Overview of Magnetic Measurement Techniques

Animesh Jain
Brookhaven National Laboratory
Upton, New York 11973-5000, USA

US Particle Accelerator School on *Superconducting Accelerator Magnets*
Santa Barbara, California, June 23-27, 2003

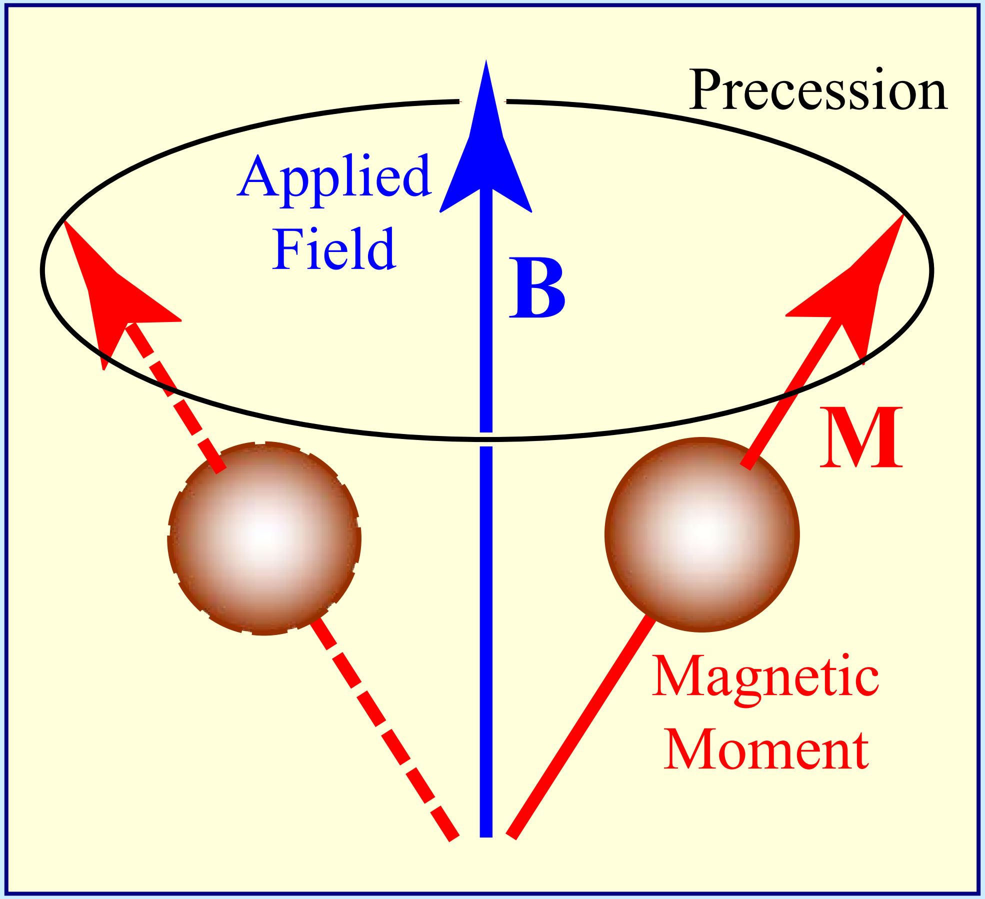
Outline

- **N**uclear **M**agnetic **R**esonance (NMR)/ **E**lectron **P**aramagnetic **R**esonance (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.

NMR/EPR Principle



I = Spin

γ = Gyromagnetic ratio

M = Magnetic Moment
= $\gamma.h.I$

Energy = **B.M**

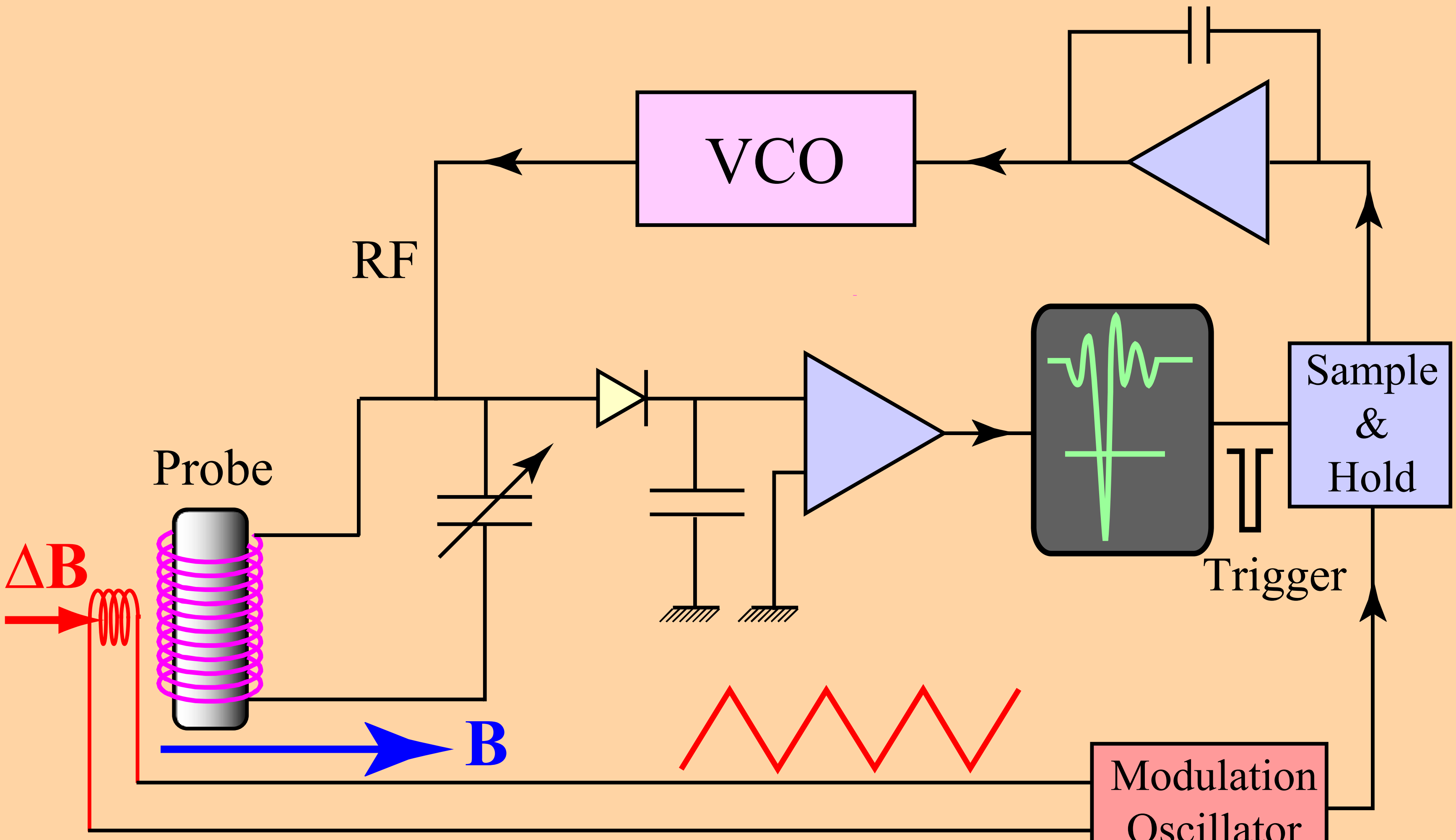
Spin component along the field direction can take integral values from $-I$ to $+I$. $\Rightarrow$ Energy gap = $\gamma.h.B$

