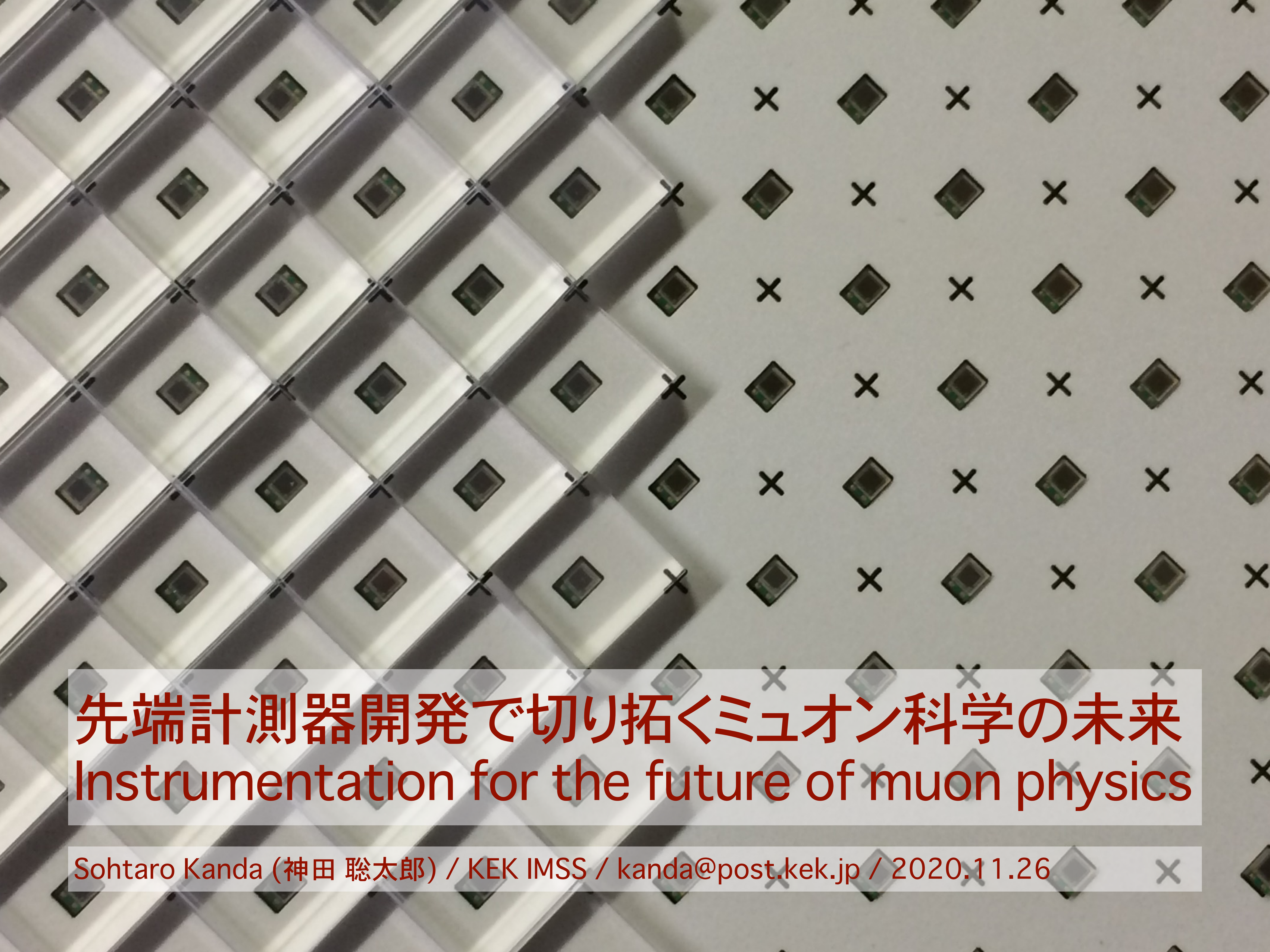


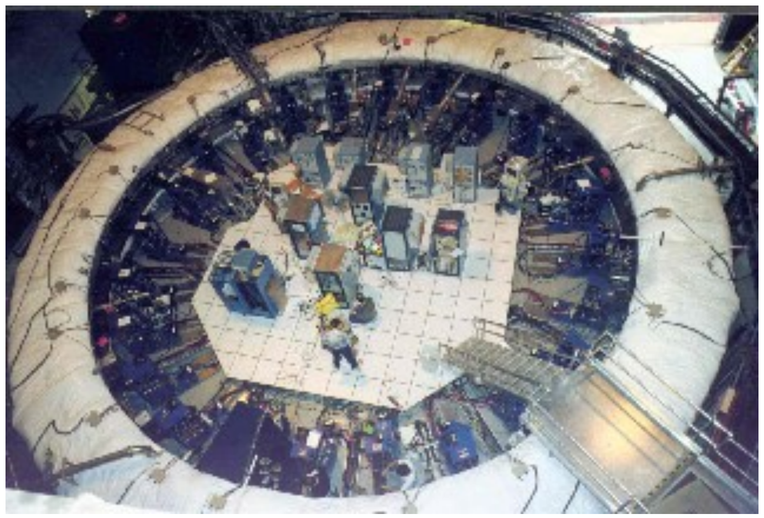
# 先端計測器開発で切り拓くミュオン科学の未来
# Instrumentation for the future of muon physics

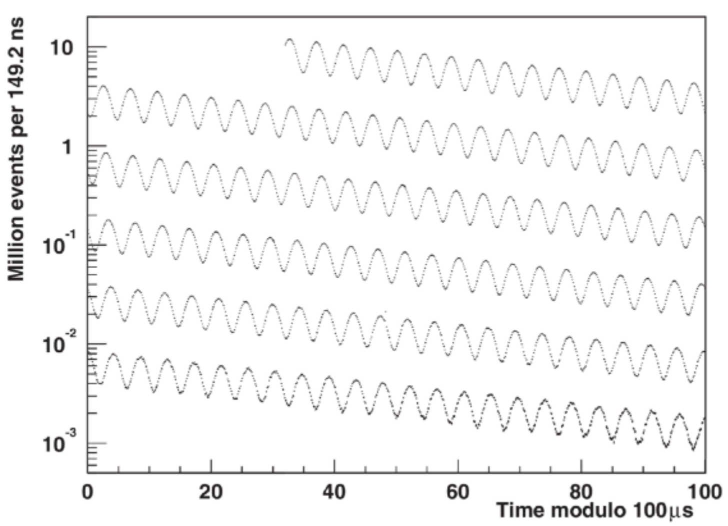
Sohtaro Kanda (神田 聡太郎) / KEK IMSS / kanda@post.kek.jp / 2020.11.26

# Muon Science

## Who ordered that?

Particle

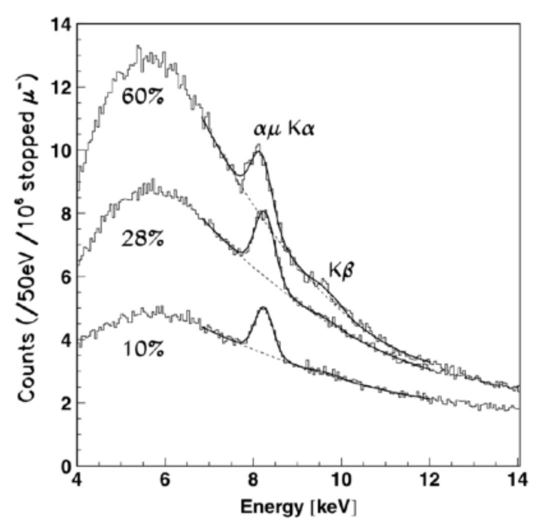





Anomalous magnetic moment

G.W.Bennet et al., Phys. Rev. D 73, 072003 (2006).

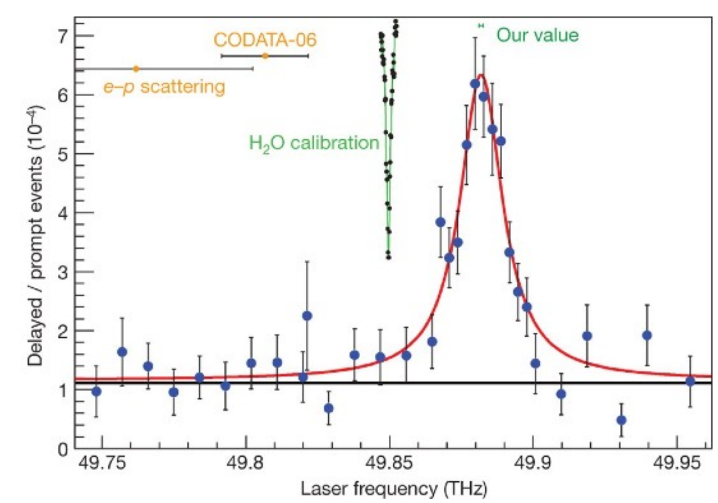
Nuclear




Muon catalyzed fusion

T. Matsuzaki et al., J. Radioanal. Nucl. Chem. 305, 889 (2015).

(sub-) Atomic



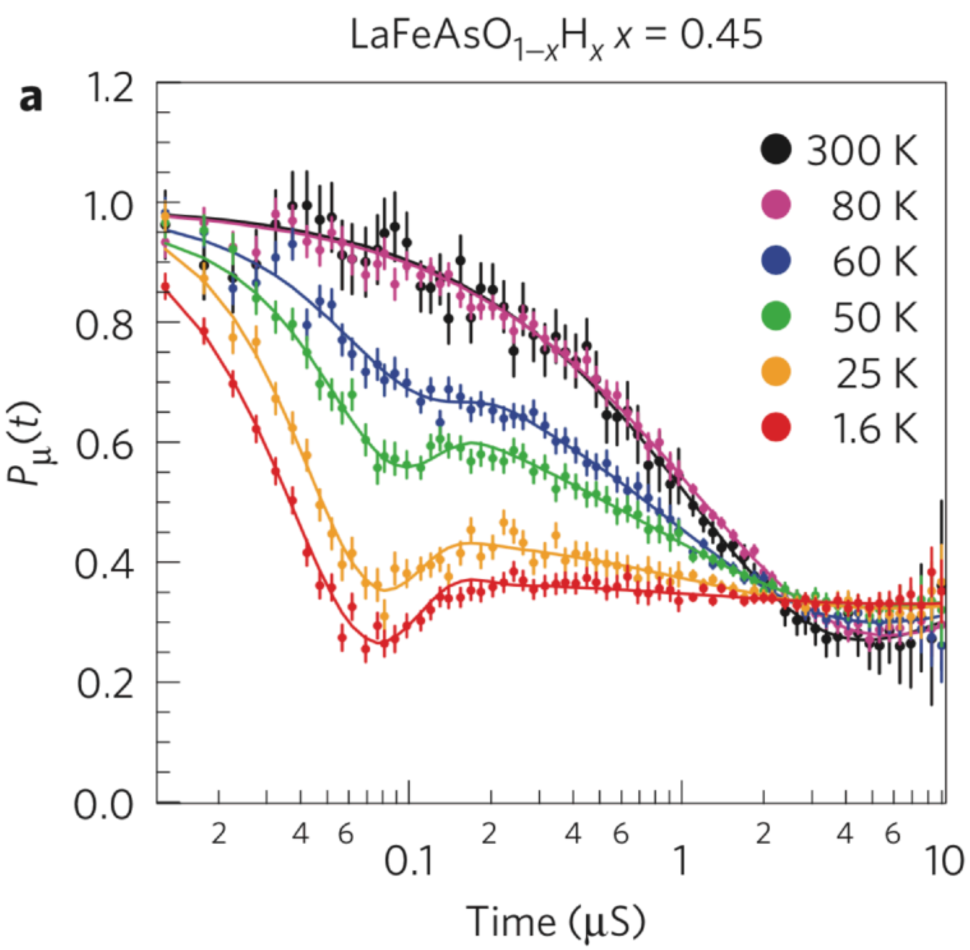

Proton radius puzzle

R. Pohl et al., Nature 466, 213 (2010).

# Muon Science

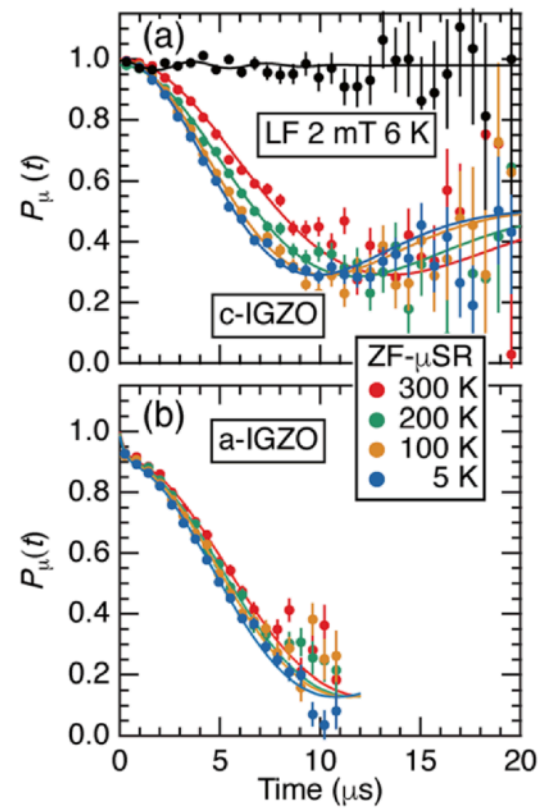
## More is different

| Superconductivity | Semiconductor | Archaeology |
|---|---|---|



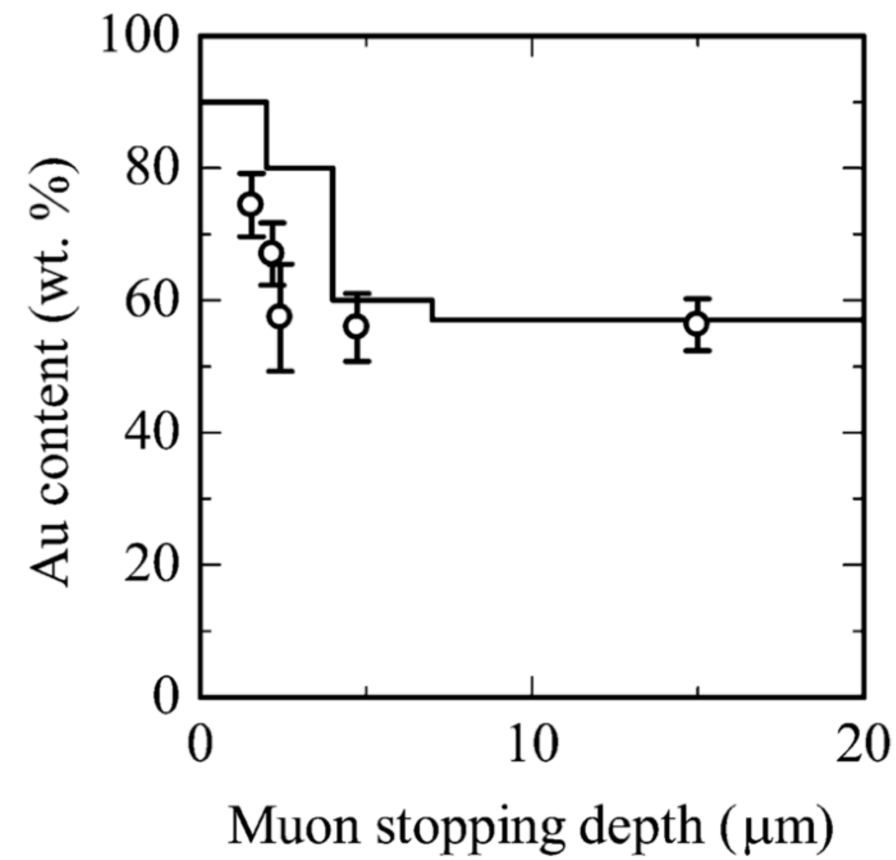

Superconductivity in LaFeAsO$_{1-x}$H$_x$

M, Hiraishi et al., Nature Phys. 10, 300 (2014).




