High Sensitivity Magnetic Field Sensor Technology overview

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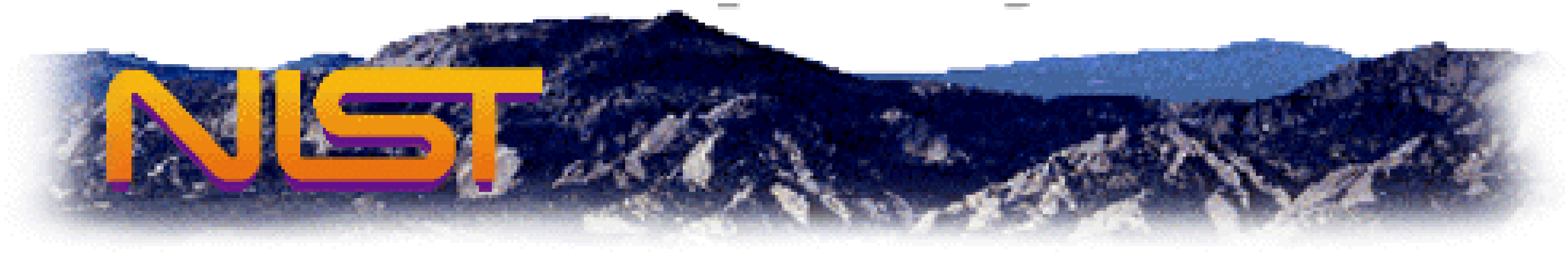
National Institute of Standards & Technology

Boulder, CO



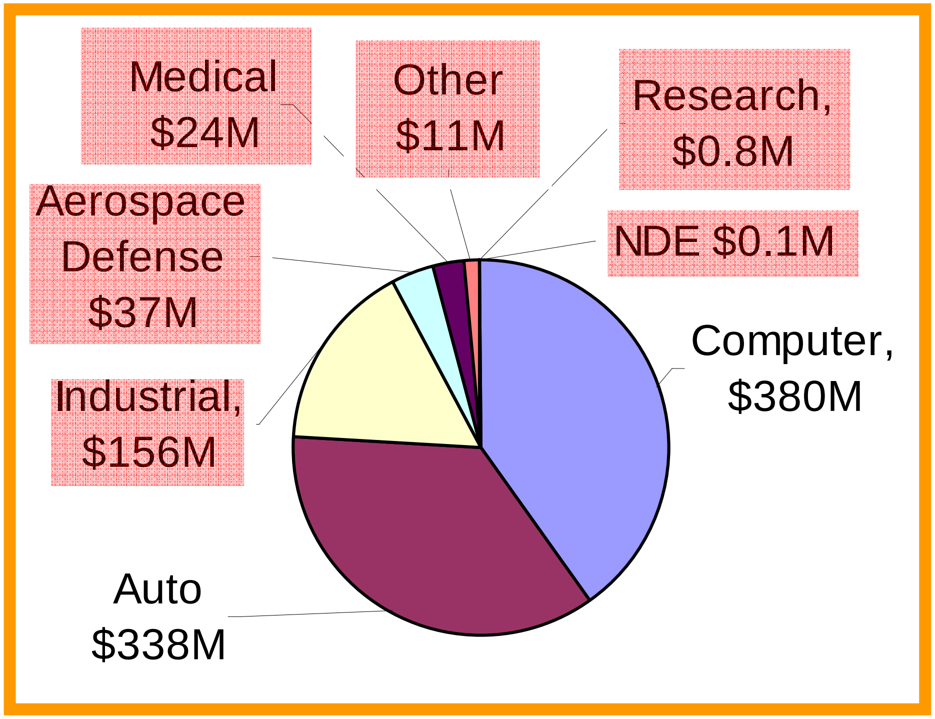
Outline

- High sensitivity applications & signal measurements
- Description of various types of sensors used
- New technologies
- Comparison of sensor metrics

