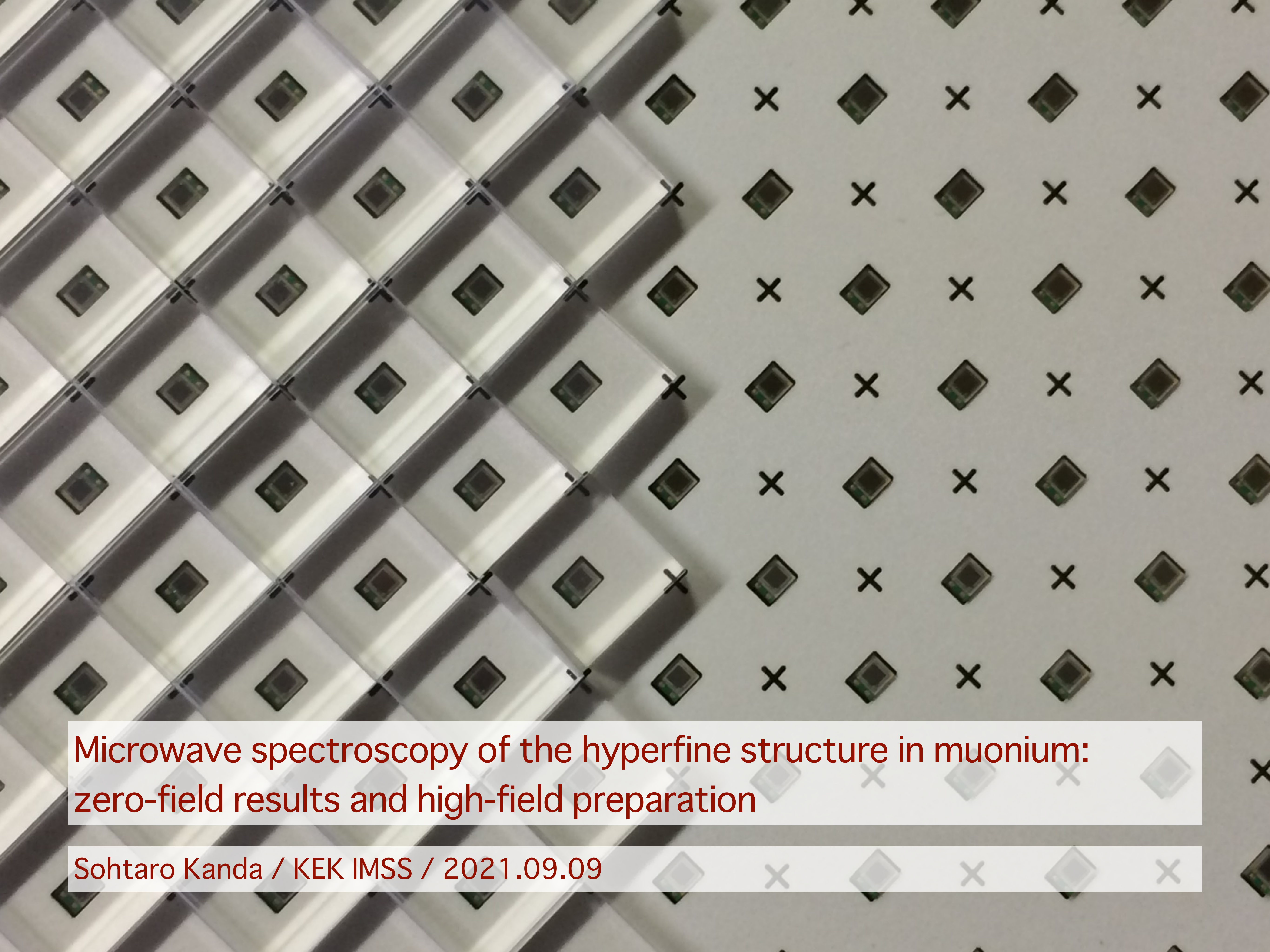


Microwave spectroscopy of the hyperfine structure in muonium: zero-field results and high-field preparation

Sohtaro Kanda / KEK IMSS / 2021.09.09

Muonium HFS

Most stringent test of bound-state QED

- Theoretical prediction $\Delta_{\mathrm{HFS}} = 4.463\ 302\ 872(511)(70)(2)$ GHz [1]

  m_μ/m_e th. α

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

237 Hz 65 Hz

- Experimental result $\Delta_{\mathrm{HFS}} = 4.463\ 302\ 776(51)$ GHz (11 ppb) [2]

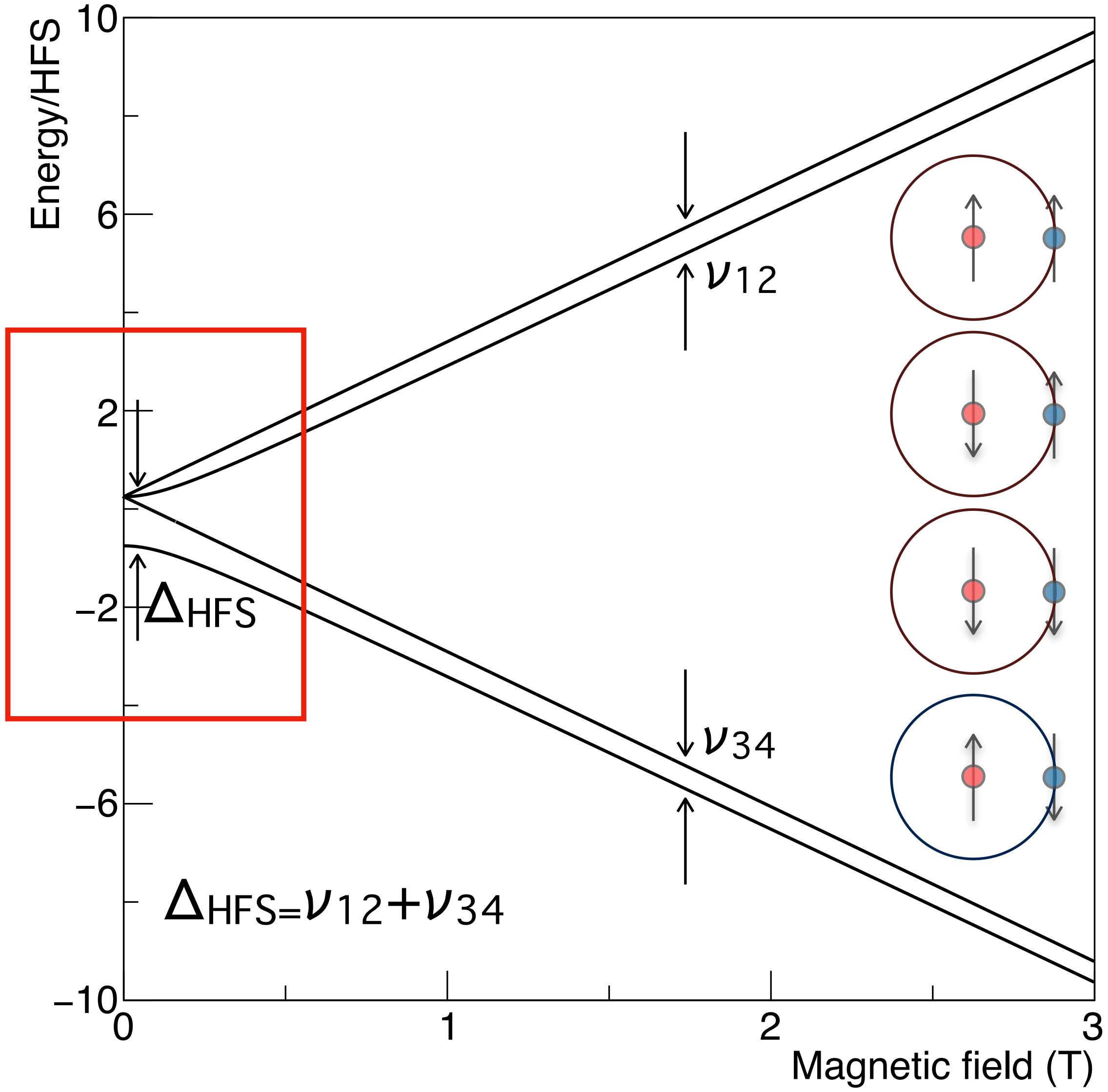
$$m_\mu/m_e = 206.768277(24) \quad (116\ \mathrm{ppb})$$

- The precision of theoretical calculation is limited by the measurement of muon mass, which can be independently obtained with the spectroscopy of muonium 1S-2S.
- We have stimulated updates on theoretical predictions [1,3] and phenomenological studies. Our goal is to improve the precision by a factor of 10.

Latest theory papers :	[1] M.I. Eides, Phys. Lett. B 795, 113(2019). [3] S. G. Karshenboim and E. Y. Korzinin, Phys. Rev. A 103, 022805 (2021).
World record experiment :	[2] W. Liu et al., Phys. Rev. Lett. 82 711 (1999).

High- and Zero-field Experiments

Two ways to measure the muonium HFS

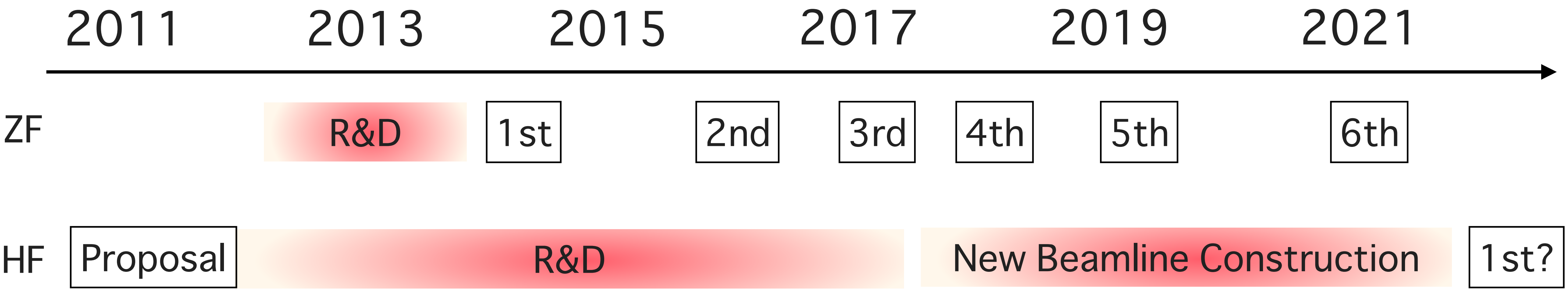


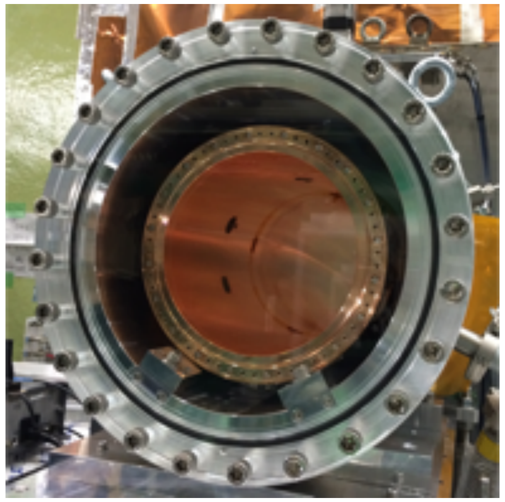
Energy levels of muonium in a magnetic field.

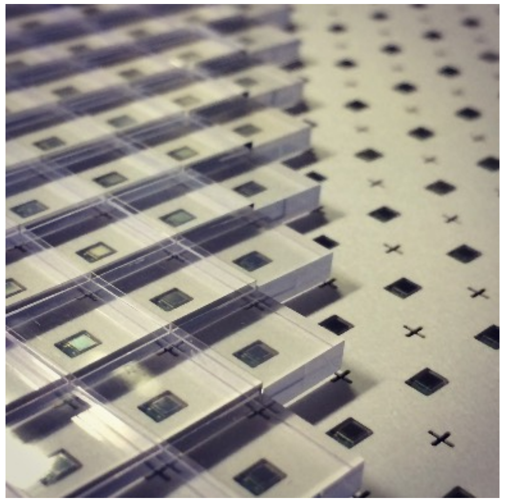
- Direct measurement at a near-zero magnetic field (ZF).
  - Simple and can be realized quickly as a phase-1 experiment. Muonium polarization becomes half.
- Zeeman-sublevels measurement in a high magnetic field (HF).
  - Careful treatment of magnetic field is necessary. High polarization, field focusing.
  - Determination of the magnetic moment ratio μ_μ/μ_p.

Project Timeline of MuSEUM

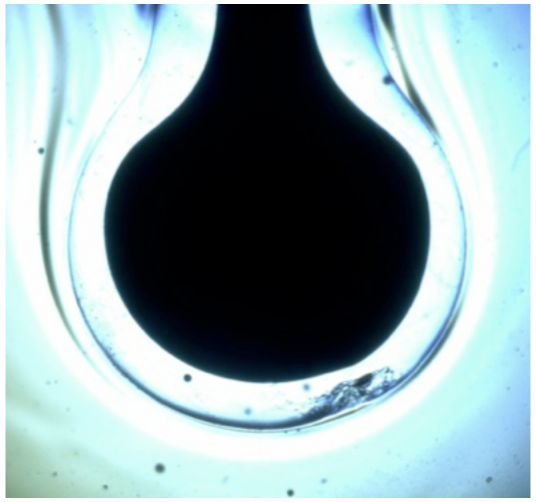
Since the experiment was proposed

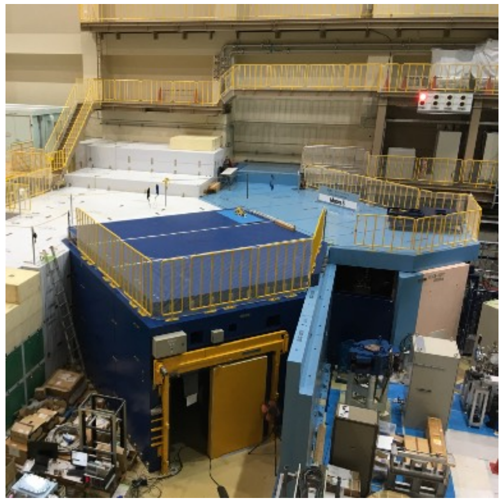



RF Cavity


Detector


Magnet

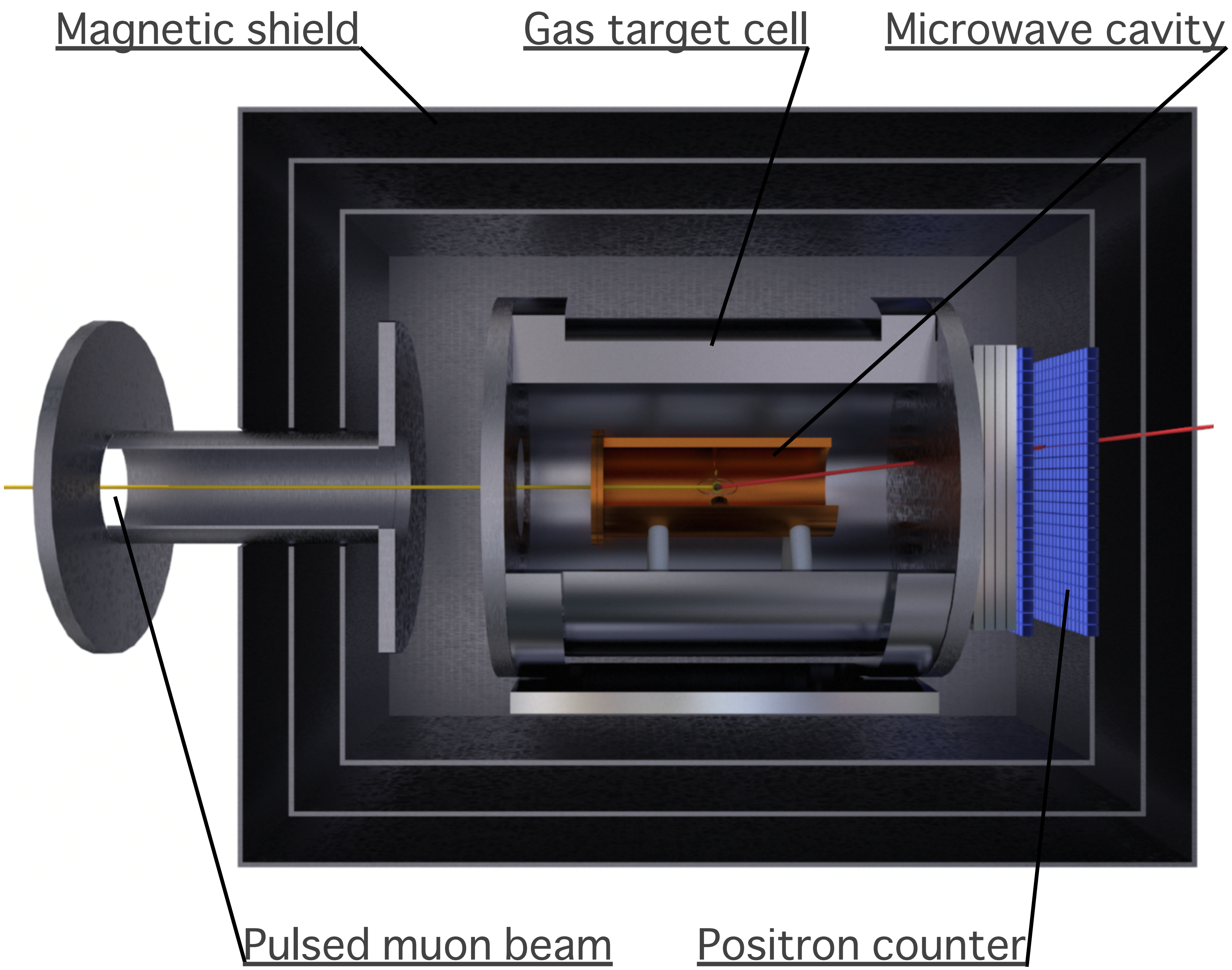

Field probe

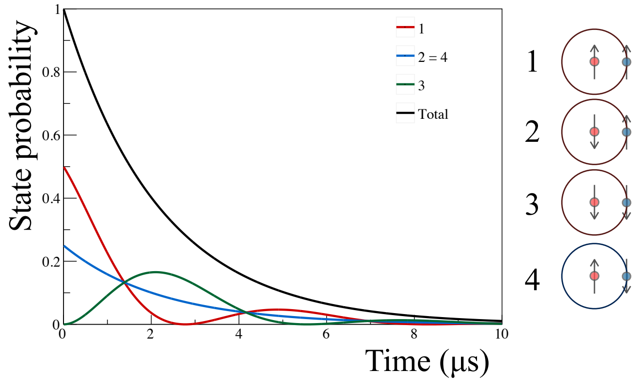

New beamline

- The final ZF experiment was conducted in May 2021.
- We are preparing for the first HF experiment.