Hydrogen impurity in IGZO

K.M. Kojima et al., Appl. Phys. Lett. 115, 122104 (2019).



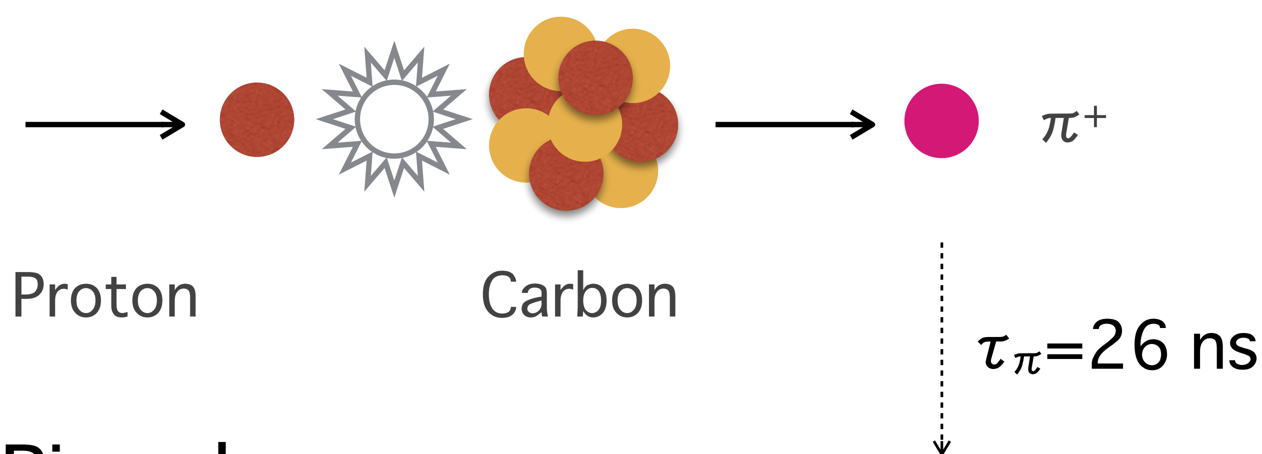

Depth profile of gold in Tempo-koban

K. Ninomiya et al., Anal. Chem. 87, 4597 (2015).

# Production and Decay of Muon

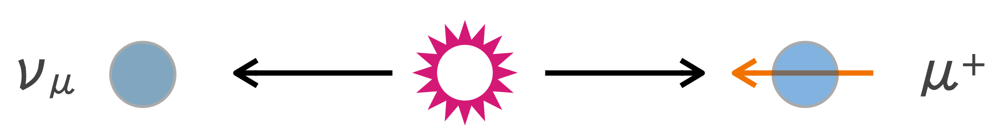
## Accelerator driven muon source

○ Proton-driver



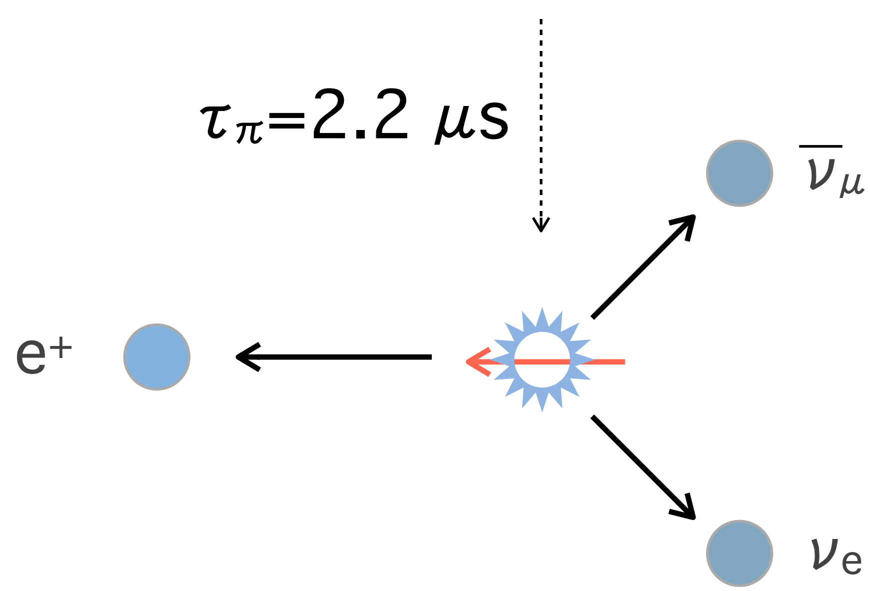

Pions are produced by the nuclear reaction.

○ Pion decay




Muon is spin polarized.

○ Muon decay

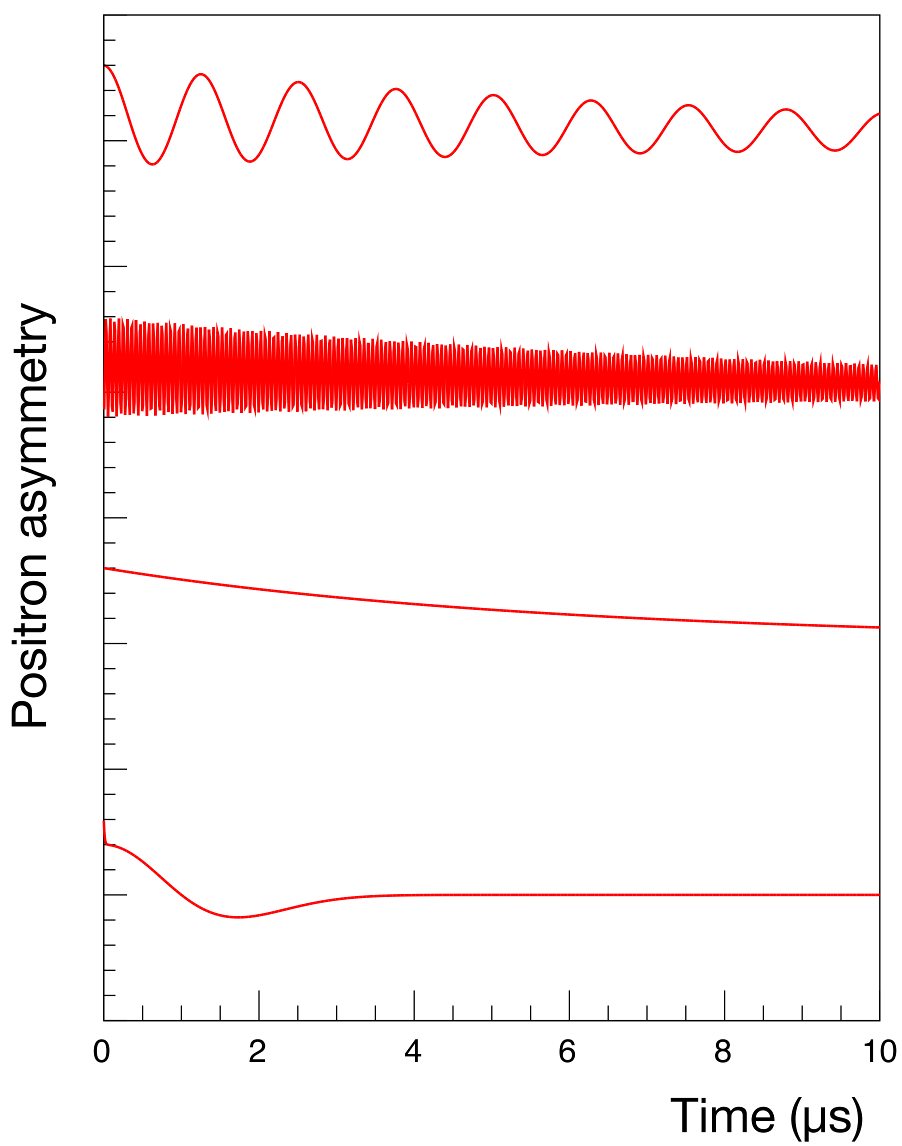



Positron is likely to be emitted in parallel to the muon spin.

# $\mu$SR Technique

## Muon spin rotation, relaxation, resonance

- Muon inside a material acts as a high-sensitivity, radiative, local magnetometer.

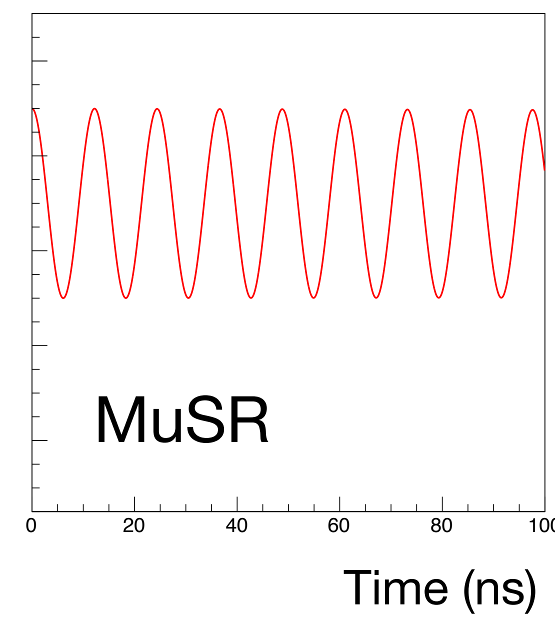


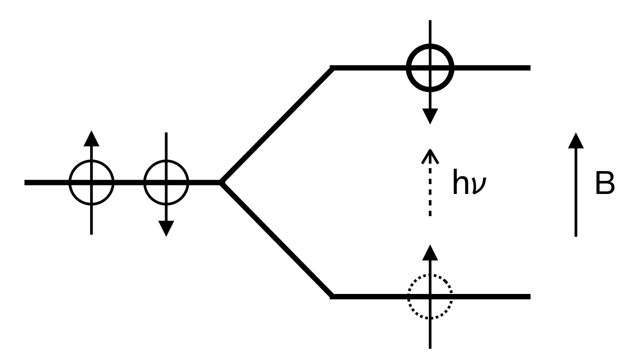

Muon spin rotation in magnetic order phase

Muonium spin rotation 103 times faster than $\mu$SR

Muon spin relaxation due to interaction with the electron magnetic moment

Muon spin relaxation due to interaction with the nuclear magnetic moment



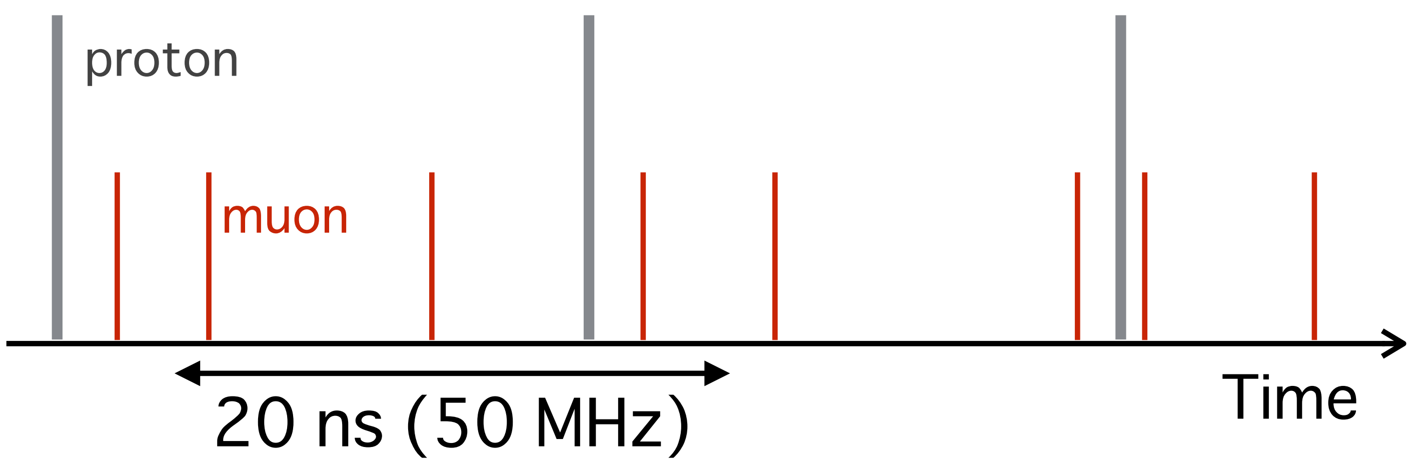




Muon spin resonance (similar to ESR)

# Continuous and Pulsed Muon Beams

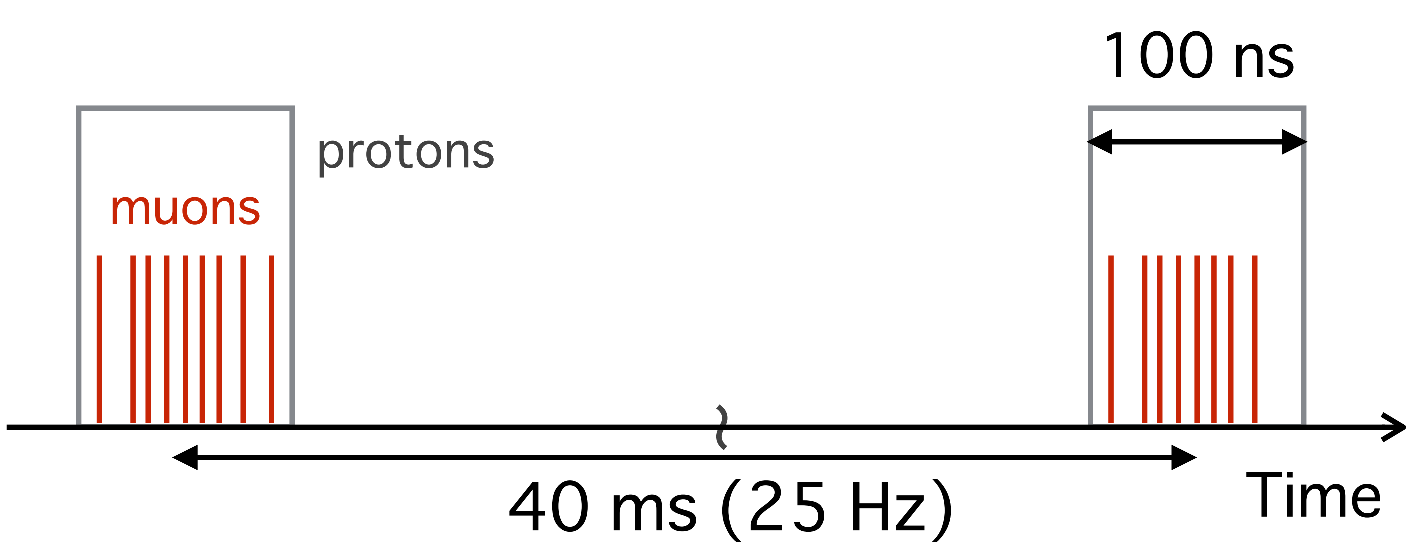
## Two complementary timing structure

○ Continuous beam (PSI)




- High beam-related background
- Limited beam rate due to trigger pileup
- High timing resolution
- One-by-one analysis

