Low-energy muons update and future developments

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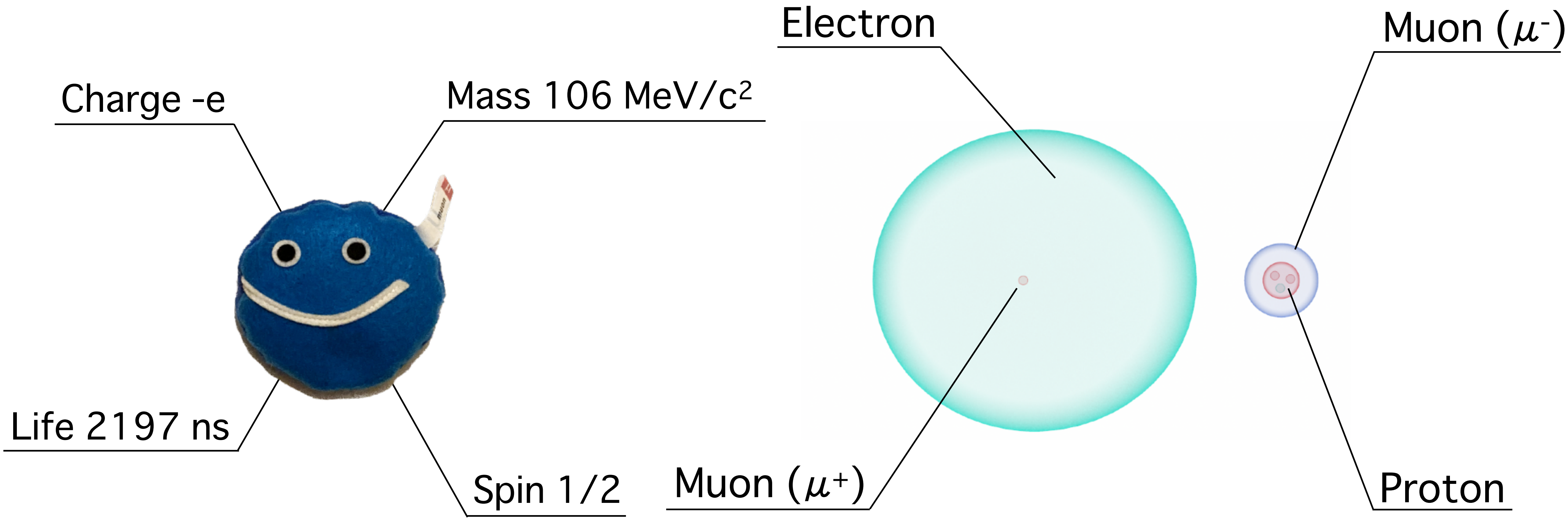
Muons and Muonic Atoms



"Who ordered that?"

Muonium

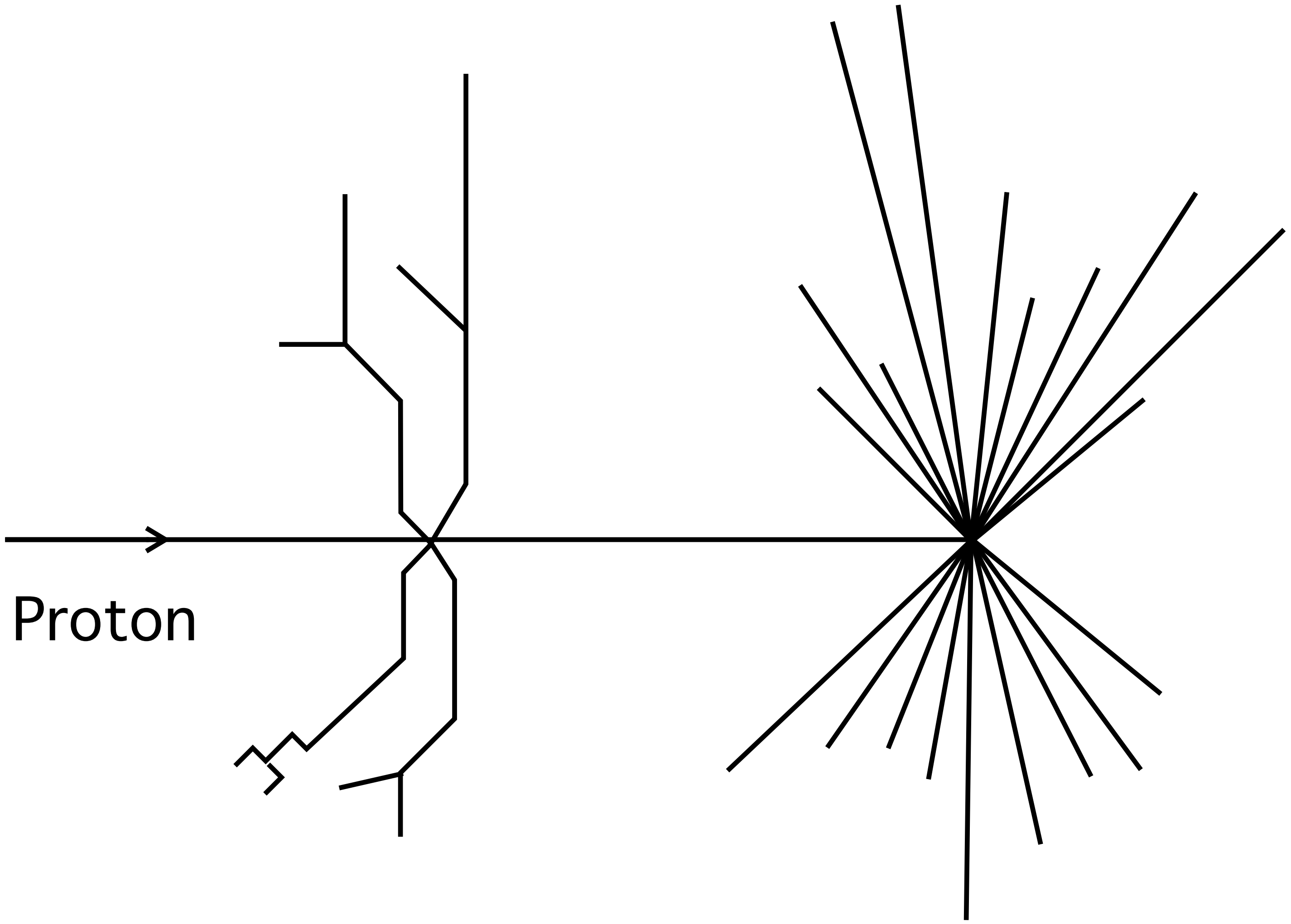
$r_{e\mu+} = 0.53$ Å

Muonic hydrogen

$r_{\mu\text{-}p} = 0.00256$ Å

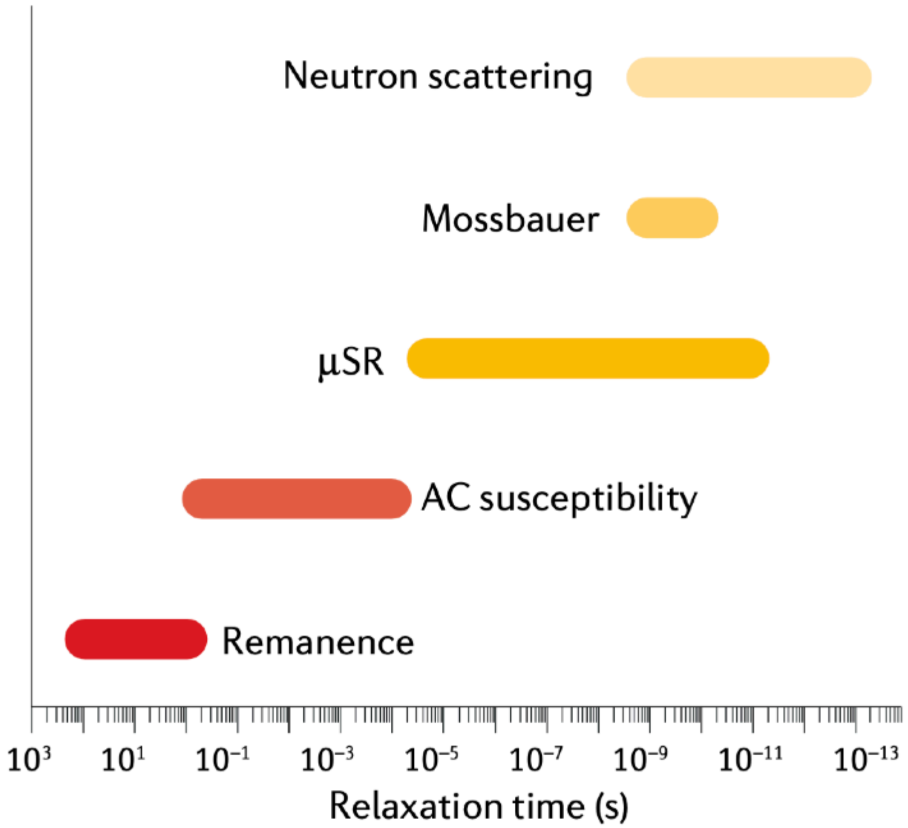
- Muon is 207 times heavier than electron and decays in 2.2 μs of the lifetime.
- Muons are widely applied in materials science as highly-sensitive local magnetometers.

Neutrons and Muons



Muon beamlines

Neutron beamlines



Time windows

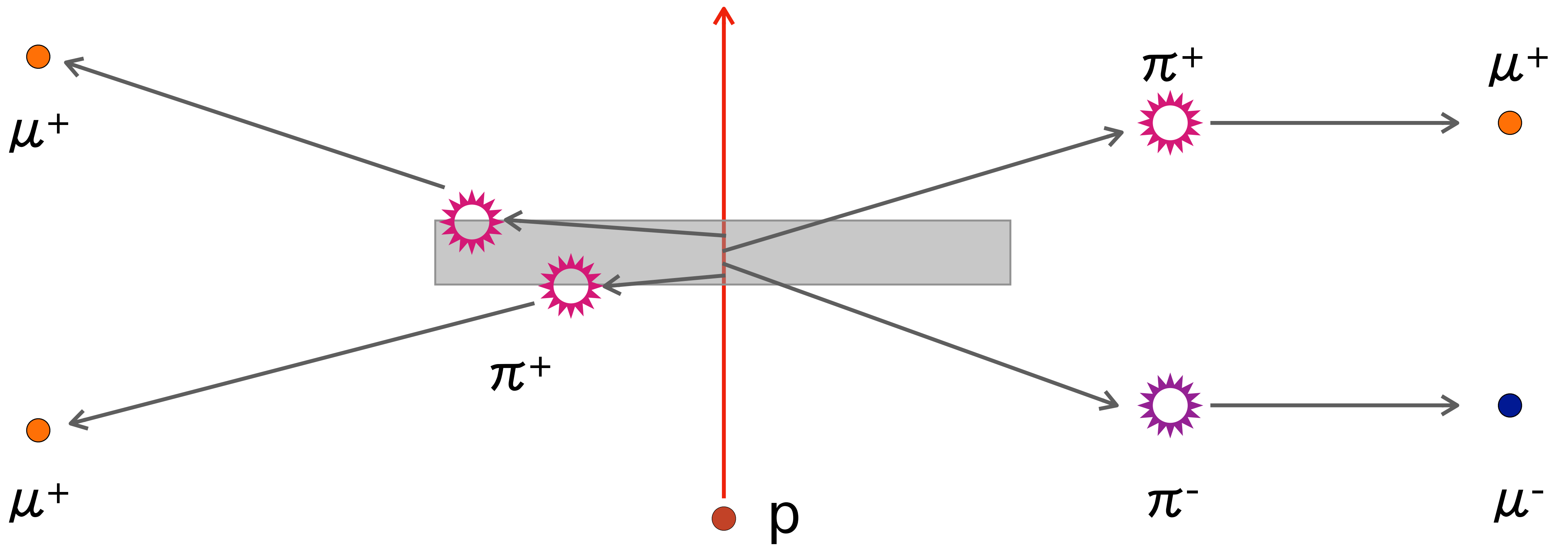
A.D. Hillier et al., “Muon spin spectroscopy”,
Nat. Rev. Methods Primers 2, 4 (2022).

- Charged particle
- Magnets for energy selection
- Decay product measurements

- Neutral particle
- Moderator for energy selection
- Beam measurements

- Complementary quantum beams

Muon Beams



Surface muons

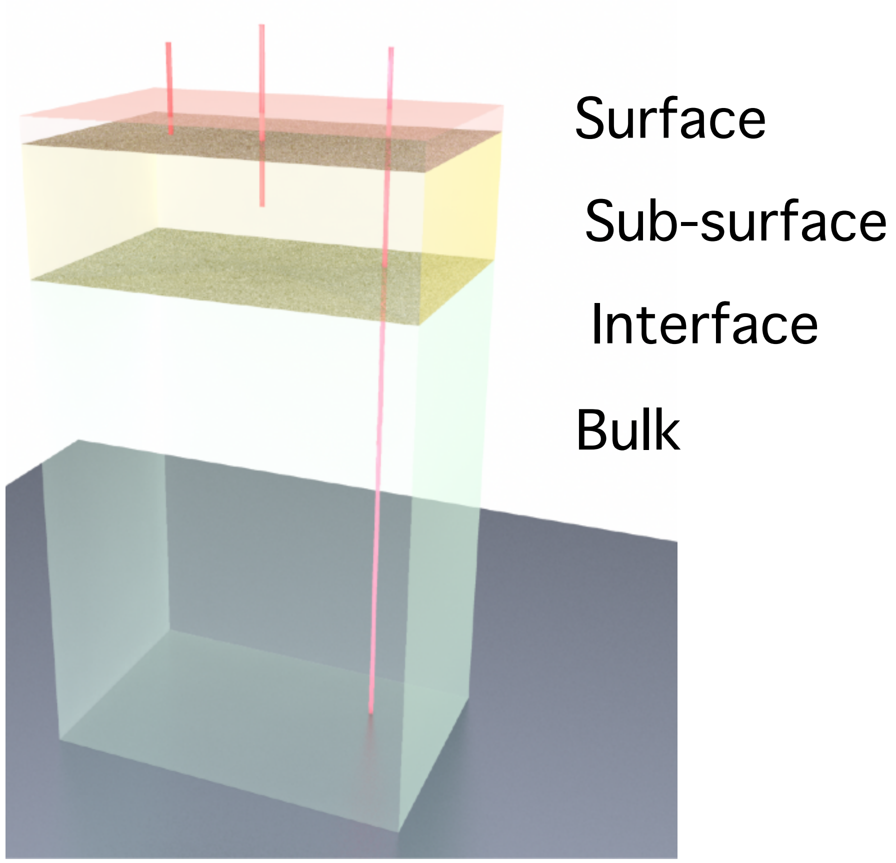
- Muons from pions stopped at the production target surface
- 4 MeV monochromatic
- 100% polarization
- Only available for μ^+

Decay muons

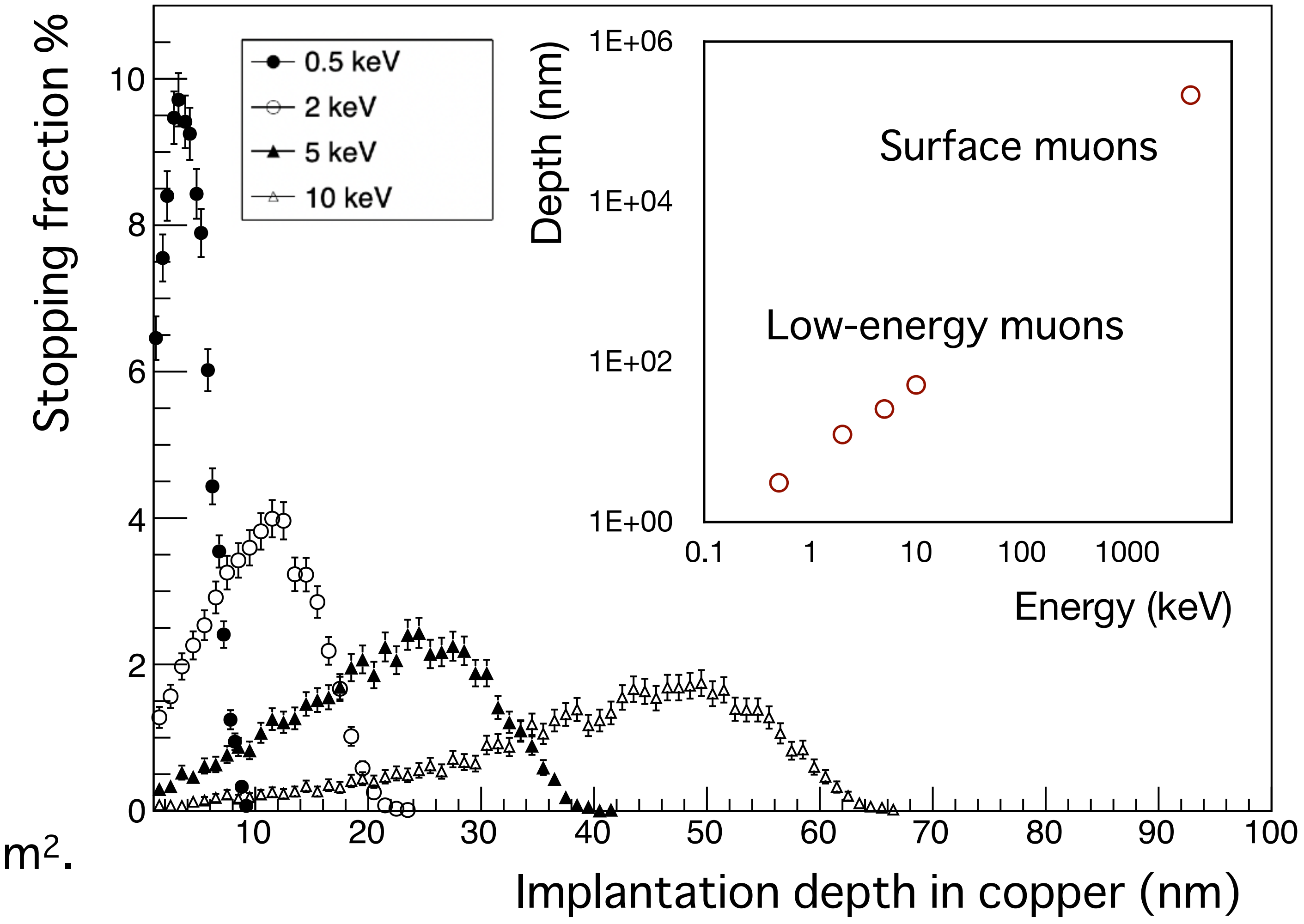
- Muons from pion decays in-flight
- Energy tunable
- Polarization depends on kinematics
- Both μ^+ and μ^- are available.

