Precise Measurement of Muonium Hyperfine Structure in J-PARC -MuSEUM-

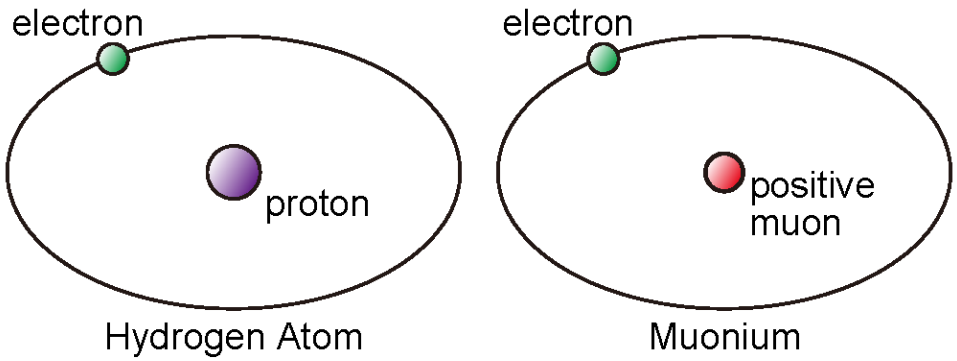
K. Shimomura (KEK)

on behalf of the MuSEUM Collaboration

What is Muonium ?

Muon:

- Elementary particle (lepton)
- 200 times heavier than an electron
- Lifetime of 2.2 microseconds.



Muonium:

- Bound state of a positive muon and an electron.
- Hydrogen-like atom free from the finite size of the nucleon.
- Most suitable for validation of bound state quantum electrodynamics (QED).
- Theoretical and experimental precision of the hyperfine structure comparable.

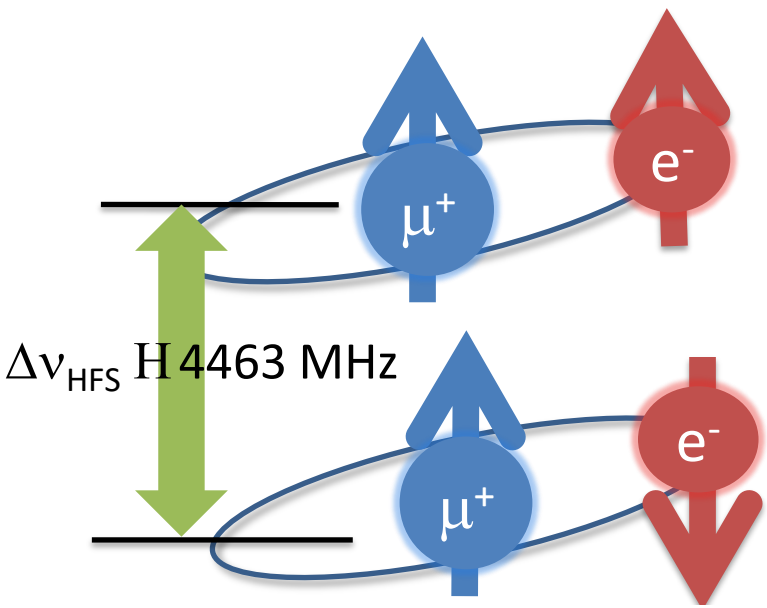
Precision of the hyperfine structure (HFS, $\Delta\nu$):

Hydrogen-like atom	Experiment	Theory	$(\Delta\nu_{theo} - \Delta\nu_{exp})/\Delta\nu_{exp}$
Hydrogen	0.2 ppt	1.2 ppm	(-0.45 ± 1.2) ppm
Positronium	3.3 ppm	2.0 ppm	(15 ± 4) ppm
Muonium (Zero-Field)	310 ppb	61 ppb	(150 ± 320) ppb
Muonium (High-Field)	12 ppb	61 ppb	(23 ± 62) ppb

Muonium Hyperfine Structure

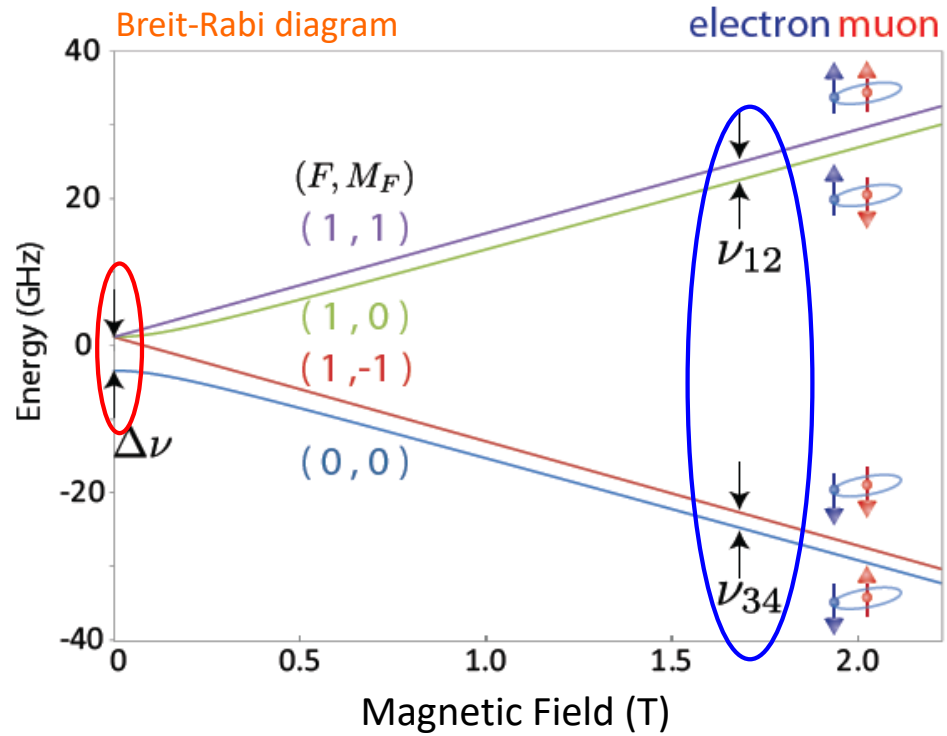
$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

$\Delta\nu_{HFS}$: Mu Hyperfine Structure



Pure lepton
= point particle

Zeeman Splitting



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

Purpose of MuSEUM

- Measure the two RF resonances (ν_{12} and ν_{34}) at high magnetic field (1.7 T), and $\Delta\nu$ directly at zero field.
  - Different systematics from the magnetic field (negligible at ZF)
- Muonium ground state HFS ($\Delta\nu_{HFS}$)
  - Precise test of bound-state QED
  - Current uncertainty: 12 ppb
  - Test of CPT and Lorentz Invariance
- Muon magnetic moment relative to that of the proton
  - Basic property of muon
  - Current uncertainty: 120 ppb
  - Basic input parameter for the muon g-2 experiment

We aim to improve the uncertainties of both quantities by a factor of 10, taking advantage of the high intensity beam at J-PARC/MUSE.

Most Precise Test of Bound State QED

Experiment:

LAMPF Experiment (1999)

ν_{HFS}(exp) 4463.302 765 (53) MHz [12 ppb]

μ_μ/μ_p = 3.18334524(37) [120ppb]

m_μ/m_e = 206.768277(24) [120ppb]

Theory:

ν_{HFS}(theory) 4463.302 868 (271) MHz [61 ppb]

ν_{HFS}(QED) 4463.302 720 (253) (98) (3) MHz

(m_μ/m_e) (QED) (α)

ν_{HFS}(weak) -65 Hz

ν_{HFS}(had. v.p.) 232 (1) Hz

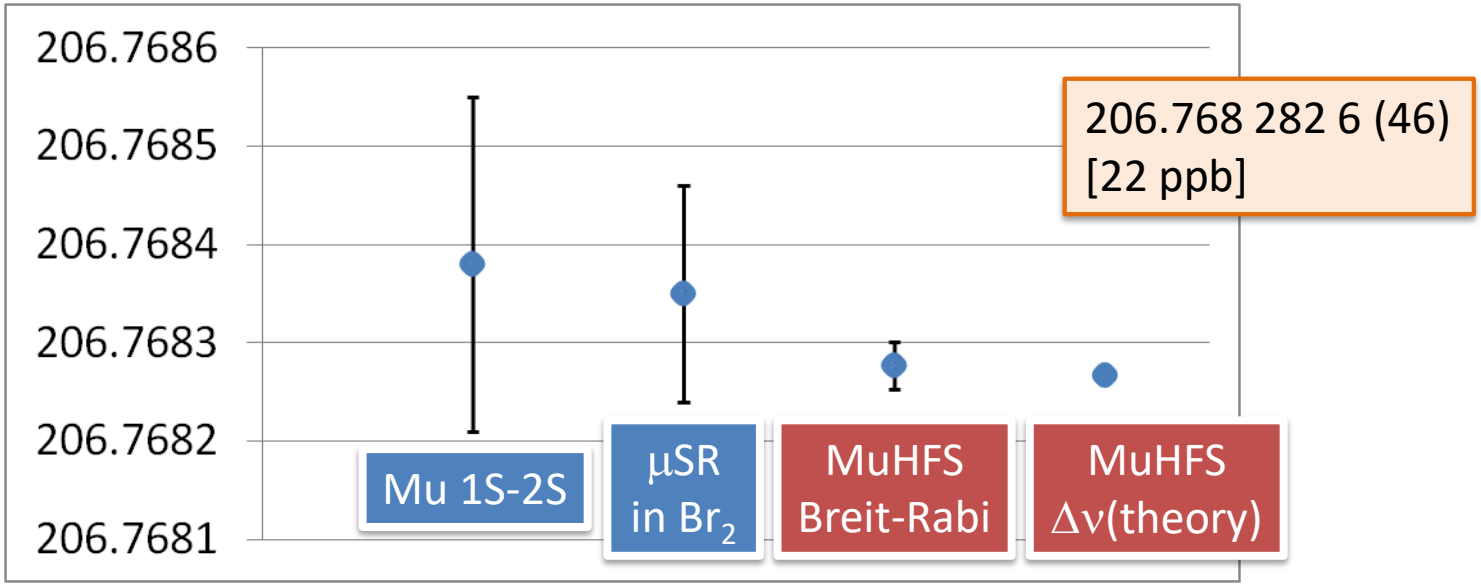
ν_{HFS}(had. h.o.) 5 (2) Hz

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

Progress: PRA 86 (2012) 024501, PRL 112 (2014) 173004, PRD 89 (2014) 014034

Determination of the Muon Mass

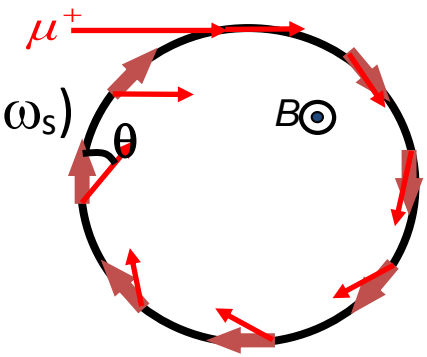
μ_μ/μ_p, a_μ, μ_p/μ_B → m_μ/m_e



Muon mass (CODATA2016) determined by MuHFS (LAMPF 1999)

