Status of the Facility/Accelerator/Beam-line for Muon Programs at J-PARC

Hajime NISHIGUCHI, *KEK* · *J-PARC*

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J-PARC
&
Its muon facilities

J-PARC


Hadron Experiment Facility
Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)
Accelerator-driven
Transmutation exp facility
Neutrino Experiment Facility
(T2K, towards SK)
Linac
(330m, 400MeV)
3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)
30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

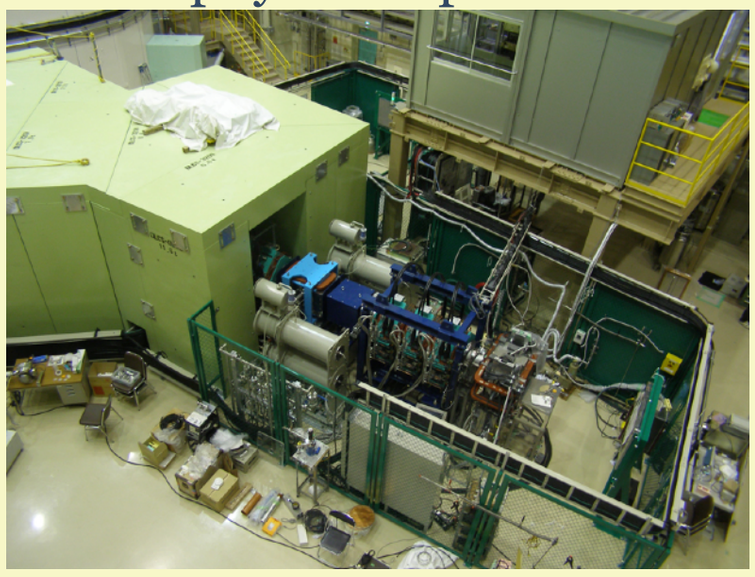
Muon Facilities for High Energy Physics

Hadron Experiment Facility

Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)

— MLF —

Muon beam lines are operated for material-science experiments, but a new beam line is under construction for several physics experiments.



Linac
(330m, 400MeV)

3GeV Synchrotr
(350m ring, 25Hz,

— HEF —

No dedicated beam line for muon experiments is operated so far.
New muon facility is constructed and new beam line is under preparation.

Muon Programs at J-PARC

— MLF —

- **g-2/EDM**
  muon magnetic moment anomaly and electric-dipole moment
- **MuSEUM**
  Hyperfine splitting on Muonium
- **DeeMe**
  Alternative μ-e conv Search

Needs New Secondary Beam-line

— HEF —

- **COMET**
  Search for μ-e Conversion

Needs New Primary & Secondary Beam-line, both

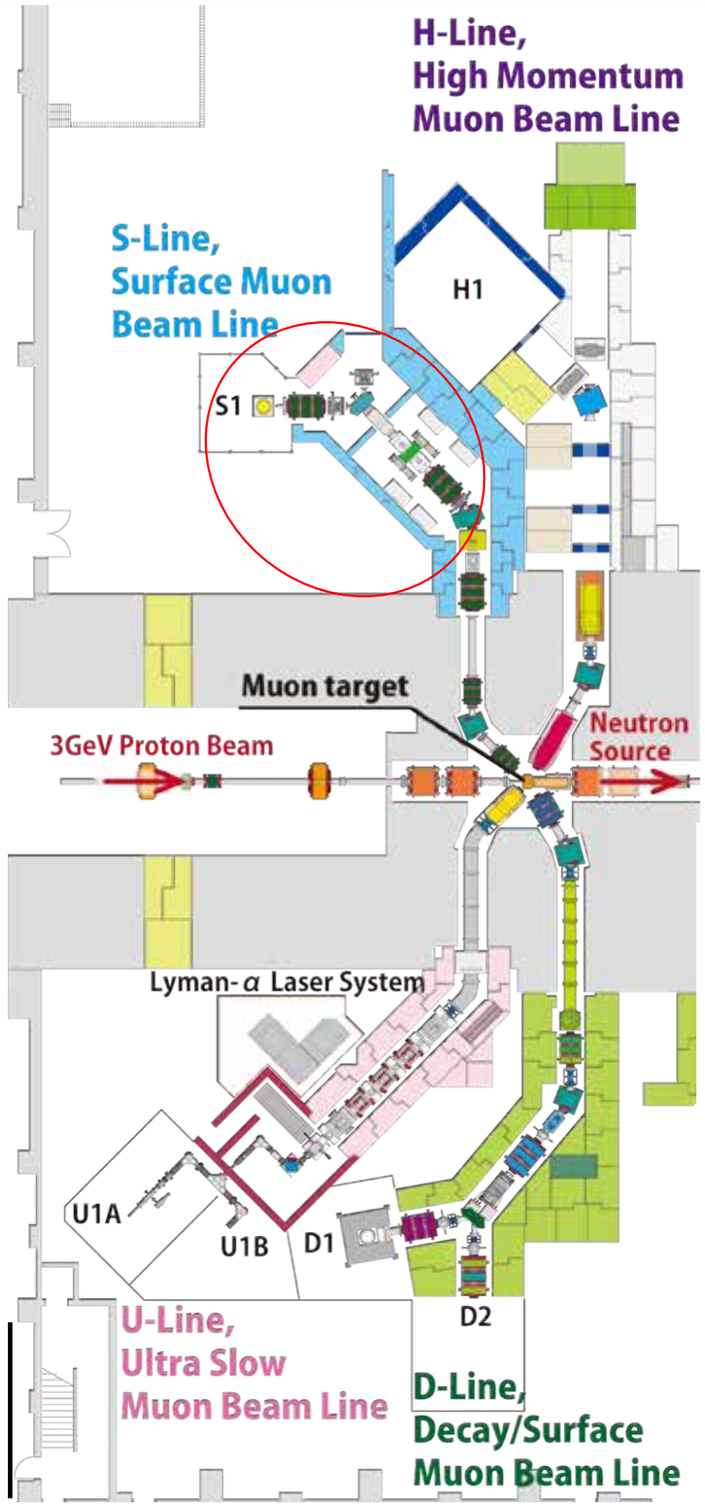
Current Status of Facility/Beam-line Construction

Muon beam @ Material Life-science Facility (MLF)

- **MUSE (MUon Science Establishment)**

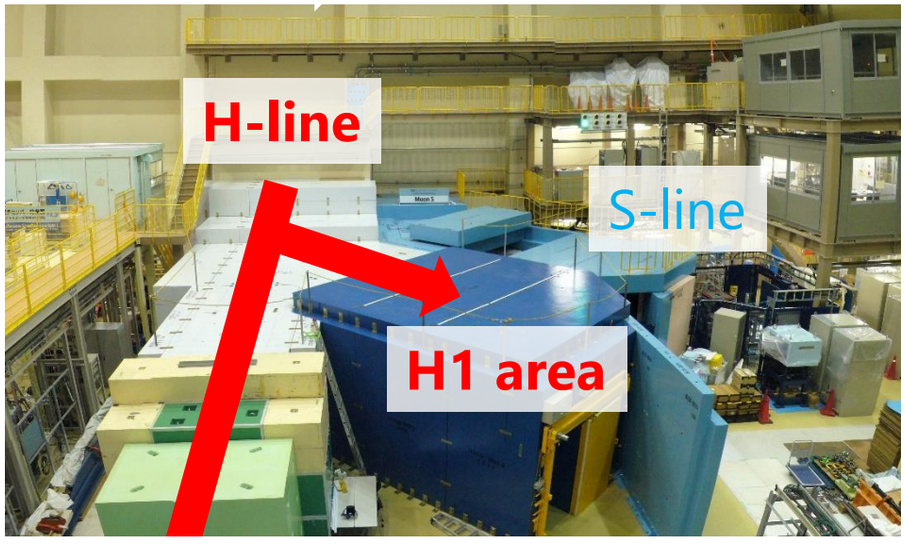
- Four Secondary Beam-Lines
  1) D-Line : Decay Surface Muon Beam Line
  2) U-Line : Ultra Slow Muon Beam Line
  3) S-Line : Surface Muon Beam Line
  4) **H-Line : High Momentum Muon Beam Line**

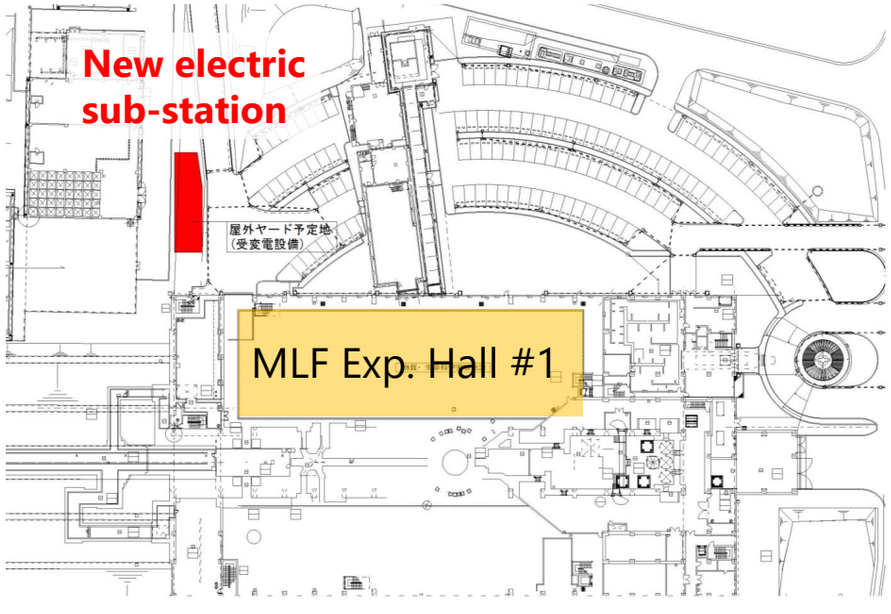
- D, U and S are in operation
- H-Line is under construction and dedicated for High Energy Physics Experiment
  - Decay μ/e (<120MeV/c) and surface μ (30MeV/c)
  - **H1 area for DeeMe & MuSEUM**
  - **H2 area for g-2/EDM** and transmission muon microscopy
    - **H2 needs extra-building** to re-accelerate ultra slow muons up to 300 MeV/c



H-Line construction

- Beam line construction is ongoing in parallel with facility renovations
  - **Beam line** : Shield blocks installed, Preparation for magnet installation
  - **Facility** : New power sub-station (bedding done, wall renovation is ongoing)





2017 summer :
Renovation of the MLF wall for the electric power transmission line
* The renovation work must be done during summer shutdown due to radiation safety

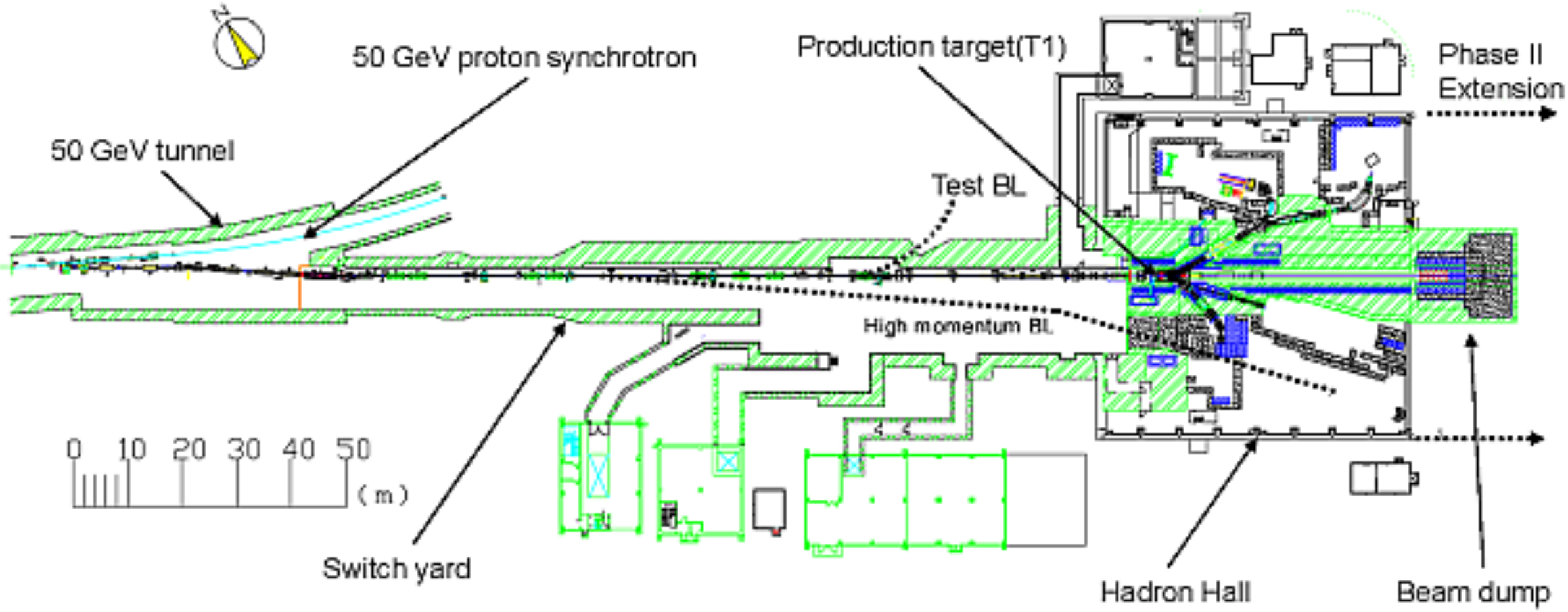
Prospects for muon programs at MLF

- There are 3 muon experiments at MLF MUSE

- H-line is dedicated for these experiments
  1) H1 area (for DeeMe / MuSEUM) will be constructed first
     - Shield blocks were ready
  2) No electricity, No cooling water, No magnet for Hall#1
     - New Power sub-station is under construction
     - Cooling, Magnet construction will follow soon
  3) H2 area (for g-2/EDM) will be constructed later
     - Need new extra-building

