Hall Devices:  
Physic & Application to Field Measurements

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Scope (and limitations) of the course

Answers to the questions:

- Hall effect: what is it? $V \leftrightarrow B$
- Hall devices: basic parameters, practical aspects, type of Hall probes
- Multi axis Hall sensors: status and future challenges
- Magnetic field measurements with Hall probes: advantages and limitations.
- Applications for field measurements in accelerator magnets:
  (examples of measurements at CERN and at the Paul Scherrer Institute)

$$Q_P + Q_C > Q_i^*$$

* T. Friedman, “the World is flat” (2006)

Not in that course:

- The technology of fabrication like CMOS and (sub) micrometer Hall devices
- Magnetic measurements in inhomogeneous magnetic field
- Hall measurements in a fast AC magnetic field
- High frequency effects
- The Hall device as means for characterizing the semiconductors (see Popovic-2004)
- Hall effect in sensing applications (see Ramdsen-2006)
Outline

1. Hall sensors: Overview of the basic properties
   – Hall effect: physical effect
   – Some basic properties:
     • Sensitivity & Offset
     • Noise, Temperature sensitivity, linearity
     • Calibration
     • Zoology of Hall probes

2. Three axis Hall magnetic devices.
   – Three axis sensors
   – The new generation: Magnetometers with IC Hall sensors
   – Future challenges

   Summary: Advantages and limitations in magnetic field measurements

3. Application in magnetic field measurements in beam line magnets
   – Ex 1: Measurements of conventional magnets at the Paul Scherrer Institute
   – Ex 2: Sextupole measurements in CERN LHC dipoles
   – Ex 3: Field measurements in Insertion Devices

4. Summary
Hall effect : The physical principle
The Hall effect: physical principle

When a current is flowing in a (semi)conductor placed in a magnetic field not parallel with the current direction, an electric field $E_H$ will be generated perpendicular with respect to the current and the field direction.

Lorentz Force: $F_n = e [v_{dn} \times B]$

Hall field: $E_H = -v_{dn} \times B = E_e \times B$

Balance magnetic/electric force $e E_H$

V_{dn}: velocity, $e = -q$

Carriers "pressed" on the strip edges

Movement of carriers parallel to the longitudinal direction (C1C2) restored

Assumptions: $n$ doped semiconductor, plate infinitively long, no thermal agitation
The Hall effect: physical principle (2)

\[ |E_H| = v_{dn} \cdot B \cdot \cos \gamma \]

\[ v_{dn} = \mu_n E_e \]

\[ J_n = qn\mu_n E_e \]

\[ I = J_n \cdot t \cdot w \]

\[ V_H = \int_{S_1}^{S_2} E_H ds \]

\[ V_H = \frac{R_H}{t} I B \cos \gamma \]

\[ R_H = \text{sign}[e] / nq \]

\[ R_H (\text{m}^3 \text{C}^{-1}) \text{ is the hall constant: the efficiency to generate an Hall electrical field} \]

\[ R_H \text{ depends on the scattering process} \]

\[ R_H \text{ depends on the magnetic field:} \]

\[ R_H(B) = R_{H0} \left( 1 - \alpha \mu_n B^2 \right) \]

\[ n, p (\text{cm}^{-3}): \text{density of carriers} \]

\[ t (\text{mm}): \text{thickness} \]

\[ q (\text{C}): \text{charge} \]

\[ V_{dn}: \text{drift velocity (electron)} \]

\[ \mu_n: \text{electron mobility} \]

\[ \mu_p: \text{hole mobility} \]

\[ \sigma: \text{conductivity} \]

-1 /nq electrons

+1 /pq holes

If we consider two types of carriers (electrons n and holes p):

\[ R_H = \frac{-n\mu_e^2 + p\mu_h^2}{q(n\mu_e + p\mu_h)^2} \]
Choice of the material

\[ V_H = \frac{R_H}{t} I B \cos \gamma \]

\[ R_H = \text{sign}[e]/nq \]

\[ R_H = \frac{\mu n}{\sigma} \]

\[ V_H/\rho^{1/2} \propto (\mu n/nt)^{1/2} B \]

High sensitivity:
- Low density carrier (High \( R_H \))
- Small plate thickness

High mobility carriers

Metals (low mobility): not favored
Alloys (high resistivity causes heating)

Semiconductors used: InSb, InAs, GaAs, Si

Ex: n doped Si, \( T=300 \text{ K}, n=4.15 \times 10^{15} \text{ cm}^{-3}, R_H=1.39 \times 10^{-3} \text{ C}^{-1}\text{m}^{3} \)

Remarks
- InAs and InSb have a small gap and the sensitivity is strongly temperature dependent.
- Si is interesting as it is compatible with integrated electronic technology.
- The Hall effect is polarity dependent: \( R_H \) determines the sign of the charge carriers \( q \).
- If \( I \) or \( B \) change direction, the polarity of the Hall voltage flips.

