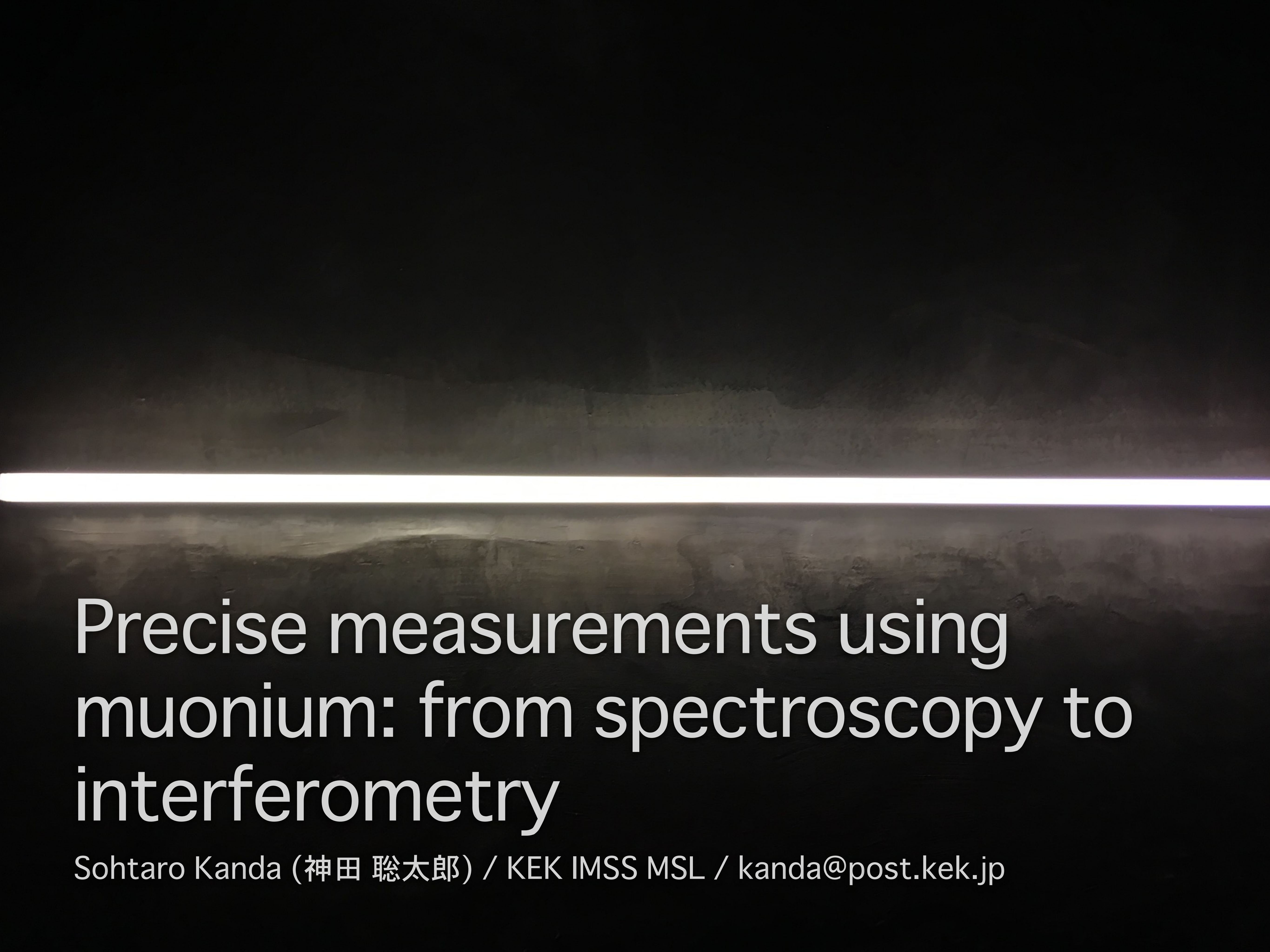
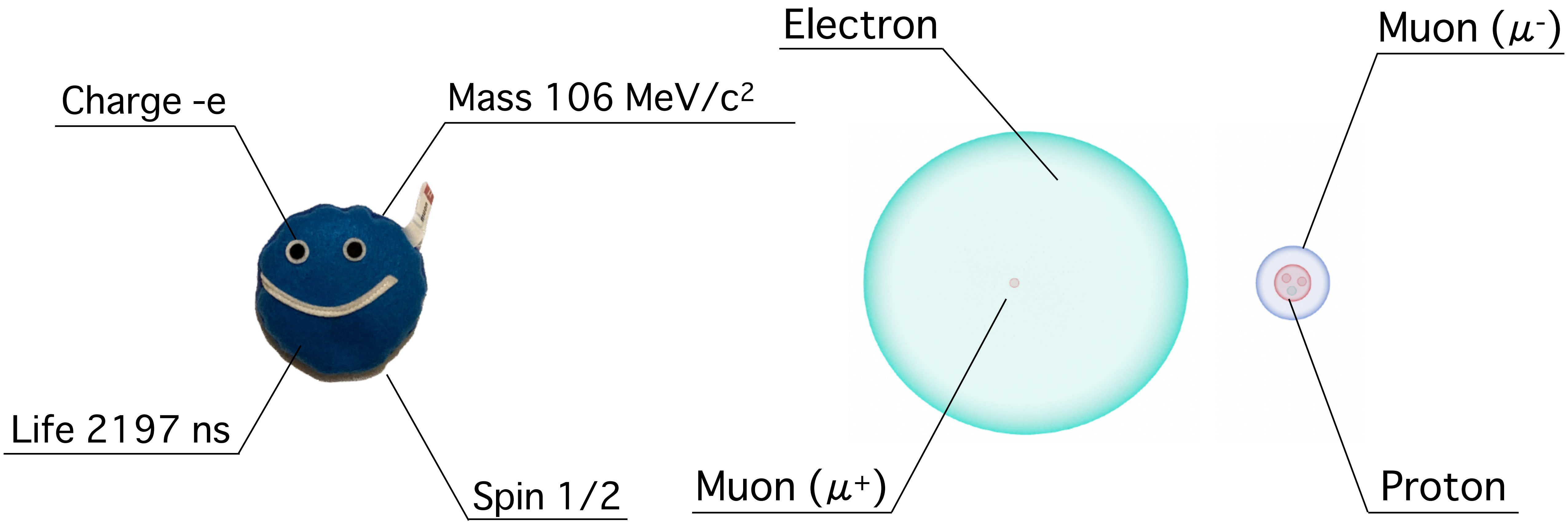


Precise measurements using muonium: from spectroscopy to interferometry

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

Muons and Muonic Systems

Second-generation charged-leptons



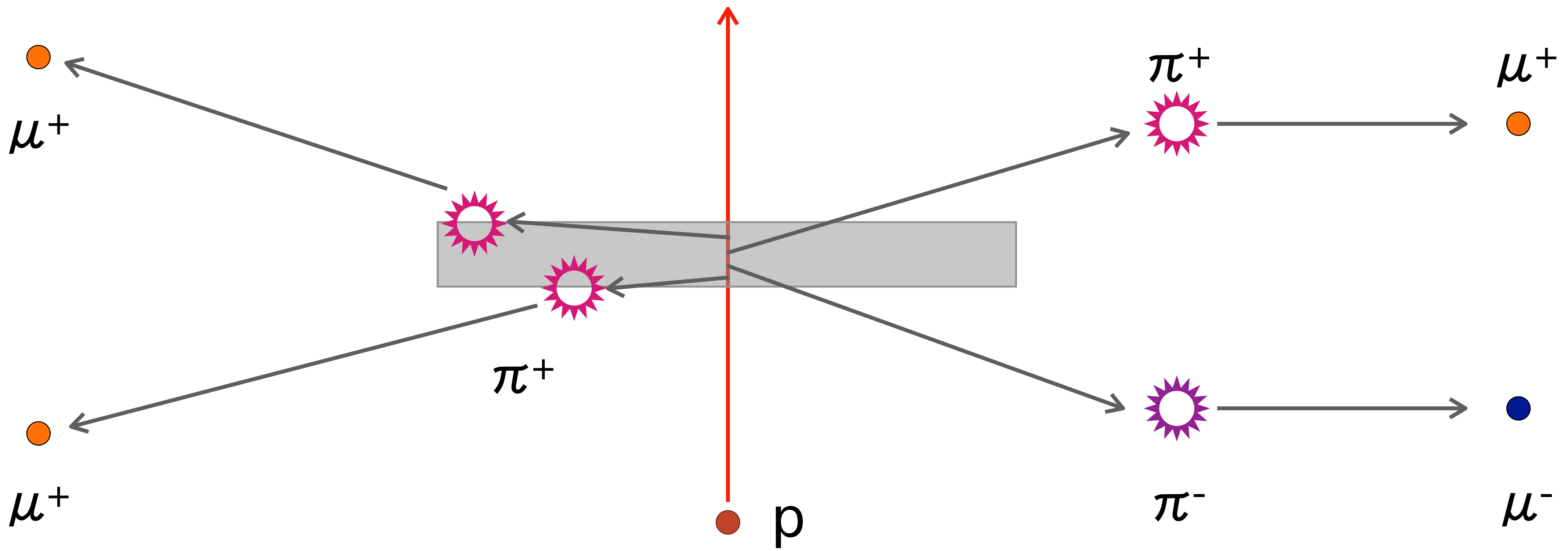
"Who ordered that?"

Muonium
$r_{\mu p}$ = 0.532 Å

Muonic atom
$r_{\mu p}$ = 0.00256 Å

- ○ Muon is 207 times heavier than electron and decays in 2.2 μs of the lifetime.
- ○ Muonic systems provide unique opportunities to determine the fundamental physical constants and to search for physics beyond the Standard Model.

Muon Beams



Surface muons

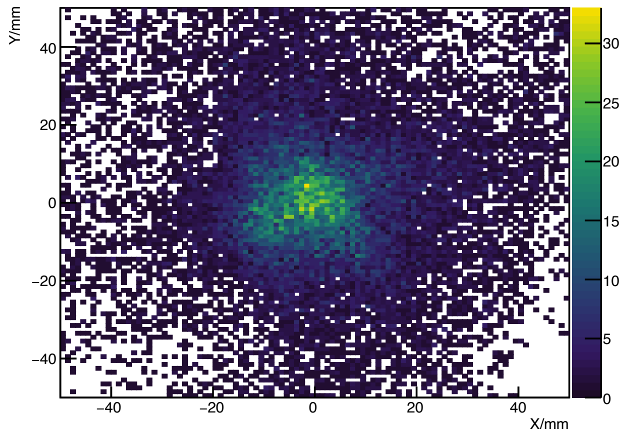
- Muons from pions stopped at the production target surface
- 4 MeV monochromatic
- 100% polarization
- Only available for μ^+

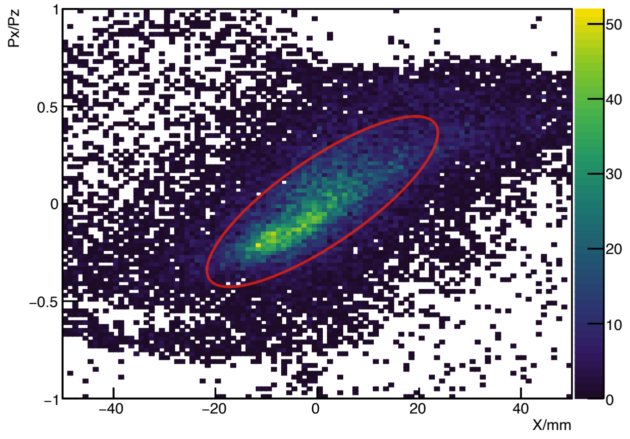
Decay muons

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

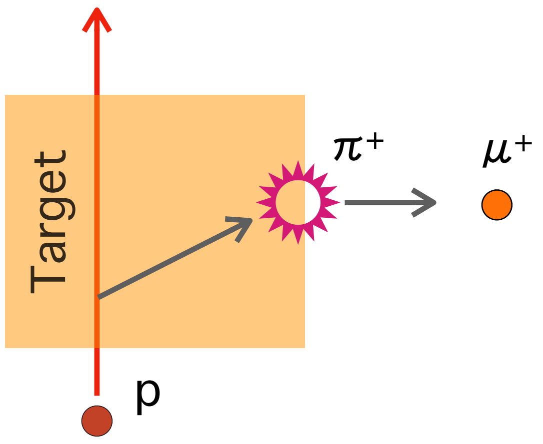
Limitation of the Surface Muon

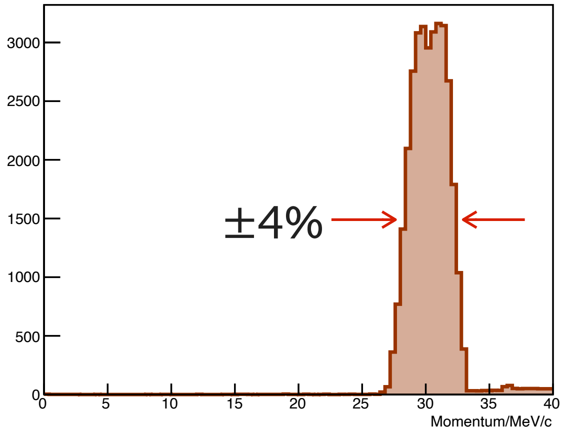
Beam spread and emittance





An example of surface muon beam profile: simulation using G4beamline (J-PARC MLF MUSE H1 Case).
top left: profile at the exp. area,
top right: emittance,
bottom right: momentum.





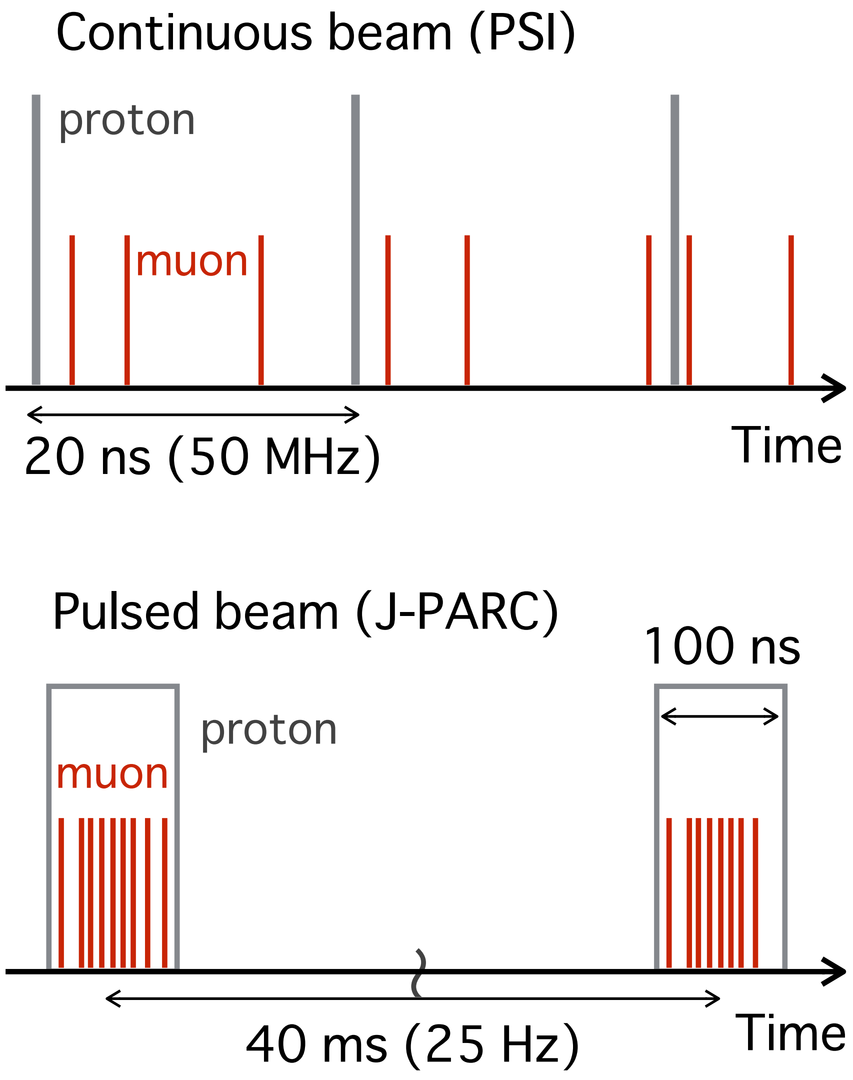
Beam width ~ 2 cm (std. dev.)
RMS emittance ~ 360 π cm mrad
Momentum bite ~ ±4%

G4BL model: A. Toyoda et al.,
J. Phys.: Conf. Ser. 408 012073 (2013).

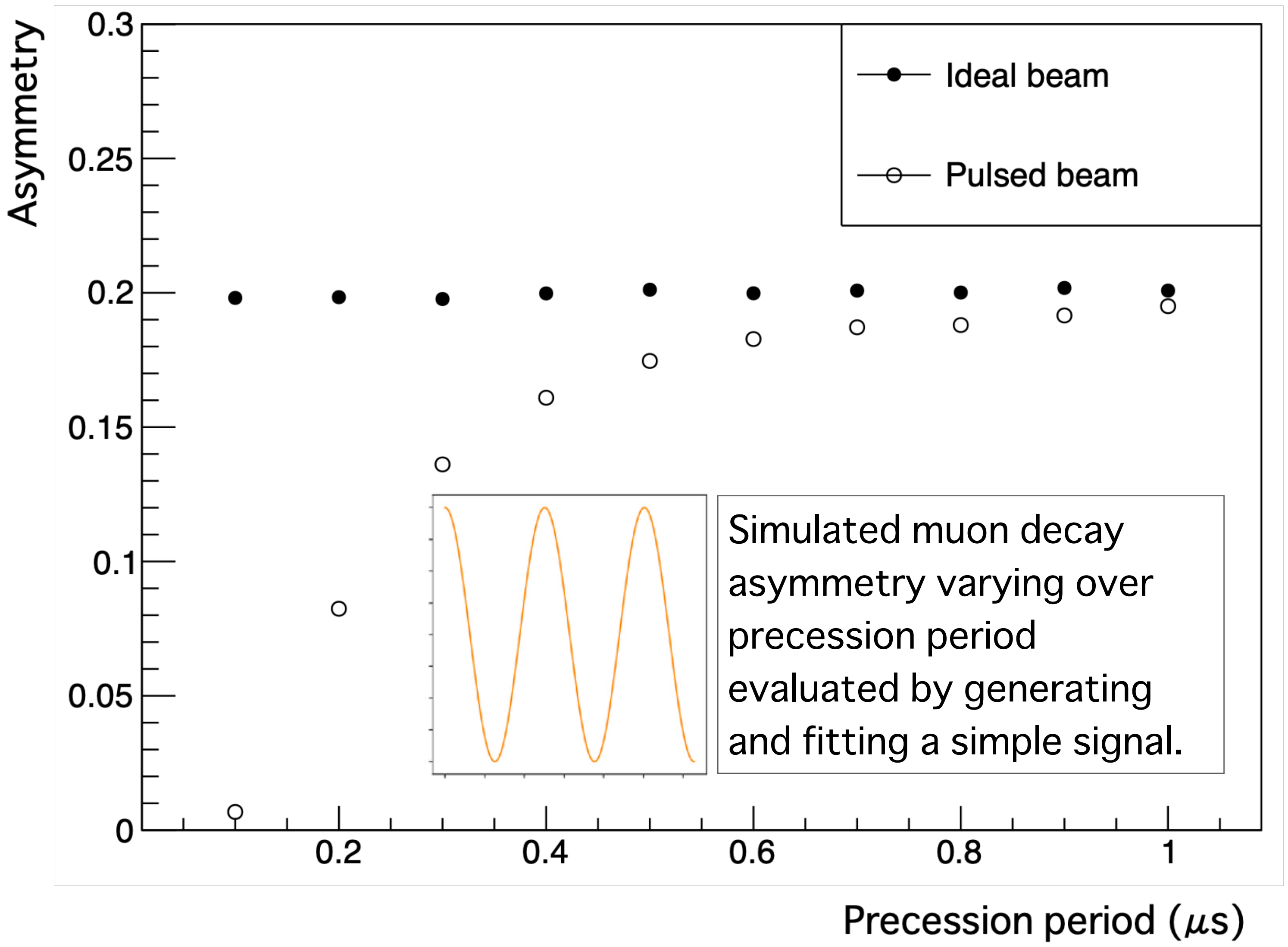
- Surface muons are widely employed, yet their emittance is large.
- With the achievement of high beam intensity, measurement precision and resolution are now limited by the beam quality.
- Efficient muon cooling is essential for breakthroughs in muon science.
  - Muon collider, g-2/EDM at J-PARC, etc…

Limitation of the Pulsed Muon

Time resolution


Continuous beam (PSI)

