CERN Accelerator School, “MAGNETS”

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 ⇔ 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 meansfor 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

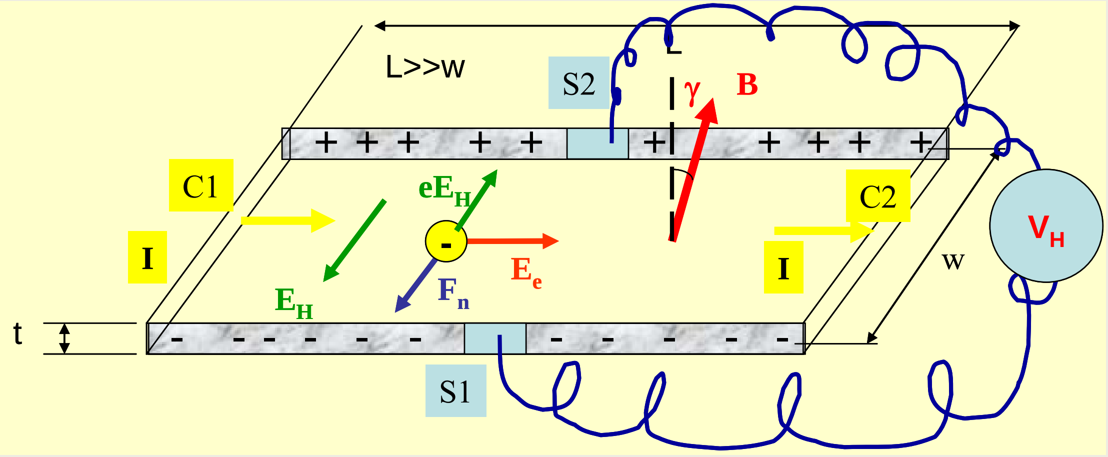
   Summary : Advantages and limitations in magnetic field measurements

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



Slab (L,w,t), L>>w

C1,C2: bias contacts

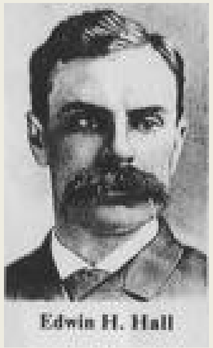
S1,S2: sensing contacts

B magnetic field

I: bias current (along y)

γ: angle (B, z axis)

V_H: Hall voltage (transverse)



1879

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: $F_n = e\,[\mathbf{v}_{dn} \times \mathbf{B}]$

V_{dn}: velocity, e= -q

Carriers "pressed" on the strip edges

Hall field: $\mathbf{E}_H = -\mathbf{v}_{dn} \times \mathbf{B} = \mathbf{E}_e \times \mathbf{B}$

Balance magnetic/electric force e $\mathbf{E}_H$

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)

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

$$v_{dn} = \mu_n E_e$$

$$J_n = qn\mu_n E_e$$

$$I = J_n\cdot t\cdot w$$

$$V_H = \int_{S_1}^{S_2} E_H ds$$

$$\Downarrow$$

$$V_H = \frac{R_H}{t} I.B\cos.\gamma$$

- n,p (cm^{-3}): density of carriers
- t (mm): thickness
- q (C): charge
- V_{dn}: drift velocity (electron)
- μ_n: electron mobility
- μ_p: hole mobility
- σ: conductivity

Measurable Quantity
Access to B!

with R_H= ***sign[e] /nq***

- -1 /nq electrons
- +1 /pq holes

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

R_H depends on the scattering process

R_H depends on the magnetic field:

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

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= ***sign[e]*** /nq ↔

High sensitivity:
Low density carrier (High $\mathbf{R_H}$)
Small plate thickness

$$R_H = \frac{\mu_n}{\sigma}$$

$$V_H \big/ P^{1/2} \propto \left(\mu_n \big/ nt \right)^{1/2} B$$

↔ High mobility carriers

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

metals (low mobility): **not favored**
alloys (**high resistivity causes heating)**

⇒ Doped semiconductors

Semiconductors used: InSb, InAs, GaAs, Si

Material	Eg [eV]	μ_n [$m^{-2}V^{-1}s^{-1}$]
Si	1.12	0.15
InSb	0.17	8
InAs	0.36	3.3

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

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.

Geometry consideration

Infinitely long strip (w<<L)

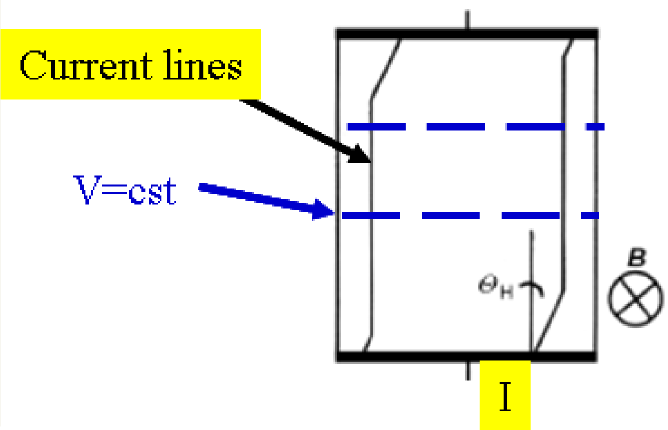
$$V_{H\infty} = \frac{R_H}{t} I.B\cos.\gamma$$

conformal mapping
“all shapes are equivalent”

Finite dimensions

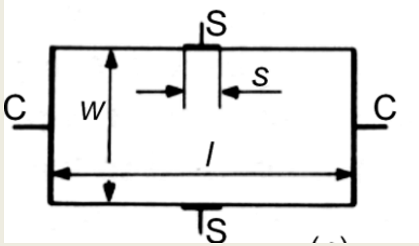
$$V_H = G({}^{L}\!/_{w}\,B)\cdot V_{H\infty}$$

G (0…1) : **correction factor**
G values available in the literature



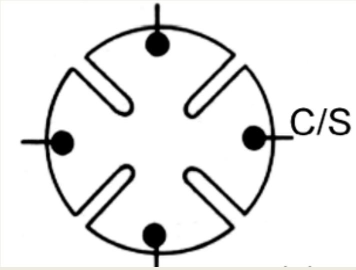
Examples of geometries

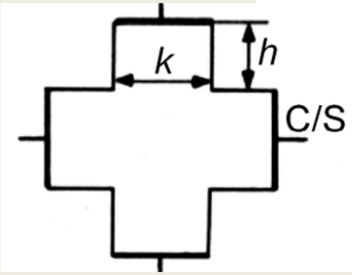
Rectangular
Ok if small sense contacts



From Popovic [3]

“Van der Paw”
G~1

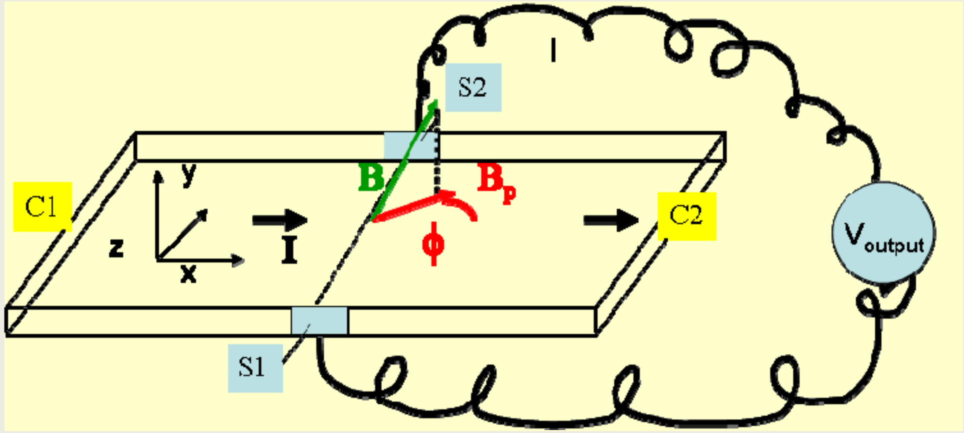




Cross-shaped
G~1

Rem :Van der Paw and cross-shaped are compact and invariant by a rotation of π/2.
(sense and biasing contact are equivalents)

"Planar" Hall effect (Goldberg&Davis 1954, B.Berkes 2001)



B_p affects the velocity component ⊥ to B_P!

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

$$V_{output}=V_H+U_{planar}$$

$$E_x = \rho_0 J + P_H (B_p.\cos\phi)^2 J$$

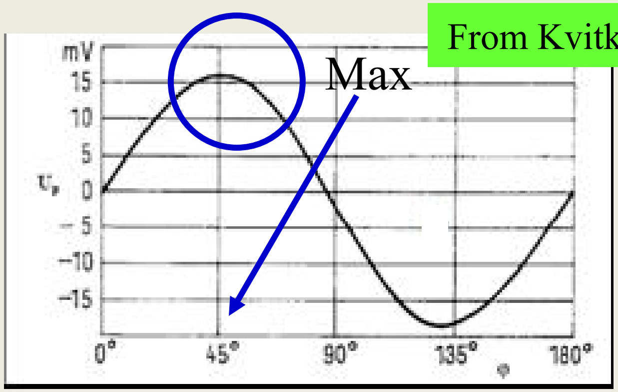
$$E_y = \boxed{-P_H (B_P.\sin\phi)\cdot(B_P.\cos\phi)}\; J - R_H B_z J$$

Additional transverse voltage!

Hall

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: $\Delta\rho_b \sim -P_H B_p^2$



From Kvitkovic [12]

Angular dependence of U_{planar}

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

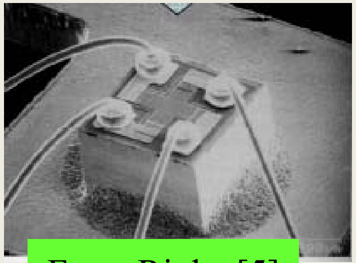
U_{planar} is important when mapping 3-D fields

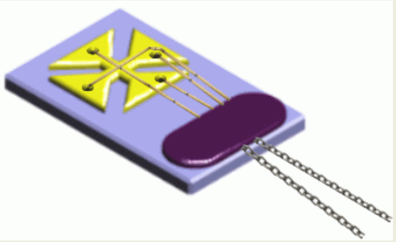
NB : can be eliminated by flipping the probe at 180°, inverting the field direction, turning the probe ($\Phi=0$)

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.

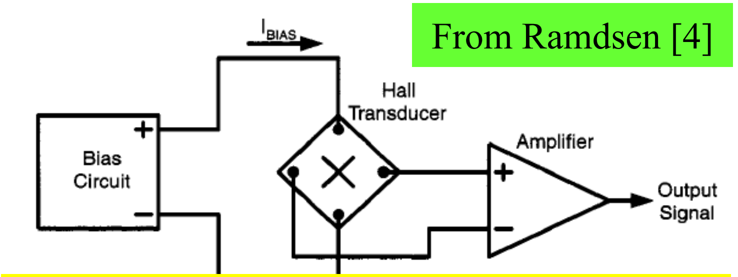




From Ripka [5]

Active part (InAs film) and construction scheme

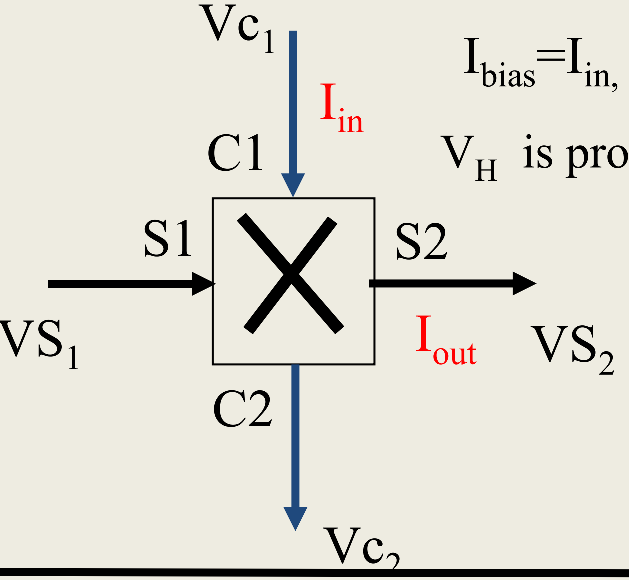
From Ramdsen [4]



Minimal component of a Hall sensor system

Symbolic representation: **Multiplier**

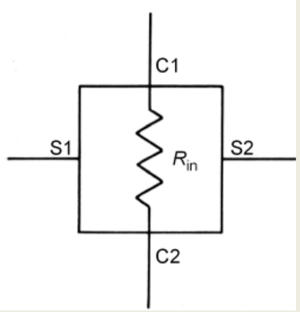
In practical applications, I is usually kept constant so that the output voltage is proportional to the field

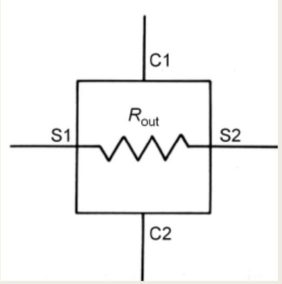


$I_{bias}=I_{in},$

V_H is proportional to I_{bias} and B.

