Development of muonium hyperfine structure measurement with high magnetic field

10th International Workshop on Fundamental Physics using Atoms (1/8-1/9/2018) @ Nagoya University

Toya Tanaka (UTokyo) for MuSEUM collaboration

MuSEUM

東京大学
THE UNIVERSITY OF TOKYO

Outline

- Introduction
- Precision of the previous research of LAMPF
- Development of the magnets and NMR probes for MuSEUM experiment

Outline

- Introduction
 - About MuSEUM collaboration
 - How to measure
 - Related physics - muon g-2
 - Setup and roadmap of MuSEUM experiment

- Precision of the previous research

- Development of the magnets and NMR probes for experiment

MuSEUM collaboration

Muonium **S**pectroscopy **E**xperiment **U**sing **M**icrowave

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Goals of MuSEUM collaboration

- **High precision measurement of muonium hyperfine structure (MuHFS) in Zero field & High field**

(See Y. Ueno's poster No.26 about ZF experiment)

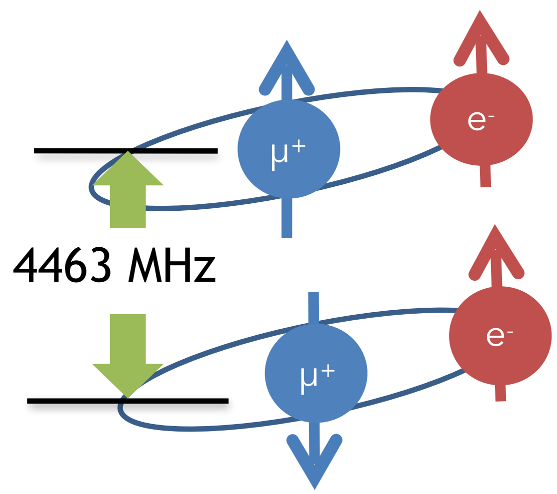
- Stringent test of bound state QED by comparing to the theoretical calculation

$$\Delta\nu_{\mathrm{HFS}}(theo) = 4\ 463\ 302\ 891(272)\mathrm{Hz}\ (63\mathrm{ppb})$$

D. Nomura and T. Teubner, Nucl. Phys. B **867**, 236 (2013).

$$\Delta\nu_{\mathrm{HFS}}(exp) = 4\ 463\ 302\ 765(53)\mathrm{Hz}\ (12\mathrm{ppb})$$

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



- Relative uncertainty of 1.7 T measurement at LAMPF
  MuHFS : 12ppb, μ_μ/μ_p and m_μ/m_e :120ppb

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

- MuSEUM's goal : Improve the precision by a factor of 10
  MuHFS : ~1ppb, μ_μ/μ_p and m_μ/m_e :10ppb

MuHFS measurement with HF

- Hamiltonian describing energy splitting of the muonium $1^2S_{1/2}$ state

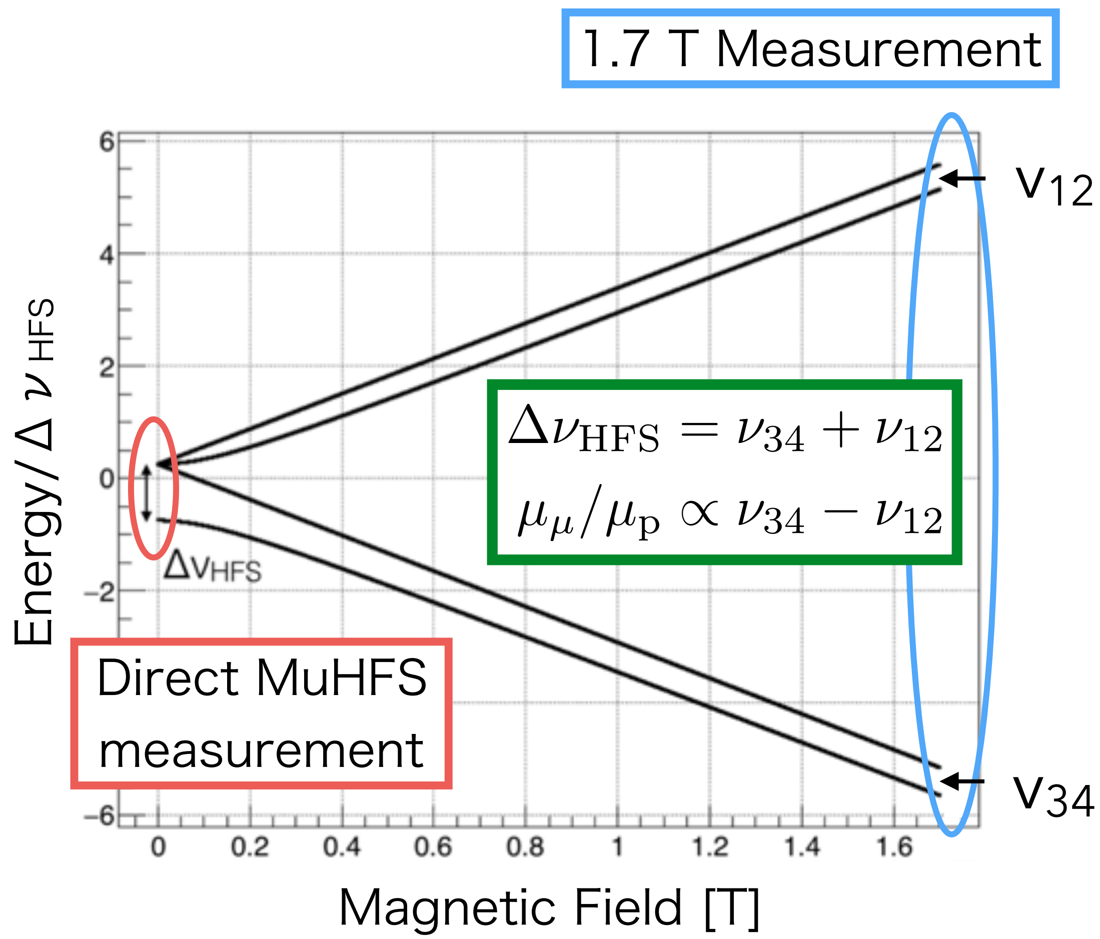
$$\mathcal{H} = \underbrace{h\Delta\nu_{\mathrm{HFS}}\vec{I}\cdot\vec{J}}_{\text{HFS}} + \underbrace{g_J\mu_B^e\vec{J}\cdot\vec{H} - g'_\mu\mu_B^\mu\vec{I}\cdot\vec{H}}_{\text{Zeeman splitting}}$$

- Spin states splits to substructure

$$\nu_{12} = -\frac{\mu_B^\mu g'_\mu H}{h} + \frac{\Delta\nu_{\mathrm{HFS}}}{2}\left[(1+x) - \sqrt{1+x^2}\right]$$

$$\nu_{34} = +\frac{\mu_B^\mu g'_\mu H}{h} + \frac{\Delta\nu_{\mathrm{HFS}}}{2}\left[(1-x) + \sqrt{1+x^2}\right]$$

$$(x \propto H)$$



- In the limit of a strong magnetic field (x>>1, x ~ 10.7 with 1.7 T)

$$\nu_{12} + \nu_{34} = \Delta\nu_{\mathrm{HFS}} \qquad \frac{\mu_\mu}{\mu_{\mathrm{p}}} = \frac{1}{2}\frac{(\nu_{34}-\nu_{12})}{\nu_{\mathrm{p}}}\frac{g_\mu}{g'_\mu} \qquad \frac{m_\mu}{m_e} = \frac{g_\mu}{2}\frac{\mu_{\mathrm{p}}}{\mu_\mu}\frac{\mu_B^e}{\mu_{\mathrm{p}}}$$

Related physics - muon *g*-2

- ~3σ discrepancy between theory and experiment

$$a_\mu(exp) - a_\mu(th) = 250(89) \times 10^{-11}$$

(from CODATA 2014)

- μ_μ / μ_p : essential parameter for muon *g-2* measurement

$$a_\mu(exp) = \frac{(g-2)_\mu}{2} = \frac{R}{\lambda - R}$$

$$R = \omega_\mu / \omega_p \ \ (540\text{ppb})$$

G.W. Bennett et al., Phys. Rev. D **73** 072003 (2006).

$$\lambda = \mu_\mu / \mu_p \ \ (30\text{ppb})$$

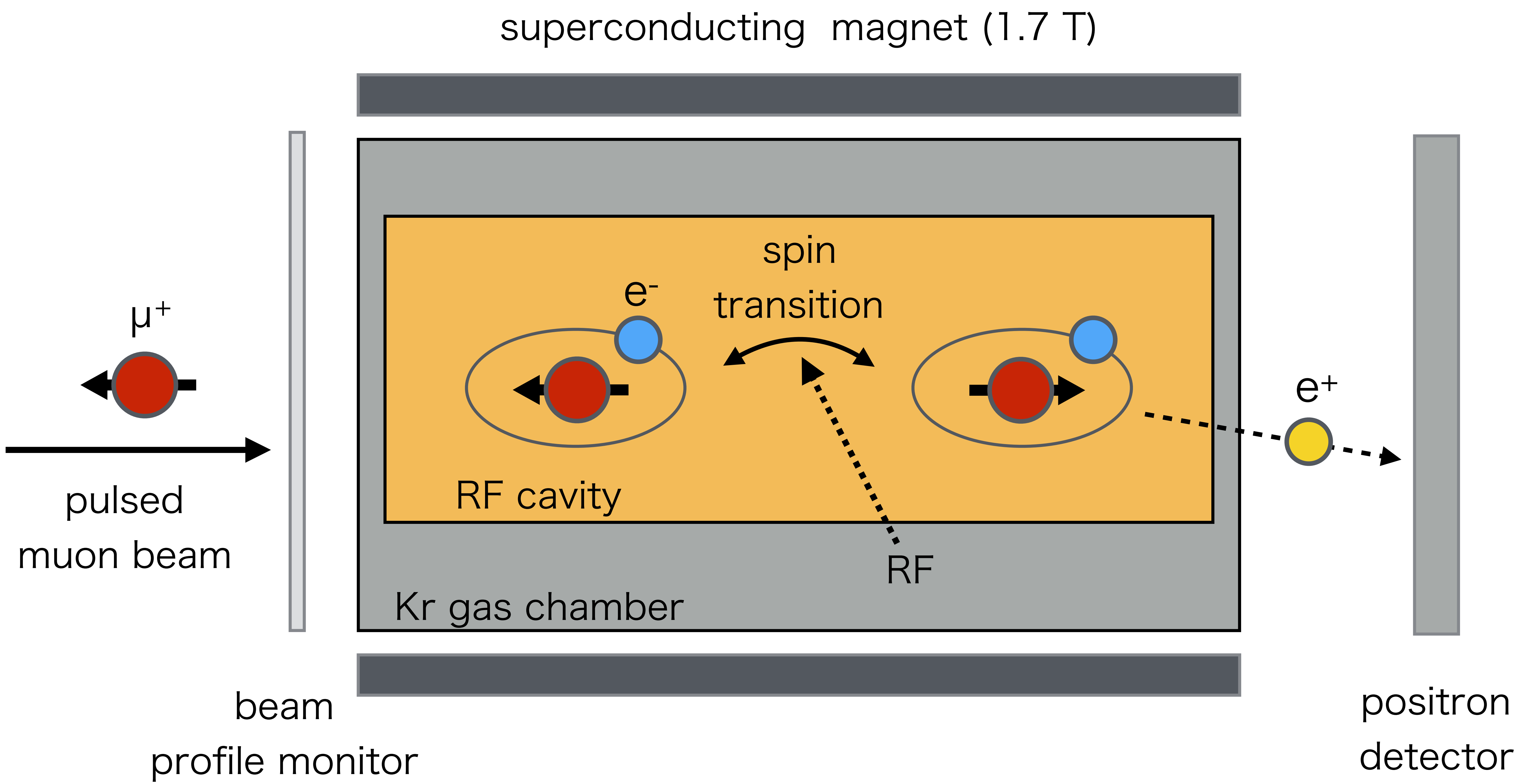
W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).
D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).

