Extinction Measurement at J-PARC MR with Slow-Extracted Pulsed Proton Beam for COMET Experiment

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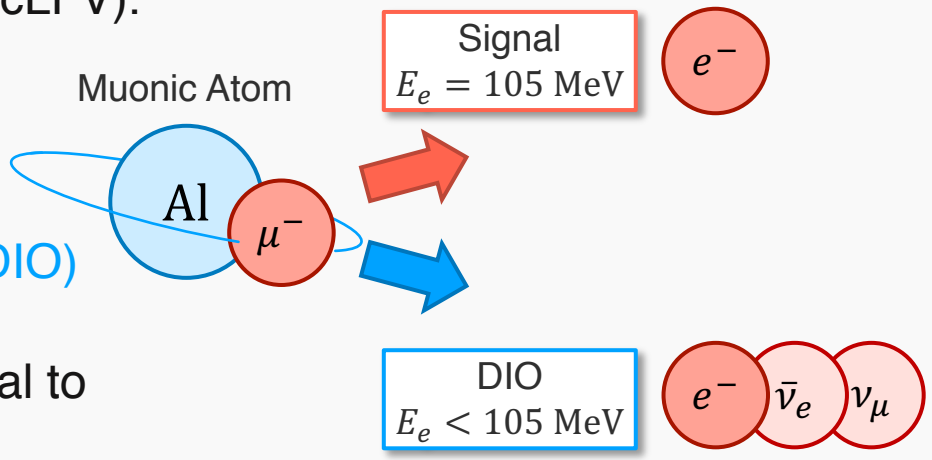
Muon to Electron Conversion (μ-e conversion)

The μ-e conversion is neutrinoless muon to electron conversion that is **charged lepton flavor violation** (cLFV).



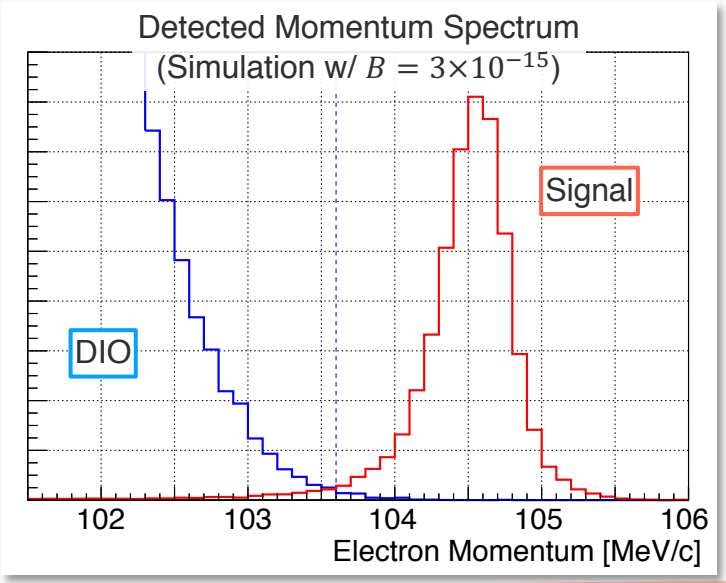
- Signal
  - $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
  - Mono-energetic signal electron
- Bound Negative Muon Decay In Orbit (DIO)
  - $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
  - Electron energy is lower than and equal to the signal electron energy.
- Branching Ratio
  - Standard Model (SM) $<$ 10^{-54} (*)
  - Beyond the SM $\sim$ 10^{-15}

O(10^{40})

  - μ-e conversion is a good probe of new physics.

The COMET (COherent Muon to Electron Transition) experiment [1] searches for μ-e conversion.

- **Background rejection** is important because μ-e conversion is a rare process.

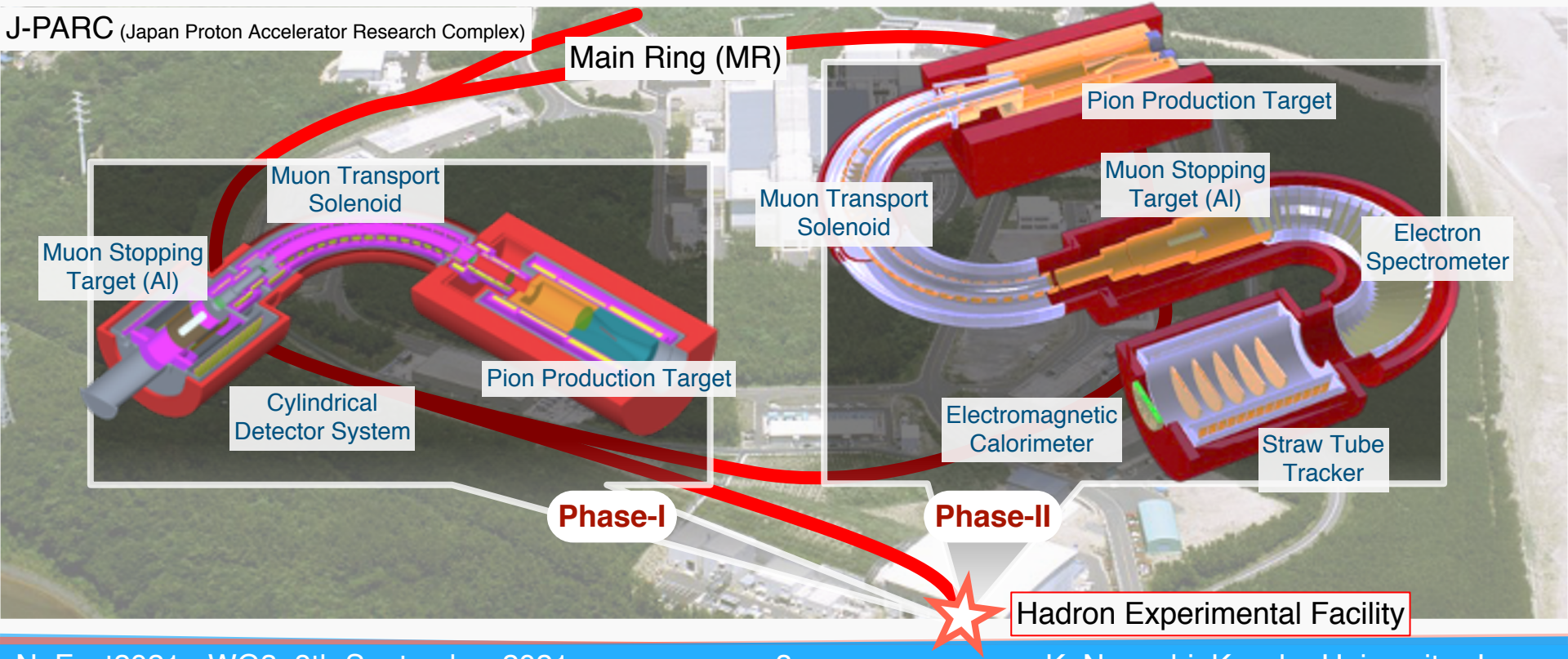


(*) To be precise, it is the SM w/ neutrino mixing.

