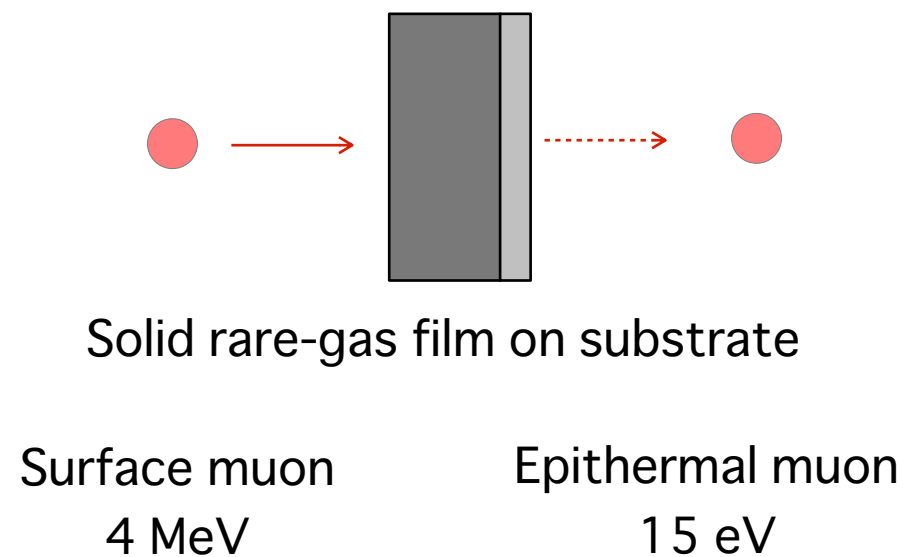


Depth-Resolved μ SR Using Ultra-Slow Muons at J-PARC MUSE

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

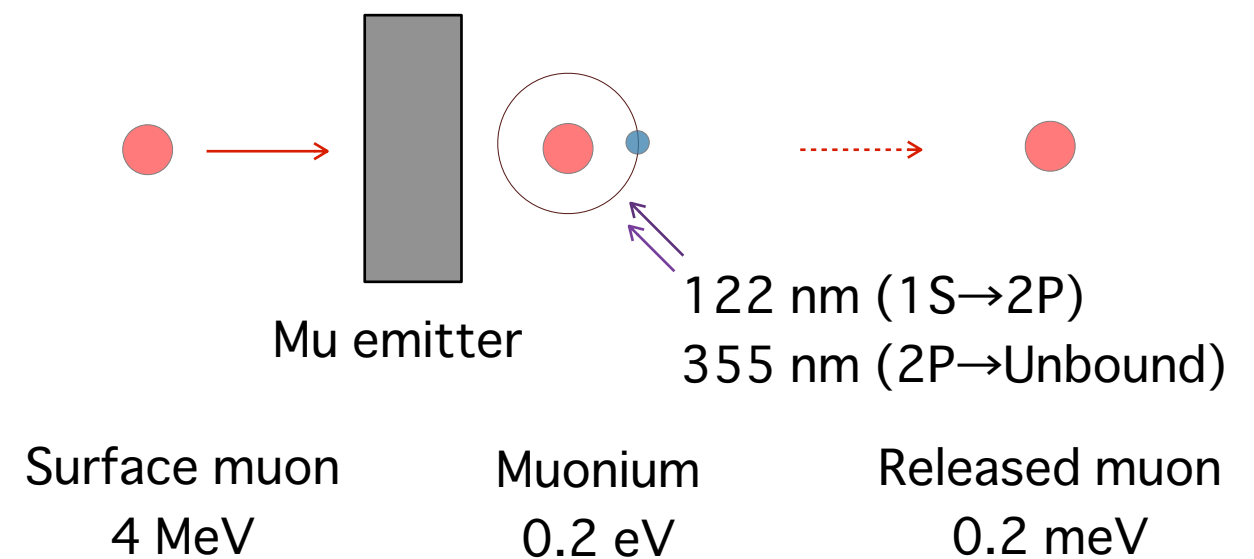
Low-Energy and Ultra-Slow Muons

Cold rare-gas moderator (LEM)



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

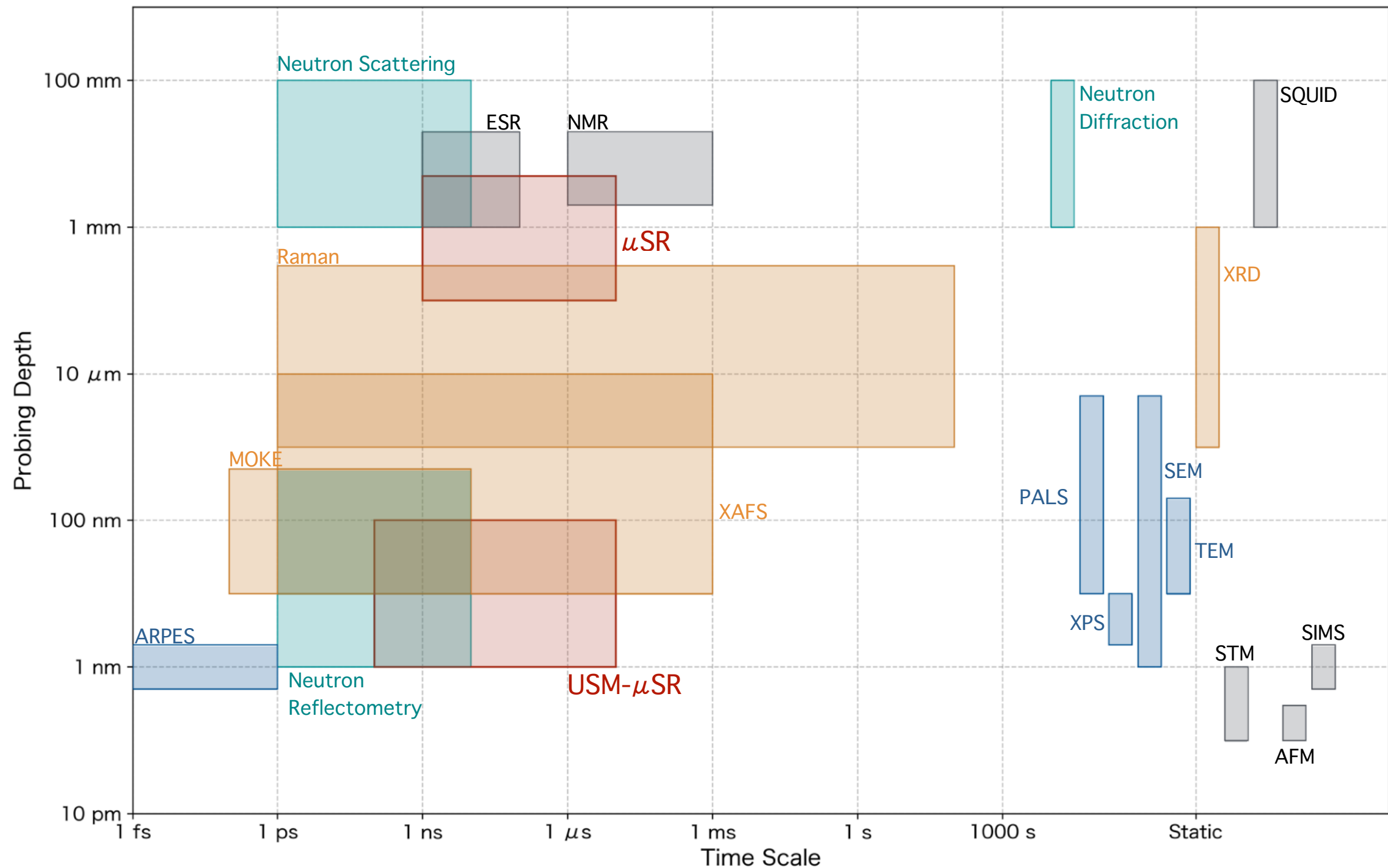
Laser ionization of muonium (USM)



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

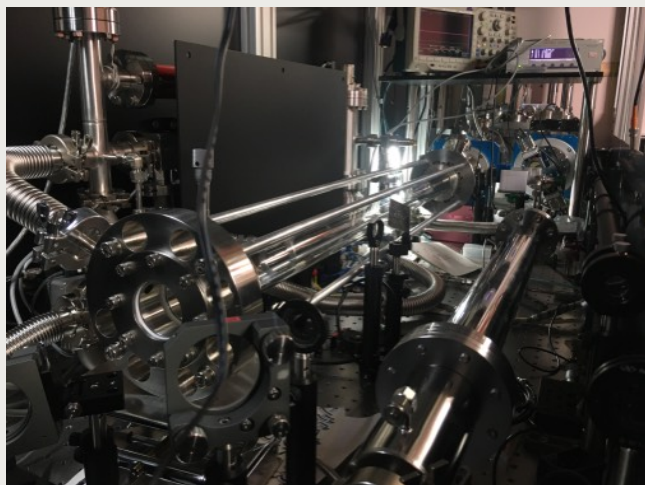
at J-PARC MLF MUSE

The Super-Omega
Surface muon beamline

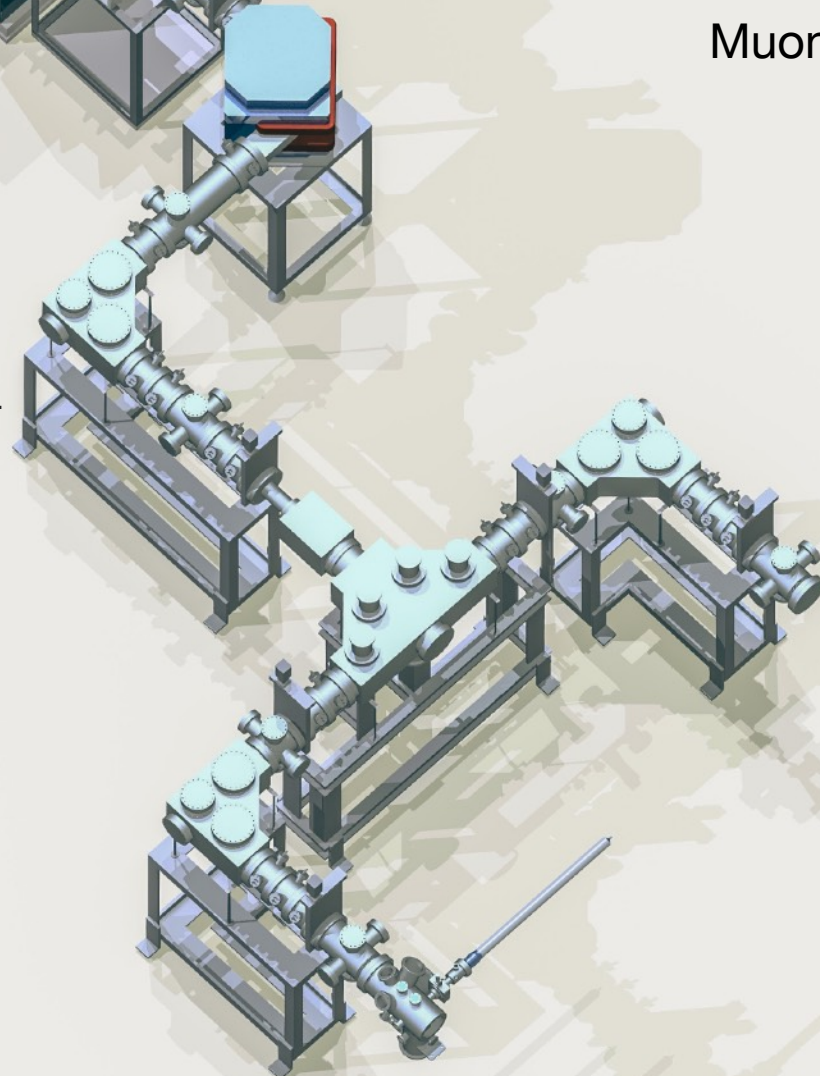


K. Nakahara et al., NIM A 600 (2009) 132-134.
P. Strasser et al., NIM B 317 (2013) 361-364.
Y. Ikedo et al., NIM B 317 (2013) 365-368.
N. Teshima et al., J. Phys. Conf. Ser. 2462, 012036 (2023).