Pulsed beam (J-PARC)

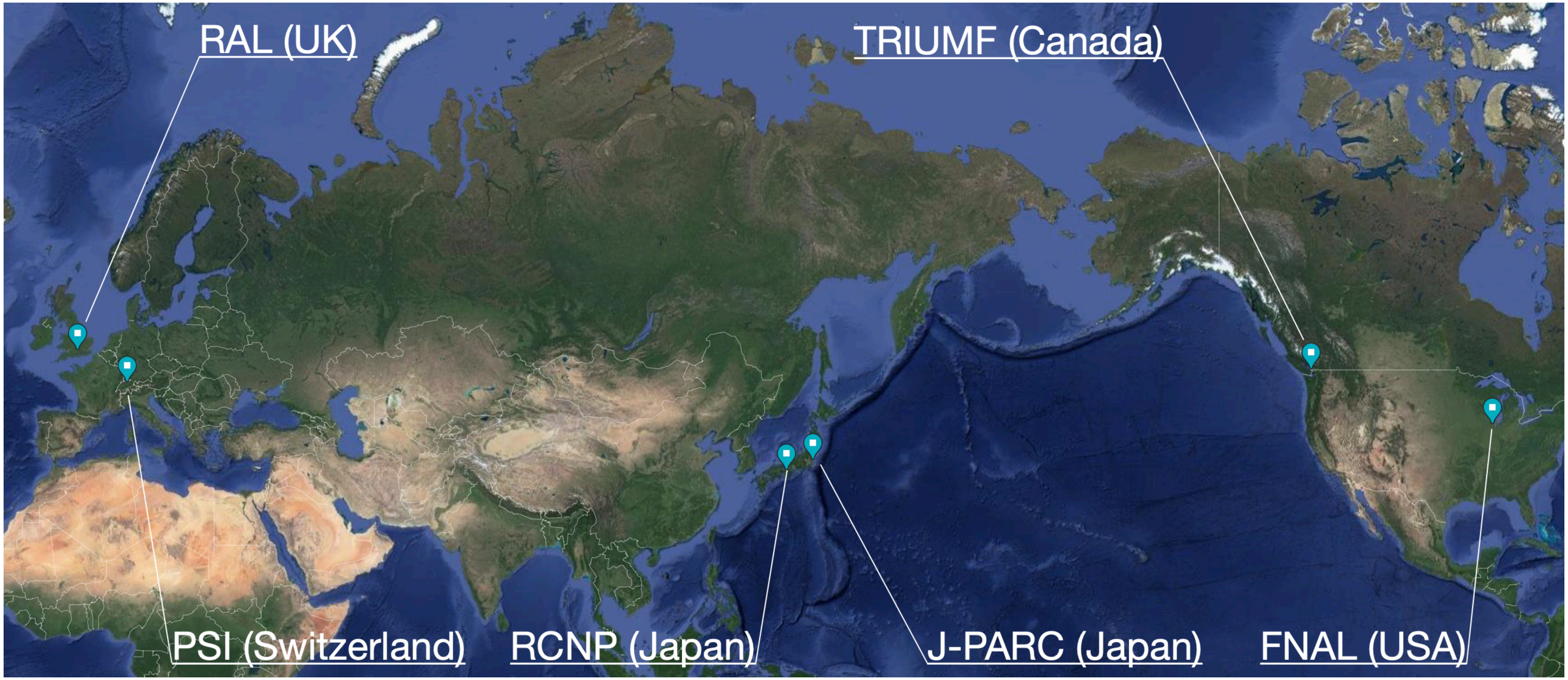


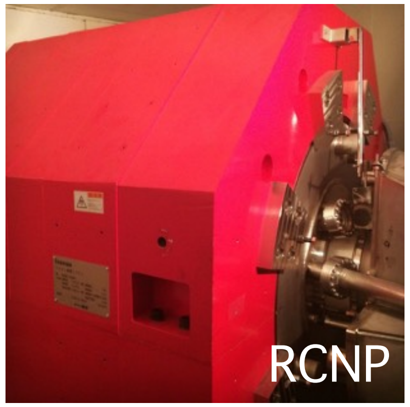
Simulated muon decay asymmetry varying over precession period evaluated by generating and fitting a simple signal.

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

Muon Facilities

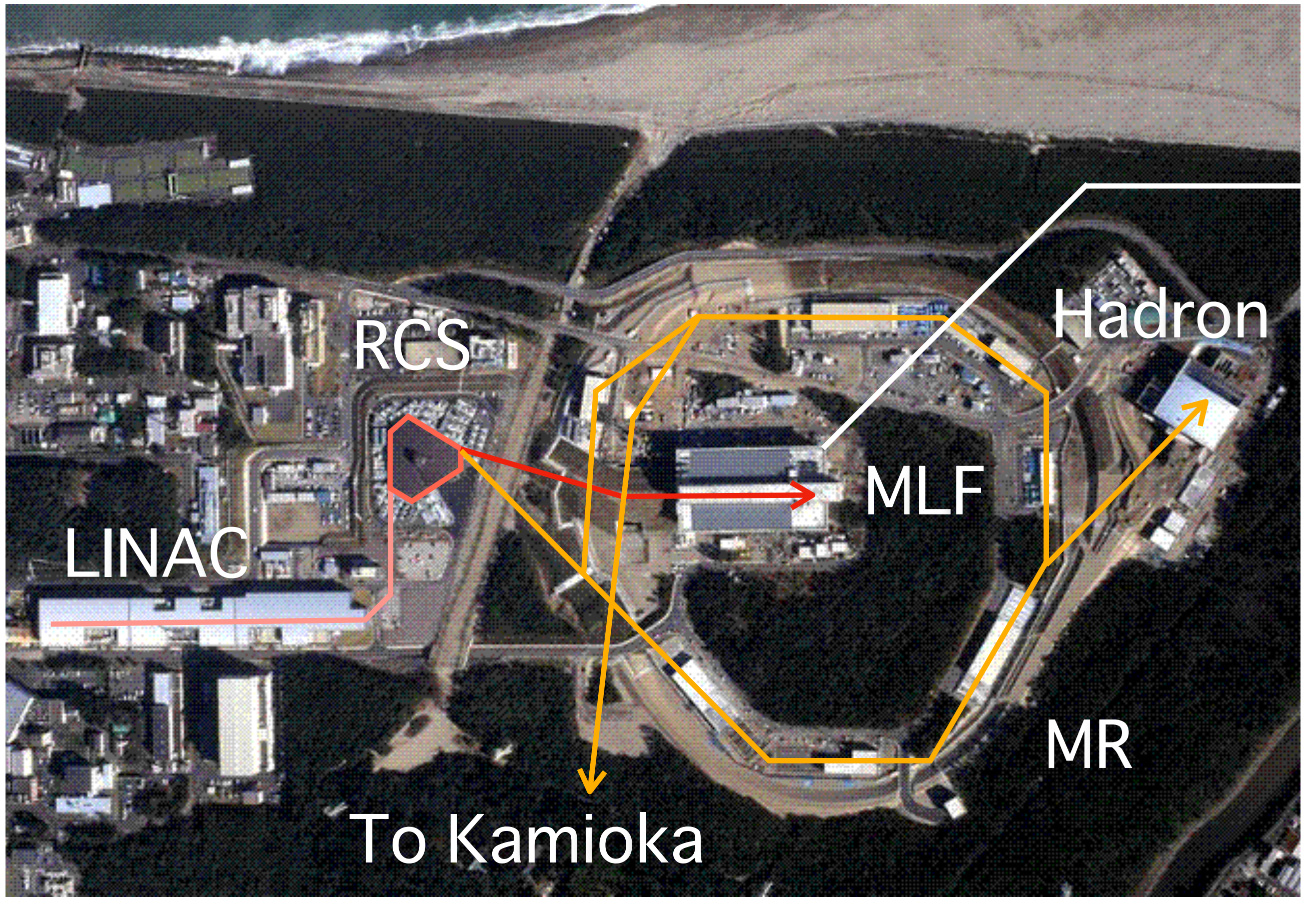
around the world

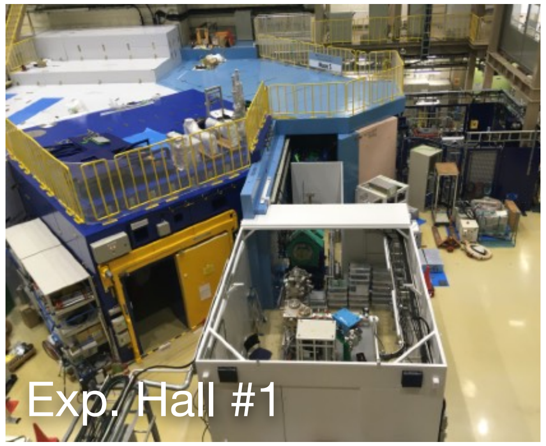


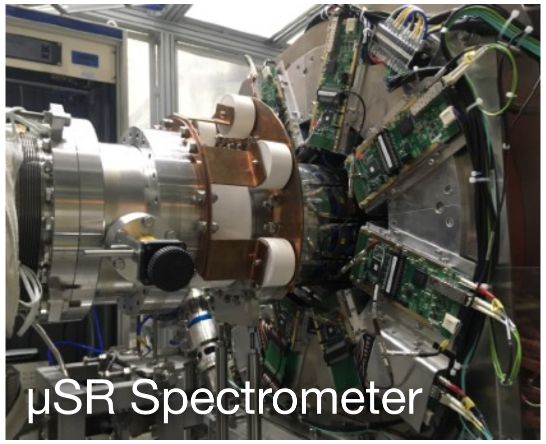


J-PARC

Japan Proton Accelerator Research Complex





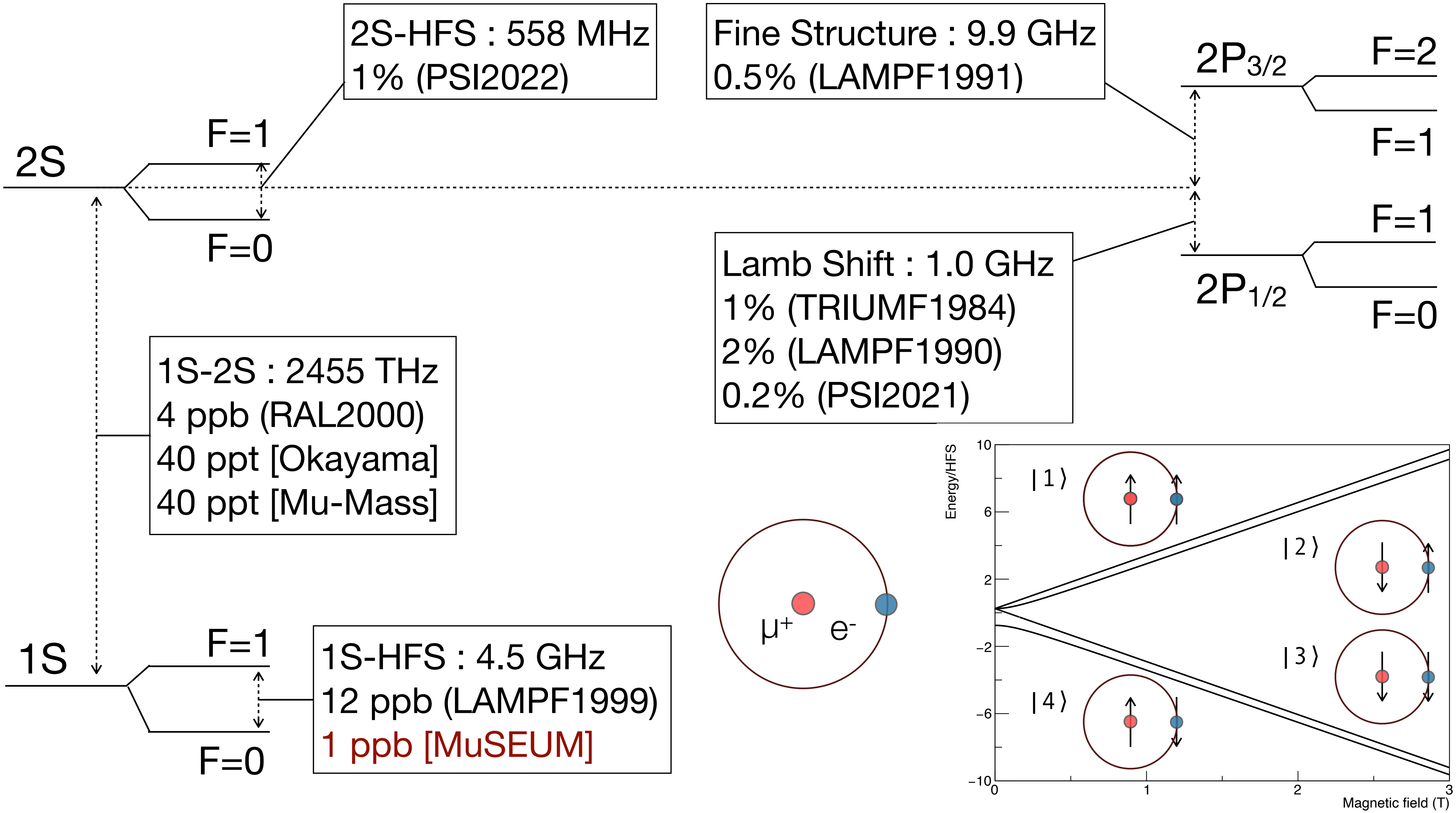


- ○ World most intense pulsed proton driver.
- ○ RCS provides 3 GeV protons for muon production at MLF.
- ○ MR delivers higher energy protons for the COMET, hadron, and neutrino experiments.

Muonium Spectroscopy

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

Muonium Spectroscopy



2S-HFS : 558 MHz
1% (PSI2022)

Fine Structure : 9.9 GHz
0.5% (LAMPF1991)

Lamb Shift : 1.0 GHz
1% (TRIUMF1984)
2% (LAMPF1990)
0.2% (PSI2021)

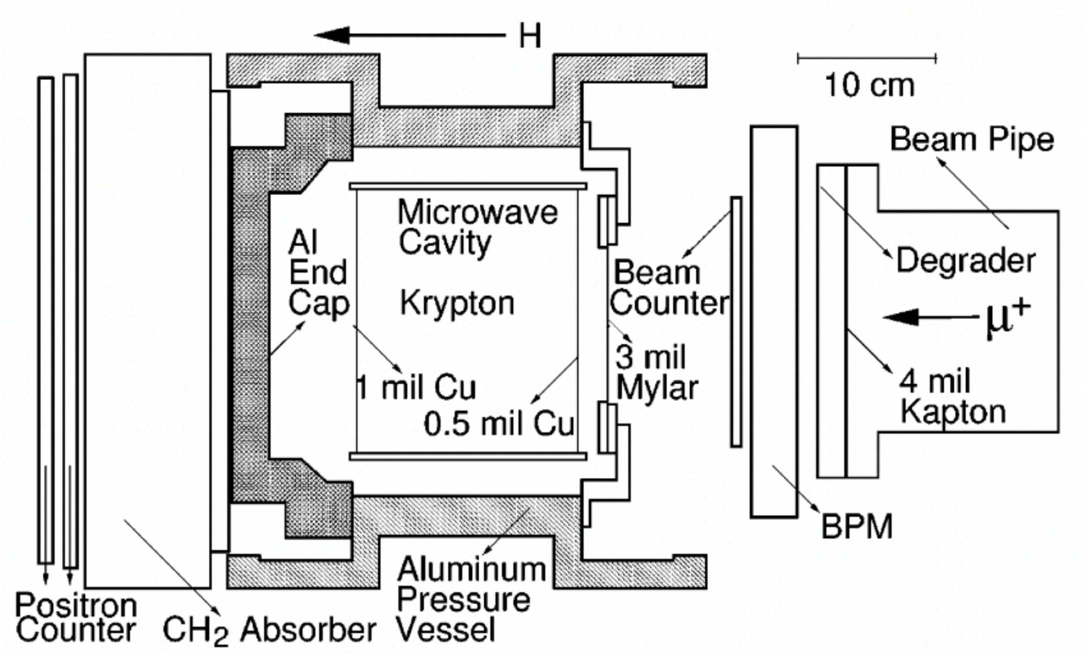
1S-2S : 2455 THz
4 ppb (RAL2000)
40 ppt [Okayama]
40 ppt [Mu-Mass]

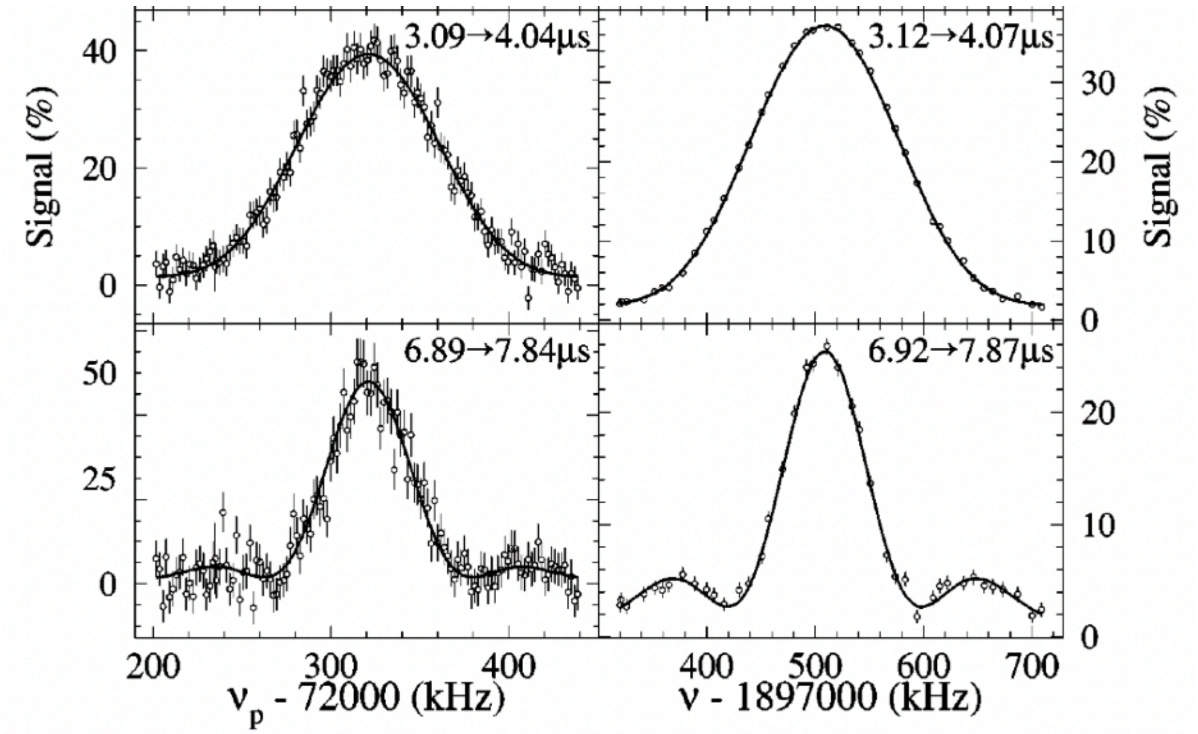
1S-HFS : 4.5 GHz
12 ppb (LAMPF1999)
1 ppb [MuSEUM]

- ○ Precise tests of the Standard Model and BSM searches.
- ○ Determination of the fundamental constants.

Muonium Hyperfine Splitting

Experiment at LAMPF





- Muonium 1S-HFS microwave spectroscopy under a high magnetic field.
- The final result was published in 1999.
- The precision of HFS was 12 ppb, statistically limited.
- The muon-to-proton magnetic moment ratio was determined with 120 ppb precision.
- The largest systematics was field uniformity.

W. Liu et al., “High Precision Measurements of the Ground State Hyperfine Structure Interval of Muonium and of the Muon Magnetic Moment”, Phys. Rev. Lett., 82 711 (1999).

