Development of the magnetic field mapping method for the precise spectroscopy of the muonium hyperfine splitting with 1.7 T magnetic field

NUFACT 2017 (9/28/2017) @ Uppsala University

Toya Tanaka (UTokyo) for MuSEUM collaboration

MuSEUM

東京大学
THE UNIVERSITY OF TOKYO

Outline

- Introduction
- Precision of the previous research
- Development of the magnetic field improvement

Outline

- Introduction
  - About MuSEUM collaboration
  - How to measure
  - Physical incentive - muon g-2
  - Setup and roadmap of experiment
- Precision of the previous research
- Development of the magnetic field improvement

MuSEUM collaboration

MuSEUM

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

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Goal of MuSEUM collaboration

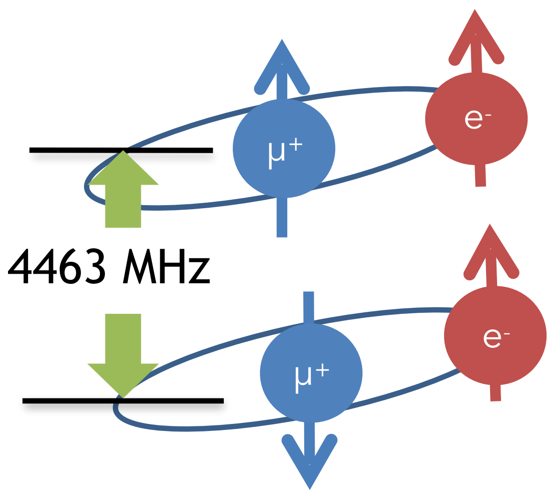
- **High precision measurement of muonium hyperfine structure (MuHFS) in Zero field & High field**
- Stringent test of bound state QED by comparing to the theoretical calculation

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

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 in ZF & HF

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

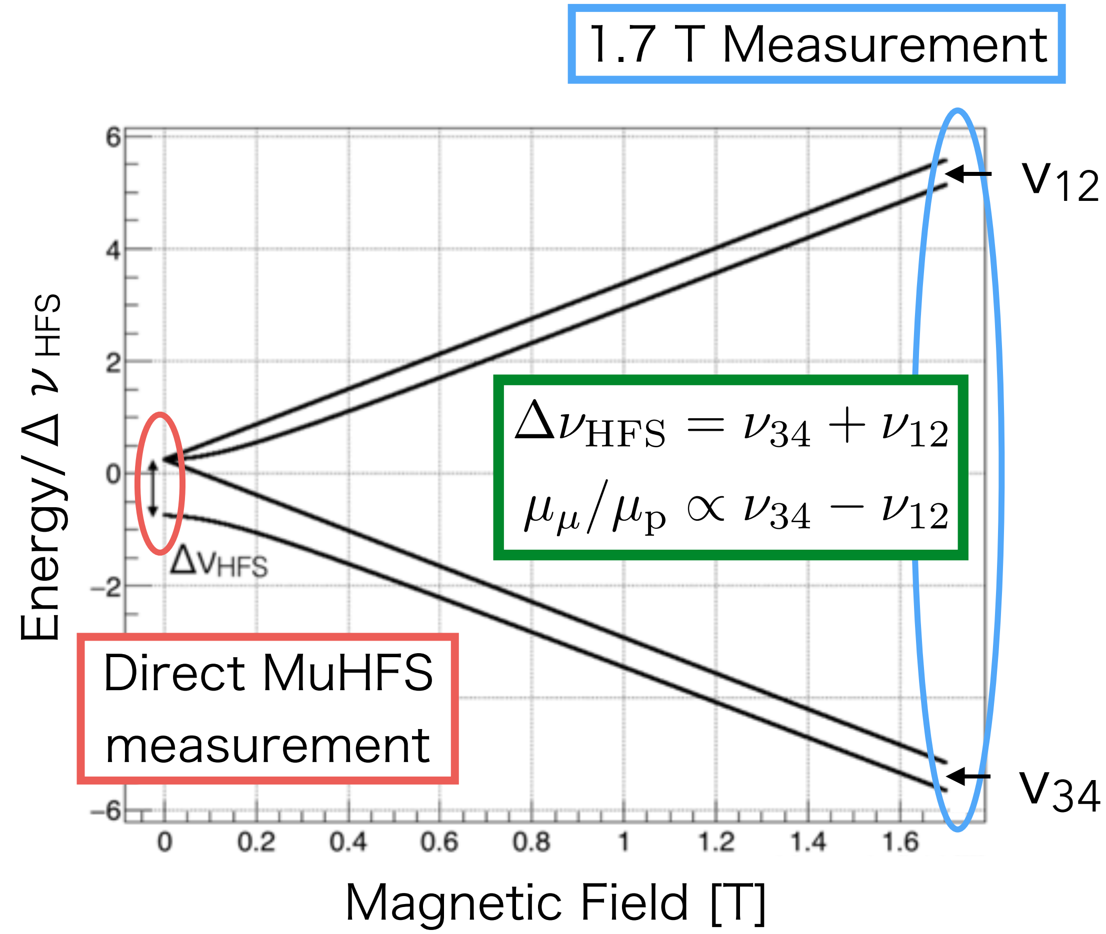
$$\mathcal{H} = \underbrace{h\Delta\nu_{\mathrm{HFS}}\vec{I}\cdot\vec{J}}_{\text{HFS}} + \underbrace{g_J\mu_B^e\vec{J}\cdot\vec{H} - g'_\mu\mu_B^\mu\vec{I}\cdot\vec{H}}_{\text{Zeeman splitting}}$$

- 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 experiment

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

$$R = \omega_\mu/\omega_{\mathrm{p}} \ \ (540\mathrm{ppb})$$

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

$$\lambda = \mu_\mu/\mu_{\mathrm{p}} \ \ (30\mathrm{ppb})$$

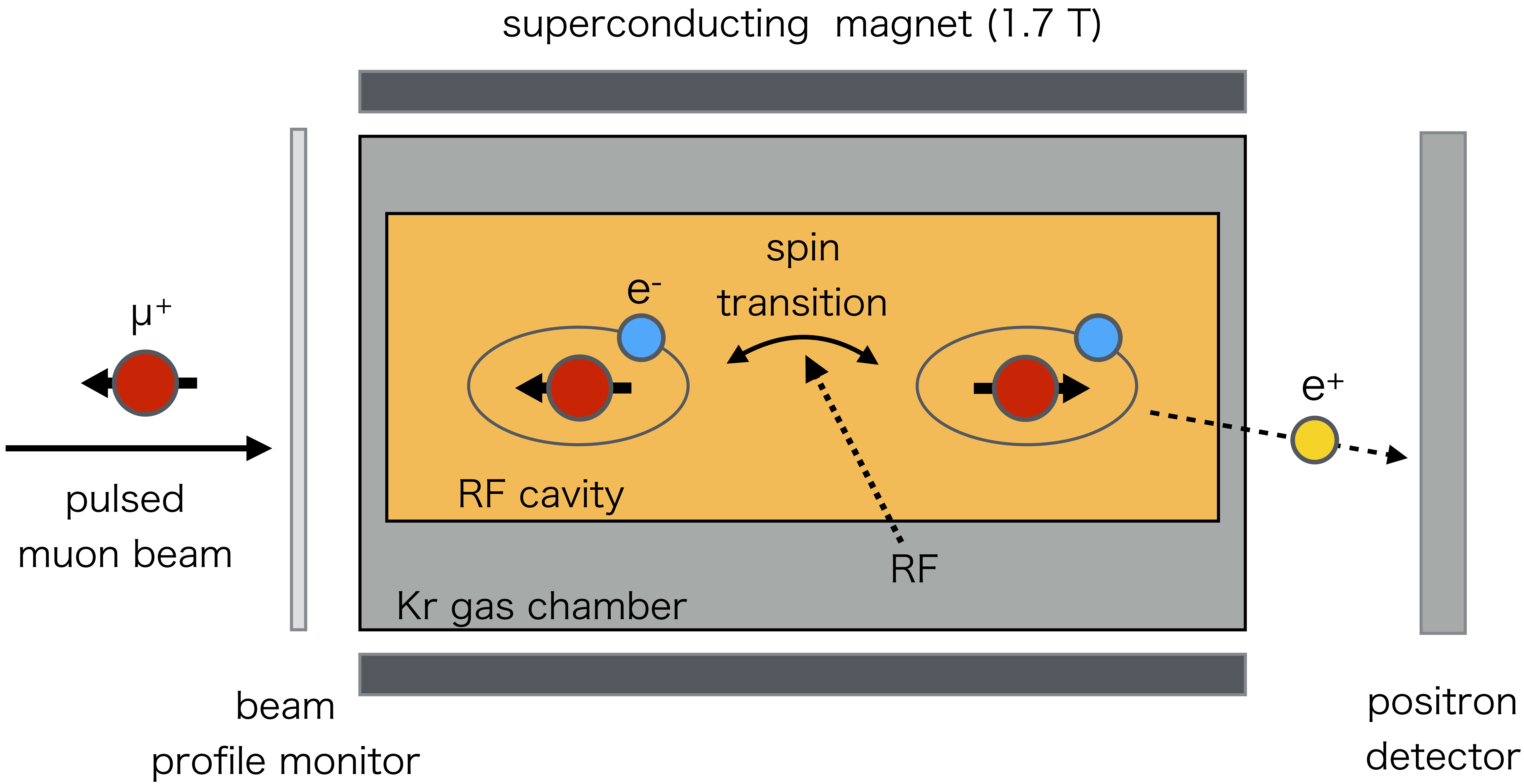
W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).
D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).

- 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).

