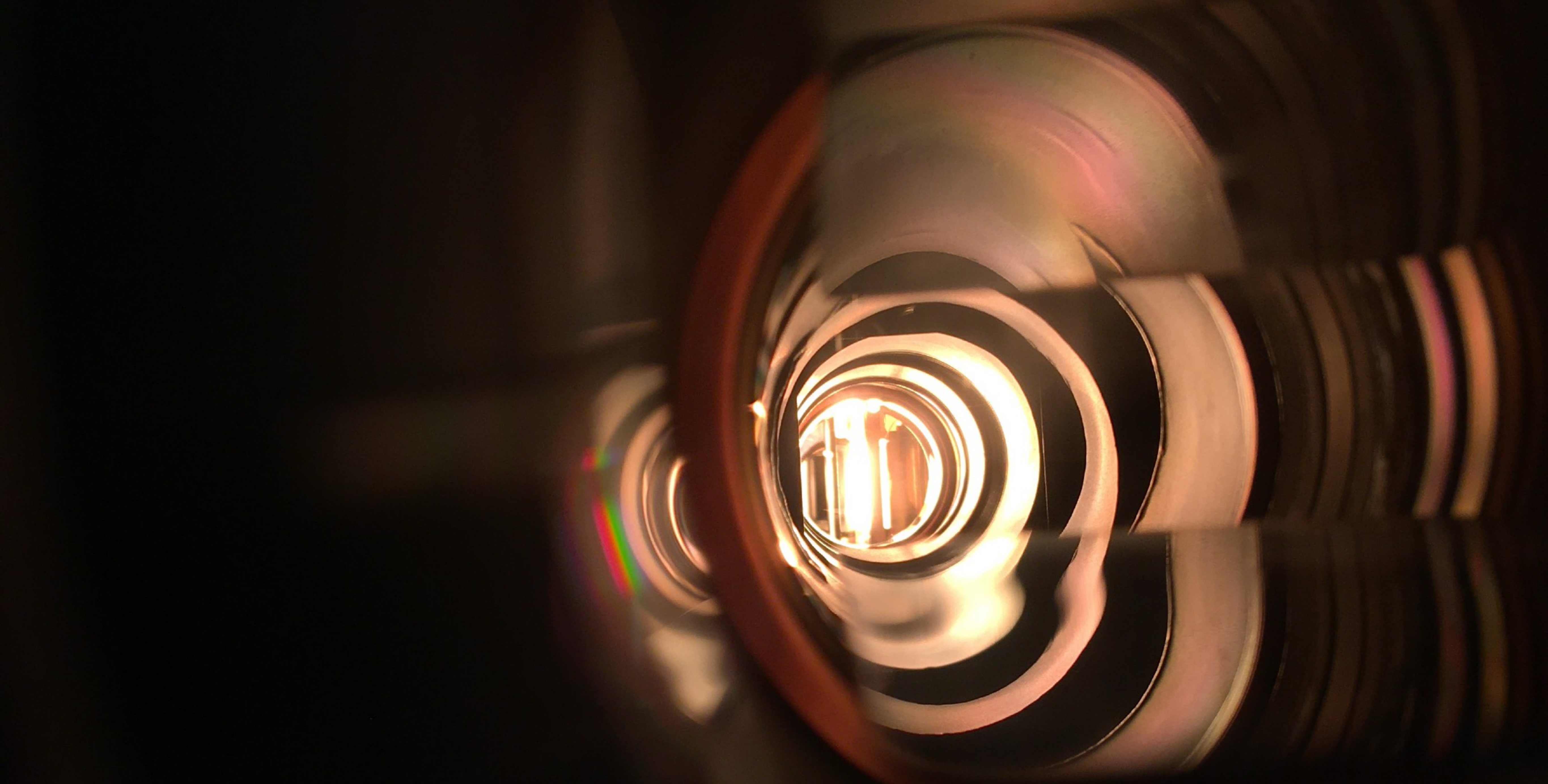
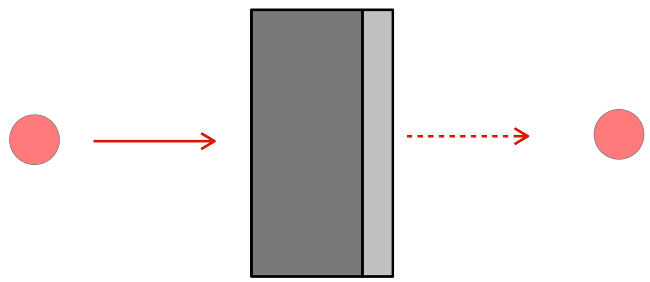


Depth-Resolved μSR Using Ultra-Slow Muons at J-PARC MUSE

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

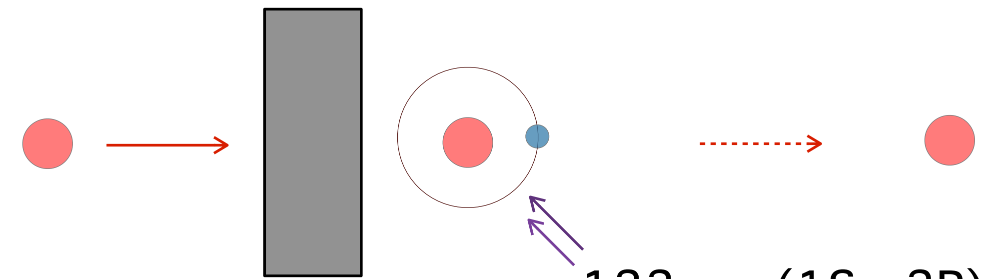
Low-Energy and Ultra-Slow Muons

Cold rare-gas moderator (LEM)



E. Morenzoni et al., PRL 72, 2793 (1994).

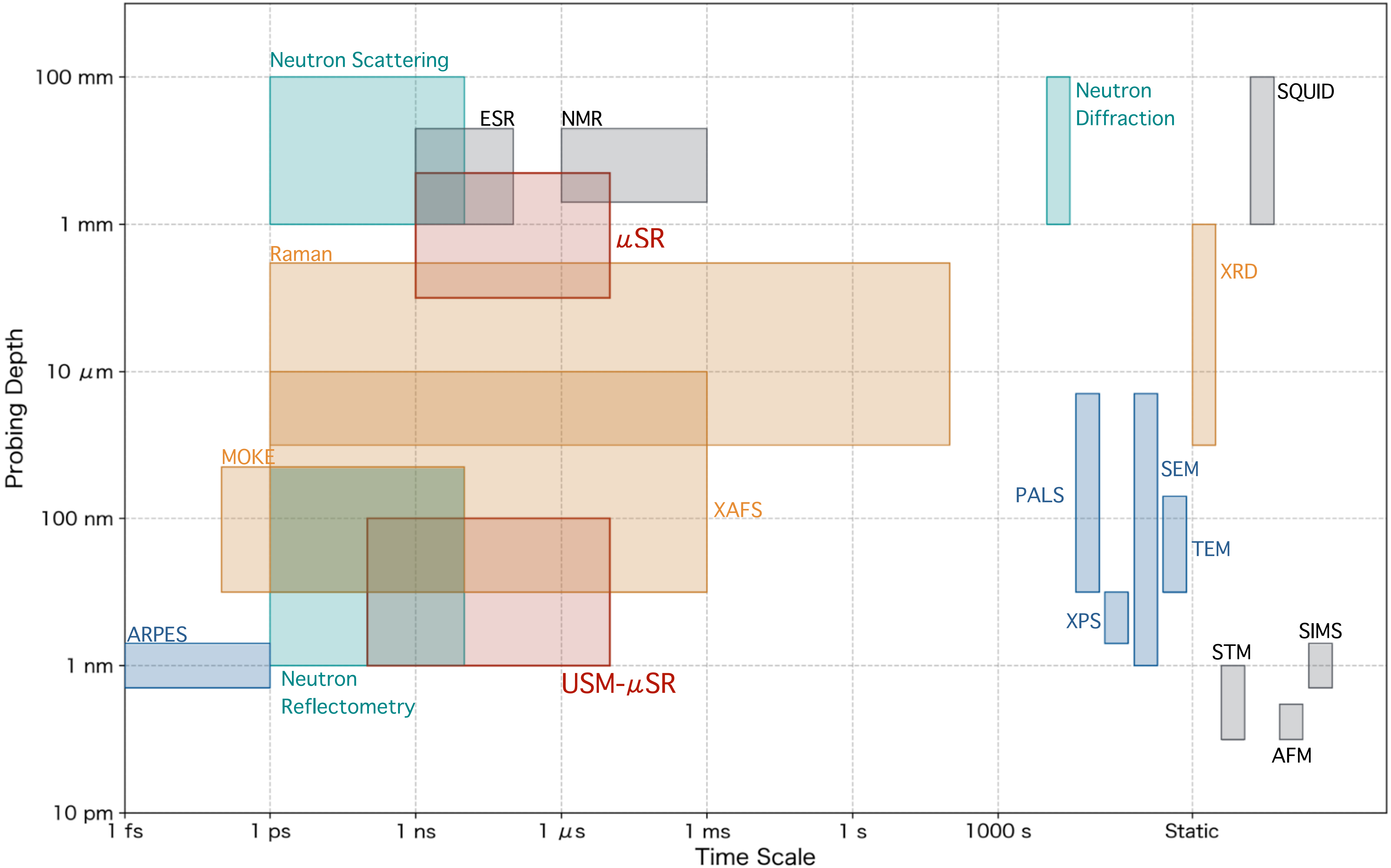
Laser ionization of muonium (USM)



K. Nagamine et al., PRL 74, 4811 (1995).

- Since surface muons act as a bulk probe, studying thin films and interfaces requires low-energy muons with a narrow energy spread.
- Due to the short lifetime of muons, the slowing down and cooling methods for stable atoms are not applicable.
- USM and LEM are promising methods to obtain slow muons.
- In particular, the USM technique defines the measurement's time origin using the ionization laser. This makes it possible to achieve high time resolution, even with a pulsed beam.

Landscape of Mat. Sci. Techniques

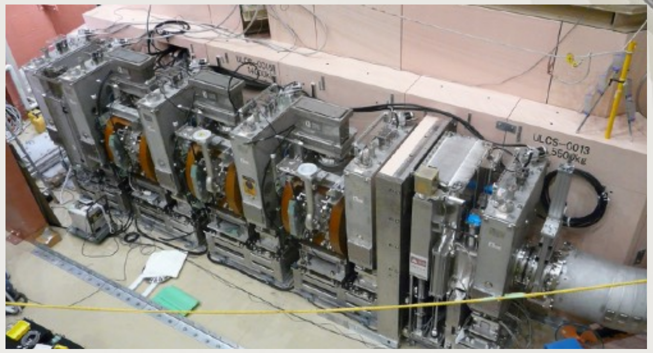


- Complementarity of multi-probes (dynamic/static, surface/sub-surface/bulk).

Ultra-Slow Muon Facility

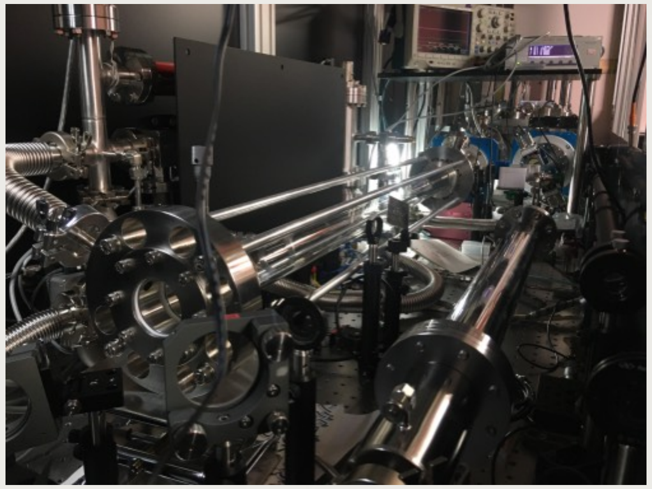
at J-PARC MLF MUSE

The Super-Omega
Surface muon beamline



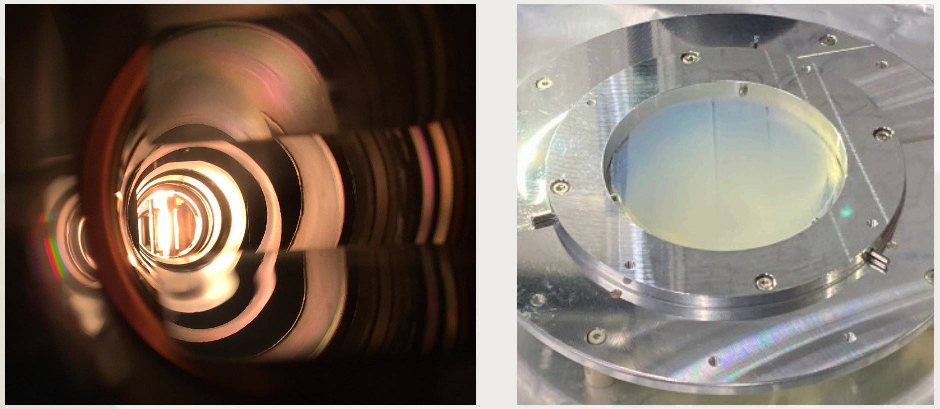
K. Nakahara et al., NIM A 600 (2009) 132-134.
P. Strasser et al., NIM B 317 (2013) 361-364.
Y. Ikedo et al., NIM B 317 (2013) 365-368.
N. Teshima et al., J. Phys. Conf. Ser. 2462, 012036 (2023).