$R_{in}=V_{in}/I_{bias}$





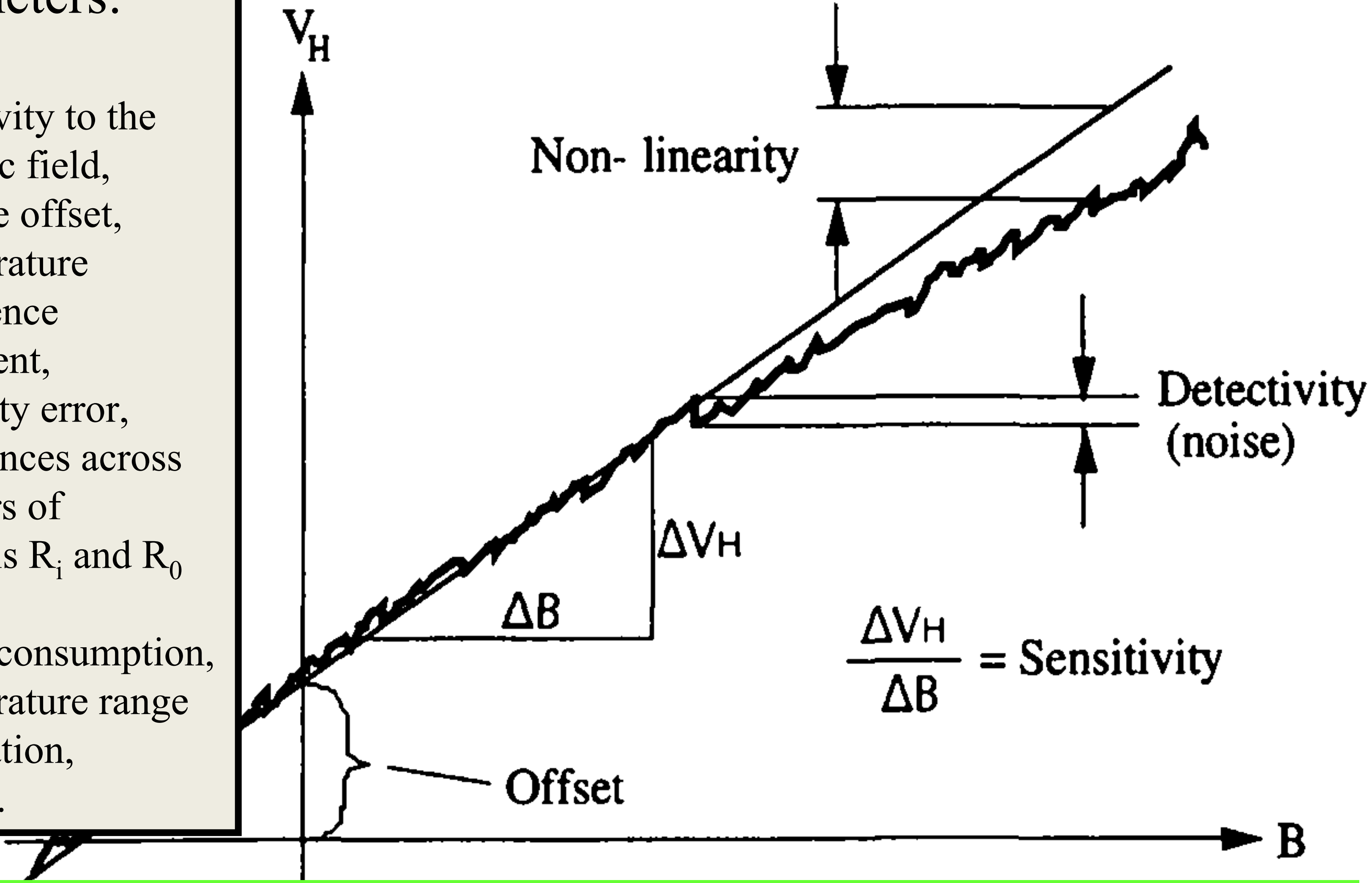
$R_{in,}$ Input resistance : through which the control current flows

R_{out} Output resistance : across the Hall Voltage develops

Hall sensor Characteristics

Parameters:

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



From Thesis H. Blanchard “Hall sensors with integrated magnetic flux concentrators", Thesis 2021 EPFL (1999)

Transfer function and sensitivity

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

$$S=\frac{V}{B_\perp}$$

in [V/T], $B_\perp$ is the normal component to the Hall plate

Other figure of merits : The Current related sensitivity S_I

$$S_I=\frac{V}{B_\perp I_{bias}}$$

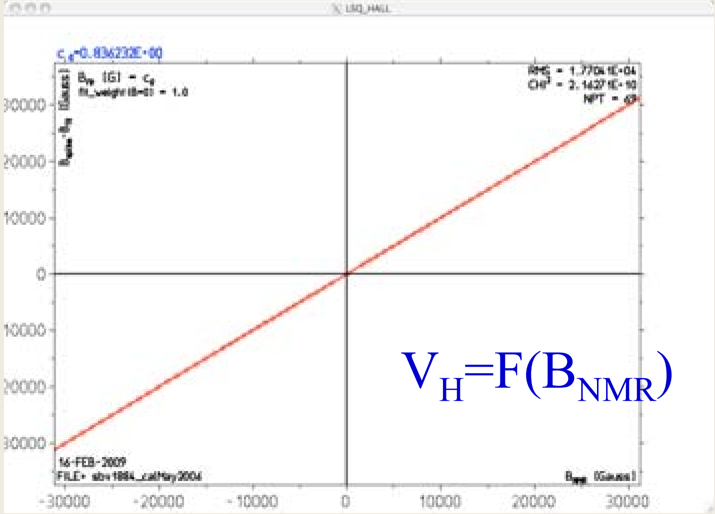
in [V/AT], I_{bias} is the biasing current

Hall ”plate like” sensors (range 0-5 T, 1.5K-300 K): S_I~ 1-100 V/AT

Sensitivity is changing with time ☞ periodic re-calibration $V_H=F(B)$

Hall probe calibration

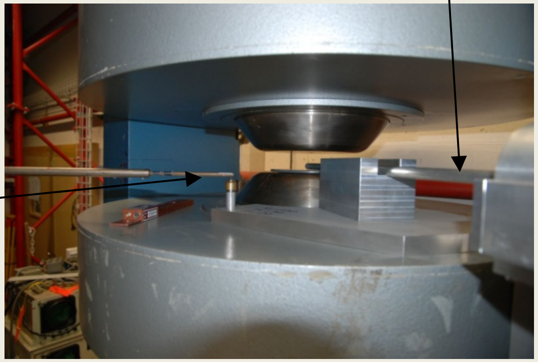
- High Homog. field (~10^{-5}) calibration magnet
- NMR probes (reference for B reading)
- Stable HP current source (0.01%)
- DVM to read V_H (integ. time 20 ms)
- Hall probe perpendicular to B_{cal} (within 0.1°) and NMR at the center of the calibration magnet
- Temperature regulation



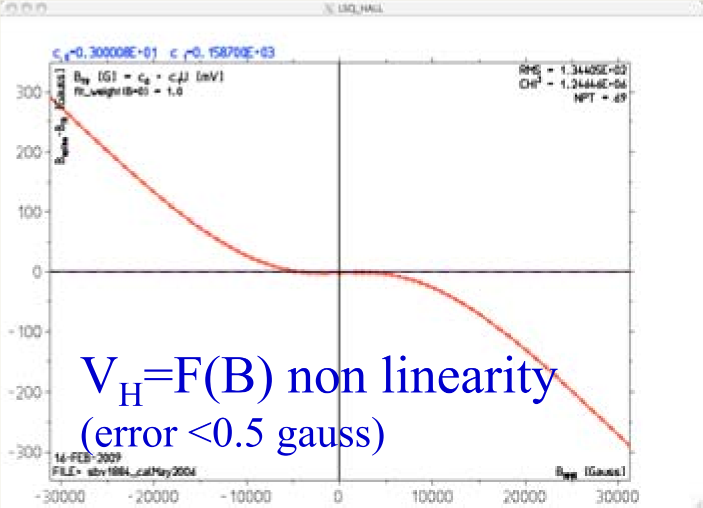
$V_H = F(B_{NMR})$

Cal .magnet

NMR



Hall probe



V_H=F(B) non linearity

(error <0.5 gauss)

To treat the non linearity : B = c0 + c1•U + c2•U2 + … cn•Un (n=9 in that case)

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

Offset

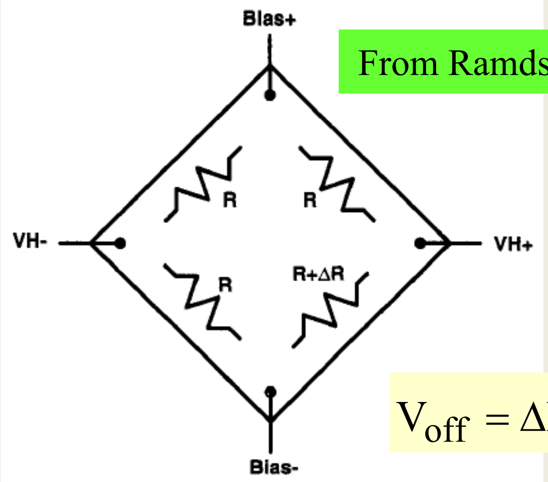
- **Offset : Parasitic voltage that exists without magnetic field (B=0, V_{output}≠0)** Offset V_{off} or equivalent magnetic induction B_{off} (typically 0.1-10 mT…)

- **Main Origins :** Bellekom and Mounter, “Sensors and Materials”,5 (1994)

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_{coeff} of offset.

Model: The Wheatstone resistor bridge



From Ramdsen [4]

$$V_{off} = \Delta R \cdot \left(1 + \gamma \cdot \mu \cdot B^2\right) \cdot I$$

Offset = imbalance in a resistive bridge

Offset to be compensated

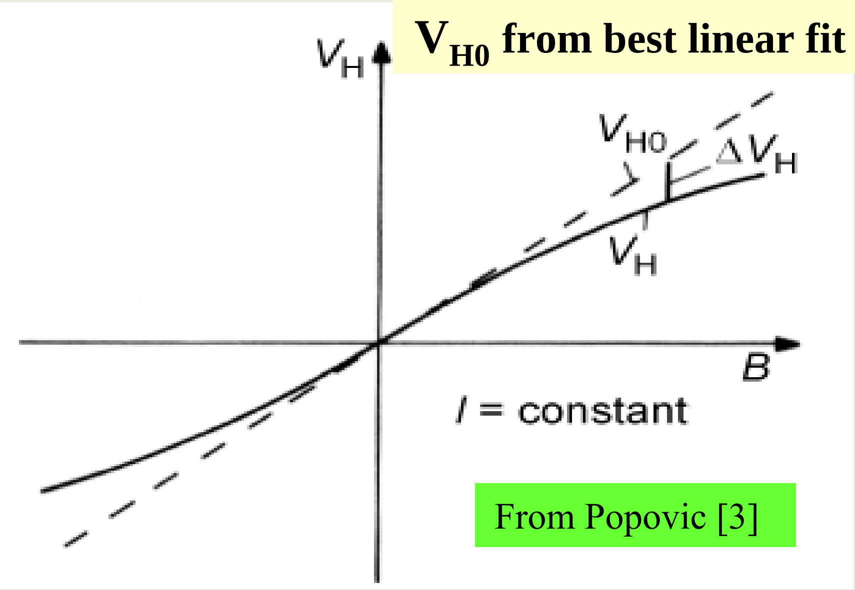
- B_{off} measured and removed: Zero- field Gauss chamber

- B_{off} reduced:
  - Pairing technique
  - Spinning current technique (see 3D sensor part)

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 %…)



V_{H0} from best linear fit

From Popovic [3]

Non linearity

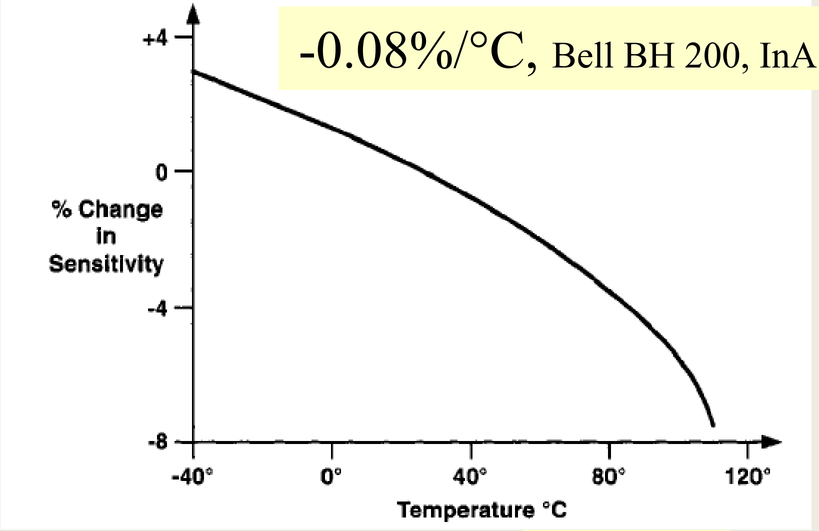
$$NL \cdot [\%] = \frac{V_H - V_{H0}}{V_{H0}} \times 100$$

calibration

Temperature dependence of S_I

- **Intrinsic semiconductor** $n_i \equiv n_0 \exp{}^{-E_g/kT}$
- **T-dependence of the mobility:** $\mu = \mu_0 (\frac{T_0}{T})^{\alpha}, 2 \le \alpha \le 2.3$
- **large gap E_g or strongly doped: better**
- **γ_T often expressed in %/°C**

(typically 0.01- 0.1 **%/°C**)



-0.08%/°C, Bell BH 200, InAs

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

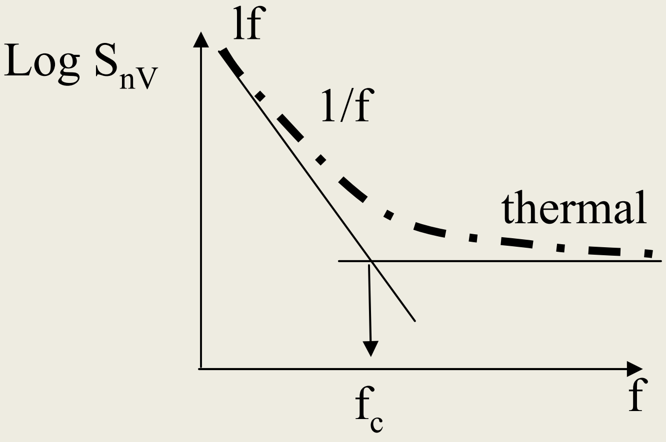
Many sources of noise voltage occurred during a measurements with an Hall generator :

•**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 Δf of the detector.

$$< V_{th}^2 >= 4 \cdot k_B \cdot T \cdot R_{out} \cdot \Delta f$$

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



Voltage noise spectral density

And also….