- 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. 12-14 (60h) - 1st measurement
  - 2017 Feb. 1-4 (96h) - 2nd measurement
  - 2017 Jun. - 3rd measurement
  - Next beam time at 2018 spring
- High field measurement @MLF H-line
  - Will be ready in 2018 Autumn

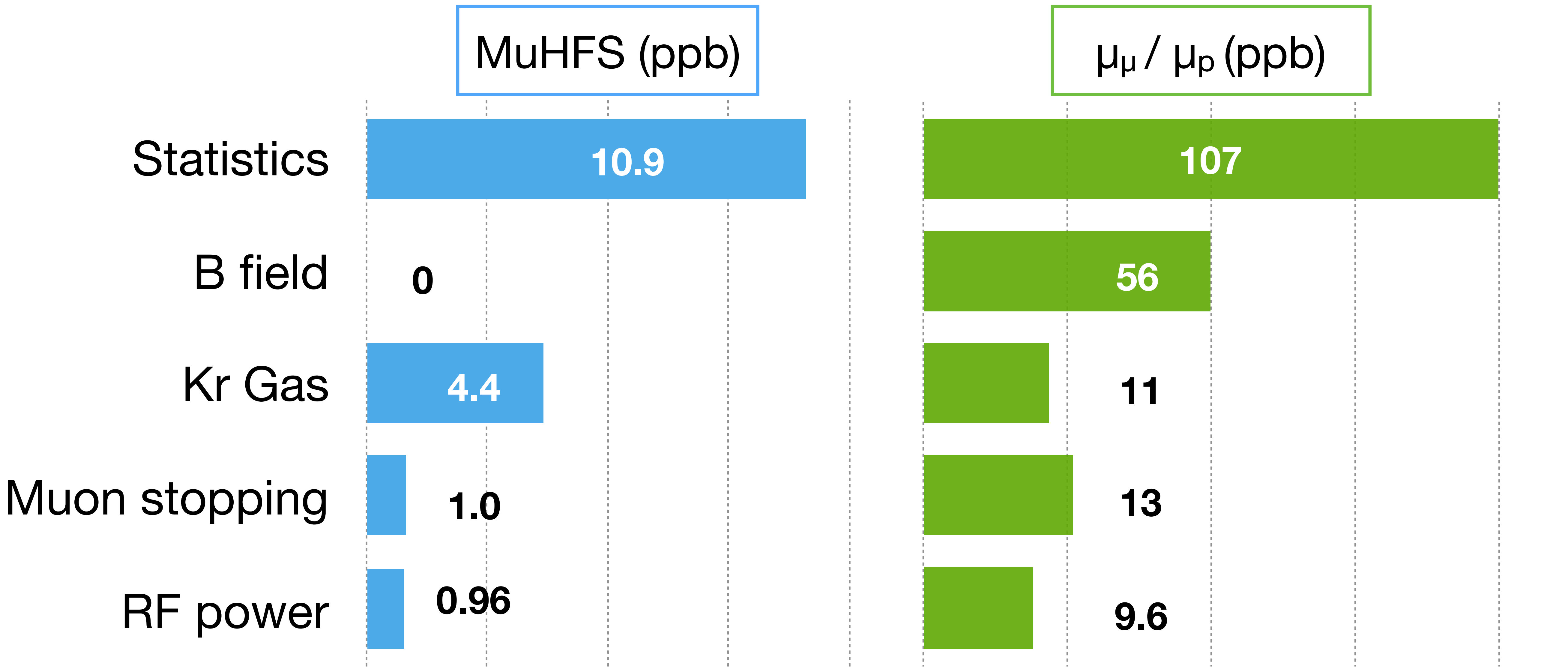
Outline

- Introduction

- Precision of the previous research
  - List of uncertainties
  - Improvement of statistics
  - Improvement of systematics - B-field inhomogeneity

- Development of the magnetic field improvement

Uncertainties of LAMPF experiment



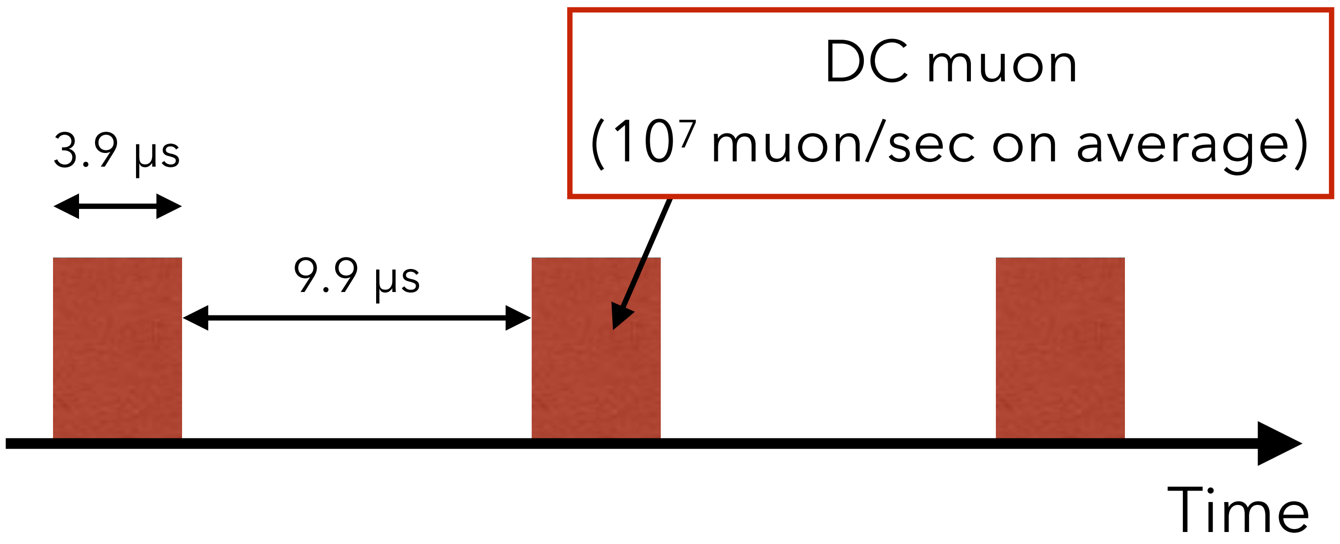
W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).

- 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

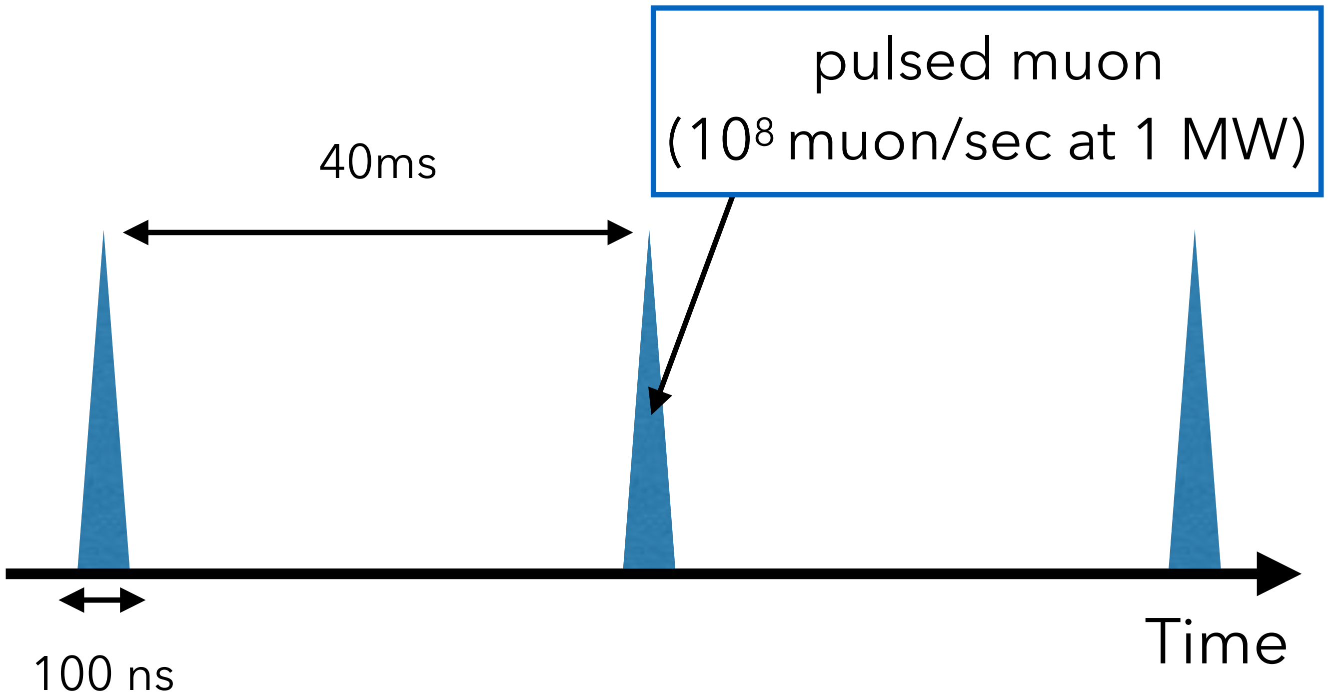
Experiment at LAMPF

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



MuSEUM experiment

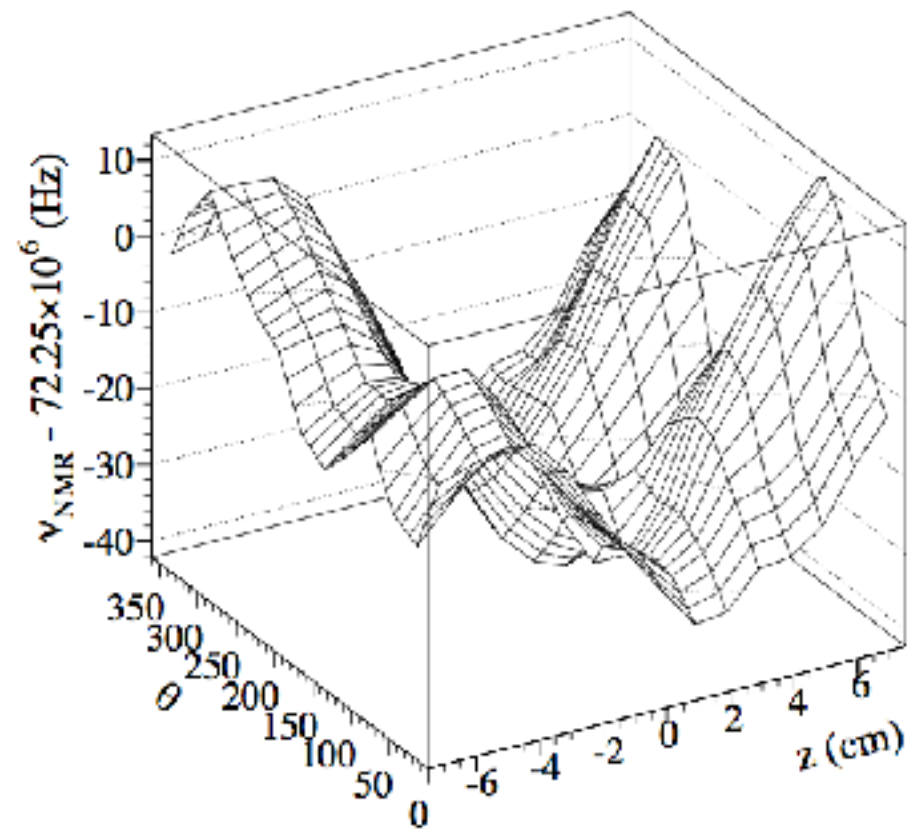
- Pulsed beam @ J-PARC MLF H-line
- All muon can be used
- Total : ~10^{15} muons (~100 days data taking)
- **Improve to ~1ppb (MuHFS)**
  ~10ppb (μ_μ / μ_p)