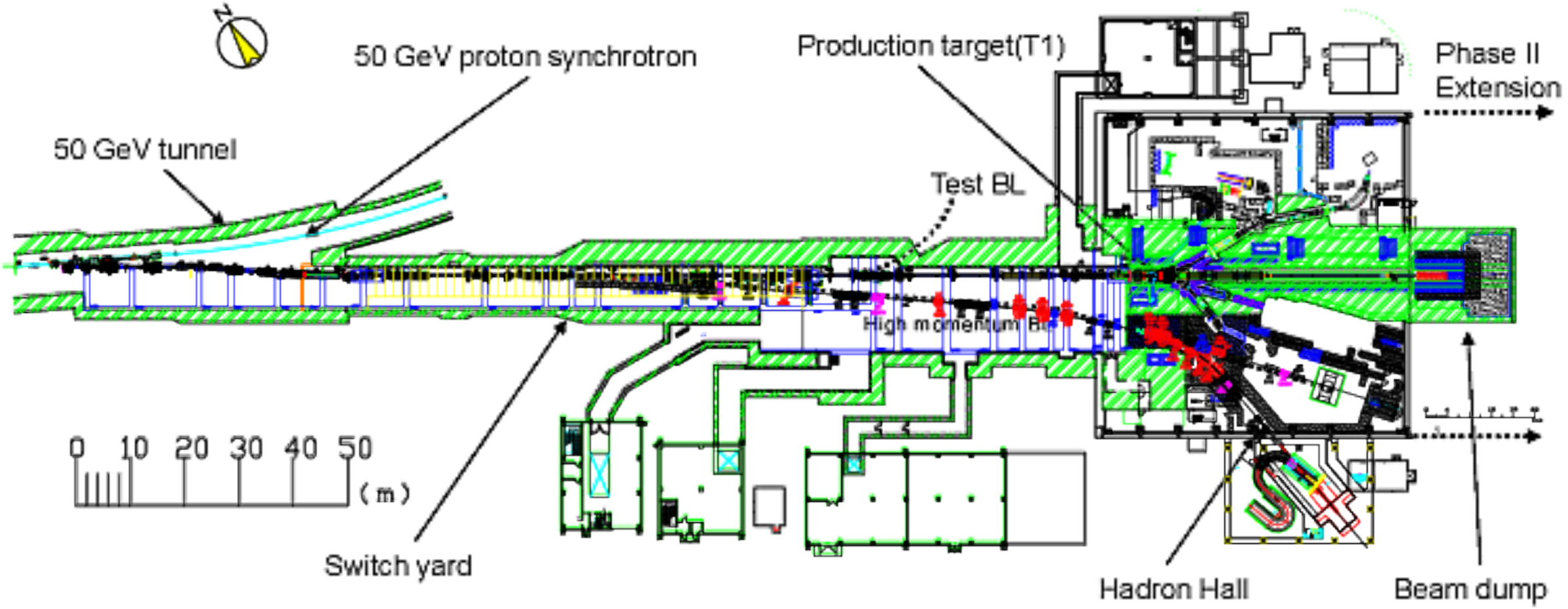
- DeeMe is ready for physics data acquisition and MuSEUM was partially started, they will be completed as soon as H1 will be ready.

Hadron Experimental Facility (HEF)



- HFE accepts the Slow-Extracted proton beam to provide high intensity secondary beams, such as kaon and pion, for Nuclear and High Energy Physics Experiments.
- In order to add two more secondary beam lines, high momentum beam and **high intensity muon beam**, **new branch of primary proton beam line, B-Line, is under construction in parallel to the facility construction for new Muon Program** at HFE, South Building, so-called "**COMET Hall**".

Hadron Experimental Facility (HEF)



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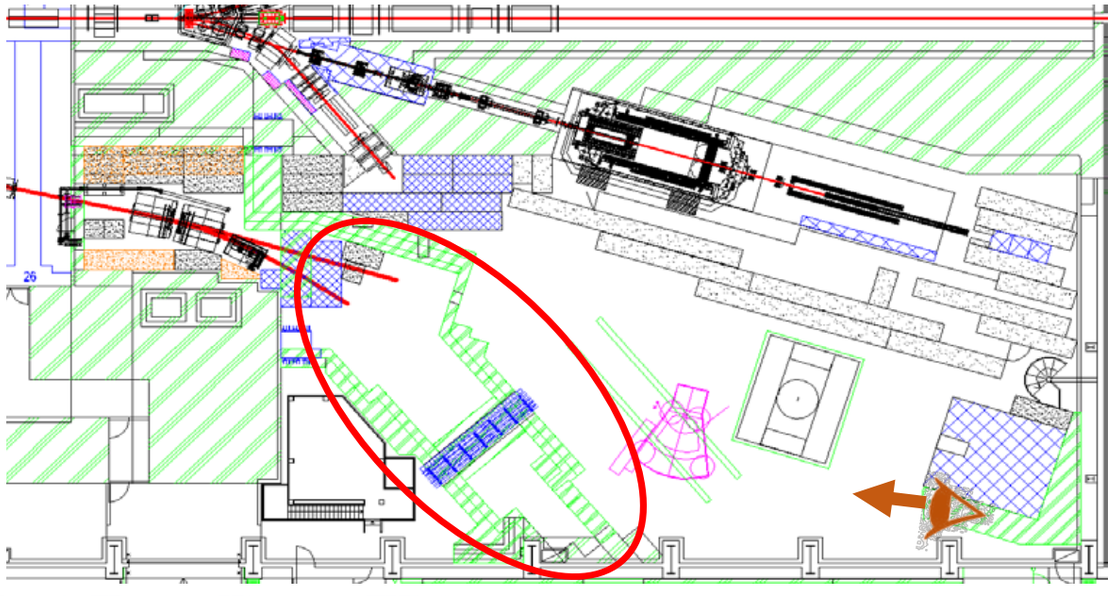
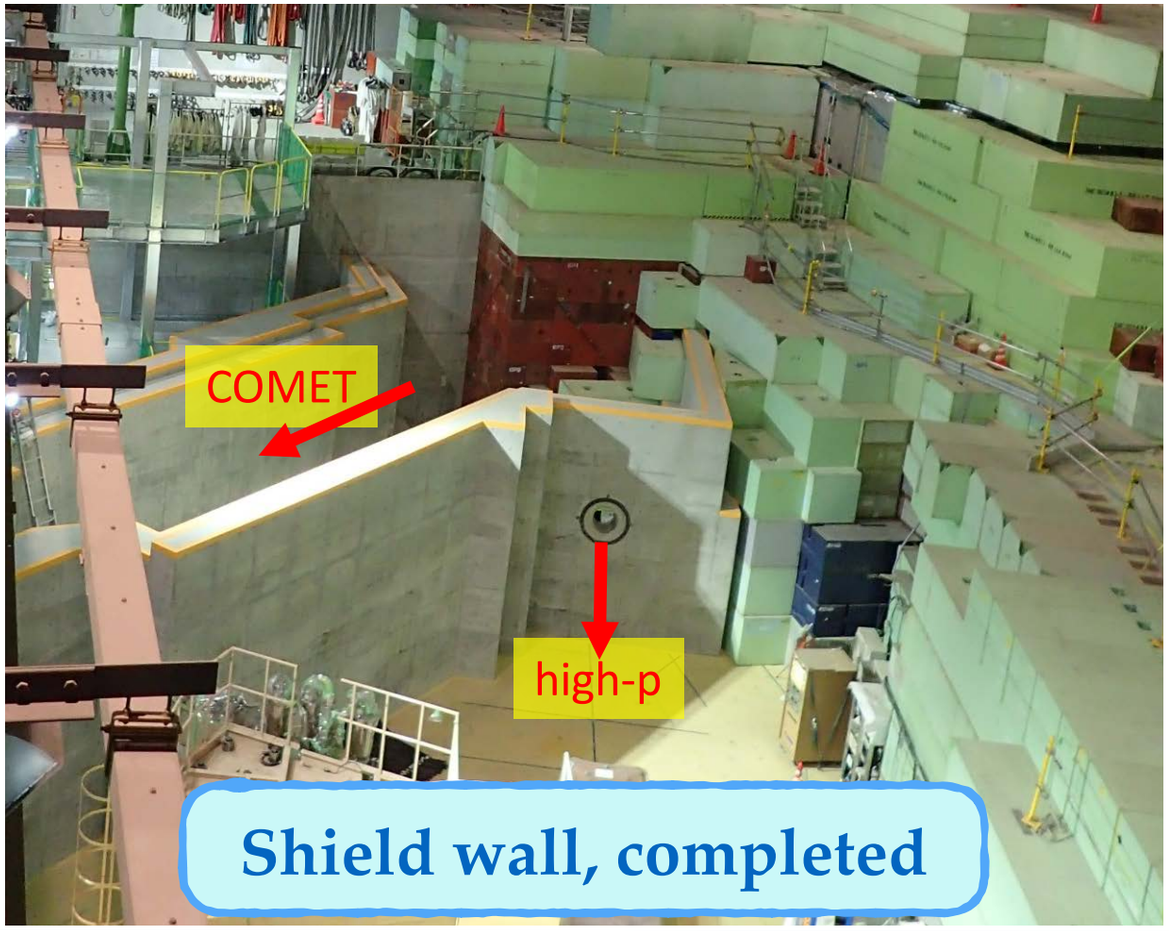
New primary proton beam line

- Construction for the new primary beam line, “B-Line”, is ongoing.
- Construction of “Shield Wall” and “Power station” is already completed.
- Magnet & Power installation starts soon.
- Expected to be completed JFY2019

