Development of NMR probes for 1.7 T MuHFS measurement

mini workshop (9/18/2017) @ Seoul National University

Toya Tanaka (UTokyo) for MuSEUM collaboration

Outline

- Introduction
- Setup and precision of latest LAMPF experiment
- Improvement and development status of magnetic field measurement for the high field MuHFS experiment

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MuSEUM collaboration

- ***Mu****onium* ***S****pectroscopy* ***E****xperiment* ***U****sing* ***M****icrowave*

- Collaborators

M. Aoki, M. Fukao, H. Iinuma, Y. Ikedo, K. Ishida, T. U. Ito, M. Iwasaki, Y. Ueno, R. Kadono, O. Kamigaito, S. Kanda, D. Kawall, N. Kawamura, A. Koda, K. M. Kojima, M. K. Kubo, Y. Matsuda, T. Mibe, Y. Miyake, K. Nagamine, S. Nishimura, T. Ogitsu, R. Okubo, N. Saito , K. Sasaki, S. Seo, K. Shimomura, P. Strasser, M. Sugano, K. S. Tanaka, **T. Tanaka**, D. Tomono, H. A. Torii, E. Torikai, A. Toyoda, K. Ueno, D. Yagi, A. Yamamoto, M. Yoshida

- Institutes

Graduate School of Arts and Sciences, University of Tokyo, Department of Physics, Osaka University, KEK, RIKEN, JAEA, University of Massachusetts, ICU, School of Science, the University of Tokyo, Tohoku University, Ibaraki University, RCNP, Osaka University, University of Yamanashi

Goal of MuSEUM collaboration

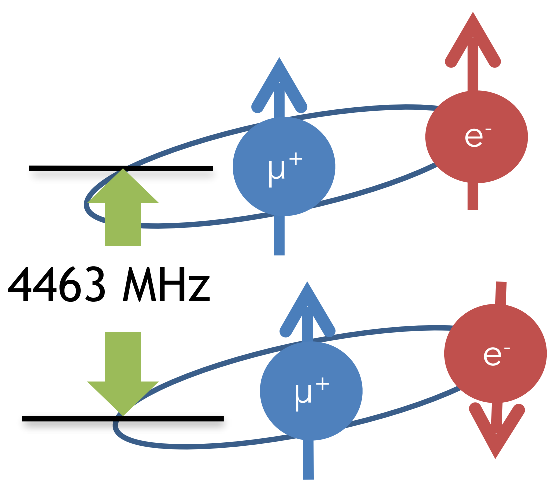
- High precision measurement of muonium hyperfine structure (MuHFS) in Zero field & High field
- Stringent test of bound state QED by comparing to the theoretical calculation

$$\Delta\nu_{\mathrm{HFS}}(theo) = 4\ 463\ 302\ 868(271)\mathrm{Hz}\ (61\mathrm{ppb})$$

(from CODATA 2014)

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

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 measurement in ZF & HF

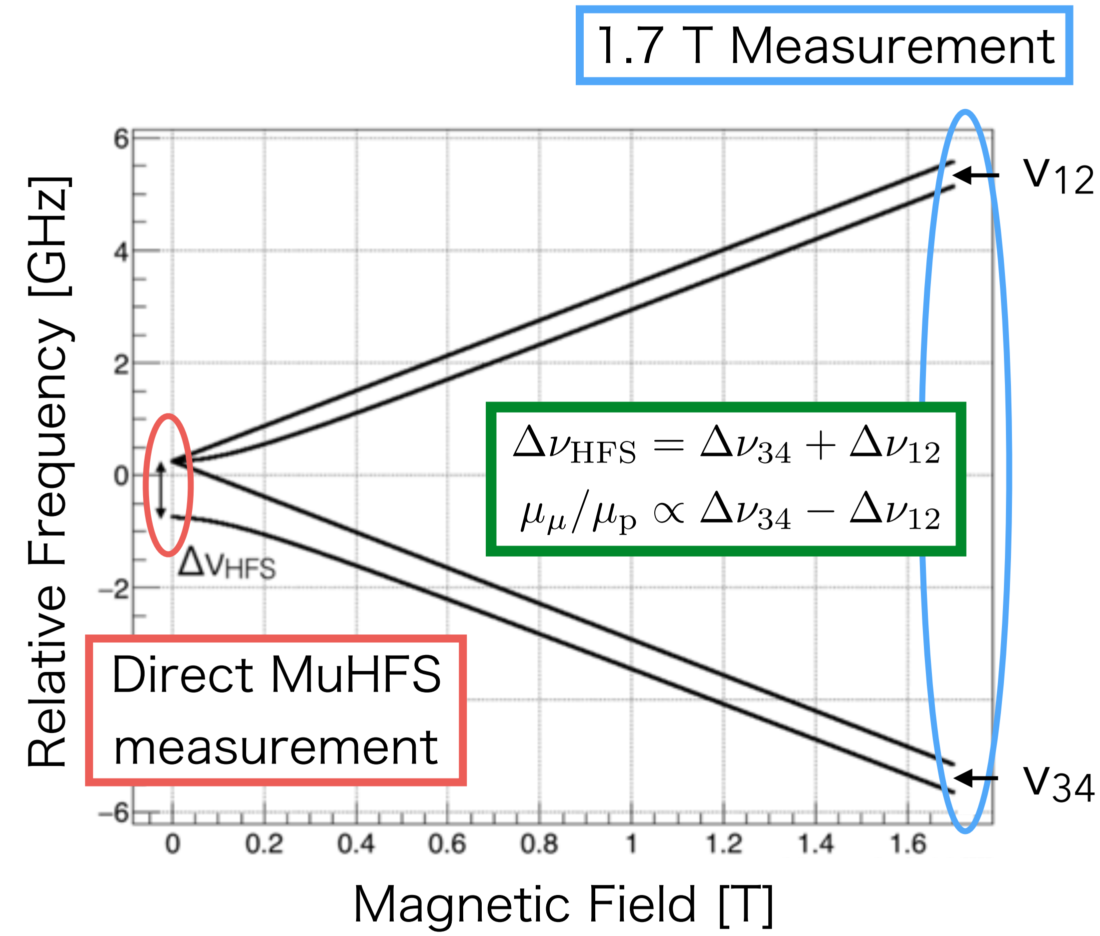
- Hamiltonian of Muonium

$$\mathcal{H} = a\vec{I}\cdot\vec{J} + g_J\mu_B^e\vec{J}\cdot\vec{H} - g'_\mu\mu_B^\mu\vec{I}\cdot\vec{H}$$

- Splits to substructure (Zeeman effect)

$$\nu_{12} = -\frac{\mu_B^\mu g'_\mu H}{h} + \frac{\Delta\nu_{\mathrm{HFS}}}{2}[(1+x) - \sqrt{1+x^2}]$$
$$\nu_{34} = +\frac{\mu_B^\mu g'_\mu H}{h} + \frac{\Delta\nu_{\mathrm{HFS}}}{2}[(1-x) + \sqrt{1+x^2}]$$

$$(x \propto H)$$



- 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*

- μ_μ / μ_p : essential parameter for muon g-2 experiment

$$a_\mu = \frac{g_\mu - 2}{2} = \frac{R}{\lambda - R} \; (\lambda = \frac{\mu_\mu}{\mu_p}, R = \frac{\omega_\mu}{\omega_p})$$