Necessity of Low-Energy Muons

Implantation depth



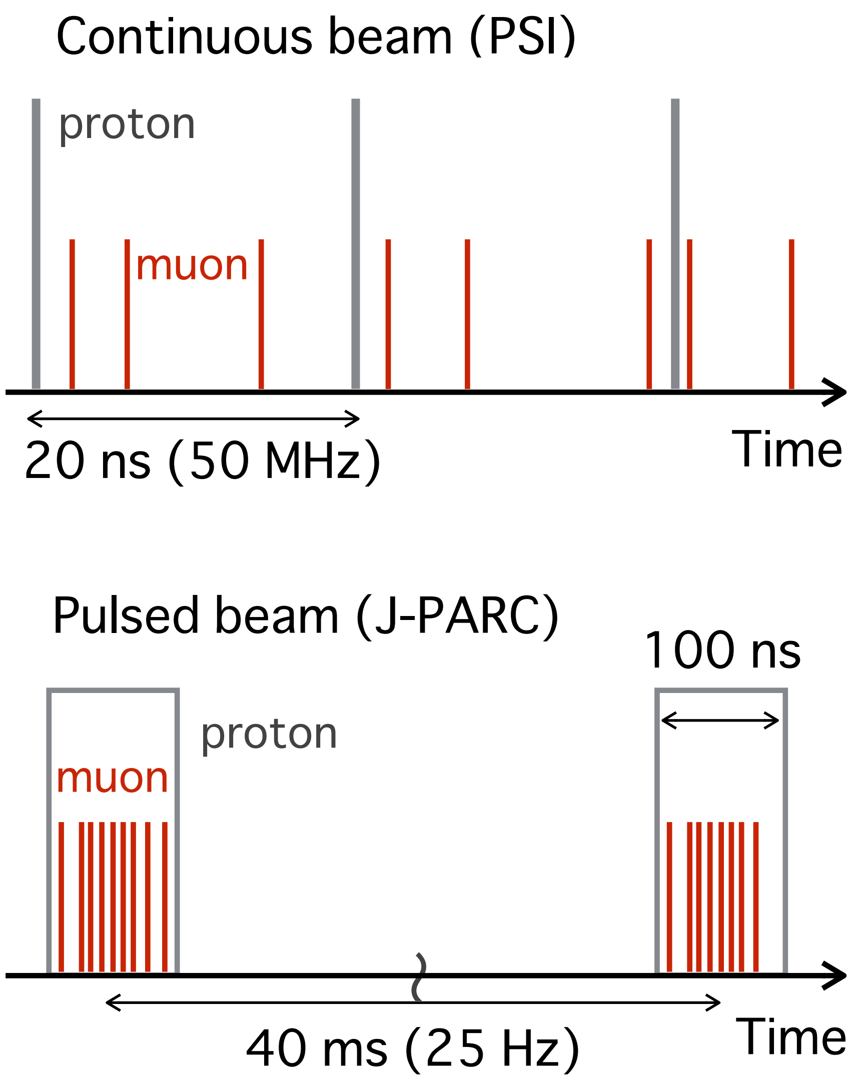
Range of surface muon is 100~200 mg/cm^2.
(The range is 0.2 mm in copper.)

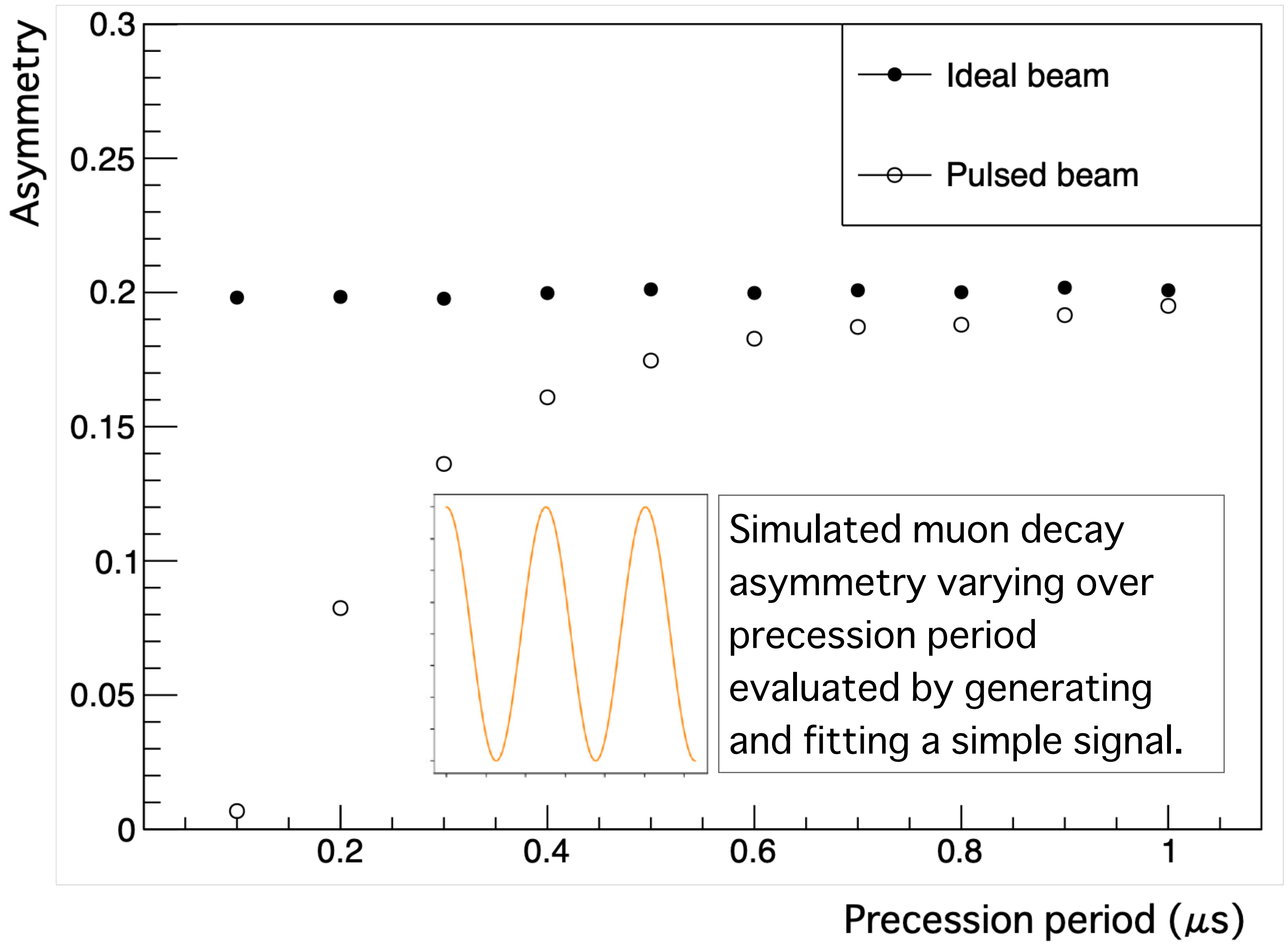


- ○ The surface muon is a bulk probe.
- ○ Low-energy muons are essential to investigate surface and interfaces.

Limitation of the Pulsed Muon

Time resolution





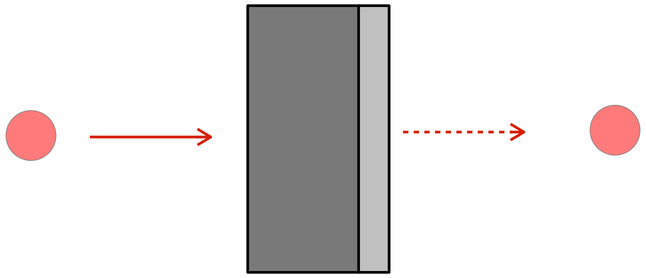
Simulated muon decay asymmetry varying over precession period evaluated by generating and fitting a simple signal.

- ○ A pulsed muon beam provide high statistics while fast precession is difficult to observe.

Low Energy Muons

for low-emittance muon beams

Cold rare-gas moderator (LEM)



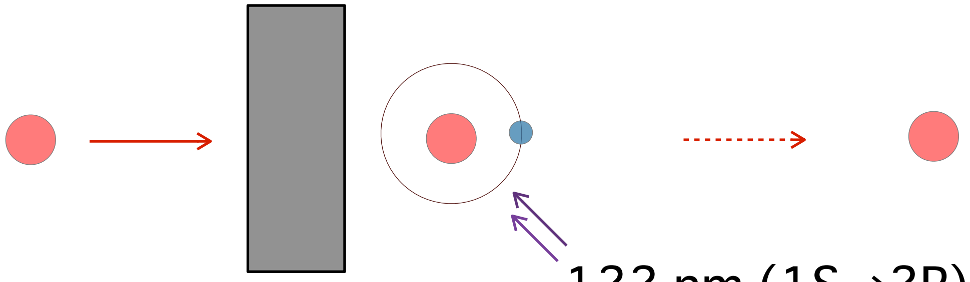
Solid rare-gas film on substrate

Surface muon
4 MeV

Epithermal muon
15 eV

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

Laser ionization of muonium (USM)



Mu emitter

122 nm (1S→2P)
355 nm (2P→Unbound)

Surface muon
4 MeV

Muonium
25 meV

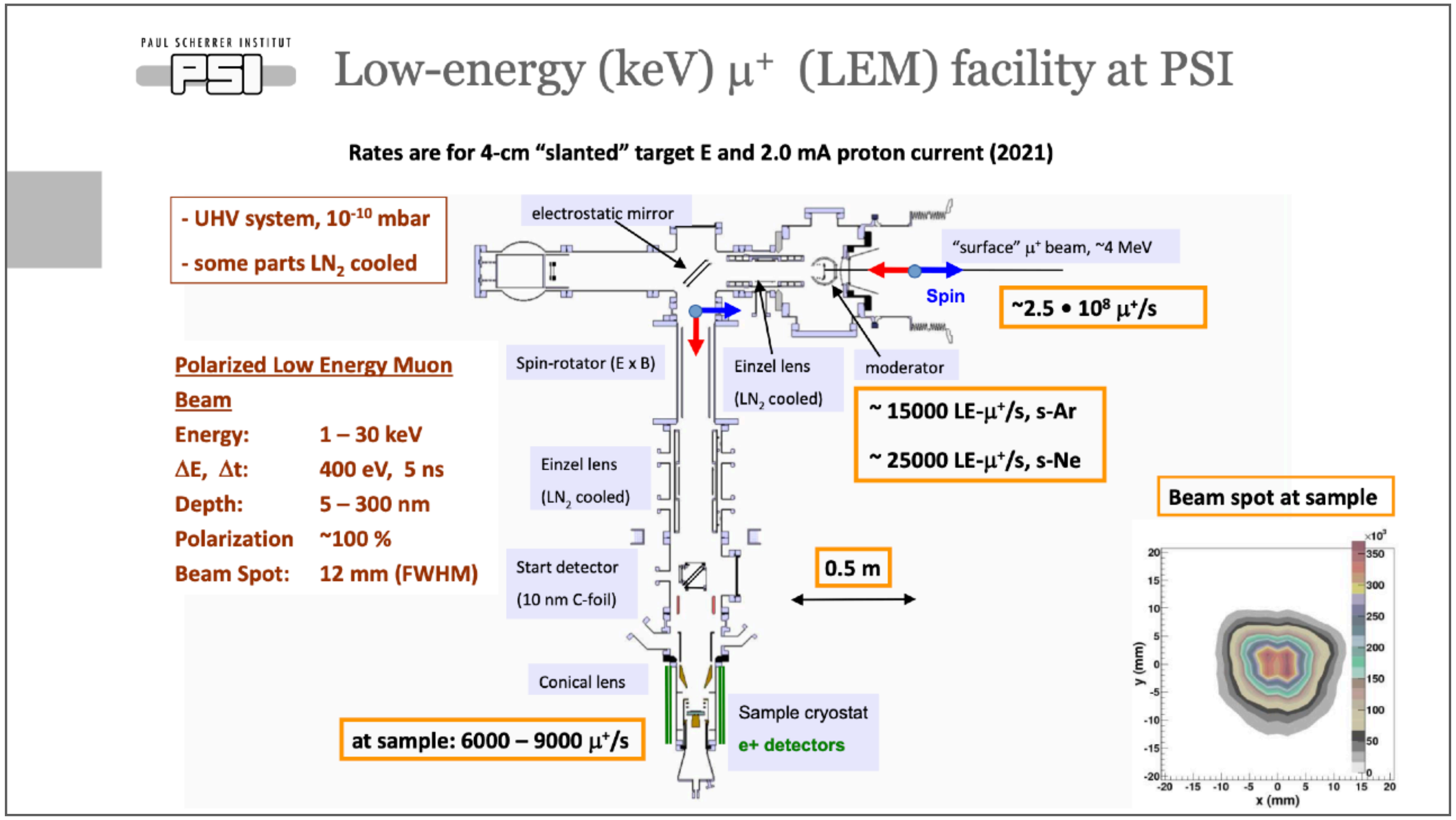
Released muon
25 meV

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

- 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.
- USM has high timing resolution because the time origin is redefined by the laser light pulse.

Low Energy Muons

at Paul Scherrer Institute



PAUL SCHERRER INSTITUT PSI

Low-energy (keV) μ^+ (LEM) facility at PSI

Rates are for 4-cm "slanted" target E and 2.0 mA proton current (2021)

- UHV system, 10^{-10} mbar
- some parts LN_2 cooled

Polarized Low Energy Muon Beam

Energy:	1 – 30 keV
ΔE, Δt:	400 eV, 5 ns
Depth:	5 – 300 nm
Polarization	~100 %
Beam Spot:	12 mm (FWHM)

~2.5 • 10^8 μ^+/s

~ 15000 LE-μ^+/s, s-Ar

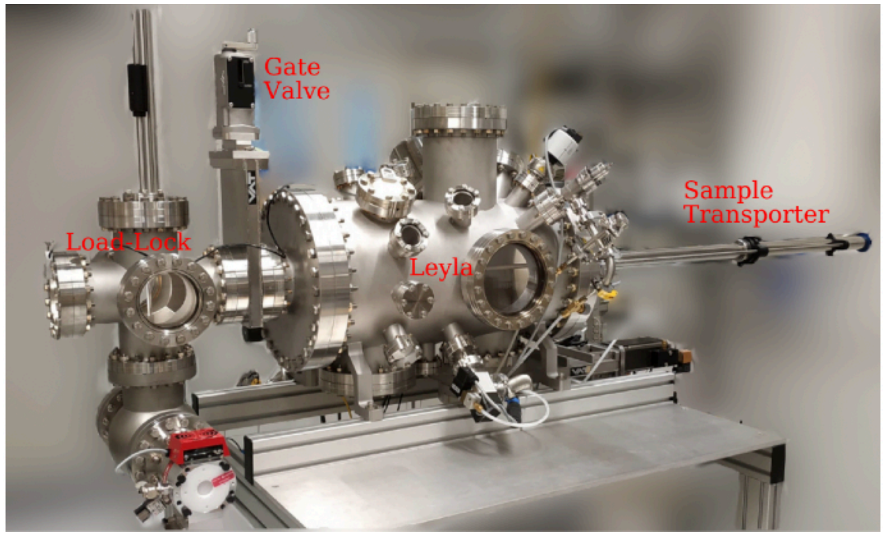
~ 25000 LE-μ^+/s, s-Ne

at sample: 6000 – 9000 μ^+/s

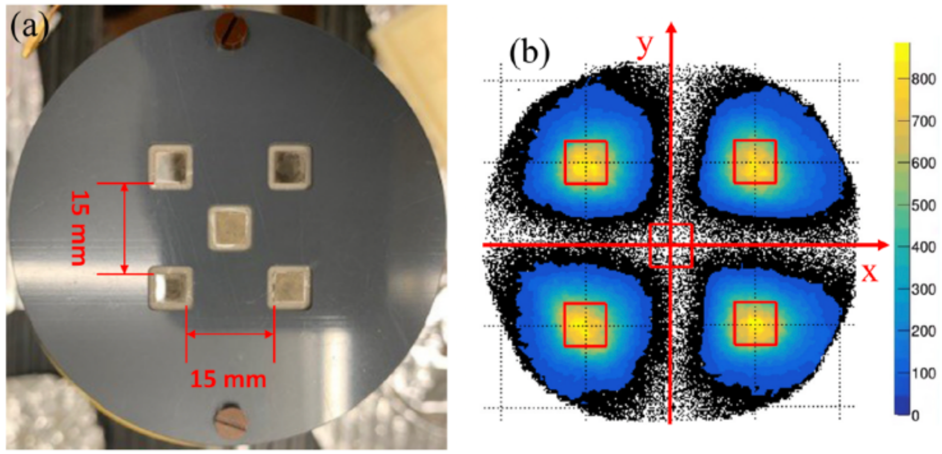
Beam spot at sample

T. Prokscha, presentation at BRIDGE2023.
https://indico.psi.ch/event/14832/

○ LEM is currently the only user-accessible low-energy muon facility in the world.



