Precision Measurements of Muonium and Muonic Helium Hyperfine Structure at J-PARC

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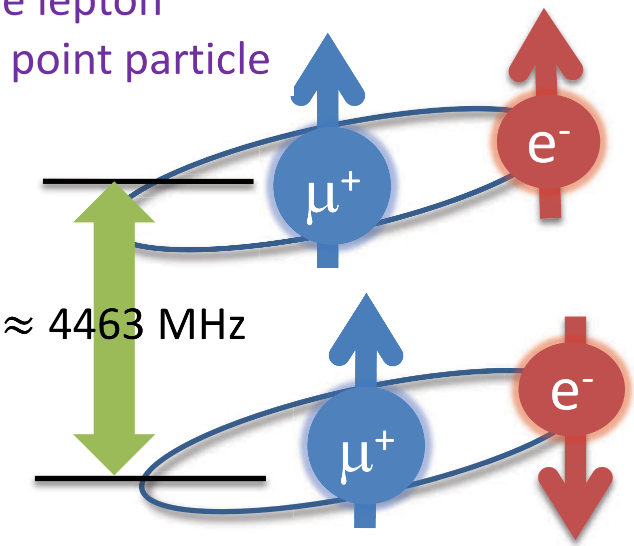
On behalf of the MuSEUM Collaboration

International Conference on Precision Physics of Simple Atomic Systems
ETH Zurich - Hönggerberg Campus, Zurich, Switzerland, June 10-14, 2024.

Muonium Hyperfine Structure

Muonium: bound state of μ^+ and e^-



Pure lepton
= point particle

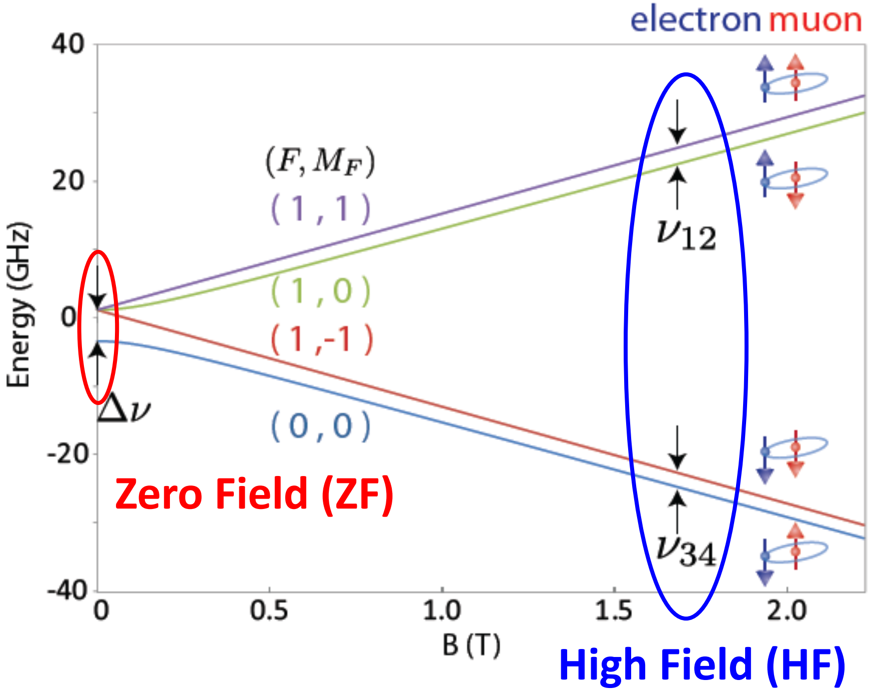
$\Delta\nu \approx 4463$ MHz

$\Delta\nu$: Muonium Hyperfine Structure

$$\mathcal{H} = h\Delta\nu\,\mathbf{I}_\mu\cdot\mathbf{J} - \mu_B^\mu g'_\mu\,\mathbf{I}_\mu\cdot\mathbf{H} + \mu_B^e g_J\,\mathbf{J}\cdot\mathbf{H}$$

Breit-Rabi Energy level diagram

Zeeman Splitting



$$\nu_{12} + \nu_{34} = \Delta\nu$$
$$\nu_{12} - \nu_{34} \propto \mu_\mu/\mu_p$$

Experimental value $\Delta\nu_{HFS}$:

ZF: 4 463 302.2(14) kHz (310 ppb)
HF: 4 463 302.765(51)(17) kHz (12 ppb)

Statistic uncertainty
is dominant !

Our goal: ~2ppb

ZF: D. E. Casperson *et al.*, Phys. Lett. B **59** (1975) 397-400
HF: W. Liu *et al.*, Phys. Rev. Lett. **82** (1999) 711-714

Most Precise Test of Bound-State QED

Experiment:

LAMPF Experiment (1999)

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

$\nu_{\mathrm{HFS}}(\mathrm{exp})$ 4463.302 765 (53) MHz [12 ppb]

$\mu_\mu/\mu_p = 3.18334524(37)$ [120ppb]

$m_\mu/m_e = 206.768277(24)$ [120ppb]

Theory:

M. I. Eides Phys. Lett. B **795** (2019) 113

$\nu_{\mathrm{HFS}}(\mathrm{theory})$ 4463.302 868 (515) MHz [120 ppb]

$\nu_{\mathrm{HFS}}(\mathrm{QED})$ 4463.302 720 (511) (70) (2) MHz

(m_μ/m_e) (QED) (α)

$\nu_{\mathrm{HFS}}(\mathrm{weak})$ -65 Hz

$\nu_{\mathrm{HFS}}(\mathrm{had.\ v.p.})$ 232 (1) Hz

$\nu_{\mathrm{HFS}}(\mathrm{had.\ h.o.})$ 5 (2) Hz

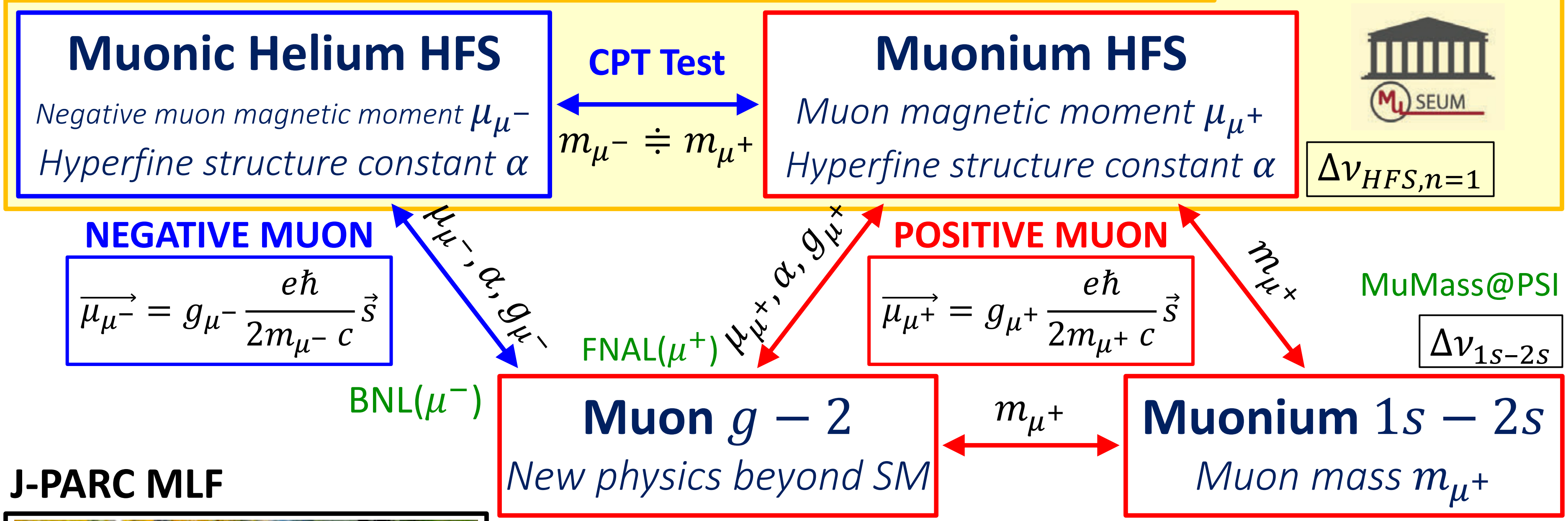
$$\nu(\mathrm{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \boxed{\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}}$$

QED calculation: Effort for 10 Hz accuracy in progress (by Eides *et al.*)

Muon Precision Measurement @ J-PARC MLF

MuSEUM

Diagram borrowed from Klaus Jungmann



Muonic Helium HFS

Negative muon magnetic moment μ_{μ^-}

Hyperfine structure constant α

CPT Test

$m_{\mu^-} \doteqdot m_{\mu^+}$

Muonium HFS

Muon magnetic moment μ_{μ^+}

Hyperfine structure constant α

MuSEUM

$\Delta\nu_{HFS,n=1}$

NEGATIVE MUON

$$\overrightarrow{\mu_{\mu^-}} = g_{\mu^-} \frac{e\hbar}{2m_{\mu^-} c} \vec{s}$$

$\mu_{\mu^-}, \alpha, g_{\mu^-}$

BNL(μ^-)

FNAL(μ^+)

$\mu_{\mu^+}, \alpha, g_{\mu^+}$

POSITIVE MUON

$$\overrightarrow{\mu_{\mu^+}} = g_{\mu^+} \frac{e\hbar}{2m_{\mu^+} c} \vec{s}$$

m_{μ^+}

MuMass@PSI

$\Delta\nu_{1s-2s}$

Muon $g-2$

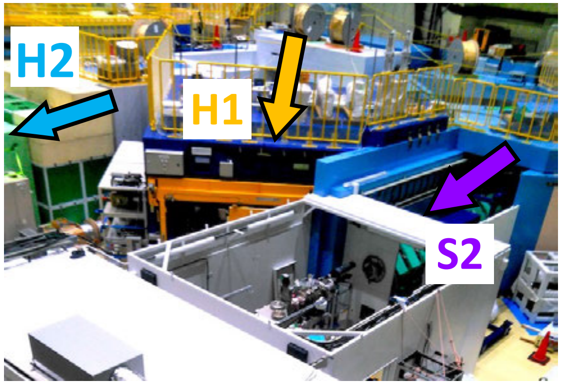
New physics beyond SM

m_{μ^+}

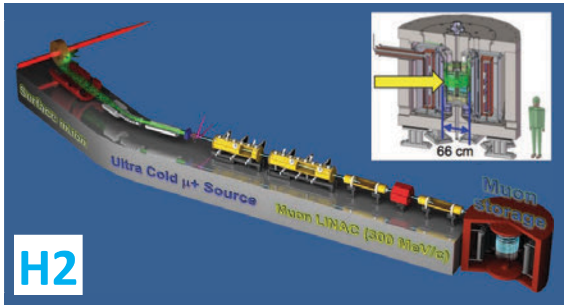
Muonium $1s-2s$

Muon mass m_{μ^+}

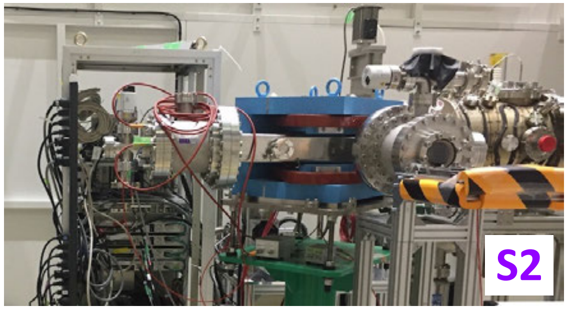
J-PARC MLF



J-PARC Muon *g*-2/EDM



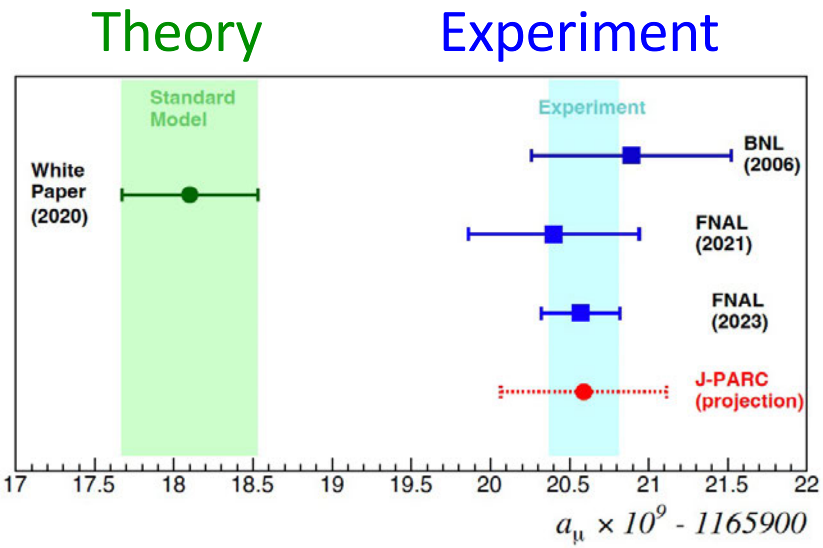
J-PARC Muonium $1s-2s$



Relation between Muon g–2 & MuHFS

Muon $g-2$ $\quad a_\mu = \frac{g-2}{2}$

- 5σ discrepancy between theory and exp.
- Exp. precision value: 0.2 ppm (FNAL 2023)
- Exp. goal at J-PARC and FNAL: ~0.1 ppm
- Independent precise measurement of muon mass required !
  - ➢ Exp. value obtained using Muonium HFS result



From Y. Okazaki's Talk at NuFACT2023

$$\boxed{a_\mu = \frac{R}{\lambda - R}}$$

$$\boxed{R \equiv \frac{\omega_a}{\omega_p}} \qquad \boxed{\lambda \equiv \frac{\mu_\mu}{\mu_p}}$$

From g-2 storage ring

From Muonium HFS

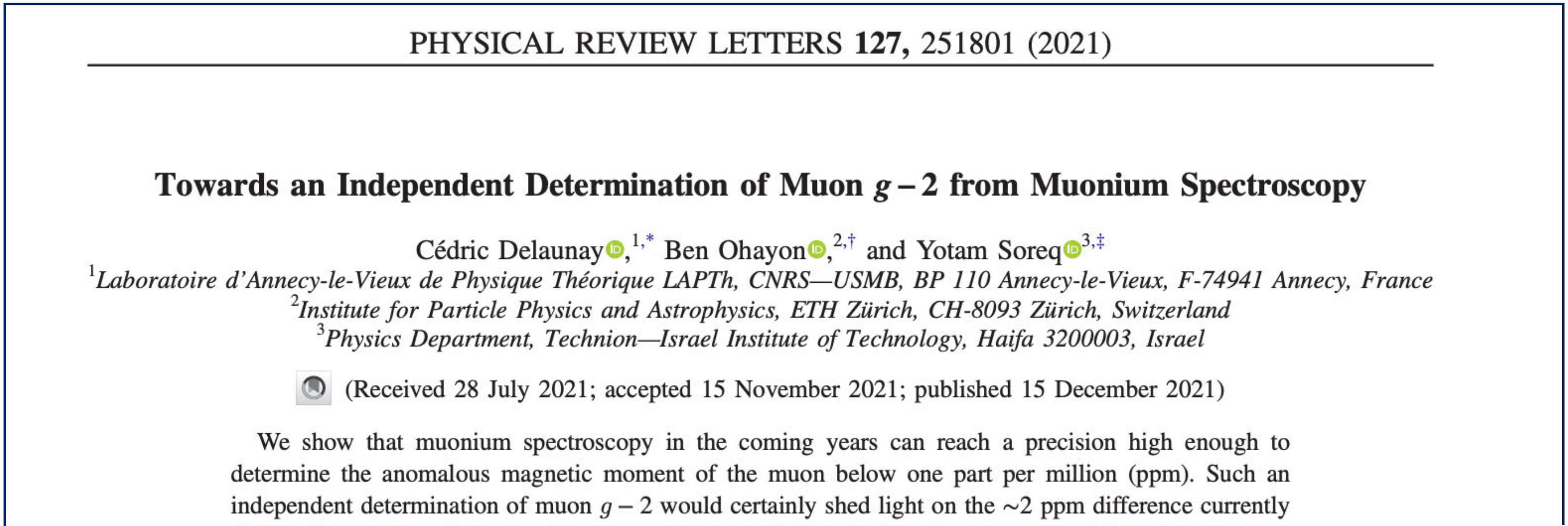
$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu\left(\frac{eB}{mc}\right)}{g_\mu\left(\frac{eB}{2mc}\right)} = \frac{a_\mu}{\left(\frac{g_\mu}{2}\right)} = \underline{\frac{a_\mu}{1+a_\mu}}$$

$$= \frac{\omega_a}{\omega_L(p)}\frac{\omega_L(p)}{\omega_L(\mu)} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_\mu} = \underline{\frac{R}{\lambda}}$$

μ_μ/μ_p accuracy from direct measurement: 120 ppb

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

MuHFS + Mu $1s - 2s$ = $g - 2$



PHYSICAL REVIEW LETTERS **127,** 251801 (2021)

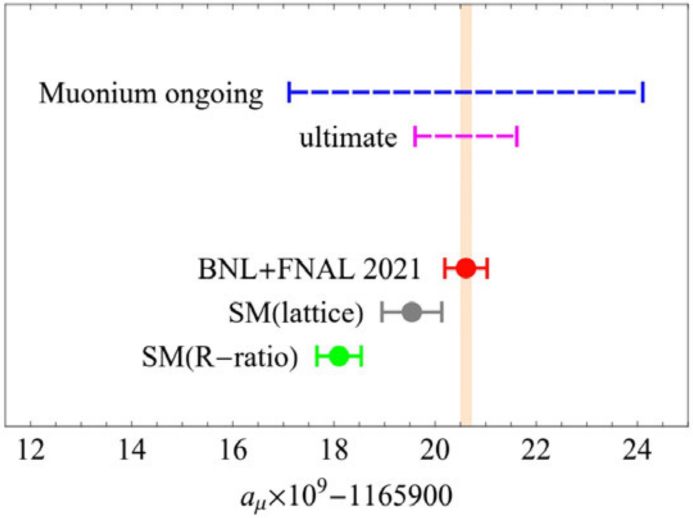
Towards an Independent Determination of Muon $g-2$ from Muonium Spectroscopy

Cédric Delaunay,[1,*] Ben Ohayon,[2,†] and Yotam Soreq[3,‡]
[1]*Laboratoire d'Annecy-le-Vieux de Physique Théorique LAPTh, CNRS—USMB, BP 110 Annecy-le-Vieux, F-74941 Annecy, France*
[2]*Institute for Particle Physics and Astrophysics, ETH Zürich, CH-8093 Zürich, Switzerland*
[3]*Physics Department, Technion—Israel Institute of Technology, Haifa 3200003, Israel*