B-field of LAMPF experiment

- B-field evaluated with

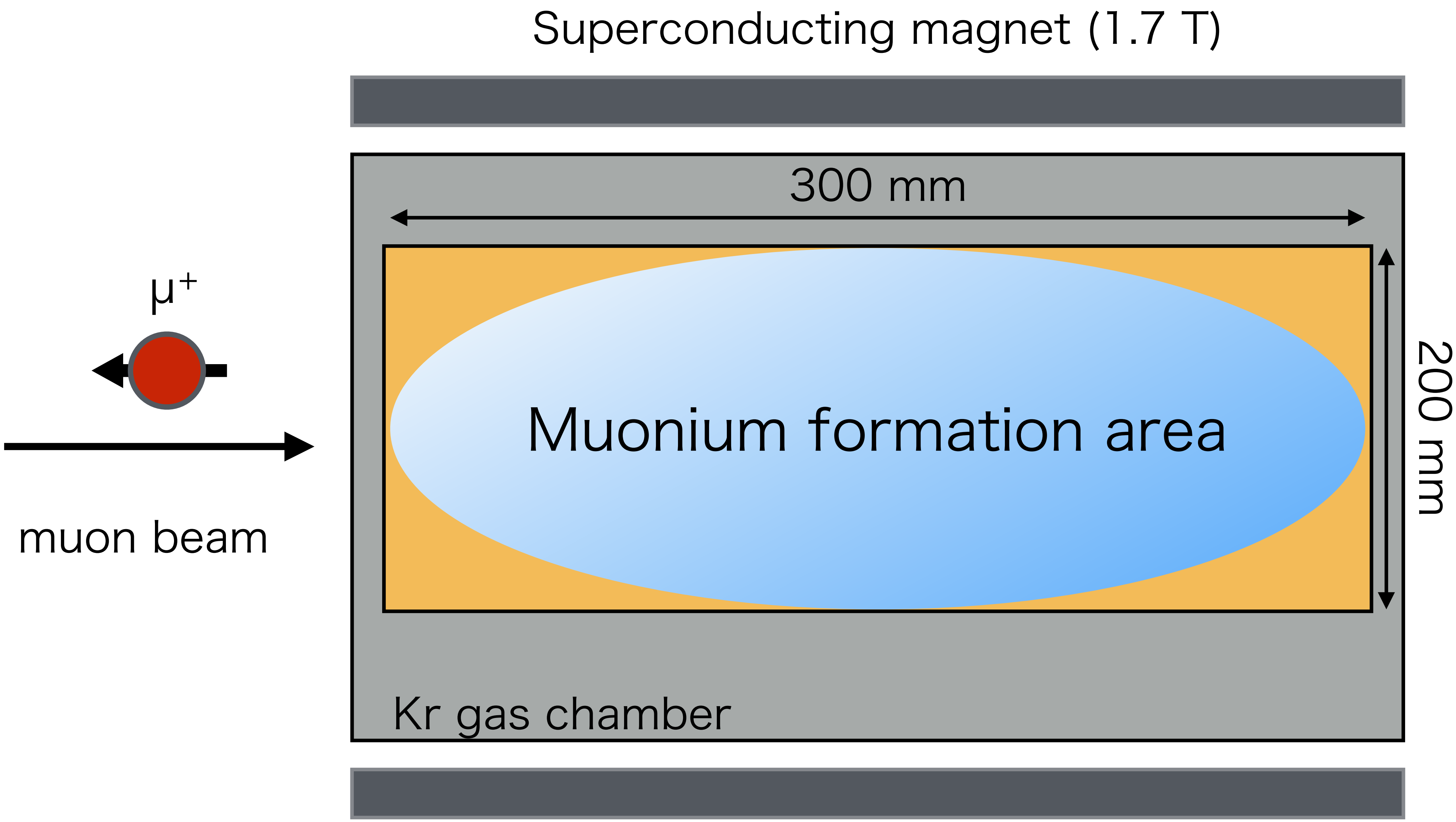
1. Magnet :1ppm in 10 cm diameter sphere volume
2. B-field mapping : 0.7ppm peak-to-peak homogeneity in cylindrical surface



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 -> magnet spec & shimming
- Calibration of NMR probes -> high precision probes

Required B-field at MuSEUM



- Required ~1ppm homogeneity of 1.7 T in the spheroid muonium formation area (z= 300 mm, r=100 mm)

Outline

- Introduction
- Precision of the previous research
- Development of the magnetic field improvement
  - Highly homogeneous superconducting magnet
  - High precision NMR probes - on progress

B-field improvement - magnet

- Solenoid superconducting magnet for MuSEUM
  - Maximum 2.9 T, used in 1.7 T

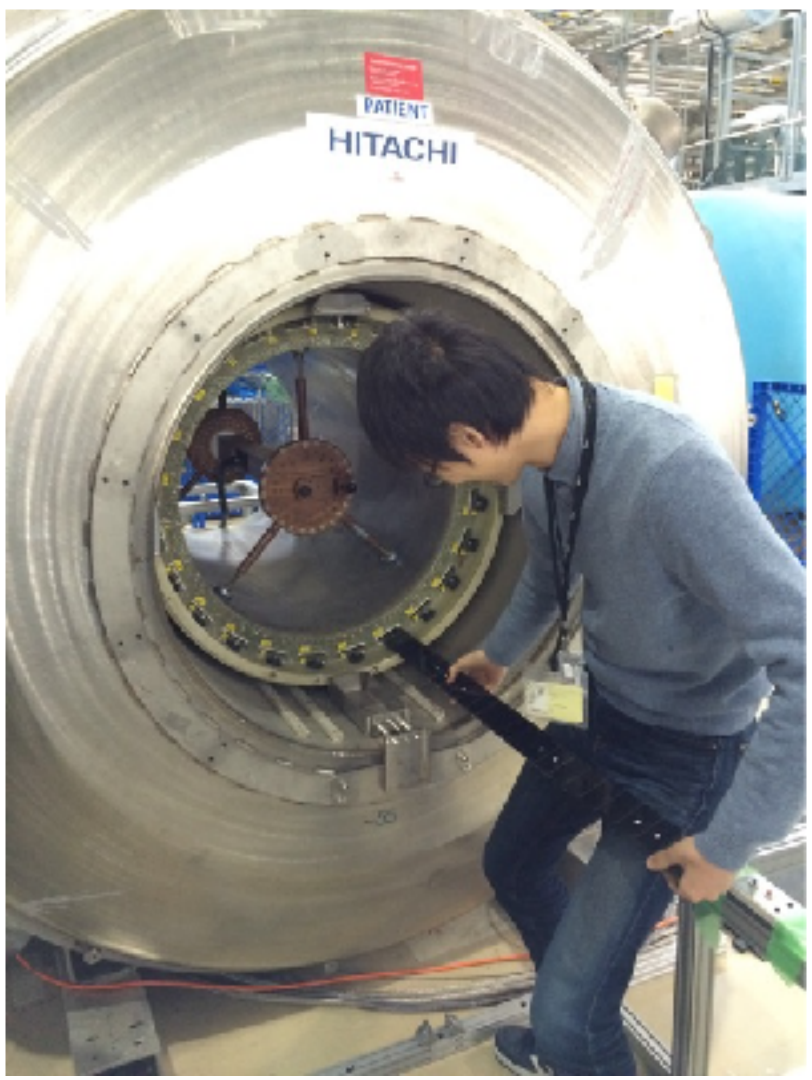
Superconducting MRI magnet
(Hitachi)

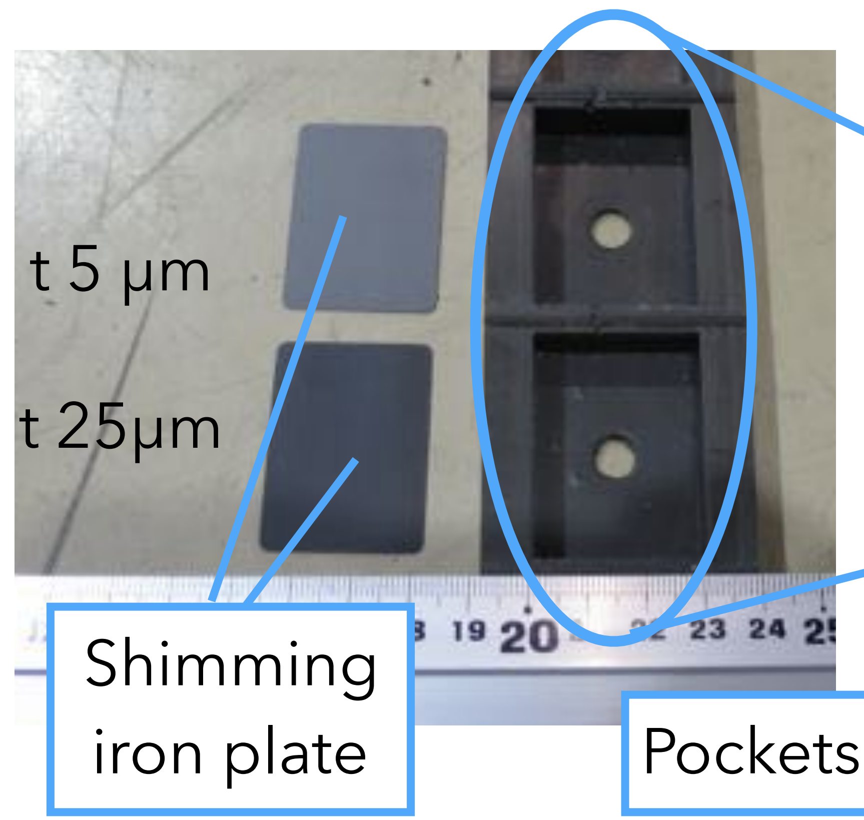
- Requirements
  - Field homogeneity <1ppm
  - Stability <0.1ppm/h