Ionization laser

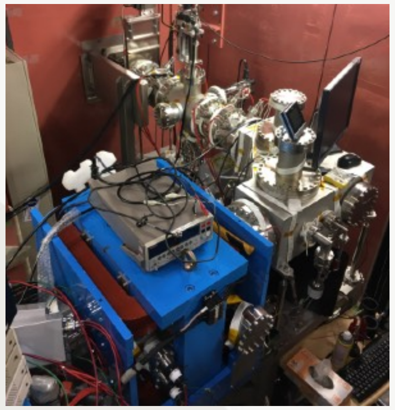


Y. Oishi et al., JPS Conf. Proc. 2, 010105 (2014).
N. Saito et al., Optics Express 24, 7566 (2016).
Y. Oishi et al.,, J. Phys.: Conf. Ser. 2462 012026 (2023).

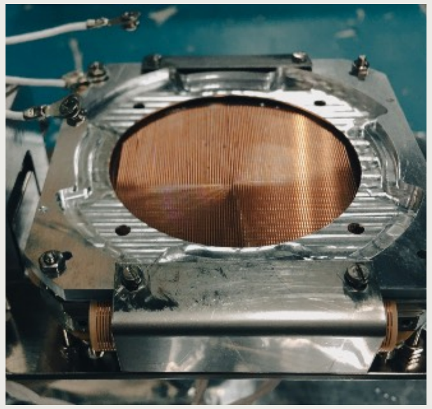
T. Nagatomo et al., JPS Conf. Proc. 2, 010102 (2014).
T. Adachi et al., JPS Conf. Proc. 8, 036017 (2015).
A. D. Pant et al., NIM A 929, 129 (2019).
S. Kanda et al., J. Phys. Conf. Ser. 2462, 012030 (2023).



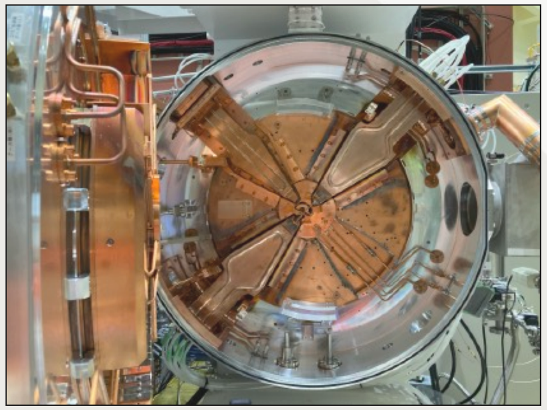
Muonium emitters



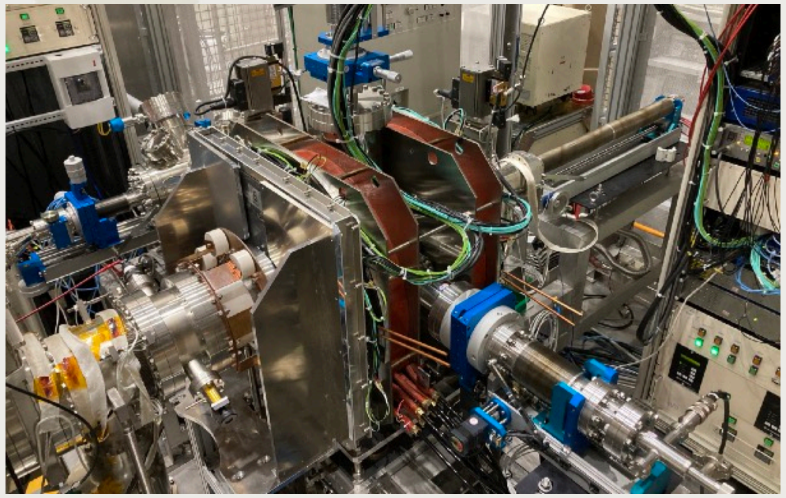
Transport optics



MCP-DLD
Beam monitor



Cyclotron at U1B
→Next talk



μSR Spectrometer at U1A

USM Development Timeline

2012 — First beam of Super-Omega
Y. Ikedo et al., NIM B 317 (2013) 365-368.

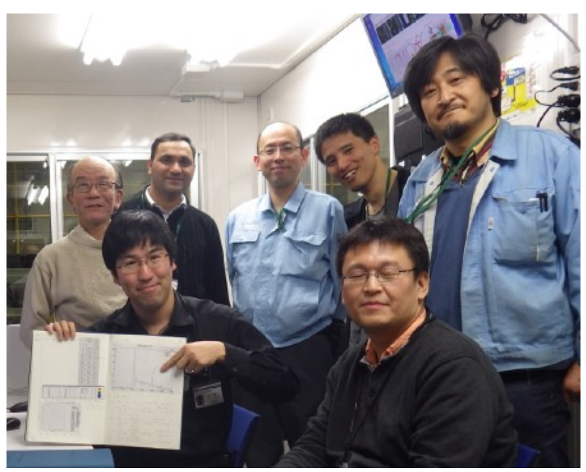
2013 — Lyman-α generation with all-solid laser
Y. Oishi et al., JPS Conf. Proc. 2, 010105 (2014).

2016 — USM generation
T. Adachi et al., KEK-MSL Progress Report. 2016-3 (2016) 13.

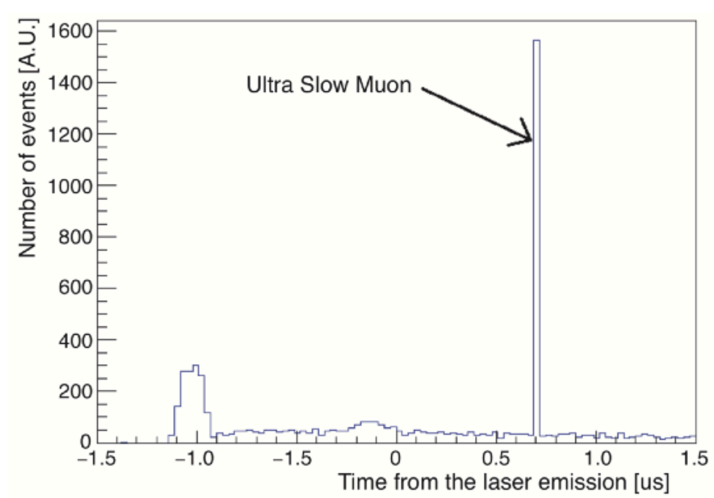
2018 — First USM-μSR
T. Adachi et al., KEK-MSL Progress Report. 2018-2 (2018) 13.

2020 — Multilayer USM-μSR
S. Kanda et al, J. Phys.: Conf. Ser. 2462 012030 (2023).