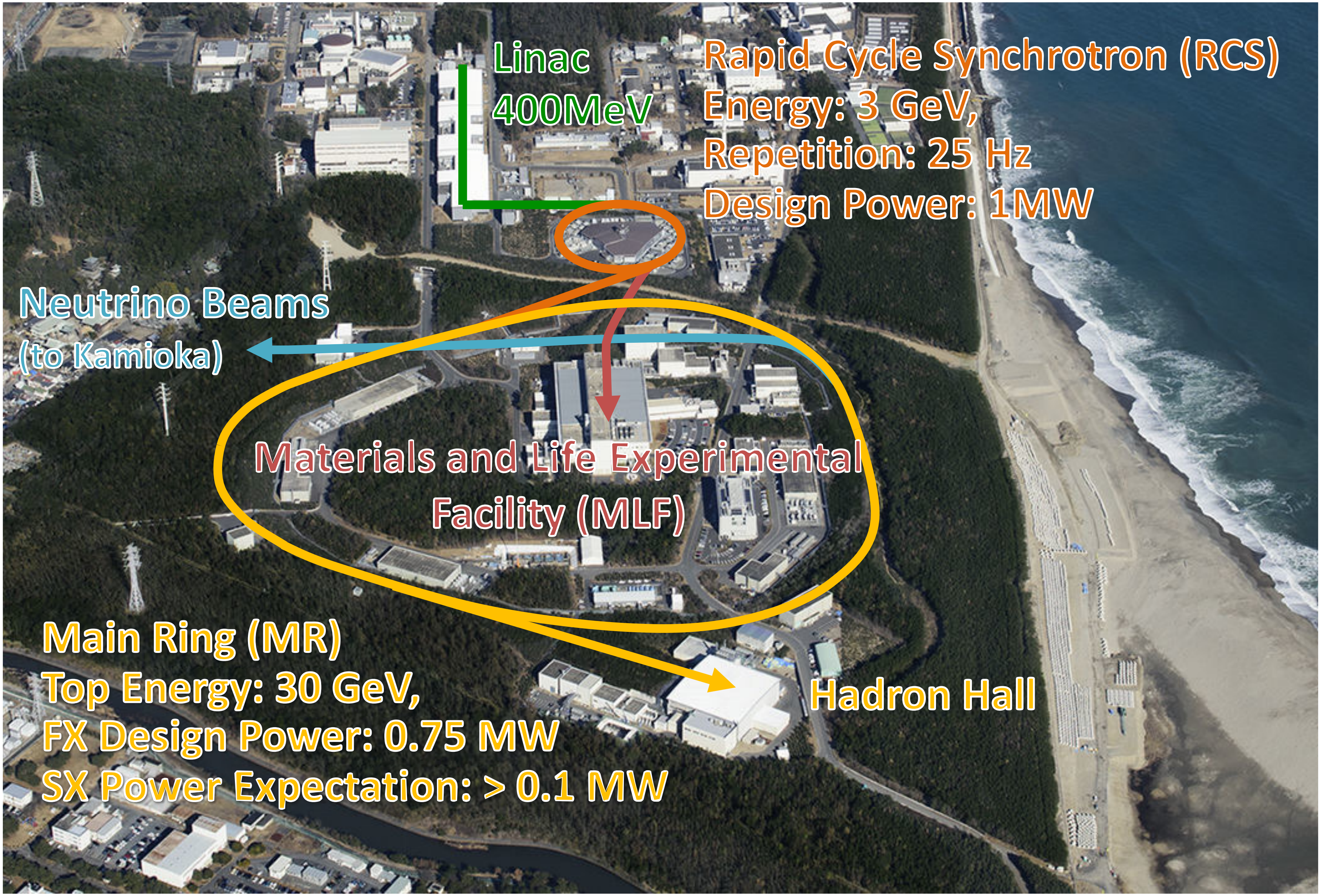
(Received 28 July 2021; accepted 15 November 2021; published 15 December 2021)

We show that muonium spectroscopy in the coming years can reach a precision high enough to determine the anomalous magnetic moment of the muon below one part per million (ppm). Such an independent determination of muon $g-2$ would certainly shed light on the ~2 ppm difference currently observed between spin-precession measurements and (R-ratio based) st
magnetic dipole interaction between electrons and (anti)muons bound in m
splitting (HFS) of the ground state which is sensitive to the muon anomal
comparison of the muonium frequency measurements of the HFS at J-PAR
with theory predictions will allow us to extract muon $g-2$ with high preci
QED calculations of these transitions by about 1 order of magnitude is al
agreement between theory and experiment for the electron $g-2$ indicates
unlikely to affect muonium spectroscopy down to the envisaged precisi

DOI: 10.1103/PhysRevLett.127.251801



J-PARC Facility (KEK/JAEA）



Linac
400MeV

Rapid Cycle Synchrotron (RCS)
Energy: 3 GeV,
Repetition: 25 Hz
Design Power: 1MW

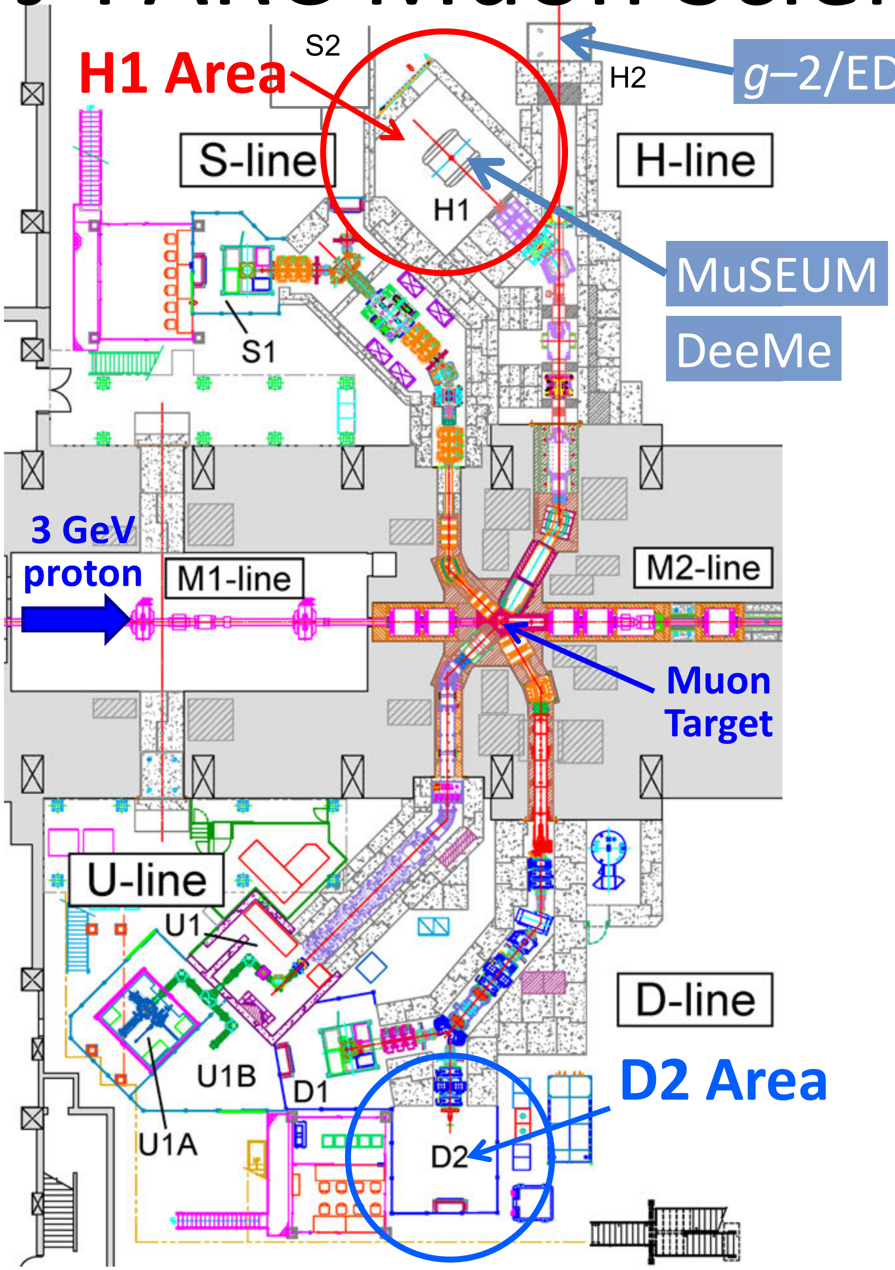
Neutrino Beams
(to Kamioka)

Materials and Life Experimental Facility (MLF)

Main Ring (MR)
Top Energy: 30 GeV,
FX Design Power: 0.75 MW
SX Power Expectation: > 0.1 MW

Hadron Hall

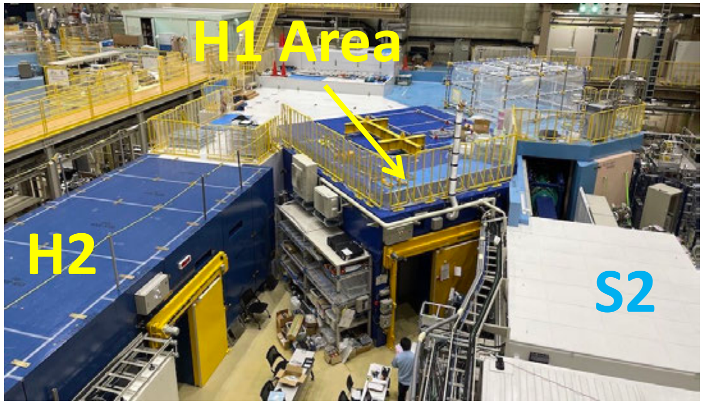
J-PARC Muon Science Facility (MUSE)



Under Commissioning

H-Line: for particle and atomic physics large scale experiments, "precision frontier"

Higher intensity tunable (4 – 50 MeV) μ^+ & μ^- beam.
(Exp.: MuSEUM, Deeme, *g*–2/EDM, …)



MLF Experimental Hall No. 1 (May 2023)

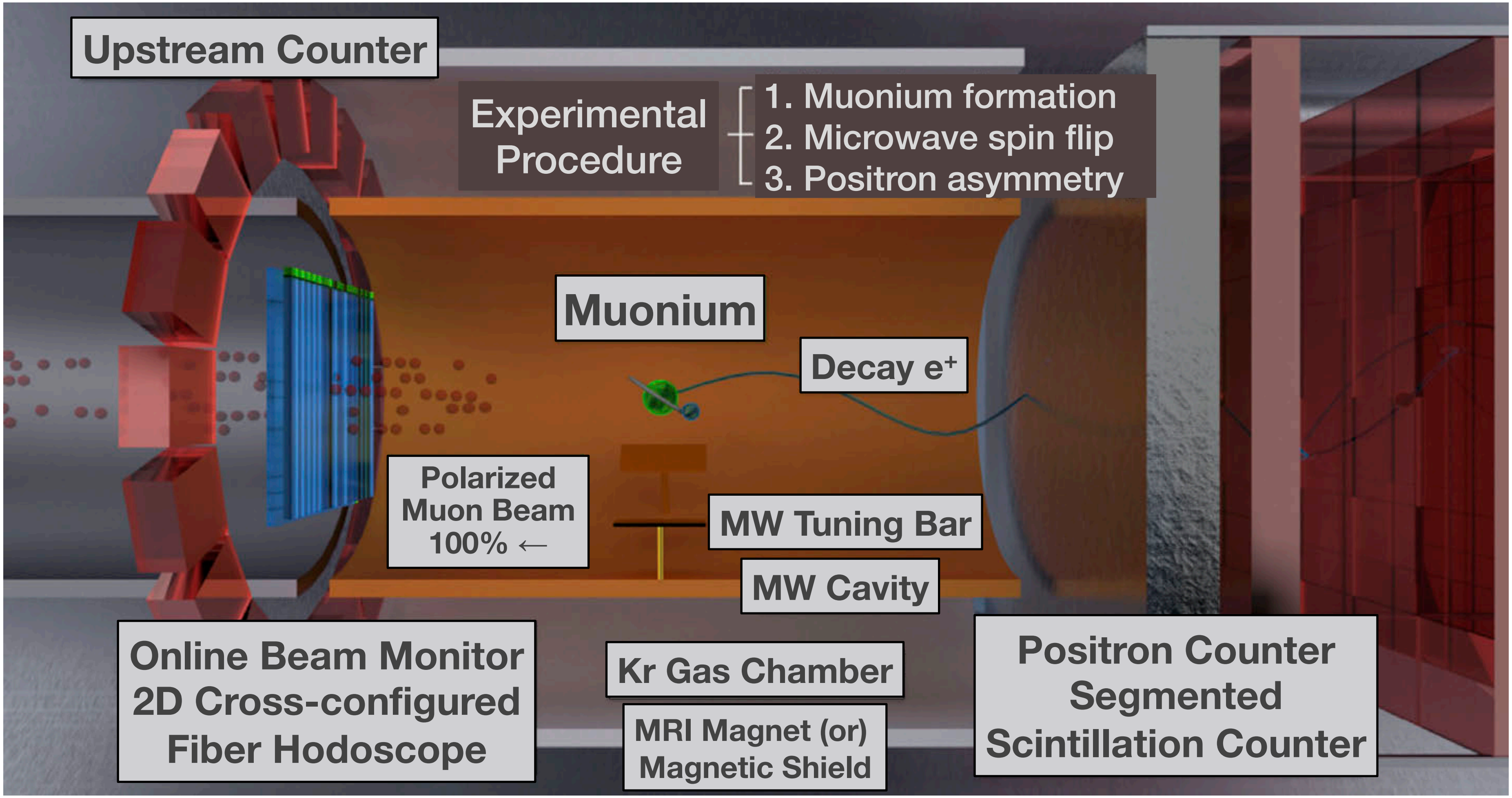
Beamlines in Operation

S-Line: Surface muon (μ^+)
Slow (4 MeV) beam for condensed matter physics.

D-Line: Decay muon (μ^+ & μ^-)
Slow (50 keV) – fast (50 MeV) beam, general purpose.

U-Line: Ultra-slow muon (μ^+)
Ultra-slow (0.1 – 30 keV) beam for near-surface condensed matter physics, chemistry, etc.

MuSEUM Setup



$$\boxed{\text{Signal} = \frac{N_{ON} - N_{OFF}}{N_{OFF}}}$$

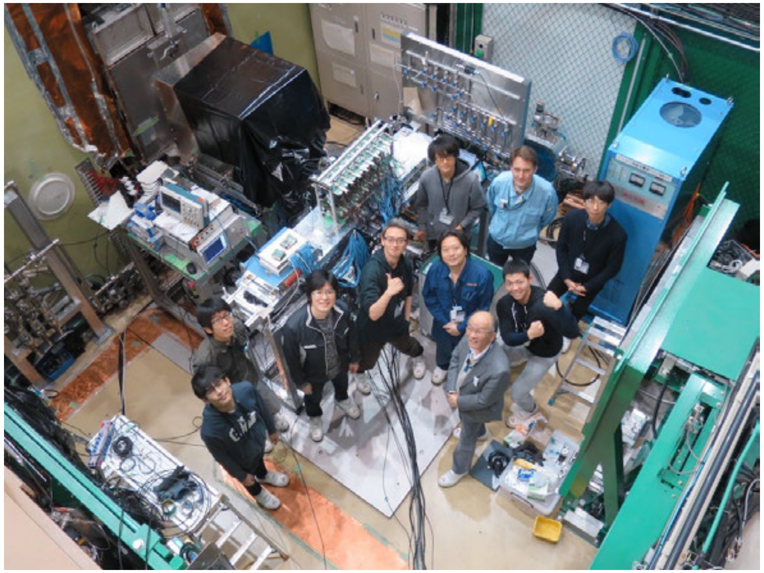
N_{ON} : number of positrons when microwave ON

N_{OFF} : number of positrons when microwave OFF

MuSEUM Experiment Timeline

2017

- Mu HFS resonance measured at **zero field** and Kr 1 atm

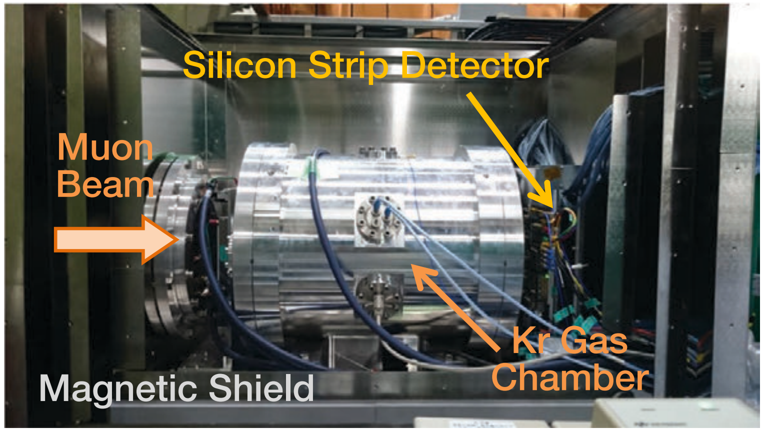


2018

- Measurements at Kr 0.3, 0.4, 0.7 atm
- Lower pressure than previous experiments
- Development of **Rabi-oscillation spectroscopy**

2019

- Measurement with Kr-He mixture gas
- Upgrade with **silicon strip detector**



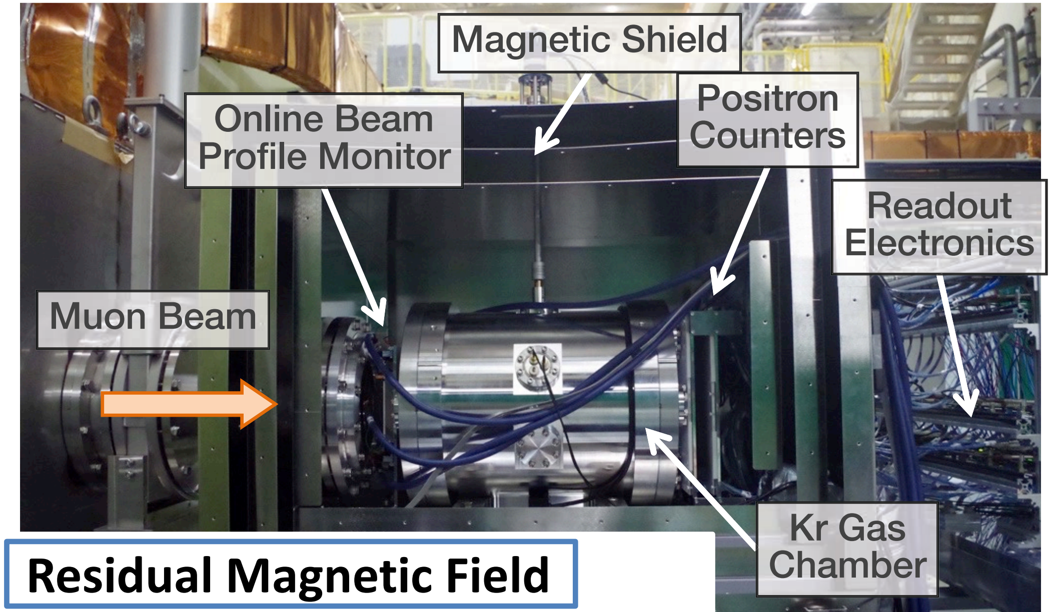
Zero-Field Experiment

2022 ～

- H-line commissioning …
- Preparation for high-field experiment …

MuSEUM Zero-Field Experiment

Experimental Setup


Magnetic Shield

Online Beam Profile Monitor

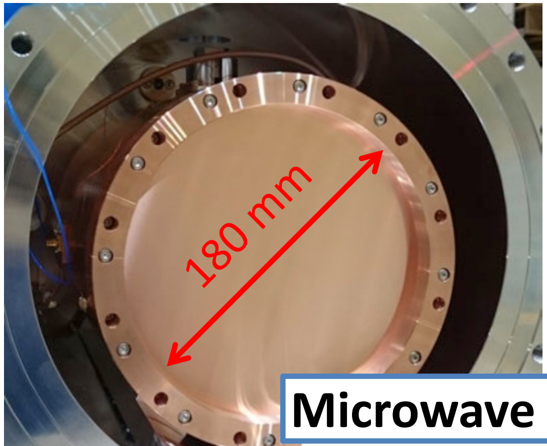
Positron Counters

Readout Electronics

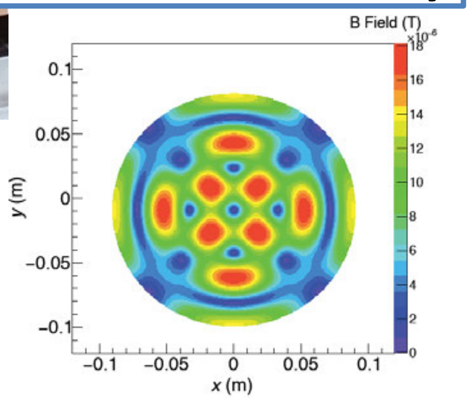
Muon Beam

Kr Gas Chamber

Microwave Cavity for Zero Field


180 mm

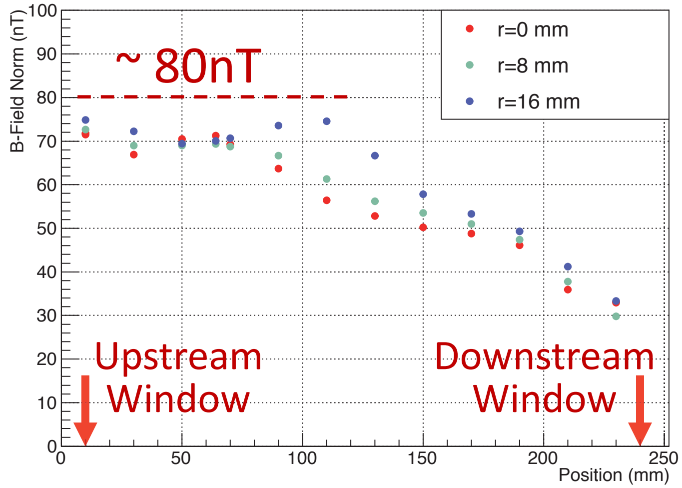
Microwave Intensity



$\Delta\nu$ = 4.463 GHz

TM220 mode
Larger cavity
More muon stop
Q-Value: 20,000 (calc.)