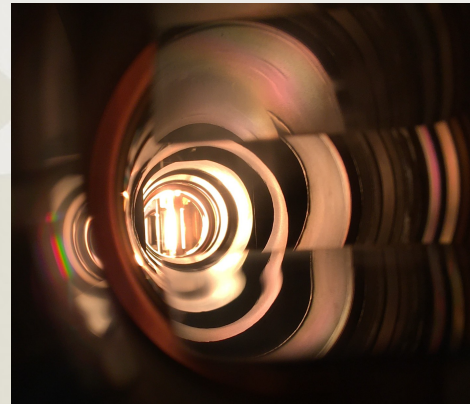
Ionization laser



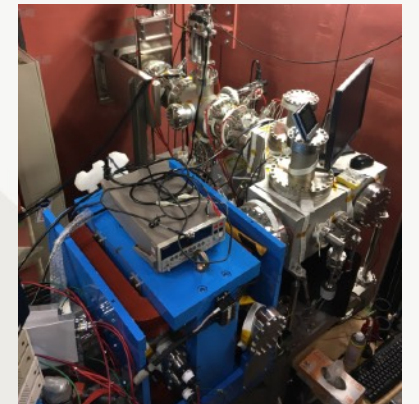
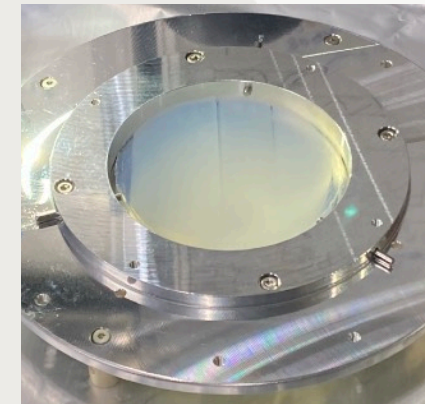
Y. Oishi et al., JPS Conf. Proc. 2, 010105 (2014).
N. Saito et al., Optics Express 24, 7566 (2016).
Y. Oishi et al., J. Phys.: Conf. Ser. 2462 012026 (2023).



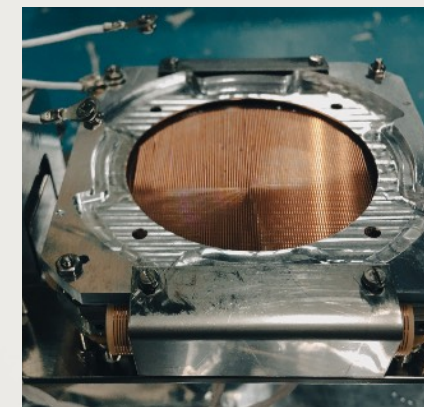
T. Nagatomo et al., JPS Conf. Proc. 2, 010102 (2014).
T. Adachi et al., JPS Conf. Proc. 8, 036017 (2015).
A. D. Pant et al., NIM A 929, 129 (2019).
S. Kanda et al., J. Phys. Conf. Ser. 2462, 012030 (2023).