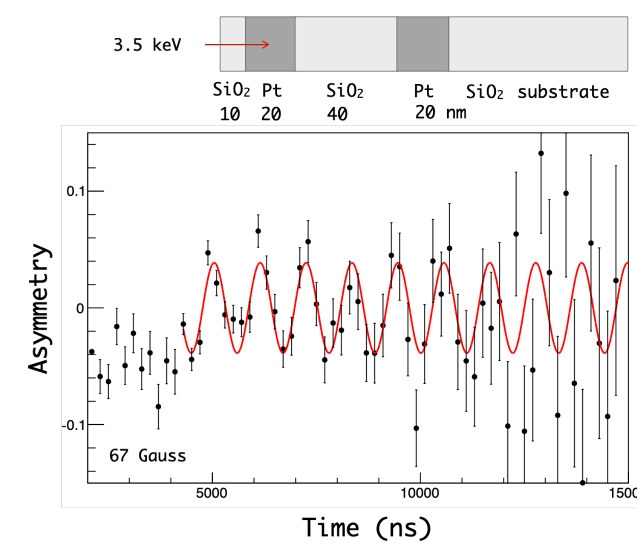
First Ly-α
2013



First USM
2016

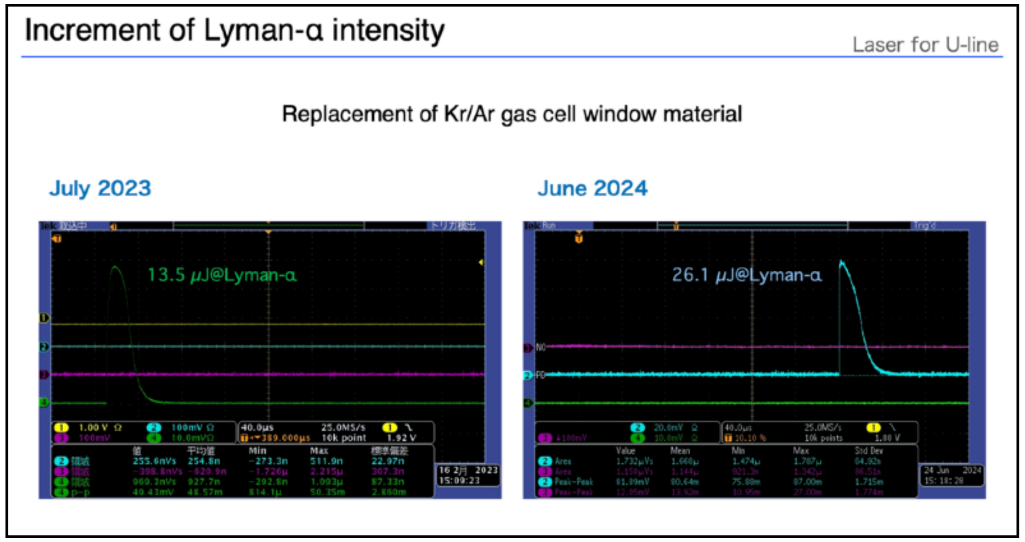


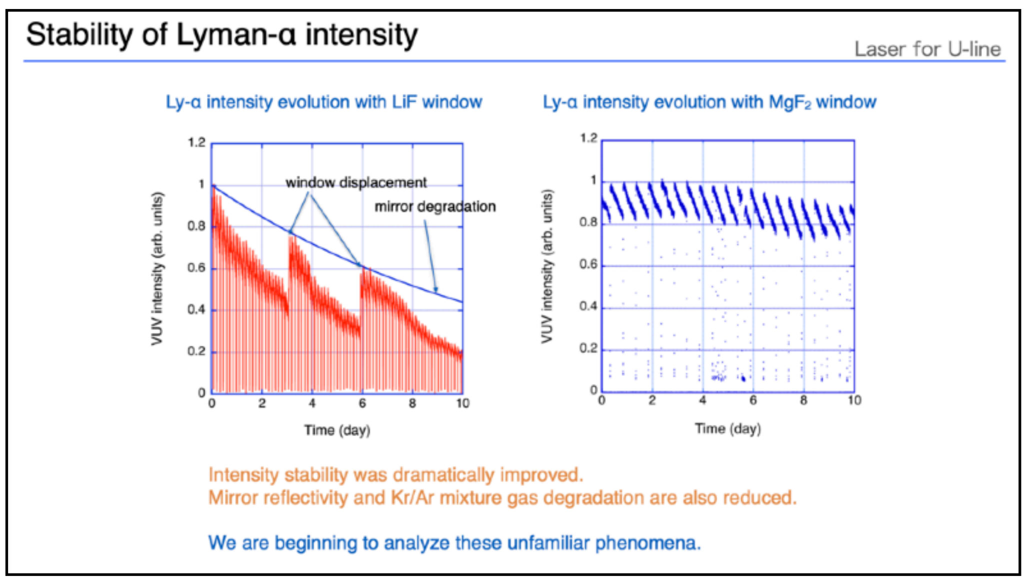
USM time-of-flight
2016



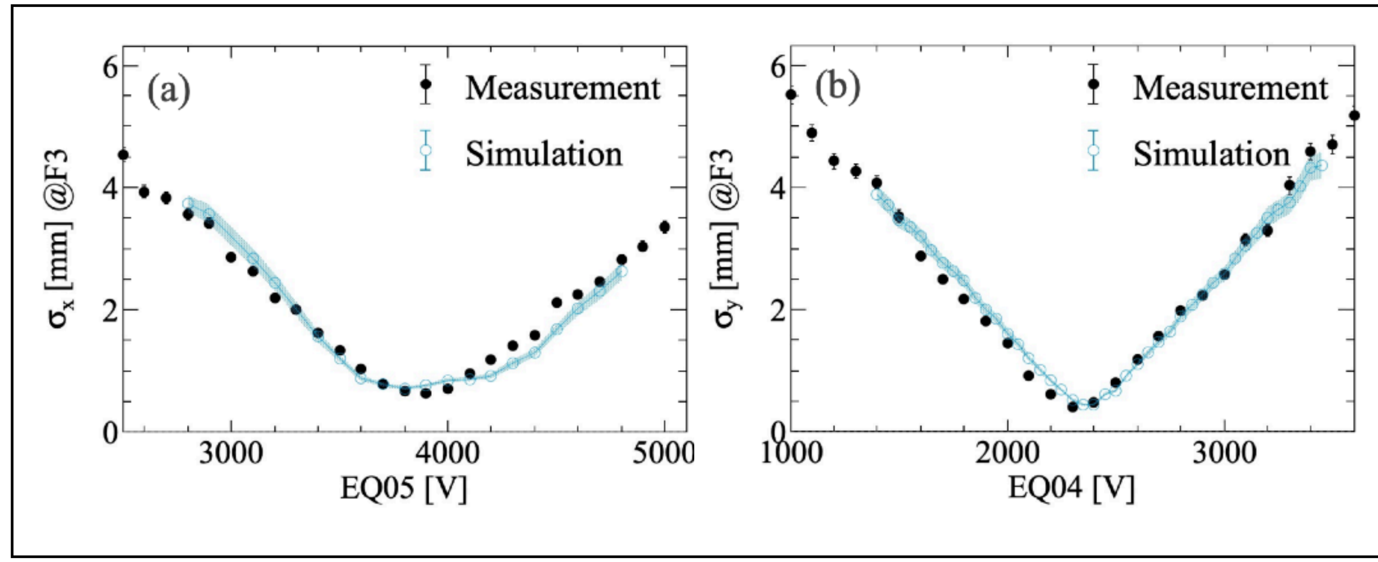
USM-μSR asymmetry
2020

Recent USM Development

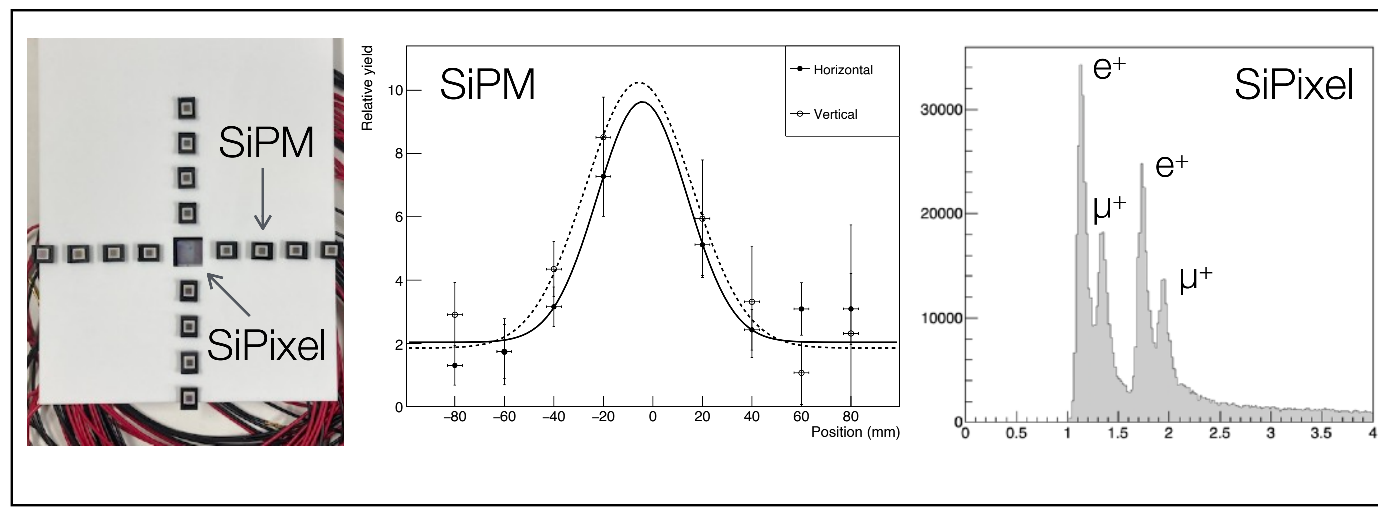




Laser improvements (Y. Oishi)



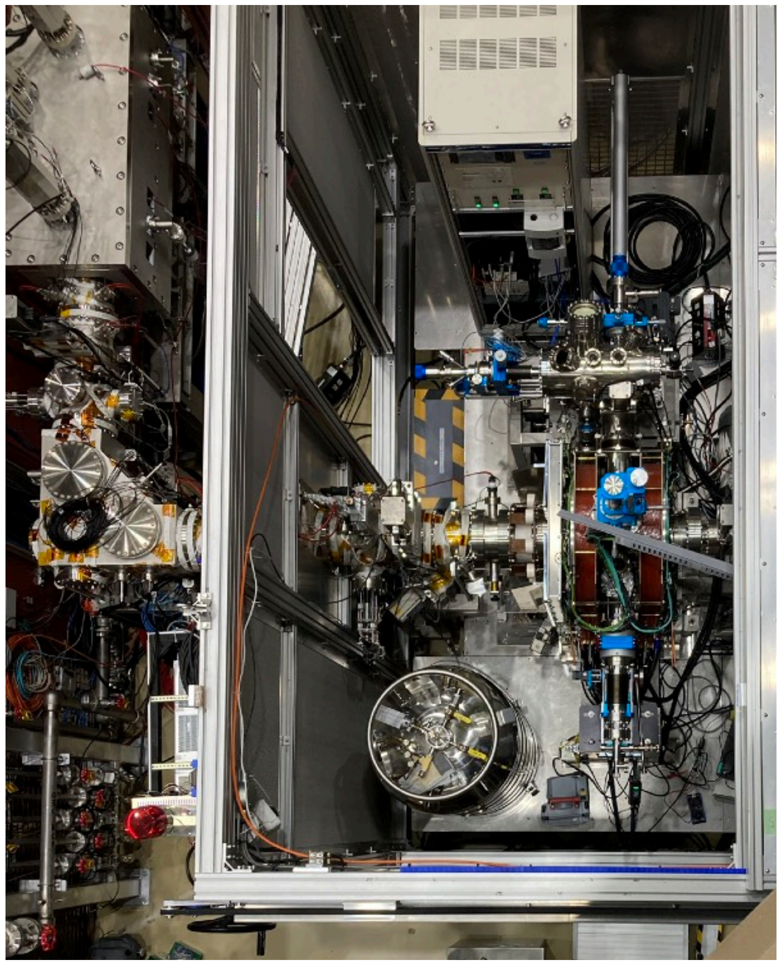
Detailed beam optics study (Y. Nakazawa)

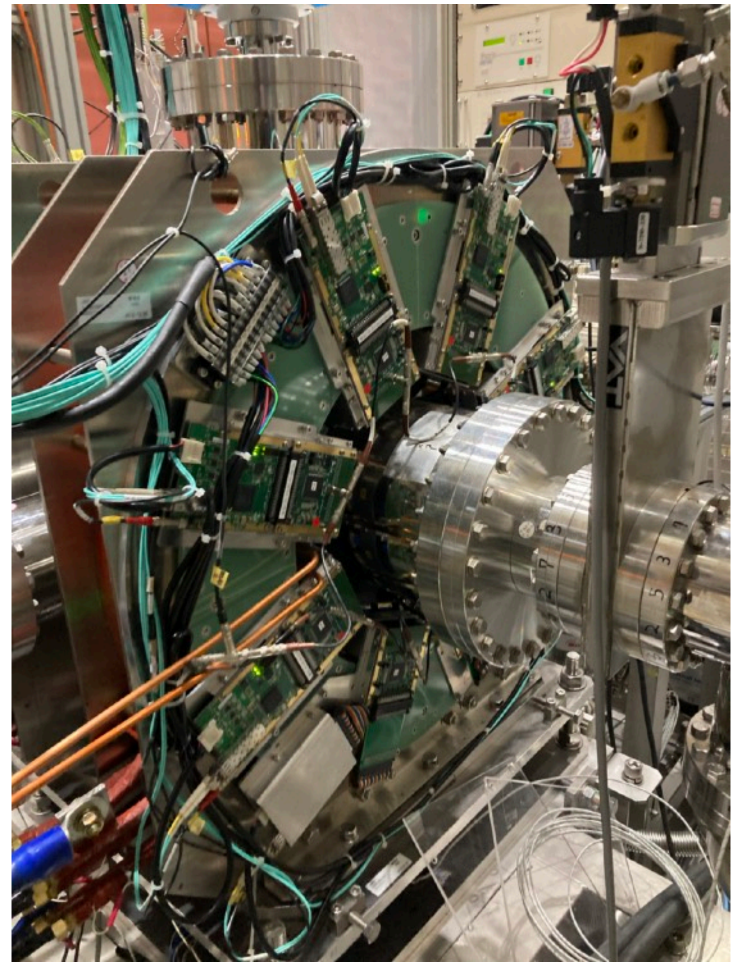


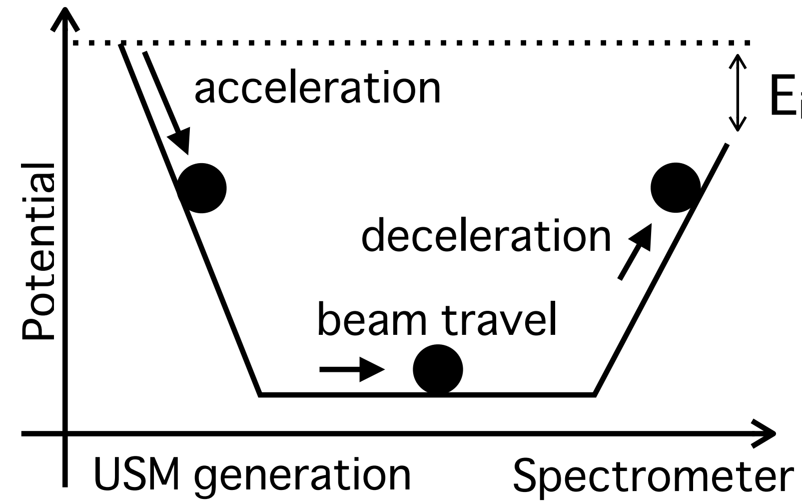
Surface muon beam monitor (works w/ A. Miura)

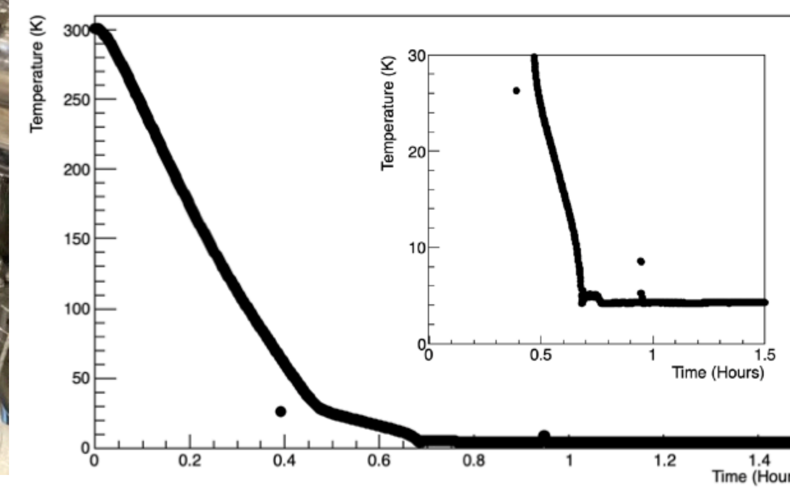
- Laser: Pulse energy was doubled by improving the Lyman-α light generation gas cell.
- Simulation: good agreement between detailed simulations and measurements.
- Surface muons: A new monitor was developed to optimize the surface muon beam.