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

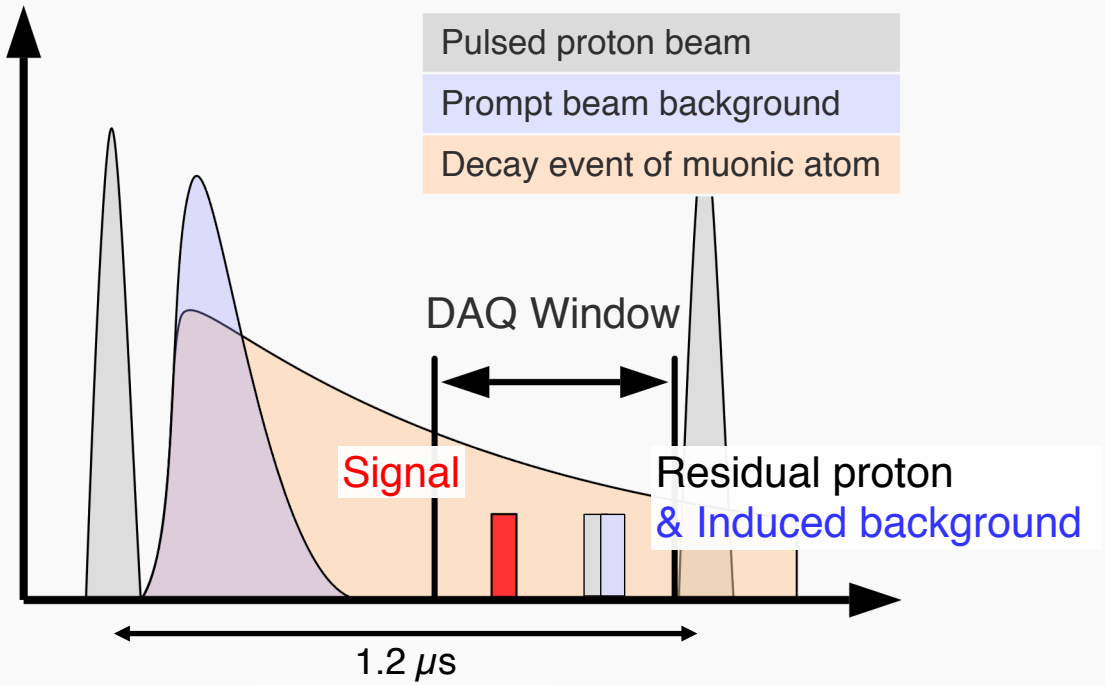
The COMET Experiment

- The experiment will be carried out in the **hadron experimental facility at J-PARC**.
  - The world's **most intense pulsed proton beam** will be used.
- The experiment will be conducted in two phases.
  - Phase-I / II aims 10^{-15} / 10^{-17} sensitivity, respectively.
  - This ultimate sensitivity goal is a factor of about **10,000 better** than the current experimental limit from SINDRUM-II at PSI (Paul Scherrer Institute).
- COMET Phase-I is currently under construction at J-PARC.



The Background of COMET

- One of the most severe source of background is the prompt beam backgrounds produced by protons
  - e.g., in-flight muon decay and pions in a beam
- They are removed by **pulsed proton beam** and performing measurements in **a delayed DAQ window**.

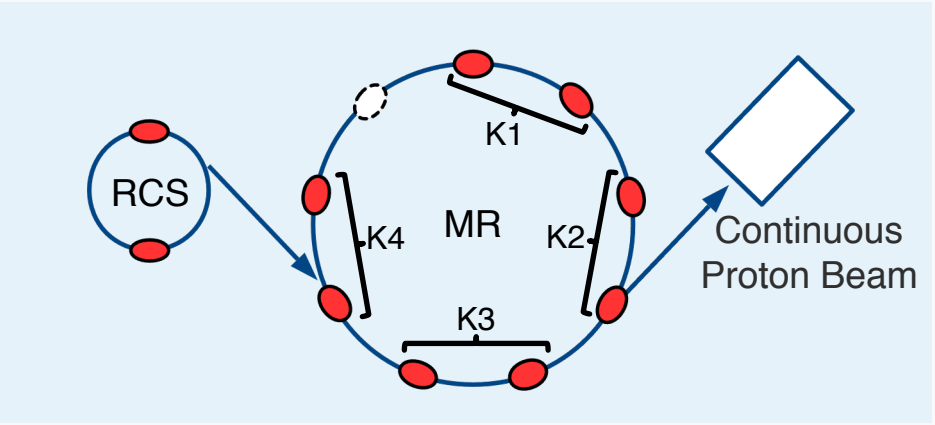


- Inter-bunch residual protons which induce background also must be removed.
- Proton extinction of inter-bunch residual protons is required to be $< 10^{-10}$.

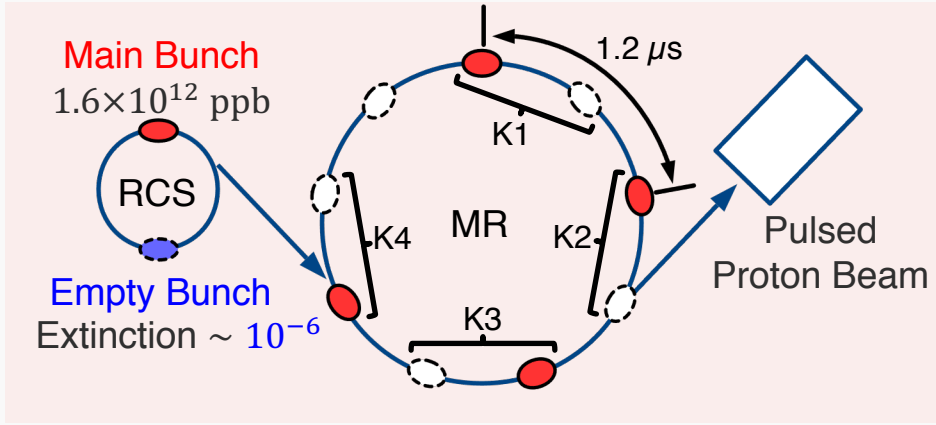
Proton Extinction := # of inter-bunch protons / # of in-bunch protons

The COMET Beam Operation

- The COMET experiment needs dedicated beam operation.



