown in Figure 8 (a). In order to avoid any inconvenience for the current users of the K1.8 beam line (E03 and E40), the extinction measurement set-up was installed by simply adding the hodoscope system and ionisation chambers to the existing series of beam counters, without making any changes to the E03 and E40 detectors. The main hodoscope consists of 16 plastic scintillator bars of 4 cm width, and 16 finemesh PMTs that are directory glued to them. All pions that were delivered to the K1.8 secondary beam line, including both bunched and leaked protons were counted using this hodoscope system, and irrelevant hits were vetoed by beam-line counters and the upstream hodoscope. The detection efficiency of the hodoscope was carefully monitored with an ionization chamber system which was equipped into the same beam line. The final setup is pictured in Figure 8 (b).

Because one of the critical concerns was misacquisition of DAQ due to the bunched beam-timing structure, three independent TDC systems were prepared. TDC-1 is an in-house developed TDC based on the on-board programmable logic circuit FPGA. TDC-2 is another FPGA-based long range TDC. And TDC-3 is a commercial multi-stop TDC. TDC-1 is designed to have a good rate capability at the expense of timing resolution. TDC-2 has been developed for another experiment at HD to be compatible with Hadron-Universal-Logic system, but the rate capability is worse than TDC-1. TDC-3 has an excellent timing resolution of 50 psec, but the rate capability is worst among the three TDCs. This combination of three complementary TDC systems allowed measurements to be made with excellent accuracy.

The obtained timing distribution of secondary pions is shown in Figure 9. This plot was extracted from the TDC-1 data, with the two other TDCs providing consistent results. In the raw data, the timing of secondary pions is recorded with respect to the bunched SX structure, which is then converted into times relative to the MR injection times, so that it is possible to find whether any leakage has occured. In this test, all front buckets were filled with proton bunches while the rear buckets were left empty, and then the injection kicker timing was shifted forward by 600 nsec, while keeping the MR RF voltage at 180 kV. As shown in Figure 9, perfect extinction was accomplished in K1, K2 and K3. However, there is small residual signal which corresponds to the K4-rear bucket time.

The total number of pions seen in this measurement was 1.7×10^{10} (corresponding to 23 hours of DAQ live-time), and the number in the inter-peak region was 202, *i.e.* the extinction factor is 1.2×10^{-8} which does not satisfy the requirement for COMET. By excluding events belonging to the K4 injection batch, *i.e.* using the data from K1, K2 and K3 only, the extinction factor is $< 1.0 \times 10^{-10}$ which satisfies the requirements. In this case, a quarter of the proton beam would be discarded. If the leakage at K4-rear can be solved, an extinction factor of $< 6.0 \times 10^{-11}$ is feasible.

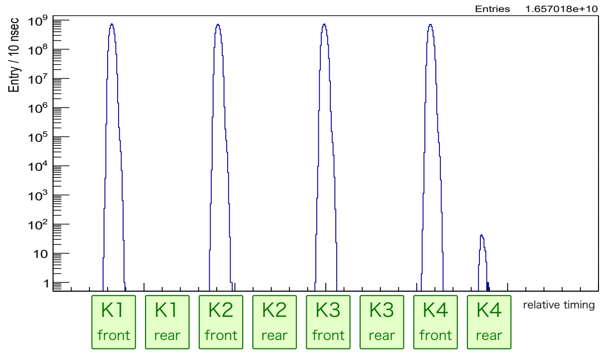


Figure 9: Timing distribution of secondary pion (Converted to be synchronised wrt. MR timing)

3 Proposal for the Next 8 GeV Campaign

In the previous 8 GeV campaign in 2018, three studies were performed. Thanks to the accelerator study, the full 8 GeV operation chain, "injection", "acceleration" and "bunched slow extraction", was established. Customised MR operation for COMET was successfully demonstrated at the MR Abort Line with FX beam. In particular, SBK-mode runnning was investigated with the RF voltages being varied, and excellent extinction levels of $\mathcal{O}(10^{-12} - 10^{-11})$ was confirmed. Bunched-SX beam was transported to HD, and secondary pions at the K1.8 beam line were carefully measured, and an sufficient extinction of $<1.0 \times 10^{-10}$ was confirmed. However, the residual protons at the K4 rear bucket were also observed.