Why Mu HFS measurement is so important?

g-2 E821(BNL) 0.5ppm 3.6σ deviation



- Measurement of the deviation of muon spin direction (ω_s) and muon momentum direction (ω_c) $\omega_a \propto (g-2)/2 = a_\mu$

$$\Rightarrow \vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\beta \times \vec{E}}\right]$$

a_μ *an independent precise muon mass measurement is required!*

- The ratio to the proton NMR frequency is important!

$$\Rightarrow \boxed{a_\mu = \frac{R}{\lambda - R}} \qquad \boxed{R \equiv \frac{\omega_a}{\omega_p}} \qquad \boxed{\lambda \equiv \frac{\mu_\mu}{\mu_p}}$$

From g-2 storage ring From Muonium HFS

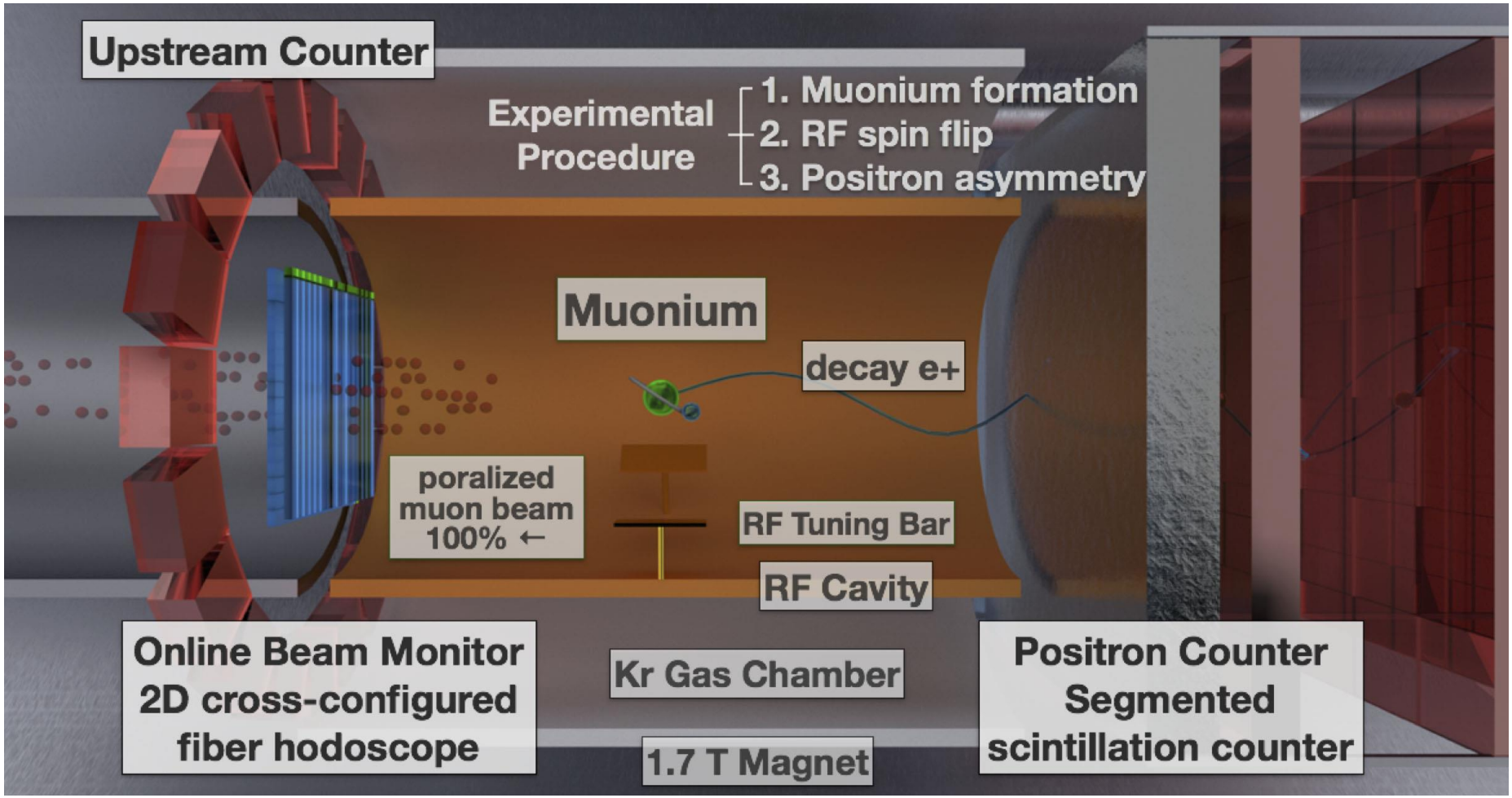
$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu\left(\frac{eB}{mc}\right)}{g_\mu\left(\frac{eB}{2mc}\right)} = \frac{a_\mu}{\left(\frac{g_\mu}{2}\right)} = \frac{a_\mu}{1+a_\mu}$$

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

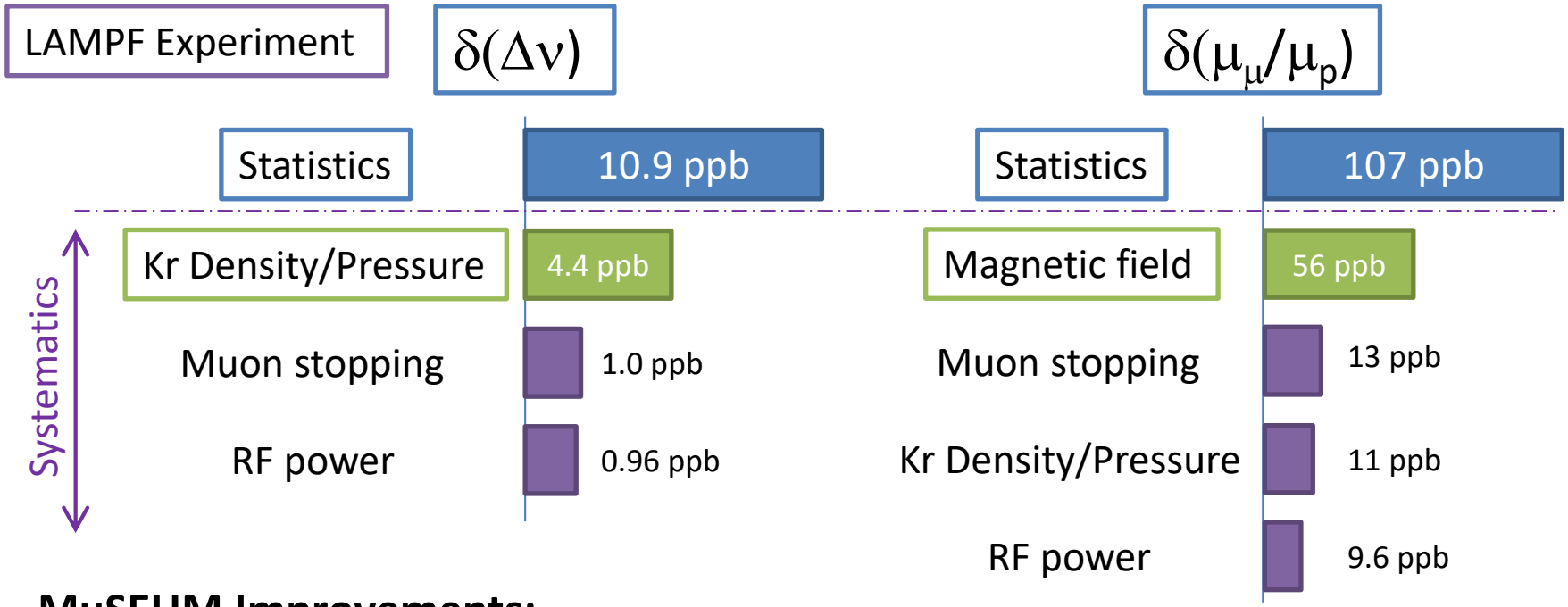
μ_μ/μ_p accuracy from direct measurement of 120 ppb.