<table>
<thead>
<tr>
<th>Material</th>
<th>( E_g ) [eV]</th>
<th>( \mu_n ) [m(^2)V(^{-1})s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>0.15</td>
</tr>
<tr>
<td>InSb</td>
<td>0.17</td>
<td>8</td>
</tr>
<tr>
<td>InAs</td>
<td>0.36</td>
<td>3.3</td>
</tr>
</tbody>
</table>

(P dissipated in the device, \( P=V_{in} I \))
Geometry consideration

Infinitely long strip \((w << L)\)

\[ V_{H\infty} = \frac{R_H}{t} I B \cos \gamma \]

Finite dimensions

\[ V_H = G(\frac{L}{w} B) \cdot V_{H\infty} \]

Conformal mapping

“All shapes are equivalent”

Rem: Van der Paw and cross-shaped are compact and invariant by a rotation of \(\pi/2\).

(sense and biasing contact are equivalents)

Examples of geometries

- Rectangular
  - Ok if small sense contacts
  - "Van der Paw" \(G \sim 1\)

- Cross-shaped \(G \sim 1\)

From Popovic [3]
Planar Hall effect (Goldberg & Davis 1954, B. Berkes 2001)

B: (B_p, B_z) \quad B_x = B_p \cos \phi, \quad B_y = B_p \sin \phi

V_{output} = V_H + U_{planar}

E_x = \rho_0 J + P_H (B_p \cos \phi)^2 J
E_y = -P_H (B_p \sin \phi) \cdot (B_p \cos \phi) \cdot J - R_H B_z J

Additional transverse voltage!

Angular dependence of U_{planar}

B_p affects the velocity component \perp to B_p!

Max

Additional transverse voltage: U_{planar} \sim B_p^2 \sin 2\phi

Additional term that are equiv. to an anisotropic change of the magneto resistance: \Delta \rho_b \sim -P_H B_p^2

U_p = 0 for \phi = 0 and \phi = k\pi

U_{planar} is important when mapping 3-D fields

NB: can be eliminated by flipping the probe at 180°, inverting the field direction, turning the probe (\Phi = 0)
Hall sensors: Basic characteristics
Hall sensor description

- **Active part**: semiconductor element (bulk or film) ("sensing material", 0.01..0.1 mm)
- **Four terminals**: sensing and biasing contacts
- **Substrate** (ceramic): support and thermal stability
- Encapsulated or not.

Symbolic representation: **Multiplier**
In practical applications, I is usually kept constant so that the output voltage is proportional to the field

\[ V_H \propto I_{bias} \text{ and } B. \]

\[ I_{bias} = I_{in}, \]

\[ R_{in} = \frac{V_{in}}{I_{bias}} \]

\[ R_{in}, \text{ Input resistance: through which the control current flows} \]
\[ R_{out}, \text{ Output resistance: across the Hall Voltage develops} \]
Parameters:

- Sensitivity to the magnetic field,
- Voltage offset,
- Temperature dependence coefficient,
- Linearity error,
- Resistances across both pairs of terminals $R_i$ and $R_0$,
- Noise,
- Power consumption,
- Temperature range of operation,
- Cost….

Sensitivity $S$ is defined as the change in output (V) for a given change in input (B). It expresses the response of the output voltage to a magnetic field.

- Measured in units of output quantity per units of input quantity (V/T)
- $S$ depends on the operating conditions (T,B).
- $S$ not a constant in the all the domain of B-interest: calibration $V_H=F(B)$ needed.

\[
S = \frac{V}{B_\perp} \quad \text{in [V/T], \quad B_\perp \text{ is the normal component to the Hall plate}}
\]

Other figure of merits: The Current related sensitivity $S_I$

\[
S_I = \frac{V}{B_\perp I_{bias}} \quad \text{in [V/AT], \quad I_{bias} \text{ is the biasing current}}
\]

Hall "plate like" sensors (range 0-5 T, 1.5K-300 K): $S_I \sim 1-100 \text{ V/AT}$

Sensitivity is changing with time \(\smiley\) periodic re-calibration $V_H=F(B)$
Hall probe calibration

- High Homog. field (≈10⁻⁵) calibration magnet
- NMR probes (reference for B reading)
- Stable HP current source (0.01%)
- DVM to read $V_H$ (integ. time 20 ms)
- Hall probe perpendicular to $B_{\text{cal}}$ (within 0.1°) and NMR at the center of the calibration magnet
- Temperature regulation

$V_H=F(B_{\text{NMR}})$

To treat the non linearity: $B = c_0 + c_1 U + c_2 U^2 + \ldots + c_n U^n$ ($n=9$ in that case)

More complex in the case of a 3D Hall sensor (planar effect)!

Stéphane Sanfilippo, “Hall Devices”, CAS Magnets, 16-25 June 2009
Offset

• Offset: Parasitic voltage that exists without magnetic field (B=0, \( V_{\text{output}} \neq 0 \)) Offset \( V_{\text{off}} \) or equivalent magnetic induction \( B_{\text{off}} \) (typically 0.1-10 mT…)

• Main Origins:
  - Fabrication variables: Impurities, crystal defects, photo mask misalignment, misalignment to the crystal plane, misalignments in sense contacts.
  - Thermal effect: Temperature gradients along the hall element.
  - Stress effect: Electrical resistance changes due to mechanical (piezo-restivity)

• Offset varies: in time, B, temperature (packaging stress effect), : \( T_{\text{coeff}} \) of offset.