From
MuHFS experiment

λ : 120ppb

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

From
g-2 storage ring

R : 540ppb

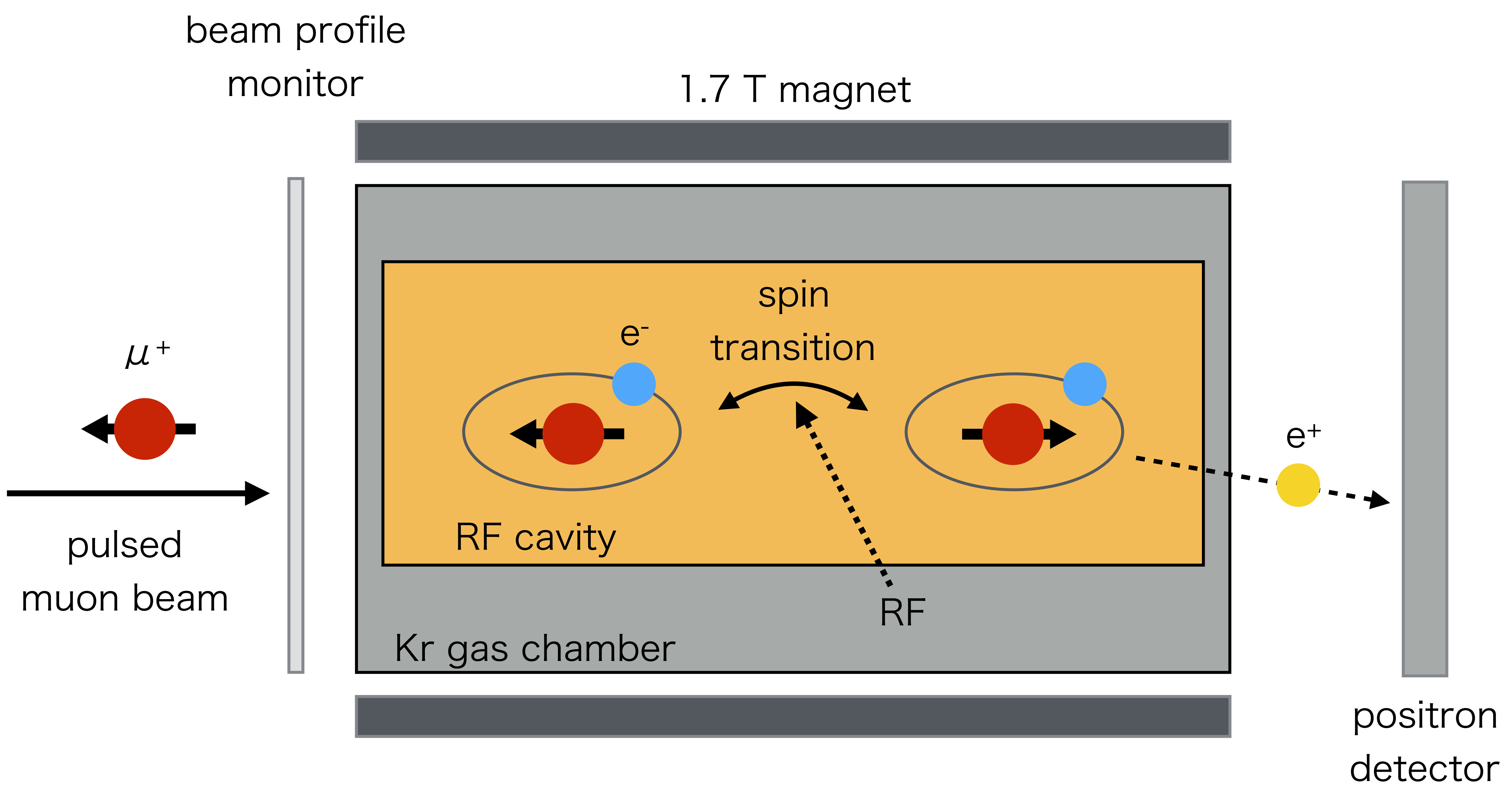
G.W. Bennett et al., Phys. Rev. D **73** 072003 (2006).

- ~2.9σ discrepancy between theory and experiment

$$a_\mu(exp) - a_\mu(th) = 250(89) \times 10^{-11}$$ (from CODATA 2014)

- Measurement planned at J-PARC and Fermi lab

High field MuHFS measurement



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

Road map of MuSEUM experiment

- Zero field measurement @MLF D2-line - ongoing
  - 2016 Jun. 3 Beam profile measurement
  - 2016 Jun. 12-14 (60h) - 1st measurement
  - 2017 Feb. 1-4 (96h) - 2nd measurement
  - 2017 Jun. - 3rd measurement with TM220 cavity
- High field measurement @MLF H-line
  - First measurement planned from 2018 Autumn

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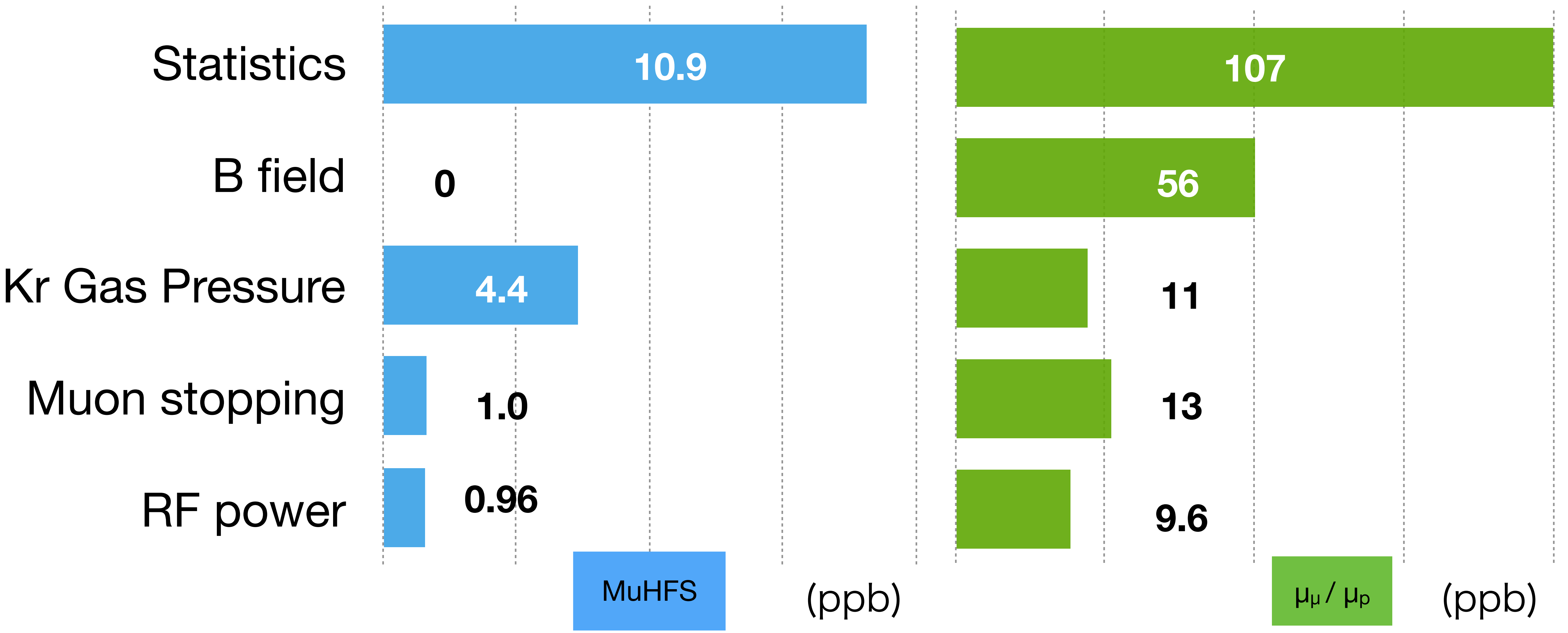
Uncertainties of LAMPF experiment



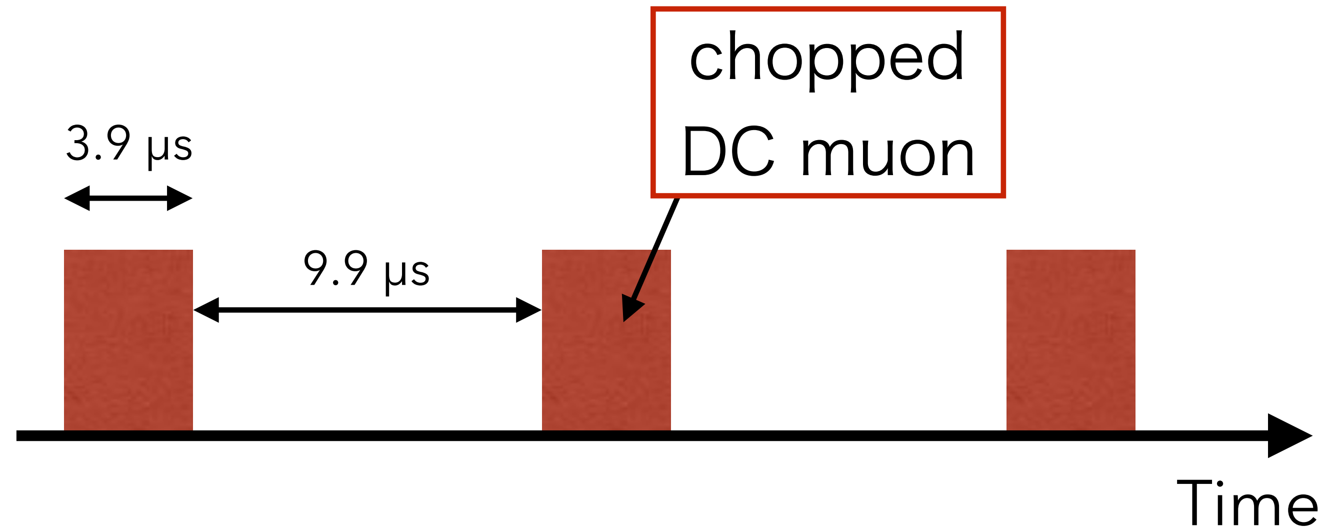
W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999).