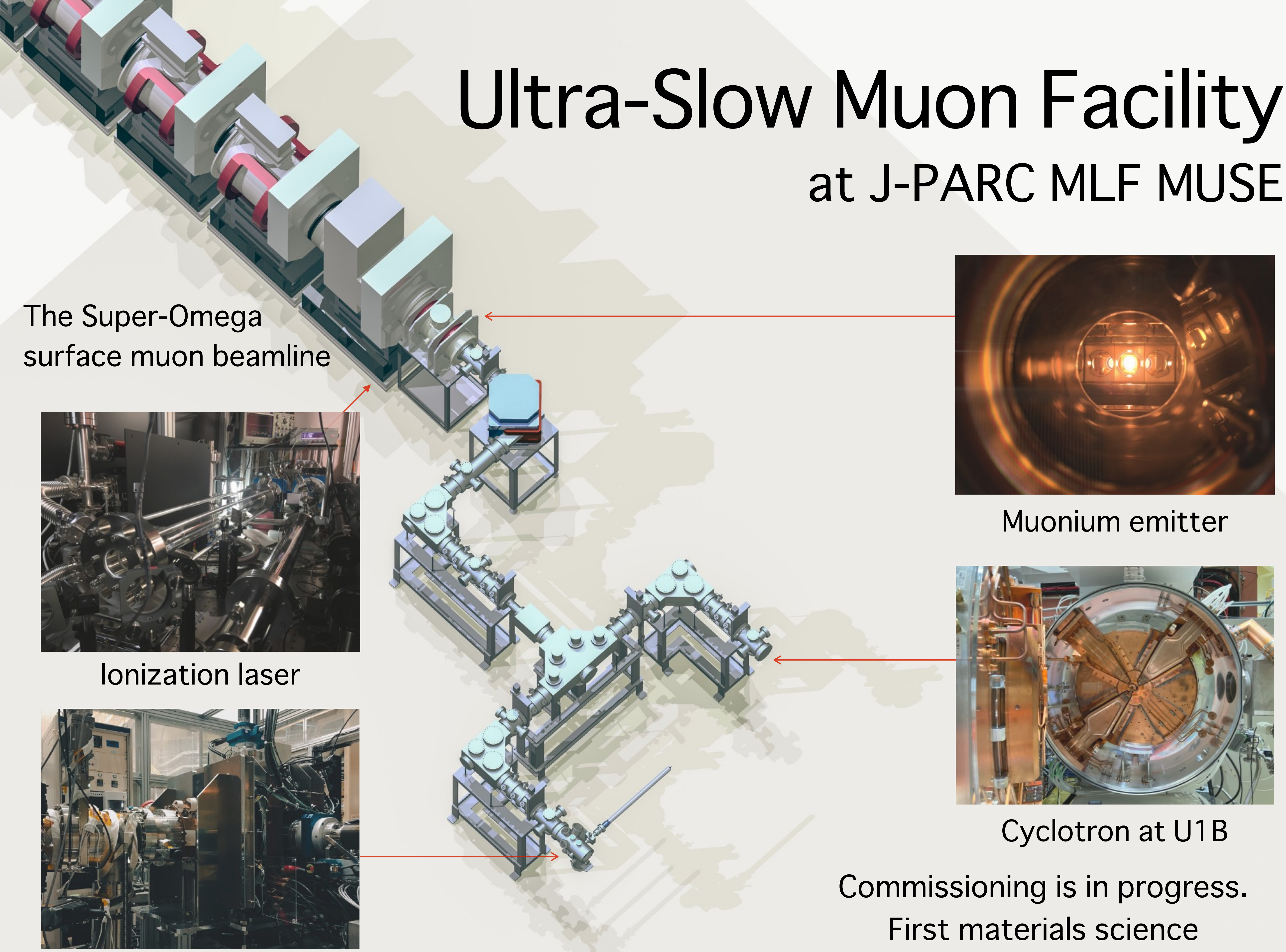
New sample preparation chamber.
H. Teuschl et al., J. Phys.: Conf. Ser. 2462, 012050 (2023).



Small sample measurements.
X. Ni et al., NIM A 1054, 168399 (2023).

Ultra-Slow Muon Facility

at J-PARC MLF MUSE



The Super-Omega surface muon beamline

Muonium emitter

Ionization laser

Cyclotron at U1B

Spectrometer at U1A

Commissioning is in progress.
First materials science
measurement started in 2023.

Project Timeline

at J-PARC MLF MUSE

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.

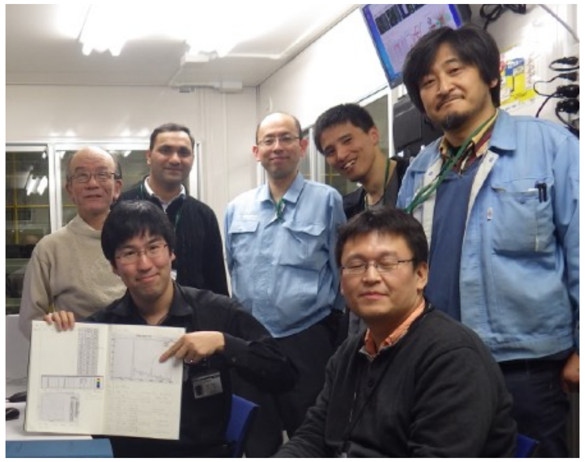
2018

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

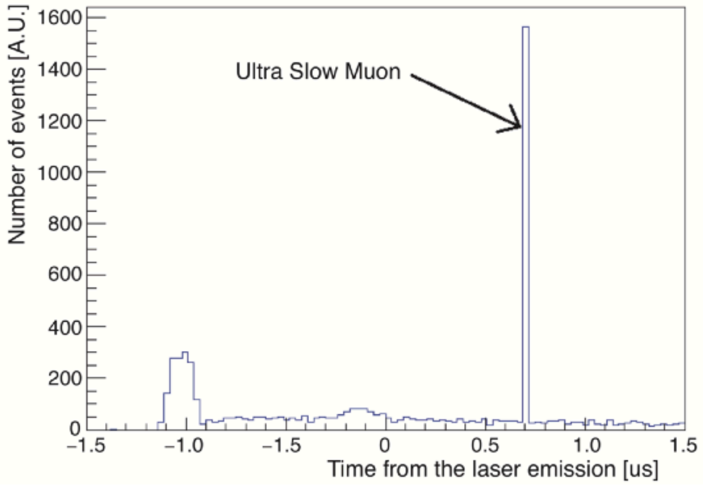
2020

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

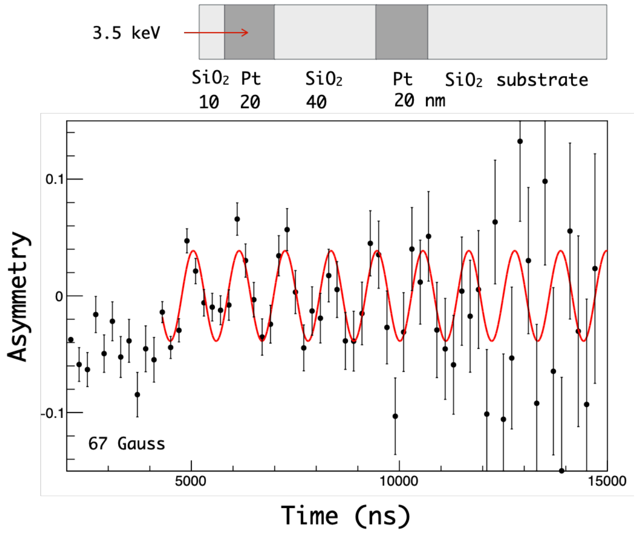
First Ly-α
2013



First USM
2016



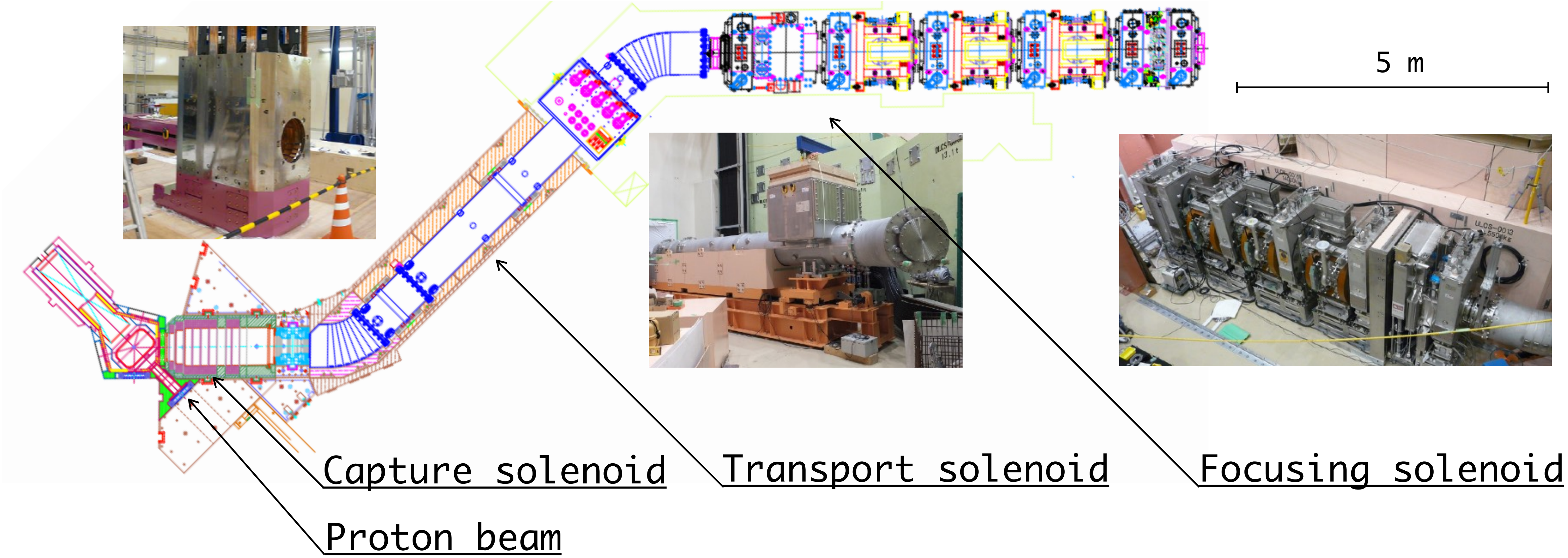
USM time-of-flight
2016



USM-μSR asymmetry
2020

Surface Muon Beam

Super-Omega, all-solenoids high-flux beam line

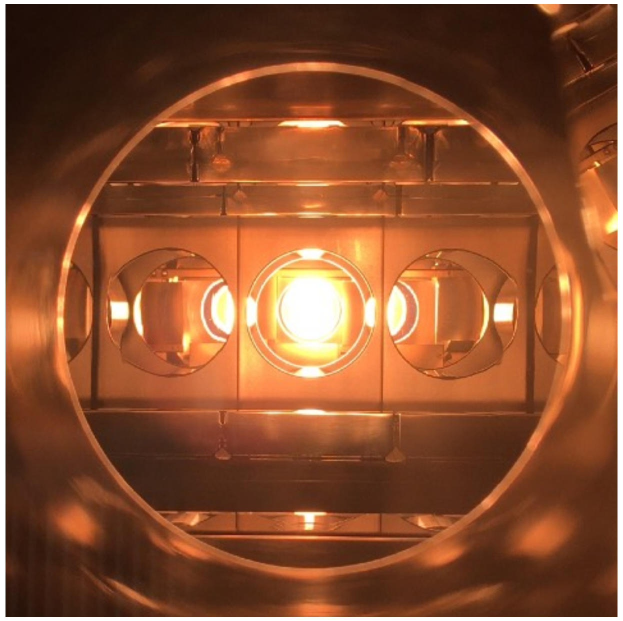


- Highest-flux beamline consisting of a large-acceptance capture solenoid [1], a curved solenoid for charge-selection [2], and axial-focusing solenoids with Wien filters [3].
- The total beam flux is at order of 10^8 μ^+/s.

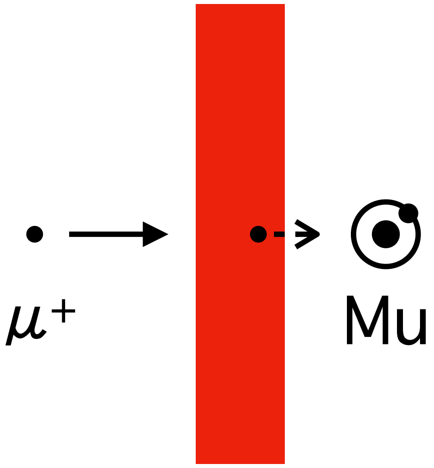
[1] K. Nakahara et al., “The super omega muon beamline at J-PARC”, NIM A 600 (2009) 132-134.
[2] P. Strasser et al., “Superconducting curved transport solenoid with dipole coils for charge selection of the muon beam”, NIM B 317 (2013) 361-364.
[3] Y. Ikedo et al., “Positron separators in Superomega muon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

Muonium Emitter

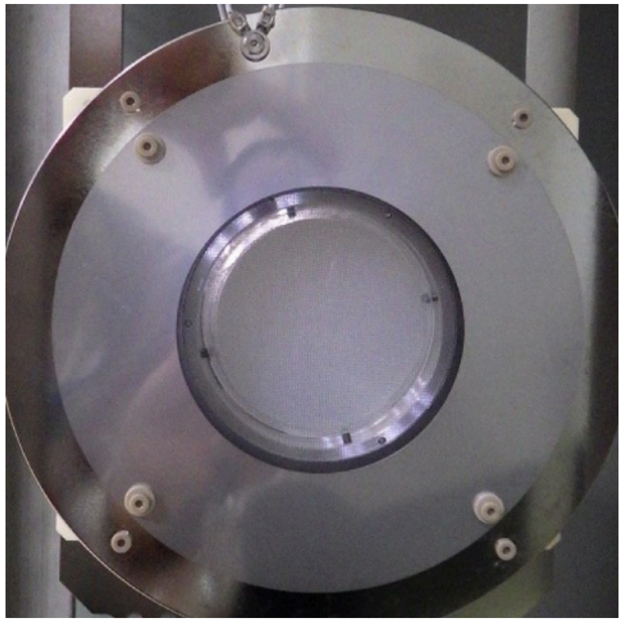
Muonium production target



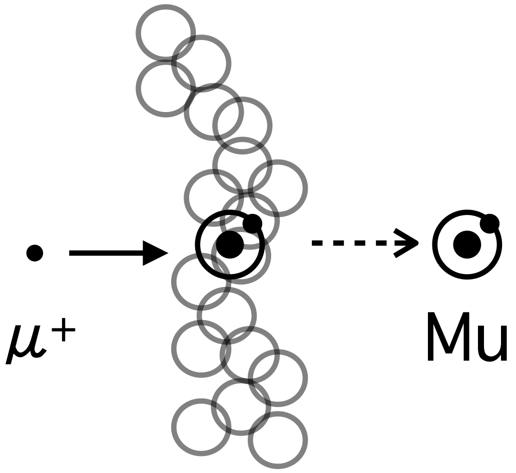
Tungsten



2000 K
22 mm/μs



Silica aerogel

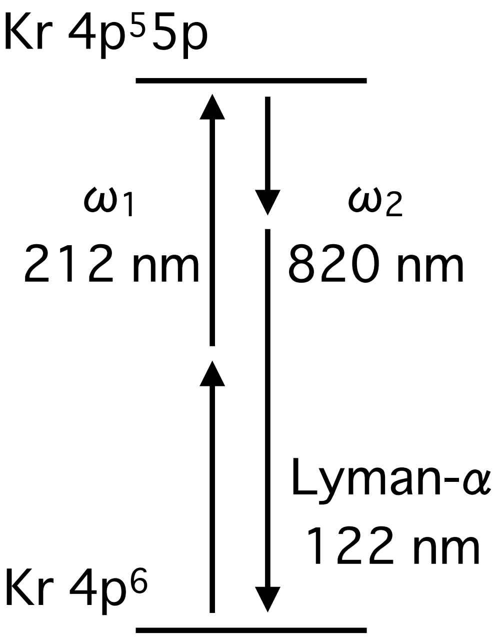


300 K
7 mm/μs

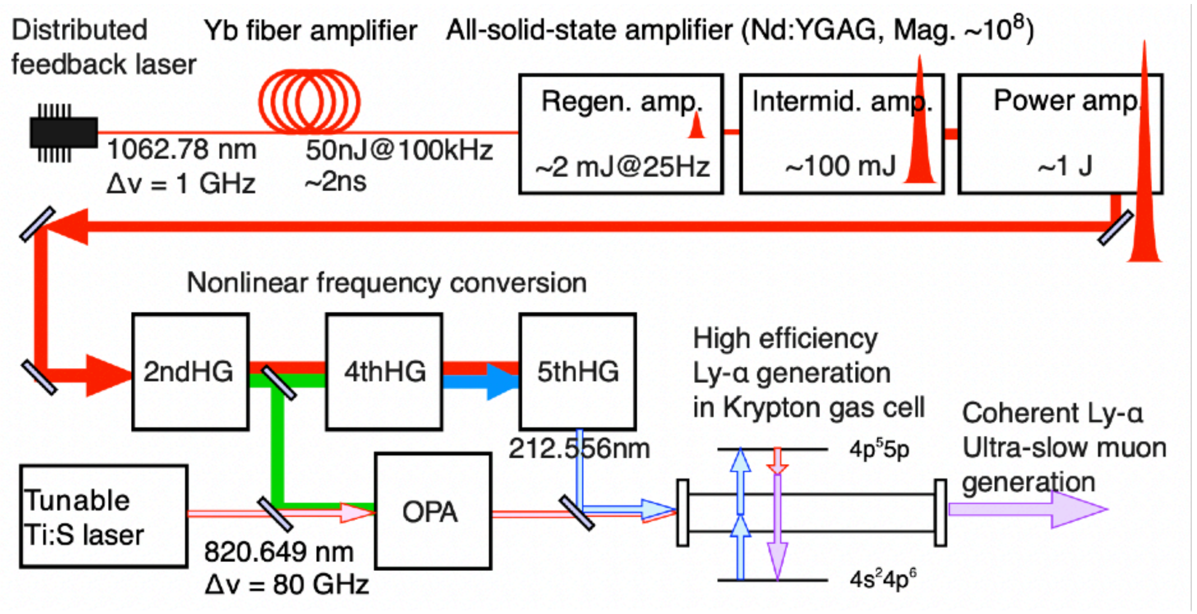
- ○ At the U1 beamline, a Joule-heated tungsten foil and a laser-ablated silica aerogel disk are used as a muonium emitter.
- ○ Emission mechanism is different; shaking off muonium from hot metal, diffusion and ejection of muonium from insulator.

