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RACE TO ENERGY EFFICIENCY

Optimization of an AC/DC High-T_c SQUID Magnetometer Detection Unit for Evaluation of Magnetic Nanoparticles in Solution

Mohd Mawardi Saari, Yuichi Ishihara, Yuya Tsukamoto, Toki Kusaka, Koji Morita, Kenji Sakai, Toshihiko Kiwa, Keiji Tsukada

Graduate School of Natural Science and Technology,Okayama University

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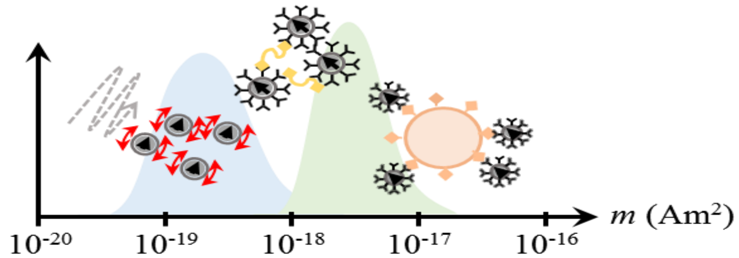
Introduction

- Magnetic nanoparticles (MNPs) : *nm*-order particles with magnetic cores



Magnetic Particle Imaging | Magnetic immunoassay | Magnetic hyperthermia applications etc.

- High frequency response of harmonics
- Narrow distribution of particle size etc.

The performance of MNPs in each applications is influenced by fundamental characteristics ❯ Evaluation of **magnetic properties** by magnetic susceptibility method

Conventional low-T_c SQUID magnetometer

Pro
- High sensitivity (low-T_c SQUID)

Con
- **High-running cost** (multi-sample measurement)

Alternative to a highly sensitive magnetometer for evaluation of MNPs

Introduction

We developed a magnetometer using high-T_c SQUID

- ✓ Compact and highly sensitive
- ✓ Low-running cost
- ✓ Measurement of MNPs in solution
- ✓ AC and DC magnetization measurement functions

M. M. Saari et al., *J. Phys. Conf. Ser.*, vol. 507, no. 4, p. 042035, May 2014.

Outline

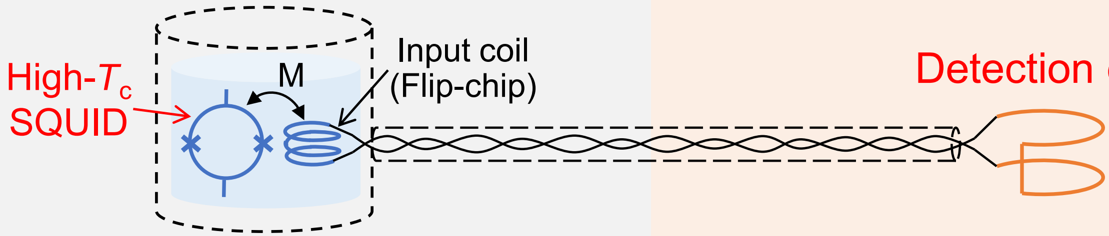
I. AC/DC high-T_c SQUID magnetometer

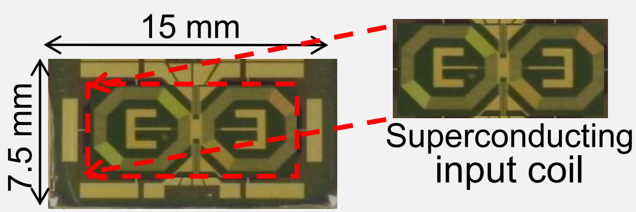
II. Optimizations of AC/DC detection unit
   1. Excitation field
   2. AC/DC detection coil