- Long term stability test (2015/3/30 - 2015/4/9)
  - 64Hz drift per 9 days = 3ppb/h stability

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)

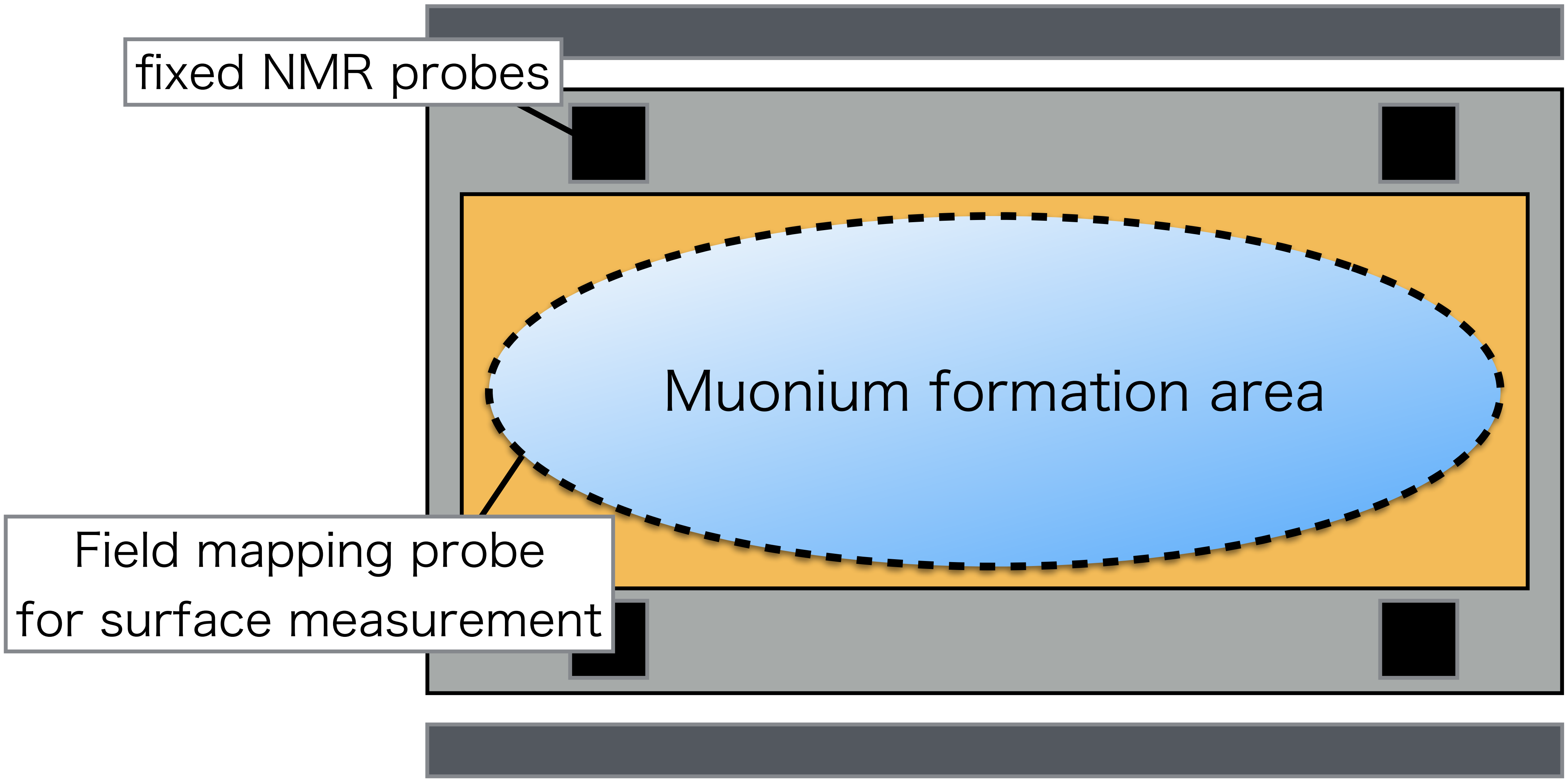




Thin and thick iron plates for shimming (W 40 mm, D 30 mm, t 5 or 25μm)

Shim tray

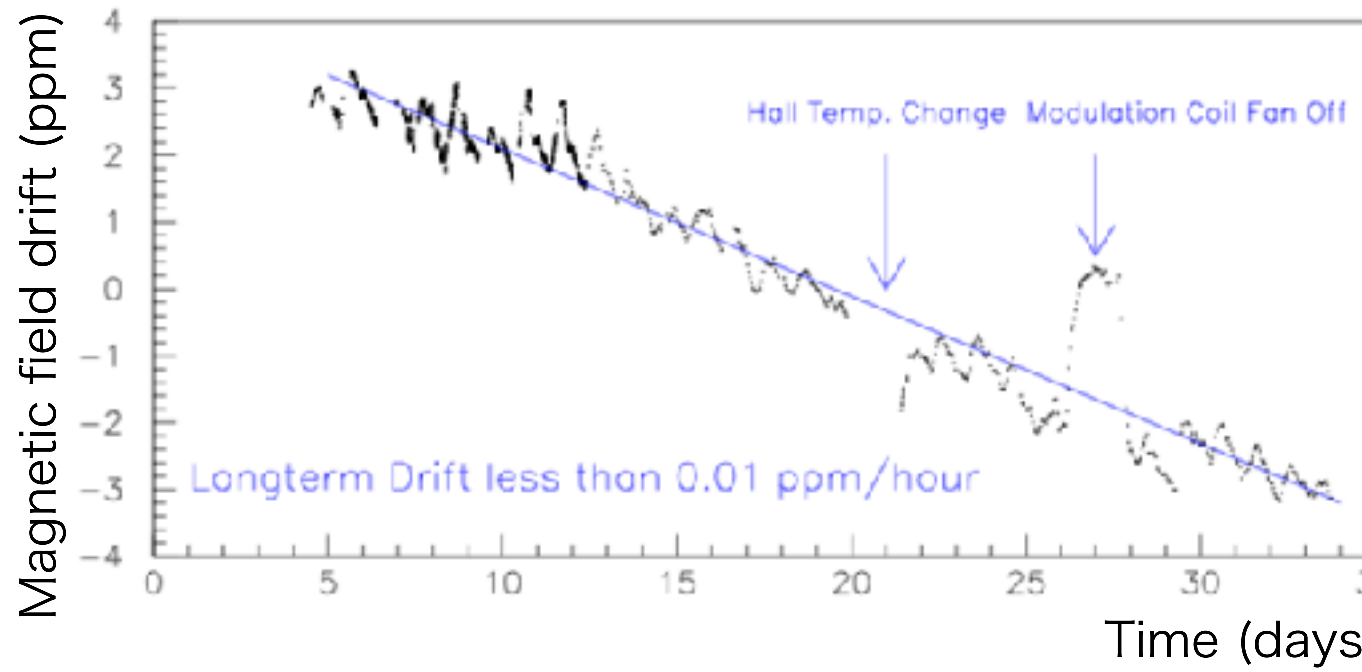
NMR probes for MuSEUM experiment



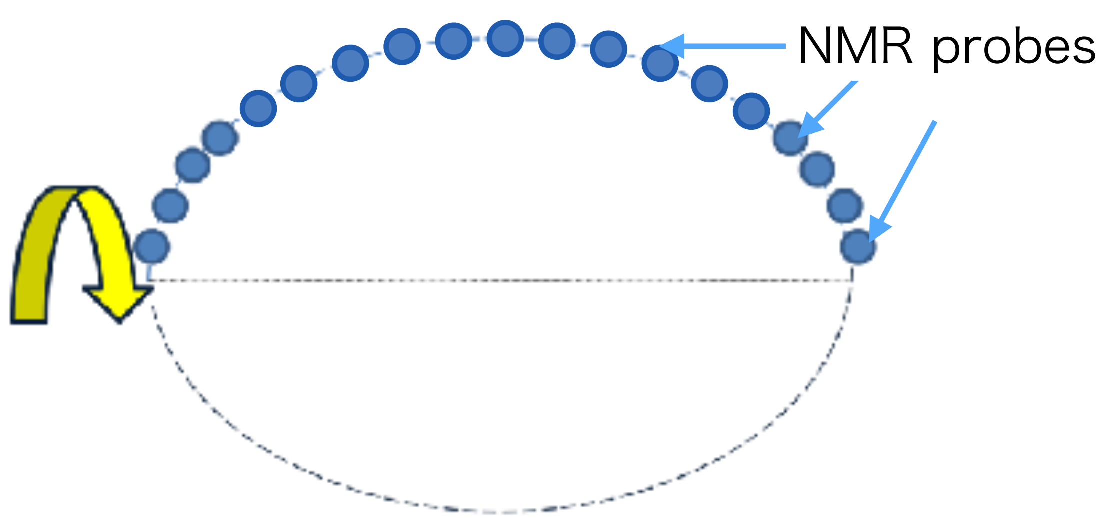
- Stability - Online monitor by fixed NMR probes
- Homogeneity - Measurement by the multi channel field mapping probe