Ionization Laser

A state-of-the-art VUV laser system



- For efficient muonium ionization, high pulse-energy of Lyman-α light is essential.
- Four-wave mixing in krypton gas generates an intense Lyman-α emission.
- All-solid-state laser system has been developed.



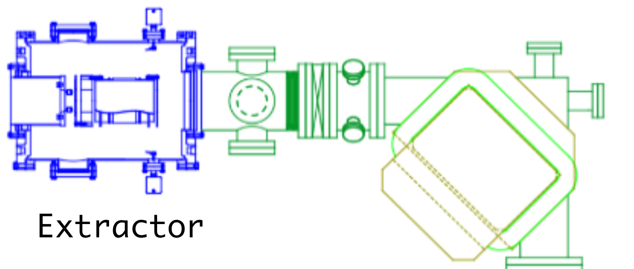
N. Saito et al., "High-efficiency generation of pulsed Lyman-α radiation by resonant laser wave mixing in low pressure Kr-Ar mixture", Optics Express 24, 7566 (2016).

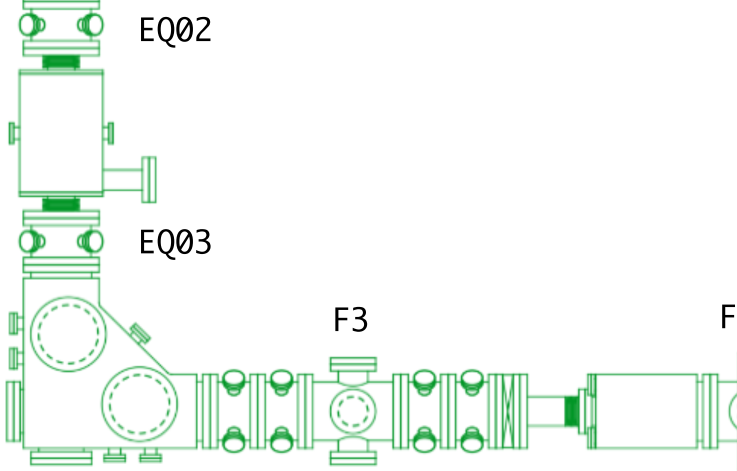
Y. Oishi et al., "All-solid-state laser amplifiers for intense Lyman-α generation", J. Phys.: Conf. Ser. 2462 012026 (2023).

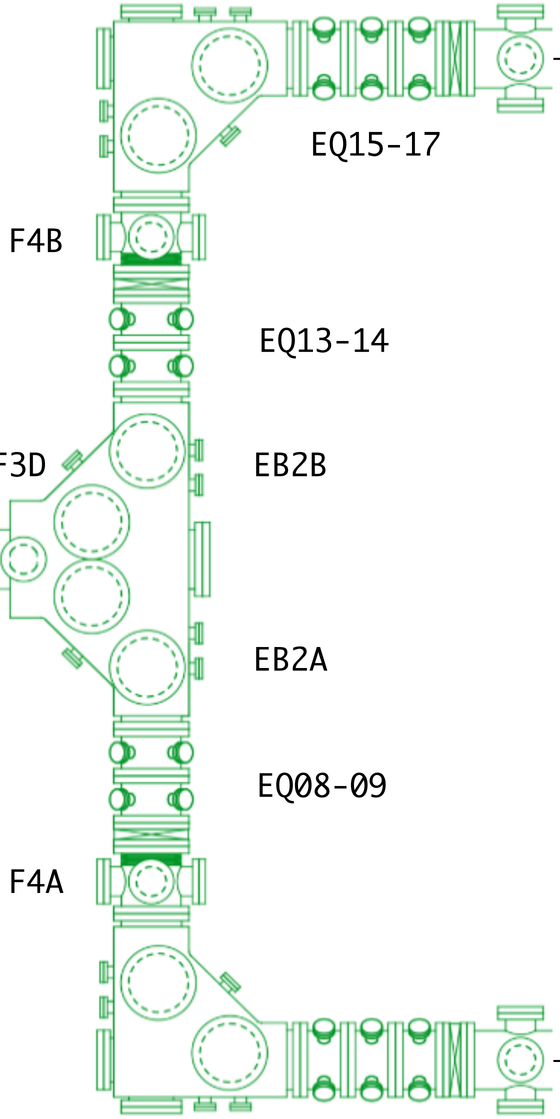
Transport Optics

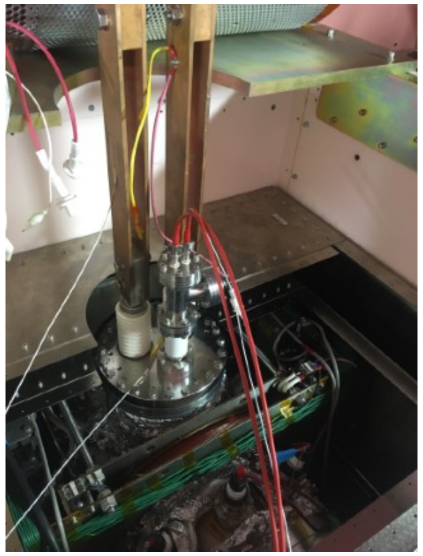
Slow-muon optics toward the exp. areas

Surface muon
from Super-Omega



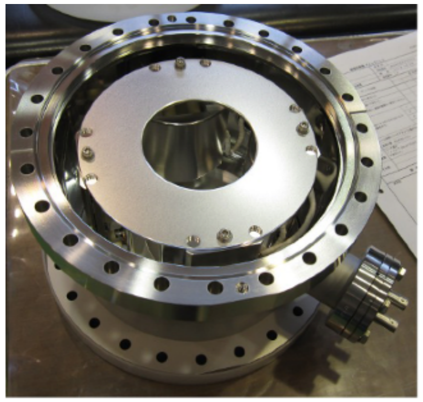




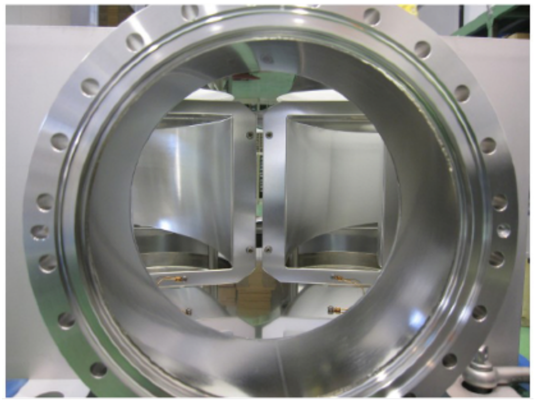


Mu Target

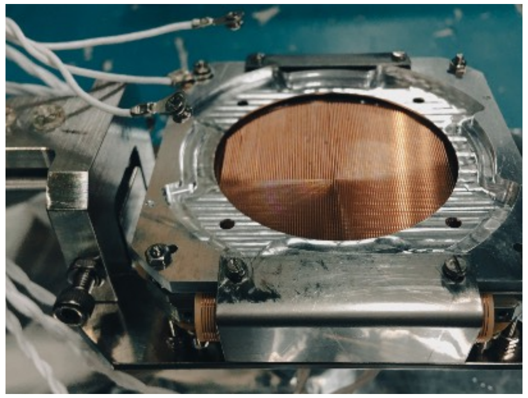
Transport Optics



EQ

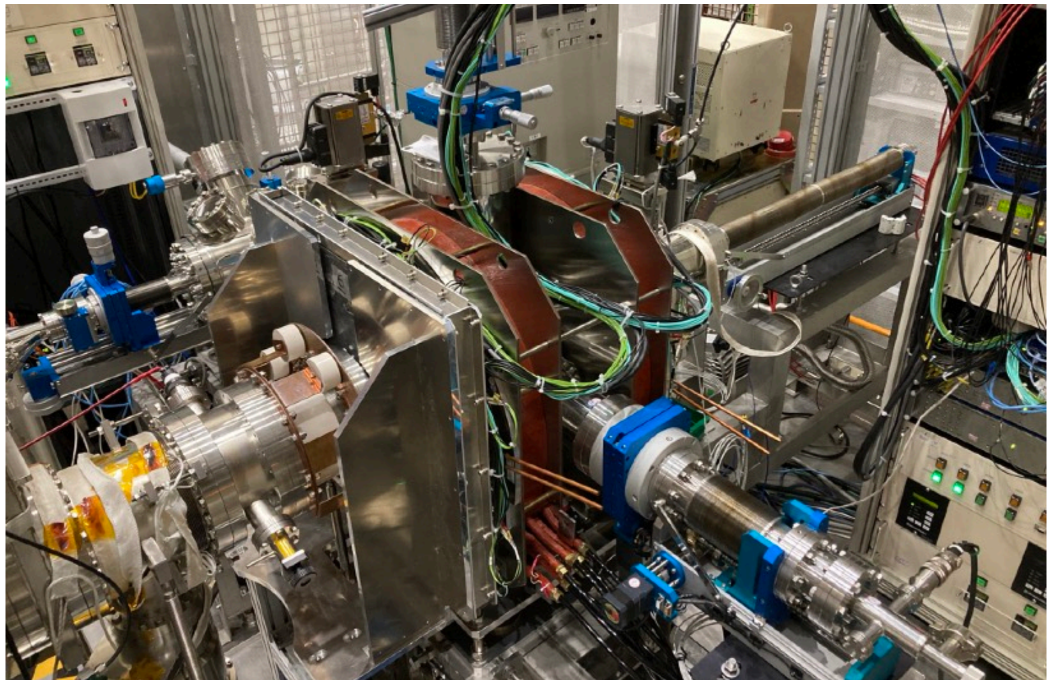


ED+EB

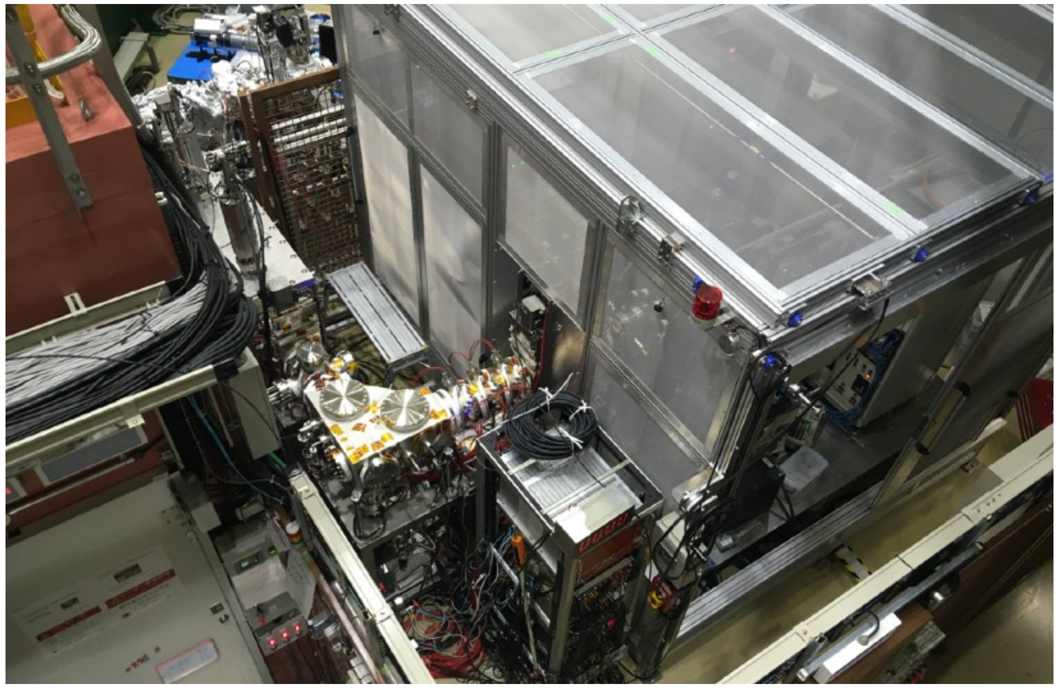


MCP-DLD Beam Monitor

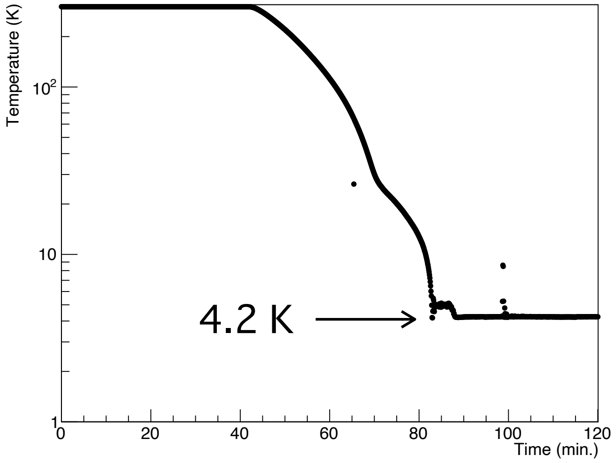
Muon Spin Spectrometer at U1A



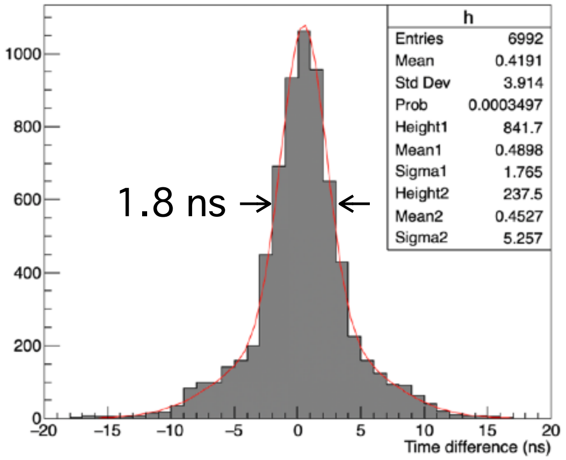
Muon spin spectrometer on the high-voltage platform.



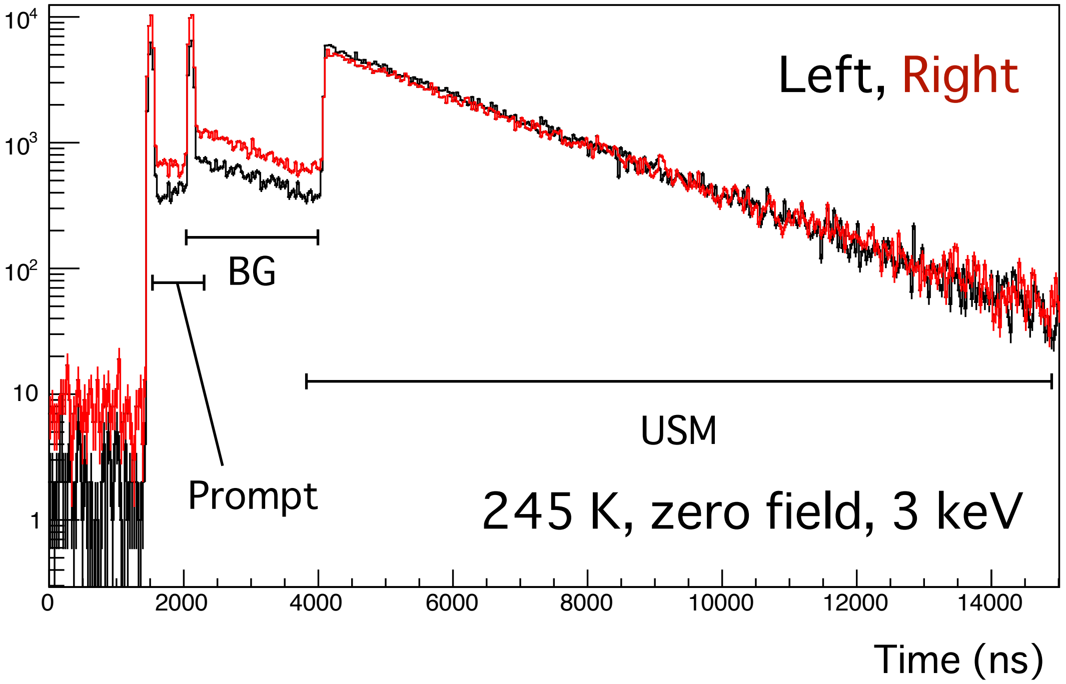
The U1A experimental area.