Model: The Wheatstone resistor bridge

![Wheatstone Bridge Diagram](image)

From Ramdse [4]

Offset = imbalance in a resistive bridge

Offset to be compensated

• \( B_{\text{off}} \) measured and removed:
  - Zero-field Gauss chamber

• \( B_{\text{off}} \) reduced:
  - Pairing technique
  - Spinning current technique

Temperature and field dependence of the Sensitivity

**Linearity error**
- Deviation of the $V_H = f(B)$ from the prescribed straight line
- NL often expressed in % (typically 0.01..0.1 %...)

**Temperature dependence of $S_I$**
- Intrinsic semiconductor
  \[ n_i = n_0 \exp \left( \frac{-E_g}{kT} \right) \]
- T-dependence of the mobility:
  \[ \mu = \mu_0 \left( \frac{T_0}{T} \right)^\alpha, 2 \leq \alpha \leq 2.3 \]
- Large gap $E_g$ or strongly doped: better
- $\gamma_T$ often expressed in %/°C (typically 0.01-0.1 %/°C)

**Non linearity**
\[ NL \cdot [\%] = \frac{V_H - V_{H0}}{V_{H0}} \times 100 \]

**Temp. coefficient**
\[ \gamma_T = \frac{1}{S_I} \frac{\delta S_I}{\delta T} \]

**T-regulation, computing compensation**
Noise Voltage

It limits the detestability of the magnetic field and the stability of the output signal

Many sources of noise voltage occurred during a measurements with an Hall generator:

• Inherent Noise
  ✓ Very low frequency noise $V_{lf}$ due to $T$-variation of $R_{in}$.
  ✓ Noise from the bias current and offset voltage drifts
  ✓ The noise coming from the amplifiers.
  ✓ Thermal noise: Random motion of carriers: It varies with $T$ and the bandwidth $\Delta f$ of the detector.  

$\langle V_{th} \rangle = 4 \cdot k_B \cdot T \cdot R_{out} \cdot \Delta f$

✓ 1/f noise due to the current flow through the generator (pronounced below 100 Hz)

And also….

• Transmitted noise from external sources like:
  ✓ 50 Hz power
  ✓ the switching noise (spinning current technique)
  …..

Typical cures:
Filtering and bandwidth reduction, spinning current technique above $f_c$….
Types of Hall sensors (plate like)

- Horizontal
- Axial
- Packaged
- Uncovered

Example of specifications (AREPOC)

- Active area: 0.625 mm²
- High linearity
- Low input and output resistance
- Wide magnetic field range ± 30 T
- Temperature range: 1.5 - 350 K
- Low offset voltage

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field range</td>
<td>[T]</td>
<td>0 - 30</td>
</tr>
<tr>
<td>Temperature range</td>
<td>[K]</td>
<td>1.5 - 350</td>
</tr>
<tr>
<td>Nominal control current I&lt;sub&gt;n&lt;/sub&gt;</td>
<td>[mA]</td>
<td>100</td>
</tr>
<tr>
<td>Maximum control current</td>
<td>[mA]</td>
<td>150</td>
</tr>
<tr>
<td>Sensitivity at I&lt;sub&gt;n&lt;/sub&gt;</td>
<td>[mV/T]</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Linearity error at 300K, B = 0 - 1 T</td>
<td>[%]</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Linearity error at 77K, B = 0 - 0.2 T</td>
<td>[%]</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Linearity error at 4.2K, B = 0 - 5 T</td>
<td>[%]</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Mean temp coefficient of sensitivity at temperature range 4.2 - 77 K</td>
<td>[K&lt;sup&gt;-1&lt;/sup&gt;]</td>
<td>2.10&lt;sup&gt;-4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean temp coefficient of sensitivity at temperature range 77 - 300 K</td>
<td>[K&lt;sup&gt;-1&lt;/sup&gt;]</td>
<td>3.10&lt;sup&gt;-5&lt;/sup&gt;</td>
</tr>
<tr>
<td>Residual voltage</td>
<td>[µV]</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Temperature coefficient of residual voltage</td>
<td>[µV/K]</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>Input resistance at 4.2 K (in zero field, including leads)</td>
<td>[Ω]</td>
<td>0.9</td>
</tr>
<tr>
<td>Input resistance at 77 K (in zero field, including leads)</td>
<td>[Ω]</td>
<td>1.1</td>
</tr>
<tr>
<td>Input resistance at 300 K (in zero field, including leads)</td>
<td>[Ω]</td>
<td>1.5</td>
</tr>
<tr>
<td>Output resistance at 4.2 K (in zero field, including leads)</td>
<td>[Ω]</td>
<td>1.3</td>
</tr>
<tr>
<td>Output resistance at 77 K (in zero field, including leads)</td>
<td>[Ω]</td>
<td>1.8</td>
</tr>
<tr>
<td>Output resistance at 300 K (in zero field, including leads)</td>
<td>[Ω]</td>
<td>3</td>
</tr>
<tr>
<td>Quantum oscillations beginning at 4.2 K</td>
<td>[Ω]</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Amplitude of quantum oscillations at 4.2K, B = 0 - 5 T</td>
<td>[%]</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Active area</td>
<td>[mm²]</td>
<td>0.625</td>
</tr>
<tr>
<td>Control current leads (green, black)</td>
<td>[mm]</td>
<td>⊘ 0.1</td>
</tr>
<tr>
<td>Hall voltage leads (orange, red)</td>
<td>[mm]</td>
<td>⊘ 0.08</td>
</tr>
</tbody>
</table>