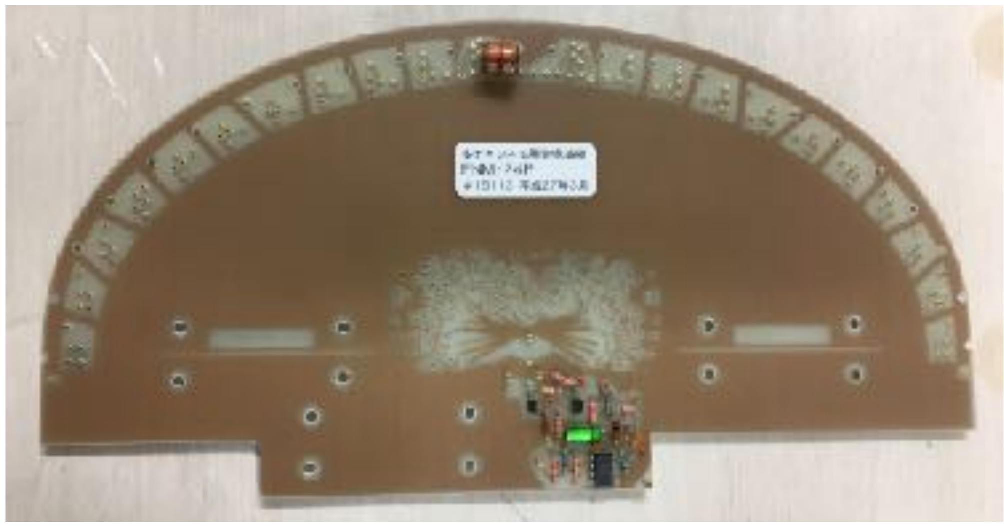
Concept of field mapping probe

- Concept : Want to suppress the effect of B-field drift at measurement
- 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

Timeline of development

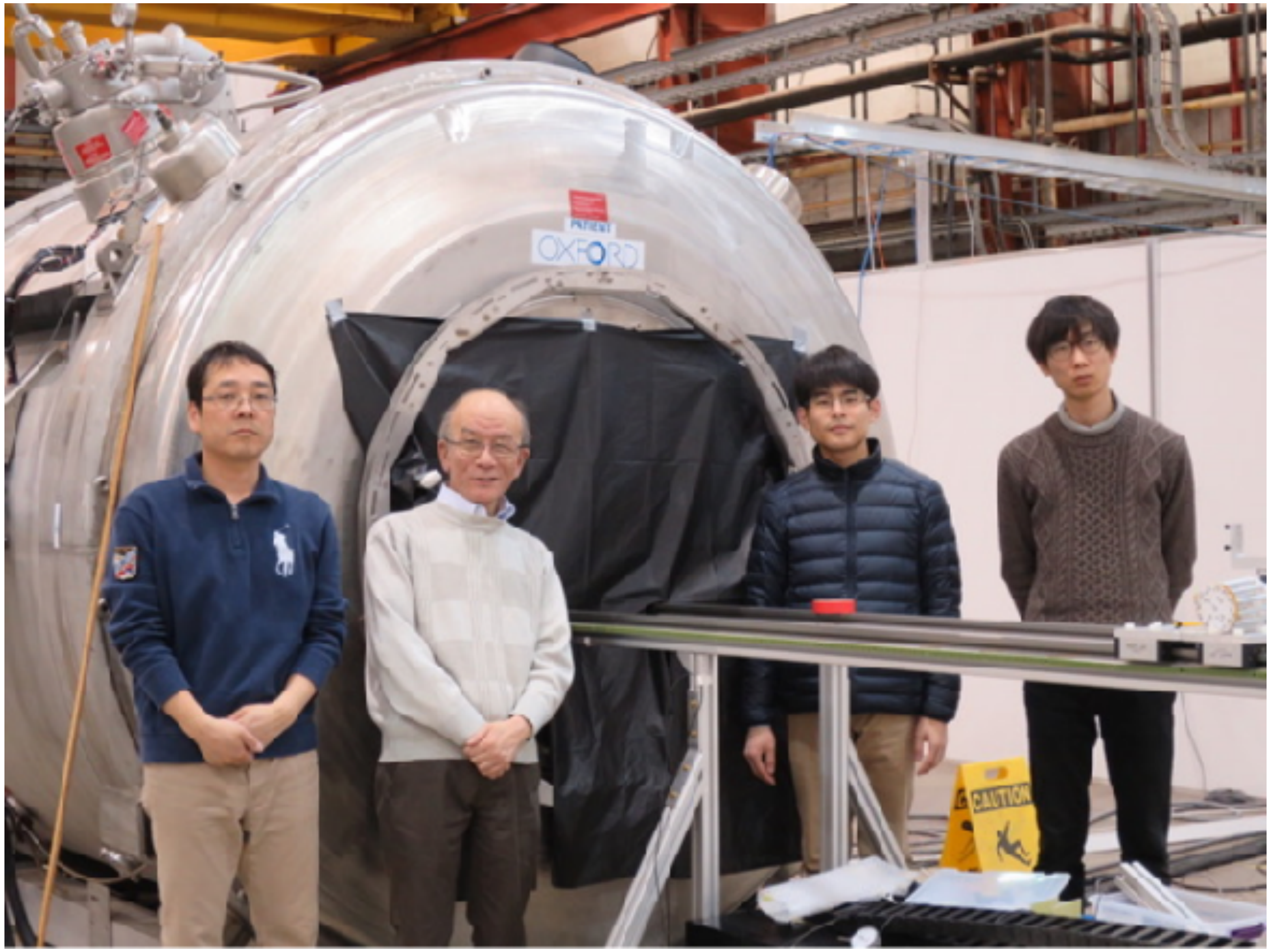
1. R&D of Single channel NMR probe - in progress
   - Prototype design for fixed & field mapping probe
   - The effect by the circuit element itself is crucial

2. Fixed probe, Field mapping probe design

3. Installation to HF MuHFS measurement

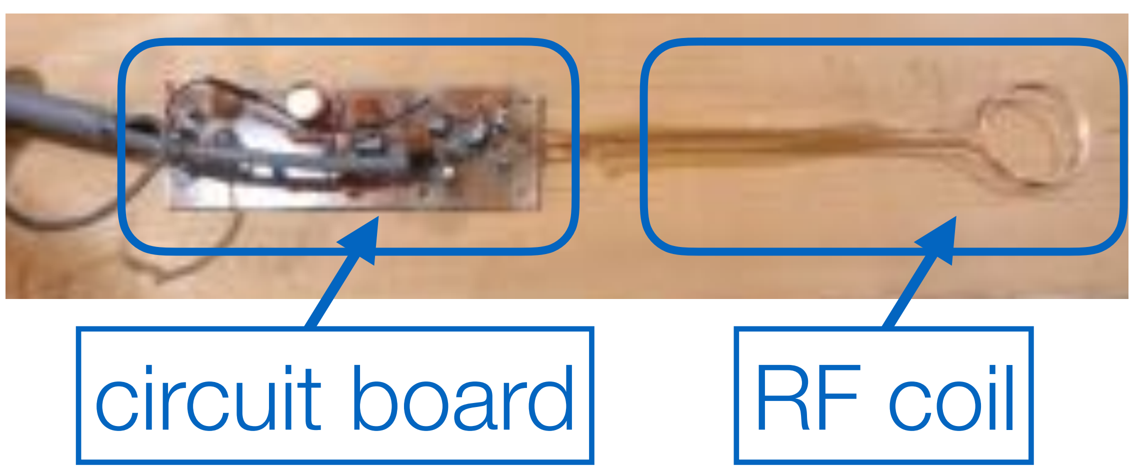
Test of the standard probe

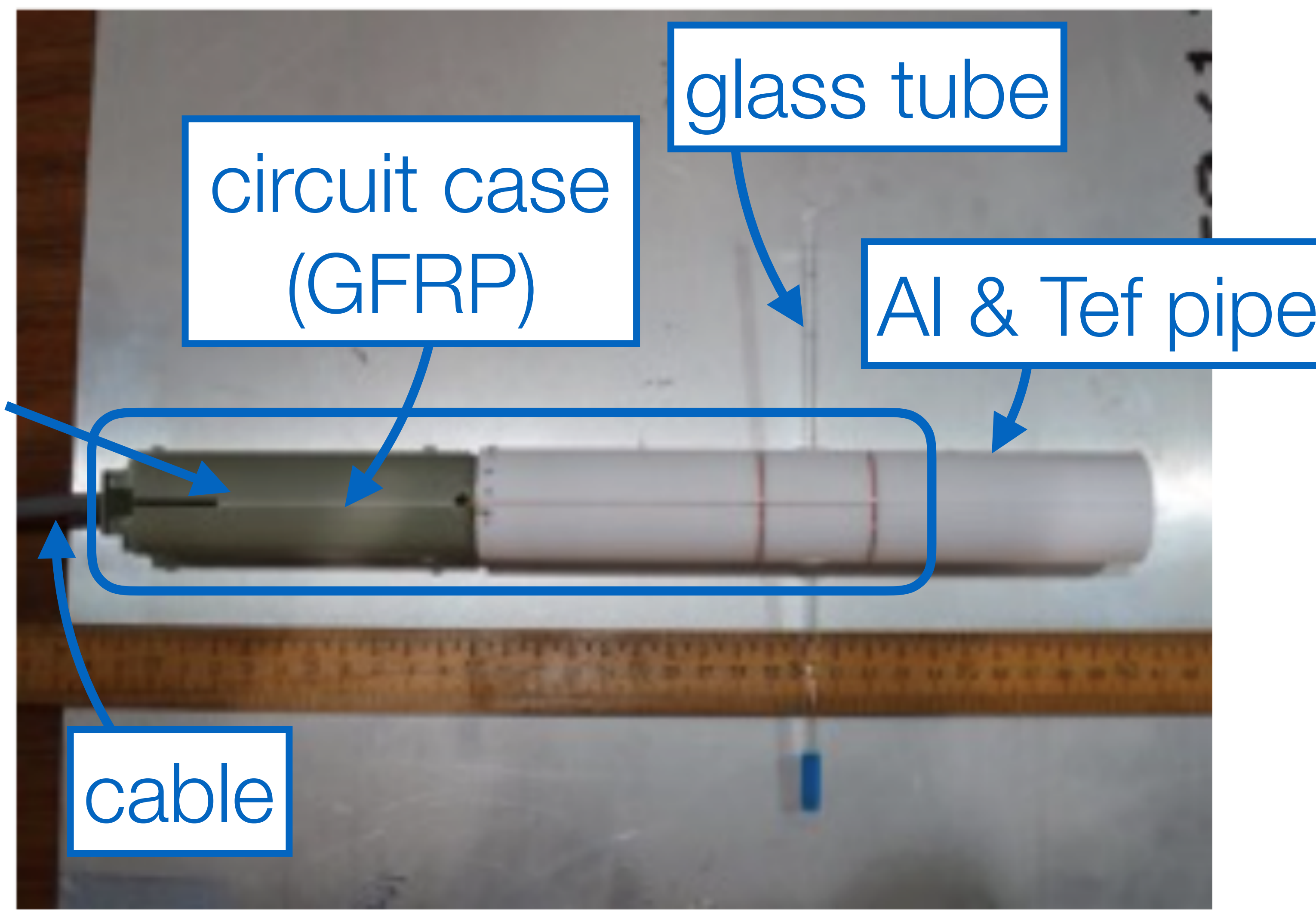
- NMR probe cross calibration test with 1.45 T @Argonne national laboratory, USA