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

Experimental Layout



Improvement of statistics



MuSEUM Improvements:

Statistics:

LAMPF: DC 10^7/s
total 10^{13}

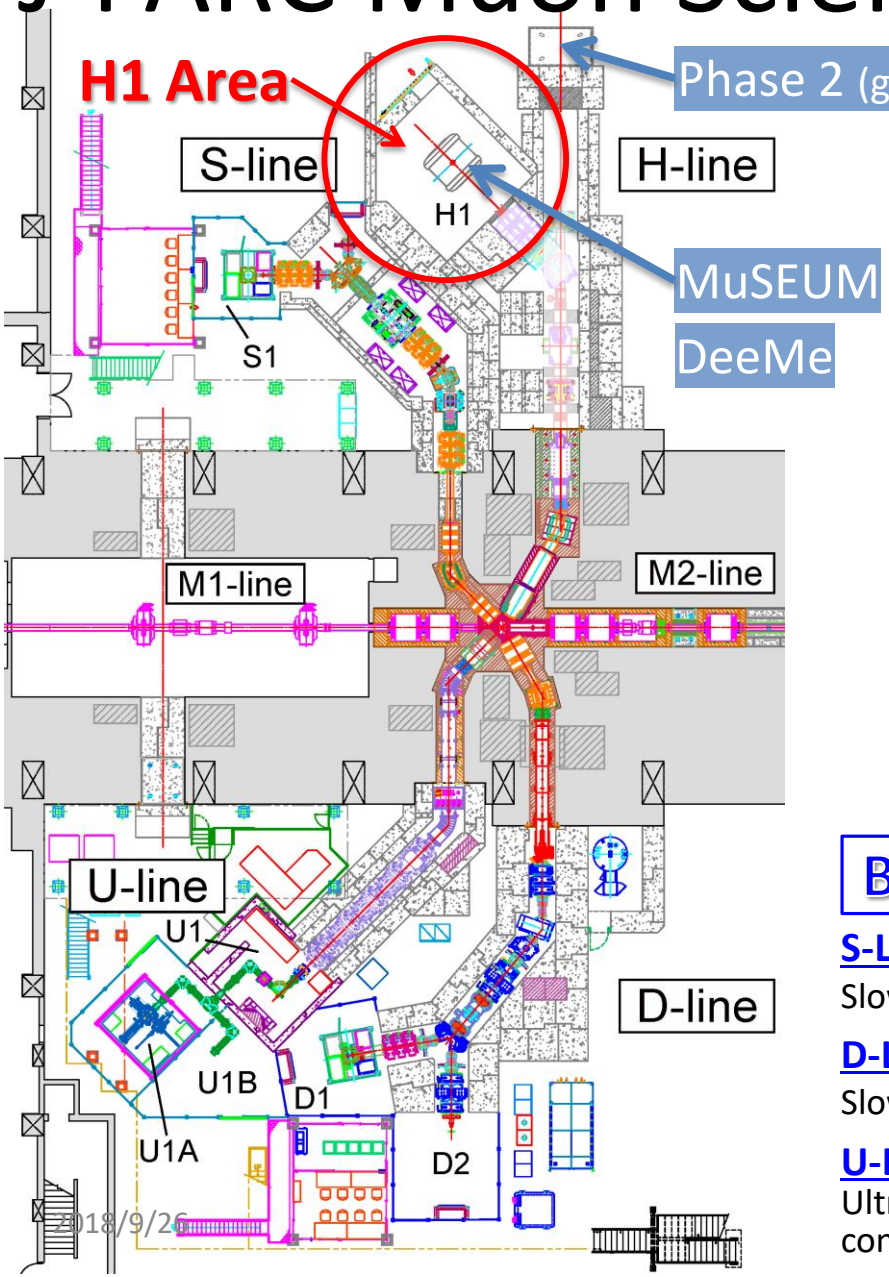
x200 →

J-PARC/MUSE: **Pulsed 1×10^8**/s
H-Line total 2×10^{15}

Systematics:

- magnetic field accuracy & uniformity
- pressure dependence (longer cavity lower pressure)
- muon stopping distribution measurement
- RF power stability

J-PARC Muon Science Facility (MUSE)



Under construction

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

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

MLF Experimental Hall No. 1 (2018)

Beamline in Operation

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

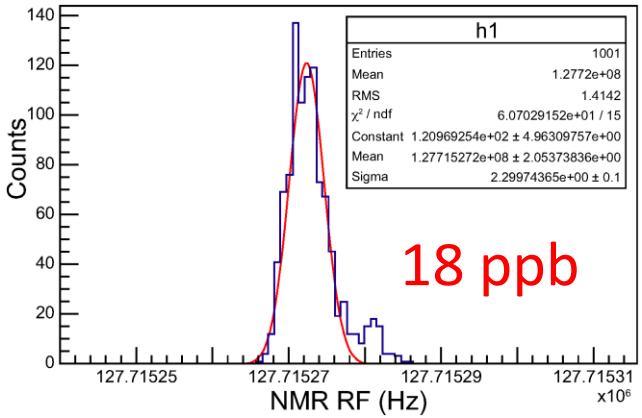
D-Line: Decay muon (μ^+ & μ^-)
Slow (50 keV) – fast (50 MeV) beam, general purpose.

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

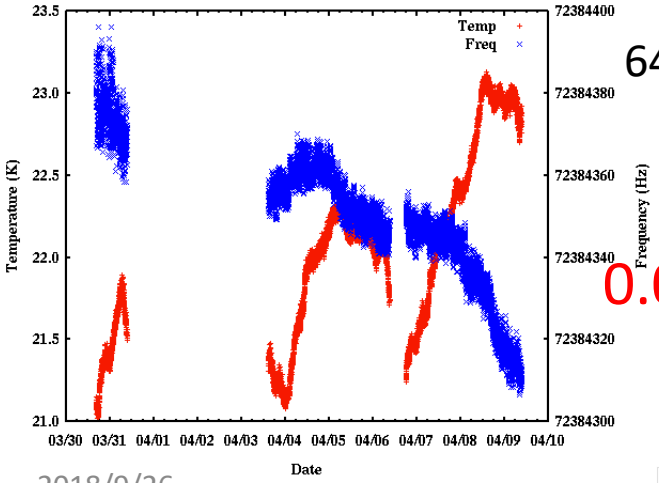
MRI Magnet for High-Field Experiment

Second-hand 2.9 T MRI magnet

CW-NMR Field Monitoring System



Long Term Stability



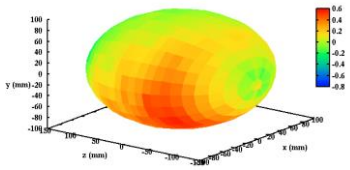
64 Hz / 9.7 days

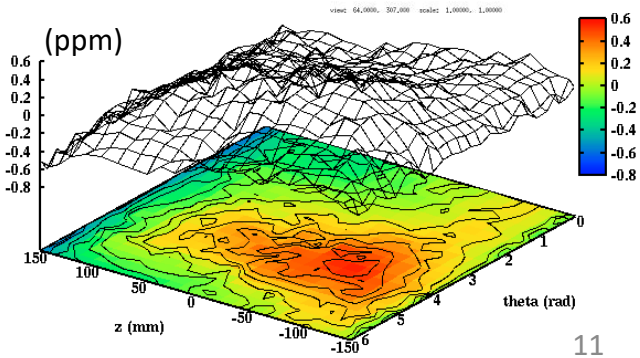
0.003 ppm /h

Field Homogeneity (after shimming)

