# Precision measurement of the magnetic field for J-PARC muon experiments

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2017/09/18

# Contents

- Introduction
- R&D status
  - NMR probe
  - Hall probe
- Summary

# Introduction

- Magnetic field is closely related to the physics using accelerator
  - Bending, Focusing, et.
  - Measure momentum, energy of particles
- For g-2/EDM and MuSEUM
  - Key word : High homogeneity in the muon storage region
  - Field measurement of spatial distribution is so important to generate and validate homogeneous field

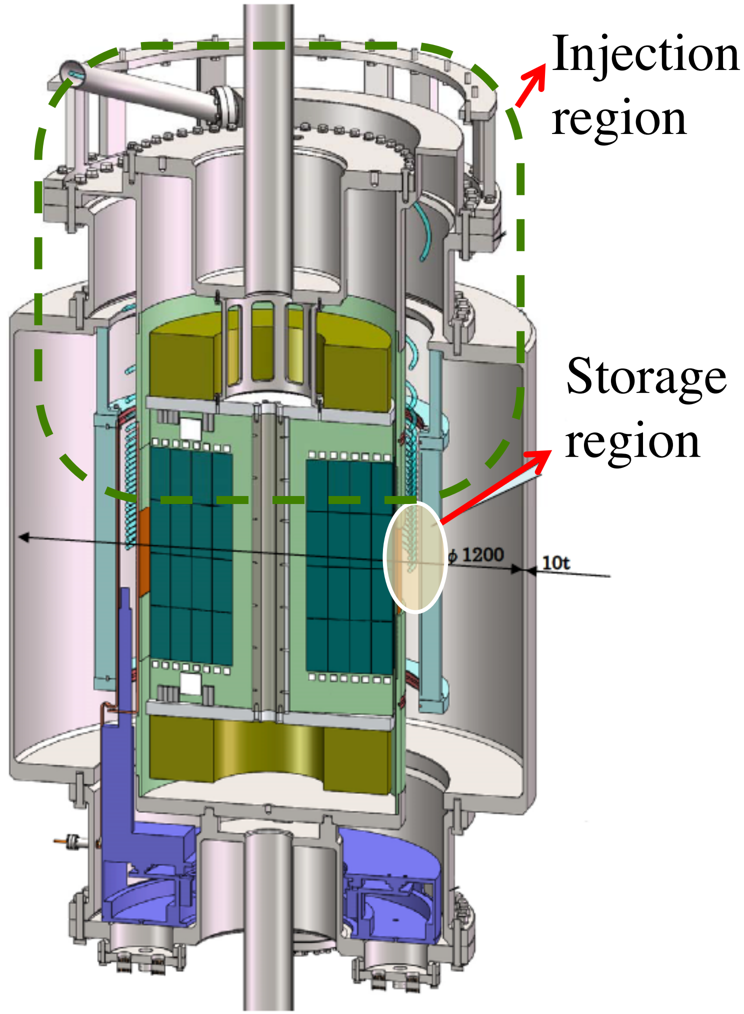
not sufficient : measure only field uniformity

More measurement of magnetic field is really required to realize physics experiment

# Required measurements for g-2

1. Homogeneity in the storage region
2. Time variation of field strength in the storage region
3. Vector field map in the beam injection region
4. Radial field distribution of weak focus field
5. Cross calibration between standard probe and all probes which are practically installed in the magnet system.

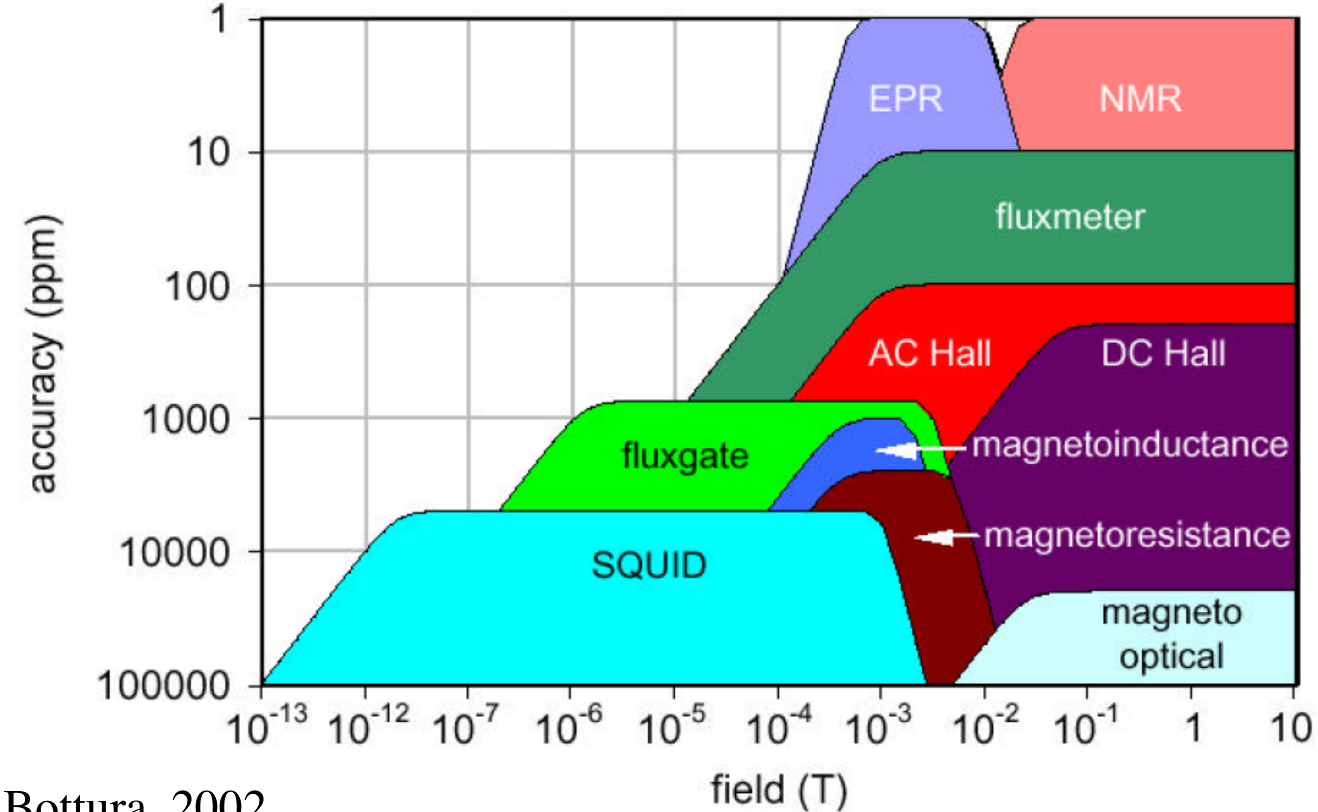
In MuSEUM : 1, 2, 5




✓ All measurements have to be properly carried out. Otherwise physics experiments are not completed.

# Overview of field measurement methods

✓ No perfect method could be applied to all types of field measurement




L. Bottura, 2002

- J-PARC g-2/EDM
  - NMR probe: measurement with high accuracy
  - Hall probe: measurement requiring field vector

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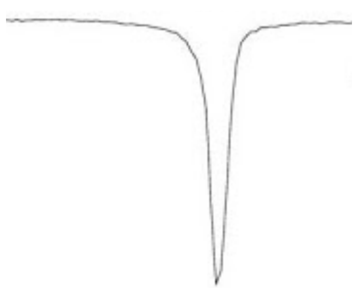
# Field measurement method ~ NMR

- NMR
  - Utilize a resonant absorption of RF energy in a particle
    - $f = \gamma B$

      $f$: RF frequency, $\gamma$: gyromagnetic moment, $B$: magnetic field
  - 😀 High precision in high magnetic field
    - < 1 ppm, > 0.1 T
  - 😞 Field direction could not be measured
  - 😞 Field must be homogeneous

Proton ($^1$H):
$\gamma$=42.576396(3) (MHz/T)



Homogeneous field

Signal width

<

Inhomogeneous field

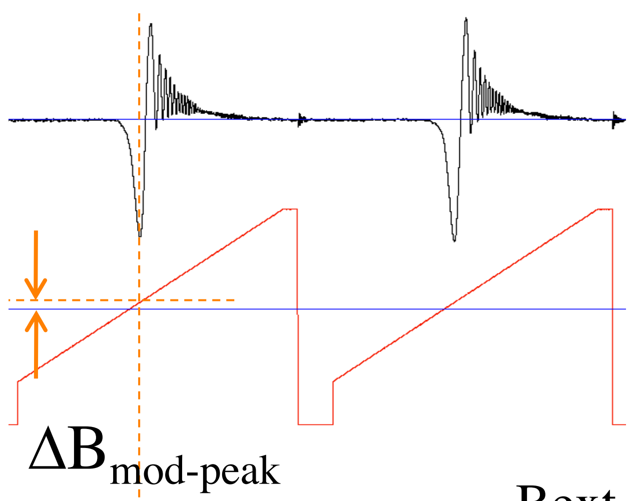
# CW(Continuous Wave)-NMR

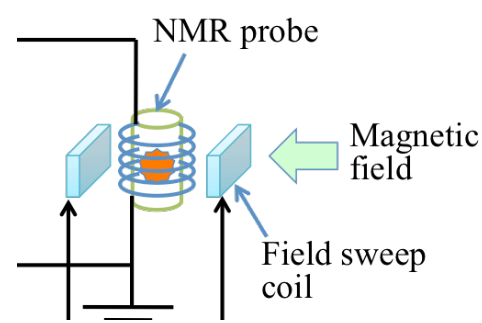
- Schemes of NMR
  - Pulse NMR
  - CW NMR
    - Frequency modulation, Field modulation
- Observe the resonant absorption peak
  - Apply constant RF frequency (RF0)
  - Sweep magnetic field by using modulation coil (+/-$\Delta B_{mod}$)