III. Measurement of low concentrated iron oxide nanoparticles solutions

Detection Method

- High-T_c SQUID with flux-transformer





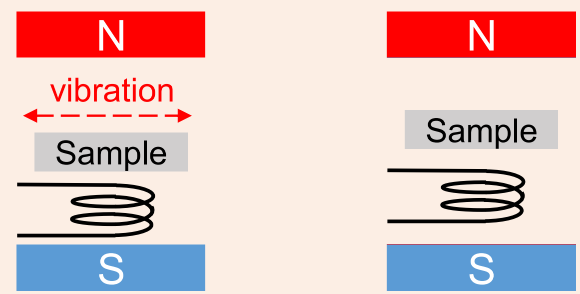
SQUID substrate

Input coil :	59 turns
Mutual inductance :	1.88 nH
SQUID inductance :	40 pH
Josephson Junction :	Ramp-edge

- Developed by SRL-ISTEC Japan
  (Superconductivity Research Laboratory-International Superconductivity Technology Center)

- 1st order differential Cu coil
  (Reduction of the environmental noise)

DC measurement | AC measurement



Measurement System

Measurement method

Excitation of magnetic field

⇩

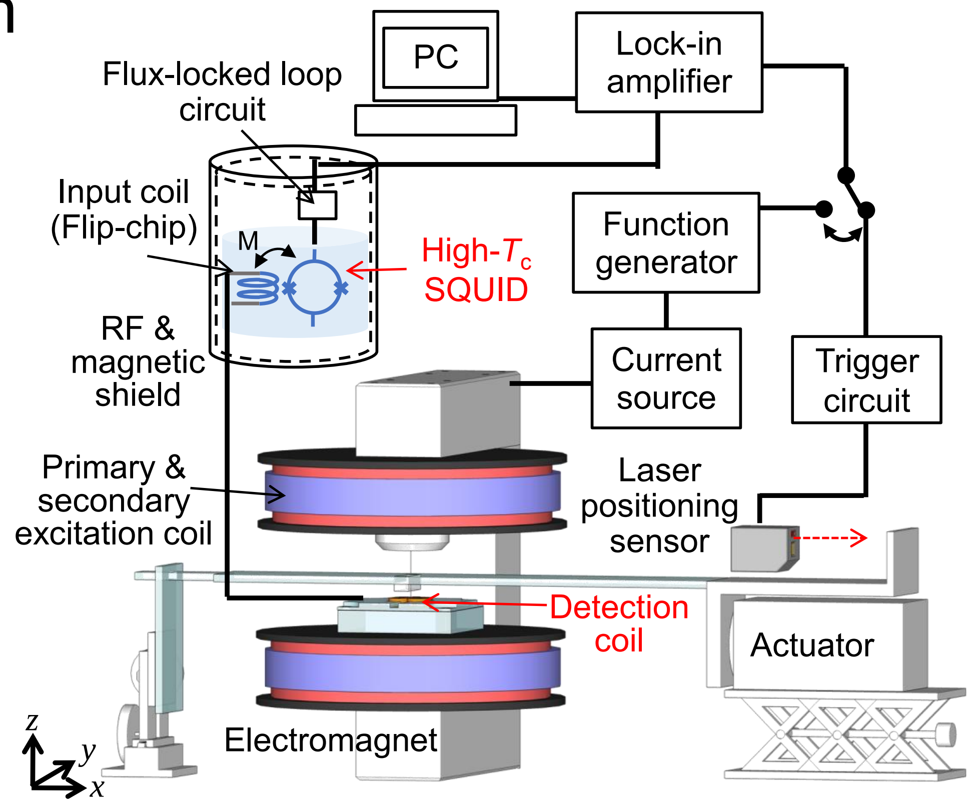
Sensing of magnetization by detection coil at RT