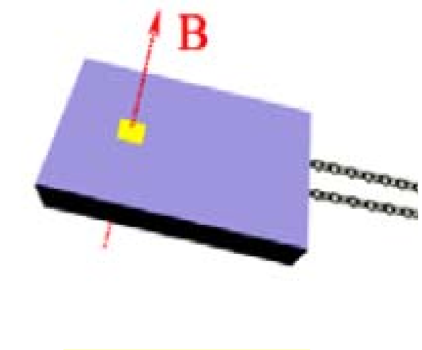
•**Transmitted noise from external sources like:**

✓ 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



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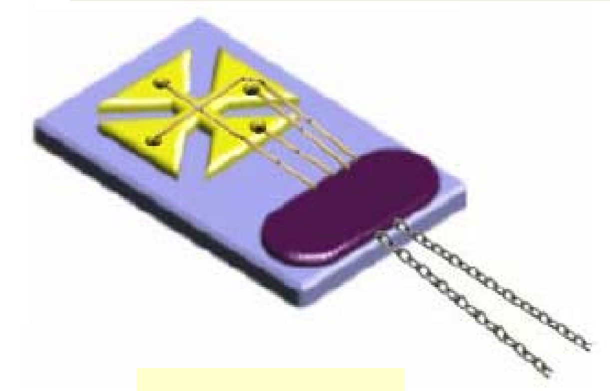
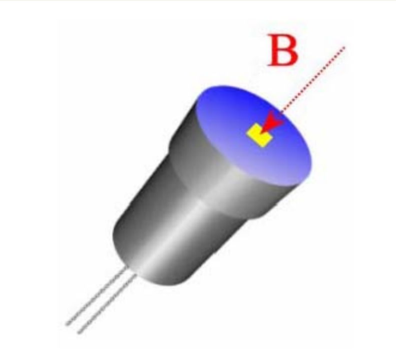


uncovered

axial



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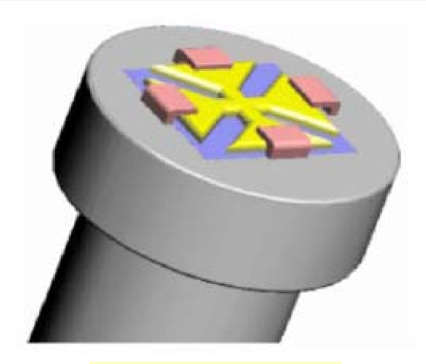
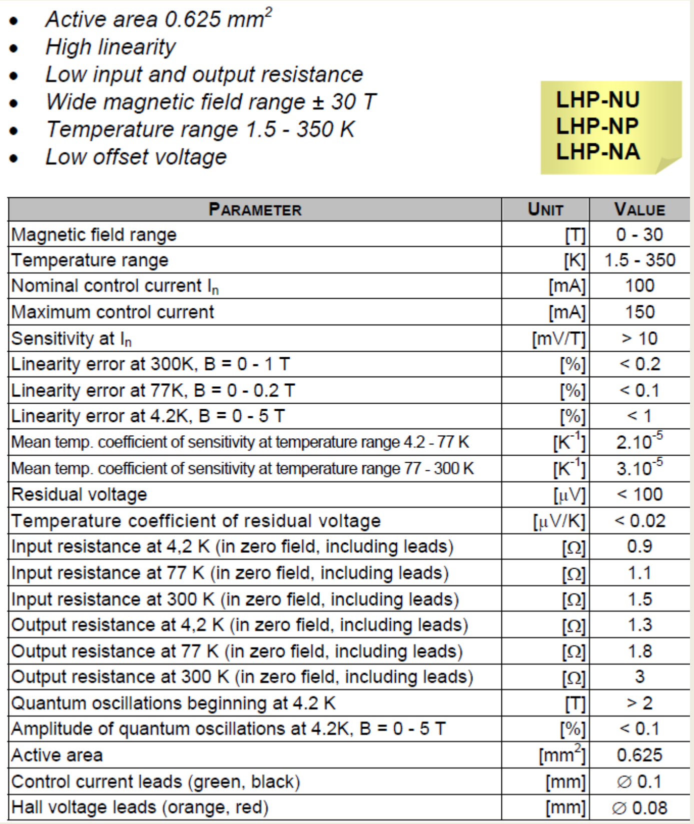


uncovered

Example of specifications (AREPOC)



- *Active area 0.625 mm^2*
- *High linearity*
- *Low input and output resistance*
- *Wide magnetic field range ± 30 T*
- *Temperature range 1.5 - 350 K*
- *Low offset voltage*

LHP-NU
LHP-NP
LHP-NA

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

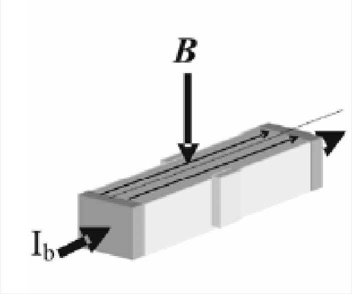
Measurements of B
B along the axe
like in solenoids

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

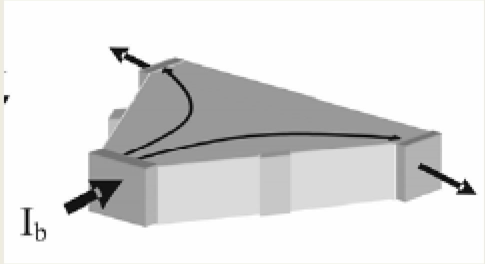
Vertical Hall sensors

From Schurrig [15]

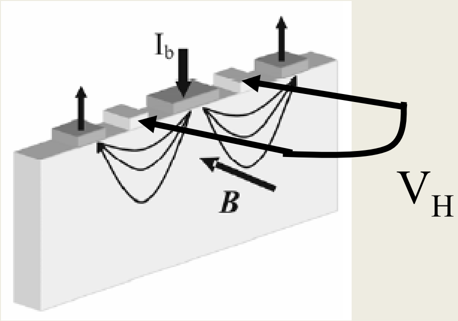
Genesis of a vertical Hall sensor (Popovic,1984)



Conventional :
Sensitive to $B_\perp$

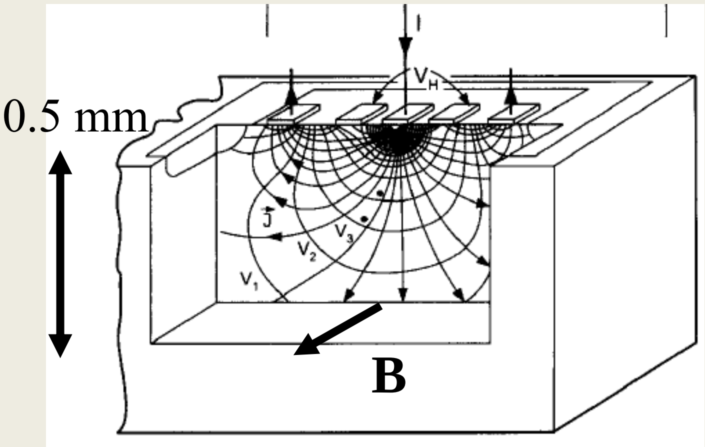


Split the current in two parts



Rotation:
Active part ⊥ to the chip

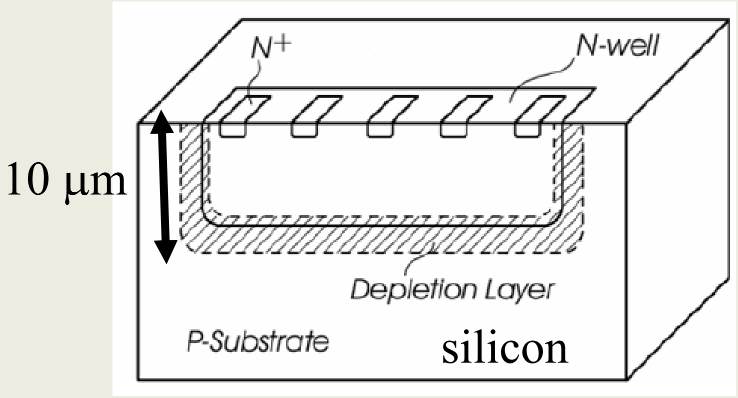
Three conditions :1) $E_H = J \perp B$, 2) $V_H = \int_{S_1}^{S_2} E_H ds$, 3) $B=0, V_H=0$ i.e. $E \perp E_H$



Bottomless vertical device

$$S_I \propto \frac{1}{t.N_d}$$

t thickness
N_d carrier density



N-well-CMOS technology:
S_I~400 V/AT

From popovic [3]

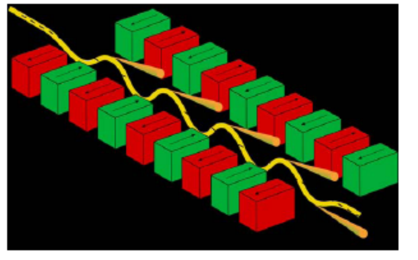
Three-axis Hall magnetic devices

Three axis sensors

Magnitude and direction of **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 **B**

but…

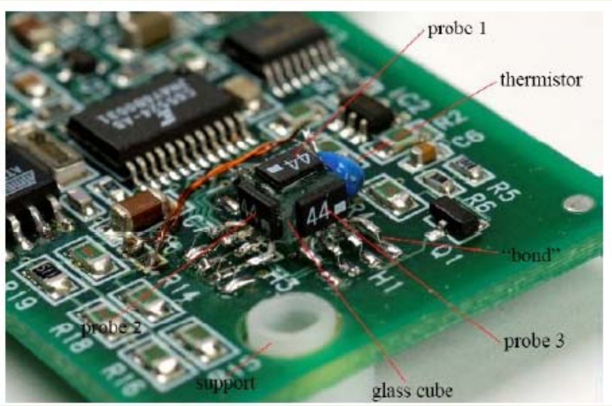
Cross sensitivity between axes to be removed

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

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

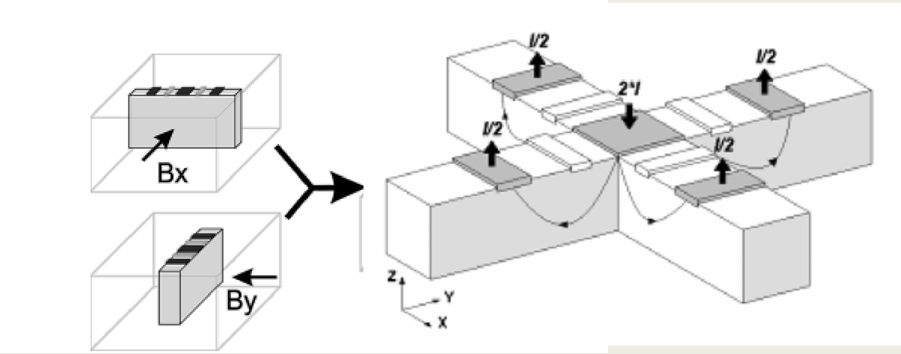


Three sensors glued in a glass cube

From R. Ruber, "Magnets for accelerator applications ", (2008)

From non plate like sensors to 3D sensors

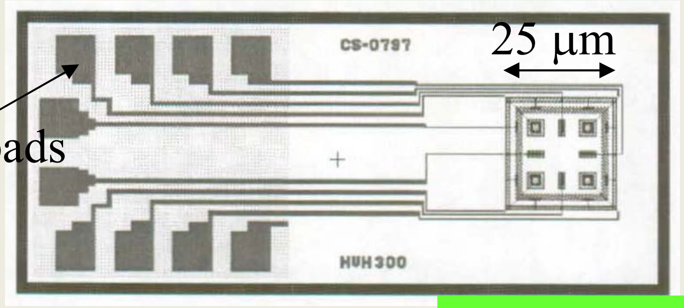
2 vertical hall sensors



Measure Bx, By (2D)