Commercially available in Japan

NMR signal

Modulation field




$$\mathrm{Bext} = B_{RF0} - \Delta B_{mod\text{-}peak}$$

# Measurement using NMR probe

1. Homogeneity in the storage region
2. Time variation of field strength in the storage region
3. Vector field map in the beam injection region
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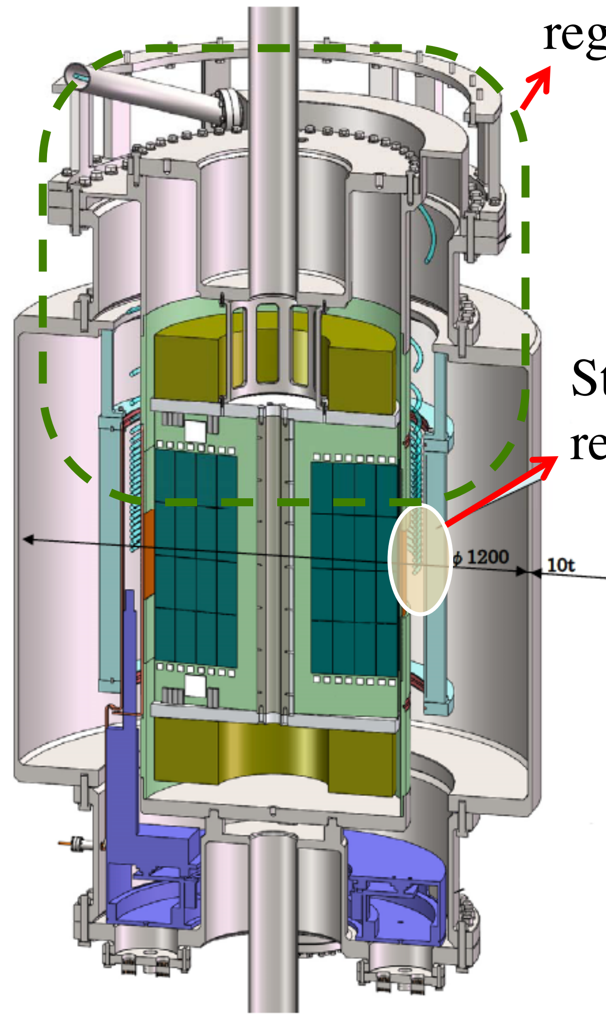
5. Cross calibration between standard probe and all probes which are practically installed in the magnet system.

In MuSEUM : 1, 2, 5




Mainly focusing to develop the standard probe

# Standard NMR probe

- Why standard probe is required?
  - Many probes will be used in the practical system
    - Each probe has individual character -> different error from each other
  - strongly need the probe with the high resolution and accuracy
    - to obtain the absolute field strength used as standard field to check the consistency of all probes.

- Objective
  - Develop ultimate NMR probe with the highest accuracy and resolution

# Effect causing error in NMR probe

- Roughly 5 causes of error

$$B_p = (1 - \delta_t)B. \qquad (2)$$

$B_p$ : Magnetic field at the location of a proton
$B$ : External magnetic field

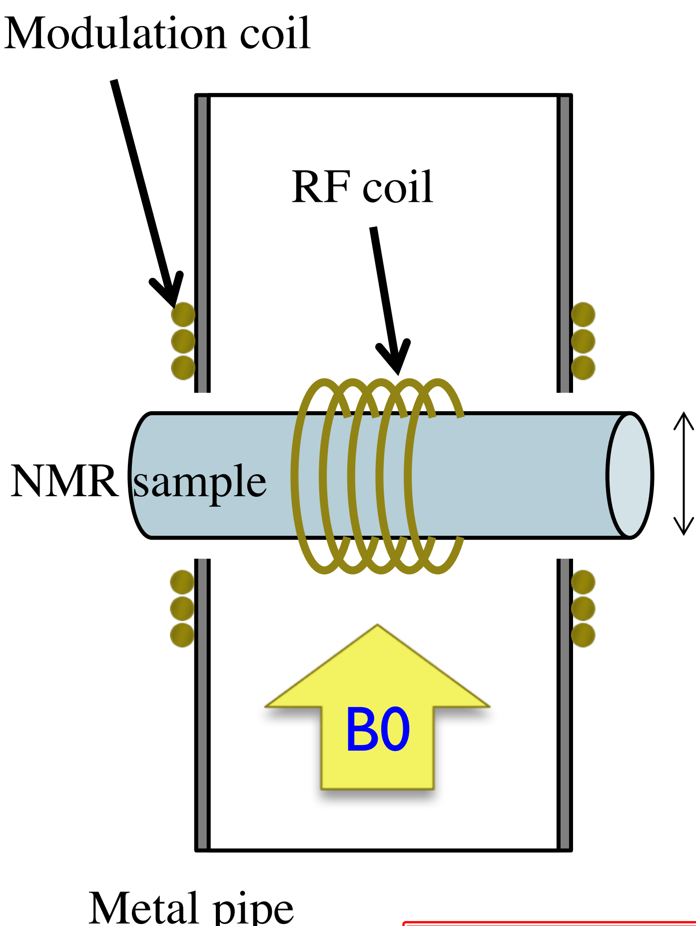
$$\delta_t = \sigma(H_2O) + \delta_b + \delta_p + \delta_s + \delta_c \qquad (3)$$

1. $\sigma(H2O)$ : Internal diamagnetic shielding in the water molecule
2. $\delta_b$: Bulk diamagnetism of the water sample (shape effect)
3. $\delta_p$: Paramagnetic impurities in the water sample
4. $\delta_S$: Paramagnetic and diamagnetic materials in the probe structure
5. $\delta_c$ : Error from signal processing scheme

1,2,3 : from Nature of NMR sample. Inevitable, but well-know
4, 5 : different in each probe -> try to minimize the effects

# Material effect

4. $\delta_S$: Paramagnetic and diamagnetic materials in the probe structure → Material effect