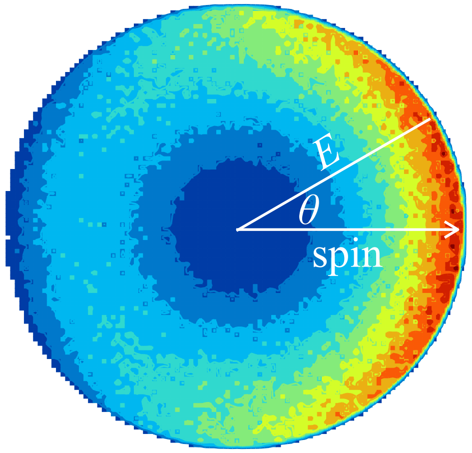
Outline of the Experiment

Experimental setup for a zero-field measurement

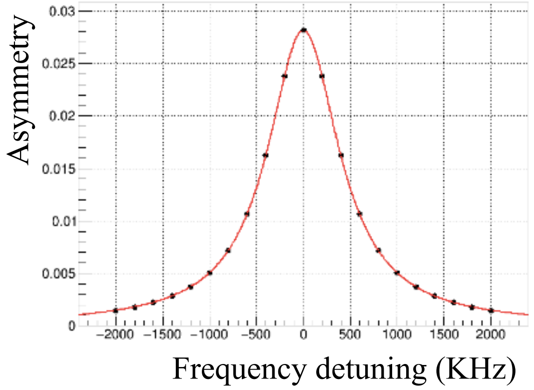




State transition



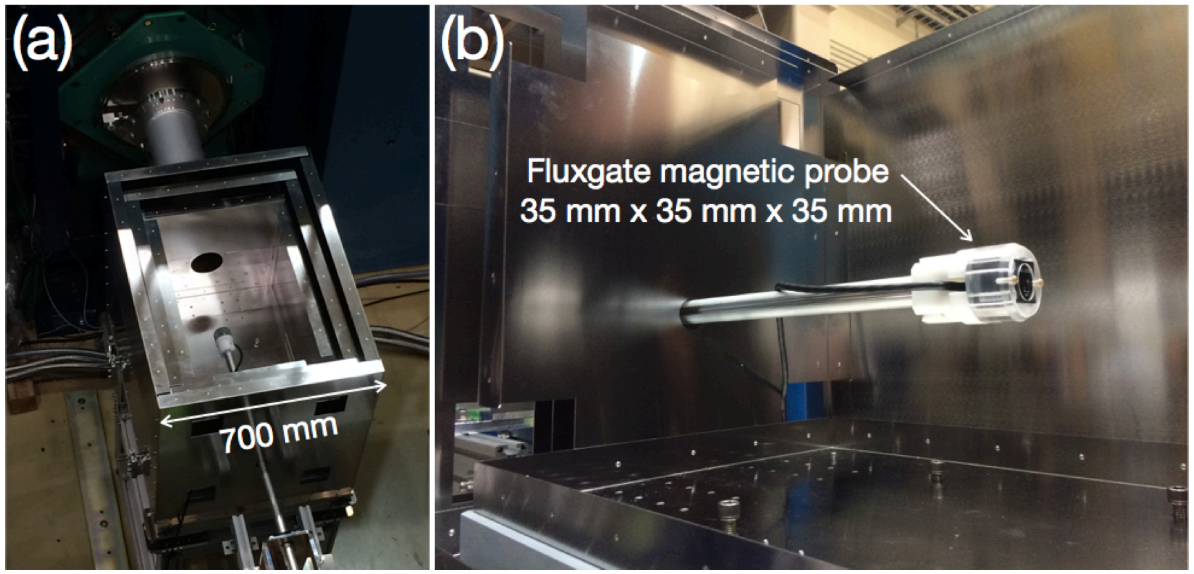
Muon decay asymmetry



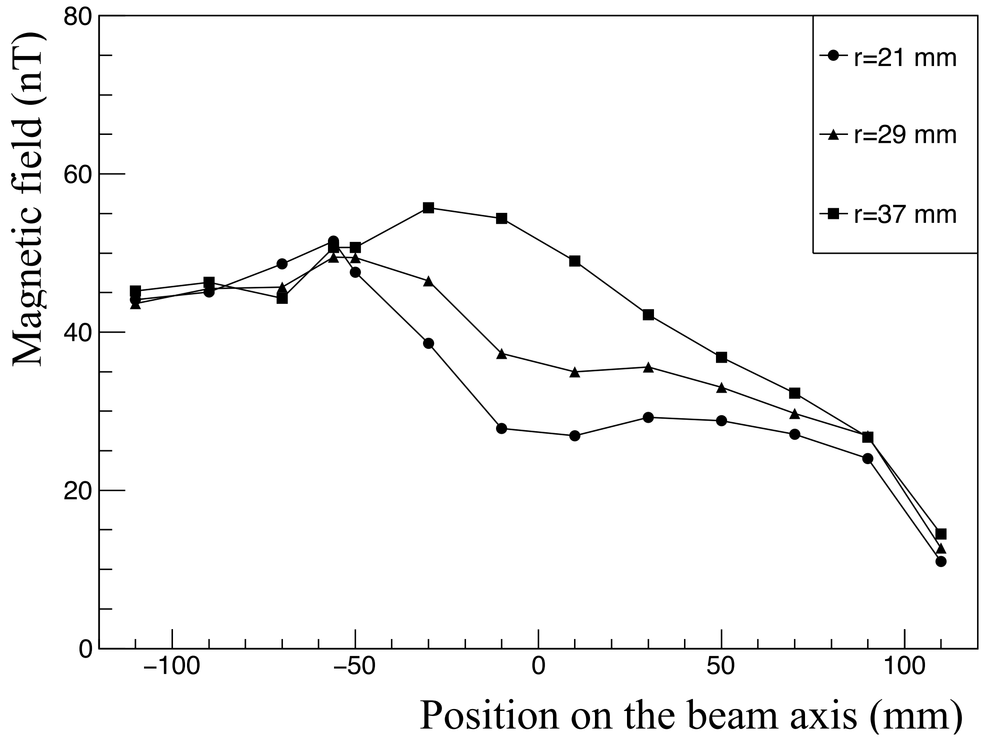
Resonance curve

Magnetic Shield

For suppression of the stray field and geomagnetism



(c)



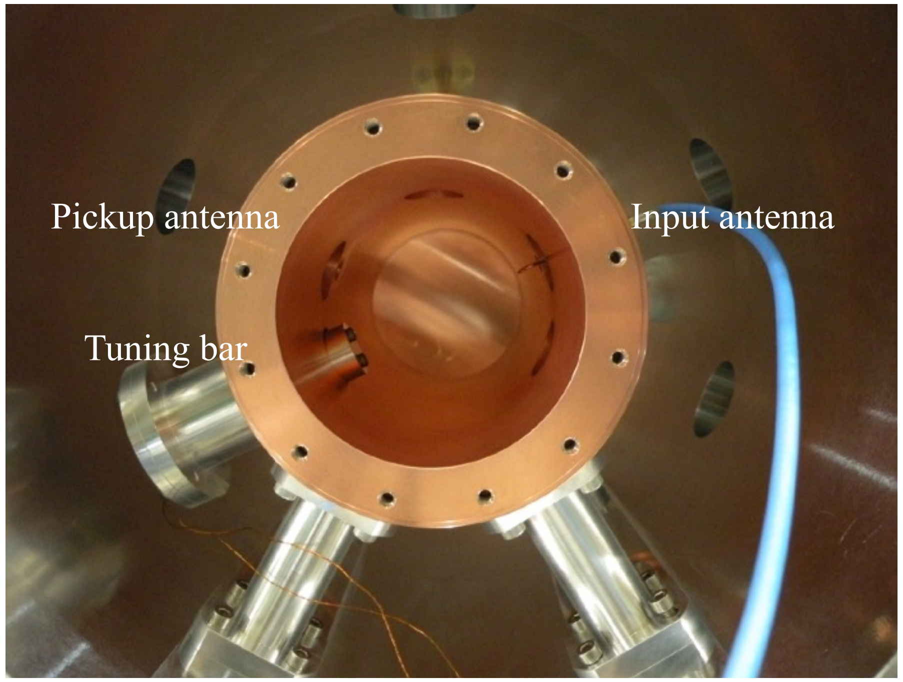
- A precise controlled near-zero field was achieved by three-layers of permalloy shield.
- (a, b) Magnetic shield and fluxgate probe for field measurement [1].
- (c) Magnetic field inside the shield [2].
- The stray field was reduced by a factor of 1700 (from 100 μT to 60 nT).

[1] S. Kanda, RIKEN Accelerator Progress Report Vol. 49 (2017) 227. [2] publication is in preparation.

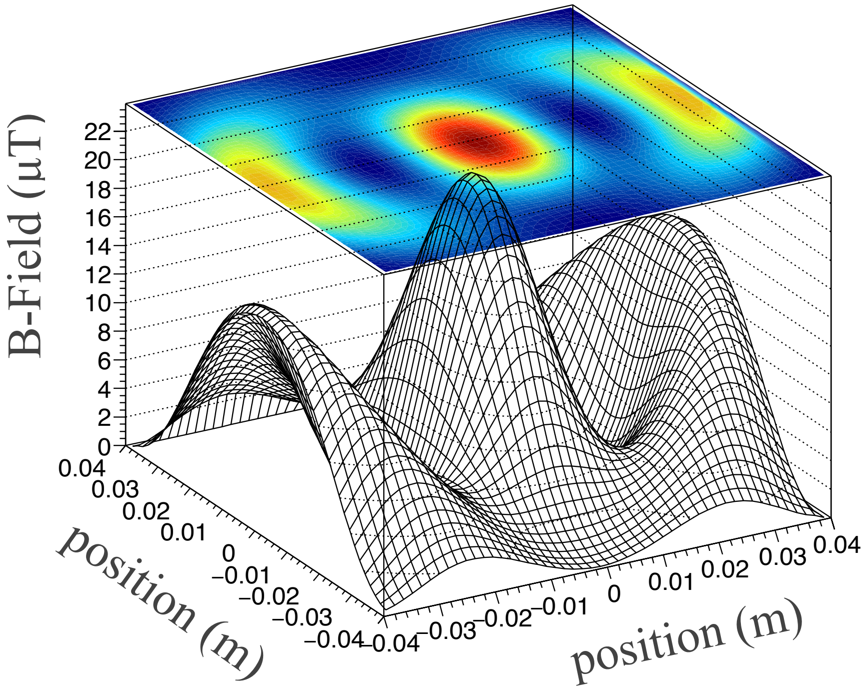
Microwave Cavity

For zero-field experiments

(a)



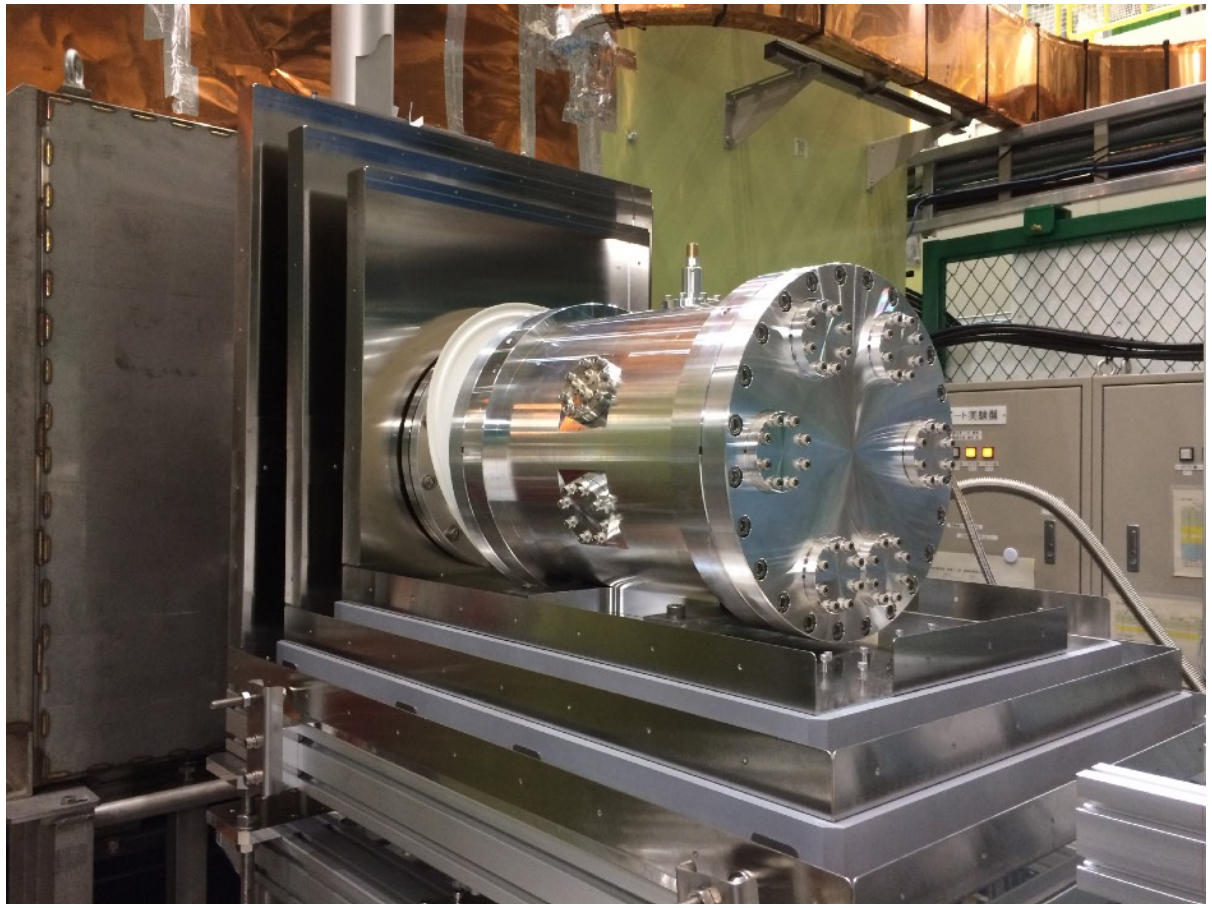
(b)



- ○ A cylindrical cavity made of copper with an inner diameter of 81.8 mm.
- ○ An inner axial length of the cavity was 230 mm so that muons could be sufficiently stopped in the gas target.
- ○ The microwave resonated in TM_{110} mode with a quality factor of 5000 at 4463.302 MHz.
- ○ (a) Photo of the cavity viewed from downstream.
- ○ (b) Calculated microwave field map.

