Magnetometry

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Materials from Eun Sang Choi – Leads Magnetization Program
Keep in mind…

Every measurement perturbs the system, the question is how much…

Every measurement measures something, the question is what…
B, H and M

SI: \[ B = \mu H = \mu_0 (H+M) = \mu_0 (1+\chi)H \]
CGS: \[ B = H + 4\pi M \]

B = Magnetic flux density, Magnetic induction \(\rightarrow\) Susceptometer
H = Magnetic field strength from external source \( (\nabla \times H = J_f + \partial D/\partial t) \)
M = (Volume) Magnetization from sample \(\rightarrow\) Magnetometer

<table>
<thead>
<tr>
<th></th>
<th>cgs</th>
<th>SI</th>
<th>conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>G</td>
<td>T, Wb/m²</td>
<td>1 G = 10⁻⁴ T</td>
</tr>
<tr>
<td>H</td>
<td>Oe</td>
<td>A/m</td>
<td>1 Oe = 10³/4\pi A /m</td>
</tr>
<tr>
<td>M</td>
<td>emu/cm³</td>
<td>A/m</td>
<td>1 emu/cm³ =10³ A/m</td>
</tr>
<tr>
<td>m Magnetic moment</td>
<td>emu/cm</td>
<td>A/m³</td>
<td>1 emu = 10³ A/m²</td>
</tr>
</tbody>
</table>

For \( H \gg M \)
\( B(T) \approx \mu_0 H (T) \) with conversion \( 1 \text{ T} = 10^4 \text{ Oe} \)

M is a vector! How does this affect the measurement!
Method 1: Induction / flux techniques

Gauss’ Law

\[ \Phi = \oiint \hat{B} \cdot \hat{a} \]

Faraday’s Law

\[ V = -\frac{d\Phi}{dt} \]
SQUIDs

Josephson effect device (superconducting weak link)

Flux quantum: $\Phi_0 = 2.068 \times 10^{-15}$ Wb
Quantum Design SQUID Magnetometer (MPMS)

Extremely Sensitive!
Calibrated
Limited to low fields
Vibrating Sample Magnetometer (VSM)

- Absolute magnetic moment can be measured
- Driving mechanism: motor, pneumatic, piezo-actuator
- Feedback and phase-sensitive detection
  - capacitative detection
  - eddy current sensor
  - servomotor

$V_{rms} \sim mA_\omega$

$V_{rms}$: VSM signal
$m$: moment
$A$: amplitude
$\omega$: frequency

First generation VSM design
NHMFL High Field VSM  B \leq 35 \, T, \, T \geq 0.6 \, K

EG&G (Lakeshore) VSM system
Vibrating freq. \sim 82 \, Hz
Amplitude \sim 0.1 \, mm
10^{-3} \sim 10^{-5} \, emu sensitivity
Pick-up coil designed for better stability\textsuperscript{16}

- sample tube (filled with exchange gas)
- heaters
- Pick-up coils
  46 AWG, 3000 turns
- BeCu

He3 can
- driving head
- x-y adjustment
- z adjustment
- sample rod
- High field cryostat
- cryostat positioner
- isolator
- magnet

\textbf{EMU vs. Height (mm)}
NHMFL High Pressure VSM, B ≤ 9 T, T ≥ 1.4 K

High Pressure Self-Locking Pressure Clamp

- Material: High Purity (Co-free) BeCu
- Sample size: ~ 1 mm³
- Sample mass: < 10⁻² gm
- Clamp mass: ~ 13 gm

Symmetrical design made of high purity BeCu¹⁷
\textbf{AC Susceptibility}

**Induction method**
- change of flux is given by oscillating magnetic field
- oscillating magnetic field by AC current in a solenoid
\[ H_{ac} = \mu n I_{ac} \sim H_0 \cos(\omega t) \]

**Measures** $\frac{dM}{dH}$
for small $H_0$, $M(H) = M(H_{dc} + H_{ac}) \sim M(H_{dc}) + \frac{dM}{dH} \cdot H_0 \cos(\omega t)$
\[ \Rightarrow \text{signal} = -\frac{d\Phi}{dt} \sim \left(\frac{dM}{dH}\right) \omega H_0 \sin(\omega t) \]

**Time dependent, dynamic magnetic susceptibility** (0.1 $\sim$ 100 kHz, 10 $\sim$ 10 $\mu$s)
- $\chi_{ac}$: complex susceptibility ($\chi' - i \chi''$)
  - $\chi'$: in-phase to $H_{ac}$, similar response to $\chi_{dc}$ at low frequency ($1/f \gg$ relaxation time)
  - $\chi''$: out-of-phase, dissipative process
- sensitive to relaxation time: spin glass below $T_f$, superparamagnetism below $T_b$, domain wall movement in FM
**AC Susceptibility**

\[ I_{ac}(t) = I_0 \cos \omega t \]  
ac current for primary coil

\[ V_B(t) = (M_1 - M_2) \frac{dI_{ac}}{dt} = -(M_1 - M_2) I_0 \omega \sin \omega t \]  
Background voltage (without sample)

\[ V_1(t) = V_B(t) + V_{s1}(t) \]  
Sample in coil 1

\[ V_2(t) = V_B(t) - V_{s2}(t) \]  
Sample in coil 2

\[ V_{s1}(t) = -N_1 S_1 f \chi_{ac} \frac{dh_{ac}(t)}{dt} \]