- 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

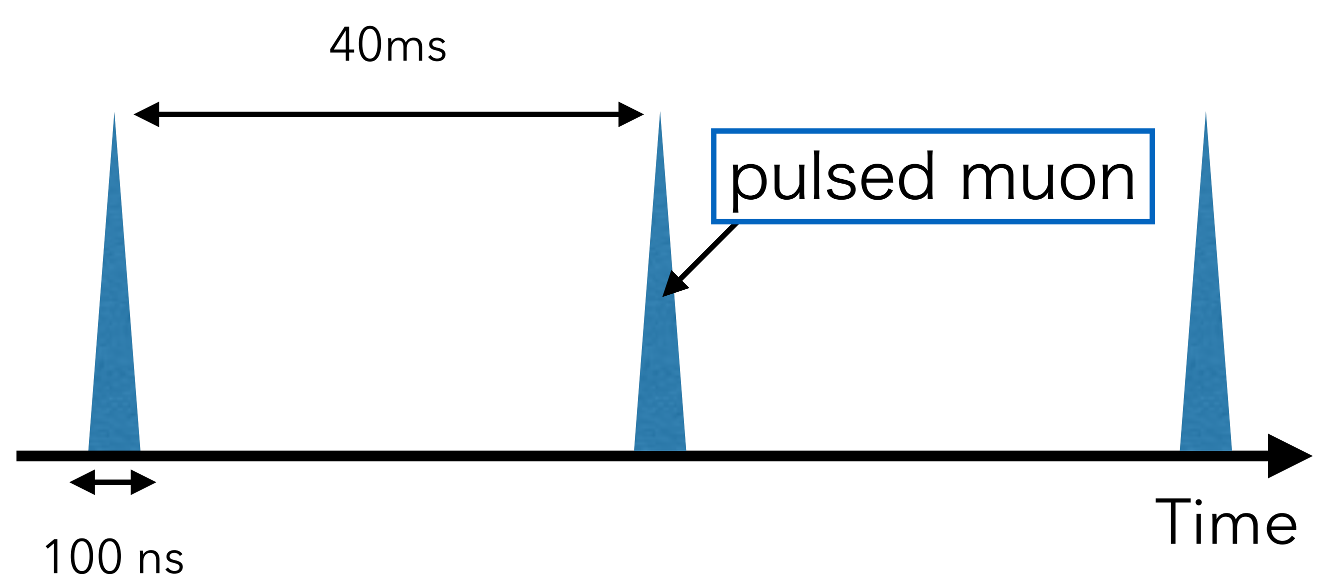
<u>LAMPF experiment</u>

- DC beam @ LAMPF
- 10^7 muons/sec on average
- Beam chopped - lose efficiency
- Beam time : 6 weeks
- Total : ~10^{13} muons



<u>MuSEUM experiment</u>

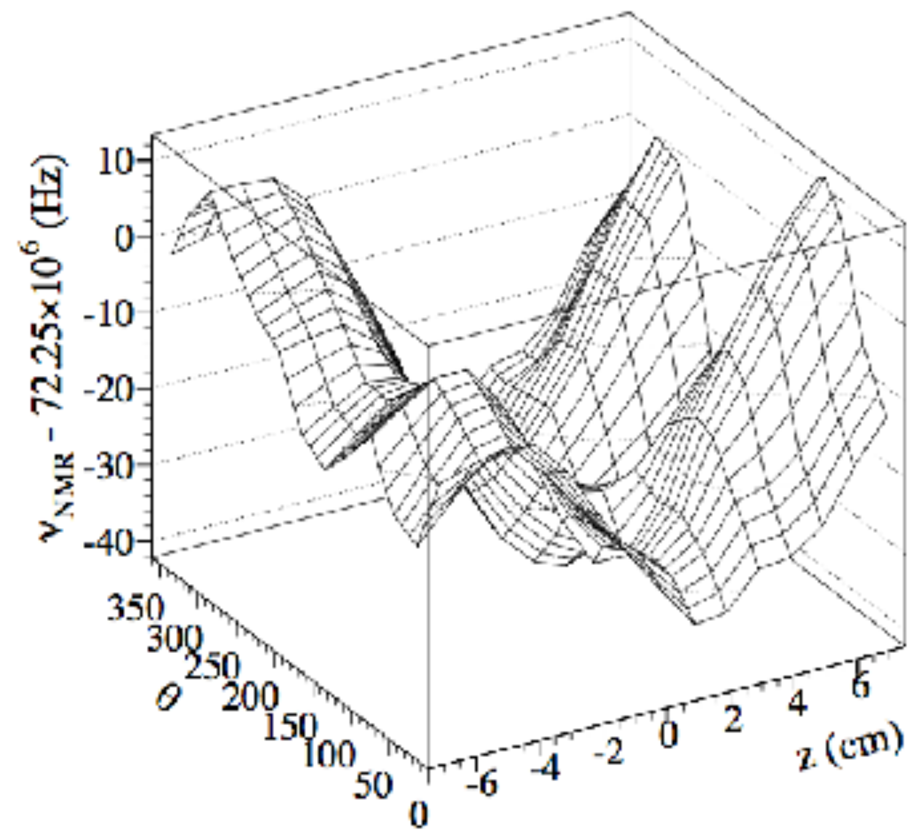
- Pulsed beam @ J-PARC MLF
- planned 10^8 muons/sec by MLF H-line (1MW)
- All muon can be used
- Total : ~2 x 10^{15} (~100days)
- **<u>Statistics by a factor of 10</u>**



B-field of LAMPF experiment

- B-field evaluated with

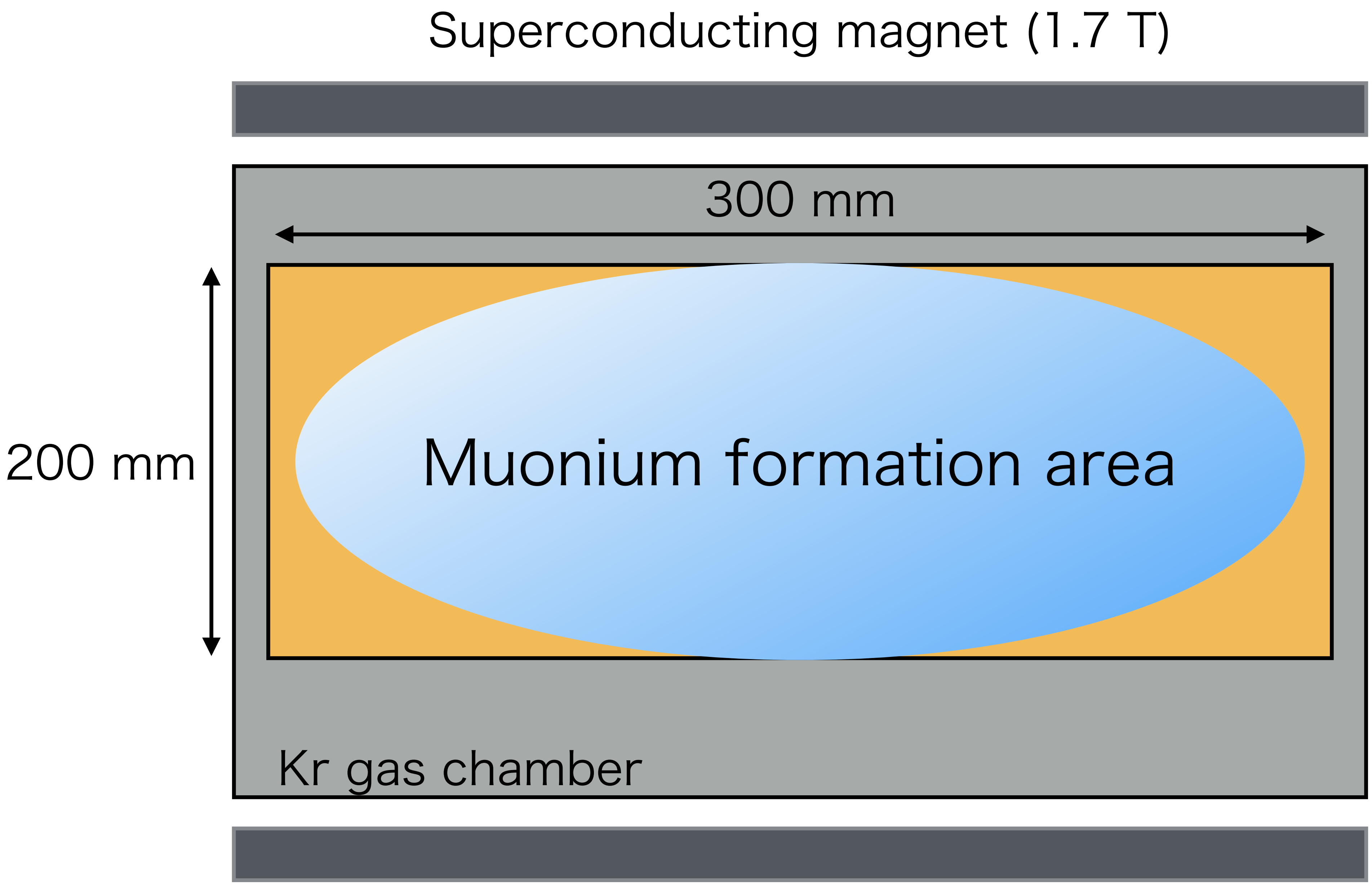
1. Magnet spec :1ppm in 10 cm diameter sphere volume
2. B-field mapping : 0.7ppm peak-to-peak homogeneity in r = 3.5 cm, *z* = 12 cm cylindrical surface



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 z=30 cm, r=10cm spheroid muonium formation area

B-field improvement - magnet

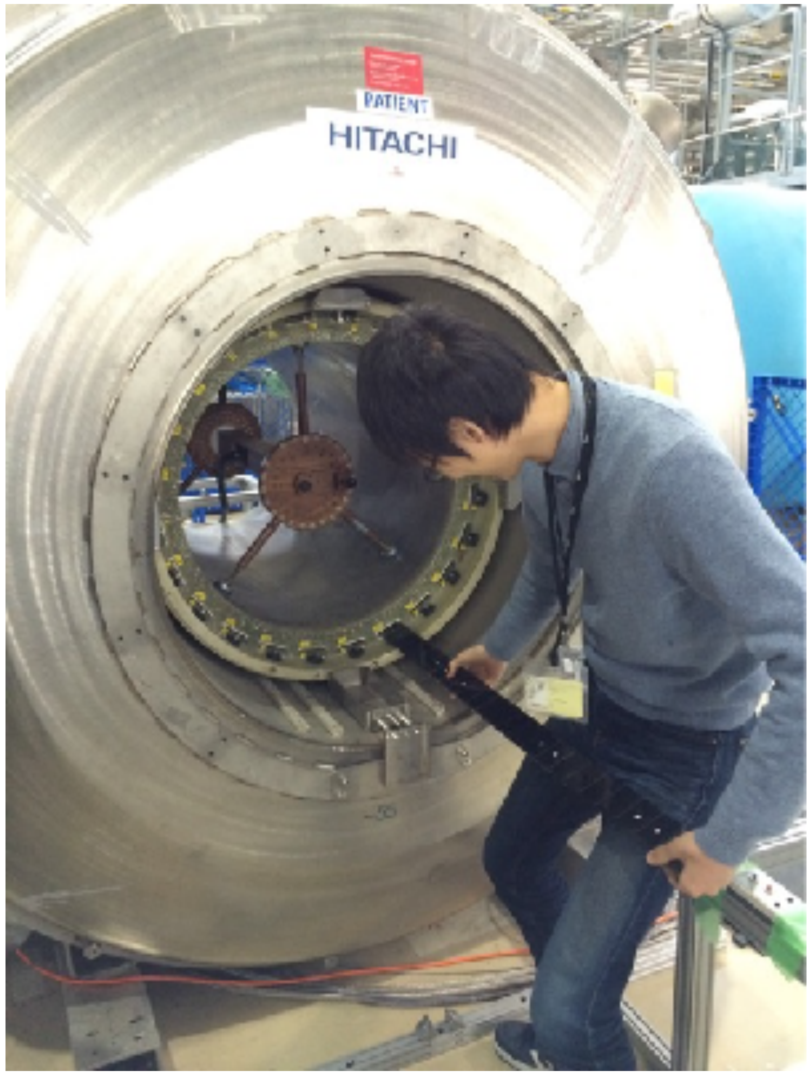
- Solenoid superconducting magnet for MuSEUM
  - Maximum 2.9 T, used in 1.7 T
  - Required homogeneity <1ppm
  - Required stability <0.1ppm/h

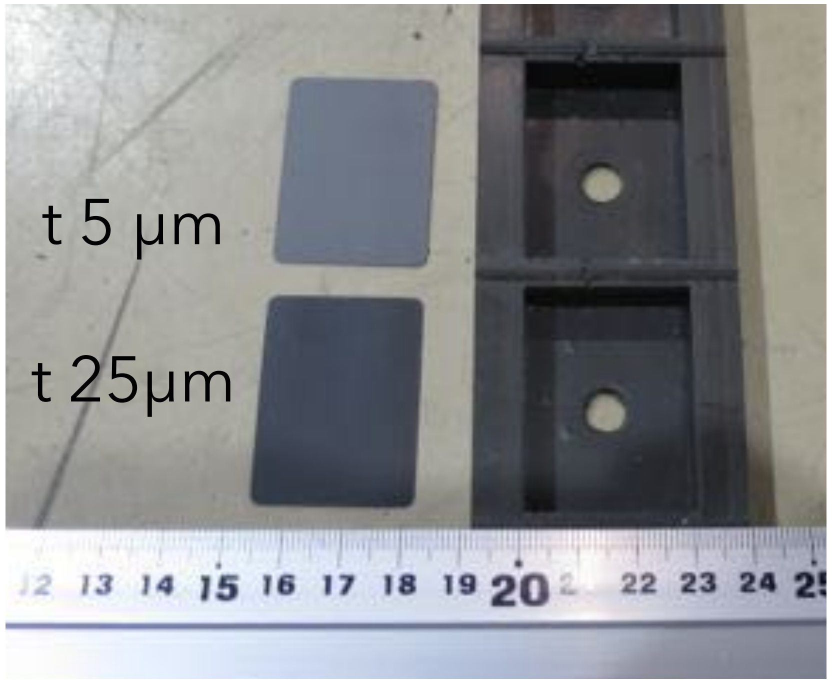
Superconducting magnet

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

B-field improvement - shimming

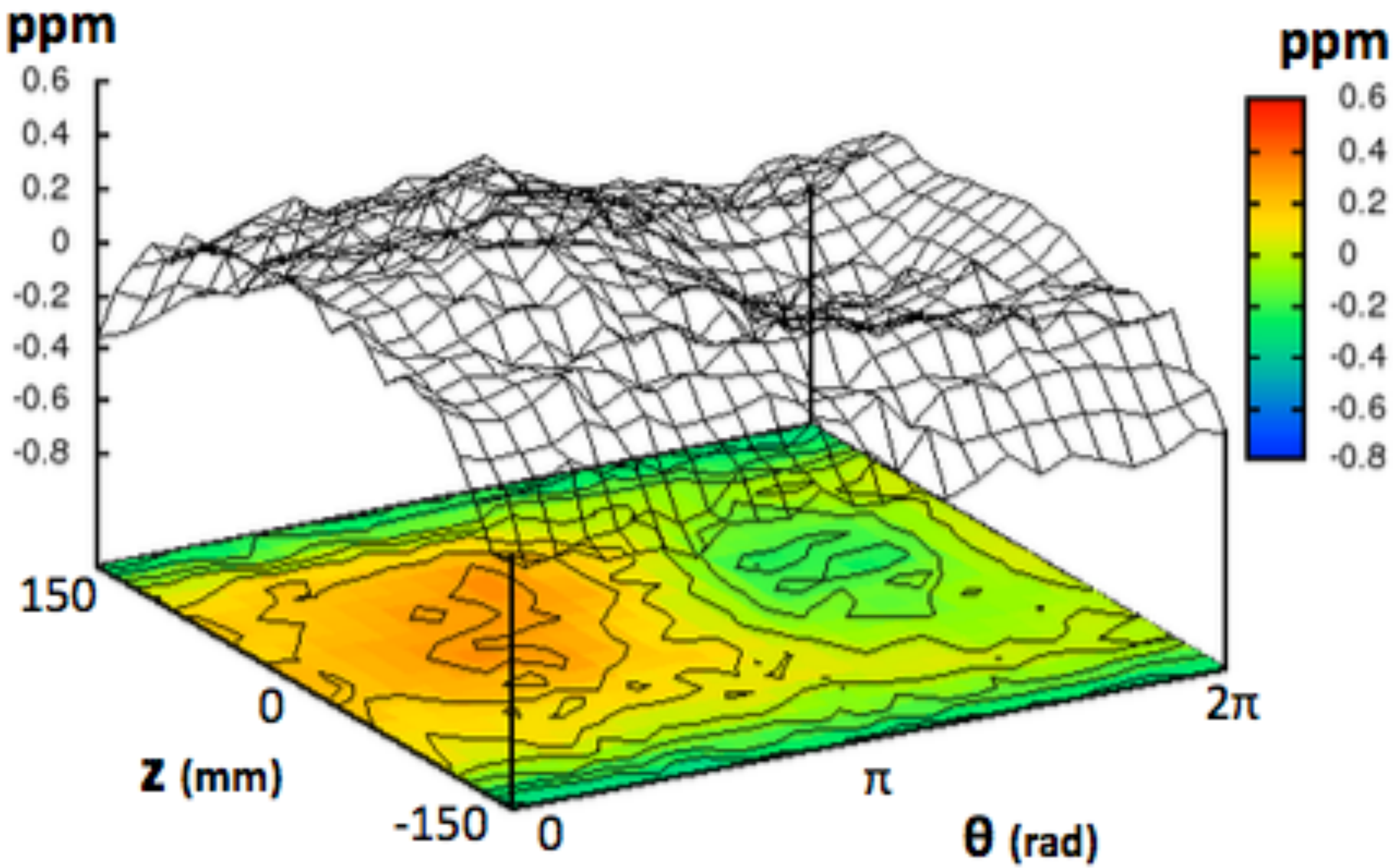
- Shimming by placing iron plates (5 & 25um thickness) in 24 pockets* 24 trays = 576 pockets inside the magnet
- Optimized homogeneity to 0.80ppm of 1.7 T in target area