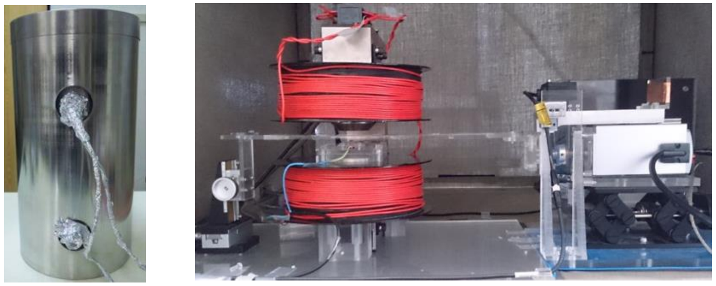
⇩

SQUID

⇩

Lock-in amplifier





Magnetic shield　　Detection unit

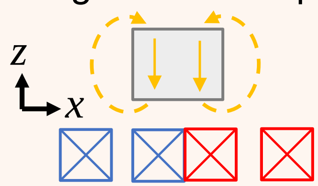
Optimization of DC Detection Coil

Optimization of gradient characteristic

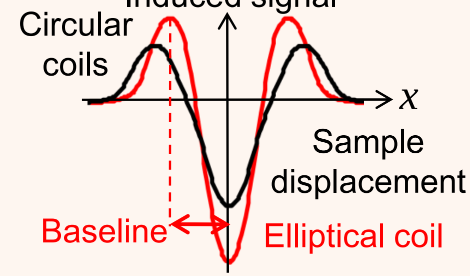
- Increase of flux-change rate

We fabricated and compared 2 types of coils with a similar magnetic noise characteristic.

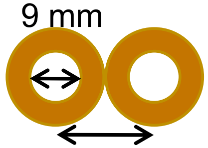
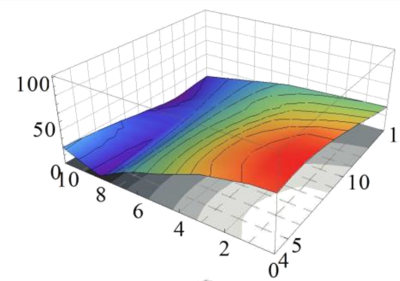
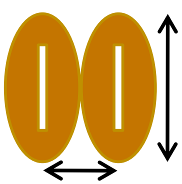
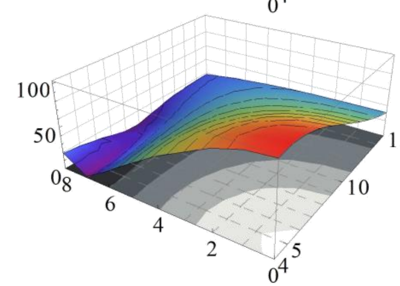
Magnetized sample

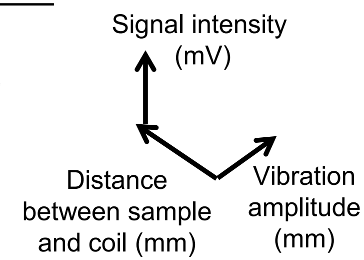


1st order planar differential coil



Gradient characteristic

Detection coil	One coil parameters	Fundamental component
 Circular Coils	No. of turns : 200 turns Int. diam. : 9 mm Ext. diam. : 17 mm Length : 5 mm Wire diam. : 0.3 mm Resistance : 2.08 Ω Inductance : 446.2 μH	
 Elliptical Coils	No. of turns : 200 turns Ext. major axis : 26 mm Ext. minor axis : 13.5 mm Length : 4 mm Wire diam. : 0.3 mm Resistance : 2.99 Ω Inductance : 451.6 μH	



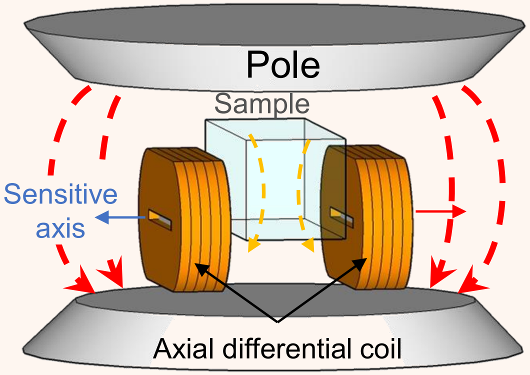
Signal intensity was improved in the **elliptical coils**