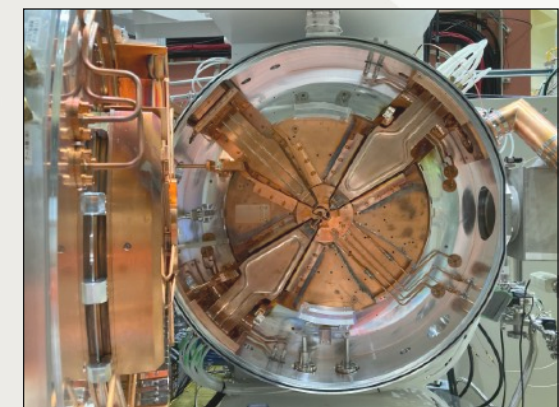
Muonium emitters



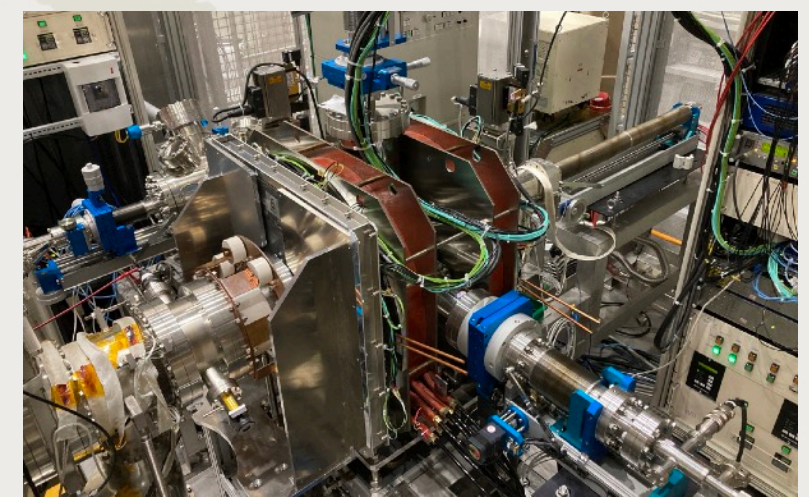
Transport optics



MCP-DLD
Beam monitor

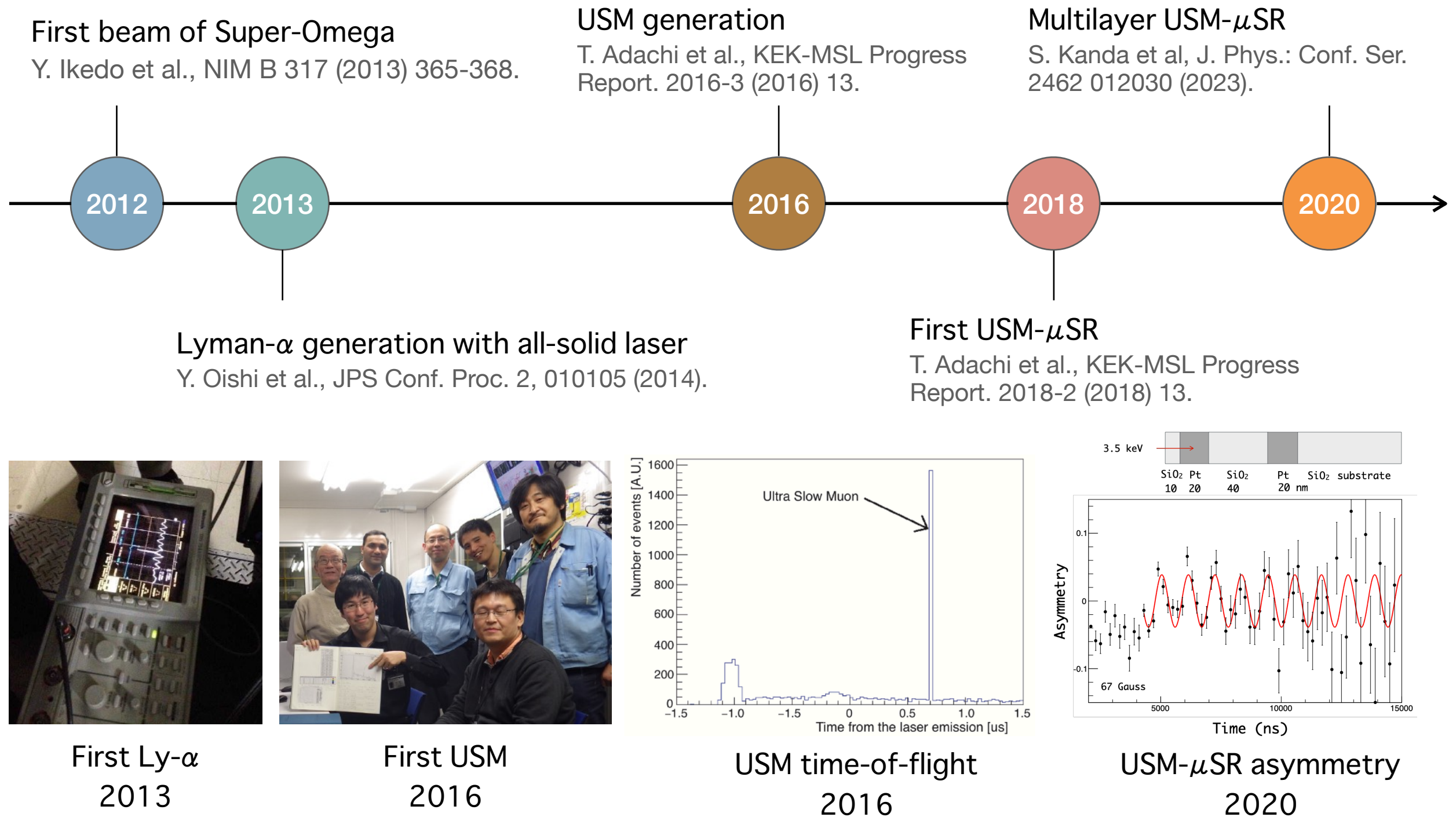


Cyclotron at U1B
→Next talk

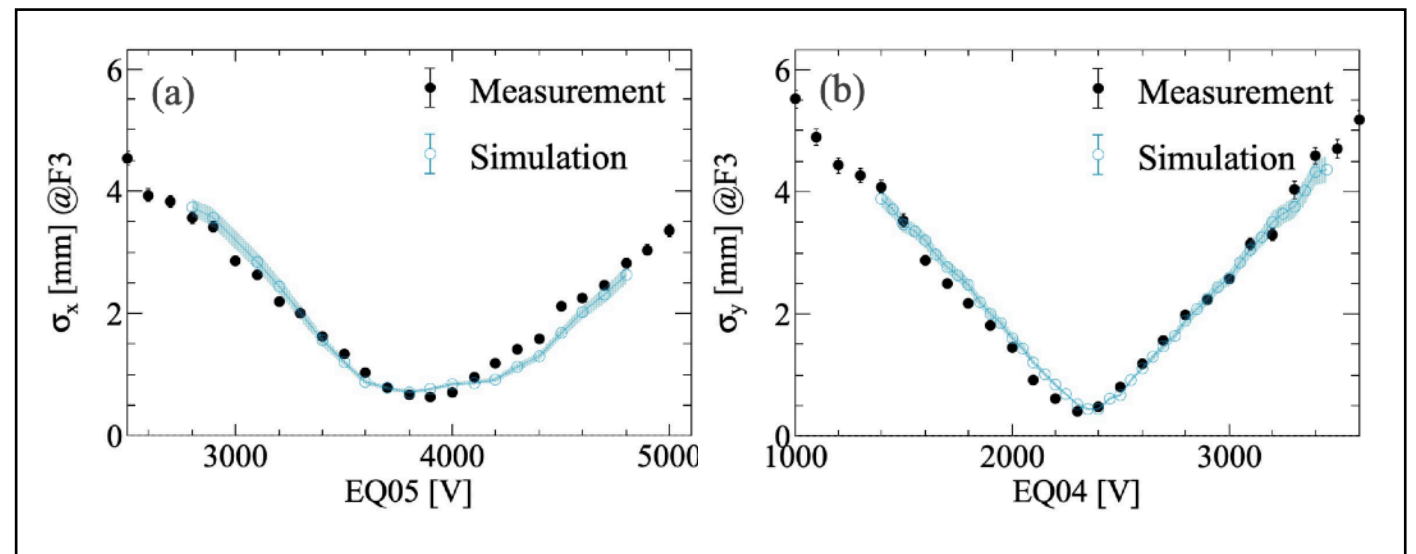
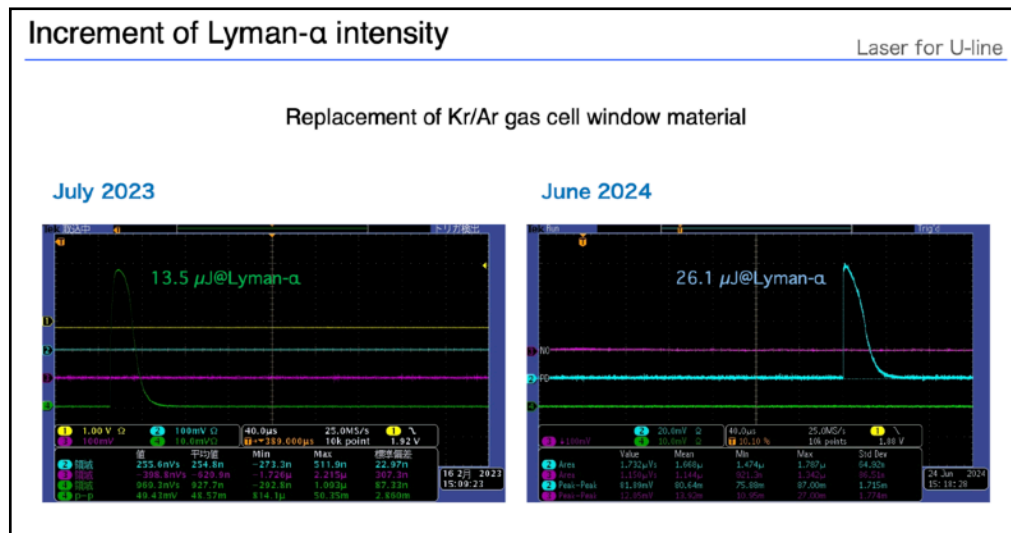


μ SR Spectrometer at U1A

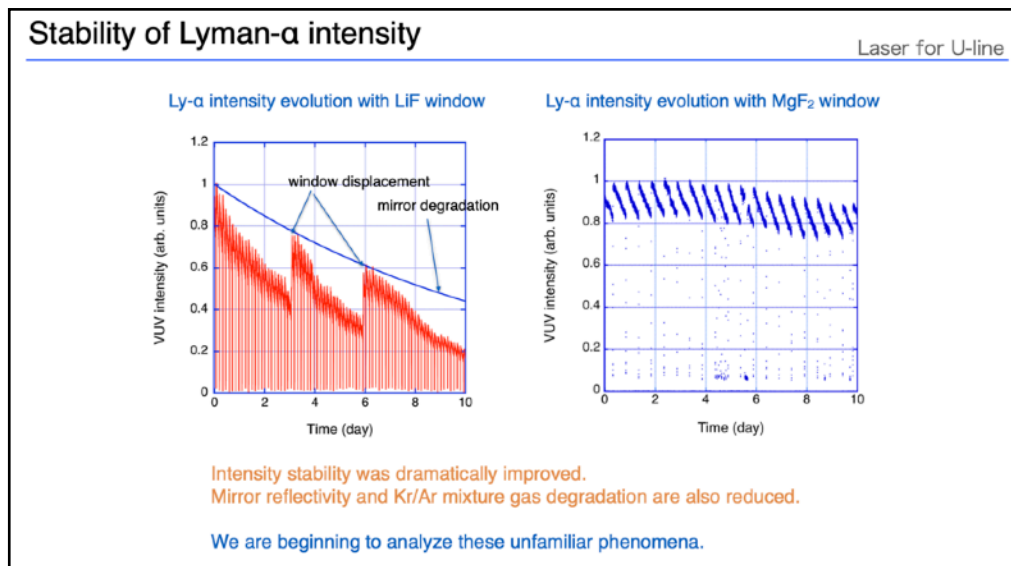
USM Development Timeline



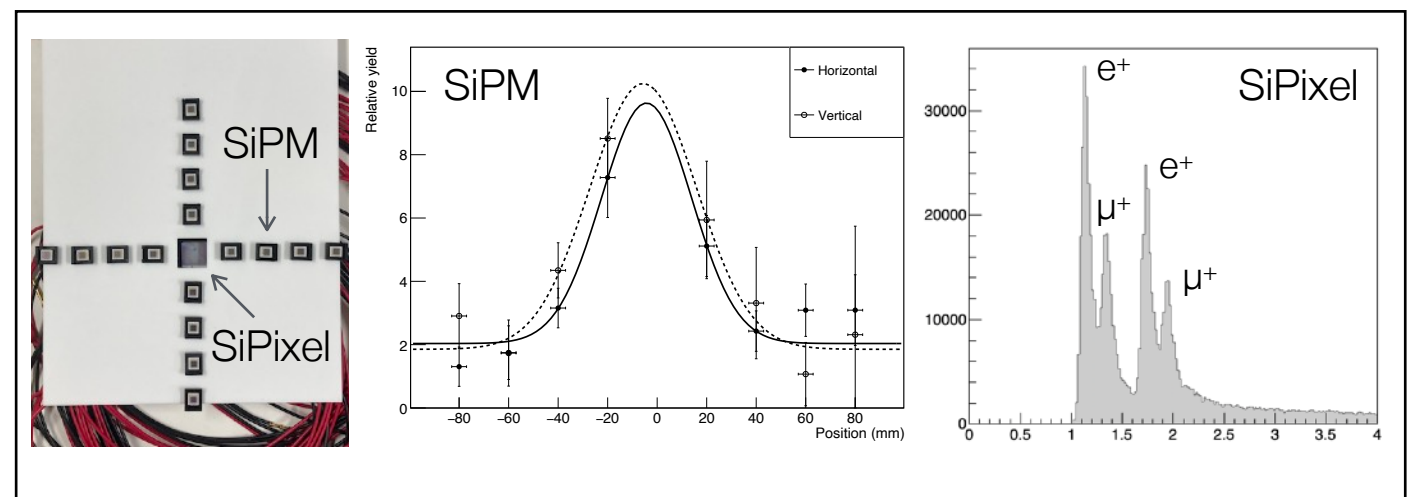
Recent USM Development



Detailed beam optics study (Y. Nakazawa)