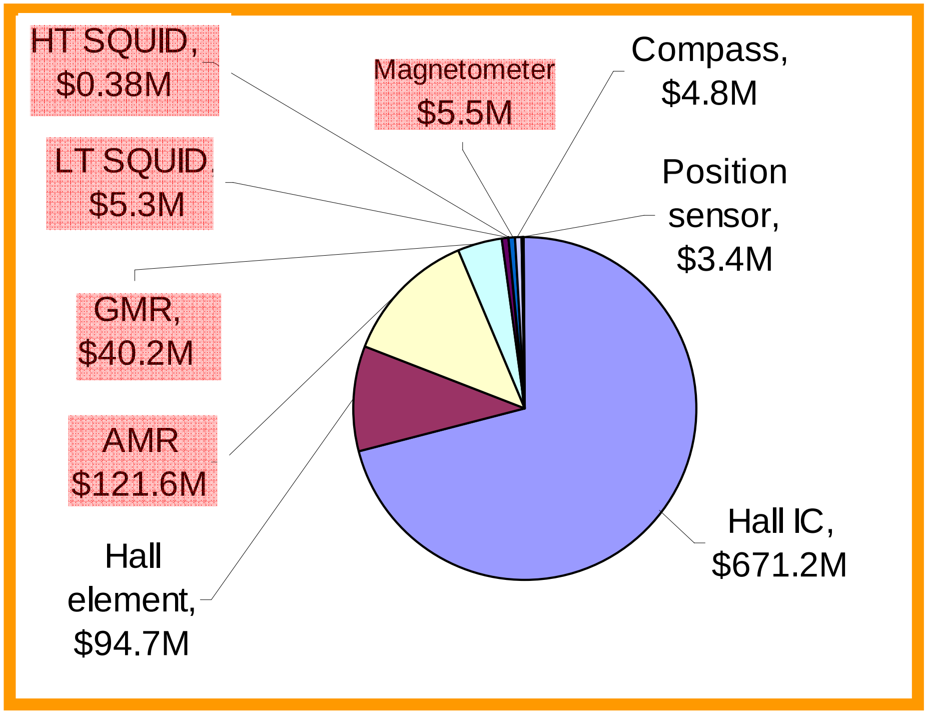
Market analysis - magnetic sensors

- 2005 Revenue Worldwide - $947M
- Growth rate 9.4%

Application



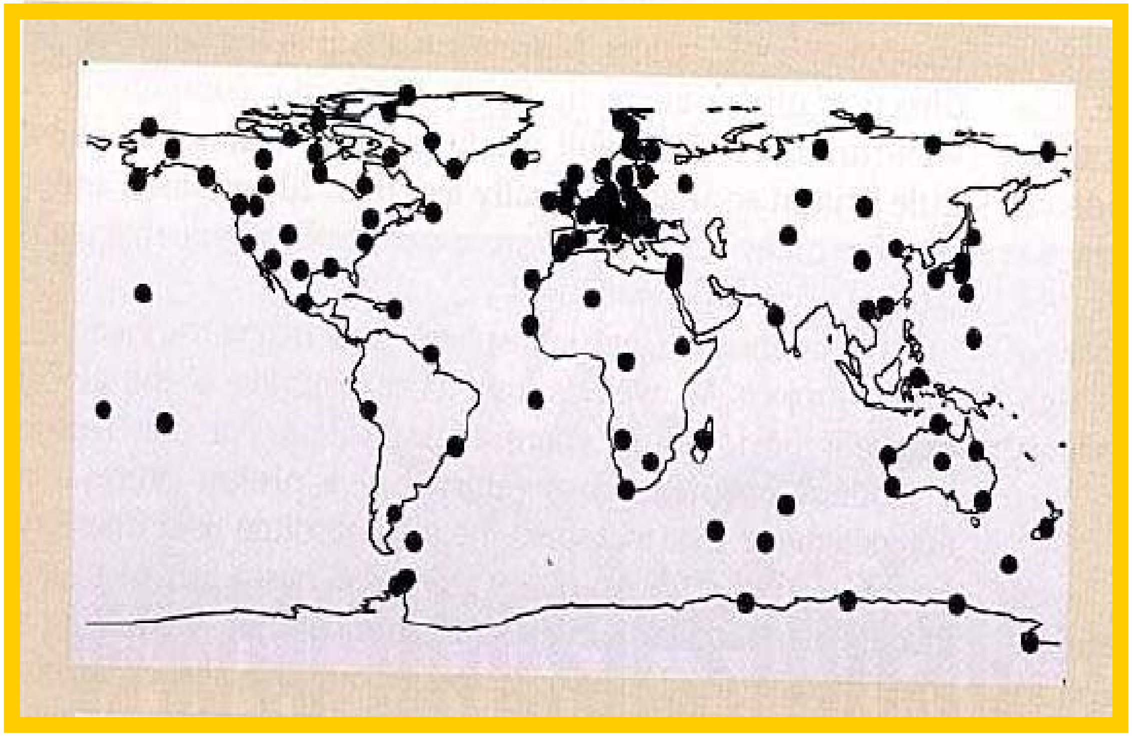
Type

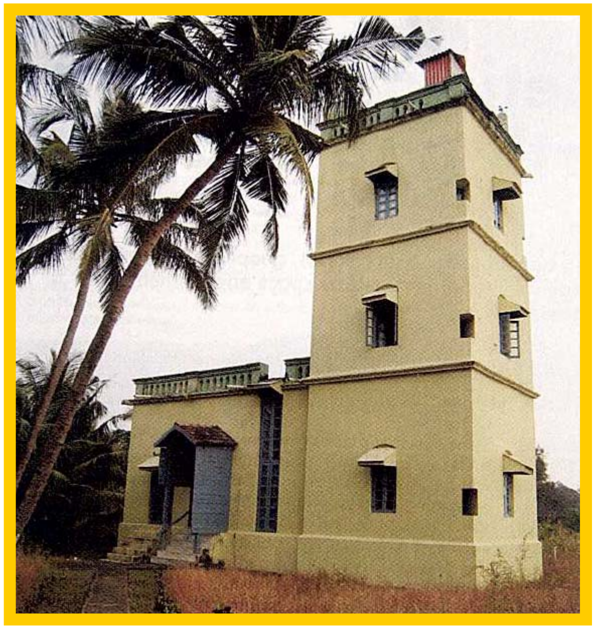


"World Magnetic Sensor Components and Modules/Sub-systems Markets"
Frost & Sullivan, (2005)