Measurements of B along the axe like in solenoids

From Arepoc catalog, http://www.arepoc.sk/PDF/HallProbes.PDF
Vertical Hall sensors

Genesis of a vertical Hall sensor (Popovic, 1984)

Conventional: Sensitive to $B_\perp$

Split the current in two parts

Rotation: Active part $\perp$ to the chip

Three conditions:
1) $E_H = J \perp B$
2) $V_H = \int_{S_1}^{S_2} E_H ds$
3) $B=0$, $V_H=0$ i.e. $E \perp E_H$

Bottomless vertical device

N-well-CMOS technology:
$S_I \sim 400 \text{ V/AT}$

From Schurrig [15]
From Popovic [3]
Three-axis Hall magnetic devices
Three axis sensors

Magnitude and direction of $\mathbf{B}$
- Magnetic field maps
- Field not homogeneous
- Two or three components in a small volume

Ex: Phase measurement in a undulator

Measure the 3 components of $\mathbf{B}$

Cross sensitivity between axes to be removed

$$
\begin{bmatrix}
V_x \\
V_y \\
V_z \\
\end{bmatrix} =
\begin{bmatrix}
S_{xx} & S_{xy} & S_{xz} \\
S_{yx} & S_{yy} & S_{yz} \\
S_{zx} & S_{zy} & S_{zz}
\end{bmatrix}
\begin{bmatrix}
B_x \\
B_y \\
B_z
\end{bmatrix}
$$

Conventional solution...

Inconveniences:
- Spatial resolution limited by the distance of single elements
- Orthogonality of the sensitivity axes
- Flux density for the three axis is not measured in the same spot

Three sensors glued in a glass cube

From non plate like sensors to 3D sensors

2 vertical hall sensors

Measure Bx, By (2D)
Tri-axial chip on a single crystal by merging:
- vertical device + horizontal non plate one
- Four bias current contacts in the corner of a silicon block
- Four sense contacts in the middle

The Square Hall sensor (C. Schott, 1999)

Chip layout


From Rivka [5],

Stéphane Sanfilippo, “Hall Devices”, CAS Magnets, 16-25 June 2009
IC Hall sensors: the architecture

- Multi-axes Hall sensor + Integrated circuitry
  - Increase current and amplify the voltage,
  - Offset & planar effect reduction (spinning current technique, pairing)

Planar + vertical elements  $S=5V/T$

Complementary Metal Oxide Technology
(oxide growth, ion implantation, deposition, etching, epitaxy) + N well

Depletion Layer: Isolation

Integrated 3 axes Hall probe chip
Sensitivity volume: 0.1 mm x 0.1 mm x 0.01 mm

- Offset, 1/f noise, planar effect cancellation,
- Current supply

D.R. Popovic et al., IEEE TRANS. ON INSTRU. MEAS, VOL. 56, NO. 4, 2007

Stéphane Sanfilippo, “Hall Devices”, CAS Magnets, 16-25 June 2009
3 D Hall magnetometers with IC: an example

- Multi-axes Hall sensor
  + Integrated circuitry:
  Integrated hall sensors

- External electronic:
  • 5 V power supply supplied by USB,
  • a circuit board (14x55 mm²) to digitize (16 bits), compensate temperature variation and gain offset

- Firmware (standard compatible with USB protocols)

- Software in Labview (USB driver included)

P. Keller, Metrolab Instruments, Switzerland, ”A new generation of Hall Magnetometers” Magnetics Conference 2008
Offset reduction by orthogonal coupling

Principle: Mutual compensation of asymmetries.
When the current is turned off by 90°
- Offset inverted
- \( V_H \) remains the same.

Devices electrically connected in parallel with orthogonal current directions

Coupling of 2 sensors

- Systematic offset components are cancelled out.
- Time varying offsets are also compensated.
- Offset can be reduced by one or two orders of magnitude.

Not sufficient if the Hall devices matching is not sable in time.
Draw back: Increase the chip size and the biasing current.

From Popovic [3]
Offset reduction by “Spinning current technique”

- Goal: Minimize $V_{\text{off}}$ (also the $1/f$ noise and the $V_{\text{planar}}$ contribution)

- Sensor element: Symmetrical (cross-shape) geometry

- Principle (based on orthogonal sensor pairing)
  - Terminals of the Hall device are periodically commutated and alternatively used as the current (input) and the sense (output) contacts
  - If the biasing state of a Hall plate is turned by 90° than its offset changes its sign while the Hall voltage remains unchanged.