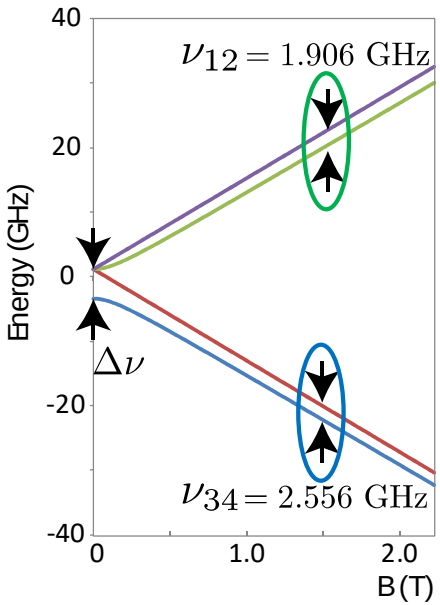
Spheroid :
r=100 mm, z=300 mm

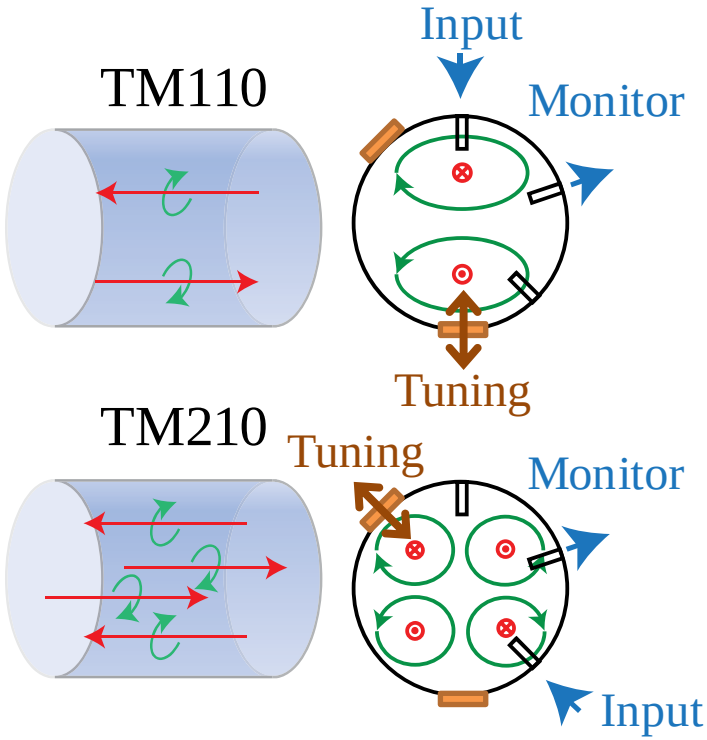
1.4 ppm p-p

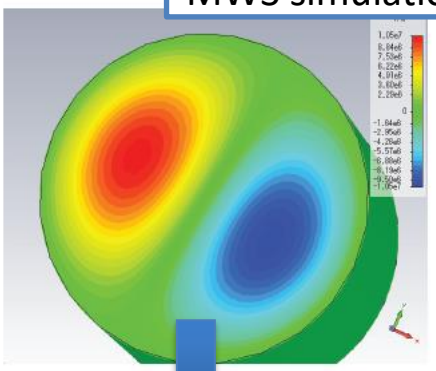


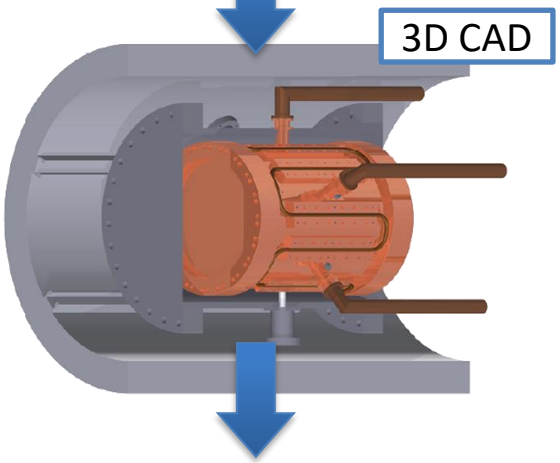


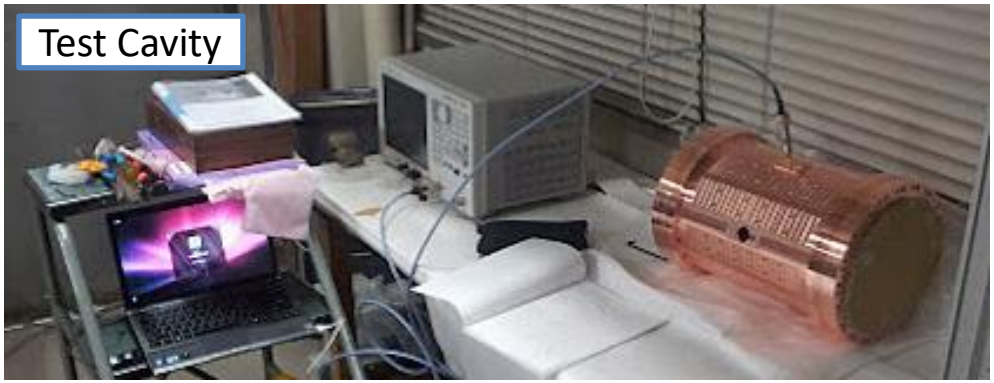
RF Cavity for High Field Experiment









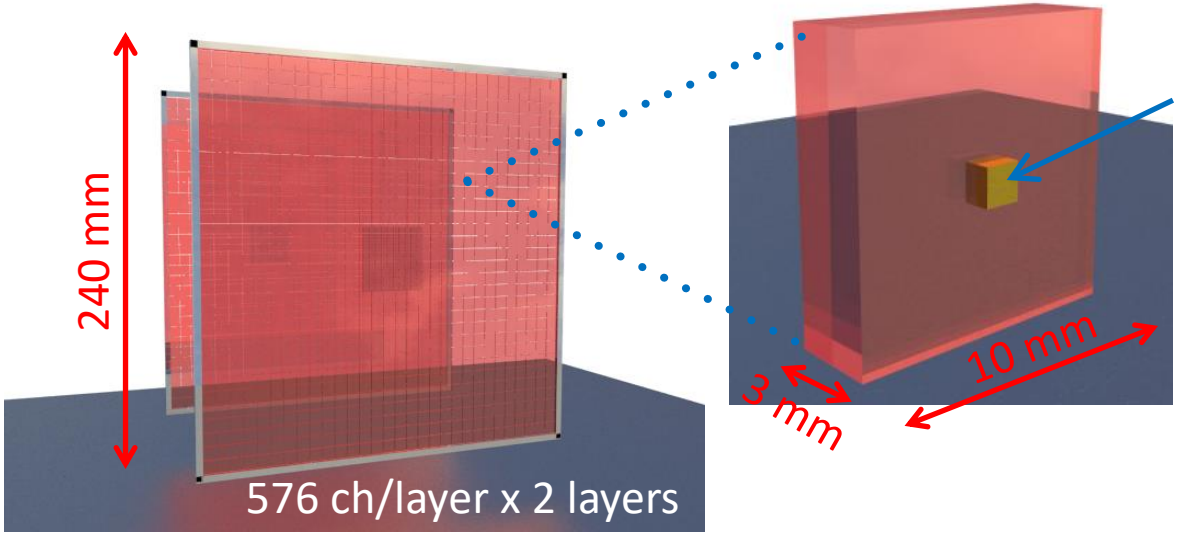


Q Value

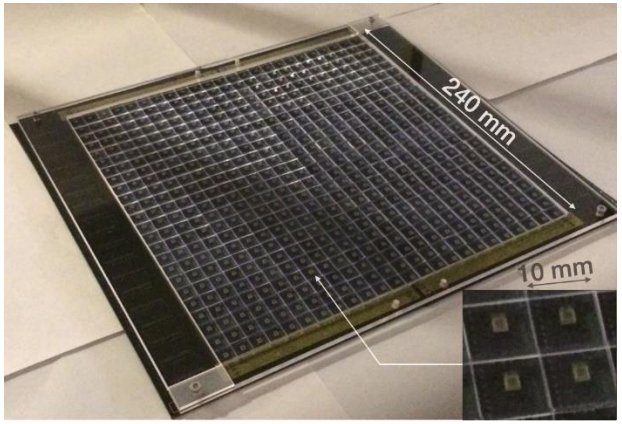
Modes	Q (measured)	Q (simulation)
TM110	11,300	29,700
TM210	8,050	28,900

Positron Counter (1): Scintillation Position Detector

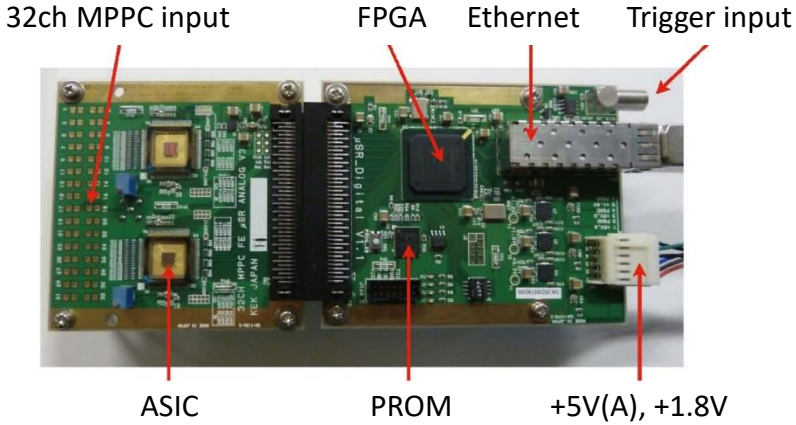
Kanda, Kojima



MPPC (Multi-Pixel Photon Counter)
1.3 mm x 1.3 mm active area
(Hamamatsu)



Plastic scintillator + MPPC + Kaliope readout circuit



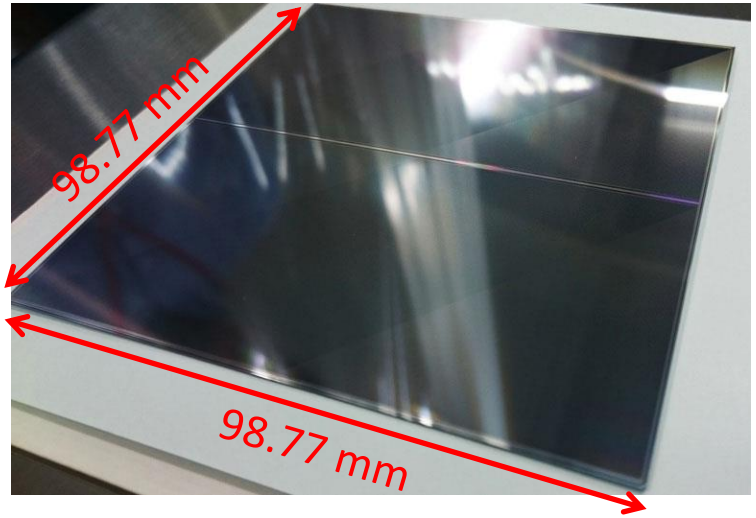
Segmented scintillation detector

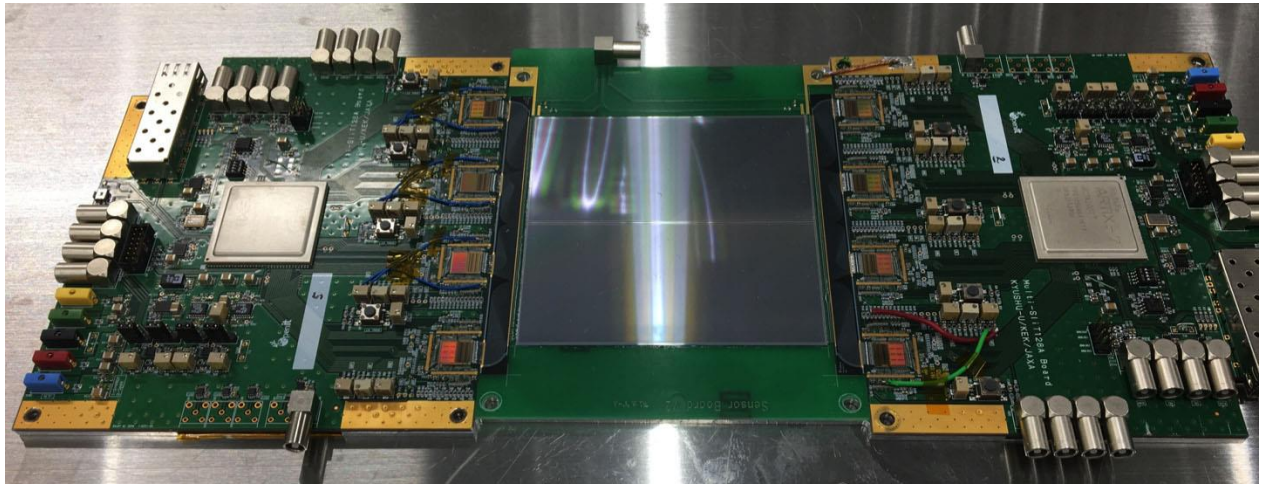
- Scintillation counter with SiPM readout
- Unit cell: 10 mm × 10 mm × 3 mm^t
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch
- High-rate capability required
- Pileup loss at 3 MHz/ch ~ 2%

Positron Counter (2): Silicon Strip Detector

Nishimura

Item	Specification
Sensor type	single-sided, p+ on n
Size	98.77 mm × 98.77 mm
Active Area	97.28 mm × 97.28 mm
Strip pitch	0.19 mm
Strip length	48.575 mm
No. of strips	512 x 2 blocks
Thickness	0.32 mm