Normal Operation

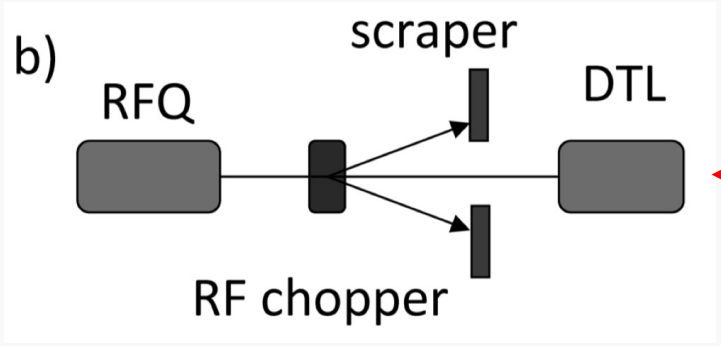


COMET Operation

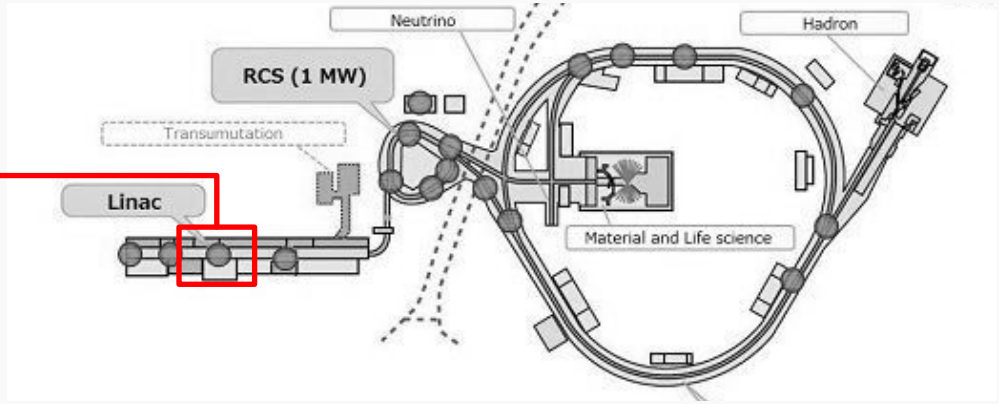
- **8 GeV protons** instead of 30 GeV
  - To avoid antiproton-related backgrounds
- **Slow extracted** pulse proton beam
  - To avoid pile-up of detector system
- **1.2 μs bunch separation** instead of 0.6 μs bunch separation
  - To keep bunch separation long enough to accommodate the lifetime of muonic atom in aluminum ($\tau \sim 864$ ns)
  - Each injection batch (K1, K2, K3 and K4) in the COMET operation is structured with proton filled bunch (main bunch) and empty bunch.

Improvement Method of Extinction

- At first, an empty bunch can be made by RF chopper in the Linac.
- But at this stage, the extinction is only 10^{-6}, which is not sufficient.

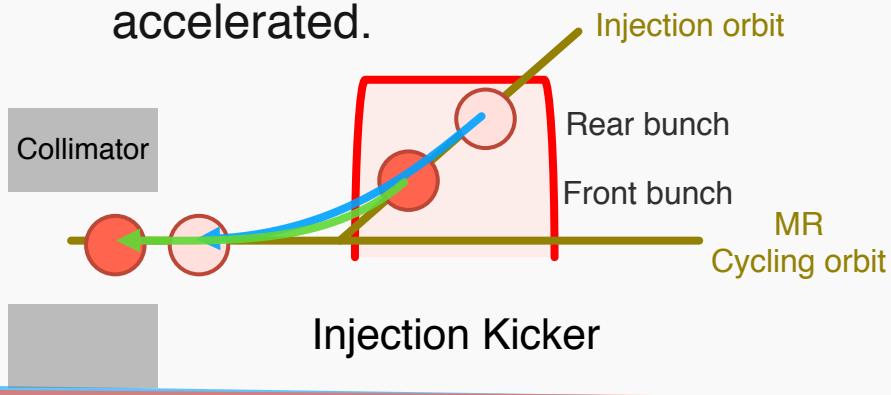


Empty bucket production procedure at Linac



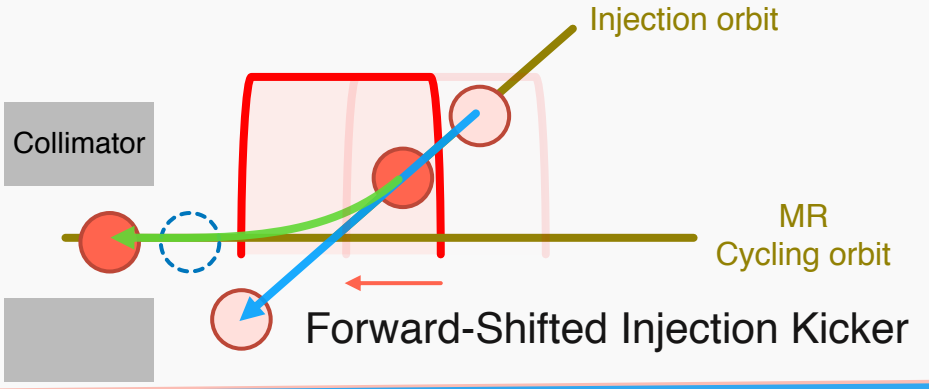
❖ Normal Injection

- Both front main bunch and residual protons in rear bunch are kicked by injection kicker.
- Residual protons are injected and accelerated.



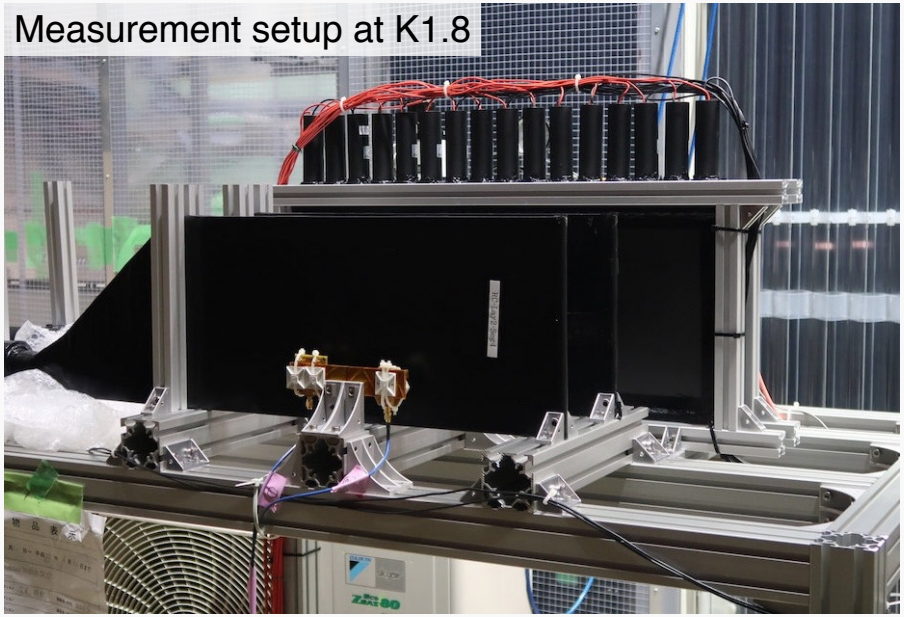
❖ Single Bunch Kicking (SBK)