1. R : Planning 140ppb measurement at J-PARC and Fermilab

M. Otani, JPS Conf. Proc. **8**, 025008 (2015).
J. Grange Fermilab g-2 experiment technical design report (2015).

2. λ : 30ppb (indirect) -> **direct** 10ppb measurement

Setup of high field MuHFS measurement



RF cavity resonant to ν_{12} with TM110 mode & ν_{34} with TM210 mode

Road map of Experiment

- Zero field measurement @MLF D2-line - ongoing
  - 2016 Jun. - 1st measurement
  - 2017 Feb. - 2nd measurement
  - 2017 Jun. - 3rd measurement
  - 2017 Dec. - Beam monitor test
  - Next beam time at 2018 March

- High field measurement @MLF H-line
  - Will be ready in 2018 Autumn

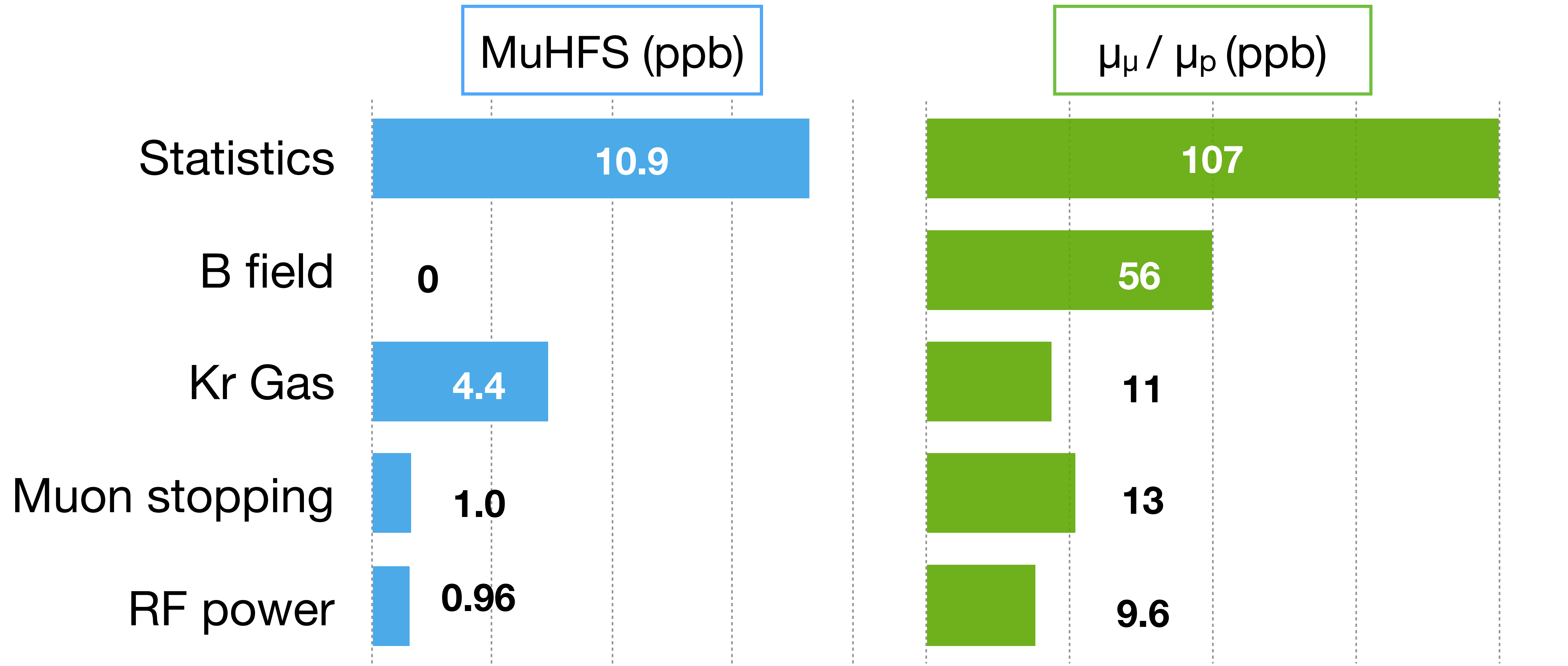
Outline

- Introduction

- Precision of the previous research
  - List of uncertainties
  - Improvement of statistics - high intensive muon beam
  - Improvement of systematics - B-field inhomogeneity

- Development of the magnet and NMR probes for experiment

Uncertainties of LAMPF experiment



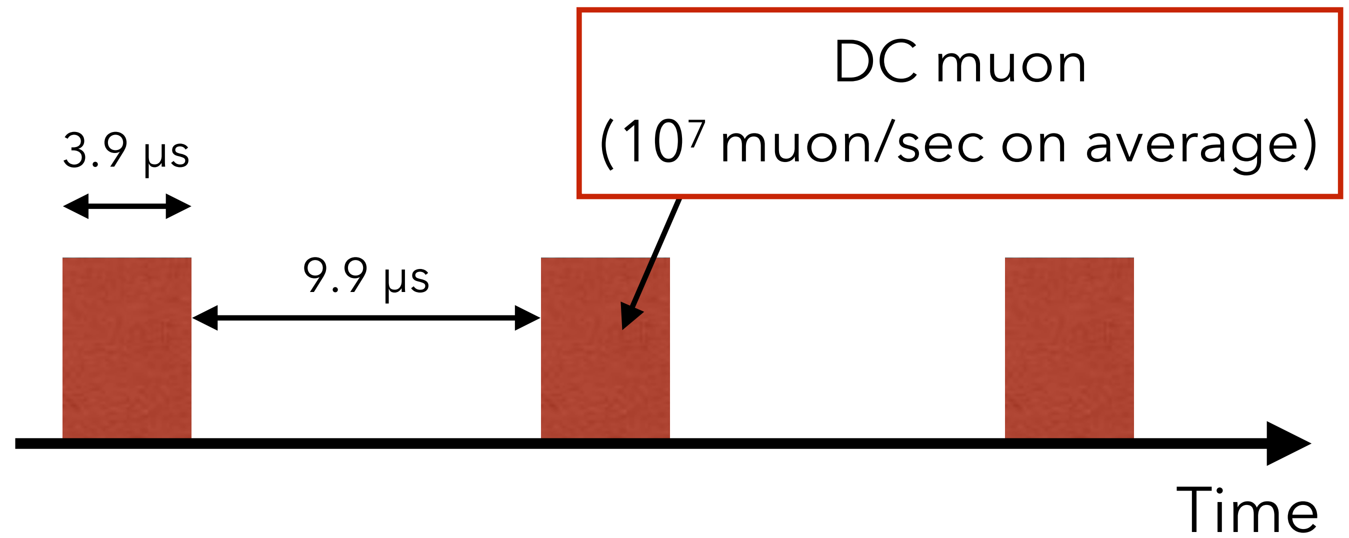
W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).

- Mainly limited by statistics - installation of H-Line @ J-PARC MLF
- Systematic uncertainty caused by B-field should be improved

High statistics by using pulsed muon beam

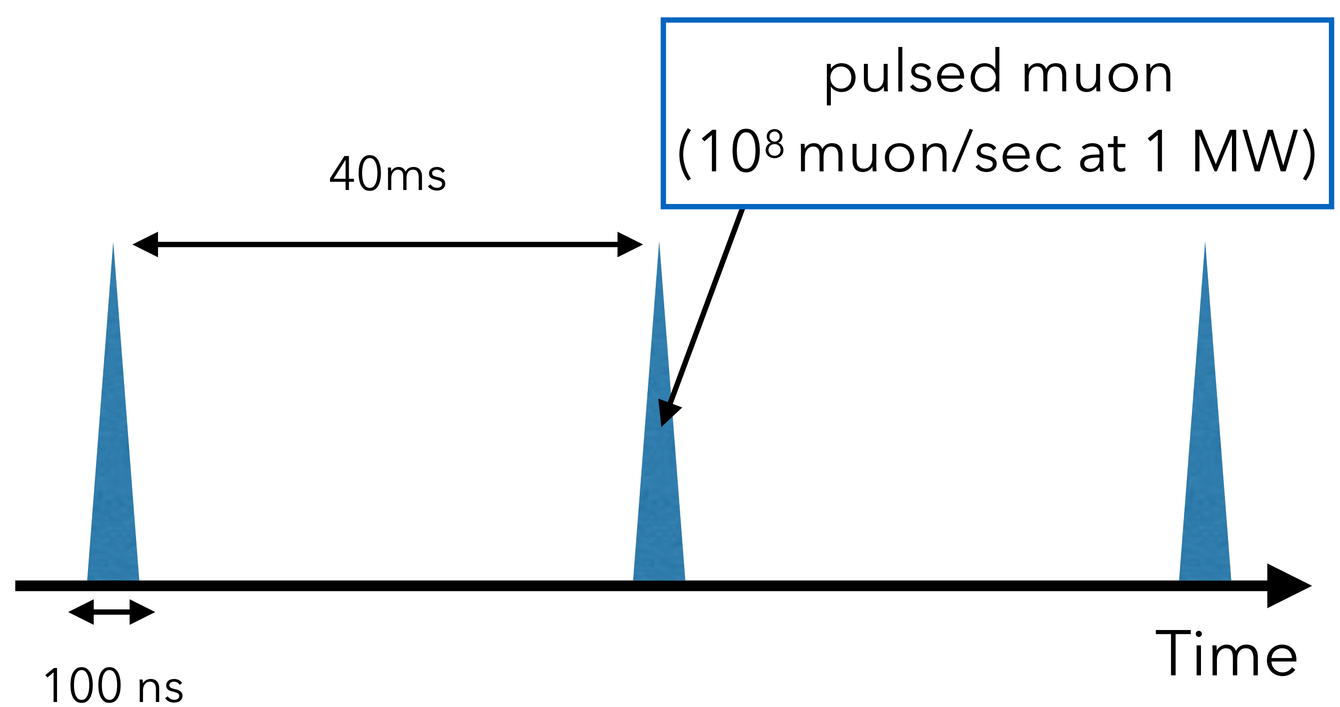
Experiment at LAMPF

- DC beam @ LAMPF
- Beam chopped for "old muonium" method
- Data taking : 6 weeks
- Total : ~10^{13} muons