Muonium Hyperfine Splitting

- Theoretical prediction: $\Delta_{\text{HFS}} =$ 4. 463 302 872(511)(70)(2) GHz

m_μ/m_e QED α

$$\Delta_{\text{HFS}} = \frac{16}{3} Z^4 \alpha^2 \frac{m_e}{m_\mu} \left(1 + \frac{m_e}{m_\mu}\right)^{-3} cR_\infty + \Delta_{\text{QED}} + \Delta_{\text{QCD}} + \Delta_{\text{EW}}$$

237 Hz 65 Hz

- Experimental result: $\Delta_{\text{HFS}} =$ 4. 463 302 776(51) GHz (11 ppb)

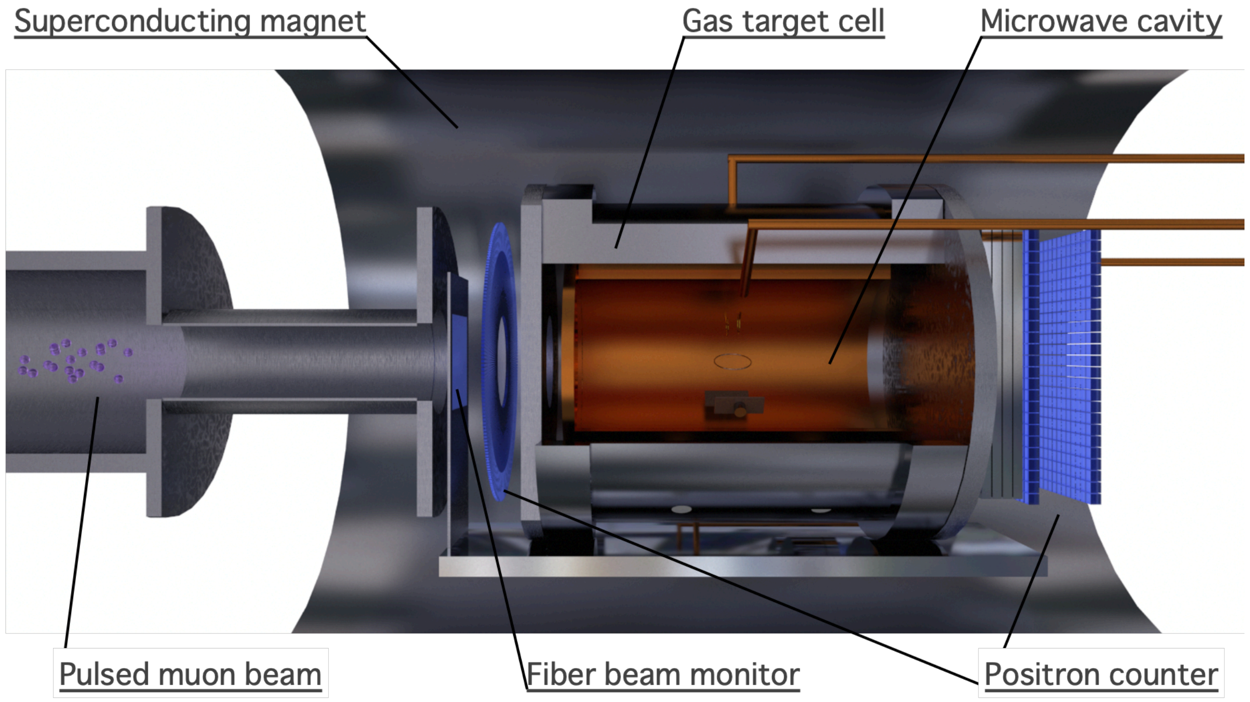
$m_\mu/m_e = 206.768277(24)$ (116 ppb)

Theory : M. I. Eides, Phys. Lett. B 795, 113(2019).
S. G. Karshenboim and E. Y. Korzinin, Phys. Rev. A 103, 022805 (2021).
Experiment : W. Liu et al., Phys. Rev. Lett., 82 711 (1999).

- The precision of the experimental result is dominated by statistics.
  - A high-intensity pulsed muon beam is beneficial.
- The theoretical uncertainty is limited by the measurement result of muon mass.
  - The mass can be independently obtained by the muonium 1S-2S spectroscopy and muonium interferometry.

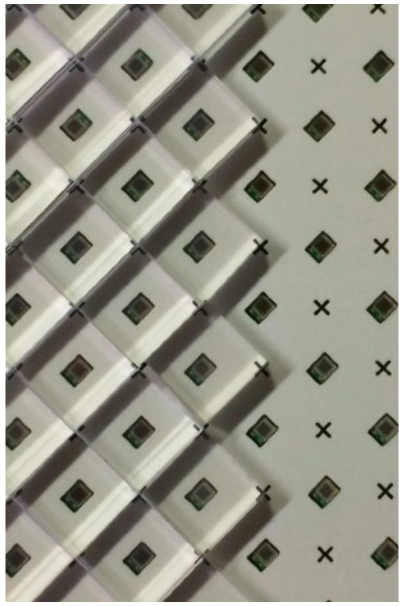
Muonium Hyperfine Splitting

MuSEUM Experiment at J-PARC



Magnet

NMR probe

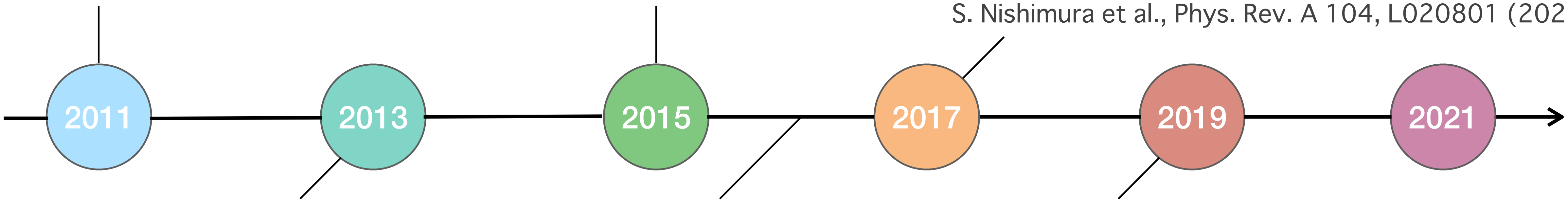


Positron detector

- Muonium 1S-HFS microwave spectroscopy using a high-intensity pulsed beam at J-PARC.
- A segmented positron detector for precise signal counting.
- Improved field uniformity and precise mapping of the field.
- The target precision is 1 ppb for HFS, 12 ppb for μ_μ/μ_p.
- Measurements under a zero-field have been completed.
- Preparing for the high-field exp.

Project Timeline of MuSEUM

Since the experiment was proposed



Proposal submitted

K. Shimomura, AIP Conf. Proc. 1382, 245 (2011).

Detector R&D

S. Kanda, et al., PoS(PhotoDet2015)039 (2016).

Second ZF Result

S. Kanda et al., Phys. Lett. B 815, 136154 (2021).

Rabi-oscillation Spectroscopy

S. Nishimura et al., Phys. Rev. A 104, L020801 (2021).

Cavity R&D

K.S. Tanaka et al. PTEP 2021, 053C01(2021).

First ZF Result

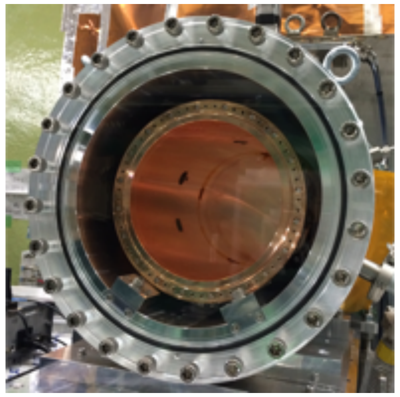
S. Kanda, PoS(INPC2016)170 (2017).

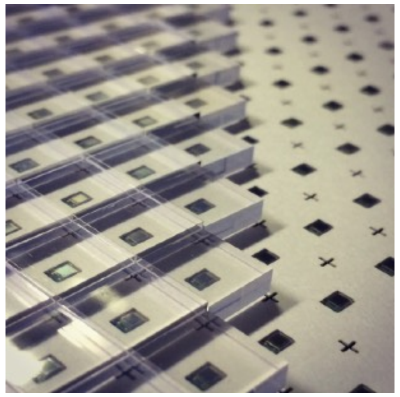
NMR Probe R&D

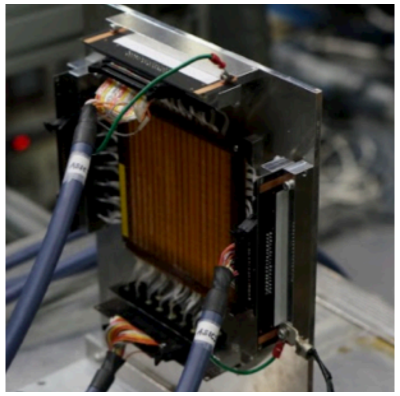
H. Yamaguchi et al., IEEE Trans. Appl. Supercond. 29, 9000904 (2019).

Shimming R&D

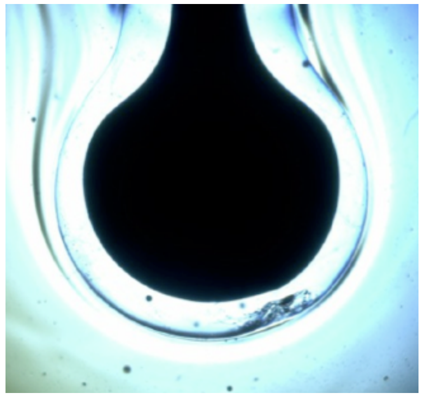
M. Sugita et al., Proc. Ann. Mtg Part. Accel. Soc. Jpn, 13 (2020).

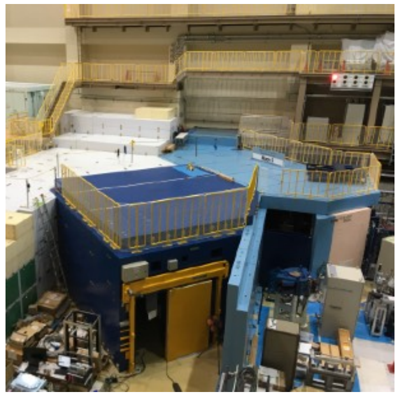

Microwave Cavity


Positron Detector


Beam Monitor

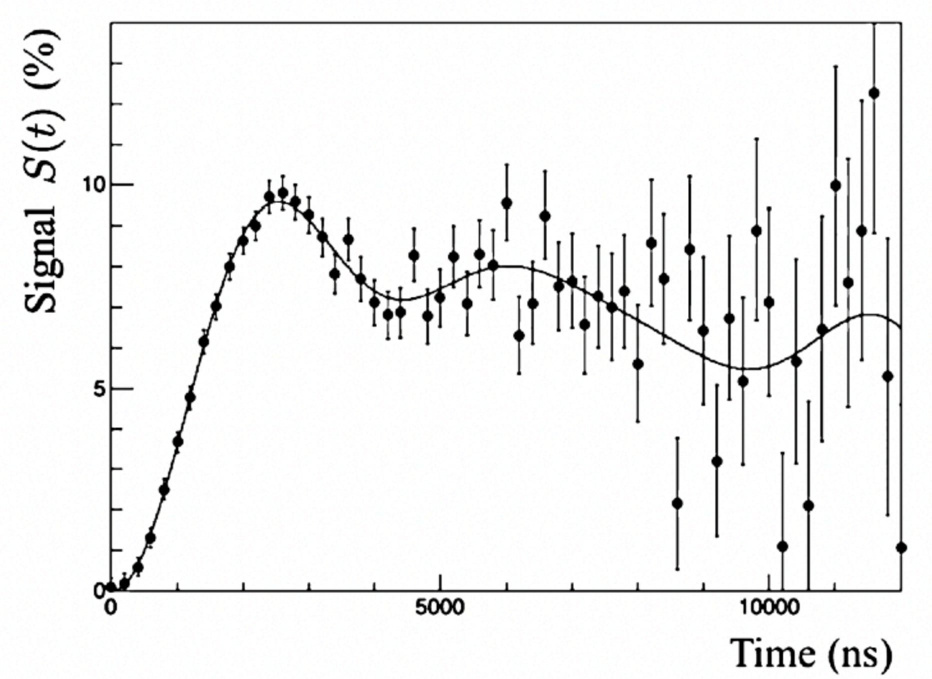

Magnet


NMR Probe

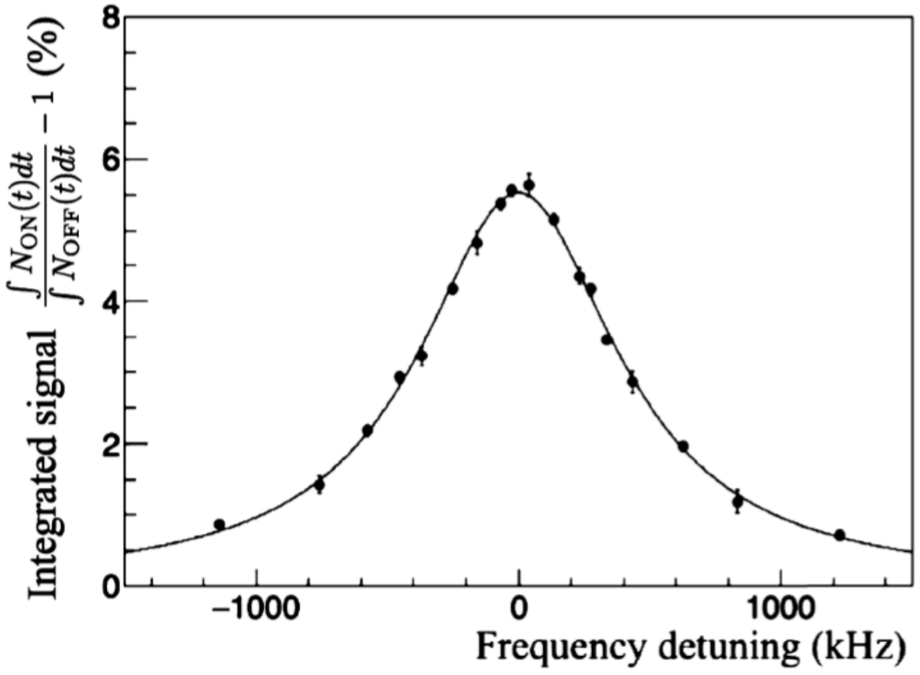

Muon Beamline

Zero-Field Results

First Letter has been published in 2021



Rabi-oscillation of muonium



○ Phase-1 experiment under a zero-magnetic field.

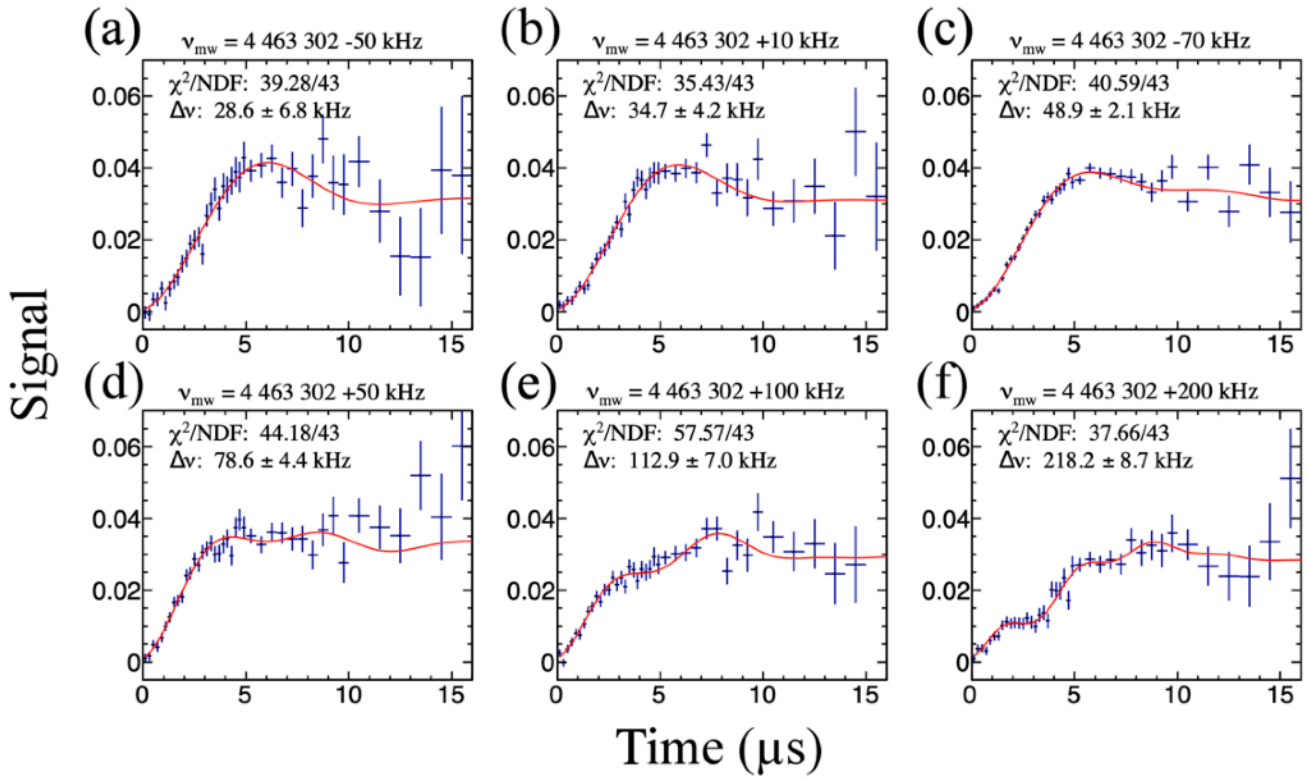
○ Direct observation of the hyperfine transition with a microwave at 4.463 GHz.

○ The first precise spectroscopy of muonium HFS using a pulsed beam (900 ppb).

S. Kanda et al., “New precise spectroscopy of the hyperfine structure in muonium with a high-intensity pulsed muon beam”, Phys. Lett. B 815 (2021) 136154.

Zero-Field Results

A new analysis technique to improve precision



Fitting results for different microwave frequencies

Rabi-oscillation formula

$$f\left(t;\ A,\ |b|,\ \Delta\omega\right) = A\sum N_i\left(\frac{G_i^+}{\Gamma_i}\cos G_i^- t + \frac{G_i^-}{\Gamma_i}\cos G_i^+ t - 1\right)$$

$$G^\pm = \frac{\Gamma \pm \Delta\omega}{2},$$

$$\Gamma = \sqrt{(\Delta\omega)^2 + 8\,|b|^2},$$

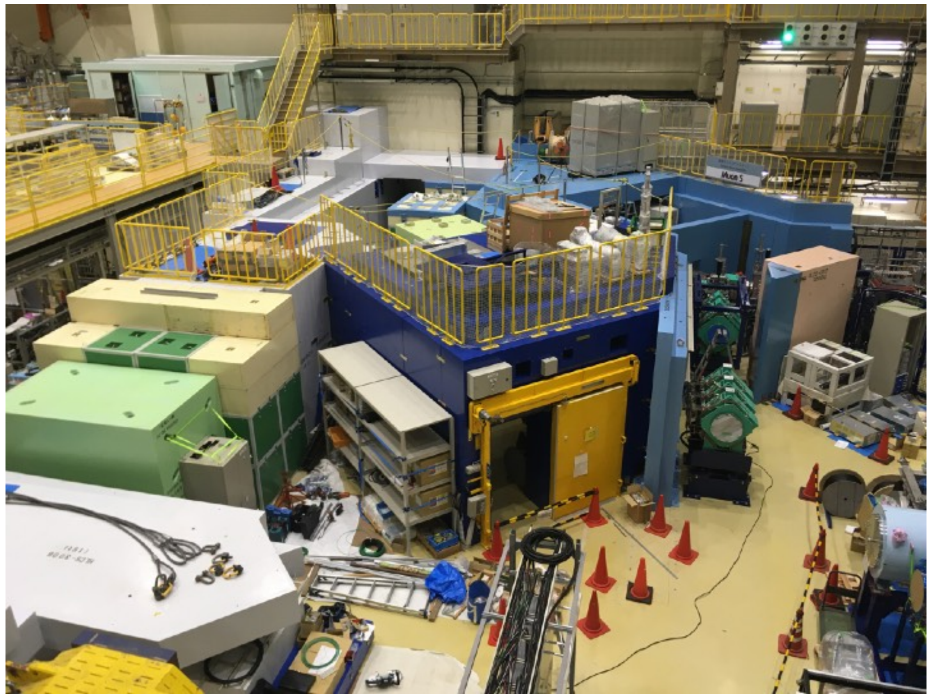
$\Delta\omega$: freq. detuning
b: microwave power

- A new method to directly analyze the Rabi oscillation was developed.
- Tolerant to time-varying systematic errors such as microwave power drift.
- The highest precision among zero-field measurements was achieved (159 ppb).

S. Nishimura et al., “Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms”, Phys. Rev. A 104, L020801 (2021).

New Surface Muon Beamline

H-Line at J-PARC MLF MUSE

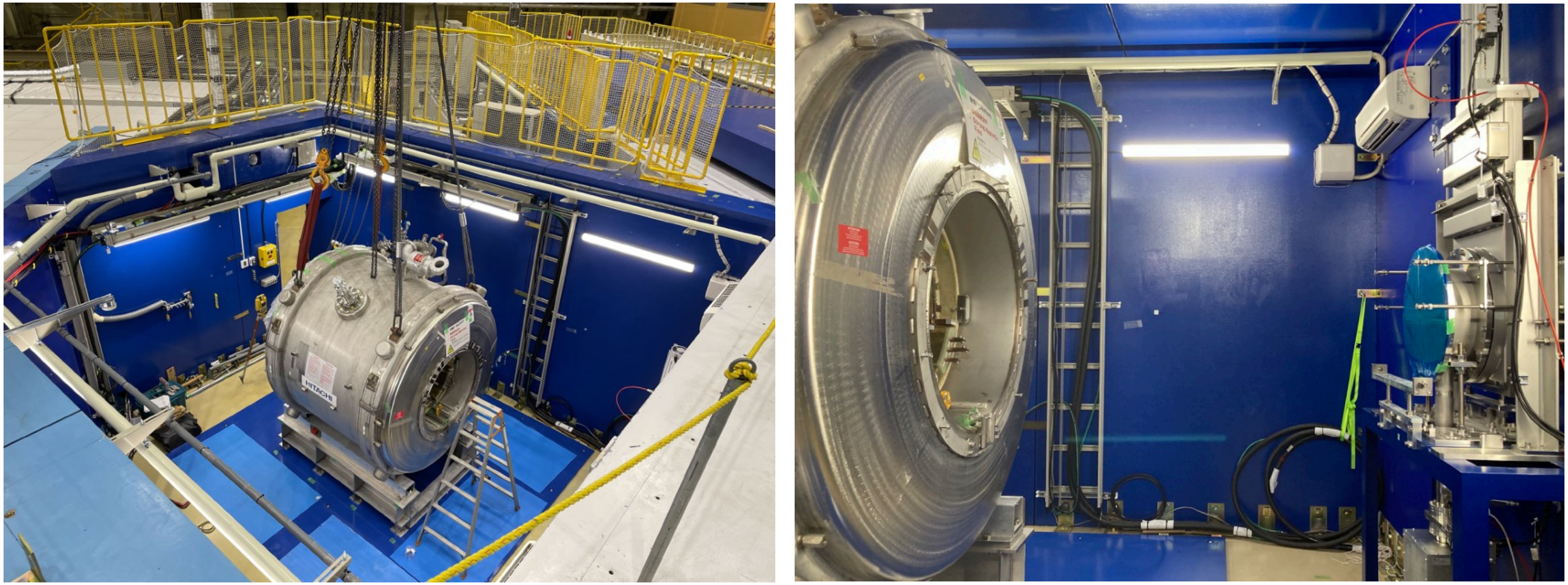


- A brand-new beamline delivering a high-intensity beam of 1x 10^8 μ^+/s or more.
- Dedicated for fundamental physics experiments that require long-term measurements.
- First beam extraction succeeded in Jan. 2022. Commissioning is underway.
- MuSEUM will start measurements under high-fields from January 2024.

T. Yamazaki et al., “New beamlines and future prospects of the J-PARC muon facility”, EPJ Web of Conferences 282, 01016 (2023).

MuSEUM High-Field

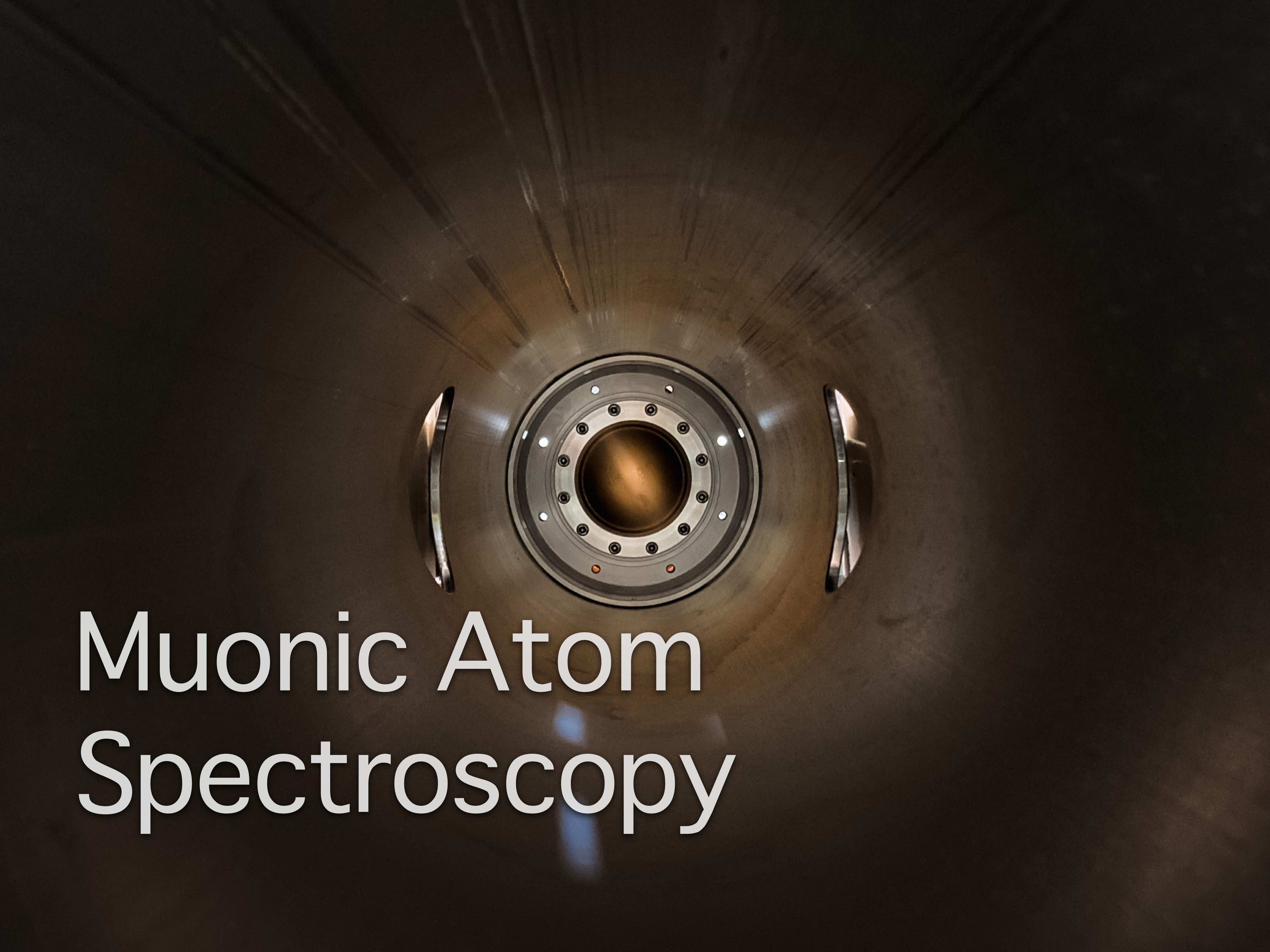
The superconducting magnet was installed



Photos in November 2023.

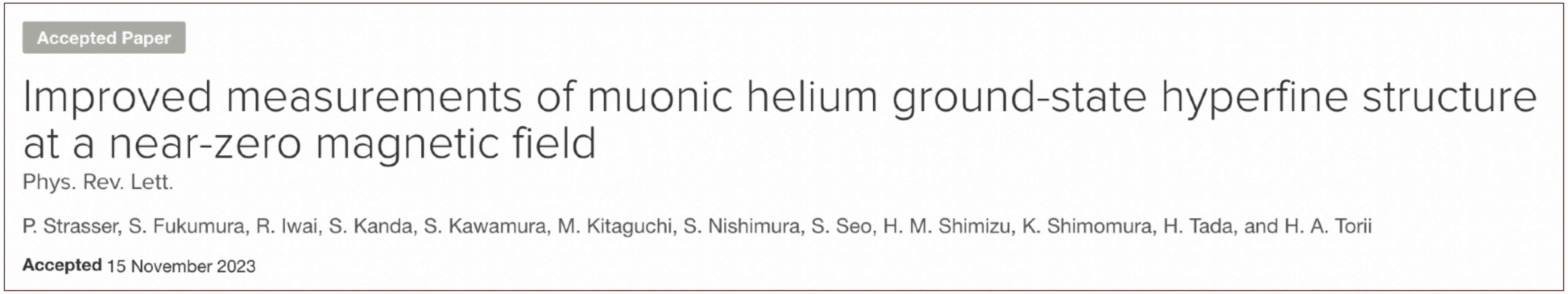
- The superconducting solenoid was successfully installed in the H1 experimental area.

Works by T. Yamazaki, K. Sasaki, N. Kurosawa et al.



Muonic Atom Spectroscopy

Muonic Helium HFS



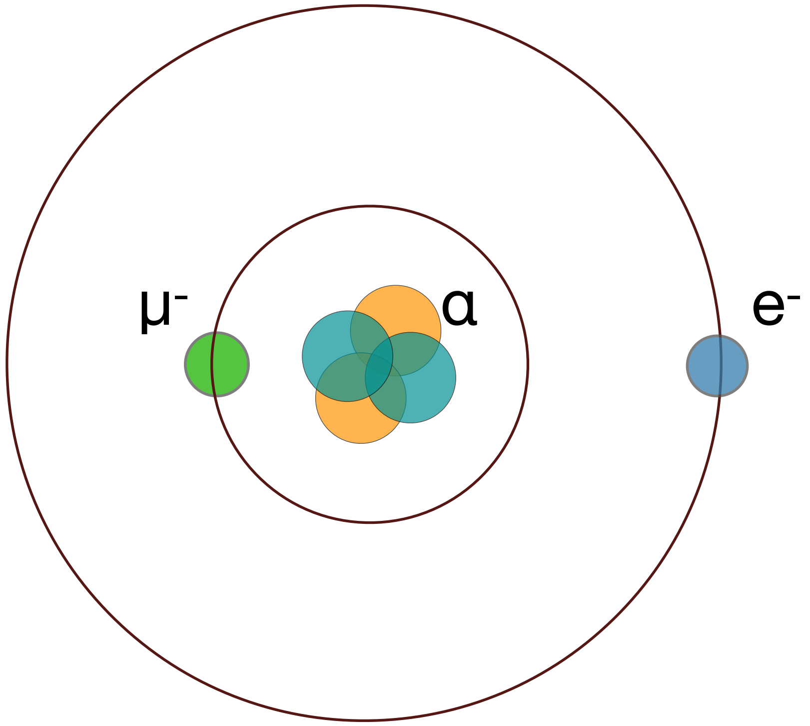
Accepted Paper

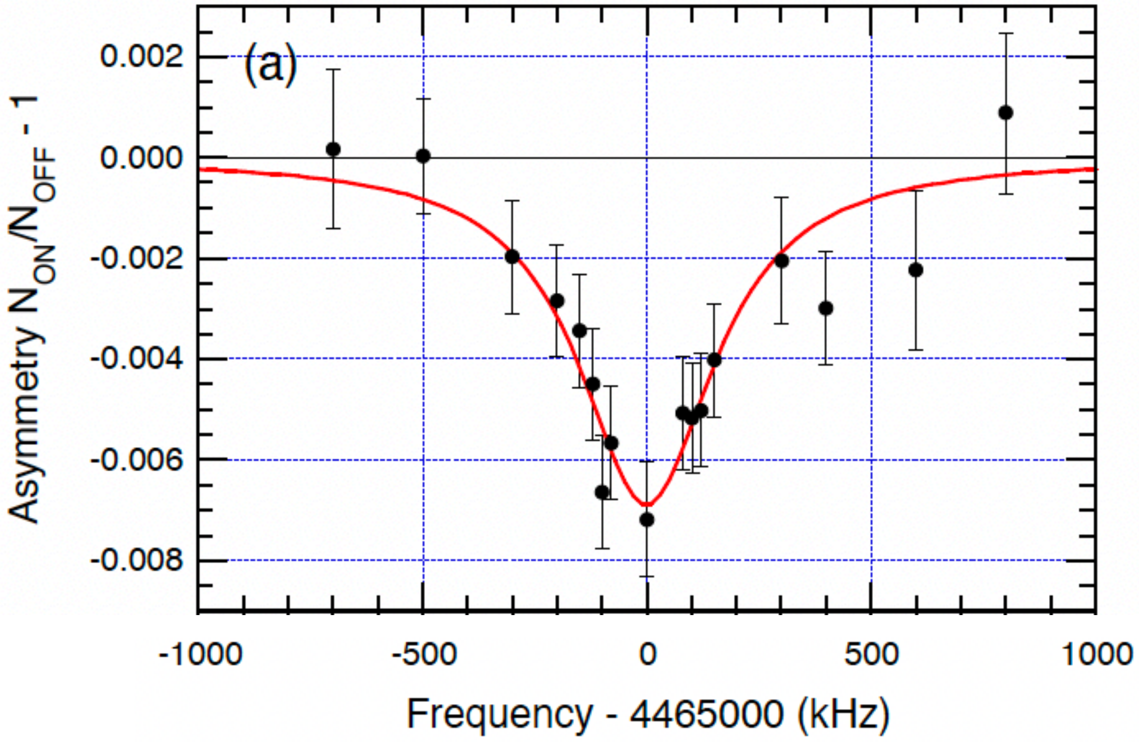
Improved measurements of muonic helium ground-state hyperfine structure at a near-zero magnetic field

Phys. Rev. Lett.

P. Strasser, S. Fukumura, R. Iwai, S. Kanda, S. Kawamura, M. Kitaguchi, S. Nishimura, S. Seo, H. M. Shimizu, K. Shimomura, H. Tada, and H. A. Torii

Accepted 15 November 2023



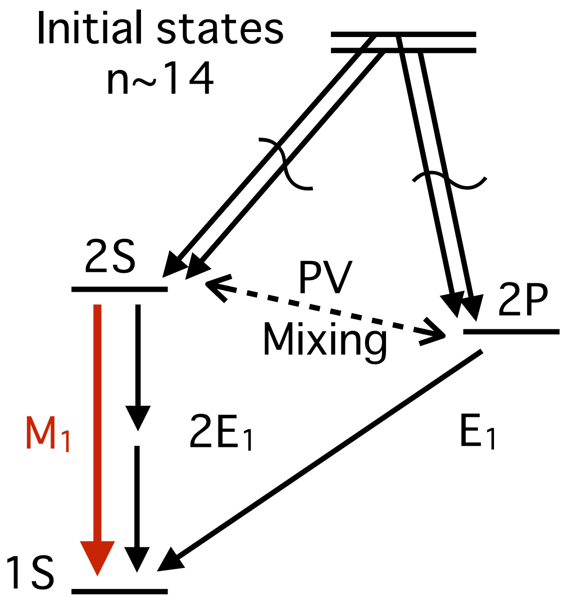


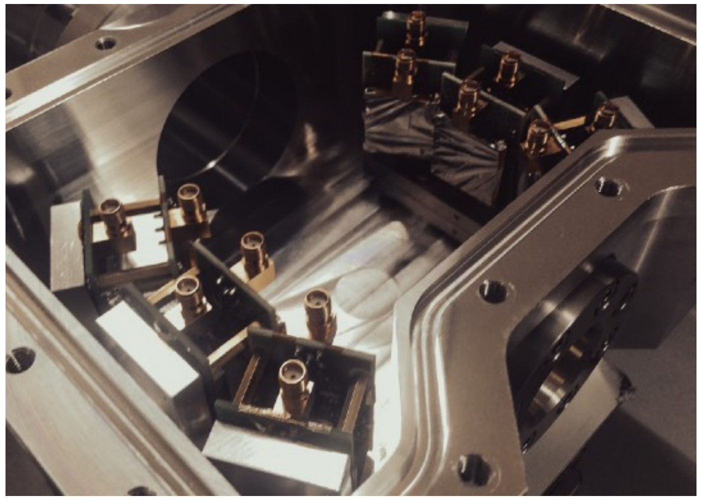
- A spin-off project of the MuSEUM aiming to measure the HFS in muonic helium (^{4}He μ^- e$^-$) for testing 3-body QED and CPT.
- The result is 4464.979(20) MHz (4.5 ppm), the most precise among the results obtained so far.

https://arxiv.org/abs/2306.07533

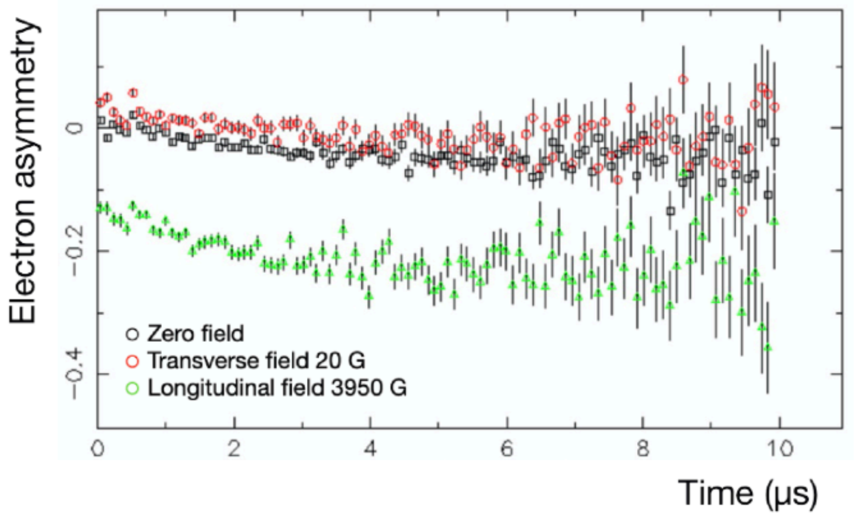
Muonic Atom Parity Violation

- A new exp. to measure the Weinberg angle by observing muonic APV.
- Cascade approach





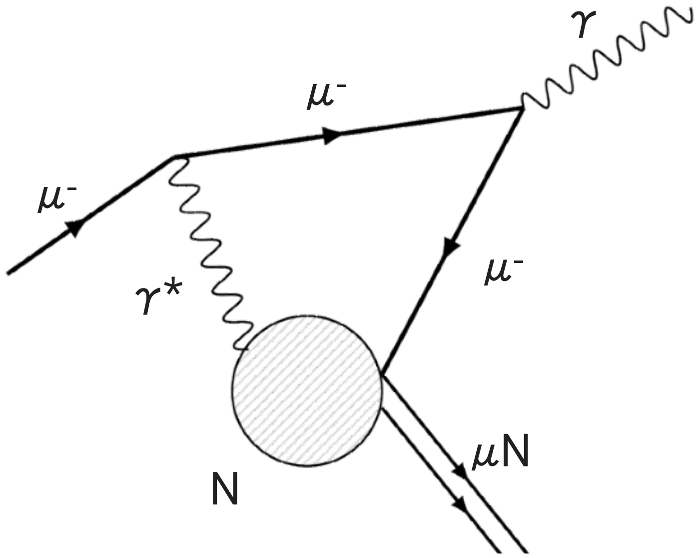
Target gas cell+ LYSO calorimeter

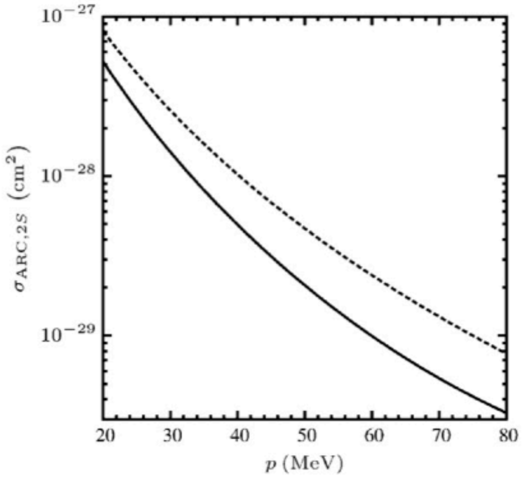


μ^-SR with a methane gas target

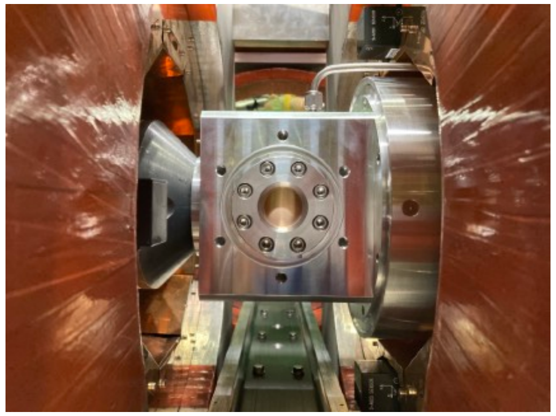
S. Kanda et al., EPJ Web of Conferences 262, 01010 (2022).