Frequency = $\gamma.B$

Gyromagnetic Ratio

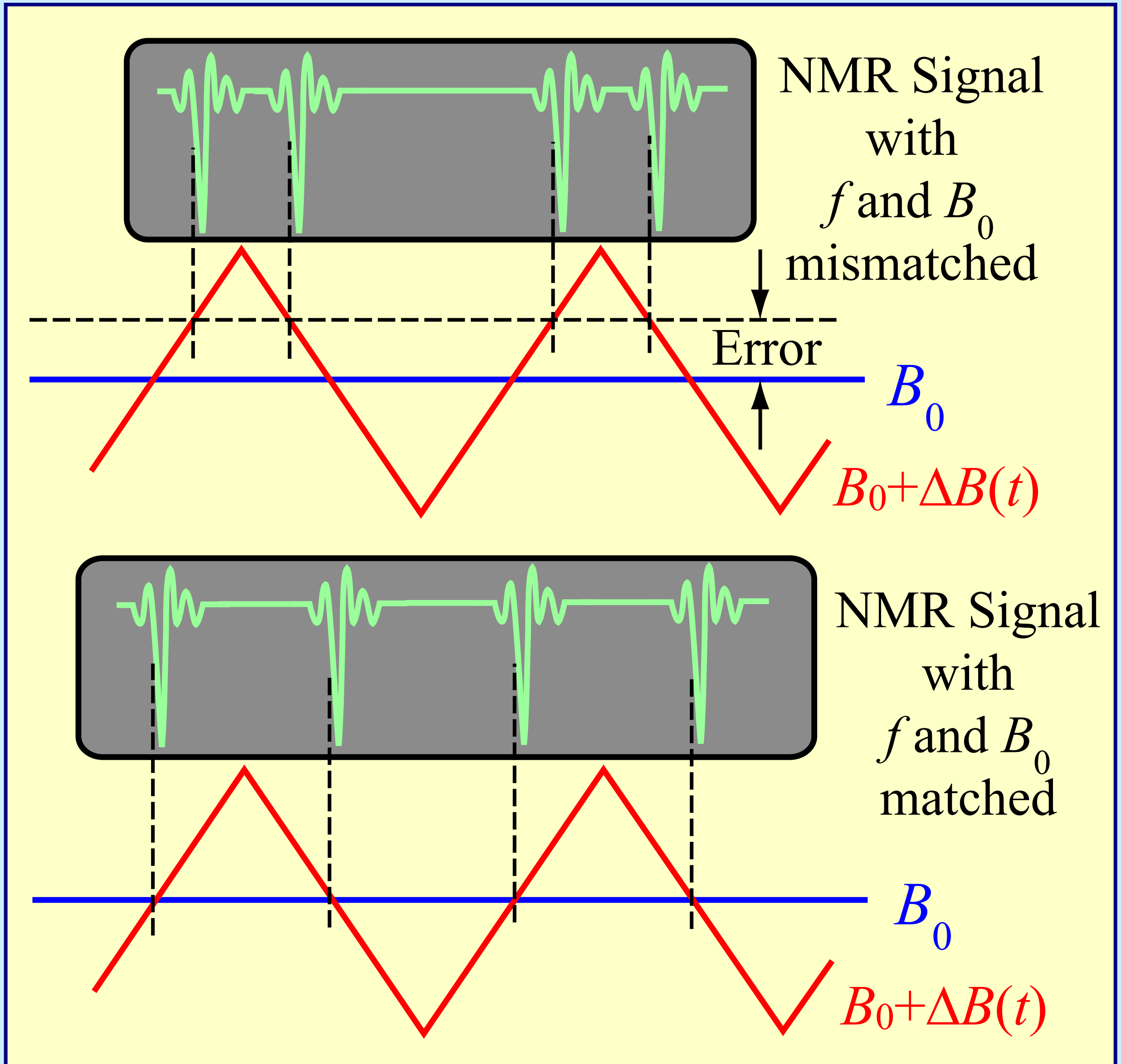
Particle	γ (MHz/T)	Application
e^-	28026.5	0.5 to 3.2 mT
^1H	42.576396	0.04 to 2 T
^2H	6.53569	2 T to 14 T
^3He	32.4336	Cryogenic
^{27}Al	11.0942	Cryogenic

NMR Magnetometer



$\Delta B/B \sim 10^{-4}$ to 10^{-3}; 30-70 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.

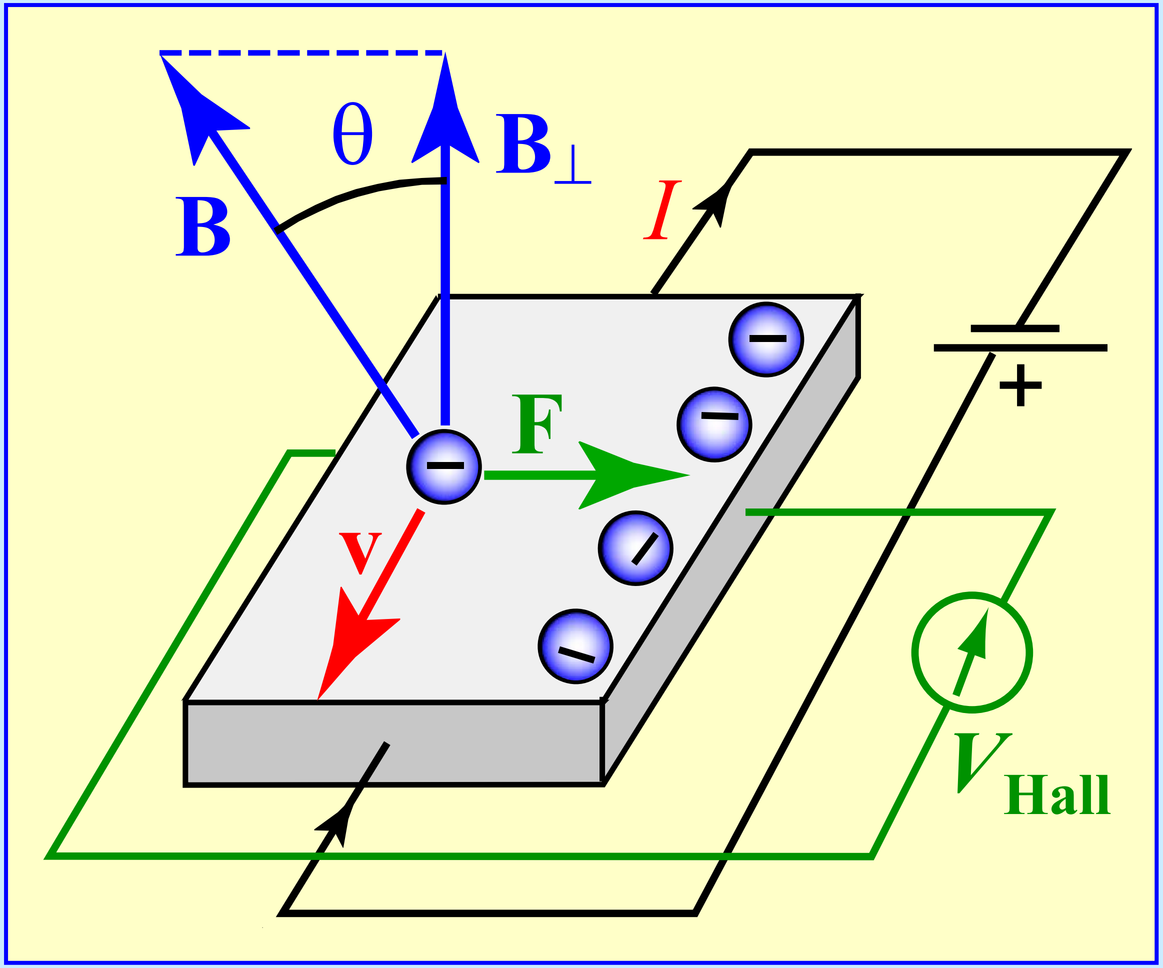
Requirements for NMR

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.