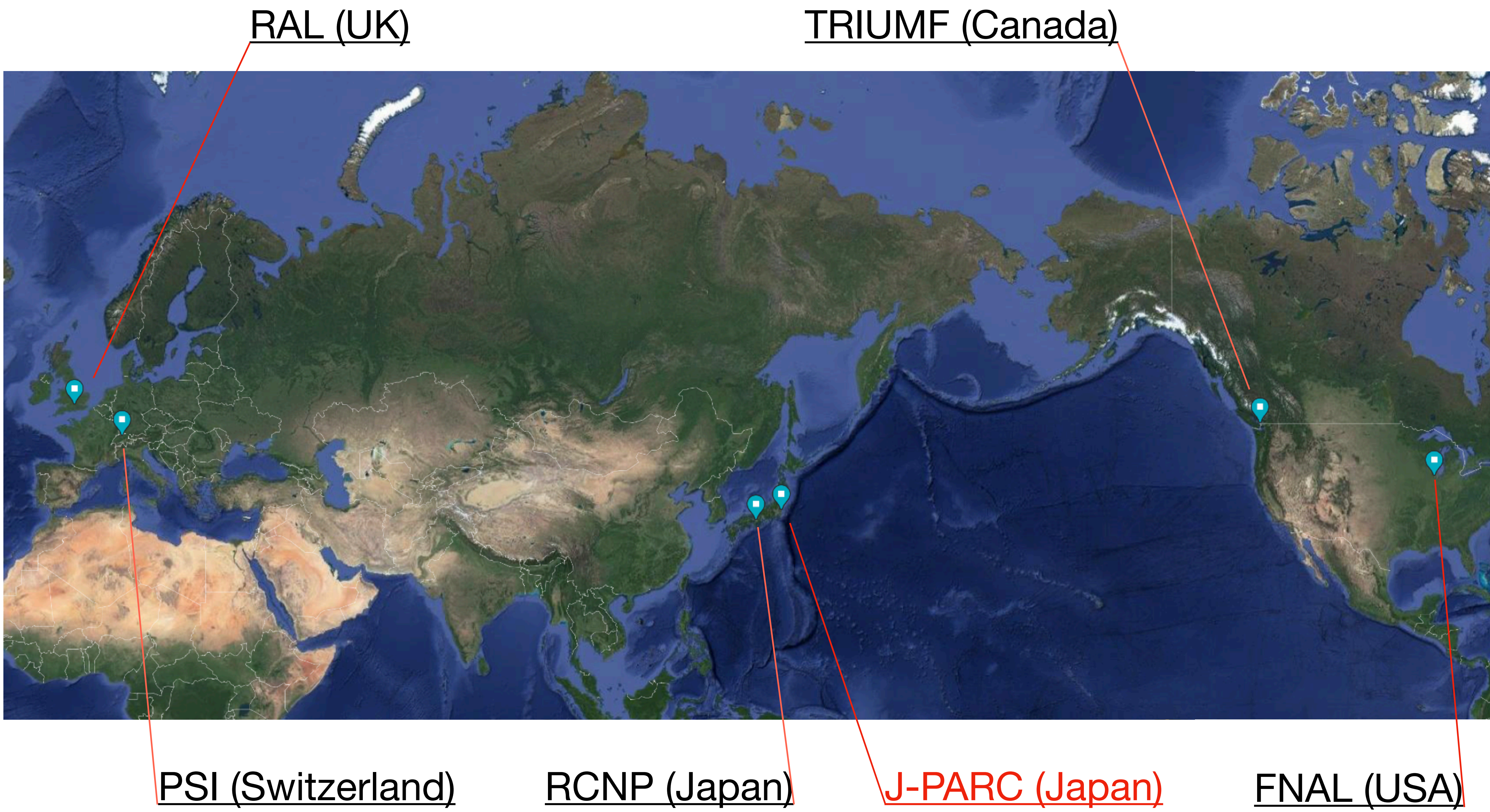
○ Pulsed beam (J-PARC)




- Low intrinsic background
- High beam intensity to the limit of the accelerator.
- Limited timing resolution due to a pulse width
- All muons in a bunch

# Muon Facilities

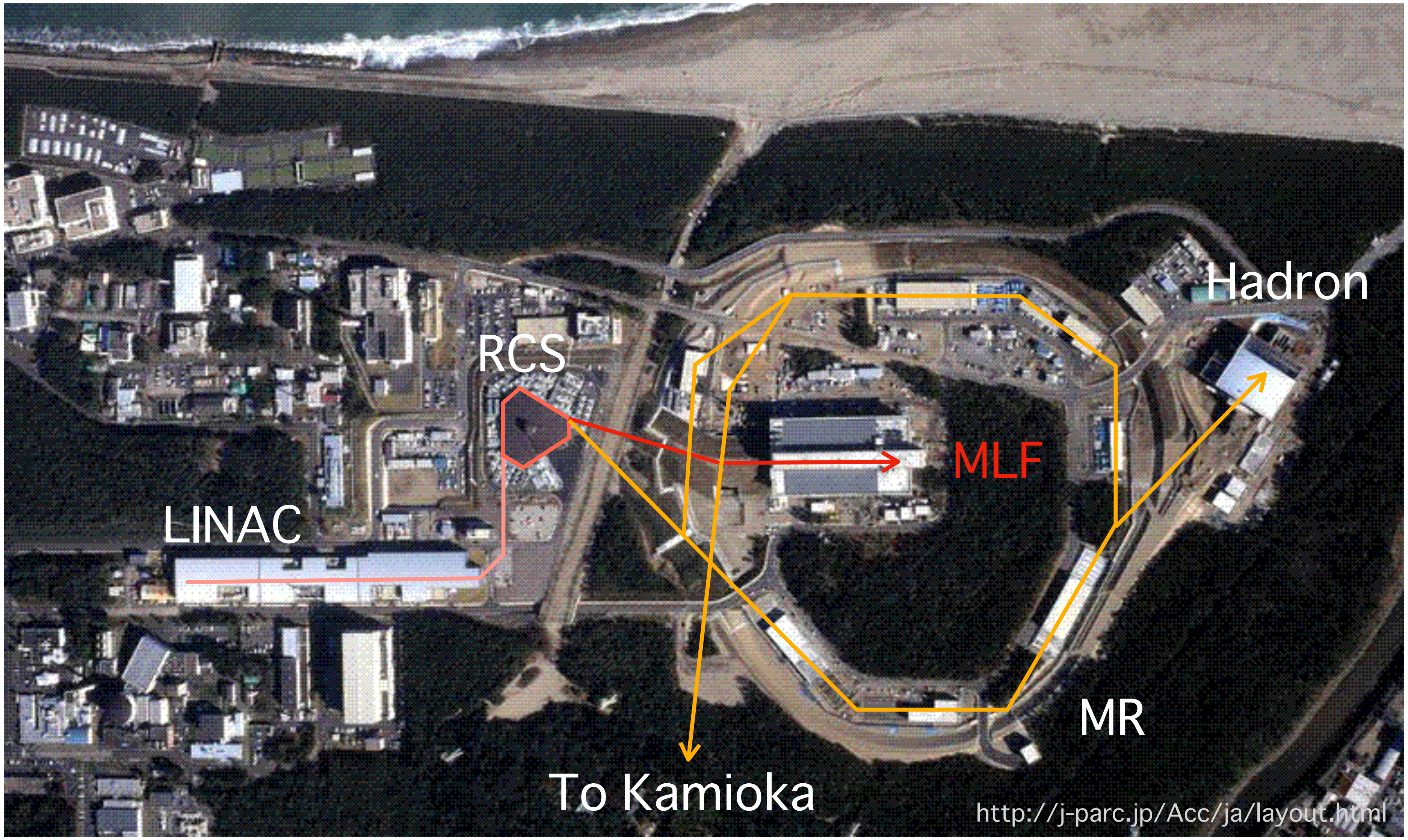
## Experimental sites delivering muon beams



# J-PARC

## Japan Proton Accelerator Research Complex

- World's highest intensity proton driver ($20 \times 10^{12}$ p/s at 0.3 MW).

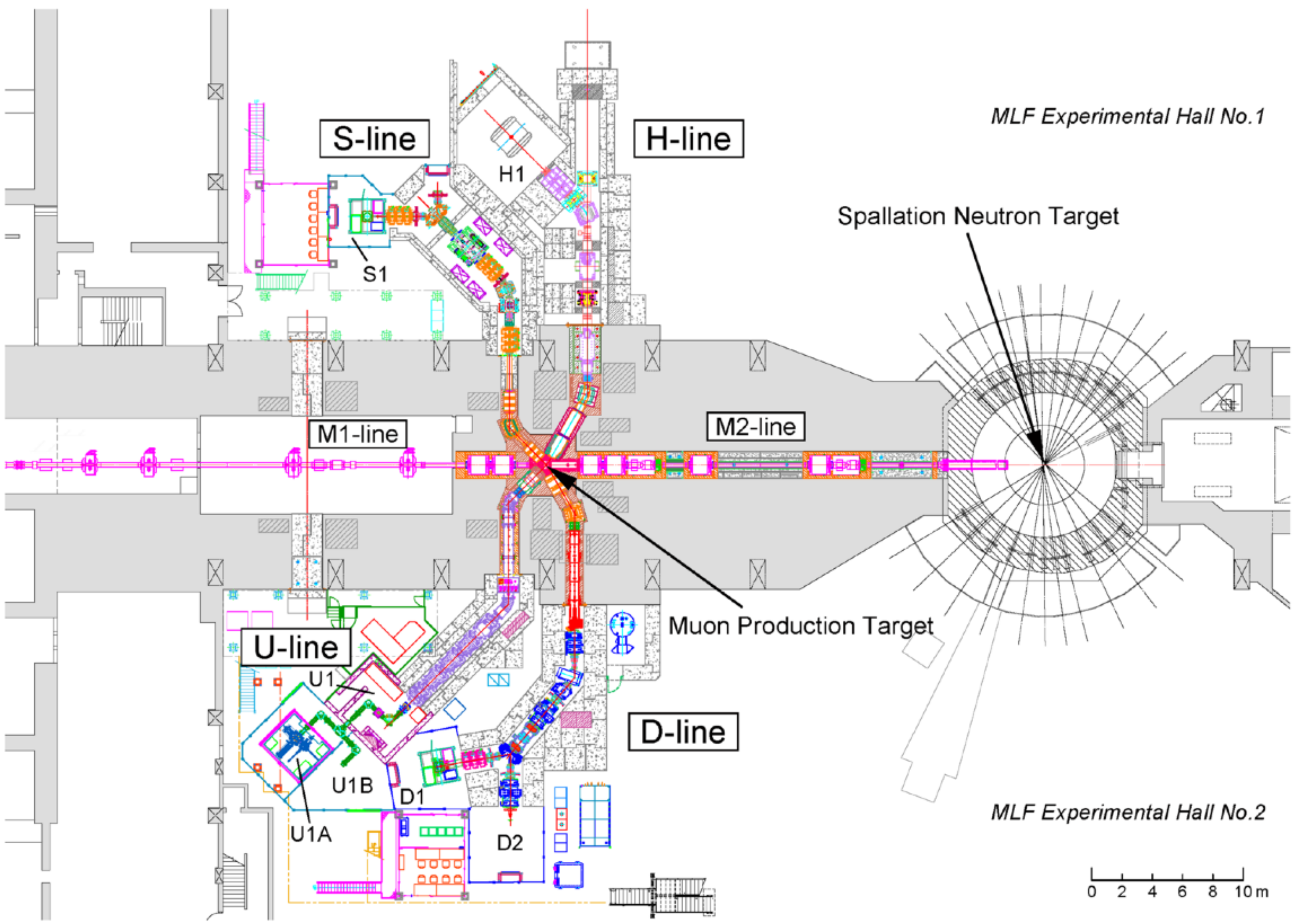


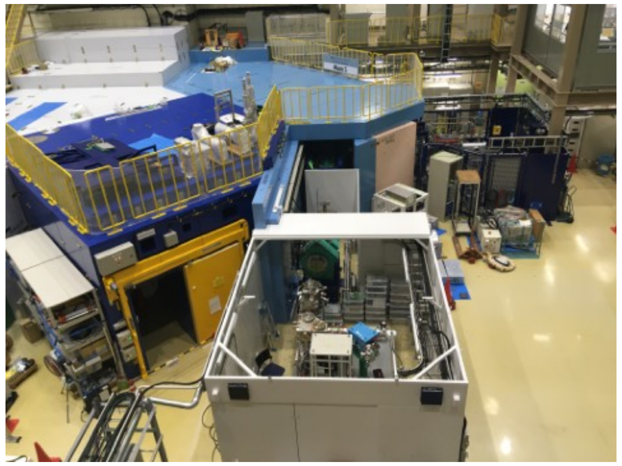

- 400 MeV LINAC, 3 GeV RCS, and 30 GeV Main Ring.

# MUSE

## Muon Science Establishment

- World's highest intensity pulsed muon beam ($3 \times 10^6$ $\mu$/s at 0.3 MW).
- 4 beamlines, 10 branches (5 in operation).