Optimization of AC Detection Coil

Reduction of AC magnetic field interference

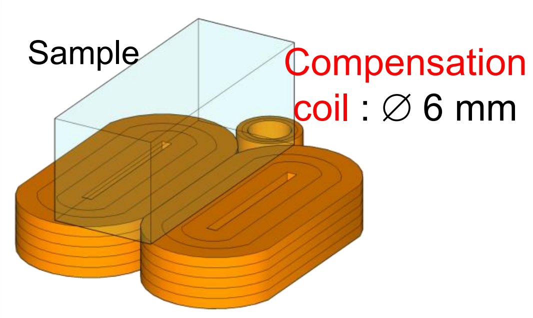
- Previous system: sensitive axis of **axial type differential coil** was placed perpendicular to the excitation field.
- Substantial reduction in interference was difficult.
  (Gradient of magnetic field, slight differences in alignment and characteristics of each coils)

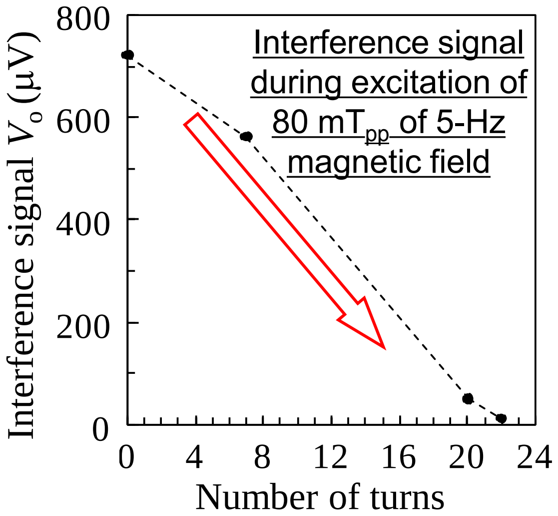
We proposed **a compensation coil technique**.



Improvement of usable dynamic range: Planar differential coil in series with a compensation coil