Tri-axial chip on a single crystal by merging :

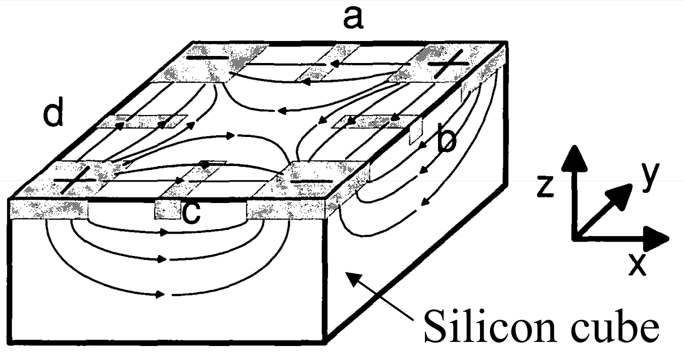
- **-vertical device+ horizontal non plate one**
- -Four **bias current contacts in the corner** of a silicon block
- -Four **sense contacts in the middle**

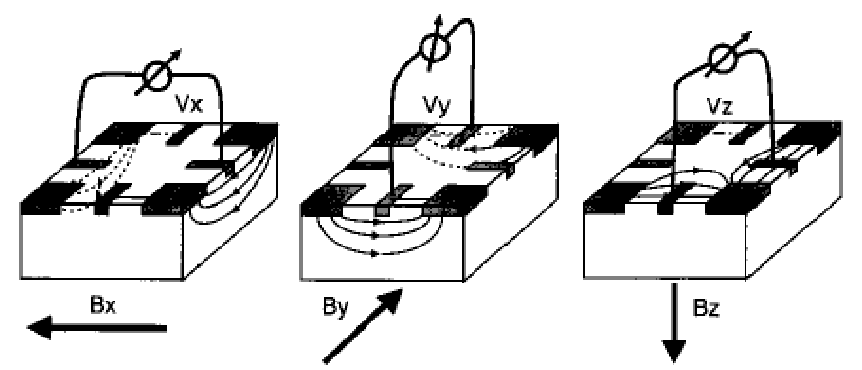


Chip layout

C. Shott thesis EPFL 1985 (1999)

The Square Hall sensor (C.Schott,1999)





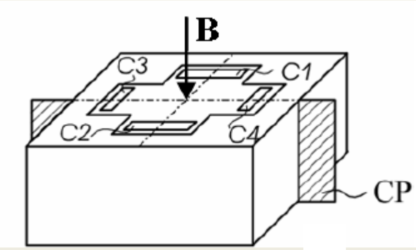
V_a, V_b, V_c, V_d ⇒ V_x, V_y, V_z ⇒ B_x, B_y, B_z

From Rivka [5],

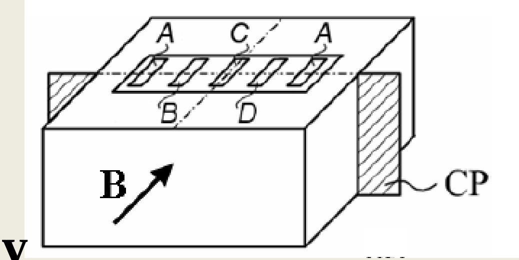
IC Hall sensors: the architecture

➢Multi-axes Hall sensor+ Integrated circuitry

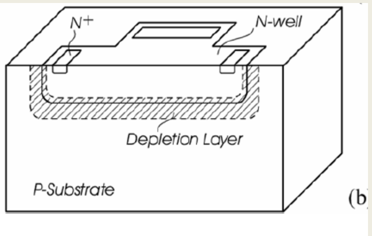
- Increase current and amplify the voltage,
- offset & planar effect reduction (spinning current technique, pairing)

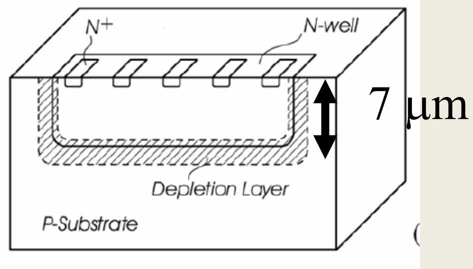


Planar + vertical elements S=5V/T



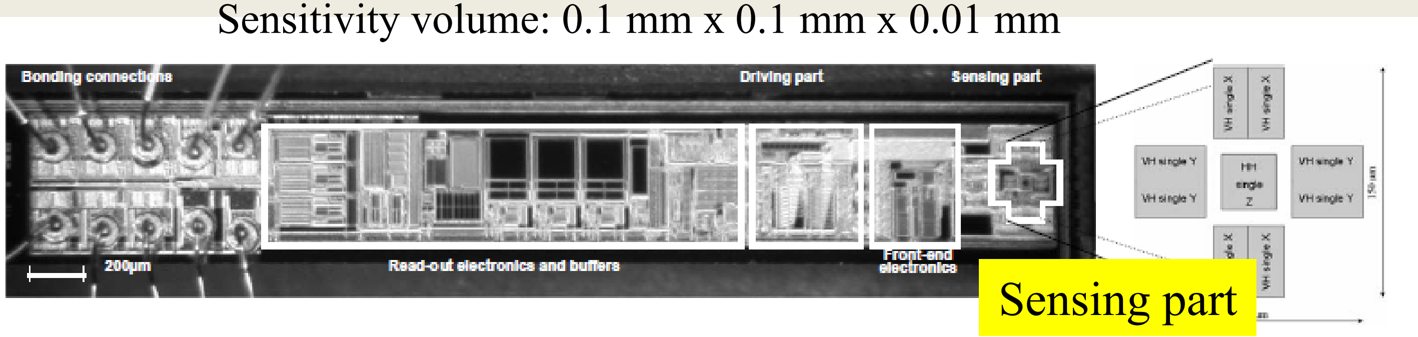
Complementary Metal Oxide Technology (oxide growth, ion implantation, deposition, etching, epitaxy) + N well





Depletion Layer: Isolation

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

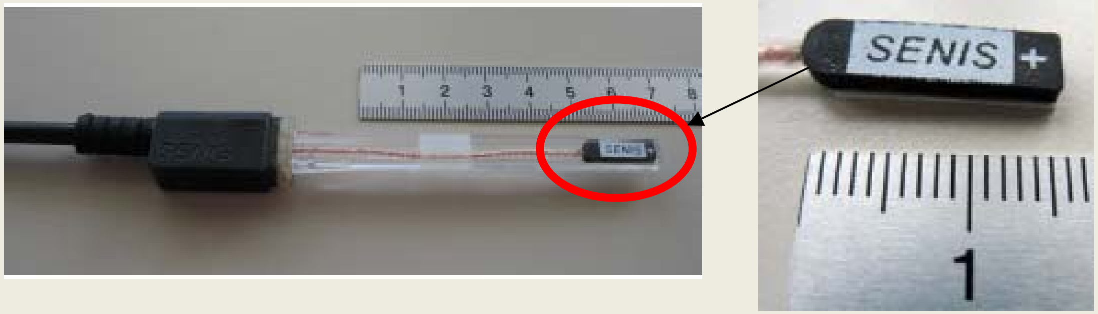


Sensing part

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

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

3 D Hall magnetometers with IC: an example



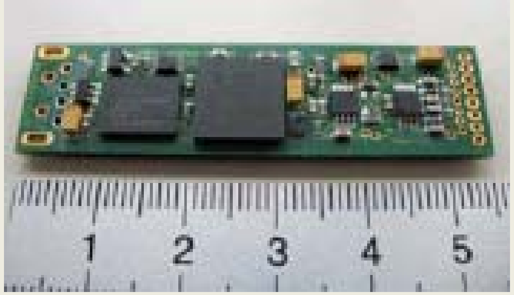
Sensor IC: 16x4x2 mm^3

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

- ➢External electronic:
  - •5 V power supply supplied by USB,
  - •a circuit board (14x55 mm^2) 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

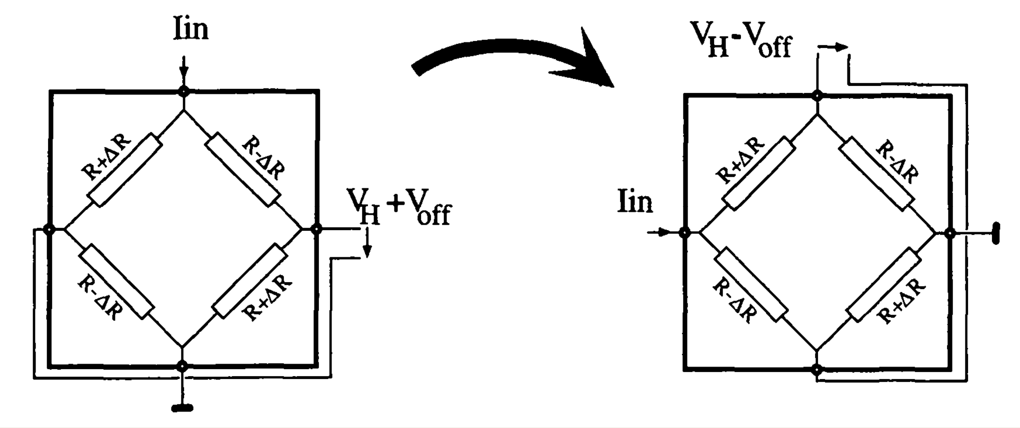
Offset reduction by orthogonal coupling

Principle : Mutual compensation of asymmetries.

When the current is turned off by 90°

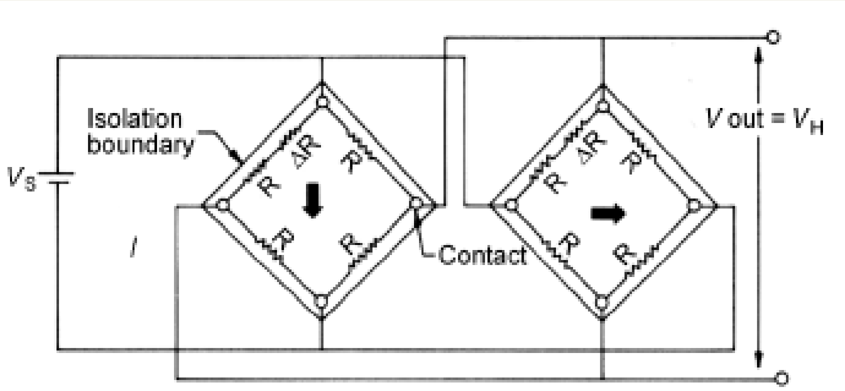
-Offset inverted

-V_H remains the same.



Devices electrically connected in parallel with orthogonal current directions

Coupling of 2 sensors

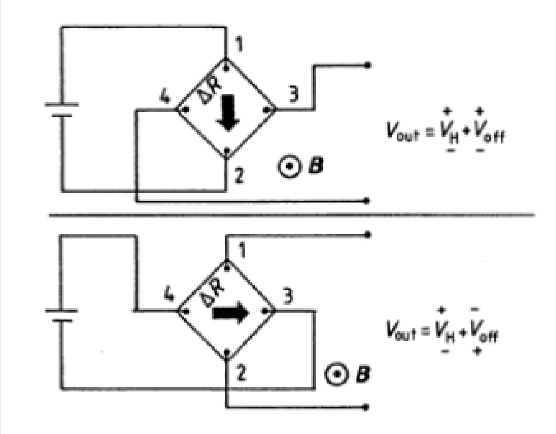


From Popovic [3]

- 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.