- Conditions of filtering: spinning frequency is significantly higher than the highest frequency of the measured magnetic field and of the corner frequency of the $1/f$ noise

- Result: $V_{\text{off}}$ appears as AC voltage and $V_H$ like a DC one, AC part can be filtered.

  Residual offset equivalent to 10-100 $\mu$T

*NB: Time-varying offset e.g. due to temperature and stress remains a problem associated with orthogonal coupling.*
Also the planar effect is reduced.

- Bridge model (example of a horizontal device)
- Hall planar effect and magneto resistance have the same physical origin.
- Increase of the resistance for the velocity carrier component perpendicular to the magnetic field.
- Apparition of a $\Delta R$ for direction perpendicular to $B$
- $V_{PH}$ treated like the offset in voltage

Without a spinning current, the ratio

$$\frac{V_P}{V_H} = 1.3\%$$

With a spinning current, $V_P / V_H = 0.02\%$.

**Reduction** of the planar voltage $V_{PH}$

D.R Popovic et al., IEEE TRANS. ON INSTRU. MEAS, VOL. 56, NO. 4, 2007
### Three axis Teslameter specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full scale (nominal)</td>
<td>± 2 T differential</td>
</tr>
<tr>
<td>Output voltages</td>
<td>5 V/T (0.5mV/G)</td>
</tr>
<tr>
<td>Sensitivity to d.c. magnetic field</td>
<td>&lt; ± 0.1 %</td>
</tr>
<tr>
<td>Tolerances of sensitivity (B = 1T d.c)</td>
<td>&lt; 100 ppm /°C</td>
</tr>
<tr>
<td>Temp. coefficient of sensitivity</td>
<td>&lt; 0.05 %</td>
</tr>
<tr>
<td>Non-linearity of output (B &lt;= 2T)</td>
<td>&lt; 0.01%</td>
</tr>
<tr>
<td>Planar Hall effect: Vplan / Vvert (B = 1T)</td>
<td>&lt; 1 % over 10 years</td>
</tr>
<tr>
<td>Long-term instability of sensitivity</td>
<td>&lt; ± 1 mV (0.2mT)</td>
</tr>
<tr>
<td>Offset (B = 0T)</td>
<td>&lt; (0.02mT/°C)</td>
</tr>
<tr>
<td>Temp. coefficient of offset</td>
<td></td>
</tr>
</tbody>
</table>

D.R Popovic et al., IMMW14, 2005

**Standard accuracy ~ 0.1 %**

Can be improved up to 0.01% only with an appropriate (and careful) calibration
3D Hall Magnetometers : Challenges

Status

- **Total field component** (Bx, By, Bz),
- **Strength**: Field up to 20 T
- **Hall planar, offset, temperature effects compensated**
- **Routinely 1% of accuracy**, 0.01% reachable with proper (and careful) calibration.
- **Mapping**: Point like-active volume and 2000 samples (Bx, By, Bz)/sec
- **Compact, flexible, easy to handle**
- **Standard USB interface**
- **Simple to program and customize**

Challenges

- **Improve accuracy (routinely to 0.05%?)**
  - Sensors architecture: Improve the orthogonality of the sensors
  - 3D Calibration (simplified method, small calibrator)
  - Noise reduction (1/f low frequency)
  - Drift of the offset in time
  - Encapsulation process to improve (reduce packaging stress)
- **Cryogenic application with IC sensors** (freezing, quantum Hall effect), a redesign of the sensor is needed
- **Miniaturization** (magnet with sub millimeter gap)
- **Performance/price ratio**
Overview of a 3D calibration method

**Old method:** only **main axes calibration** of the sensor

**New method:** **3D Full scan**

**Principle of the method:**
- Rotate sensor over two orthogonal axes in constant homogeneous field, \( \theta \) and \( \phi \) should be measured very precisely [0.02 mrad] by 3 small coils.
- Decompose the Hall-voltage in orthogonal functions: spherical harmonics for \( \theta \) and \( \phi \), Chebyshev polynomials for \( |B| \).
- Repeat for several field strengths and temperatures.
- Find the coefficients \( c_{klm}, d_{nlm} \)

\[
V(|B|, t, \theta, \phi) = \sum_{k} \sum_{n} \sum_{l} \sum_{m=0}^{l} c_{klm} T_k(B) d_{nlm} T_n(t) Y_{lm}(\theta, \phi)
\]

Solve inverse problem:

\[
\begin{align*}
\text{Vhall}_1, \text{Vhall}_2, \text{Vhall}_3, T \\
\text{c}_{klm}, \text{d}_{nlm}
\end{align*}
\]

\[\Rightarrow B_x, B_y, B_z\]

Measurement of 3 x V hall and T at \( \theta, \phi = n \times 22.5 \) degree


F. Bergsma, “Progress on the 3D calibration of hall probes”, presented at 14th IMMW, Geneva, Switzerland (2005) [17]
3D Magnetic sensor calibrator

Calibrator (Patent 7259550)

Results for a test with 3 x siemens KSY44 HP at 1.5 T, 20° C

From Bergsma [17]

Scale in Gauss

Plotted in figure: |Bold-Bnew|(θ,φ)

Color scale = |Bold|-|Bnew| Blue = -31 Gauss. Red=0

No error along the axes, 2°/°° off axes

Not very easy!: “Mass” production => simplify hardware and software!