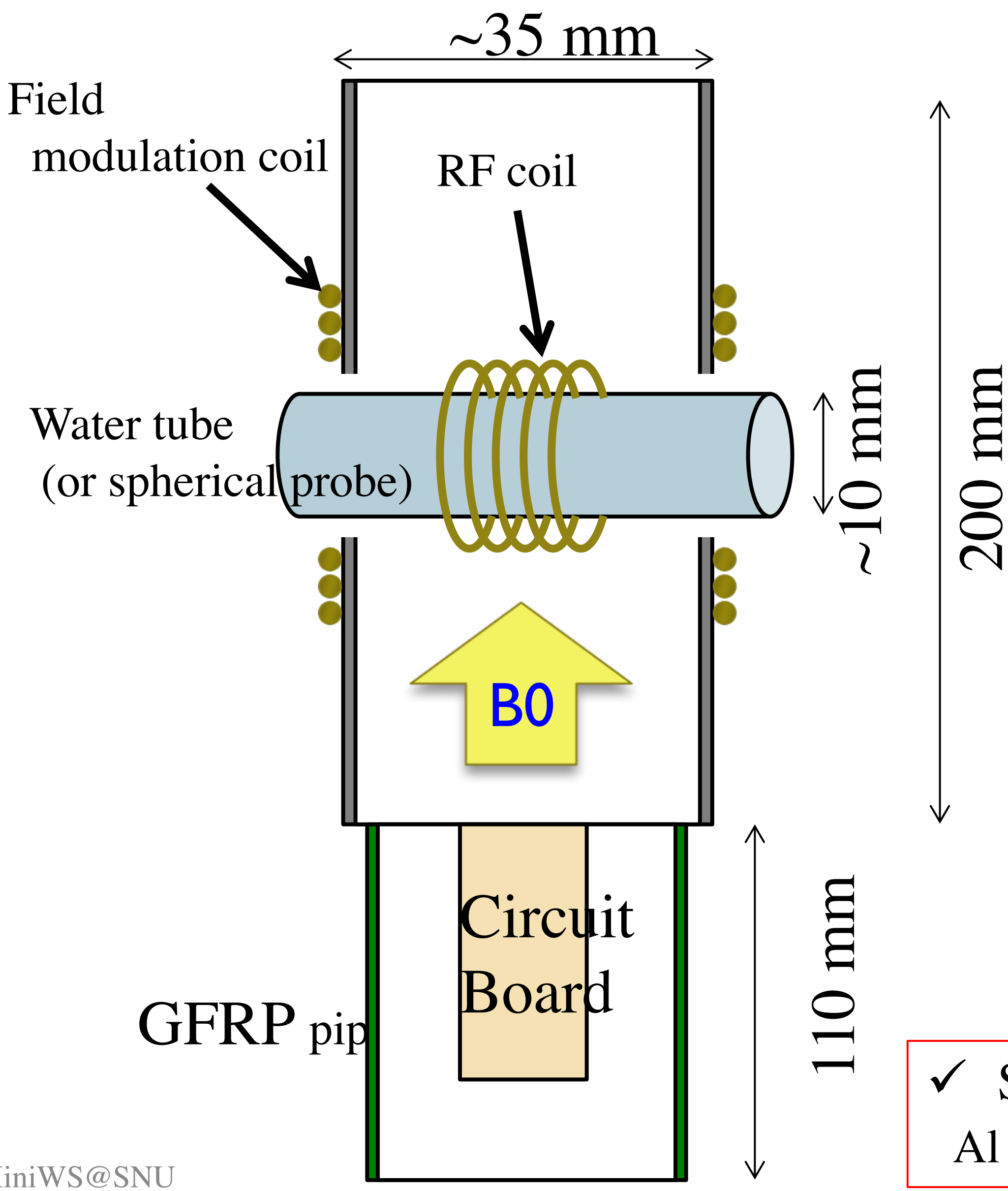



- Basic structure
  - NMR sample
    - produce particle occurring magnetic resonance
  - RF coil
    - Apply RF power
  - Modulation coil
    - sweep magnetic field slightly
  - Metal pipe
    - Noise shield and winding core of modulation coil

***<u>Materials have para- or dia- magnetism.</u>***

> ➢ Try to minimize the net magnetism by using combination of para- and dia- magnetic materials at the same time

# CW-NMR standard probe

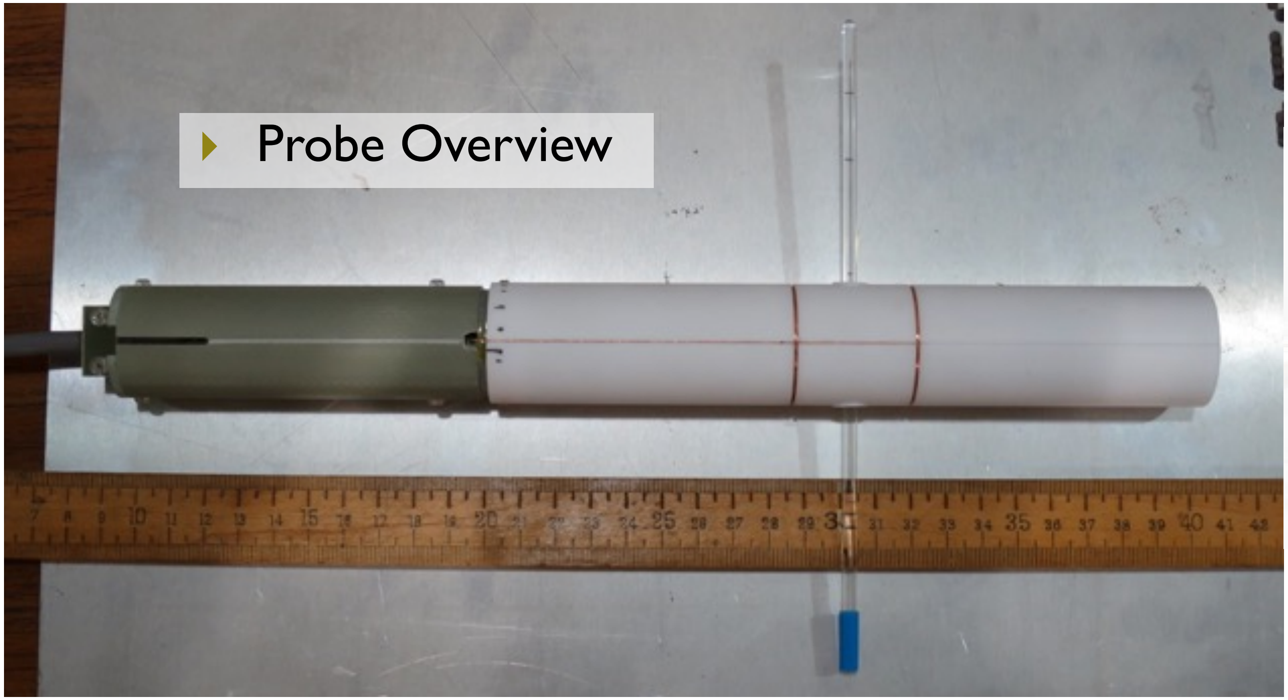



A. Water tube : glass
   - O.D.(I.D.) : 4.0(3.3) mm
   - Len. : 180 mm
B. RF coil : Cu pipe and Al wire
   - Cu pipe
     - O.D.(I.D.): 1.0(0.7) mm
   - Al wire
     - Dia. : 0.4 mm
C. Pipe : Al and Teflon
   - Al O.D.(I.D.) : 30(28) mm
   - Al O.D.(I.D.) : 34(20) mm
   - Length : 200 mm
E. Modulation coil
   - Cu wire
   - O.D. : 0.1 mm
   - 60 turns in total
F. GFRP pipe
   - O.D.(I.D) : 32(28) mm
   - 60 turns in total
G. Circuit board
   - W25 mm x L97.5 mm

✓ Susceptibility

Al : 2.22e-5; Cu : -9.8e-6, Teflon: -1.03e-5

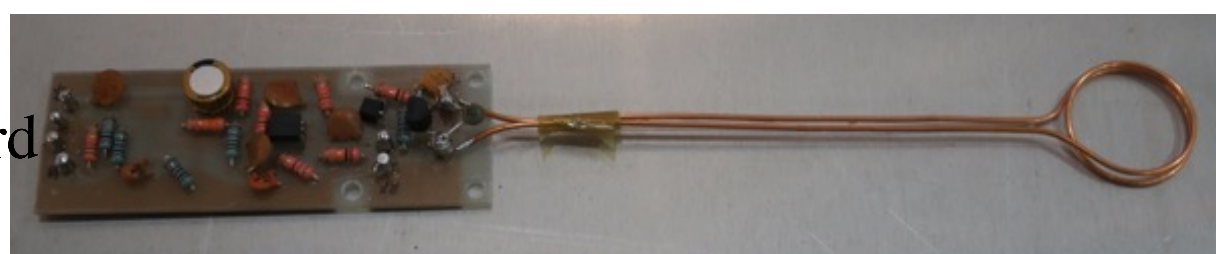
# Photos of standard probe



- Probe Overview

RF coil
+
Glass tube

Circuit board
+
RF coil



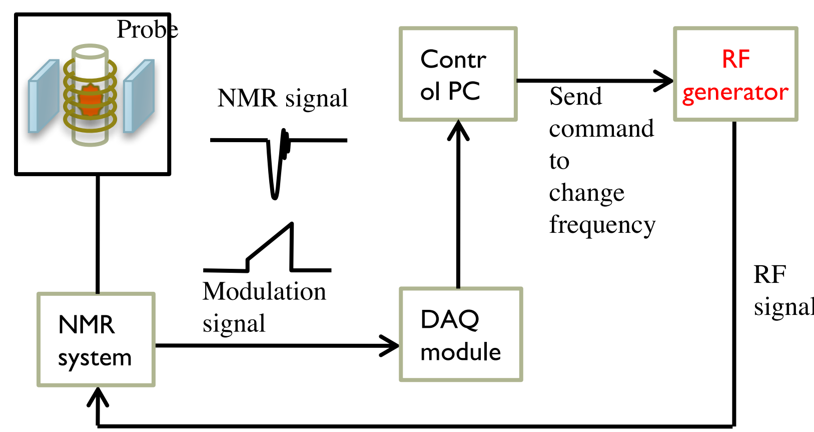
# Modification of signal processing scheme

## 5. $\delta_c$ : Error from signal processing scheme

*-> CW NMR with field modulation : non-uniformity of modulation field*

- *Digital signal processing scheme*
- *Feed back loop of RF frequency*

- DAQ module: NI PXI6132
- Control software: Labview
  - retrieve data from DAQ module
  - calculate phase difference between peak of NMR signal and zero-cross point of modulation signal.
  - send command to adjust RF frequency for making phase coincident among peak of NMR signal and zero-cross point of modulation signal.