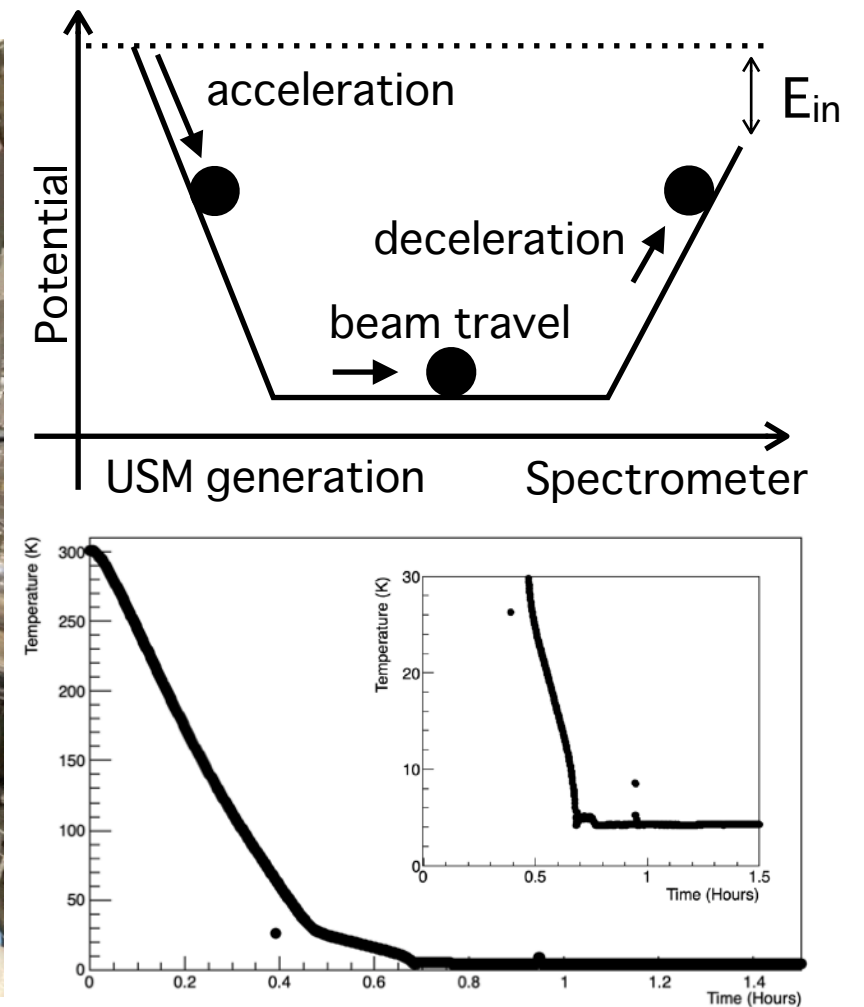
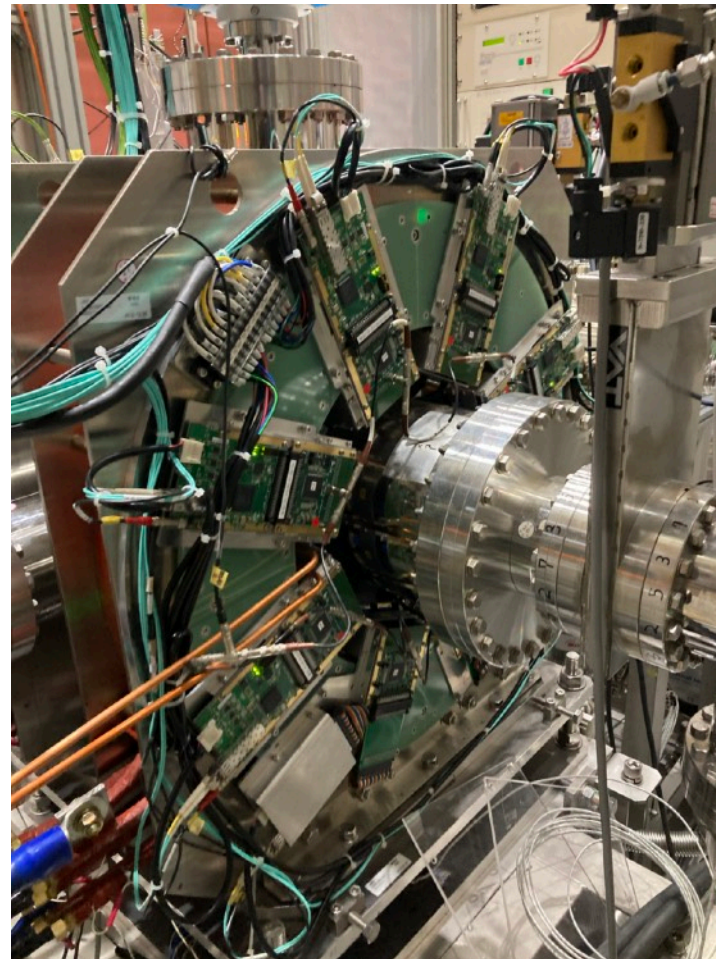
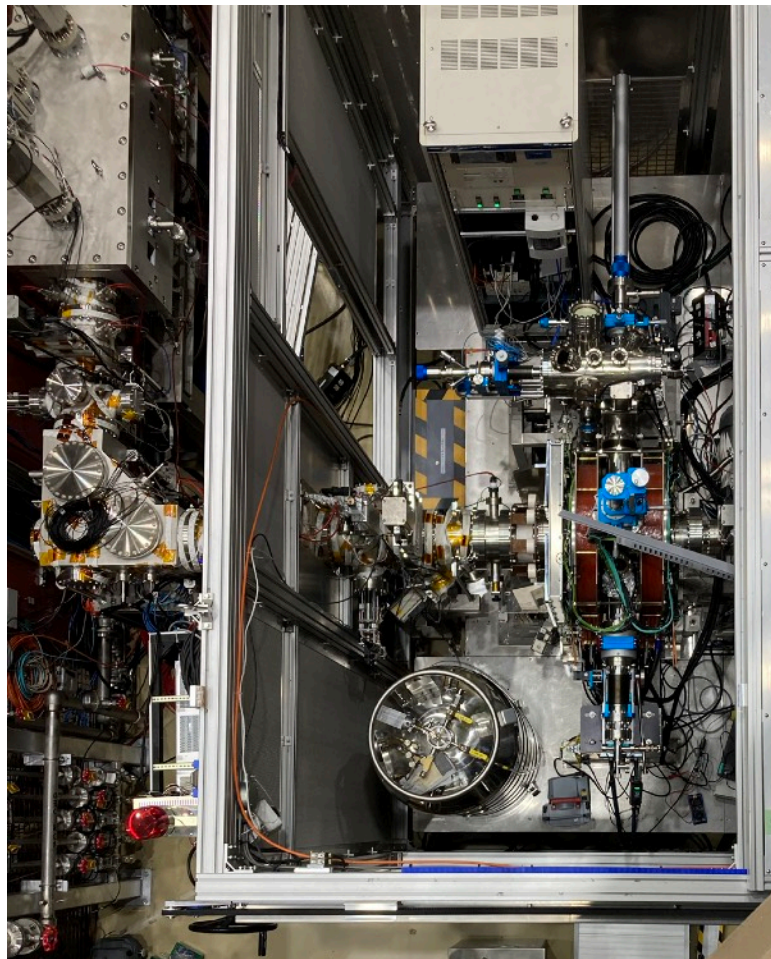
Laser improvements (Y. Oishi)



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

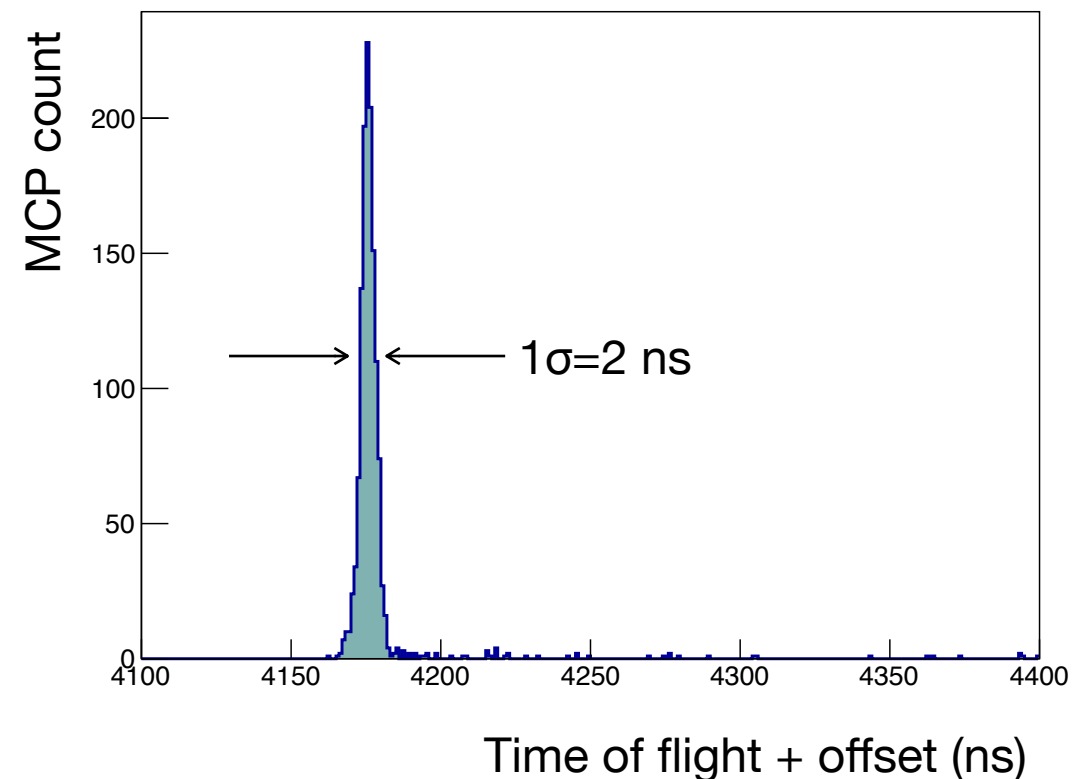
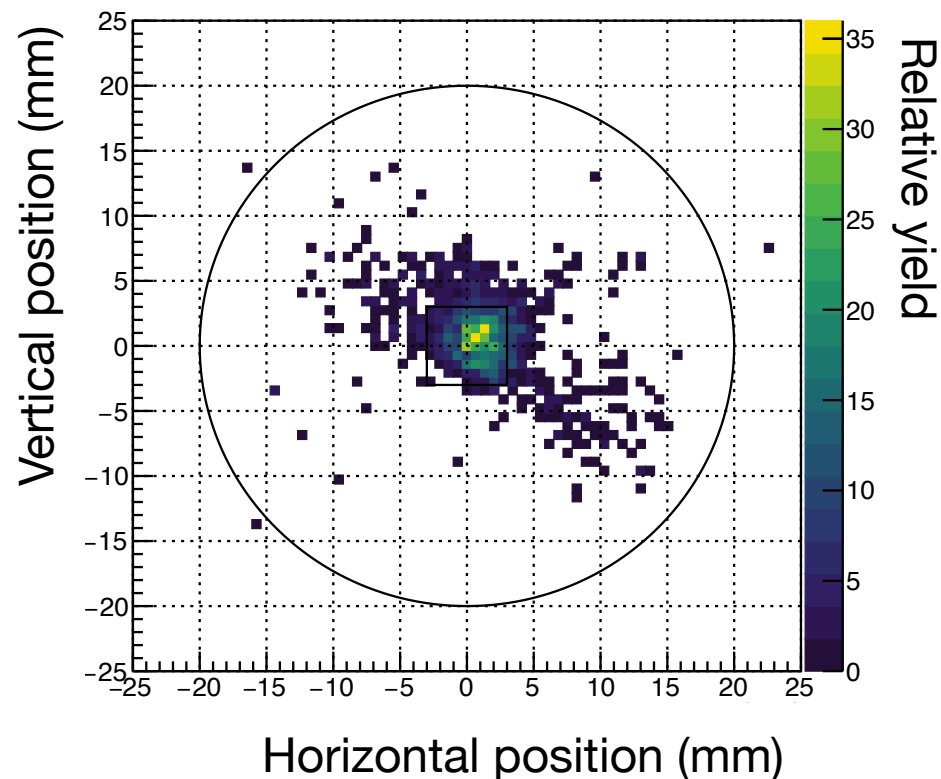
- Laser: Pulse energy was doubled by improving the Lyman- α light generation gas cell.
- Simulation: good agreement between detailed simulations and measurements.
- Surface muons: A new monitor was developed to optimize the surface muon beam.

USM- μ SR 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.

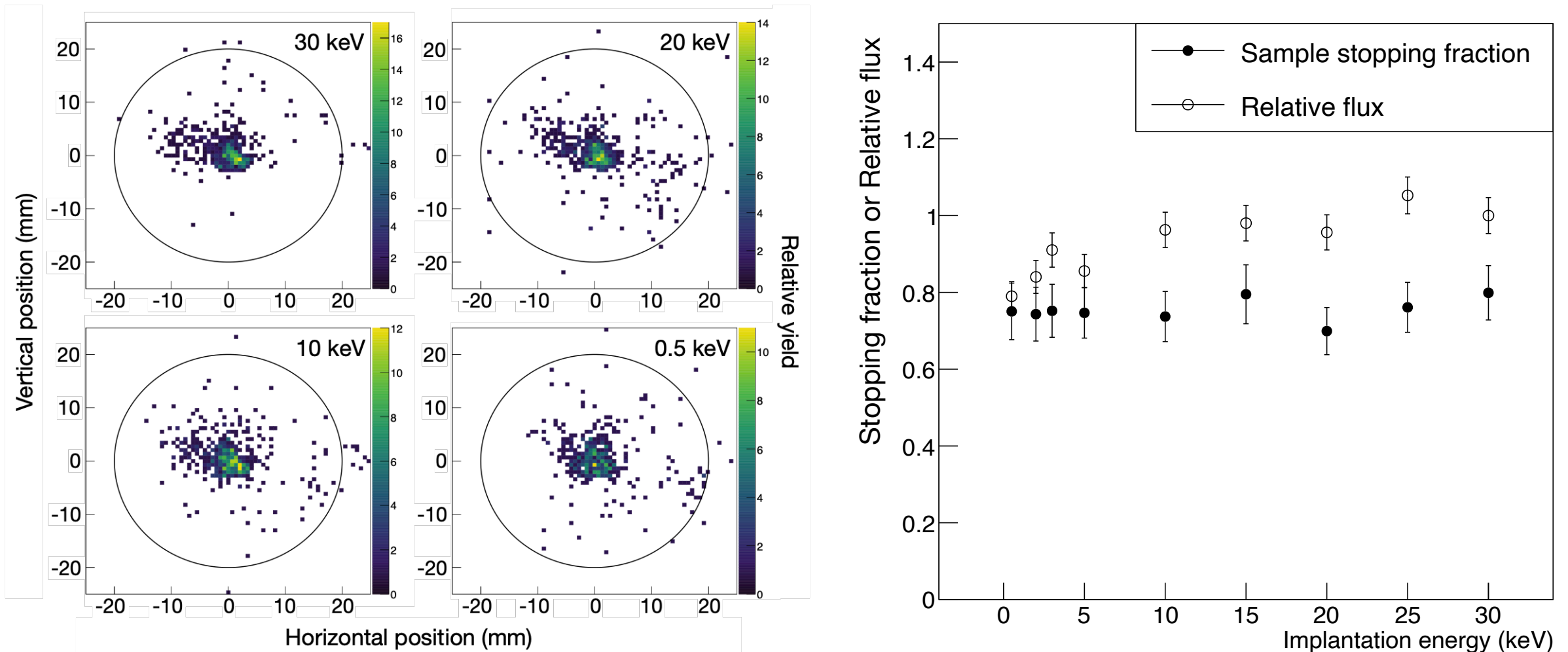
Beam Spec. at the Sample Pos.