USM-μSR Spectrometer



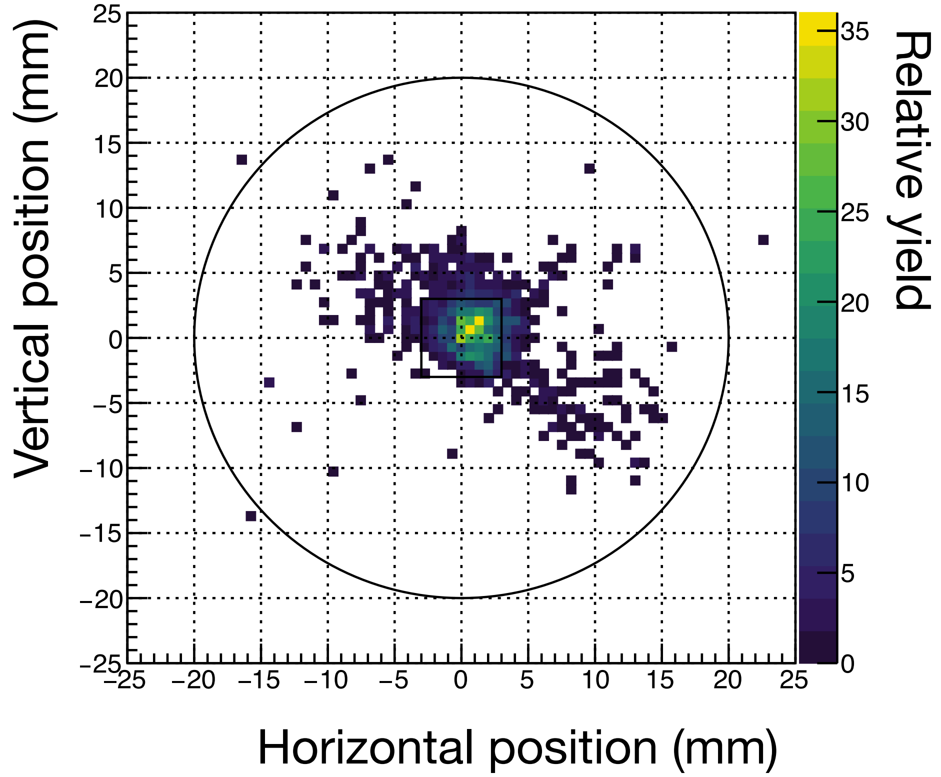


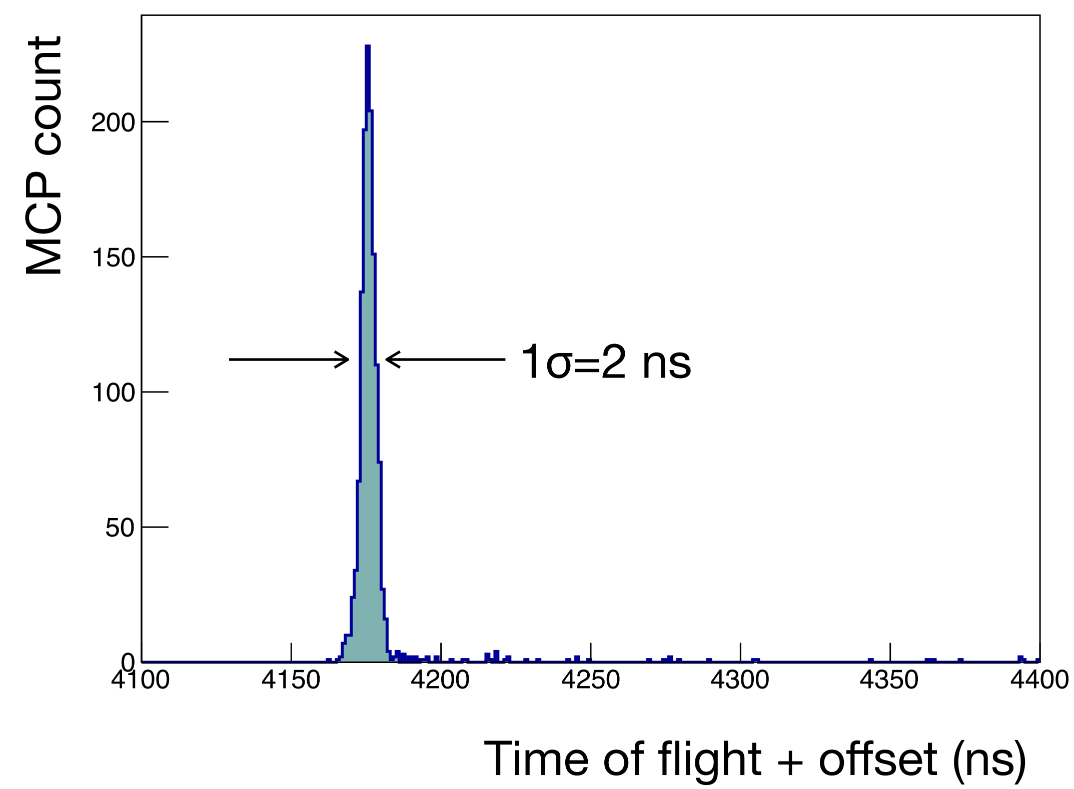




- Magnet: Applies a magnetic field up to 0.1 T perpendicular to the sample/
- Cryostat: Cools the sample down to 4 K using a helium gas stream.
- Particle Detectors: 512-segment counter array (plastic scintillator + SiPM)
- The entire apparatus is on a high-voltage platform, to provide implantation depth control by varying the muon energy from almost-zero to 30 keV.
- Load-lock chamber for rapid sample exchange without breaking the main vacuum.
- Retractable MCP detector to measure the beam profile at the sample position.

Beam Spec. at the Sample Pos.

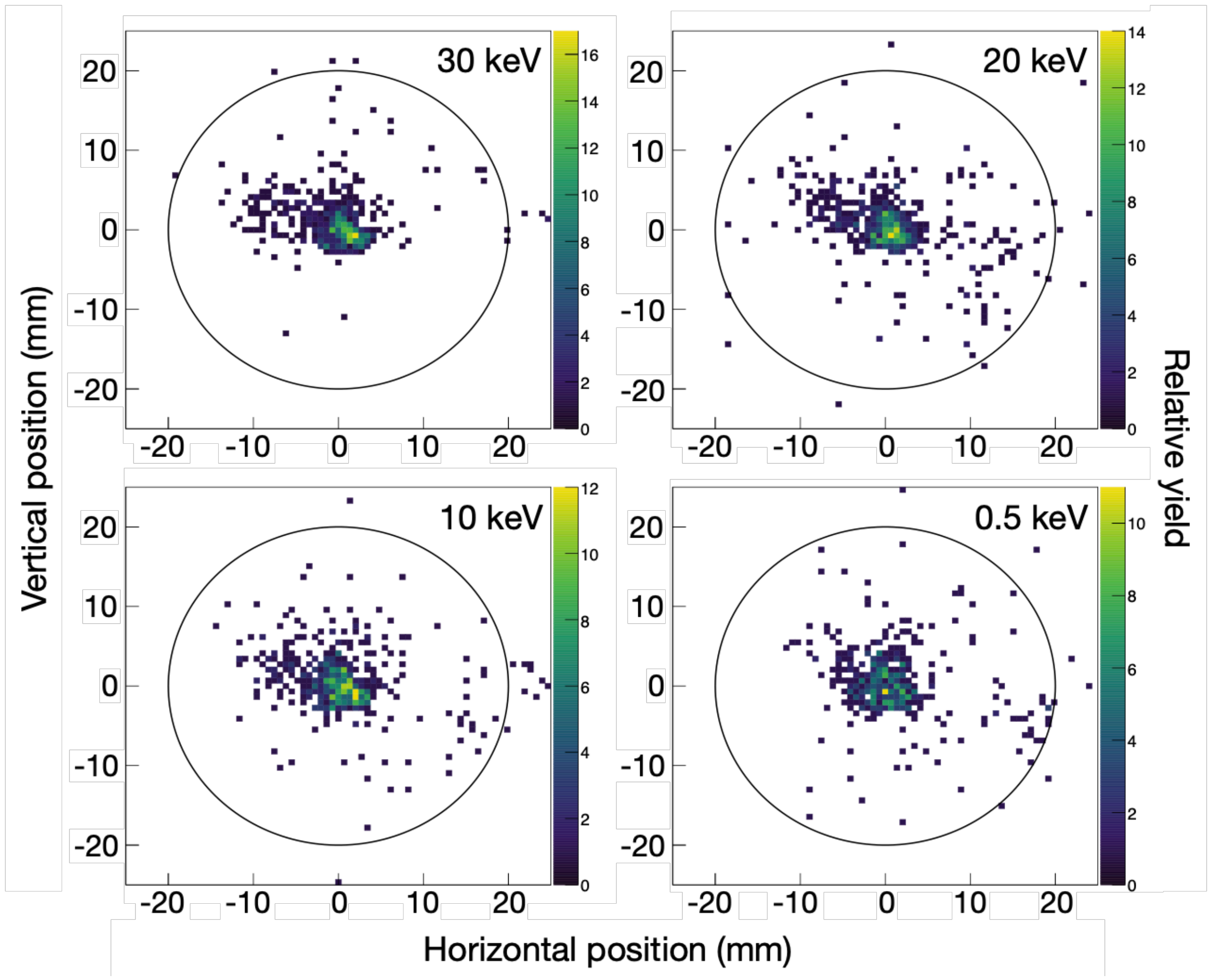


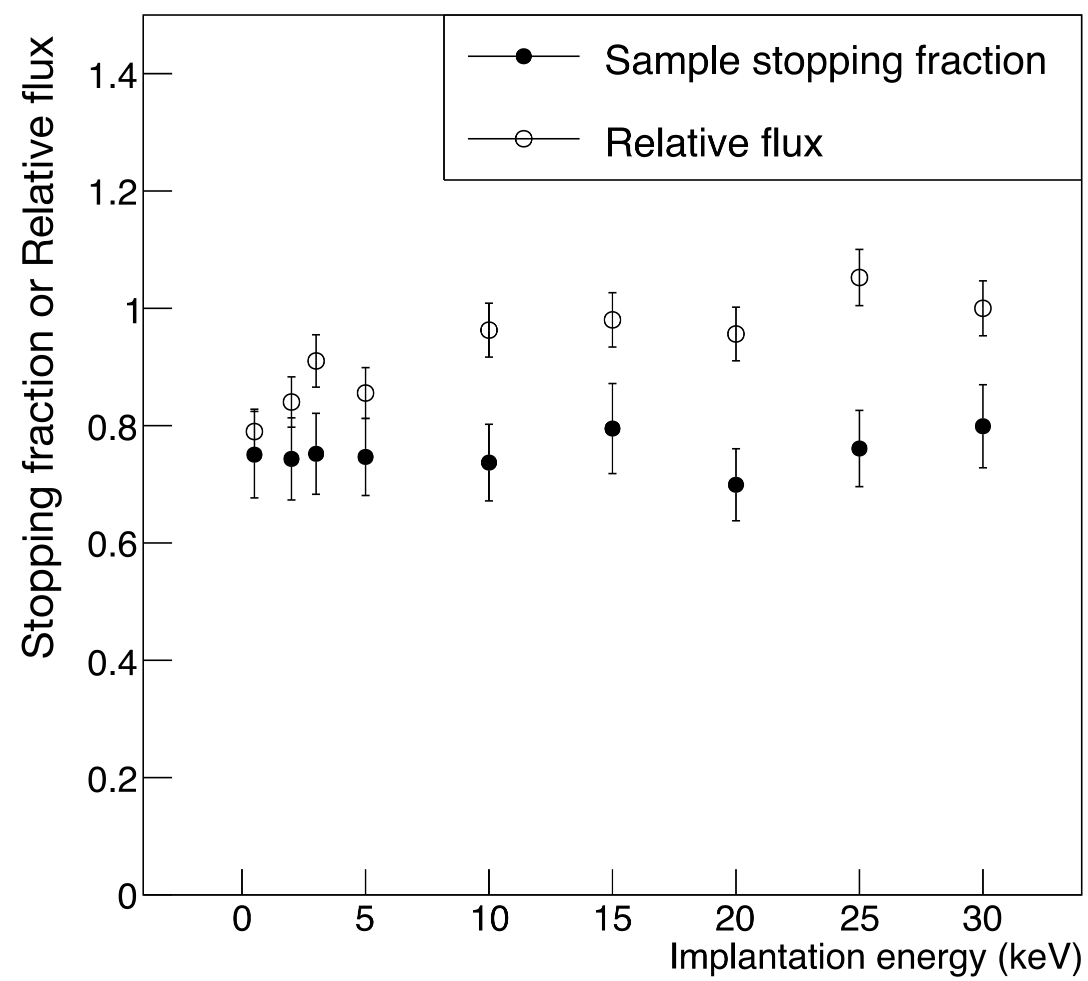


- USM beam profile at the sample position of the spectrometer:
  (Left) spatial distribution, (Right) temporal distribution.
- The spatial spread of the beam was approximately 4 mm FWHM in both the horizontal and vertical directions, while the time width was around 2 ns (1σ).
- These values represent an order of magnitude improvement compared to typical pulsed surface muon beams.
- Under typical transport conditions, the USM beam flux at the sample position was estimated to be approximately 230 muons per second*.

* Data prior to the laser gas cell window modification. We expect a twofold increase starting next beam operation.