Here, we propose the next 8 GeV campaign to complete the agenda revealed in the previous campaign; **i) achieve perfect extraction**, and **ii) perfect extinction**. In the previous campaign, the extraction efficiency ultimately reached 97%, while it is usually 99.5 % for normal SX. And the mystery at K4 rear should be solved to ensure the success of COMET.

3.1 Investigation to pursue a perfect extinction

After the previous campaign, an intensive study was performed to understand the mechanism of K4 leakage and to pursue the origin of this leakage. In addition, by this study, an approach to improve the extinction factor was also drawn up.

The true identity of *K4-Mystery* is becoming clearer. Figure 10 shows the injection kicker-excitation waveform and the timing of the front and rear RF buckets. As shown clearly, kicker field has a certain trailing component. Thus, even if SBK is applied (Figure 10 (b)), some residual protons in the empty bucket is affected by the tail of the kicker field, and can be injected into the MR.

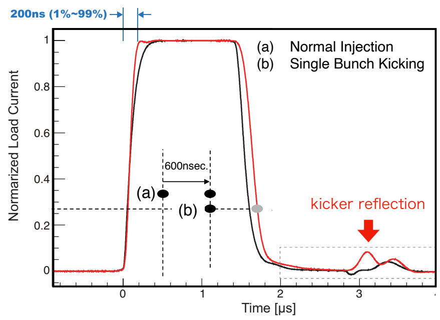
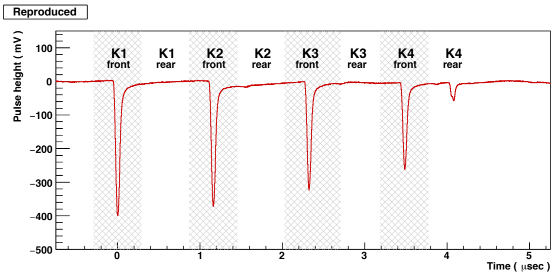
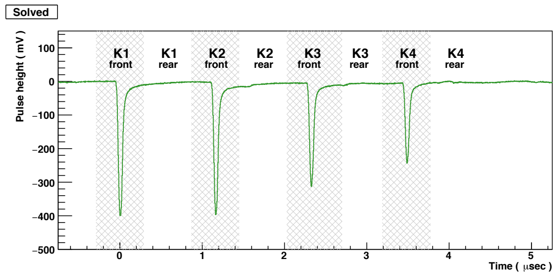


Figure 10: Waveform of injection kicker and position of RF buckets



(a) Normal SBK (600nsec shift)



(b) Further kicker shift added (+150nsec)

Figure 11: Quick test of K4 leakage at MR/Abort

This "mis-injection" does not happen if another full kicker excitation follows immediately, as shown schematically in Figure 3. The K4 injection batch, however, does not have an injection that follows it, while all other batches, K1, K2 and K3, are followed by the next excitation. This can explain why residual protons are left only at K4 while all other buckets exhibited perfect extinction.

This assumption was quickly investigated and verified. By taking an opportunity of MR commissioning in February 2019, the injection kicker timing was further modified to investigate the effect of the kicker tail. Figure 11(a) shows the signal from XM at MR/Abort (see Section 2.2) with SBK as previously described which shifts the kicker timing by 600 nsec forward**, where one can see some leakage being reproduced in the K4 rear bucket. In order to avoid the effect of the kicker tail, the kicker timing was further shifted by 150 nsec, where the small leakage into K4 rear has vanished as shown in Figure 11(b).

This demonstrated the feasibility of the alternative SBK timing which can completely solve the effect of kicker tail, *i.e.* fill the rear buckets and shift the kicker backward instead. The original idea for SBK was to fill the front buckets and shift the kicker forward (see Figure 3), because there is a severe reflection in the kicker field as shown in Figure 10. This reflection is known to disrupt the any injection batches that follow. In order to compensate for this reflection, a correction kicker (CK) system was added to the MR in 2014, and it is normally in use for FX. If the CK is adapted for use also for SX, it might be possible to bring in an alternative form of SBK running, namely **backwards SBK**.