- 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.

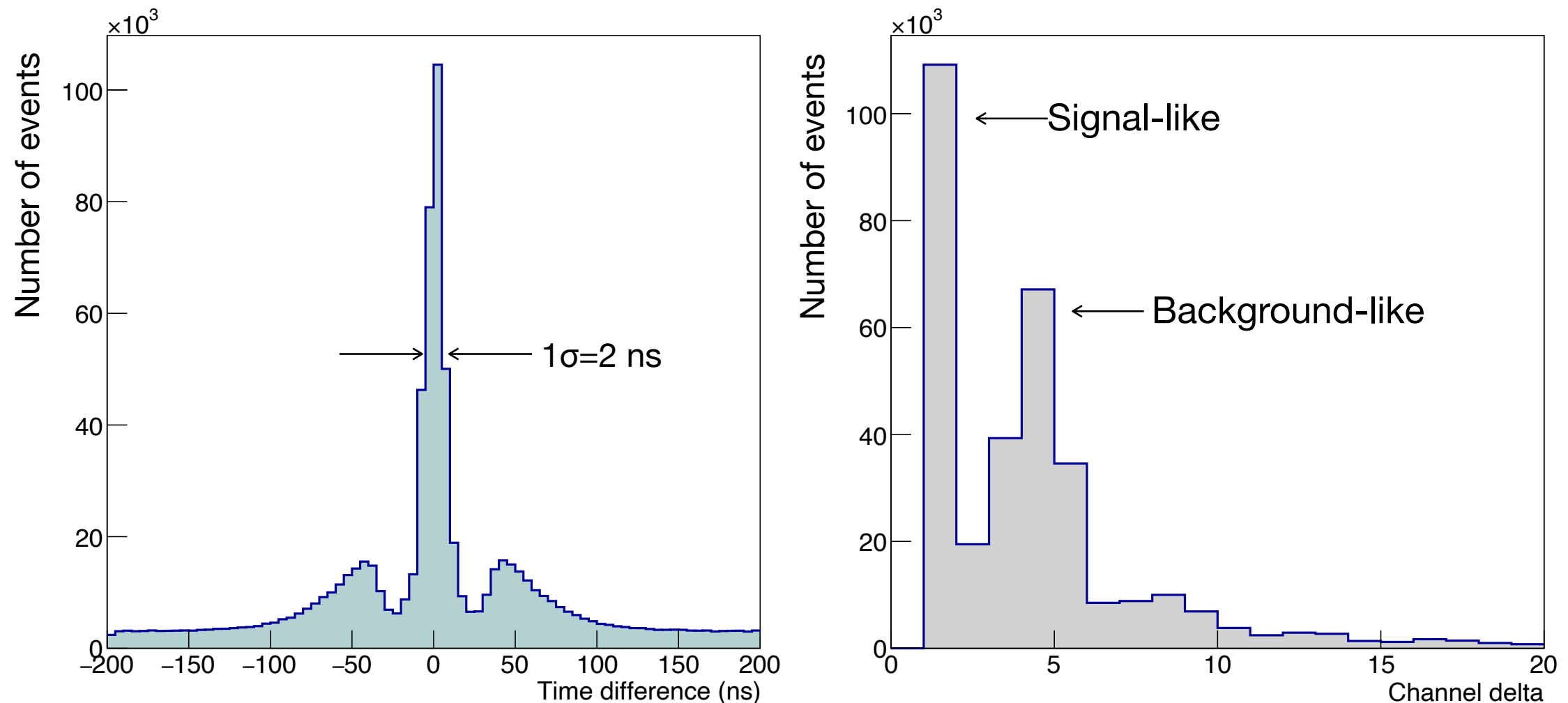
USM Beam Energy Scan



- 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.

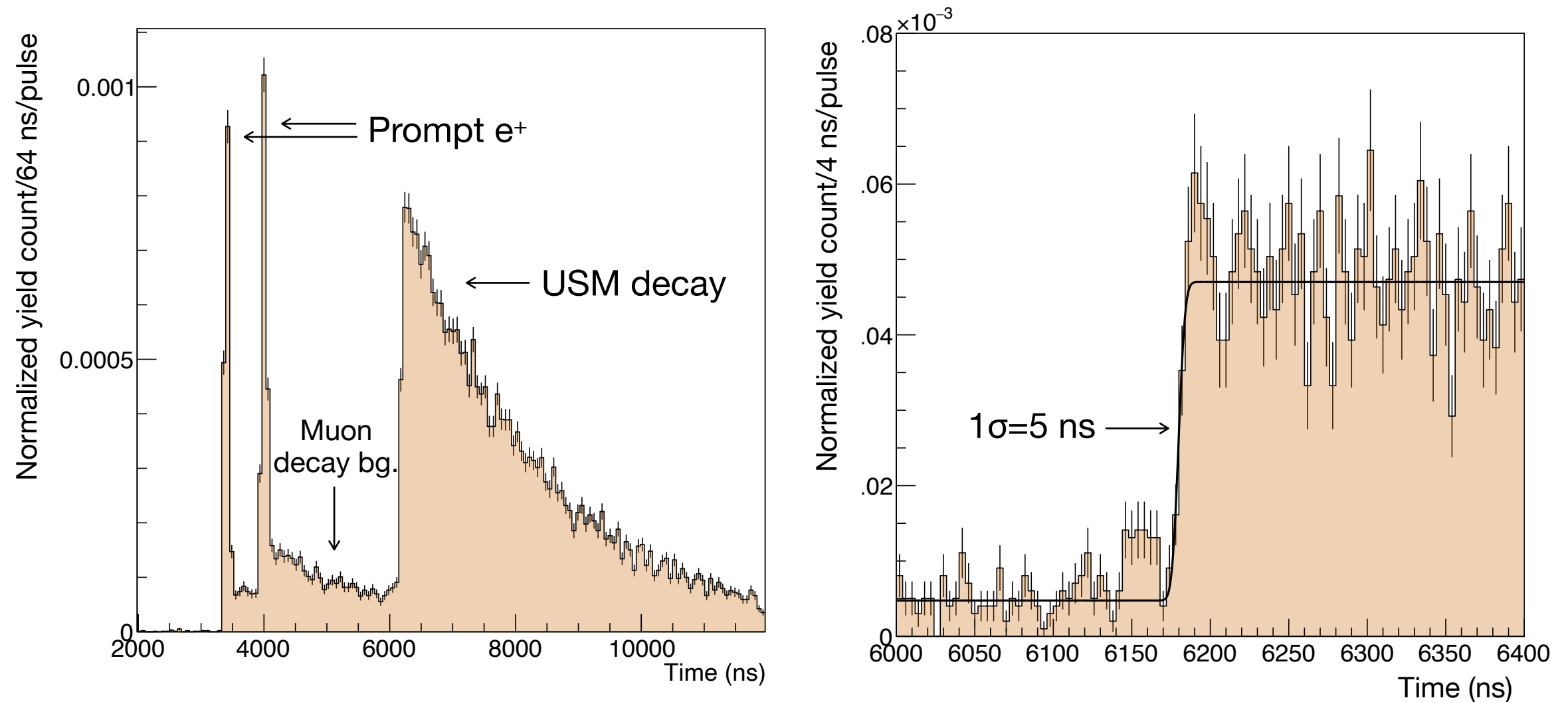
S. Kanda et al., accepted for publication in the proceedings of J-PARC2024 conference.

Spectrometer Performance



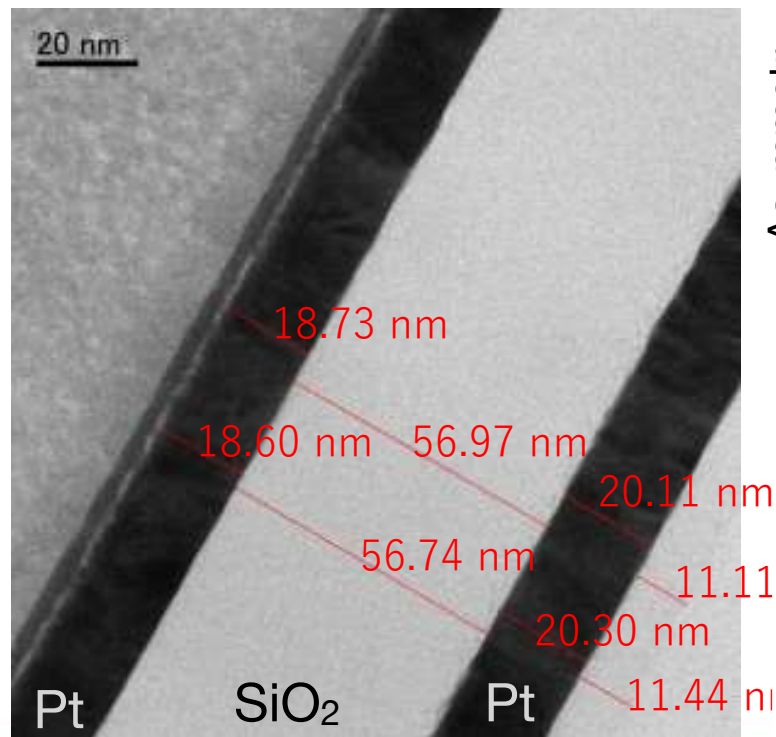
- The detector uses a two-layer (inner/outer) coincidence analysis to improve the signal-to-noise ratio.
- By fitting the main coincidence peak, the detector's time resolution was determined to be 2 ns (1σ).
- Signal (from muons in the sample) and background (from muons stopped upstream) can be distinguished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