Offset reduction by "Spinning current technique"



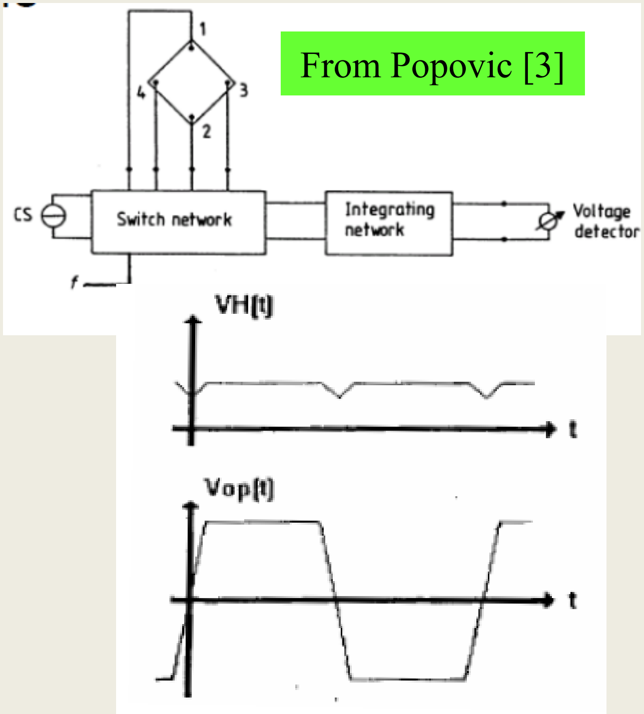
- **Goal** : Minimize V_{off} (also the 1/f noise and the V_{planar} contribution)

- **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

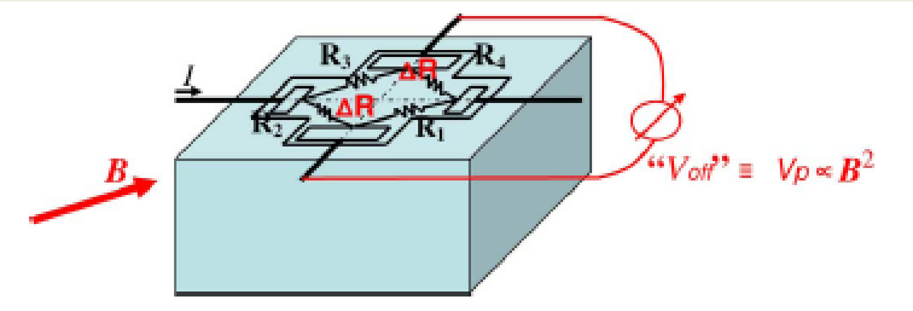
- **Result** : **V_{off} appears as AC voltage and V_H like a DC one, AC part can be filtered.**


From Popovic [3]

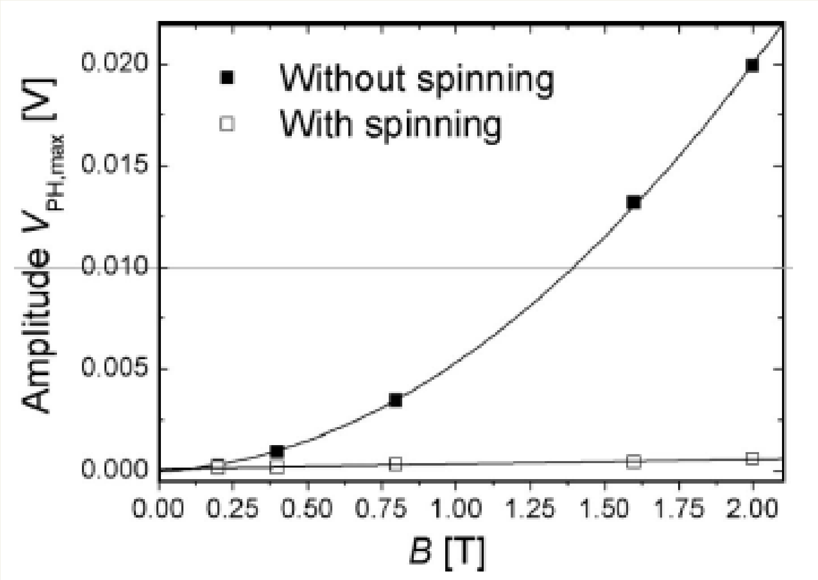
Residual offset equivalent to 10-100 µT

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 ΔR for direction perpendicular to B
- V_{PH} treated like the offset in voltage



Reduction of the planar voltage V_{PH}

Without a spinning current, the ratio

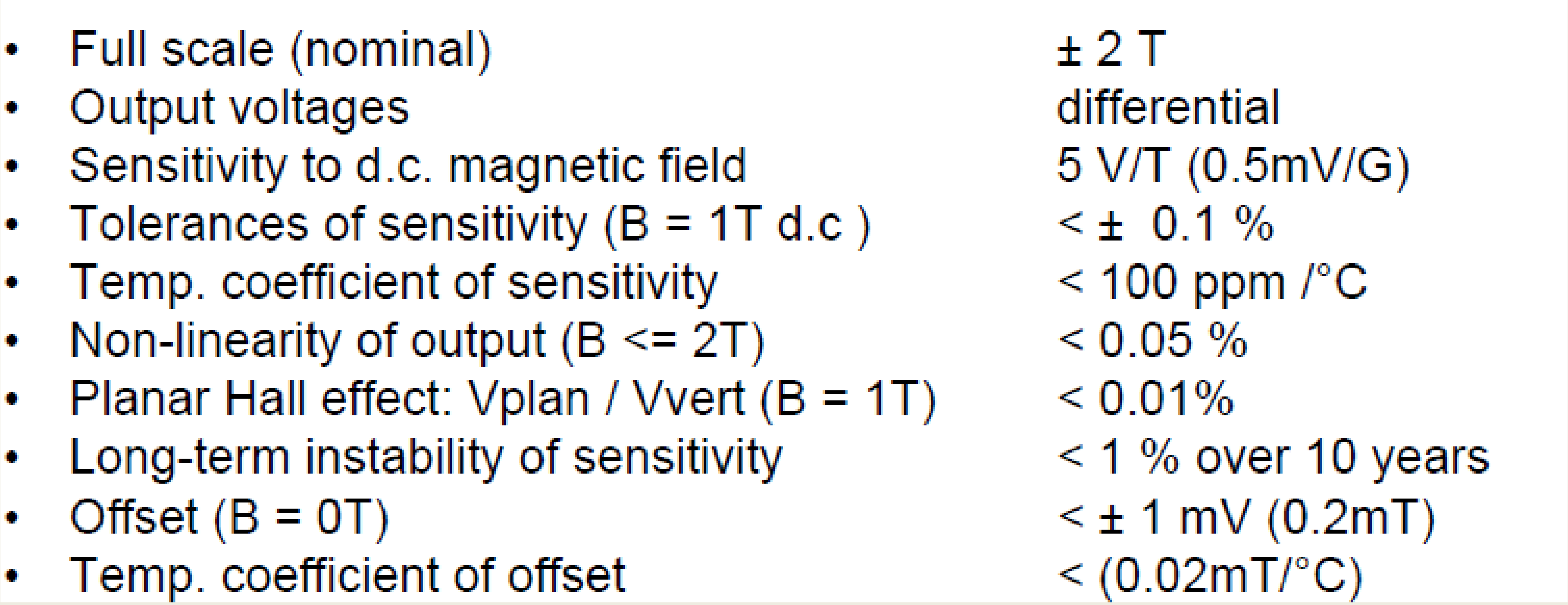
$$V_P / V_H = 1.3\%;$$

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

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

Three axis Teslameter specifications

Example of the SENIS 3-Axis Teslameter



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

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**

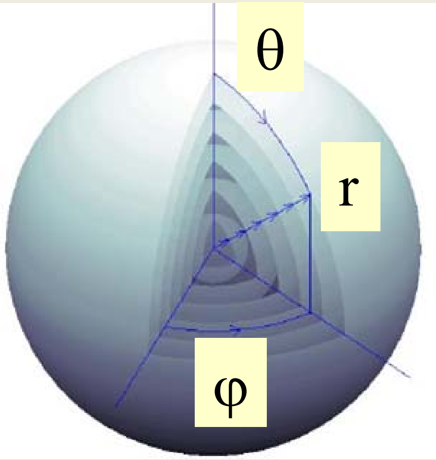
Overview of a 3D calibration method

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 , θ and φ should be measured very precisely [0.02 mrad] by 3 small coils. |B| from NMR coils
- Decompose the Hall-voltage in orthogonal functions: spherical harmonics for θ and φ, Chebyshev polynomials for |B|.
- Repeat for several field strengths and temperatures.
- Find the coefficients c_{klm}, d_{nlm}



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

Solve inverse problem :

$$\left.\begin{array}{l}\text{Vhall}_1,\ \text{Vhall}_2,\ \text{Vhall}_3,\ T\\ \\ \\ c_{klm},\ d_{nlm}\end{array}\right\}\ \Rightarrow\ \ B_x,\ B_y,\ B_z$$

Measurement of 3 x V hall and T at θ, φ = n x 22.5 degree

Y00 = offset

Y10 = cos Θ
Y11 = 0 by rotation

Y20 = non-linearity
Y21
Y22 = planar Hall effect

Y30 = non-linearity
Y31
Y32 = 3D? Hall effect
Y33

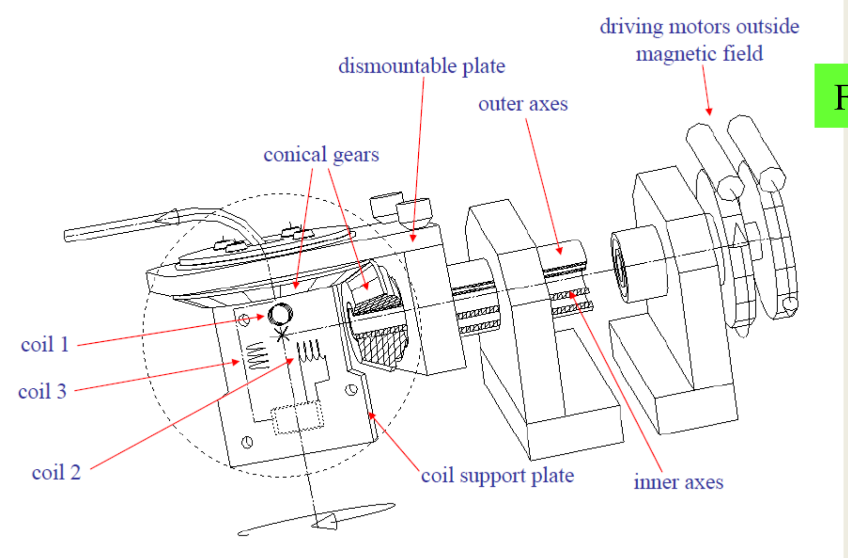
Y40 = non-linearity

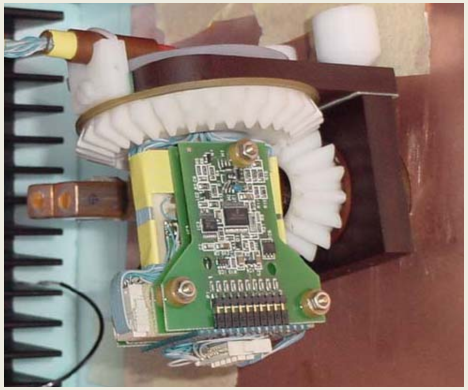
F. Bergsma "Calibration of hall sensors in three dimensions", presented at 13th IMMW 2003, Stanford, California [17]

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

3D Magnetic sensor calibrator

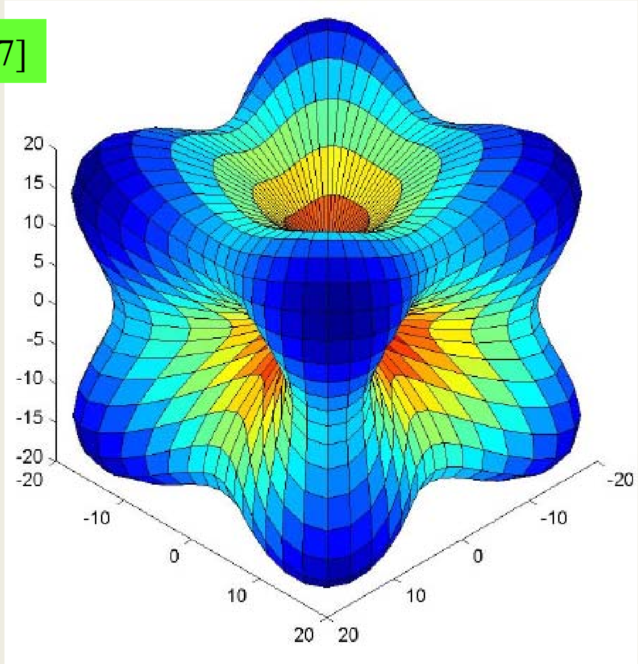
Calibrator (Patent 7259550)





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

From Bergsma [17]



Scale in Gauss

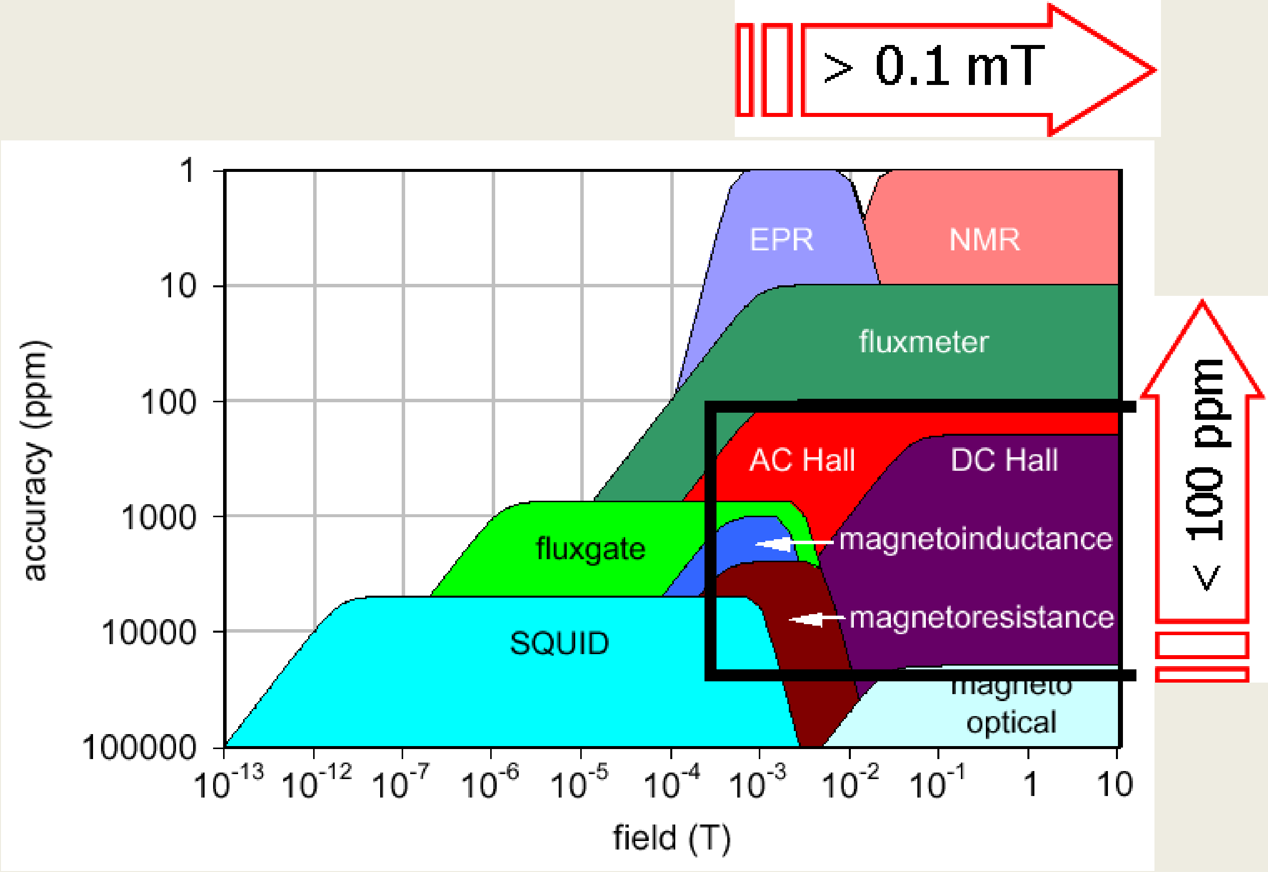
Plotted in figure: |Bold-Bnew|(θ,φ)
Color scale = |Bold|-|Bnew| Blue = -31 Gauss. Red=0
No error along the axes, 2°/oo off axes

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

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..