by T. Mizutani

- Expect to minimize uncertainty coming from characteristic of modulation field

# Test at ANL, USA

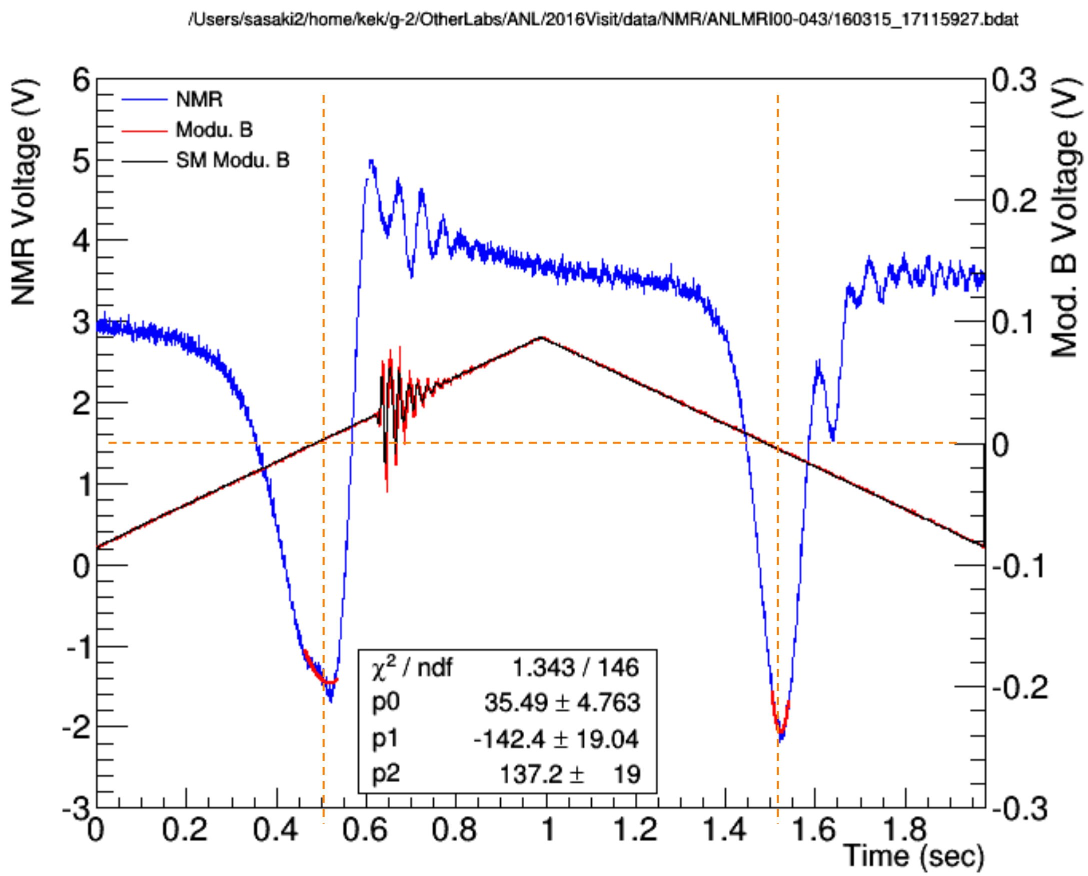
- Tested using MRI magnet in Argonne National Laboratory, USA
  - can be generated up to 4 T that is sufficient for J-PARC g-2/EDM
  - cross-calibration between our probe and pulse standard probe which is developed by US group for Fermilab g-2 experiment

✓ *Collaboration with ANL to improve the robustness of field measurement for Muon experiment through the cross-calibration test*


- Magnet (OR66)
  - Max Field : 4 T
  - LHe : 3300 L
  - Size : W2300mm, H2800mm, L2750mm
  - Single cryocooler
  - Bore size : I.D. 0.68 m

# Signal example

- Apply triangular wave modulation field




Peak position coincides with zero-crossing point of modulation field

- Signal processing scheme worked well

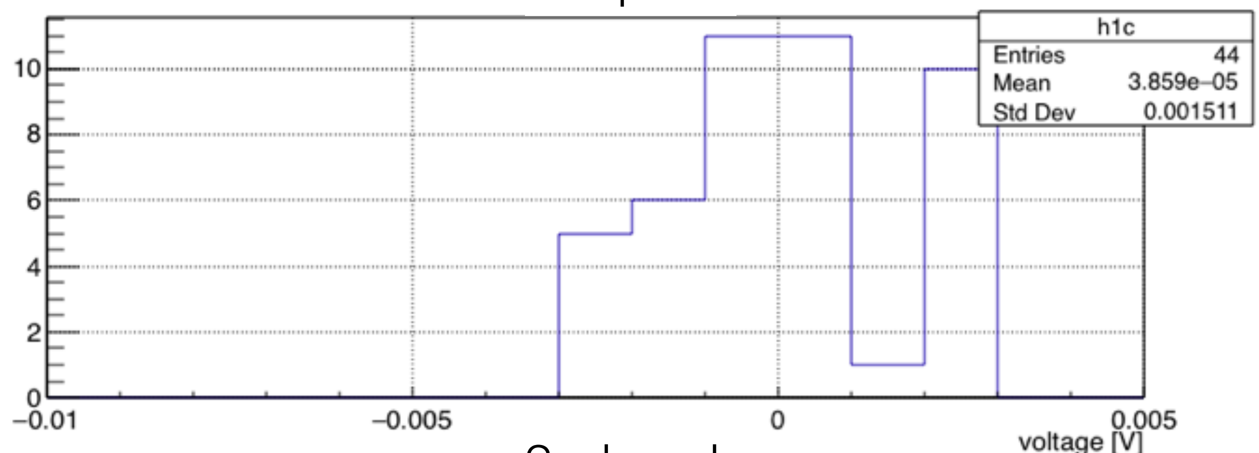
Shapes of NMR signals are different

# 1st peak and 2nd peak difference

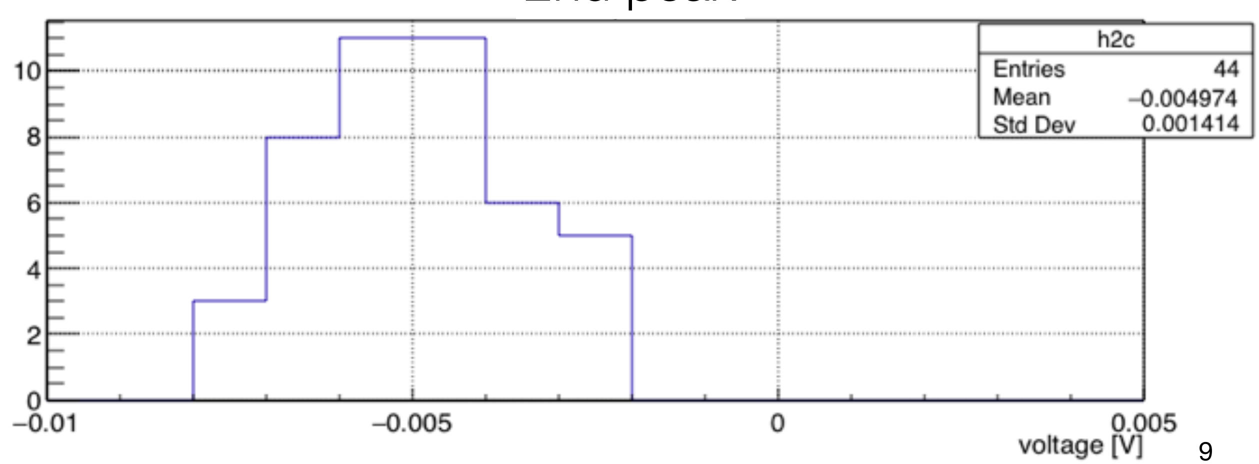
- 1st peak - 2nd peak is $(5.07 \pm 0.06) \times 10^{-3}$ V
- correspond to 1.57 ± 0.04 Hz = 25.5 ± 0.7 ppb

Previous test :
6.2 Hz ~ 100 ppb

1st peak




2nd peak



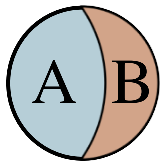
# Cause of Peak difference

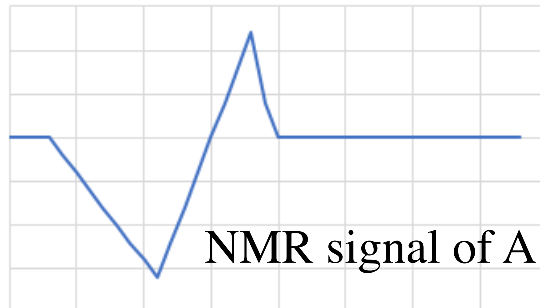
- Convolution of analog signals in non-uniform magnetic field

Ex.)