Gas Target

Low-density gas for muonium production

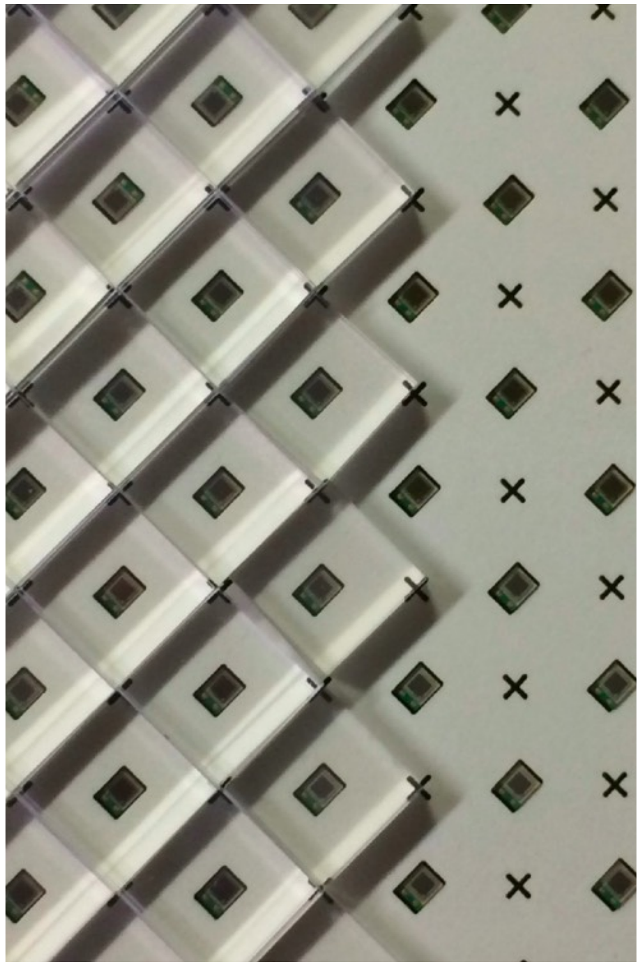


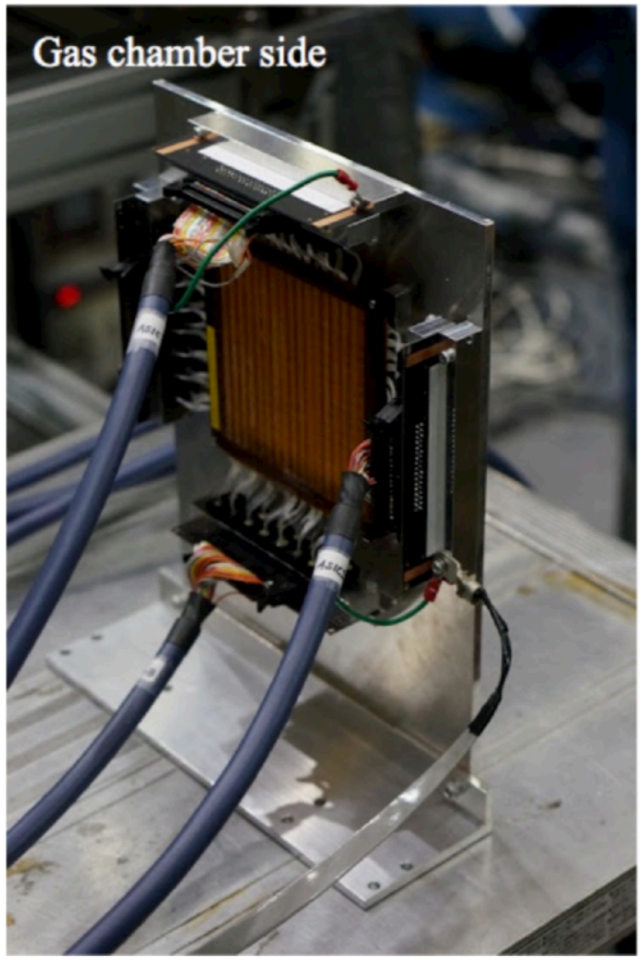
- S. Seo, H. Yamauchi (U. Tokyo), Y. Ueno (RIKEN), K.S. Tanaka (Tohoku U.), N. Kurosawa, P. Strasser (KEK).
- K. S. Tanaka, “Measurement of muonium hyperfine structure at J-PARC”, Ph.D Thesis, U. Tokyo (2016).

- ○ Krypton is an ideal target in terms of ionization energies.
- ○ A cylindrical aluminum vessel with almost no magnetism.
- ○ Efficient muon stopping with a low-density of 0.3 atm.
- ○ Semi-online measurement of impurity using a Q-Mass.
- ○ Precise gas density monitoring with 0.02% accuracy.
- ○ Modification for higher pressure (up to 4 atm) was done.

Particle Detectors

Positron counter and muon beam profile monitors



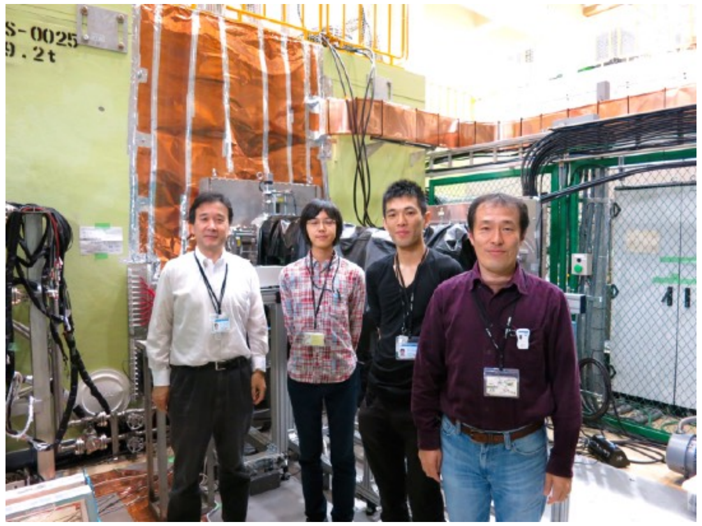


- S. Kanda, et al., PoS(PhotoDet16)039 (2016).
- S. Kanda, RIKEN APR 48, 278 (2016).
- S. Kanda et al., KEK-MSL Prog. Rep., 2014A0201(2014).

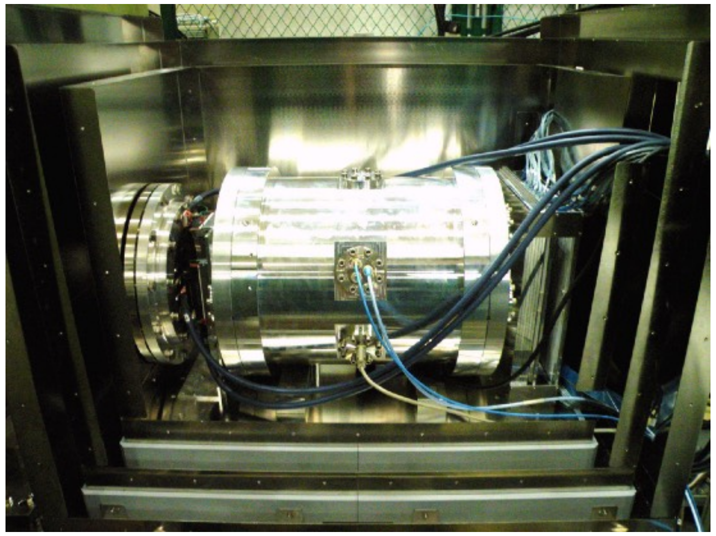
- High-rate capable, segmented scintillation counter with SiPM readout for positron detection.
- Extremely thin fiber hodoscope having a thickness of 300 μm for muon beam monitoring.
- Three-dimensional reconstruction of muon stopping distribution using a CCD-based imager.

Zero-Field Highlights (2014-16)

Continuous efforts since the experimental proposal

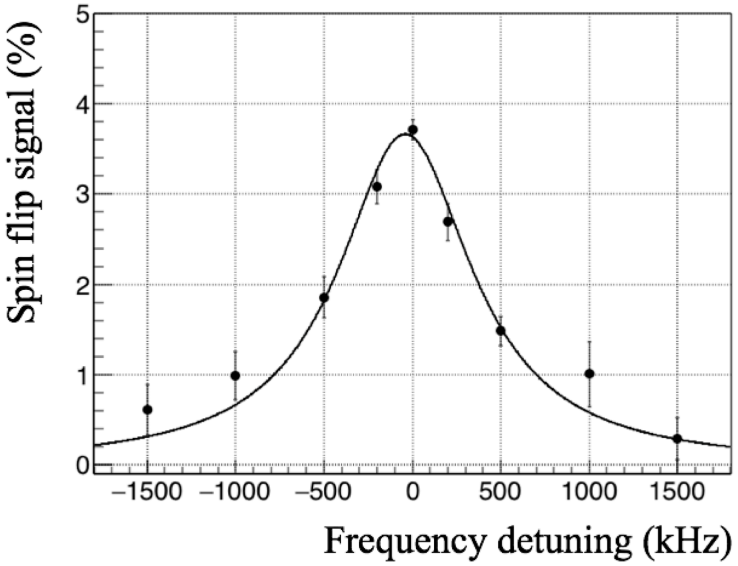


Experiment in 2014



Experimental setup at
J-PARC MLF MUSE D2 area

Experiment in 2016



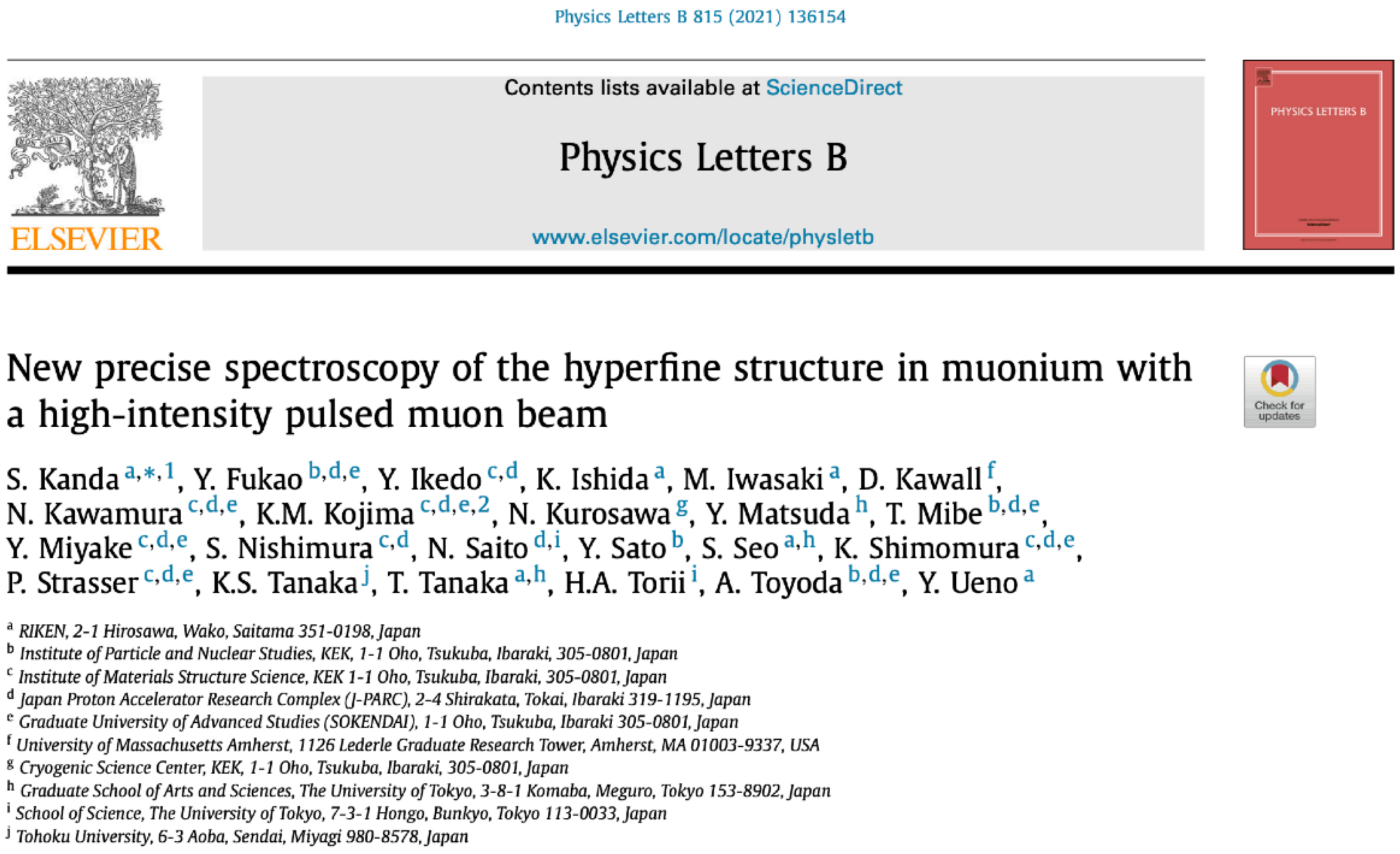
First resonance result

- First trial in 2014.
  - No resonance was observed. Small signal, severe background.
- No beam delivery in 2015 due to the trouble with the mercury target.
- Second trial in 2016.
  - Improvements in the microwave system and suppression of beam-derived background events.
  - First observation of the muonium HFS resonance with a pulsed muon beam.
  - S. Kanda Ph.D Thesis, U. Tokyo (2017).
  - S. Kanda, Proc. of Science, PoS(INPC2016)170 (2017) 1-6.

Zero-Field Highlights (2017)

First Letter has been published in 2021

Based on the results obtained in the third experiment in 2017.



Physics Letters B 815 (2021) 136154

Contents lists available at ScienceDirect

Physics Letters B

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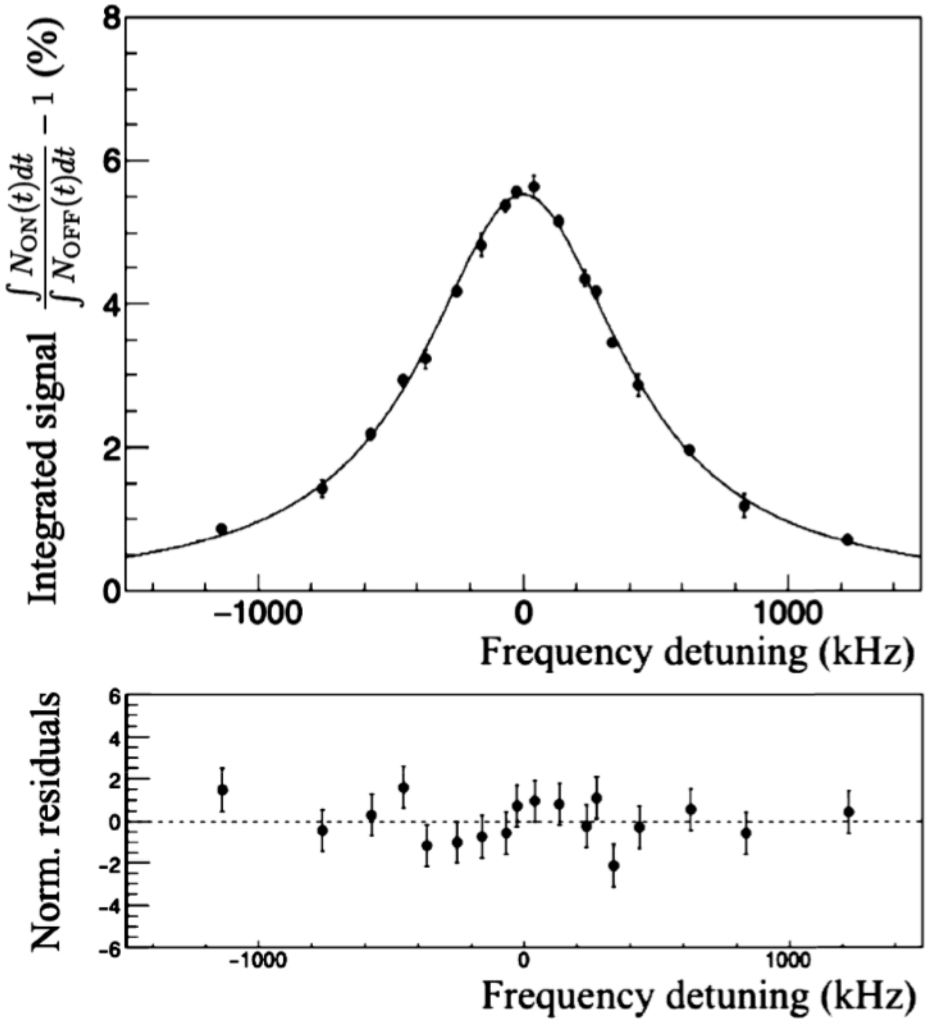
New precise spectroscopy of the hyperfine structure in muonium with a high-intensity pulsed muon beam

S. Kanda [a,*,1], Y. Fukao [b,d,e], Y. Ikedo [c,d], K. Ishida [a], M. Iwasaki [a], D. Kawall [f], N. Kawamura [c,d,e], K.M. Kojima [c,d,e,2], N. Kurosawa [g], Y. Matsuda [h], T. Mibe [b,d,e], Y. Miyake [c,d,e], S. Nishimura [c,d], N. Saito [d,i], Y. Sato [b], S. Seo [a,h], K. Shimomura [c,d,e], P. Strasser [c,d,e], K.S. Tanaka [j], T. Tanaka [a,h], H.A. Torii [i], A. Toyoda [b,d,e], Y. Ueno [a]

[a] *RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[b] *Institute of Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan*
[c] *Institute of Materials Structure Science, KEK 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan*
[d] *Japan Proton Accelerator Research Complex (J-PARC), 2-4 Shirakata, Tokai, Ibaraki 319-1195, Japan*
[e] *Graduate University of Advanced Studies (SOKENDAI), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[f] *University of Massachusetts Amherst, 1126 Lederle Graduate Research Tower, Amherst, MA 01003-9337, USA*
[g] *Cryogenic Science Center, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan*
[h] *Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan*
[i] *School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[j] *Tohoku University, 6-3 Aoba, Sendai, Miyagi 980-8578, Japan*

https://www.sciencedirect.com/science/article/pii/S0370269321000940

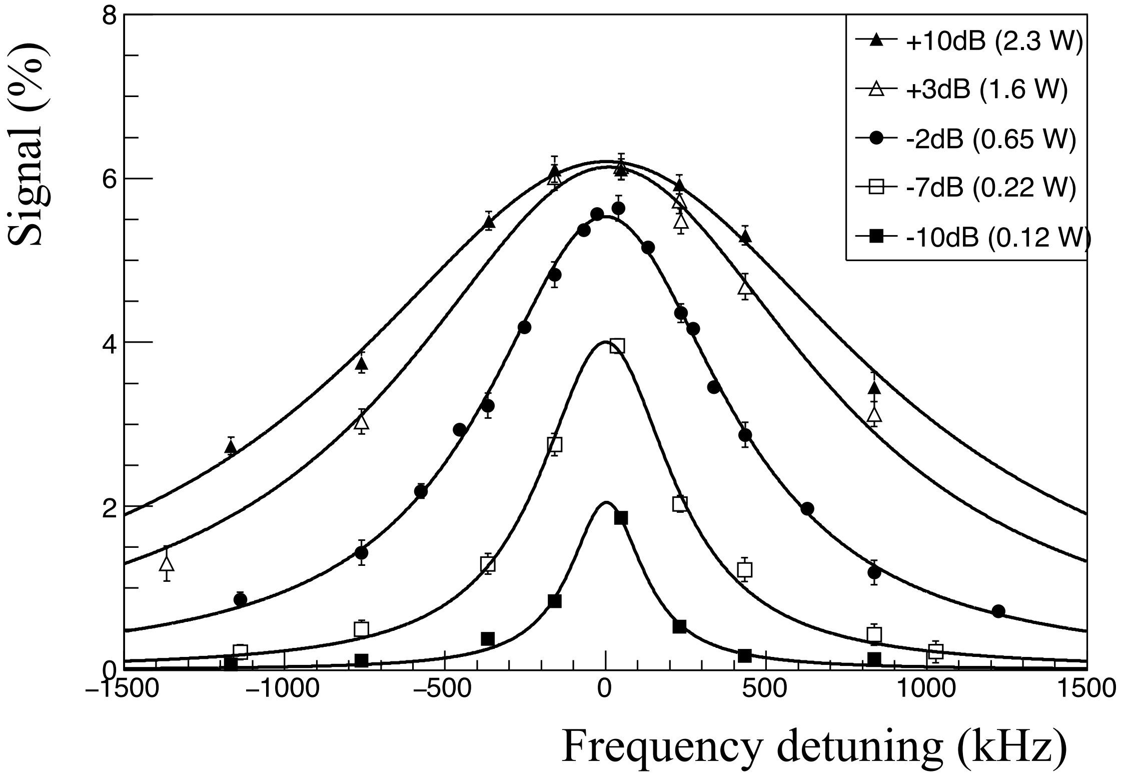


S. Kanda et al., Phys. Lett. B 815 (2021) 136154.

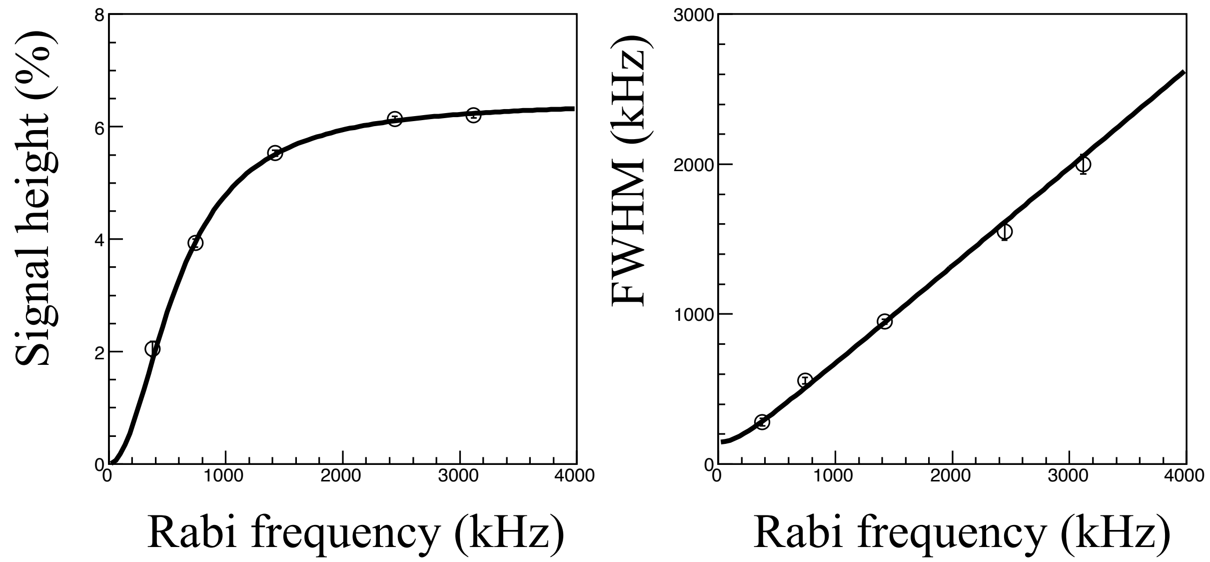
Press release : https://www.kek.jp/wp-content/uploads/2021/04/PR20210416.pdf

Zero-Field Highlights (2017)

Continuous efforts since the experimental proposal



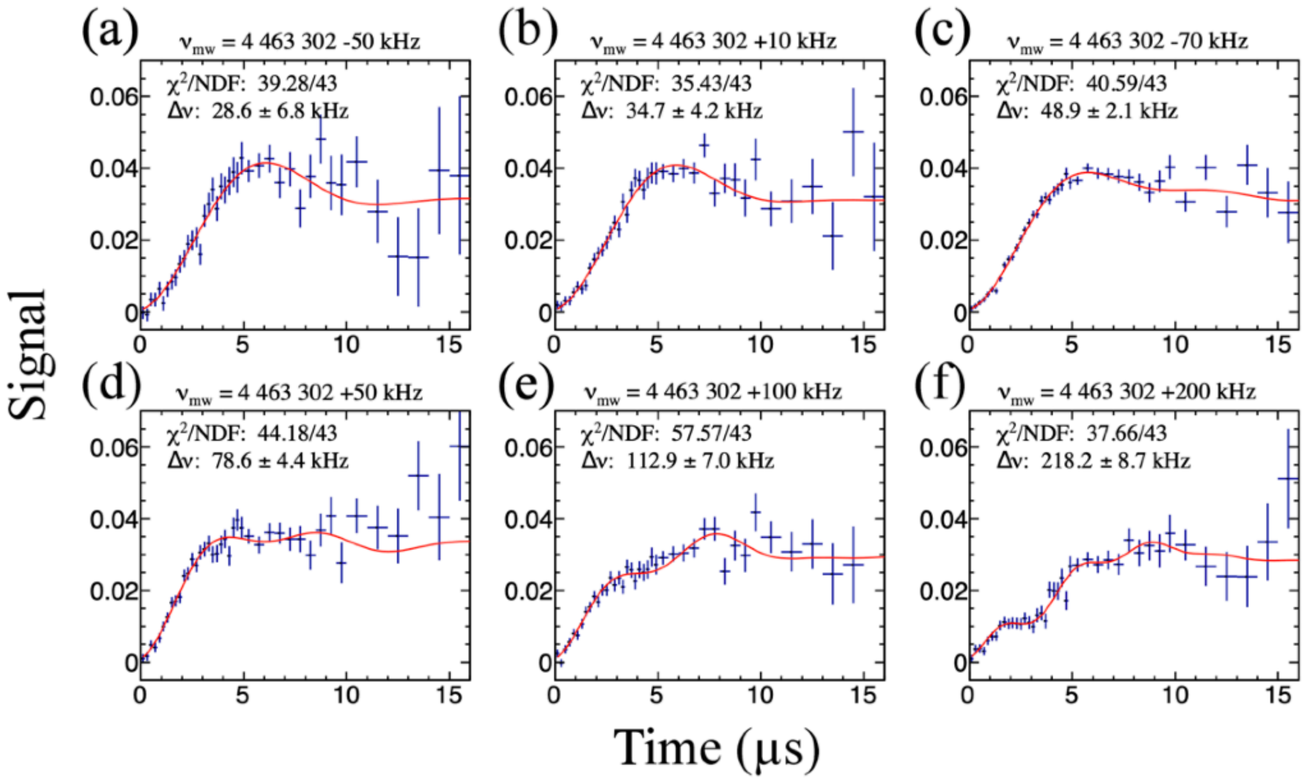
Microwave power dependence of the resonance



- ○ Third experiment in 2017.
  - ○ Improvements in background suppression with a thick absorber to cut duct-streaming positrons.
  - ○ Microwave power dependence of the signal height and curve width was studied.
  - ○ The power was optimized in terms of resonance center determination.
  - ○ A full-paper is being prepared.

Zero-Field Highlights (2017)

Continuous efforts since the experimental proposal



Fitting results for different microwave frequencies

Rabi-oscillation formula

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

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

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

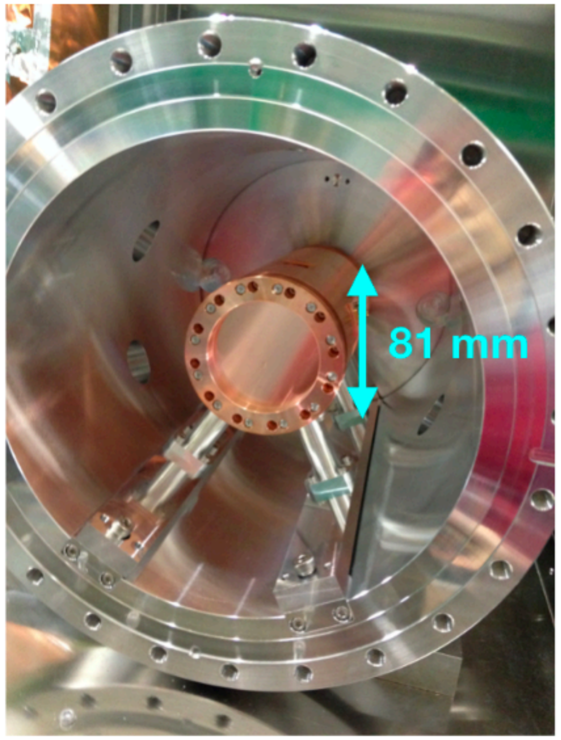
$\Delta\omega$: freq. detuning

b: microwave power

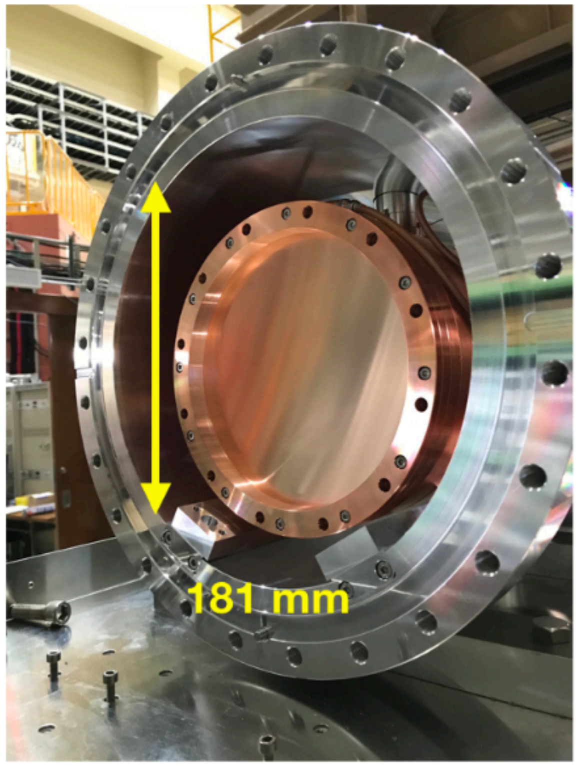
- Third experiment in 2017.
    - A new method to directly analyze the Rabi oscillation was developed.
    - Tolerant to time-varying systematic errors such as microwave power drift.
    - S. Nishimura, Ph.D Thesis, U. Tokyo (2018).
    - S. Nishimura et al., Phys. Rev. A 104, L020801 (2021).

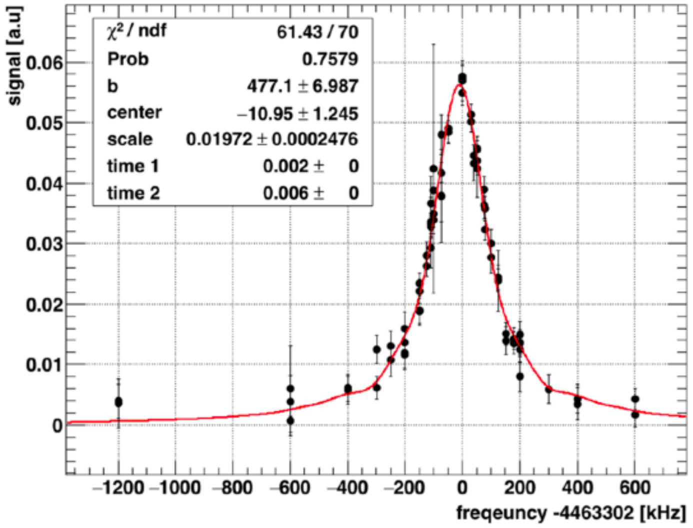
Zero-Field Highlights (2018)

Continuous efforts since the experimental proposal

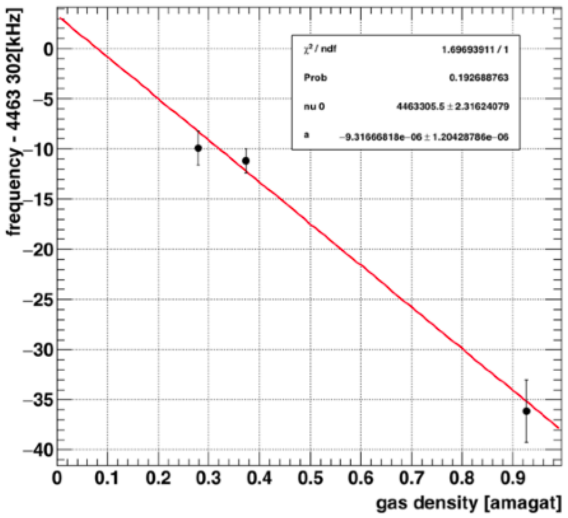


upgrade





Old muonium analysis 2~6 μs

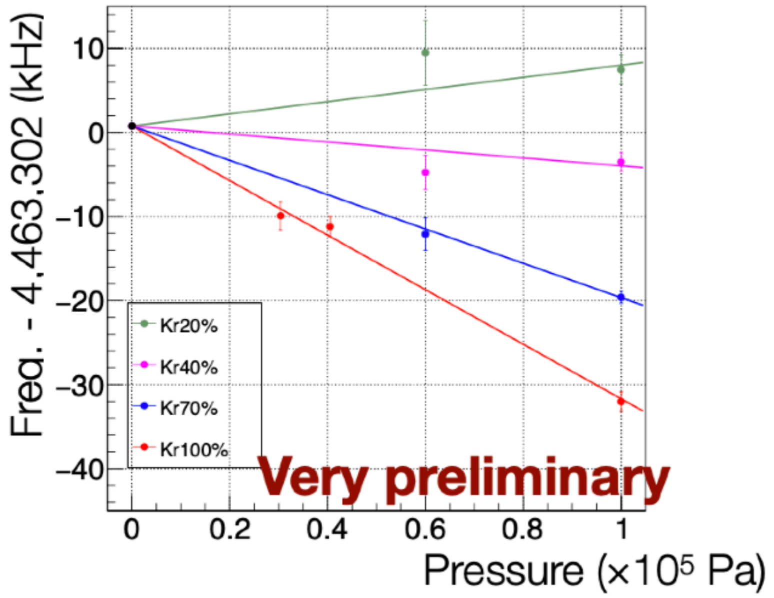


Density dependence of the HFS

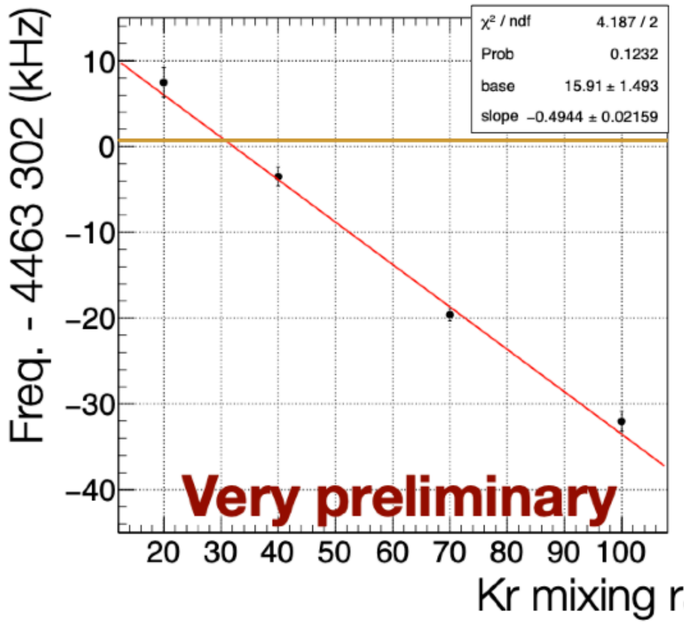
- Forth experiment in 2018.
  - A larger microwave cavity with resonance in TM220 mode.
    - The effect of muons stopping at the wall was reduced and the S/N was improved.
  - Gas pressure dependence was studied at a lower pressure than in the previous experiment.
  - “Old muonium” analysis was studied to improve precision.
  - Y. Ueno, Ph.D Thesis, U. Tokyo (2018).
  - A full-paper is being prepared.

Zero-Field Highlights (2019)

Continuous efforts since the experimental proposal



Density dependence for different mixing ratios



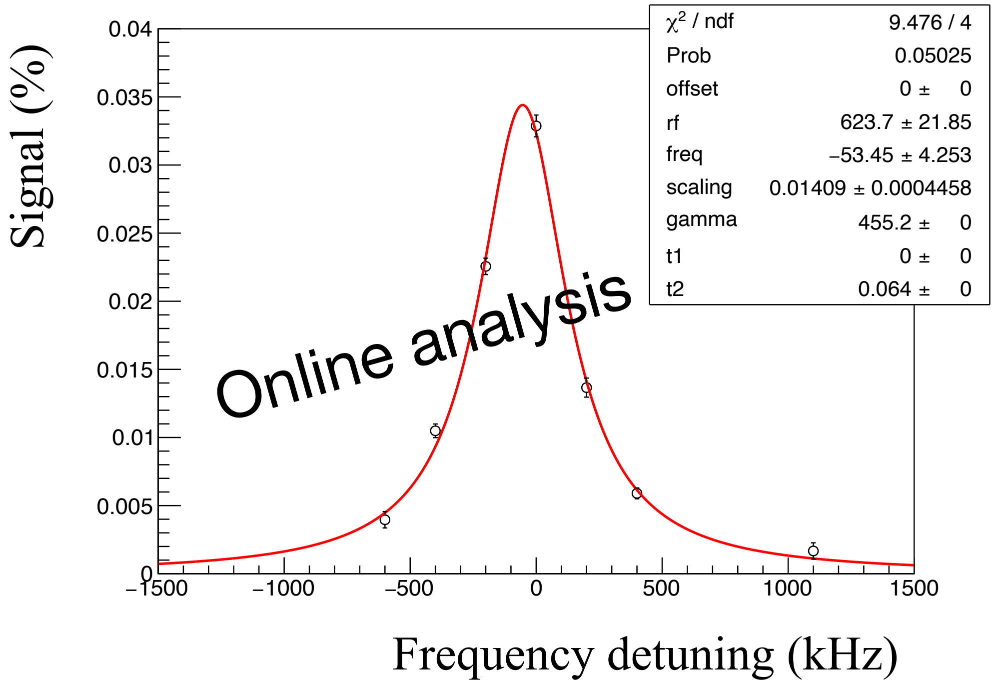
Δ_{HFS} (LAMPF1999)

Determination of the optimal mixing ratio

- ○ Fifth experiment in 2019.
  - ○ Compensation of the gas density shift by Kr/He gas mixture.
    - ○ Kr indicates a negative shift by van der Waals interaction.
    - ○ He indicates a positive shift due to Pauli exclusion.
  - ○ Mixing at Kr:He~3:7 can cancel the shift.
    - ○ S. Seo, talk at ICHEP2020.

The Last Zero-field Experiment

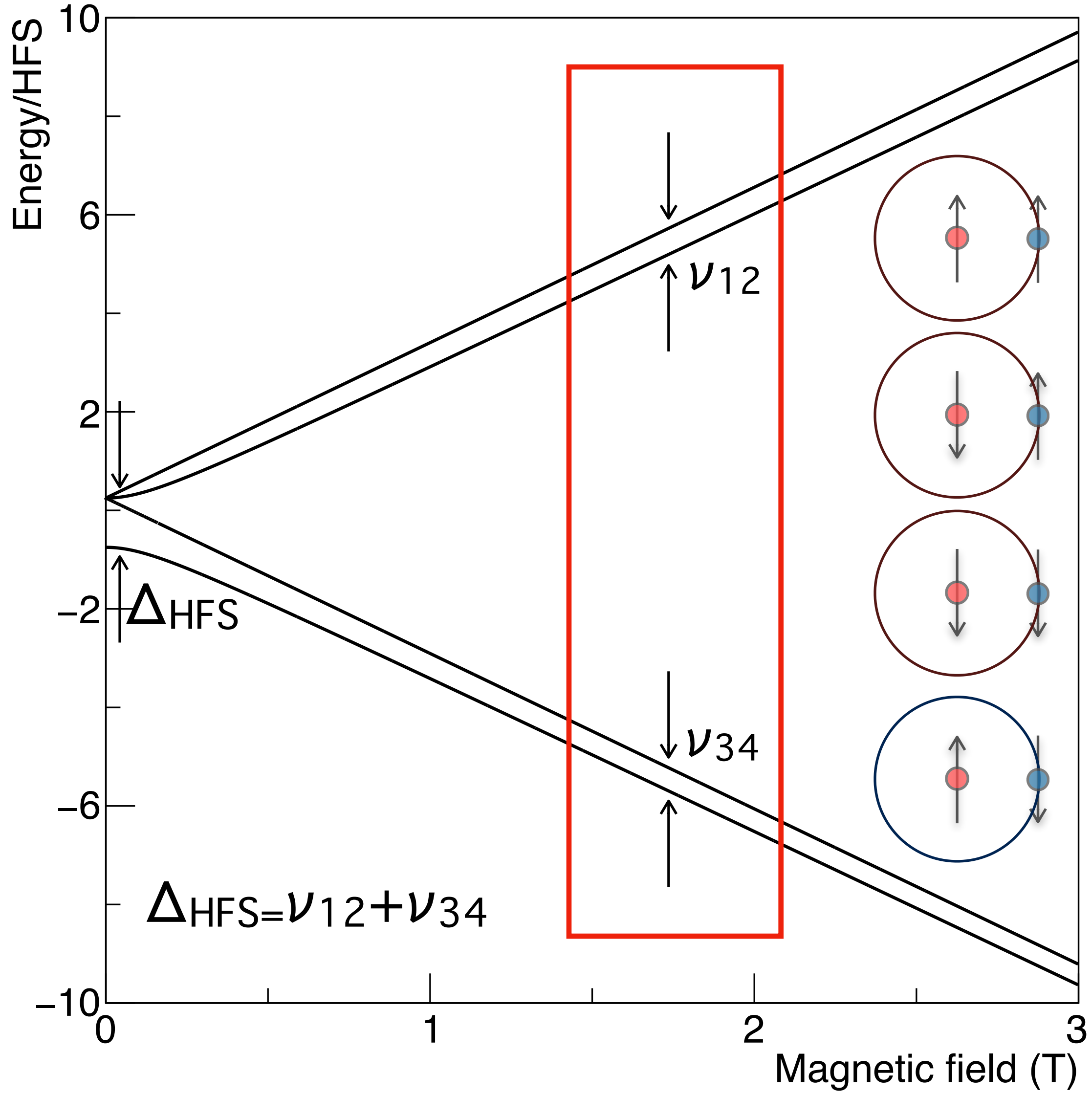
Kr/He mixing study at higher densities



- Sixth experiment in 2021.
  - The last experiment using the existing beamline (MUSE D2).
  - Kr/He gas mixture study at higher gas densities.
    - The gas chamber was modified to increase the pressure resistance to 4 atm.
  - The experiment was completed on May 29.
    - Detailed data analysis is in progress.

High- and Zero-field Experiments

Two ways to measure the muonium HFS

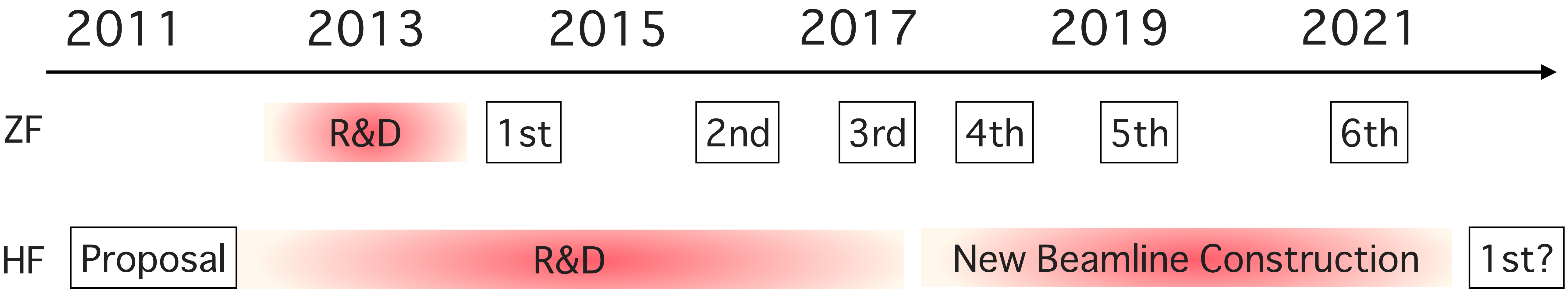


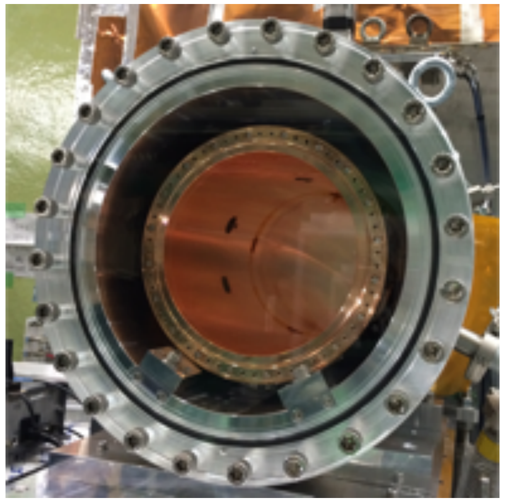
$$\frac{\mu_\mu}{\mu_p} = \frac{4\nu_{12}\nu_{34} + \nu_p\mu_e/\mu_p(\nu_{34} - \nu_{12})}{\nu_p[\nu_p\mu_e/\mu_p - (\nu_{34} - \nu_{12})]}$$

- Direct measurement at a near-zero magnetic field (ZF).
  - Simple and can be realized quickly as a phase-1 experiment. Muonium polarization becomes half.
- Zeeman-sublevels measurement in a high magnetic field (HF).
  - Careful treatment of magnetic field is necessary. High polarization, field focusing.
  - Determination of the magnetic moment ratio μ_μ/μ_p.