Sample cooling



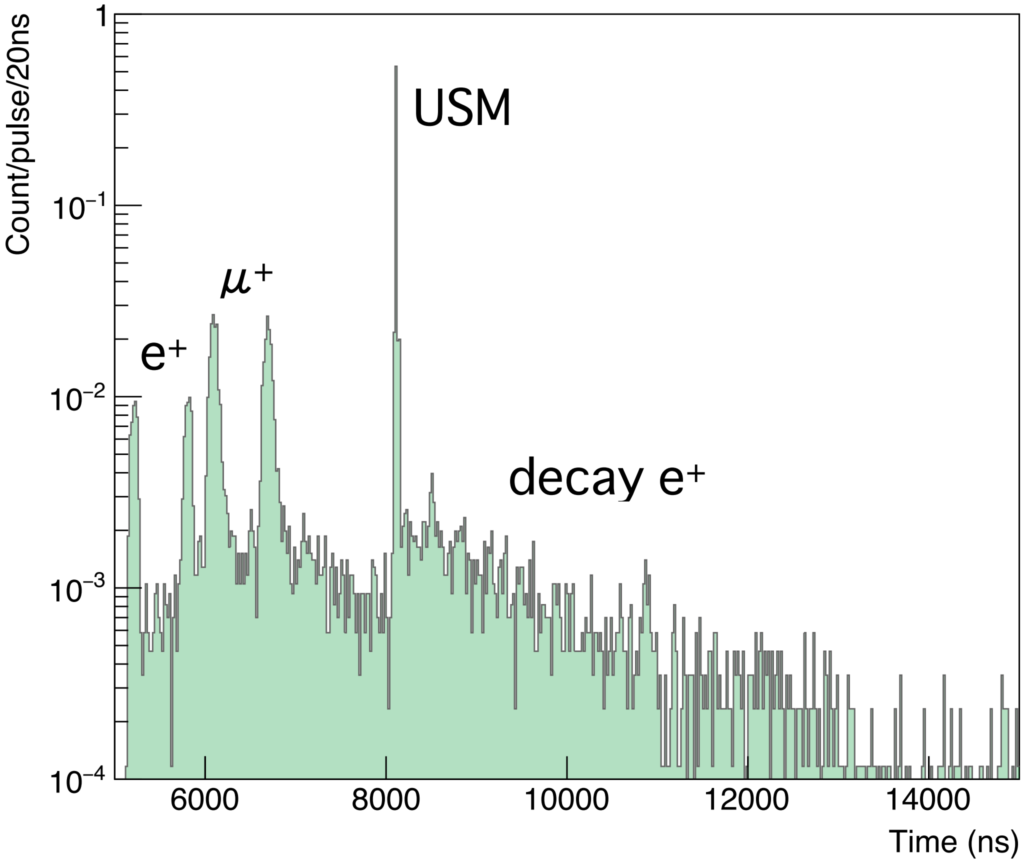
Detector’s time resolution



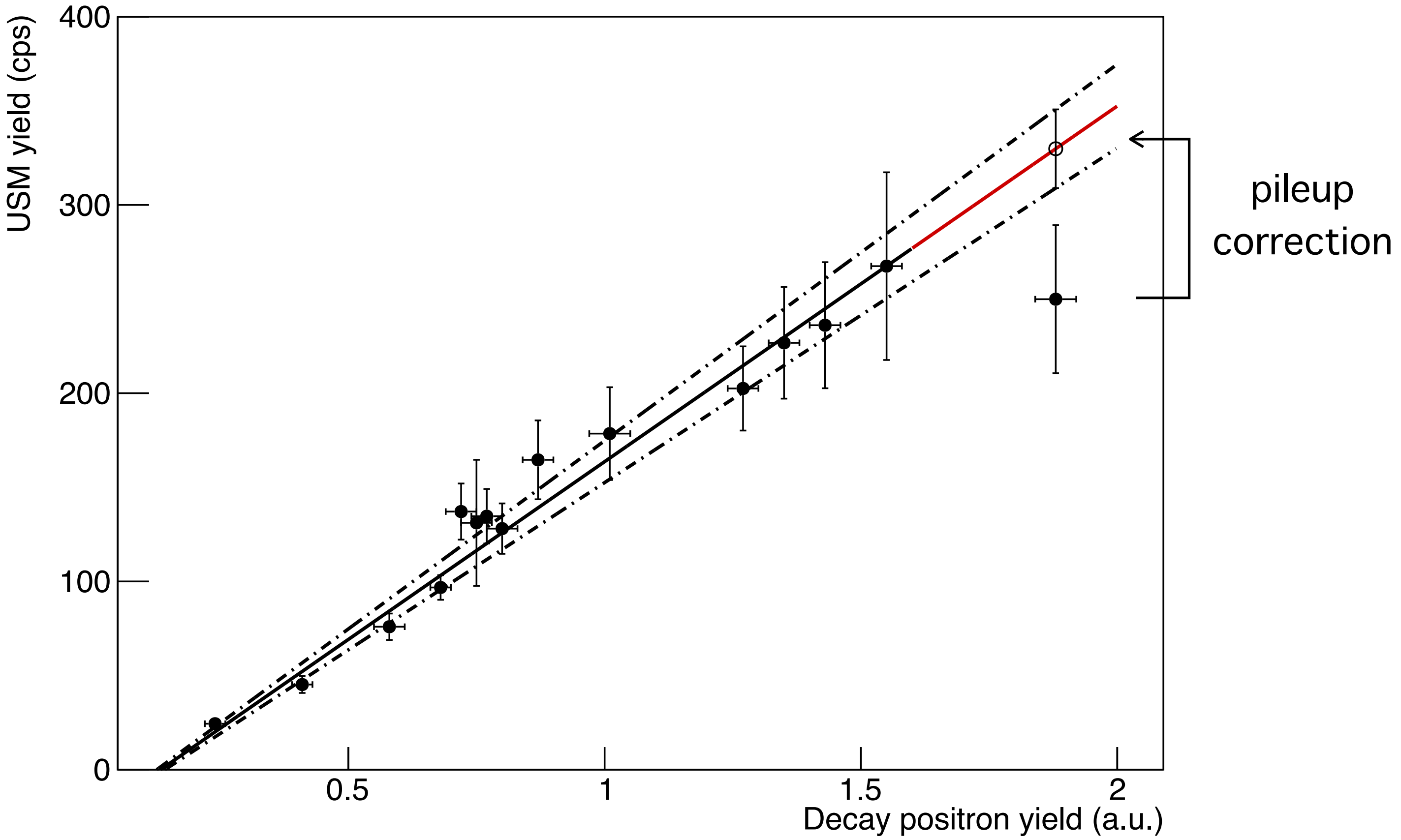
- High-voltage platform for implantation energy tuning.
- Helium-flow cryostat for sample cooling down to 4 K.
- Segmented positron counter with SiPM-readout.

USM Yield Analysis

to obtain the total flux of the beam



TOF spectrum



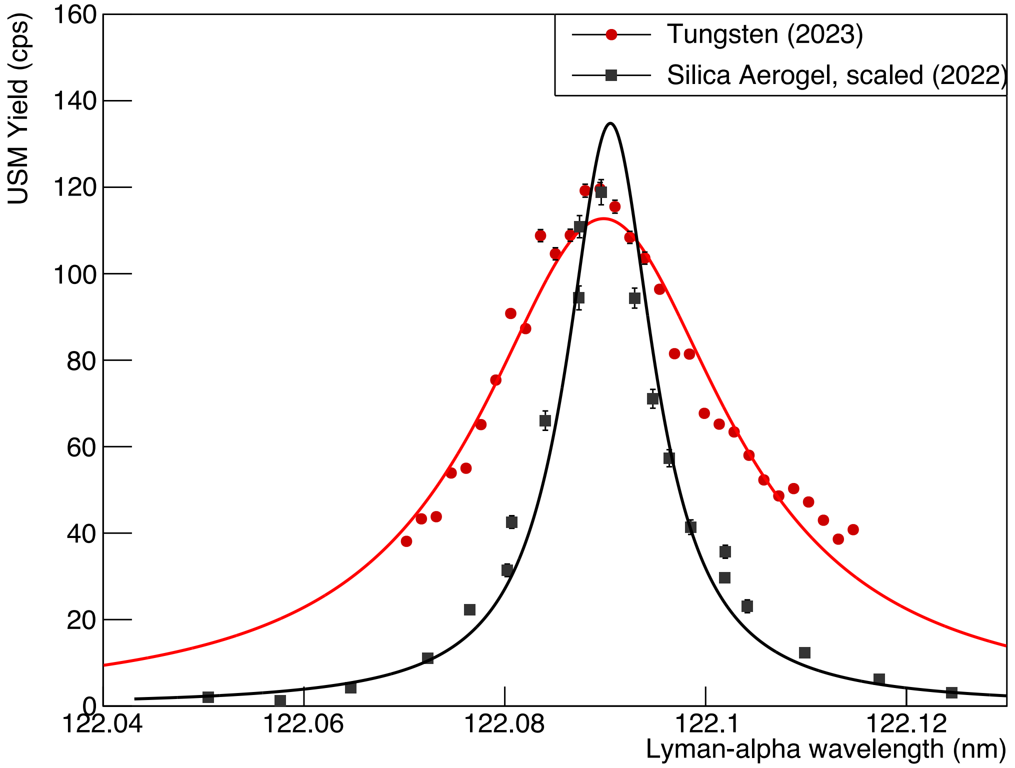
USM and decay positron yields

- ○ The MCP-DLD measures the position and time of muons and positrons.
- ○ Early four peaks correspond to prompt positrons and degraded muons.
- ○ The USM flux is obtained by counting the number of USM hit per pulse and decay positrons.

*These results are obtained at the intermediate focus.

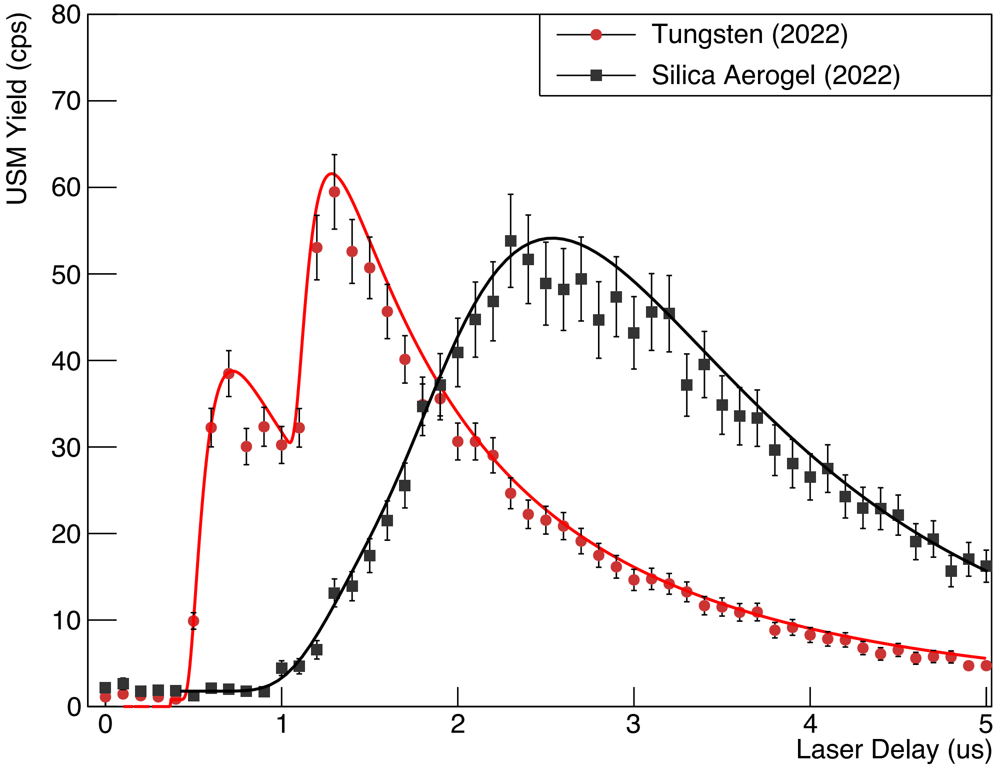
Laser Tuning

to maximize the USM yield



VUV wavelength scan

(fitting by a Voigt function)



Laser timing scan

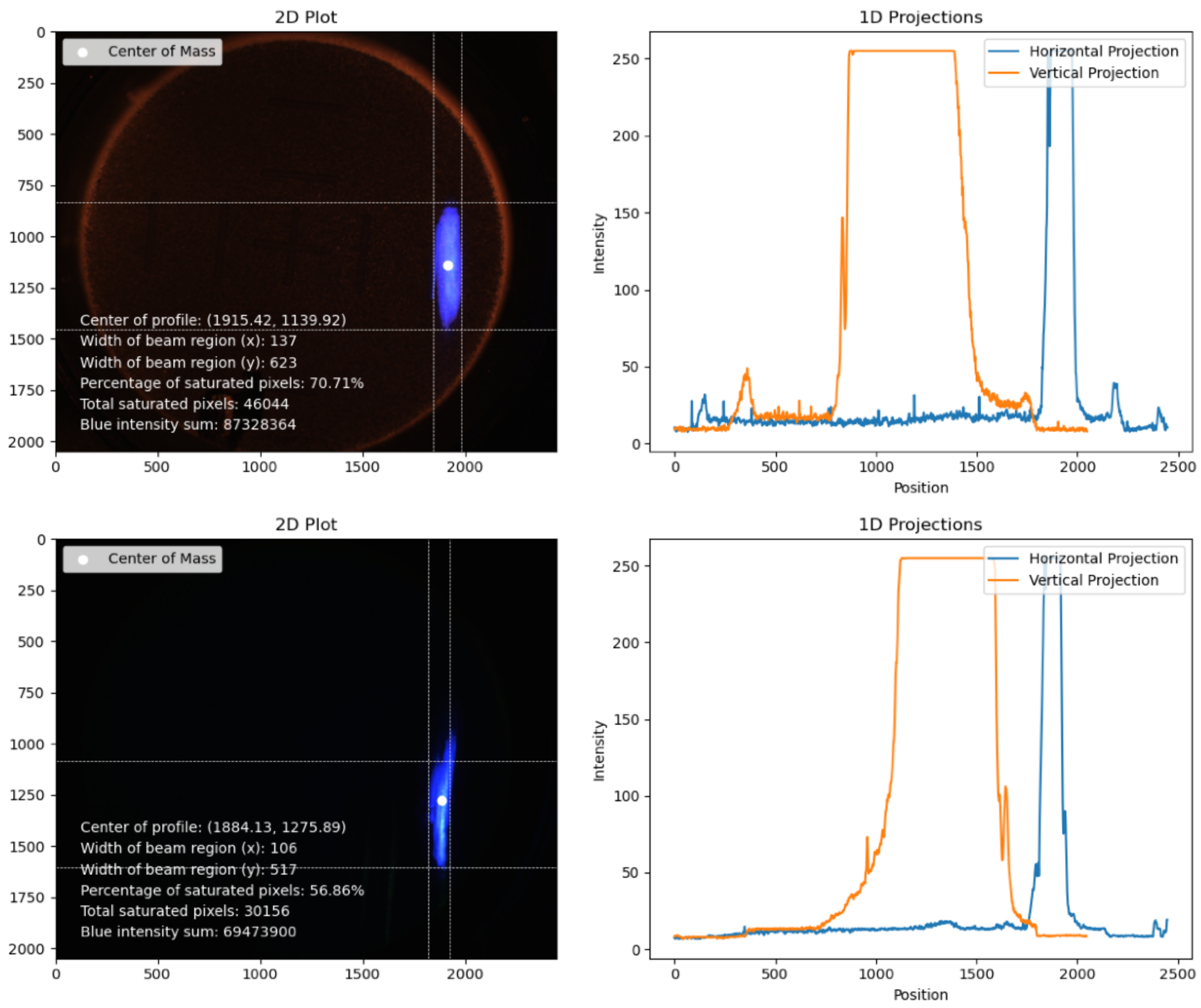
(fitting by a Maxwell distribution)

- The width of resonance curve is 160 GHz for silica aerogel. The temperature dependence is reasonable, but the width is wider than expectation (80 GHz).
- Muonium velocity from silica aerogel is slower.

Note that the yield cannot be directly compared between targets due to different laser pulse energies and other conditions.