Field
A<B

Field distribution
in NMR sample

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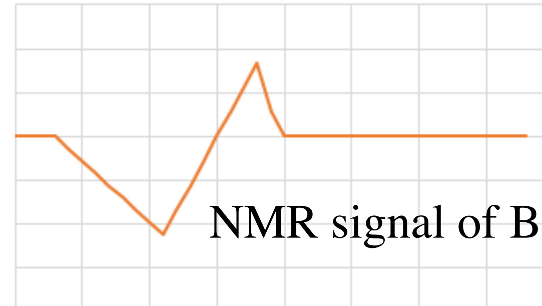
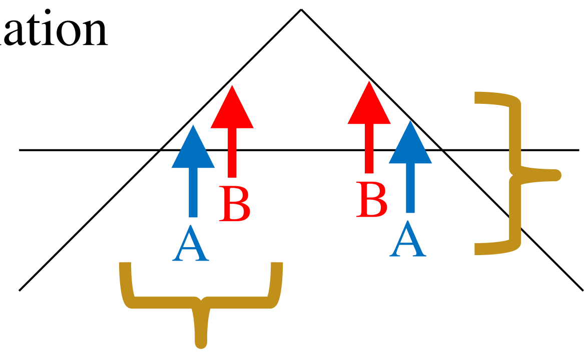
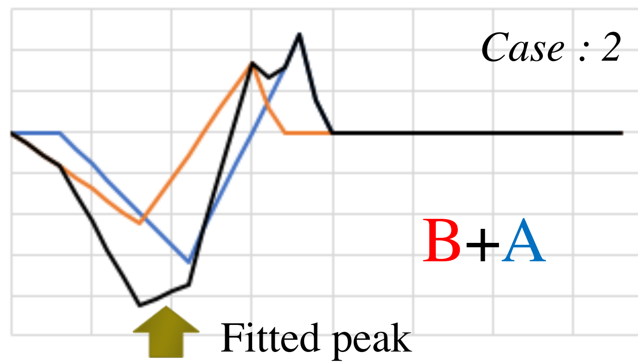
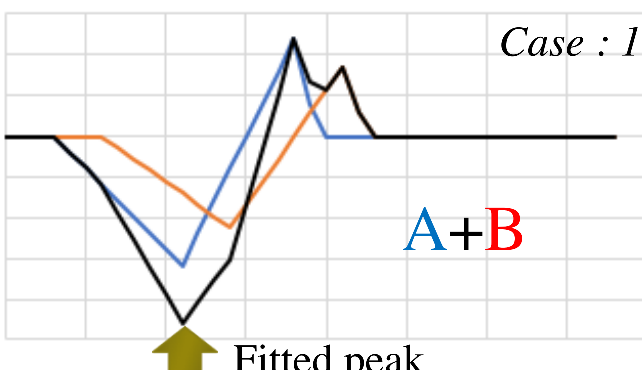



Modulation
Field



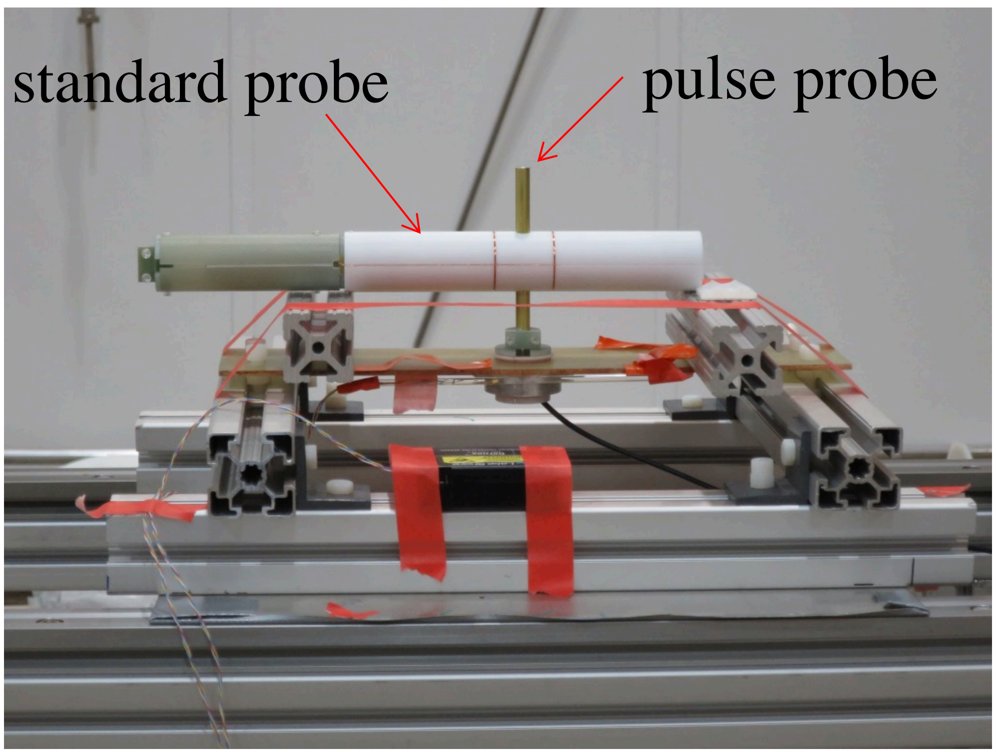




<u>Peak positions look different from each other</u>

Simple way to prove:
obtain the signal in homogeneous field

# Material effect

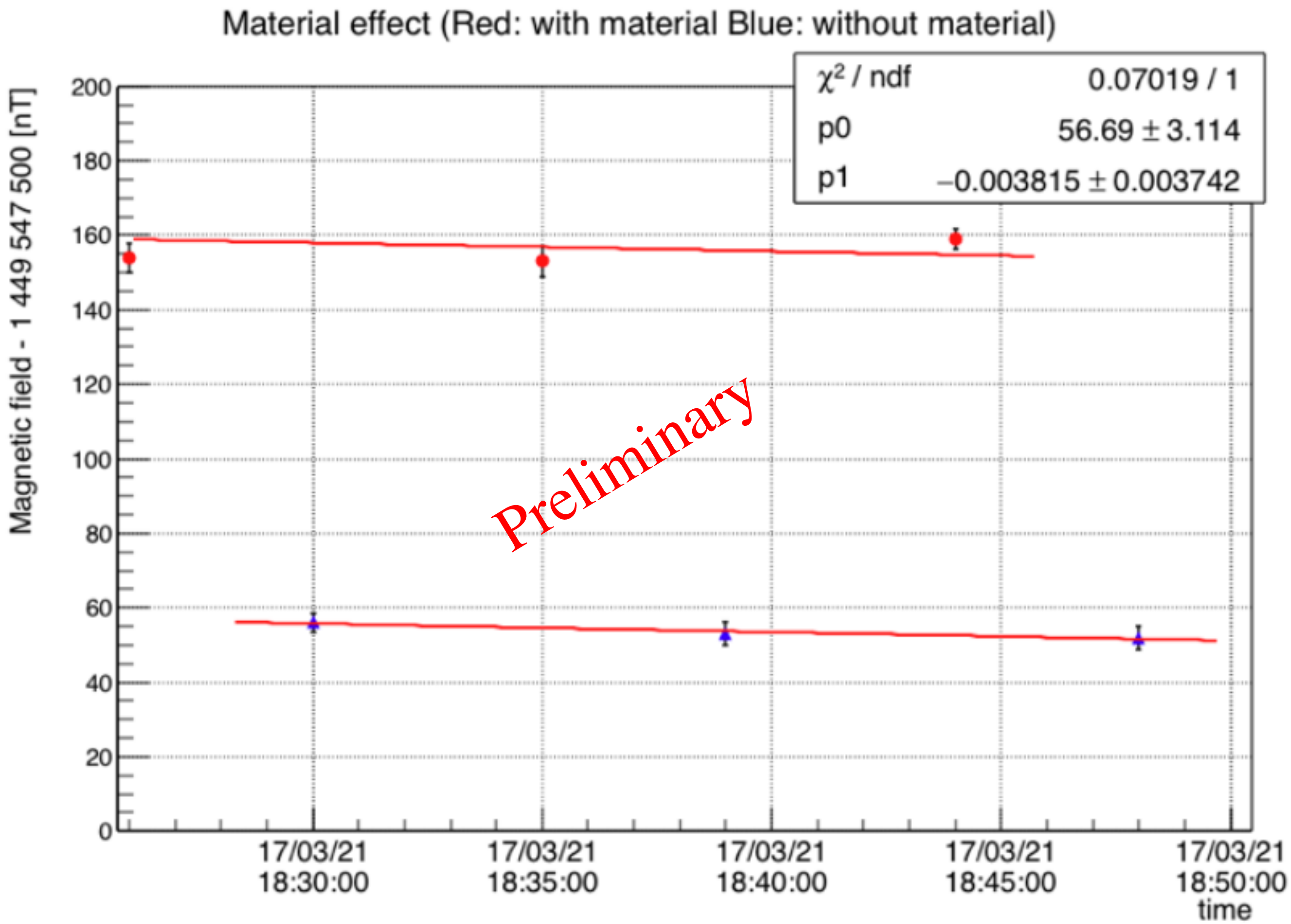
- Probe structure materials have magnetic susceptibility and these disturb the magnetic field
- Measured the field shift by pulse probe




Measure the magnetic field with and w/o probe

# Material effect

- Results: difference 102 +/- 4 nT = 71 +/- 3 ppb




by S. Seo

# Summary of material effect measurement

| | Shift (ppb) |
|---|---|
| All materials | +71±3 |
| | |
| Glass tube | +0.1±0.4 |
| Al pipe | +32±3 |
| Teflon pipe | -75±3 |
| Teflon & Al pipe | -14±1 |
| Circuit board | +96±0.4 |
| Pipe, Circuit & GFRP | +86±4 |
| Pipe, Circuit, RF coil & Cable | +72±14 |

* Biggest error : circuit board

- Effect of just RF coil cannot be measured
  - cannot prepare test setup due to time limitation
- Pipe
  - confirm the reduction of net permeability by the combination of Al and Teflon pipe
  - not exactly coincides with the total of each measured value
    - Position uncertainty of using probe ?