- \( N \): # of turns
- \( S \): cross section area
- \( f \): filling factor
- \( h_{ac} \): oscillating external field
- \( \chi_{ac} \): complex susceptibility (\( \chi' - i \chi'' \))
- \( \chi' \): in-phase signal
- \( \chi'' \): out of phase signal

\[ V_{1, \text{rms}} - V_{2, \text{rms}} = V_{s1, \text{rms}} + V_{s1, \text{rms}} = \{(N_1 S_1 + N_2 S_2) f \sigma\} h_0 \chi_{ac} \]

\[ C_\chi = \frac{1}{(N_1 S_1 + N_2 S_2) f \sigma} \]  
calibration factor (sensitivity)
**AC Susceptibility**

**Balancing (compensation) techniques**\(^{18,19}\)

1. Matched counter-wound coils $\rightarrow$ minimize $V_B$
2. Sample translation between two pick-up coils
3. Subtraction of an ac waveform equal to that of empty pick-up coil
   i) balance (minimize $V_B$) using external compensator without sample
   ii) use differential amplifier for sample and balance signal

**Calibration**

- Paramagnetic standard (Al, Pt, Pd, Tutton’s salt)
- Ferromagnets
- Superconducting materials

**Other issues**

- Skin depth for metallic samples (use smaller freq.)
- Eddy current effect (heating, phase shift)

\[ \delta = \left( \frac{\rho}{\pi f \mu} \right)^{1/2} \]

\[ I_{\text{eddy}} \sim \frac{1}{\rho} \frac{d\Phi}{dt} \]
AC Susceptibility

Application
- Phase transitions (FM, AFM)
- Spin glass, superparamagnetism, domain in FM (frequency dependence)
- Superconductors (transition, irreversibility)
- de Haas van Alphen oscillation (increased sensitivity with modulation coil)
- Can be used at extreme conditions: low T, high pressure, high (low) field

Ferromagnetic transition with different AC field strength

Frequency dependence of Spin glass system

FIG. 5. Zero-field susceptibility $\chi'$ as a function of temperature for sample IIc (Cu-0.94 at.% Mn, powder). Measuring frequencies: $\square$, 1.33 kHz; $\triangle$, 234 Hz; $\times$, 10.4 Hz; and $\Delta$, 2.6 Hz.
AC Susceptibility

CePtPb antiferromagnet

AFM

Antiferromagnetic transition under pressure

AC susceptibility with DAC

Secondary coils (1000/428 turns)
Primary coil (600 turns)
Gasket bore containing sample, ruby chip, pressure fluid (He)

SC transition measured by AC susceptometer with DAC
**NHMFL High Field Susceptometer**

**Instrumentation**
- Sample position controlled by stepper motor
- AC current calibrator (e.g. Valhalla 2500) used for constant amp/phase ac current
- Lock-in technique for phase sensitive detection
- Ratio transformer for balancing\(^{27}\)
- Field modulation technique\(^ {28}\) with modulation coil (1.81 mT/A) can be used for dHvA

**Diagram:**
- **Primary coil**: 34 AWG copper, 1000 turns
- **Secondary coils**: 50 AWG copper, 2700 turns each
Method 2: Torque / force techniques

\[ U = -\vec{m} \cdot \vec{B} \quad \vec{\tau} = \vec{m} \times \vec{B} \quad \vec{F} = \nabla(\vec{m} \cdot \vec{B}) \]
Torque Magnetometer

\[ \tau = m \times B \]

\[ \vec{F} = \nabla (m \cdot \vec{B}) \]

\[ F \sim 0 \text{ for homogenous field (sample at field center)} \]

Torque \( \sim d \) (deflection of beam)

- metal film cantilever \( \rightarrow \) capacitance \((10^{-3} \sim 10^{-8} \text{ emu})\)
- piezoresistive cantilever \( \rightarrow \) resistance \((10^{-9} \sim 10^{-11} \text{ emu})\)
Torque Magnetometer

\[ \mathbf{B} = B \hat{z} \]

single crystal sample placed in field center

When expressed in coordination of crystal axes with cubic symmetry

\[ \mathbf{B} = B \sin \theta \hat{a} + B \cos \theta \hat{c} \]
\[ \mathbf{m} = \chi_\parallel B \sin \theta \hat{a} + \chi_\perp B \cos \theta \hat{c} \]

\[ \mathbf{\tau} = \mathbf{M} \times \mathbf{B} \sim \mathbf{m} \times \mathbf{B} = B^2 (\chi_\parallel \sin \theta \hat{a} + \chi_\perp \cos \theta \hat{c}) \times (\sin \theta \hat{a} + \cos \theta \hat{c}) \]
\[ = B^2 (\chi_\parallel \sin \theta \cos \theta (\mathbf{b}) + \chi_\perp \cos \theta \sin \theta (\mathbf{b})) \]
\[ = B^2 (\chi_\perp - \chi_\parallel) \sin \theta \cos \theta (\mathbf{b}) \]

(1) \( \tau = 0 \) if \( \chi_\parallel = \chi_\perp \) (isotropic magnetization)
   or if \( \theta = 0 \) or 90, parallel to in-plane or inter-plane.