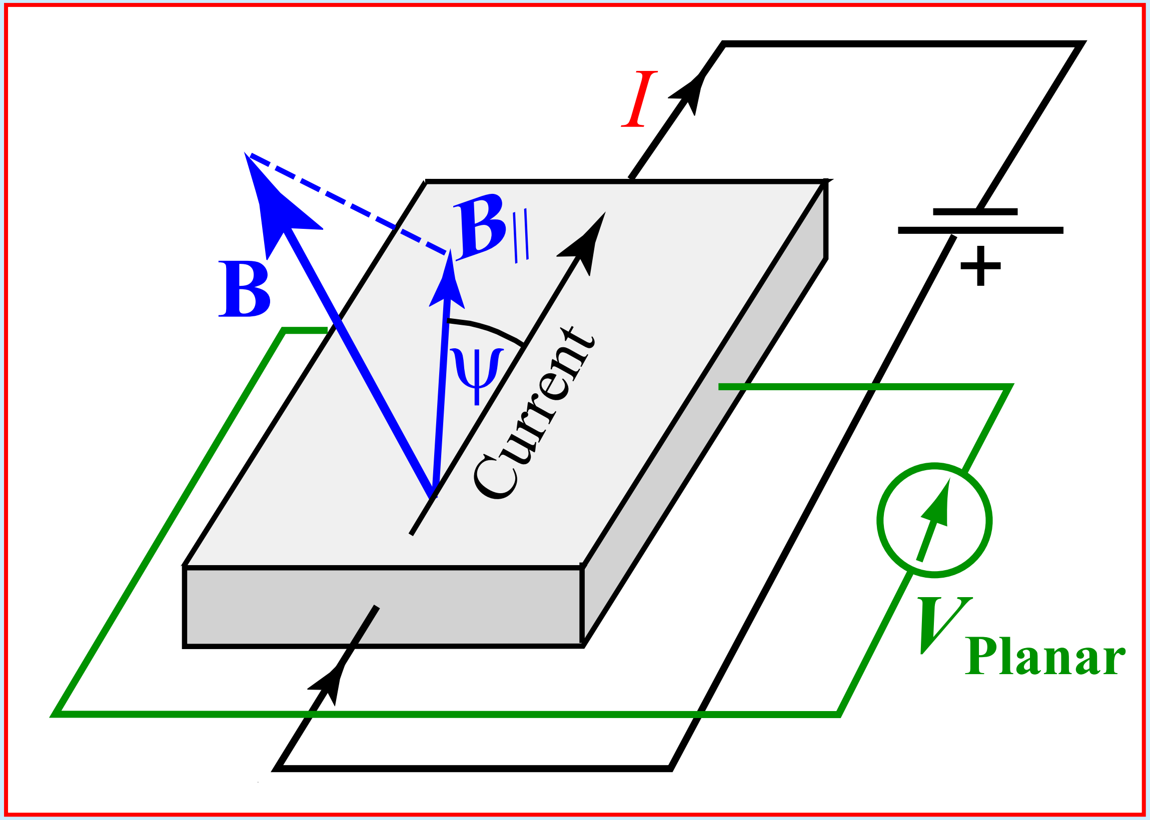
This produces a steady state voltage in a direction perpendicular to the current and field.

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

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:

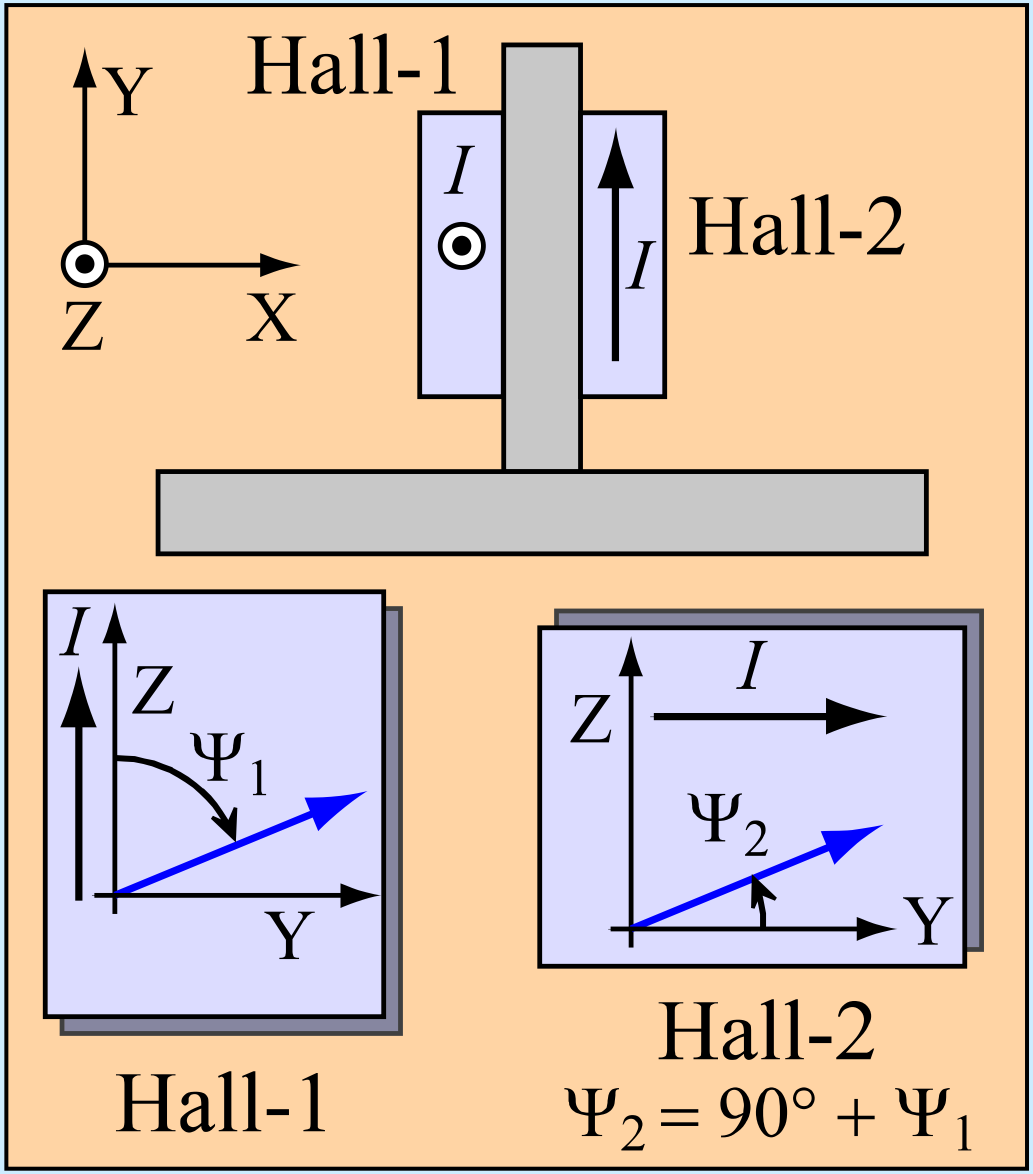
$$V_{\text{Planar}} \propto I \cdot B_{\parallel}^2 \sin(2\psi)$$