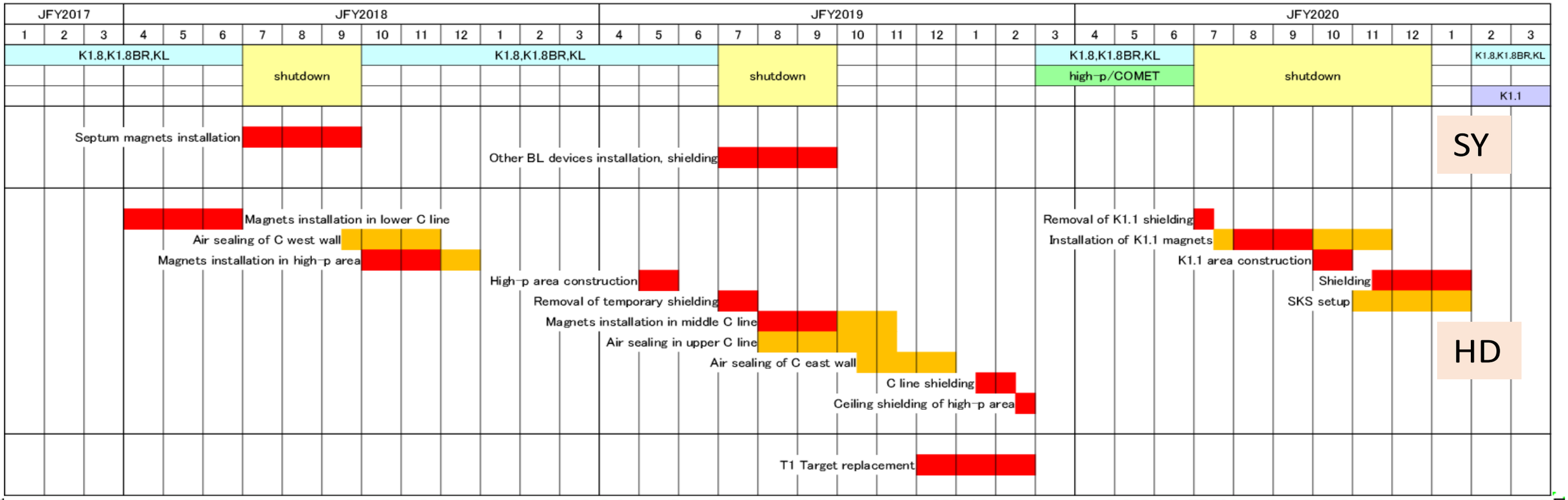


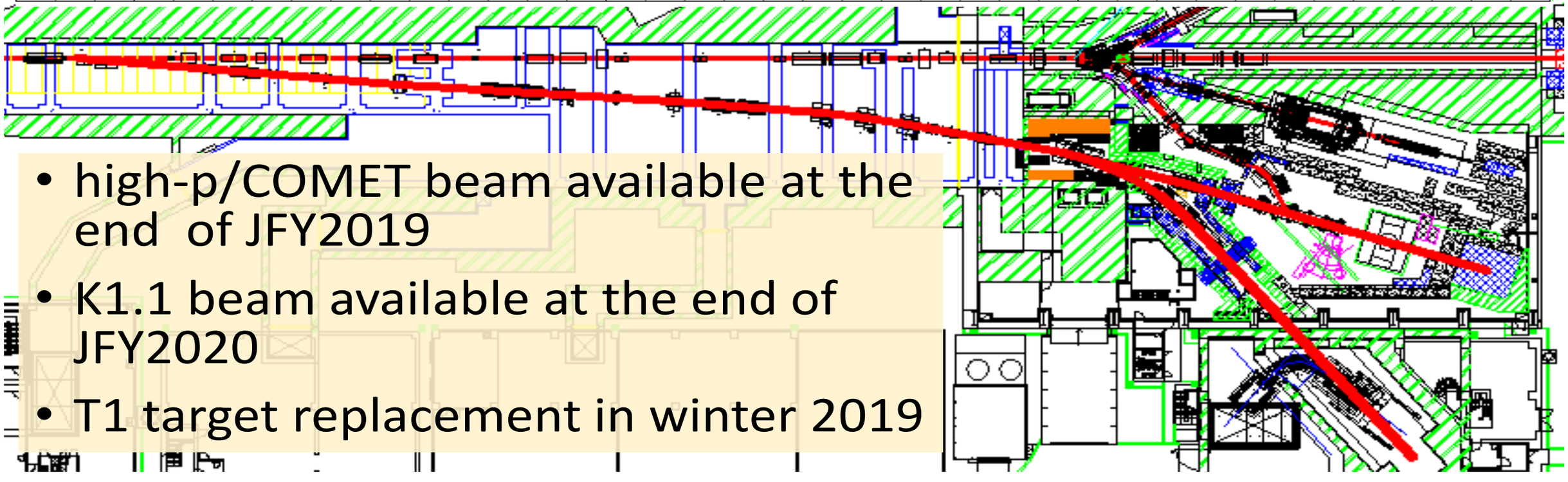


Shield wall, completed

Power station, Constructed

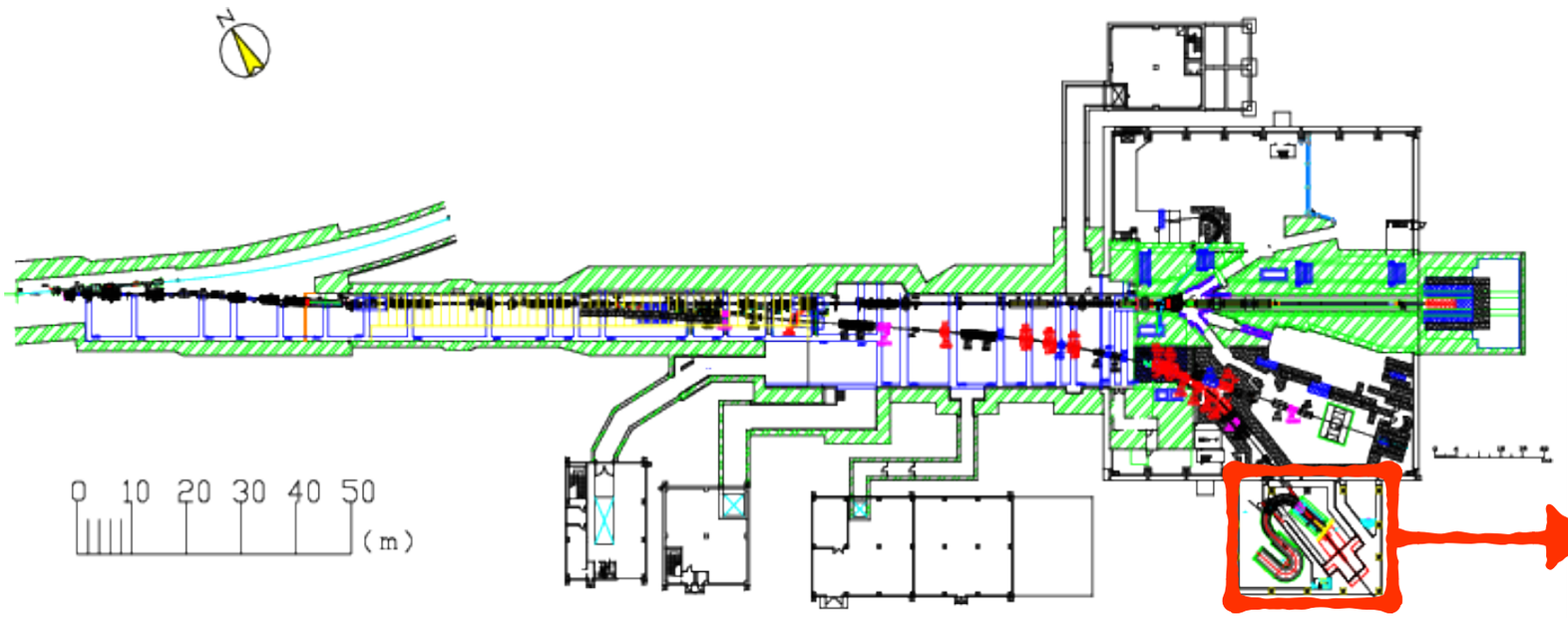
“B-Line” Construction Schedule

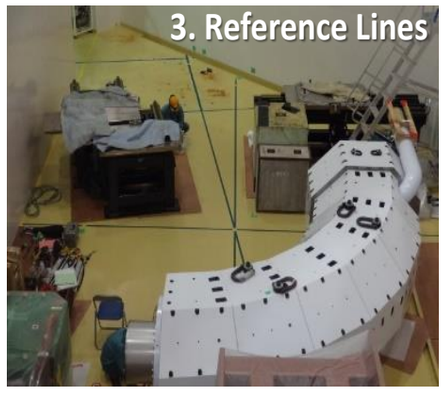


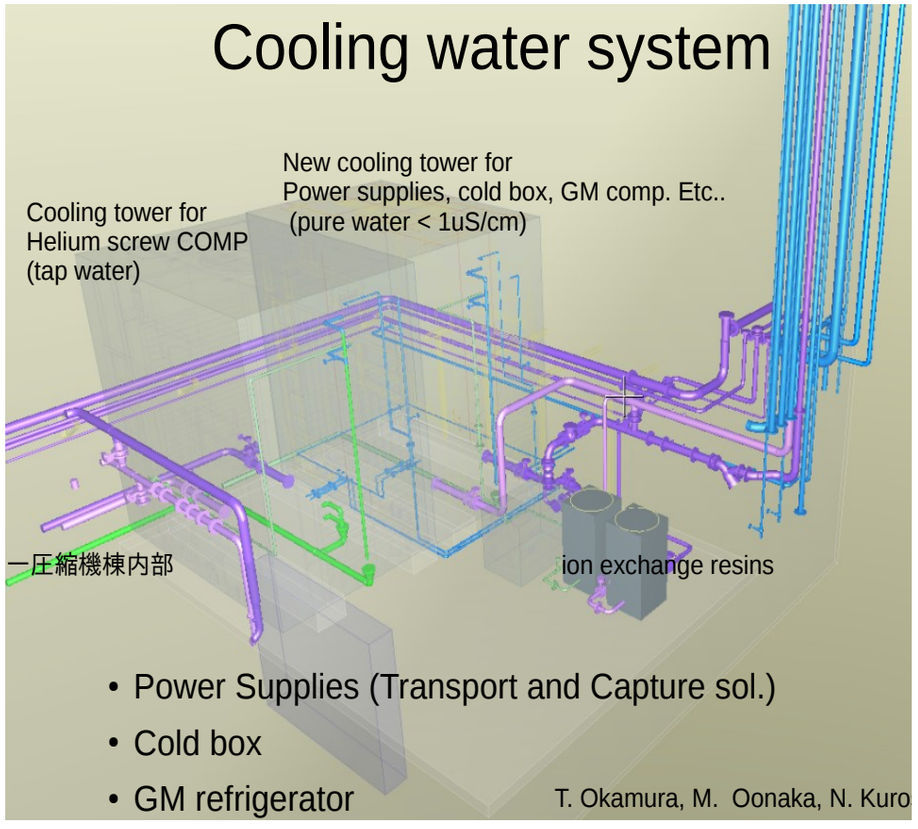


- high-p/COMET beam available at the end of JFY2019
- K1.1 beam available at the end of JFY2020
- T1 target replacement in winter 2019

COMET Facility







- Building completed
- Transport solenoid was installed
- Cryogenic system is under construction
- Remaining solenoids, capture, bridge and detector, will be constructed and ready in 2019-2020.

Highlights !!

Highlights

— MLF —

- **g-2/EDM**
  muon magnetic moment anomaly and electric-dipole moment
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World First Muon Acceleration !!

— HEF —

- **COMET**
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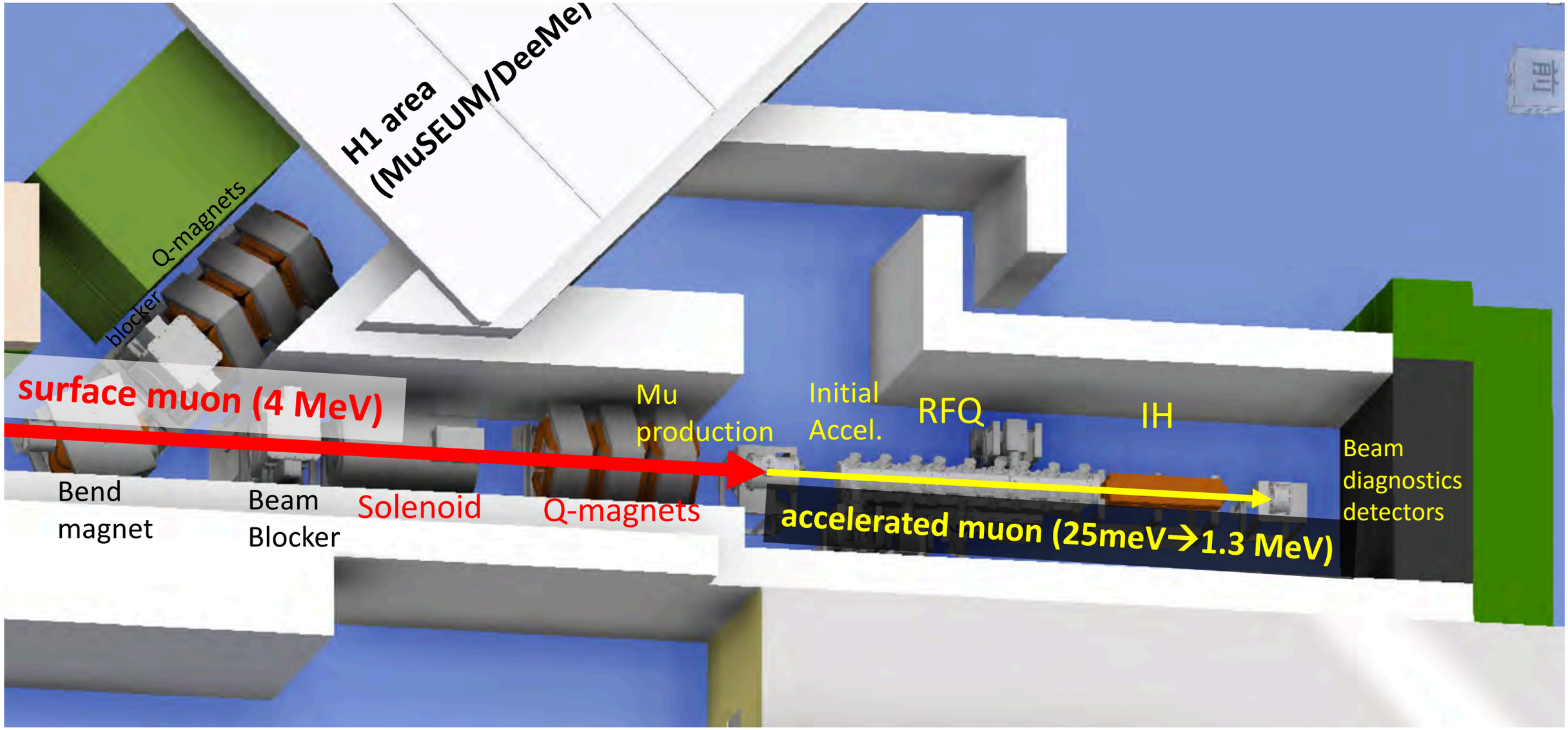
8GeV Operation & Extinction Measurement

Muon acceleration for g-2/EDM

- New g-2/EDM experiment needs to produce "ultra-cold" muon beam
- Surface μ → Mu → Ionize and μ-beam → **Re-acceleration** → Injection to Storage
- "Initial Acceleration by RFQ" + "Final Acceleration by IH-DTL"
- **Muon Acceleration by RFQ was demonstrated World First & Successfully !!**



Acceleration test (Oct. 24th – 30th, 2017)

M.Otani (J-PARC)