Stéphane Sanfilippo, “Hall Devices”, CAS Magnets, 16-25 June 2009
Hall probes as field measurement technique

Questions to answer:

• **Measurements**: Field component, total (Bx, By, Bz), field integral to measure?

• **Field characteristics**: Strength, uniformity, AC/DC?

• **Accuracy needed**: % or 10 ppm?

• **Access**: What access do you have to the region measured? Precision and reproducibility of the positioning?

• **Environment**: cryogenic, room temperature?

• **Constraints**: Time schedule, cost, human resources..

Accuracy Medium: $10^{-4}$ to $10^{-2}$ of the reading range
Field range: mT…20-30 T

From Bottura [8]
### Hall probes as field measurement technique (2)

#### Pro
- Easy to use, easily portable/moved
- Inexpensive, big market
- Can be inserted in narrow apertures (undulators)
- Variable sensitivity (as function of $I_{bias}$)
- Easy element to integrate in a electronic circuit
- Fast measurement (instantaneous response)
- Medium accuracy for single component measurement ($\sim 0.01\%$), resolution $\sim 0.5$ G.
- Covers a very broad range of $B$
- Can be used for time varying magnetic field
- Works in non-uniform field
- Can be used for low temperature measurements
- Field mapper (measure the three components)

#### Cons
- Temperature sensitivity
- Non linearity $V = f(B)$
- Offset to be compensated
- Drift of offset, NL and temperature sensitivity with time
- Lower accuracy for integrated circuit sensor: below $\%$ is difficult to achieve
- Cross talk between axes (Planar hall effect)
- Noise coming from the circuitry
- Calibration (delicate for multi axes sensors)
Application to field measurements
Field measurements

Field measurement and Mapping in conventional magnets
Magnetic measurements of resistive magnets at the Paul Scherrer Institute

Harmonic measurements
Sextupole measurements in the 15 m long LHC dipoles during injection phase.

Field measurements in Insertion Devices
Undulator measurements at the Paul Scherrer Institute.
Hall probe measurements at the Paul Scherrer Institute

<table>
<thead>
<tr>
<th>Hall Probe</th>
<th>Siemens SVB 601S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semicond. material</td>
<td>InAs</td>
</tr>
<tr>
<td>I max</td>
<td>400 mA</td>
</tr>
<tr>
<td>U_{Hall}</td>
<td>60 mV@1T</td>
</tr>
<tr>
<td>Longitudinal range</td>
<td>2100 mm</td>
</tr>
<tr>
<td>Horizontal range</td>
<td>650 mm</td>
</tr>
<tr>
<td>Vertical range</td>
<td>360 mm</td>
</tr>
<tr>
<td>Long./Transv./Vert. Resolution</td>
<td>10 mm</td>
</tr>
<tr>
<td>Maximum calibrated Field</td>
<td>3.1 T</td>
</tr>
<tr>
<td>Hall Probe absolute accuracy</td>
<td>100 ppm</td>
</tr>
<tr>
<td>Hall probe resolution</td>
<td>1 μT</td>
</tr>
<tr>
<td>Temperature sensibility</td>
<td>70 ppm/°C</td>
</tr>
</tbody>
</table>

**Measurement procedure:**

- Leveling of the magnet
- Probe position measurement w.r.t magnet coordinates
- Longitudinal variation on the probe (step of 2 mm, 20 ms time) (line integral)
- DAQ of voltage (HP/Agilent 3458A digital multimeter)
- Proceed with next line or next current
- Post processing of the data
  - Local field, field integral, magnetic length
  - Field quality
  - 2D/3D field maps (volume in scanning five vertical planes)
Hall probe measurements at the Paul Scherrer Institute (2)

**X** and **Y** offset w.r.t geo axis

- **First coil**
- **Second coil**

<table>
<thead>
<tr>
<th>Offset w.r.t geo center (mm)</th>
<th>200</th>
<th>150</th>
<th>100</th>
<th>50</th>
<th>0</th>
<th>-50</th>
<th>-100</th>
<th>-150</th>
<th>-200</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X</strong> direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Y</strong> direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Z** position (mm)

- Accuracy: 0.1 mm

**Excitation curve 4 MeV Quad**

- **ramp up**
- **ramp down**

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Field Gradient (Gauss)</td>
<td>0</td>
<td>500</td>
<td>1000</td>
<td>1500</td>
<td>2000</td>
<td>2500</td>
</tr>
</tbody>
</table>