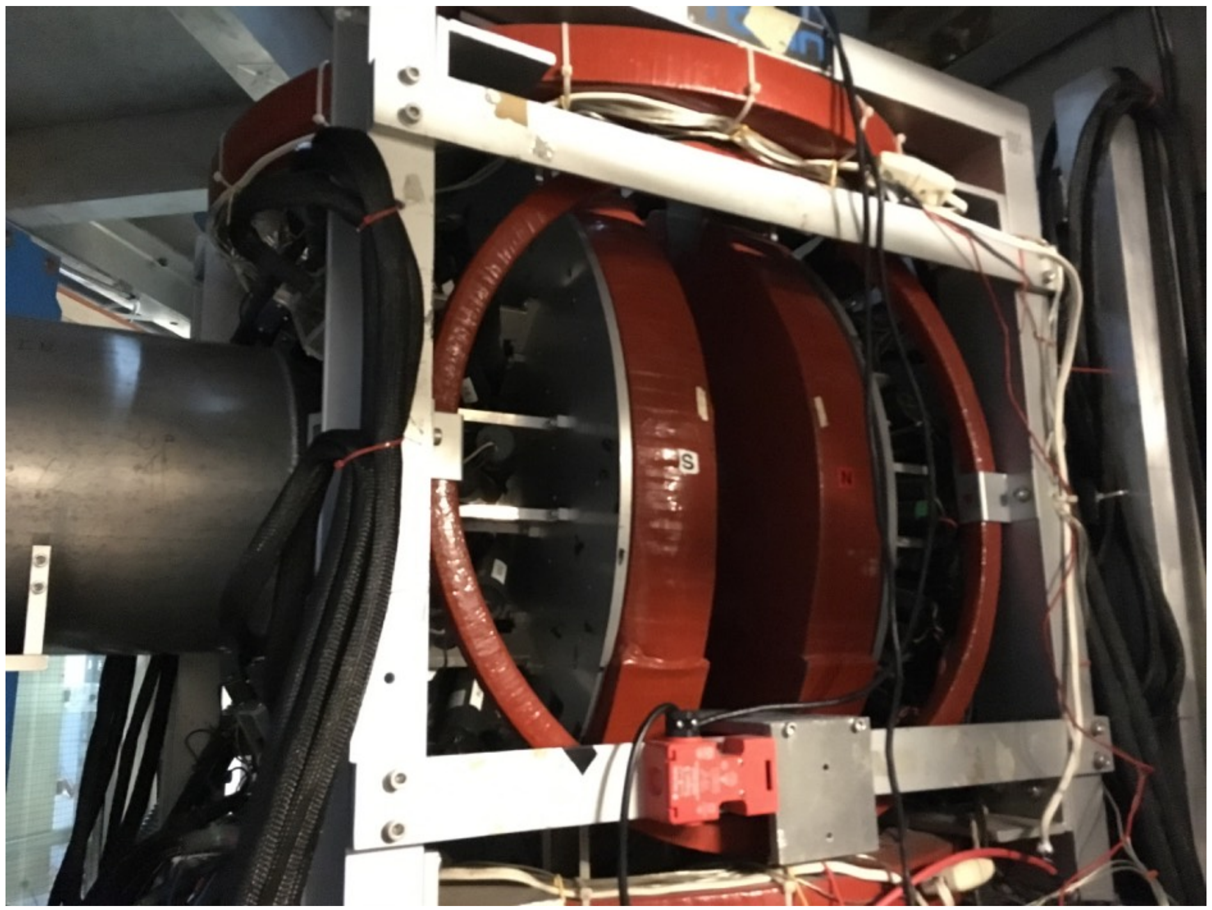
Exp. hall 1

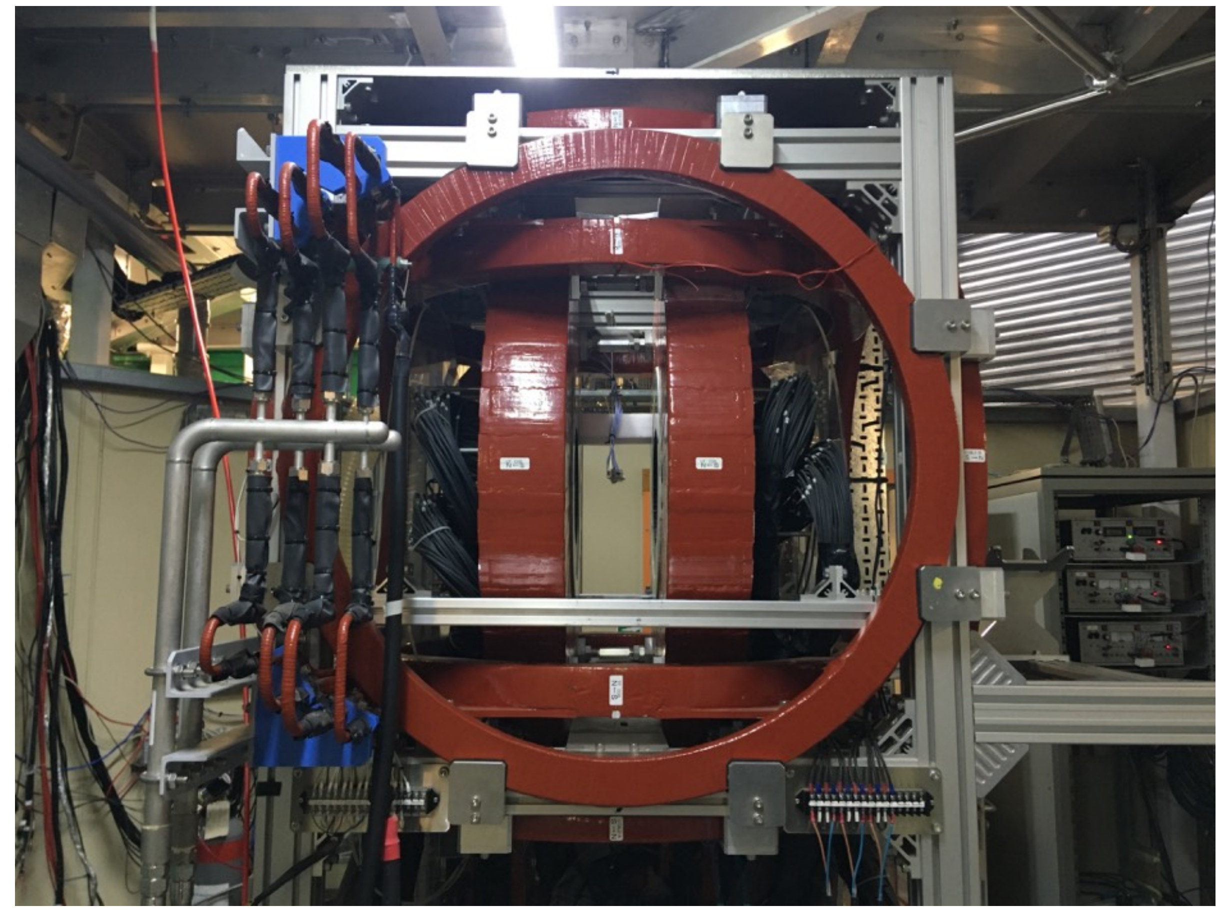
Muon source

Exp. hall 2

# $\mu$SR Spectrometer

## Instruments at RIKEN-RAL in UK





ARGUS at Port2
Plastic scintillator+PMT
VME-based DAQ, 192 channels

CHRONUS at Port4
Plastic scintillator+Wavelength shifting fiber+Multi-anode PMT
VME-based DAQ, 606 channels

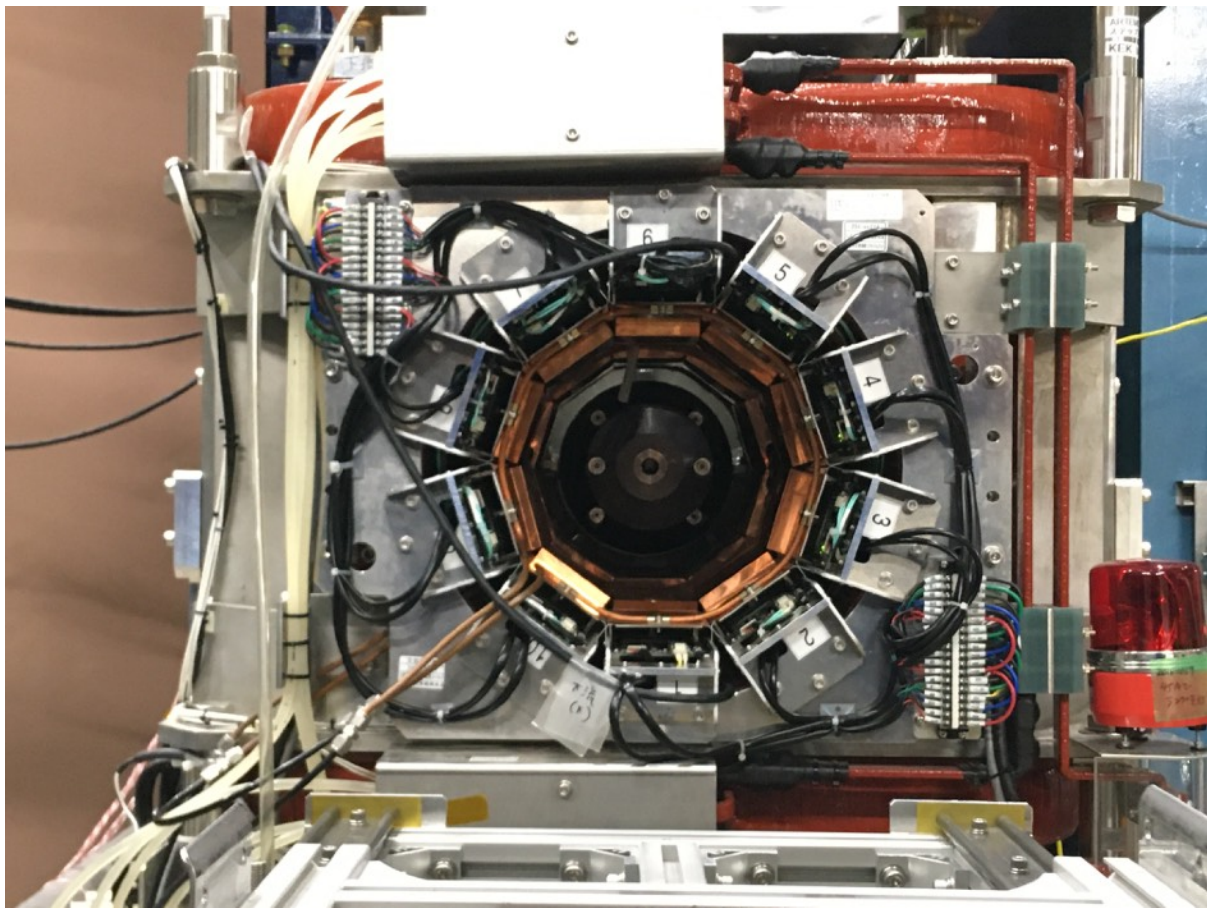
R. Kadono, et al., “Development of a New μSR Spectrometer ARGUS”, RIKEN Accel. Prog. Rep. 29, 196 (1996).

Beam intensity : $10^6$ $\mu^+$/s

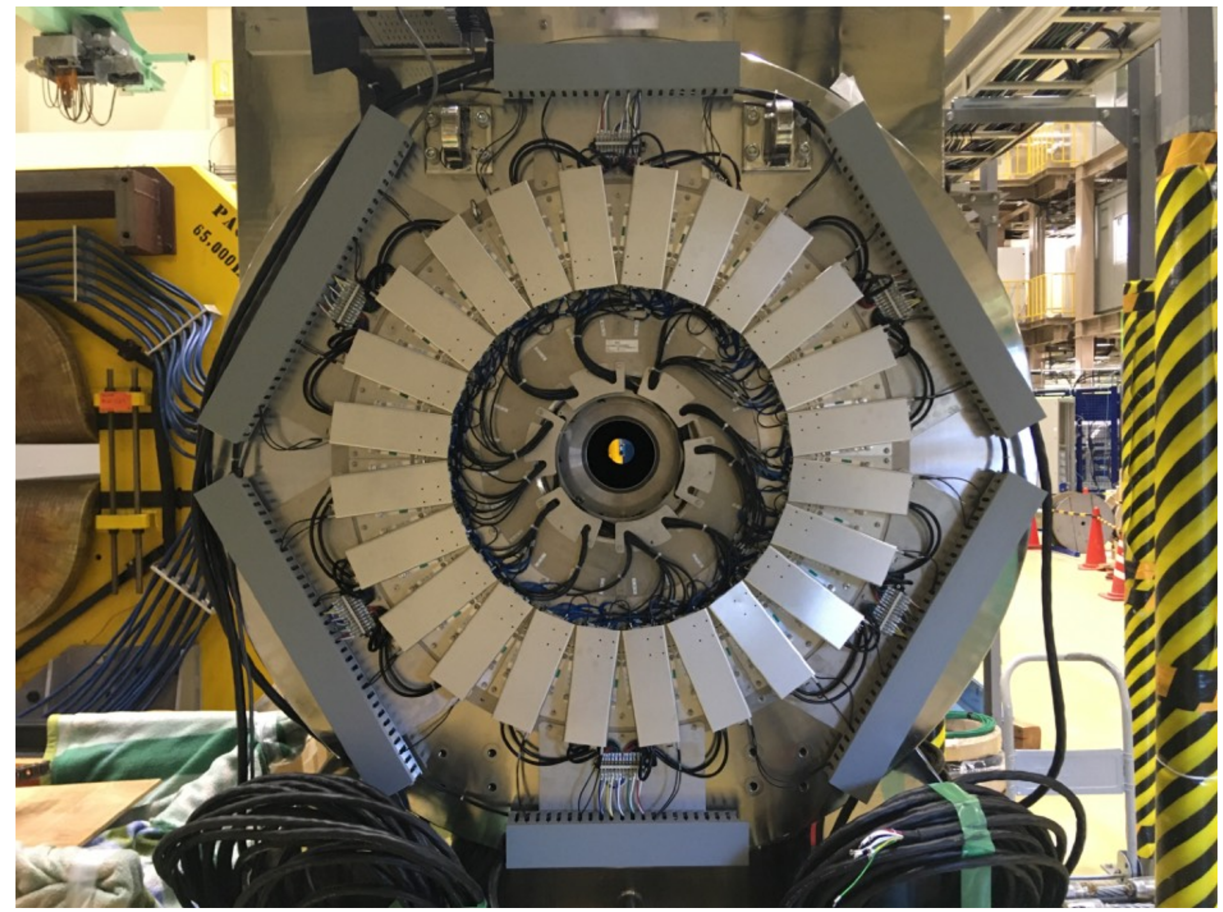
D. Tomono et al., “Development of new m–e decay counter in new multi-channel mSR spectrometer for intense pulsed muon beam”, NIM A 600, 44 (2009).

# $\mu$SR Spectrometer

## Instruments at J-PARC



ARTEMIS at S1
Plastic scintillator+SiPM
+ASIC+FPGA+SiTCP, 1280 ch.



CYCLOPS under commissioning
Scintillating fiber+SiPM
+ASIC+FPGA+SiTCP, 3008 ch.

K. M. Kojima et al., "Development of general purpose μSR spectrometer ARTEMIS at S1 experimental area, MLF J-PARC", JPS Conf. Proc. , 011062 (2018).

Beam intensity : $10^7$ $\mu^+$/s (~ $10^8$ $\mu^+$/s)

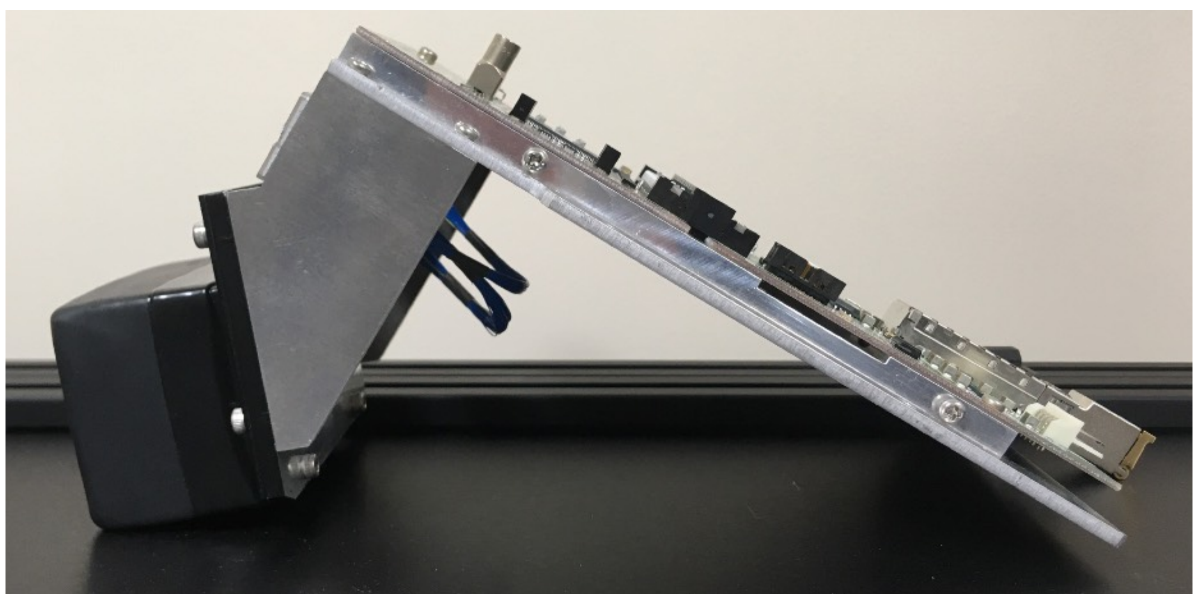
M. Miyazaki et al., the 69th JPS Annual Meeting, 30aAB-11 (2013).
S. Nishimura et al., the 75th JPS Annual Meeting, 17pB42-8 (2020).