(2) \( \tau > 0 \) if \( \chi_\parallel < \chi_\perp \)

(3) \( \tau < 0 \) if \( \chi_\parallel > \chi_\perp \)

cf) Shape effect: torque for isotropic non-spherical sample \((\tau \sim \chi^2 H)^8\)
(1) Metal film cantilever

\[ z(L) = \frac{W L^3}{3EI}; \]

Deflection of a beam

Dynamic range vs. sensitivity
- cantilever design (thickness, length, ..)
- sample placement on the cantilever
  - choose optimal angle for sensitivity or dynamic range

Material (hard, non-magnetic): MP35N, Beryllium Copper alloy, Phosphor Bronze

Consideration of torsion (twisting)

Metallic sample as cantilever
Torque Magnetometer

Instrumentation
- Capacitance measurement
- Eddy current effect
- Background due to gravitational force
- Mechanical noise (vibration isolation)

Induced diamagnetic moment due to eddy current: depend on ramp rate, field direction

for sweeping up field

Analog: GR 1615 Bridge
- Use external oscillator and lock-in amp
- Fast data acquisition
- Conversion required

Wein bridge

Digital: AH Bridge
- 0 ~ 15 V, 50 – 20 kHz
- Automatic balancing

Coax cable with proper grounding required
Torque Magnetometer

(2) Piezoresistive cantilever

Figure 1. Torque magnetometry of [Ni(tmdt)$_2$]. (a) Microcrystal on AFM cantilever, (b) An example of raw torque magnetometer signals versus the applied magnetic field at 1.44 K. $\theta$ is the angle between the $-a^*$ direction and external magnetic field.

- Piezoelectric AFM tip is used
- Measure resistance change using a Wheatstone bridge type circuit
- Good for small moment samples
- Low temperature heating of the piezoresistor (use less than 0.1 mA at 0.5 K)
Application of torque magnetometry

- Fermiology (dHvA)
- Magnetic Phase transitions
- Magnetization anisotropy
- Superconductors (vortex, anisotropy..)

Torque and resistance from field induced phase transition

Torque signal from metamagnetic transition
Torque Magnetometer

- BeCu foil 12 ~ 75 μm thickness
- Commercial AFM tip Seiko PRC 120
- Interchangeable spacer G-10
- (TMTSF)$_2$ClO$_4$ sample
- Compensation loop
- Silicon beam cantilever
Method 3 (4, 5…): Indirect techniques

- Magneto-Optical Kerr effect (Faraday effect)
- ESR, NMR, Mössbauer
- Galvanomagnetic sensor (Hall effect, Magnetoresistance)
- Ferromagnetic sensor\(^1\): Fluxgate sensor, Thin-film sensor

![Ferromagnetic core](image)

**Fluxgate sensor\(^1\)**

![Hall sensor\(^7\)](image)

**Hall sensor\(^7\)**
## Summary

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (high field)</th>
<th>Dynamic range</th>
<th>Applications</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\chi_{ac})</td>
<td>(10^{-9} (10^{-4} \sim 10^{-6}))</td>
<td>wide</td>
<td>phase transitions</td>
<td>demanding instrumentation</td>
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<tr>
<td></td>
<td></td>
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<td>spin glass, superparamag.</td>
<td>low T/high pressure</td>
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<td></td>
<td></td>
<td></td>
<td>superconductors</td>
<td>not quite abs. magnetization</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>dHvA oscillation</td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>(10^{-3} \sim 10^{-8}) (cap.)</td>
<td>narrow</td>
<td>dHvA oscillation</td>
<td>small signal for polycrystal</td>
</tr>
<tr>
<td></td>
<td>(10^{-9} \sim 10^{-11}) (piezo)</td>
<td>very narrow</td>
<td>phase transitions</td>
<td>difficult to calibrate</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>magnetization anisotropy</td>
<td>can’t apply pressure</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>superconductors</td>
<td></td>
</tr>
<tr>
<td>VSM</td>
<td>(10^{-7} (10^{-3} \sim 10^{-5}))</td>
<td>wide</td>
<td>all above</td>
<td>low sensitivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>absolute magnetization</td>
<td>not for hybrid magnet</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>high pressure is possible</td>
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**Useful references**