A quick test was performed in February 2020 by taking an opportunity during MR commissioning. In this test, the timing and power of CK was scanned to be optimum for 30 GeV SX. Figure 12 shows the injection error for three different CK conditions, and also for the optimised CK parameters which were found. This indicates that backwards SBK running in conjunction with the CK is possible.

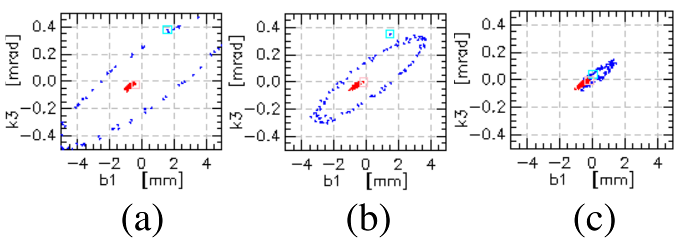


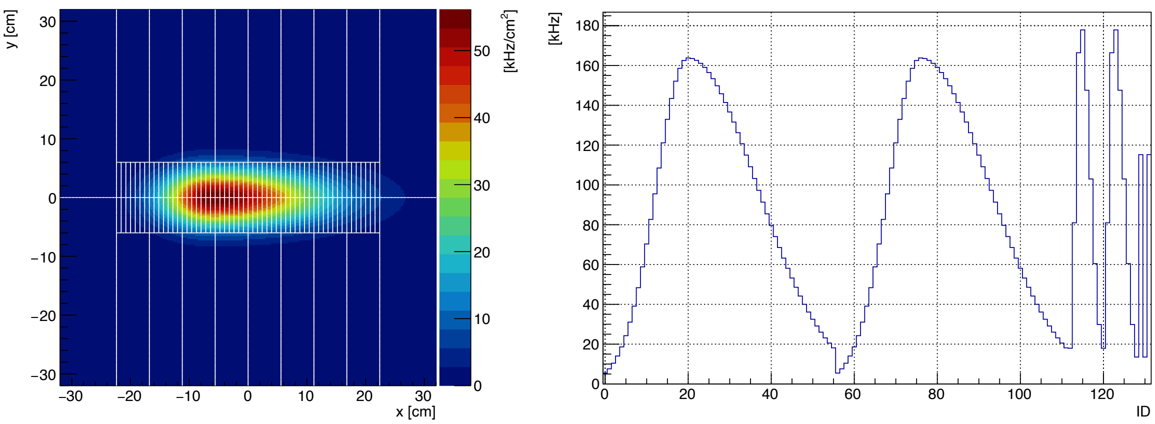
Figure 12: Injection error space for K3 injection; (a) without CK, (b) with CK (not optimised), and (C) with the optimised CK

**In this demonstration, a reduced number of protons ($\sim 10^6$ ppp) was filled into front buckets, while full beam was filled into rear buckets usually for the extinction measurement at MR/Abort with FX, because the extinction monitor is not sensitive enough for residual protons in the rear bucket due to PMT saturation.

3.2 Experimental setup

The experimental setup for the next 8 GeV campaign has been developed based on the intense studies which followed the previous campaign. An XM installed in MR/Abort will be reused for the study with FX beam. However, at the HD with bunched-SX beam, the hodoscope system needs to be upgraded, since the rate capability should be enhanced to achieve more statistics. In consequence, the DAQ system also needs to be upgraded accordingly.