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

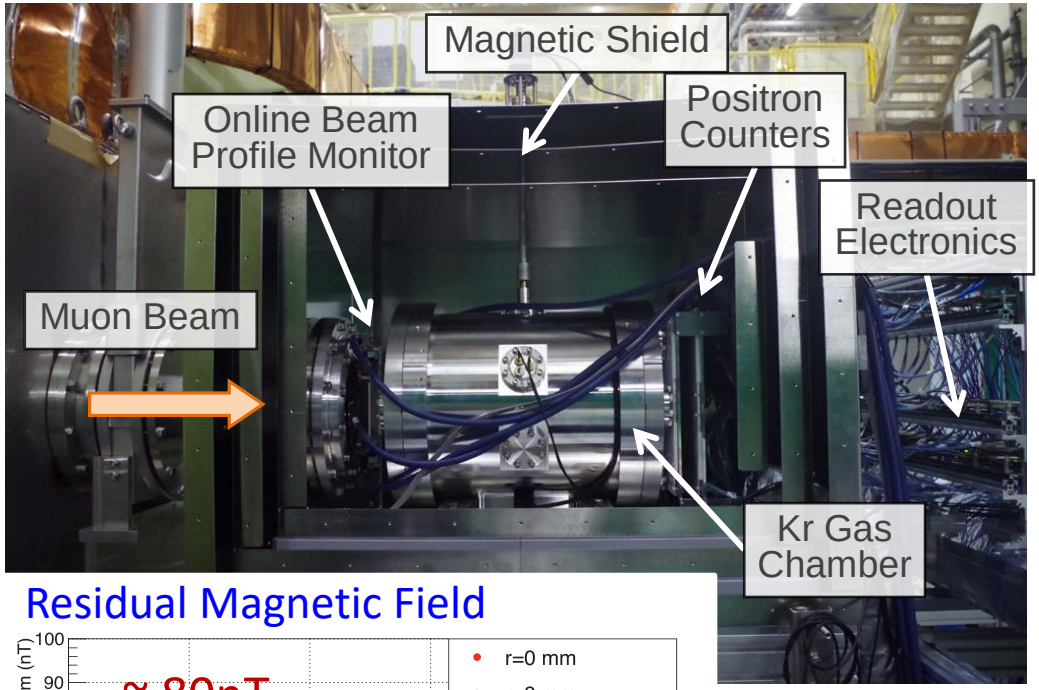
Preliminary Systematic Error (HF)

	Accuracy	ν_{12} and ν_{34}	$\delta(\Delta\nu_{HFS})$	$\delta(\mu_\mu/\mu_p)$
Magnetic Field*	30 ppb		0.0 ppb	15 ppb
RF power	0.2 %	4 Hz	0.8 ppb	8 ppb
Kr gas temperature	0.2 deg.	< 2 Hz	0.4 ppb	4 ppb
Kr gas pressure	1 Pa	1 Hz	0.2 ppb	0 ppb
H impurity	<50 ppm	1 Hz	0.5 ppb	0 ppb
Quadratic dependence		5 Hz	1.0 ppb	5 ppb
Muonium position (x,y)	1 mm	3 Hz	0.6 ppb	6 ppb
Muonium position (z)	1 mm	< 1 Hz	0.2 ppb	2 ppb
Beamline	10(e-4)	< 1 Hz	0.2 ppb	2 ppb
Detector pile-up	w/o absorber w/ absorber	2.8 Hz 0.3 Hz	0.5 ppb < 0.1 ppb	3 ppb < 1 ppb

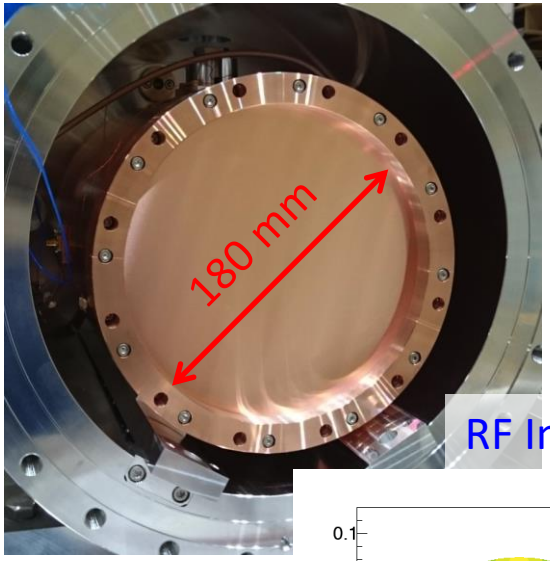
*should be re-estimated by latest progress and further MC simulation.
Total systematic error of $\Delta\nu_{HFS}$~2 ppb, and μ_μ/μ_p ~ 20 ppb

Zero Field Measurements at D-Line

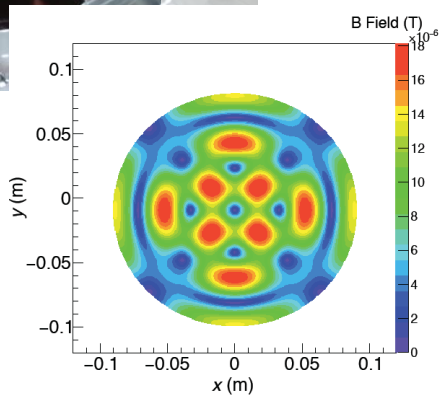
Experimental Setup



New RF Cavity for Zero Field



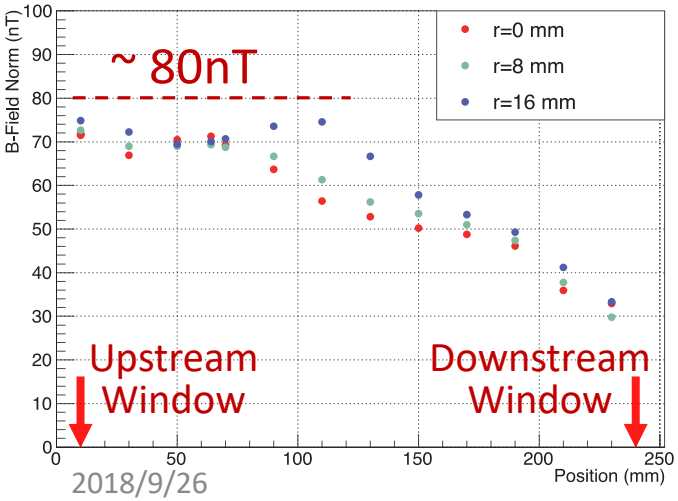
RF Intensity

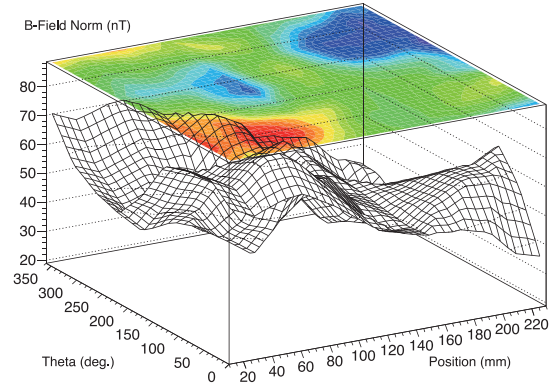


$\Delta\nu$ = 4.463 GHz

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

Residual Magnetic Field

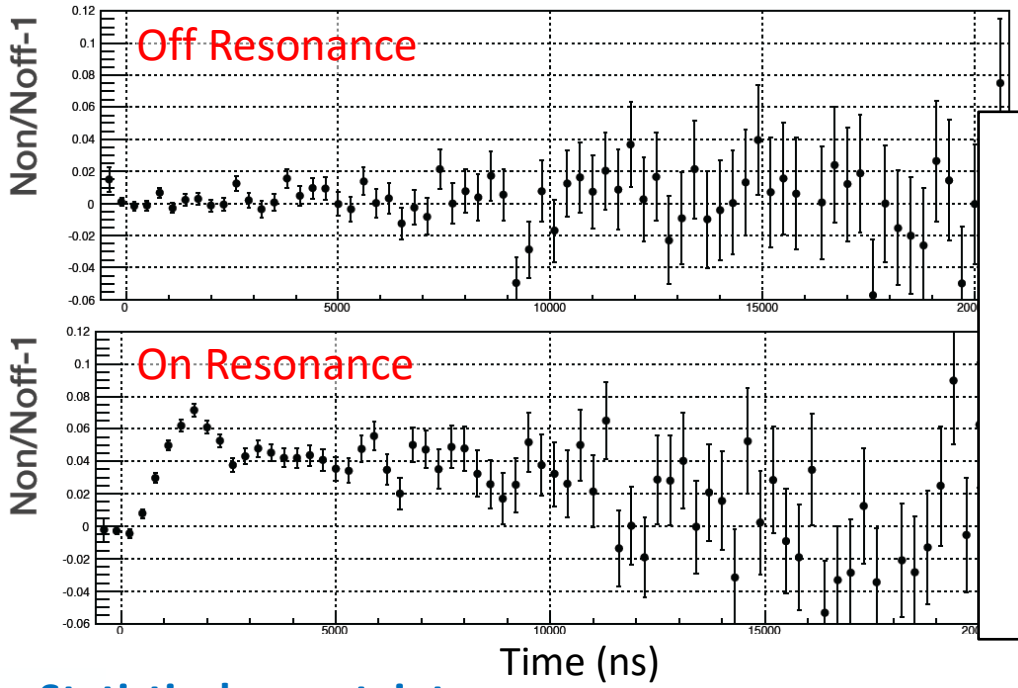




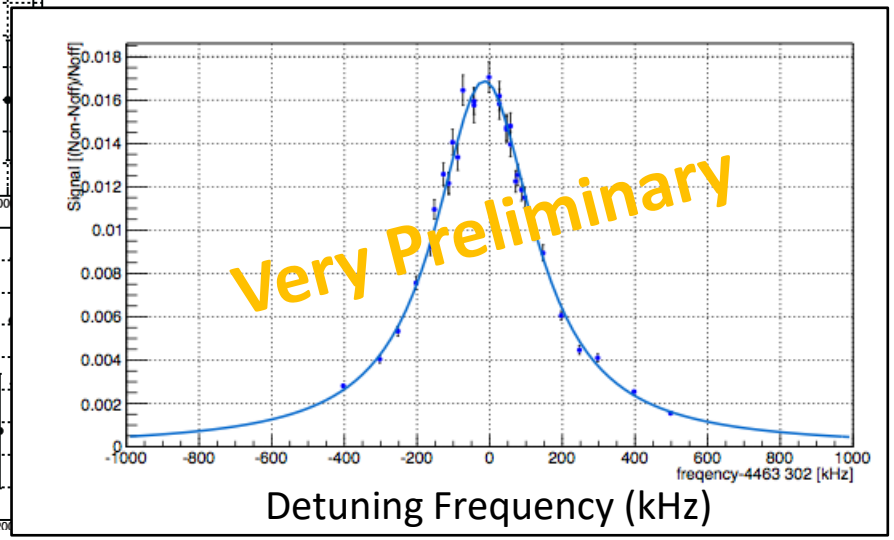
Results (1): Time Integral Method

Conventional Method

– Scintillation Position Detector Data –



Resonance Line Shape (2018 March)