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

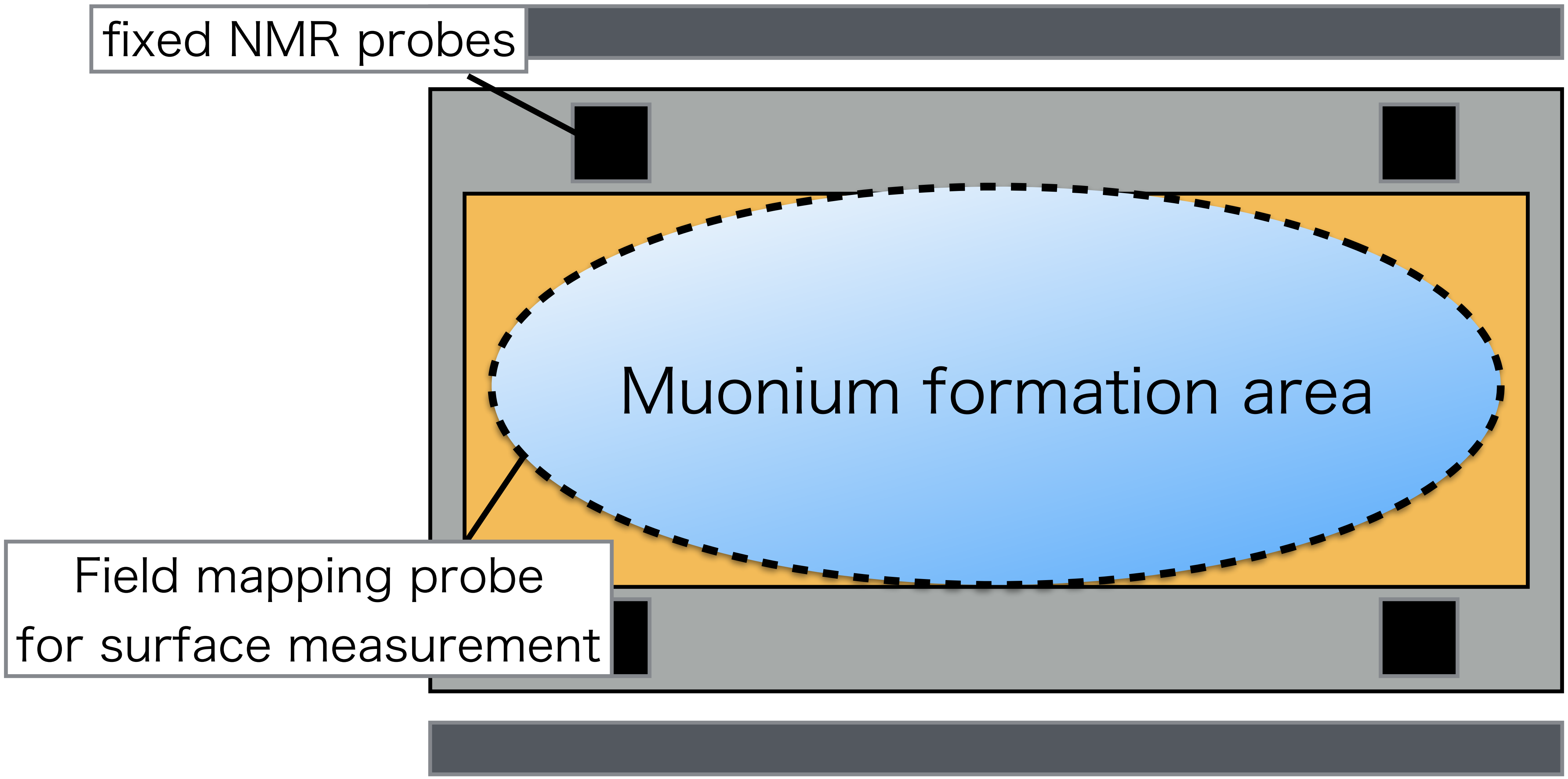
B-field improvement - result of shimming



(taken from Y. Higashi's master thesis)

0.8ppm homogeneity in 300 mm * 200 mm spheroid
(576 points measured by single NMR probe)

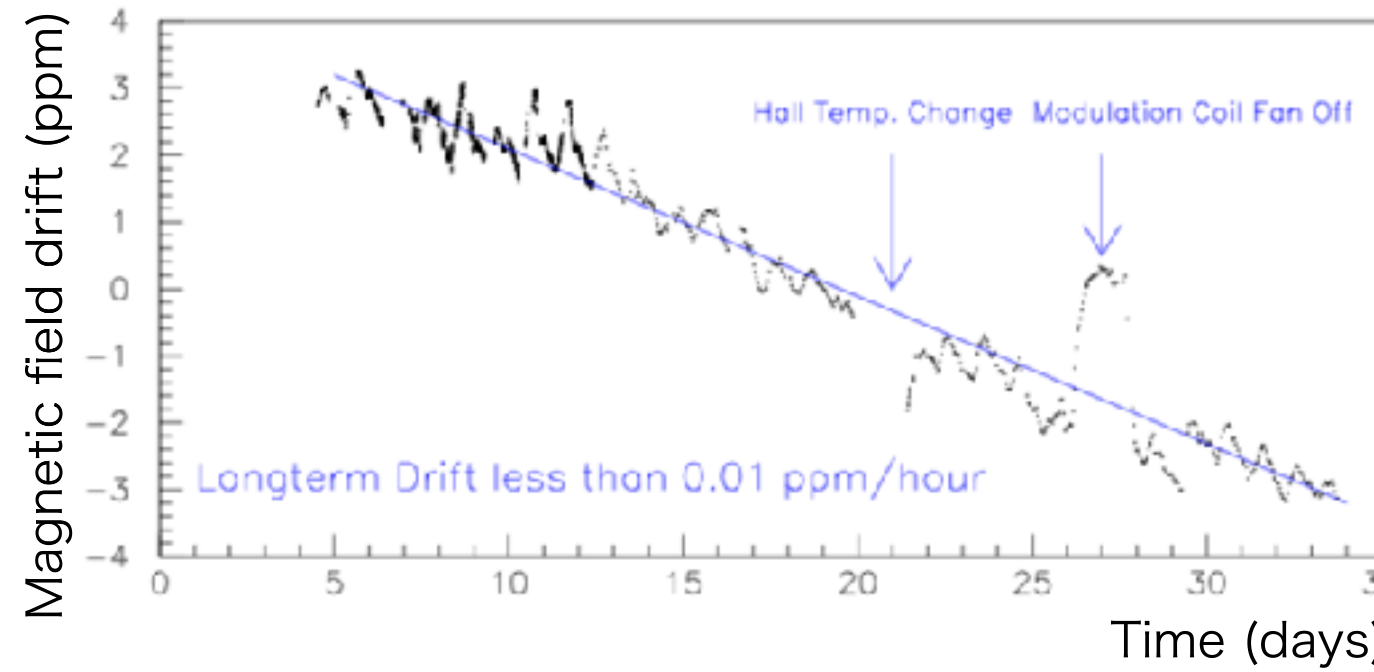
NMR probes for MuSEUM experiment



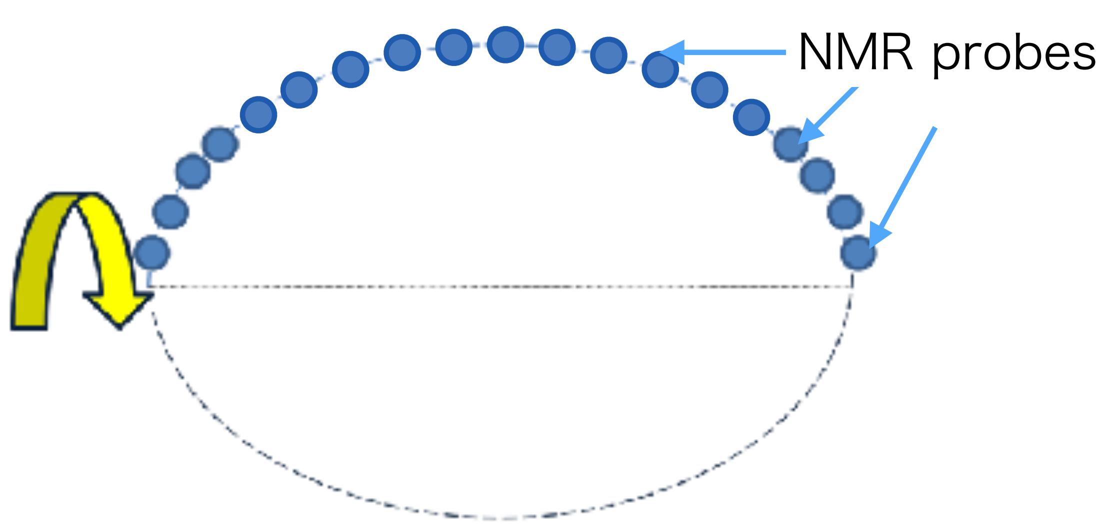
- Stability - Online monitor by fixed NMR probes
- Homogeneity - Absolute B-field measurement by field mapping probe