- Atomic radiative capture (ARC) approach

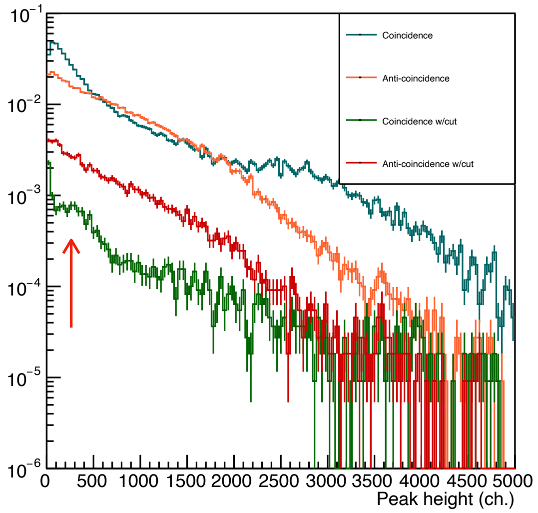




D. McKeen and M. Pospelov,
Phys. Rev. Lett. 108, 2263401 (2012).

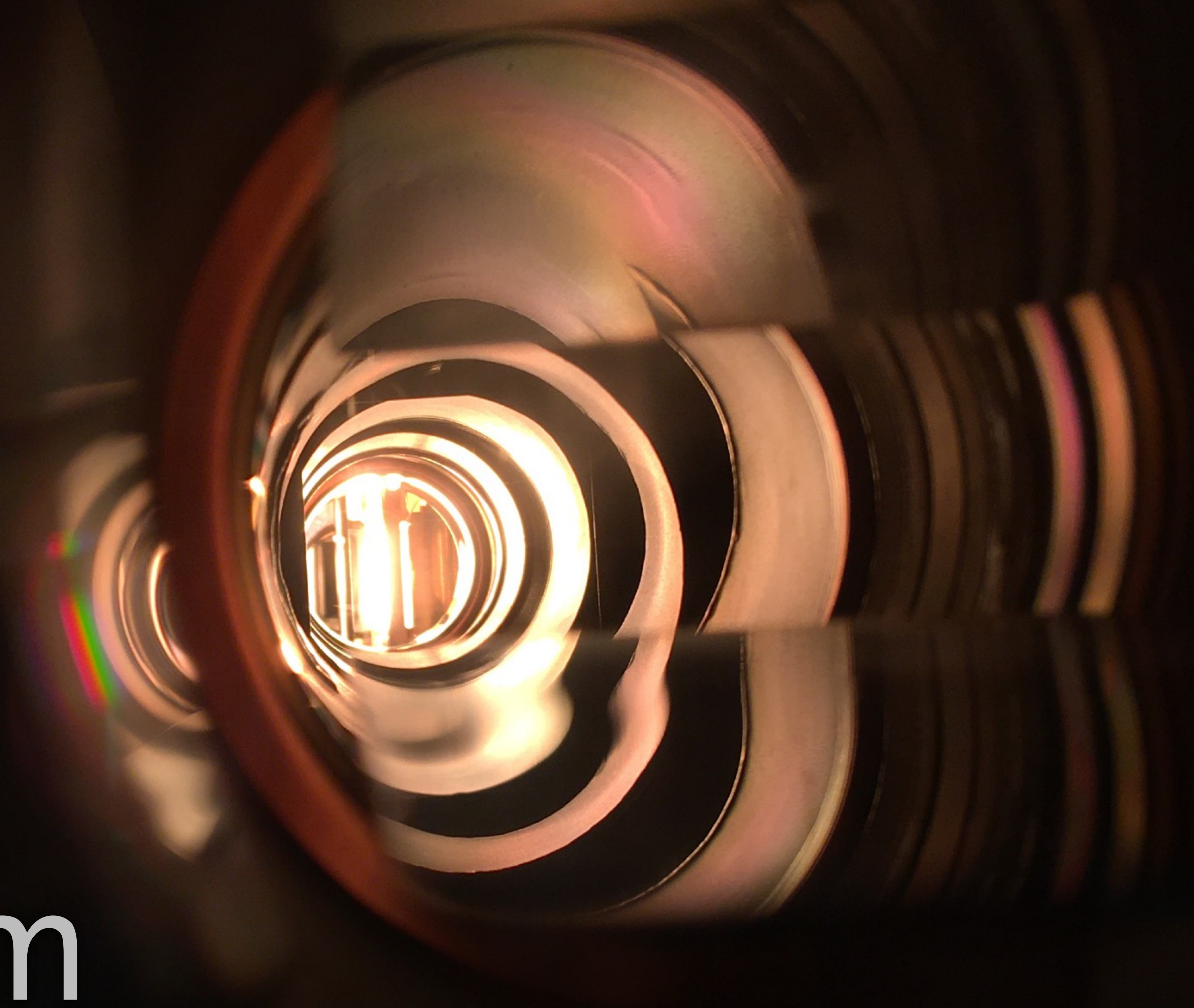


Target cell



Energy spectrum

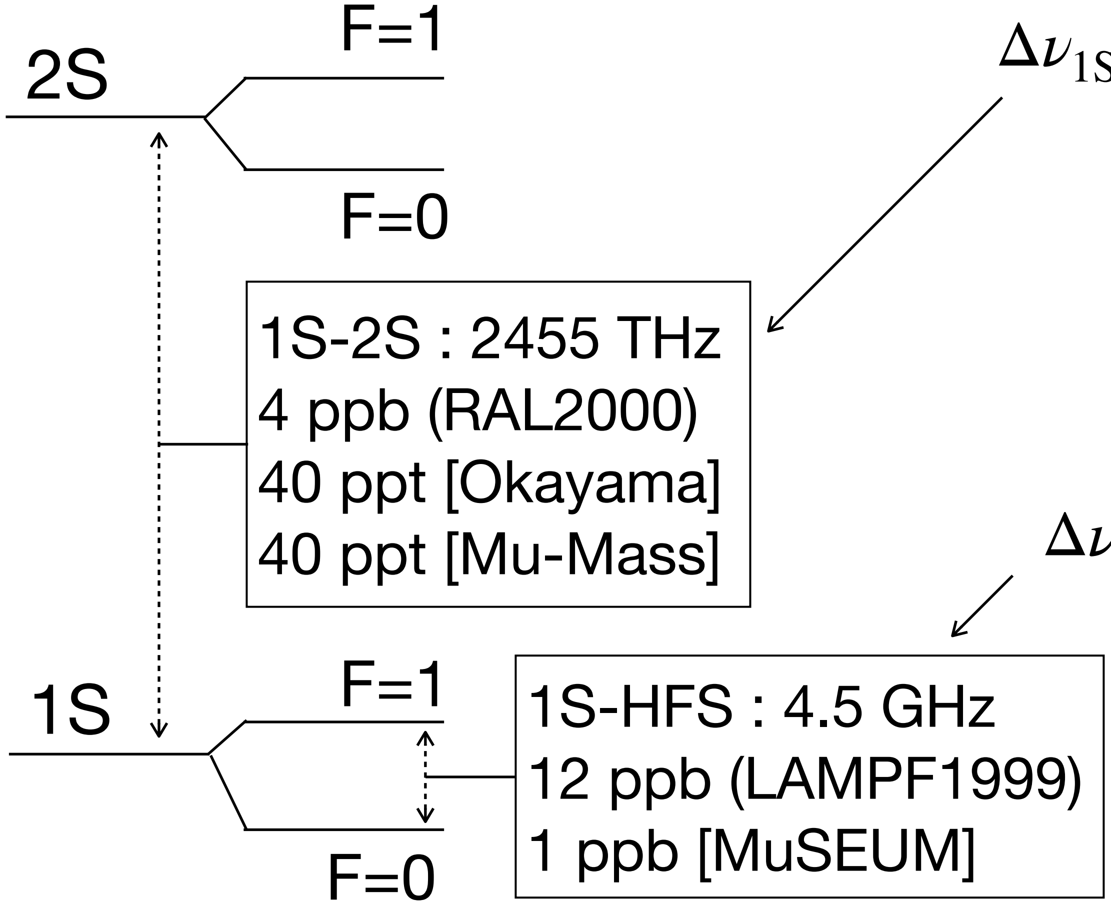
S. Kanda et al., KEK-MSL Report 2022 (to be published).



Muonium Interferometry

Muon Mass Measurements

from spectroscopy to interferometry



1S-2S : 2455 THz
4 ppb (RAL2000)
40 ppt [Okayama]
40 ppt [Mu-Mass]

1S-HFS : 4.5 GHz
12 ppb (LAMPF1999)
1 ppb [MuSEUM]

$$\Delta\nu_{1S-2S} = \frac{3}{8h}\alpha^2(1+\frac{m_e}{m_\mu})^{-1}m_e c^2$$

- Uncertainty 9.8 MHz (4 ppb)
- Mass-ratio precision 822 ppb

V. Meyer et al., Phys. Rev. Lett., 84, 1136 (2000).

$$\Delta\nu_{\mathrm{HFS}} = \frac{16}{3}Z^4\alpha^2\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}cR_\infty$$

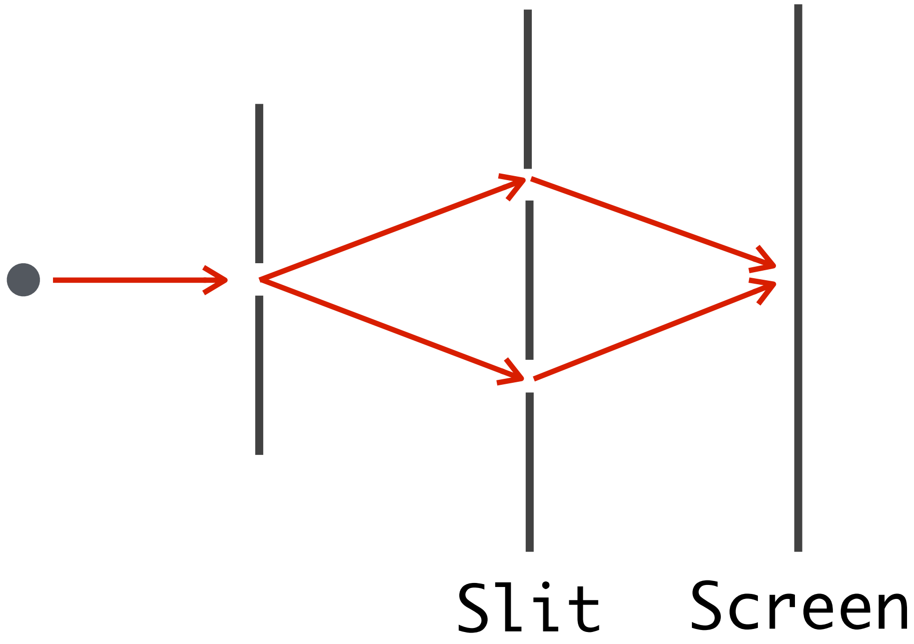
- Uncertainty 53 Hz (11 ppb)
- Mass-ratio precision 116 ppb

W. Liu et al., Phys. Rev. Lett., 82, 711 (1999).

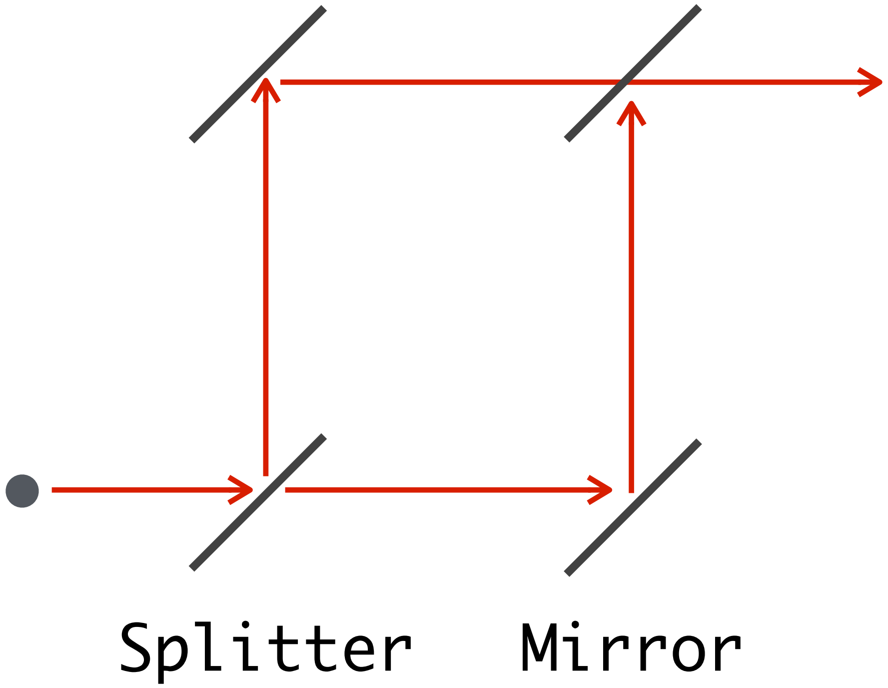
- ○ The muon-to-electron mass ratio can be determined by muonium spectroscopy.
- ○ For testing QED and the Standard Model, independent determination of the muon mass can greatly enhance precision → muonium interferometry.

Atom Interferometer

a powerful tool of AMO physics



Young interferometer



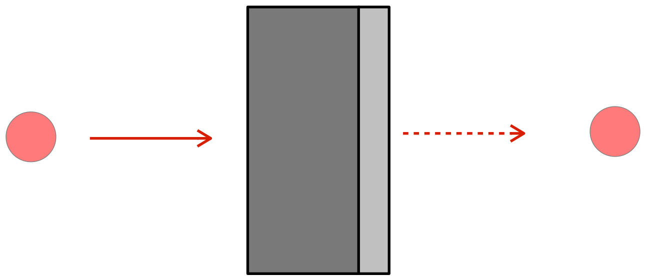
Mach-Zehnder interferometer

- ○ Matter-wave Interferometry is promising as a method for determining the muon mass.
- ○ For this purpose, a bright, low-energy muon beam is necessary.

Low Energy Muons

for low-emittance muon beams

Cold rare-gas moderator (LEM)



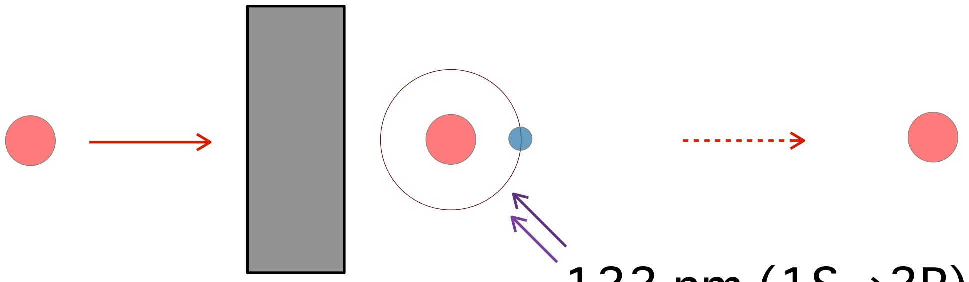
Solid rare-gas film on substrate

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

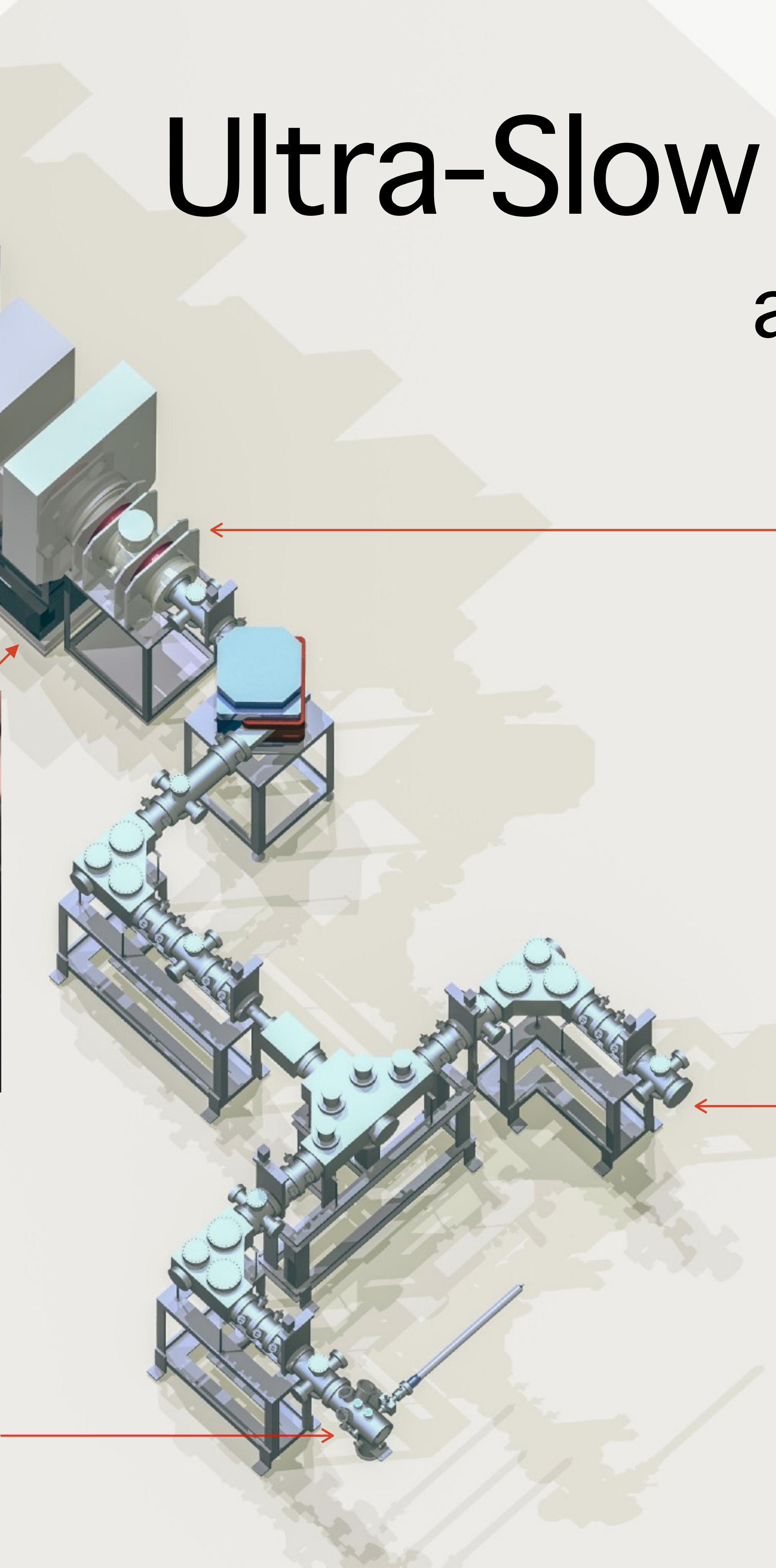
K. Nagamine et al., PRL 74, 4811 (1995).

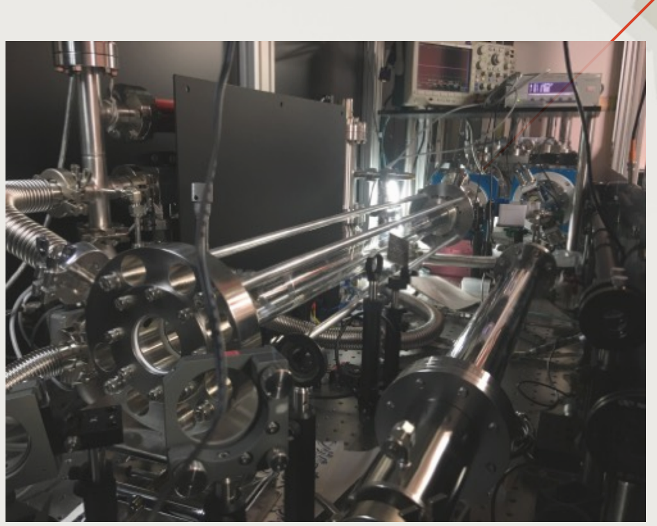
- Due to the short lifetime of muons, the slowing down and cooling methods for stable atoms are not applicable.
- USM and LEM are promising methods to obtain slow muons.
- At PSI, MuCool is under development (Angela's talk in this workshop).