We request the use of either the K1.8 or K1.8BR secondary beam lines[††] for this proposal. The basic design for the setup remains very similar to that for the previous study as shown in Figure 8 (a). To avoid any inconvenience for users of the secondary beam line, the only changes to be made in the experimental area for the extinction measurement would be to add the hodoscope system and some ionisation chambers. The main hodoscope will be upgraded, and the upstream beam-line hodoscope will be replaced by the previous hodoscope. In order to improve the rate capability, the granularity of the hodoscope will be improved. Beam line simulations were used to optimise the design of the hodoscope. Figure 13(a) shows the simu-



(a) Simulated beam profile at K1.8BR

(b) Estimated hit rate of each scintillator tiles

Figure 13: Simulation-base studies to optimise the hodoscope design

lated beam profile at K1.8BR based on certain assumptions. Using this simulated profile, the segmentation of the hodoscope is optimised as indicated by the white lines in Figure 13(a). Further improvements would come from a two-dimensional segmentation that is finer in the centre. Then, the hit rate of the hottest channel is successfully reduced down to 160kHz, as shown in Figure 13(b), which corresponds to an instantaneous rate of about 10 MHz, taking the duty factor into account. The inner scintillator tiles will be read out directly by MPPC, and the outer scintillator bars will be read out by PMTs. Based on this design, 128 scintillator-tile-and-MPPC channels are needed for the readout for the inner part. The COMET experiment group has already developed a similar two-dimensional beam counter 128 readout channels with scintillating fibres and MPPCs for the test-beam experiment of the detector prototypes, *i.e.* there is no technical concern to construct such a fine-grained hodoscope system.

[††]Secondary beam lines of HD are fully occupied by several approved experiments. Thus we do not decide which beam line would be requested, and prepare the setup to be appropriate for both beam lines.

Based on the simulation study described above, the new hodoscope is designed as shown in Figure 14. The MPPCs for the scintillation fibre counter will be reused for the new hodoscope. A light yield study and some design work on the support structure are ongoing. As soon as these studies are finalised, the new hodoscope will be constructed.

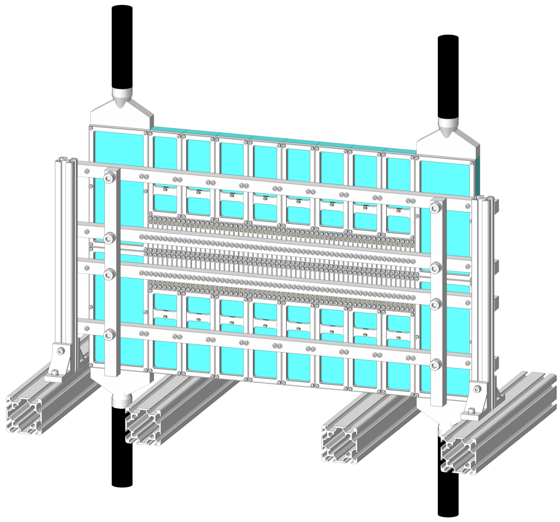


Figure 14: Design of new hodoscope

The DAQ system also needs to be upgraded accordingly. The highest instantaneous hit rate of the previous hodoscope was 2∼4 MHz[‡‡], and therefore it is necessary to improve the DAQ capability by one order of magnitude. In order to realise such a dedicated DAQ system, three individual FPGA-based TDCs are under development to keep the DAQ redundancy similar to the previous campaign.

- **Readout-A** : In-house developed FPGA-based TDC (Upgrade of the previous TDC-1)
- **Readout-B** : RECBE, an FPGA-based integrated front-end readout board
- **Readout-C** : FCT, a custom FPGA readout and trigger board for COMET

Readout-A was originally developed for the previous 8 GeV campaign, TDC-1, as described in Section 2.3. This TDC uses the KC705, Xilinx Kintex-7 evaluation kit, and the data transfer is via SiTCP [10]. The rate capability of TDC-1 was limited by SiTCP and its buffer size, and so this can be improved by using either a faster network link or a larger data buffer, *e.g.* using PCIe or doubling the board. On the other hand, it is also possible to replace the firmware of TDC-1 to be a multi-channel scaler so that the data transfer can be much faster. For Readout-B, the COMET collaboration is using many RECBE boards, which was originally developed for the Belle-II Cylindrical Drift Chamber readout [11]. This board integrates the analogue I/O, preamplifier, shaper discriminator, and digitizer, and the local-bus control is implemented using an FPGA. Reading out the MPPC signal in serial through a matched capacitor and 10 RECBE boards, it is possible to manage a high instantaneous rate. For Readout-C, an FCT (Fast-Control-and-Timing) board, developed in the UK for the COMET trigger system to connect each detector I/O and trigger boards via a GBT (Giga Bit Transceiver)-base mother board, the FC7 [12]. A similar application with Readout-B is also possible by using 10 FCT boards. Based on these three individual FPGA-based DAQ systems, it is possible to manage an instantaneous rate of up to ∼10 MHz. This is to say that it will be possible to make an extinction measurement that is sensitive to rates of $\mathcal{O}(10^{-12} - 10^{-11})$.