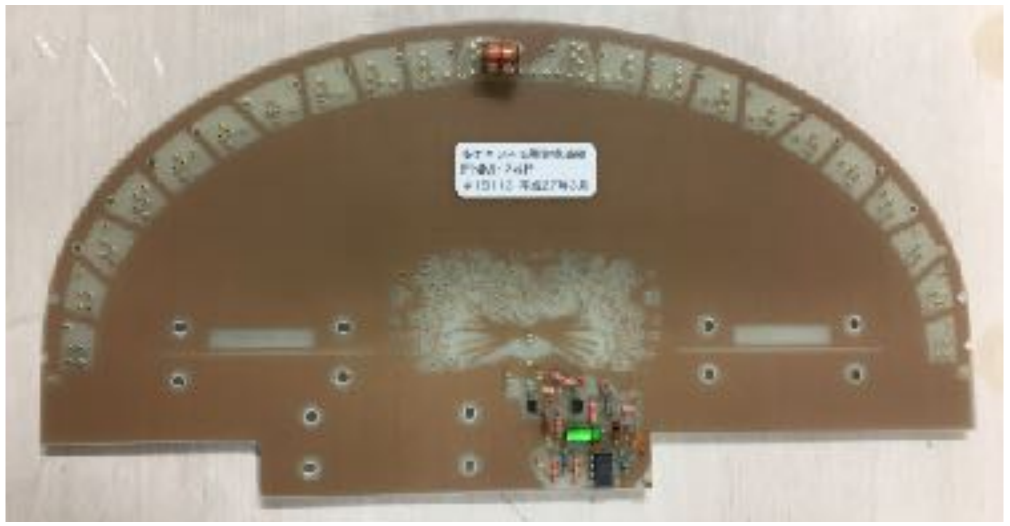
Concept of field mapping probe

- 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 the 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. Single channel NMR probe - in progress
   - Deicide the absolute B-field with high precision
   - The effect by the circuit element itself is crucial

2. Fixed probe, Field mapping probe design

3. Test with our superconducting magnet

4. Installation to the HF experiment

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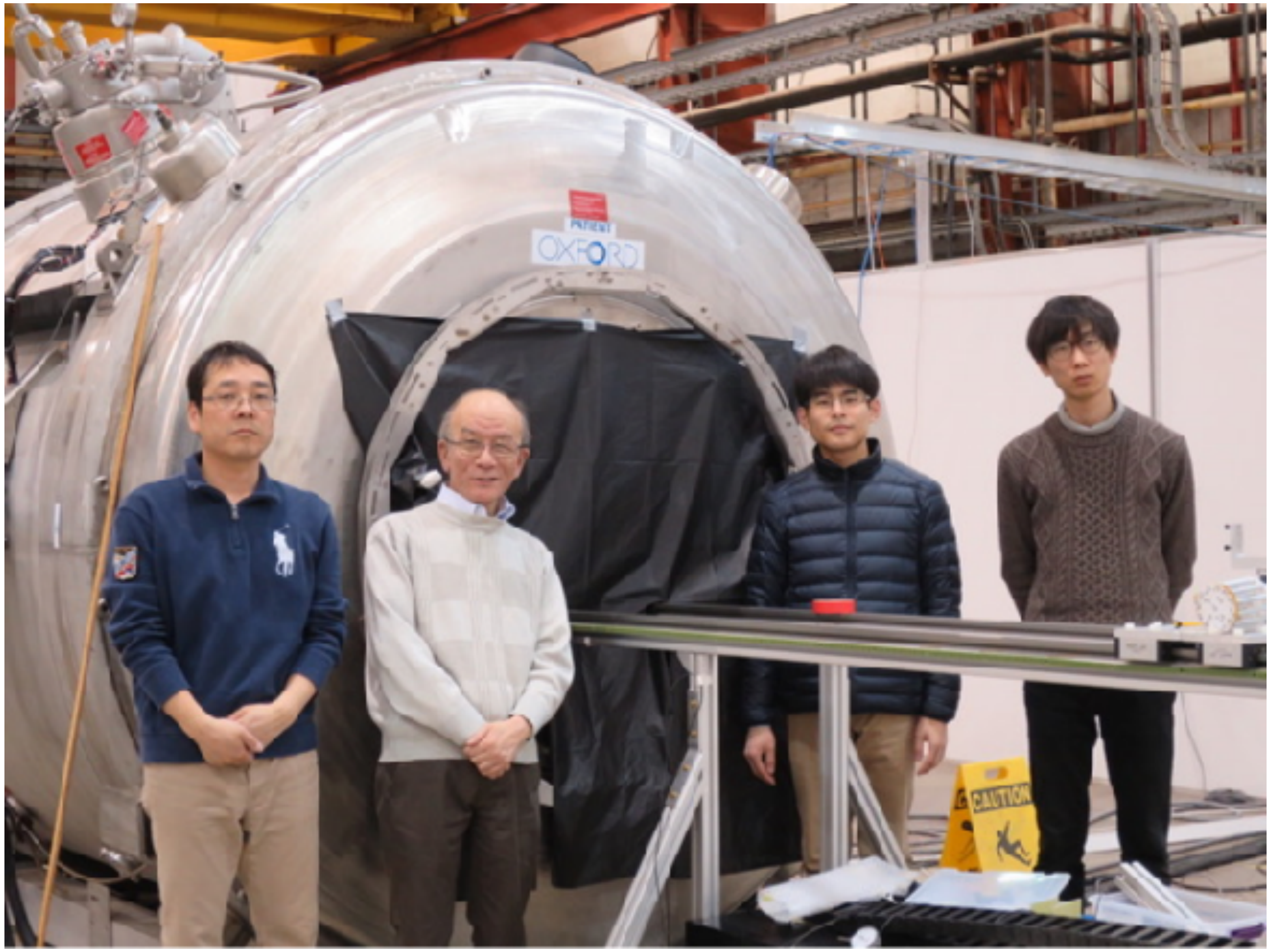
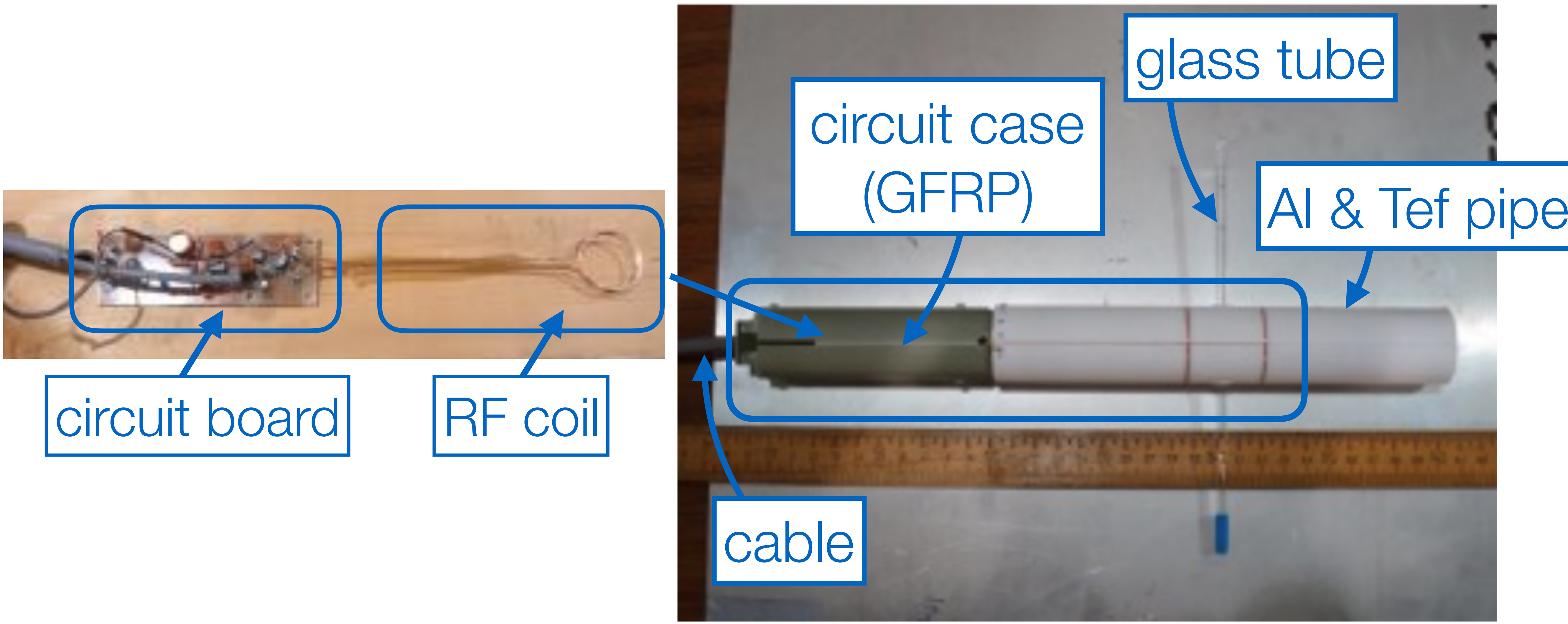
Test of the standard probe