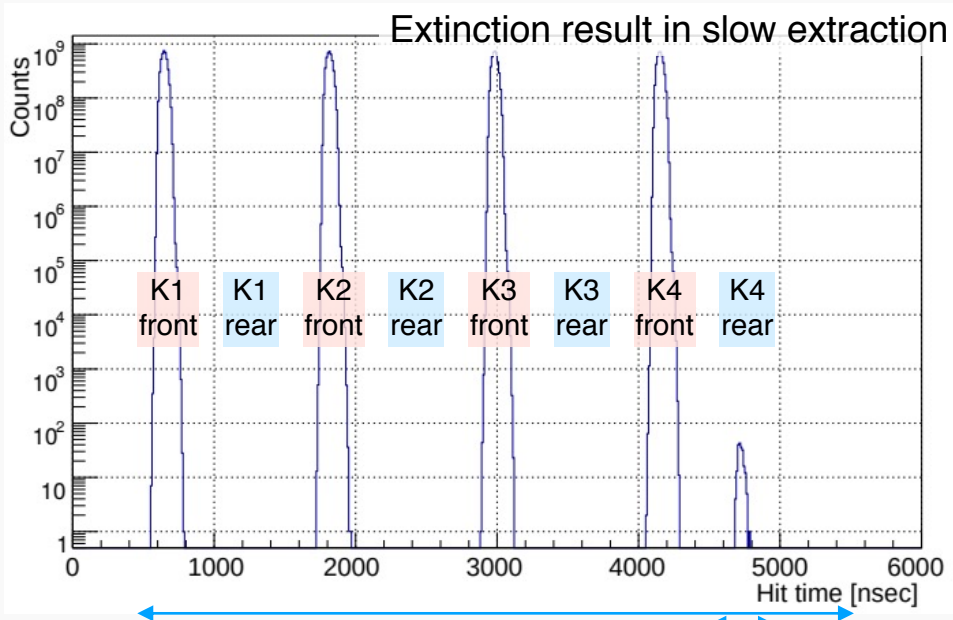
- The Injection kicker is shifted to kick front main bunch only.
- Not-kicked residual protons are eliminated by collimator.



The Previous 8 GeV Commissioning

- The COMET operation w/ forward SBK was tested, and the extinction was measured in 2018 [2]
- Front buckets were filled with protons of COMET Phase-I intensity (1.6×10^{12} ppp) and injection kicker was shifted 600 ns forward





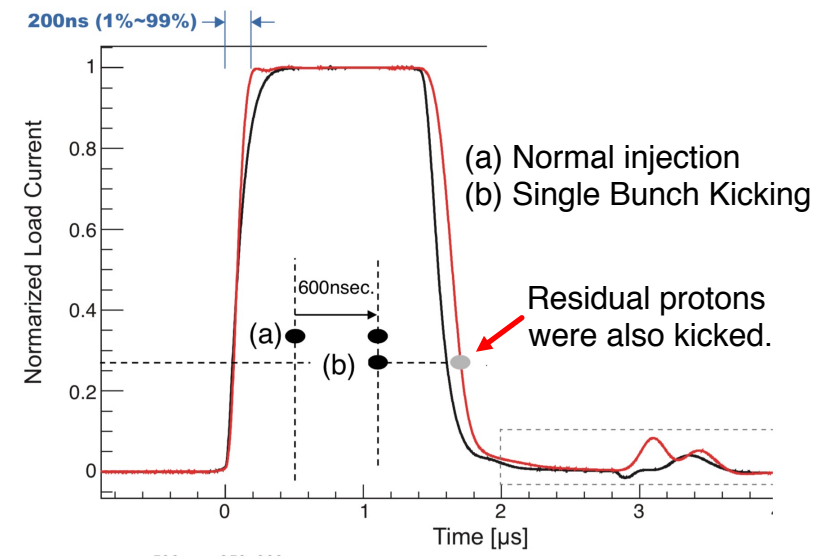
→ There were residuals after 4th bunch…

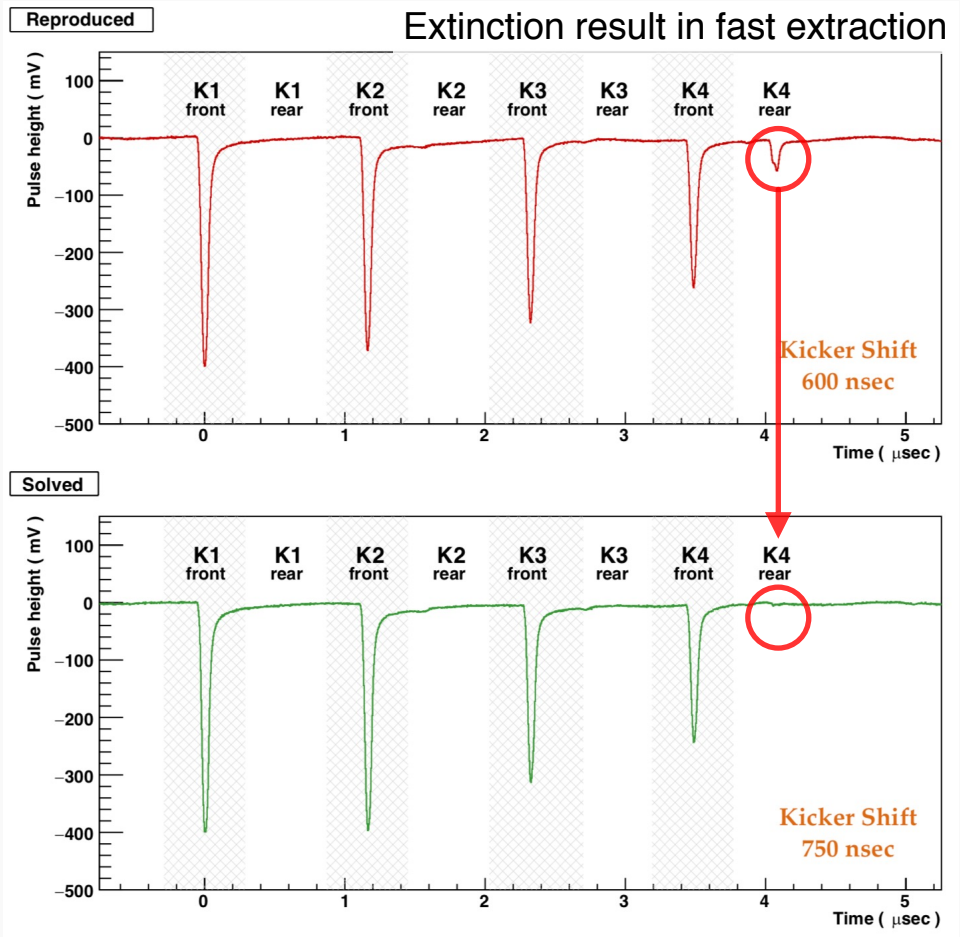
- Extinction (requirement $< 10^{-10}$)
  - $= 202/(1.7\ \times10^{10}) = 1.2\times10^{-8}$
  - $< \quad 1/(1.28\times10^{10}) = 7.8\times10^{-11}$ w/o 4th bunch (statistics 3/4)

[2] 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

The Previous 8 GeV Commissioning

- Injection kicker field has a small but a certain trailing component.
- Shift of 600 ns might not be large enough.