Test of the standard probe

- CW(continuous wave)-NMR probe was used
- B-field shift effect caused by the probe material itself is evaluated



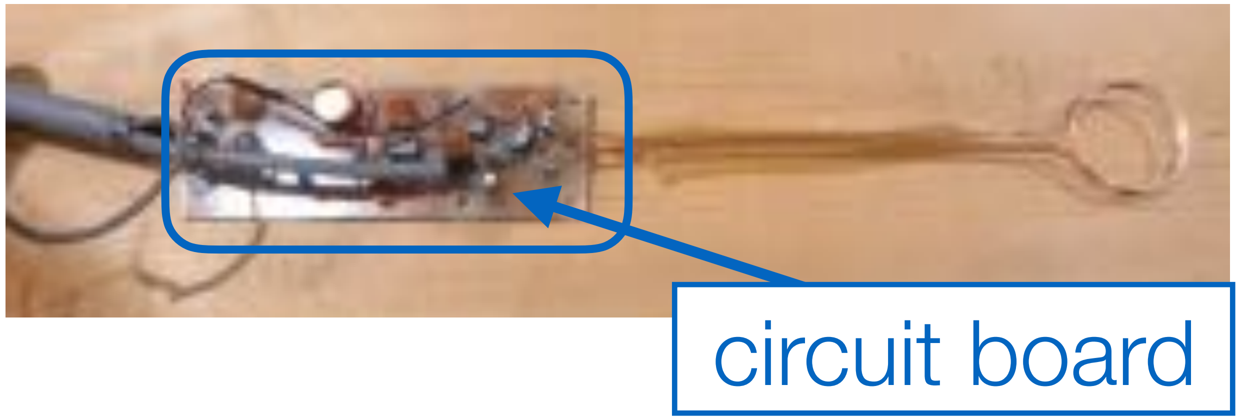


Results of the material test

	Shift (ppb)	Shift (Hz)
All materials	**+70.6 ± 2.5**	**+4.36 ± 0.15**
Circuit boad	+96.4 ± 0.4	+5.95 ± 0.02

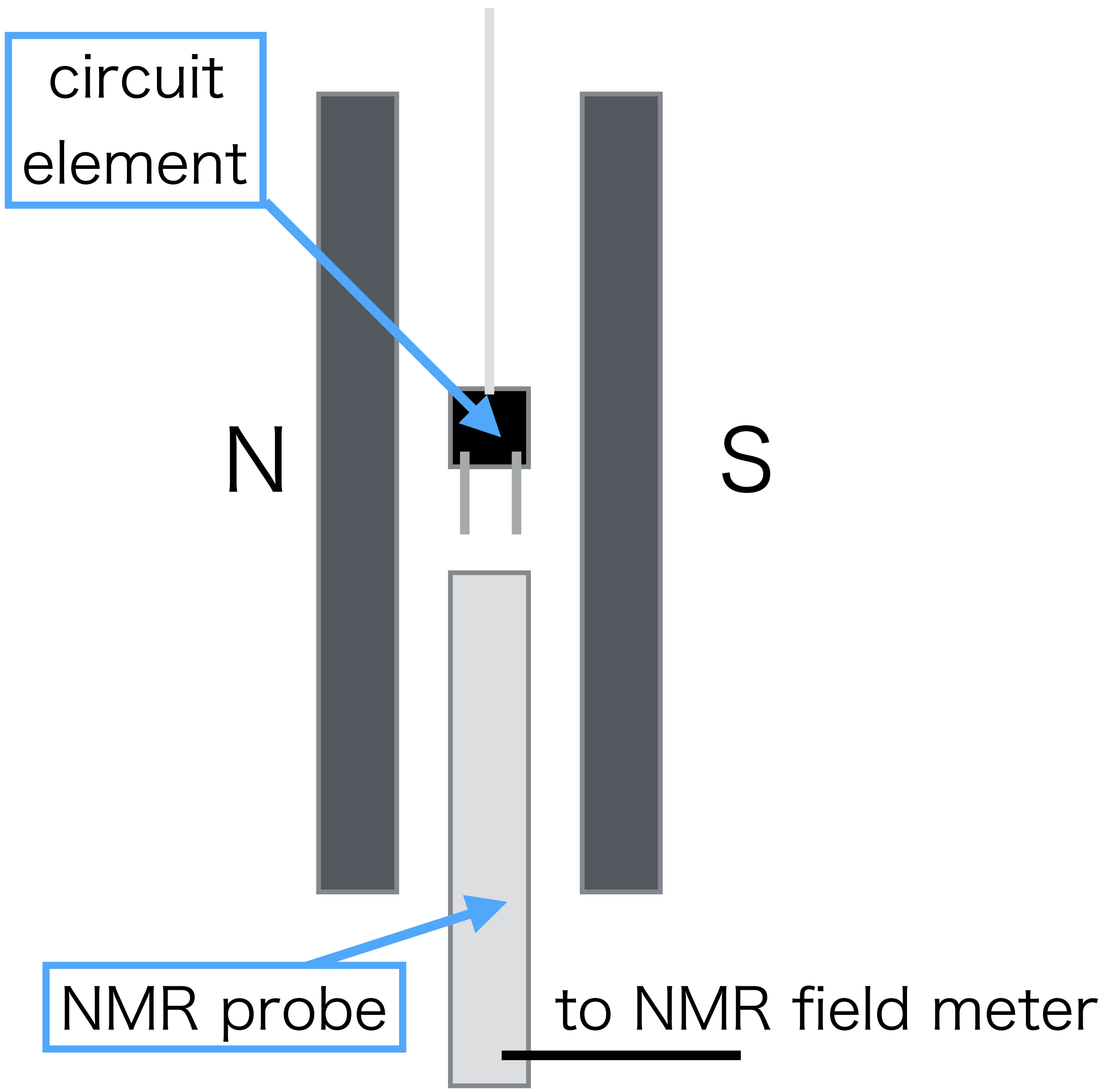
(Analyzed by S. Seo)

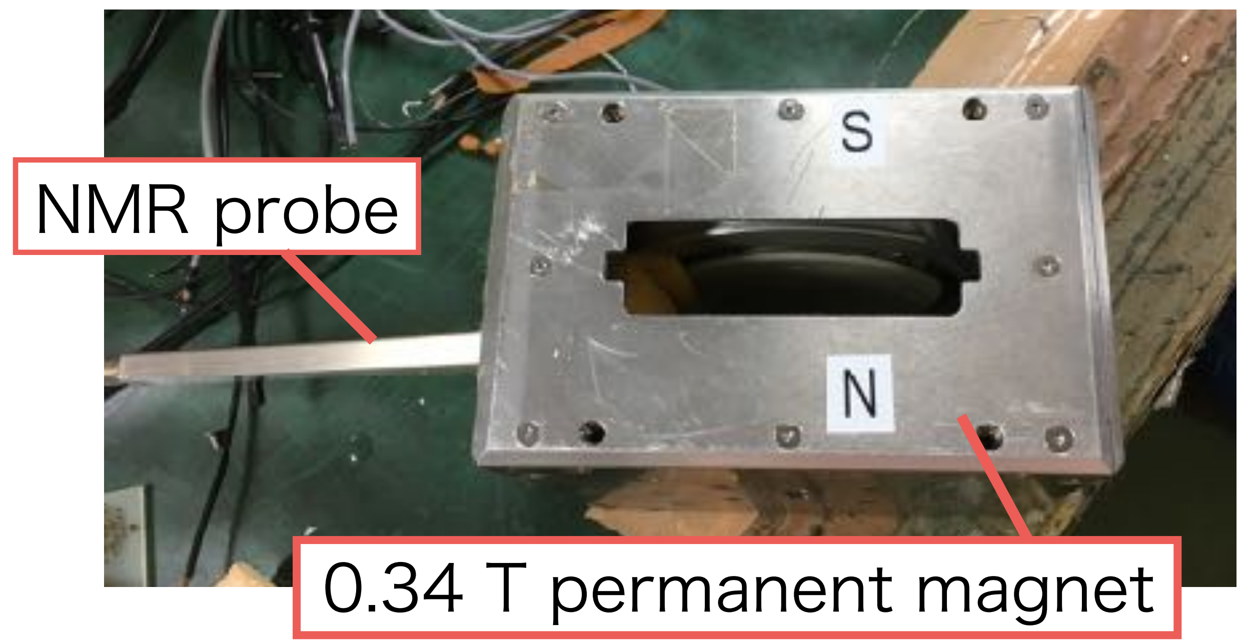
- NMR probe material should be tested in the circuit element level