# Kalliope

## Front-end electronics for SiPM readout

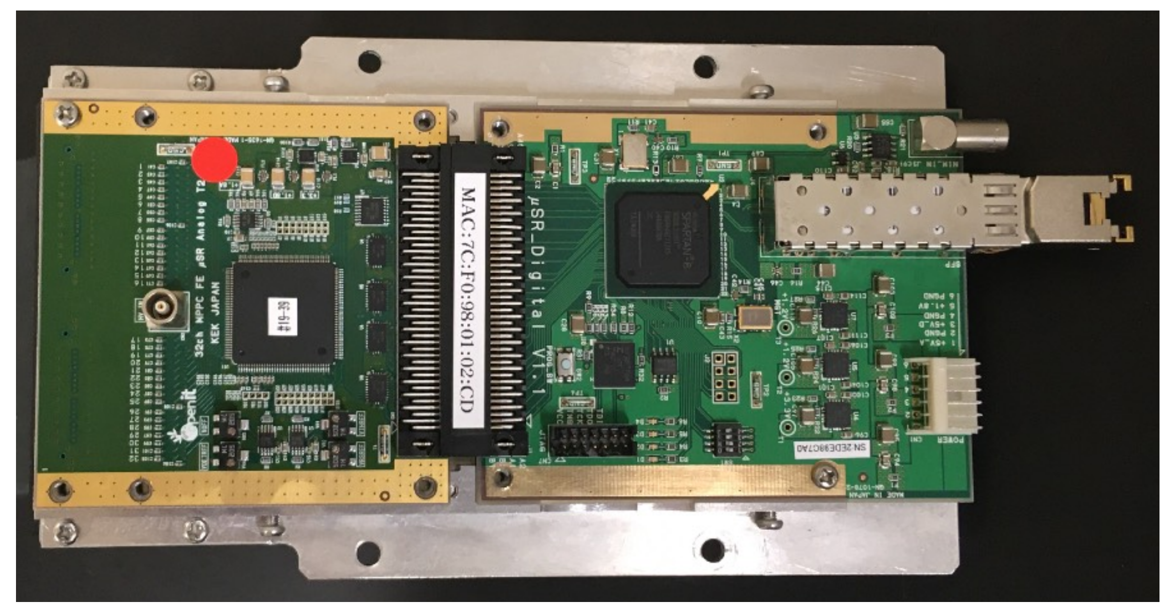
- Open-It Project : MPPC-TDC-SiTCP

  →http://openit.kek.jp/project/lists/mppc-tdc-sitcp/public/mppc-tdc-sitcp



Plastic scintillator+SiPM
(Hamamatsu MPPC)

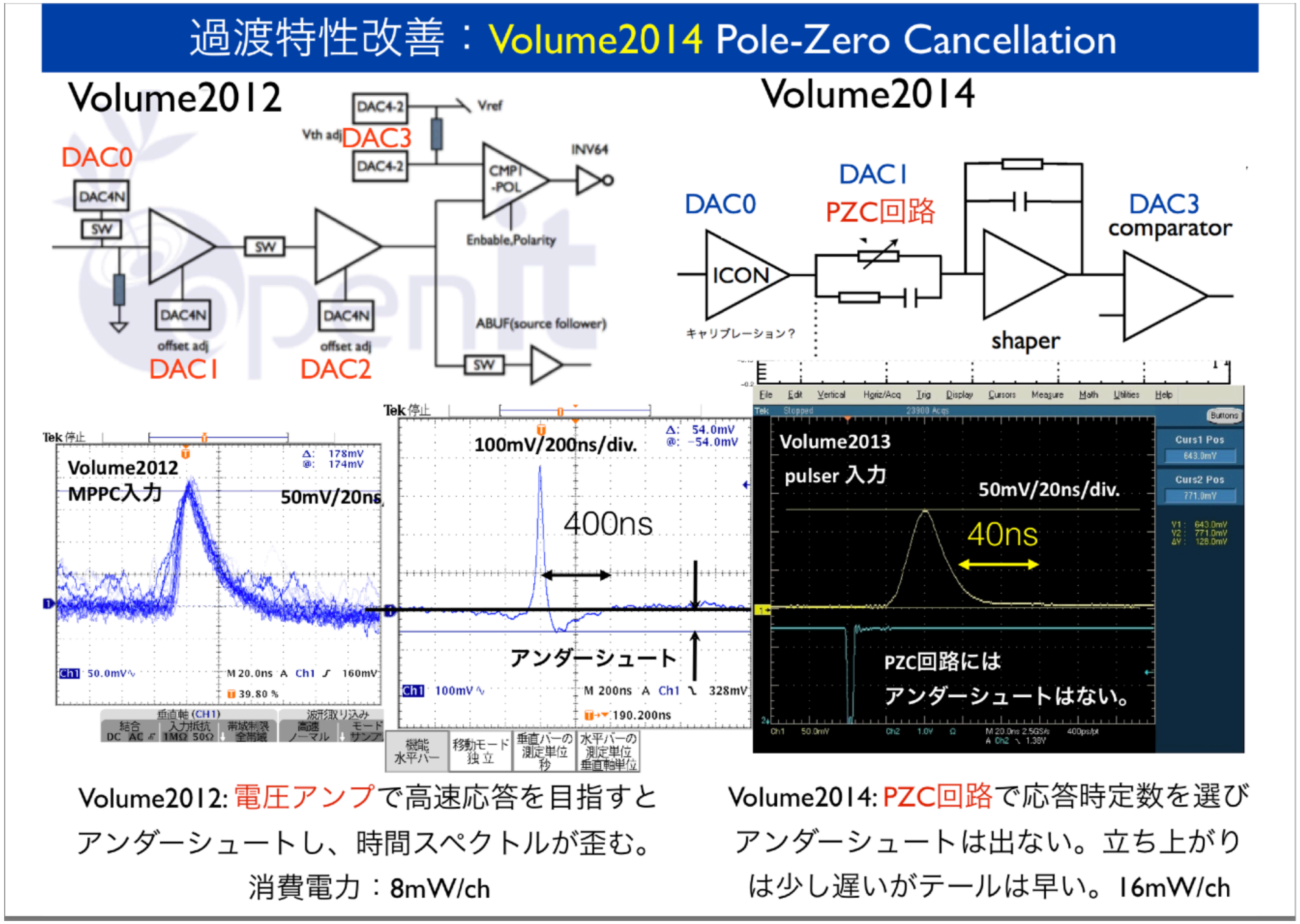
[ref.] K. M. Kojima et al., “New μSR spectrometer at J-PARC MUSE based on Kalliope detectors”, J. Phys.: Conf. Ser. 551 (2014) 012063(1-6).




ASIC-based amplifier, shaper, discriminator
+Multi-hit TDC implemented in FPGA.
32 channels per unit.

# Kalliope Families

## Two versions with different characteristics

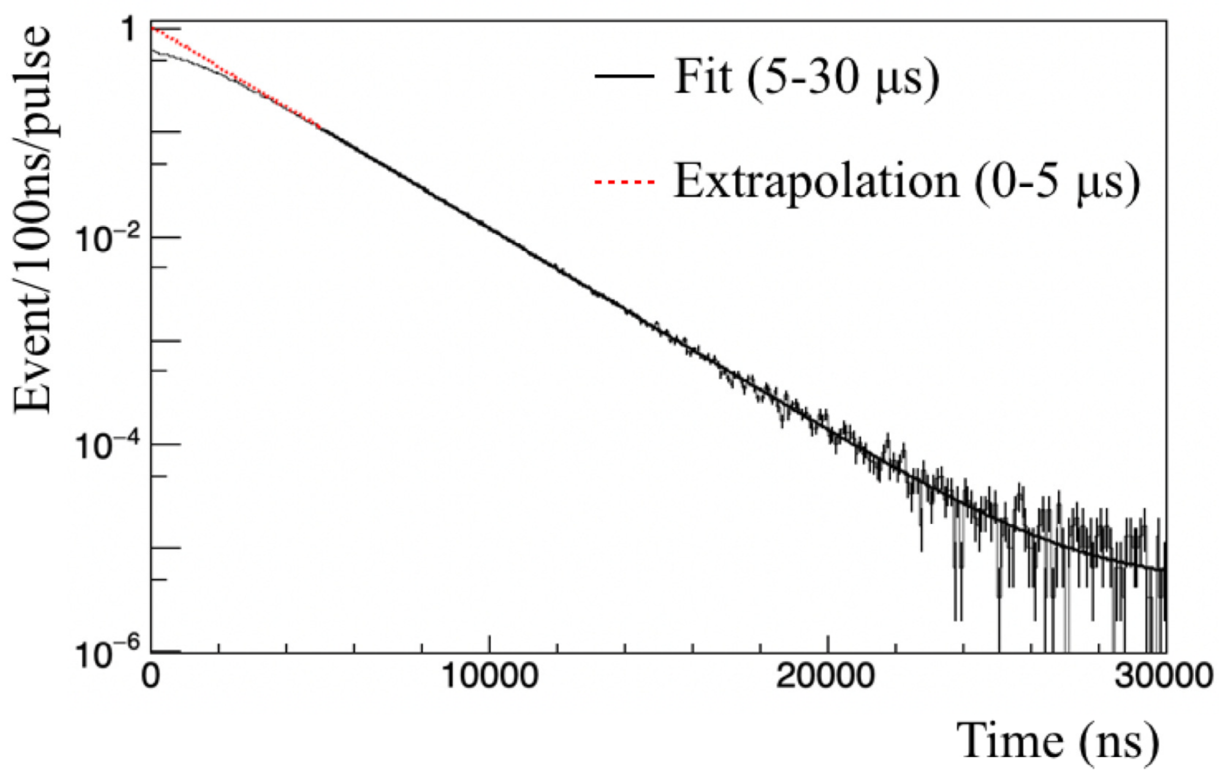



[ref.] K.M. Kojima, 計測システム研究会(2016).

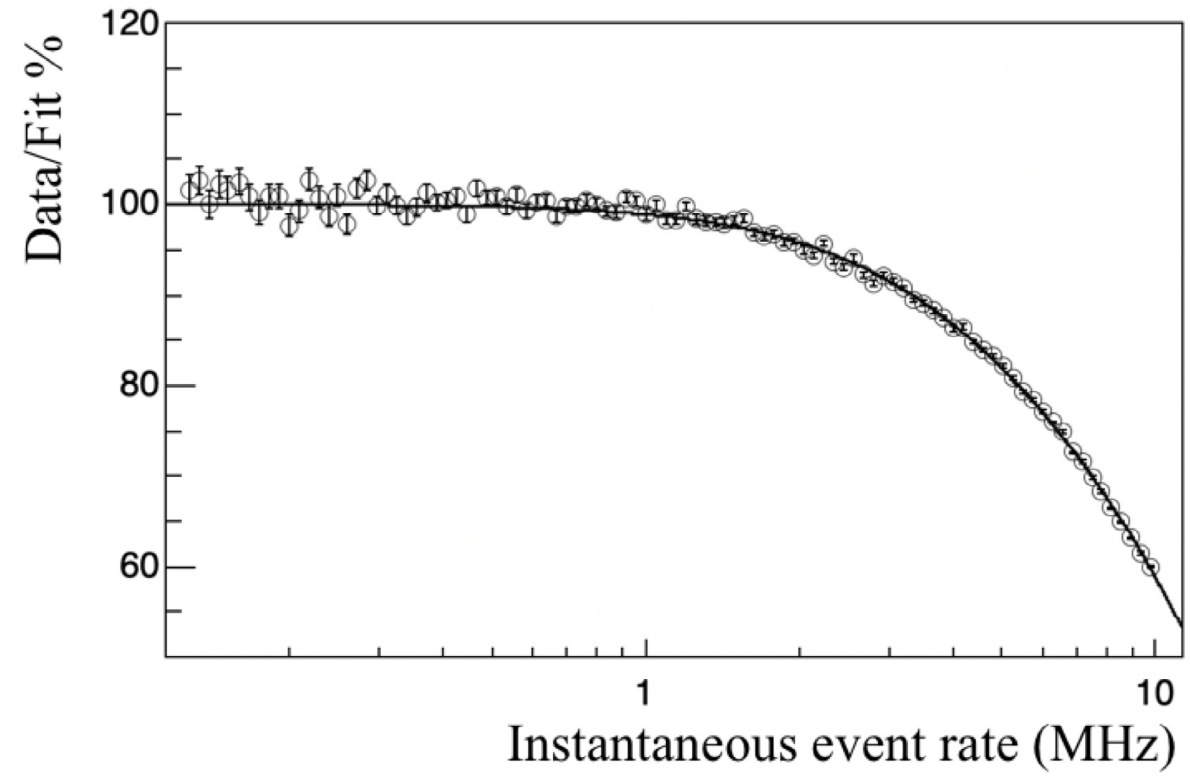
V2012 is fast with undershoot, V2014 has a longer tail without undershoot.

# Decay Positron Time Spectrum

## Pileup counting loss




Decay positron time spectrum and a result of exponential fitting.



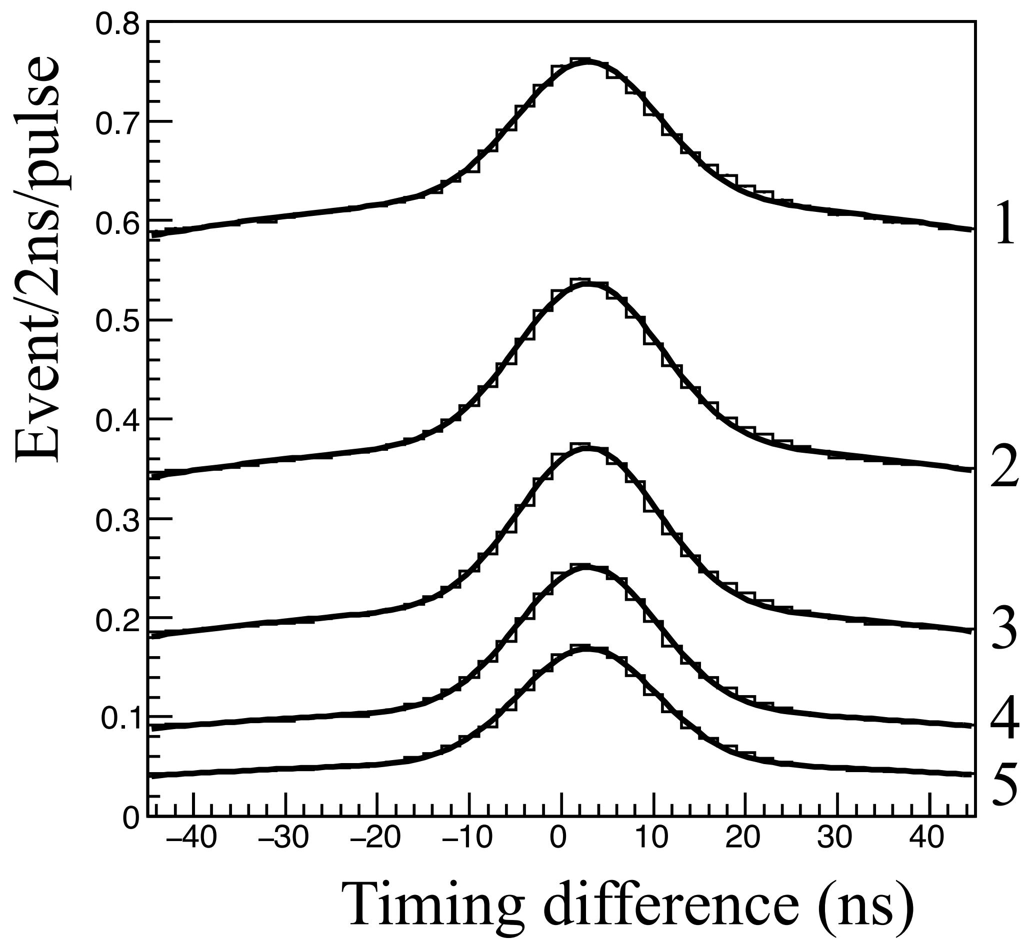

Pileup event loss as a function of the positron counting rate.