- It can be tested quickly just shift the kicker timing little more

→ It was confirmed that the residuals could be removed in fast extraction

❖ **Solution Candidates**

1. To shift kicker timing forward more
2. To shift kicker timing backward instead (backward SBK)

Test these solutions at J-PARC again!

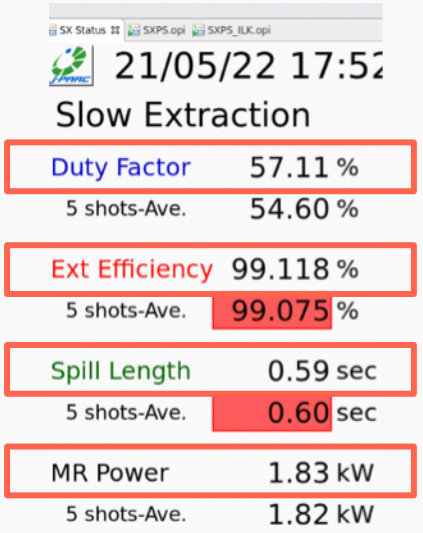
8 GeV Proton Beam Commissioning

- The 8 GeV proton beam commissioning aimed to optimize the accelerator operation and demonstrate low enough extinction.

The test was performed from 19th to 25th May 2021.
Both **accelerator study** (42h) and **extinction study** (100h) were completed successfully.

❖ Beam Status

Parameter	Previous Test (2018)	This Test (2021)
Beam Power	1.8 kW (5.2 s cycle)	
# of Bunches	4	
# of Protons	7.4×10^{12} ppp	
Extraction Efficiency	97%	99.1% (preliminary)
Spill Duty Factor	16%	55%
Spill Length	0.65 s	0.6 s

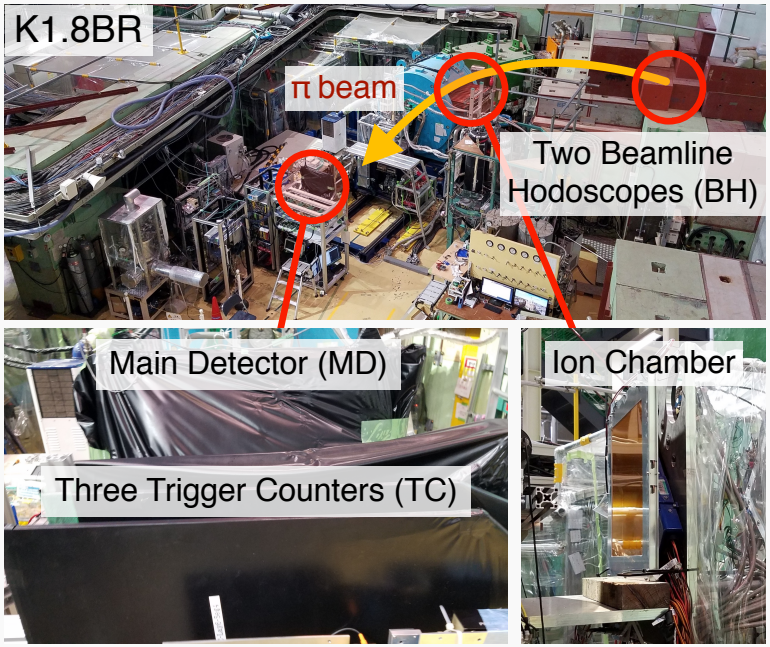


Extraction Information

When the beam cycle is set to 2.4 s,
the beam intensity is equivalent to Phase-I (3.2 kW).

Extinction Study @ K1.8BR Beamline

- The extinction was measured by counting secondary pions at the K1.8BR beamline of Hadron Experimental Facility of J-PARC.



Experimental Setup

- For counting, the coincidence was taken with all of six detectors.
- Three independent TDC systems were used in parallel to guarantee measurement reliability.
  - HUL measures TOT also with 1 ns time resolution.
- Both the main detector and all TDC systems were developed to deal with a high hit rate of ~ 10 MHz at the bunch period of ~ 0.5 s.
  - Detailed information was presented by K. Oishi in poster session on 8th Sep.

Detector	Efficiency
BH1&2	79.2%
MD	97.8%
TC1&2	92.8%
TC3	96.2%
Total	**69.2%**

TDC	FCT	KC705	HUL
Time resolution	7.5 ns	5 ns	1 ns
TDC length	24 bits	27 bits	19 bits
# of boards	8	2	8

Run Summary and Analysis Scenario

Run Summary

- All the planned operation modes were tested.
  - Extinction w/o SBK, extinction w/ forward SBK and backward SBK
  - The extinction was successfully measured.
- The main measurement of backward SBK was measured with $O(10^{10})$ statistics.

Data Analysis

- In this commissioning, secondary beam intensity was increased (×3 previous) to achieve good sensitivity quickly.
  - **Severe problem is an accidental overlap event.**
- TDC values of each detectors were measured.
- Software coincidence is performed in the analysis.

Following Topics

1. Event selection
2. The confirmation of reproduction from the previous test (2018)
   a. Extinction w/o SBK
   b. Extinction w/ forward SBK
3. The results of the new approach (backward SBK)
   a. Signal/background discrimination

Event Selection

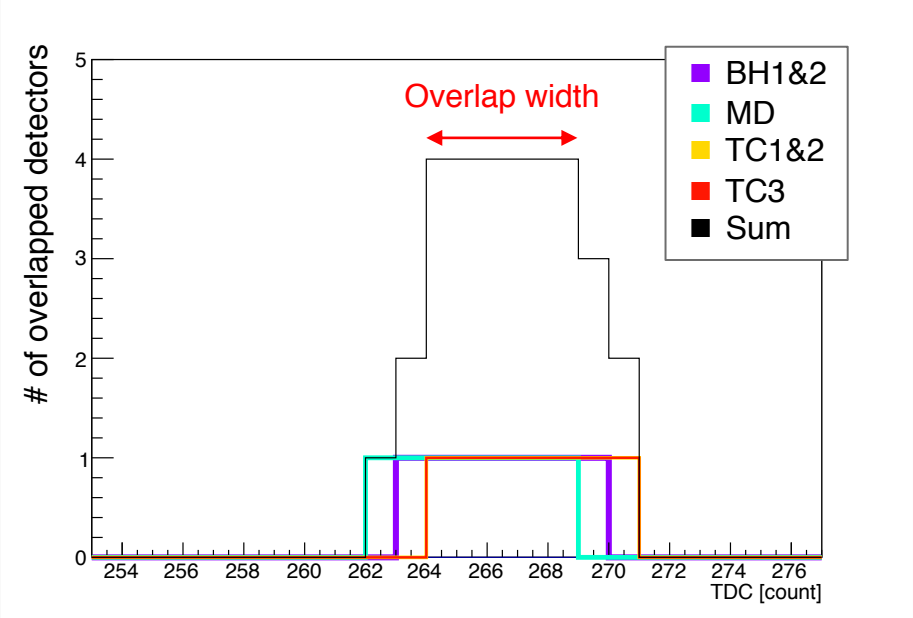
Coincidence Logic

1. A gate with time width of 50 ns is generated from the TDC value of each signal.
   - Signals include Beam passed event, cosmic-ray passed event, after pulse, etc..
2. When gates of all detectors were overlapped, it is judged as an event.
   - Time width of all detectors overlapping is defined as overlap width.