In parallel to TDC development, an alternative DAQ mode is also under development, which we can call the "masked-DAQ" mode. This mode vetoes the data process during the main bunch so that an instantaneous high rate can be avoided. This means that the beam

[‡‡]At the previous campaign, to operate DAQ properly, the beam slit of K1.8 secondary beam line was required to narrow down to be 0.8-1.5$\times 10^{6}$ pions a spill.

	Day-1	Day-2	Day-3	Day-4	Day-5	Day-6
Daytime (0900-2100)	Accelerator Study (1-shot, w/o SX)	Accelerator Study (1-shot, w/ SX)	Accelerator Study (continuous SX)	Accelerator Study (extinction improvement)		Extinction Study (main measurement)
Night (2100-0900)	Extinction Study (MR/Abort, FX)	HD beam commissioning				
		Extinction Study (DAQ commissioning)	Extinction Study (masked DAQ w/ variable configuration)		Extinction Study (main measurement)	

Figure 15: A brief schedule of 8 GeV campaign

intensity can be increased, unlike the previous campaign where the secondary beam lines slit width had to be reduced. This will allow us to perform a programme of extinction studies with many different configuration variables. *e.g.* backward SBK, different kicker timing, variable RF voltage, *etc.* In masked mode, however, only the leaked particles between bunches are countable, leading to an indirect measurement of the extinction rate.

3.3 Campaign Programme

The structure of campaign programme mirrors the previous campaign, with **an accelerator study**, **an extinction study at MR/Abort with FX beam**, and **an extinction study at HD with bunched-SX beam**. However, the period of campaign can be shorter (it was 8 days in 2018), as a result of the improvements in the measurement set-up.

The beam time assignment for each study is outlined in Figure 15. The daytimes (09:00 - 21:00) are designated for accelerator studies, except for the last day, to secure enough time for the extinction measurement. Because a stable bunched-SX might not be possible by Day-1, an extinction study at MR/Abort with FX beam is assigned to Day-1 night. Then, all other nights will be used for extinction studies at HD with bunched-SX beam. At the beginning of each beam time at HD, *i.e.* Day-2 to Day-5, beam line commissioning by the Hadron Beam Line Group is necessary to establish stable beam steering onto the production target including adjustments of the interlock system. A breakdown of each study is given below.

Day-1

- Accelerator Study; Injection tuning, Beam transfer and collimator tuning between RCS and MR, Momentum matching on bending magnet, RF frequency tuning, COD corrections, FX orbit and timing measurement, Injection error measurement, Injection kicker timing tuning, Tune measurements, adjusting with quads, Chromaticity measurements and adjustment, Profile measurement at MR/Abort with flying-wire, Beta-function measurements. **No extraction to HD and 1-shot operation only. Beam destination is MR/Abort.**
- Extinction Study at MR/Abort; Reproducibility check, Intensity scan, Kicker timing scan, CK study, Extinction measurement with various RF voltages. In parallel, a beam irradiation test for proton beam monitor would be performed.

Day-2

- Accelerator Study; Optics correction by the beta function measurements, Tune measurements, adjusting with quads, Injection matching, Skew and Optics correction based on the beta function measurement, Fixed bump by MICAD, SX test. **SX 1-shot operation. Beam destination is HD with defocus-bump.**
- HD beam line commissioning
- Extinction Study at HD; DAQ test with 1-shot beam, Beam intensity scan based on ionization chamber