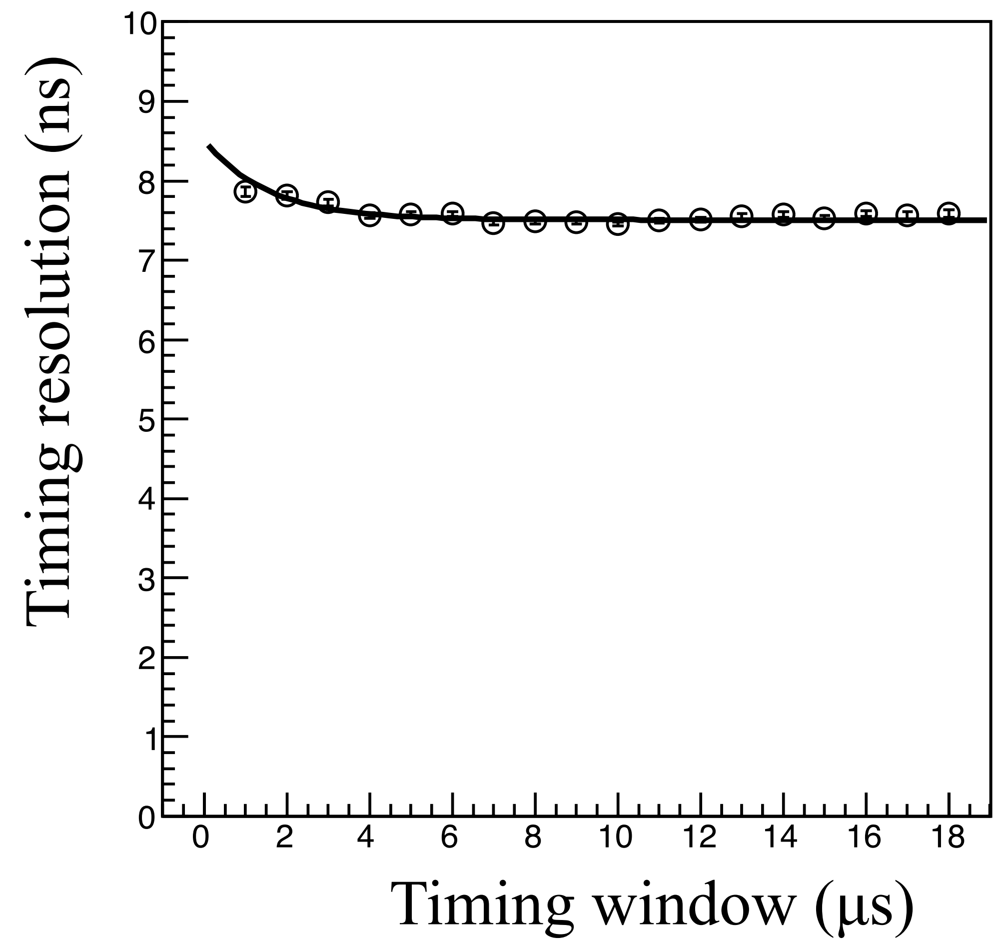
- Data from a positron detector for the MuSEUM experiment [1].
- An extended pulse-height analyzer (PHA) windowing model[2] well fits data.


[1] S. Kanda et al., arXiv:2004.05862 [hep-ex], submitted to Phys. Lett. B.
[2] T. Ida and Y. Iwata, J. Appl. Cryst. 38, 426-432 (2005).

# Timing Resolution

## Hit timing difference between coincidence hits




- Better performance is expected with the $\mu$SR spectrometer because the scintillator is thicker (3 mm->10 mm).
- Even with this performance, the pulse width of the beam is 100 ns, which is sufficient for practical use.

# Kalliope Upgrade

## Why necessary?

○ Xilinx Spartan6 is discontinued.

→ Migrating to 7-series.

○ Beam intensity will increase.

→ x10 at H-Line, x50~100 at the 2nd-target station??

○ Ultra slow muon with a short pulse width (10 ns ~ sub-ns).

→Better timing resolution is necessary.

→ A new electronics using FGATI [1]?

→Better S/N is necessary.

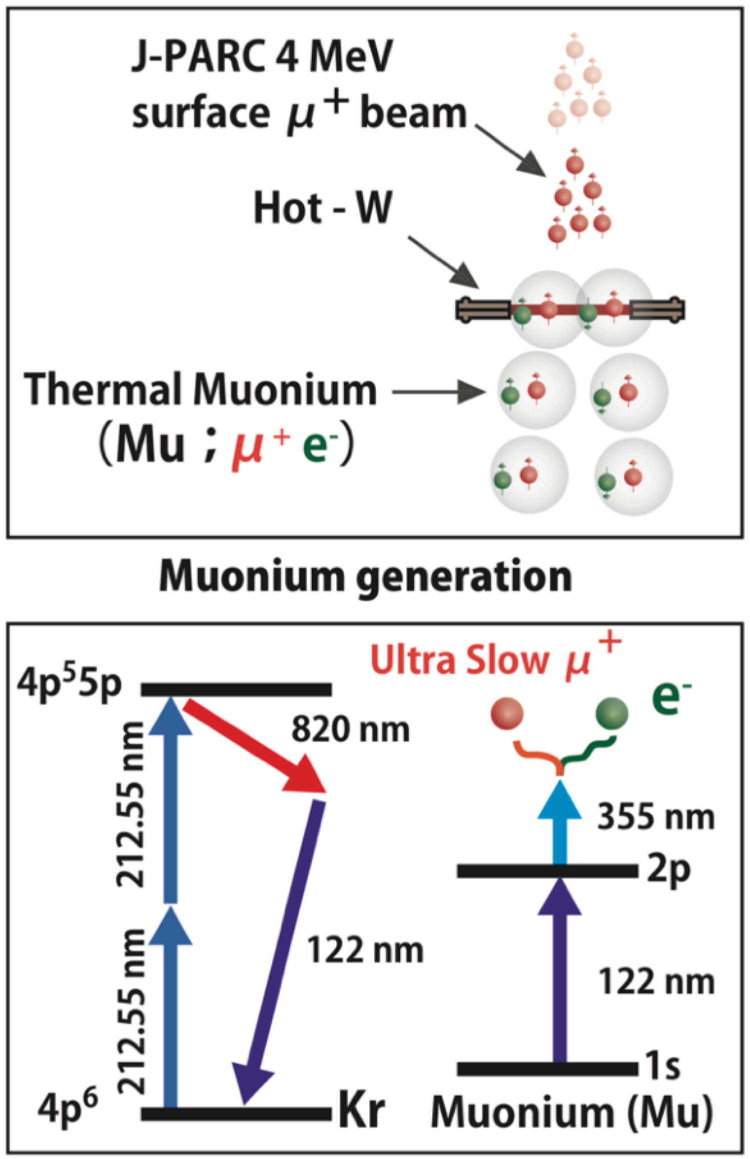
→ Energy measurement (or waveform measurement)?

→ Positron tracking?

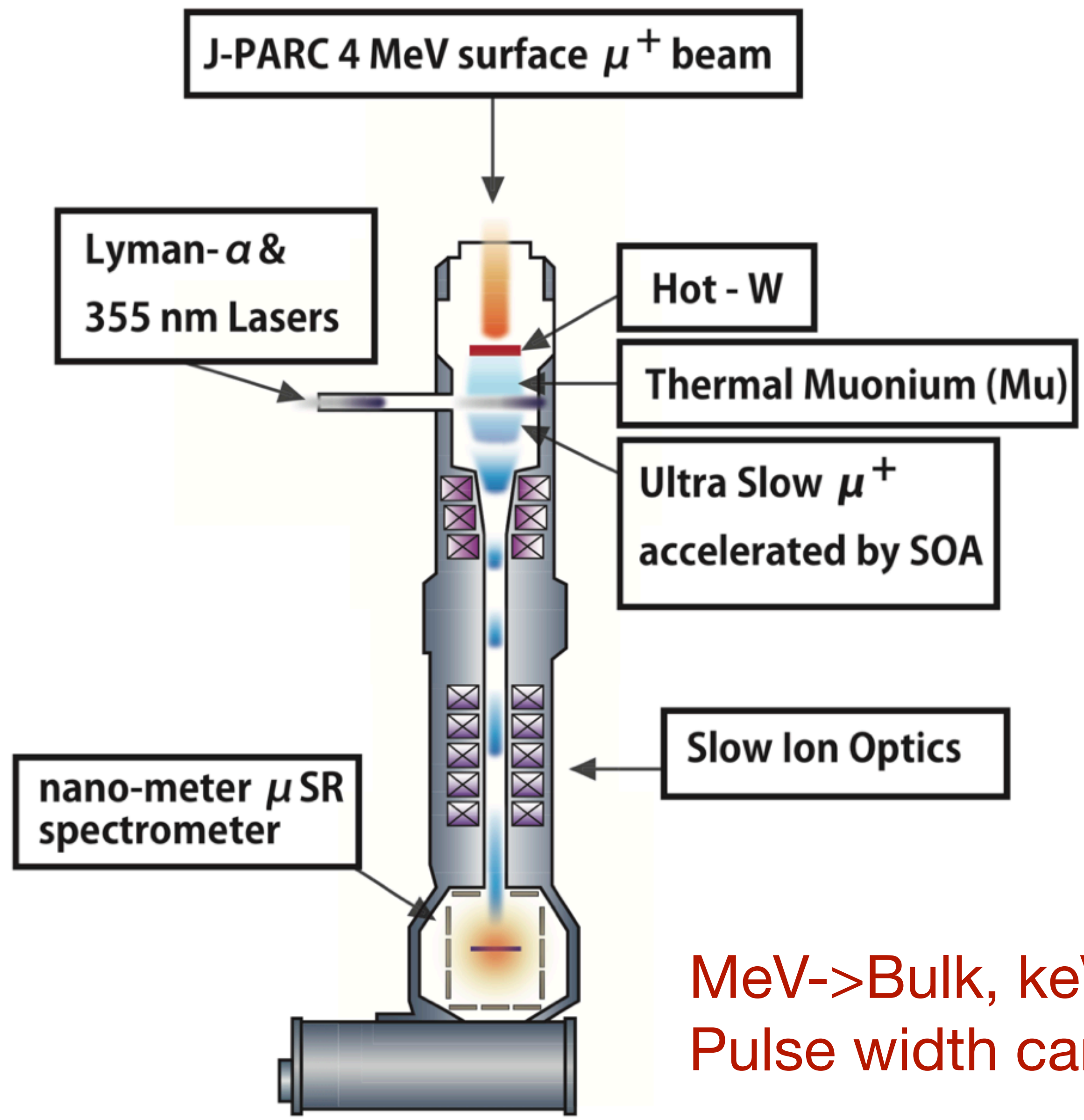
[1] Designed by M.Tanaka (KEK), tested by T. Ishida (Osaka pref. Univ.), K.M. Kojima (TRIUMF), J. deGooyer (Dalhousie Univ.), M. Miyahara (KEK) and M. Shoji (KEK).

# Ultra Slow Muon

## Resonant Ionization of Thermal Muonium




Ultra Slow $\mu^+$ generation by
Laser Resonant Ionization of Mu




MeV->Bulk, keV->Surface
Pulse width can be ~1 ns

Y. Miyake et al., “Current status of the J-PARC muon facility, MUSE”, J. Phys.: Conf. Ser. 551,012061(1-7) (2014)

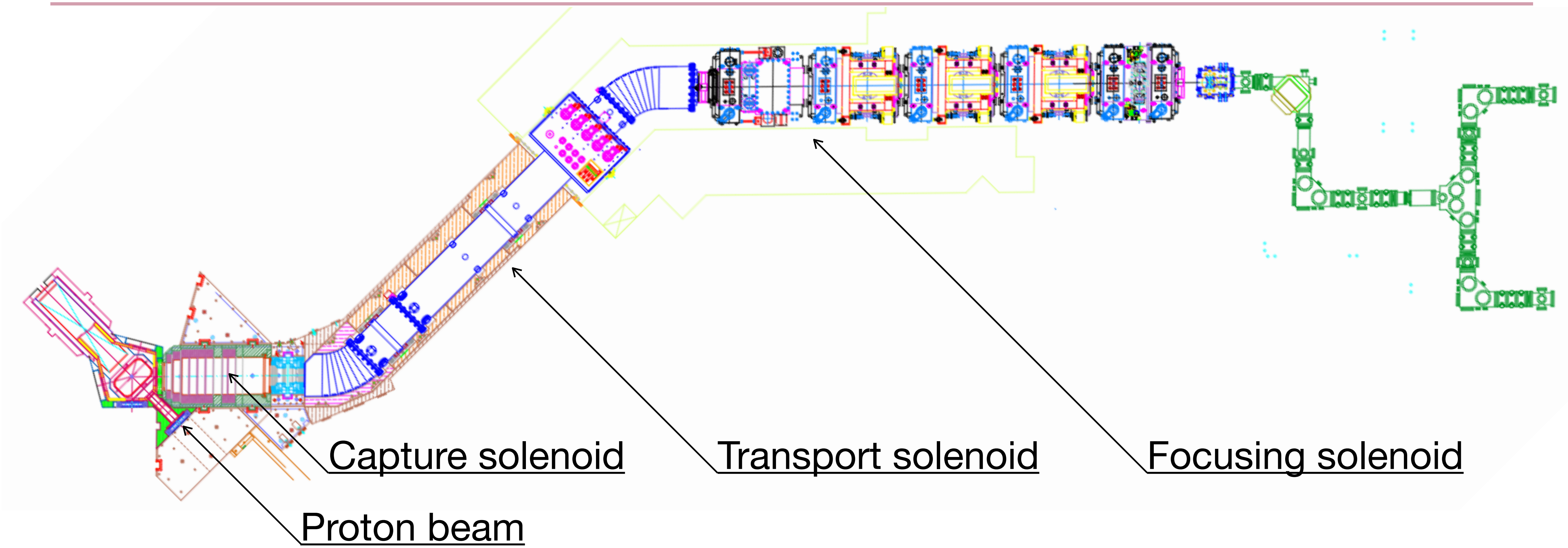
# Ultra Slow Muon

## Key technology for the future of muon science

- USM has good points of continuous beams (high timing resolution) and pulsed beams (high intensity)
- For material science
  - Depth-scanning measurement with nm-resolution.
- For particle/nuclear physics
  - Essential process towards muon/muonium cooling for future precise experiments.
  - Muon g-2/EDM, Muon Trapping, Muonium BEC···

# U-Line at J-PARC MLF MUSE

## Super-Omega, all-solenoids high-intensity beam line

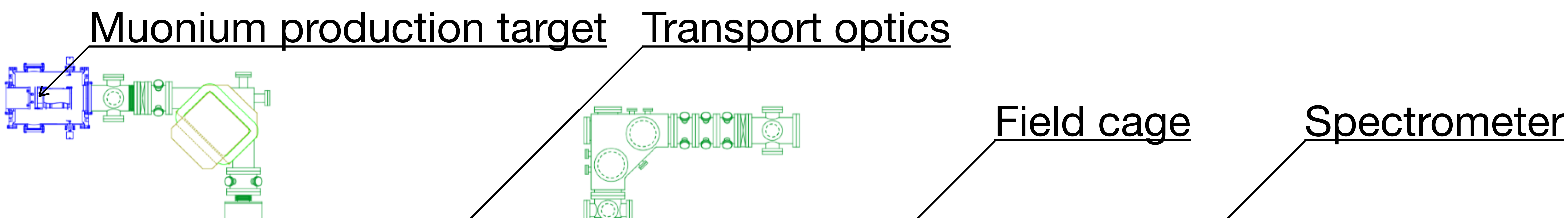


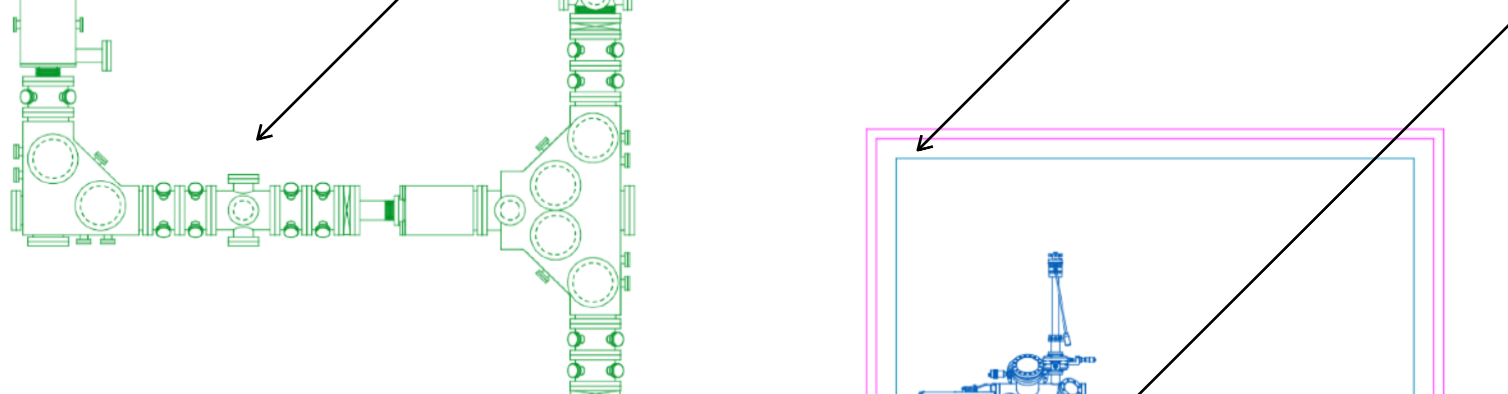

- Highest-intensity muon beam line consisting of a capture solenoid with large-acceptance [1], a curved solenoid for charge-selection [2], and axial-focusing solenoids with Wien filters [3].
- The intensity of surface muon is $6.4 \times 10^7$ $\mu^+$/s at 212 kW [4] (~$3 \times 10^8$ $\mu^+$/s at 1 MW).