- Optimization of number of turns of the compensation coil

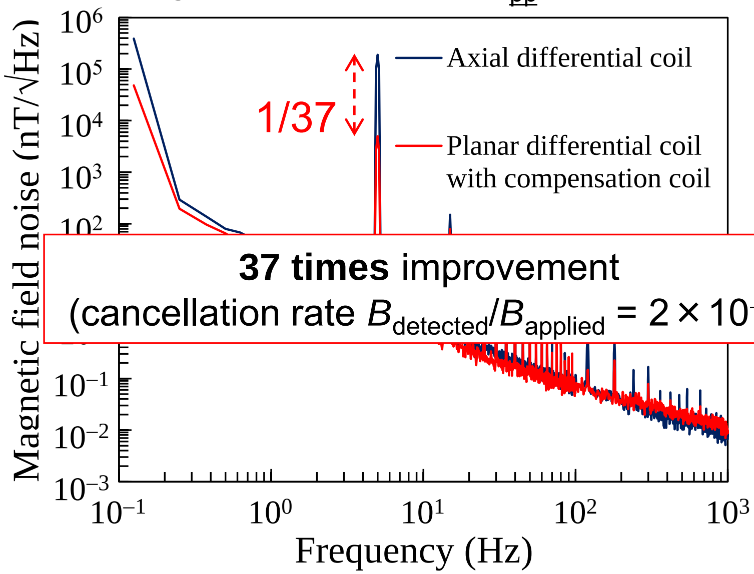




The interference of magnetic field was reduced effectively

Characteristics of Detection Coil

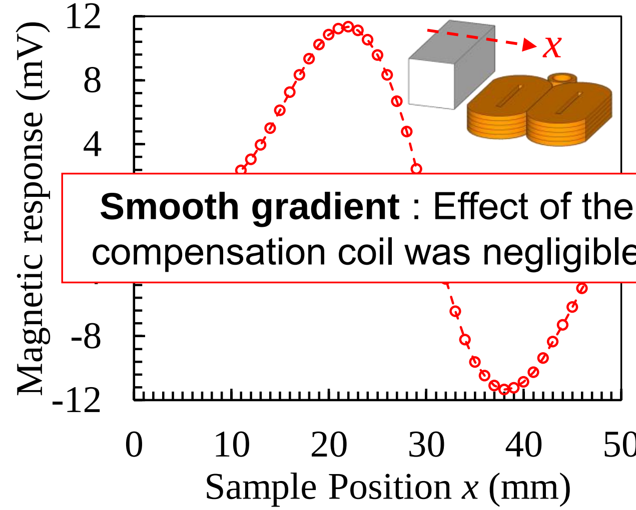
Magnetic noise during excitation magnetic field of 30 mT_{pp} and 5 Hz



37 times improvement
(cancellation rate $B_{detected}/B_{applied} = 2 \times 10^{-4}$)

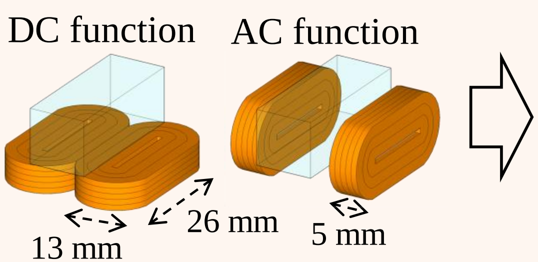
Line measurement across baseline

Sample : 15 mm × 20 mm × 10 mm MnF_2
B_{ext} : 10 mT_{pp}, 5 Hz

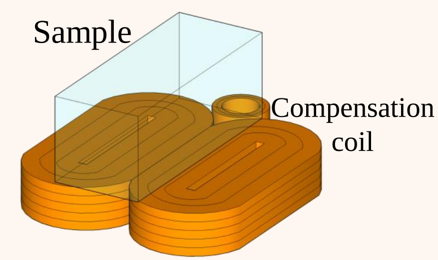


Smooth gradient : Effect of the compensation coil was negligible

Optimized detection coil



AC and DC functions

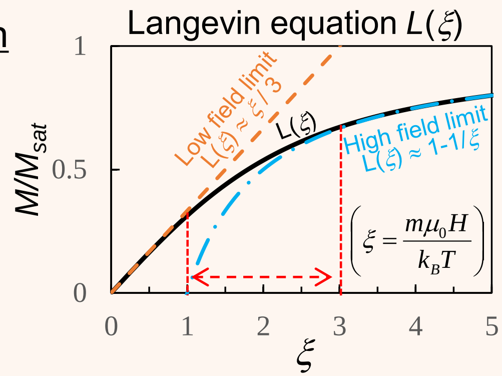


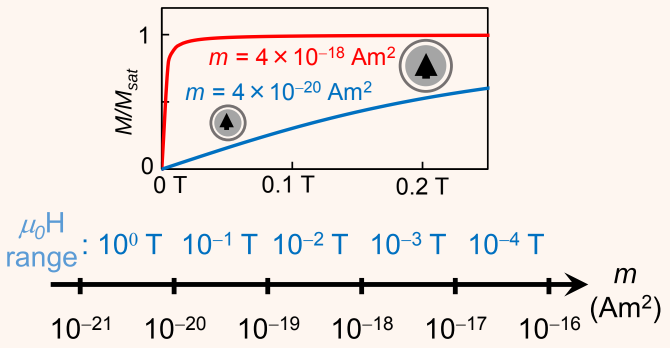
- Improved dynamic range and sensitivity
- One SQUID for both functions