Statistical uncertainty:

2016 Feb. ~ 20 kHz (5ppm)
2017 Feb. ~ 4 kHz (1ppm)
2017 June ~ 2 kHz (0.5ppm)
2018 March ~ 1kHz, measured at 0.4, 0.55, 0.7 atm.
2018 June ~ 1kHz, measured at 0.3 atm Kr gas pressure.

} New world record at ZF ???
Data analysis on going

Previous ZF Experiment at LAMPF:
$\Delta\nu_{HFS} = 4\,463\,302.2 \pm 1.4$ kHz (0.3 ppm)

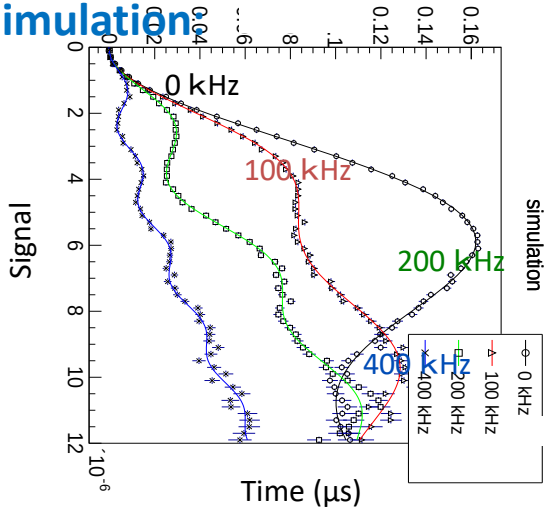
Systematic uncertainty: Estimation in progress

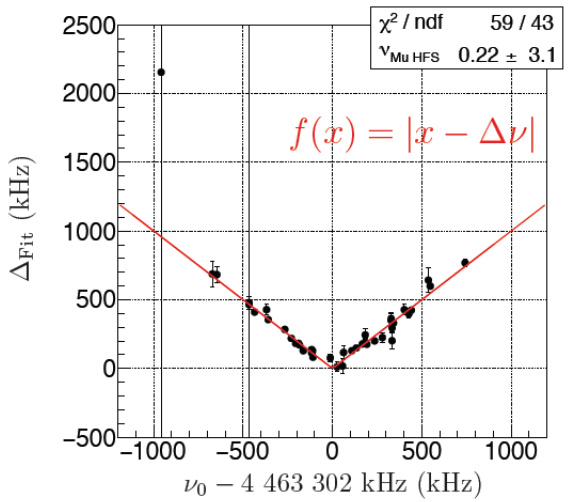
Results (2): Time Differential Method

– Silicon Strip Detector Data –

Nishimura thesis

Simulation:





Preliminary

$\Delta\nu_{HFS} = 4\,463\,302.2$ kHz $\pm$ 3.1 $\pm$ 0.2 kHz

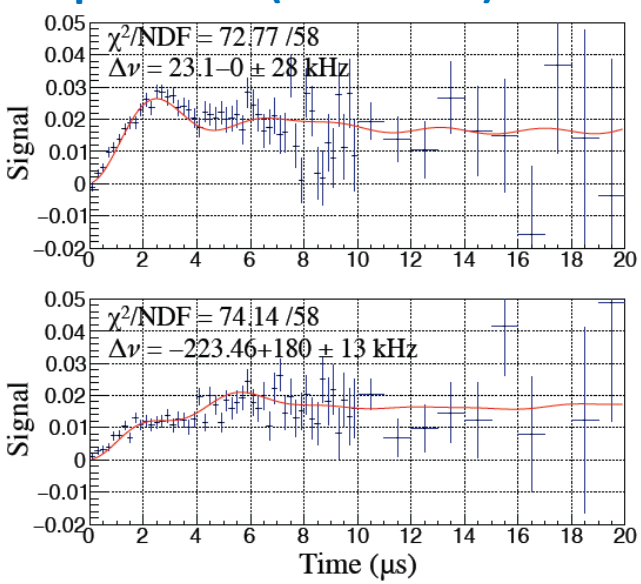
Statistics:

- less data (smaller detector area)

Systematics (main):

- RF power drift (200 Hz)
- gas pressure extrapolation (66 Hz) (only one pressure data !)

Experiment (2017 June):



Possible advantages of this method:

- Each detuning frequency data fitted individually.
- Can determine $\Delta\nu_{HFS}$ with only one frequency data.
- Most sensitive detuning frequency is ~60 kHz.
- Can improve statistical uncertainty by 3.2 times compared to the conventional method.
- Can reduce systematics of RF power variation (free fitting parameter).
- Need high-statistics data.

Possible Accuacy

Item	2016 June	2017 June	Prospects
Analysis method	Time integral	Time differential	Time differential
Beam line	D line	D line	H line (D line × 10)
Beam power	200 kW	150 kW	1 MW
Measurement period	8 hours	31 hours	80 days
Microwave cavity	TM110	TM220	TM220
Detector area	240 × 240 mm^2	98.77 × 98.77 mm^2	98.77 × 98.77 mm^2 × 4
Statistic Uncertainty	22,000 Hz	3,100 Hz | 690 ppb	24 Hz | 5 ppb

Summary and Next Step

- New Precise muonium HFS measurements at high magnetic field will be carried out in a few years (H-Line).

- Present expected systematic error estimated as

HFS	~ 2 ppb (~8Hz)	*preliminary*
Magnetic moment (μ_μ/μ_p)	~ 20 ppb	

- Zero-field measurements at existing beamline (D-Line) in progress for engineering run of the apparatus.
  - Muonium HFS resonance clearly observed !
  - Soon new world record at zero field ! (data analysis in progress)
  - Time-Differential Method promising to improve statistics and reduce RF power fluctuation systematics.
  - Need improvement of the RF power stability (systematics) !!!

Stay tuned !

MuSEUM Collaborators

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

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Thank You
For
Your Attention

Backup Slides

https://indico.cern.ch/event/687183/contributions/2928847/attachments/1627584/2592472/SWICH2018_Crivelli.pdf

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Muon g-2
FNAL

- → hadronic contribution
- → hadronic lbl contribution
- → New Physics

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_B}$$

QED

μ_μ, α, g_μ

$$\mu_\mu = g_\mu \frac{e\hbar}{2m_\mu}$$

QED

m_μ

MUSEUM -HFS

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

- → μ_μ
- → α
- → QED corrections
- → weak contribution

QED

m_μ

Mu-MASS

$\Delta\nu_{1S\text{-}2S}$

- → m_μ
- → QED corrections
- → Rydberg

From K. Jungmann

How to improve the accuracy of m_μ/m_e?

Comparison between theoretical and experimental value of $\Delta\nu$

$$\Delta\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1 + \frac{m_e}{m_\mu}\right]^{-3}.$$ ＋higher order

where recoil term 800kHz (120ppm) and so on are included.

R_∞＝10973731.568639(91)m^{-1}(0.09ppt)

（Cs atomic beam interferometory）

α^{-1}=137.03599958(52) (3.8ppb)

（from electron *g-2*）

m_μ/m_e=206.7682670(55) (27ppb), μ_μ/μ_p=3.183345396(94) (30ppb)

This value is used for the determination of *g-2*.

Test of CPT and Lorentz Invariance

CPT broken Theory ⇒ Lorentz symmetry is broken

O.W. Greenberg, PRL 89 (2002) 231602
R. Blihm, V.A. Kosteleky, C.D. Lane, PRL 84 (2000) 1098
V.W. Hughs et al., PRL 87(2002) 111804