USM Beam Energy Scan

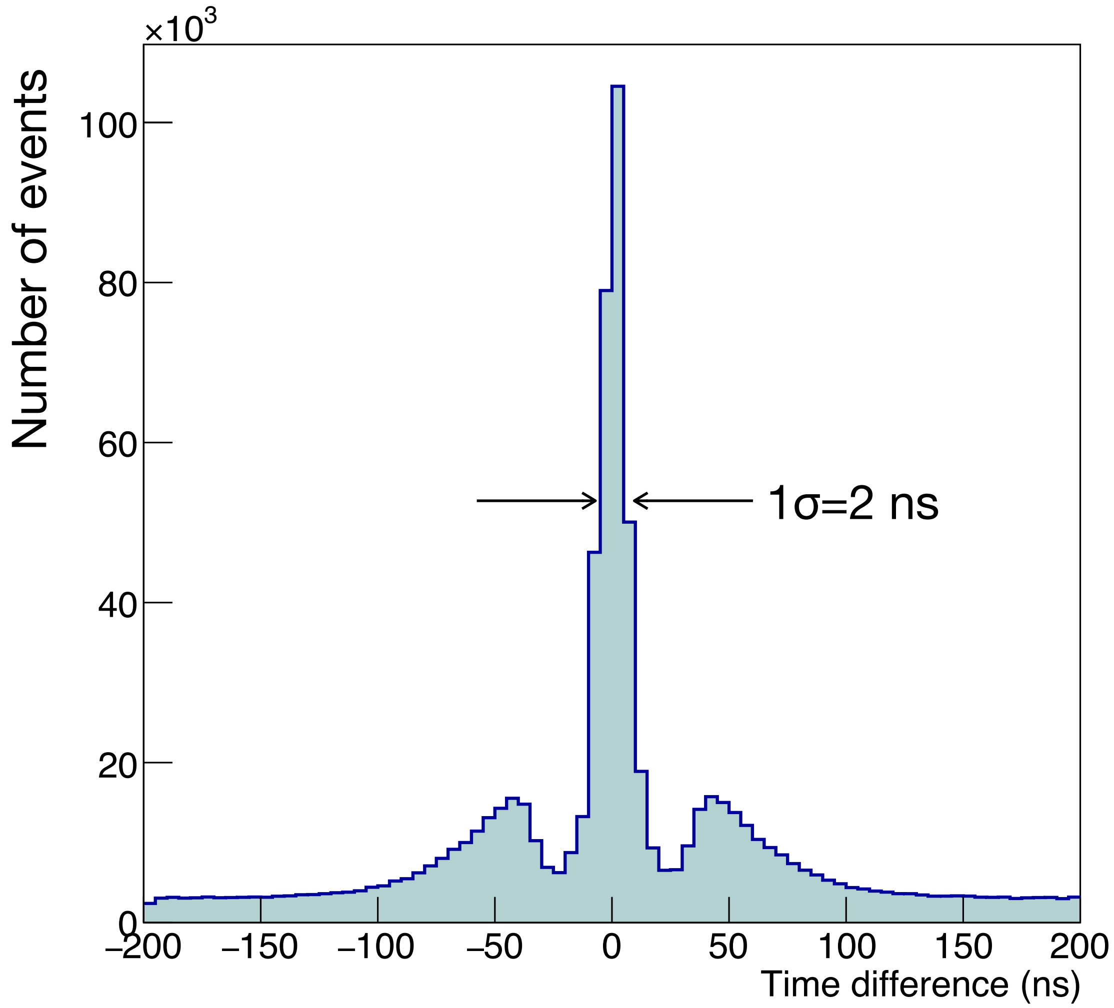


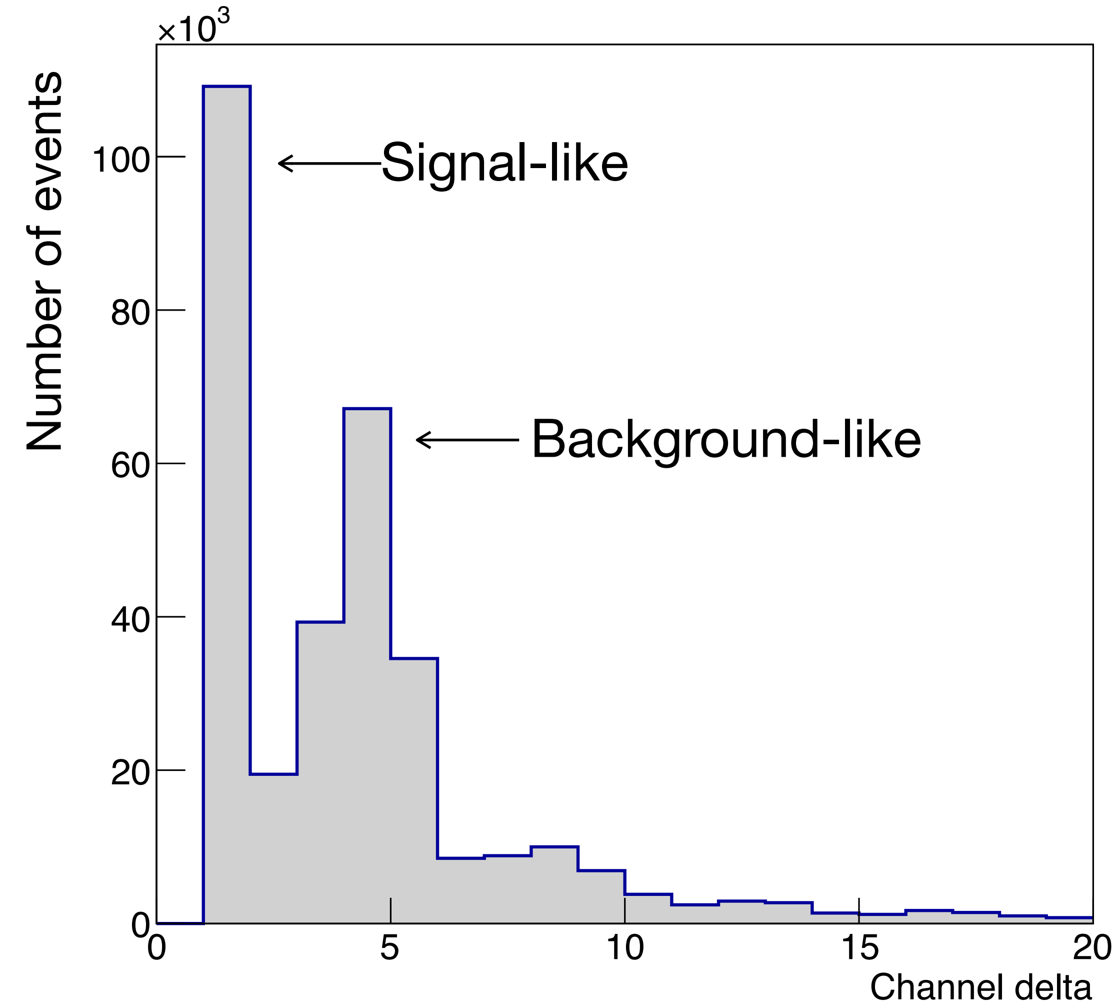


- Changing the implantation energy could shift the beam spot position on the sample, affecting energy-scan measurements.
- Extensive beam tuning was performed to align the beam with the beamline's axis.
- The beam spot now remains stable and fixed during a full implantation energy scan.
- Currently, the minimum stable implantation energy is 0.3 keV.

S. Kanda et al., accepted for publication in the proceedings of J-PARC2024 conference.

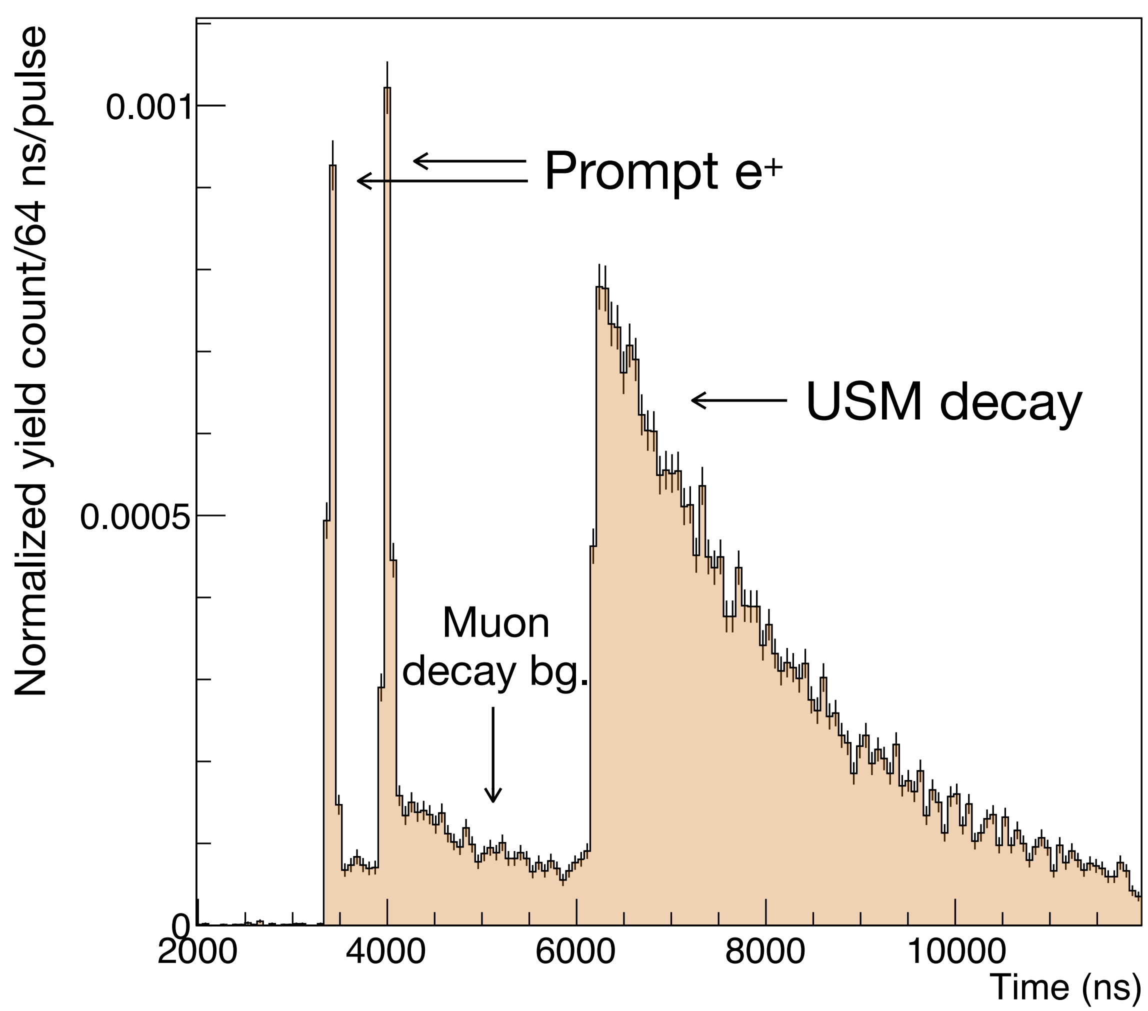
Spectrometer Performance

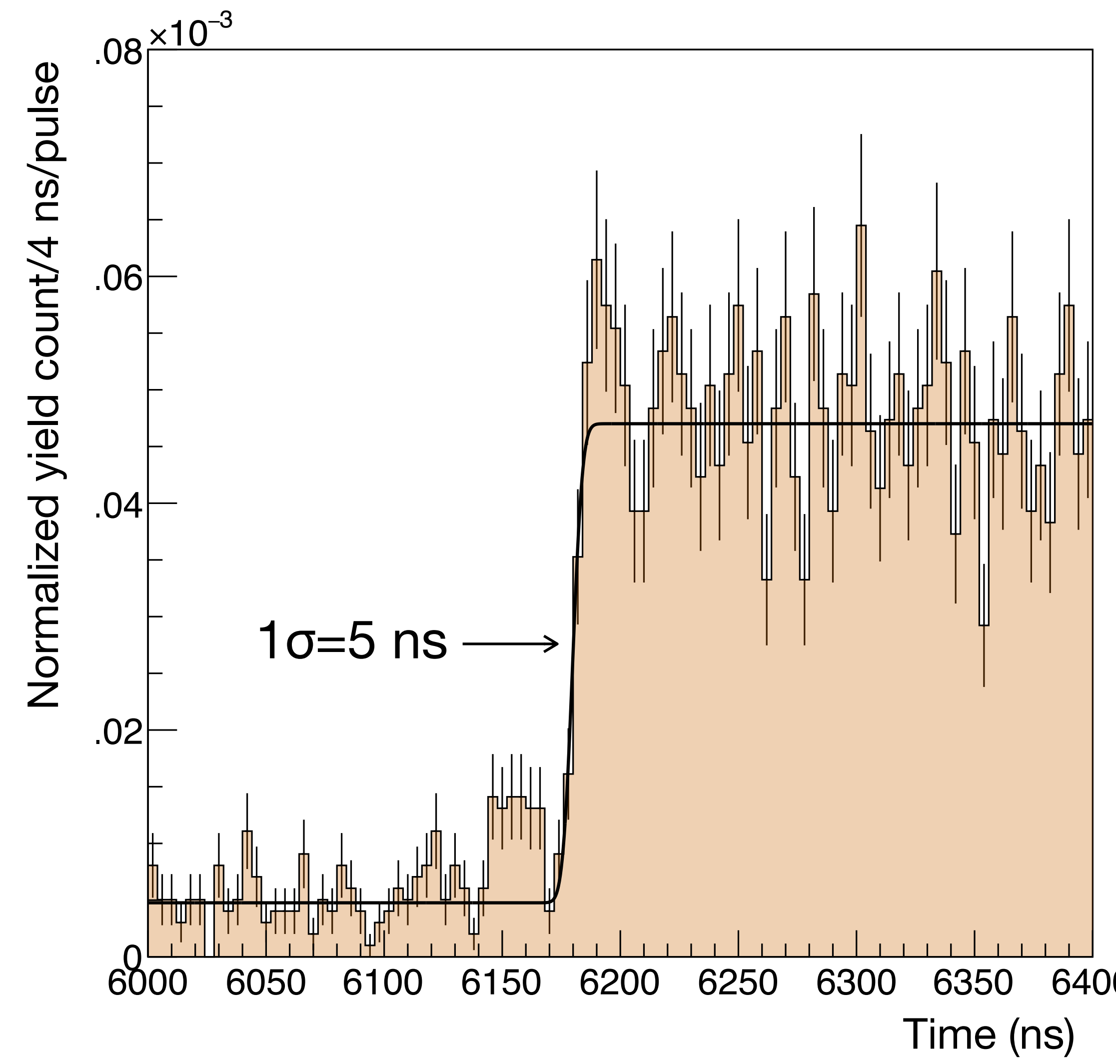




- The detector uses a two-layer (inner/outer) coincidence analysis to improve the signal-to-noise ratio.
  - By fitting the main coincidence peak, the detector's time resolution was determined to be 2 ns (1σ).
- Signal (from muons in the sample) and background (from muons stopped upstream) can be distinguished by analyzing the detector hit pattern.