Spectrometer Performance



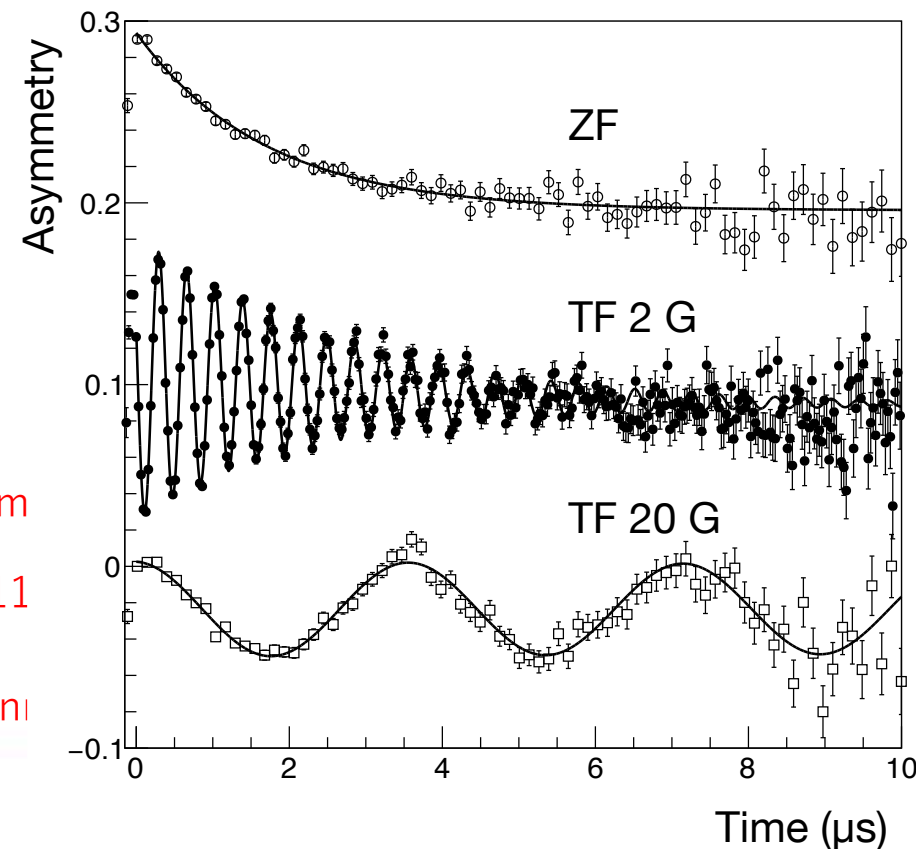
- Two sharp peaks from prompt positrons created by the pulsed proton beam.
- An exponential signal rising at ~6200 ns, which is the USM signal.
- An earlier exponential decay, identified as background from scattered muons.
- The time resolution of USM-μSR was estimated to be 5 ns (1σ) by analyzing the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

SiO₂/Pt Multilayer Sample



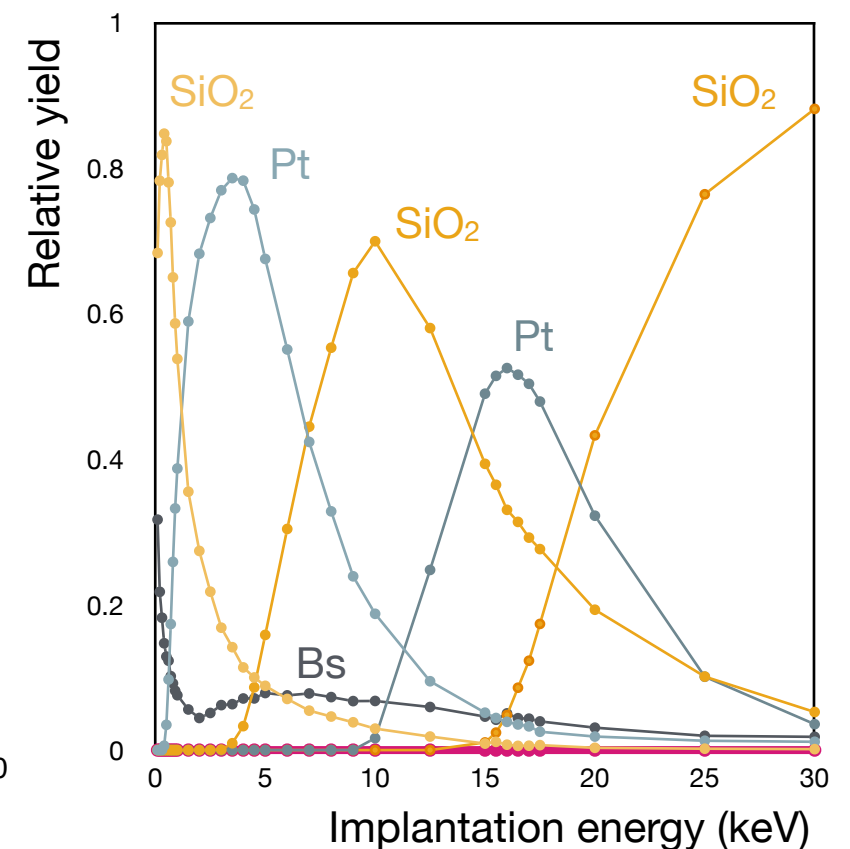
TEM image

provided by NTT-AT



μ SR spectra of surface muons

$$A_{\text{Mu}} = (9.9 \pm 0.1)\%, \quad A_{\mu} = (1.5 \pm 0.1)\%$$

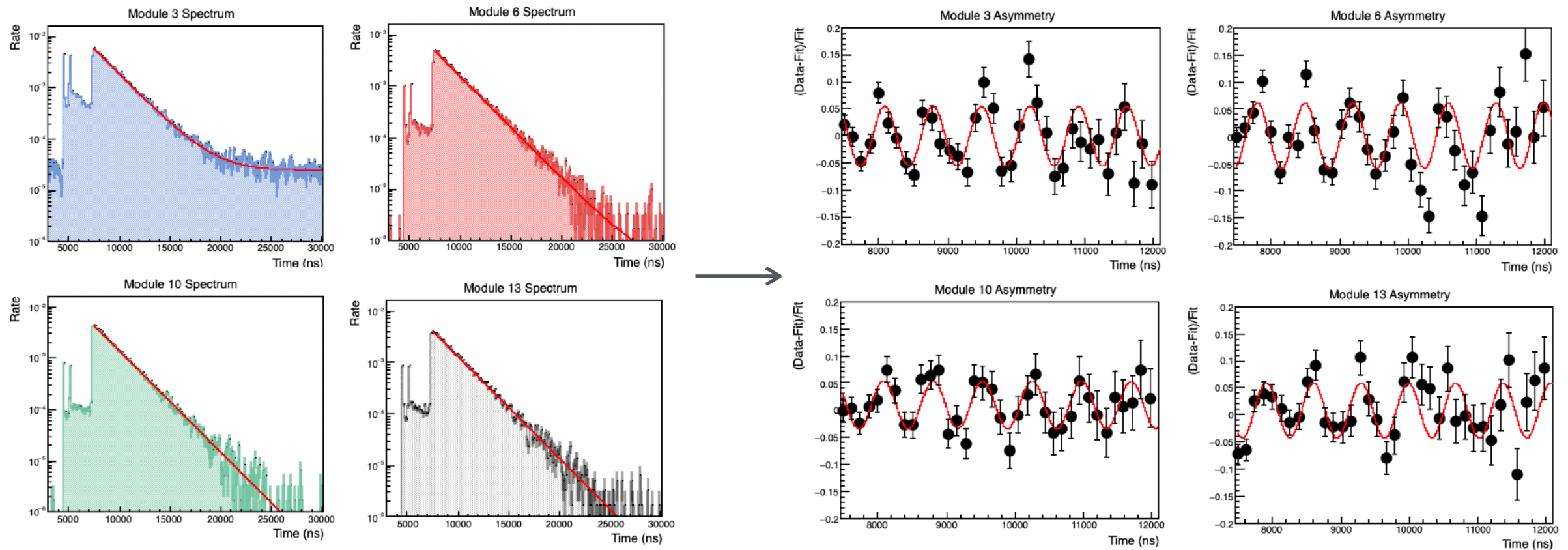


TRIM.SP stopping calc.

(BS = back scattering)

- A multilayer film designed to demonstrate implantation depth control.
- Alternating layers of silica (SiO₂) and platinum (Pt) were deposited on a synthetic quartz substrate.
- The signal from the bulk quartz substrate was confirmed with bulk μ SR.
- Implantation depth profiles were calculated using the TRIM.SP simulation code.

USM- μ SR Data Analysis

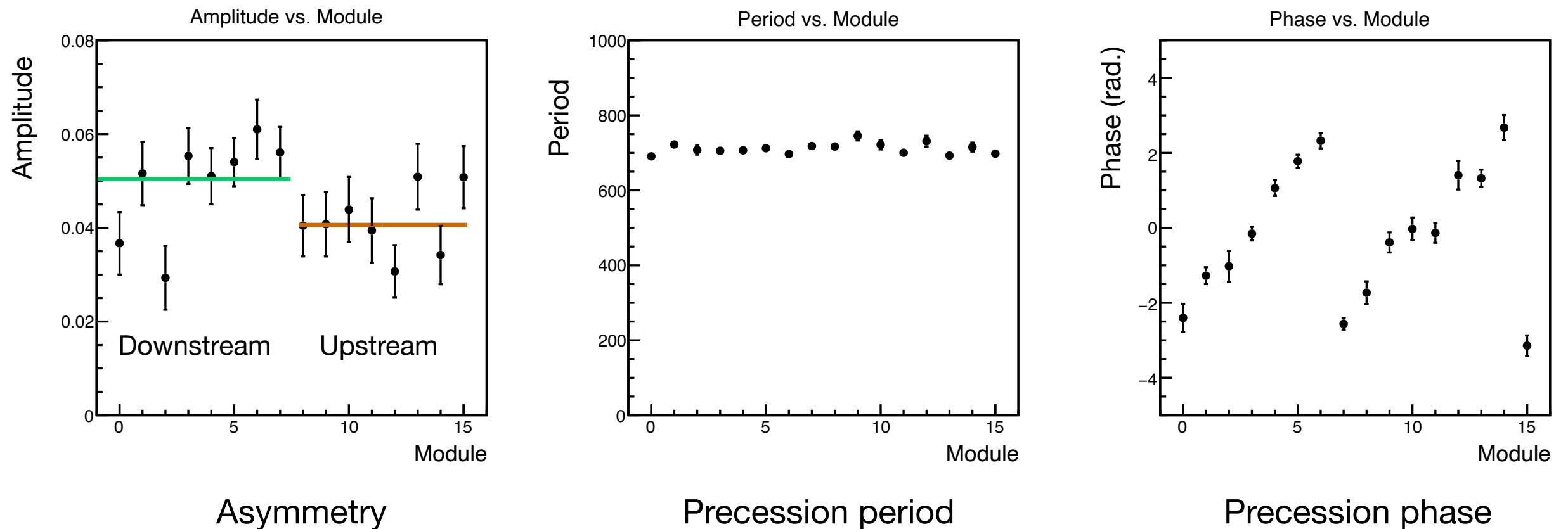


Time spectrum of each module (16 in total)