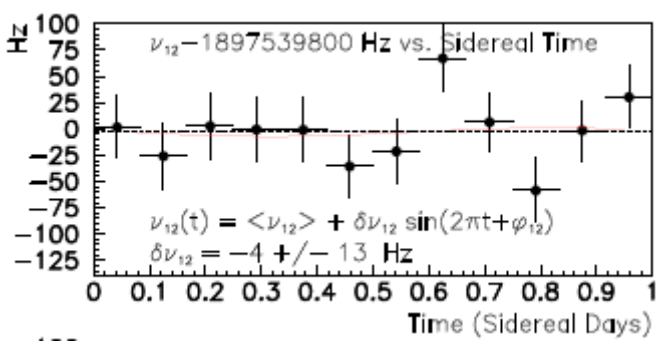
CPT violation search

Ex: Muon difference $g_{\mu+}/ g_{\mu-}$ 10^{-8}

g_μ-2/MuHFS precise measurement

Lorentz symmetry violating term in STE Lagrangian b
Corresponding MuHFS $\Delta\nu_{12/34}$
These value might change in sidereal time (23h56m)

$$\tilde{b}_3^{\mu}/\pi=-\delta\Delta\nu_{12}=\delta\Delta\nu_{34}$$



LAMPF Exp. Figure of Merit

$$2\sqrt{(b^{\mu+}{}_X)^2+(b^{\mu+}{}_Y)^2}\,/\,m_\mu < 5\times10^{-22}$$

$m_\mu/M_P \sim 10^{-20}$

Plank scale sensitivity

V.A. Kostelecky, A.J. Vargas, PRD 92 (2015) 056002

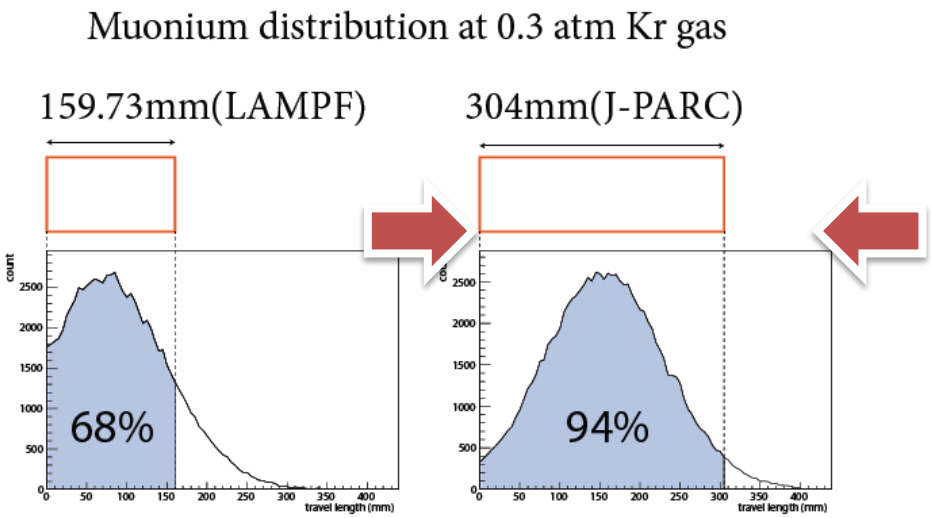
Key Components

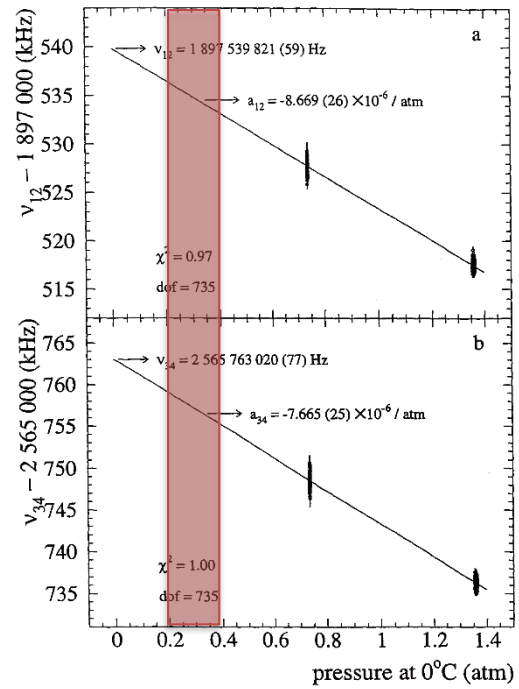
• Intense Muon Beamline	Kawamura, Toyoda
• Superconducting Magnet (HF)	Sasaki, Mizutani, Higashi, Ueno
• Permalloy magnetic shield (ZF)	Tanaka, Kanda, Ueno
• RF Cavity	Tanaka, Matsuda, Yoshida
• Kr Chamber & Gas Handling	Tanaka, Torii, Strasser
• Positron Detector	Kanda, Fukao, Mibe, Kojima
• Beam Profile Monitors	Ueno, Kanda, Toyoda, Ito
• Systematic Error Study	Tanaka, Kanda, Ishida

Improvement from LAMPF

Tanaka, Matsuda, Torii

Cavity Length



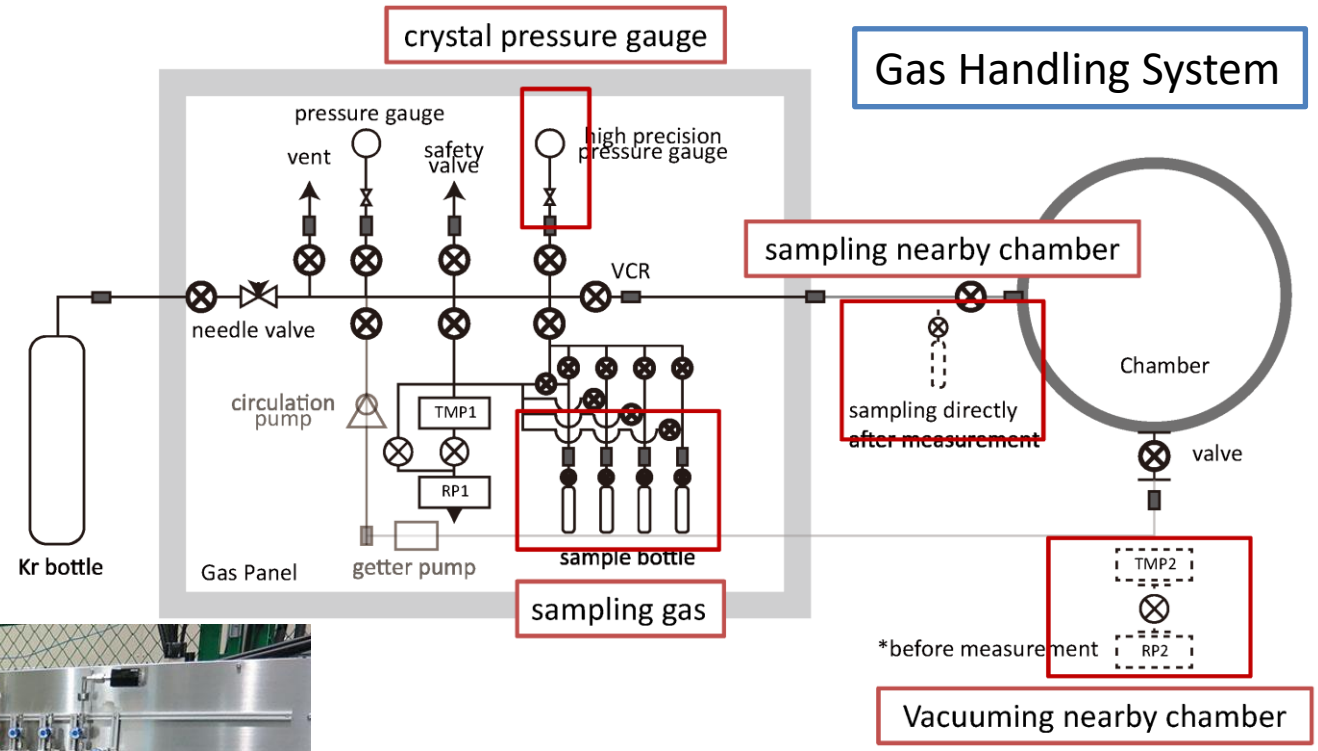


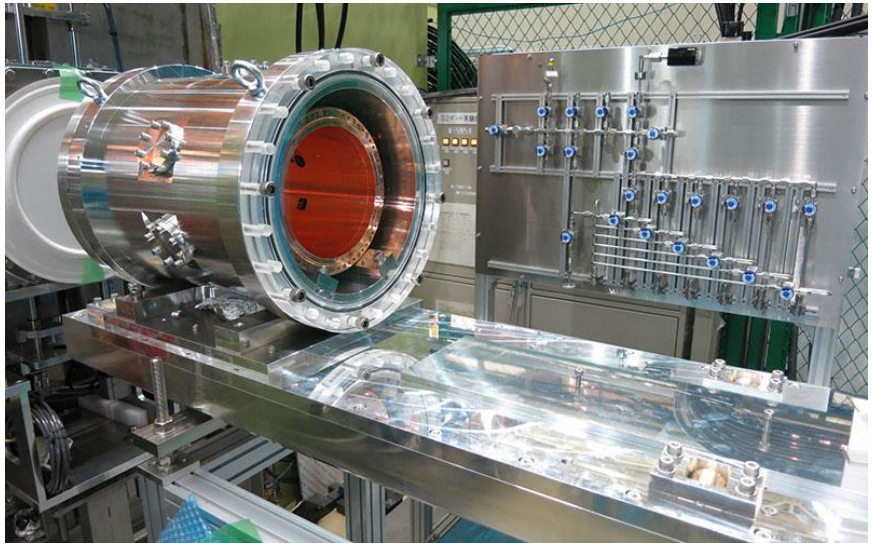
The transition frequency of muonium in gas vary with the gas pressure due to atomic collision between Mu and Kr.

⇒ Fitting 0.8 and 1.5 atm data, old quadratic dependence parameter was used (Los Alamos).

⇒ We need data at lower pressure for improved fitting.