From Bottura [8]

Accuracy Medium: 10^{-4} to 10^{-2} of the reading range

Field range : mT…20-30 T

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 (~0.01%)., resolution ~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

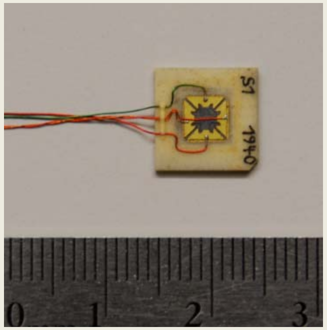
Sextupole measurements in the 15 m long LHC dipoles during injection phase.

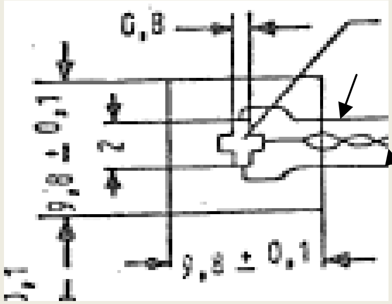
Field measurements in Insertion Devices

Undulator measurements at the Paul Scherrer Institute.

Hall probe measurements at the Paul Scherrer Institute

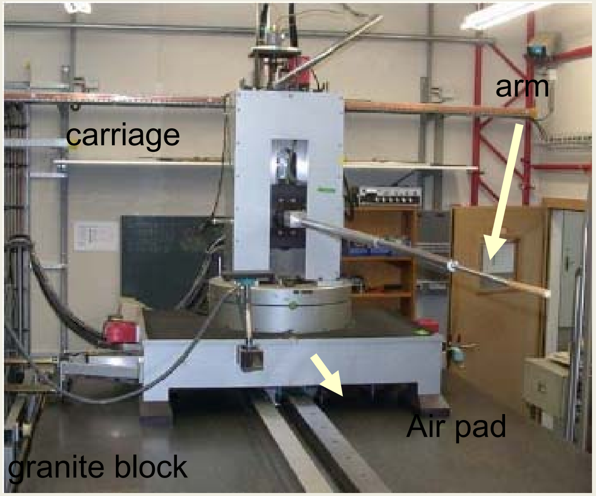
Hall Probe	Siemens SVB 601S1
Semicond. material	InAs
I max	400 mA
U_{Hall}	60 mV@1T
Longitudinal range	2100 mm
Horizontal range	650 mm
Vertical range	360 mm
Long./Transv./Vert. Resolution	10 mm
Maximum calibrated Field	3.1 T
Hall Probe absolute accuracy	100 ppm
Hall probe resolution	1 µT
Temperature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





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)**

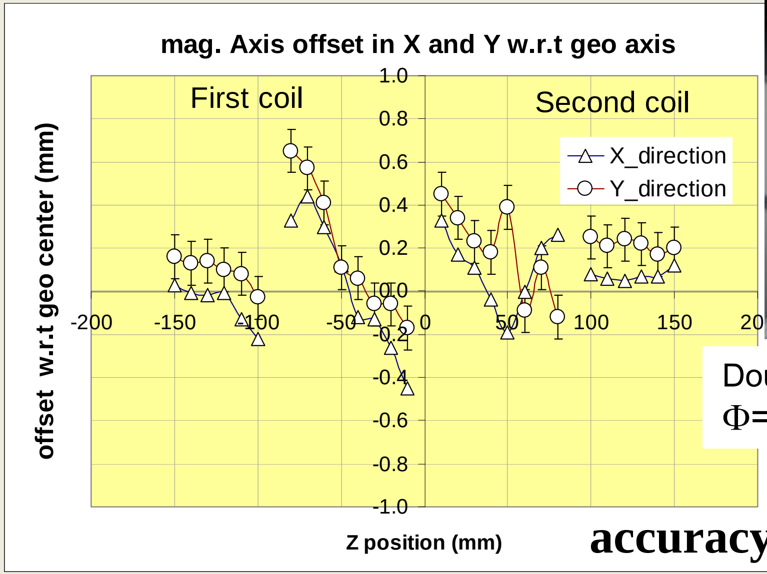


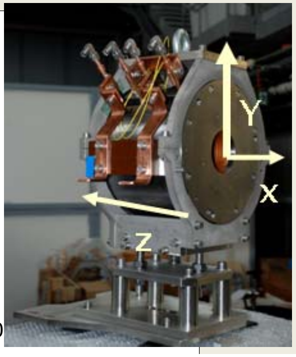
Digital multimeters (2)

Set positions
X 0.0
Y 0.0
Z 0.0
Phi 0.0
Psi 0.0
PS MSG1
Set 0.0
0.0000 0.0000 0.0000
0x1A00 = Remote Off EXT INT
Status line
LoopTime 12704
CurrentState 0
LastStatus 0
X -0.0040
Y -0.0125
Z 105.9520
Phi 0.0167
Psi 0.0025
ADC[0] nan
ADC[1] nan
ADC[2] nan
ADC[3] nan
7

Program interface

Hall probe measurements at the Paul Scherrer Institute (2)



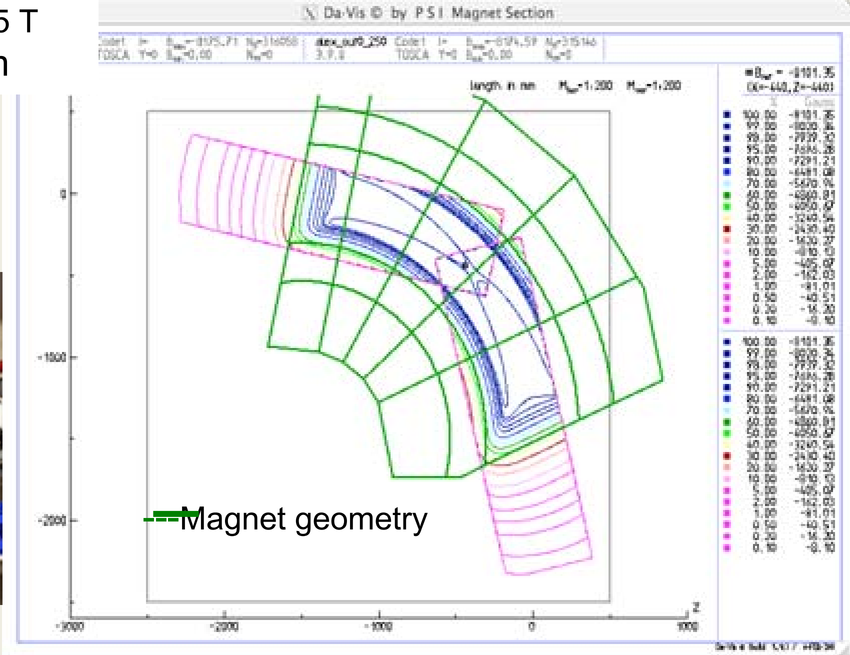


Double Solenoids 0.25 T

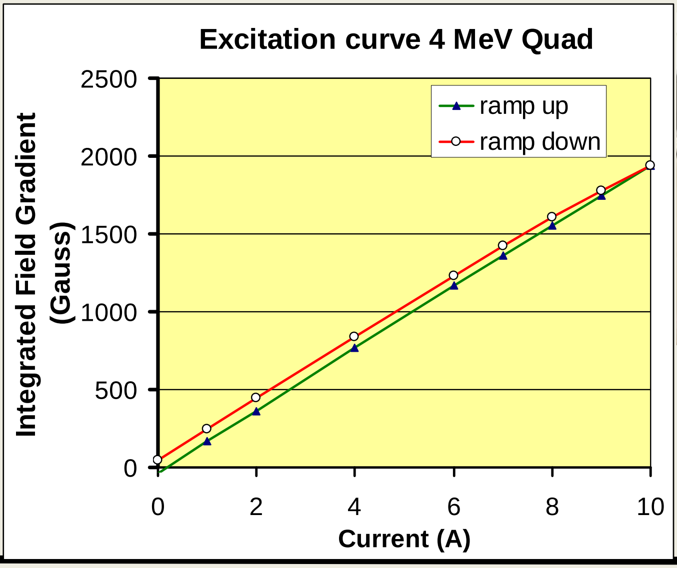
Φ=80 mm, L=0.2 m

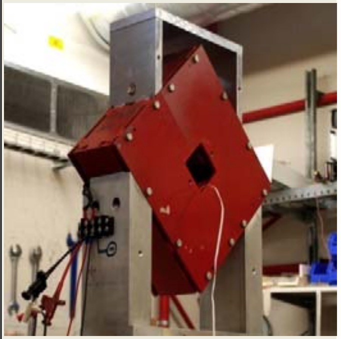
accuracy: 0.1 mm

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



Field contour plot (B=0.8T)
AMF3 dipole mid-plane



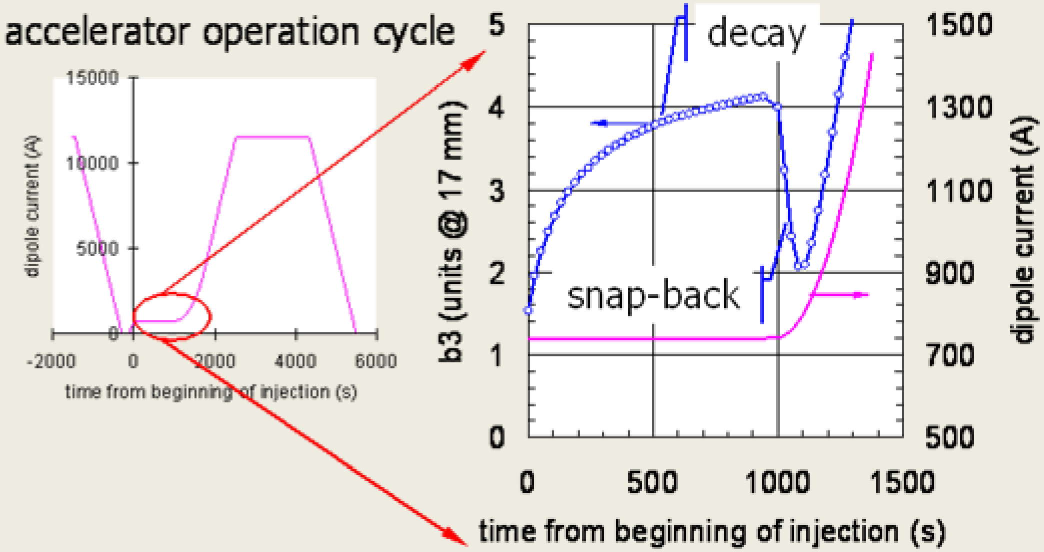


Quadrupole for 4 MeV

phase of the PSI-XFEL.