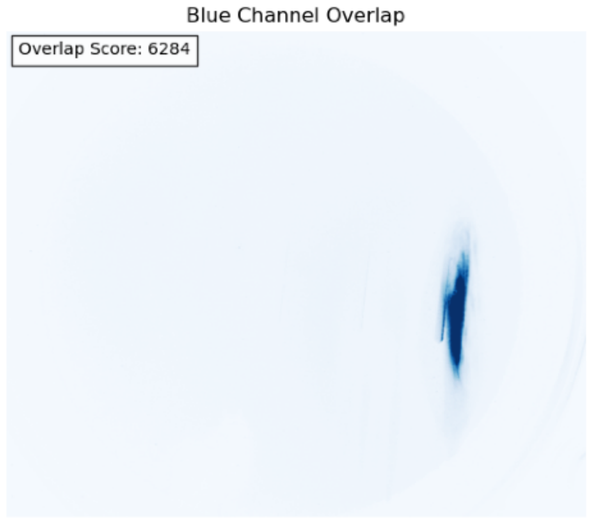
Laser Beam Profile Monitoring

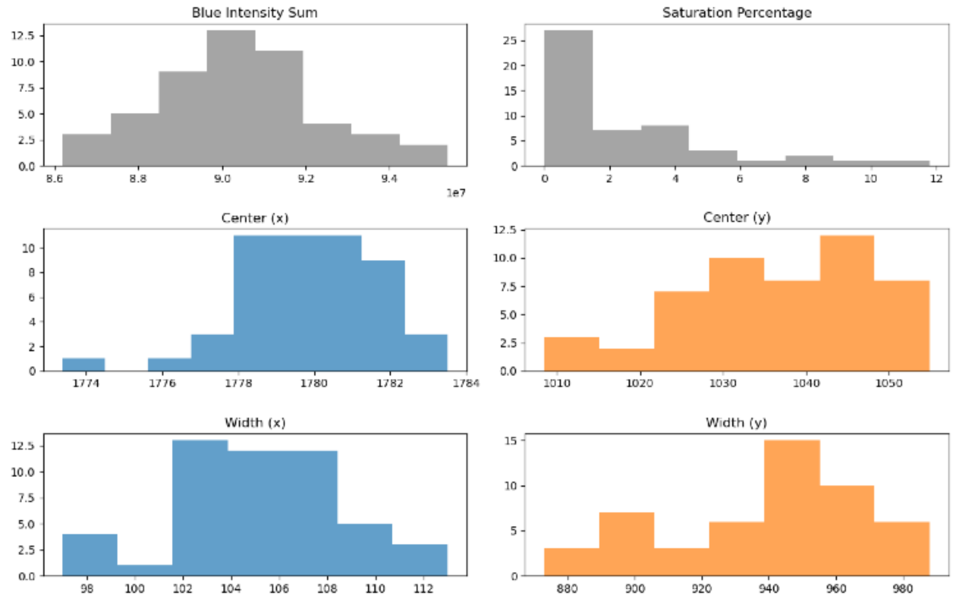
for efficient and stable USM generation



Center of profile: (1915.42, 1139.92)
Width of beam region (x): 137
Width of beam region (y): 623
Percentage of saturated pixels: 70.71%
Total saturated pixels: 46044
Blue intensity sum: 87328364

Center of profile: (1884.13, 1275.89)
Width of beam region (x): 106
Width of beam region (y): 517
Percentage of saturated pixels: 56.86%
Total saturated pixels: 30156
Blue intensity sum: 69473900



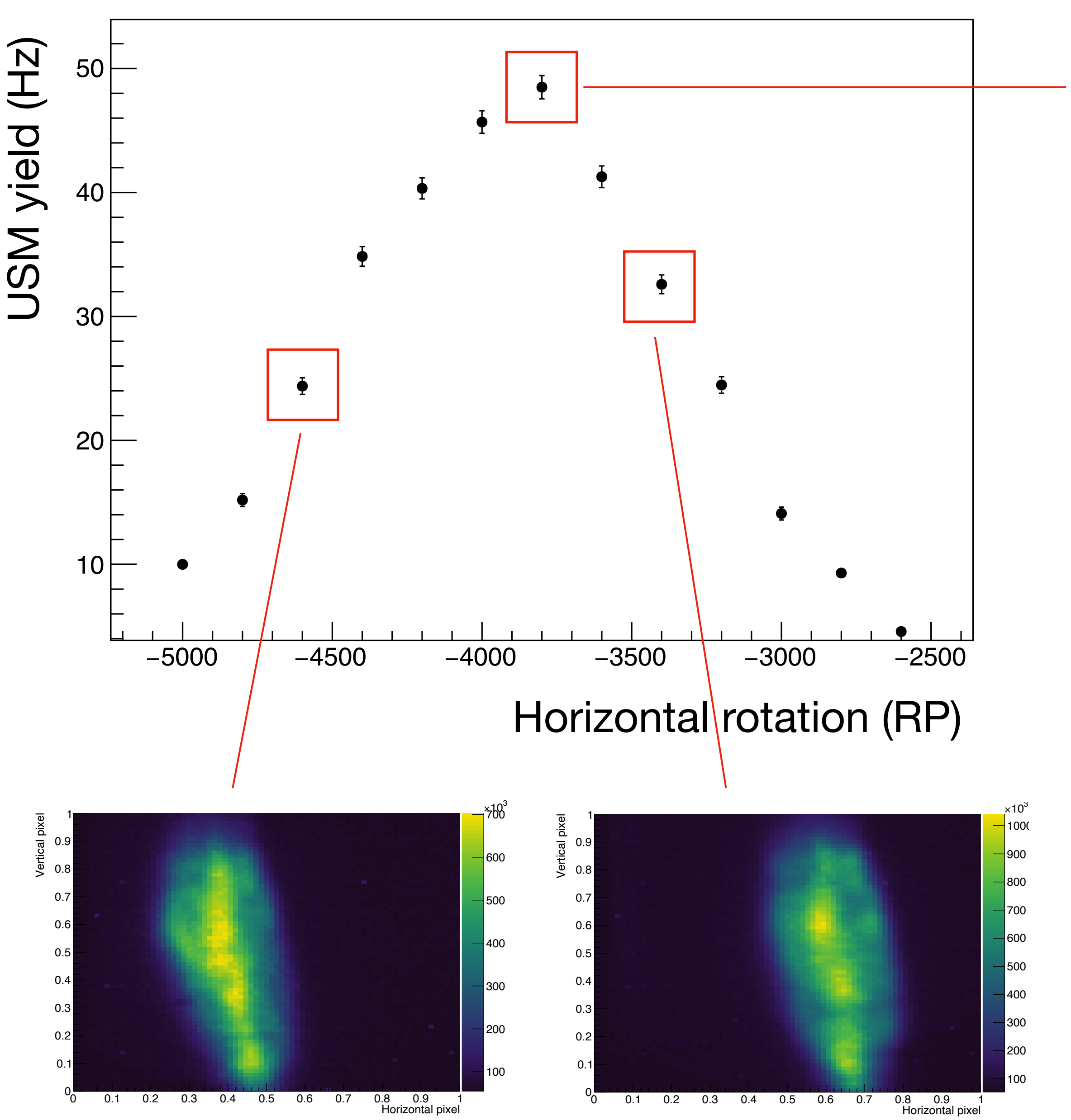


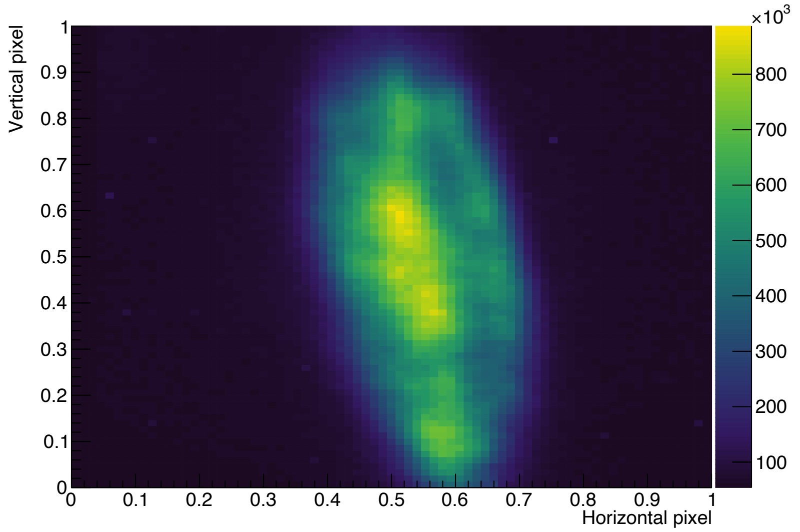
- ○ Quantitative and statistical analysis tools for laser beam profile monitoring.

Works with T. Umezawa from S. Nakamura’s group of Ibaraki University.

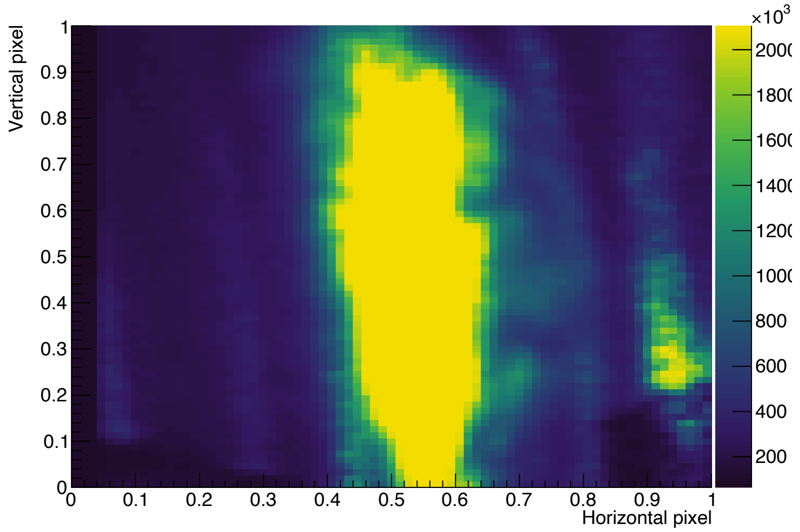
Laser Beam Steering

to optimize the overlap of Lyman-α and 355-nm lights





Lyman-α



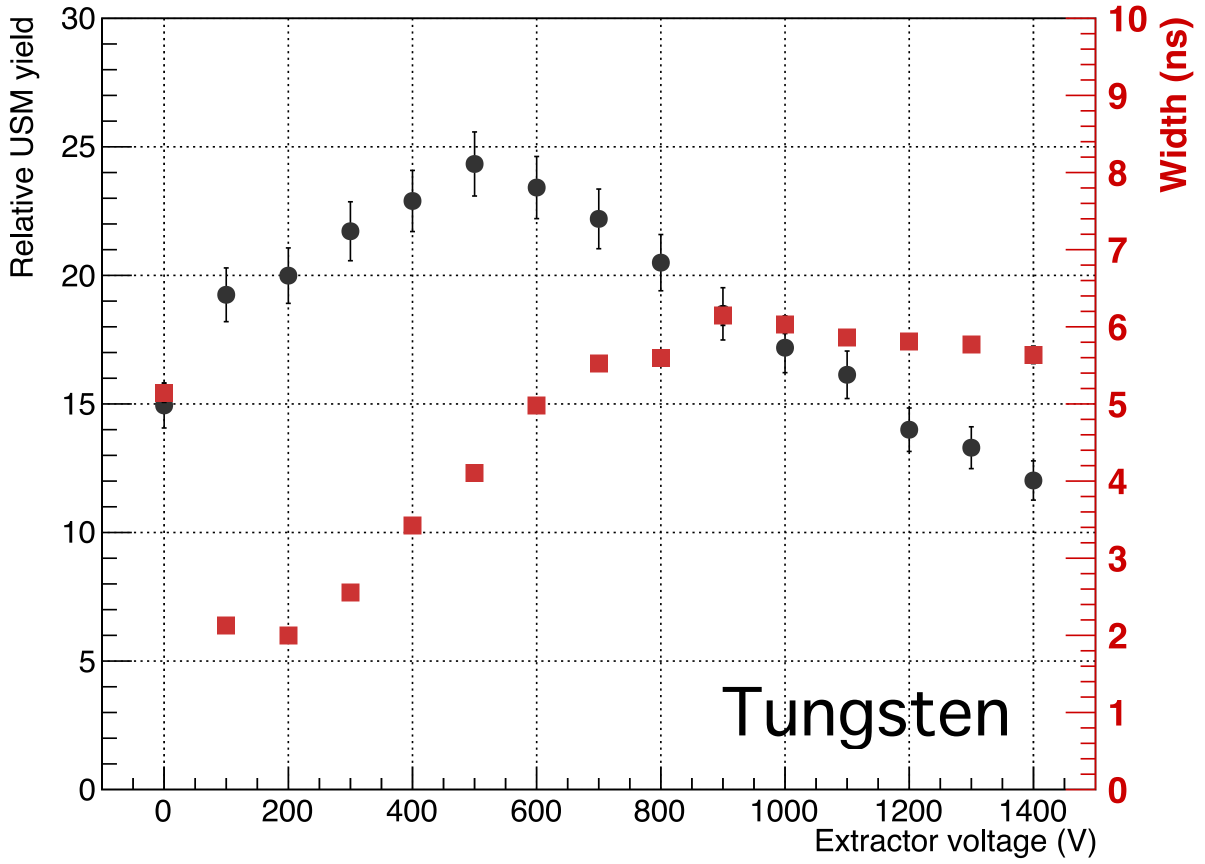
355 nm

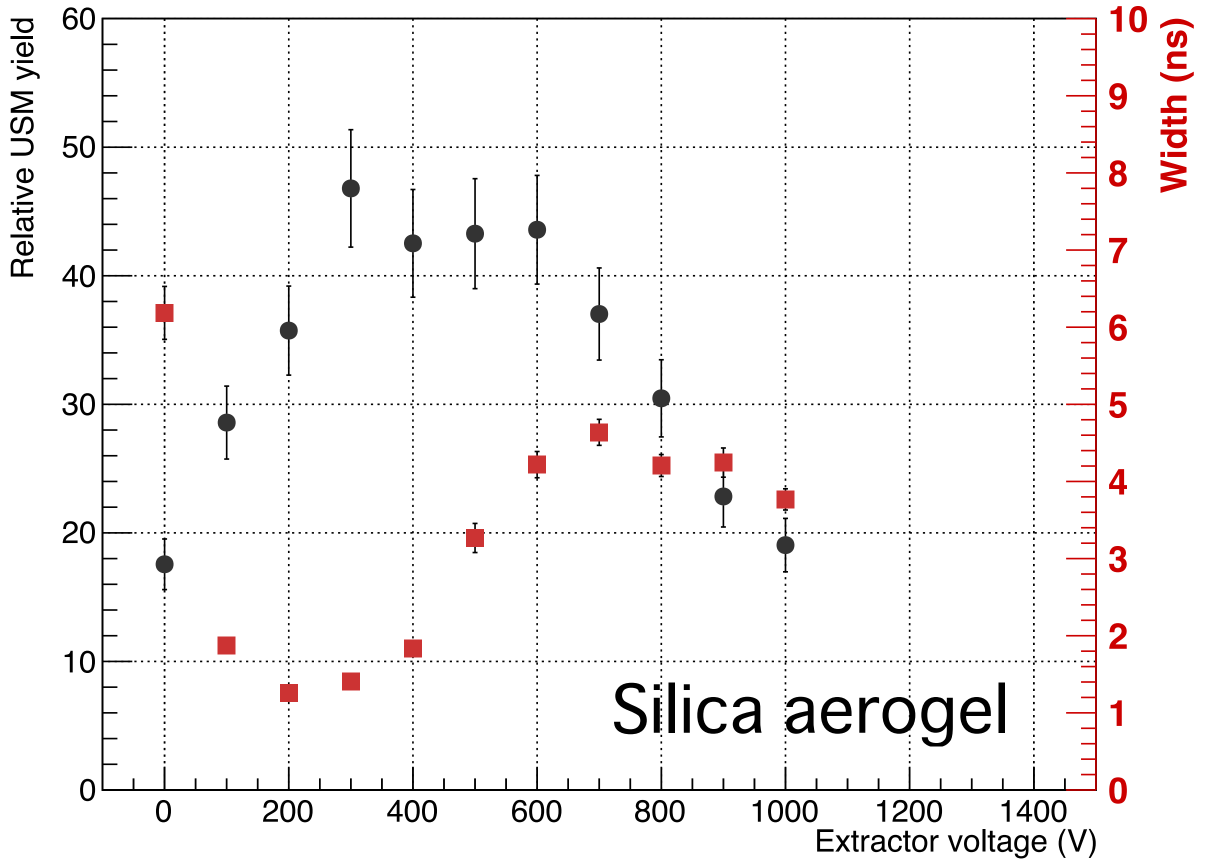
- ○ Optimizing profile overlap can maximize yields.

Works with T. Umezawa from S. Nakamura's group of Ibaraki University.

Extractor Tuning

to maximize the USM yield



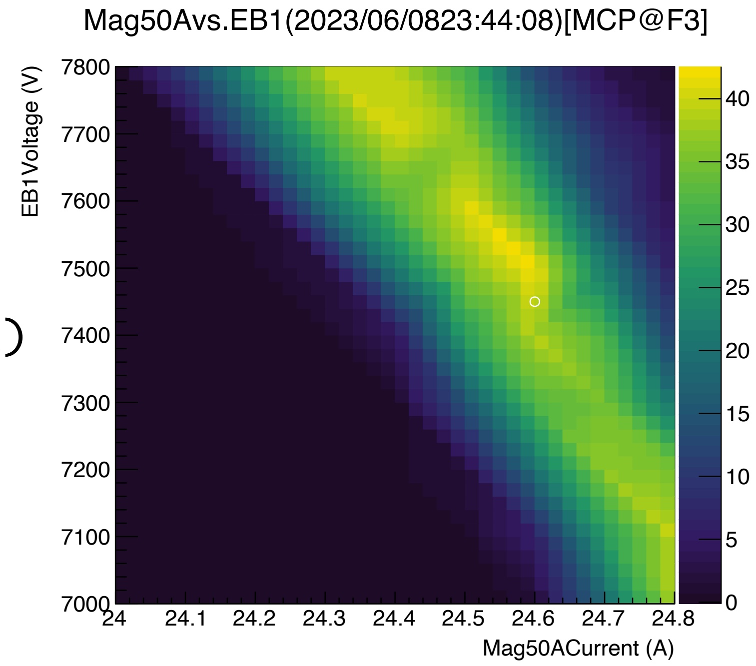


- ○ Recently, a power supply for the extractor (an electrode for USM initial acceleration) was upgraded for extraction voltage optimization.
- ○ Extraction voltage at the first electrode of the immersion lens can be optimized in terms of yield or time width.
- ○ Silica aerogel results in the half timing spread compared to tungsten.