Ultra-Slow Muon Facility

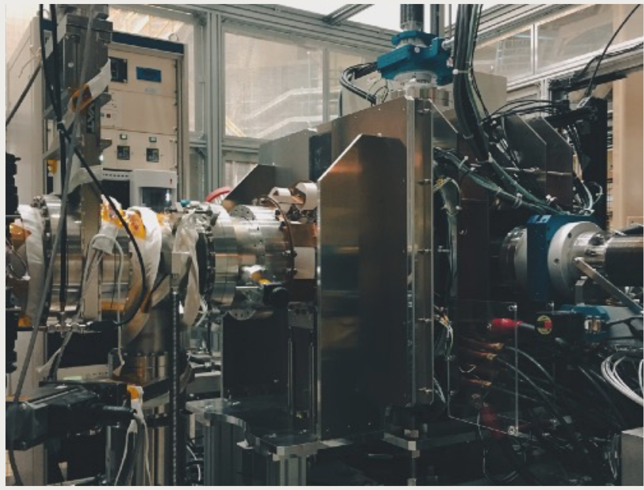
at J-PARC MLF MUSE

The Super-Omega
surface muon beamline

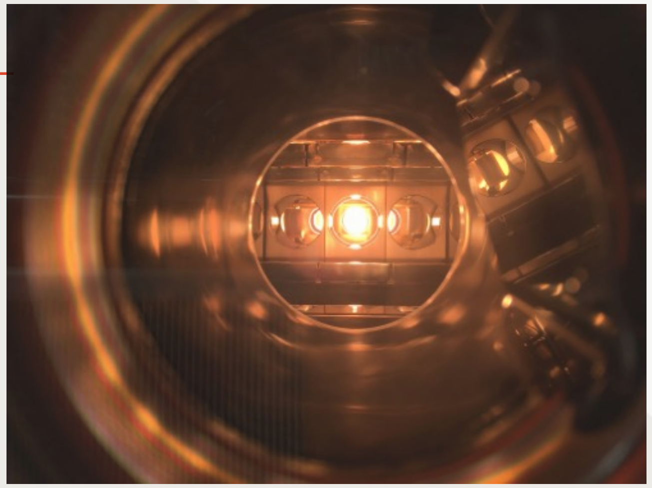




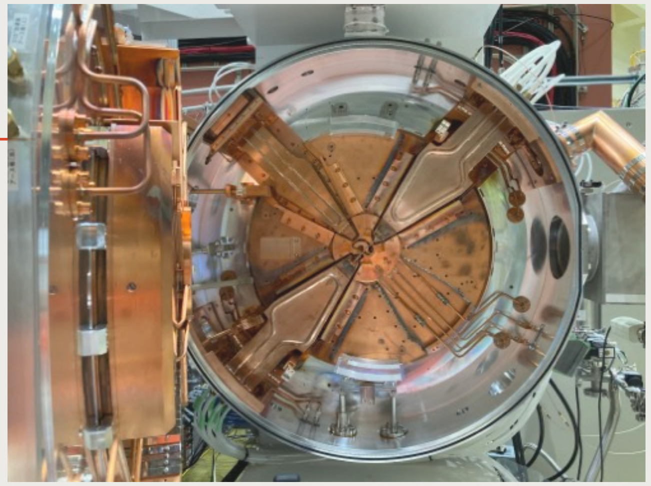
Ionization laser



Spectrometer at U1A



Muonium emitter



Cyclotron at U1B

Commissioning is in progress.
First materials science
application started 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

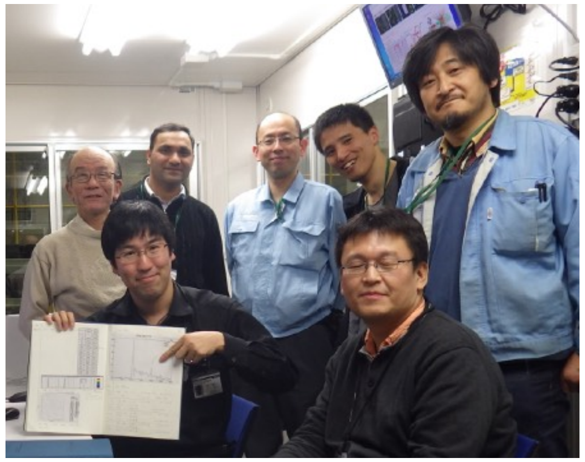
T. Adachi et al., KEK-MSL Progress Report. 2018-2 (2018) 13.

2020

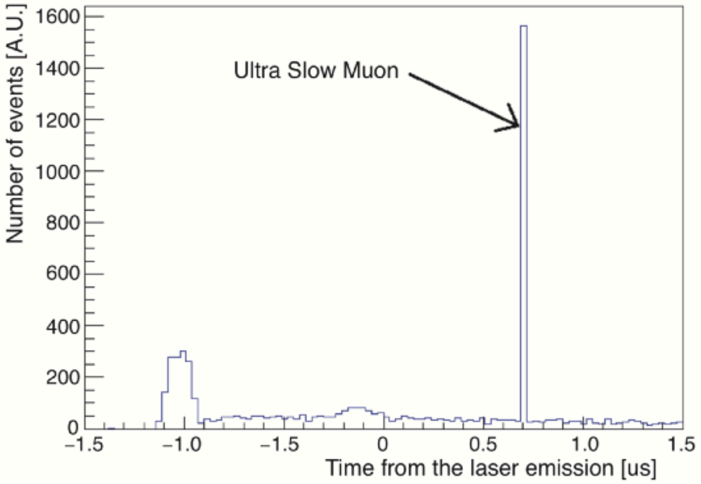
Multilayer USM-μSR

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

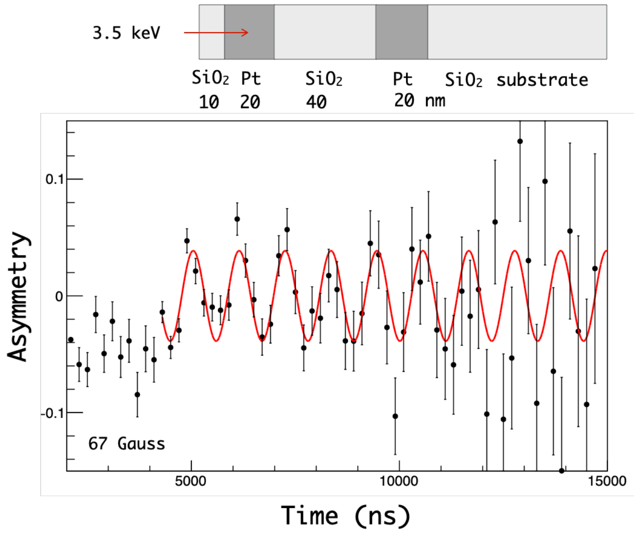
First Ly-α
2013



First USM
2016



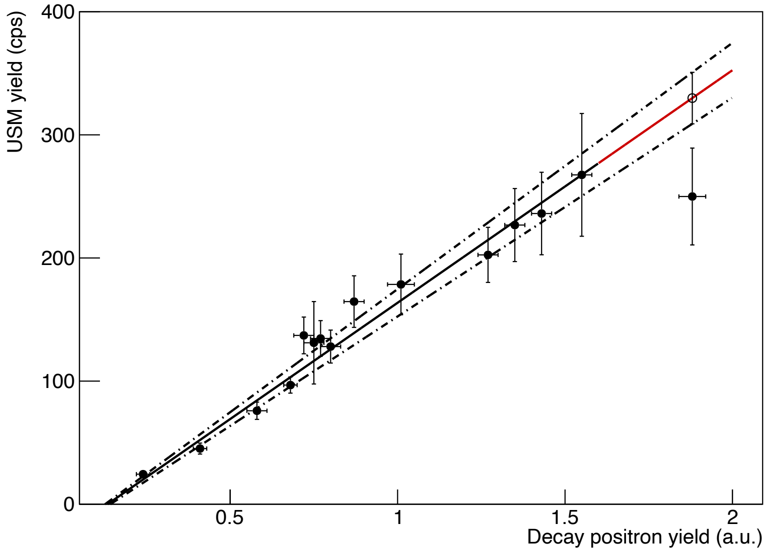
USM time-of-flight
2016



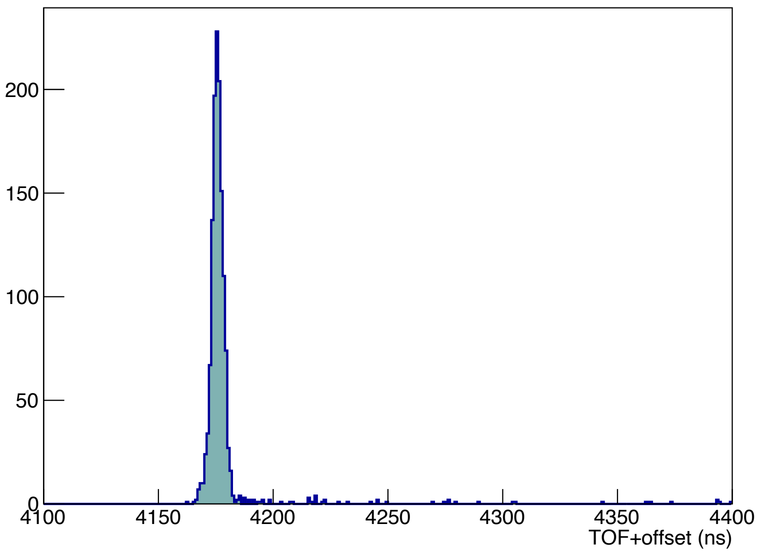
USM-μSR asymmetry
2020

Specifications of the Beam

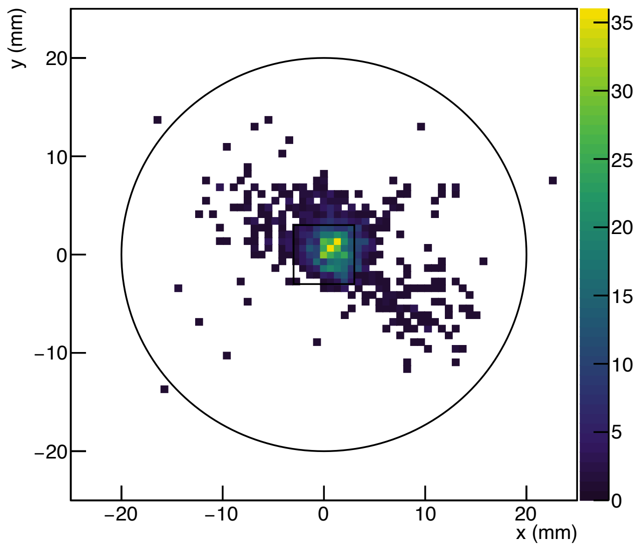
Flux, time and spacial profiles



Flux: 330 USM/s



Time width: σ_t=2 ns

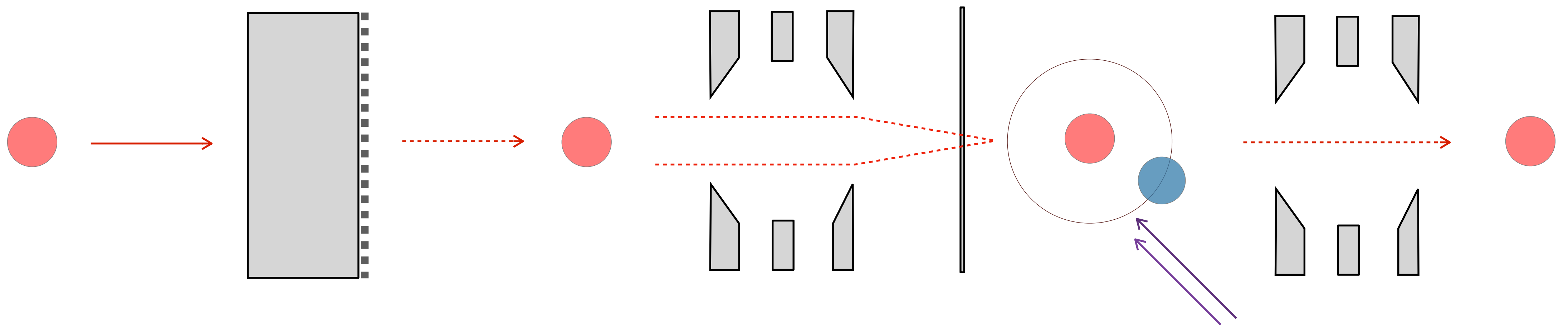


σ_x=2 mm, σ_y=2 mm

- The total flux of 330/s was achieved at the intermediate focus.
- 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.
- USM-μSR measurements became feasible and the first experiment has been started.

Multistage Muon Cooling

A proposal to combine LEM and USM



Solid rare-gas moderator
on nano-structured substrate

Electrostatic lens
1 kV

Muonium

Bright and cooled
muon beam

Surface muon
4 MeV

Epithermal muon
15 eV

Graphite foil

Laser ionization

$\varepsilon \sim 10^{-4}$

$\varepsilon \sim 0.8$

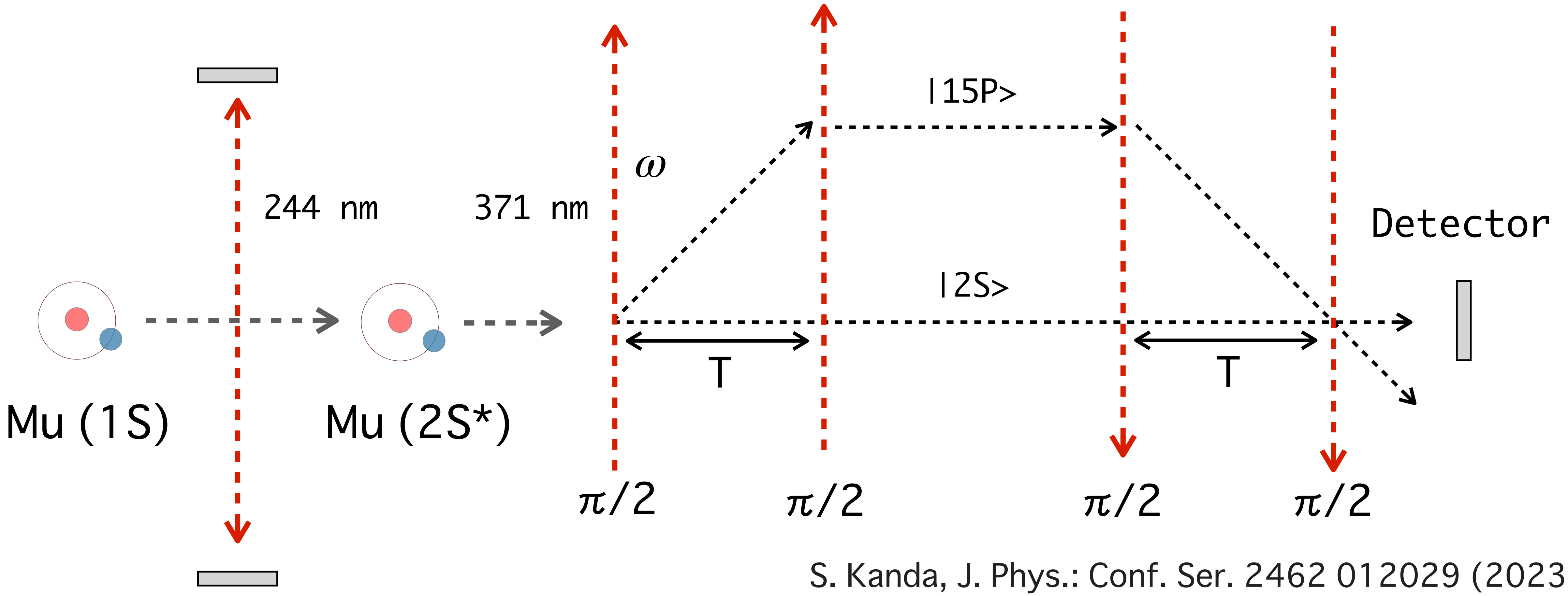
$\varepsilon \sim 0.2$

overall $\sim 2\mathrm{x}10^{-5}$

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

Ramsey-Bordé Interferometry

for a precise muon mass measurement



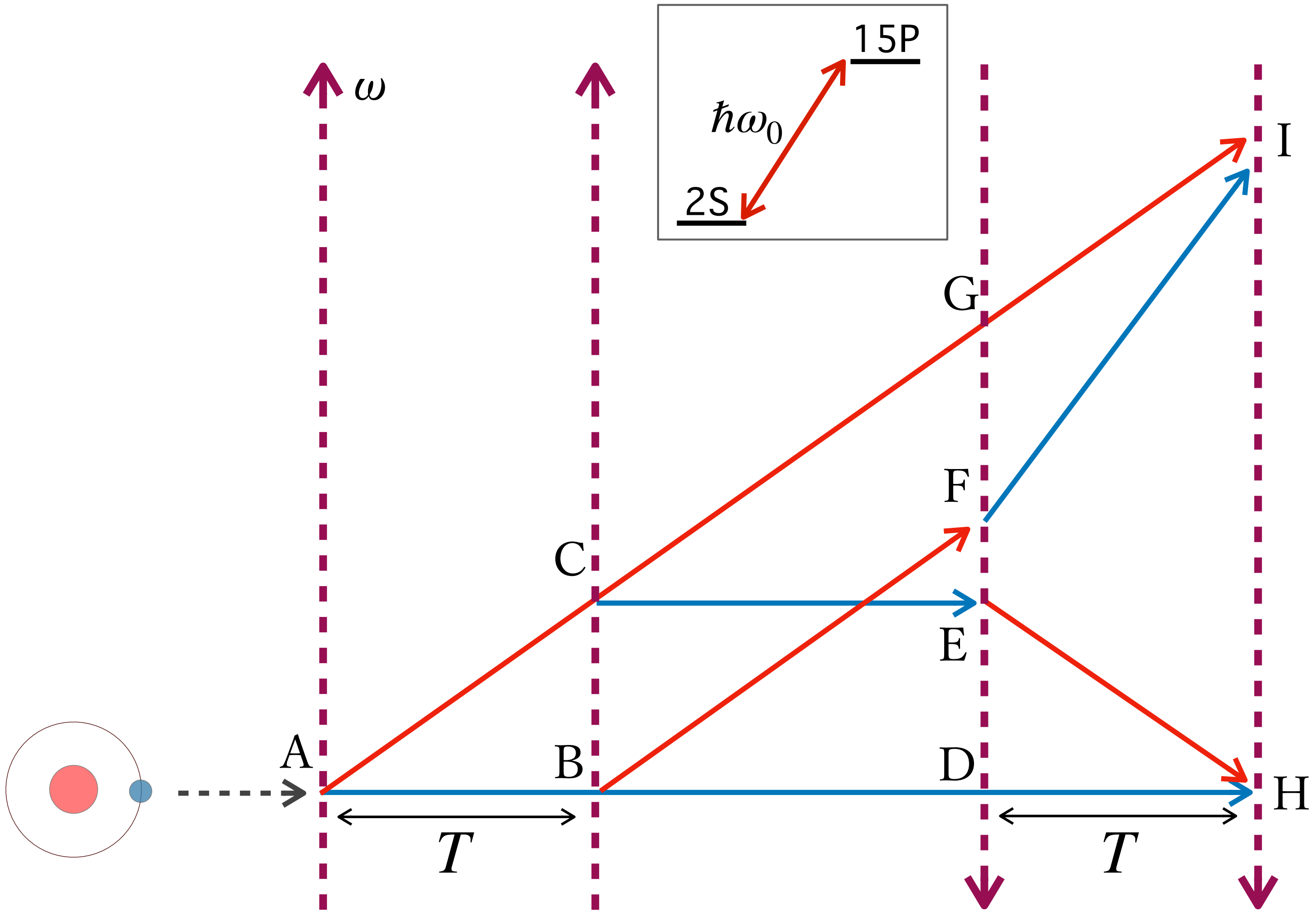
S. Kanda, J. Phys.: Conf. Ser. 2462 012029 (2023).

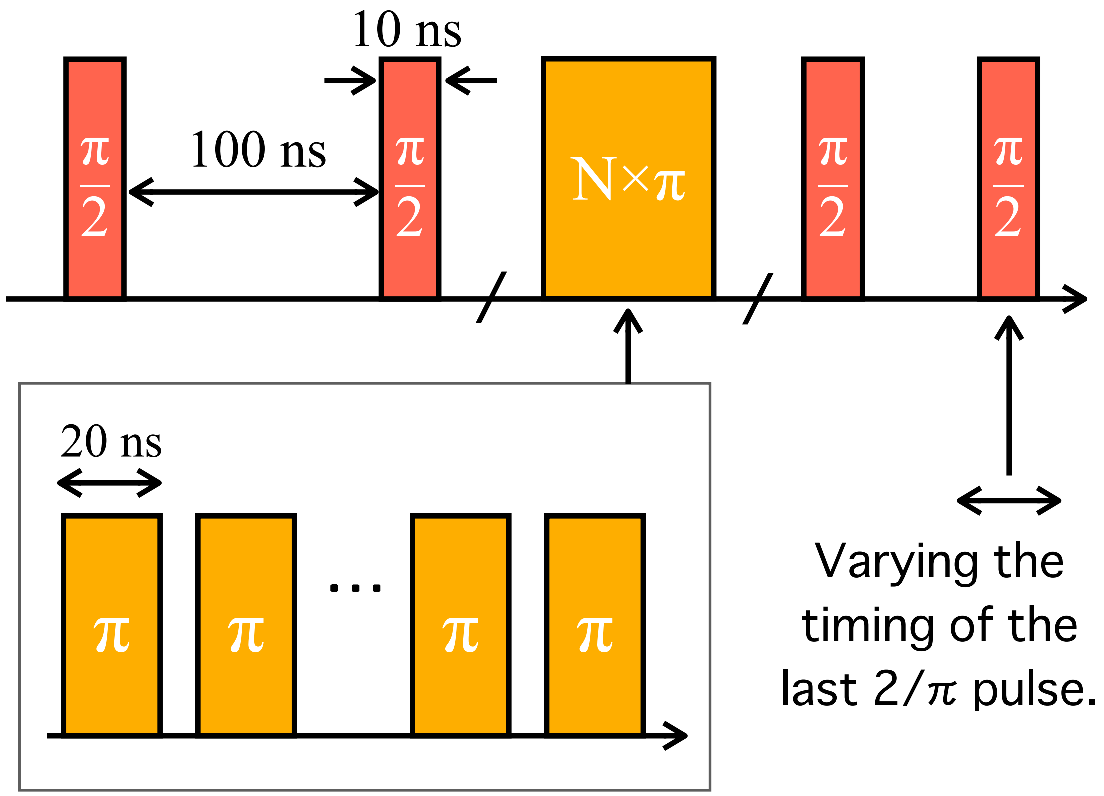
- ○ The ratio h/m can be determined by observing the interference fringe due to the photo-recoil shift in a Ramsey-Bordé interferometer.
- ○ No experiment has been performed for muonium. A hydrogen atom interferometer using a photon echo scheme has been reported.