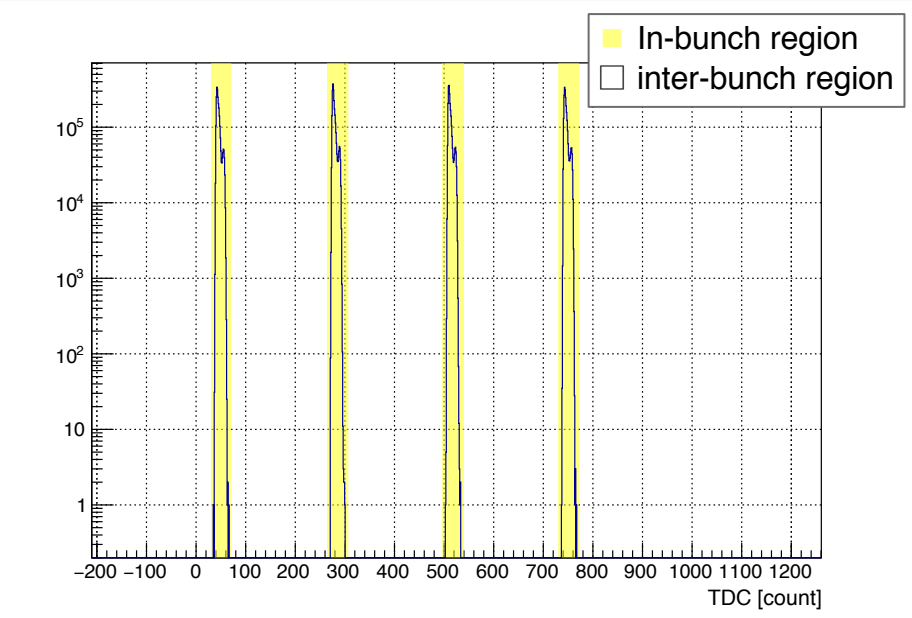
- Accidental overlap will be discriminated from signal by the overlap width.

Inter-Bunch Event Selection

- The events immediately around the main bunch were assigned in-bunch events.
- The rest of the events were assigned inter-bunch events.



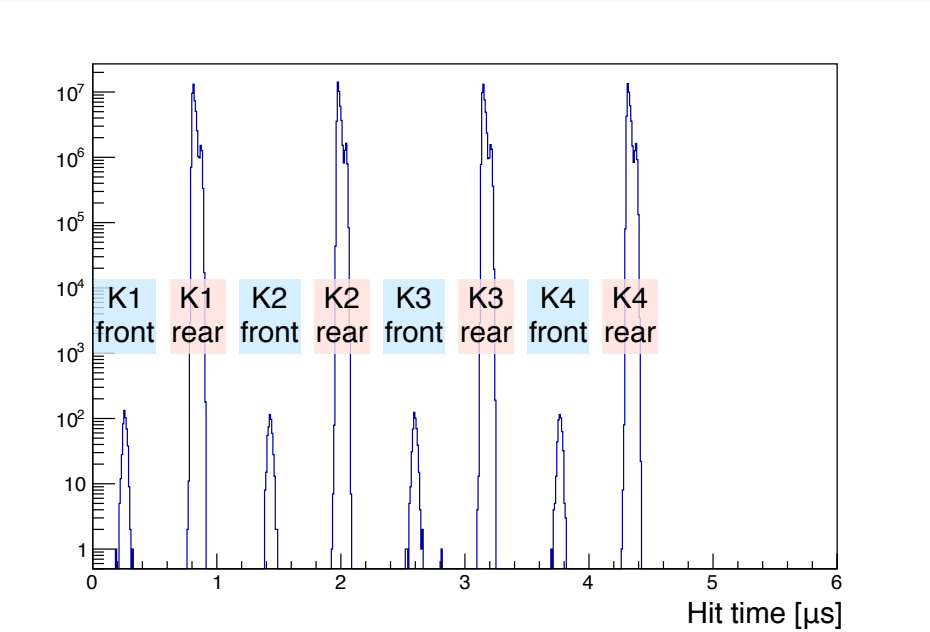
A sample of coincidence



Inter-bunch event selection (low intensity/statistics data)

Reproduction – Extinction w/o SBK

- Setup: **Rear main bunch** + **Normal injection** (no kicker shift)