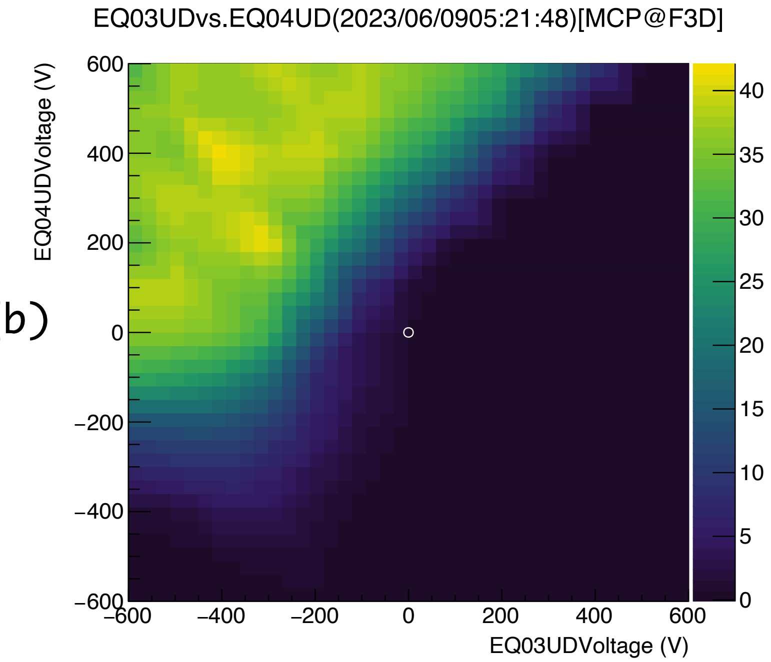
Beam Tuning

to optimize the transport optics

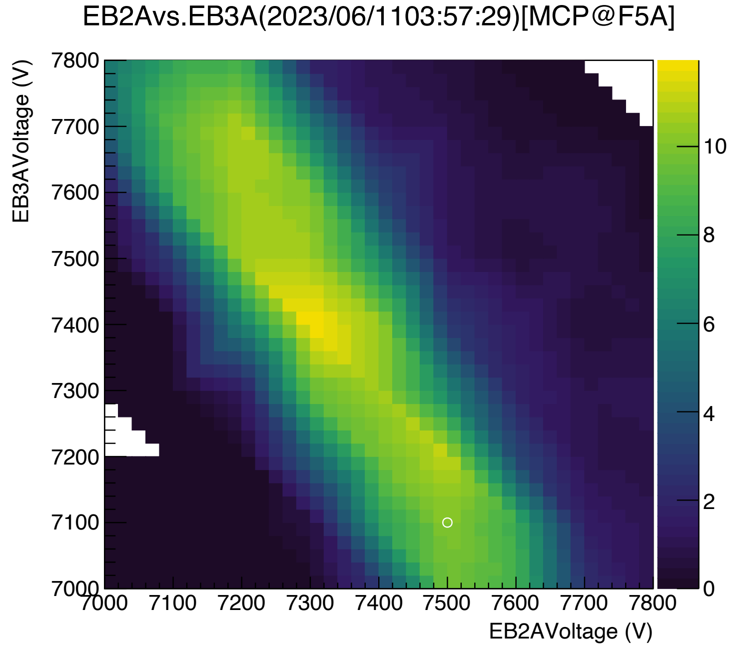
(a)


Mag50Avs.EB1(2023/06/0823:44:08)[MCP@F3]

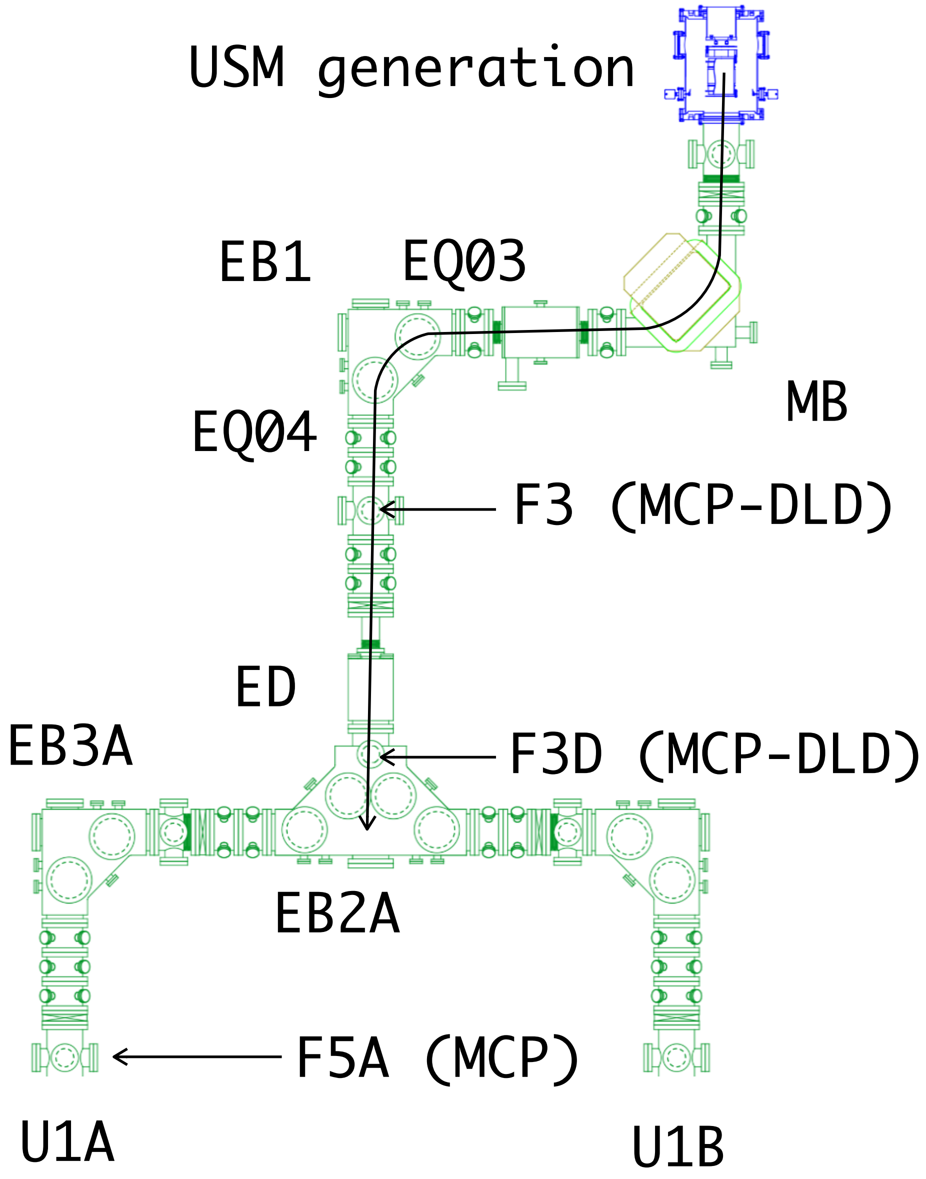
(b)


EQ03UDvs.EQ04UD(2023/06/0905:21:48)[MCP@F3D]

(c)


EB2Avs.EB3A(2023/06/1103:57:29)[MCP@F5A]

(a) MB:EB1 scan to find a way to transport 30 keV muons.
(b) EQ up/down asymmetry scan to compensate beam deflection arising from stray B-fields and y-kick in the EBs.
(c) EB2A:EB3A scans varying over ED voltages to ensure that the beam goes straight into the area.



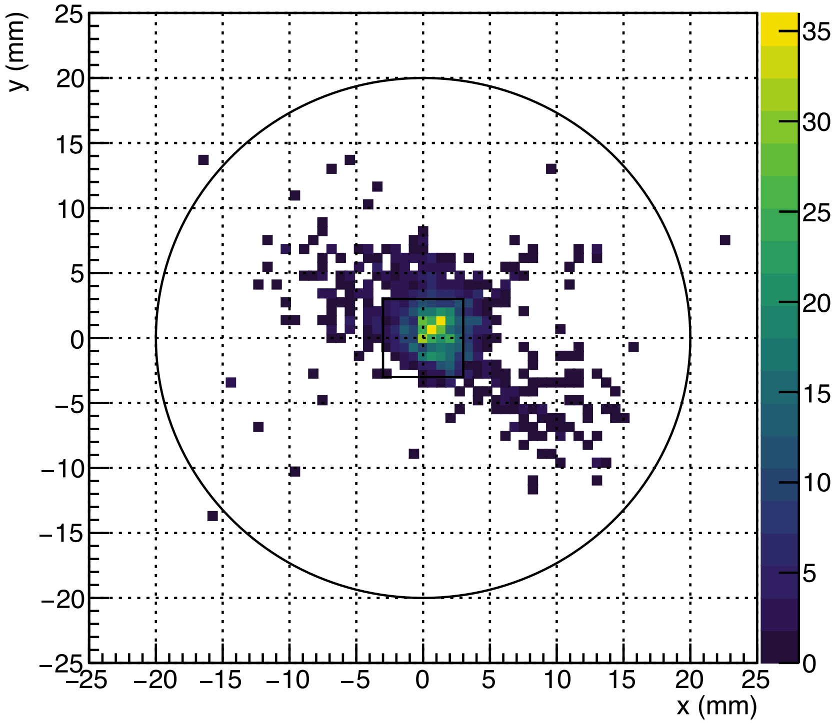
Status Monitors

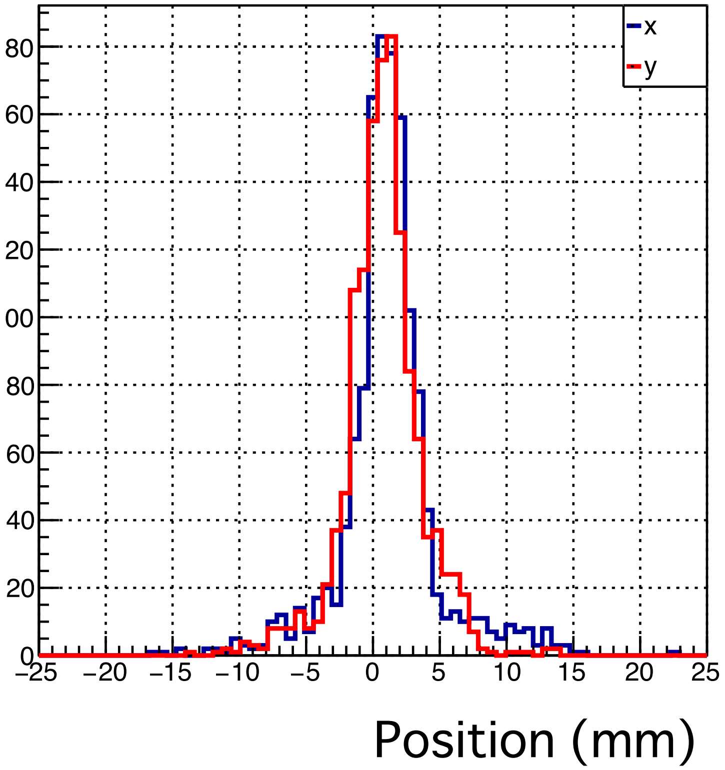
for the beamline and laser system

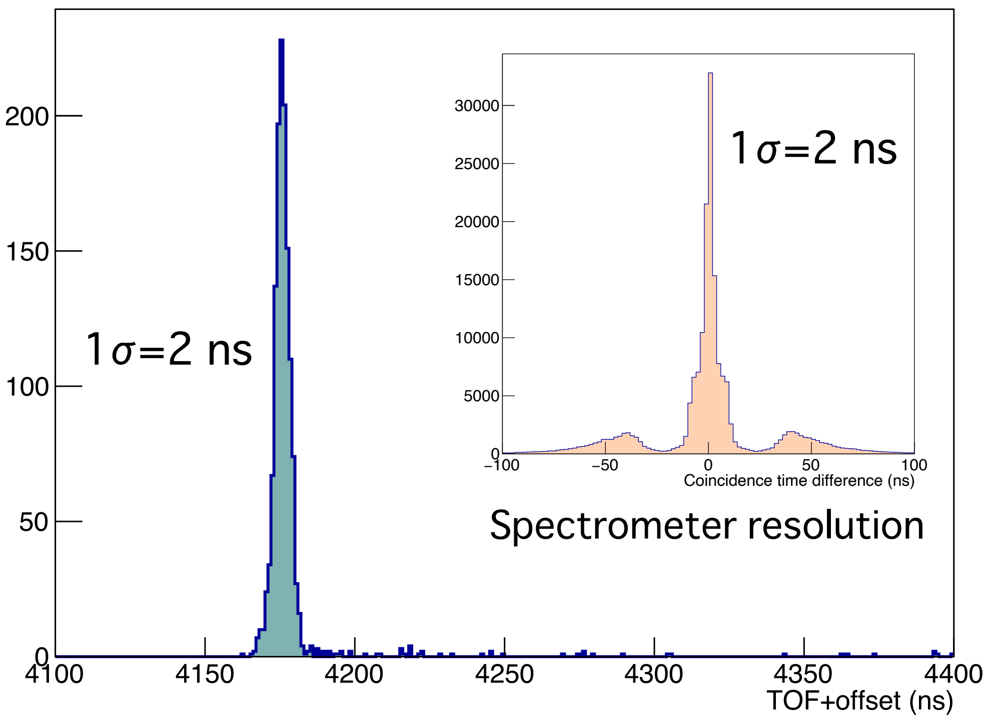
- Sophisticated beamline monitor implemented using Grafana and EPICS archive appliance.

Specification of the Beams

at the sample position





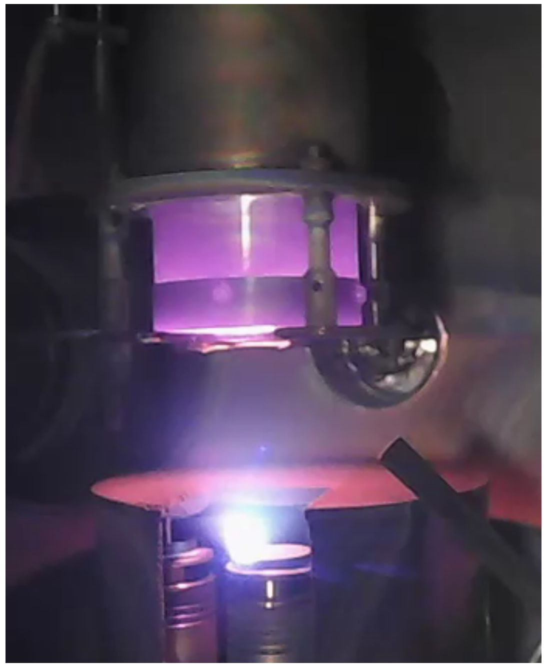


- ○ The transport optics were optimized to improve the USM profile.
- ○ The beam width at the μSR-sample position are 4 mm for the horizontal and vertical directions.
- ○ The time width of USM is 2 ns (1σ), which is approximately 1/20 of a typical pulse beam, allowing for the observation of fast dynamics.

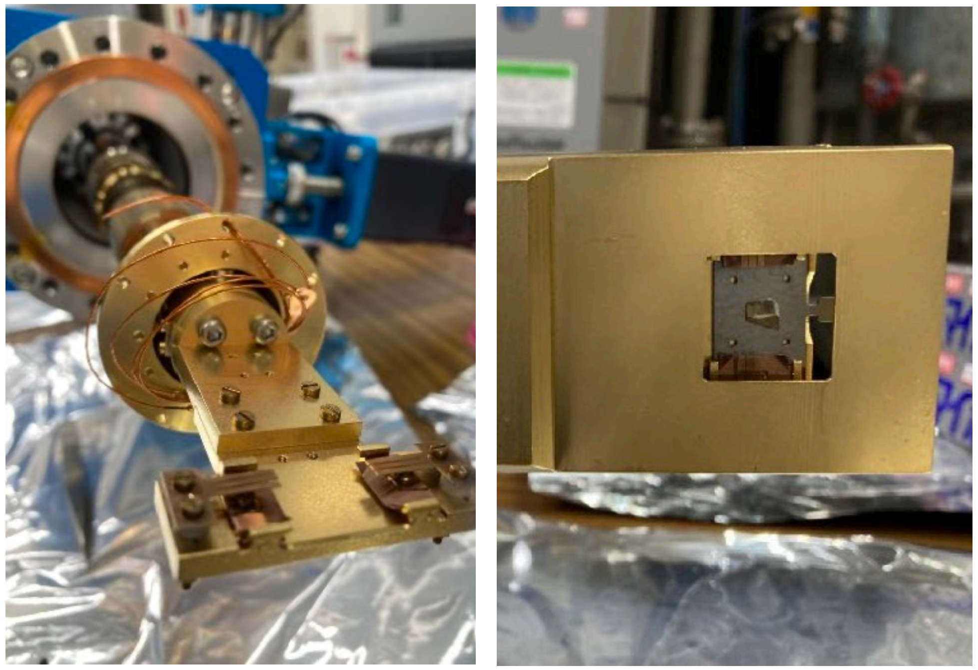
Extraction voltage = 30 kV, platform potential = 27 kV.