MuSEUM experiment

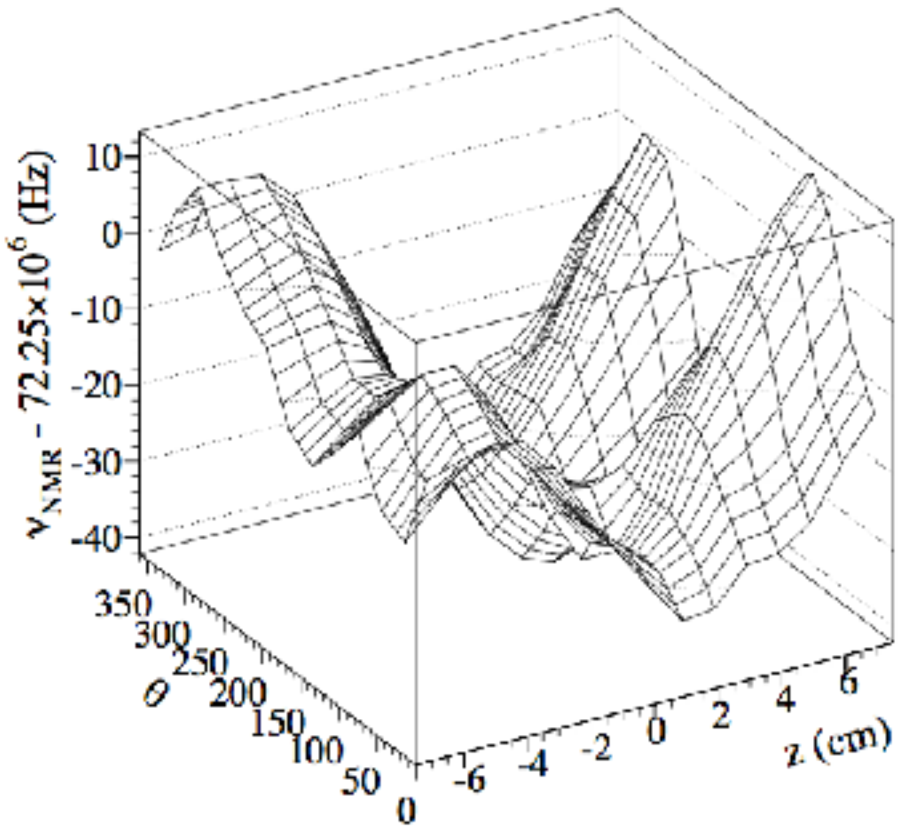
- Pulsed beam @ J-PARC MLF H-line
- All muon can be used
- Total : ~10^{15} muons (~100 days data taking)
- **10 times improvement**



B-field of LAMPF experiment

- B-field evaluated with

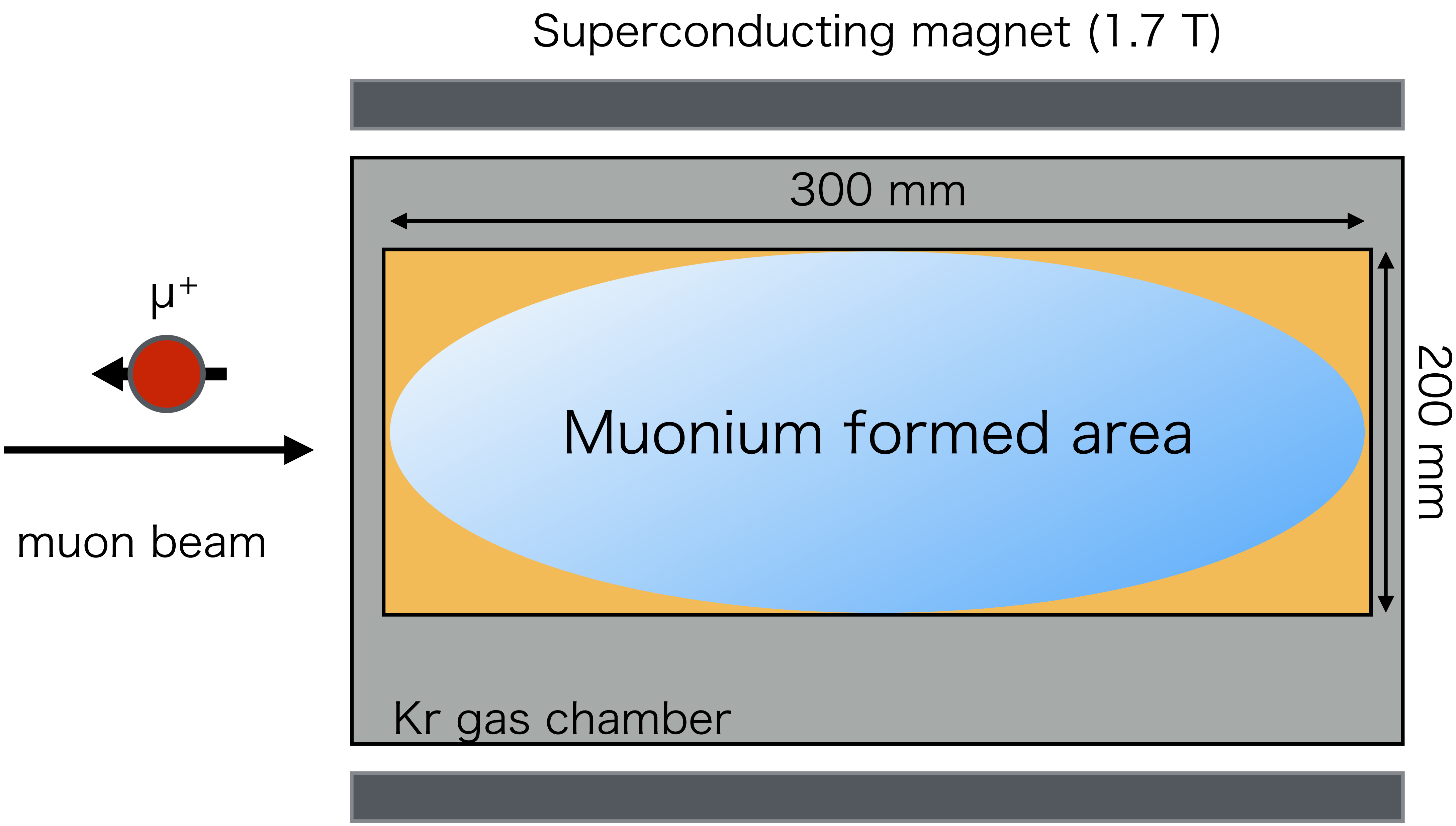
1. Magnet :1ppm in 10 cm DSV
2. B-field mapping : 0.7ppm peak-to-peak homogeneity in cylindrical surface
3. 30ppb precision pulsed NMR probes are used



Magnetic field map over r=3.5 cm cylindrical surface. z=0 cm corresponds to the cavity center.(taken from W. Liu's PhD thesis)

- Systematic uncertainty in B-field is mainly caused by
- Inhomogeneity of B-field -> MRI magnet & shimming method
- Calibration of NMR probes -> high precision NMR probes

Required B-field at MuSEUM



- Required ~0.1ppm homogeneity of 1.7 T in the spheroid muonium formed area (z= 300 mm, r=100 mm)

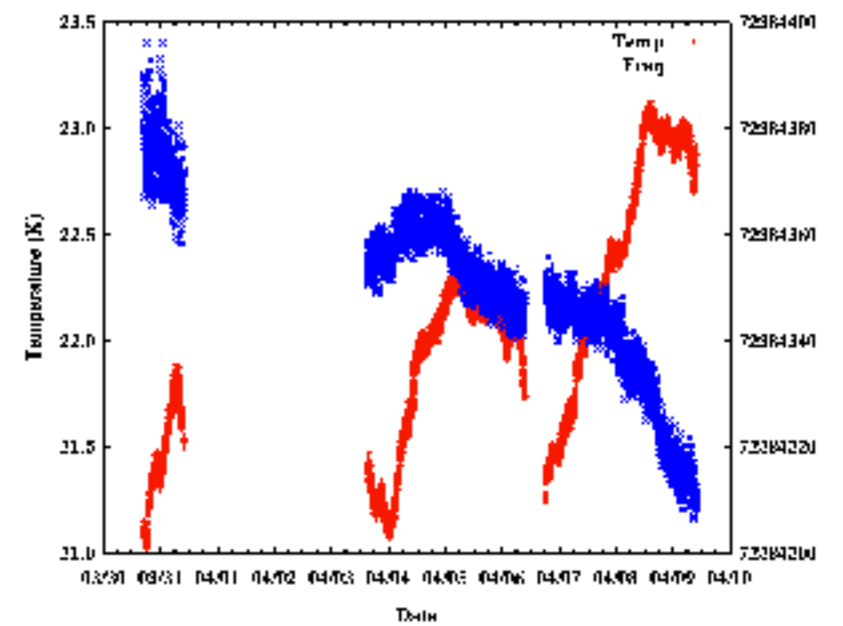
Outline

- Introduction
- Precision of the previous research of LAMPF
- Development of the magnets and NMR probes for MuSEUM experiment
  - Precision of the MRI magnet
  - NMR probes required in MUSEUM experiment
  - Development of the CW-NMR probe

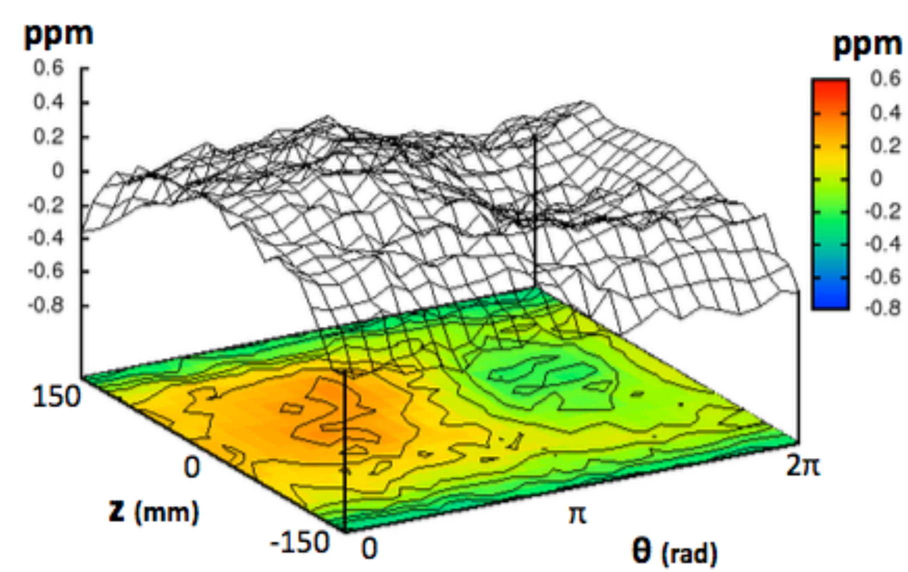
MRI magnet status

- Solenoid MRI magnet for MuSEUM @ J-PARC (max 2.9 T, used in 1.7 T)