➢ Try to optimize volume ratio of materials in order to minimize the material effect

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  - Hall probe
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# Field measurement method ~ Hall sensor

- Hall
  - Utilize the Hall effect
  - 😄 Simple measurement
    - Apply current and measure voltage
  - 😄 Better accuracy
    - 100 ppm feasible
  - 😄 Small size
  - 😄 Vector components could be measured
  - 😞 Calibration is required
    - Calibrate Hall coefficient
    - Non-linear device
    - Planar Hall effect
      - In the magnetic field in parallel with sensor plane

$$V_H = R_H G I B \cos(\theta) + V_{Planar}$$

$R_H$: $Hall\ coefficient$

$G$: Geometry factor

$B$: magnetic field

$V_{\mathrm{Planar}}$ : Planar effect

$$V_{\mathrm{Planar}} \propto I B_{\parallel}^2 \sin(2\Psi)$$

$I$: $Current$

$B$: magnetic field

# Measurement using Hall probe

1. Homogeneity in the storage region
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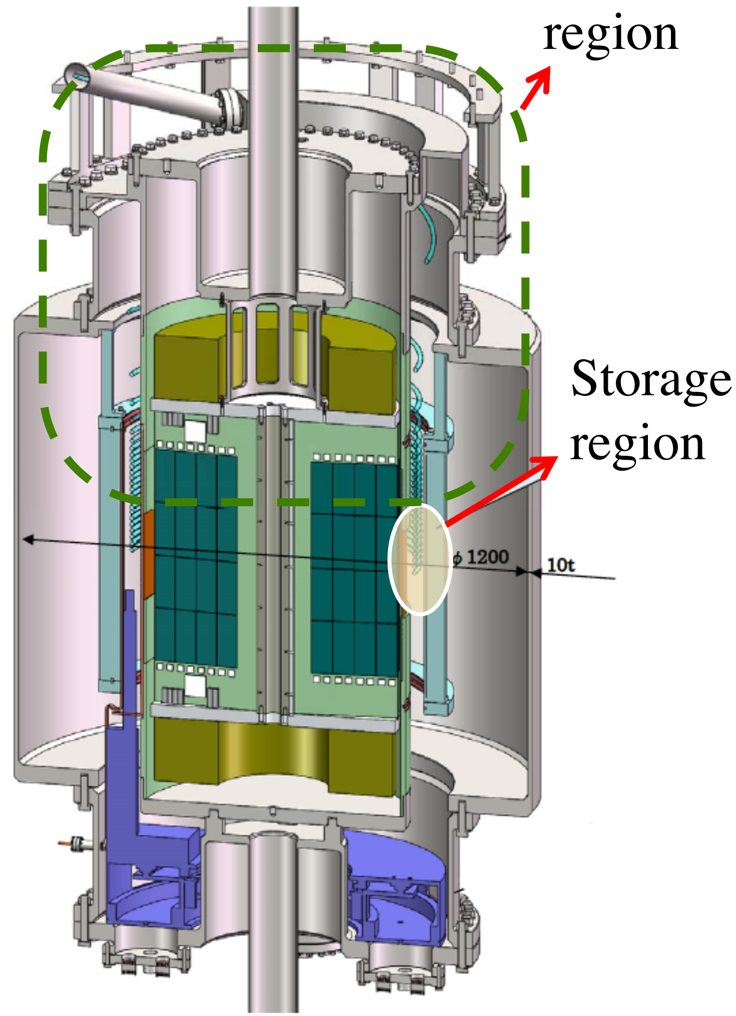
In MuSEUM : 1, 2, 5

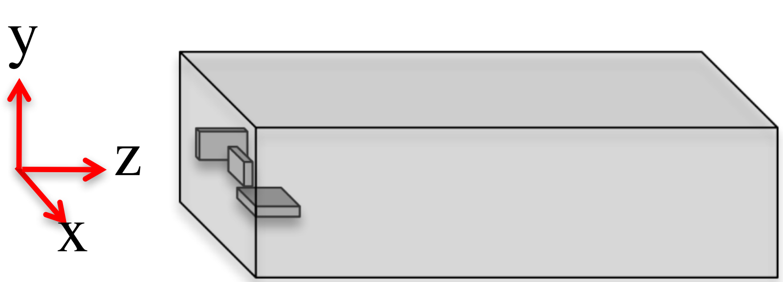


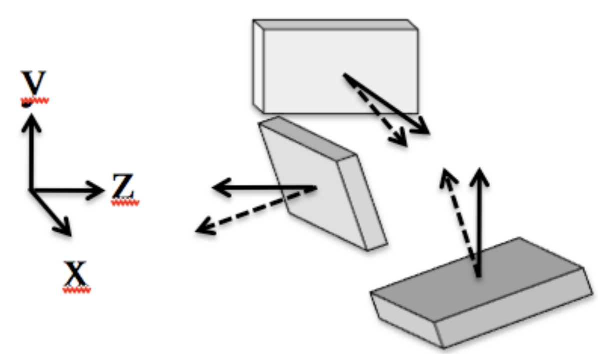

✓ 3-axis Hall probe system is being developed

# Hall Probe system

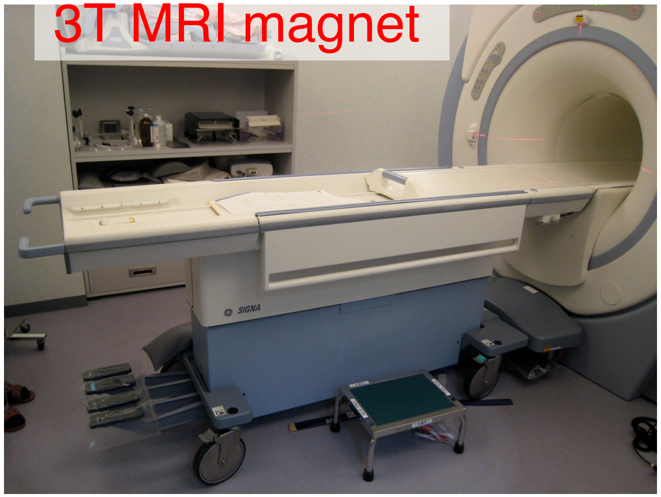
- Hall sensors are intended to be used for the field measurement of the beam injection region.
    - Sensitive to field direction

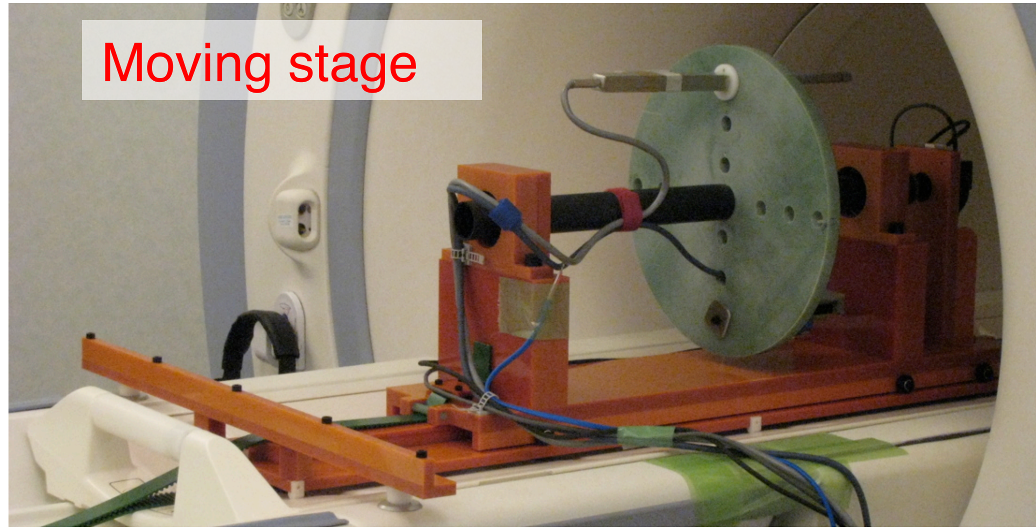
- Present issue
    - Misalignment of the sensors with respect to the x-y-z axis.
    - Apparent field caused by the tilt disturbs
      the precise field measurement with 3-axes Hall probe.

