Overview of Magnetic Measurement Techniques

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Outline

• **Nuclear Magnetic Resonance (NMR)/ Electron Paramagnetic Resonance (EPR)**
• Hall Probes
• Magnetoresistors
• Fluxgate Magnetometers
• Flux Measurements with Pick Up Coils
• Magnetic Alignment – center and direction
• Summary
NMR/EPR Principle

• A particle with a spin and a magnetic moment precesses around an applied field.

• The quantum energy levels are split into several discrete levels, depending on the spin of the particle.

• The energy gap between these levels is proportional to the applied field.

• A resonant absorption of RF energy occurs at a frequency corresponding to energy gap.
\[ I = \text{Spin} \]
\[ \gamma = \text{Gyromagnetic ratio} \]
\[ M = \text{Magnetic Moment} = \gamma h I \]

Energy = \( B \cdot M \)

Spin component along the field direction can take integral values from \(-I\) to \(+I\).

\[ \Rightarrow \text{Energy gap} = \gamma h B \]

Frequency = \( \gamma B \)
## Gyromagnetic Ratio

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\gamma$ (MHz/T)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>e$^-$</td>
<td>28026.5</td>
<td>0.5 to 3.2 mT</td>
</tr>
<tr>
<td>$^1$H</td>
<td>42.576396</td>
<td>0.04 to 2 T</td>
</tr>
<tr>
<td>$^2$H</td>
<td>6.53569</td>
<td>2 T to 14 T</td>
</tr>
<tr>
<td>$^3$He</td>
<td>32.4336</td>
<td>Cryogenic</td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>11.0942</td>
<td>Cryogenic</td>
</tr>
</tbody>
</table>
NMR Magnetometer

\[ \Delta B/B \sim 10^{-4} \text{ to } 10^{-3} \text{; } 30-70 \text{ Hz} \]
Locking RF to NMR Resonance

Resonance occurs at non-zero value of modulating signal. NMR signals arrive at uneven intervals.

Resonance occurs at Zero value of modulating signal. NMR signals arrive at even intervals.

Error

\[ B_0 \]

\[ B_0 + \Delta B(t) \]

NMR Signal with \( f \) and \( B_0 \) mismatched

NMR Signal with \( f \) and \( B_0 \) matched

NMR, Santa Barbara, June 23-27, 2003

Animesh Jain, BNL
Requirements for NMR

NMR can provide measurement of magnetic field with absolute accuracy of 0.1 ppm. However, certain requirements must be met:

• Field must be stable (< 1% per second).

• Field must be homogeneous (< 0.1% per cm):
  – The signal deteriorates; difficult to lock
  – Probe positioning accuracy becomes critical.

One may locally compensate for the gradient using small gradient coils, to make measurements in inhomogeneous fields.
The Hall Effect

Charge carriers experience a Lorentz force in the presence of a magnetic field. This produces a steady state voltage in a direction perpendicular to the current and field.

\[ V_{\text{Hall}} = G \cdot R_H \cdot I \cdot B \cos \theta \]

- \( G \) = Geometric factor
- \( R_H \) = Hall Coefficient
The Planar Hall Effect

If the field has a component in the plane defined by current flow and voltage contacts, then a signal is produced given by:

\[ V_{\text{Planar}} \propto I \cdot B_{\parallel}^2 \sin(2\psi) \]

Important for mapping of 3-D fields.

The Planar Hall Effect can be minimized by a suitable choice of geometry \( \Rightarrow \sin(2\psi) = 0 \).

In practice, the response of a Hall probe to the field direction is considerably more complex, requiring elaborate calibration.
Compensating Planar Hall Effect

- 2 Matched Hall probes
- $I$ directions as shown
- Major component = $B_y$

is in the plane of the Hall probes.

Sum of Planar Hall Voltages is proportional to:

$$[\sin(2\psi_1) + \sin(2\psi_2)] = 0; \quad [\psi_2 = 90^\circ + \psi_1]$$

Based on:

R. Prigl, IMMW-11, BNL.
Hall Measurement Specifications

• Typical Range: < 1 mT to 30 T
• Typical Accuracy ~ 0.01% to 0.1%
• Typical dimensions ~ mm
• Frequency response: DC to ~ 20 kHz
  (~ a few Hz for fully compensated signal)
• Time Stability: ±0.1% per year
Hall Measurement Advantages

• Simple, inexpensive devices, commercially available.

• Small probe size makes it suitable for a large variety of applications.

• Can measure all components of field.

• Particularly suited for complex geometries, such as detector magnets.

• Can be used for fast measurements.

• Can be used at low temperatures.
Hall Measurement Disadvantages

• Non-linear device, requires elaborate calibration of sensitivity for each probe.
• Sensitive to temperature: Calibrate as a function of temperature; Keep temperature stable; Design compensated probes.
• Long term calibration drift.
• Planar Hall effect can pose a problem for mapping 3-D fields. Special geometries are needed for measuring minor components.
Magneto-Resistors

Field bends the current path, thus altering the resistance. Hall voltage tends to reduce this effect.

NiSb precipitates “arrest” the build-up of charge on the sides; Non-linear device; Insensitive to polarity; Large temperature dependence; Modest sensitivity.

Fluxgate Magnetometers

Excitation Coil: AC current drives a pair of ferromagnetic needles to saturation.