μ^+ (~3MeV)

Mu- production

5.6 keV

RFQ

89 keV

Diagnostic beamline

MCP

R. Kitamura
(Tokyo)

M. Otani
(KEK)

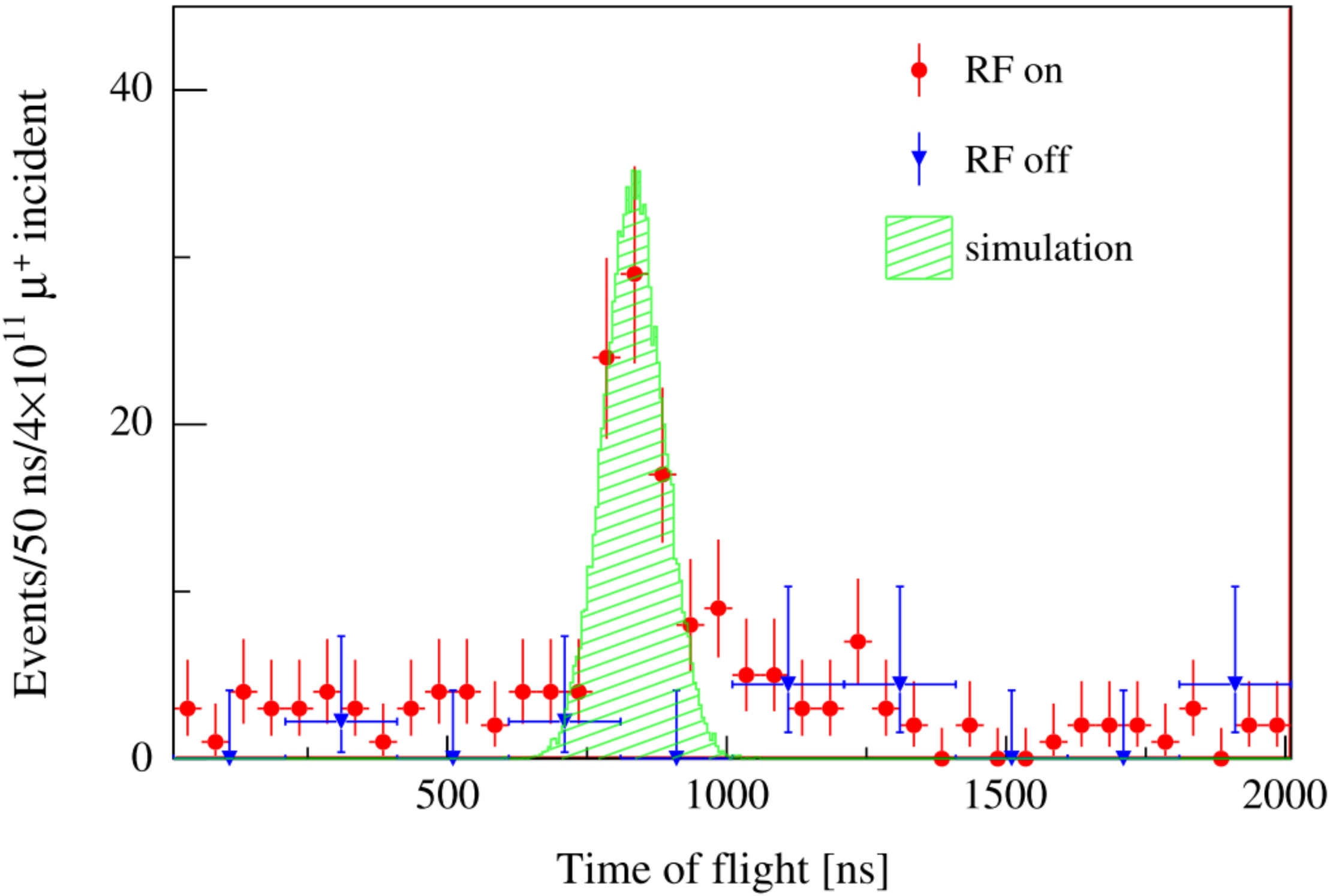
Y. Kondo
(JAEA)

Y. Sue
(Nagoya)

Y. Nakazawa
(Ibaraki)

Result

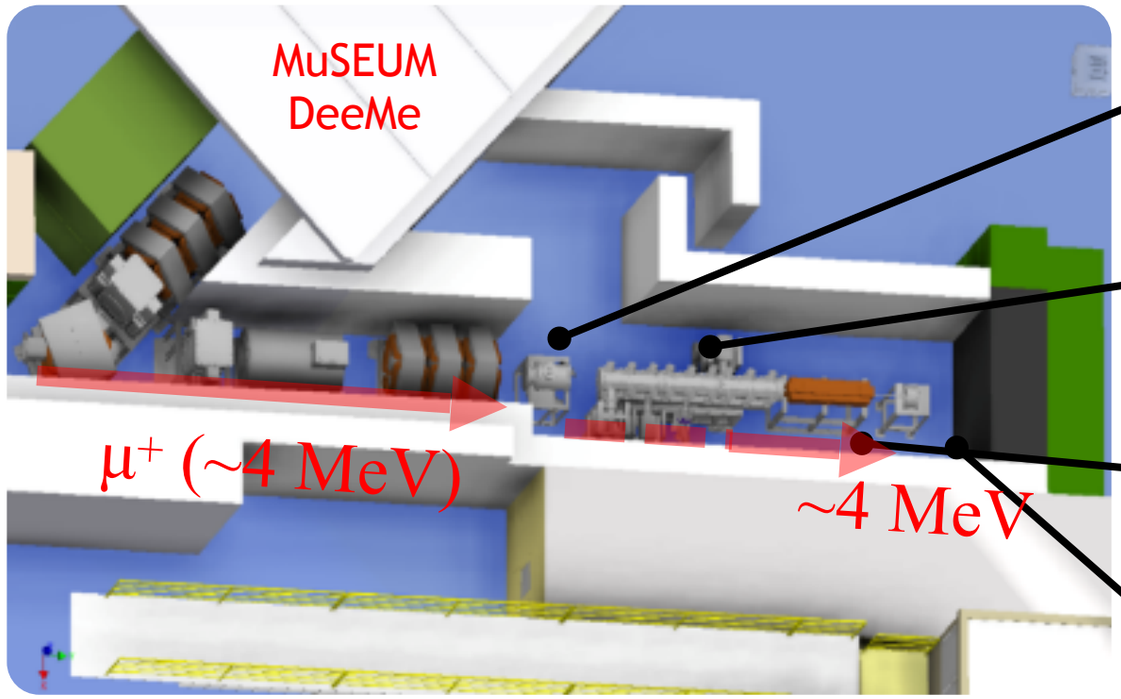
M.Otani (J-PARC)



Prospect

M.Otani (J-PARC)

- Acceleration with RFQ and IH @ g-2 beamline

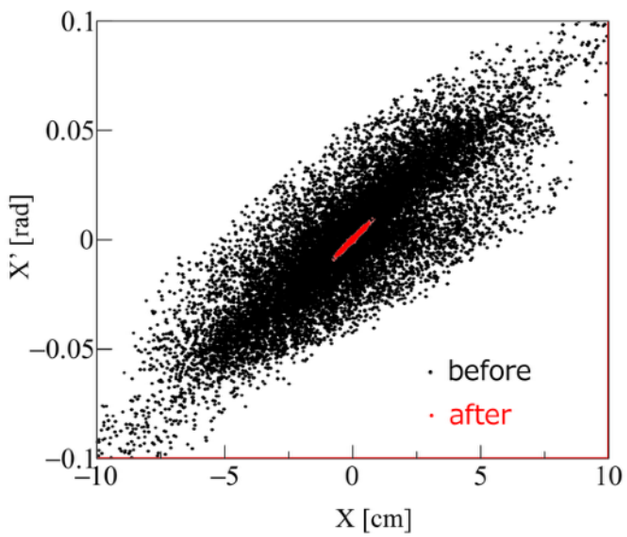


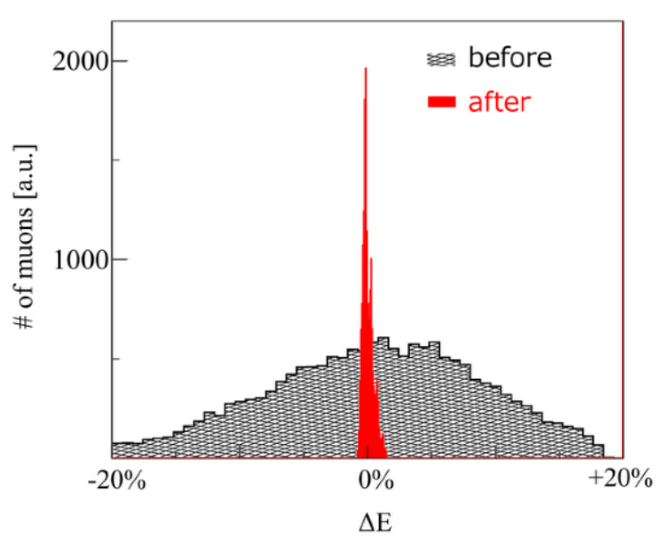
Mu⁻ generation — OK

RFQ — OK

IH-DTL

Detector — OK





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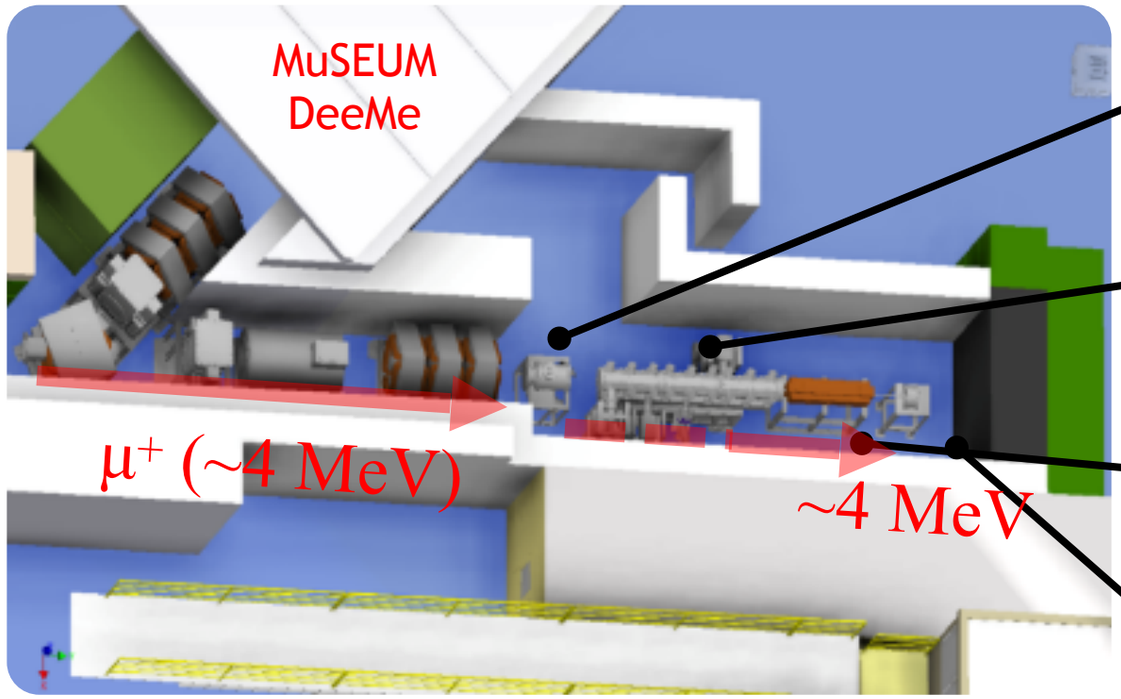
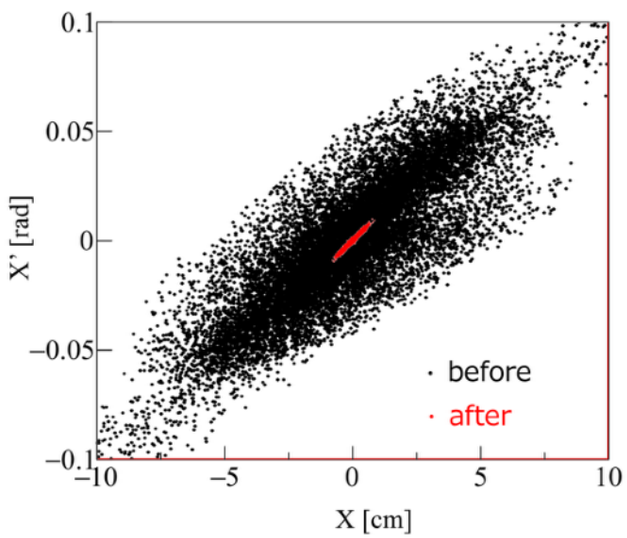
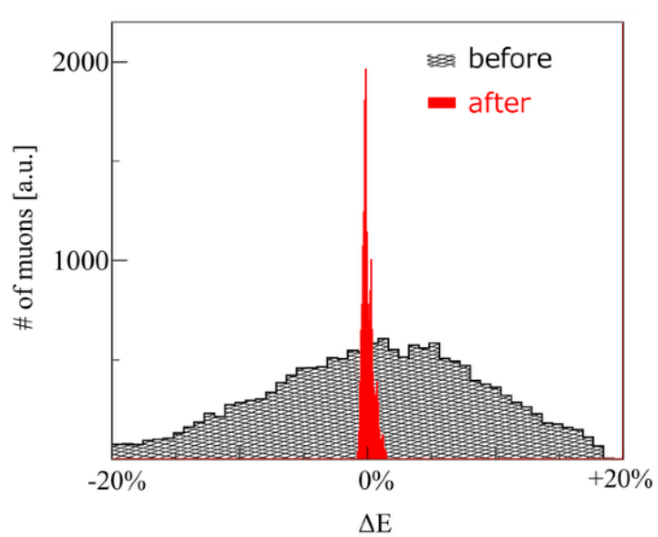
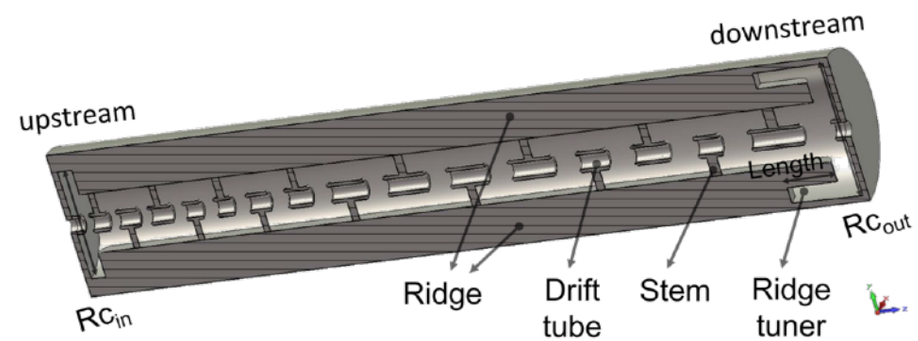