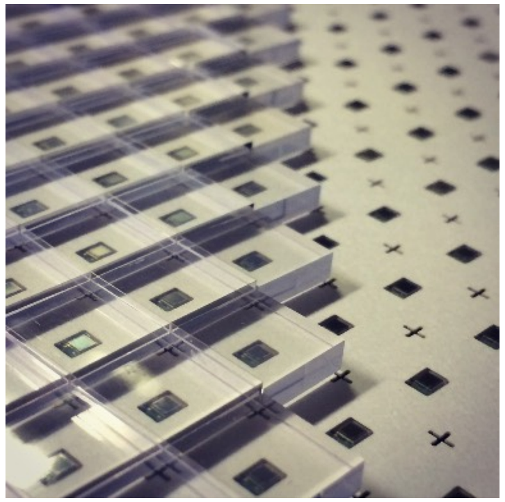
Project Timeline of MuSEUM

Since the experiment was proposed



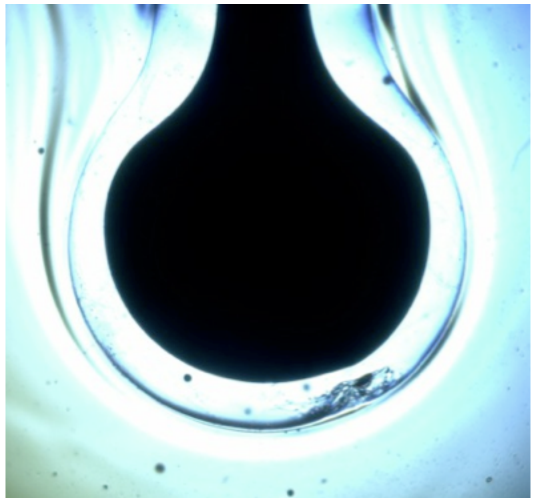


RF Cavity

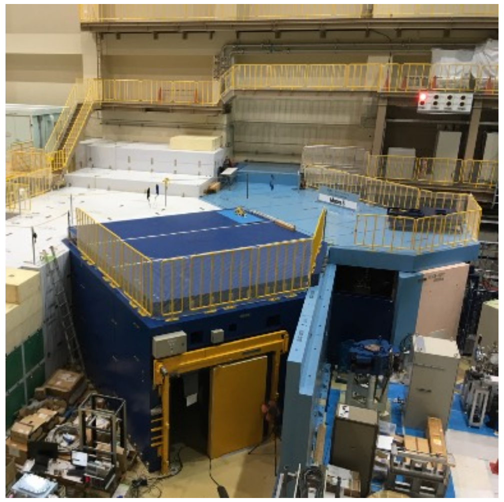


Detector

Magnet



Field probe



New beamline

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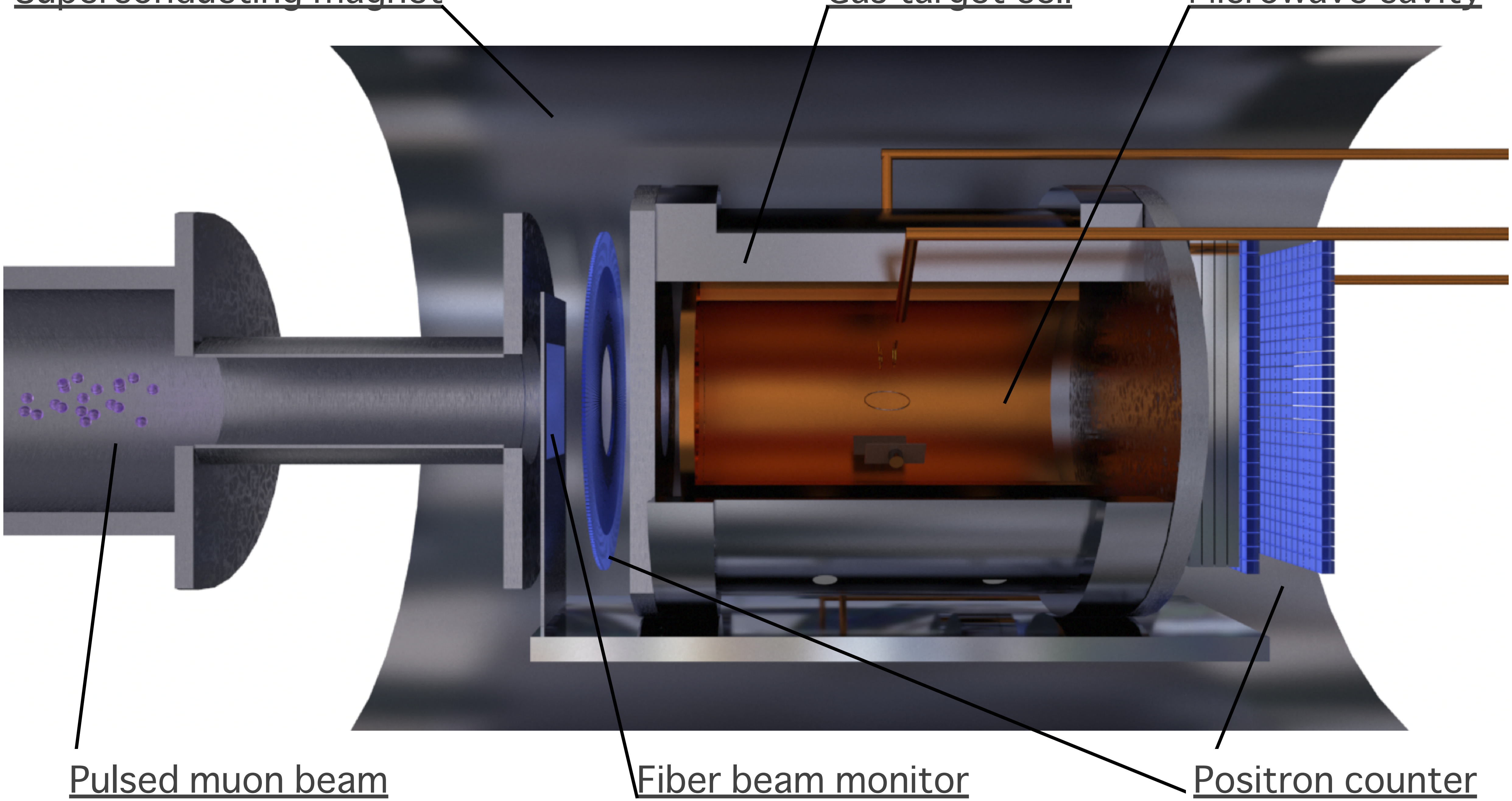
- We are preparing for the first HF experiment.

Outline of the Experiment

Experimental setup for a high-field measurement



Superconducting magnet

Gas target cell

Microwave cavity

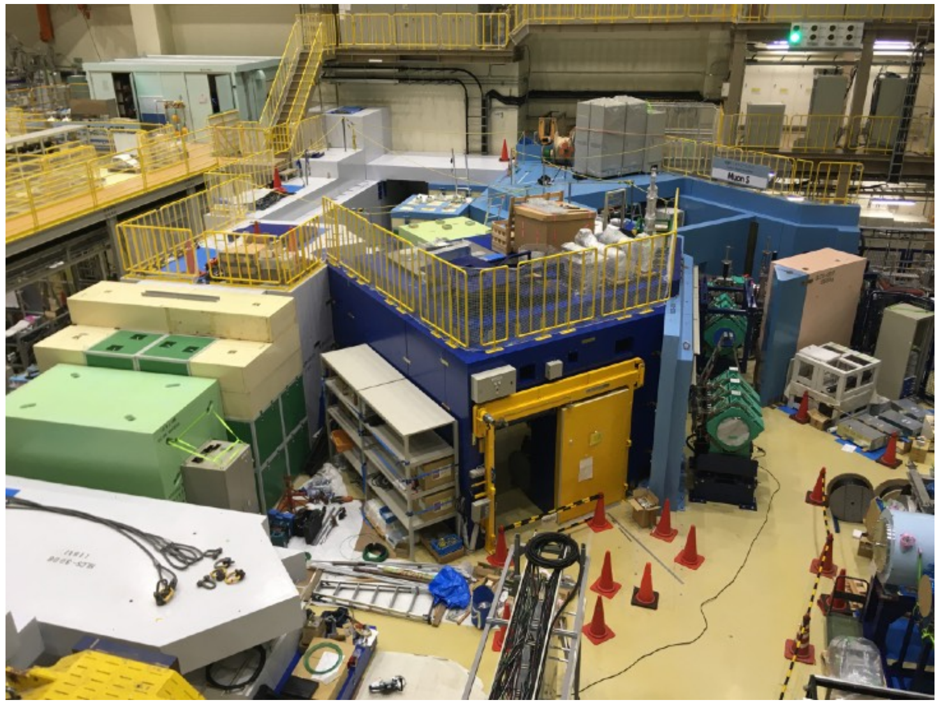
Pulsed muon beam

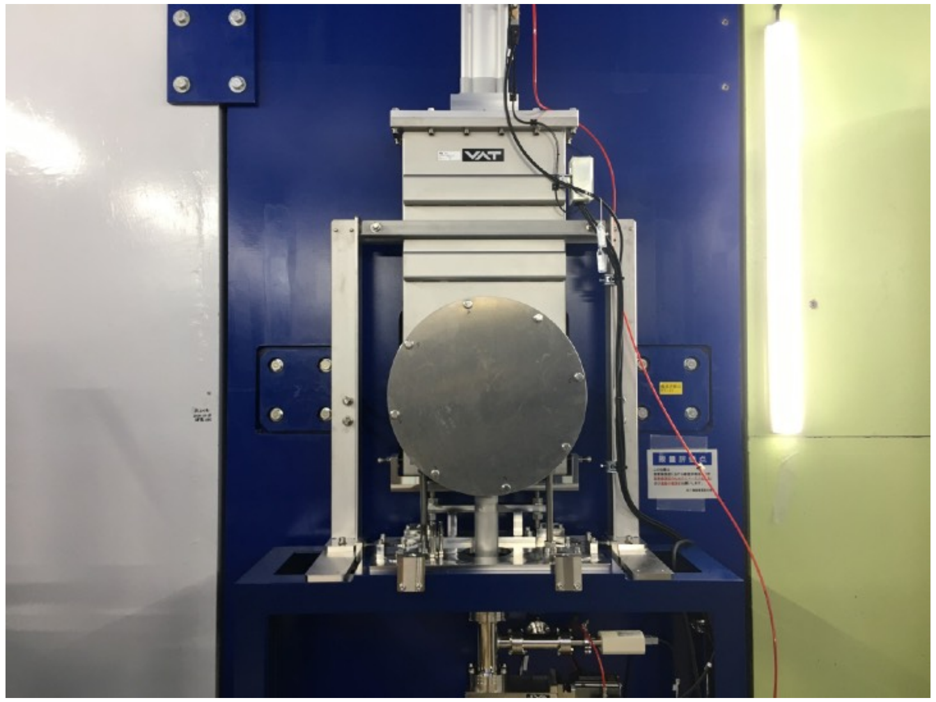
Fiber beam monitor

Positron counter

New Muon Beamline

H-Line





- ○ 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.
- ○ The beamline is under construction.
- ○ A lot of progress in the last summer.
- ○ In the earliest case, the beam will be delivered starting in May 2022.
  - T. Yamazaki, N. Kawamura, A. Toyoda (KEK).

Superconducting Magnet

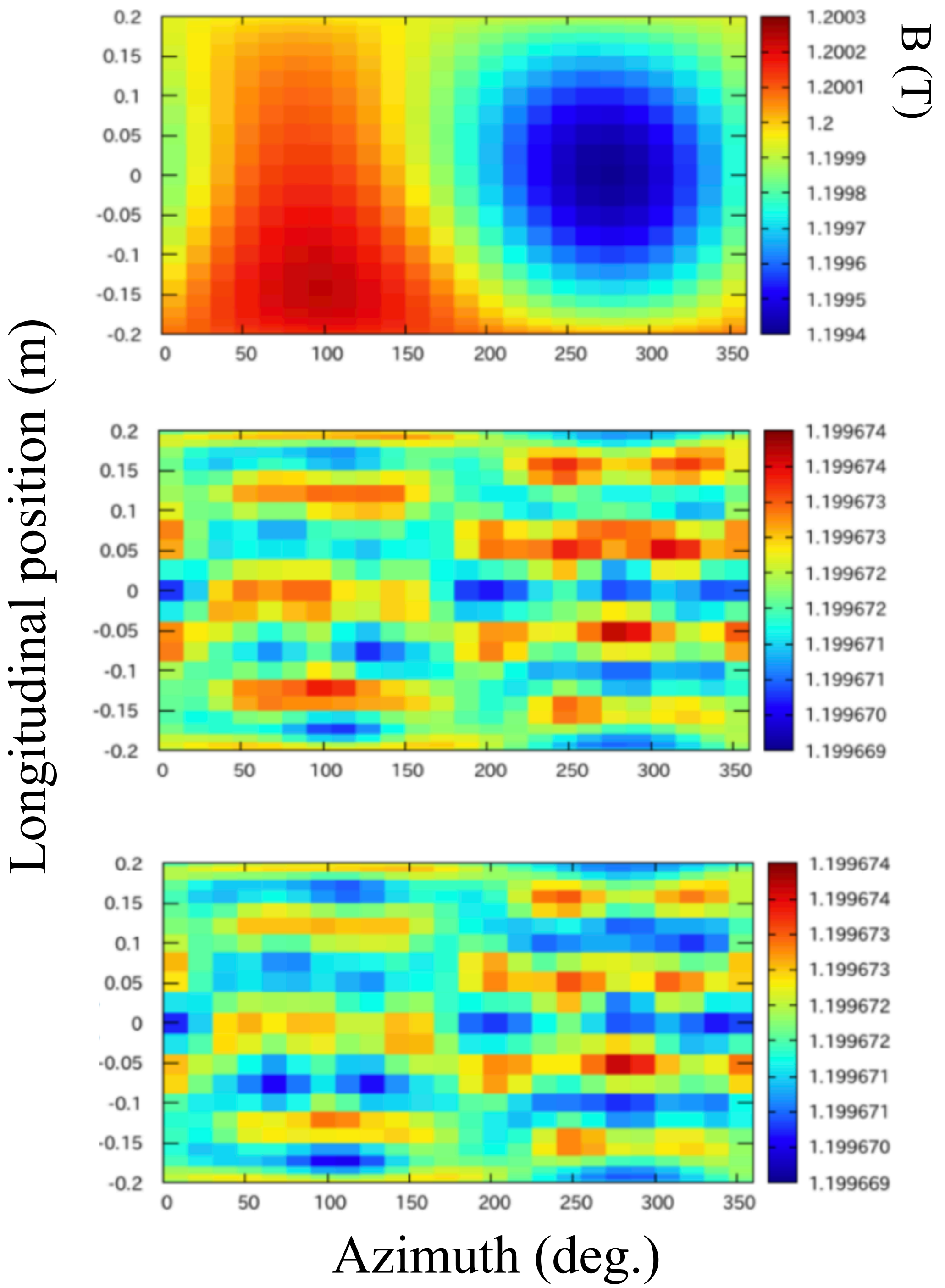
A key element for the high-field experiment

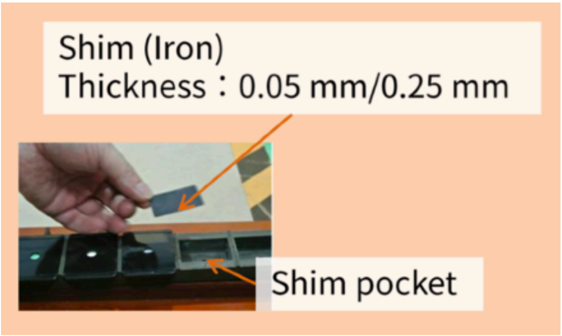
- K. Sasaki, M. Abe (KEK).

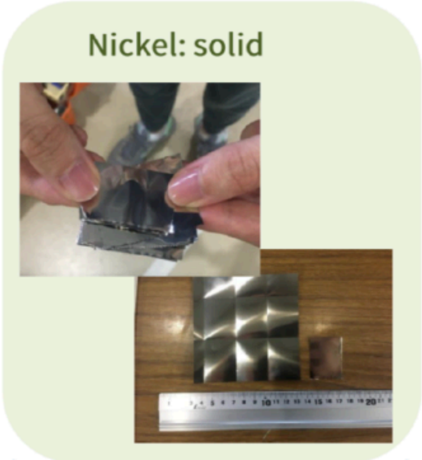
- A superconducting solenoid for a precise controlled magnetic field of 1.7 T.
    - A second-hand MRI magnet with an axial length of 2 m and a bore diameter of 925 mm.
- Requirements for the field are:
    - 0.2 ppm (peak-to-peak) uniformity in a spheroidal volume with z=30 cm, r=10 cm.
    - ±0.1 ppm stability during measurement.

Passive Shimming

For highly uniform magnetic field







Iron shim plates
341 ppm (p-p)

↓

Nickel films
0.28 ppm (p-p)

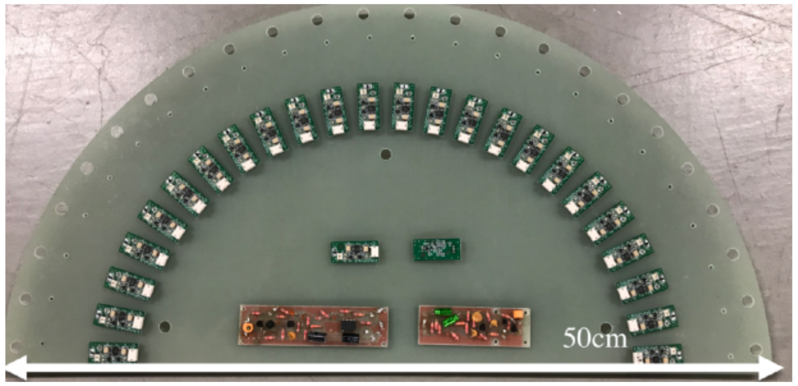
↓

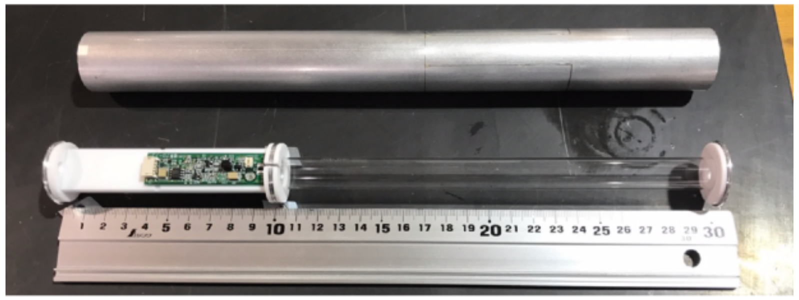
Magnetic putty
0.17 ppm (p-p)

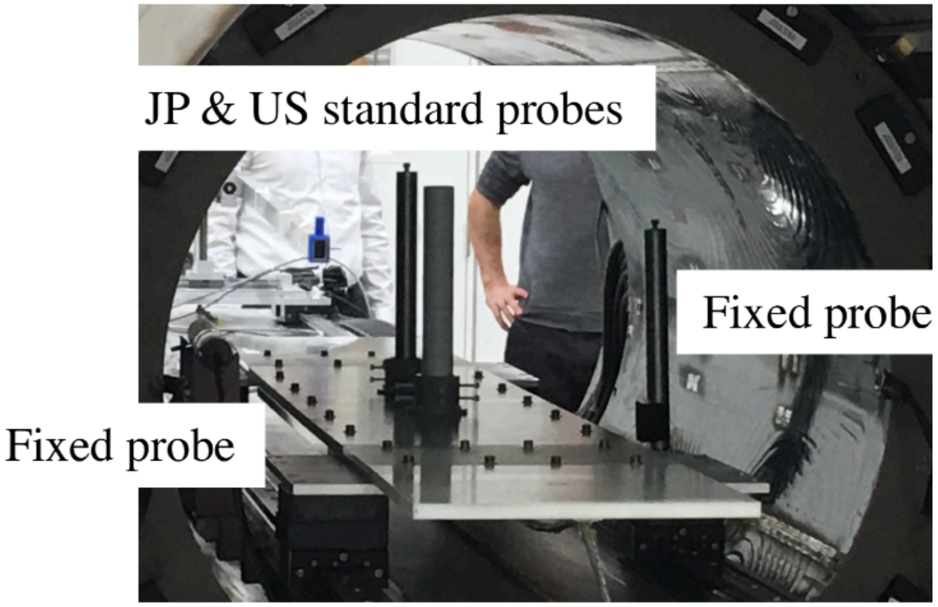
K. Sasaki, M. Abe (KEK), Y. Higashi (U.Tokyo)
M. Sugita, C. Oogane, H. Iinuma (Ibaraki U.)