Individual asymmetry of each module

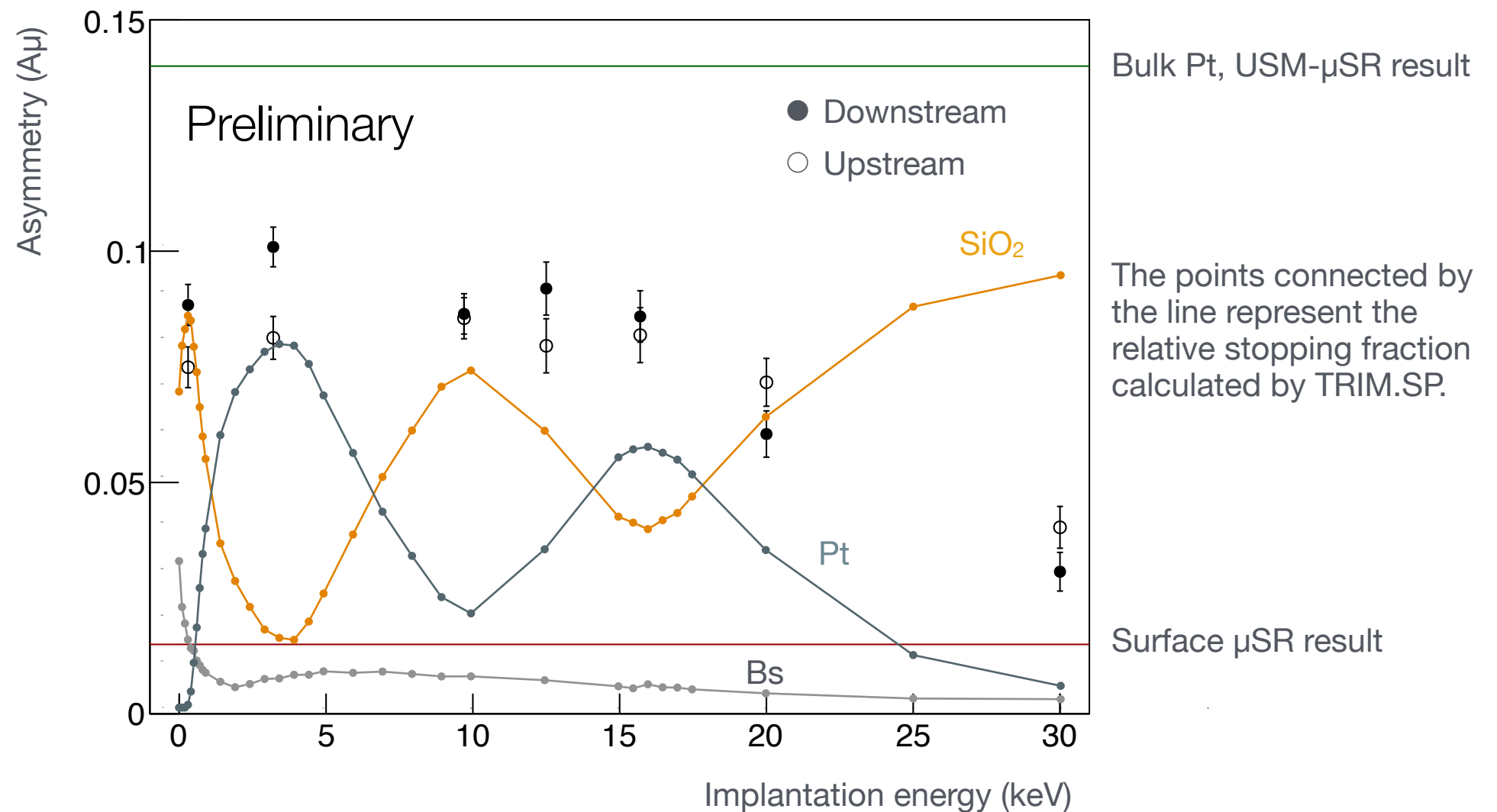
- The detector is divided into 8 upstream and 8 downstream modules. The arrangement is symmetric in the forward-backward, up-down, and left-right directions.
- The signal-to-noise (S/N) ratio may be different for each module. The phase of the rotation is different for each module.
- The time origin (t_0) 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- μ SR Data Analysis



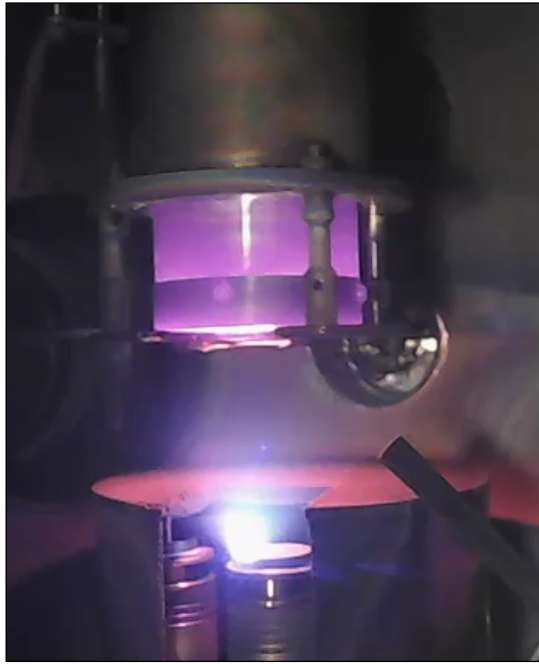
- For this analysis, we used the weighted average of the individual asymmetries.
- The rotation period was consistent across all modules. The rotation phase was consistent with the geometric arrangement of the modules.
- The fitting tended to be unstable for some modules.
- We plan to evaluate the following 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 μ SR Result

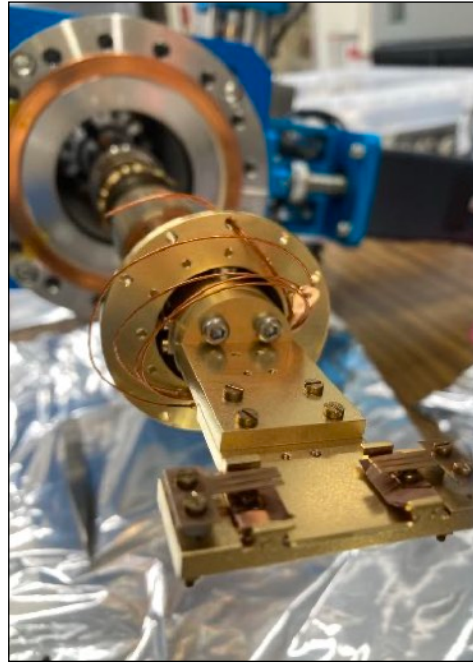


- The trend of the diamagnetic fraction in the precession was in general agreement with the calculated muon stopping profile.
- We aim to obtain the final results by increasing the number of data points in the energy scan, improving the data quality, and refining the analysis.

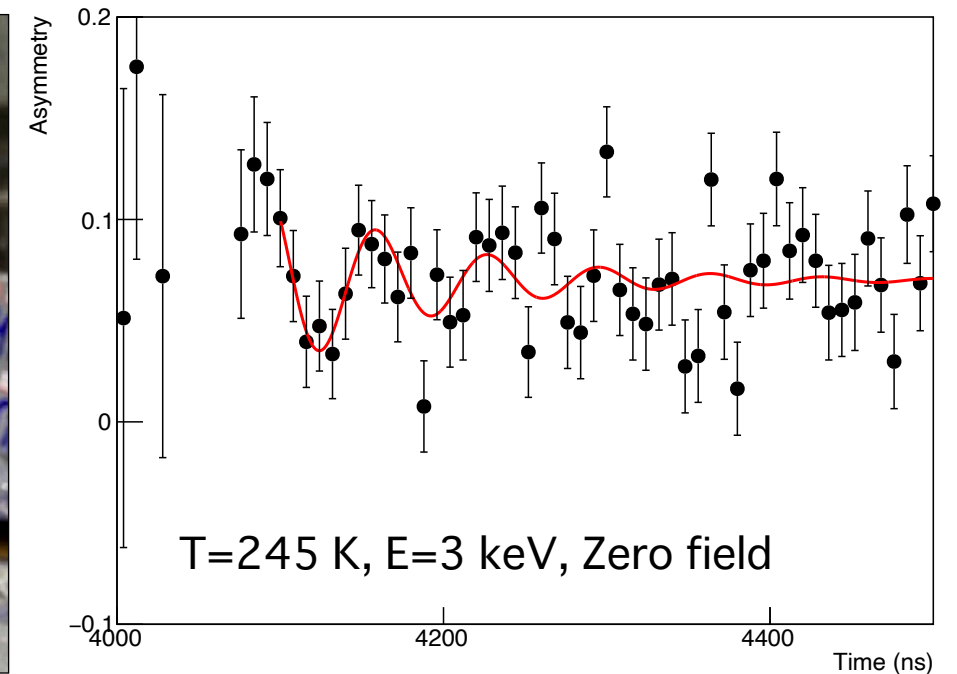
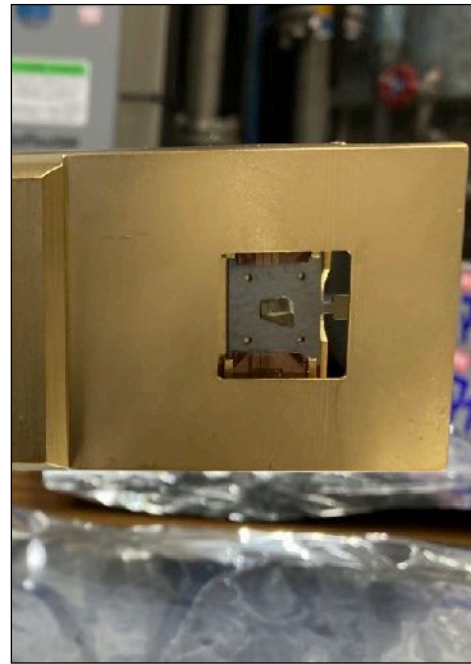
First Scientific Campaign



Sample fabrication by pulsed laser deposition.



Thin film sample of $\text{Ca}_{0.85}\text{Sr}_{0.15}\text{CuO}_2$ mounted on the cryostat.