Mu⁻ generation	OK
RFQ	OK
IH-DTL	design
Detector	OK





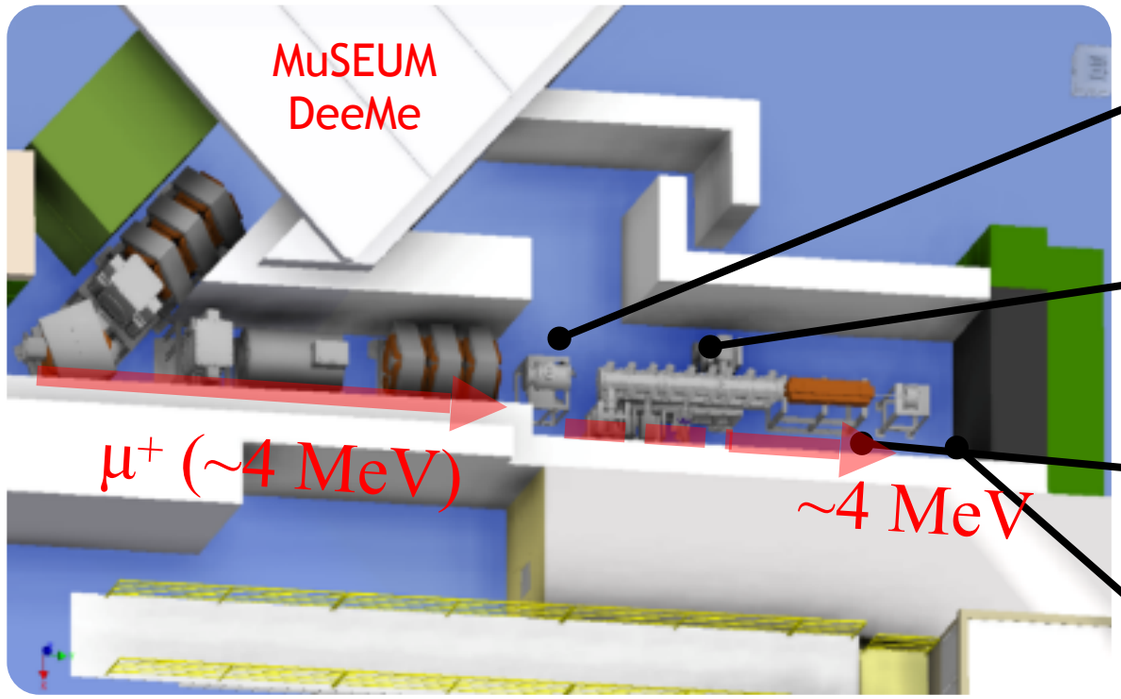


M. Otani et al., Phys. Rev. AB, 19, 040101, 2016.

Prospect

M.Otani (J-PARC)

- Acceleration with RFQ and IH @ g-2 beamline

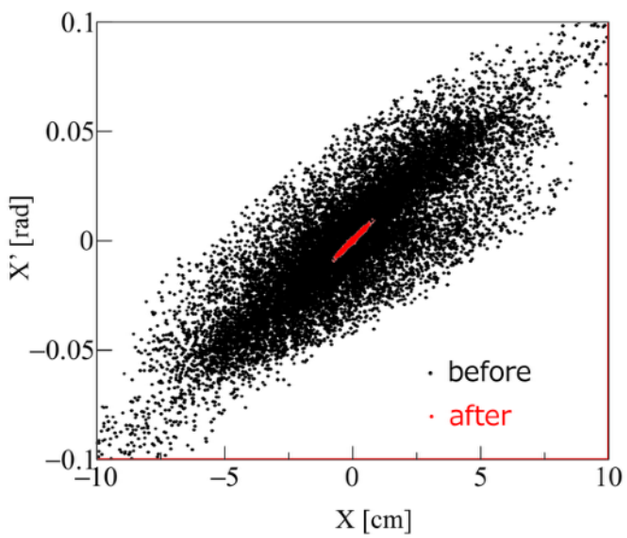


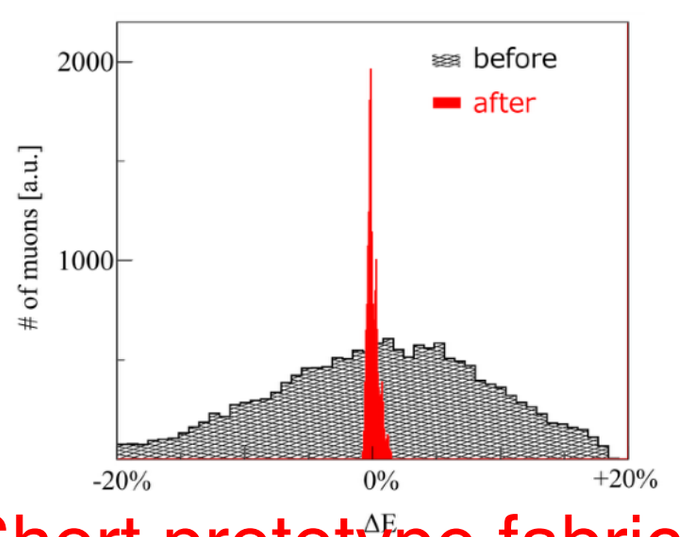
Mu⁻ generation — OK

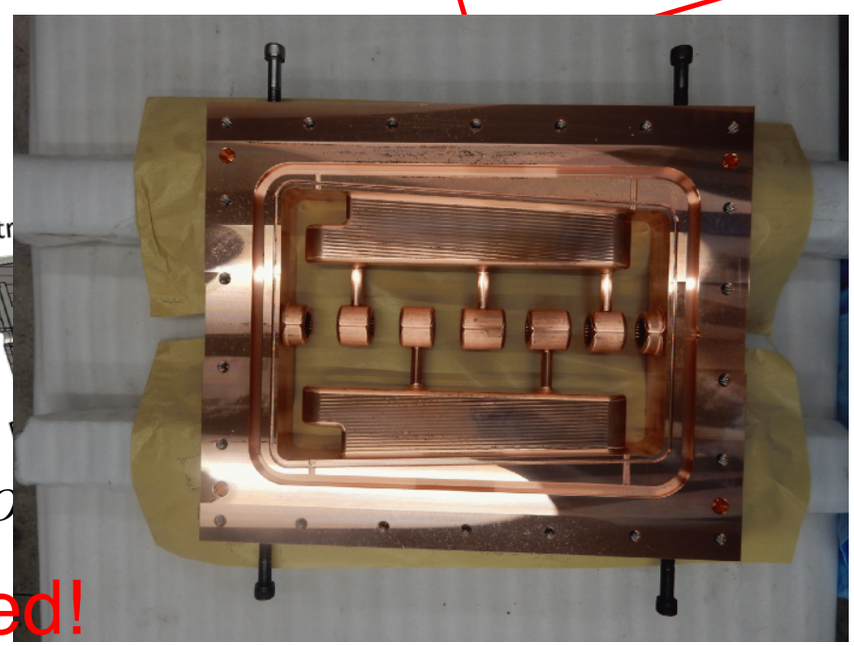
RFQ — OK

IH-DTL — design

Detector — OK







Short prototype fabricated!

First Muon Acceleration using RFQ !!!

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 050101 (2018)

First muon acceleration using a radio-frequency accelerator

S. Bae,[1,2] H. Choi,[1,2] S. Choi,[1,2] Y. Fukao,[3] K. Futatsukawa,[3] K. Hasegawa,[4] T. Iijima,[5] H. Iinuma,[6] K. Ishida,[7] N. Kawamura,[3] B. Kim,[1,2] R. Kitamura,[8] H. S. Ko,[1,2] Y. Kondo,[4,*] S. Li,[8] T. Mibe,[3] Y. Miyake,[3] T. Morishita,[4] Y. Nakazawa,[6] M. Otani,[3,†] G. P. Razuvaev,[9,10,11] N. Saito,[12] K. Shimomura,[3] Y. Sue,[5] E. Won,[13] and T. Yamazaki[3]

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[2]*Institute for Nuclear and Particle Astrophysics, Seoul National University, Seoul, 08826, Republic of Korea*
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[9]*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk 630090, Russia*
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[11]*Pulkovo Observatory, St. Petersburg, 196140, Russia*
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[13]*Korea University, Seoul 02841, Republic of Korea*

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Muons have been accelerated by using a radio-frequency accelerator for the first time. Negative muonium atoms (Mu^-), which are bound states of positive muons (μ^+) and two electrons, are generated from μ^+'s through the electron capture process in an aluminum degrader. The generated Mu^-'s are initially electrostatically accelerated and injected into a radio-frequency quadrupole linac (RFQ). In the RFQ, the Mu^-'s are accelerated to 89 keV. The accelerated Mu^-'s are identified by momentum measurement and time of flight. This compact muon linac opens the door to various muon accelerator applications including particle physics measurements and the construction of a transmission muon microscope.

DOI: 10.1103/PhysRevAccelBeams.21.050101

I. INTRODUCTION

Since its invention, the radio-frequency (rf) accelerator has accelerated a wide variety of particles from electrons to rare isotopes, and greatly contributed to the progress of various branches of science. Recently, the demand for muon acceleration has arisen not only in the field of elementary particle physics, but also in material and life sciences. For example, in muon collider and neutrino factory studies [1], it is proposed that the large transverse emittance of the muon beam can be reduced using ionization cooling [2]. A muon beam passes through a material, and subsequently the lost energy in the material is restored using rf acceleration. After all the cooling processes, muons are accelerated from a few MeV with rf accelerators. In material and life sciences, one promising application of muon acceleration is in the construction of a transmission muon microscope. If the muons can be cooled to the thermal temperature [ultraslow muon (USM)] and subsequently reaccelerated, transmission muon microscopes will be realized [3]. The remarkable progress made with modern proton drivers enables the USM generator to be used as a particle source of accelerators. Because the mass of the muon is 200 times larger than that of the electron, the transmission depth of a 10 MeV muon reaches approximately 10 μm. This enables three-dimensional imaging of living cells, which is impossible with the use of transmission electron microscopes. Another application of USM acceleration is precise measurement of the muon anomalous magnetic moment $a_\mu = (g-2)_\mu/2$ and electric dipole moment (EDM). Muon acceleration is essential to realize these applications; however, it has not been demonstrated except for simple electrostatic acceleration. In this paper, the first demonstration of muon rf acceleration is presented. It was conducted during the development of the

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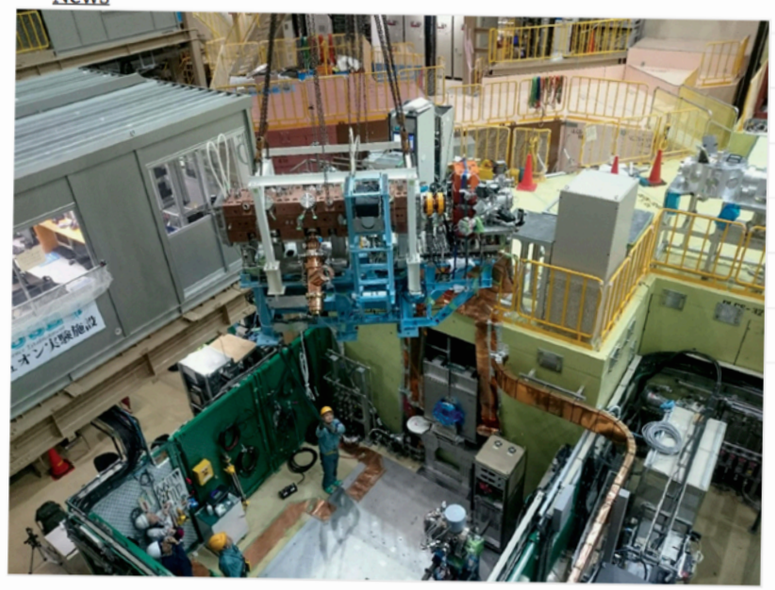
IOP