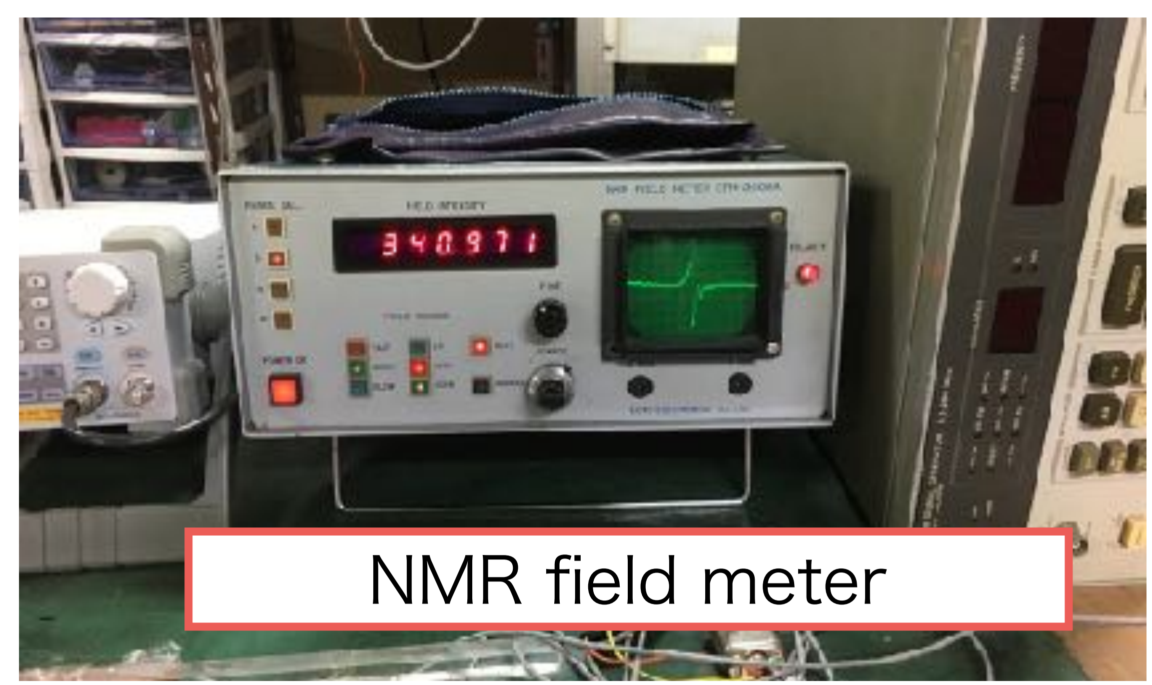


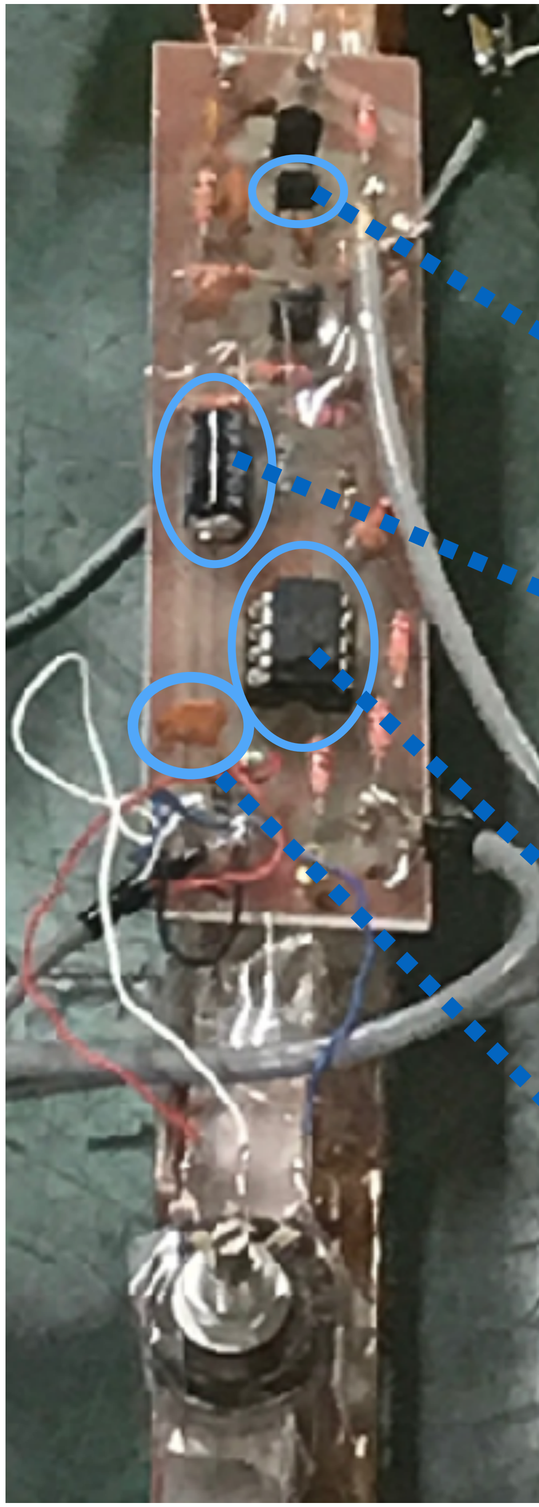
Development status - circuit element test

- Each circuit element was tested by placing in the 0.34 T permanent magnet and measuring the B-field shift (1 uT resolution)









material	shift (uT)	shift / 0.34 T (ppm)
circuit	-79 ~ -124	-231 ~ -365
silicon J-FET (2SK19)	-13	-38
electrolytic capacitor (A1504)	-37	-108
operational amplifier (LMC662) with socket	-3	-8.7
commercial ceramic capacitor	-45	-131
Voltronics NMAP40HV Trimmer capacitor	<1	< 3

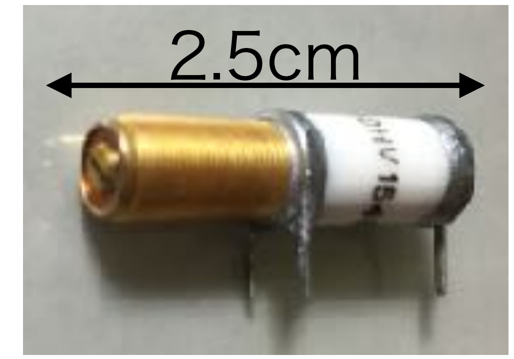
<u>**Can know which element should be excluded!**</u>

Development status - final circuit design

- Suggestions

1. select non-magnetic element

- Reliability will be tested with our magnet

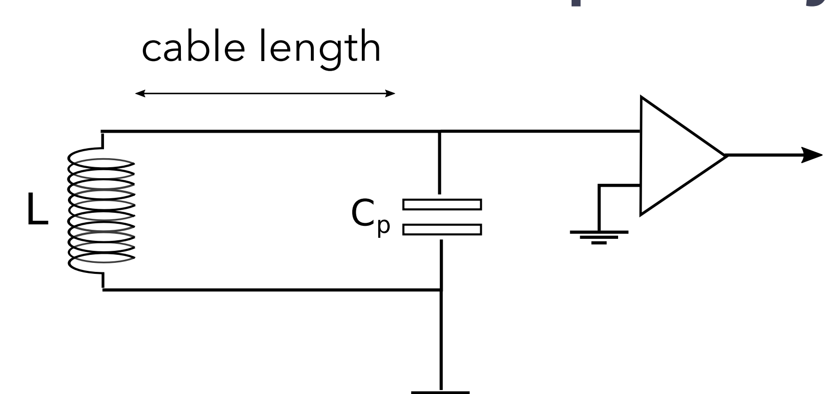


non magnetic trimmer capacitor
(Voltronics NMAP40HV)

2. put the element away

- stray capacitance shifts the resonance frequency

$$2\pi\nu_0 = \frac{1}{\sqrt{LC}}$$



- Final design should be considered by the less magnetized material and circuit characteristics

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.

Appendix

lambda used at g-2 measurement

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

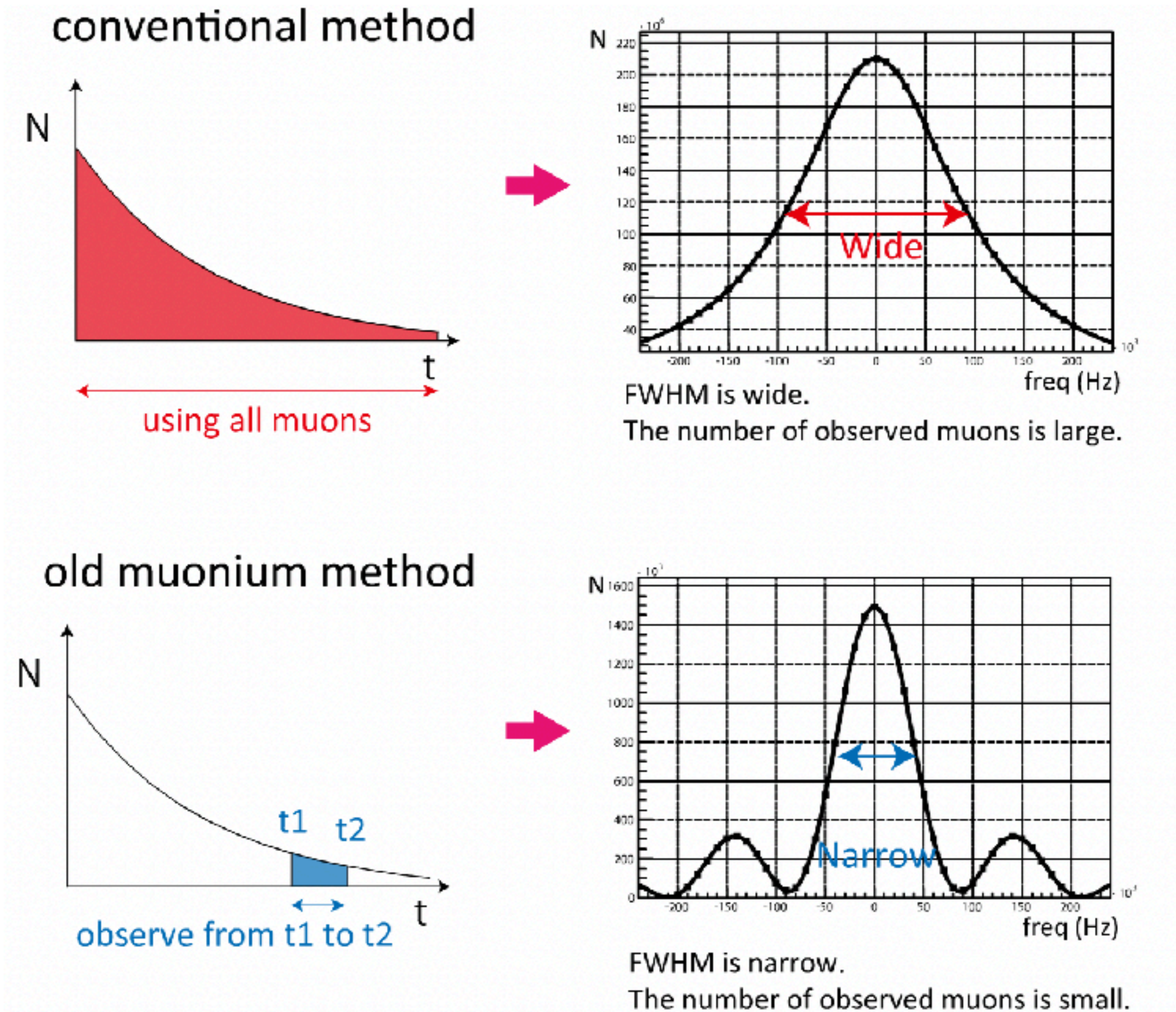
$$\Delta\nu_{\mathrm{HFS}} = \frac{16}{3}\alpha^2 c R_\infty \frac{m_{\mathrm{e}}}{m_\mu}[1 + \frac{m_{\mathrm{e}}}{m_\mu}]^{-3} + \mathrm{corrections}$$