First Scientific Measurements

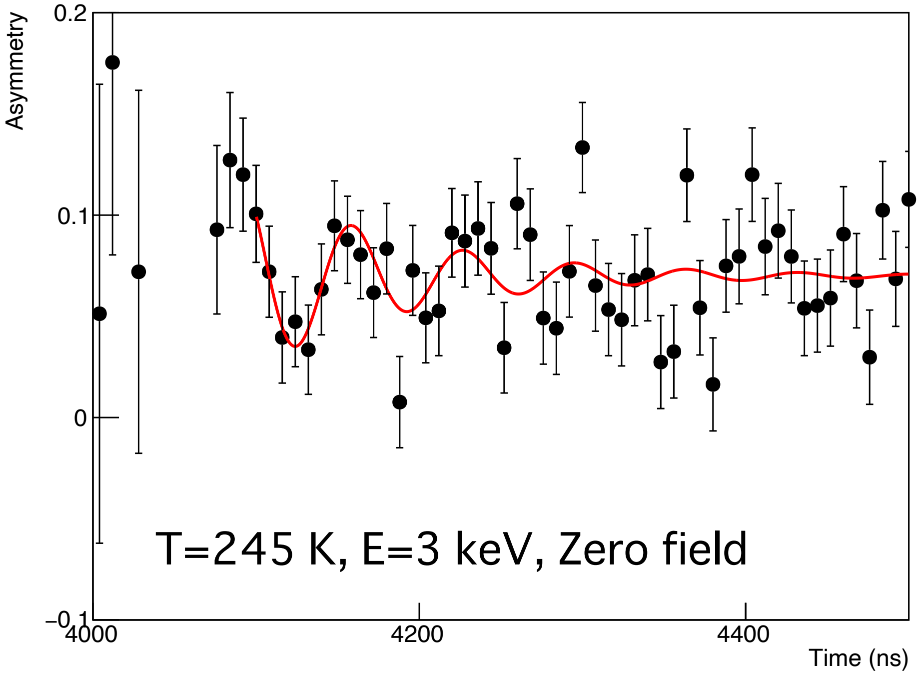
using ultra-slow muons



Sample fabrication by pulsed laser deposition.



Thin film sample (cuprate, anti-ferromagnet) mounted on the cryostat.



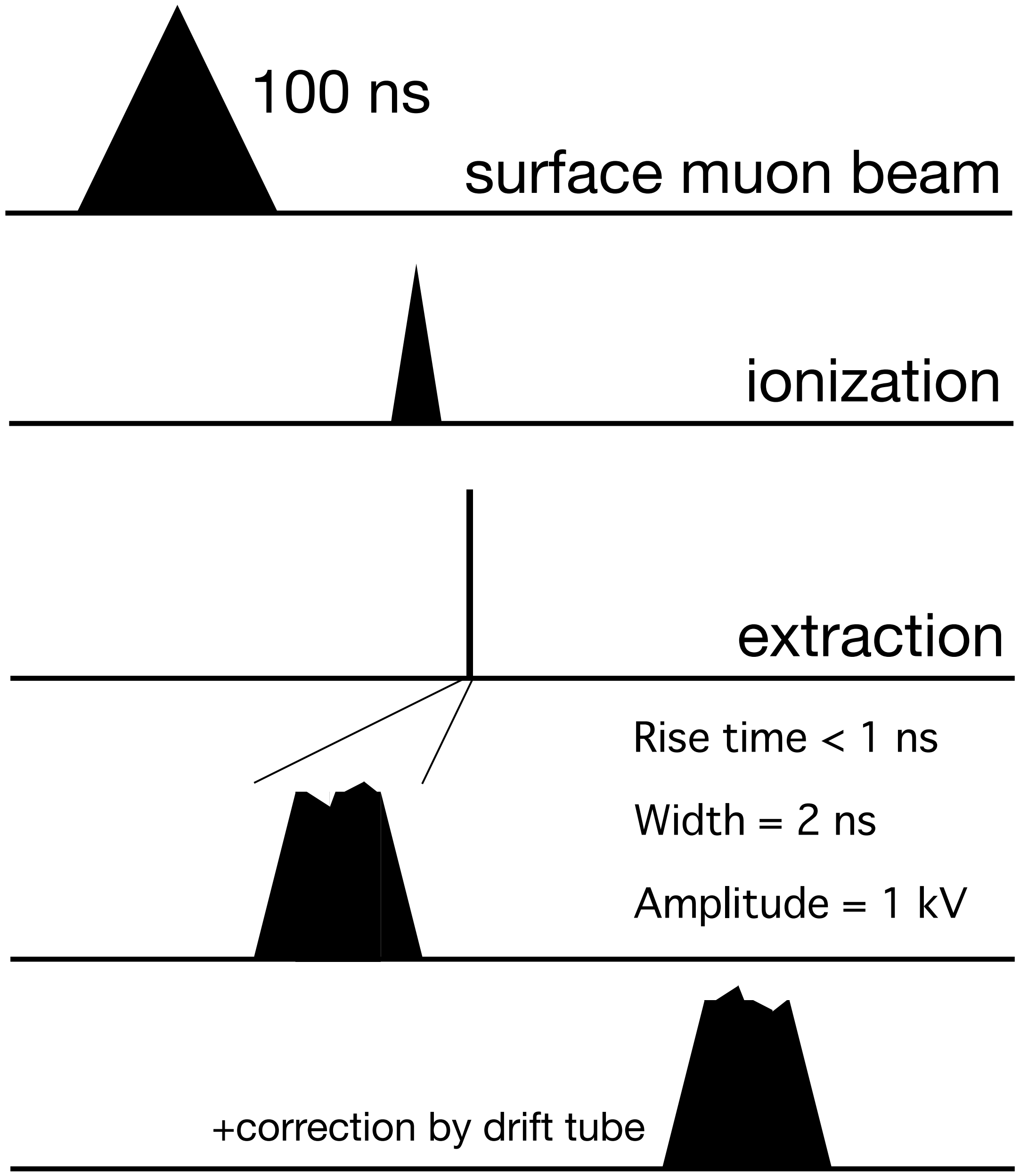
Preliminary result of the zero-field μSR measurement.

- ○ As a result of beam commissioning, beam performance suitable for material science studies has been achieved.
- ○ USM-μSR measurements became feasible and the first scientific measurement campaign has been started.

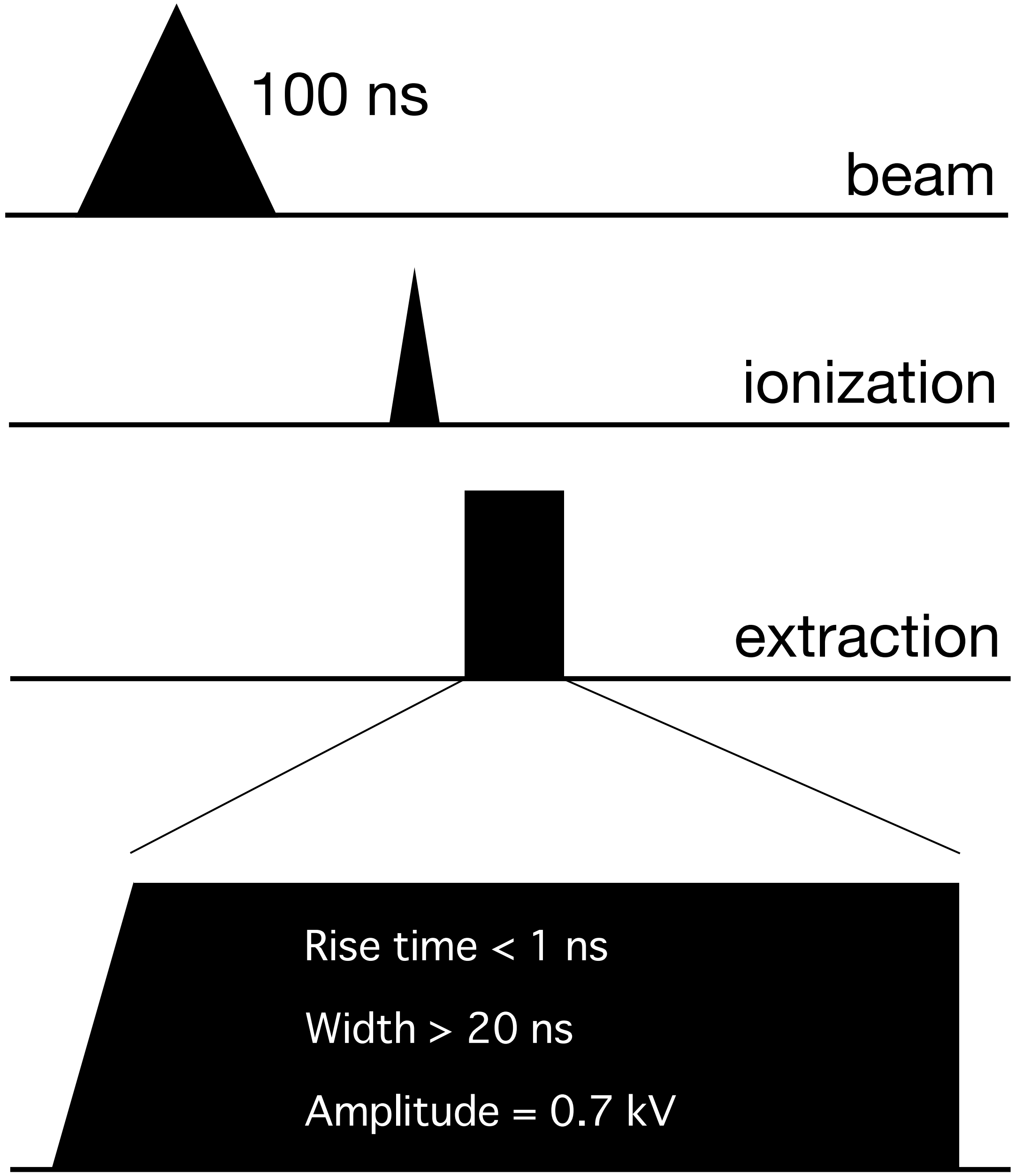
Works with T. Adachi's group of Sophia University.

Future Developments

Pulsed extraction



Scheme for small ΔE/E

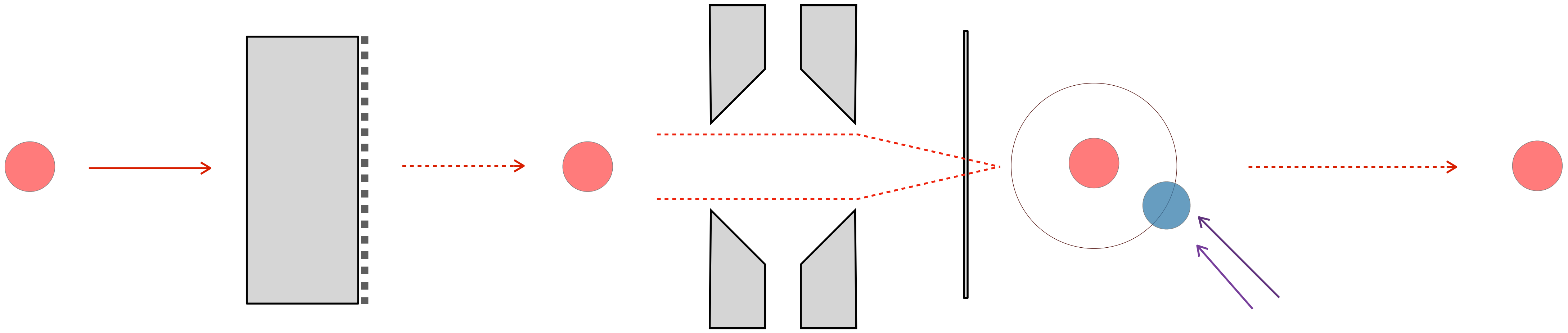


Scheme for small Δt

Works with P. Strasser and Y.Nagatani

Future Developments

Multi-stage muon cooling



Solid rare-gas moderator
on nano-structured substrate

Electrostatic lens
2 kV

Muonium

Bright and cooled
muon beam

Surface muon
4MeV

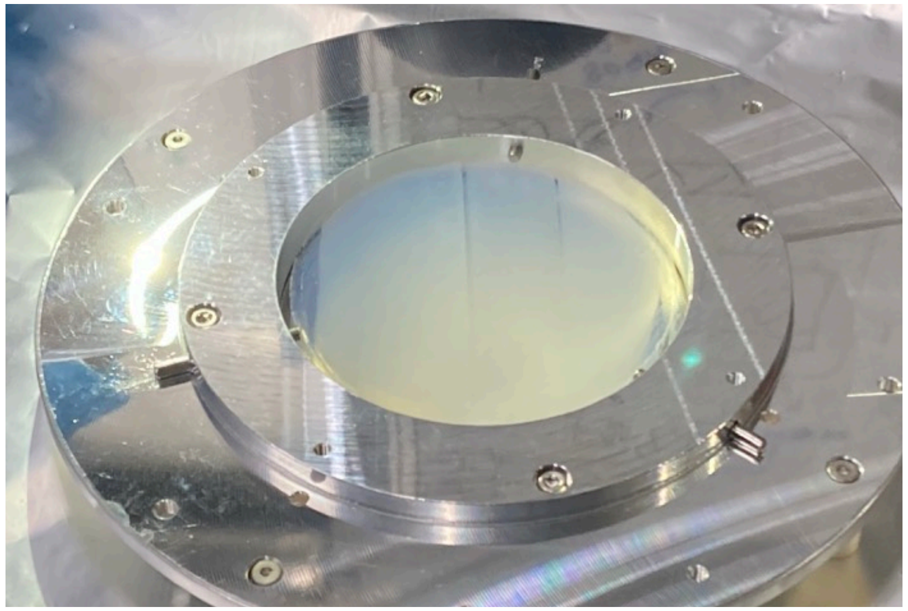
Epithermal muon
15 eV

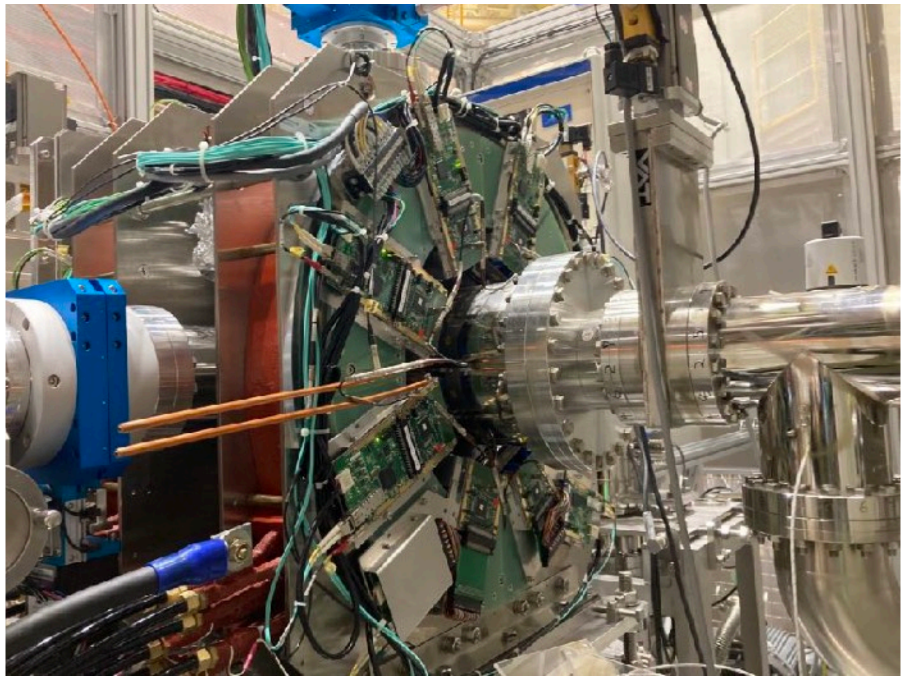
Graphite foil

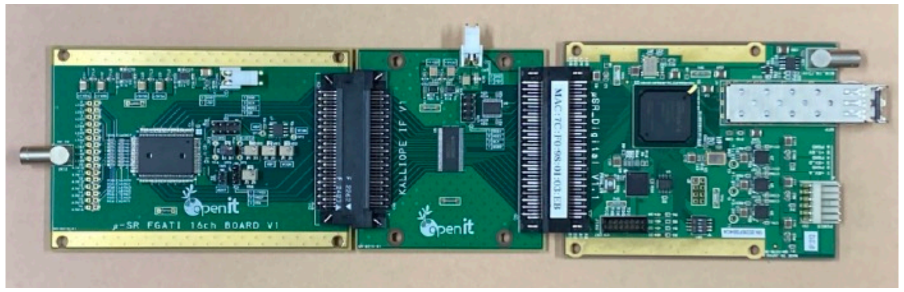
Laser
ionization

- A solid gas moderator is used to obtain epithermal muons, which are focused by an electrostatic lens before being converted to muonium through a thin foil.
- The spatial overlap between laser beams and muonium improves dramatically.

Future Developments







- Muonium production and ionization:
  - Searches for efficient muonium emitter available at a room-temperature.
  - Reflection mirrors for laser beams to improve ionization efficiency (Y. Oishi).
- USM extraction and transportation:
  - Pierce type extraction electrode for smaller beam spot (Y. Nagatani).
  - Machine-learning based autotune for beam transport tailored to the objectives of measurements.
- μSR spectrometer:
  - Re-designing of positron detectors to improve the solid angle and the full asymmetry.
  - Additional electromagnets for zero-field correction and transverse fields.
  - Pulse-synchronized stimulation applied to a sample.
  - Faster front-end electronics for better timing resolution (with R. Honda, K.M. Kojima et al.).

Summary

Low energy muons update and future developments

- The deceleration and cooling technology of muon beams will bring breakthroughs in both particle physics experiments and material science.
- At J-PARC MUSE, we have been conducting the commissioning of an ultra-slow muon beam through the laser ionization of thermal muonium.
- The quality of the beam has improved, and research in material science has been started.
- R&D for further advancement is progressing in various ways.