NEWS

Muons accelerated in Japan

9 July 2018



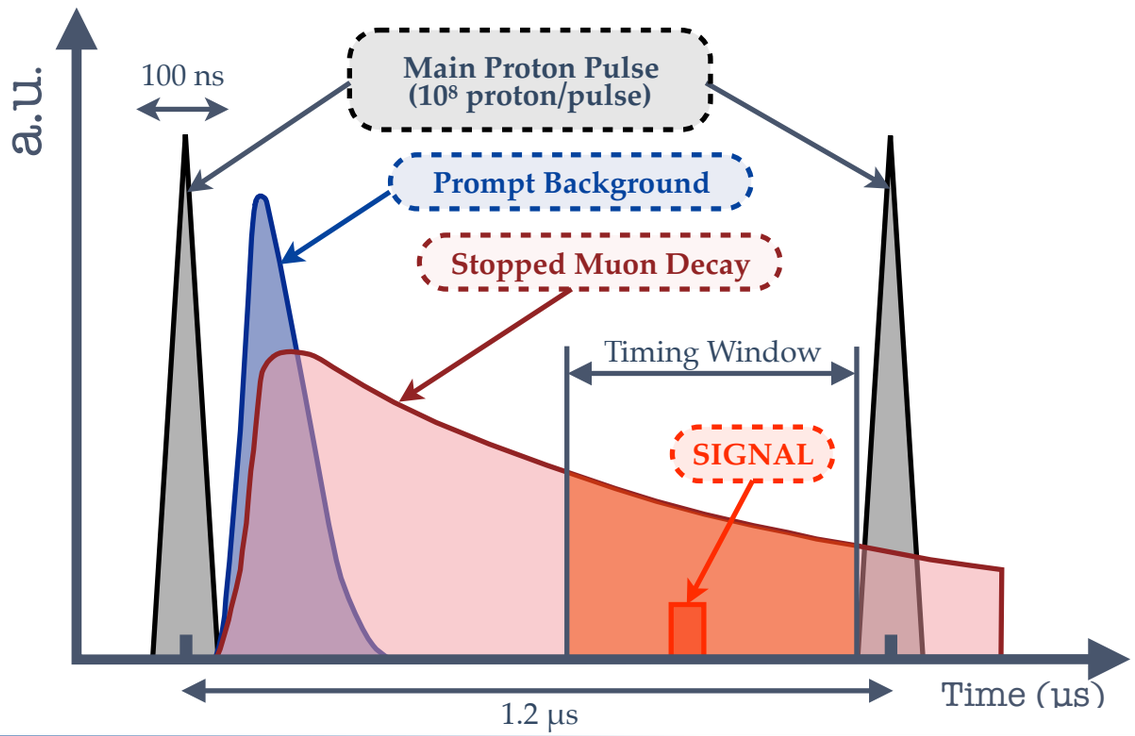
Installation

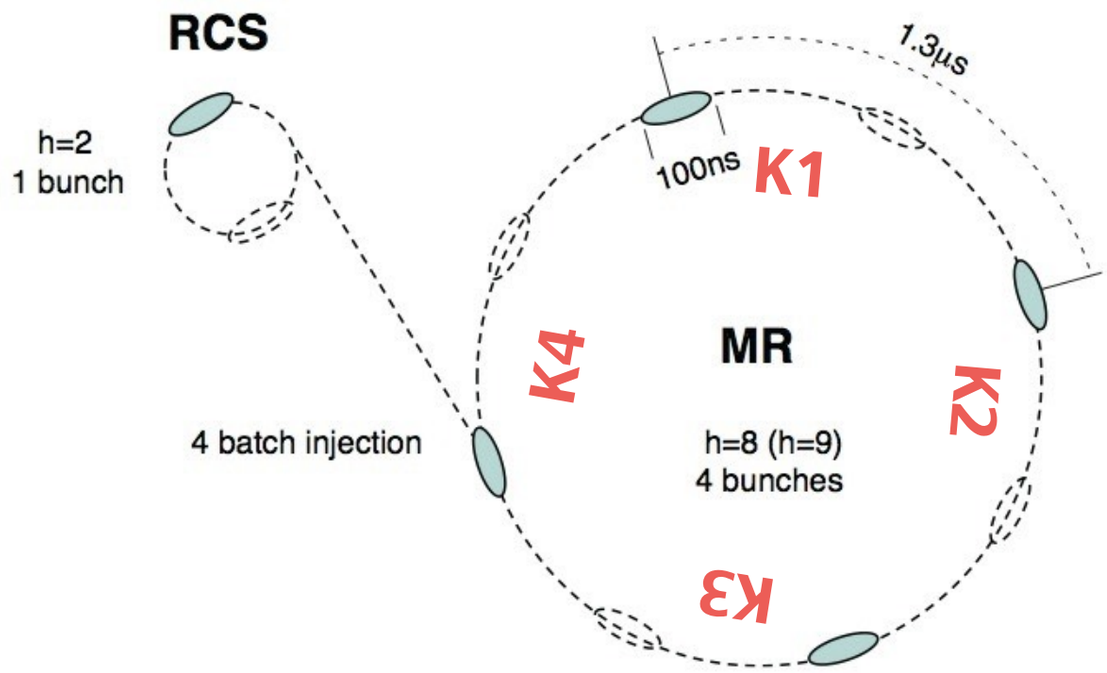
Muons have been accelerated by a radio-frequency accelerator for the first time, in an experiment performed at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan. The work paves the way for a compact muon linac that would enable precision measurements of the muon anomalous magnetic moment and the electric dipole moment.

Around 15 years ago, the E821 storage-ring experiment at Brookhaven National Laboratory (BNL) reported the most precise measurement of the muon anomalous magnetic moment (g–2). Achieving an impressive precision of 0.54 parts per million (ppm), the measured value differs from the Standard Model prediction by more than three standard deviations. Following a major effort over the past few years, the BNL storage ring has been transported to and upgraded at Fermilab and recently started taking data to improve on the precision of E821. In the BNL/Fermilab setup, a beam of protons enters a fixed target to create pions, which decay into muons with aligned spins. The

8-GeV Operation Test & Extinction Measurement

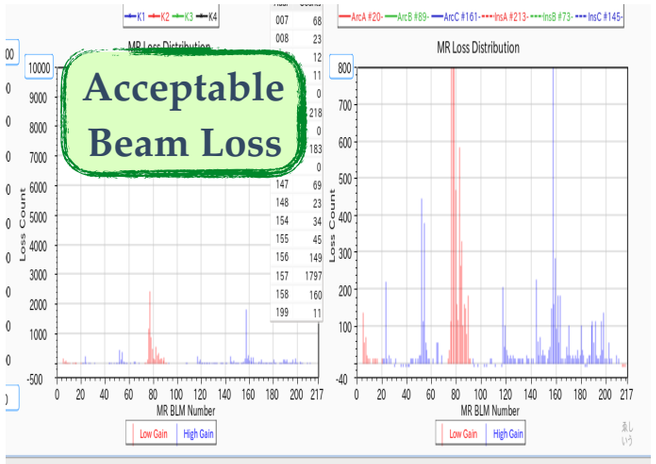
- COMET needs a special operation with J-PARC MR
  - Normal : 30 GeV → **COMET : 8 GeV** (To avoid antiproton contamination)
  - Normal : FX(for T2K) & SX(for HEF) → **COMET : Bunched-SX and 1b on RCS**
    - ➡ **Need to be demonstrated and verified to be good enough for COMET**
- COMET needs an excellent extinction of proton beam
  - **Requirement** : **Extinction < 10^{-10}** at least to achieve Sensitivity of *O*(-17)
    - **Need to Measure the extinction of J-PARC MR with 8 GeV proton beam**
  - **Need to Demonstrate the extinction treatment**

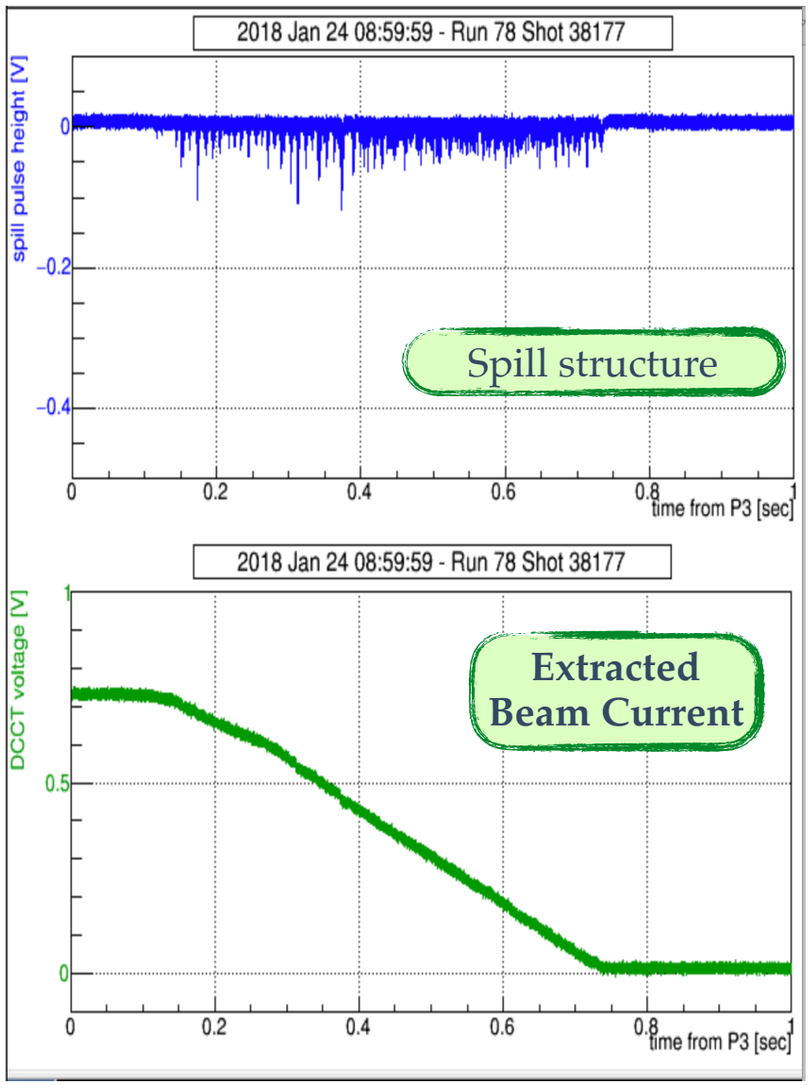


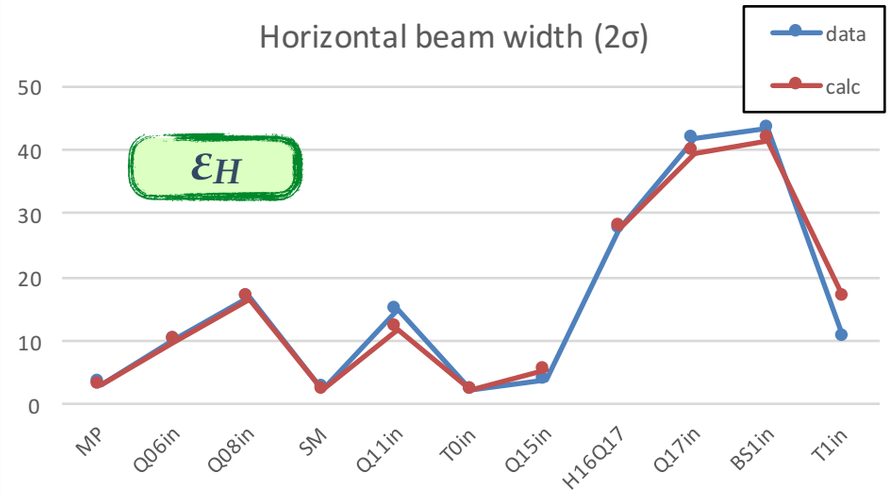


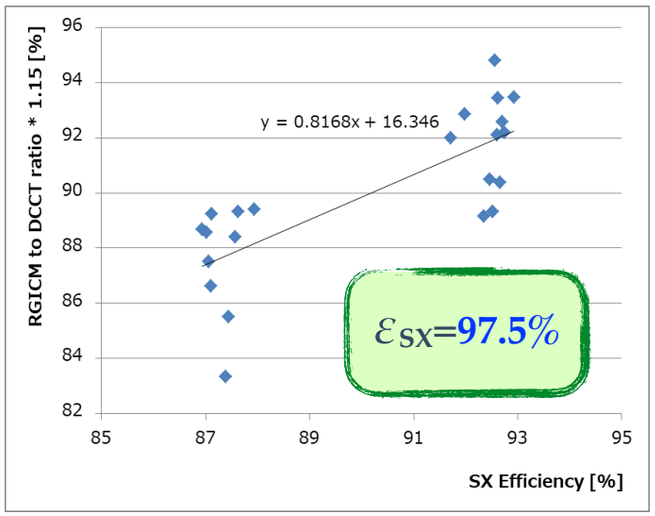
8-GeV Operation; Injection/Acceleration/Extraction