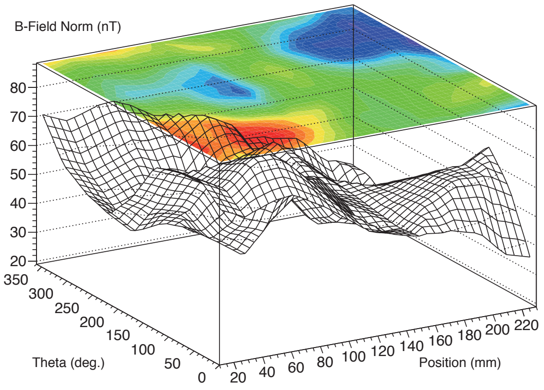
Residual Magnetic Field



~ 80nT

Upstream Window

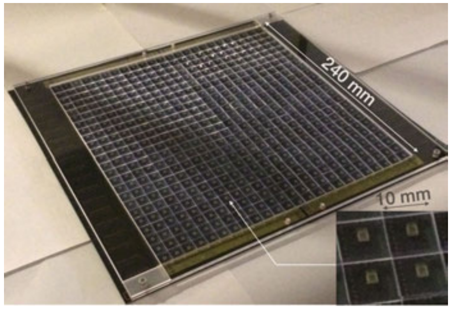
Downstream Window

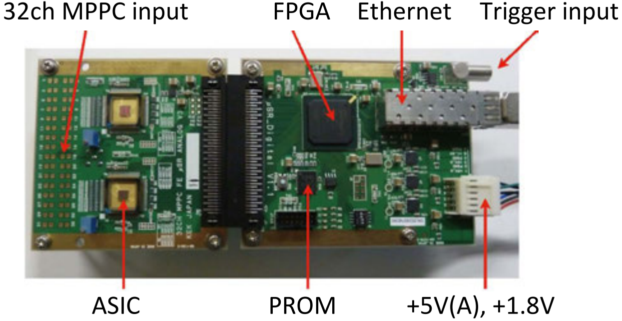


Counter Development

Positron Counter (1)

Segmented Scintillation Detector





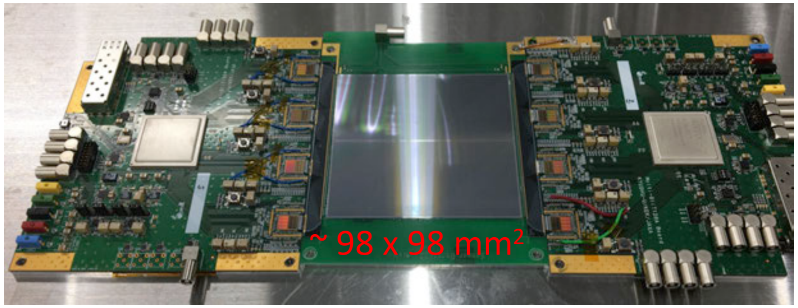
Plastic scintillator + MPPC(SiPM) + Kaliope readout circuit

- Unit cell: 10 mm × 10 mm × 3 mm^t
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch

- High-rate capability
- Pileup loss at 3 MHz/ch ~ 2%

Positron Counter (2)

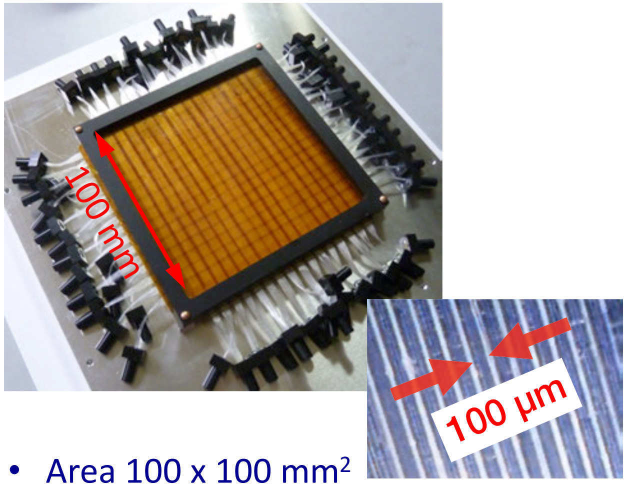
Silicon Strip Detector



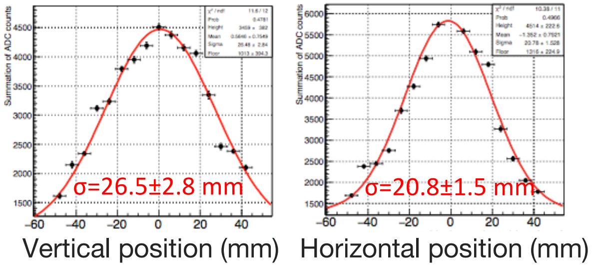
- Readout chips (SliT128A, 128 ch/chip)
- Developed for J-PARC g−2/EDM experiment
- Highly-segmented
- High-rate capability (S/N ~ 21)

- Strip pitch: 0.19 mm
- Strip length: 48.575 mm
- No. of strips: 512 x 2 blocks
- Thickness: 0.32 mm

Muon Beam Profile Monitor



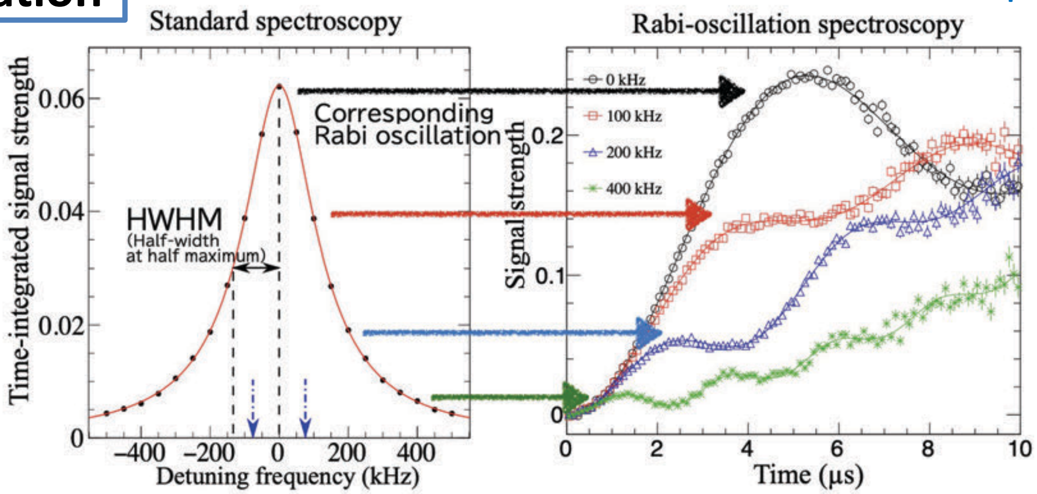
- Area 100 x 100 mm^2
- 100-μm fiber hodoscope (16 ch x 2)
- 3 x 3mm^2 active area MPPC with 15-μm pixel pitch
- EASIROC readout

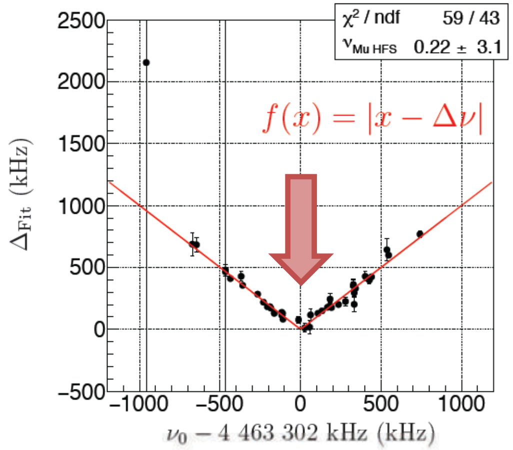


Rabi-Oscillation Spectroscopy Method

Simulation

Developed by Shoichiro Nishimura (KEK)

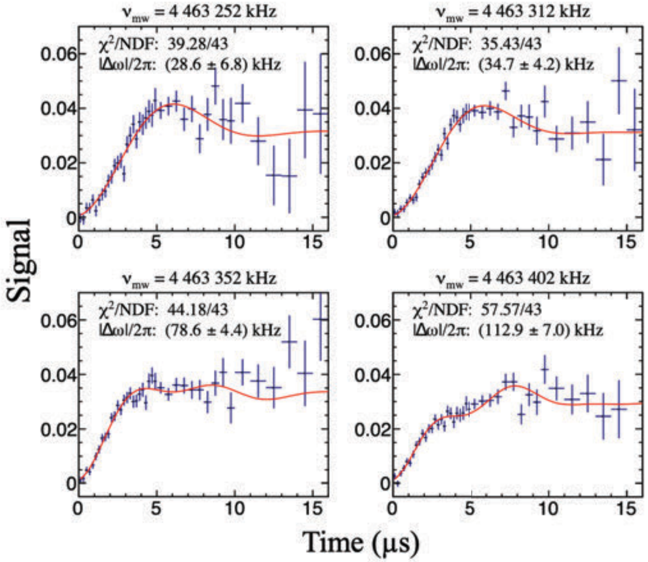




$\Delta\nu_{\mathrm{HFS}}(0)$ = 4 463 301.61(71) (160 ppb)

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

Experiment (2017 June)

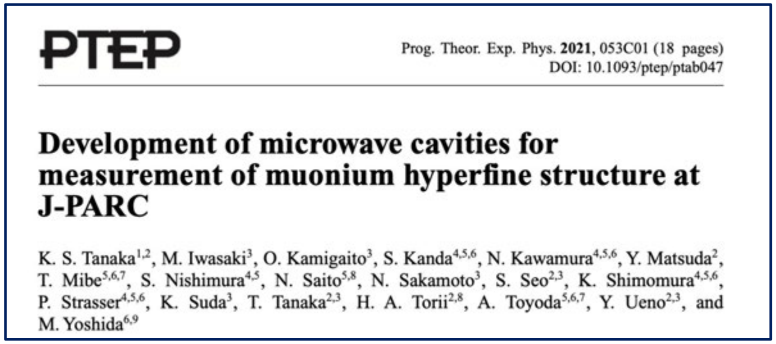


Advantages:

- Each detuning frequency data fitted individually
- Can determine $\Delta\nu_{\mathrm{HFS}}$ with only one frequency data
- **Can improve statistical uncertainty by 3.2 times** compared to the conventional method
- Can **reduce systematics** due to **microwave power** variation (free fitting parameter)
- Need fast detector and high-statistics data

MuSEUM Recent Publications

❖ Zero-Field and High-Field Microwave Cavity

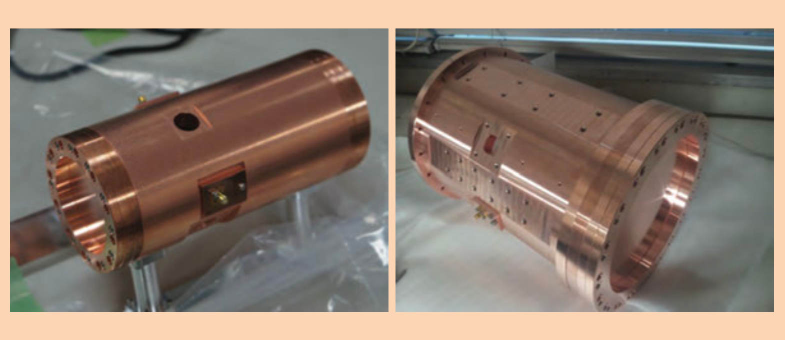


PTEP

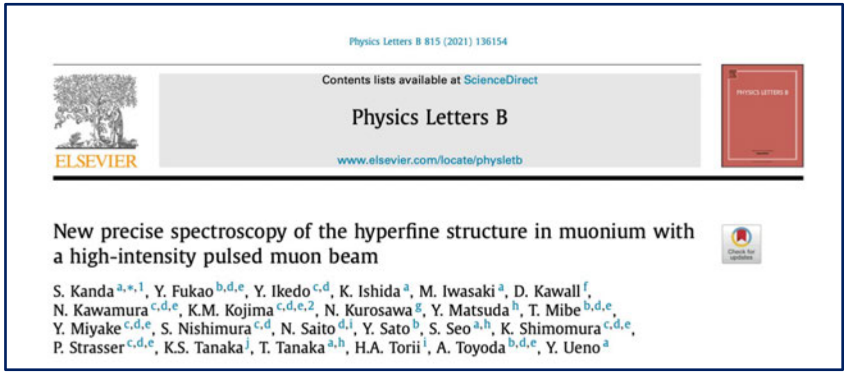
Prog. Theor. Exp. Phys. **2021**, 053C01 (18 pages)
DOI: 10.1093/ptep/ptab047

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

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



❖ Zero-Field Experimental Setup and First Result



Physics Letters B 815 (2021) 136154

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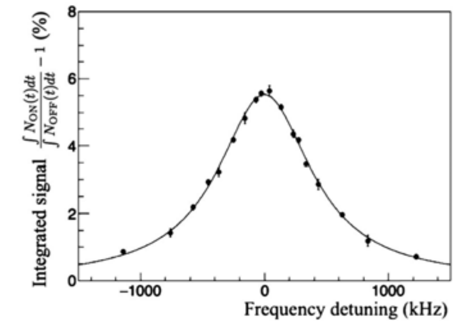
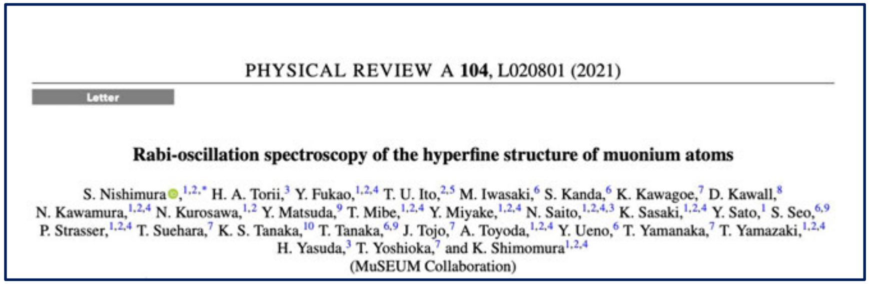
ELSEVIER

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]



❖ Rabi-Oscillation Spectroscopy

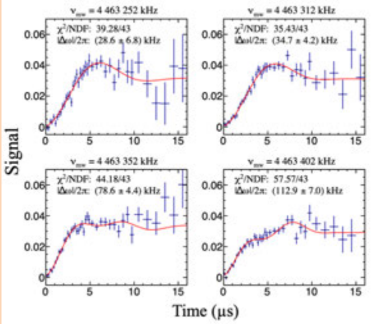


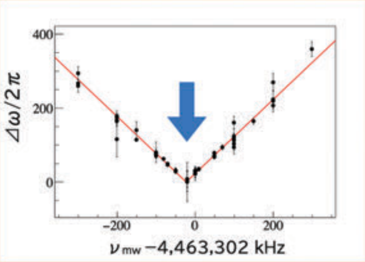
PHYSICAL REVIEW A **104**, L020801 (2021)

Letter

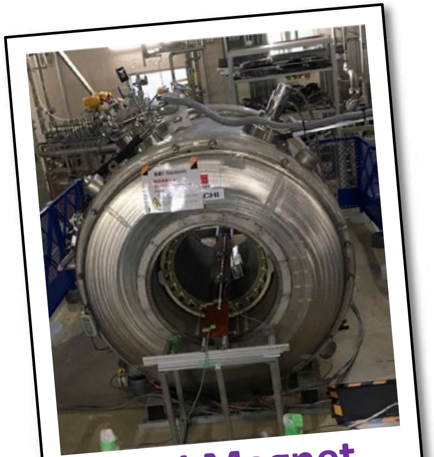
Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms

S. Nishimura,[1,2,*] H. A. Torii,[3] Y. Fukao,[1,2,4] T. U. Ito,[2,5] M. Iwasaki,[6] S. Kanda,[6] K. Kawagoe,[7] D. Kawall,[8]
N. Kawamura,[1,2,4] N. Kurosawa,[1,2] Y. Matsuda,[9] T. Mibe,[1,2,4] Y. Miyake,[1,2,4] N. Saito,[1,2,4,3] K. Sasaki,[1,2,4] Y. Sato,[1] S. Seo,[6,9]
P. Strasser,[1,2,4] T. Suehara,[7] K. S. Tanaka,[10] T. Tanaka,[6,9] J. Tojo,[7] A. Toyoda,[1,2,4] Y. Ueno,[6] T. Yamanaka,[7] T. Yamazaki,[1,2,4]
H. Yasuda,[3] T. Yoshioka,[7] and K. Shimomura[1,2,4]
(MuSEUM Collaboration)

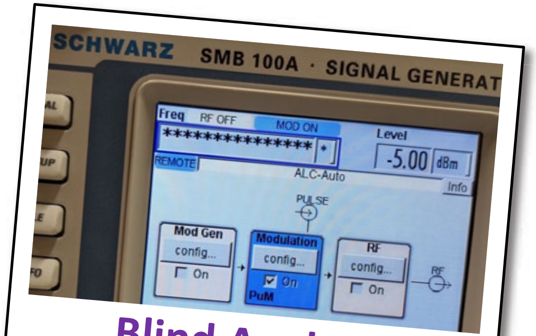




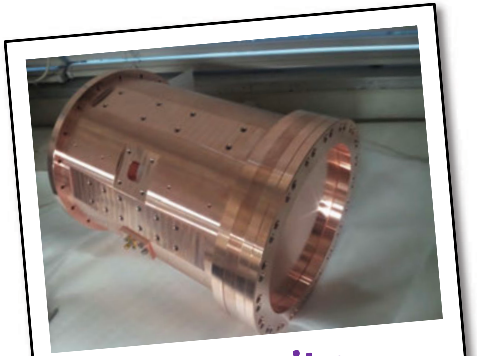
Development for High-Field Experiment



MRI Magnet

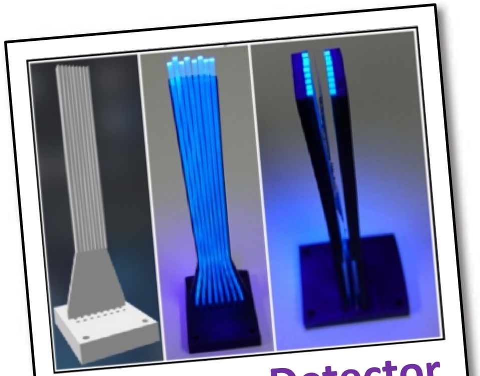


Blind Analysis

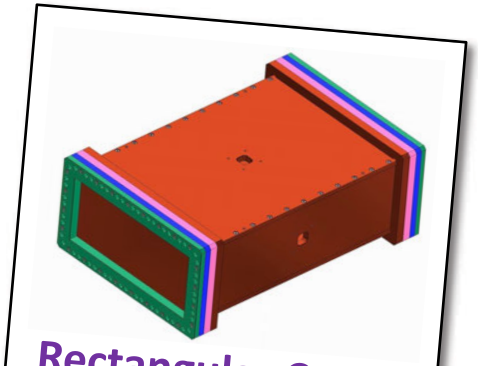


HF Cavity

Magnetic Probes



Upstream Detector



Rectangular Cavity

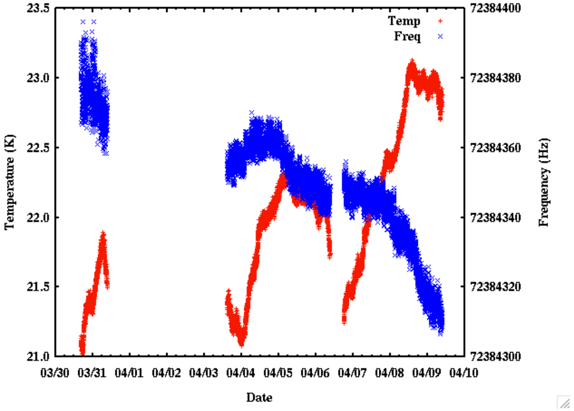
MRI Magnet for High-Field Experiment

Requirements for magnetic field

- 0.2 ppm (peak-to-peak) uniformity
- ±0.1 ppm stability during measurement

Second-hand 2.9 T MRI magnet

Long Term Stability

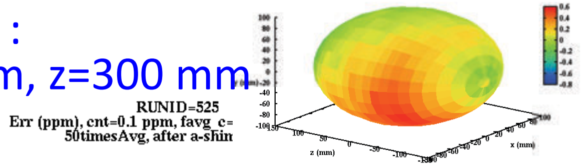


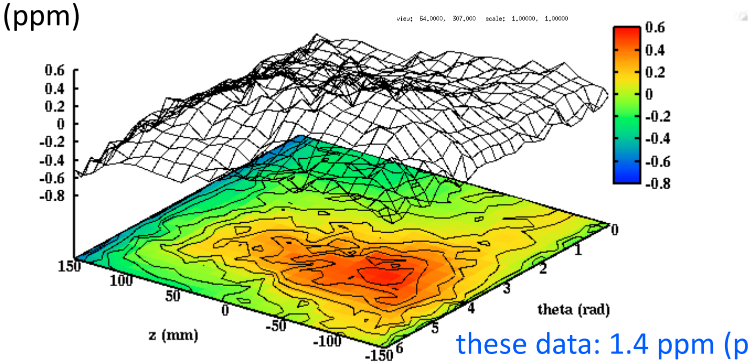
64 Hz / 9.7 days

0.003 ppm /h

Field Homogeneity (after shimming)

Spheroid :
r=100 mm, z=300 mm



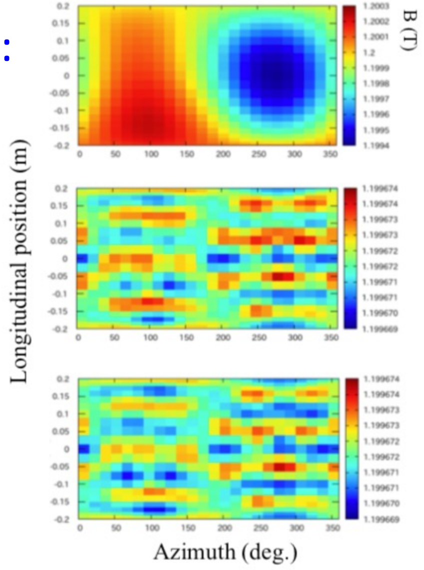


these data: 1.4 ppm (p-p)

Iron shim plates:
341 ppm (p-p)

Nickel films:
0.27 ppm (p-p)
(achieved!)