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:

$$[\sin(2\psi_1) + \sin(2\psi_2)]$$
$$= 0;\ [\psi_2 = 90° + \psi_1]$$

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

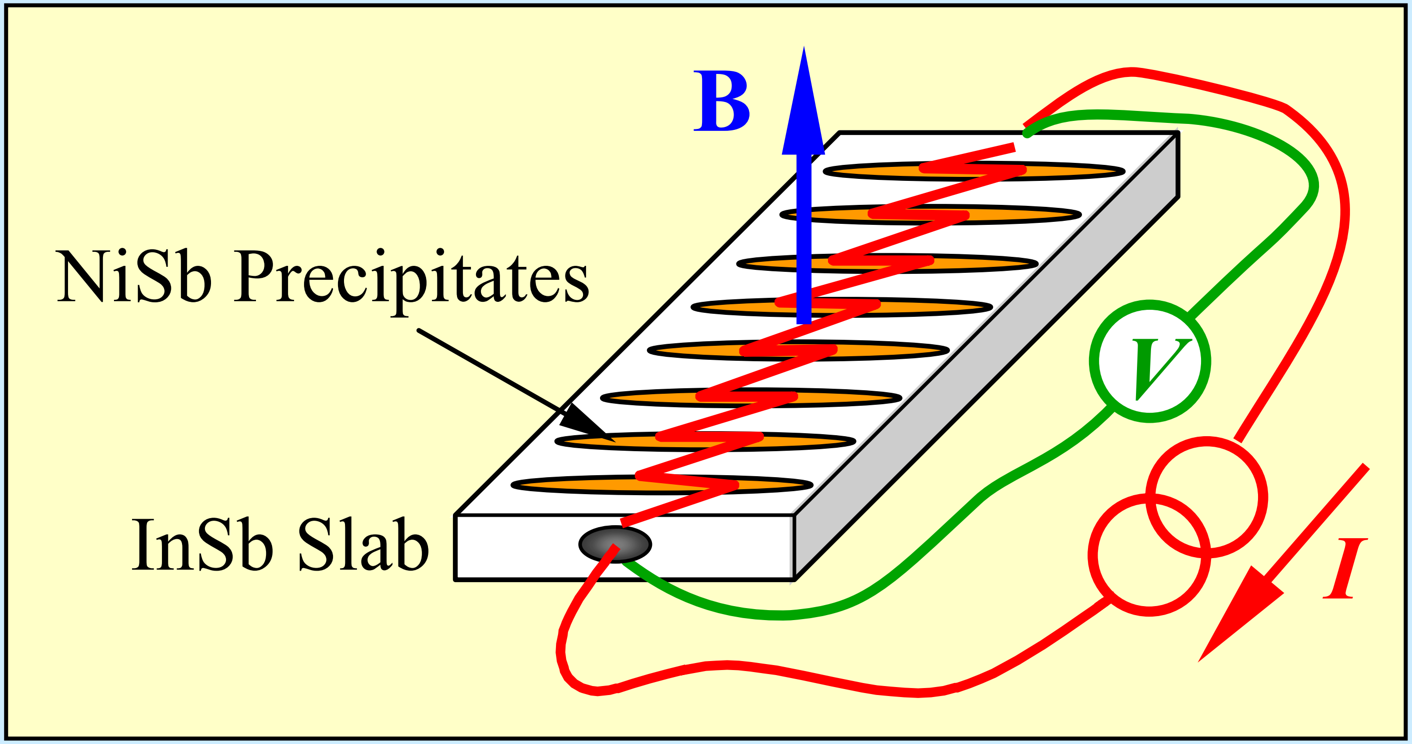
Hall Measurement Advantages

- 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



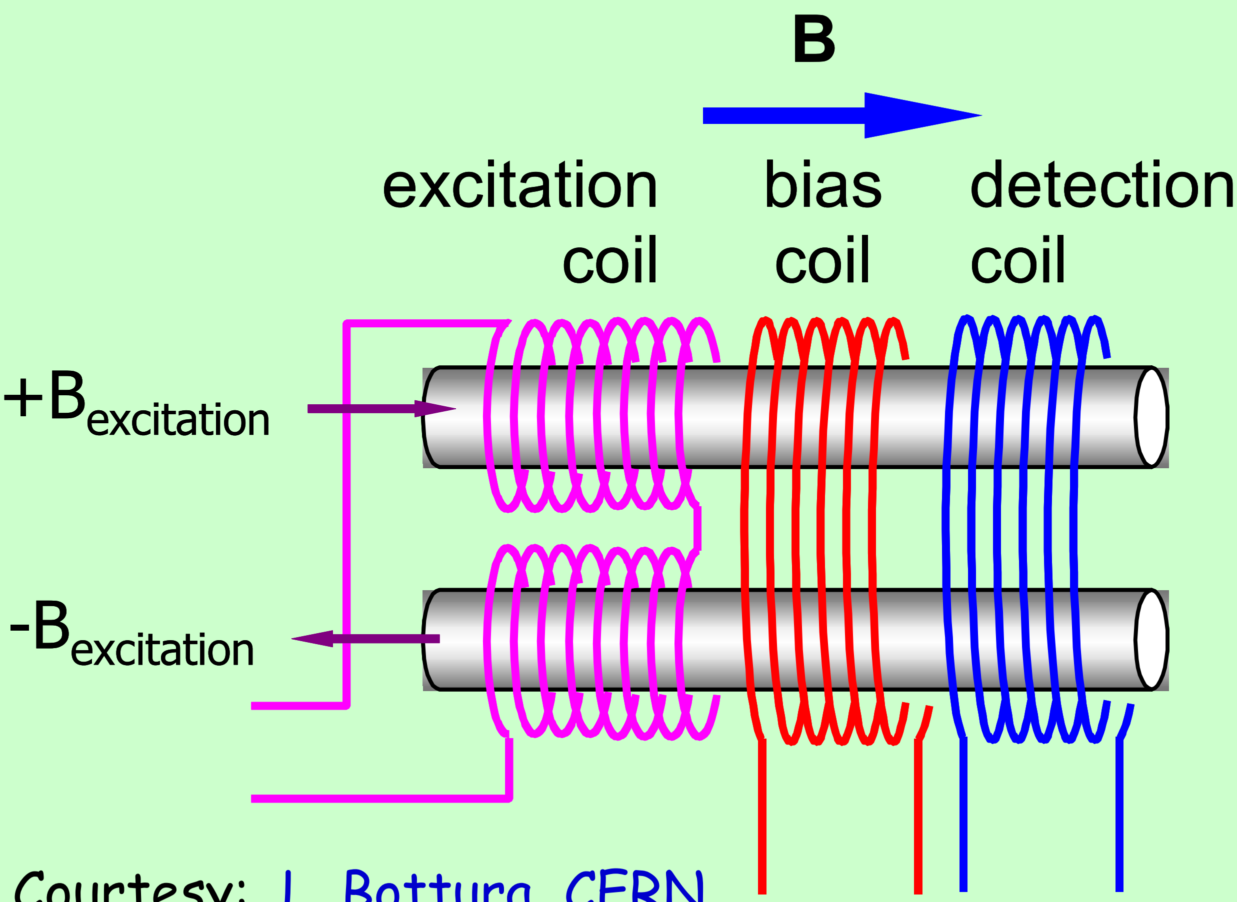
Field bends the current path, thus altering the resistance.

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.

Based on: L. Bottura, *Field Measurement Methods*, CERN School on Superconductivity, Erice, May 8-17, 2002.