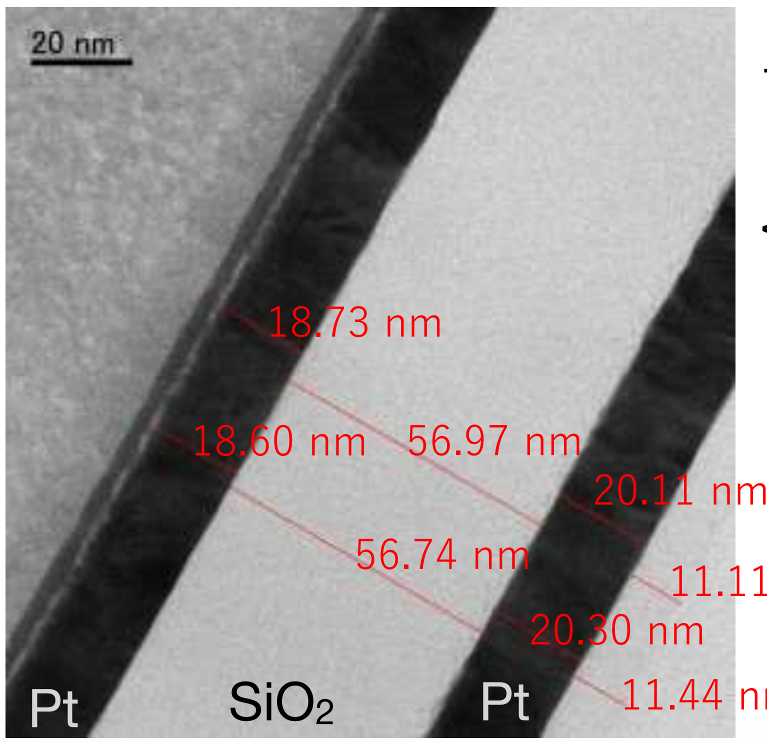
Spectrometer Performance





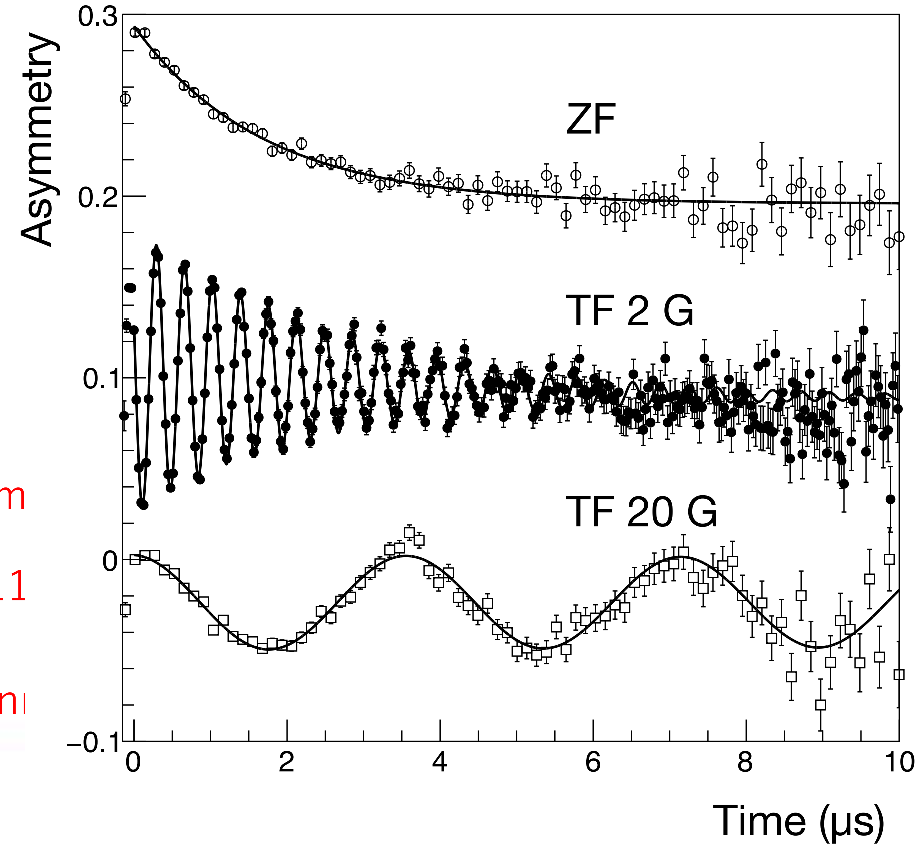
- Two sharp peaks from prompt positrons created by the pulsed proton beam.
  - An exponential signal rising at ~6200 ns, which is the USM signal.
  - An earlier exponential decay, identified as background from scattered muons.
- The time resolution of USM-μSR was estimated to be 5 ns (1σ) by analyzing the rising edge of the USM signal with an error function.

SiO_2/Pt Multilayer Sample



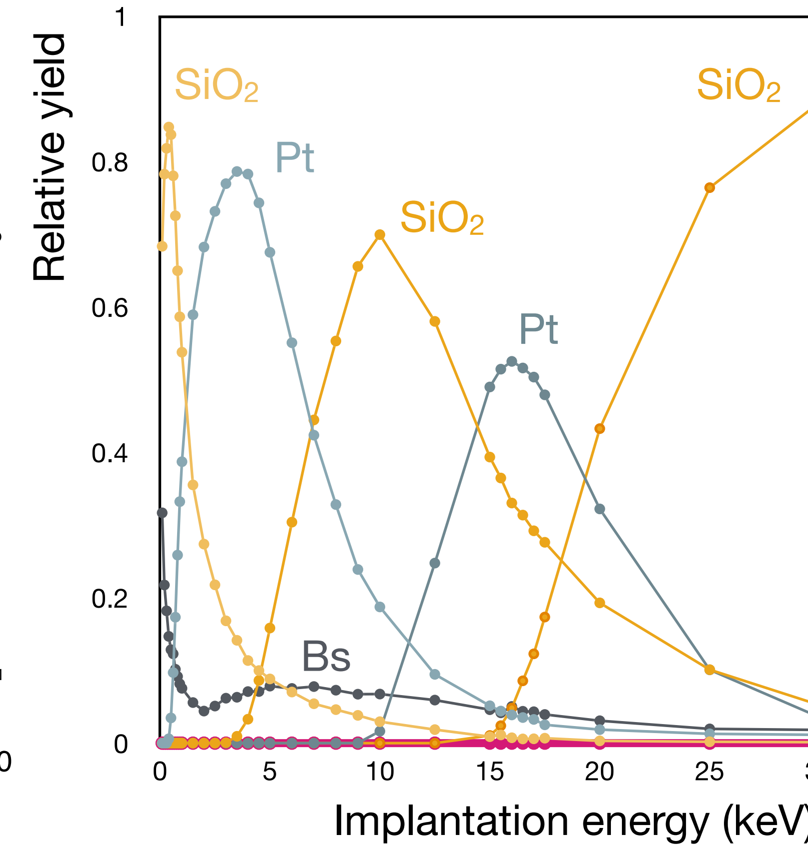
TEM image

provided by NTT-AT



μSR spectra of surface muons

$A_{Mu}=(9.9\pm0.1)\%$, $A_{\mu}=(1.5\pm0.1)\%$

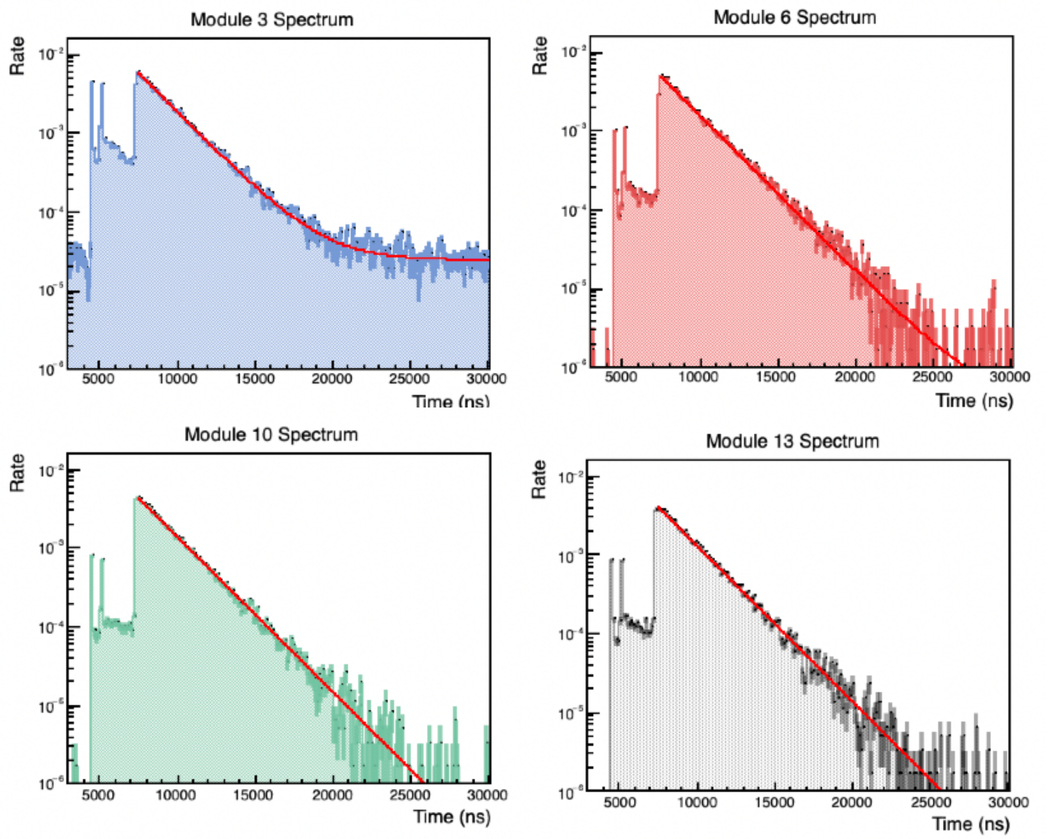


TRIM.SP stopping calc.

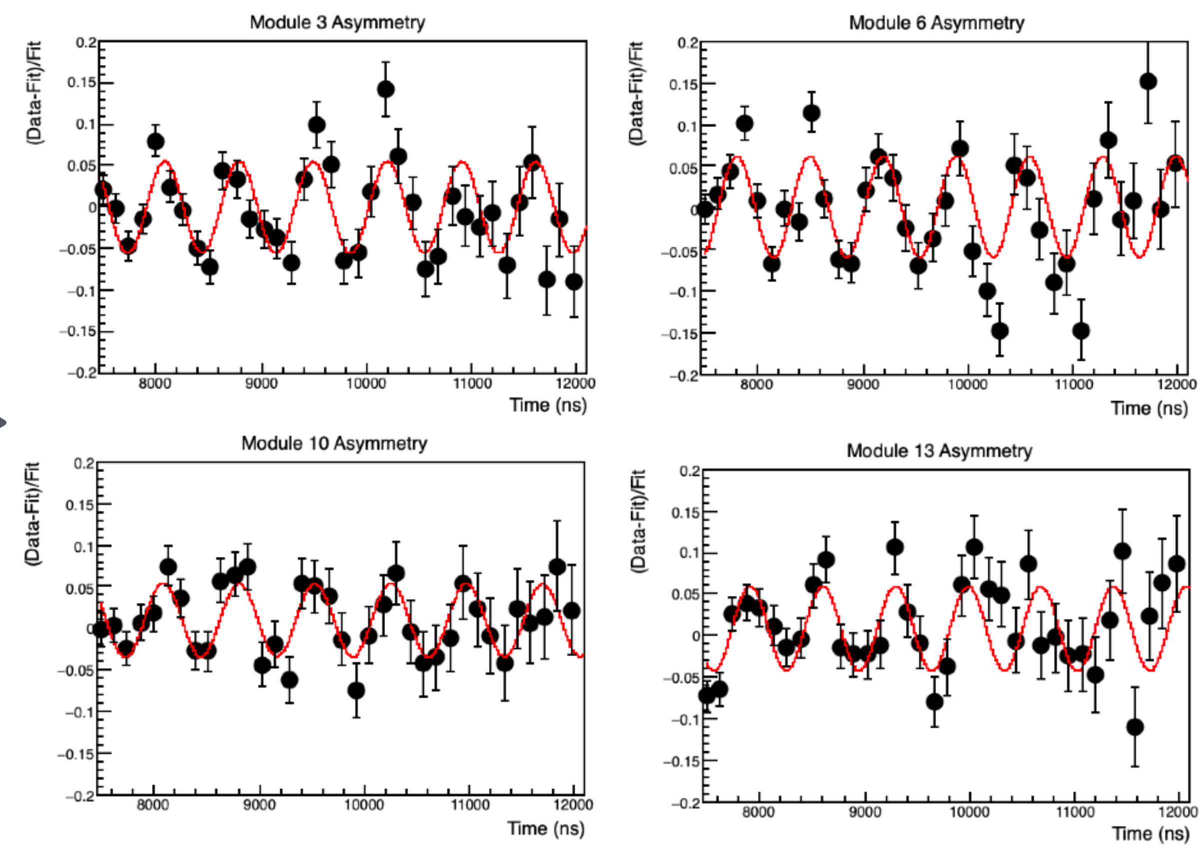
(BS = back scattering)

- A multilayer film designed to demonstrate implantation depth control.
- Alternating layers of silica (SiO_2) and platinum (Pt) were deposited on a synthetic quartz substrate.
- The signal from the bulk quartz substrate was confirmed with bulk μSR.
- Implantation depth profiles were calculated using the TRIM.SP simulation code.