Excitation Magnetic Field

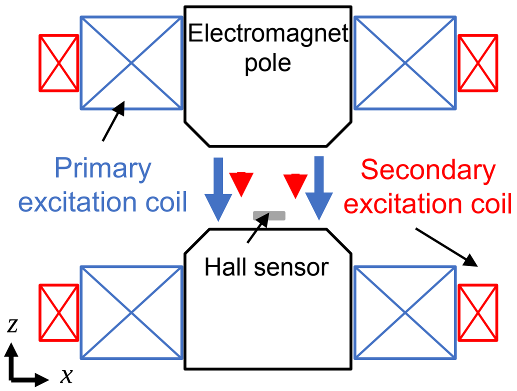
Sampling of magnetization

Appropriate sampling is important as most of the information on distribution are contained within a certain region.

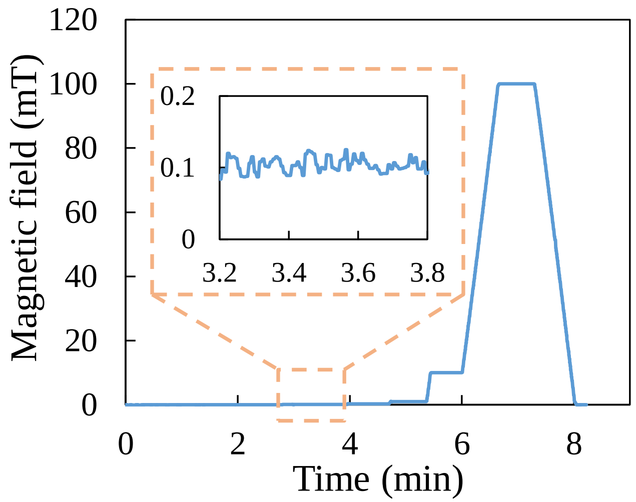




- Improvement of magnetic field resolution by secondary excitation coil



Sweeping of magnetic field with respect to time



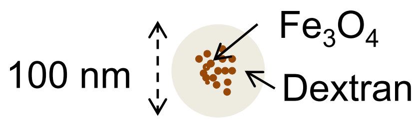
Magnetic field

DC excitation field : ≤ |500 mT |

Field resolution : 40 μT

Evaluation of Iron Oxide Nanoparticles Solutions

nanomag®-D-spio



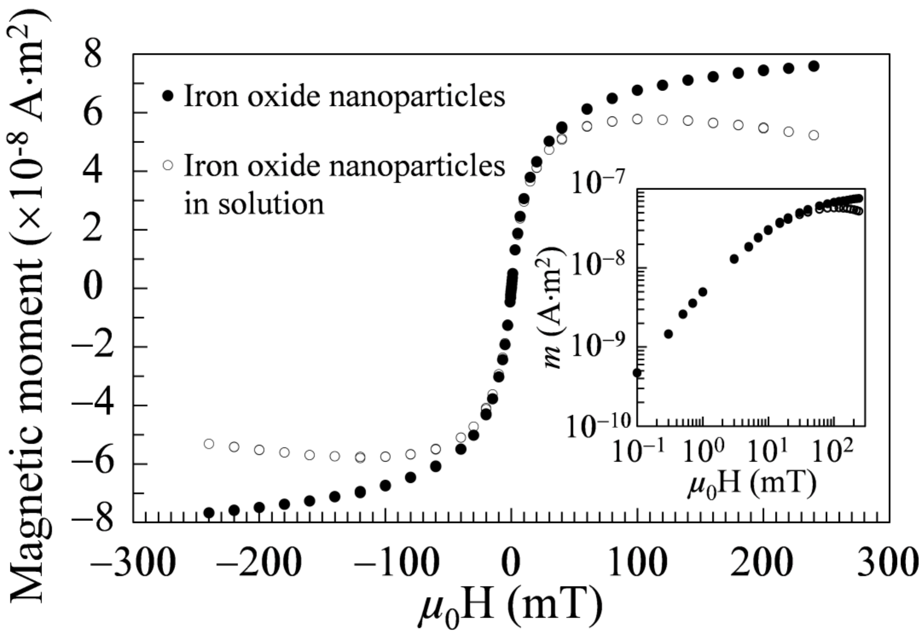
- Stock solution was further diluted in purified water
- Encased in 15 mm × 20 mm × 10 mm of acrylic cases