Fluxgate Magnetometers



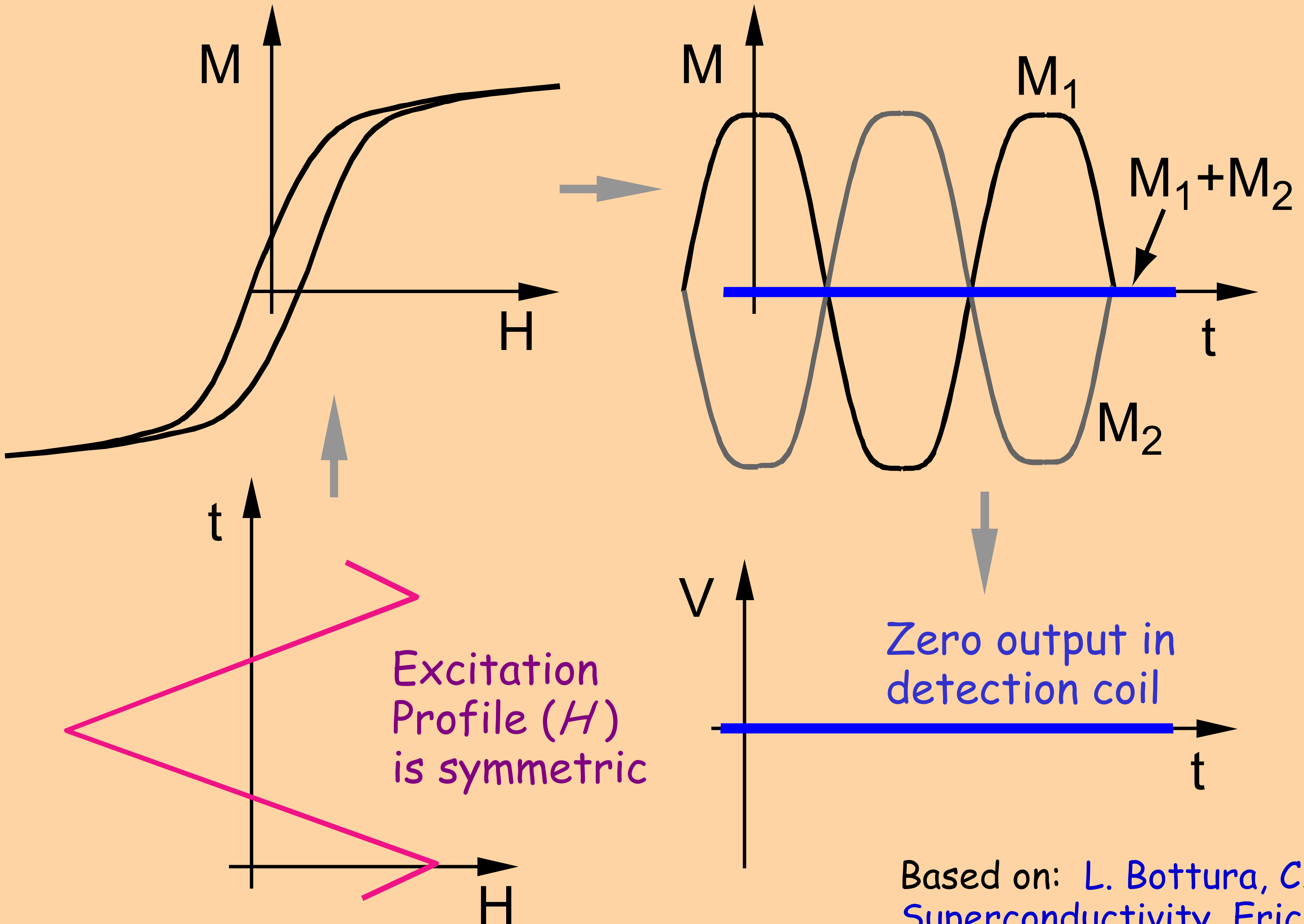
Courtesy: L. Bottura, CERN.

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

Detection Coil:
Detects Zero field condition.

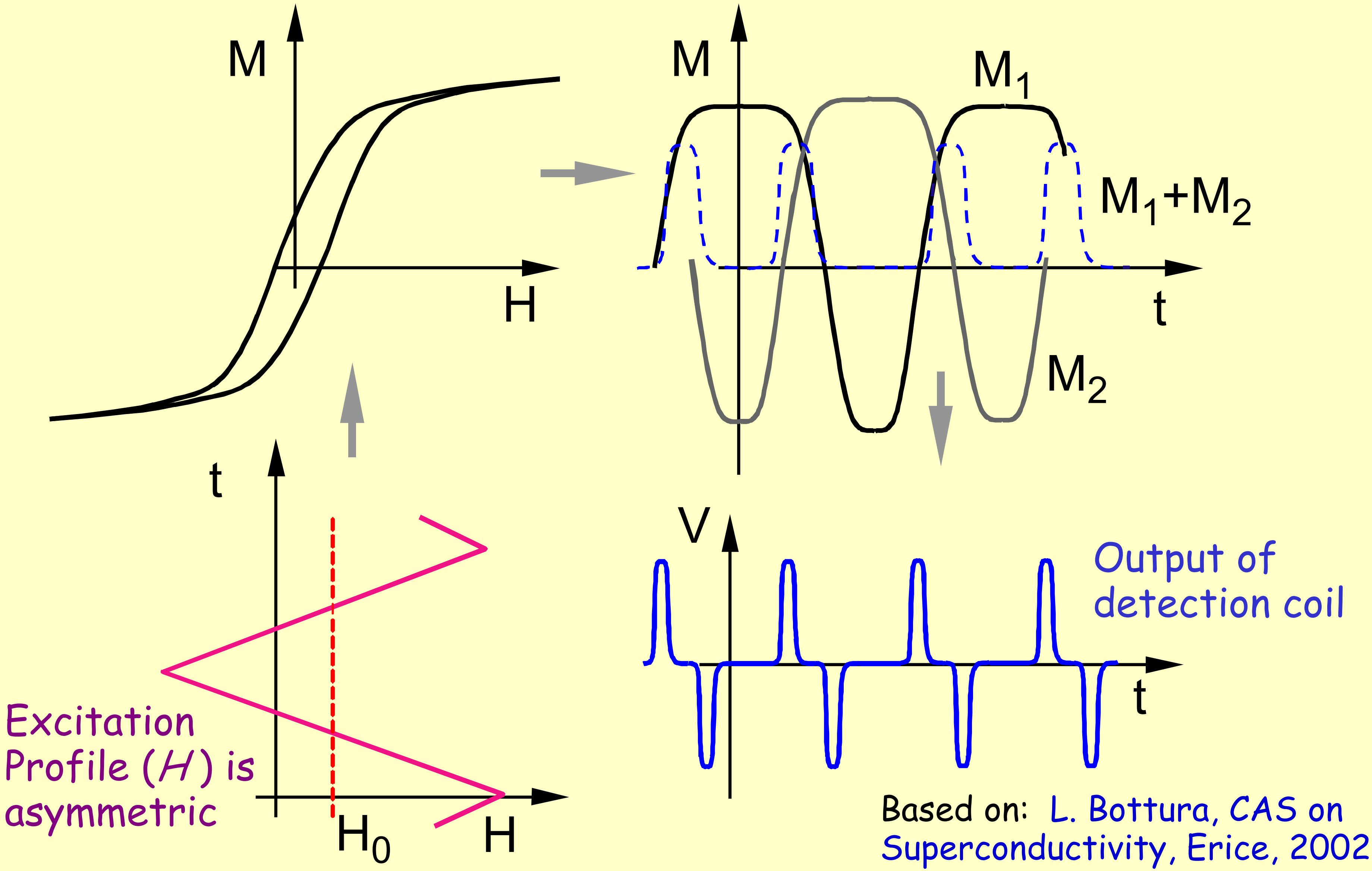
Bias Coil:
Maintains a zero field condition.