USM-μSR Data Analysis



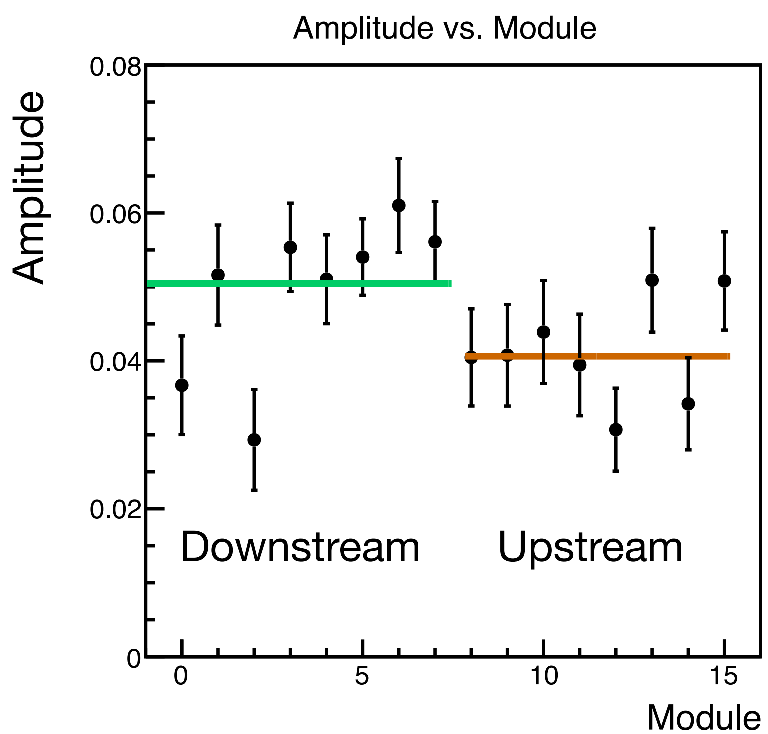
Time spectrum of each module (16 in total)



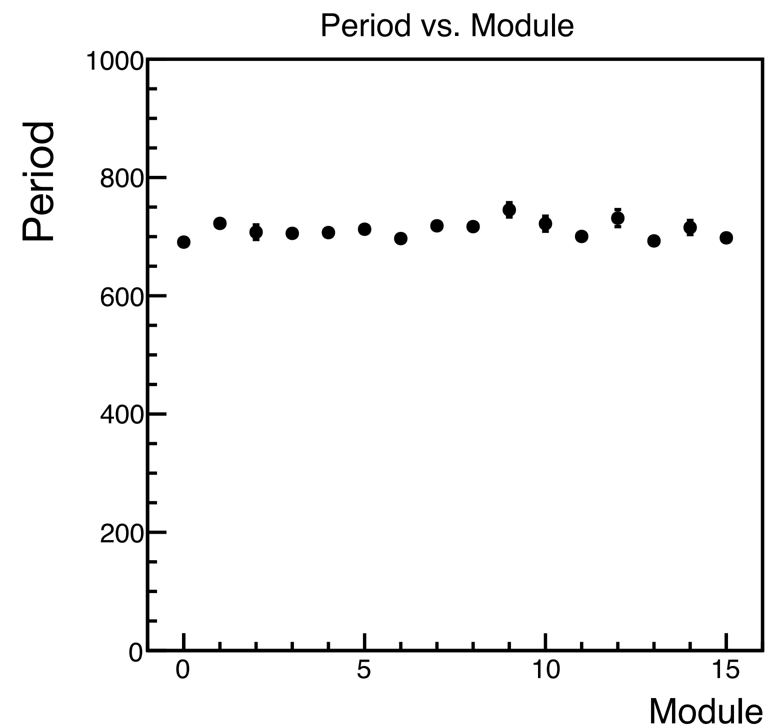
Individual asymmetry of each module

- The detector is divided into 8 upstream and 8 downstream modules. The arrangement is symmetric in the forward-backward, up-down, and left-right directions.
- The signal-to-noise (S/N) ratio may be different for each module. The phase of the rotation is different for each module.
- The time origin (t0) for each module was calibrated using the prompt timing. Then, time spectrum was fitted with an exp.+floor function. From the fitting residual, the individual asymmetry for each module was determined.

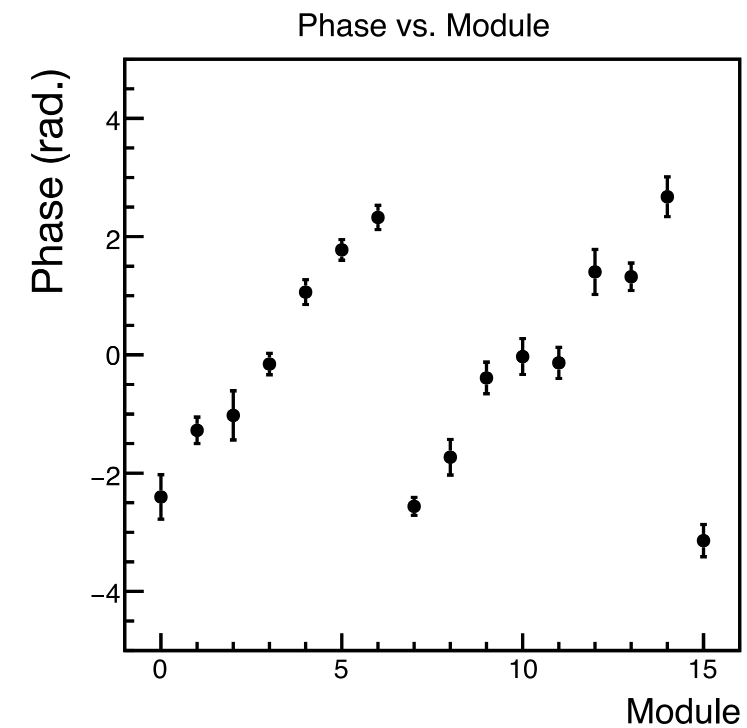
USM-μSR Data Analysis



Asymmetry



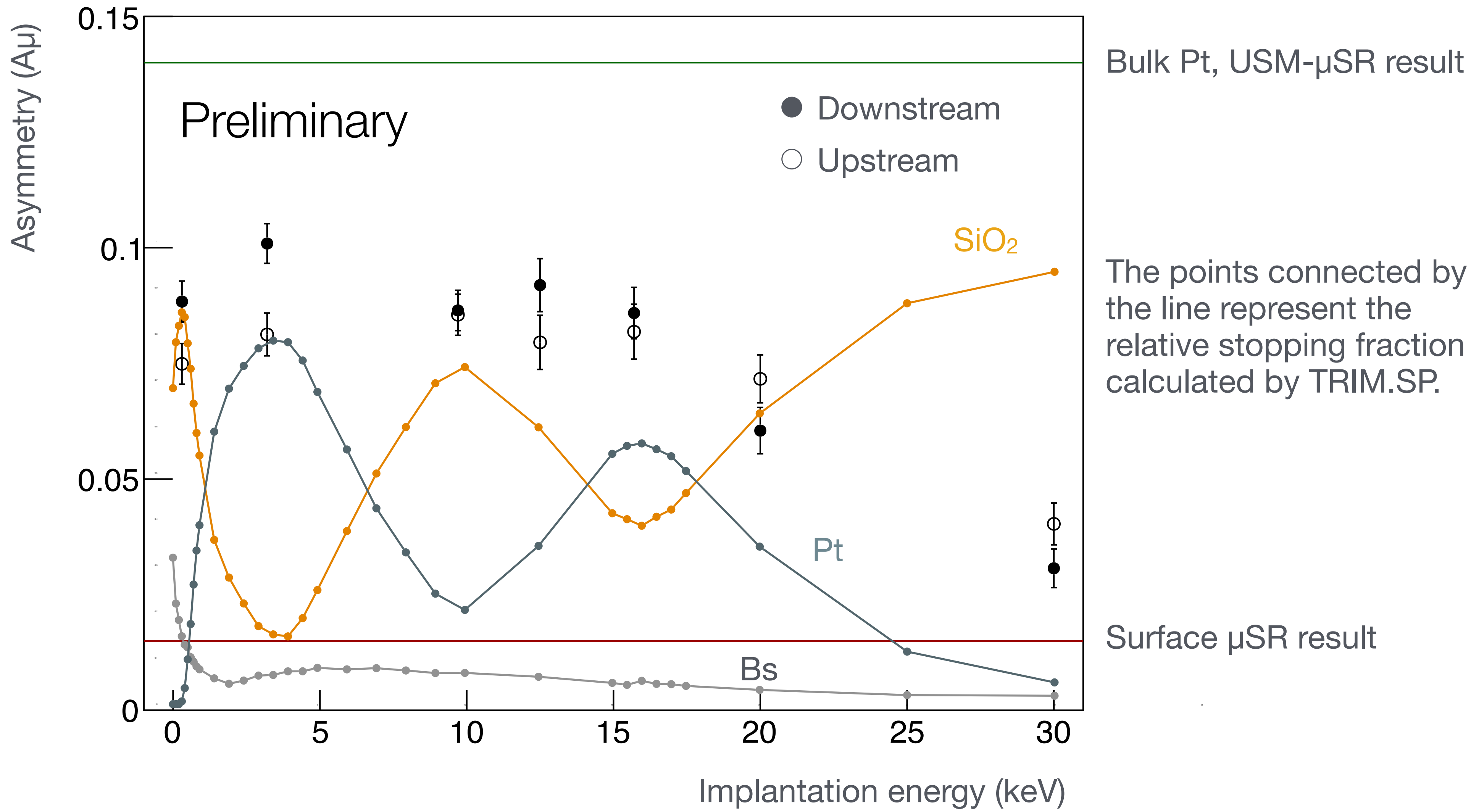
Precession period



Precession phase

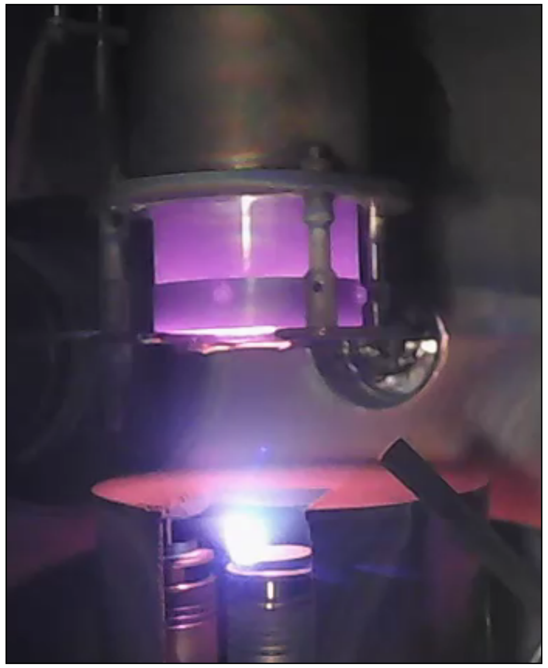
- For this analysis, we used the weighted average of the individual asymmetries.
- The rotation period was consistent across all modules. The rotation phase was consistent with the geometric arrangement of the modules.
- The fitting tended to be unstable for some modules.
- We plan to evaluate the following using both simulations and experimental data:
  - A detailed evaluation of the detector's performance.
  - The effect of background events (such as decay positrons, reflection, and back scattering) on the signal-to-noise (S/N) ratio of each module.

Depth-Resolved μSR Result

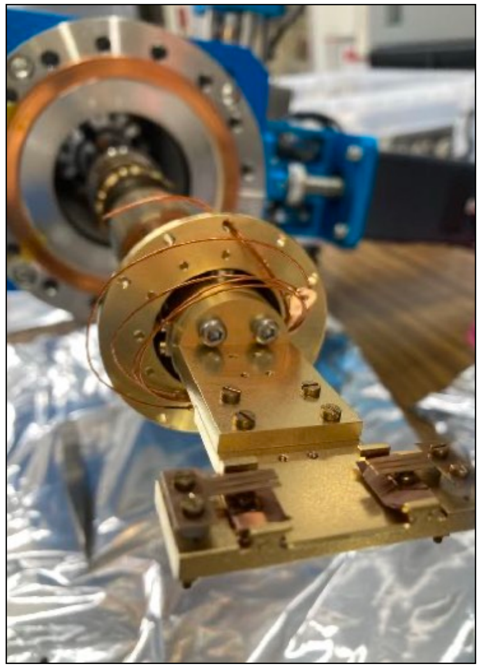


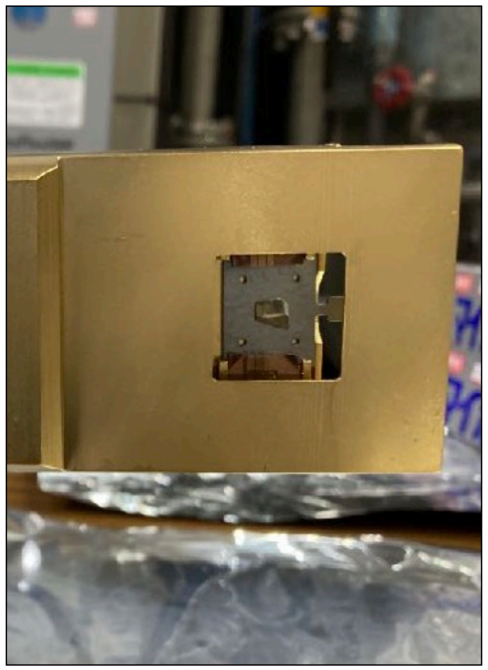
- The trend of the diamagnetic fraction in the precession was in general agreement with the calculated muon stopping profile.
- We aim to obtain the final results by increasing the number of data points in the energy scan, improving the data quality, and refining the analysis.

First Scientific Campaign

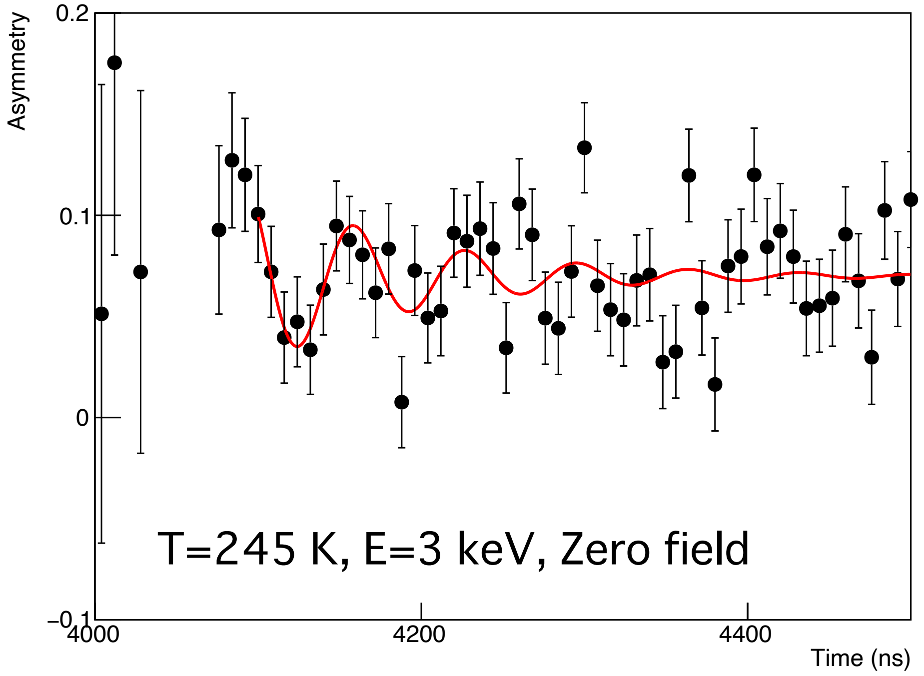


Sample fabrication by pulsed laser deposition.