Detection Coil: Detects Zero field condition.

Bias Coil: Maintains a zero field condition.

Excitation Coils:
- $B_{\text{excitation}}$
- $-B_{\text{excitation}}$

Detection Coils:
- excitation coil
- bias coil
- detection coil

Courtesy: L. Bottura, CERN.
Fluxgate Principle: Zero Field

Excitation Profile \((H)\) is symmetric

Zero output in detection coil

Based on: L. Bottura, CAS on Superconductivity, Erice, 2002
Excitation Profile ($H$) is asymmetric

Based on: L. Bottura, CAS on Superconductivity, Erice, 2002
Fluxgate Characteristics

• Highly sensitive, linear, directional device.

• Typical field range ~ a few mT. (Limited by capability of the bias coils)

• Bandwidth: DC to ~ 1 kHz.

• Sensitivity: ~ 20 pT (~1 nT commercial).

• Accuracy: ~ 0.1% (depends on calibration and stability)

• Used in navigation, geology, mapping of fringe fields, etc.
DCCT: A Special Fluxgate

DC Current Transformer
Senses magnetic field produced by a current carrying conductor passing through a toroidal core.
Used for accurate measurement of high currents (~10-100 ppm typical)

Courtesy: L. Bottura, CERN.
Flux Measurements: Induction Law

Flux through a coil defined by the surface $S$ is:

$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{S}$$

If the flux linked varies with time, a loop voltage is induced, given by:

$$V(t) = -\frac{d\Phi}{dt} = -\frac{d}{dt} \left[ \int_S \mathbf{B} \cdot d\mathbf{S} \right]$$

The time dependence may be caused by either a varying field or a varying surface area vector, or both.
Flux Measurements

Time dependence of flux gives:

\[ V(t) = -\frac{d\Phi}{dt} = -\frac{d}{dt} \left[ \int_{S} B \cdot dS \right] \]

The change in flux is given by:

\[ \Phi_{\text{end}} - \Phi_{\text{start}} = -\int_{t_{\text{start}}}^{t_{\text{end}}} V(t) \cdot dt \]

and can be measured by integrating the voltage signal.

To know the flux at a given instant, one needs to know \( \Phi_{\text{start}} \):

\( \Rightarrow \) (1) Use \( \Phi_{\text{start}} = 0 \); (2) Flip Coil/Rotating coil: \( \Phi_{\text{end}} = \mp \Phi_{\text{start}} \)
Common Coil Geometries

**Point Coil**
Insensitive up to 4th order spatial harmonic with proper choice of height and radii.

**Flat Coil (Line or Area Coil)**
- Fixed coil; Varying field
- Flip Coil/Moving Coil; Static field
- Rotating Tangential/Radial

**Multipole Coil**
Sensitive to only odd multiples of a specified harmonic (Morgan Coils)
Flux Measurements: Hardware

**Digital Integrator:**
Directly gives change in flux.
10-100 ppm accuracy.

**Digital Voltmeter:**
Gives rate of change of flux. Numerical integration and/or well controlled coil movement is needed.
Measurements with Pick up Coils

- *Simple, passive, linear, drift-free* devices.
- Require *change in flux* ⇒ ramp field with static coil, or move coil in a static field. Pay attention to ramping/moving details.
- Measure *flux*, not *field*. ⇒ *Calibration of geometry* very important; limits *accuracy*.
- Field variations across the coil area must be accounted for ⇒ *harmonic analysis*.
- Field harmonics can be measured at ppm level.
- *Field direction* can be measured to ~ 50 µrad.
Determination of Magnetic Center

Stretched Wire Measurements
- Move a stretched wire in a magnet
- Measure change in flux for various types of motion.
- Use expected field symmetry to locate the magnetic center.

Colloidal Cell
- Place ferromagnetic fluid in the field
- Illuminate with polarized light
- Observe with crossed analyzer
Determination of Field Direction

Rotating Coils
- Angular Encoder and Gravity Sensors
- Accuracy 50-100 $\mu$rad
- Frequent re-calibrations

Encoder
Coil
Gravity Sensors

Mirror & Needle
- For solenoids
- Resolution $\sim 10$ $\mu$rad

Based on: C. Crawford et al., FNAL and BINP, Proc. PAC'99, p. 3321-3
Summary

• Numerous methods exist for measurement of magnetic fields. Only some of them are in common use for measuring accelerator magnets.

• NMR technique is the standard for absolute accuracy, but cannot be used in all situations.

• Hall probes are very popular for point measurements, such as for field mapping of detector magnets.

• A variety of pickup coils are the most often used tools for characterizing field quality in accelerator magnets.

• Innovative techniques have been developed for alignment measurements to suit various applications.
For More Information

• Knud Henrichsen’s bibliography:
  http://mypage.bluewin.ch/hera/magnet

• CERN Accelerator Schools on Magnetic Measurements:
  – March 16-20, 1992, Montreux (CERN 92-05, 15 Sep. 1992)
  – April 11-17, 1997, Anacapri (CERN 98-05, 4 Aug. 1998)

• Proceedings of Magnet Measurement Workshops:
  – IMMW-1 (1977) to IMMW12 (2001); IMMW13 (May 2003)

• Proceedings of Particle Accelerator Conferences:

• Proceedings of Magnet Technology Conferences: