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Development of fine shimming technique with magnetorheological fluid

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Introduction

Two physics experiments using Muon are proceeded in J-PARC

❖ g-2/EDM experiment

- Measure the following values with high precision
  - ◎Anomalous magnetic moment of positive muon (g-2) : < 0.1 ppm
  - ◎Electric dipole moment of positive muon (EDM) : 1e-21 e.cm

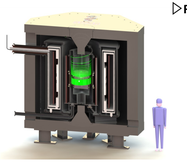


Fig. 1 : Superconducting solenoid magnet for g-2/EDM

▷**Requirements for Magnet**

- Storage region
  - Field strength : 3 T
  - Homogeneity: <±0.1 ppm
  - Size :
    - Radius: 33.3 cm ± 1.5 cm
    - Height: ±5 cm
- Injection region
  - $B_r \times B_z > 0$
- Weak Focus field
  - $B_r = -n\frac{B_{0z}}{R}z$ n: 5×10^{-5} - 2×10^{-4}

❖ MuSEUM experiment

- Measure the following values with high precision
  - ◎ground state hyperfine structure interval of Muonium : < 3 ppb
  - ◎ratio of muon and proton magnetic moment : < 10 ppb

Fig. 2: MRI magnet for MuSEUM

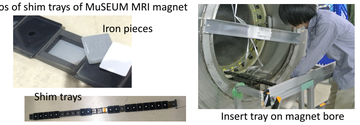
▷**Requirements for Magnet**

- Storage region
  - Field strength : 1.7 T
  - Homogeneity: <±0.1 ppm
  - Size :
    - Spheroidal volume
    - Height : 30 cm
    - Radius: 10 cm

▷ Homogeneity : very important

- How to shim magnetic field ?
  - Iron pieces (shims) put on the inner surface of magnet bore
    - Shimming scheme
      - Measure field distribution in target region
      - Calculate shim arrangement to cancel error field
      - Put iron shims in pockets of shim trays, and insert trays.

Fig. 3: Photos of shim trays of MuSEUM MRI magnet



- Iron has large magnetization
  → ~1000 ppm error could be shimmed in general

✓ NOT suitable for precise shimming : < 1 ppm
due to discrete size of pieces and large magnetization

Ex) MuSEUM Magnet

- Present homogeneity : 0.45 ppm_{pp}
  shimmed with 0.06 cc iron piece

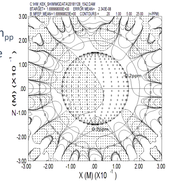


Fig. 4: Homogeneity in x-z plane interpolated from measured data on surface of 50 cm DSV.

- Simulation study
  - Attainable homogeneity with different size iron shims

Minimum unit size of iron shim	Attainable homogeneity
0.06 cc	0.39 ppm_{pp}
0.02 cc	0.27 ppm_{pp}
0.012 cc	0.27 ppm_{pp}
0.0006 cc	0.27 ppm_{pp}

due to discrete size of pieces

✓ Limitation of magnet performance

- to get maximum homogeneity, size of iron shim has to be smaller than 0.02 cc

- In principle, much smaller size of iron piece is required to reach ultimate homogeneity, but…
  - Difficult to handle and fix on shim trays; -> if it's too small, misalignment might be occurred frequently
  - Optimum size depends on magnet and magnetic condition; -> difficult to expect optimum size beforehand

◆ Ferrofluid material
Liquid having magnetism
✓ easy to get arbitrary volume
✓ much smaller magnetization than Fe

One possible candidate for fine shimming

☆R&D of shimming system with ferrofluid materials

- ❑ Feasibility study on fine shimming with ferrofluid
- ❑ Develop and test prototype shimming system
- ❑ Develop Field mapping system

will report
- basic study of ferrofluid
- development status of field mapping CW-NMR probe

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Basic study on ferrofluid

❖ **Suitable material for fine shimming**
- Moderate magnetic susceptibility compared with iron
- Easy controllability of magnetization, that is, volume

Measure magnetization of commercial ferrofluid for feasibility study of ferrofluid

- Measurement setup

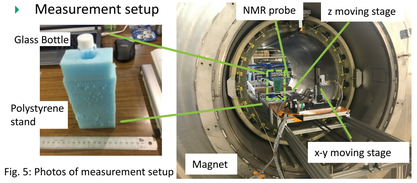


Fig. 5: Photos of measurement setup

- Schematic view of setup

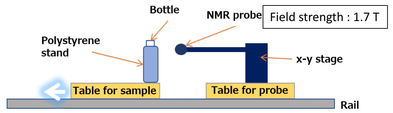


Fig. 6: Schematic side view of measurement setup

- Ferrofluid : DS-50
  - Iron oxide, Isostearic acid and Isoparaffin
  - Relative density : 1.36-1.40
  - Saturated magnetization : 45 –55 mT
- Bottle
  - Body : Borosilicate glass
  - Cap : Polypropylene
  - Size : ϕ25 mm, 50 mm height

- Scan in x-y plane to search the position where the effect of sample is maximized.
- Probe is fixed, and sample is moved in z direction by moving stage
- Measure magnetic field with and without samples
- Calculate magnetic moment from measured distribution

- How to calculate magnetic moment

*Assume point Magnetic moment
Magnetic flux density created by magnetic moment

$$\boldsymbol{B} = -\frac{\mu_0}{4\pi}\nabla\frac{\boldsymbol{m}\cdot\boldsymbol{r}}{r^3} \quad (1)$$

$$\boldsymbol{B} = -10^{-7}\times\nabla\frac{\boldsymbol{m}\cdot\boldsymbol{r}}{r^3} \quad (2)\ \boldsymbol{m} = (0,0,m_z)$$

$$\boldsymbol{B} = -10^{-7}\times\frac{m_z}{r^3}(-3xz,-3yz,r^2-3z^2) \quad (3)$$

$$B_z = 2\times10^{-7}\times\frac{m_z}{z^3} \quad (4)\ x=y=0, r=z$$

Fitting function

$$B_z = \frac{P_0}{(z-P_1)^3}+P_2 \quad (5)$$

$$P_0 = 2\times10^{-7}\times m_z \quad (6)$$

B_z: Magnetic field P_1: Error of position
m_z: Magnetic moment P_2: Error of magnetic field
z: Position

※m_z of Fe: 1.711 Am^2

- Measurement results
  - (1) One empty bottle : 5 times
    - Check the measurement error
  - (2) 5 empty bottles : 1 time each
    - Check individual differences between bottles
  - (3) 5 bottles with Ferrofluid of 1 cc
    - Check the consistency of ferrofluid volumes
  - (4) Ferrofluid 1,2,3 cc
    - Check the controllability of ferrofluid volume

3ml, 2ml, 1ml, 0ml, 0ml

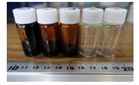
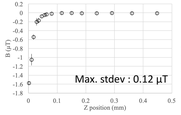


Fig. 7: Empty bottles and bottles filled with ferrofluid

(1) One empty bottle : 5 times



Symbol : Average of 5 meas.
Error bar : Standard dev. of 5 meas.

- m_z : -7.649e-5 ± 3.314e-6 (Am^2)
- P_1 : -1.309e-2 ± 3.162e-4 (m)
- P_2 : -3.264e-9 ± 7.715e-10 (T)

Fig. 8: Magnetic field shift due to empty bottle; z represents distance from bottle center.

(2) 5 empty bottles

Bottles	M_z (Am^2)	P_1 (m)	P_2 (T)
#1	-7.598e-5	-1.186e-2	-2.721e-9
#2	-7.549e-5	-1.213e-2	-3.715e-9
#3	-9.369e-5	-1.419e-2	3.467e-9
#4	-6.811e-5	-1.061e-2	-8.768e-9
#5	-9.067e-5	-1.385e-2	8.129e-9
Avg.	-8.079e-5	-1.253e-2	-7.217e-10
St. dev.	1.091e-5	1.483e-3	5.587e-9

- Bottle variation : ~ 13 % of average
  - Sufficiently smaller than ferrofluid
    - > can be neglected

✓ Next step : increase number of data to decrease statistical uncertainty

(3) 5 bottles with Ferrofluid of 1 cc

Bottles	M_z (Am^2)	P_1 (m)	P_2 (T)
#1	3.593e-2	-1.136e-2	-2.358e-8
#2	4.039e-2	-2.249e-2	-2.882e-8
#3	4.164e-2	-2.371e-2	-3.666e-8
#4	4.096e-2	-2.211e-2	-3.528e-8
#5	4.100e-2	-2.180e-2	-3.979e-8
Avg. (#2-#5)	3.998e-2 (4.100e-2)	-2.029e-2 (-2.253e-2)	-3.283e-8 (-3.514e-8)
St. dev. (#2-#5)	2.311e-3 (5.131e-4)	5.044e-3 (8.350e-4)	6.533e-9 (4.616e-9)

- m_z of 1cc ferrofluid : ~1/40 of iron of 1 cc
  - Almost agree with specification
- #1 : large difference from others
  - #1 : filled by syringe, #2-#5 : filled by spoon
  - Density might be different

✓ Next step : check reproducibility considering density control

(4) Ferrofluid 1, 2, 3 cc

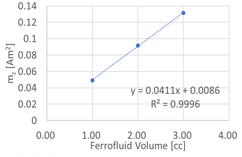


Fig. 9: Measured magnetic moment of different volume of ferrofluid

- m_z : almost linear relative to volume
  - Magnetization can be controlled by volume
- y-intercept should be zero
  - Caused by different density?

R&D of field mapping CW-NMR probe

❖ **Need precision field mapping system for fine shimming**
- NMR magnetometer is only solution for precise measurement
- Need quick measurement to neglect time variation of B.

Developing high precision multi channels CW-NMR field mapping system for MuSEUM experiment

- CW-NMR with frequency modulation
  - Sweep RF frequency to detect NMR signal
  - Need to place electronics board including RF detection circuit close to RF coil for high SNR
- Field mapping probe for MuSEUM
  - Spheroidal volume : 30 cm in length, 10 cm in radius
  - NMR probes are aligned on half of ellipse arc and they are rotated around the long axis so that the field map could be quickly obtained.

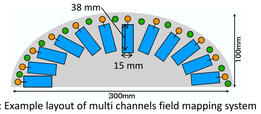


Fig. 10: Example layout of multi channels field mapping system for MuSEUM experiment with 24 probes. 12 electronics boards are implemented on this side, and others are implemented on the backside.

✓ Need a smaller board for multi channel system
➢ *Develop smaller probe including the wave detector and pre-amplifier.*

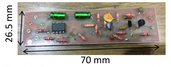


Fig. 11: Board for single probe which is commercially available by Japanese company.

◆ Replace Through Hall (TH) type components with Surface Mount (SM) type components, which have smaller magnetization
◆ Make trial board and production prototype to evaluate performance of SM tips and re-designed circuit.

Fig. 11: Trial board to evaluate SM tips performance.

Fig. 12: Production prototype board for evaluating the performance of re-designed circuit and magnetization.

- Trial board test
  - Resistors and capacitors were replaced with non-magnetic tips commercially available.
  - There are no same models of SM tips for several transistors
    - Test different types of SM alternatives considering magnetization
      1ss86 -> 1ss154; 2SK19 -> 2SK208-R; 2sc1907 -> DSC2G03;

Ex) 2sc1907 : two candidates were tested

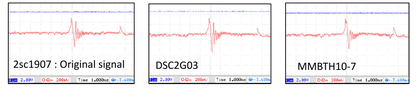


Fig. 13: NMR signals with different transistors.

- Both candidates show almost the performance as original tip.
- MMBTH10-7 has largeer magnetization than DSC2G03
  -> Choose DSC2G03

- Production prototype board
  - SM chips are selected based on trial board
  - Use 4 layers printed circuit board
- Preliminary results
  - Clear resonance peak by vector network analyzer
  - **Obtain NMR peak signal at 1.7 T**
  - Magnetization of the circuit is about 21 % of commercial one. (-17.1 ppb -> -3.76 ppb)

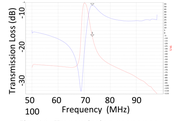


Fig. 14: Transmission response.

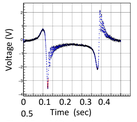


Fig. 15: NMR signal using new board.

Summary

✓ Studying shimming system with ferrofluid materials

Basic study of ferrofluid

- measure magnetic moment of glass bottles and bottles filled with ferrofluid
  - m_z was sufficiently smaller than ferrofluid so that it could be neglected in fine shimming
  - m_z of ferrofluid DS-50 was about 1/40 of iron, that is consistent with specification.
  - m_z of bottle filled with ferrofluid could be changed at will by controlling the volume of ferrofluid.

Development of high precision multi channel field mapping system

- made production prototype of electronics board
  - TH type components were replaced with SM type components with smaller magnetization
  - Could obtain NMR peak signal at 1.7 T

✓ Next step
- Increase number of data to decrease statistical uncertainty
- Check reproducibility considering density control
- Check time variation of magnetization
- Test different ferrofluid samples to determine optimum one for fine shimming
- Design and Build support system for fine shimming with ferrofluid
- Test production prototype board and measure its magnetization in detail
  - Study the performance when several channels are connected in parallel
- Make and test multi channel system

Try shimming operation with MRI magnet for MuSEUM