RF Cavity & Gas Chamber



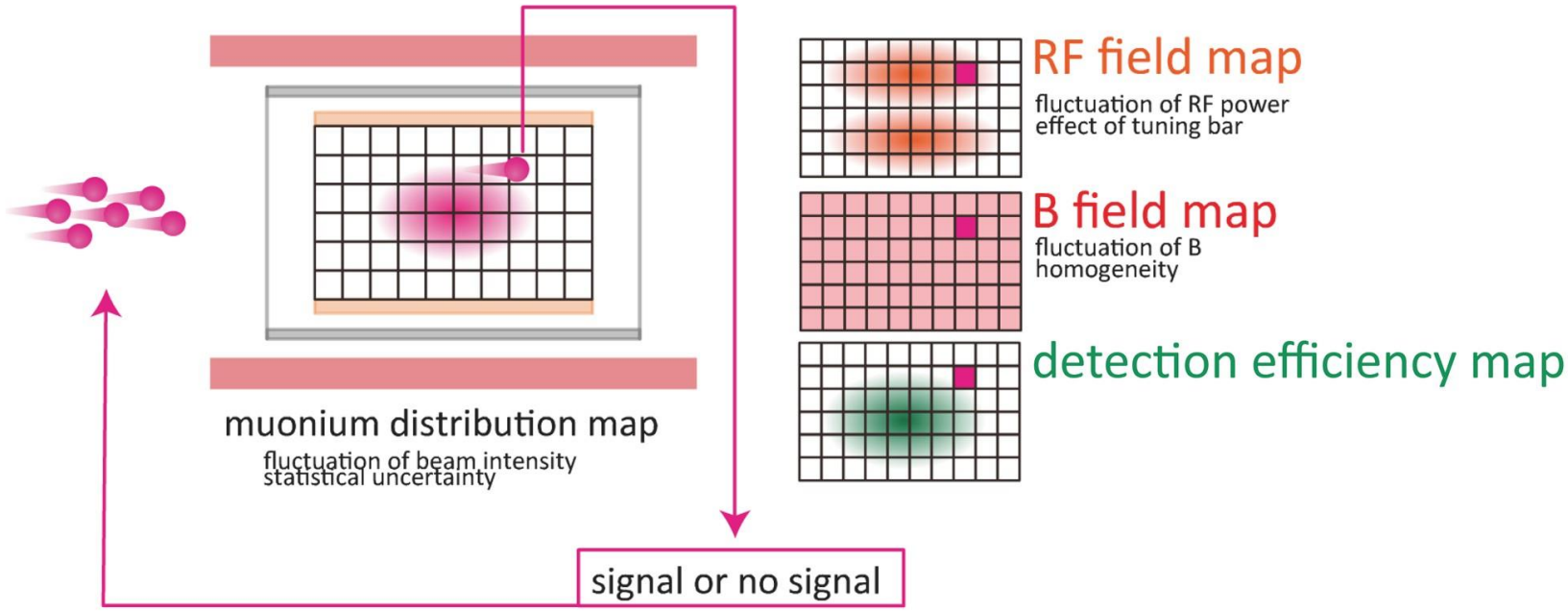


- Pressure: 0.5 – 1.5 atm
- Readout precision: several ppm (crystal gauge: 0.008% of full range)
- Contamination: below 1ppm.
- gas sampling before, during and after the experiment (several weeks).

Systematic Error

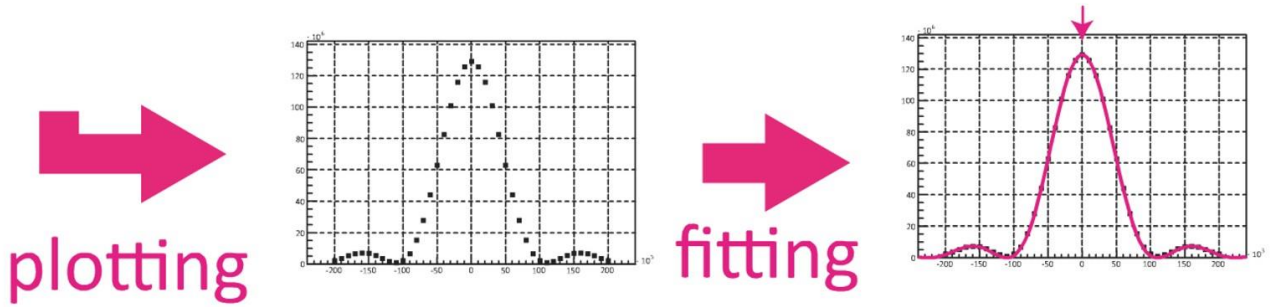
Tanaka, Kanda, Ishida

Calculate transition probability.



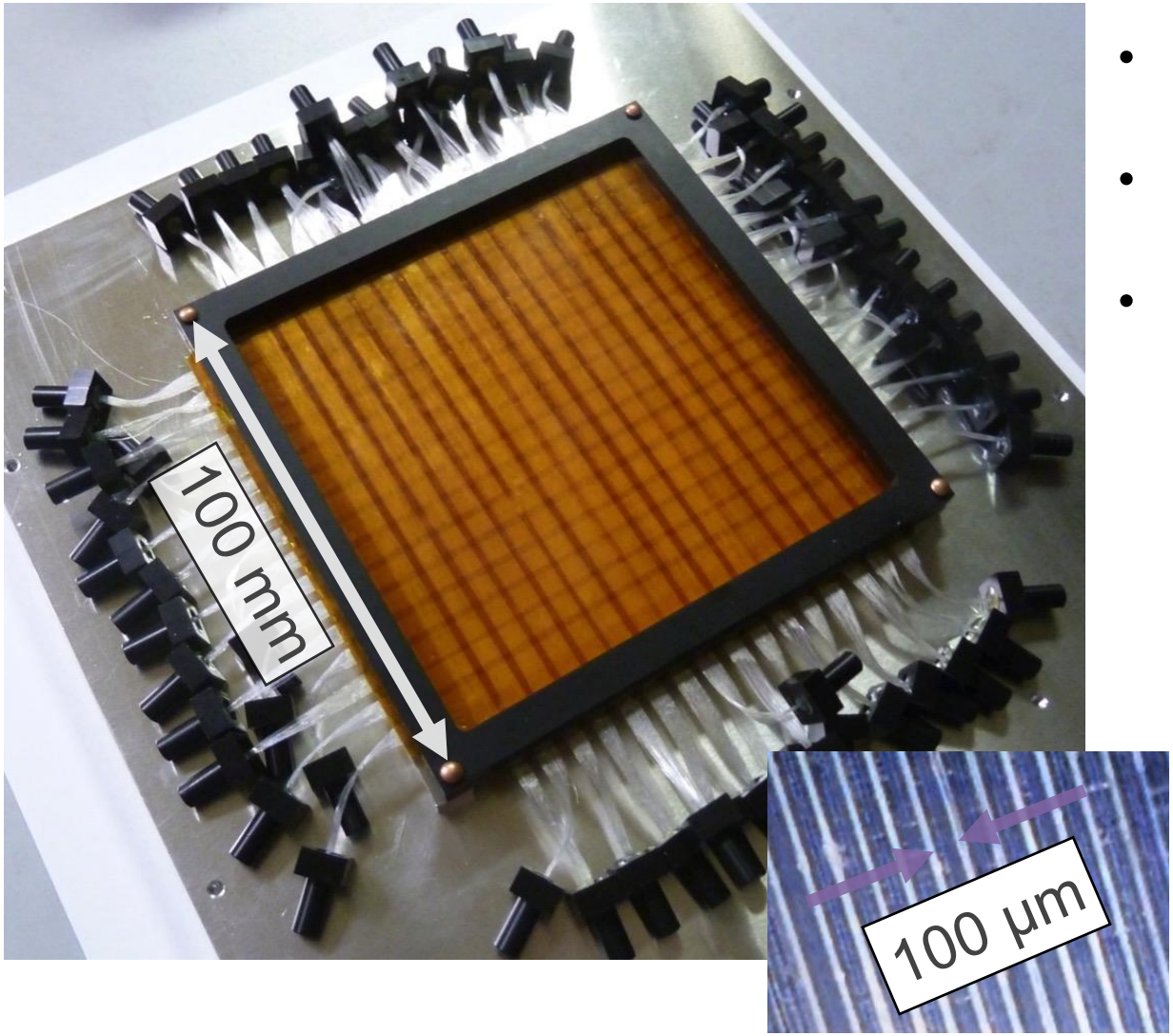
Repeat calculation for every muonium.

Center of the resonance line determined by fitting.

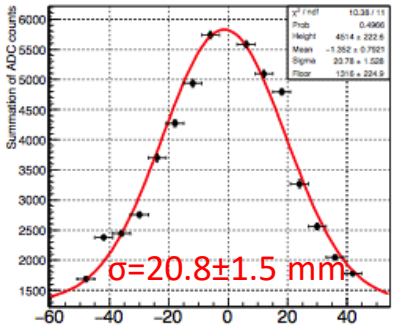


Muon Beam Profile Monitor

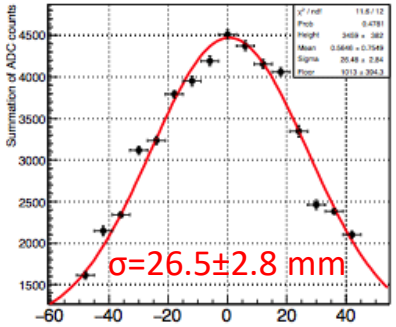
Kanda, Ueno, Toyoda



- Two layers of 100-μm fiber hodoscope (2x16ch).
- 3 x 3mm^2 active area MPPC with 15-μm pixel pitch.
- EASIROC readout



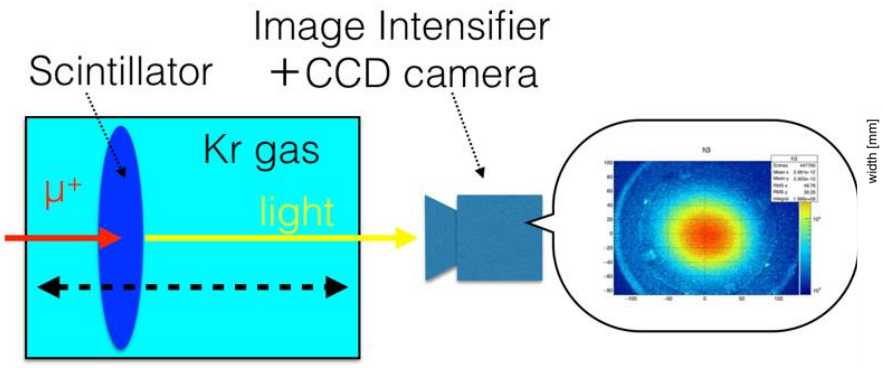
Horizontal position (mm)



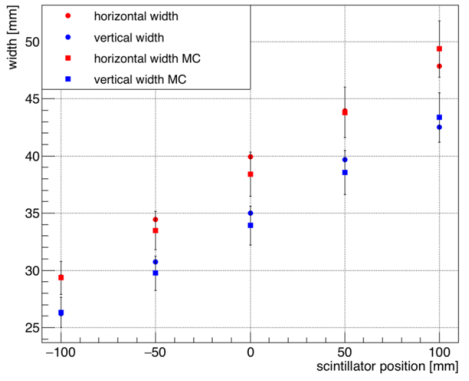
Vertical position (mm)

Offline 3D Beam Profile Monitor

Ueno, Kanda, Toyoda, Ito



Muon beam width



Muon beam center