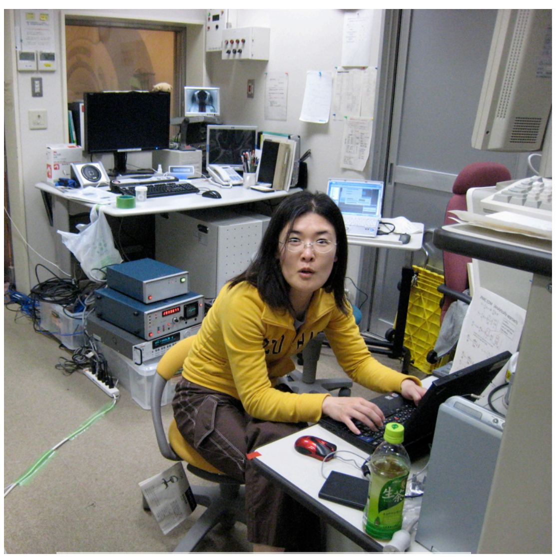


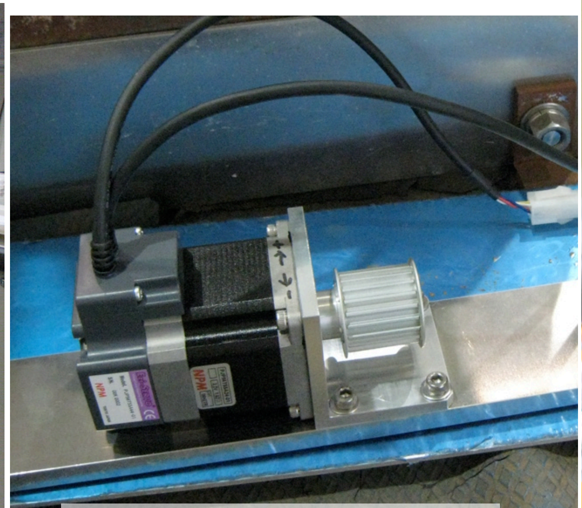
# Monitoring System Photos @ NIRS



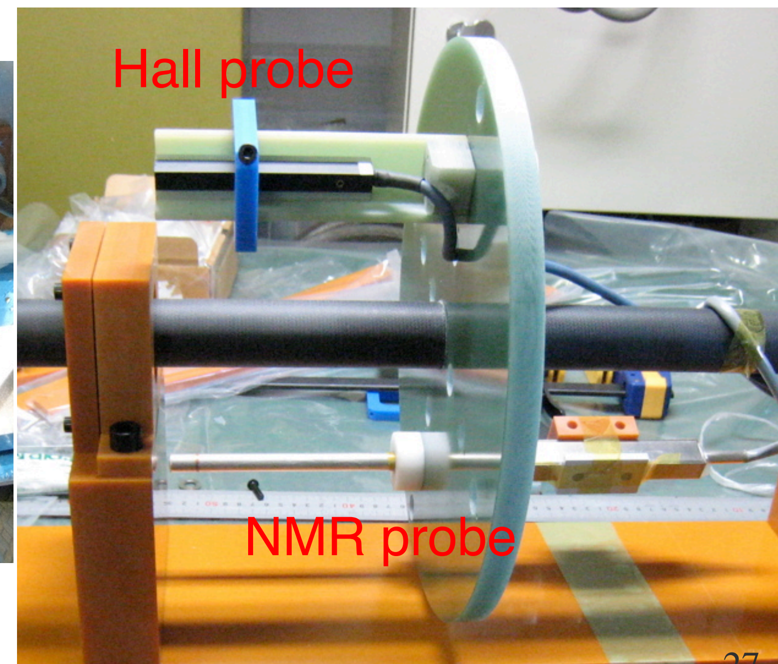



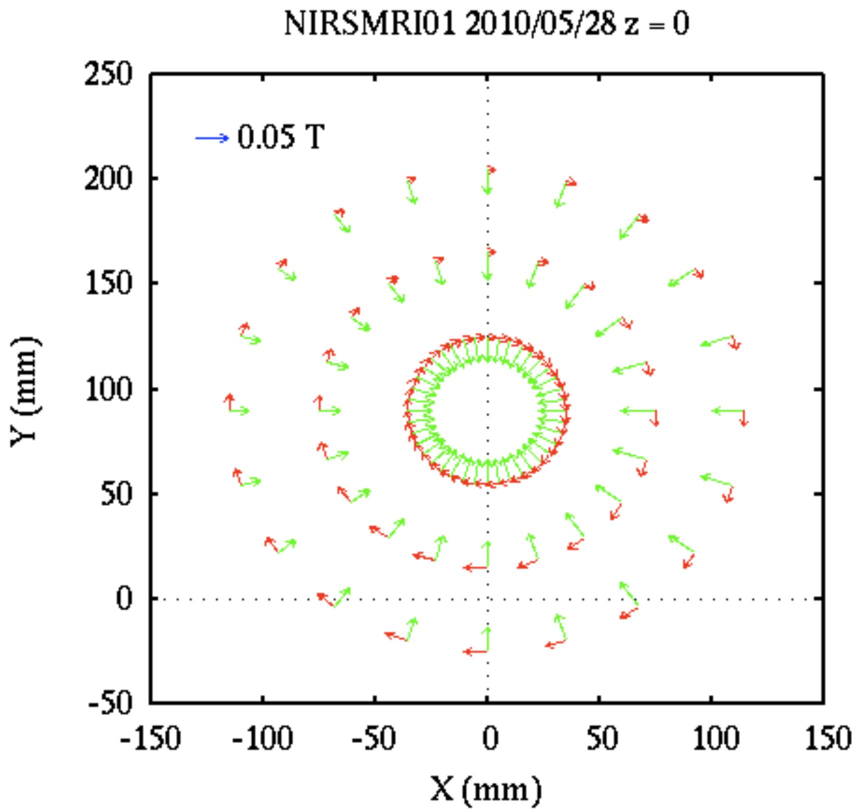
Control room

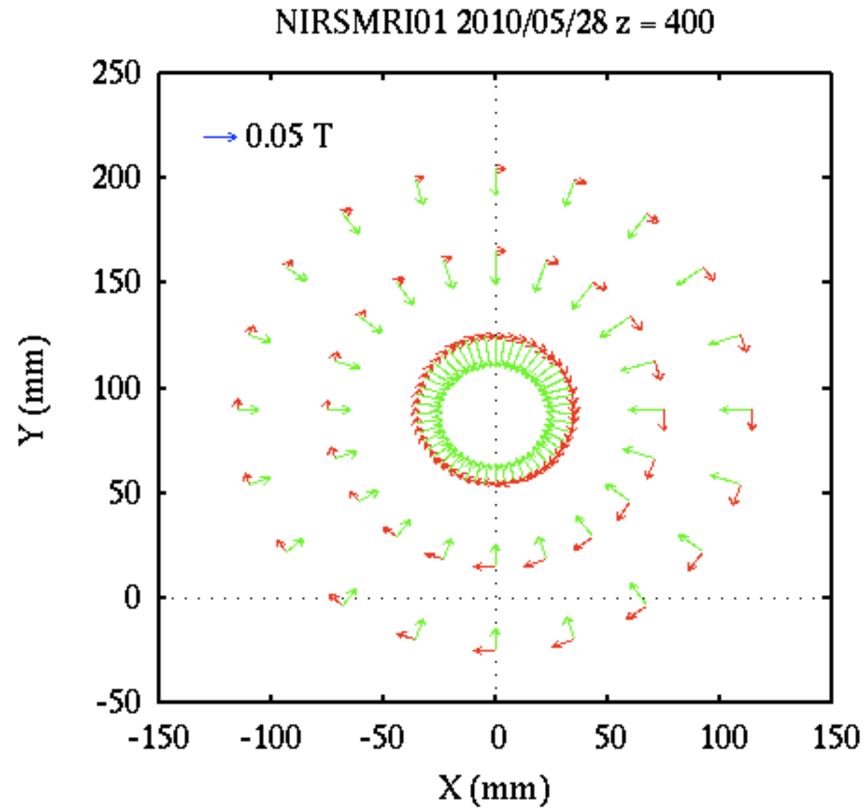


Stepping motor



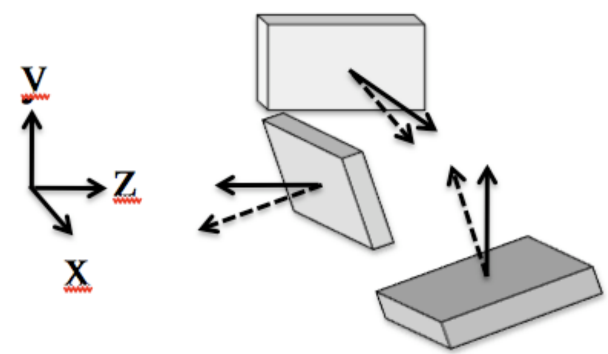
# Results ~ Hall probe (2)




- observe Br and Btheta components systematically.
  - 0.01 ~ 0.05 T

- Possible reason : sensor angles are tilted

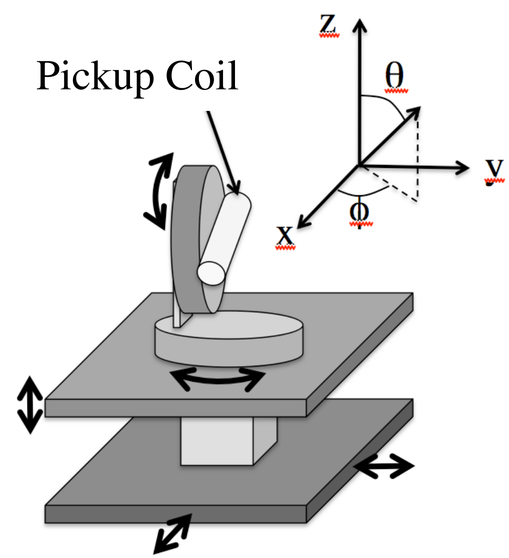


# Tilt Angle Measurement

- Considering to calibrate the tilt angle using 3-axis Helmholtz Coils
  - Uniformity : 1e-4 in 10 mm DSV.

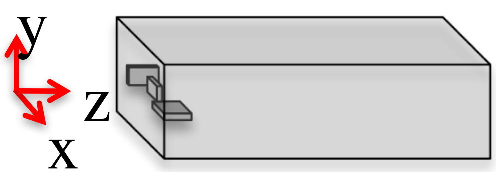
Axes of Coils are required to be set to the right angle precisely.

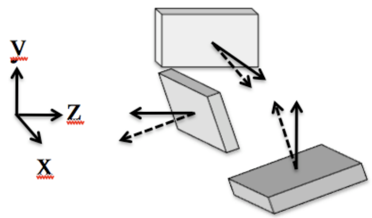
- 5 axes moving stage with pickup coil
  - calibrate the axes of the coils with the accuracy of 0.1 deg.
  - Pickup coil
    - shape and size can be arbitrarily selected
    - control of the measurement axis is easier than hall probe.



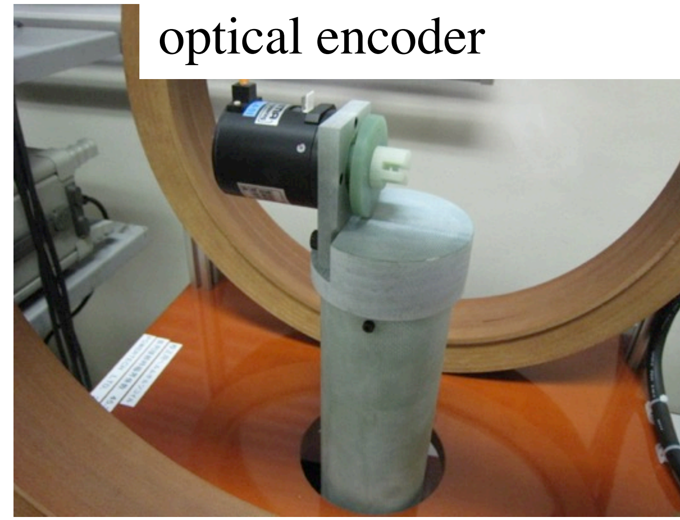
# R&D of 3D Hall probe

- Calibration system of the tilt angle of Hall sensors
  - 3-axis Helmholtz Coils
    - Uniformity : 1e-4 in 10 mm DSV
  - 5-axis moving stage with pickup coil

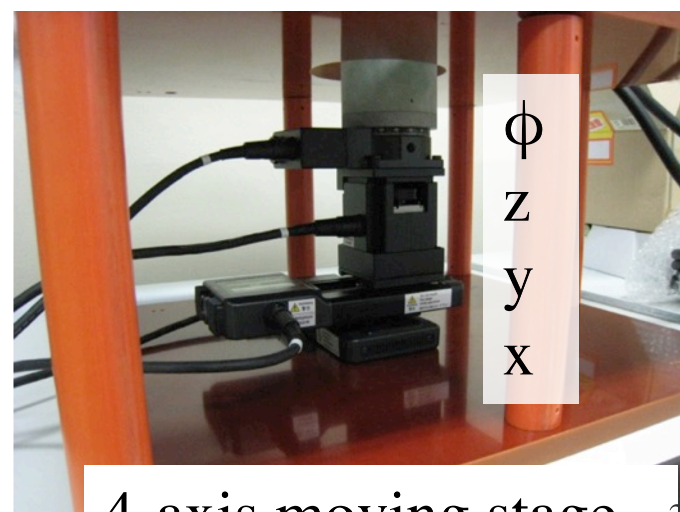



Ultra sonic motor with optical encoder



Helmholtz coil & moving stage



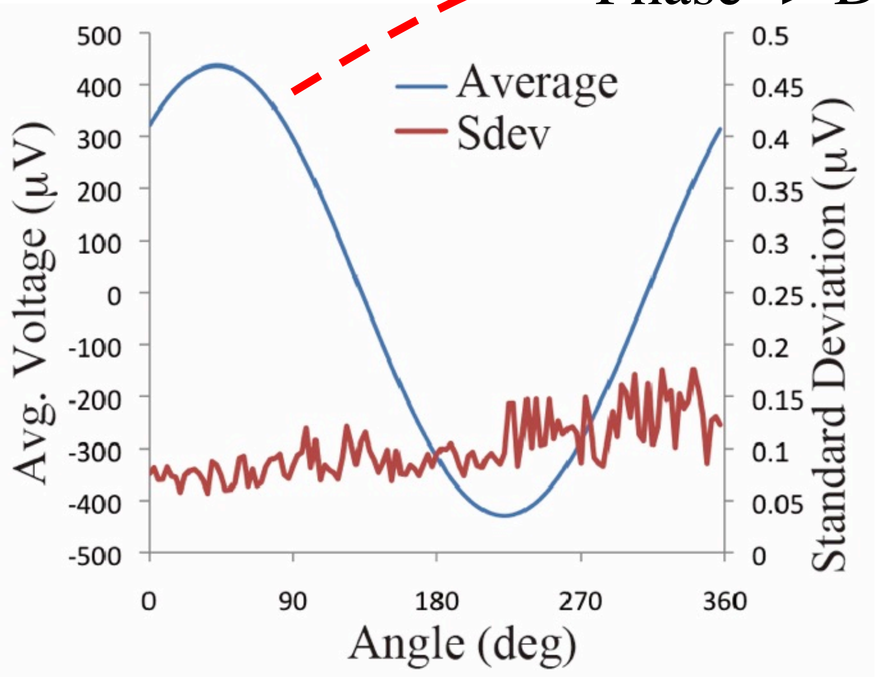

4-axis moving stage

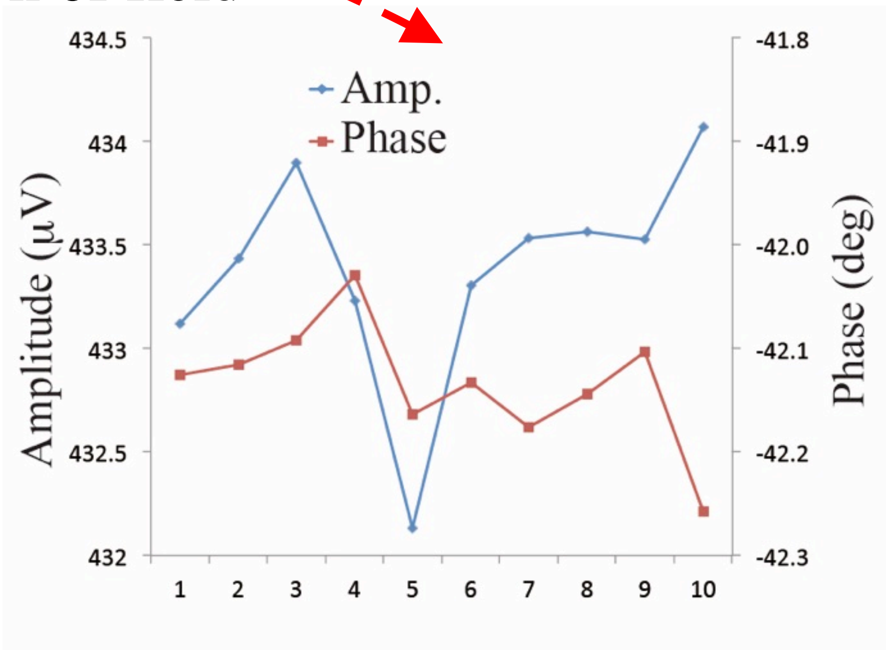
TDR

# Helmholtz coil test results

- Magnetic axis of Helmholtz coils want to be determined with an error of less than 0.01 deg.

Phase -> Direction of field




- 10 times measurement
  - Average : -42.134 degree
  - Standard deviation : 0.0597 deg.

# Summary

- Development of field monitoring system
  - NMR probe
    - Standard probe
      - Modify signal processing scheme
      - Try to minimize material effect -> some reduction could be confirmed
  - Hall probe
    - Preliminary tested 3-axis Hall probe
    - Misalignment of hall sensors in the probe
      - Make 3-axis Helmholtz coil system to calibrate the tilt angle of sensors
      - Measure the angle of coil axis.

# To do list for building practical system

- Only little part of development is now on going

- NMR probe
  - Development of standard probe
  - Finalize the cross-calibration with pulse standard probe
  - Design and built
    - Practical system of field homogeneity measurement with moving stage
    - Practical system of time variation of magnetic field
- Hall probe
  - Calibration of sensor
  - Design and build the practical system

# Near future work

- Magnet in J-PARC will be energized to 1.7 T in the beginning of this Oct.
- Make next generation of standard probe
  - Design work is on going (will be talked by Yamaguchi)
  - will test new probe
    - check the material effect and keep modifying


- KEK Magnet (OR64)
  - Max Field : 2.9 T
  - LHe : 1200 L
  - Size: W2150mm, H2700mm, L2010mm
  - Single cryocooler
  - Bore size : I.D. 0.65 m

# Task table ~ g-2/EDM and MuSEUM

All : KEK (supervise)

| g-2/EDM | MuSEUM |
|---|---|
| Field map in injection region; HS | |
| Field map of Bz in storage region; NMR | Field map of Bz in storage region; NMR UTokyo |
| Field map of Br in storage region; HS | |
| Fixed probe; NMR | Fixed probe; NMR |
| Absolute probe; NMR | Absolute probe; NMR |

KEK (US)