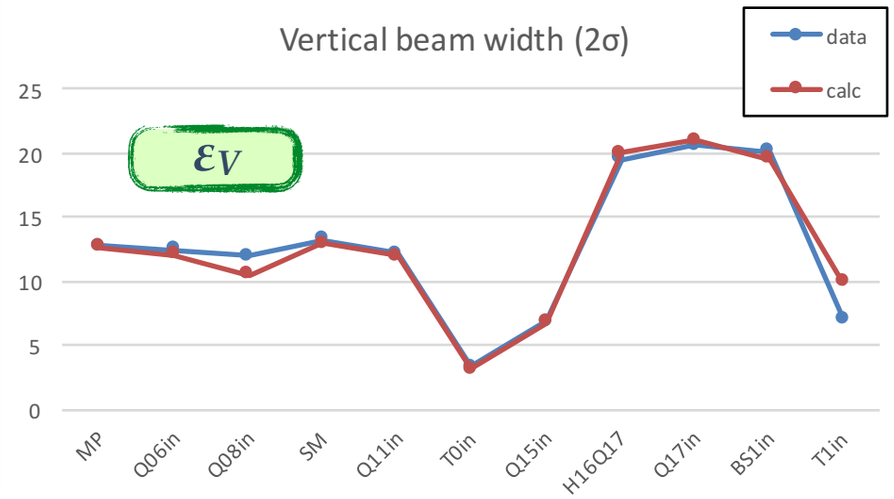
- 8-GeV Operation Test was conducted with "6×10^{12} ppb (protons/bunch)" and "5.2s cycle" = 1.8 kW, corresponding to 3.2 kW with 2.5s cycle (same as "COMET Phase-I setting")







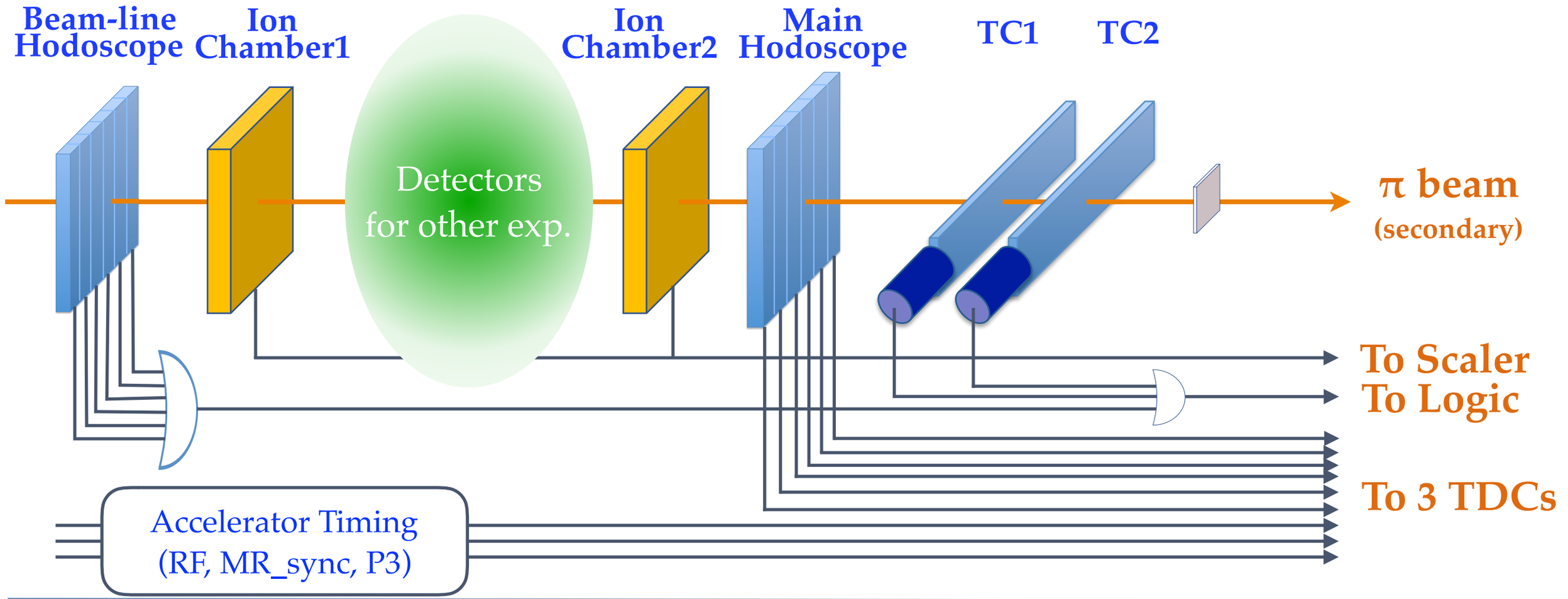




- **All the series of accelerator, "Injection/Acceleration/Extraction", was successfully performed although it needs further optimization in order to achieve full efficiency.**

Extinction Measurement

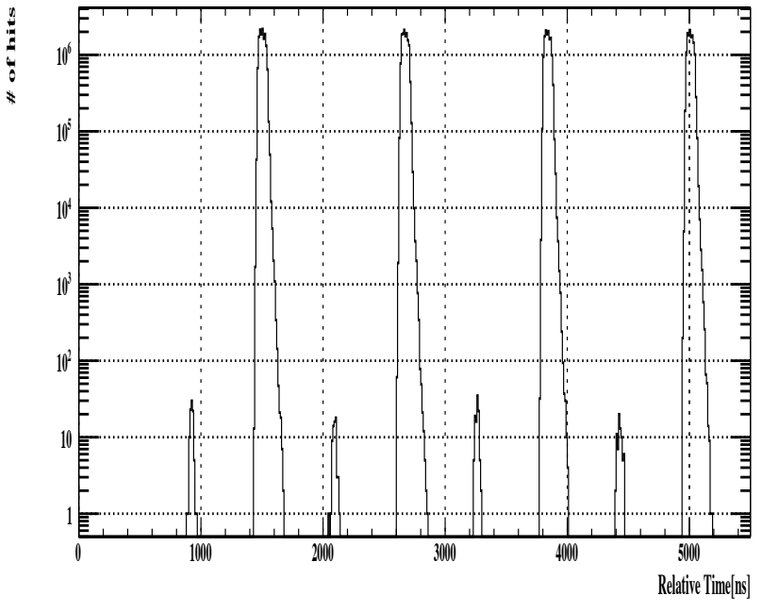
- By Counting the # of pions at the secondary beam line
- Very Simple Measurement (Particle Counting by plastic scintillation counters)
  - **Hodoscope and Ion Chamber count the # of all secondary pions**
  - **With help of beam-line hodoscope and trigger counters to ID beam particles**
- But need a special read out to handle a huge dynamic range
  - 3 dedicated TDC systems are prepared, **2 FPGA-based TDC** and **1 mTDC**



Extinction Measurement

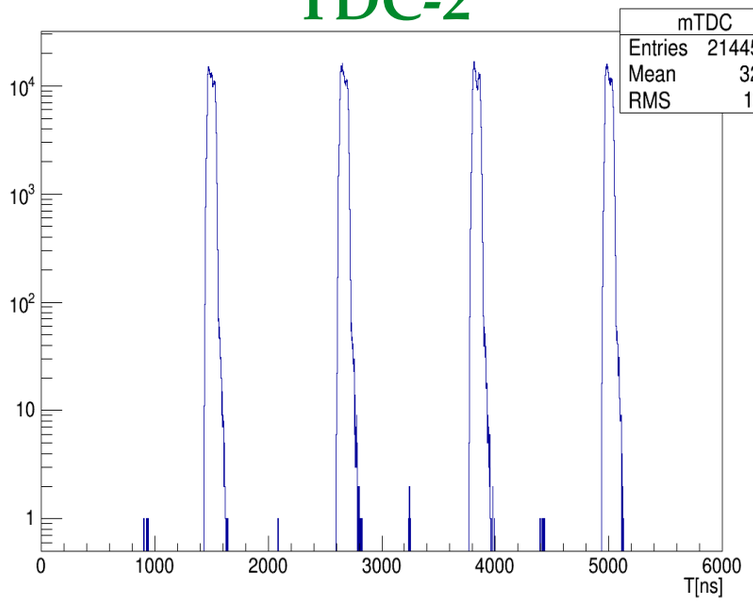
- Fill protons in all “rear” bucket of K1,2,3 and 4 batches
- Count the # of leaked protons in all “front” bucket

TDC-1

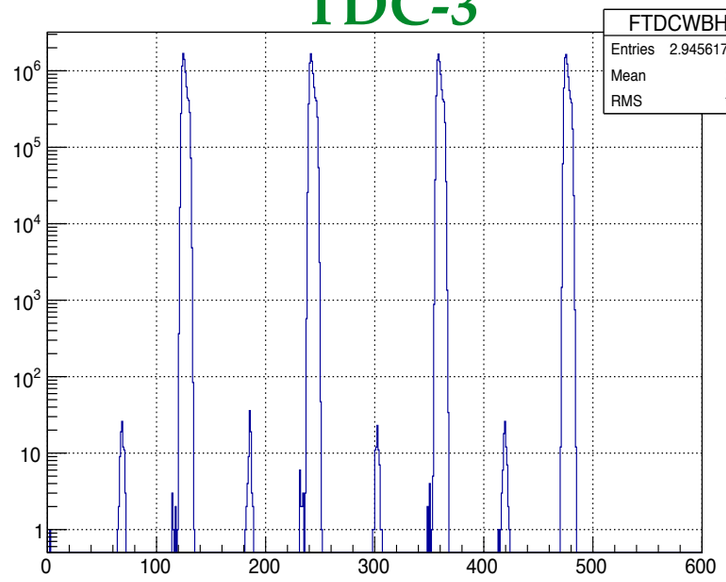


K1 front | K1 rear | K2 front | K2 rear | K3 front | K3 rear | K4 front | K4 rear

TDC-2



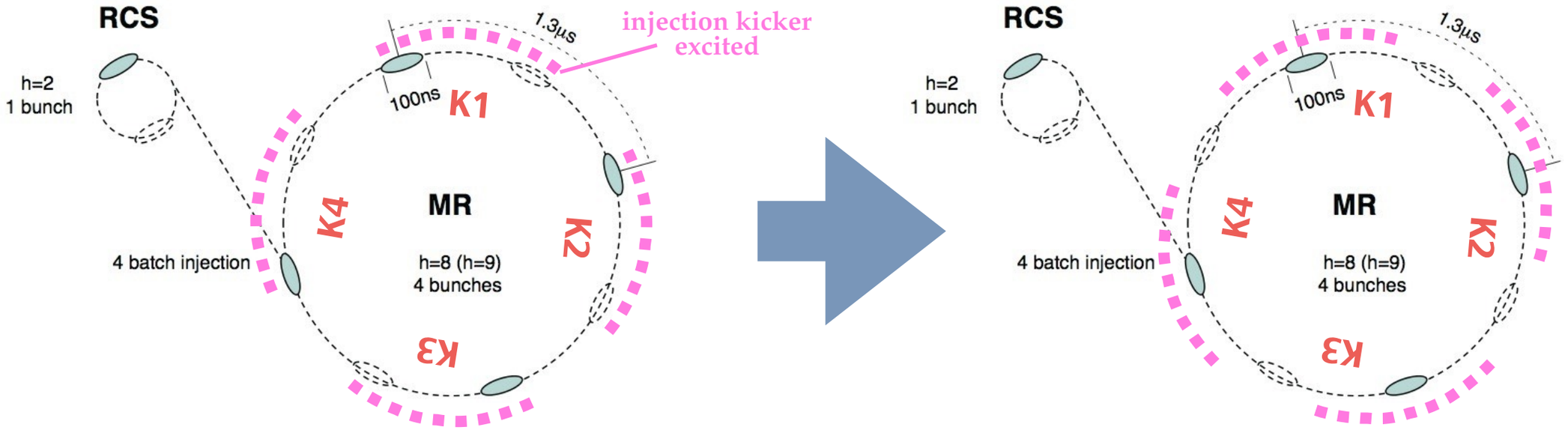
TDC-3



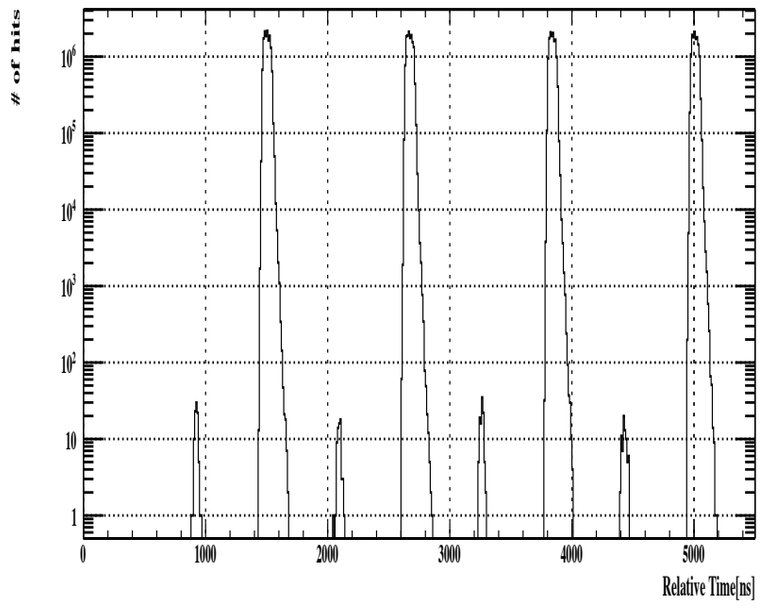
- Three TDCs show consistent results
- Obtained “*Initial*” Extinction = 7.4×10^{-6}
  - Due to the chopper inefficiency
  - Without Extinction Treatment
  - Need to improve 4 orders more to achieve the target sensitivity