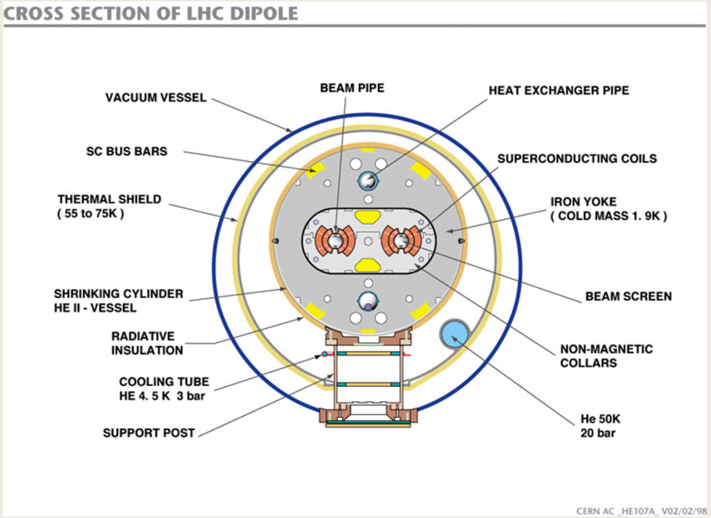
accuracy: 1 gauss

b3/b5 snap back measurements in LHC cryo-dipoles



Δb_3: 100-300 ppm

Snapback phenomena duration: 30s



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

Standard tests:

15-m long rotating coils (0.1 Hz)

One point every 10s…

Not enough!

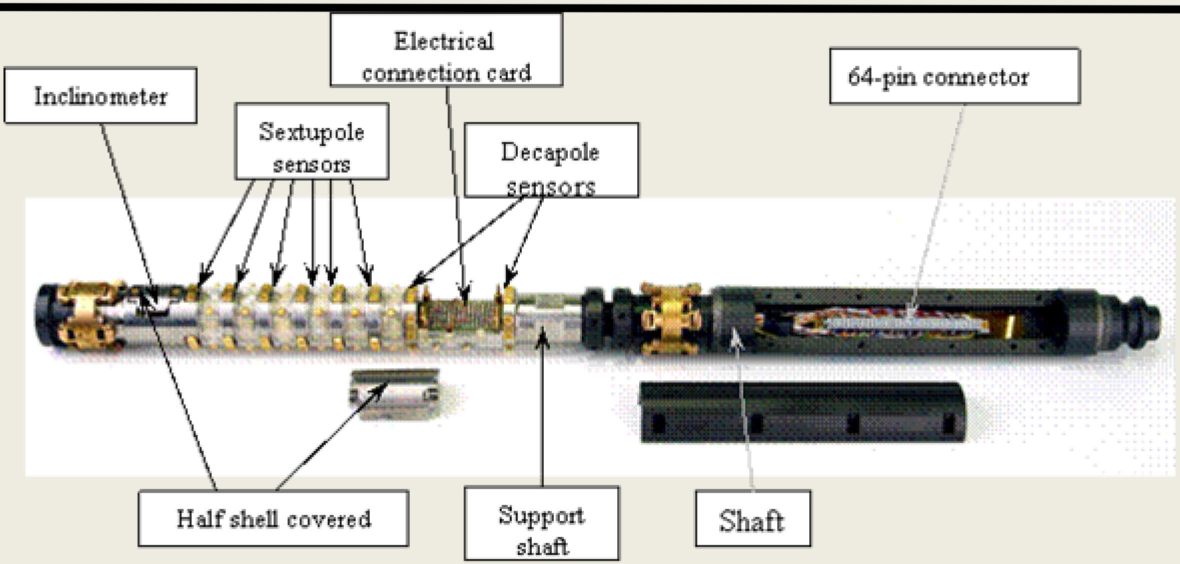
New instrument

Challenge with unique issue: time resolution (3 Hz)

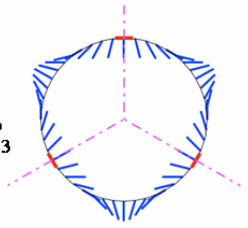
- **Resolution: few μT at least**
- **Measurement frequency: 3-10 Hz**
- **Measurement uncertainty~ 0.5 μT**

b_3/b_5 harmonic hall probe

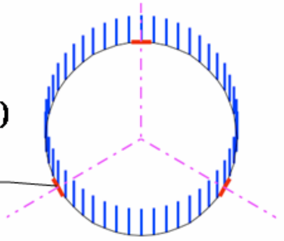
AREPOC LHP-NU (Slovakia)
- **Made of InSb**
- **Active area 0.6 mm^2**
- **220 mV/T at 50 mA**
- **Non linearity (0..1 T) : 0.2%**
- **Small Temp coeff: 10^{-4} K^{-1}**

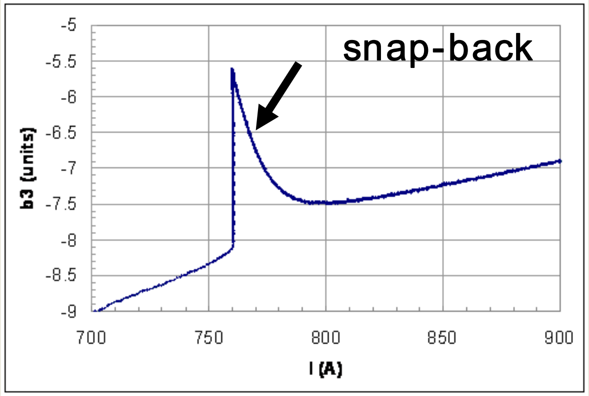


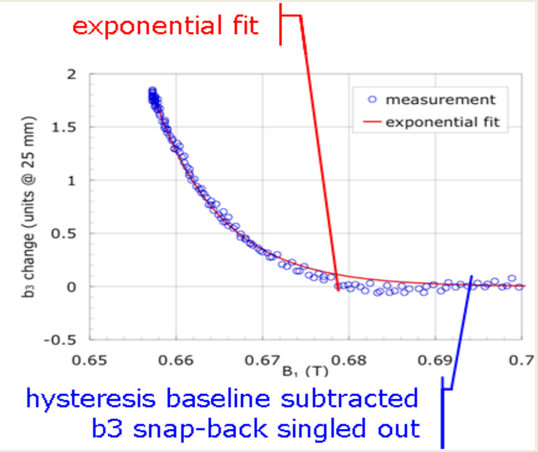
$$V = \sum_{i=1}^{3} V_i = \sum_{i=1}^{3} gB_i \approx 3gB_3$$



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





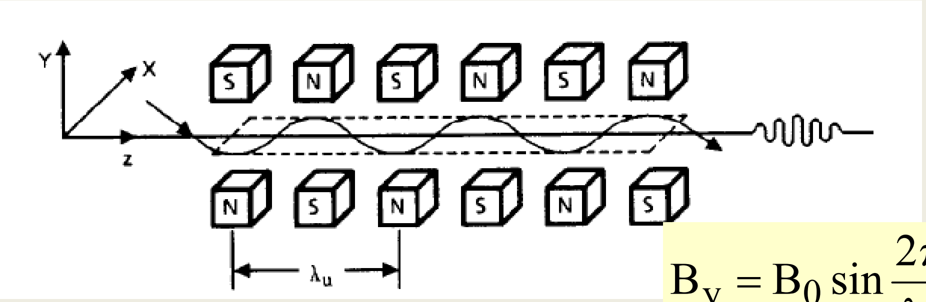


L.Bottura, T.Pieloni, N.Sammut, S.Sanfilippo et al.., CERN (2003-2007) [19]

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



$$B_y = B_0 \sin \frac{2\pi s}{\lambda_u}$$

Undulator parameter

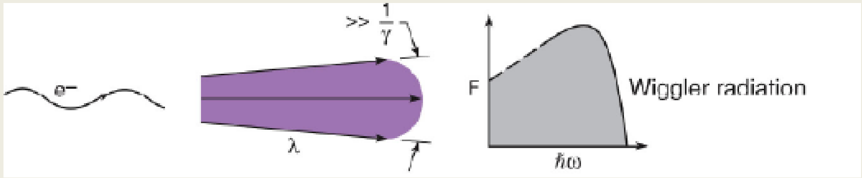
$$K = 0.0934 \cdot B[T] \cdot \lambda_u[mm]$$

Constructive interference of radiation emitted at different poles

wiggler - incoherent superposition K >> 1

Max. angle of trajectory > 1/γ

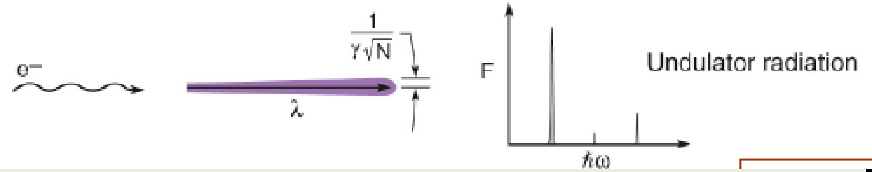
Broad band radiation, Intensity proportional to N



undulator - coherent interference K << 1

Max. angle of trajectory < 1/γ

Narrow band radiation, Intensity proportional to N



Quasi-monochromatic spectrum

Technology used for Undulator and wigglers :

- Permanent Magnets (NdFeB, Br=1.2-1.4T) or Sm_2Co_{17} (Br=1.05T)
- Electromagnet technology for long period undulators
- Superconducting technology for field higher than 2 T

From Elleaume and Onuki [20] and Shepherd [21]

Magnetic field specifications

To minimise the perturbation to the stored beam:

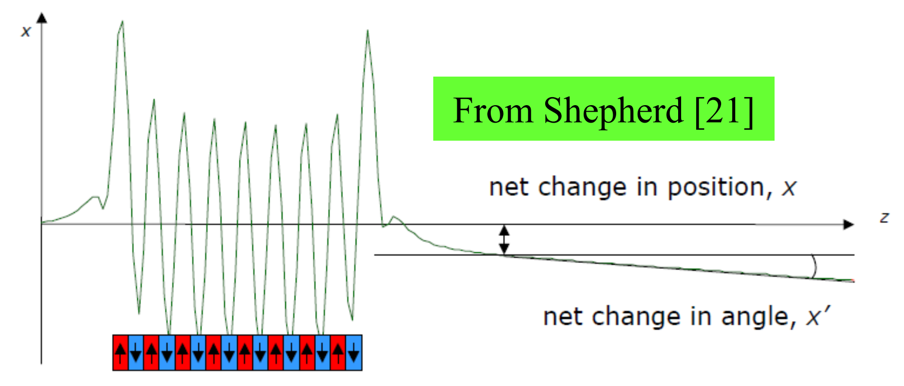
- Integral of field over length of ID
- Exit position and angle of electron beam

a) $$x' = \frac{-e\,c}{E}\int B_y\,dz$$

angle ↔ 'first field integral'

b) $$x \equiv \int x'\,dz = \frac{-e\,c}{E}\int\!\!\int B_y\,dz\,dz$$

position ↔ 'second field integral'



From Shepherd [21]

Measured with a stretched wire!

To maximize the spectral properties:

Magnetic field at each point to know the path of electron.

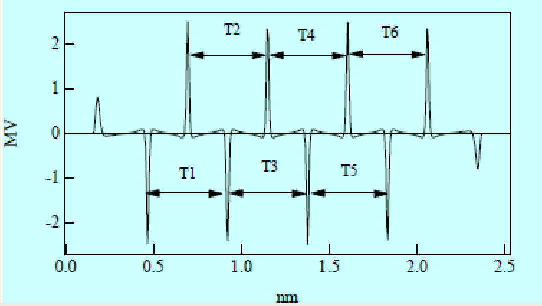
Keep the **phase error** low (1..2 degrees)

(**incomplete constructive interference, reduces the Angular flux**)

c) Phase error

$$\phi \propto \frac{\pi}{(1+K^2/2)}(1+\frac{2\gamma^2}{\lambda_0}\int_{\lambda_0/2}(\int_{-\infty}^{z} B_y(z).dz)^2 dz$$

Electric field produced by one electron



$$\textit{Phase Error} = \varphi = 2\pi\frac{\sigma_T}{\langle T\rangle}$$

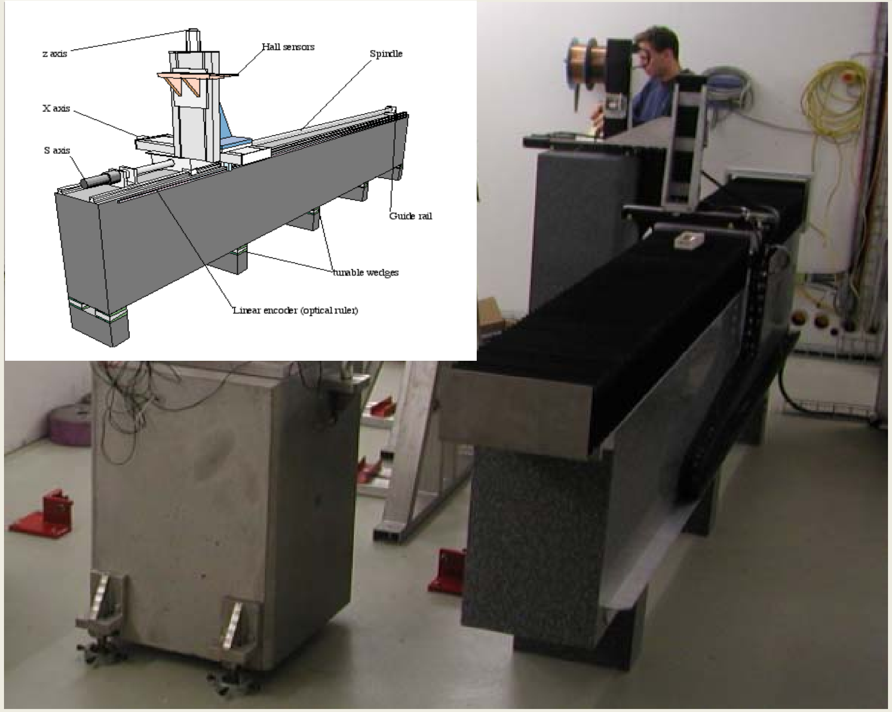
Origins of the phase error:

- Peak Field fluctuations
- Period fluctuations
- Field Shape fluctuations

From Elleaume [21]

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

Undulator measurements at the Paul Scherrer Institute (1)



Hall probe bench (ESRF design) :

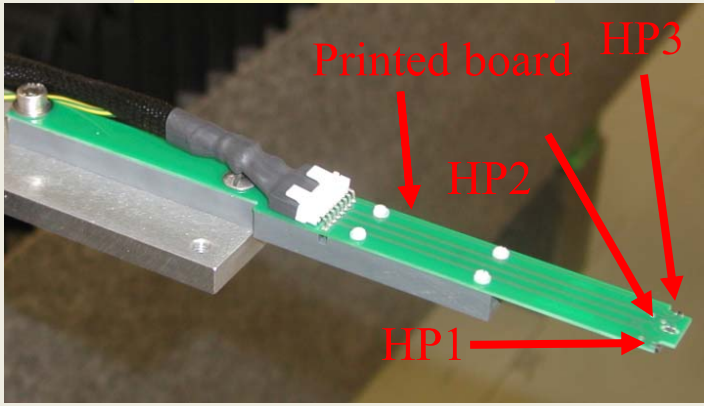
- •4 m granite support (350 x 600 mm^2, width, eight), flatness 15 µm
- •Anorad linear motor mounted on the granite
- •Heidenhain linear encoder
- •longitudinal movement (3.5 m, 0.1 µm resolution)
- •Accuracy of the sensor position <20 µm (after software correction based on laser calibration)

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)

Hall probe keeper

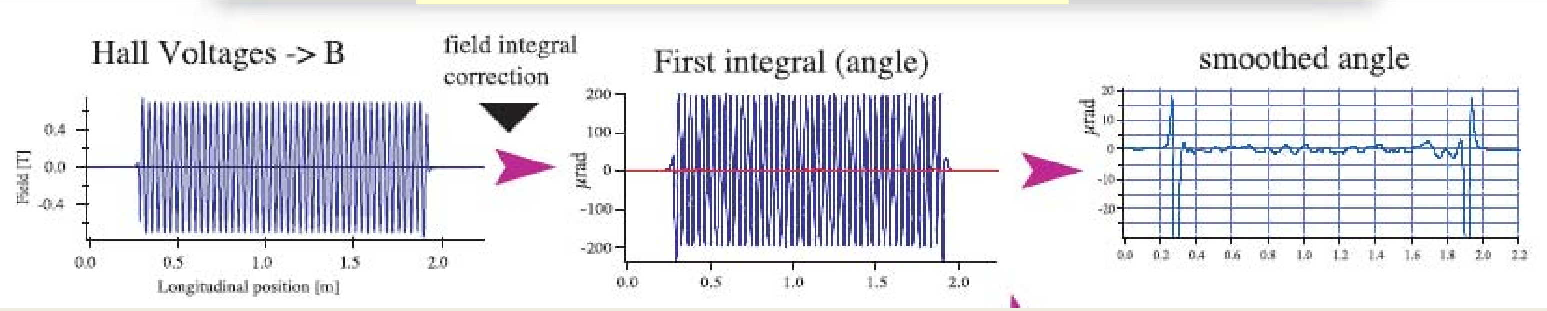


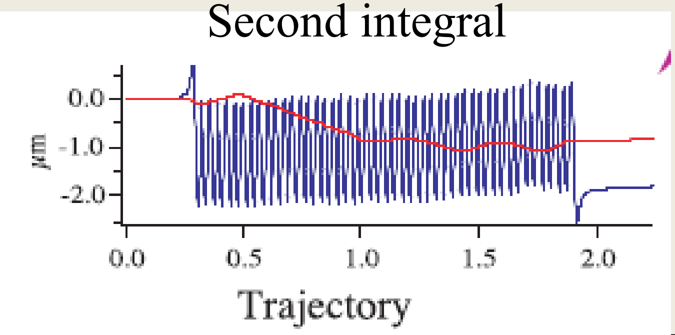
Courtesy of T. Schmidt

Undulator measurements at the Paul Scherrer Institute (2)

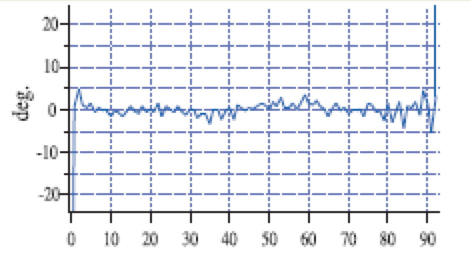
- Hall measurements based on a calibrated 3x D Hall sensor from SIEMENS and SENIS
- **On-the Fly scanning** is essential to reduce the sensor vibration (precision) and reduce the measuring time. Speed up 30mm/s, 2000-5000 points per components
- Typical scan : L=2500 mm, 1pt/mm/comp, speed=20 mm/sec. 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:





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 measureable 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 ….**

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- Dragana and Radivoje Popovic, SENIS GmbH Zürich

Any questions?

Announcement

Paul Scherrer Institut

16th International Magnetic Measurement Workshop

IMMW16

Scope

- Magnetic field measurements on accelerator magnets and insertion devices
- Field measurement techniques
- Field measurement devices

26-29 October 2009

Park-Hotel Bad Zurzach, Switzerland

http://immw16.web.psi.ch/

Paul Scherrer Institut

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/

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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.

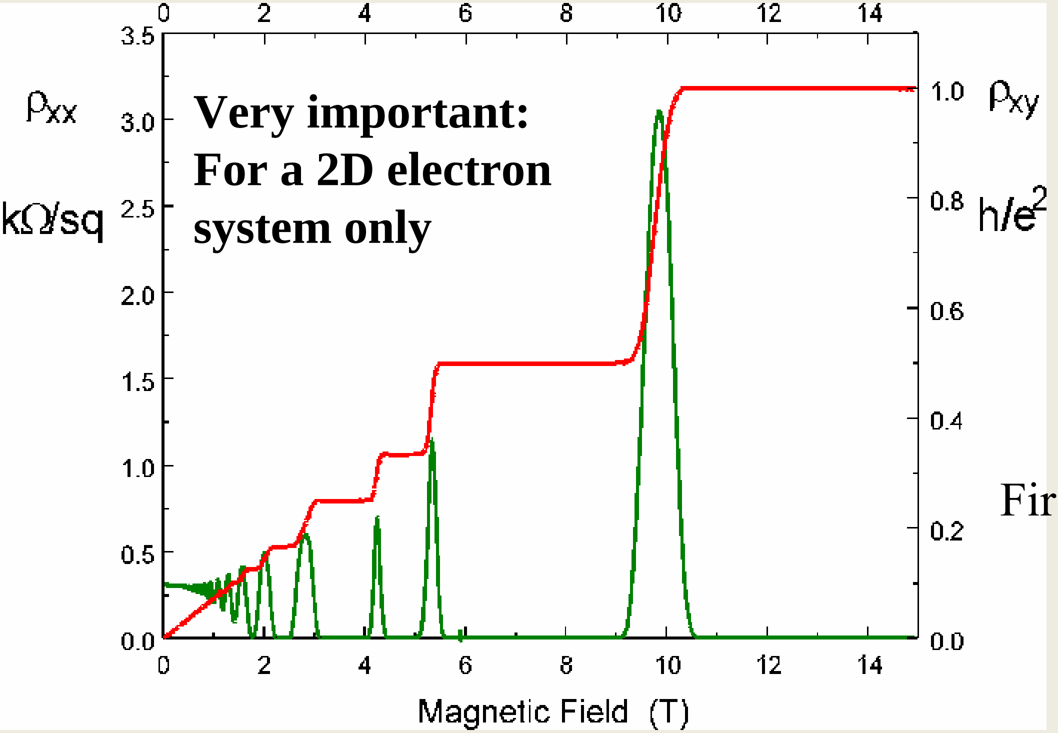
Accuracy: Degree of correctness of a measured value compared to the true value. It may be represented in percent of the input full scale.

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



Very important:
For a 2D electron system only

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

In low temperature and strong magnetic field

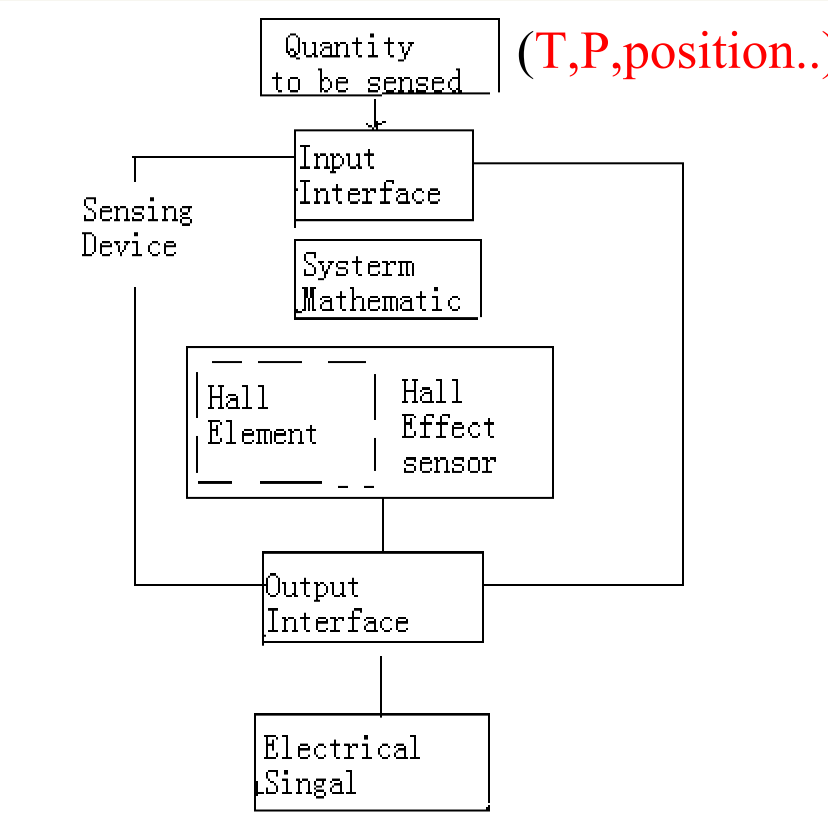
$$R_H = \frac{R_K}{n}\ ,\ n = 1,2,3,\cdots \qquad R_K = \frac{h}{e^2}$$

effect as much as 1 % on calibration coefficient

K.von Klitzing, G.Dorda, M.Pepper, Phys.Rev.Lett, Vol.45, 494-1402, 1980

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.

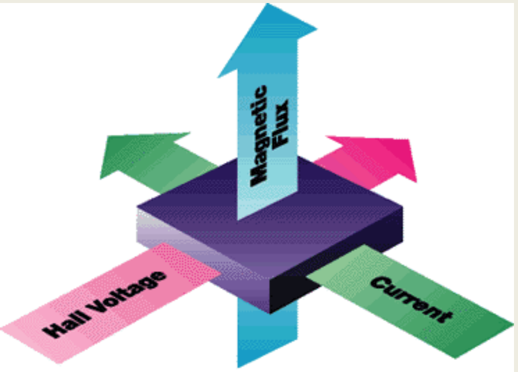


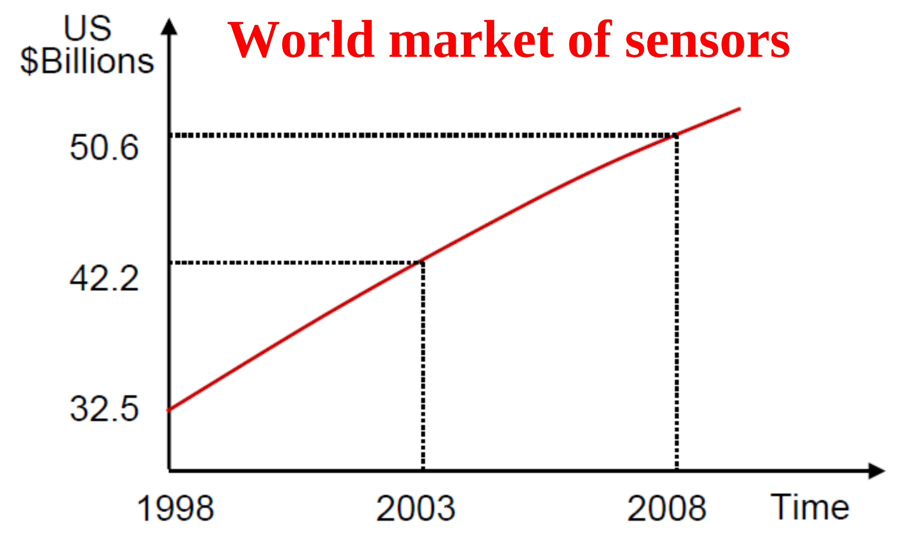
General sensor based

on the Hall effect

Applications of the Hall sensors (2)

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





Courtesy of InTechno Consulting

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

Hall sensors : 80% of the market (2003)

Foreword

Some pictures have been taken from books listed in the references and cited in the figure captions.

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