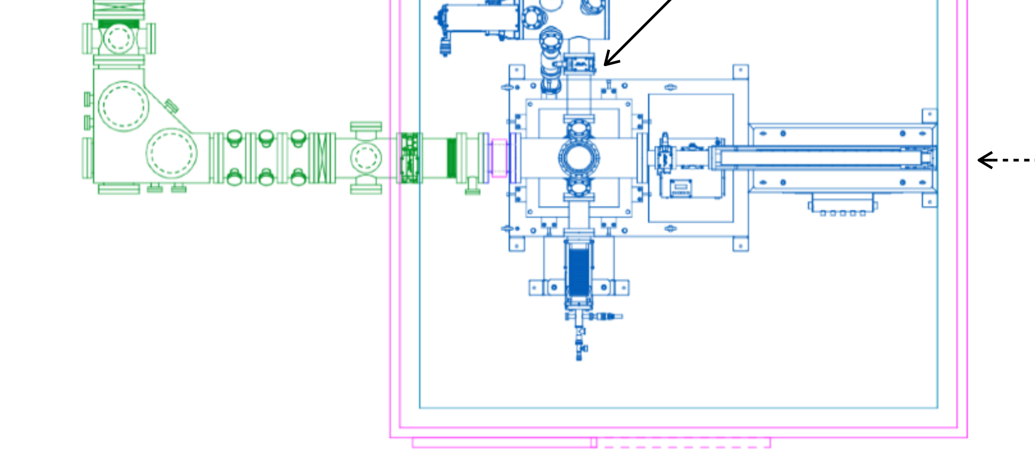
[1] K. Nakahara et al., "The super omega muon beamline at J-PARC", NIM A 600 (2009) 132-134.
[2] P. Strasser et al., "Superconducting curved transport solenoid with dipole coils for charge selection of the muon beam", NIM B 317 (2013) 361-364.
[3] Y. Ikedo et al., "Positron separators in Superomega muon beamline at J-PARC", NIM B 317 (2013) 365-368.
[4] Y. Miyake et al., "J-PARC muon facility, MUSE ", JPS Conf. Proc. 21, 011054 (2018).

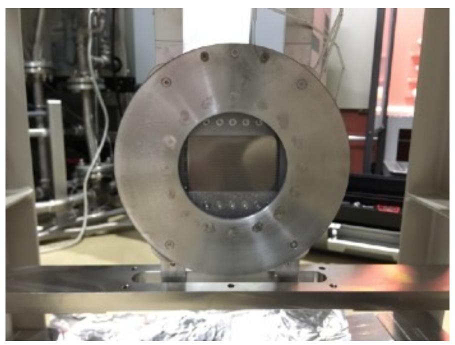
# U-Line at J-PARC MLF MUSE

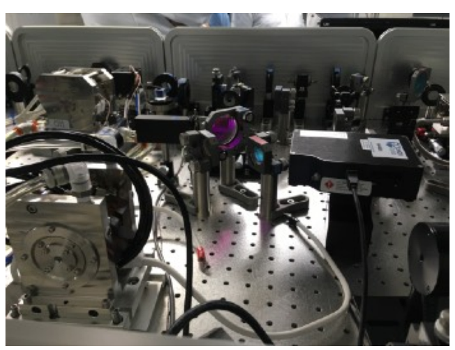
## Slow Muon Optics and $\mu$SR instruments

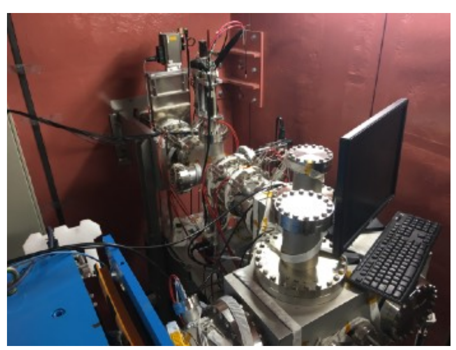


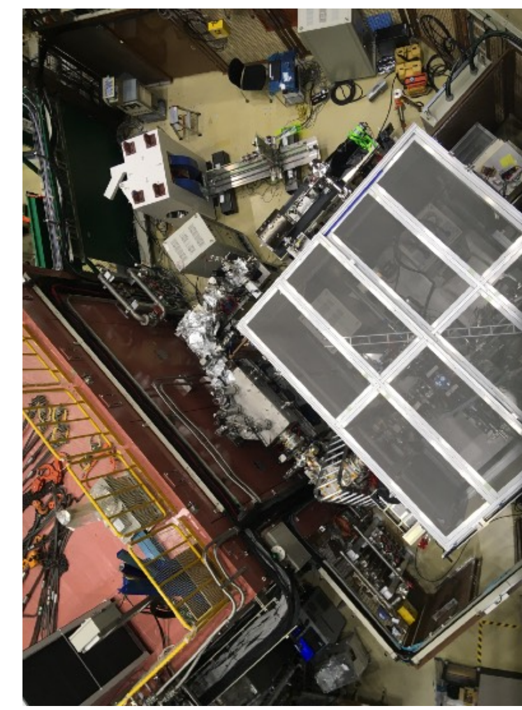






Tungsten target


Laser system


Slow optics

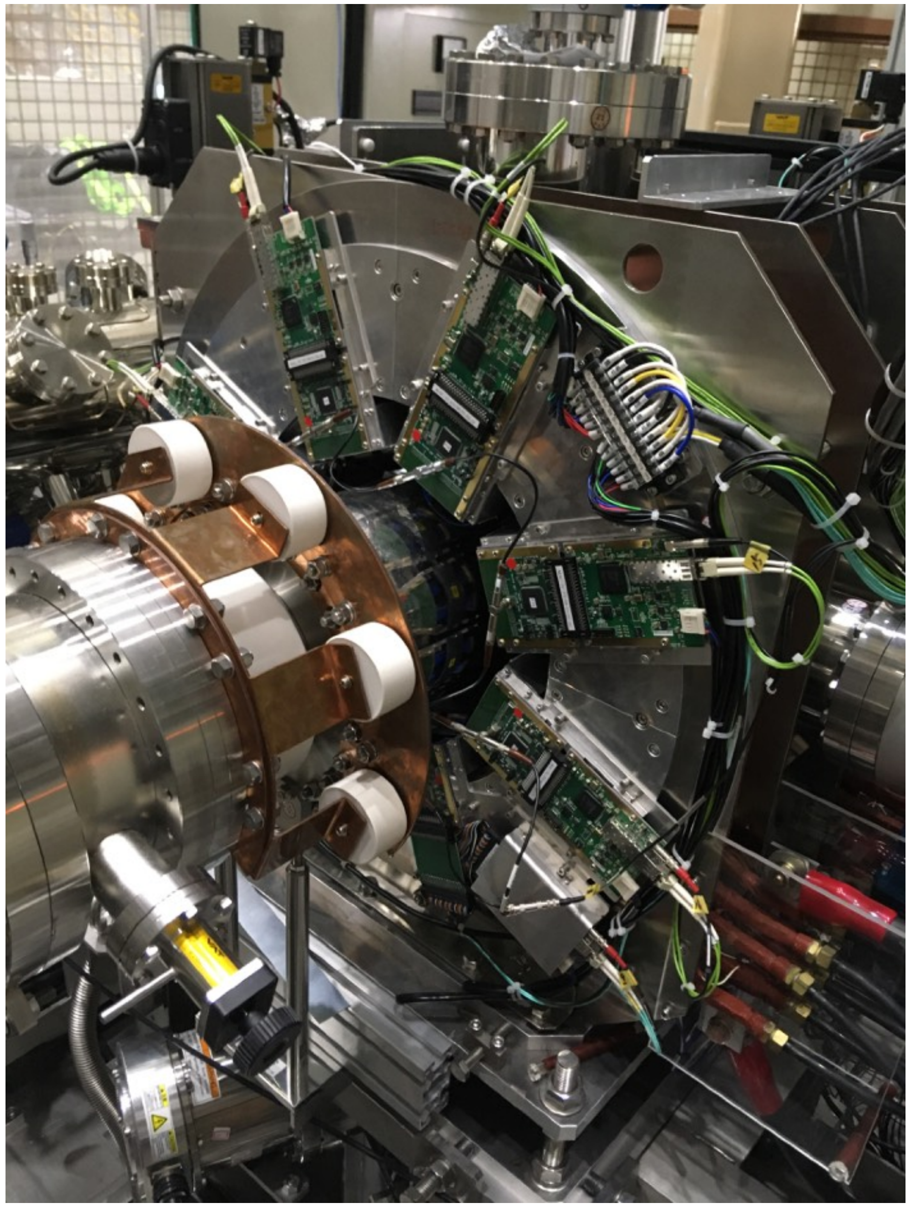

Field cage

- ○ Thermal muonium production from a hot-tungsten thin film.
- ○ Laser ionization of muonium and electrostatic acceleration of slow muons.
- ○ Energy tuning using a high-voltage stage with a spectrometer (0~30 keV).

# $\mu$SR Spectrometer for USM

## Segmented positron counters with SiPM readout

- Scintillation counter consisting of scintillator blocks, SiPMs, and Kalliope. 512 channels.
- The event rate is lower than that at neighboring ports, but the S/N should be higher, and the timing resolution muse be better (sub-ns).
- Sources of background positrons are different from other ports (Mu target, back scattering).

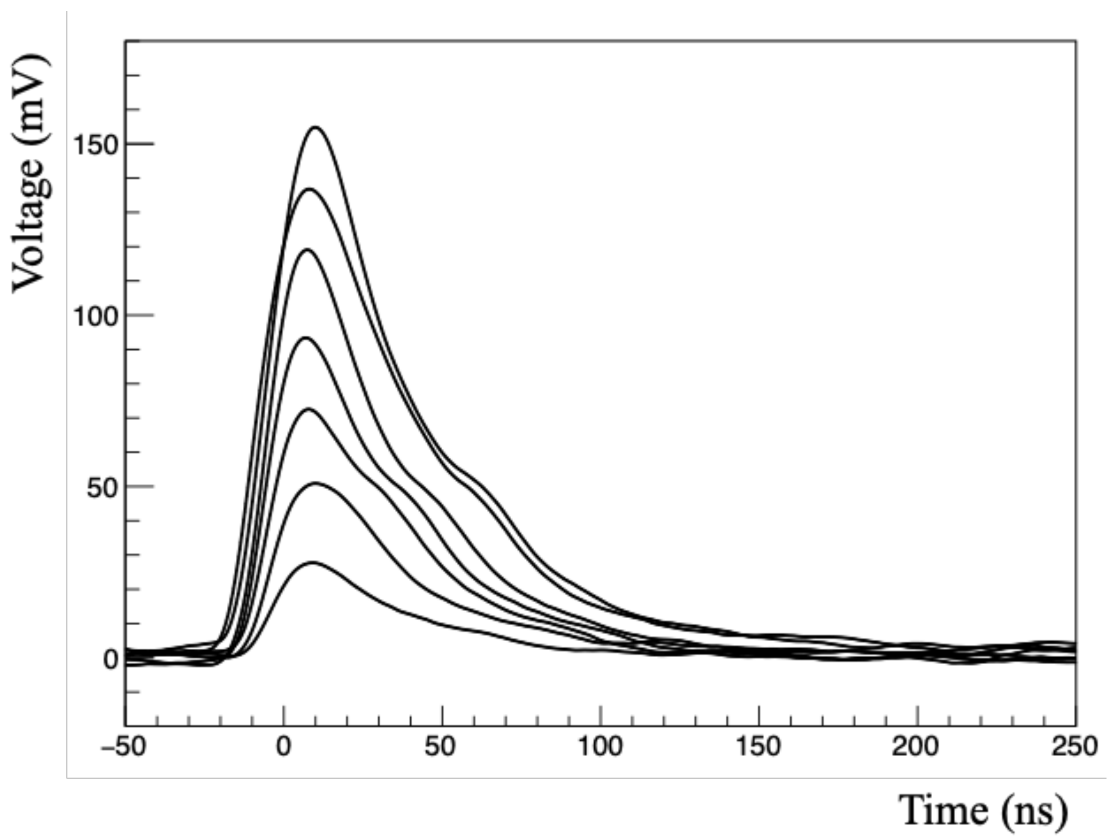


Positron rate : 1/1000 of ARTEMIS
Beam timing width : 1/10 of S1

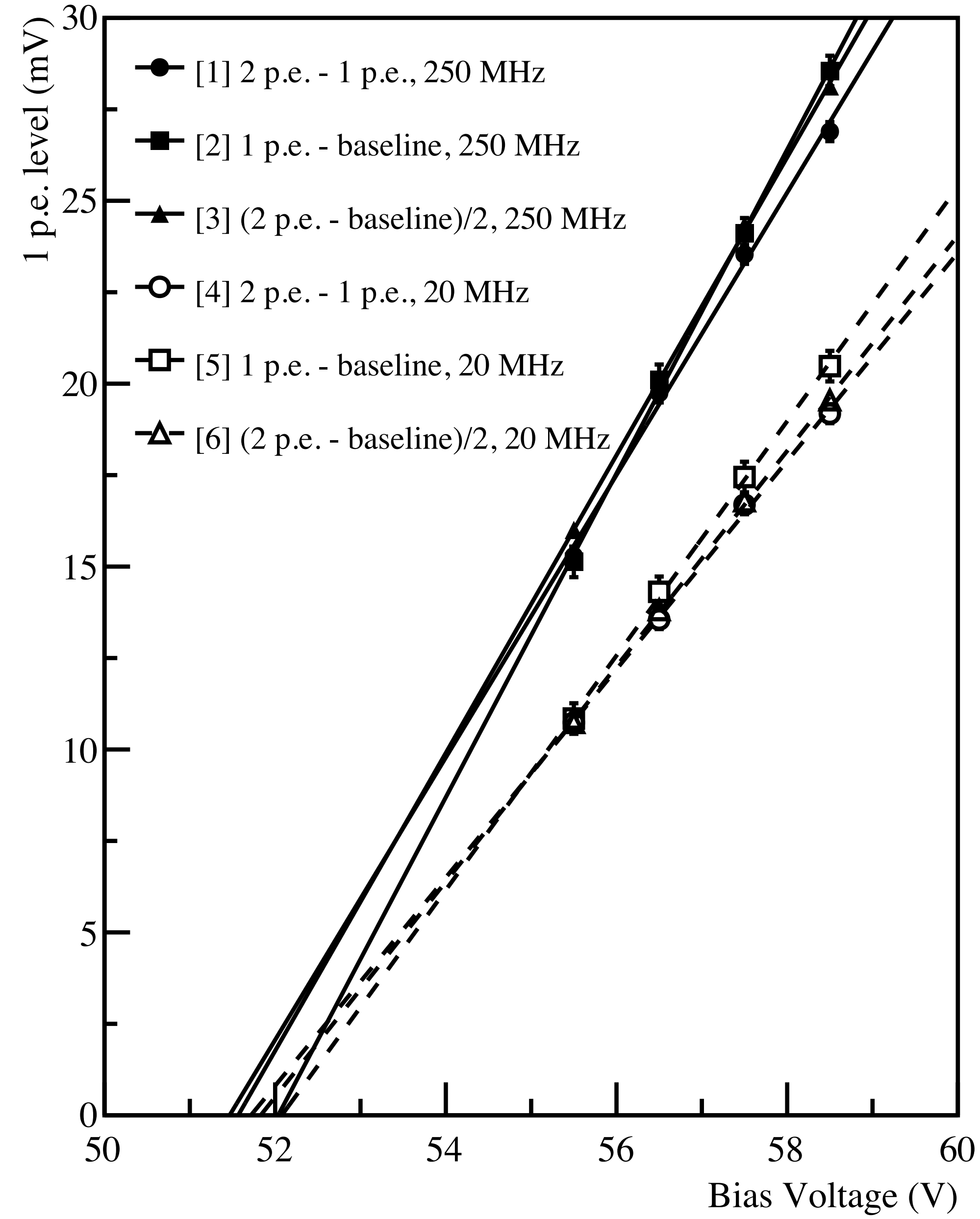
# Commissioning of the Spectrometer

## Optimization of the operation parameters

- SiPM bias voltage
- Pole-zero cancelation
- Discriminator threshold




Analog signal waveforms, quantized by the number of photons.

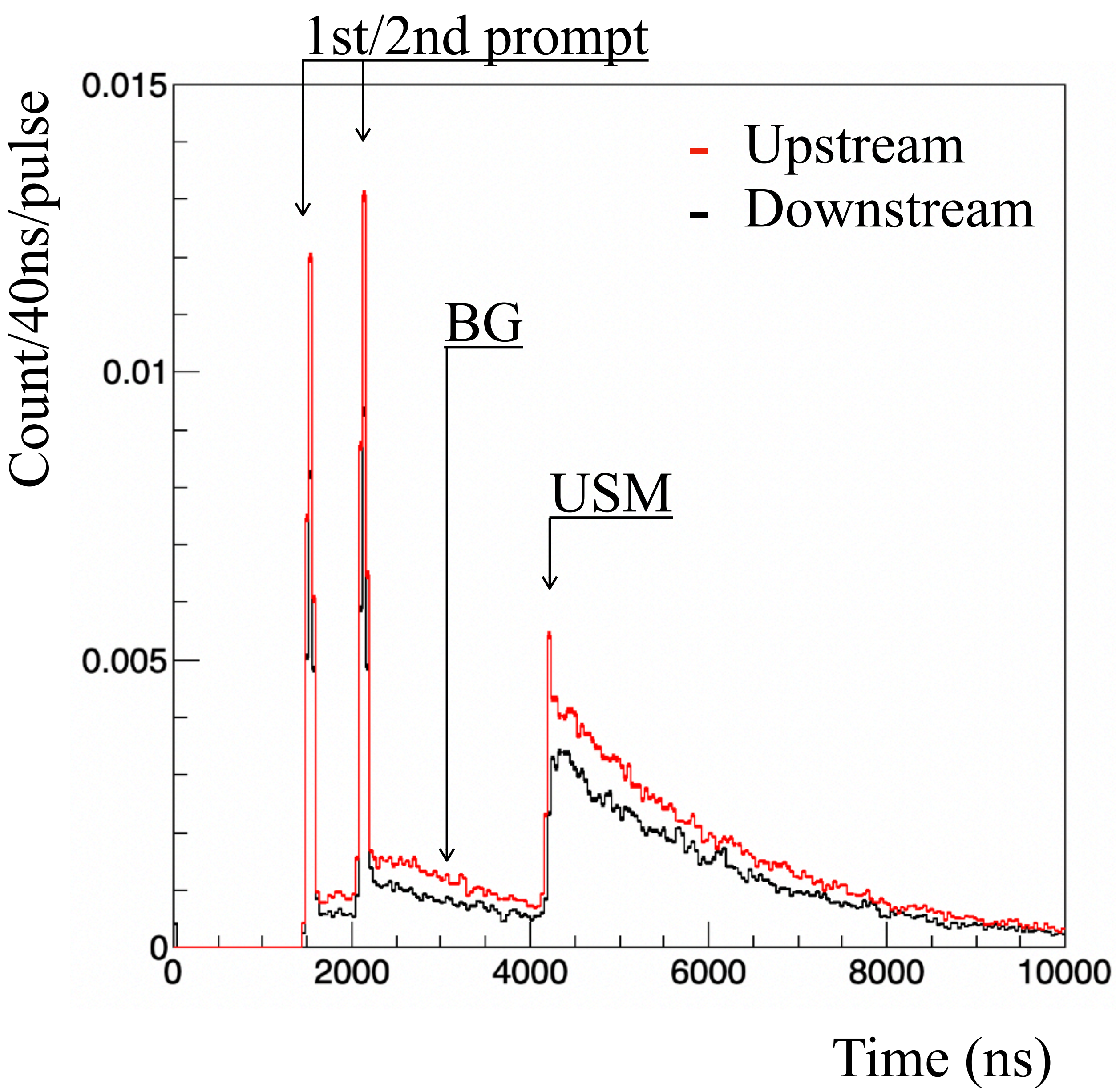


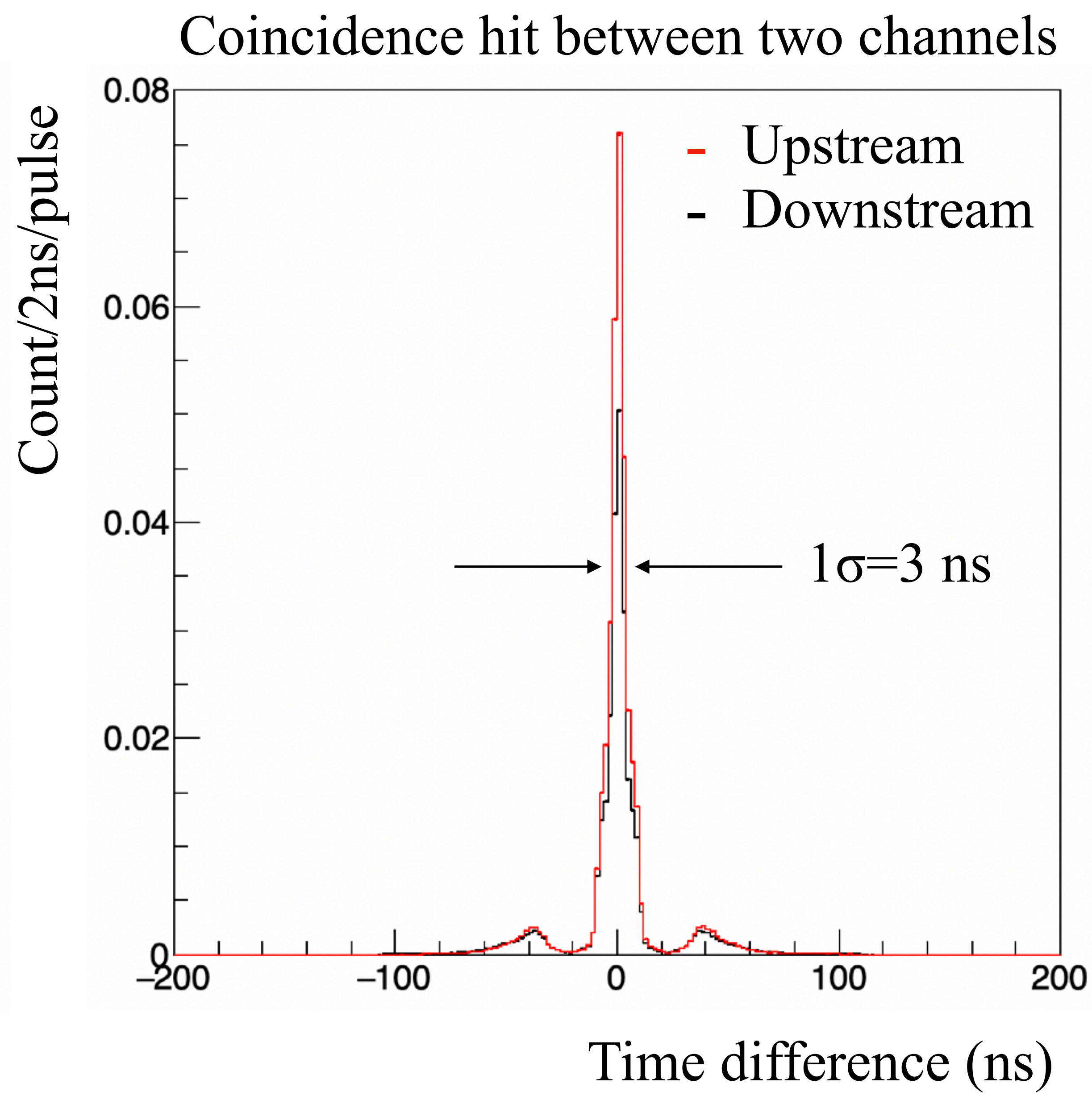

Signal height's bias voltage dependence.

# Commissioning of the Spectrometer

## Performance test using the ultra slow muon beam

- Decay positron measurement (S/N, timing resolution)

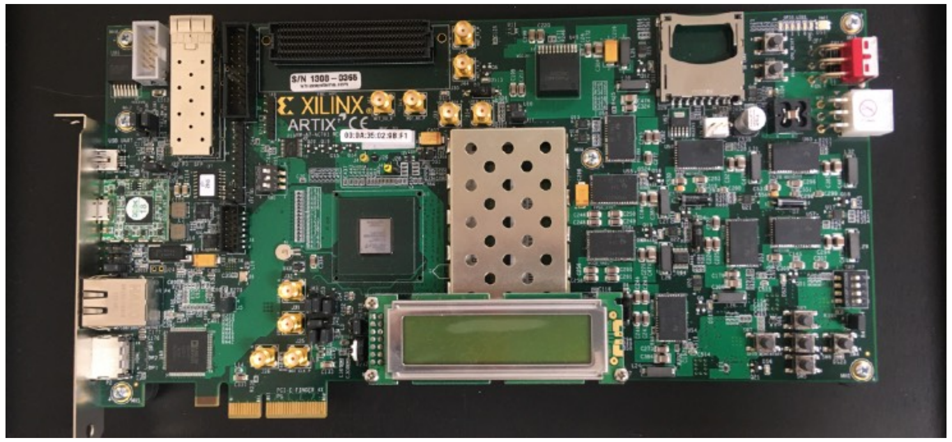


# What's Going On?

## R&D in progress

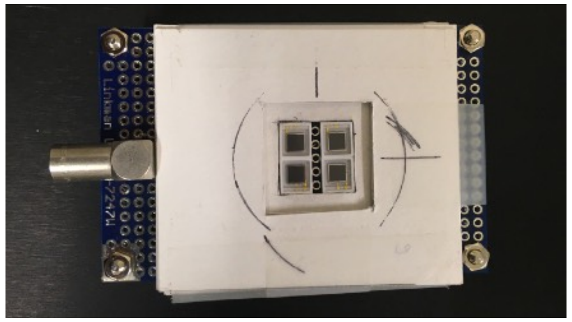
- Migration from Spartan6 to Artix7

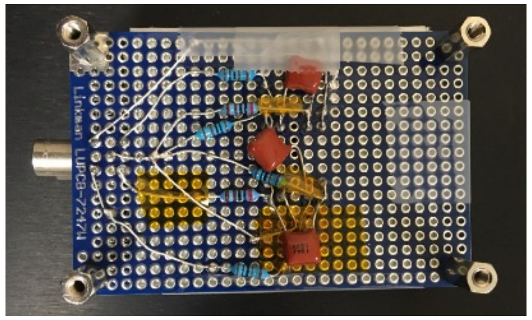



Development using an evaluation board is in progress.

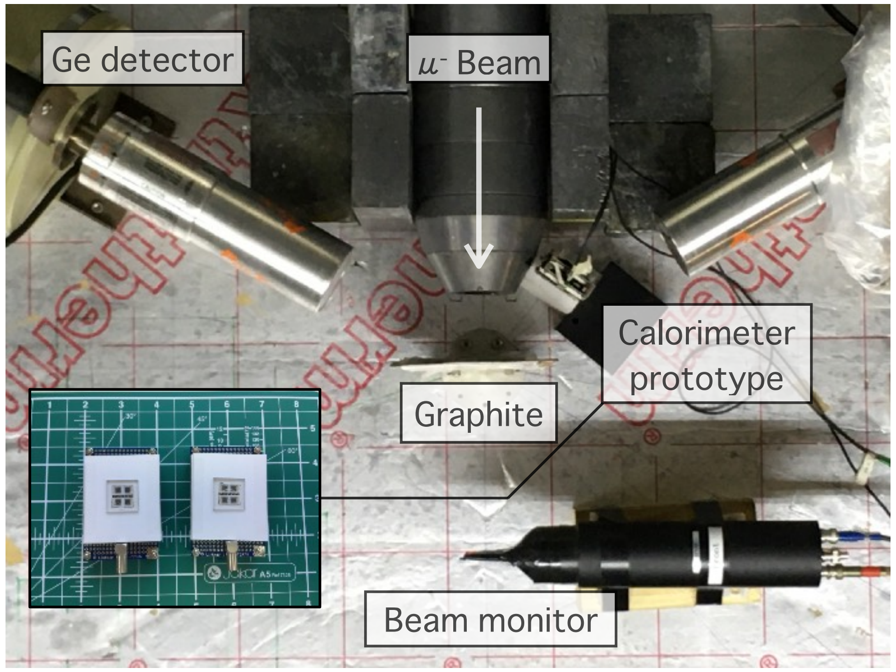
Thanks to M. Shoji (KEK), K.M. Kojima (TRIUMF),
T. Ishida (Osaka pref. Univ.), A. Sato (Osaka univ.), D. Tomono (Osaka univ.), and Open-It.

- Hybrid readout of SiPMs





A prototype with MPPCs+LYSO was developed.




The prototype was tested at RIKEN-RAL.

# Summary

## and Outlook

- Muon provides a wide range of opportunities to explore science, such as particle, nuclear, atomic, molecular, and condensed matter physics.
- J-PARC MLF MUSE delivers world's highest intensity pulsed muons, which enable experiments not possible at other facilities.
- The key is the muon spin spectrometer. A system called Kalliope is in operation.
- The sophistication of advanced instruments is indispensable for next-generation high-precision experiments. R&D for that purpose is in progress.
- Among them, the ultra slow muon beamline and the spectrometer are of importance and being commissioned.