Low-concentrated solutions

Iron oxide concentration :

- 72 μg/mL (dilution factor : 33)

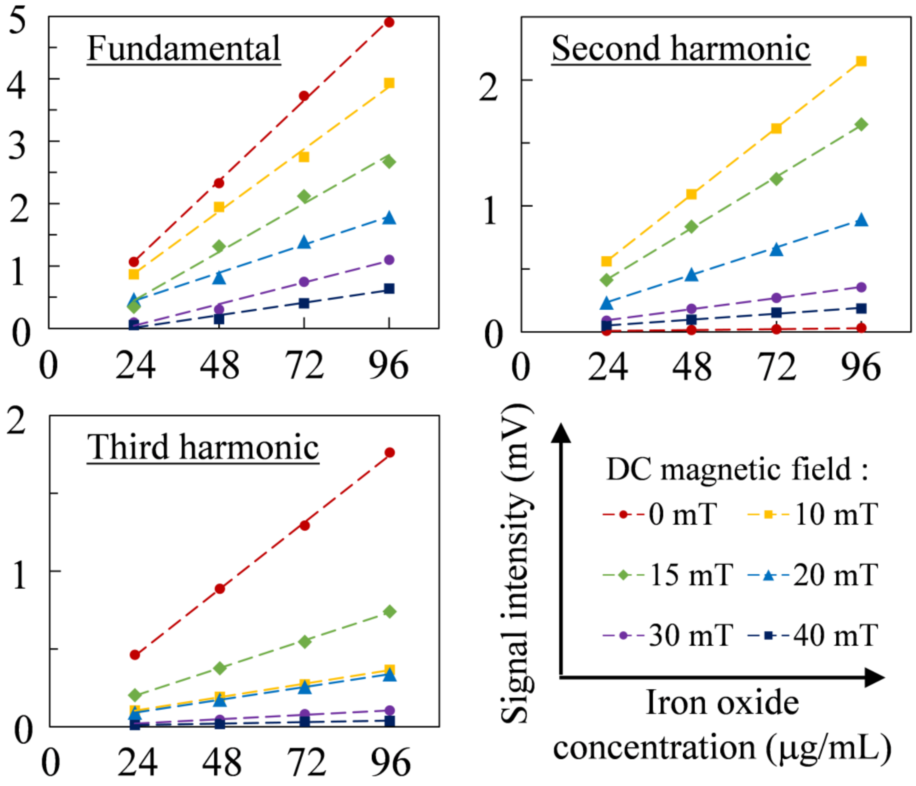
Magnetization curve of iron oxide nanoparticles solution before and after subtraction of measured diamagnetic contribution of water.



- Diamagnetism of water deformed the magnetization curve of low concentration iron oxide solution

Measurement of Harmonics

Harmonics intensity at different DC magnetic fields



AC magnetic field : 30 mT_{pp}, 5 Hz

- Harmonics were correlated with the concentrations.
- Proper bias of DC magnetic field improved the detection sensitivity.

Summary

- ✓ We developed an integrated AC/DC magnetometer using high-T_c SQUID.
- ✓ Improvements in sensitivity and usable dynamic range were achieved by optimized detection unit.
- ✓ Highly sensitive evaluation of low-concentrated iron oxide nanoparticles in solution was shown by the developed system.

Acknowledgement
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