NMR Probes

Three types of magnetometer



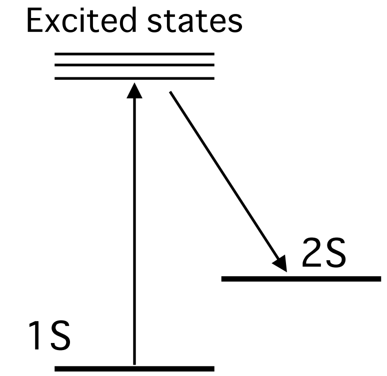




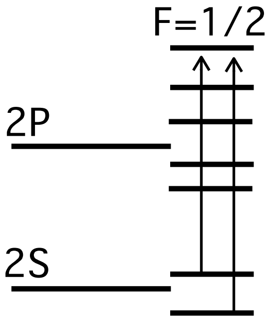
- Field camera
  - A 24-channel rotating NMR probe that maps magnetic fields in three dimensions.
  - Studies are underway for simultaneous multi-channel readouts.
  - K. Sasaki (KEK), A. Yamaguchi(KEK->JASRI), T. Tanaka, K. Shimizu, F. Yoshizu (U. Tokyo), H. Tada (Nagoya U.)
- Fixed probe
  - A compact 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), A. Yamaguchi (KEK->JASRI), T. Tanaka, S. Seo (U. Tokyo), P. Winter (ANL), D. Kawall (U. Mass.), D. Flay (U.Mass->JLab)

^{3}He NMR Probe

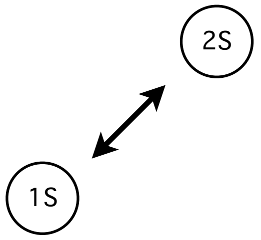
R&D aiming at the highest precision



RF discharge excitation

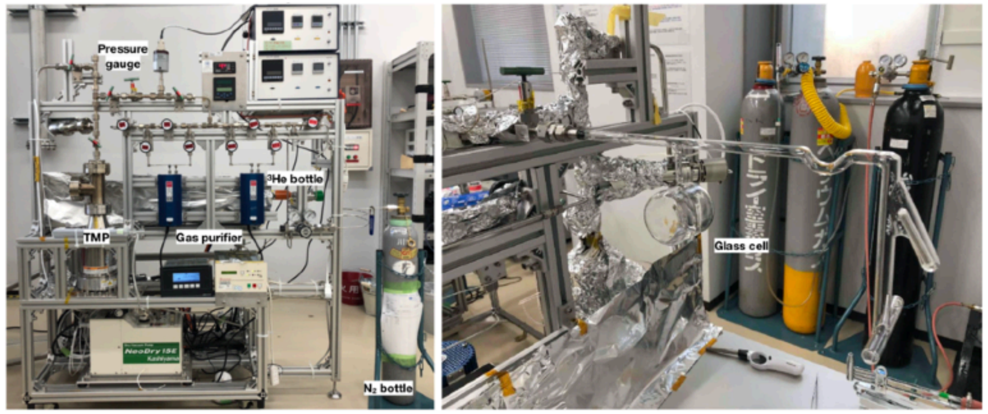


Optical pumping

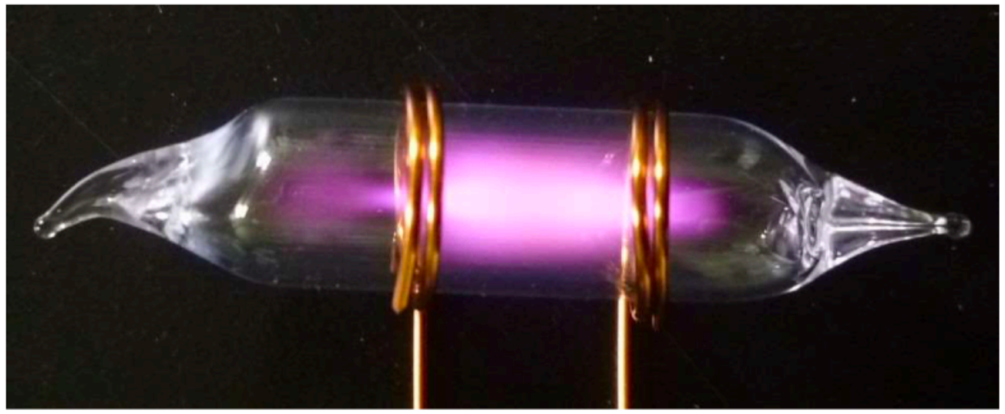


$^3He + {}^3He^*_\uparrow \rightarrow {}^3He^* + {}^3He_\uparrow$

Metastability exchange collision



Gas handling system for the neutron spin filter at J-PARC.

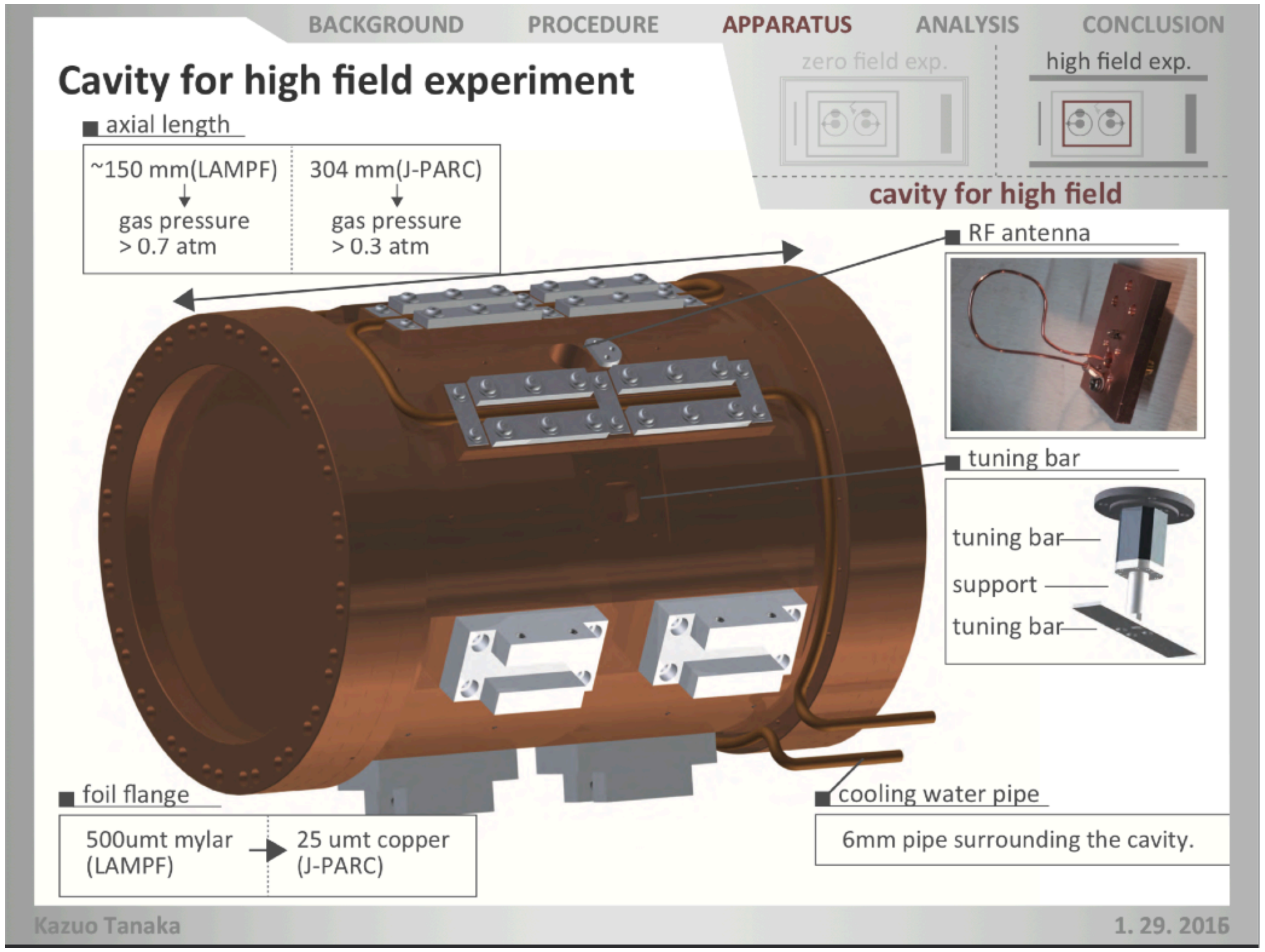


RF discharge of ^{3}He in a cell with a 4-cm length.

- ○ A precision of proton NMR using water is limited by the uncertainty of the shielding effect (10 ppb).
- ○ Higher precision can be obtained by hyper-polarized ^{3}He (0.1 ppb).
- ○ R&D for metastability exchange optical pumping (MEOP) is underway.
- ○ Collaboration of neutrons and muons in KEK.
  - ○ K. Sasaki, N. Sumi (KEK cryogenics), T. Ino (KEK neutron), T. Oku (JAEA), T. Okudaira (JAEA->Nagoya U.)

Microwave Cavity for High Field

Resonator for spectroscopy



BACKGROUND PROCEDURE APPARATUS ANALYSIS CONCLUSION

zero field exp. | high field exp.

Cavity for high field experiment

■ axial length

~150 mm(LAMPF) → 304 mm(J-PARC)

gas pressure > 0.7 atm | gas pressure > 0.3 atm

cavity for high field

■ RF antenna

■ tuning bar

■ foil flange

500umt mylar (LAMPF) → 25 umt copper (J-PARC)

■ cooling water pipe

6mm pipe surrounding the cavity.

Kazuo Tanaka 1. 29. 2016

- K.S. Tanaka (Tohoku U.), S. Seo, H. Yamauchi (U. Tokyo), Y. Ueno (RIKEN)

○ What has been achieved so far

→A cylindrical microwave cavity resonates at 1.95 GHz (TM_{110}) and 2.65 GHz (TM_{210}).

→Resonance of both modes, high Q-value of 10^4, wide sweep range of 30 MHz or more, power feedback of 0.02% stability, pulse-by-pulse switching of 25 Hz.

○ What we are currently working on

→Temperature stabilization by water cooling, field measurement

Microwave Cavity Paper

First full-paper for MuSEUM high-field R&D

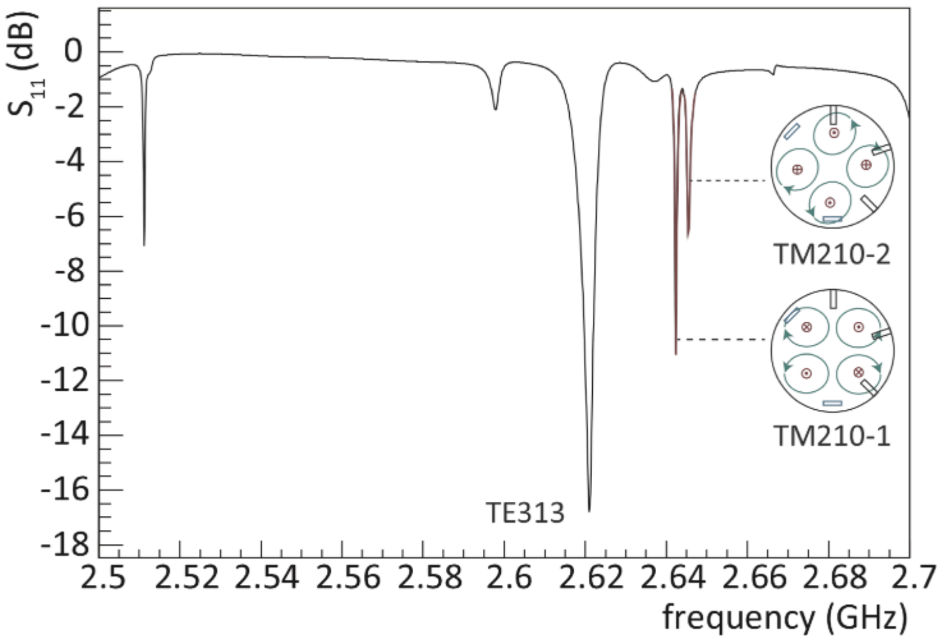
PTEP

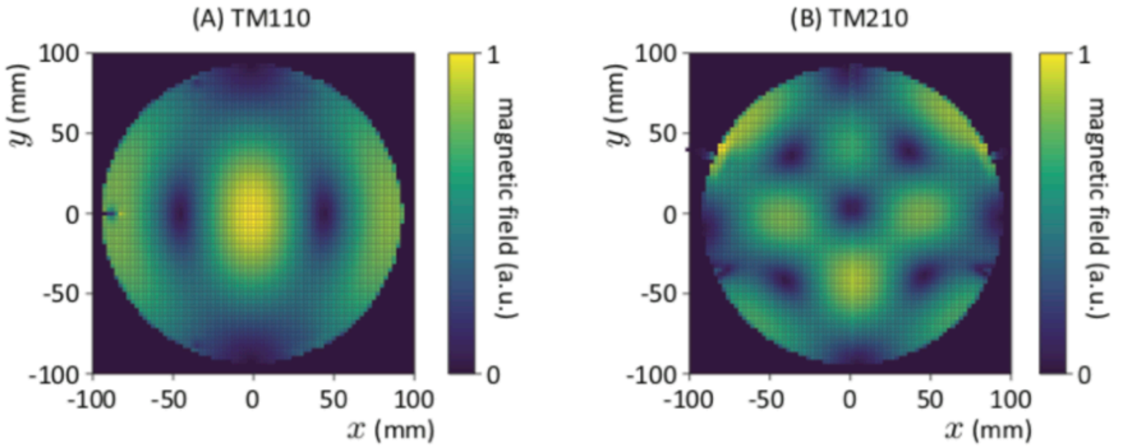
Prog. Theor. Exp. Phys. **2015**, 00000 (20 pages)
DOI: 10.1093/ptep/0000000000

Development of microwave cavities for measurement of muonium hyperfine structure at J-PARC

K.S. Tanaka[1,4], M. Iwasaki[2], O. Kamigaito[2], S. Kanda[3,6,7], N. Kawamura[3,6,7], Y. Matsuda[4], T. Mibe[5,6,7], S. Nishimura[3,6], N. Saito[6,8], N. Sakamoto[2], S. Seo[2,4], K. Shimomura[3,6,7], P. Strasser[3,6,7], K. Suda[2], T. Tanaka[2,4], H.A. Torii[4,8], A. Toyoda[5,6,7], Y. Ueno[2,4], and M. Yoshida[7,9]

[1] *Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan*
[2] *RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3] *Institute of Materials Structure Science, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[4] *Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan*
[5] *Institute of Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[6] *Japan Proton Accelerator Research Complex (J-PARC), 2-4 Tokai, Ibaraki 319-1195, Japan*
[7] *Graduate University of Advanced Studies (SOKENDAI), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[8] *School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[9] *Accelerator Laboratory, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*



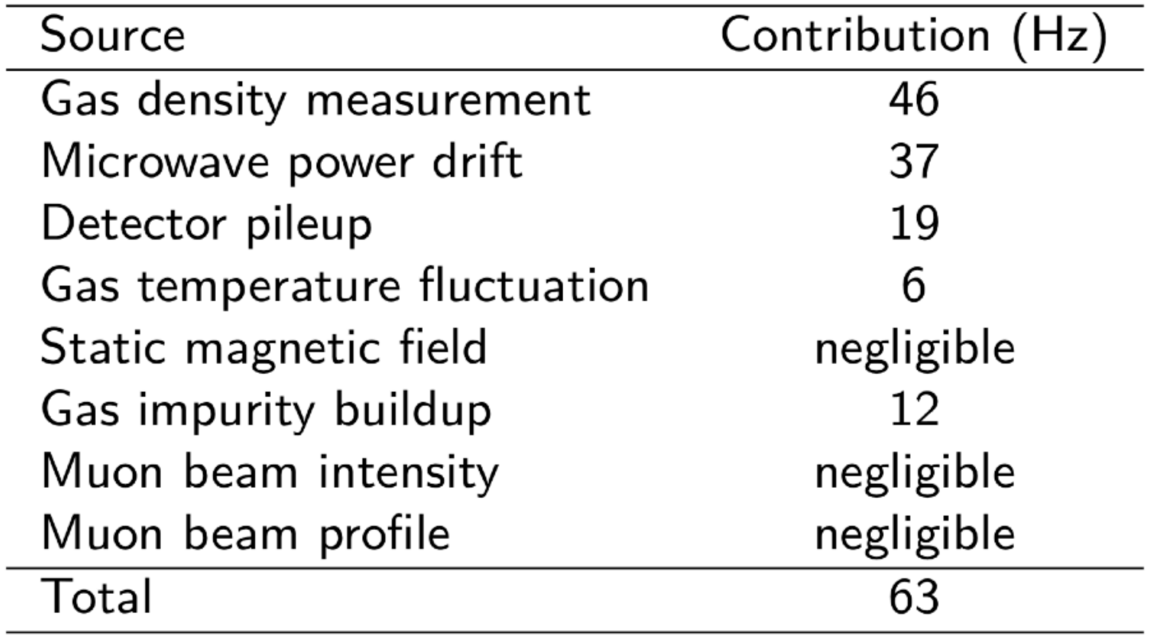


K. S. Tanaka et al., PTEP 2021;, ptab047.
https://academic.oup.com/ptep/advance-article/doi/10.1093/ptep/ptab047/6247771

Expected Precision

Statistical and Systematic Uncertainties

Systematic uncertainty in zero-field 2017A.