Magnetic putty:
0.17 ppm (p-p)
(simulation)

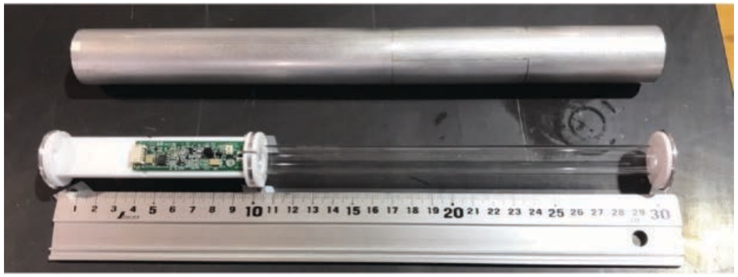


Magnetic Field Probes

Three types of probes are being developed

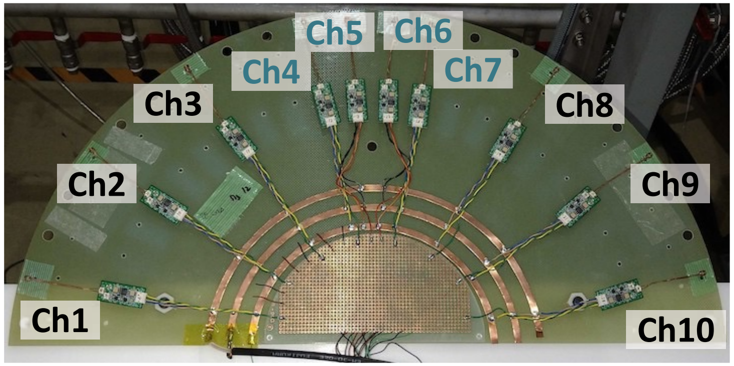
Standard Probe

- CW-NMR field monitoring system
- Precision of **15 ppb** has been achieved



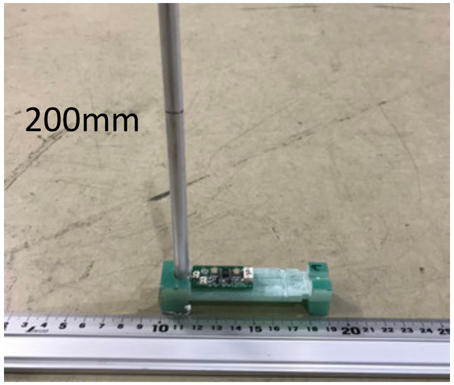
Field Camera

- 24-channels rotating NMR probe to map magnetic fields
- Used for shimming
- 10-channel prototype has been developed



Fixed Probe

- Compact probe to monitor magnetic field stability during experiment

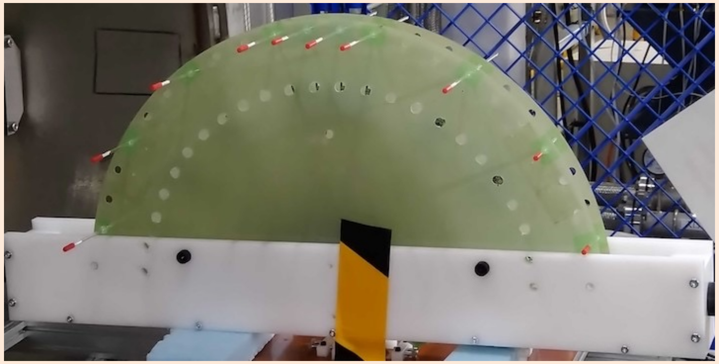


Field Camera

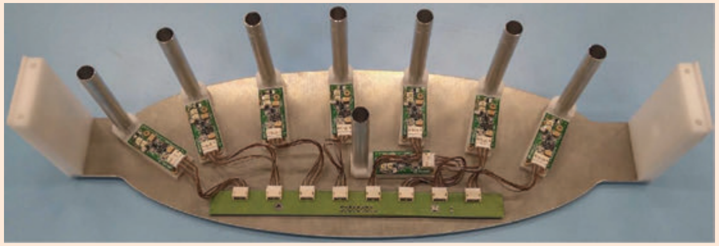
Scanning a sphere with a radius of 25 cm

Developed by Hiroki Tada (Nagoya Univ.)

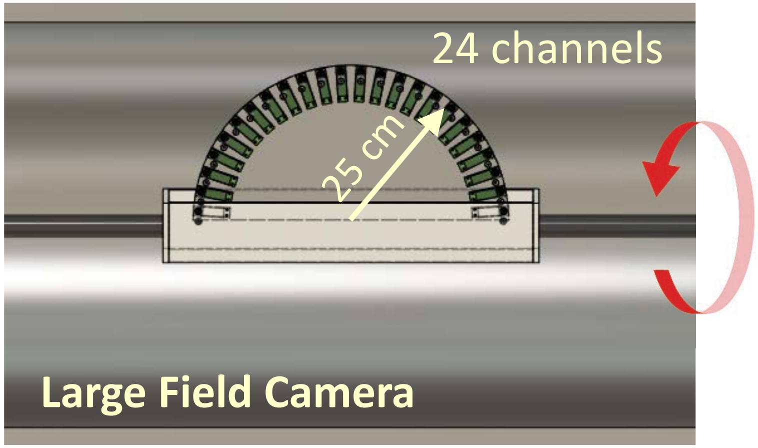
- 24-channel half-circle multi-channel system
- Scanning time: 3 hours (single probe) → 20 minutes (multi-channel system)



10-channel Prototype

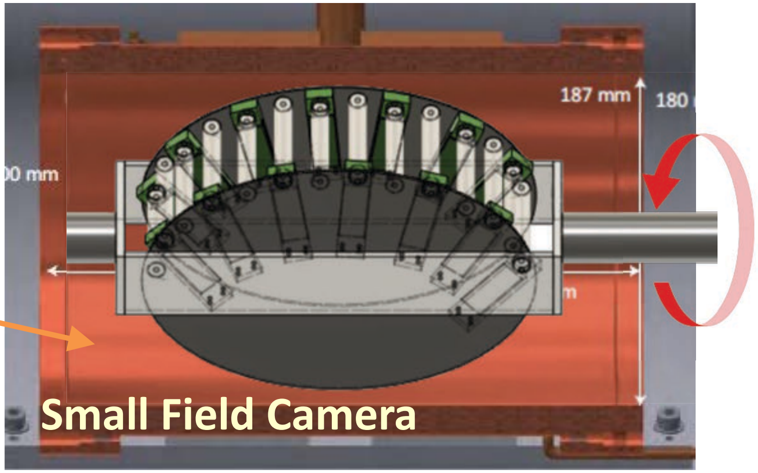


Support Structure



Large Field Camera

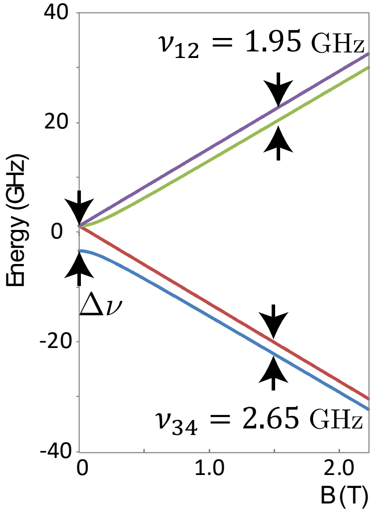
Microwave Cavity

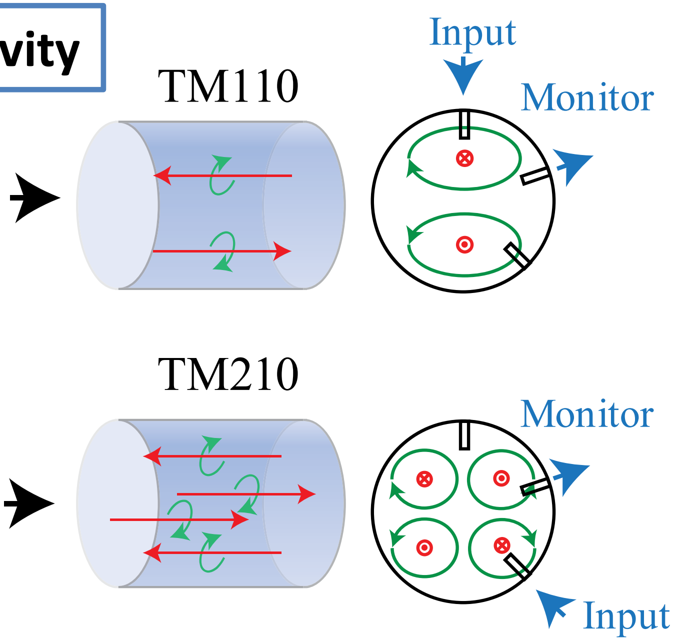


Small Field Camera

High-Field Microwave Cavity

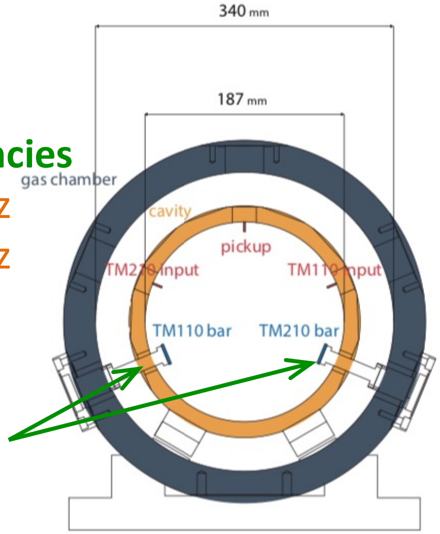
Cylindrical Cavity





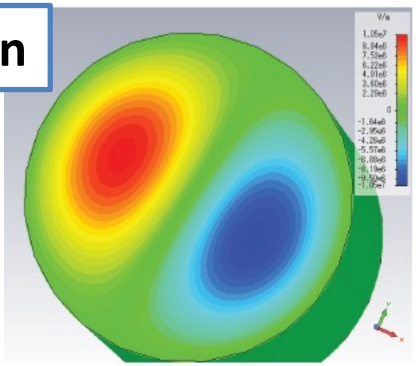
Resonance frequencies

- TM110 : 1.95 GHz
- TM210 : 2.65 GHz



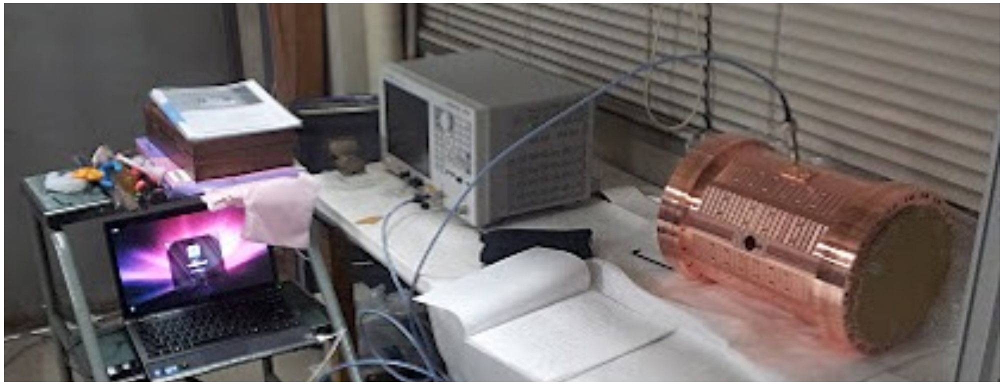
Two tuning bars

MWS Simulation



Cavity Test

Re-tuning in progress !



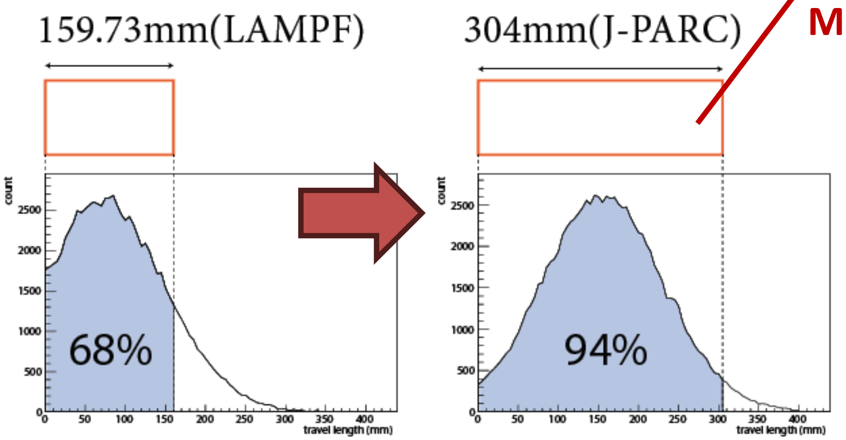
Q Value

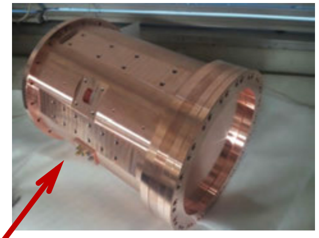
Modes	Q (measured)	Q (simulation)
TM110	1.13×10^4	2.97×10^4
TM210	8.05×10^3	2.89×10^4

Improvement from LAMPF

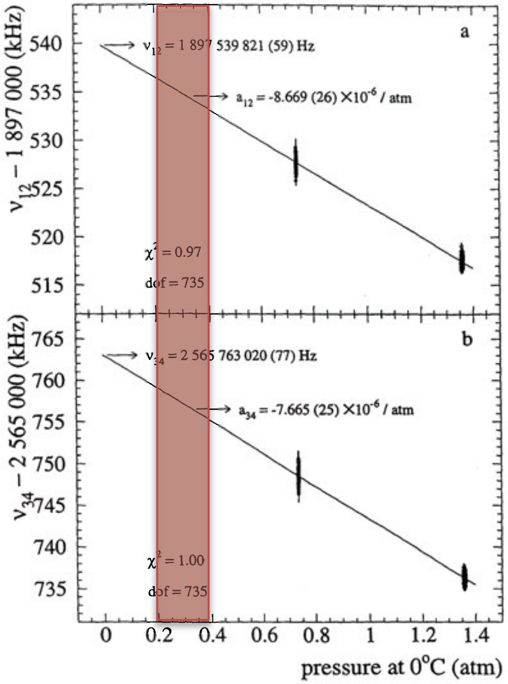
Cavity Length

Muonium distribution at 0.3 atm Kr gas





MuSEUM Cavity



- Muonium transition frequency in gas varies with the gas pressure due to atomic collisions between Mu and Kr
- Previous experiment used fitting of 0.8 and 1.5 atm data only using old quadratic dependence parameter (LAMPF)
- Data at lower pressure needed to improve uncertainty

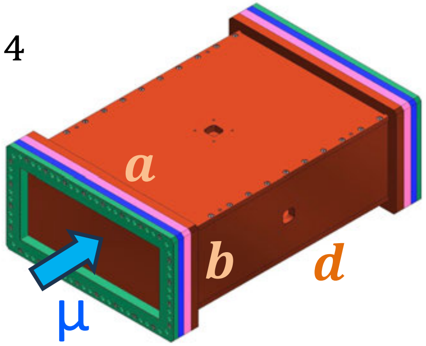
Rectangular Cavity for 2.9 T Measurement

Improve μ_μ/μ_p determination at higher field

Developed by Ryoto Iwai (KEK)

FRIB/MSU

- NMR probe has same accuracy at different magnetic field strengths
- Cylindrical cavity only works where $F_{TM110}/F_{TM210} \approx \nu_{12}/\nu_{34}$

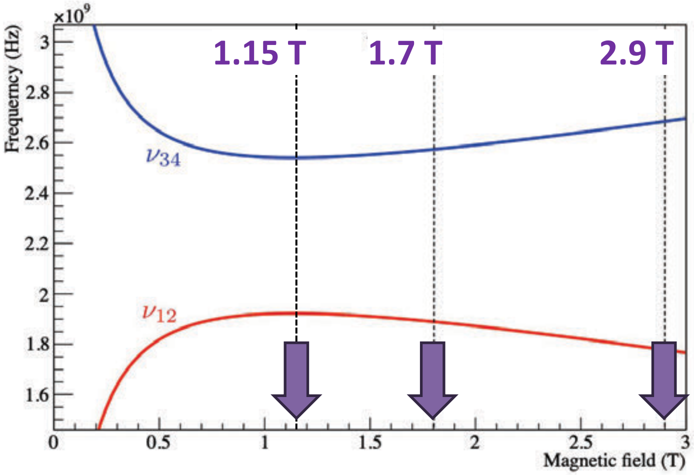


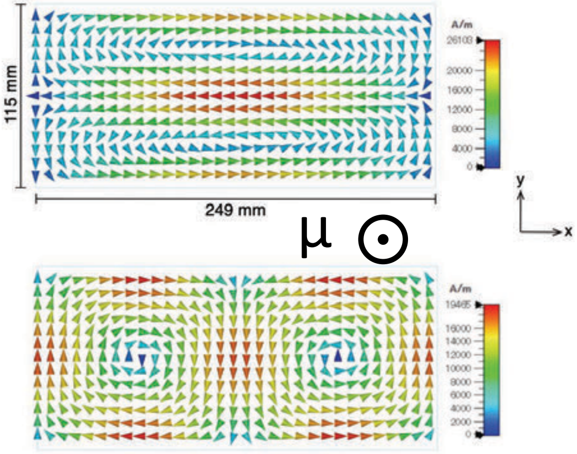
Frequencies	ν_{12} = 1.778 GHz, ν_{34} = 2.686 GHz
Cavity Size	a = 249.19 mm, b = 114.54 mm

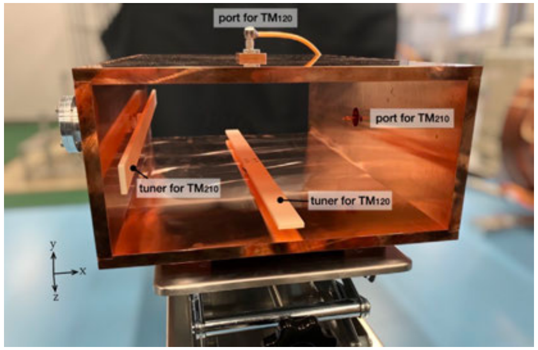
$$F_{mnl} = \frac{c}{2\sqrt{\mu_r\epsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2}$$

c: speed of light
μ_r, ϵ_r: relative permeability and permittivity
m, n, l: mode numbers
a, b, c: cavity dimensions