Hydrogen experiment: T. Heupel et al., Europhys. Lett. 57, 158 (2002).

Ramsey-Bordé Interferometry

for a precise muon mass measurement



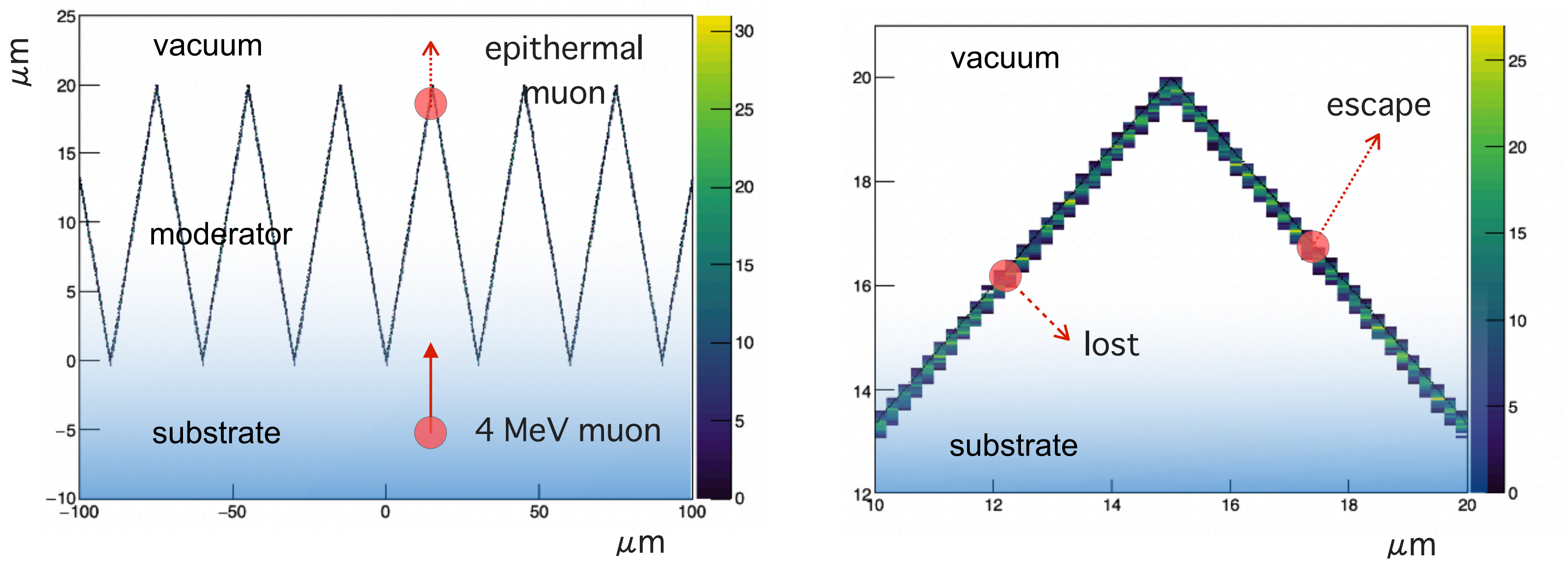


Varying the timing of the last $2/\pi$ pulse.

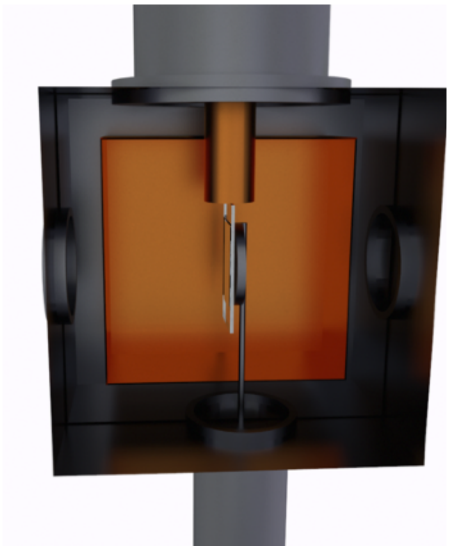
- The phase difference between ACEH and ABDH is $\delta\phi_1 = 2(\omega - \omega_0)T - \hbar k^2 T/2m$
- Similarly, for the paths ABFI and ACGI, it is $\delta\phi_2 = 2(\omega - \omega_0)T + \hbar k^2 T/2m$
- By taking the difference, $\delta\phi_2 - \delta\phi_1 = \hbar k^2 T/m$
- Goal : 1 ppb precision (10 π pulse).

R&D Progress

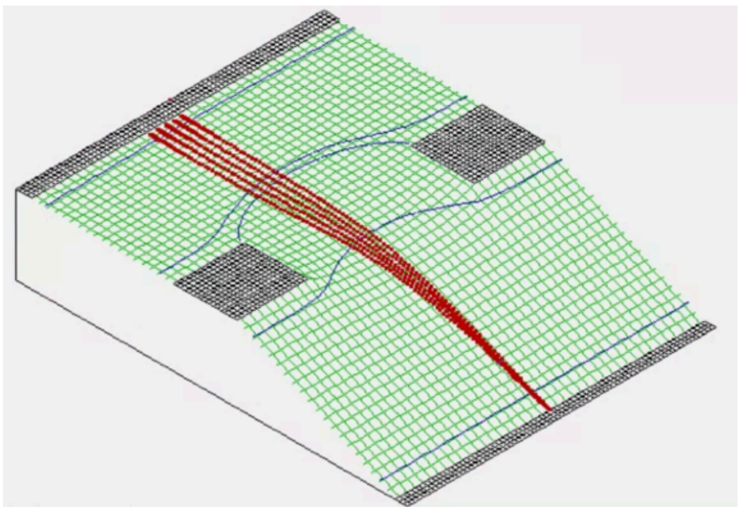
towards realizing muonium interferometry



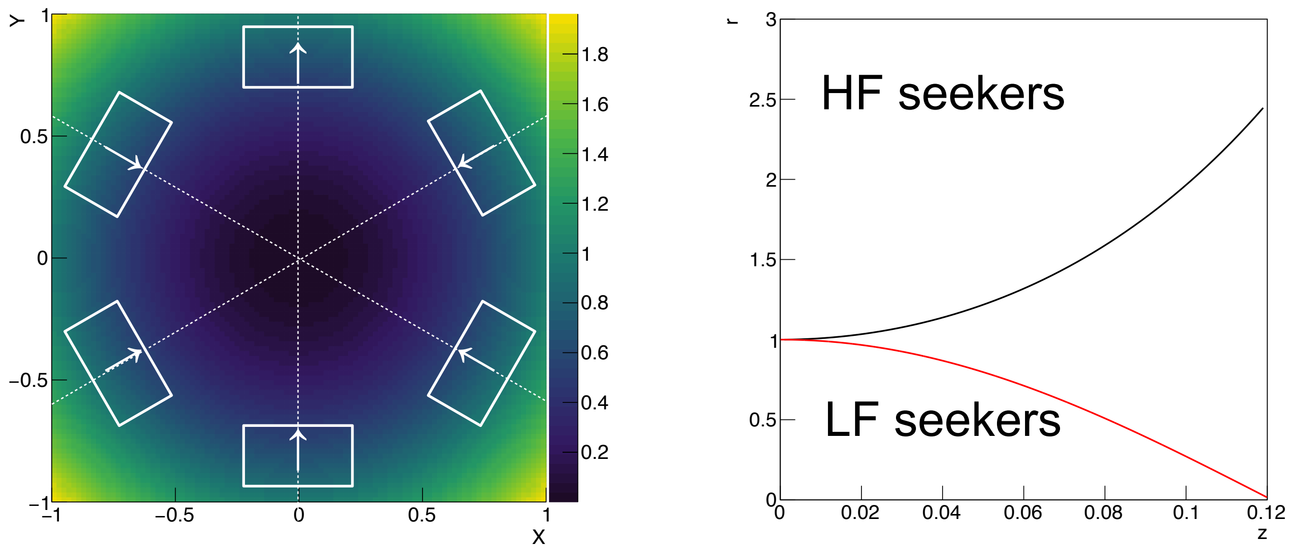
Simulation of epithermal muon emission from the moderator



Target chamber designing



Simulation of slow muon trajectories in the electrostatic lens using



Hexapole focusing of muonium

Summary

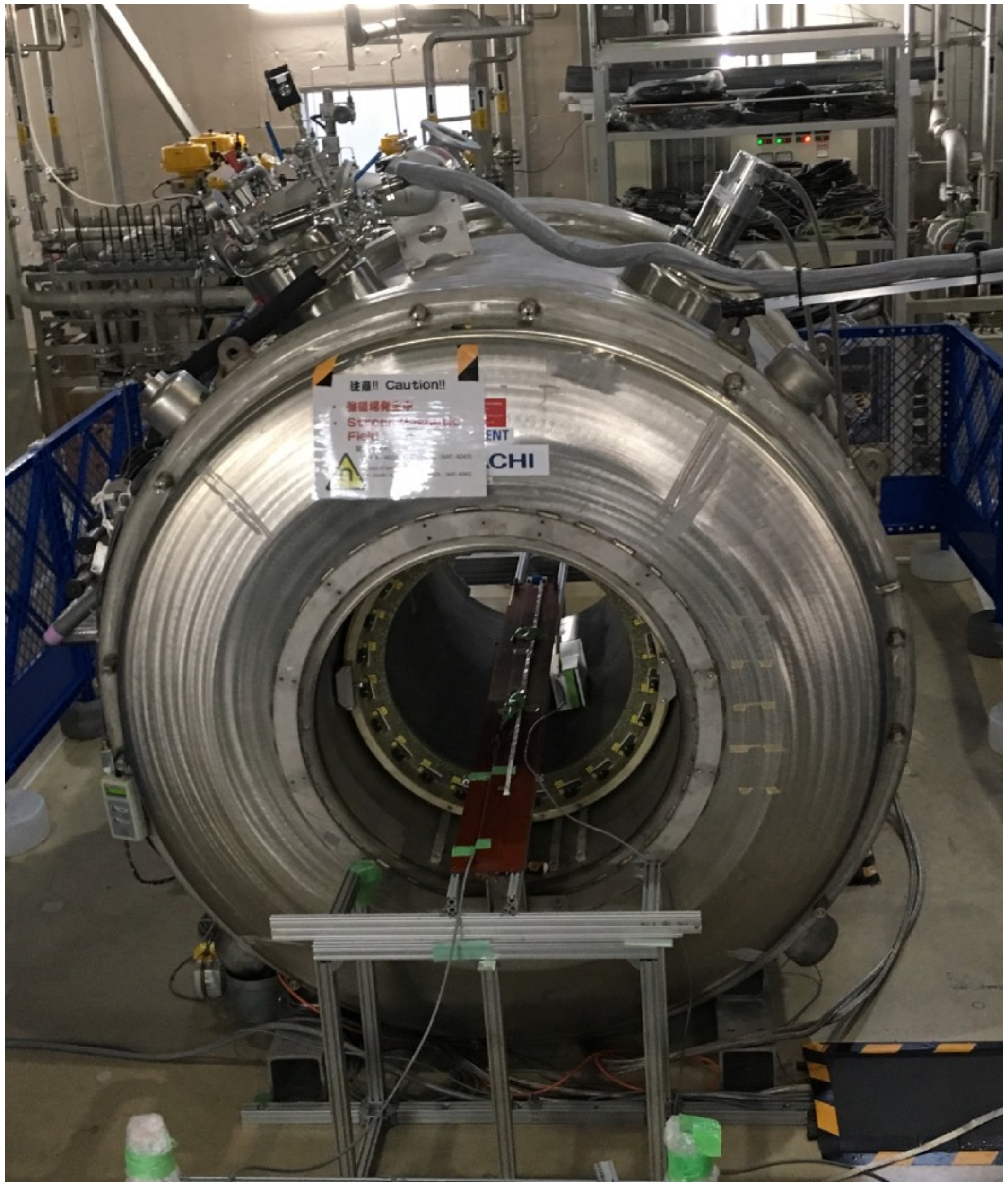
and prospects

- At J-PARC MUSE, the MuSEUM experiment is in progress for measuring the muonium HFS.
- Muon cooling and application of quantum techniques will bring a breakthrough.
- A new muon mass measurement using muonium interferometry was proposed and a proof-of-principle experiment is in preparation.

Backup Slides

Superconducting Magnet

A key element for the high-field experiment



Superconducting Magnet

- ○ A superconducting solenoid for a precise controlled magnetic field of 1.7 T.
  - ○ A second-hand MRI magnet with an axial length of 2 m and a bore diameter of 925 mm.
- ○ Requirements for the field are

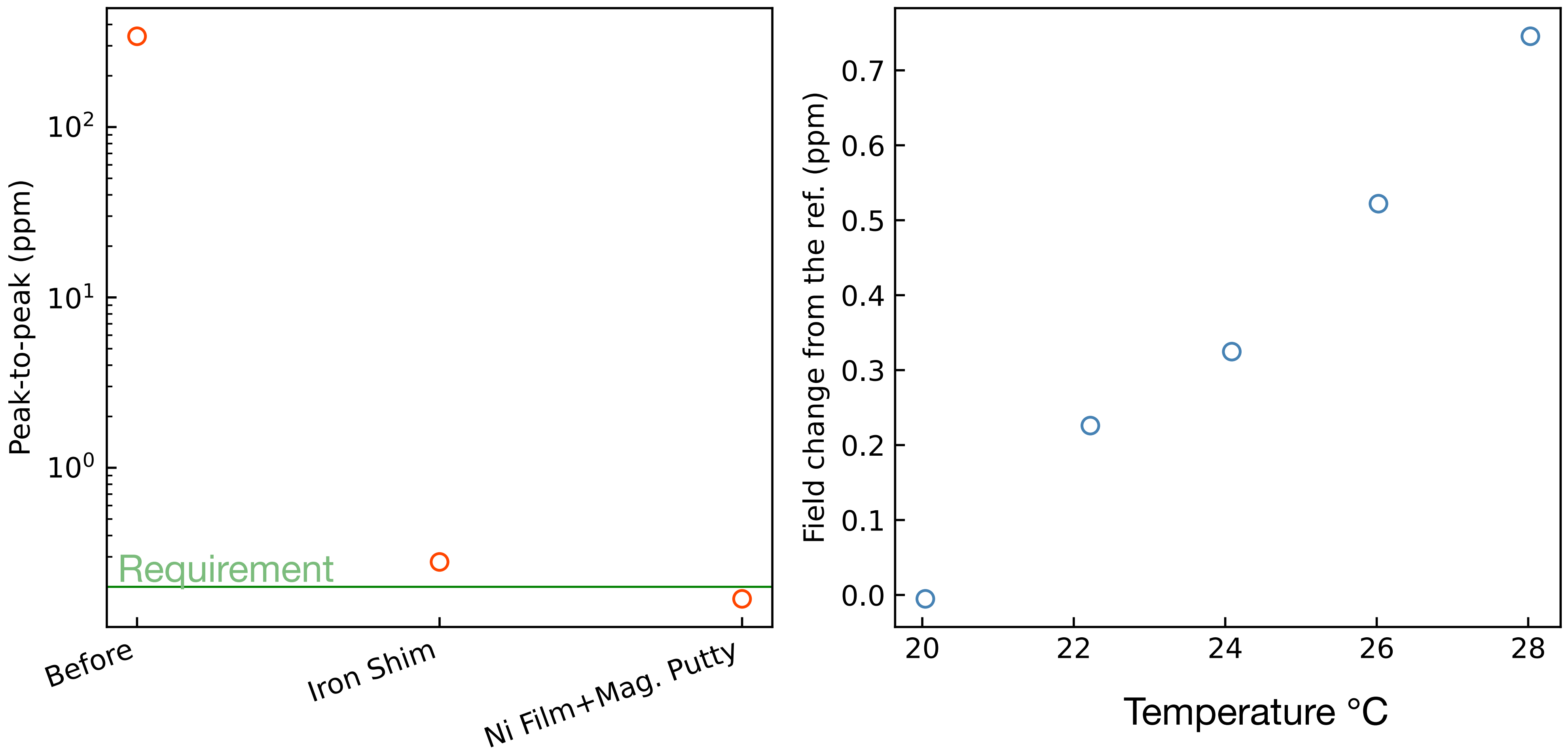
  →0.2 ppm (peak-to-peak) uniformity in a spheroidal volume with z=30 cm, r=10 cm.

  →±0.1 ppm stability during measurement.

K. Sasaki, M. Abe (KEK)

Passive Shimming

For highly uniform magnetic field



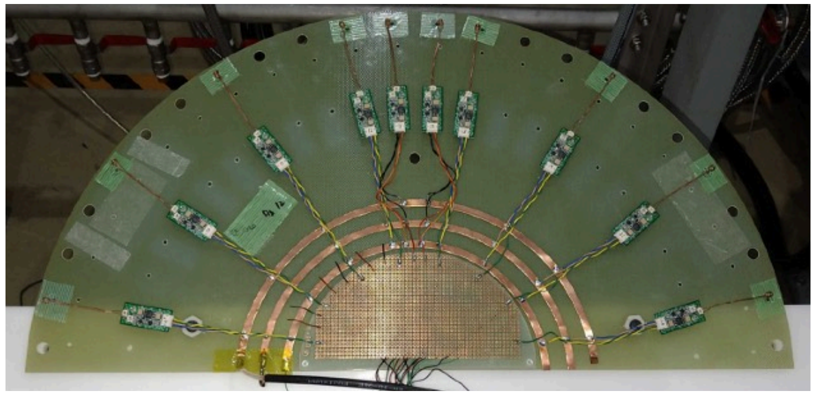
- ○ The requirement for the uniformity was achieved.
- ○ The temperature needs to be controlled with an accuracy of ±1 degree.
- ○ A precise air conditioner was prepared and to be tested.

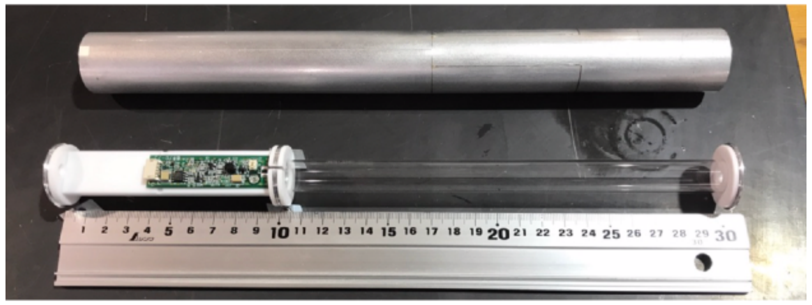
M. Sugita et al., Proc. Ann. Mtg Part. Accel. Soc. Jpn, 13 (2020).