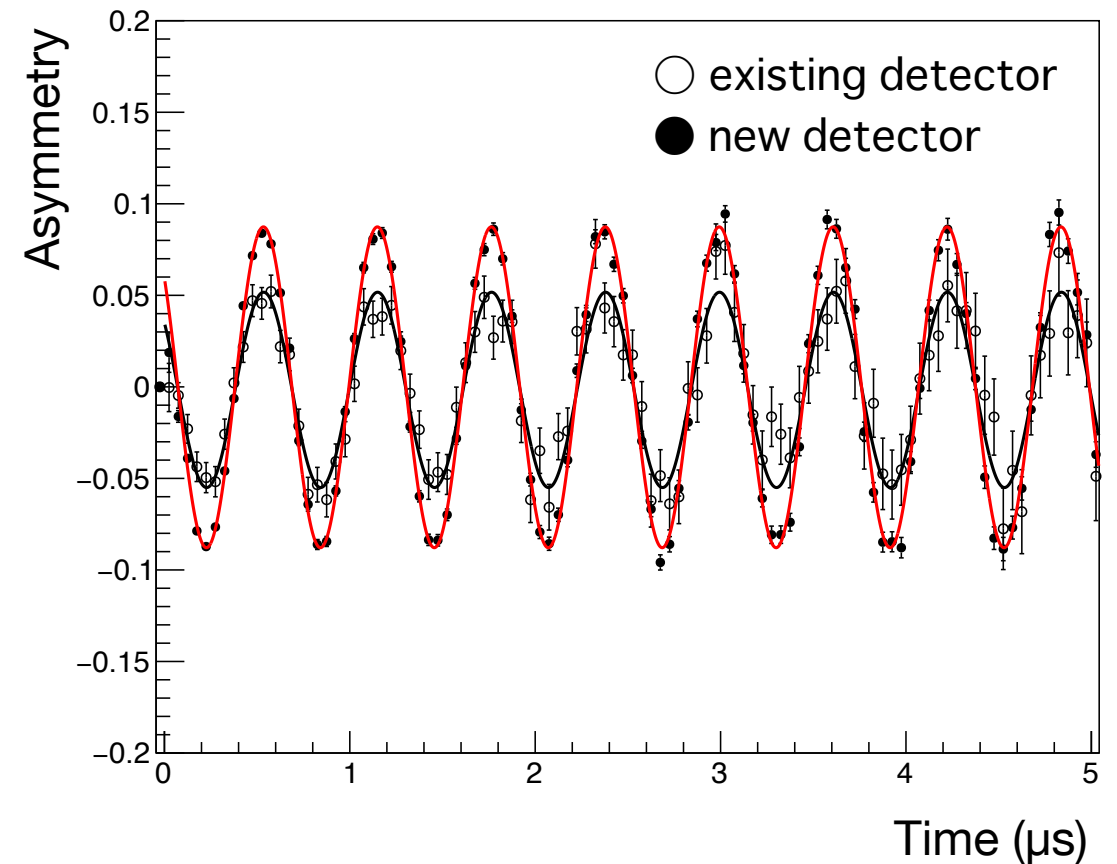
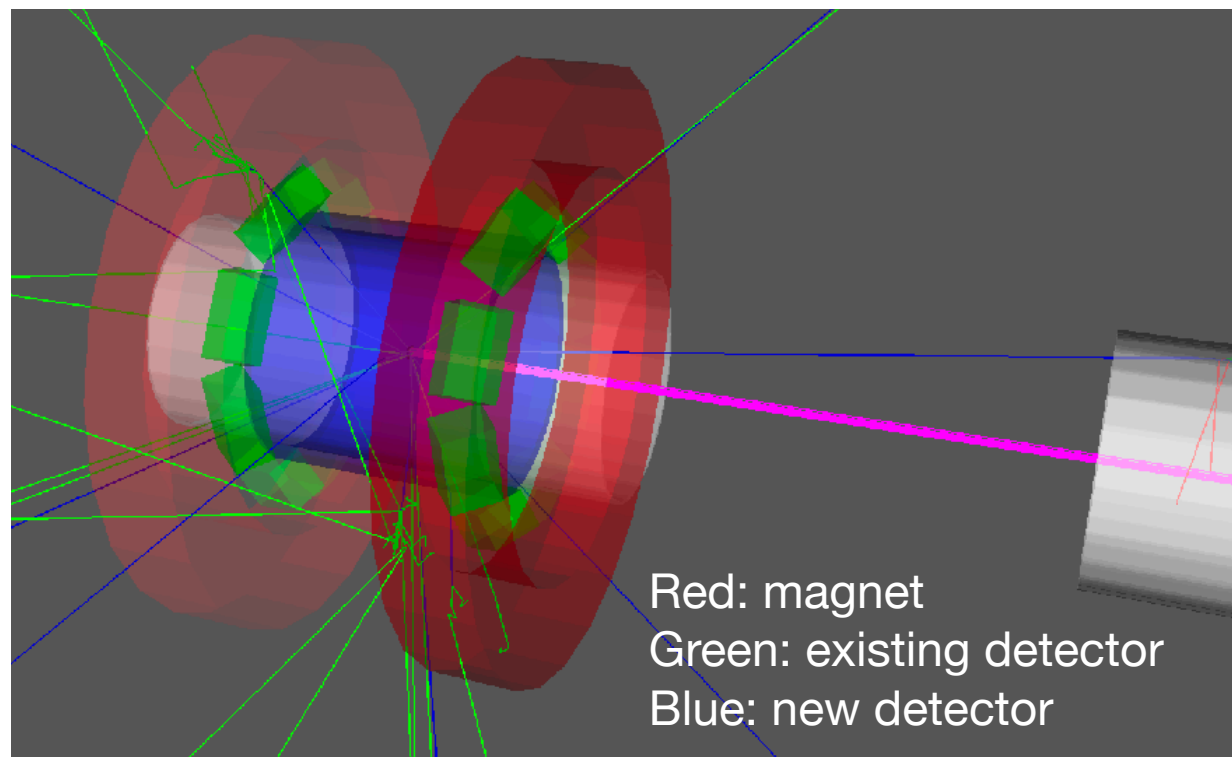


Preliminary result of the zero-field μSR measurement.

- 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 μ SR 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).

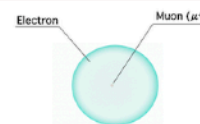
[4] S. Kanda, in Proceedings of J-PARC2024, accepted for publication.

- 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 μ SR.

Muon Cooling for Muonium Spectroscopy and Interferometry Sohtaro Kanda / KEK

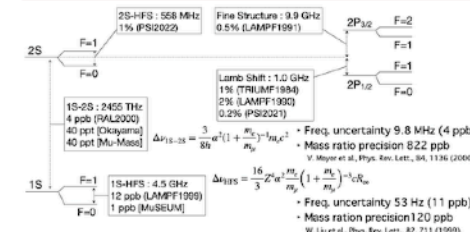
Introduction: Muonium Spectroscopy and Interferometry

Muonium



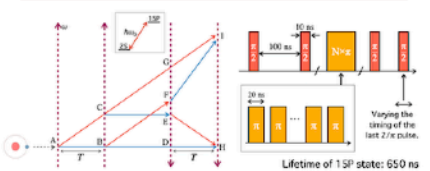
- Muons are second-generation charged lepton, with a mass 200 times that of an electron and the lifetime of 2.2 μ s.
- Muonium is a hydrogen-like atom composed of a positron and an electron, forming a pure lepton two-body system.
- It serves as an ideal testbed for bound-state quantum electrodynamics.

Spectroscopy



- The spectroscopy of muonium provides a unique gateway for precision tests of the Standard Model and searches for new physics.
 - The potential for discovering new physics using muons is constrained by muon mass precision, necessitating alternative methods for independent determination.
- S. Kanda, "In-flight muon spin resonance and muonium interferometry", J. Phys.: Conf. Ser. 2462, 012029 (2023).

Interferometry

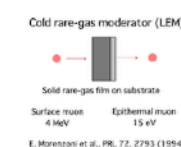


- The phase difference between ACEH and ABDH is $\Delta\phi = 2(\omega - \omega_0)T - \hbar k^2/2m$.
- Similarly, for the paths ABFI and ACGI, it is $\Delta\phi = 2(\omega - \omega_0)T + \hbar k^2/2m$.
- By taking the difference, $\Delta\phi_1 - \Delta\phi_2 = \hbar k^2/m$.
- Precise determination of the atomic mass can be achieved through the measurement of photon recoil shift in a matter-wave interferometer.
- There is no precedent for a matter-wave interferometer using muonium.
- With 10 π -pulse pair irradiations, the mass determination precision of 1 ppb is expected.

S. Kanda, "Simulations of a Muonium Atom Interferometer with Light Pulses", accepted for publication in J-PARC2024 proceedings.

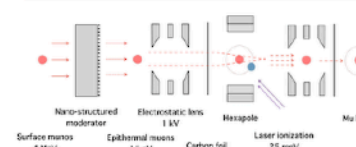
Generation of a Muonium Beam using Low-Energy Muons

Low-energy muons



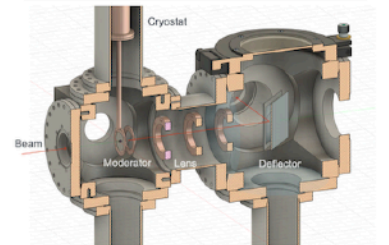
- For precision spectroscopy and matter-wave interferometry, low-energy muons are essential.
- Two established methods for obtaining low-energy muons: epithermal muons from a solid rare gas moderator (LEM) and ultra-slow muons via laser ionization of muonium in vacuum (USM).

Multi-stage Muon Cooling



- A two-stage scheme combining LEM and USM improves the brightness of Mu beam.
- By inserting LEM before USM, the spatial overlap between the laser beams and the Mu cloud improves compared to obtaining Mu in vacuo directly from the surface muon beam.

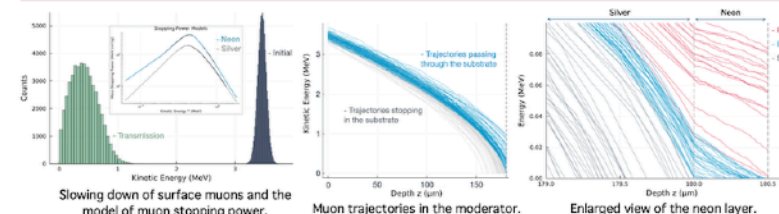
Moderator development



- A moderator assembly, transport optics, and slow muon detector are under development.
- A beam test is scheduled for fall 2025.

Simulations for Multi-Stage Muon Cooling

Generation of epithermal Muons



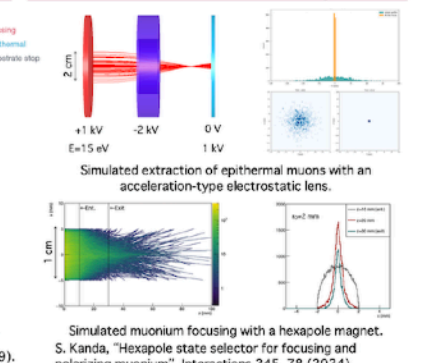
- The substrate is silver and the moderator is neon. The incident energy is tuned to the half-stop condition.
- The energy loss was calculated using the Bethe-Bloch formula for the high-energy region, the Lindhard theory for the low-energy region, and the Anderson-Ziegler model for the intermediate region.
- Estimated moderation efficiency is on the order of 10^{-4} , similar to experimental results at PSI [1].
- Referencing the MuCool collaboration's work on muon slowing in helium gas [2], the simulator will be updated.

Summary

[1] T. Prokscha et al., Appl. Surf. Sci. 172, 235 (2001), [2] I. Belosevic, Ph.D Thesis, ETH Zurich (2019).

- Precision measurements involving muons are a powerful probe for exploring new physics, but their potential is limited by the precision of muon mass measurements.
- The muon mass can be precisely determined using a Ramsey-Bordé atom interferometer involving muonium.
- Development of a bright, slow muonium beam is in progress, combining a solid rare-gas moderator and laser ionization of thermal muonium. A simulator and a prototype demonstrator are under development.

Muon and muonium focusing



Summary

- To overcome the limitations of conventional bulk μ SR 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 μ SR spectrometer has been fully commissioned, and a dedicated data analysis framework has been developed.
- Demonstrated depth-resolved μ SR 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.