Fluxgate Principle: Zero Field



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

Fluxgate Principle: Non-Zero Field

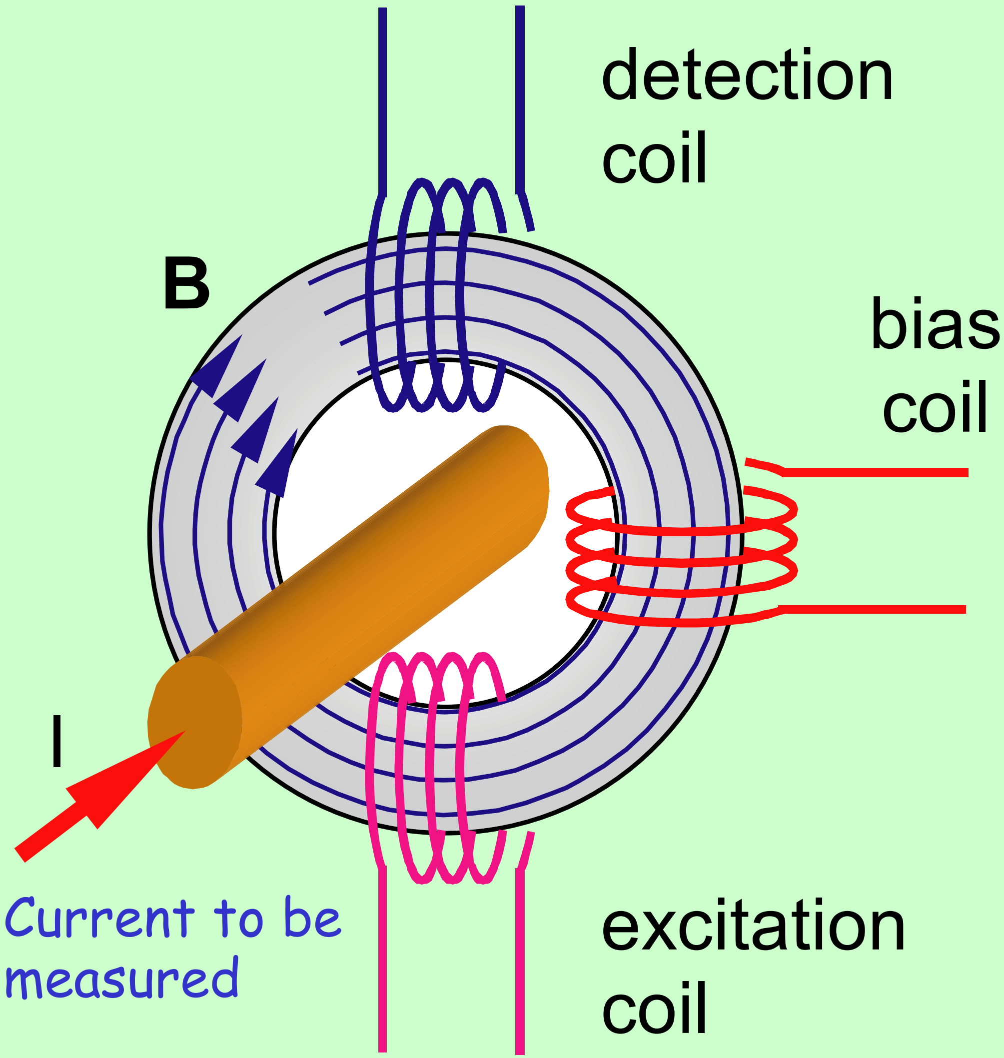


Based on: L. Bottura, CAS on Superconductivity, Erice, 2002

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



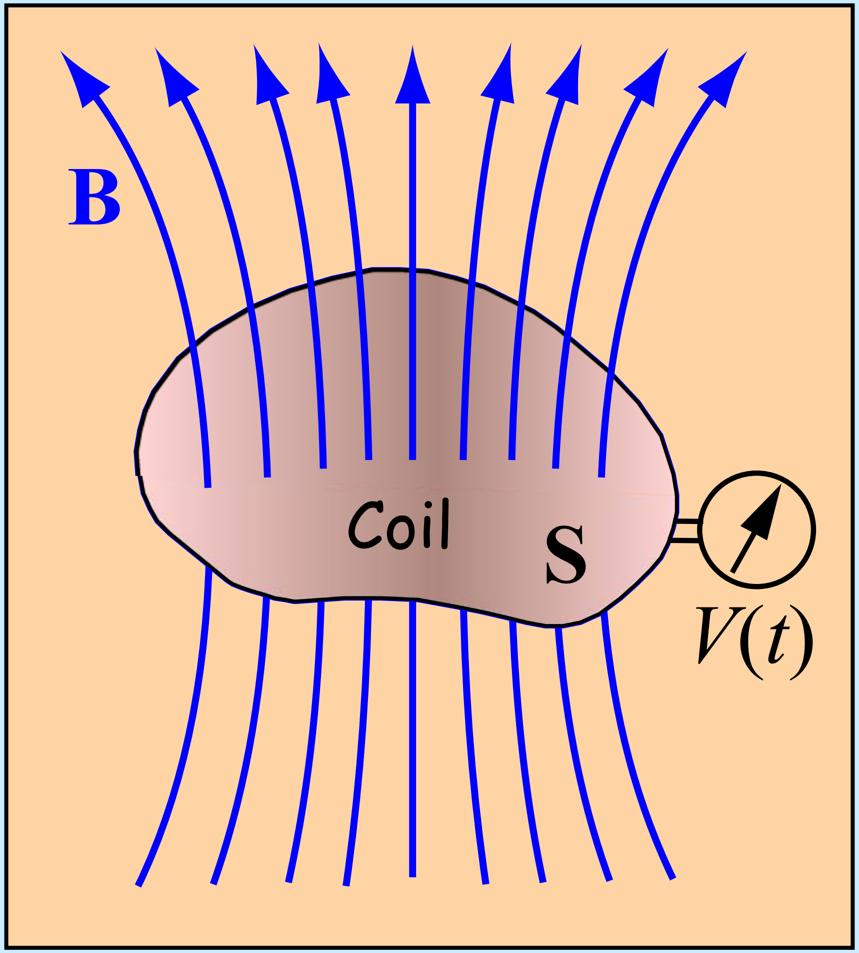
DC Current Transformer

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:

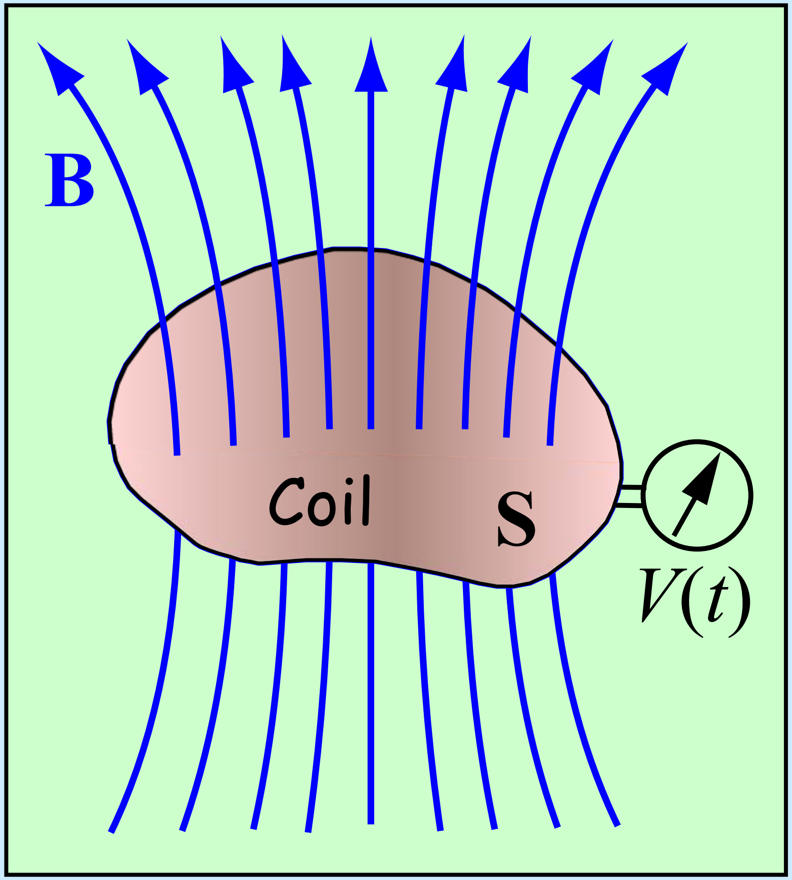
$$\Phi = \int_S \mathbf{B} \cdot d\,\mathbf{S}$$