**Field contour plot (B=0.8T)**

- **AMF3 dipole mid-plane**
- **Magnet geometry**

**Quadrupole for 4 MeV phase of the PSI-XFEL.**

- Accuracy: 1 gauss

- Double Solenoids 0.25 T
  - $\Phi=80$ mm, $L=0.2$ m
  - Accuracy: 0.1 mm

- 40 Tons-90°
  - AMF3 dipole
  - 1.5 T, $G=0.15$m

Stéphane Sanfilippo, “Hall Devices”, CAS Magnets, 16-25 June 2009
b3/b5 snap back measurements in LHC cryo-dipoles

accelerator operation cycle

\[ B(x, y) = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{R_{ref}} \right)^{n-1} = \sum_{n=1}^{\infty} C_n \left( \frac{z}{R_{ref}} \right)^{n-1} \]

\[ \Delta b_3: 100-300 \text{ ppm} \]
Snapback phenomena duration: 30s

Standard tests:
15-m long rotating coils (0.1 Hz)
One point every 10s...
Not enough!

New instrument

- Resolution: few $\mu$T at least
- Measurement frequency: 3-10 Hz
- Measurement uncertainty~ 0.5 $\mu$T

Stéphane Sanfilippo, “Hall Devices”, CAS Magnets, 16-25 June 2009
b\textsubscript{3}/b\textsubscript{5} harmonic hall probe

AREPOC LHP-NU (Slovakia)
- Made of InSb
- Active area 0.6 mm\textsuperscript{2}
- 220 mV/T at 50 mA
- Non linearity (0..1 T): 0.2%
- Small Temp coeff: 10\textsuperscript{-4} K\textsuperscript{-1}

\[ V = \sum_{i=1}^{3} V_i = \sum_{i=1}^{3} gB_i \approx 3gB_3 \]

\[ V = \sum_{i=1}^{3} V_i = \sum_{i=1}^{3} gB_i \approx 0 \]

Hall plate

L. Bottura, T. Pieloni, N. Sammut, S. Sanfilippo et al., CERN (2003-2007) [19]
**Field measurements of the insertion devices (ID)**

**Insertion Device**: Periodic array of magnetic poles providing a sinusoidal magnetic field on axis with high peak intensity and a shortest period.

Goal: High intensity source of synchrotron radiation

![Diagram of Insertion Device](image)

\[ B_y = B_0 \sin \left( \frac{2\pi s}{\lambda_u} \right) \]

**Undulator parameter**

\[ K = 0.0934 \cdot B[T] \cdot \lambda_u [\text{mm}] \]

Constructive interference of radiation emitted at different poles

**Technology used for Undulator and wigglers**:  
- Permanent Magnets (NdFeB, Br=1.2-1.4T) or Sm$_2$Co$_{17}$ (Br=1.05T)  
- Electromagnet technology for long period undulators  
- Superconducting technology for field higher than 2 T

**Wiggler** - incoherent superposition \( K \gg 1 \)

Max. angle of trajectory > \( \frac{1}{\gamma} \)

Broad band radiation, Intensity proportional to \( N_u \)

**Undulator** - coherent interference \( K \ll 1 \)

Max. angle of trajectory < \( \frac{1}{\gamma} \)

Narrow band radiation, Intensity proportional to \( N_u \)

From Elleaume and Onuki [20] and Shepherd [21]
Magnetic field specifications

To minimise the perturbation to the stored beam:
• Integral of field over length of ID
• Exit position and angle of electron beam

\[ x' = \frac{-e}{E} \int B_y \, dz \]
angle \leftrightarrow 'first field integral’

\[ x \equiv \int x' \, dz = \frac{-e}{E} \int \int B_y \, dz \, dz \]
position \leftrightarrow 'second field integral’

To maximize the spectral properties:
Magnetic field at each point to know the path of electron.
Keep the phase error low (1..2 degrees)
(incomplete constructive interference, reduces the Angular flux)

\[ \phi \propto \frac{\pi}{(1 + K^2/2)} \left(1 + \frac{2\gamma^2}{\lambda_0} \int_{-\infty}^{\infty} (\int_{-\infty}^{z} B_y(z) \, dz)^2 \, dz \right) \]
Electric field produced by one electron

\[ \text{Phase Error} = \phi = 2\pi \frac{\sigma_e}{(T)} \]

Local field measurement vs longitudinal coordinate using on-the-fly scanning Hall probes

Origins of the phase error:
• Peak Field fluctuations
• Period fluctuations
• Field Shape fluctuations

From Shepherd [21]

Measured with a stretched wire!
Undulator measurements at the Paul Scherrer Institute (1)

Hall probe bench (ESRF design):
- 4 m granite support (350 x 600 mm², width, eight), flatness 15 µm
- Anorad linear motor mounted on the granite
- Heidenhain linear encoder
- Longitudinal movement (3.5 m, 0.1 µm resolution)
- Accuracy of the sensor position <20 µm (after software correction based on laser calibration)