Cavity design is ongoing!
Prototype constructed and tested





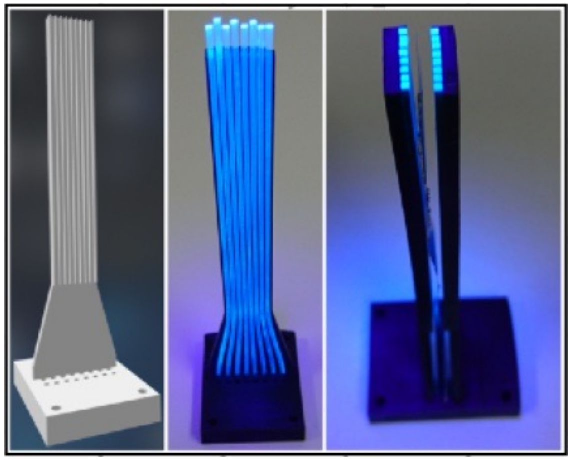


R. Iwai *et al.*, Nucl. Intrum. Meth. A **1064** (2024) 169434

Upstream Detector Development

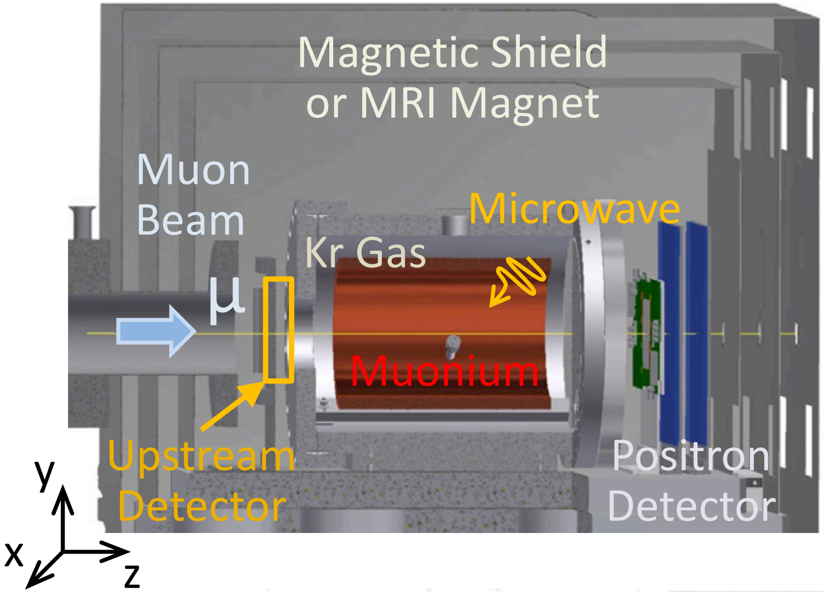
Improve statistics and systematics

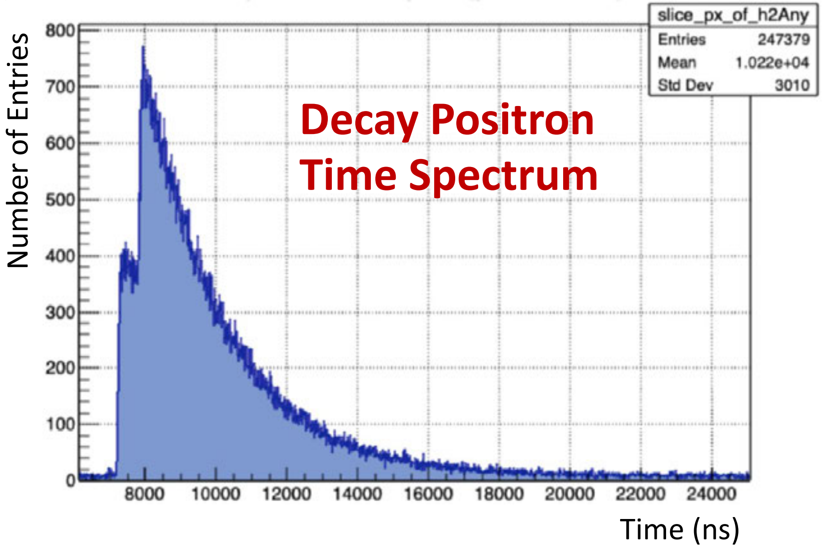
- Increase statistics and measurement of backward/forward asymmetry to study systematic uncertainties
- Fiber scintillation detector with SiPMs



- Prototype unit developed and beam tested at S-line
- Muon decay positron signal observed
- Full-scale detector design completed
- Now under construction

Developed by Hiroki Tada (Nagoya Univ.)





Blind Analysis for MuSEUM

Hidden answer method

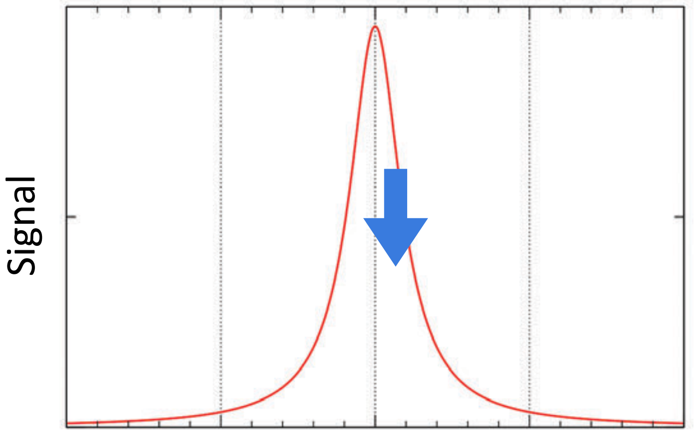
Value to be blinded: injected microwave frequency

- Microwave frequency input by user: $\boldsymbol{\nu_{set}}$
- Blinded offset: $\boldsymbol{\delta}$
- True microwave frequency: $\boldsymbol{\nu_{mw}}$

$$\boxed{\nu_{\mathrm{mw}} = \nu_{\mathrm{set}} + \boldsymbol{\delta}}$$

- δ constant for all $\boldsymbol{\nu_{set}}$ to draw a resonance curve
- If $|\boldsymbol{\delta}| <$ 8kHz
  - ○ blind value sufficient for the target precision
  - ○ rate of change in stored microwave energy < 0.07%

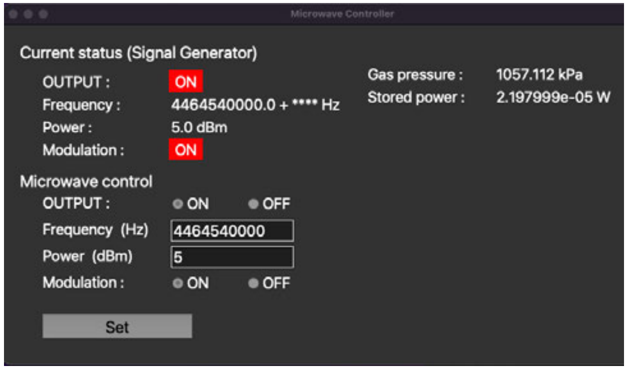
Before opening the blind



$\boldsymbol{\nu_{mw}}$ − 4,463,302 kHz − $\boldsymbol{\delta}$

= $\boldsymbol{\nu_{set}}$ − 4,463,302 kHz

Implemented in Python3



Current status (Signal Generator)

OUTPUT : ON

Frequency : 4464540000.0 + **** Hz

Power : 5.0 dBm

Modulation : ON

Gas pressure : 1057.112 kPa

Stored power : 2.197999e-05 W

Microwave control

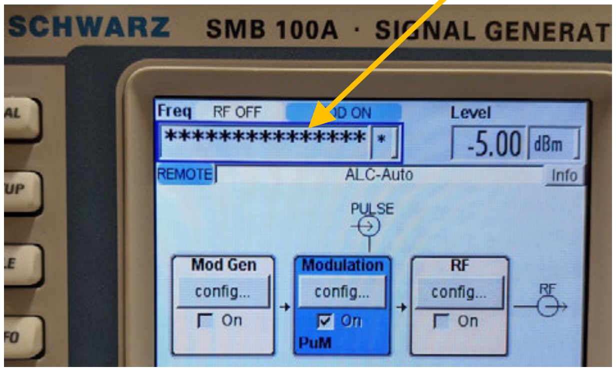
OUTPUT : ○ ON ○ OFF

Frequency (Hz) 4464540000

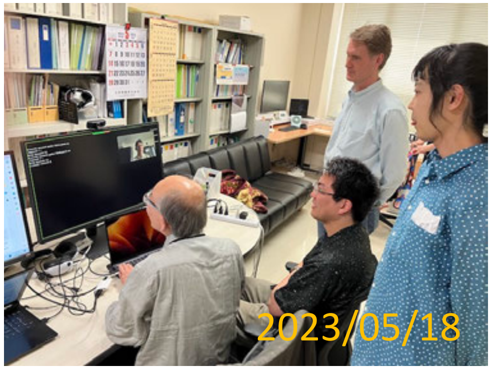
Power (dBm) 5

Modulation : ○ ON ○ OFF

True frequency hidden



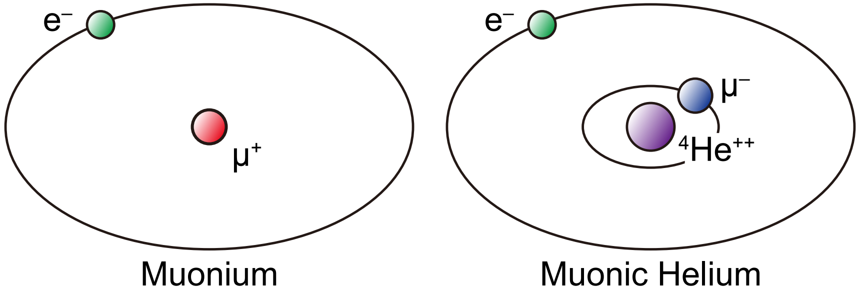
Blind Test (for μHe HFS)



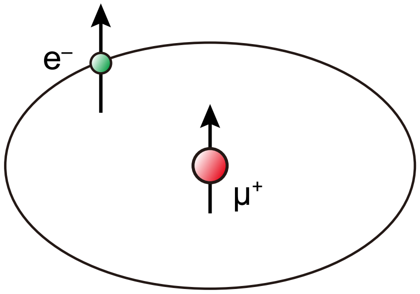
Password protected, safety/protection features to prevent mis-operation

Microwave power and gas pressure are also monitored and recorded

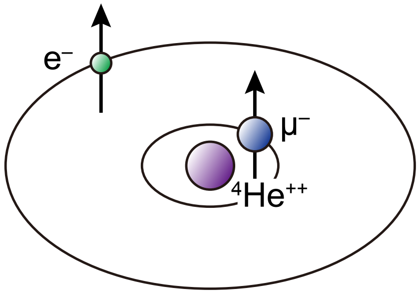
Muonic Helium Atom Hyperfine Structure



Muonic Helium Atom



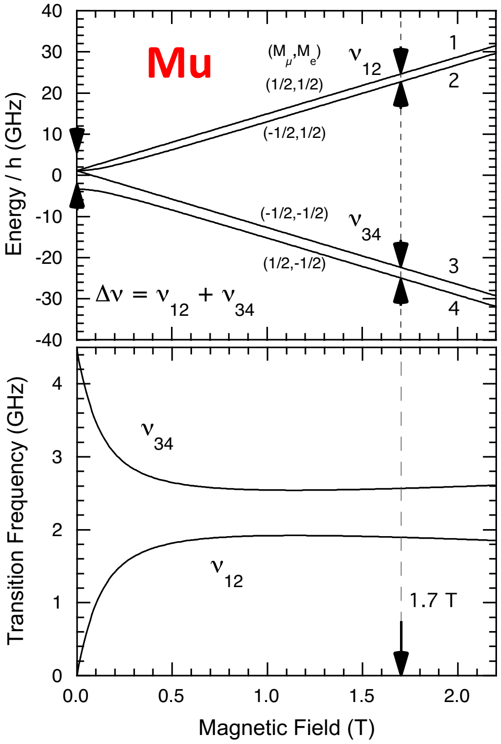
Muonium



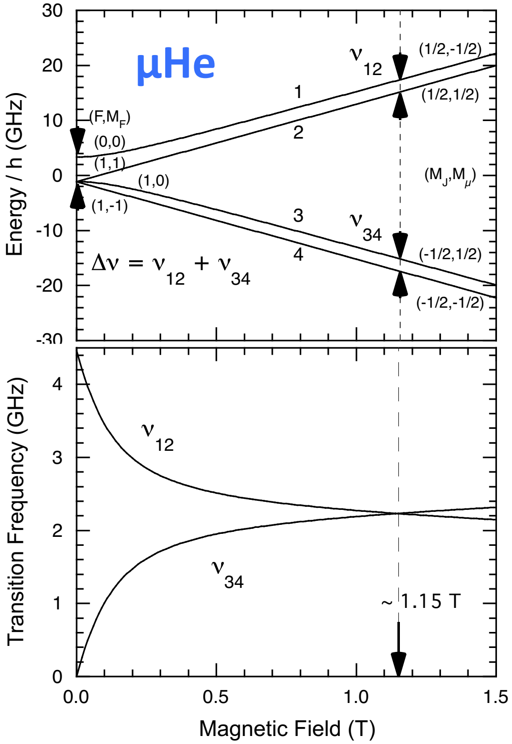
Muonic Helium

- Hydrogen-like atom similar to **muonium**
- Similar ground-state HFS but inverted
- Same technique to measure **μHe** HFS

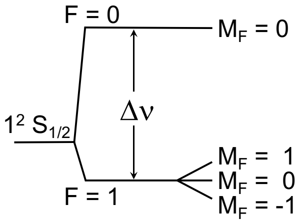
Δν(Mu) = 4463.302765(53) MHz



Δν(μHe) = 4465.004(29) MHz



Breit-Rabi energy level diagrams



Ground-state muonic helium HFS structure and low-field Zeeman splitting

Sensitive tool to …

- test **3-body atomic system** and **bound-state QED**

$$\boxed{\nu_{12} + \nu_{34} = \Delta\nu}$$

- determine **negative muon magnetic moment** and **mass**

$$\boxed{\nu_{34} - \nu_{12} \approx \frac{\mu_{\mu^-}}{\mu_p}}$$

- **CPT test with 2nd generation lepton**

Previous μHe HFS Experiments

Zero Field (SIN)

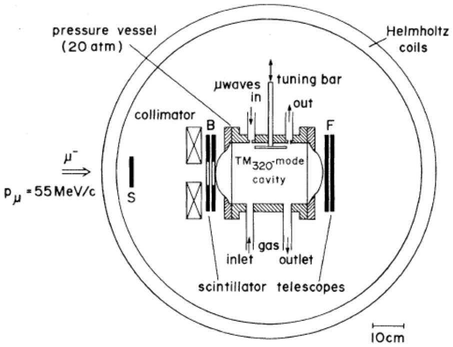


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.

$\Delta\nu$ = 4464.95(6) MHz
[13 ppm]

pressure: 20 atm

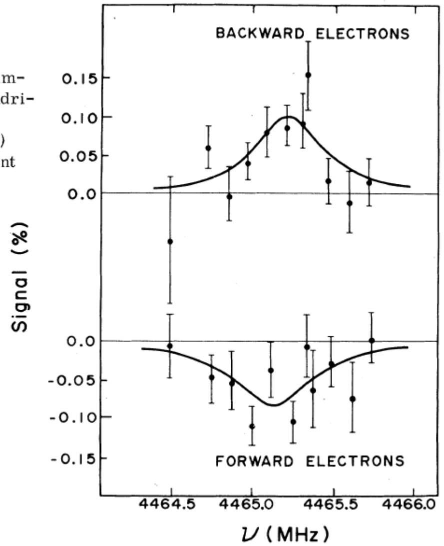


FIG. 3. Resonance curves for the $\Delta F = \pm 1$, $\Delta M_F = \pm 1$ hfs transitions in $({}^4\mathrm{He}^{++}\mu^- e^-)^0$, simultaneously observed in the backward (upper graph) and forward (lower graph) electron telescopes as a function of the microwave resonance frequency.

High Field (LAMPF)

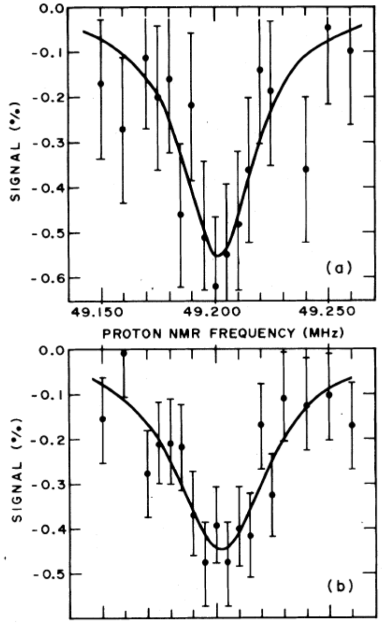


FIG. 1. Typical resonance curves for the ν_{12} transition obtained with the forward telescope at (a) 15 atm and (b) 5 atm. The data for these curves were obtained in (a) 24 h and (b) 100 h. For each curve obtained with the forward telescope there is a corresponding curve for the backward telescope.

pressure: 5 & 15 atm

$\Delta\nu$ = 4465.004(29) MHz
[6.5 ppm]

μ_{μ^-}/μ_p = 3.18328(15)
[47 ppm]

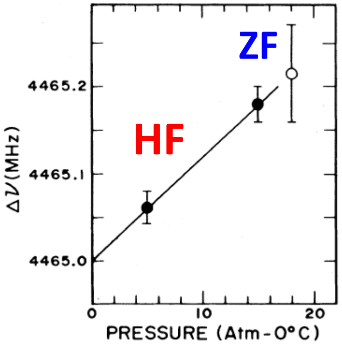


FIG. 2. Δν as a function of He + Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

ZF: H. Orth *et al.*, Phys. Rev. Lett. **45** (1980) 1483
HF: C. J. Gardner *et al.*, Phys. Rev. Lett. **48** (1982) 1168

$\Delta\nu_{HFS}$: Experiment vs. Theory

- Ground state HFS of muonic helium is very similar to muonium.
- In reality, however, muonic helium is complicated because three-body interaction has to be considered, thus limiting the theoretical approach.

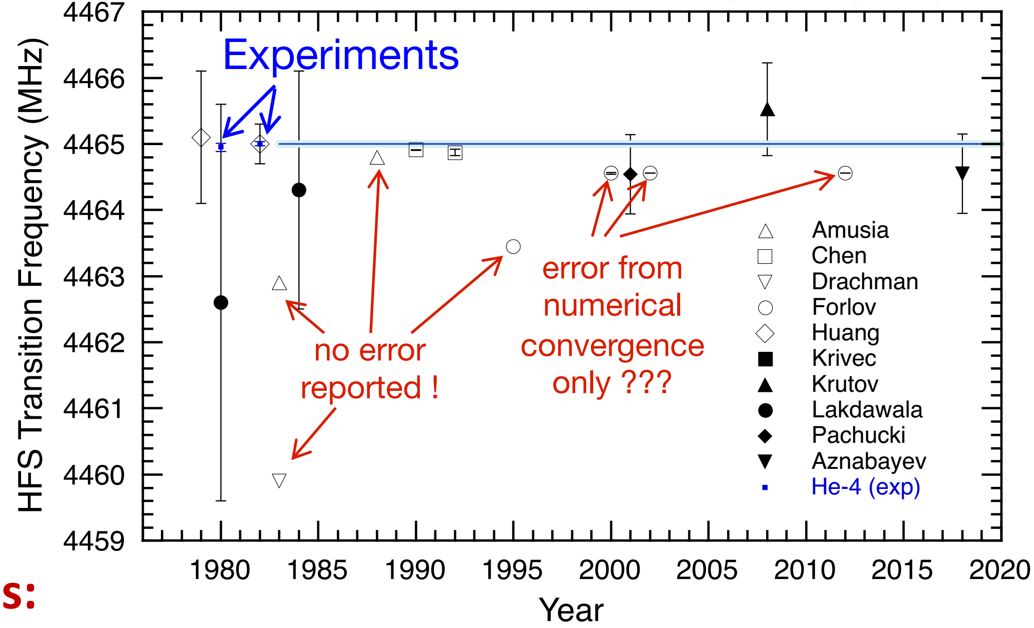
Calculations performed since the 1970s based on perturbation theory (PT), variational approach (VA), and Born-Oppenheimer (BO) theory.