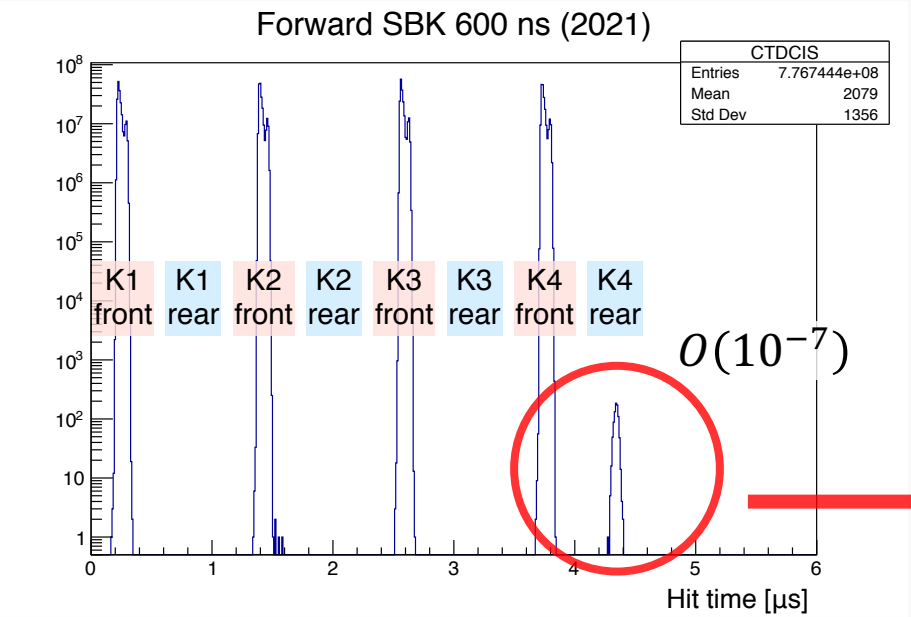
Extinction Calculation

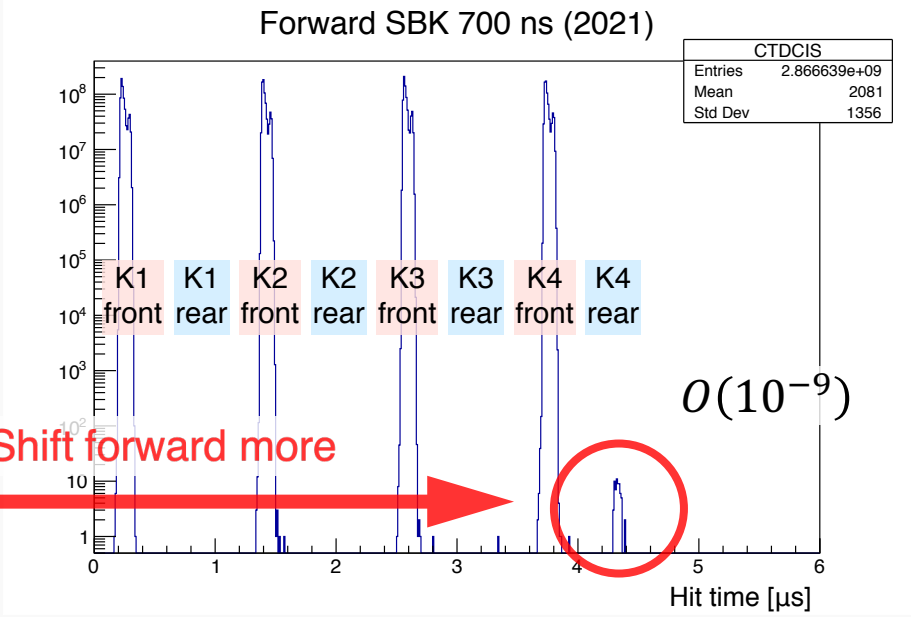
- **1915** inter-bunch events
- The total number of particles $\mathbf{1.46\times10^{9}}$ was corrected by the ion chamber from the number of hits obtained by the main detector.
  - The results of intensity scan by ion chamber were used to correct efficiency and saturation of the main detector.

→ Extinction of $\boldsymbol{O(10^{-6})}$ is consistent with previous test (2018).

Reproduction – SBK 600 ns and 700 ns

- Setup: **Front main bunch** + **Forward SBK**
- Residual particles were observed at K4 rear as well as previous test



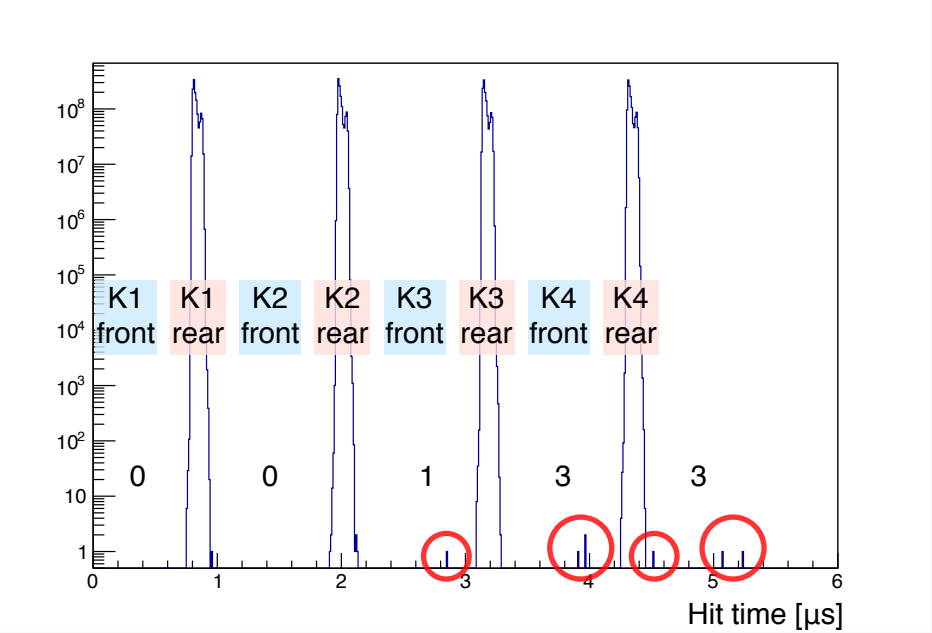


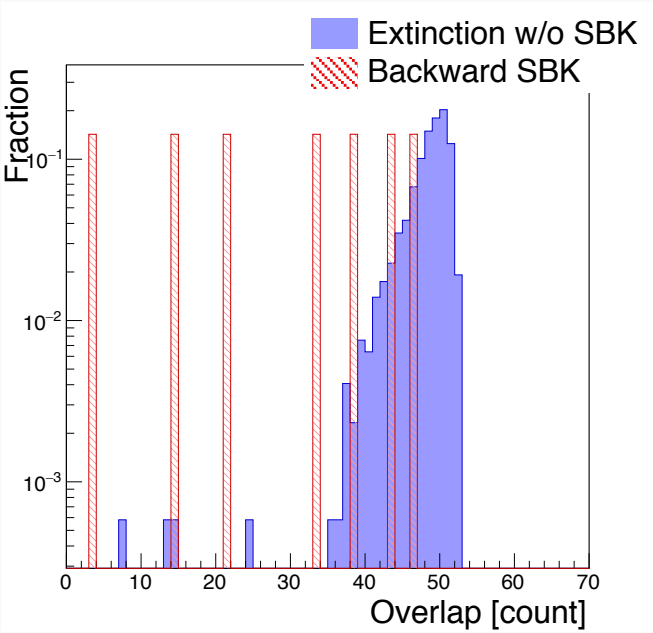
Shift forward more

- SBK 600 ns has the extinction of $O(10^{-7})$.
- The extinction of $O(10^{-9})$ in SBK 700 ns was improved from SBK 600 ns.
- Perfect extinction was not achieved in forward SBK.

New Setup – Backward SBK 600 ns

- Setup: **Rear main bunch** + **Backward SBK** w/ 600 ns injection kicker shift
- It was expected to be no inter-bunch event.



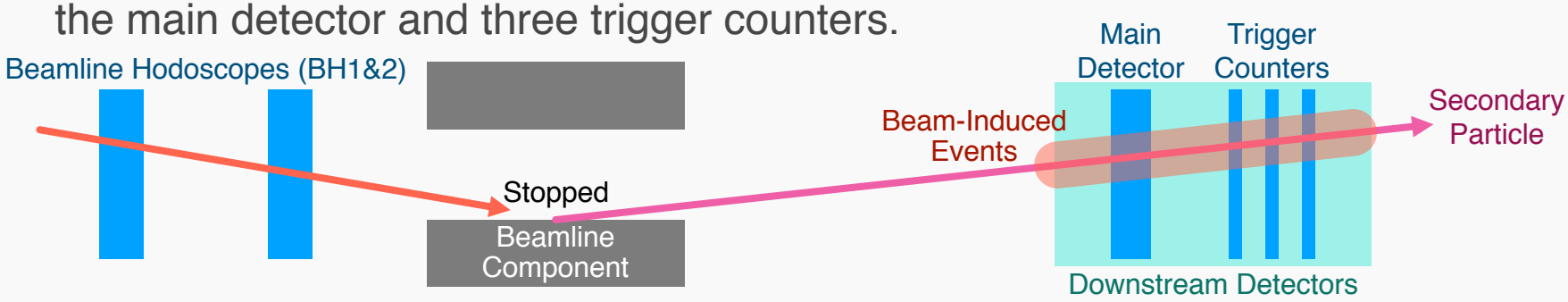


- There were 7 inter-bunch events.
  - These events are confirmed in all TDC systems.
- Most of them are **accidental like** events in comparing overlap width with data of extinction w/o SBK.