Day-3

- Accelerator Study; Closed bump orbit sets by MICAD, Fixed bump and scheduled dynamic bump setting, QFN ramping and tune measurements, SX start, Spill length and duty tuning by EQ and RQ. **Limited continuous shot, Beam destination is HD with defocus-bump.**
- HD beam line commissioning
- Extinction Study at HD; Reproducibility check without SBK, SBK test, (Masked DAQ $\rightarrow$) kicker timing study, kicker tail study, backward SBK test

Day-4

- Accelerator Study; Dynamic bump tuning, ESS/SMS beam-based alignments, Spill duty including TRF, Extinction study (Injection and correction kickers). (**Bunched SX with COMET intensity**)
- HD beam line commissioning
- Extinction Study at HD; (Masked DAQ $\rightarrow$) Kicker timing study with backward SBK, RF scan

Day-5

- Accelerator Study; Dynamic bump tuning, ESS/SMS beam-based alignments, Spill duty (continued), Extinction study (Injection and correction kickers). (**Bunched SX with COMET intensity**)
- HD beam line commissioning
- Extinction Study at HD; (without Masked-DAQ) **Main measurement of extinction with the best configuration** (The best configuration should be decided based on the result from last days with masked-DAQ.)

Day-6

- Extinction Study at HD; (without Masked-DAQ) **Main measurement of extinction with the best configuration** (36 hours DAQ-live in total at longest, which is corresponding to the extinction sensitivity of 4×10^{-12}, $\times10$ DAQ capability is supposed.)

Conclusions

Customised accelerator operations, at 8 GeV and with bunched slow-extraction, are needed for the COMET experiment to reach its sensitivity goals. In January and February 2018, a dedicated 8 GeV campaign for the accelerator tests and inter-bunch beam extinction measurements was conducted successfully, and good extinction observed. However, some leakage of protons into the inter-bunch regions was discovered in these tests. Studies performed since the previous campaign are revealing the true cause of this leakage, and some methods to suppress it have been devised.

Six days of beam time are requested for a new accelerator-test campaign, which will consist of 8 GeV running and inter-bunch extinction measurements, both of which are critical for the success of the COMET experiment.

References

[1] COMET Collaboration, COMET Phase-I technical design report, *Prog. Theor. Exp. Phys.* **2020** (2020) 033C01

[2] M. Tomizawa *et.al.*, J-PARC accelerator scheme for muon to electron conversion search, *Proceedings of EPAC'08* **MOPC128** (2008) pp.337-338.

[3] H. Nishiguchi *et.al.*, Extinction Measurement of J-PARC MR with 8 GeV Proton Beam for the New Muon-to-Electron Conversion Search Experiment – COMET, IPAC2019, FRXXPLS2 (2019) pp.4372-4375

[4] M. Tomizawa *et.al.*, Slow extraction from J-PARC main ring using a dynamic bump, *Nucl. Instrum. and Methods* **A902** (2018) pp.51-61

[5] B. Autin and Y. Marti, Closed Orbit Correction of A. G. Machines using a Small Number of Magnets, *CERN Report CERN-ISR-MA/733-17* (1973)

[6] `http://acc-physics.kek.jp/SAD/`

[7] Y. Fukao *et.al.*, Measurement of proton beam profile at 8 GeV acceleration commissioning for the J-PARC COMET experiment, *Proceedings of 15th Annual Meeting of Particle Accelerator Society of Japan* (2018)

[8] Y. Fujii, H. Nishiguchi, S. Mihara and Y. Hashimoto, Development of the proton beam monitor based on the thin diamond crystal for the COMET Experiment, *Nucl. Instrum. and Methods* **A936** (2019) pp.669-670

[9] S. Mihara *et.al.*, Proposal for Extinction Measurement of J-PARC Proton Beam at K1.8BR, *submitted to J-PARC Nuclear and Particle Physics PAC and approved as T25* (2008)

[10] `https://www.bbtech.co.jp/en/products/sitcp-library/`

[11] T. Uchida *et.al.*, Readout Electronics for the Central Drift Chamber of the Belle-II Detector, *IEEE Trans Nucl Sci* **62** (2015) pp.1741-1746

[12] M. Pesaresi *et.al.*, The FC7 AMC for generic DAQ & control applications in CMS, *JINST* **10** (2015) C030336