Demonstration of Extinction Treatment

- In order to improve extinction factor, special treatment was made at MR injection
  - Kicker timing was shifted half a phase to avoid injecting residual protons of empty bucket



Injection kicker timing was shifted half a phase (~600ns) forward



Demonstration of Extinction Treatment

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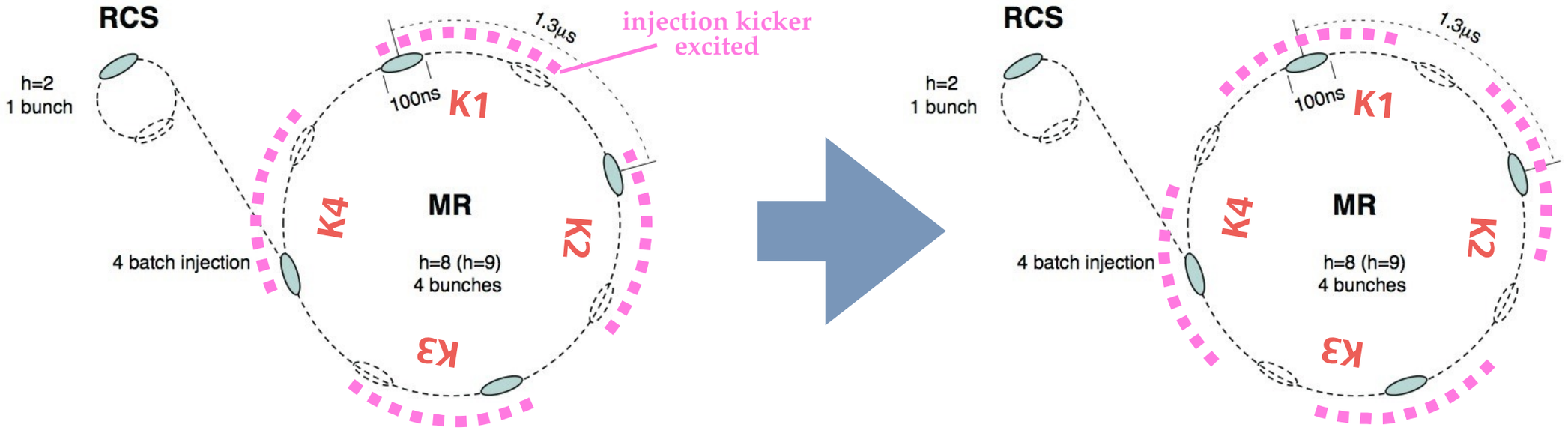
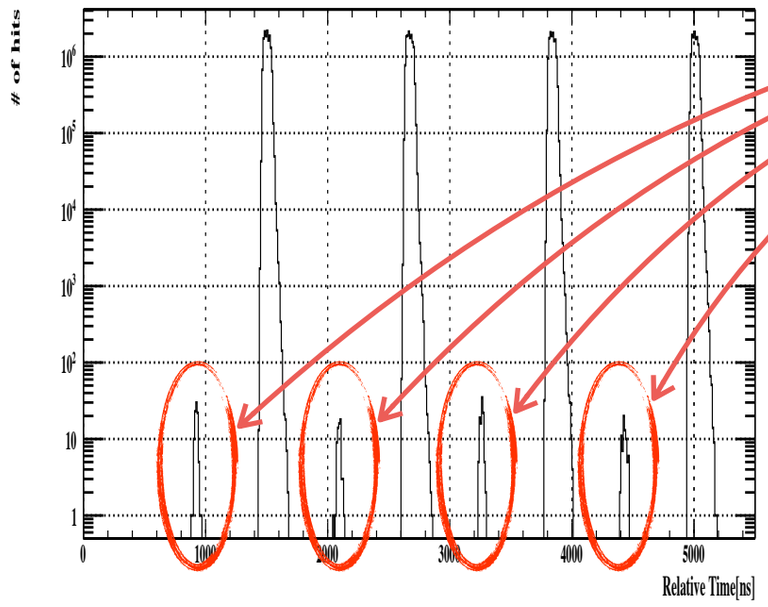


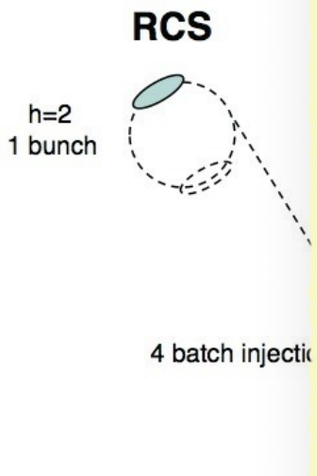
Injection kicker timing was shifted half a phase (~600ns) forward

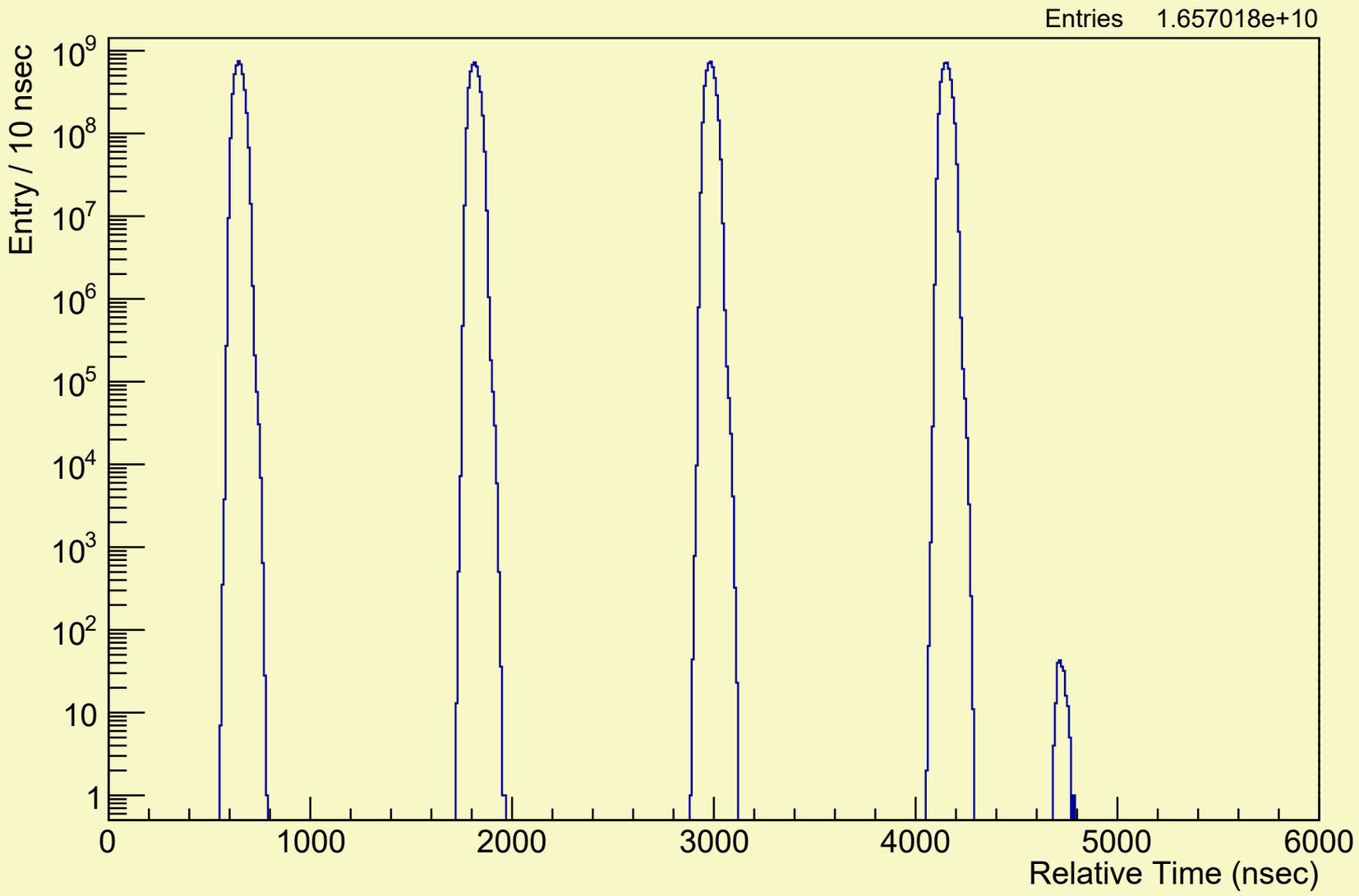


These residuals should be vanished.

Demonstration of Extinction Treatment

- In order to improve extinction factor, special treatment was made at MR injection
  - Kicker timing was shifted by 1 RF bucket

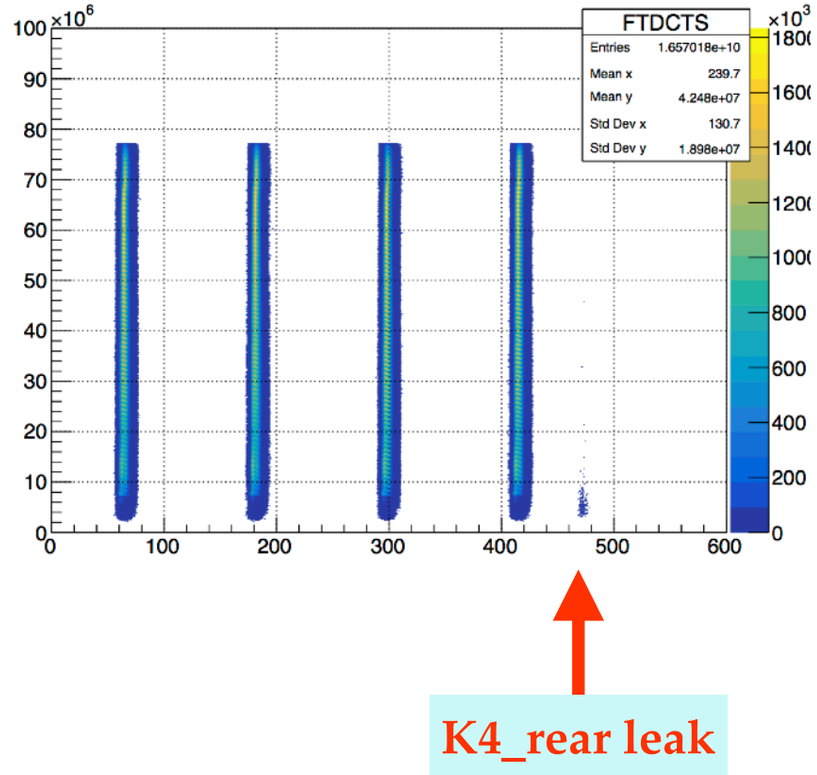




Perfect Extinction was Realized for K1,2,3 rear buckets !!!

Extinction result and prospects

- By masking K4 batch, good enough extinction of "**<1.0 × 10^{-10}**" is achieved
- If we could solve the "K4_rear mystery", we could realize further improvement on the extinction of "**<6.0 × 10^{-11}**" !
  - These "obtained" and "expected" extinction factors are limited by statistics (22 hours DAQ period this time)
- Prospects:
  - (1) **Solve K4_rear mystery**
  - (2) **Accumulate more statistics**
  - (3) **Measure the extinction with primary proton**
    - ➡ Can be realized by COMET beam line only



(Proton leak occurred only <0.1s after extraction start)

Summary

- Muon programs are under preparation at J-PARC
- In order for them, new beam lines, “H-Line at MLF” and “B-Line at HEF”, are under construction
  - H-Line @ MLF : Beam line shield up to H1 area was completed, Construction of new power station and hall renovation is ongoing.
  - B-Line @ HEF : Shield and power station was completed. Beam line construction will be completed by JFY2019.
    - COMET beam line construction is ongoing in parallel to primary B-Line construction
- Two big milestones:
  - First Muon Acceleration by RFQ
    - Successfully demonstrated for g-2/EDM experiment
  - 8 GeV Operation Test and Extinction Studies
    - Successfully tested for COMET experiment, and good enough extinction was already achieved