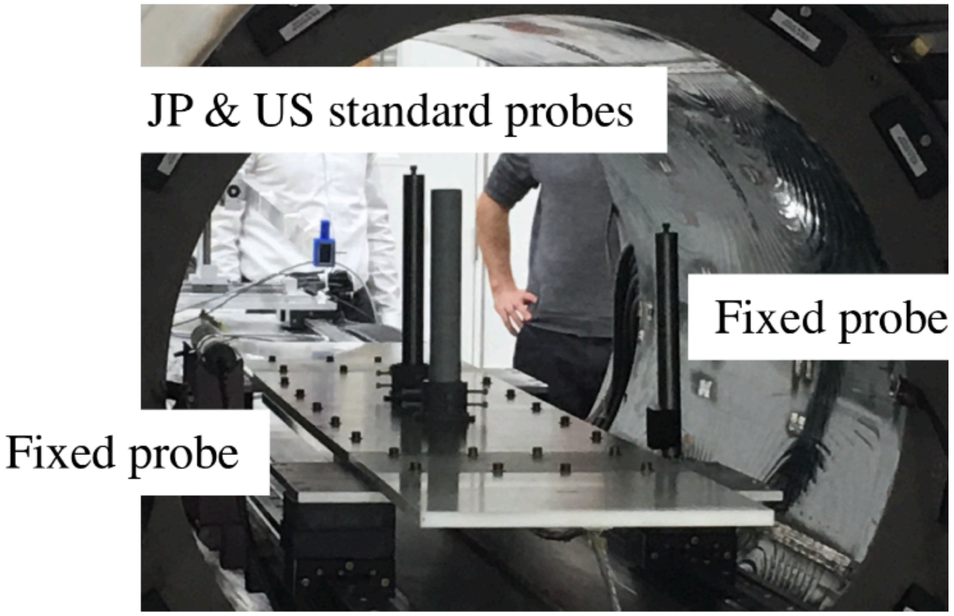
M. Sugita (JAEA),
C. Oogane, H. Iinuma (Ibaraki U.),
M. Abe, K. Sasaki (KEK)

NMR Probes

Three types of magnetometer





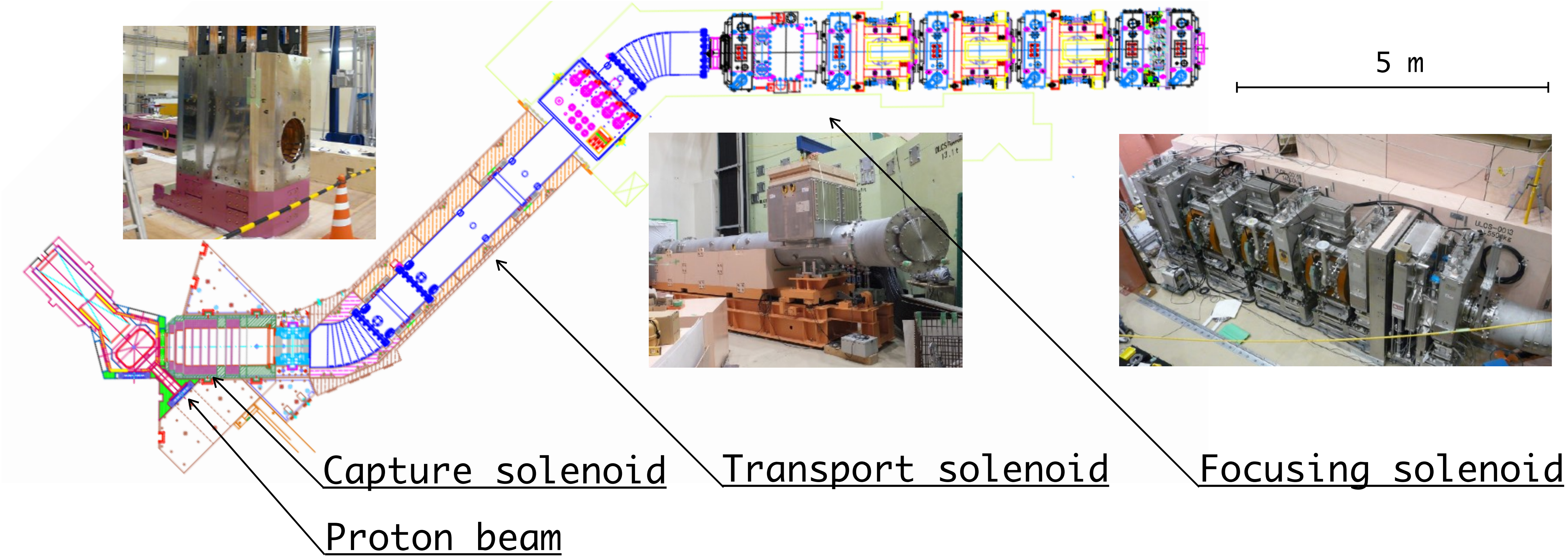


- ○ Field camera
  - ○ A 24-channel rotating NMR probe that maps magnetic fields in three dimensions.
  - ○ Studies are underway for simultaneous multi-channel readouts.
- ○ Fixed probe
  - ○ A compact probe to monitor magnetic field stability during experiment.
- ○ Standard probe
  - ○ A high-precision NMR probe to calibrate others.
  - ○ An accuracy of 15 ppb has been achieved.
  - ○ Cross-calibration is underway in a joint research project between Japan and the US.

K. Sasaki (KEK), H. Tada (Nagoya U.), S. Oyama, T. Tanaka (U. Tokyo),
H. Yamaguchi(JASRI), P. Winter (ANL), D. Kawall (U. Mass.), D. Flay (JLab)

Surface Muon Beam

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

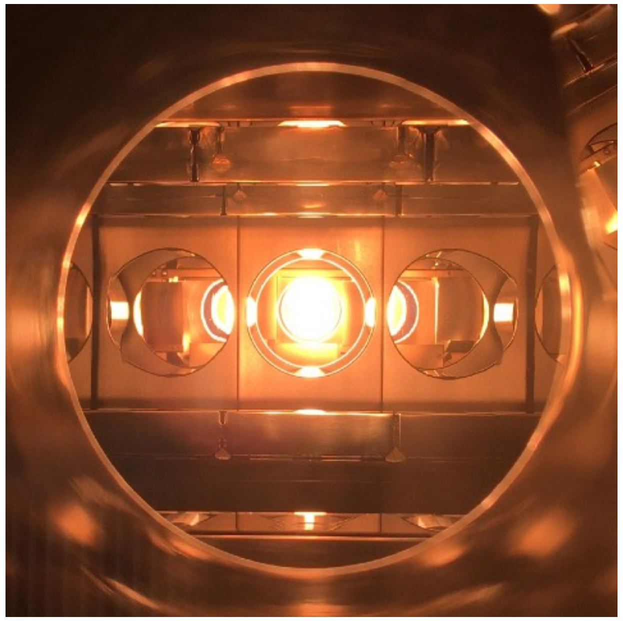


- Highest-flux beamline consisting of a large-acceptance capture solenoid [1], a curved solenoid for charge-selection [2], and axial-focusing solenoids with Wien filters [3].
- The total beam flux is at order of 10^8 μ^+/s.

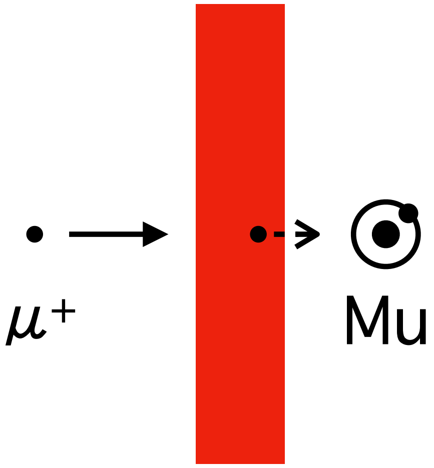
[1] K. Nakahara et al., “The super omega muon beamline at J-PARC”, NIM A 600 (2009) 132-134.
[2] P. Strasser et al., “Superconducting curved transport solenoid with dipole coils for charge selection of the muon beam”, NIM B 317 (2013) 361-364.
[3] Y. Ikedo et al., “Positron separators in Superomega muon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

Muonium Emitter

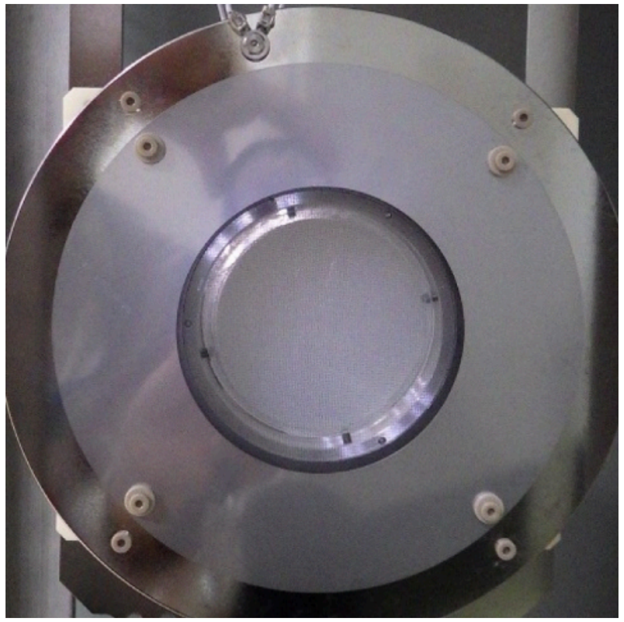
Muonium production target



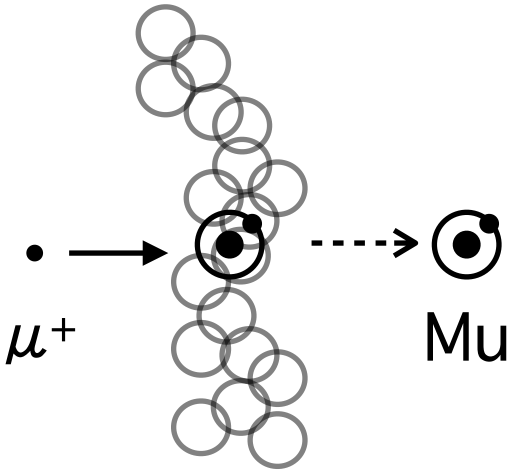
Tungsten



2000 K
22 mm/μs



Silica aerogel

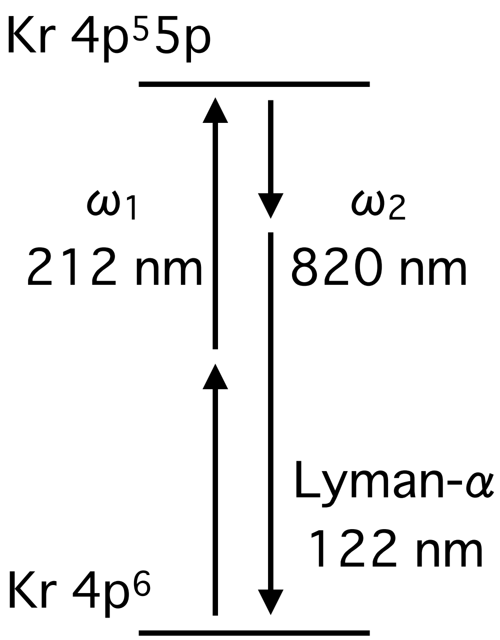


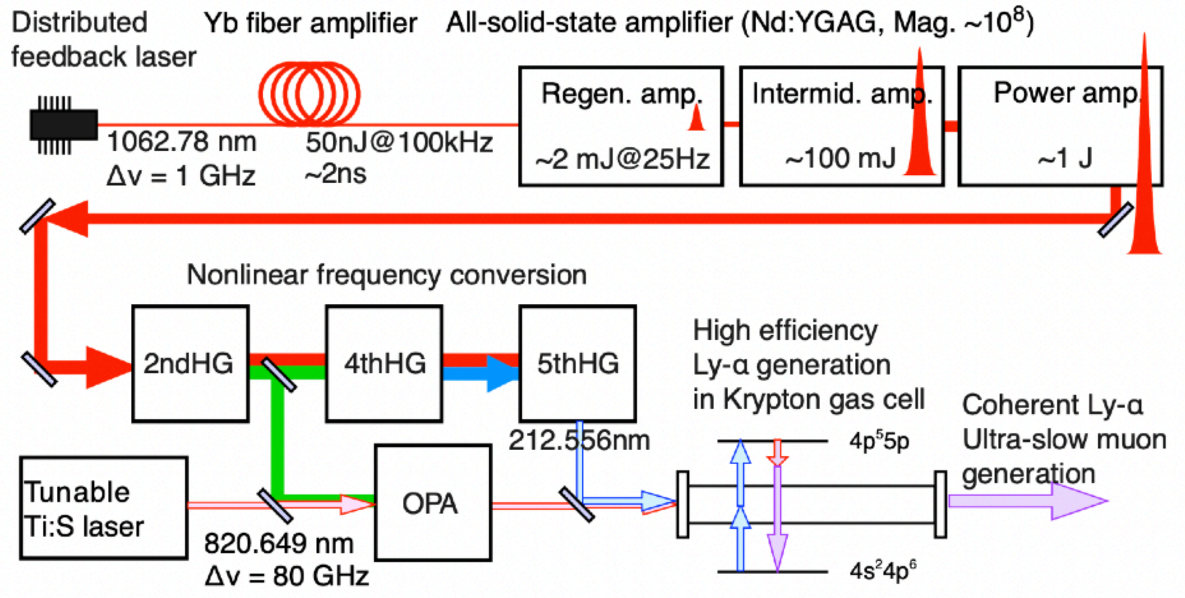
300 K
7 mm/μs

- 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



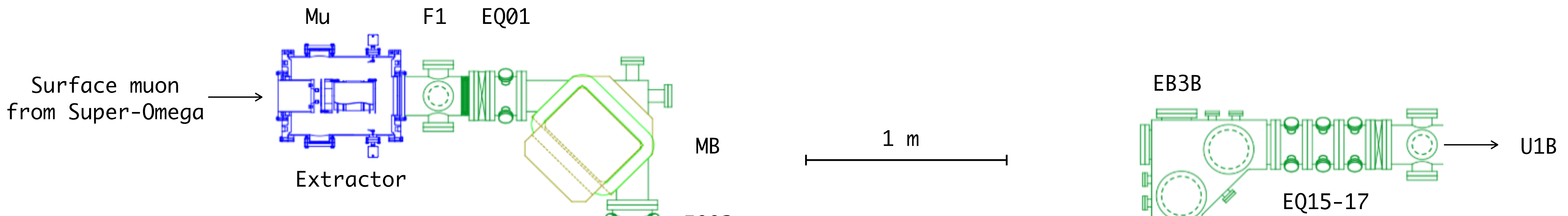


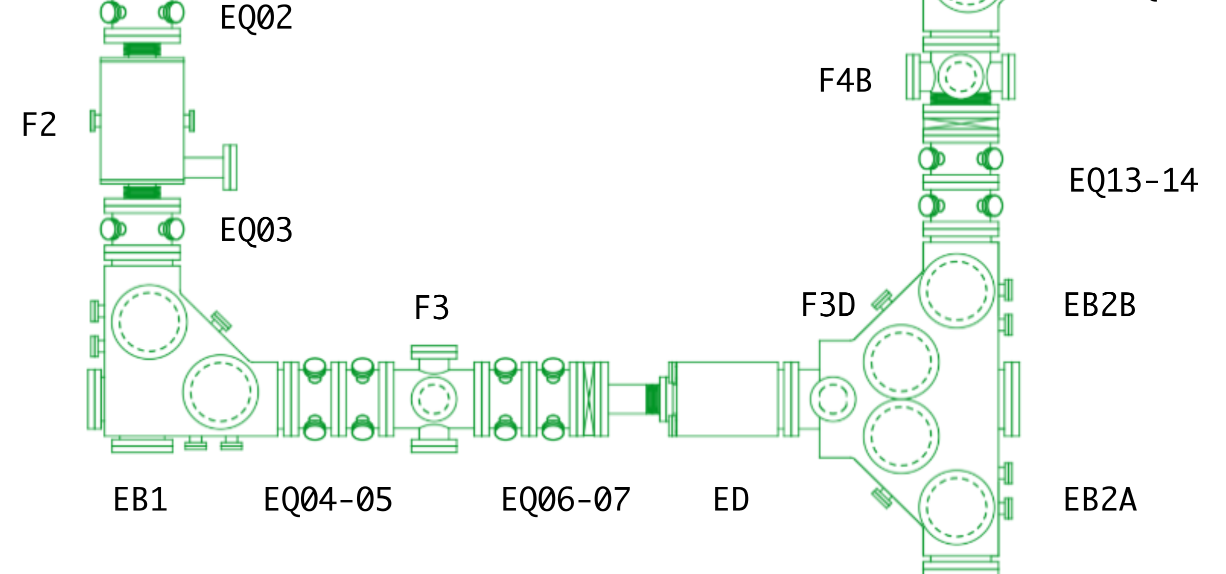
- For efficient muonium ionization, high pulse-energy of Lyman-α light is essential.
- Four-wave mixing in krypton gas generates an intense Lyman-α emission.
- All-solid-state laser system has been developed.

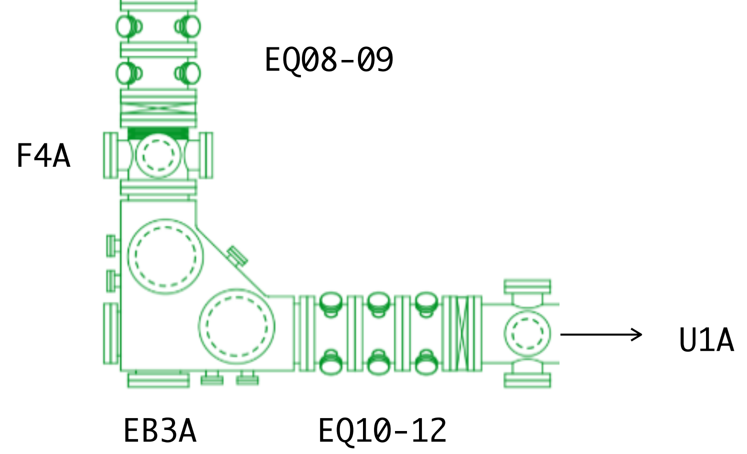
N. Saito et al., “High-efficiency generation of pulsed Lyman-α radiation by resonant laser wave mixing in low pressure Kr-Ar mixture”, Optics Express 24, 7566 (2016).
Y. Oishi et al., “All-solid-state laser amplifiers for intense Lyman-α generation”, J. Phys.: Conf. Ser. 2462 012026 (2023).

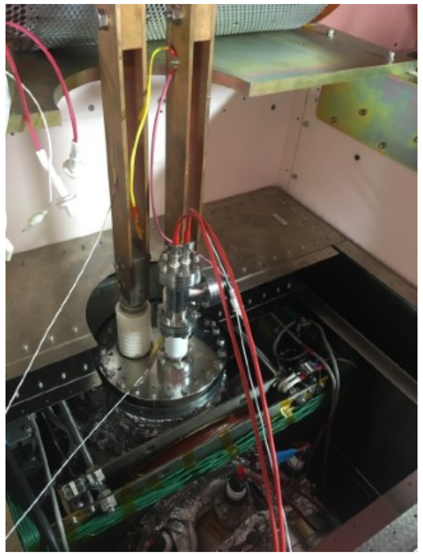
Transport Optics

Slow-muon optics toward μSR spectrometer



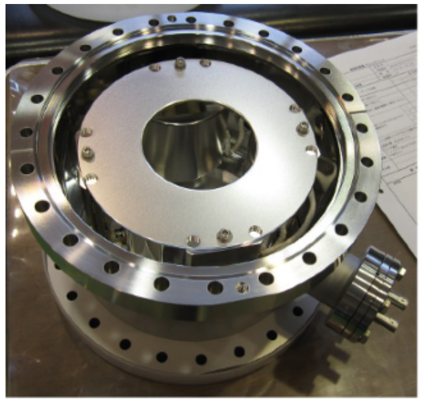




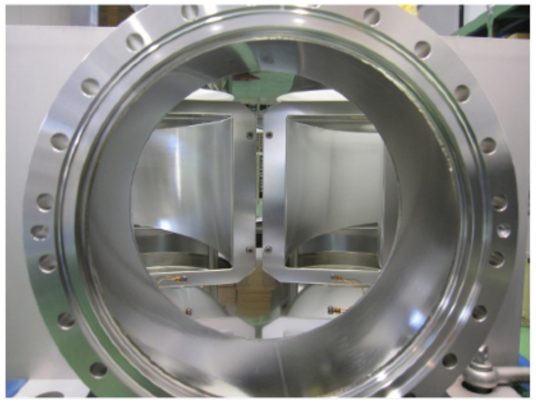


Mu Target

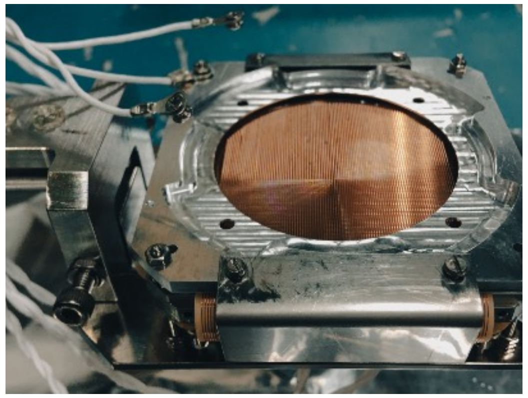
Transport Optics



EQ



ED+EB



MCP-DLD Beam Monitor