PT: Amusia, Krutov, Lakdawala, …
VA: Aznabayev, Chen, Forlov, Huang, Pachucki, …
BO: Drachman, …

$\Delta\nu$ = 4464.55(60) MHz (135 ppm)

D. T. Aznabayev *et al.*,
Phys. Part. Nucl. Lett. **15** (2018) 236

Muonic Helium-4 HFS ($^4\text{He}^{2+}\mu^-e^-$)



no error reported !

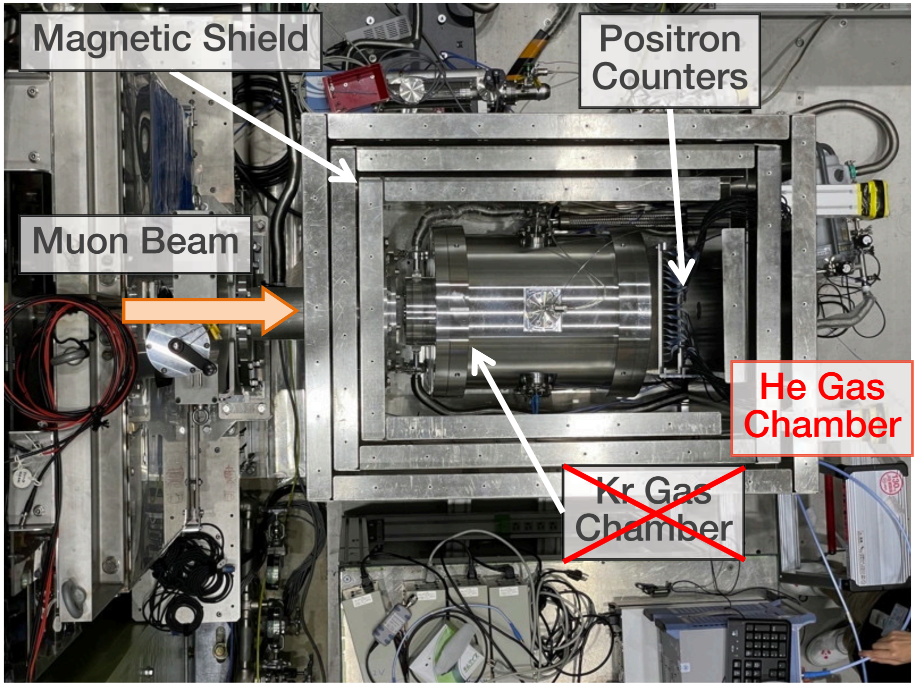
error from numerical convergence only ???

Possible theoretical improvements:

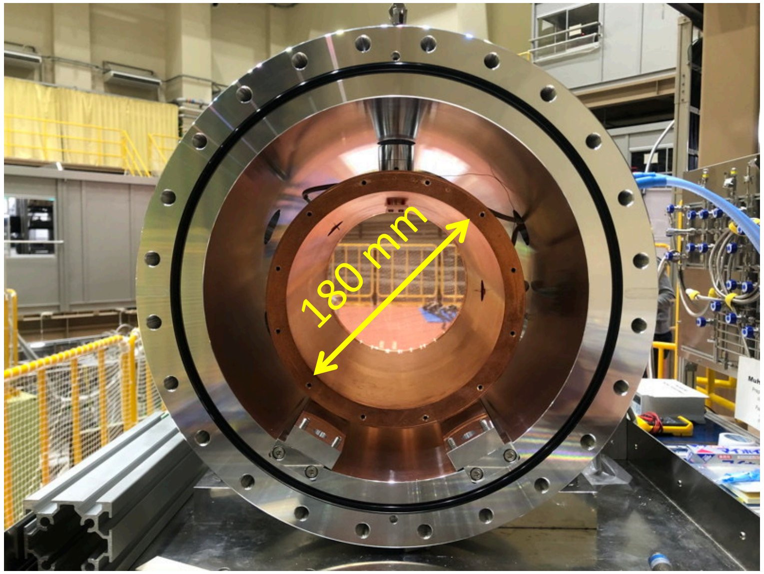
- ➢ QED effects calculation in 3-body systems could be performed more precisely in **higher orders of perturbation theory**. K. Pachucki Phys. Rev. A **63** (2001) 032508
- ➢ Recent calculations developed for HFS in ^{3}He (40-fold improvement): could it be applied to muonic helium HFS ? V. Patkos *et al.*, Phys. Rev. Lett. **131** (2023) 183001

µHe HFS Measurements at Zero-Field

MuSEUM Zero-Field Experimental Setup

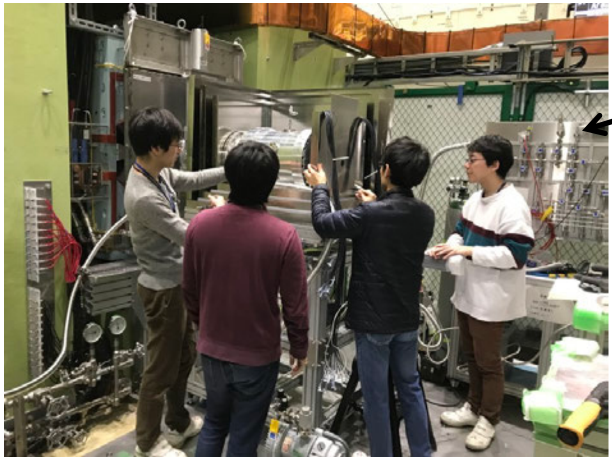


MuSEUM Microwave Cavity (TM220)



~~$\Delta\nu$ = 4.463 GHz~~

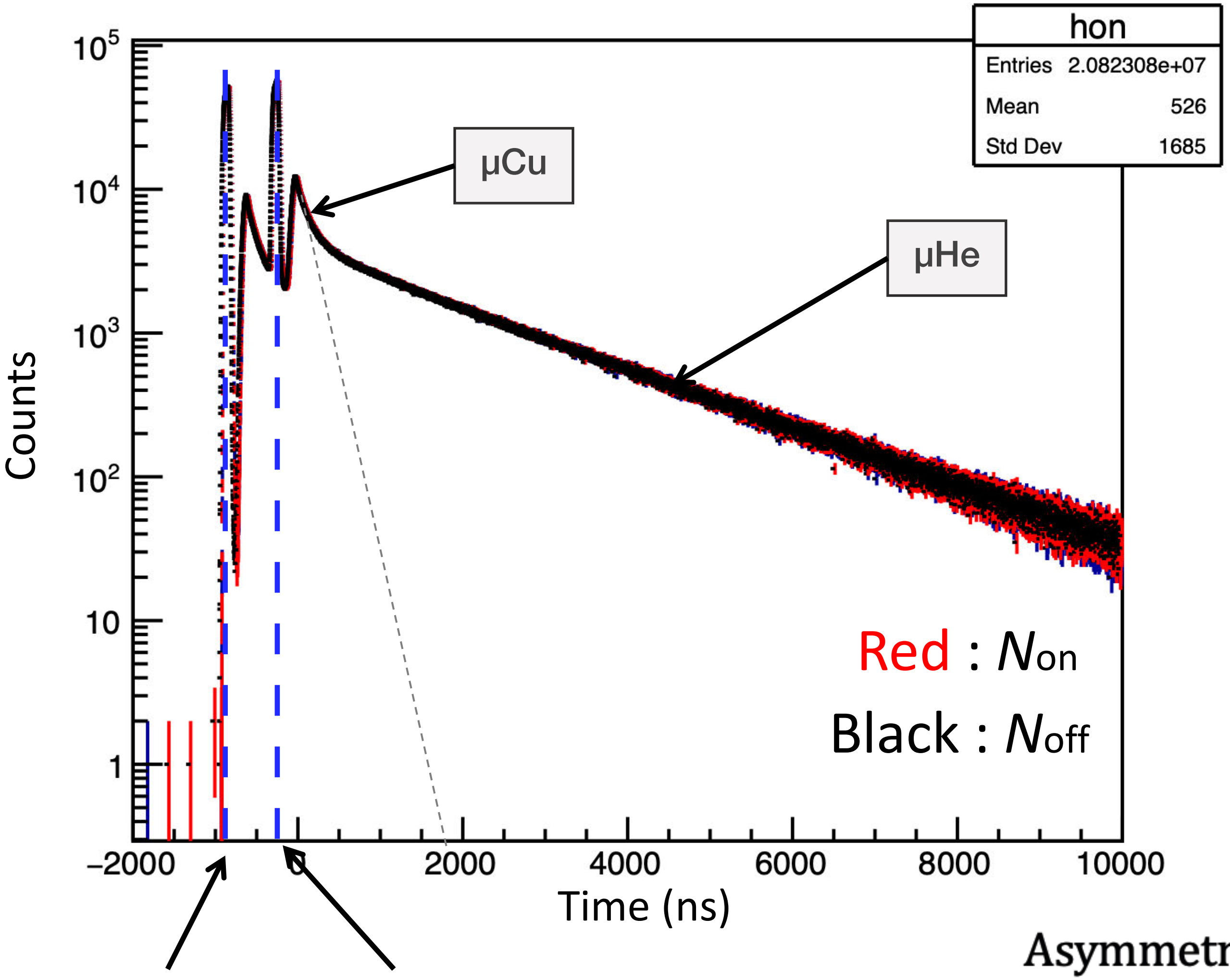
$\Delta\nu$ = 4.465 GHz



Gas Panel

Preparation of MuSEUM apparatus in D2 area at D-line (students from Nagoya University and the University of Tokyo).

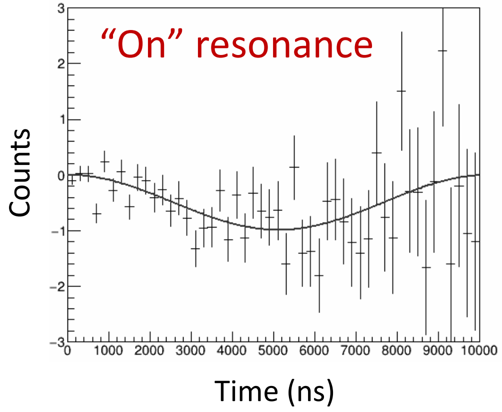
Decay Electron Time Spectra



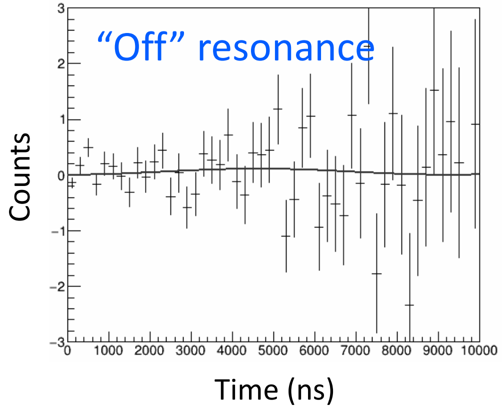
1st muon peak
(-600 ns)

2nd muon peak
(0 ns)

Frequency = 4465000 + 0 kHz



Frequency = 4465000 + 600 kHz



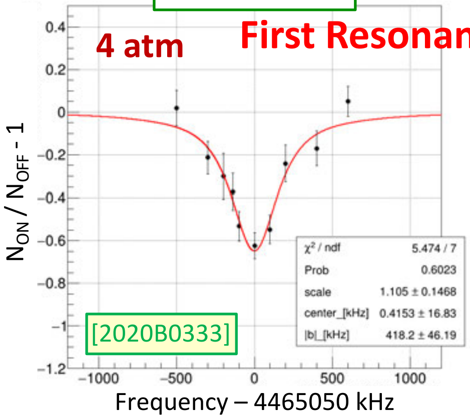
$$\text{Asymmetry} = \frac{N_{\text{off}}}{N_{\text{on}}} - 1$$

N_{on}: Number of detected e^- with microwave

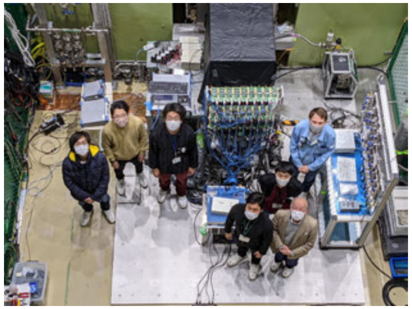
N_{off}: Number of detected e^- without microwave

μHe HFS Resonance Curve

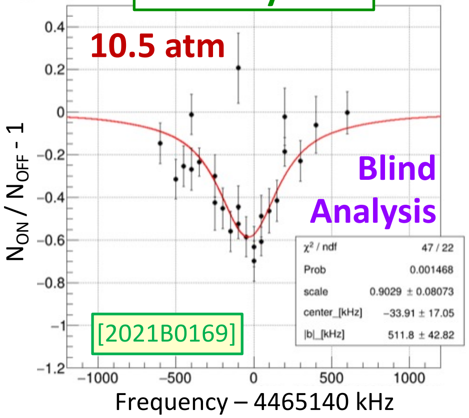
March 2021



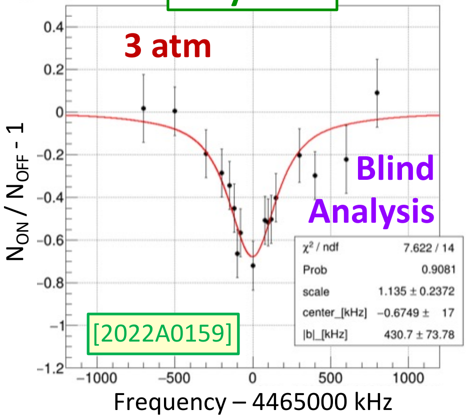
First Resonance Observed

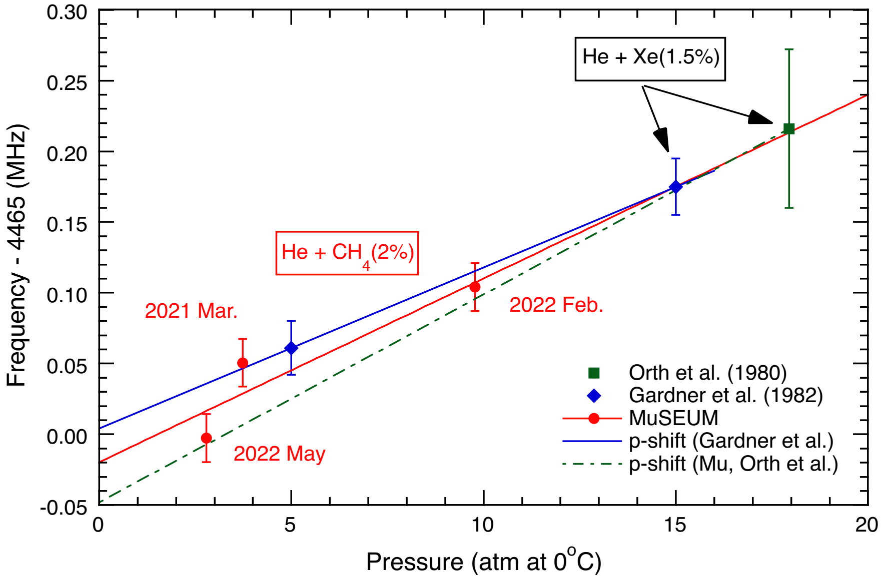


February 2022



May 2022





Time cut: electron data from 1.6 μs after second μ⁻ pulse !

ZF: H. Orth et al., PRL **45** (1980) 1483
HF: C. J. Gardner et al., PRL **48** (1982) 1168

After 40 years
New World Record!

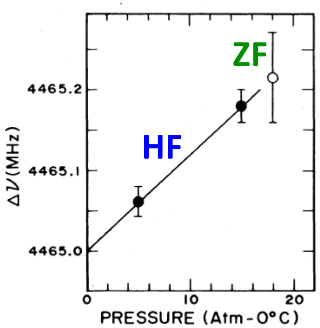


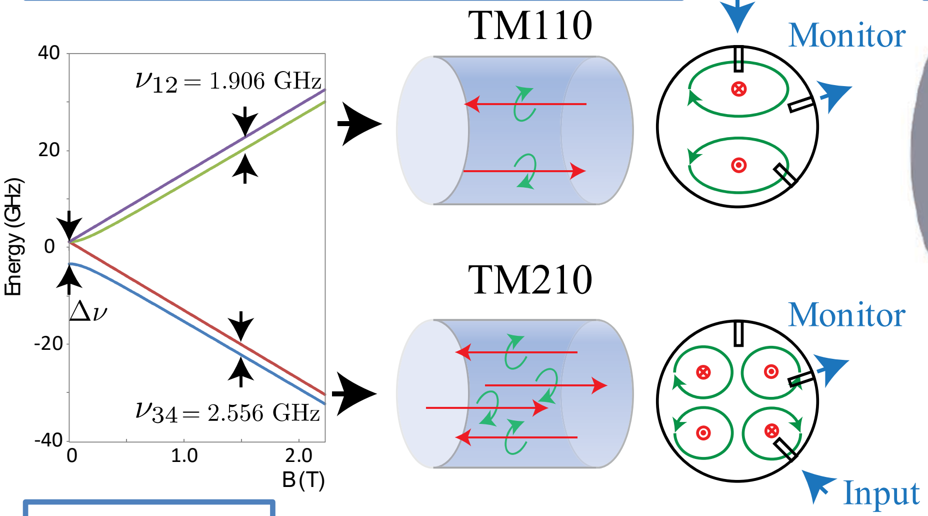
FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

Δν = 4464.95(6) MHz (Orth et al.) [13 ppm] zero field (ZF)
Δν = 4465.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)
Δν = 4464.980(20) MHz (MuSEUM) [4.5ppm] zero field

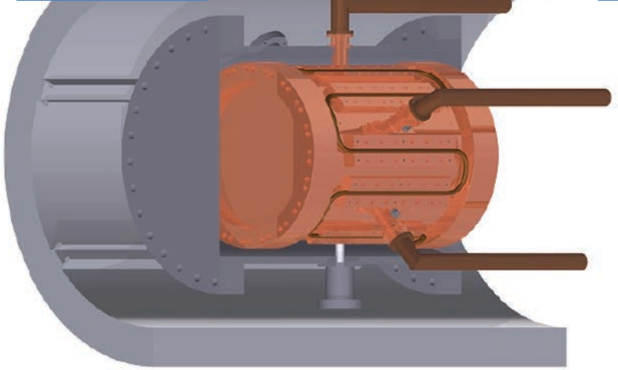
P. Strasser et al., Phys. Rev. Lett. **131** (2023) 253003

High-Field Microwave Cavity (μHe)

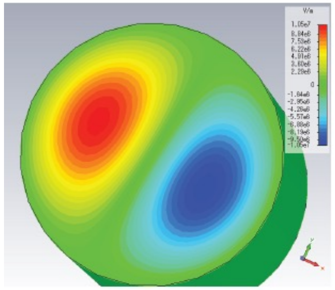
Second-hand 2.9 T MRI magnet



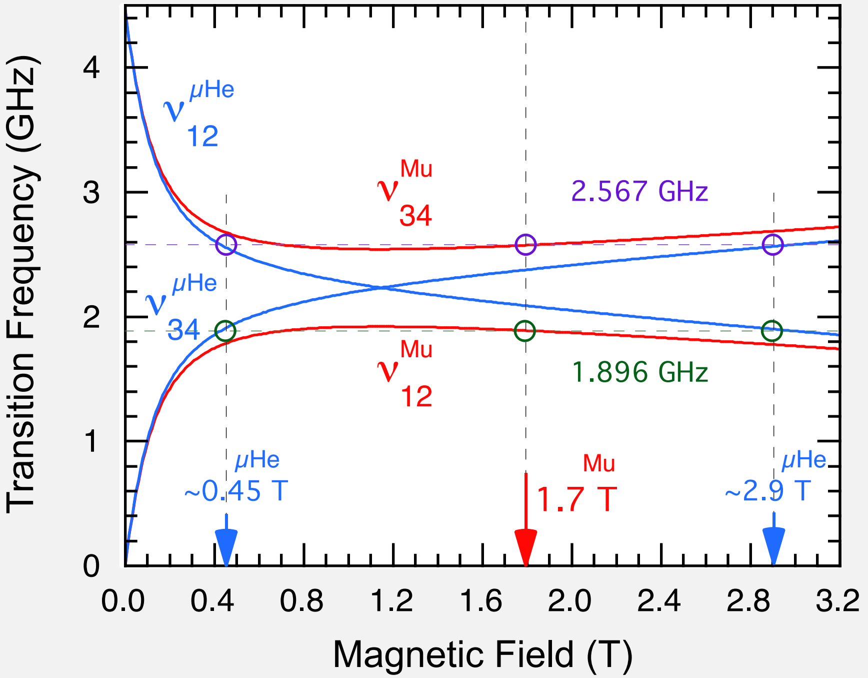
3D CAD



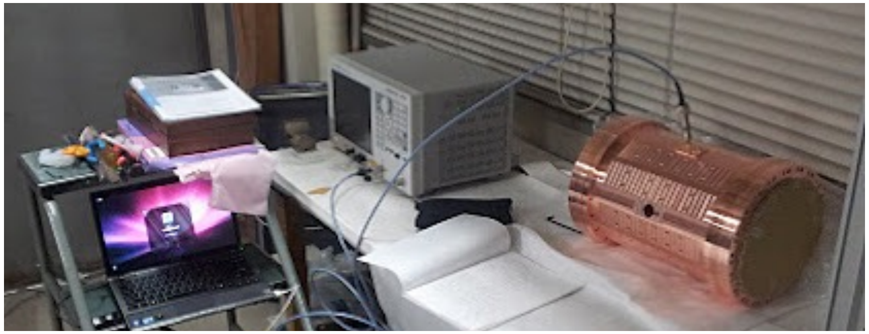
MWS Simulation



Comparison between Muonium & μHe



Cavity Test



Q Value

Modes	Q (measured)	Q (simulation)
TM110	1.13×10^4	2.97×10^4
TM210	8.05×10^3	2.89×10^4

Why so difficult compared to Mu?

Muonic helium atom residual polarization

- Depolarization during muon cascade process: **100% → ~ 5%**

Electron donor

- Helium capturing a muon forms **$(^4\mathrm{He}\mu^-)^+$** ion → need an **electron donor !!!**
- Previously 1–2% **xenon** (IP = **12.1 eV**) was used. But, **Xe** (**Z=54**) prevents efficient μ^- capture by **He** (**Z=2**), due to Fermi-Teller *Z*-law.
- Recently **methane** (**CH_4**) found more efficient because of its reduced total charge (**Z=10**) and similar IP of **12.5 eV**. Polarization of **~ 5%** reported.

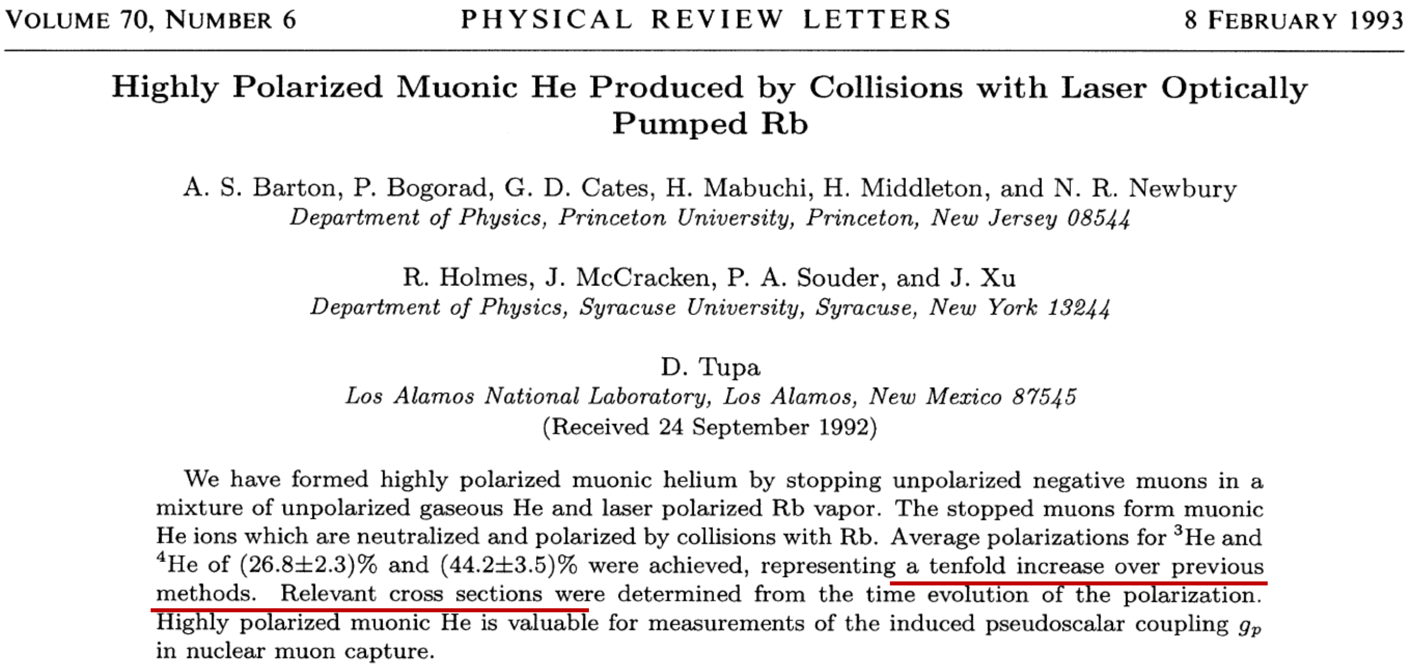
D. J. Arseneau, *et al.*, J. Phys. Chem. B **120** (2016) 1641.

Negative Muon Beam Intensity

- Negative muon beams are generally 10 – 100 times less intense than surface (positive) muon beams

Highly-Polarized Muonic He Atom

Production of highly-polarized muonic helium atom by spin exchange optical pumping (SEOP)



VOLUME 70, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1993

Highly Polarized Muonic He Produced by Collisions with Laser Optically Pumped Rb

A. S. Barton, P. Bogorad, G. D. Cates, H. Mabuchi, H. Middleton, and N. R. Newbury
Department of Physics, Princeton University, Princeton, New Jersey 08544

R. Holmes, J. McCracken, P. A. Souder, and J. Xu
Department of Physics, Syracuse University, Syracuse, New York 13244

D. Tupa
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 24 September 1992)

We have formed highly polarized muonic helium by stopping unpolarized negative muons in a mixture of unpolarized gaseous He and laser polarized Rb vapor. The stopped muons form muonic He ions which are neutralized and polarized by collisions with Rb. Average polarizations for ^{3}He and ^{4}He of (26.8±2.3)% and (44.2±3.5)% were achieved, representing a tenfold increase over previous methods. Relevant cross sections were determined from the time evolution of the polarization. Highly polarized muonic He is valuable for measurements of the induced pseudoscalar coupling g_P in nuclear muon capture.

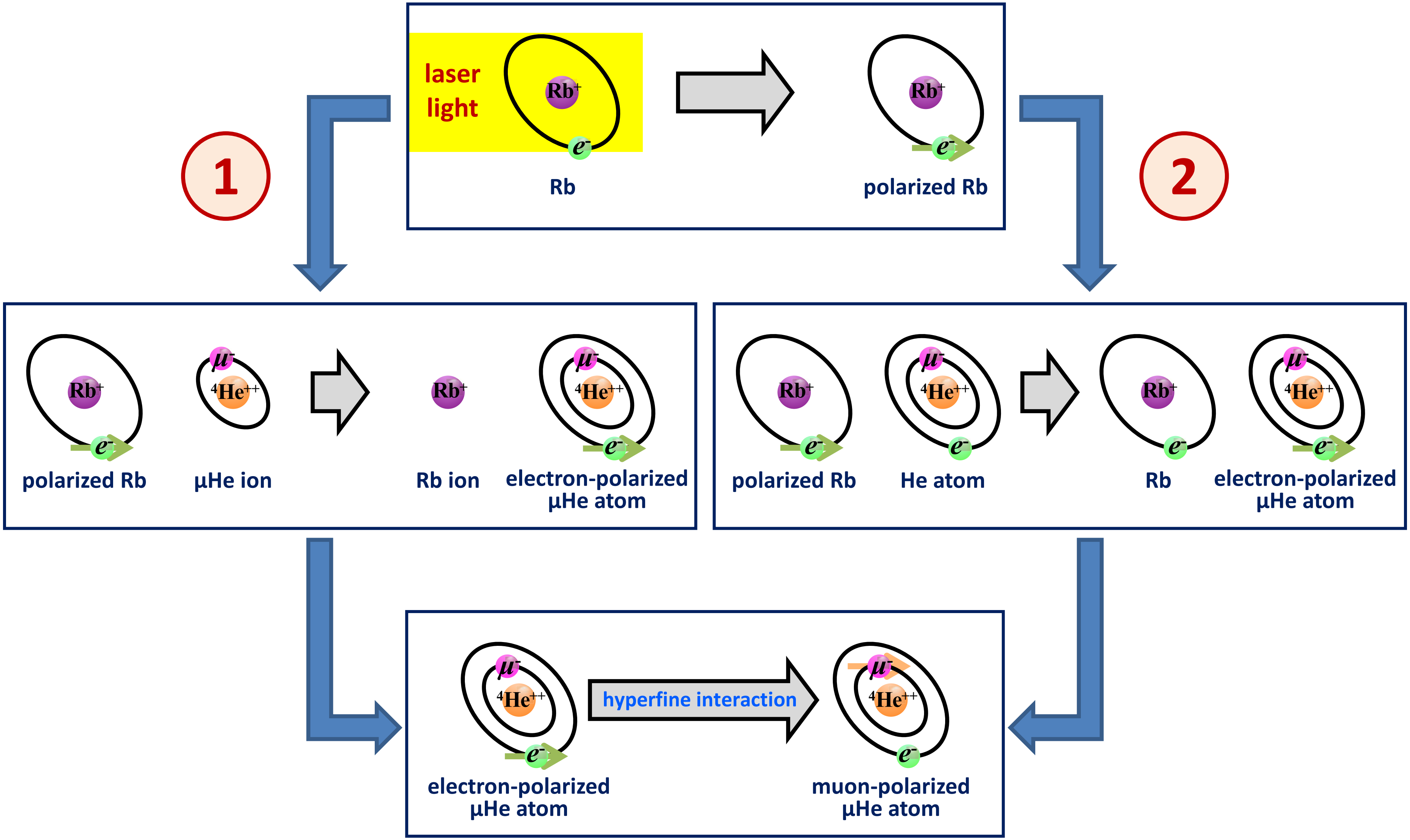
A. S. Barton et al., Phys. Rev. Lett. **70**, 758 (1993)

for μ^4He: 6% → 44%

Improvement by a factor 7 achieved !

Maximum theoretical polarization: ^{4}He = 100%, ^{3}He = 75%

Polarization of Muonic He Atom



polarized Rb
μHe ion
Rb ion
electron-polarized μHe atom

polarized Rb
He atom
Rb
electron-polarized μHe atom

electron-polarized μHe atom
hyperfine interaction
muon-polarized μHe atom

μHe SEOP Objectives

1) Demonstrate re-polarization of μHe atoms at using the **SEOP technique**
    - Test experiment at D1 area under development

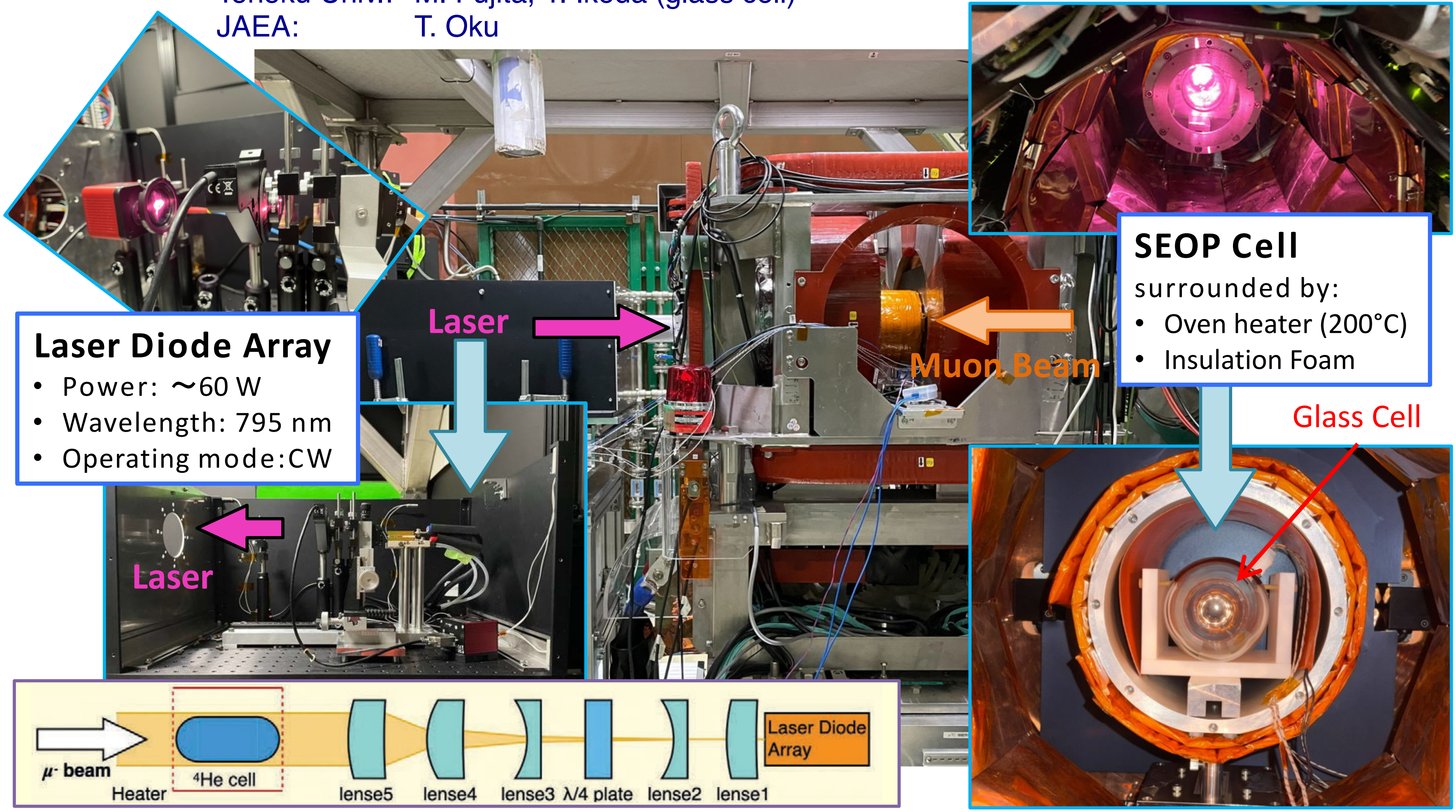
2) Further improvements expected with a **hybrid-SEOP technique**
    - Use **K/Rb** to enhance the spin-exchange efficiency
    - Rb is used as a spin-transfer agent to K, to prevent depolarization of Rb due to Rb-Rb collision.
    - K-He transfers the angular momentum with much greater efficiency than directly Rb-He (nearly 10 times greater than with pure Rb pumping).
    - Can achieve **high polarizing rate** with **high polarization**, which is very important for HFS measurements

3) Demonstrate that the **SEOP technique** can be applied to **muonic helium HFS** measurements
    - Simulation (in progress)
    - Test experiment

SEOP Experimental Setup for μHe

New MuSEUM-SEOP collaboration: MUON + NEUTRON Kakenhi(A): FY2021-2023

KEK: T. Ino, S. Kanda, S. Nishimura, K. Shimomura
Nagoya Univ.: S. Fukumura, T. Okudaira, M. Kitaguchi, H. M. Shimizu
Tohoku Univ.: M. Fujita, Y. Ikeda (glass cell)
JAEA: T. Oku



Laser Diode Array

- Power: ~60 W
- Wavelength: 795 nm
- Operating mode:CW

SEOP Cell

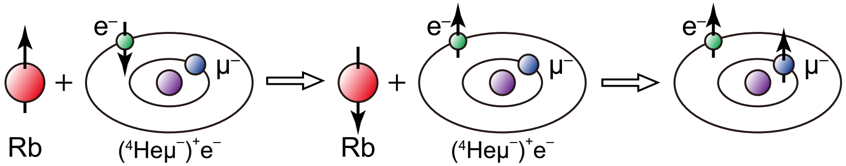
surrounded by:

- Oven heater (200°C)
- Insulation Foam

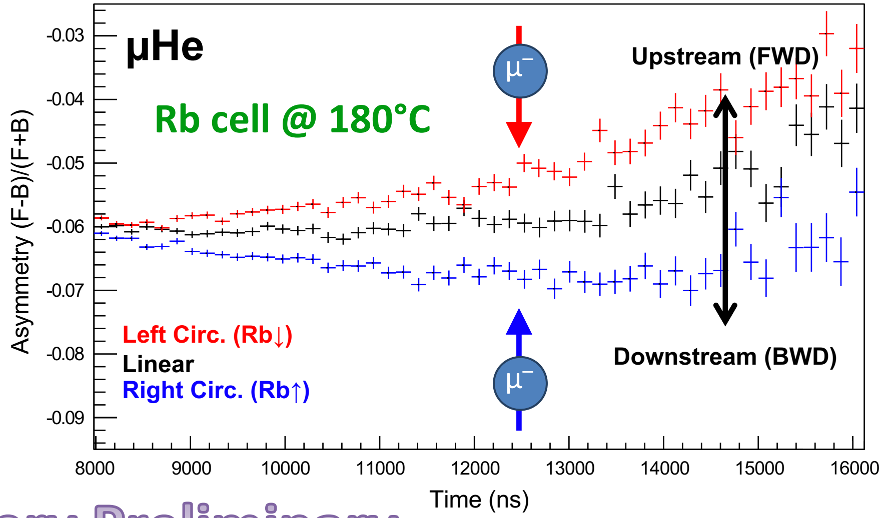
μHe SEOP Beamtime (Feb. 2023)

Muonic helium atom residual polarization

- Depolarization during muon cascade → **~5%** (muonium 50%)
- Re-polarization of muonic He atom by spin exchange optical pumping (SEOP)

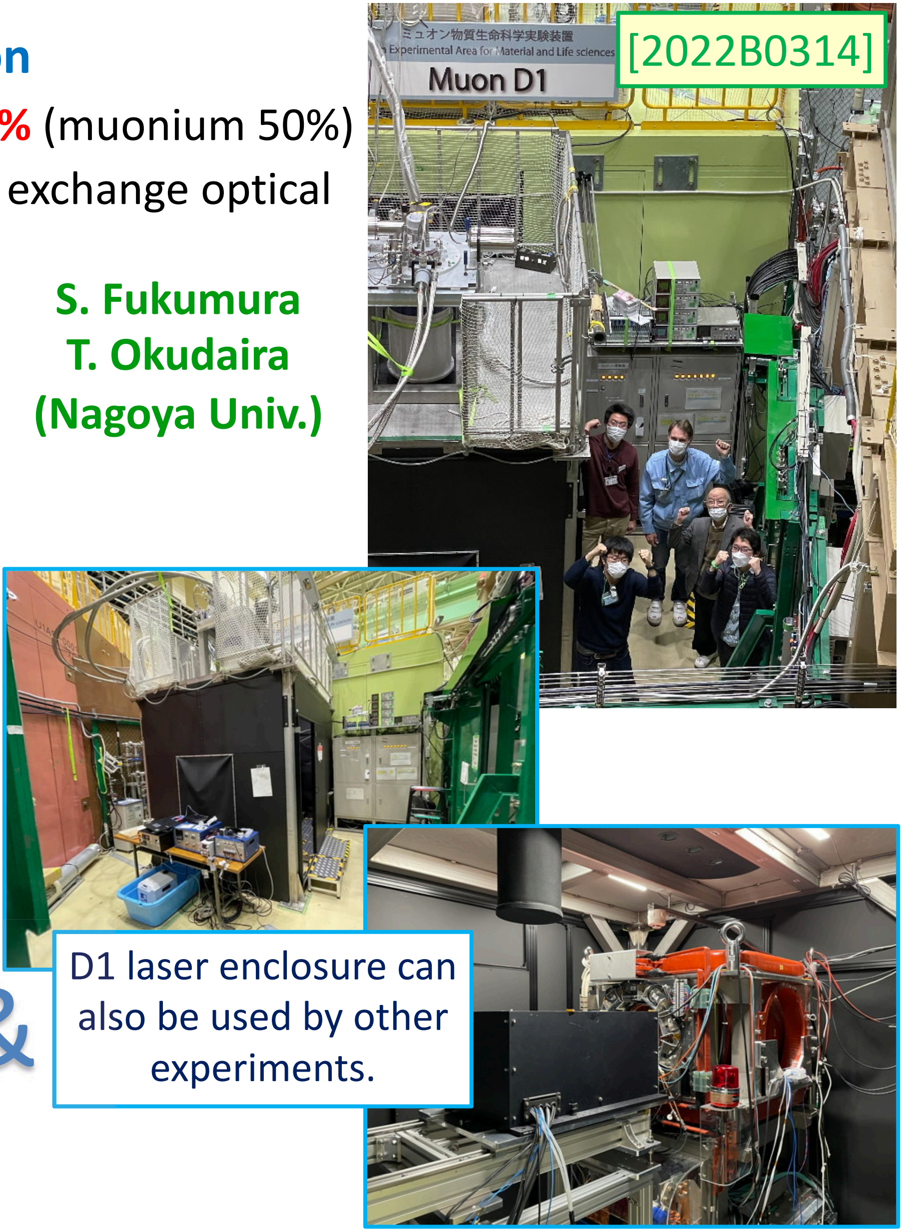


S. Fukumura
T. Okudaira
(Nagoya Univ.)



Very Preliminary

- ➢ **First laser experiment at area D1**
- ➢ **First successful μHe SEOP Results!**



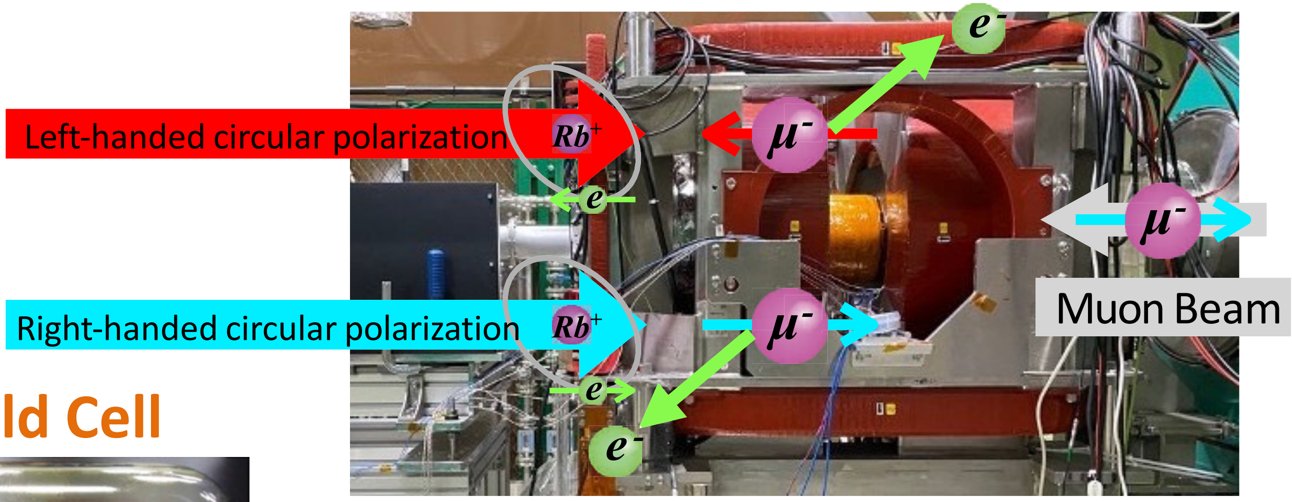
[2022B0314]

&

D1 laser enclosure can also be used by other experiments.

μHe SEOP Beamtime (Dec. 2023)

by S. Fukumura

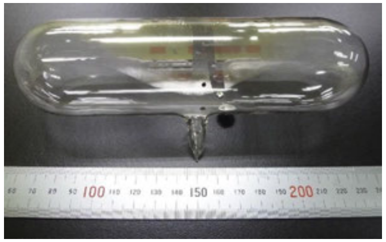


Old Cell

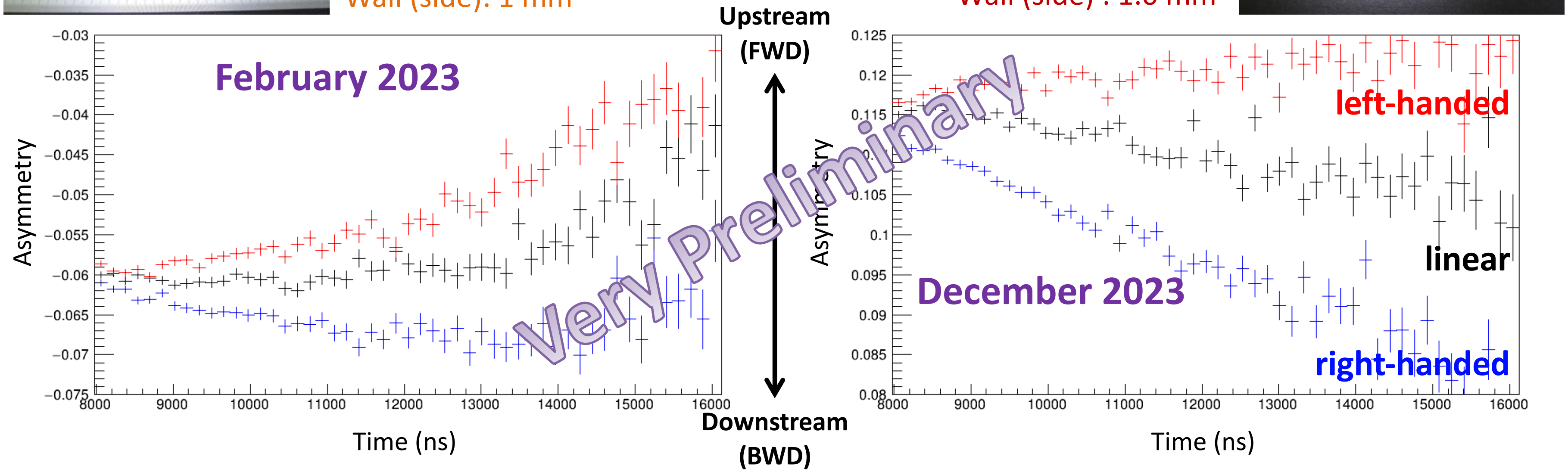
OD : 75 mm
OL : 150 mm
Wall (front): 1 mm
Wall (side): 1 mm

Rb cell: 180°C

New Cell



OD : 50 mm
OL : 180 mm
Wall (front) : 0.5 mm
Wall (side) : 1.0 mm

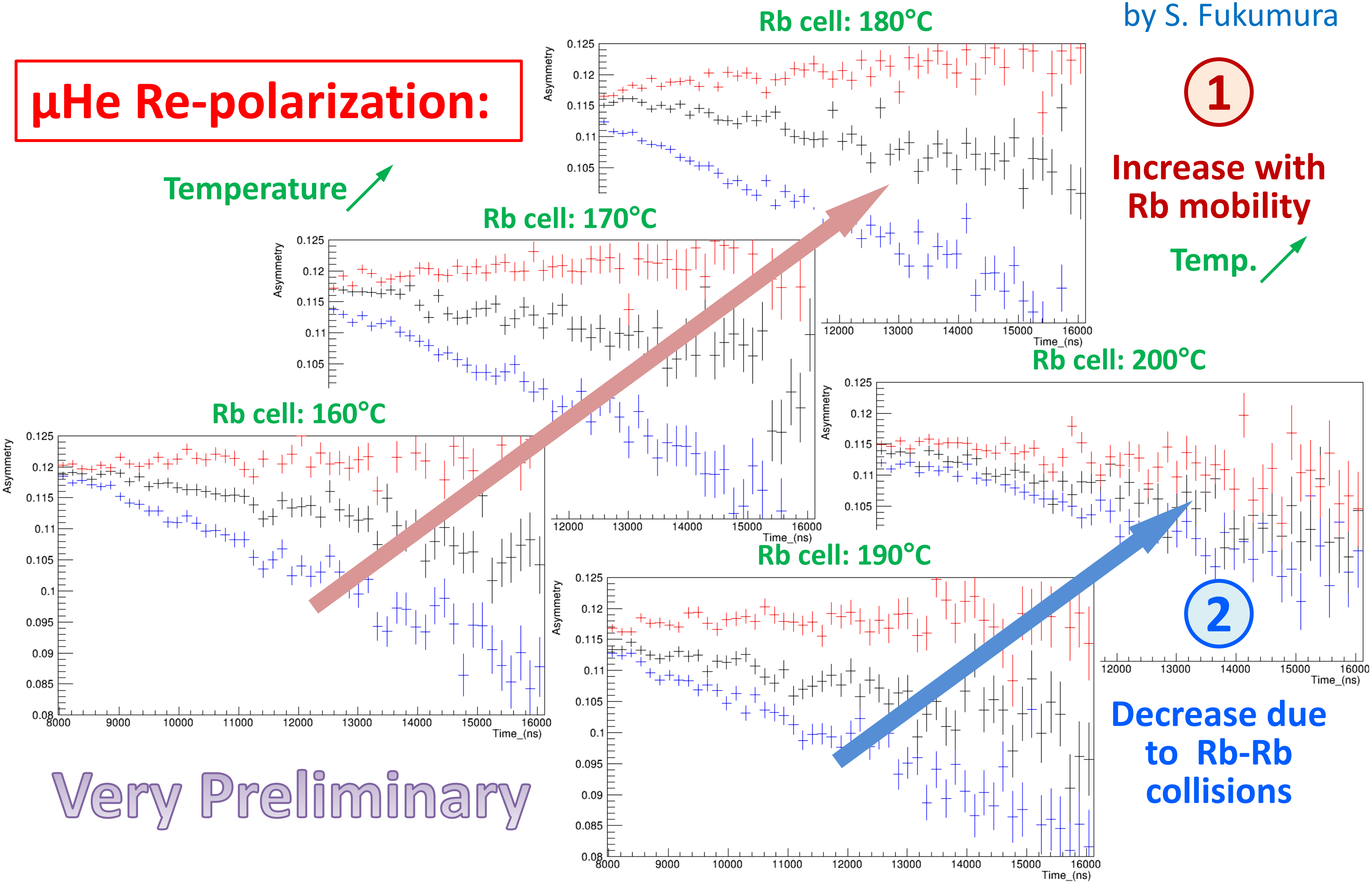


μHe SEOP Beamtime (Dec. 2023)

by S. Fukumura

μHe Re-polarization:

Temperature ↗



①

Increase with Rb mobility

Temp. ↗

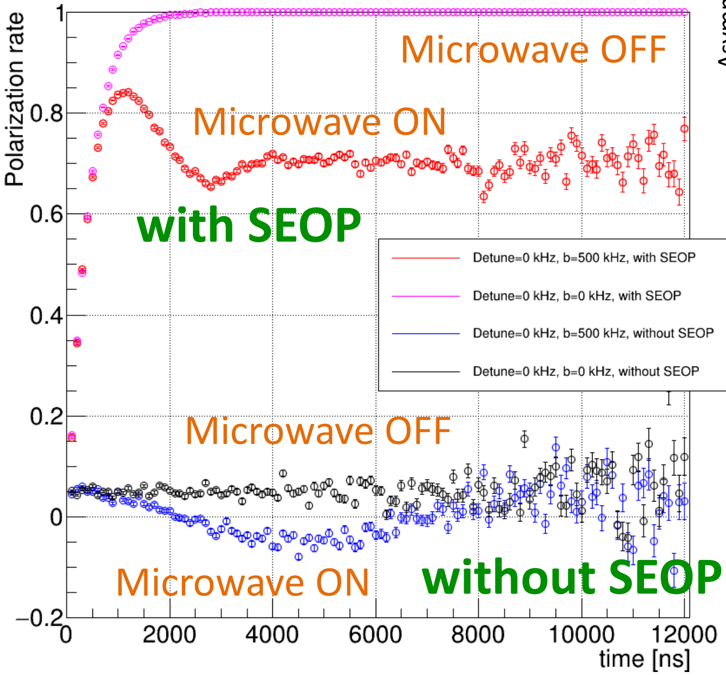
②

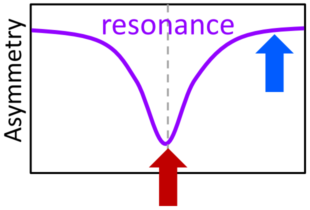
Decrease due to Rb-Rb collisions

Very Preliminary

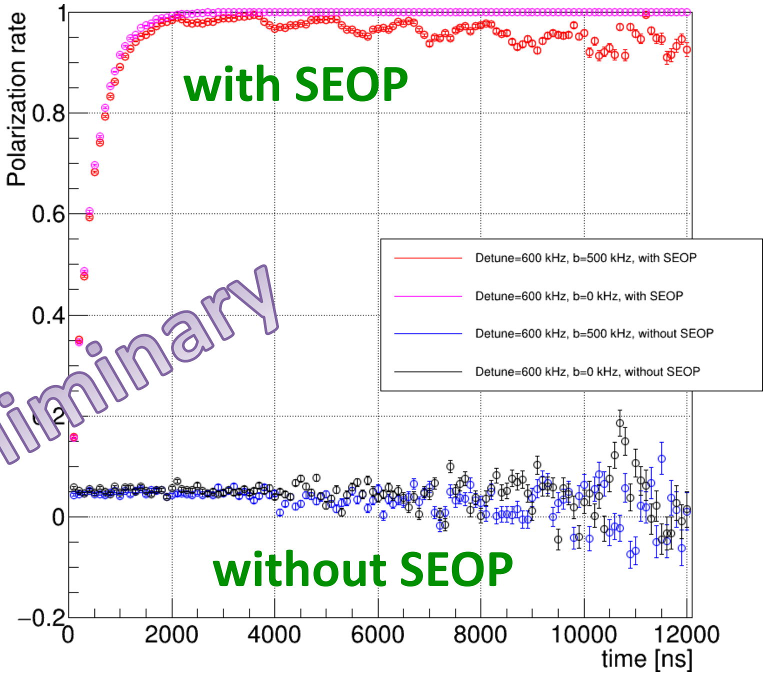
Preliminary Simulation

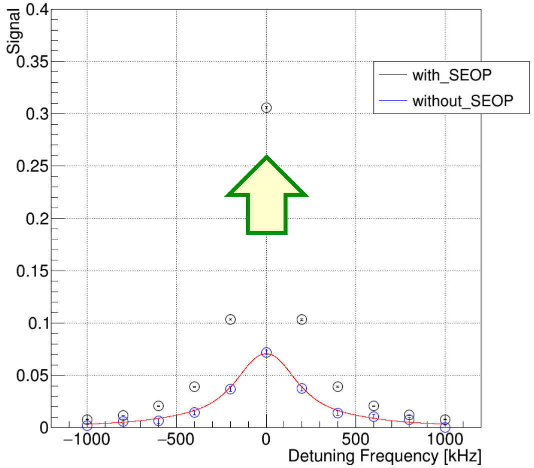
“On” resonance (0 kHz)





“Off” resonance (600 kHz)

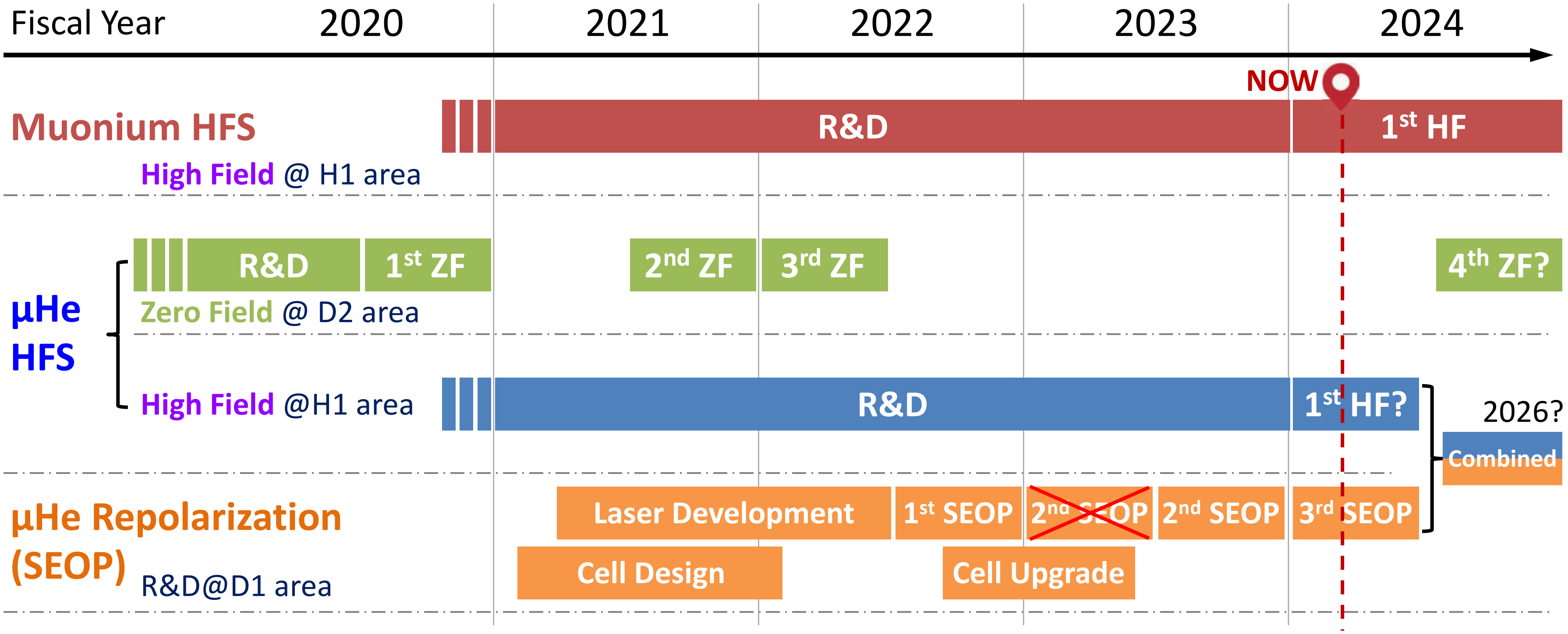




- **SEOP** can increase the resonance signal.
- But increase limited due to the competition between **SEOP** and **microwave**.
- We could use a **pulsed laser** to polarize Rb before muon injection.

Simulation by S. Fukumura

Current Schedule & Goal



Current Goal

Statistical Improvement:

- H-line: 10x intensity (D-line)
- Runtime: 100 days

	Muonium
$\Delta\nu_{HFS}$	~ 2 ppb
μ_μ/μ_p	~ 20 ppb

Systematic uncertainties:

- $\Delta\nu_{HFS}$: < 1.5 ppb
- μ_{μ^-}/μ_p : < 13 ppb

(estimation)

Very Very Preliminary !!!

	μHe	μHe (SEOP)
$\Delta\nu_{HFS}$	~ 40 ppb	~ 6 ppb
μ_μ/μ_p	~ 400 ppb	~ 60 ppb

New Systematics !!!

Summary & Future Plans

- **Muonium HFS precision measurement**
  - Precise bound-state QED test
  - Muon $g-2$ & Muonium $1s-2s$
- **Zero-Field Experiment**
  - Development of Rabi-oscillation spectroscopy
  - World's highest precision in ZF measurement: **160 ppb**
- **High-Field Experiment (H1 area)**
  - Field uniformity: **0.27 ppm** achieved
  - Development of CW-NMR magnetic probe: **15 ppb** precision achieved
  - Ready to **START** measurement **very soon !!!**
- **Muonic Helium HFS Measurement**
  - Zero-Field experiment successful; world's highest precision: **4.5 ppm**
  - Highly-polarized μHe formation by SEOP under development
  - High-field experiment planned after muonium

The μHe project was supported by a JSPS KAKENHI grant No. 21H04481 (FY2021-2023)

"High-precision measurement of the negative muon mass by muonic helium atom hyperfine structure spectroscopy"

MuSEUM Collaboration

(**Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave)

KEK

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S. Fukumura, R. Azuma

On behalf of the extended MuSEUM Collaboration

FIN