Thin film sample of $Ca_{0.85}Sr_{0.15}CuO_2$ mounted on the cryostat.

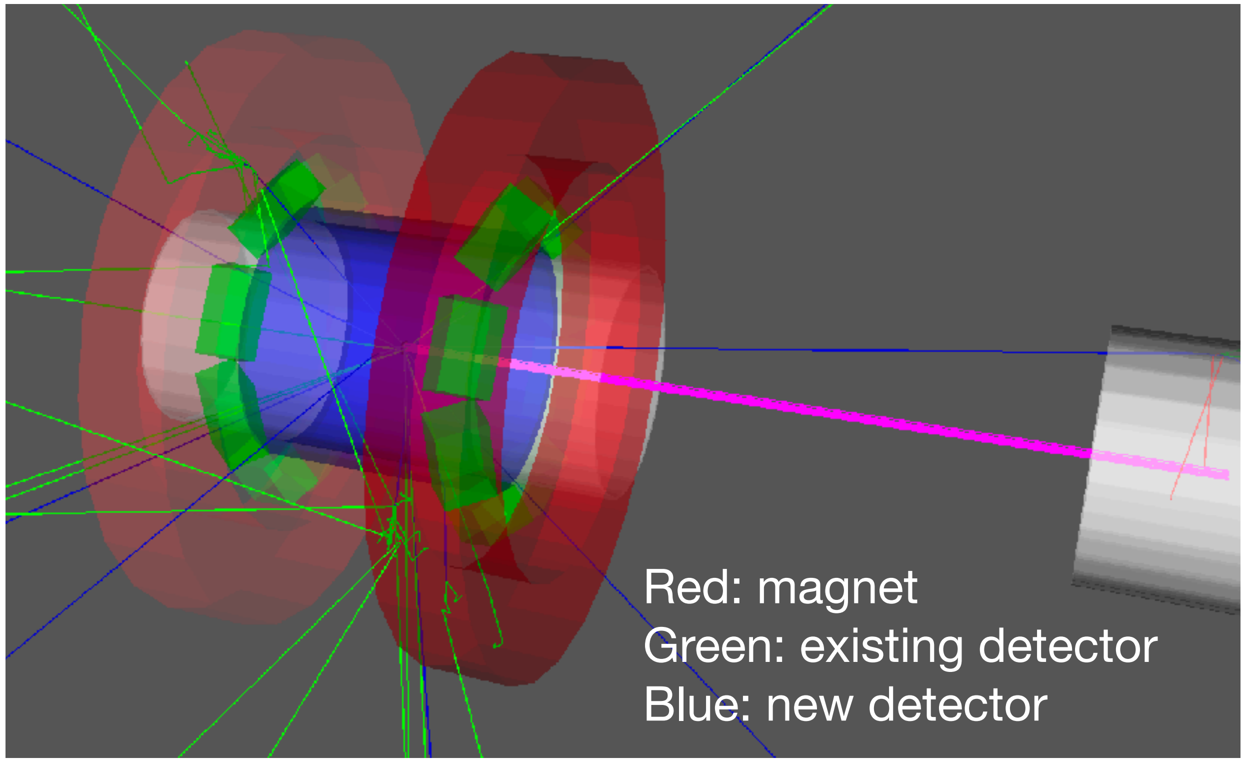


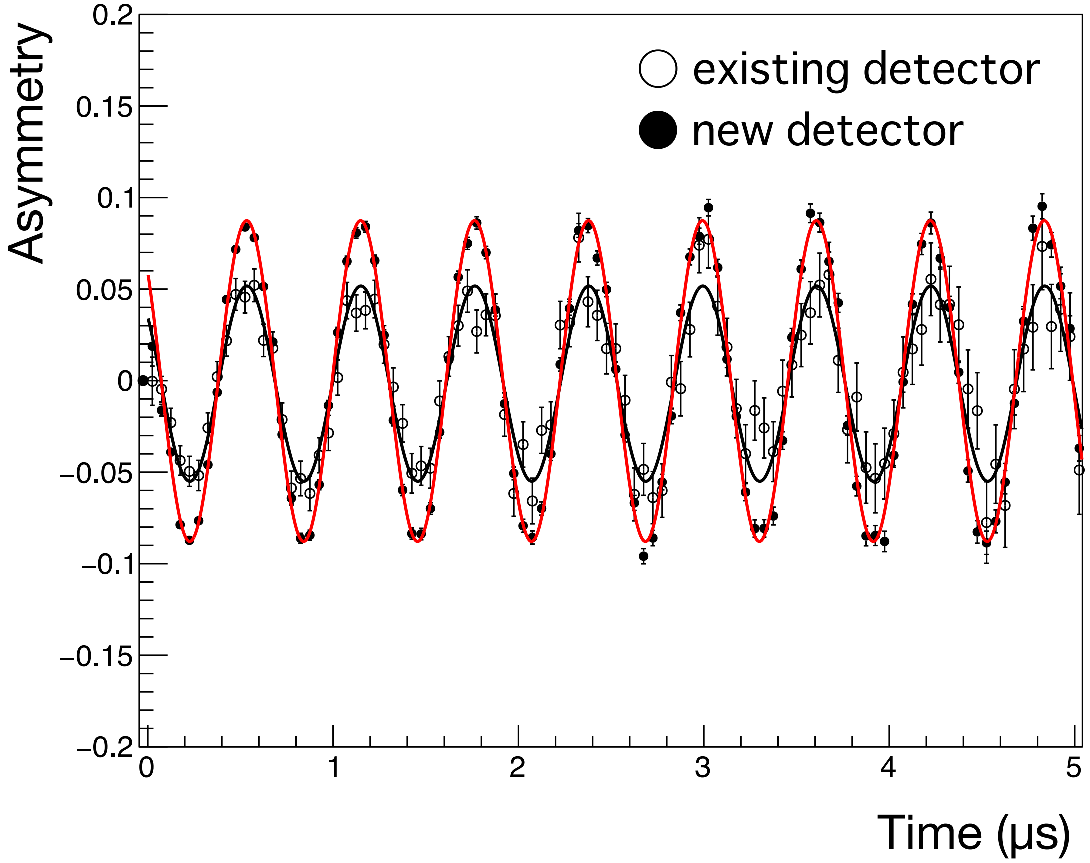
Preliminary result of the zero-field μSR measurement.

- First scientific measurements of USM-μSR has been started with a cuprate thin-film sample.
- A full-scale physics measurements involving the sample transportation, cooling, and control of implantation energy.
- Muon spin rotation originating from internal magnetic fields inside the sample was successfully observed.
- We have not been able to acquire data since the neutron source failure in June 2024. Our goal is to complete the dataset and publish the results after operations resume in November 2025.

Works with T. Adachi's group of Sophia University, J. G. Nakamura and H. Okabe (KEK IMSS).

Spectrometer Upgrade





- The detector's solid angle coverage is only 18%, and the arrangement is suboptimal, which reduces the full asymmetry.
- We are planning a major upgrade that involves rebuilding the spectrometer chamber to allow for a more ideal detector configuration.
- Simulations using musrSim (GEANT4) show the new design will significantly improve performance.
- We expect to increase the full asymmetry by a factor of 1.5 while also shortening measurement times.

Poster on Thursday

Muon Cooling for Muonium Spectroscopy and Interferometry

Not scheduled
20m

Poster Presentation | Beamlines and instr... | Poster session 2

Speaker

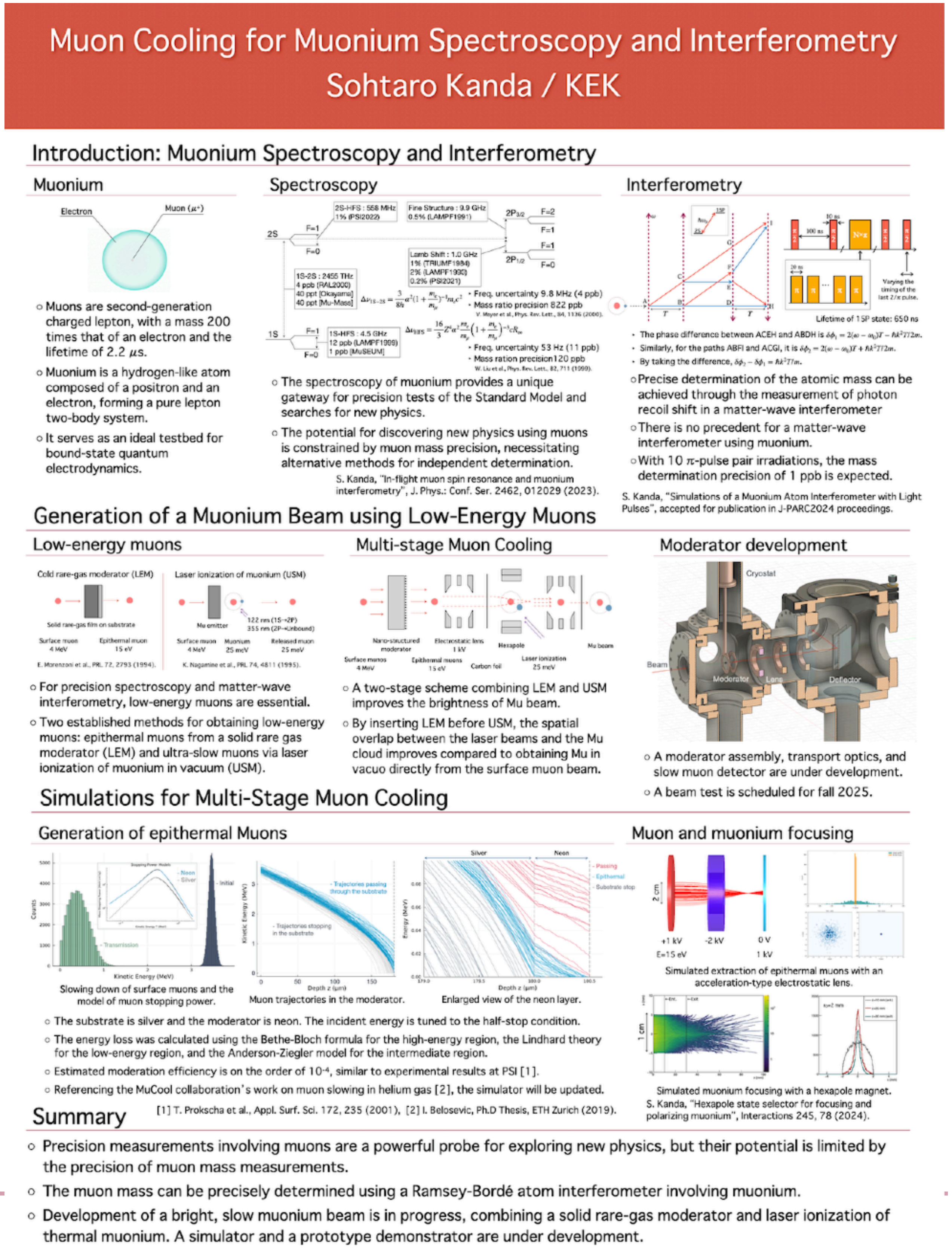
Sohtaro Kanda (KEK)

Description

Muonium, a pure leptonic two-body system, is a powerful probe for precise QED tests and new physics searches. High-precision spectroscopy of muonium provides the best determination of the muon-to-electron mass ratio. For instance, muonium ground-state HFS microwave spectroscopy determined the mass ratio to 120 ppb [1]. Uncertainty in theoretical predictions for QED tests and new physics searches using muonium HFS [2] or 1S-2S spectroscopy is predominantly limited by the precision of the mass ratio. Thus, an independent muon mass determination would be a breakthrough for new physics searches with muonium spectroscopy. We propose determining the muon mass by constructing a Ramsey-Bordé interferometer involving muonium [3]. This requires a low-energy, high-brightness muon beam. Such a beam is useful not only for muonium interferometry but also for μSR measurements and in-flight spectroscopy of excited muonium. A two-stage muon cooling scheme combining a solid rare-gas moderator (LEM) and muonium laser ionization (USM) would be effective for this purpose [4]. In this contribution, we report on the muon moderator development, the scheme's first stage.

[1] W. Liu et al., Phys. Rev. Lett. 82 711 (1999).
[2] M.I. Eides, Phys. Lett. B 795, 113 (2019).
[3] S. Kanda, J. Phys.: Conf. Ser. 2462 012029 (2023).
[4] S. Kanda, in Proceedings of J-PARC2024, accepted for publication.

- Development of a new bright and cool muonium beam by combining LEM and USM.
- While this is being considered for applications in interferometry and spectroscopy, it will also be useful for μSR.



Summary

- To overcome the limitations of conventional bulk μSR and enable the study of (sub-)surfaces, interfaces, and thin films, high-quality low-energy muon beams are essential.
- Successfully commissioned the J-PARC Ultra-Slow Muon (USM) beamline, achieving excellent beam specifications.
- The μSR spectrometer has been fully commissioned, and a dedicated data analysis framework has been developed.
- Demonstrated depth-resolved μSR on a SiO_2/Pt multilayer sample, with results showing good agreement with simulation.
- Future Work:
    - Complete the dataset for the ongoing experiments after facility operations resume in November 2025.
    - Upgrade the spectrometer to increase the signal asymmetry by improving the detector's solid angle.