Hall sensors:
- 3 X 1-dim Siemens Hall sensors mounted on a print board
- Range: up to 1.8 T
- Accuracy: 0.01%
- Non linearity: <0.05 %
- Output noise @ 20 ms integration time <0.06 G
- Input current: 5 mA

J. Chavanne, C Penel,
(ESRF Insertion Device Field Measurement Benches)

Courtesy of T. Schmidt
• Hall measurements based on a calibrated 3x D Hall sensor from SIEMENS and SENIS
• **On-the Fly scanning** is essential to reduce the sensor vibration (precision) and reduce the measuring time. Speed up 30mm/s, 2000-5000 points per components
• Typical scan : L=2500 mm, 1pt/mm/comp, speed=20 mm/sec. Time for a scan : 2min
• Correction of the file integral using stretched wire measurements
• Hall planar effect avoided by measuring only one polarization at the time
• What is observed : **Field integral, trajectory, phase error**

**Typical hall data processing:**

![Typical hall data processing diagram]

- **Hall Voltages -> B**
- **field integral correction**
- **First integral (angle)**
- **smoothed angle**
- **Second integral**
- **Phase error**

Courtesy of T. Schmidt
Summary

- Hall probes are among the most commonly used sensors for magnetic field measurement and field mapping:
  - Hall voltages are measurable quantities
  - Simple, linear, inexpensive, available in arrays
  - Sensors can be integrated within devices.

- Errors involved in measurement are mostly due to temperature, planar effects and offsets.

- Three dimensional Hall sensors are constantly improving:
  - Offset, noise and planar hall effect are minimized but…
  - Sensitivity has to be increased up to 0.01-0.05% (routine measurement)
  - Simplified calibration procedure to be found and practical calibrator to be designed.

- We invite you to join this challenging field. There are still many opportunities to invent new designs and develop techniques to measure magnetic field. So please join us ….
Acknowledgements

• Vjeran Vrankovic, Paul Scherrer Institute, Magnet section
• Thomas Schmidt, Paul Scherrer Institute, Insertion Device
• Elena Mashkina, Forschungszentrum Karlsruhe GmbH
• Philip Keller Metrolab Instrument Geneva
• Dragana and Radivoje Popovic, SENIS GmbH Zürich

Any questions?
Announcement

16th International Magnetic Measurement Workshop
IMMW16

Scope
• Magnetic field measurements on accelerator magnets and insertion devices
• Field measurement techniques
• Field measurement devices
• Stimulate world wide exchange and cooperation.

26-29 October 2009
Park-Hotel Bad Zurzach, Switzerland
http://immw16.web.psi.ch/
Some references

General Bibliography


Magnetic measurement techniques

Some references (2)

Three axis Hall sensors

Measurements of beam line magnets and insertion devices
Additional slides
**Terminology**

**Hall plate or hall element**: Semiconductor element (slice or film) sensitive to magnetic field.

**Hall generator or Hall sensor**: Hall element +electrodes glued on a substrate. Biased with a current, it converts as an active sensor the magnetic field (stimulus) in a electrical signal.

**Hall probe**: Hall generator mounted in a holder. Mostly used to measure magnetic fields and perform field mapping on magnets.

**Integrated Circuit (IC) Hall sensor**: Hall sensor with associated electronic integrated in the same chip to bias the sensor, amplify the output signals and compensate the parasitic effects.

**Accuracy**: Degree of correctness of a measured value compared to the true value. It may be represented in percent of the input full scale.

**Resolution**: The smallest distinguishable increment that the system can discriminate.

**Repeatability error**: The inability of the instrument to produce the same value among a number of consecutive measurements under identical conditions.

**Transfer function**: output (voltage)/ stimulus (magnetic field) relationship. In a linear relationship the slope of the function is called sensitivity.
The integer quantum Hall effect

First observed in 1980 by Klaus von Klitzing. Awarded Nobel prize in 1985

Very important:
For a 2D electron system only

\[ R_H = \frac{R_K}{n}, \quad n = 1, 2, 3, \ldots \]

In low temperature and strong magnetic field

\[ R_K = \frac{h}{e^2} \]

Effect as much as 1% on calibration coefficient

Applications of the Hall sensors

• Hall effect sensors can be applied in many types of sensing devices.

• Quantity (parameter) to be sensed has to incorporate a magnetic field.

• The Hall sensor senses the field produced by the magnetic system.

• The magnetic system responds to the physical quantity to be sensed (temperature, pressure, position, etc.) through the input interface.

• The output interface converts the electrical signal from the Hall sensor to a signal that meets the requirements of the application.
Applications of the Hall sensors (2)

- **Automotive Applications**
  - sensor ignition
  - timing engine speed
  - drive-by-wire
  - brake-by-wire
  - throttle position sensor
  - current measurement

- **Industrial Applications**
  - commutation of brushless DC motors
  - cooling fans
  - RPM measurement
  - wheel speed sensors
  - angle sensor
  - current measurement
  - position measurement
  - distance measurement

**World market of sensors**

Hall sensors: 80% of the market (2003)
Some pictures have been taken from books listed in the references and cited in the figure captions.

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