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.

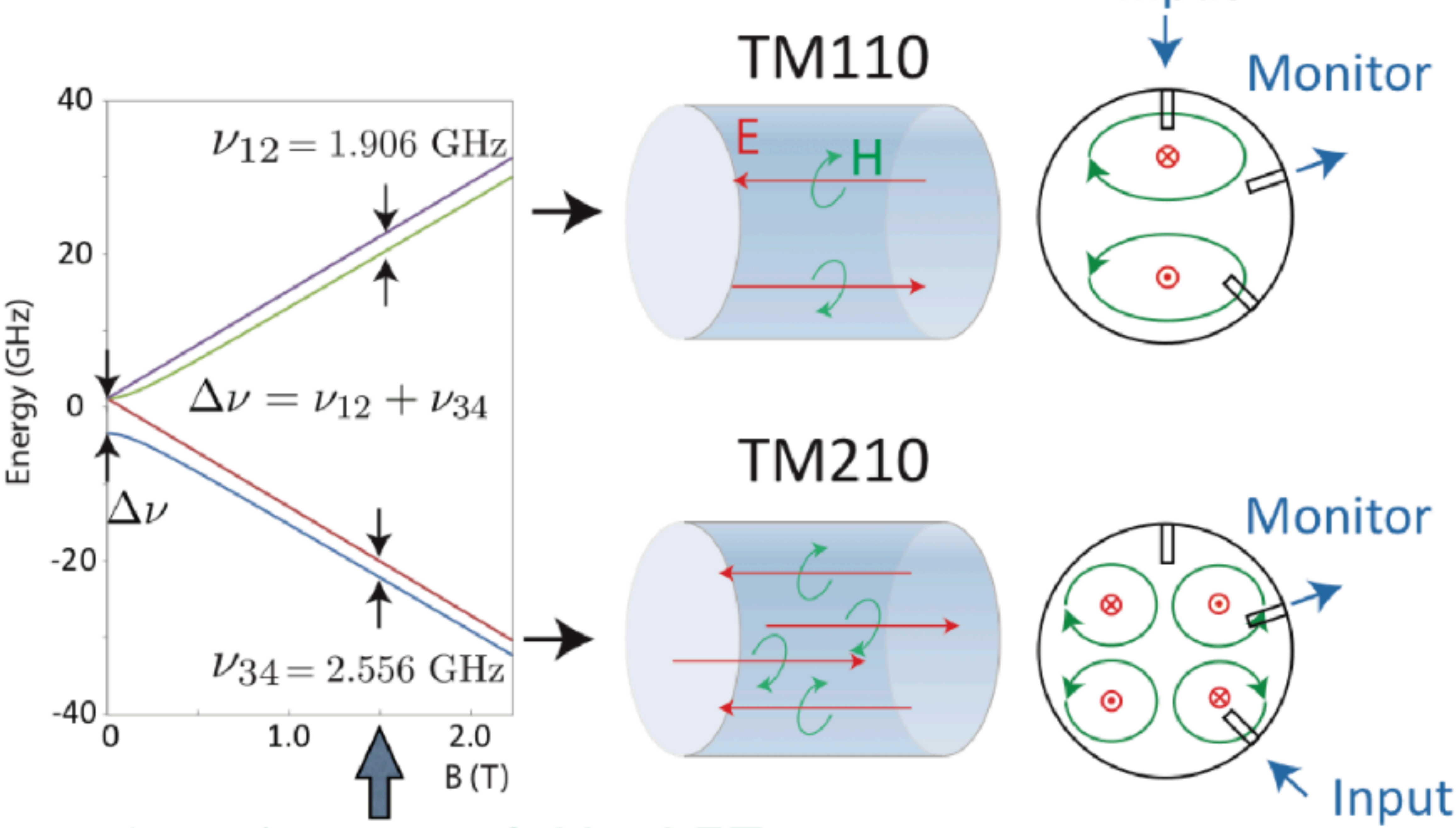
old muonium method



cavity design for HF measurement

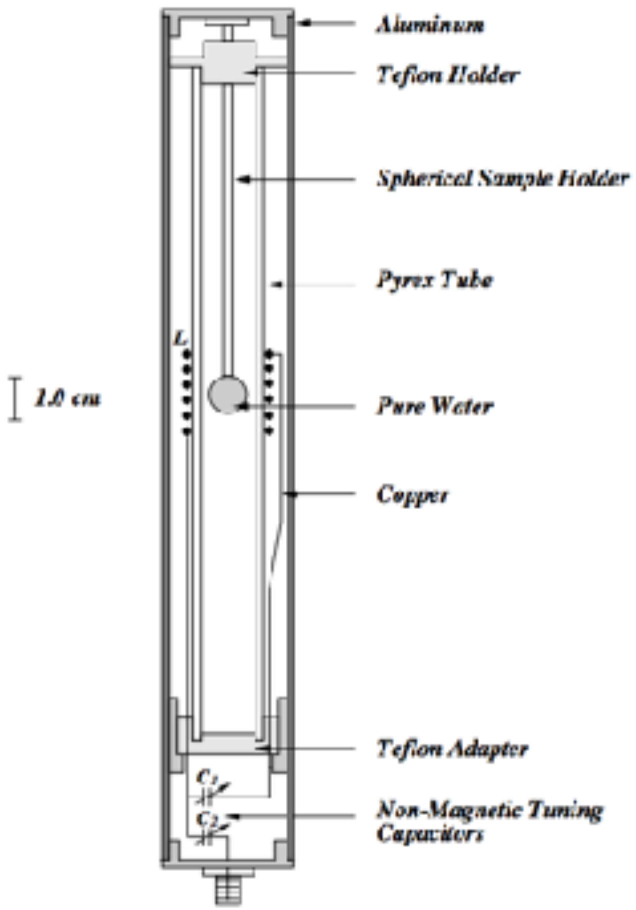
two transitions

two resonance modes

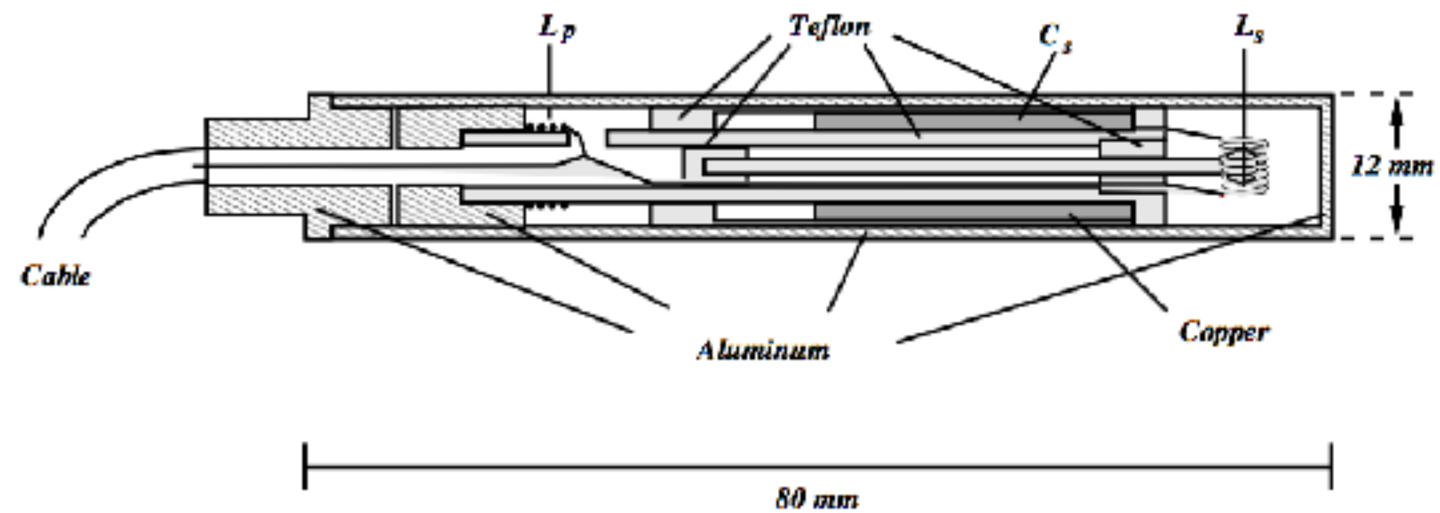


'magic' magnetic field = 1.7 T

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