→ They were evaluated using a signal sample and generated background sample.

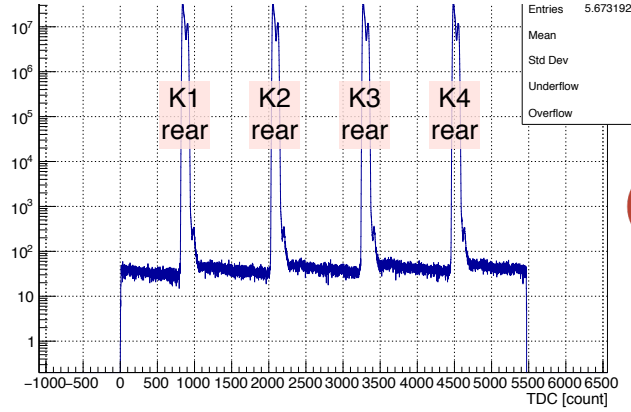
Accidental Overlap (Background) Sample

- Background candidate: Beam-induced delayed events
  - They were identified with the coincidence of downstream detectors: the main detector and three trigger counters.

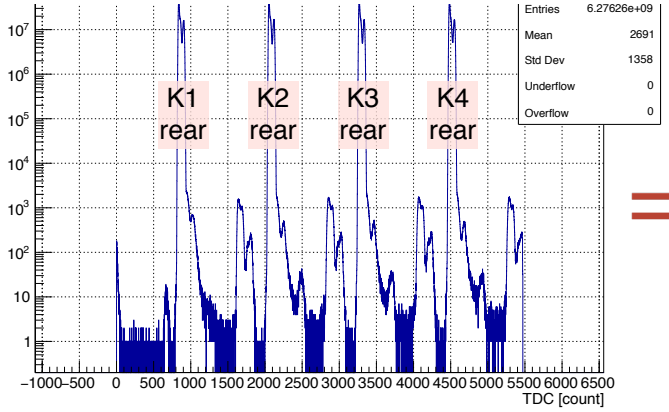


- The most probable background events are estimated accidental overlaps of beam-induced delayed events and two beamline hodoscopes.
- The background sample was generated from data-driven beam-induced delayed event data and randomly generated beamline hodoscopes data.

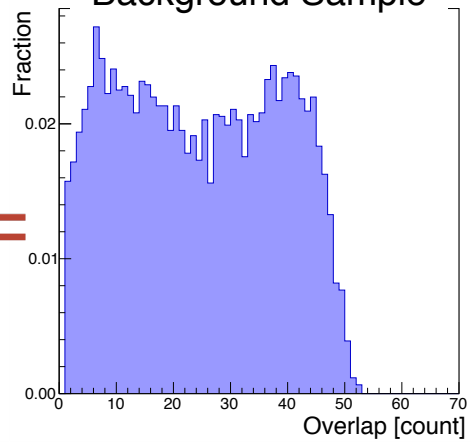
Coincidence of Downstream Detectors



BH1&2



Background Sample

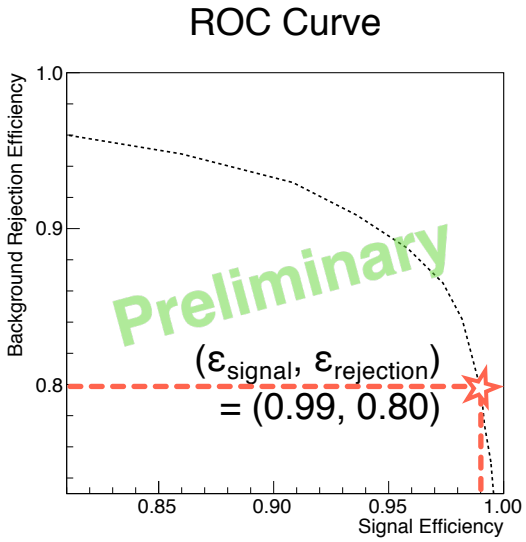


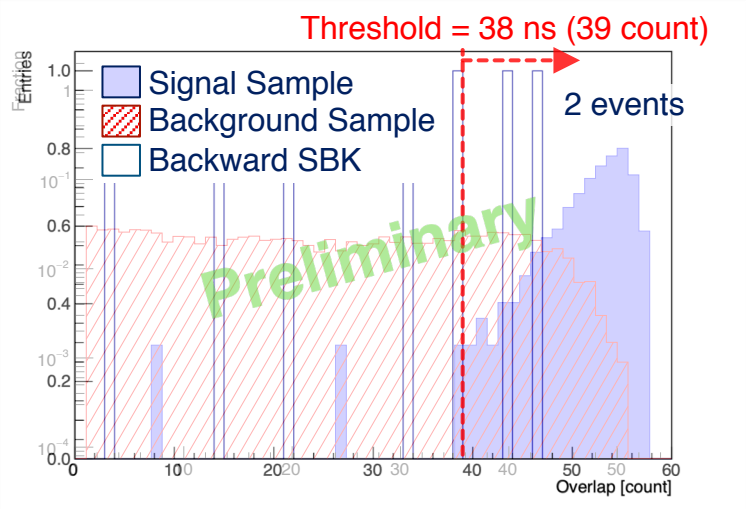
Overlap Cut Results

- Event discrimination using with overlap width was evaluated.
  - Signal Sample
    - Inter-bunch events in data of extinction w/o SBK
  - Background Sample
    - Generated background sample
- The threshold for overlap width of 38 ns was selected at the point where ε_{signal} is 99%.
- Two inter-bunch events remained

→ **The extinction is 9.3×10^{-11}**

  - Backward SBK w/ 600 ns shift achieved the extinction requirement of the COMET.





Parameters	Case 1	Case 2
# of inter-bunch particles N_{out}	2	3
Detection efficiency ε_{det}	0.692	
Cut efficiency ε_{cut}	0.990	0.992
# of residual particles $N_{res} = N_{out}/\varepsilon_{det}\varepsilon_{cut}$	2.92	4.37
# of in-bunch particles N_{tot}	3.14×10^{10}	
Extinction $R_{Extinction} = N_{res}/N_{tot}$	9.3×10^{-11}	1.4×10^{-10}

Preliminary

Summary

- The COMET experiment plans to search for μ-e conversion at J-PARC.
- The experiment requires a dedicated 8 GeV pulsed proton beam operation.
- Proton extinction of inter-bunch residual protons is critical to eliminate beam-related backgroinds.
- The extinction is required to be $< 10^{-10}$.

- The 8 GeV proton beam commissioning for COMET was completed successfully.
- The extinction measurement was performed at the K1.8BR beamline of the hadron experimental facility of J-PARC with $O(10^{10})$ statistics.

- The extinction requirement was achieved with a 600 ns backward SBK (preliminary).
- Phase-I requirement is satisfied.

- Both background estimation and analysis are ongoing.
- Online extinction monitor is under development.