- Performance of standard CW-NMR probe was tested with 1.45 T magnet @Argonne national laboratory, USA



Test of the standard probe

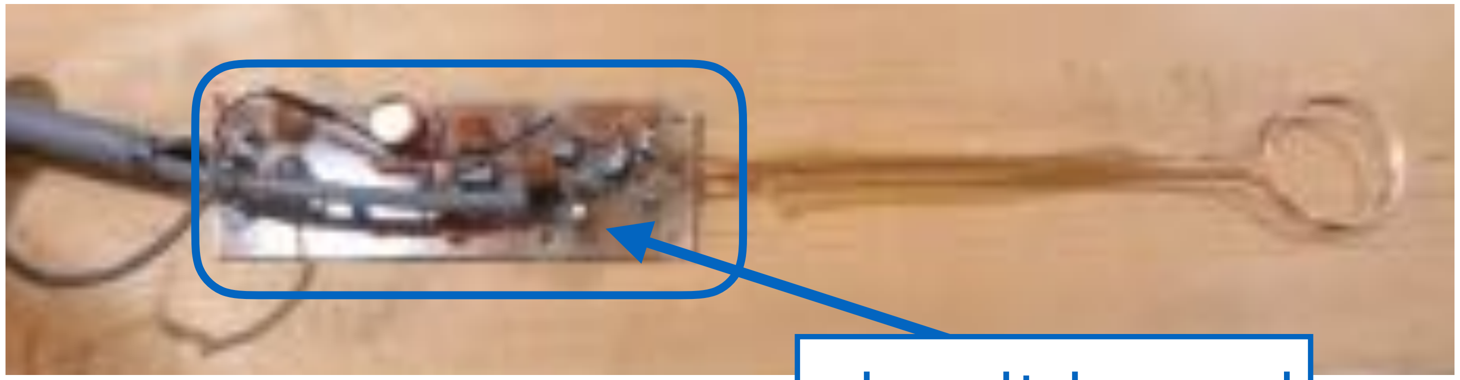
- B-field shift effect caused by the NMR probe material itself is tested



Results of the material test

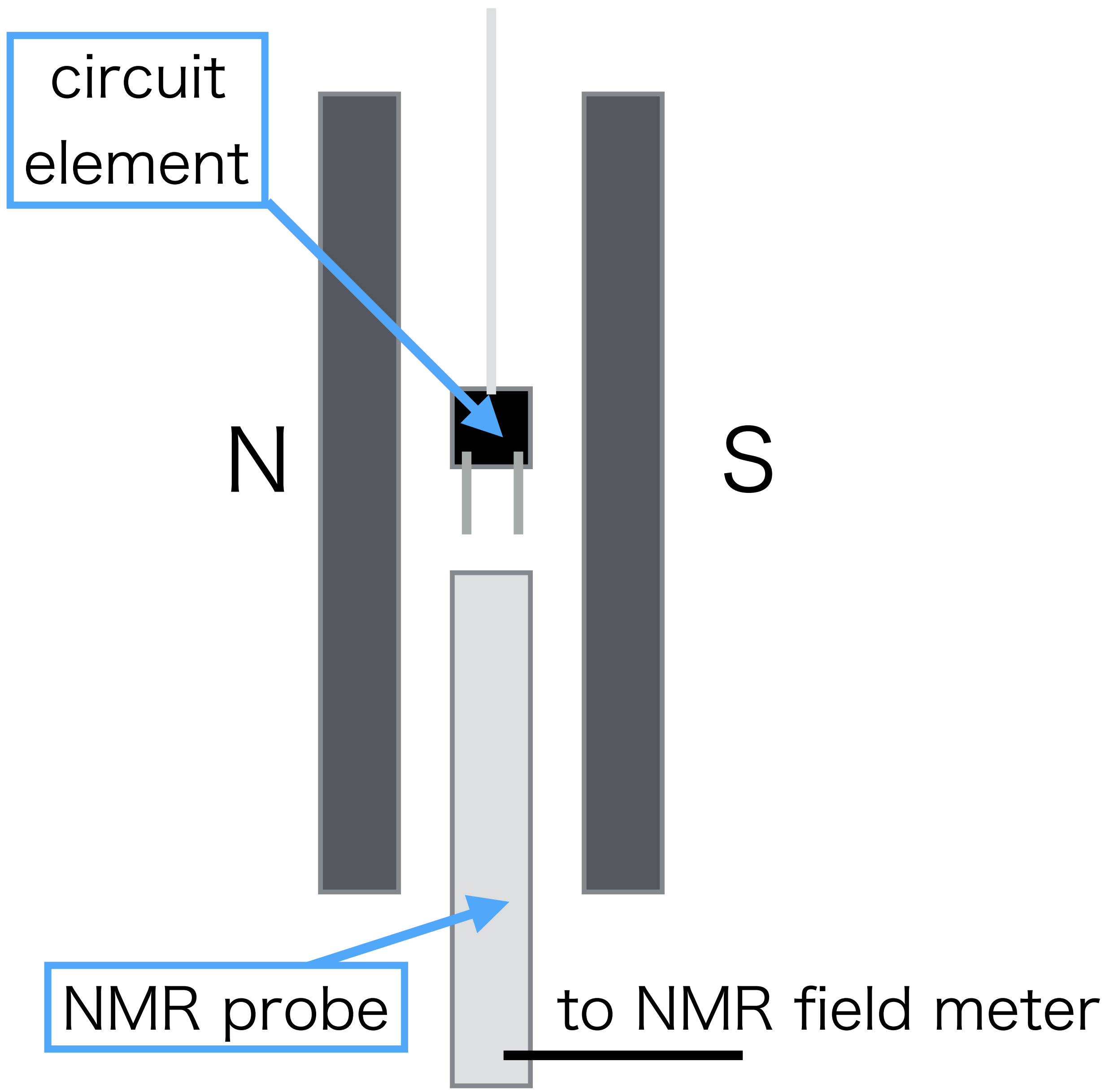
	Shift (ppb)	Shift (Hz)
All materials	**+70.6 ± 2.5**	**+4.36 ± 0.15**
Circuit boad	+96.4 ± 0.4	+5.95 ± 0.02