Source	Contribution (Hz)
Gas density measurement	46
Microwave power drift	37
Detector pileup	19
Gas temperature fluctuation	6
Static magnetic field	negligible
Gas impurity buildup	12
Muon beam intensity	negligible
Muon beam profile	negligible
Total	63

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

- ○ The statistical precision will reach 5 Hz (1.2 ppb) in 40 days of measurement.
- ○ Gas : 46 Hz → 3 Hz by using a new high-precision silicon gauge.
- ○ Power drift : 37 Hz → less than 1 Hz by power and temperature control.
- ○ Pileup : 19 Hz → 2 Hz by improvement in segmentation and front-end electronics.
- ○ Impurity : 12 Hz → less than 1 Hz by improvement in Q-Mass monitoring.

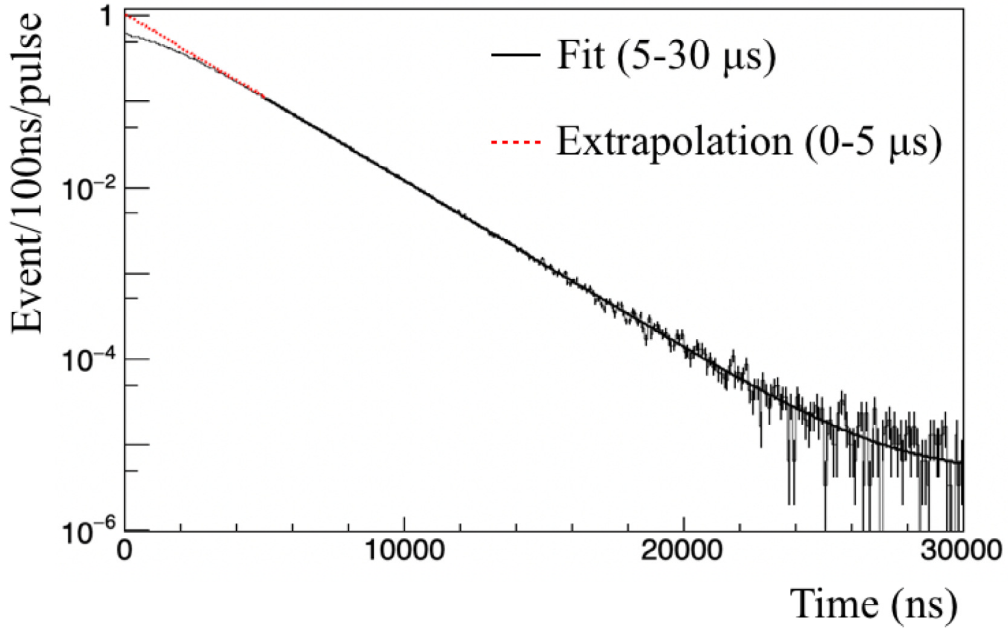
Summary

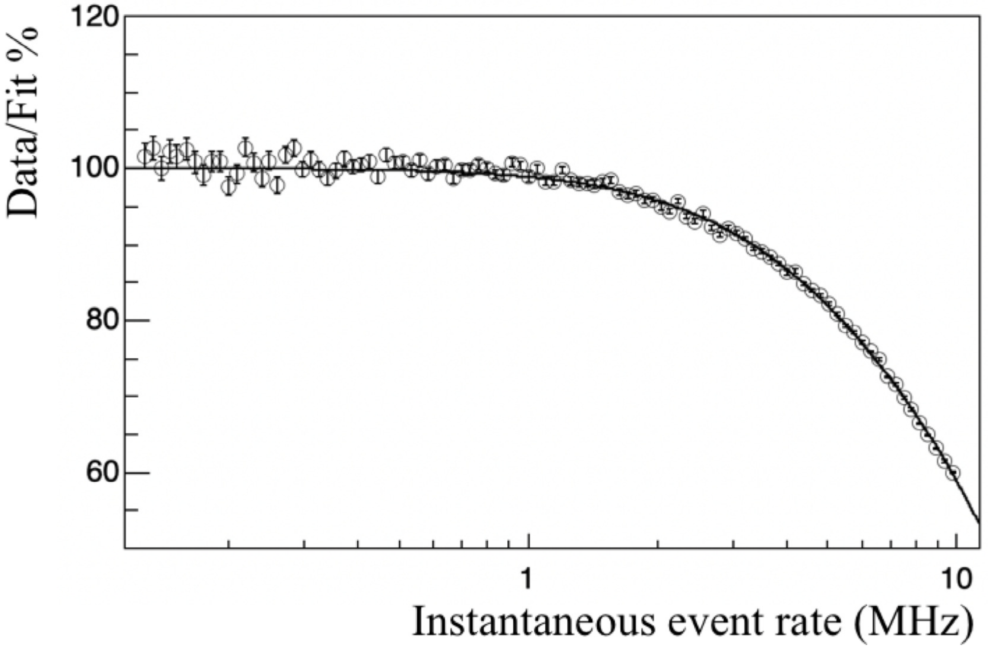
and future prospects

- MuSEUM collaboration is preparing for measurements of the muonium HFS under a high magnetic field.
  - The experimental method was established by measurements at zero magnetic field.
  - Cavity, target, detectors are ready for the DAY-1 experiment at H-Line.
  - The uniform magnetic field and NMR probe are also making steady progress.
- Approximately 10 years after the proposal submission, the experiment has finally come to fruition.

Decay Positron Time Spectrum

and pileup analysis



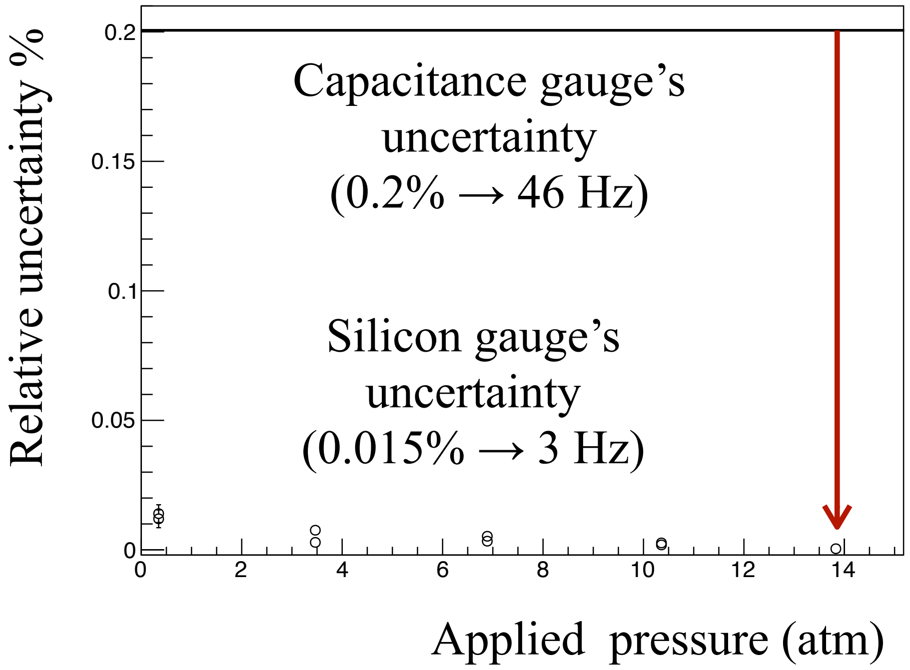


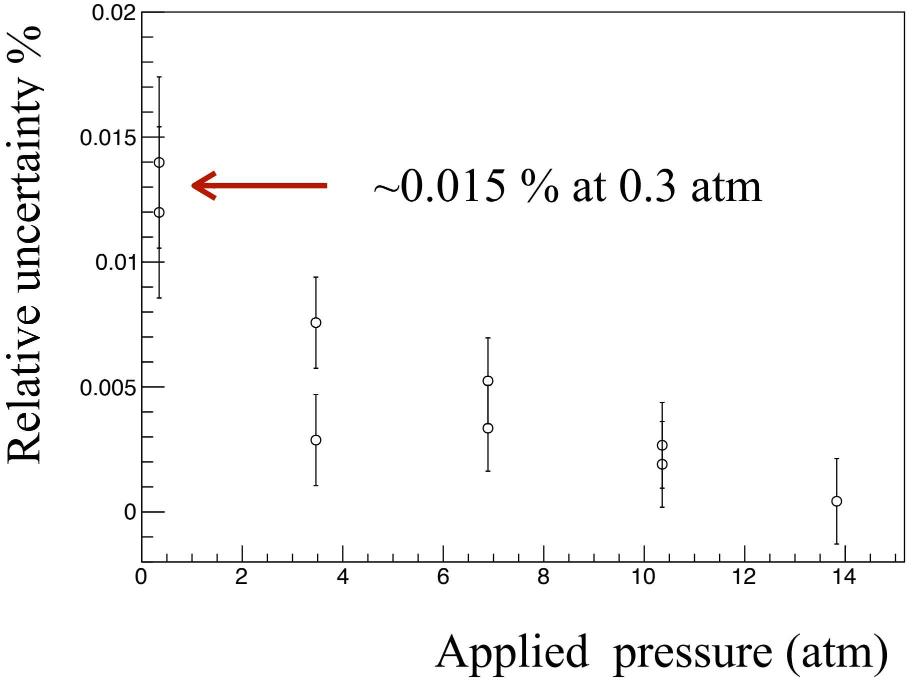
- An extended pulse-height analyzer (PHA) windowing model [2] well fits data.
- (top) Decay positron time spectrum and a result of exponential fitting.
- (bottom) Pileup event loss as a function of the positron counting rate.
- The systematic uncertainty arising from pulse pileup was estimated to be 19 Hz.
- The uncertainty will be reduced to 2 Hz by improvement of the front-end electronics and detector segmentation.

[1] S. Kanda et al., Phys. Lett. B 815, 136154 (2021).
[2] T. Ida and Y. Iwata, J. Appl. Cryst. 38, 426-432 (2005).

Gas Density Measurement

Improvement in systematic uncertainty

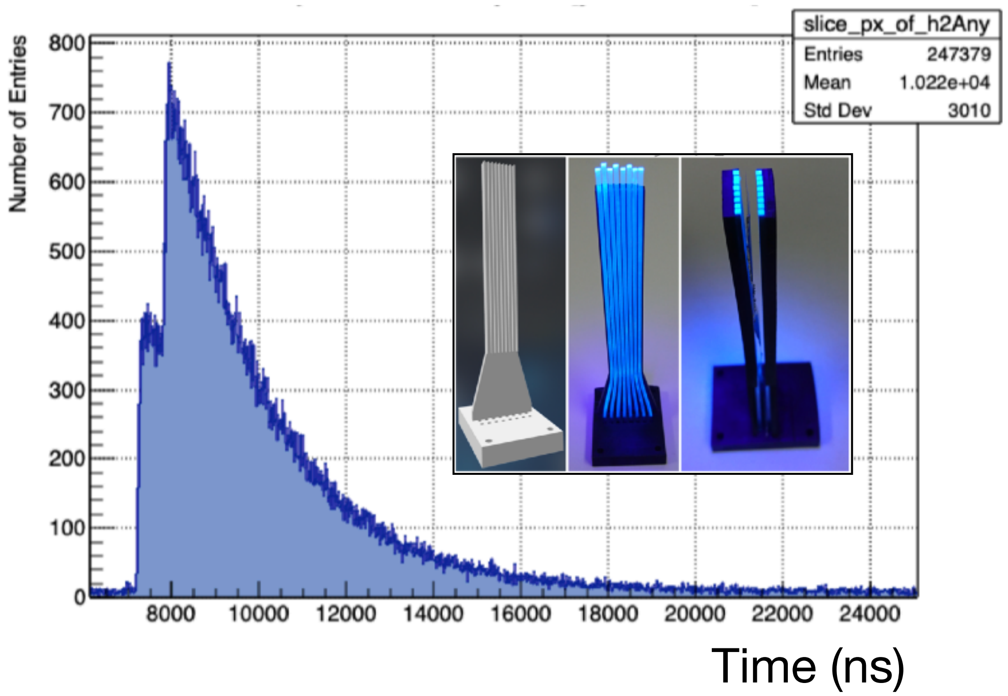


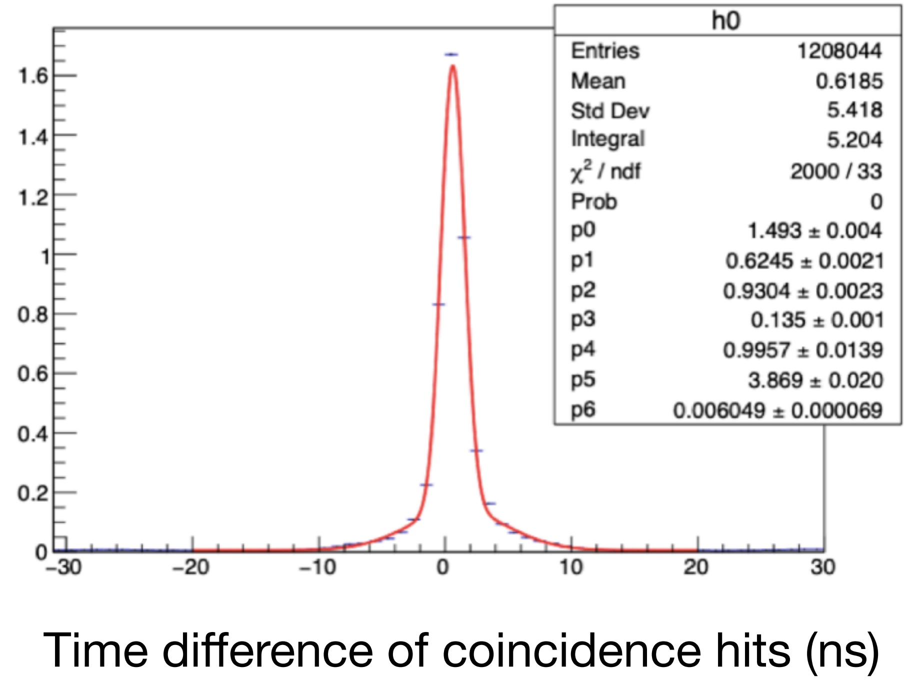


- A new silicon gauge (FLUKE RPM4) has been prepared for gas density monitoring.
- Accuracy is better than 0.02% at 0.3 atm (x10 improvement).
  - H. Yamauchi (U. Tokuyo).
- Tested at zero-field experiment in 2021.
- Answer to the question from the last CM:
  - Q: How is the pressure calibrated?
  - A: The pressure in the piston-cylinder was precisely measured using a mass standard.

Forward Detector

Additional positron counter





- Increase of statistics and measurement of forward/backward asymmetry to study systematic uncertainties.
- A prototype unit was developed and tested at S-Line.
    - Design of a full-scale detector is underway.
- H. Tada, Master Thesis, Nagoya University (2021).
- H. Tada and S. Fukumura (Nagoya U.), S. Nishimura (KEK).