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:

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

The change in flux is given by:

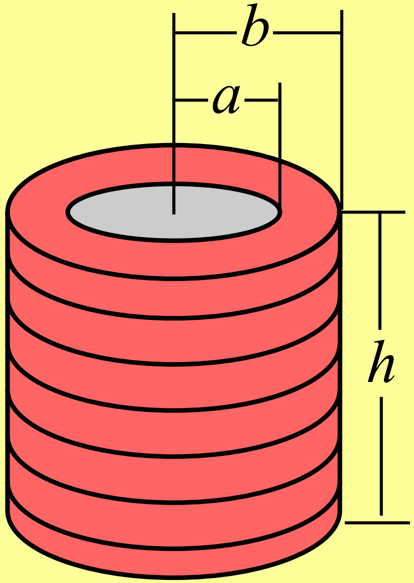
$$\Phi_{end} - \Phi_{start} = -\int_{t_{start}}^{t_{end}} V(t)\cdot dt$$

and can be measured by integrating the voltage signal.

To know the flux at a given instant, one needs to know Φ_{start}

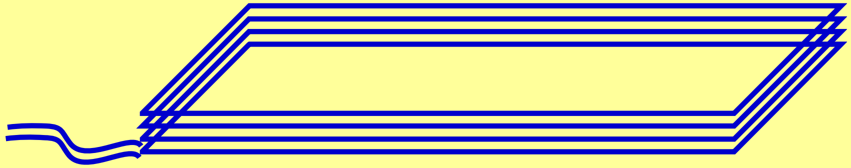
$\Rightarrow$ (1) Use $\Phi_{start} = 0$; (2) Flip Coil/Rotating coil: $\Phi_{end} = \mp\Phi_{start}$

Common Coil Geometries



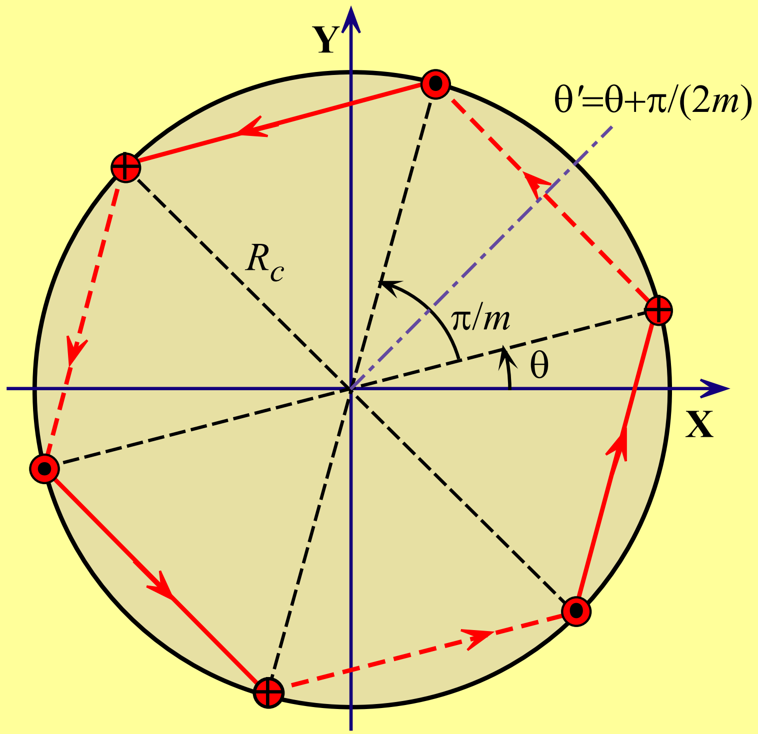
Point Coil

Insensitive up to 4^{th} order spatial harmonic with proper choice of height and radii.



Flat Coil (Line or Area Coil)

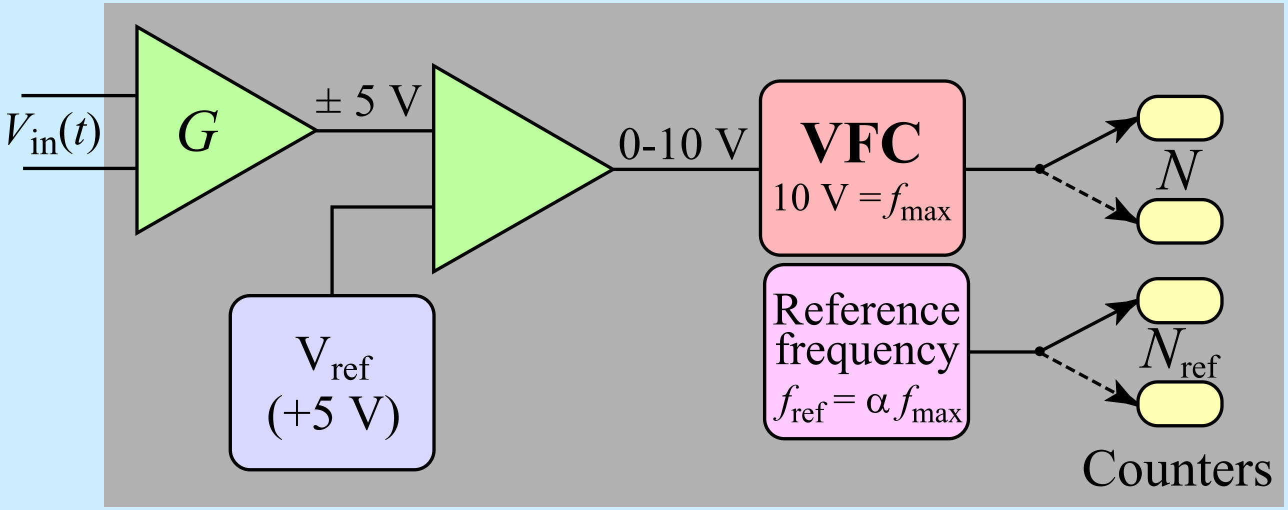
- Fixed coil; Varying field
- Flip Coil/Moving Coil; Static field
- Rotating Tangential/Radial



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.