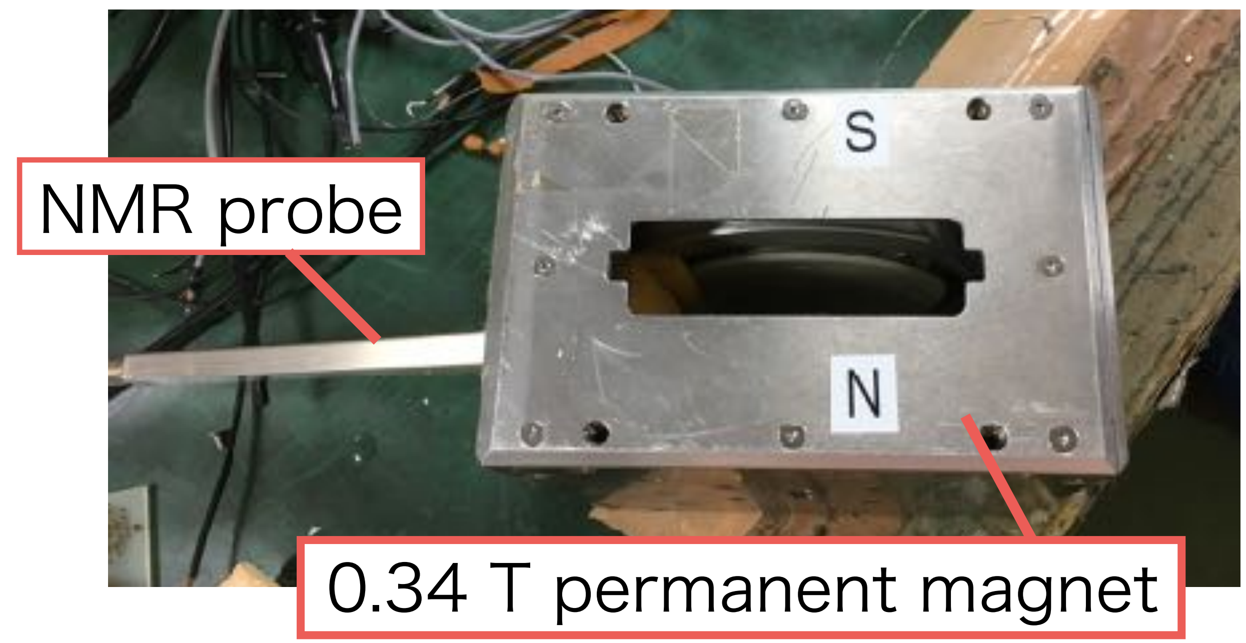
(Calculated by S. Seo)

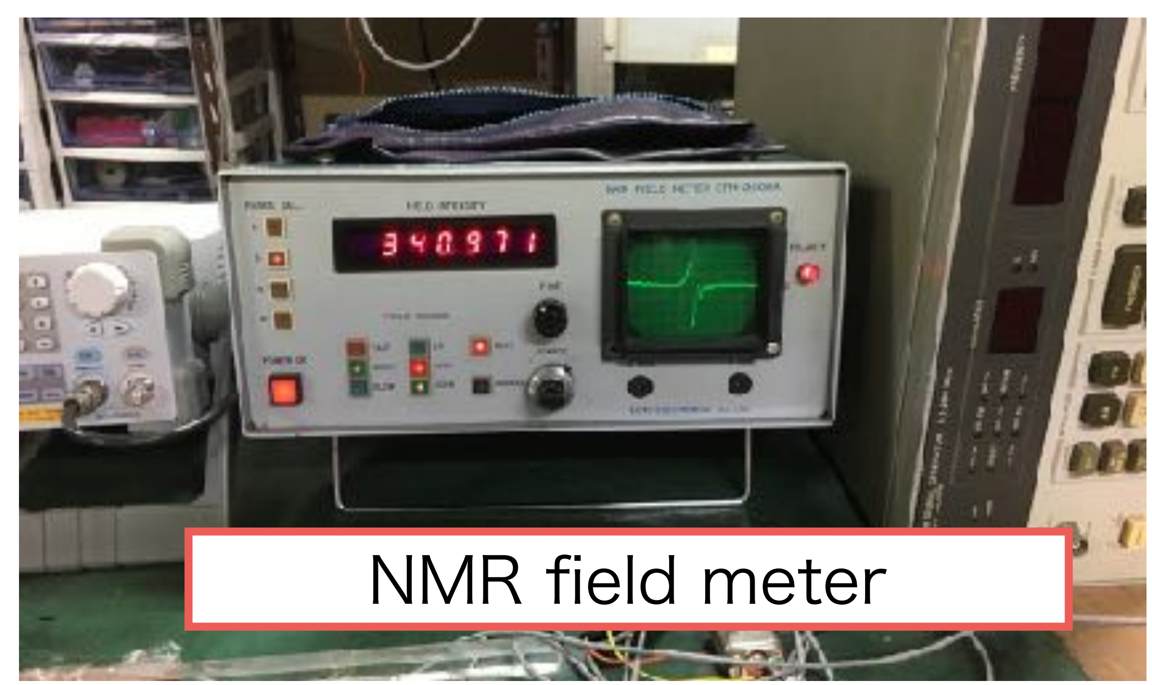


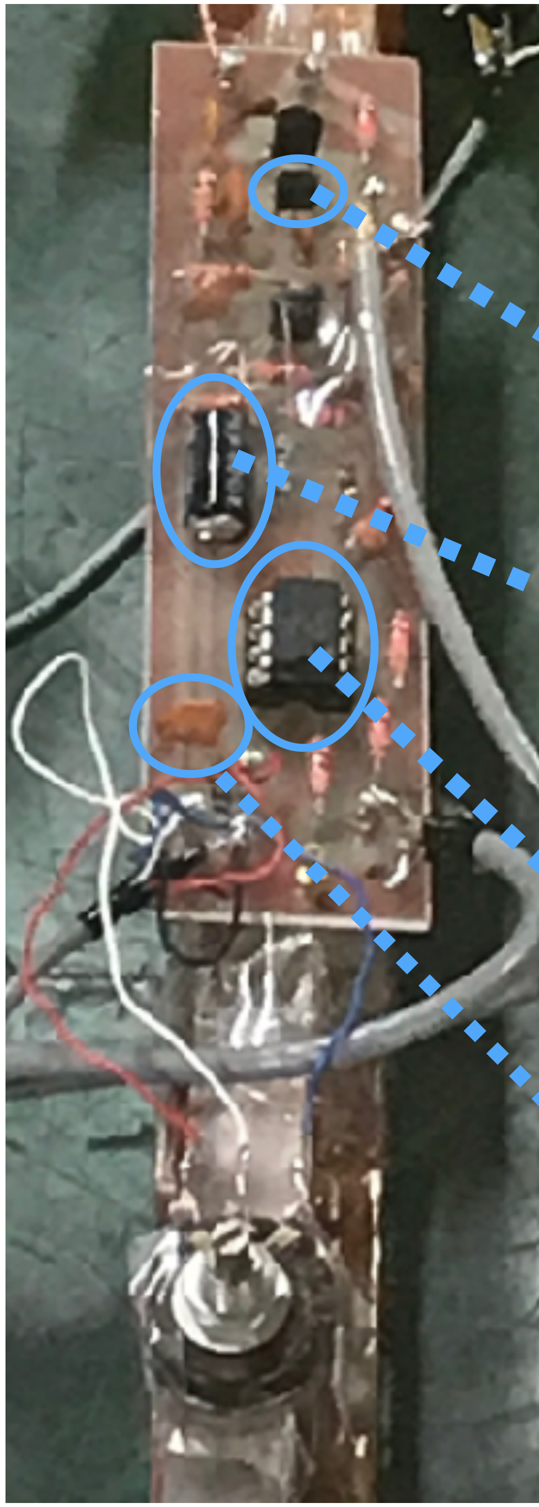
Development status - circuit element test

- 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

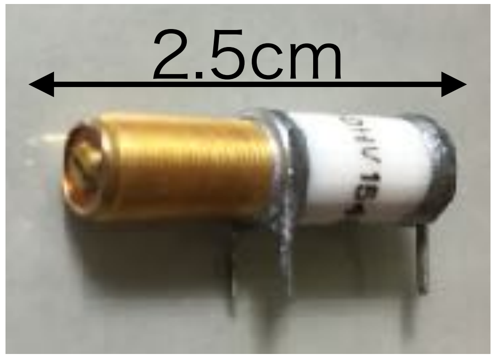
<u>**Can know which element should be excluded!**</u>

Development status - final circuit design

- Suggestions

1. select non-magnetic element

\- Reliability will be tested with our magnet

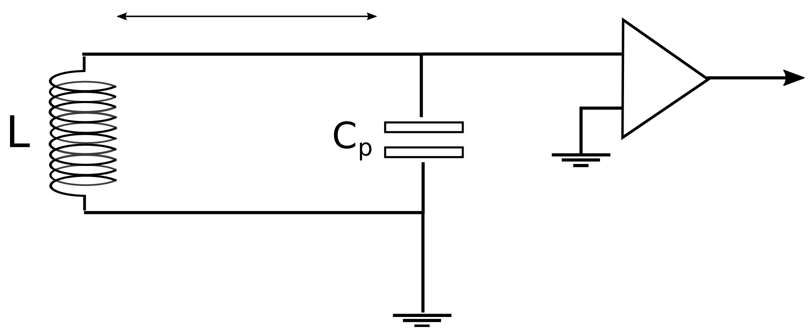


non magnetic trimmer capacitor
(Voltronics NMAP40HV)

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 with high precision.
- For the high precision measurement, more statistics and the improvement of systematic uncertainty based on magnetic field are required.
- The spec magnet fulfills the requirement of the MuSEUM experiment.
- For MuSEUM experiment, field mapping probe and fixed probes are planned to use. To develop high precision NMR probes, we found out which element should (not) be used.