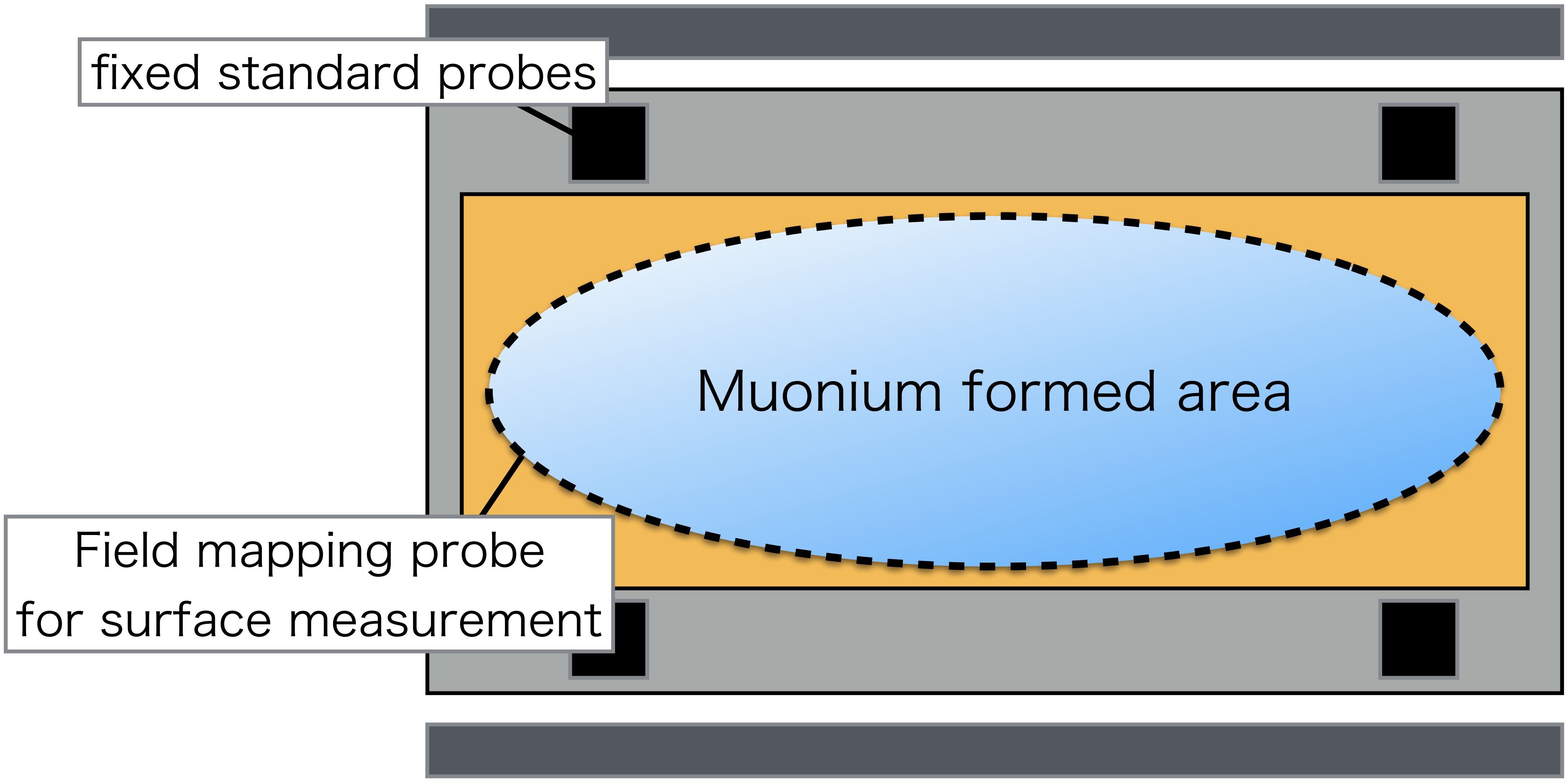
- B-field drifted 64Hz per 9 days (2015/3/30 - 2015/4/9)
- 3ppb/h stability



- B-field homogeneity suppressed to 0.8ppm by shimming the MRI magnet with shim trays
- 576 points measured by single NMR probe (including B-field drift, alignment error etc.)



NMR probes for MuSEUM experiment

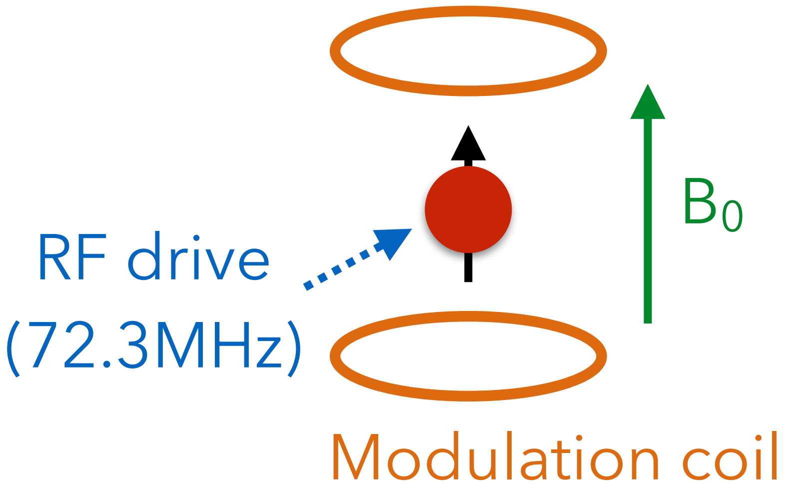


- Stability per time - Online monitor by fixed standard probes
- Homogeneity in Muonium formed area
  - Measurement by the multi channel field mapping probe

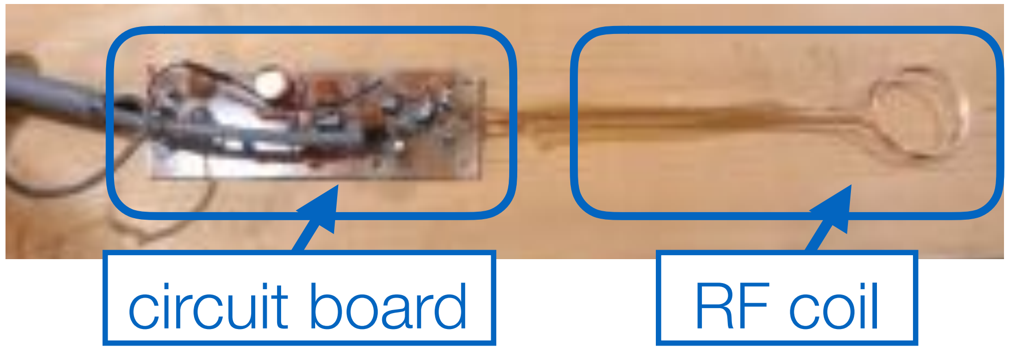
CW-NMR probe

- NMR(Nuclear Magnetic Resonance)

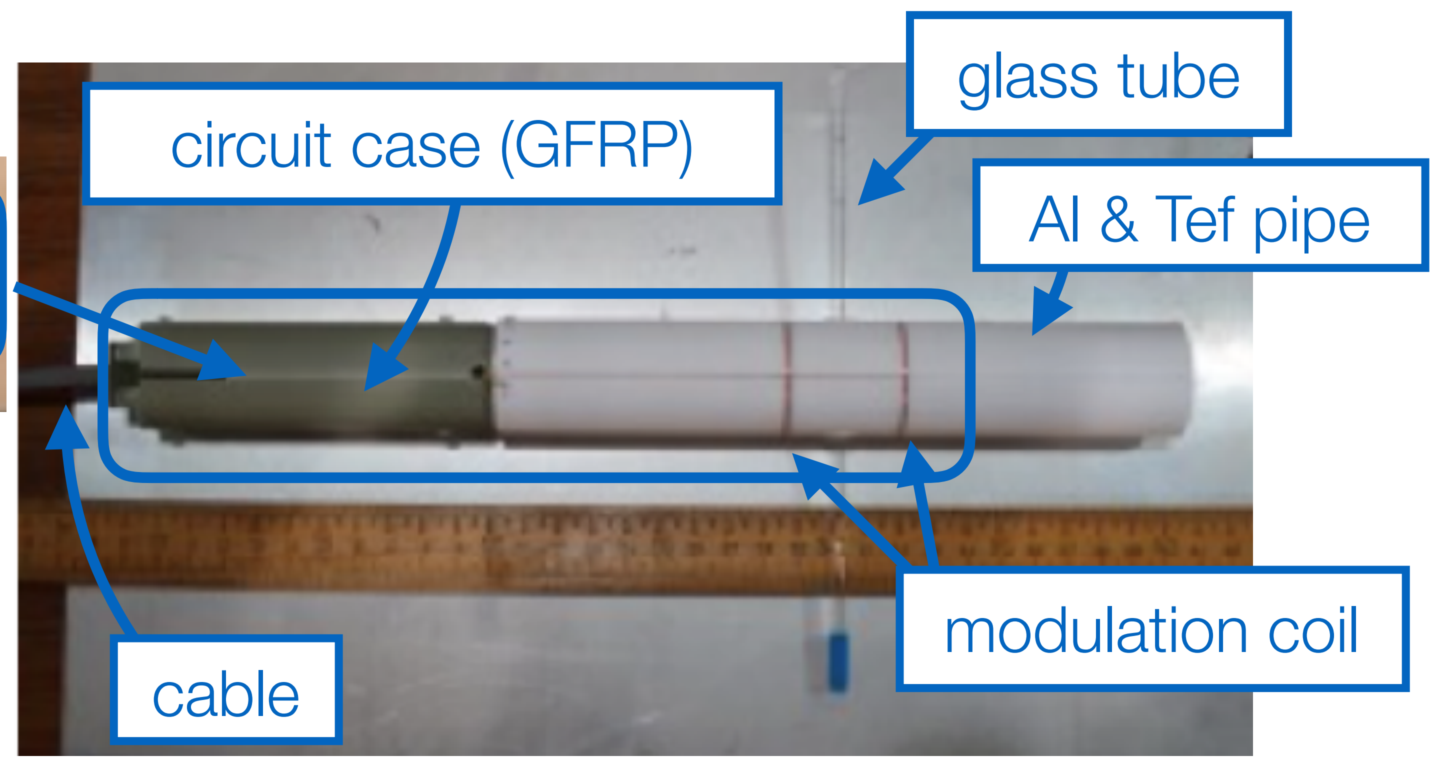
$$2\pi\nu_0 = \gamma_\mathrm{p} B \;(\gamma_\mathrm{p} = 267.52219 \times 10^6 \;[\mathrm{rad\ s^{-1}t^{-1}}])$$



- Continuous wave NMR probe (CW-NMR)
  - Sweep the B-field mandatory by the modulation coil
  - Detect the envelope signal of proton NMR

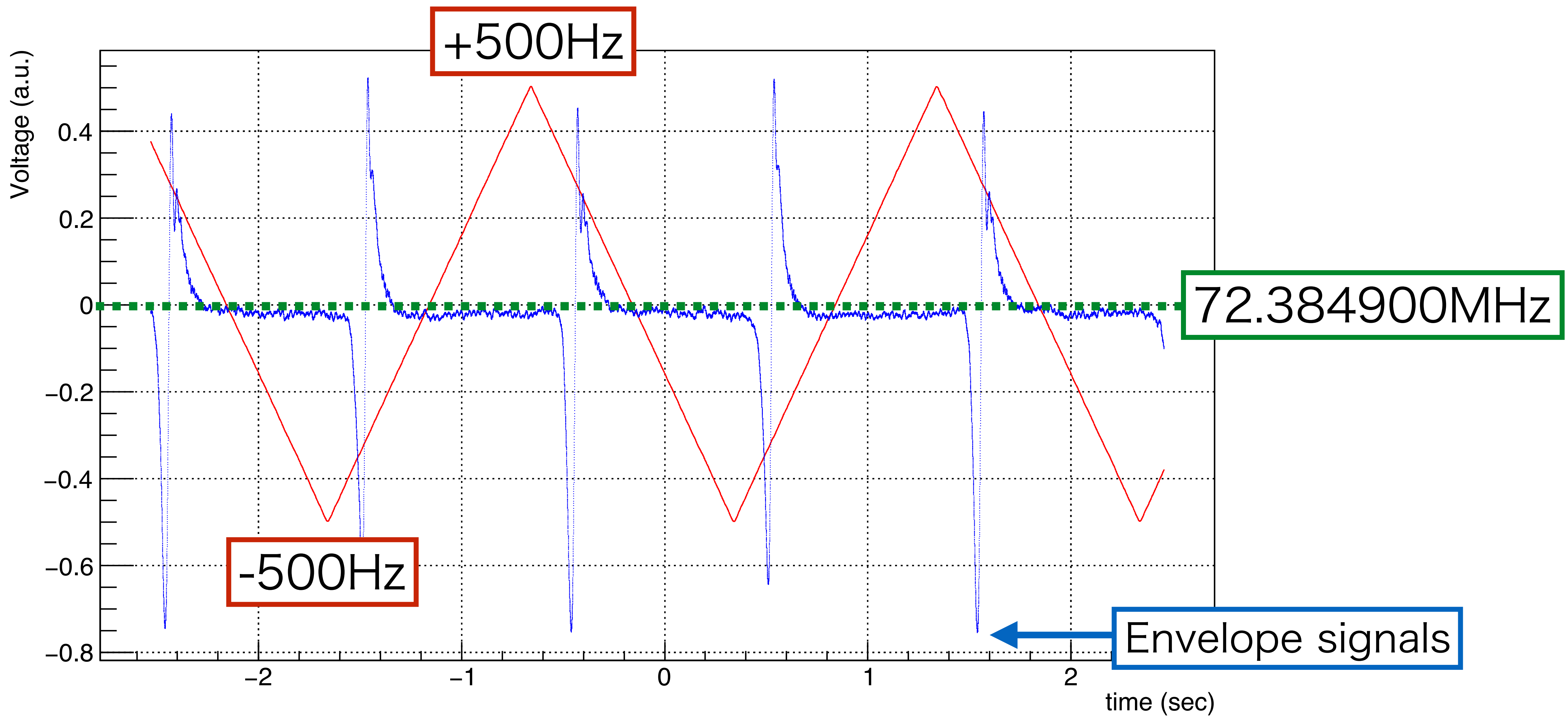


Tuned resonant to 72.3MHz (1.7 T)



NMR signal

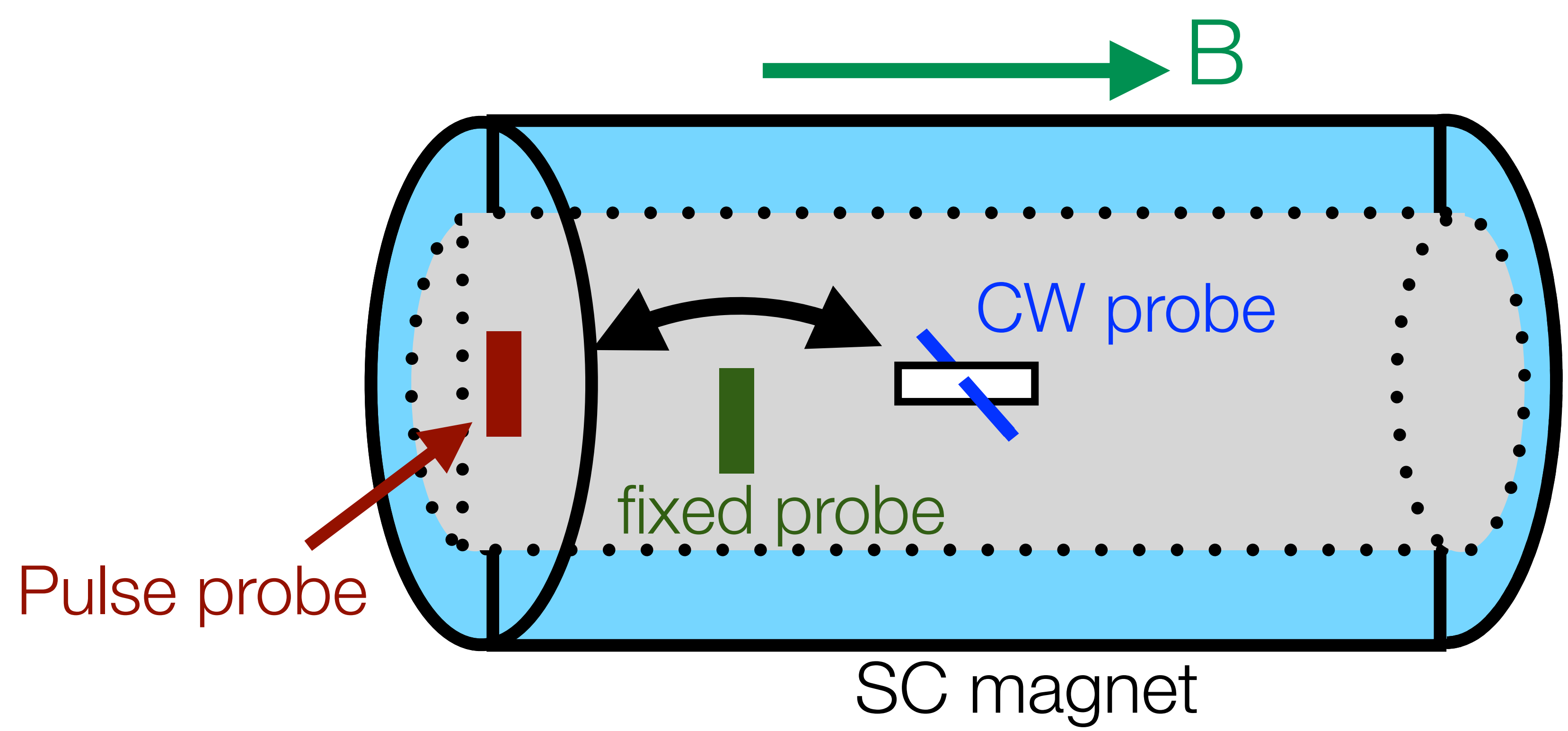
- Detected the envelope signal of the proton NMR with our magnet
- Red : Trigger of modulation , Blue : signal from NMR probe



(the raw waveform is averaged)

NMR probe cross calibration

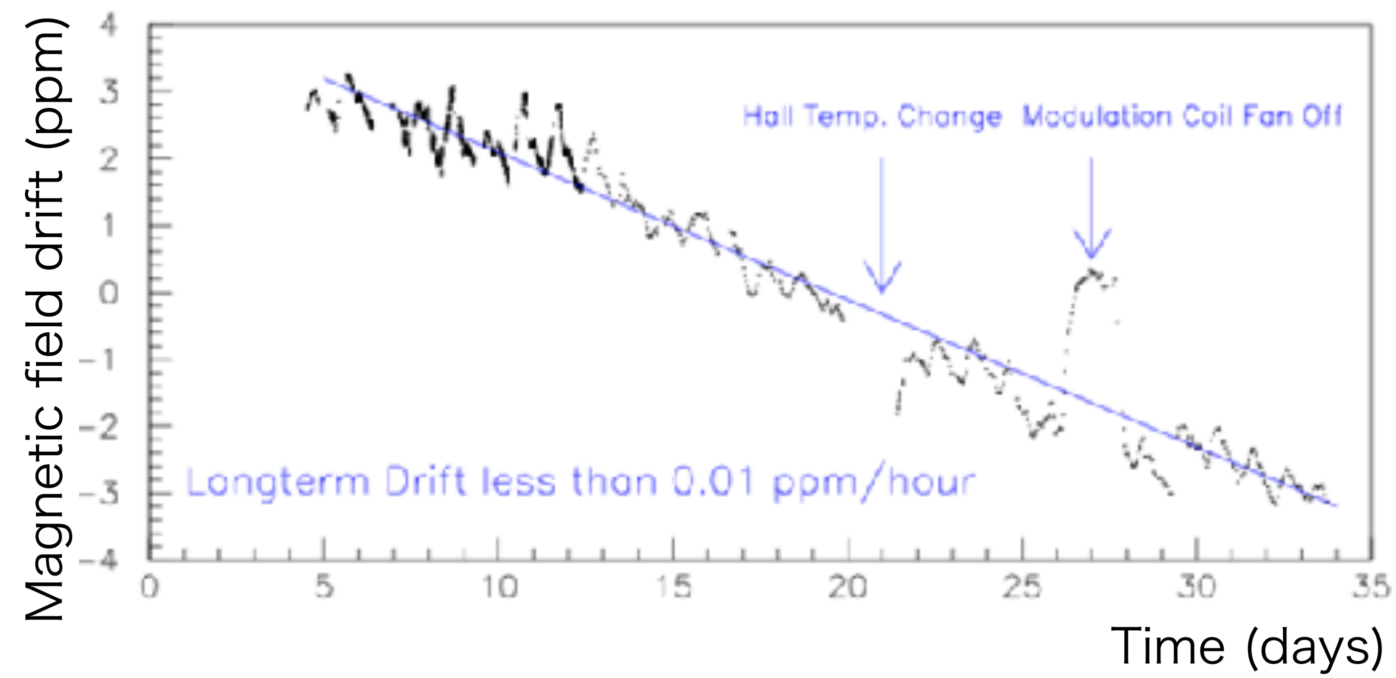
- Mar 2017 : cross calibration with FermiLab g-2 group @ANL, B=1.45 T
- 20ppb agreement at blind analysis with CW and pulse NMR probe (analyzed by S. Seo and D. Flay)



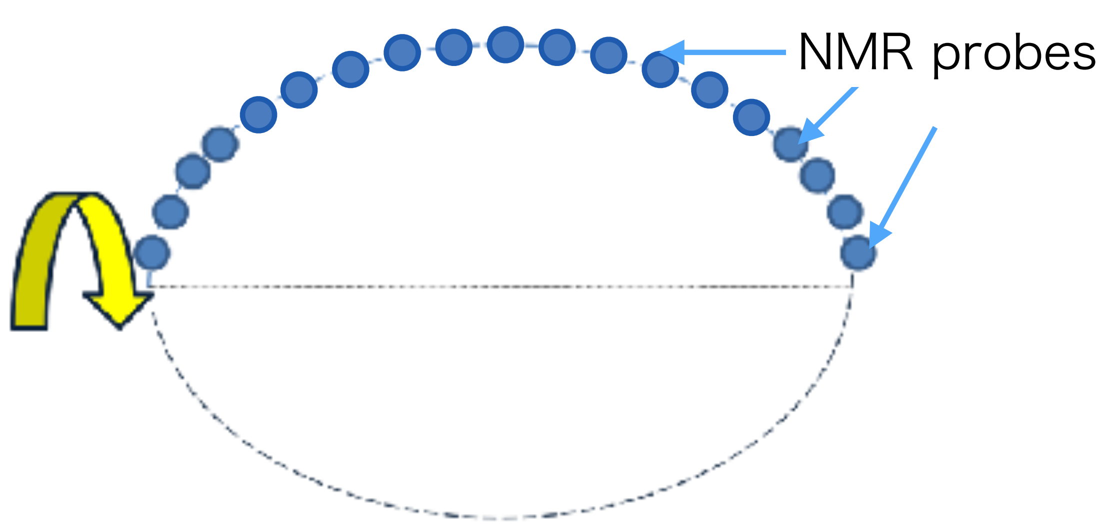
- Found uncertainties caused by the material of the NMR probe itself, especially the circuit board - replace with non-magnetic materials
- Mar 2018 : Planning next cross calibration of the new NMR probe @ANL, B=1.7 T

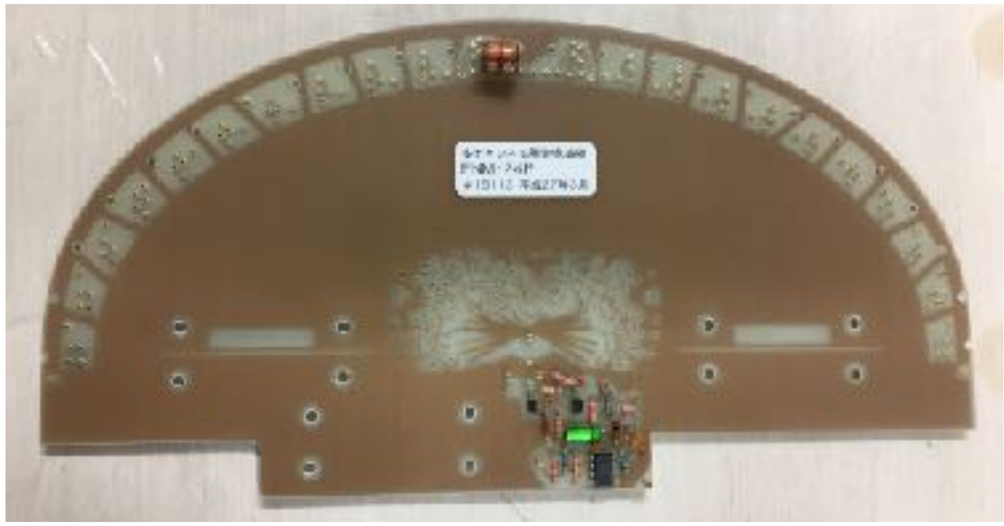
Field mapping probe

- Concept : Want to suppress the effect of B-field drift during scanning
- Drift in LAMPF experiment
  - long term drift ~ 10ppb/h
  - short term drift ~ 100ppb/h



- Fast field mapping enables B-field measurement with low drift
- Design : 24ch NMR probes on half-oval plate to scan the surface





Prototype of field mapping probe

Summary

- High field MuHFS measurement is a good probe to test the bound state QED and also μ_μ / μ_p and m_μ / m_e can be measured. For improvement, more statistics and high homogeneity of magnetic field are required.

- The spec magnet fulfills the requirement of the MuSEUM experiment.

- To develop high precision NMR probes for high precision B-field measurement, R&D is in progress, starting from development of single channel probes to multi channel field mapping probe.

Appendix

lambda used at g-2 measurement

Magnetic moment ratio values used at BNL(Brookhaven national laboratory) result was derived from $\Delta\nu_{HFS}$ results by LAMPF (12ppb) applying to

$$\Delta\nu_{\mathrm{HFS}} = \frac{16}{3}\alpha^2 c R_\infty \frac{m_\mathrm{e}}{m_\mu}[1+\frac{m_\mathrm{e}}{m_\mu}]^{-3} + \mathrm{corrections}$$

and the magnetic moment was calculated by the mass ratio as

$$\frac{\mu_\mu}{\mu_\mathrm{p}} = \frac{g_\mu}{2}\frac{m_\mathrm{e}}{m_\mu}\frac{\mu_B^\mathrm{e}}{\mu_\mathrm{p}}$$

which is called the **indirect** determination. This calculation assumes the SM of the correction terms.

(partially taken from D. Nomura-san’s slide)

Related physics : Exotic particle search

a pseudo vector boson

$$-\frac{\alpha}{r} \rightarrow -\frac{\alpha + \alpha''(\mathbf{s}_1 \cdot \mathbf{s}_2)e^{-\lambda r}}{r},$$

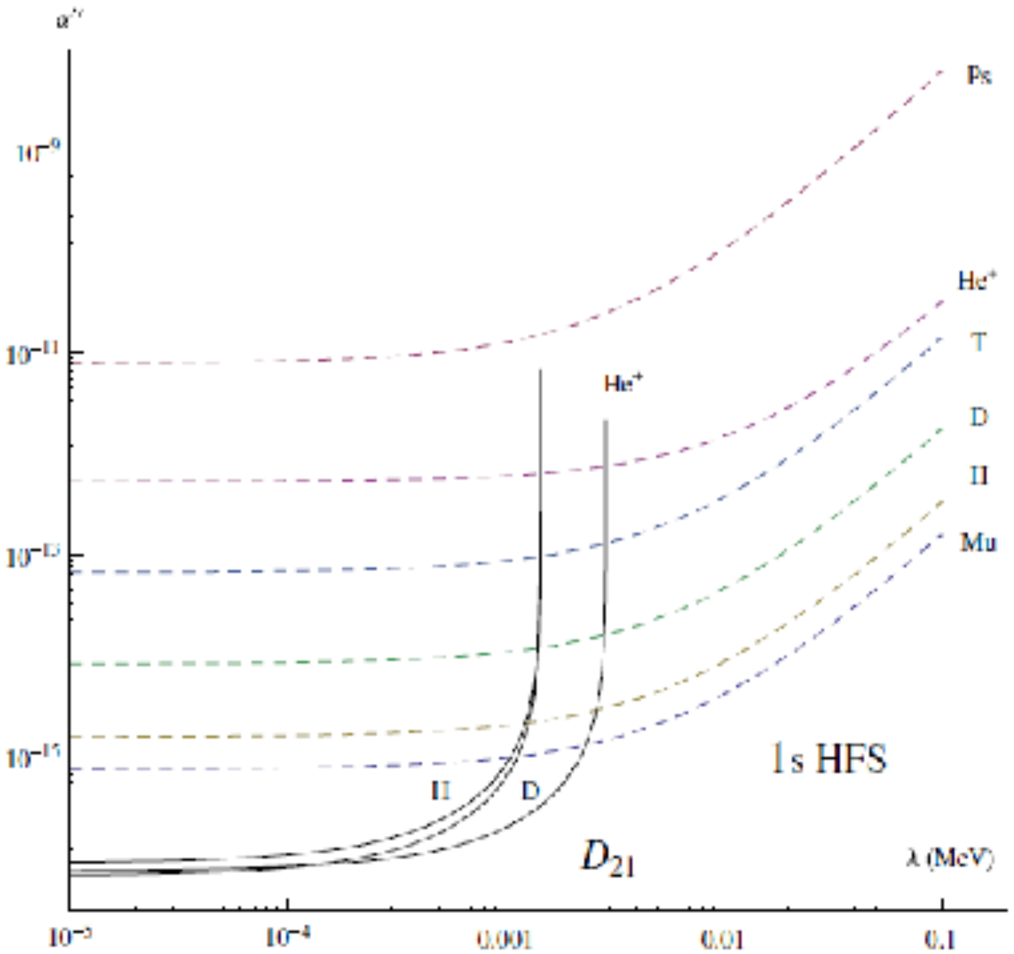


Fig. 2 on PRL 104, 220406 (2010)

a massive vector boson

$$\frac{\Delta E_{\rm hfs}}{E_{\rm hfs}} = \frac{8\alpha' m_e}{m_V} = \frac{8\alpha\kappa(\kappa + g_V/e)m_e}{m_V}.$$

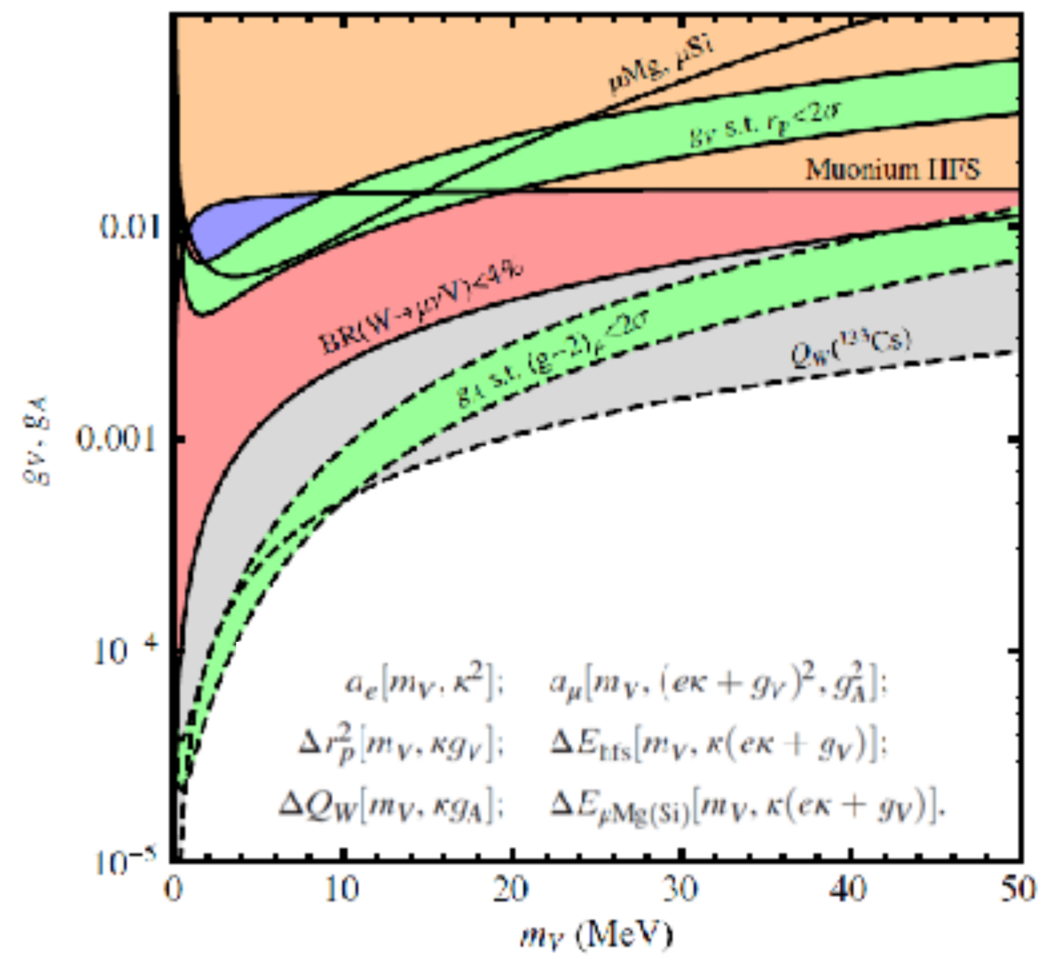


Fig. 6 on PRD90, 073004(2014).

S. G. Karshenboim *et al.*, PRL 104, 220406 (2010), PRD82, 113013(2010).
PRA 84, 064502(2011) , PRD90, 073004(2014).

(from K. Simomura-san's slide)

Related physics : Test of Loentz symmetry

CPT broken Theory⇒Lorentz symmetry is broken

R.Blihm, V.A. Kosteleky and C.D. Lane PRL84,1098(2000)
V.W. Hughs et al. PRL87,111804(2000

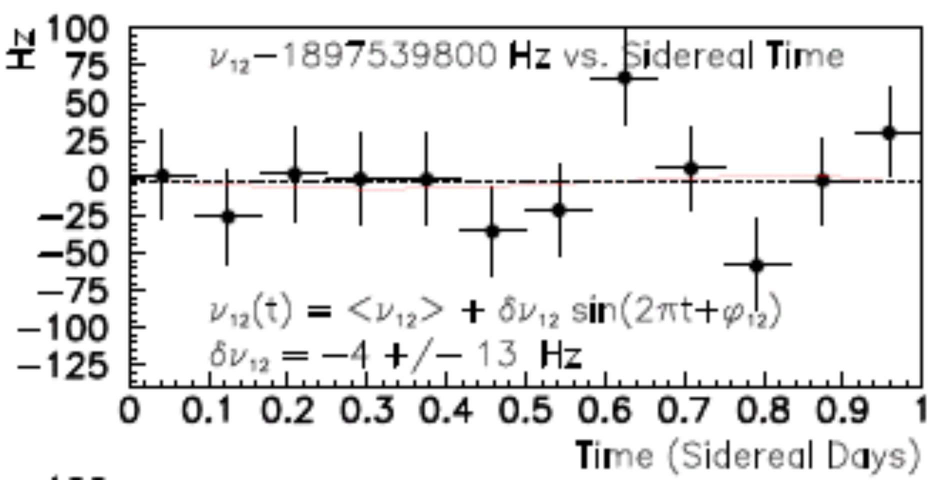
CPT violation search

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

g_μ-2/MuHFS precise measurement

Lorentz symmetry violating term in SME 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

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

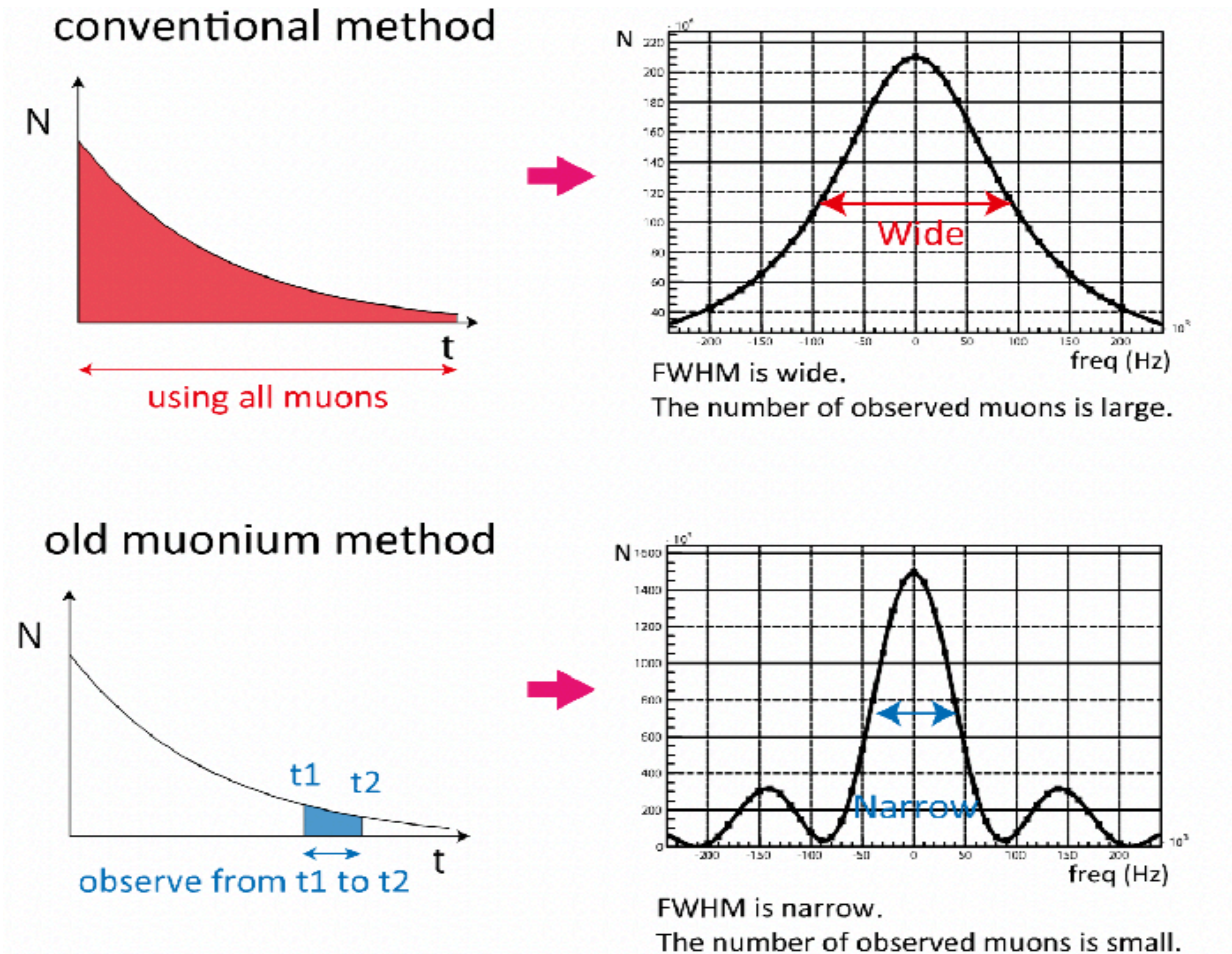
$m_\mu/m_P \sim 10^{-20}$

Plank scale sensitivity

Laboratory tests of Lorentz and CPT symmetry w/ muons
A.H. Gomes et. al., Phys.Rev.D90:076009,2014

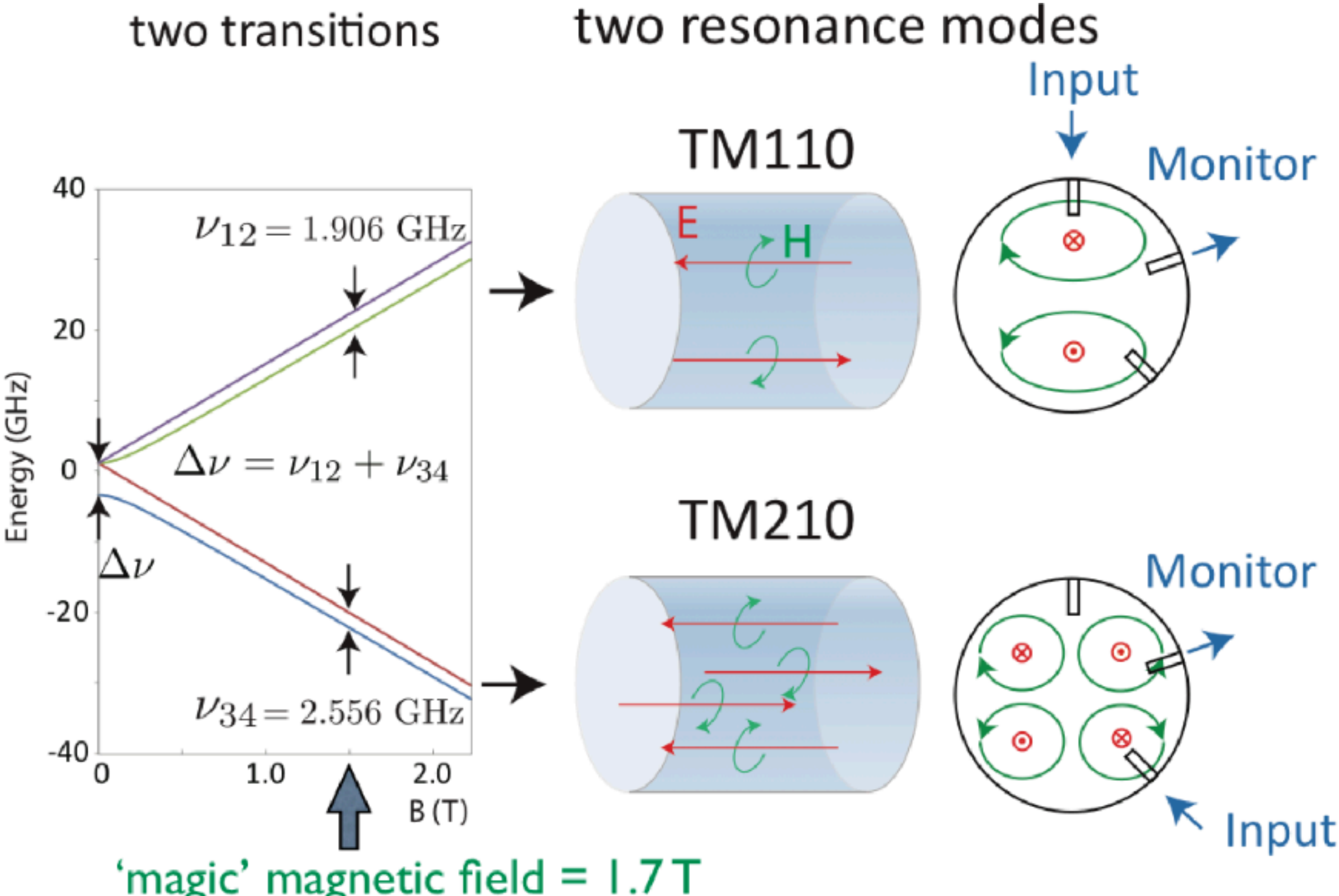
(from K. Simomura-san's slide)

old muonium method



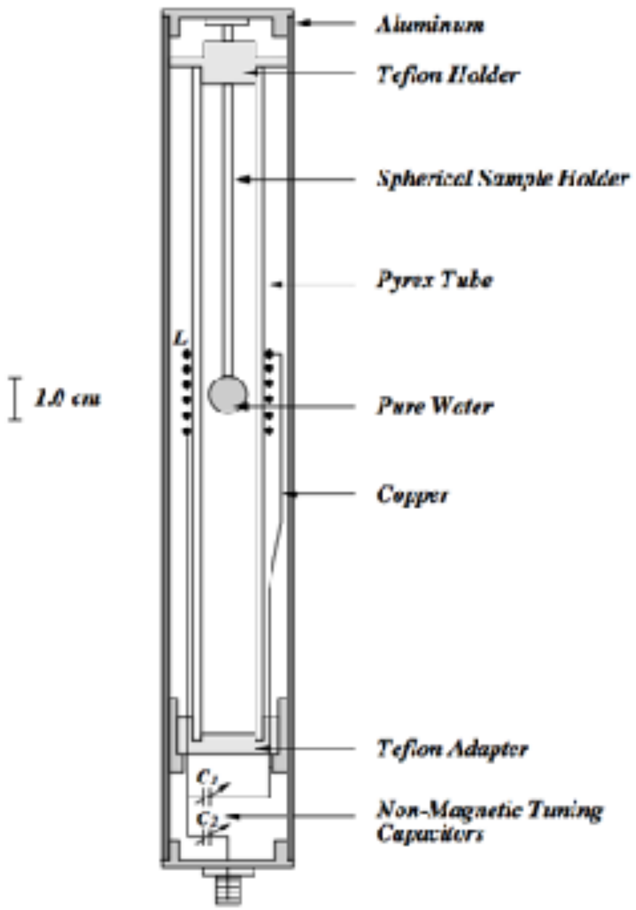
(from K.S. Tanaka-san's slide)

cavity design for HF measurement

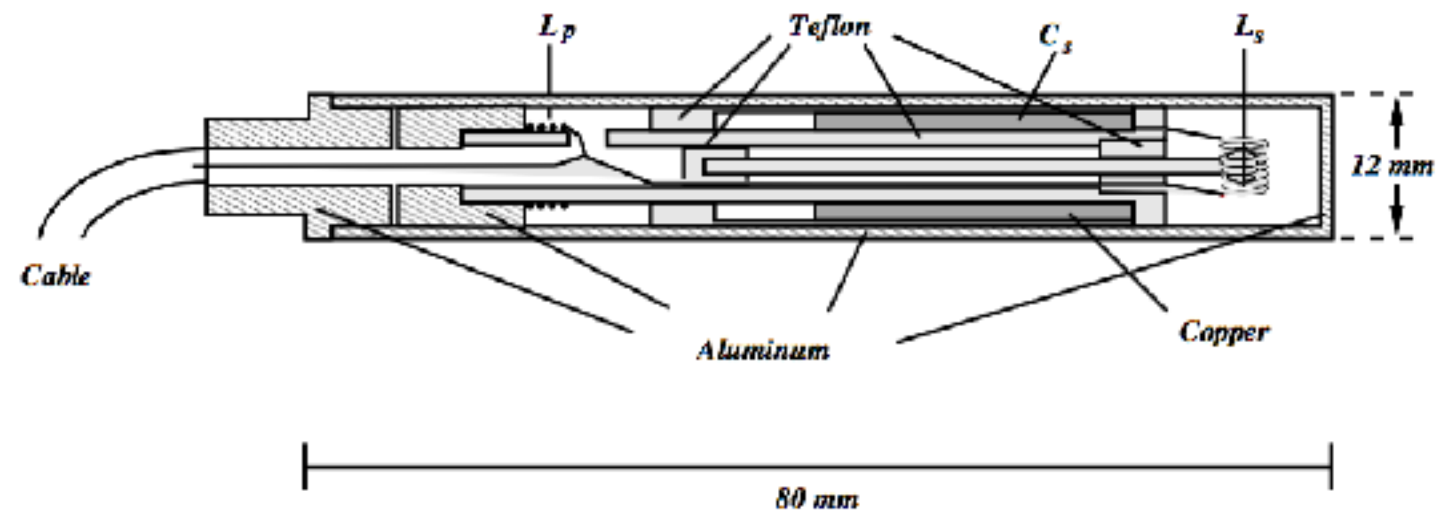


(from K.S. Tanaka-san's slide)

Probe used at LAMPF experiment



Standard probe

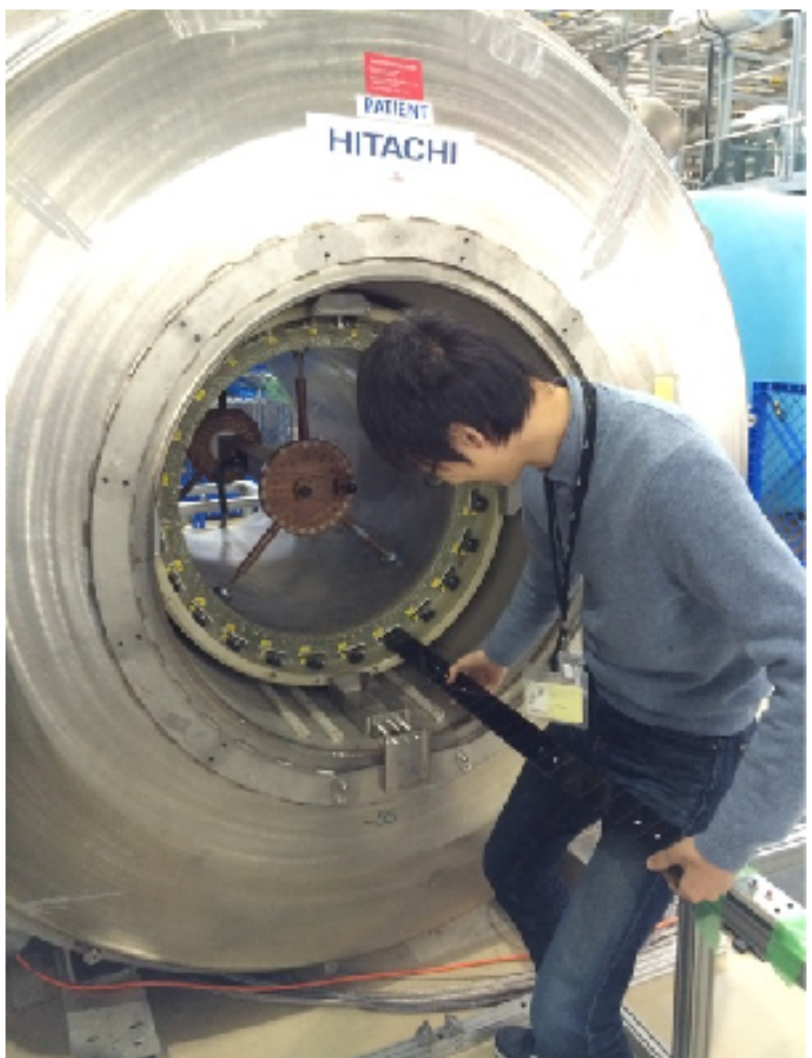


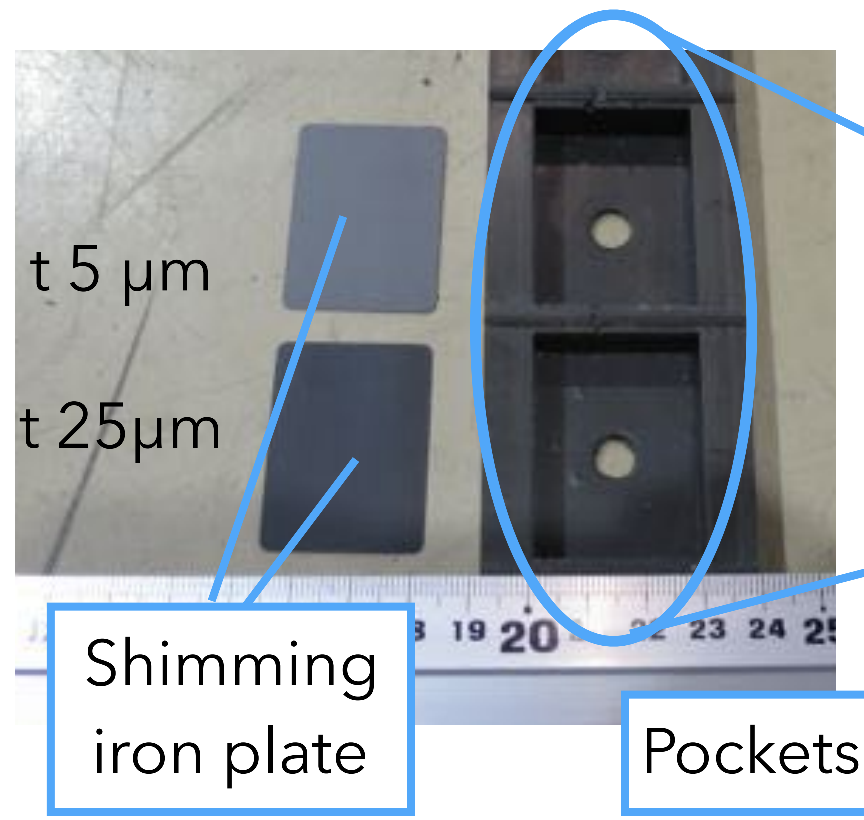
Fixed & plunging probe

- proton NMR measured by pulsed NMR magnetometer
- 30ppb precision
- 8 fixed probe outside the cavity & movable plunging probe for monitoring 5 times/sec - used solution of $CuSO_4$ or $NiCl_2$ for sample

B-field improvement - shimming

- Shimming by placing iron plates (5 & 25um thickness) in 24 pockets* 24 trays = 576 pockets inside the magnet
- Optimized homogeneity to 0.80ppm of 1.7 T in target area (mapped by single NMR probe)

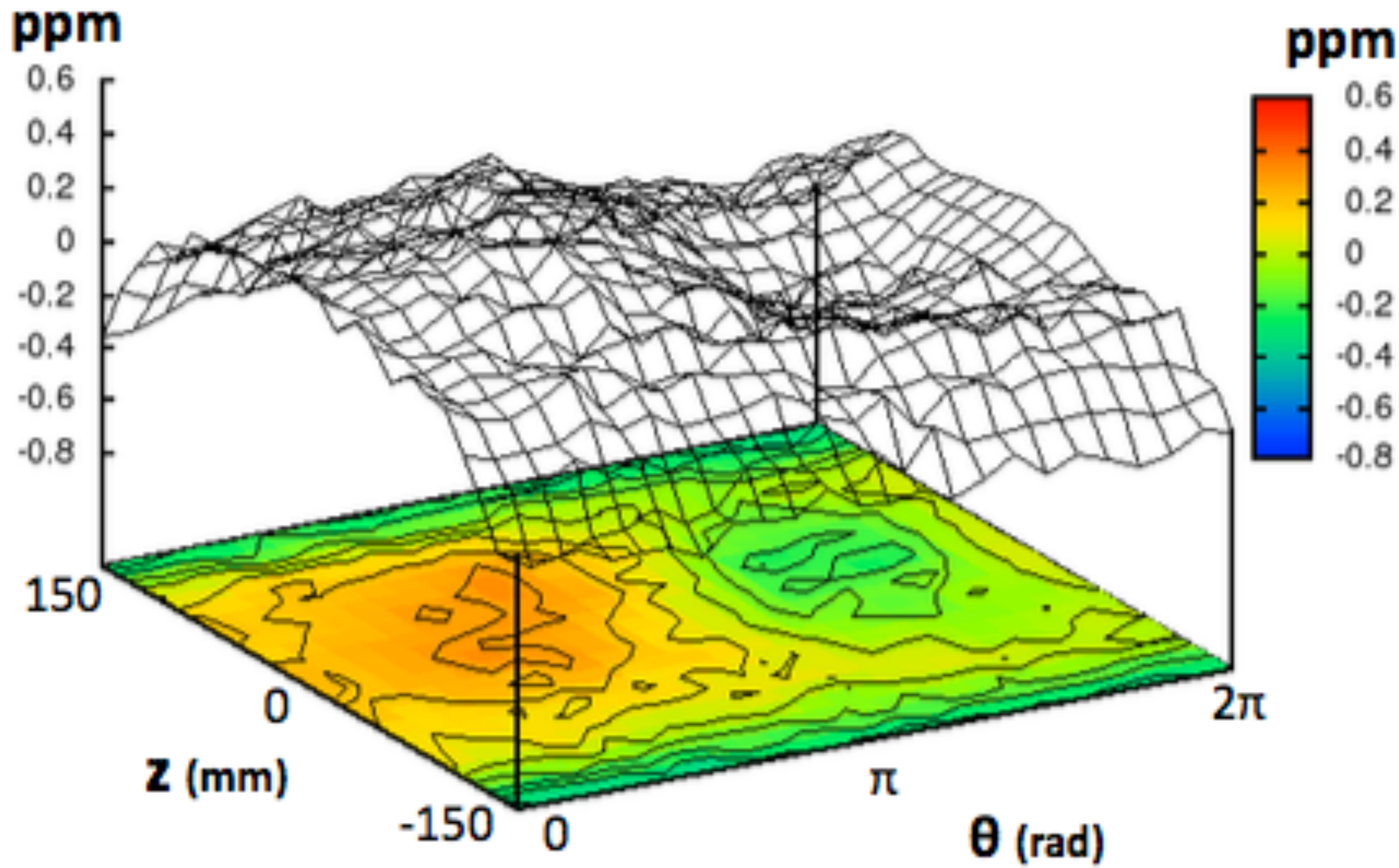




Thin and thick iron plates for shimming
(W 40 mm, D 30 mm, t 5 or 25µm)

Shim tray

B-field improvement after shimming



0.8ppm homogeneity measured at the cylindrical surface

(576 points measured by single NMR probe, work by Y. Higashi-san)