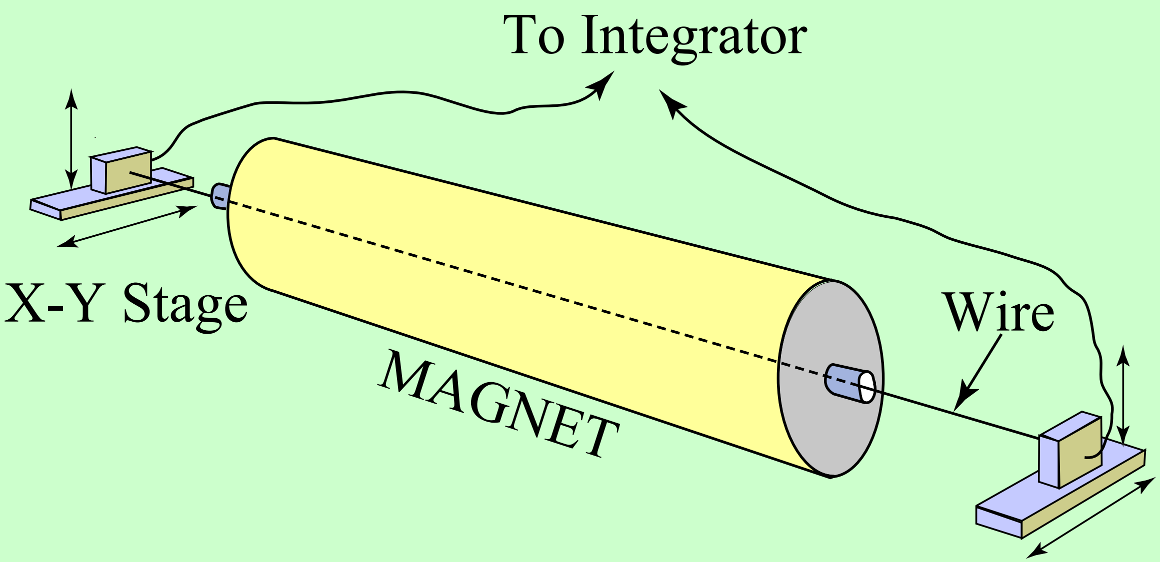
Digital Votmeter:

Gives *rate of change* of flux. Numerical Integration and/or well controlled coil movement is needed.

Measurements with Pick up Coils

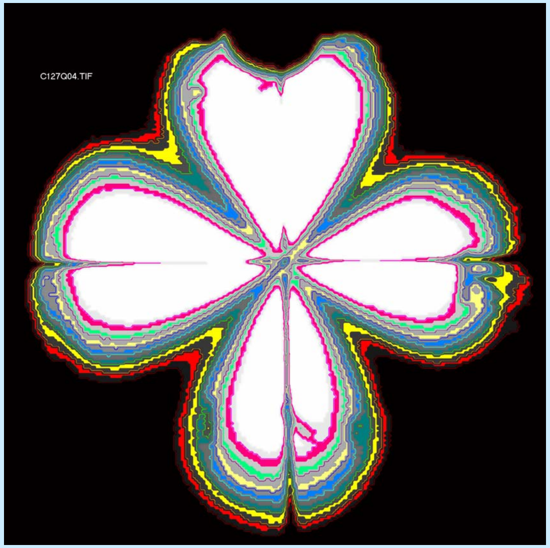
- ***Simple***, ***passive***, ***linear***, ***drift-free*** devices.
- Require ***change in flux*** ⇒ ramp field with static coil, or move coil in a static field. Pay attention to ramping/moving details.
- Measure ***flux***, not ***field***. ⇒ ***Calibration of geometry*** very important; limits *accuracy*.
- 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

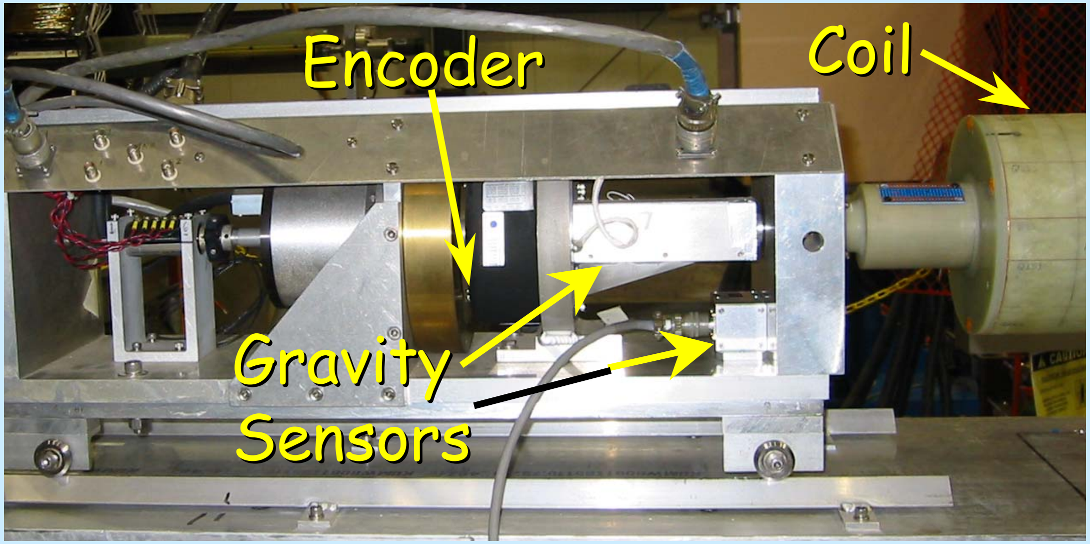
- Move a stretched wire in a magnet
- Measure change in flux for various types of motion.
- Use expected field symmetry to locate the magnetic center.



Colloidal Cell

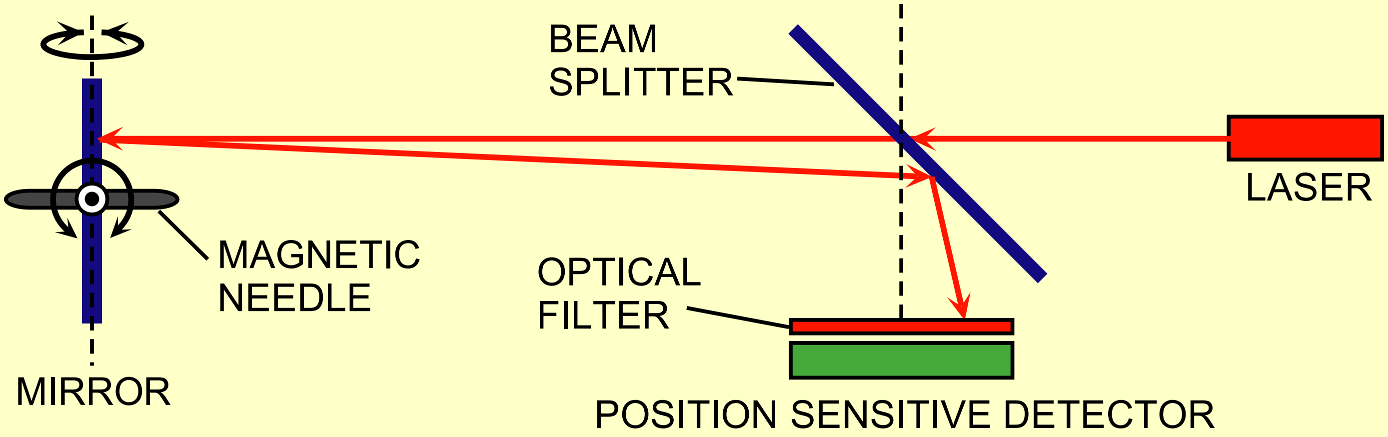
- Place ferromagnetic fluid in the field
- Illuminate with polarized light
- Observe with crossed analyzer

Determination of Field Direction



Rotating Coils

- Angular Encoder and Gravity Sensors
- Accuracy 50-100 μrad
- Frequent re-calibrations



Mirror & Needle

- For solenoids
- Resolution ~ 10 μrad

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 can not be used in all situations.
- Hall probes are very popular for point measurements, such as for field mapping of detector magnets.
- A variety of pick up 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:**
  - PAC (1965-2001); EPAC (1988-2002)

- **Proceedings of Magnet Technology Conferences:**
  - MT-1 (1965) to MT-17 (2001).