Applications

- Geophysical





120 observatories world-wide

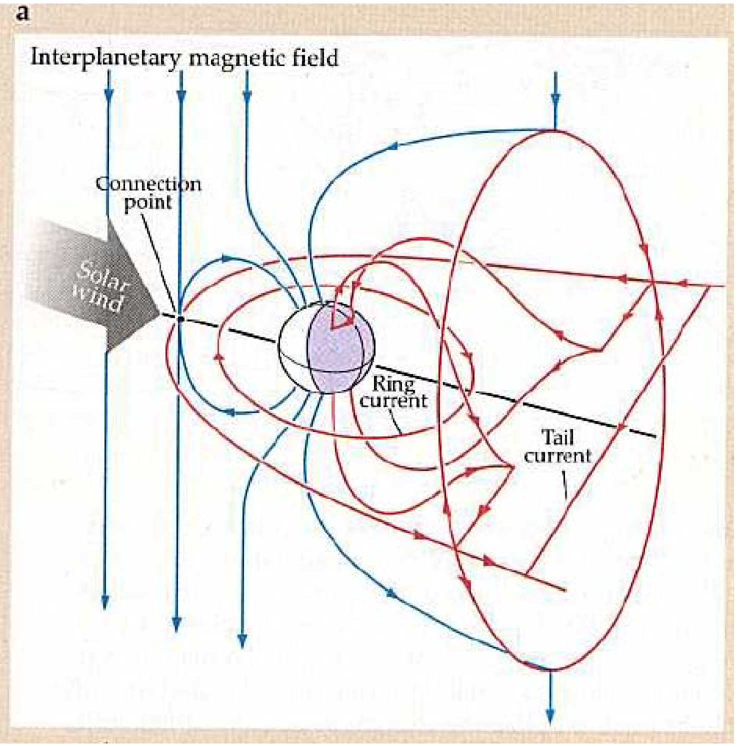
• Fluxgates
• Proton magnetometers

• Earth interior dynamics
• Mineral exploration
• GPS stability
• Satellite electronics
• Increased radiation

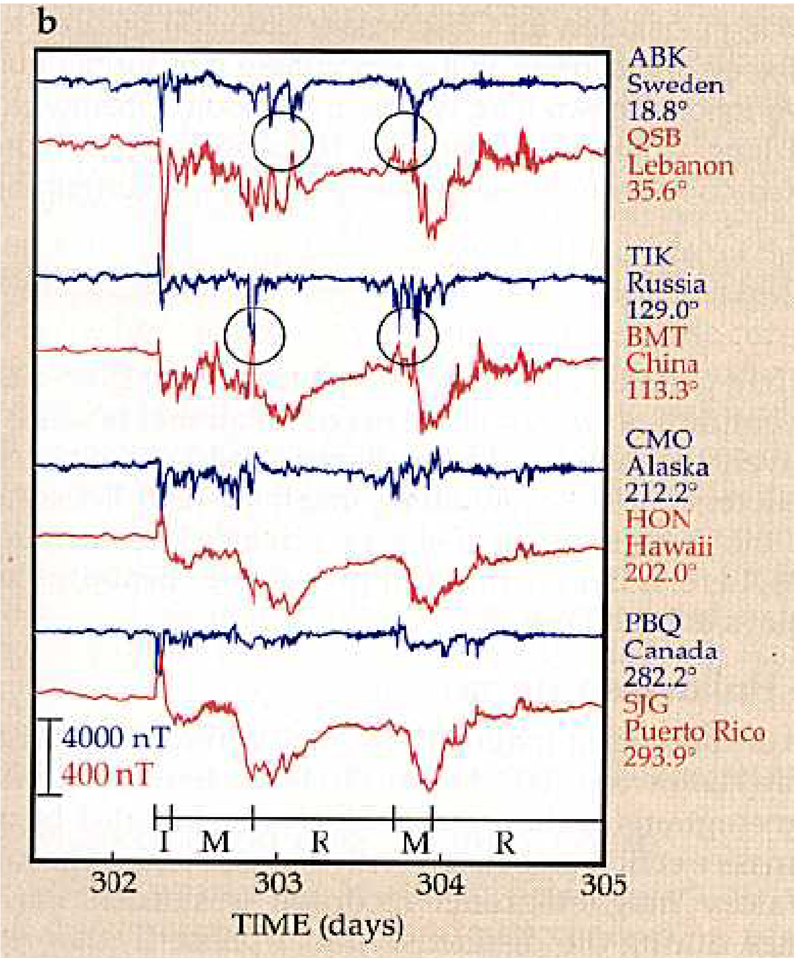
“Magnetic Monitoring of Earth and Space
Jeff Love, USGS
Physics Today Feb. 2008

Applications

- Geophysical



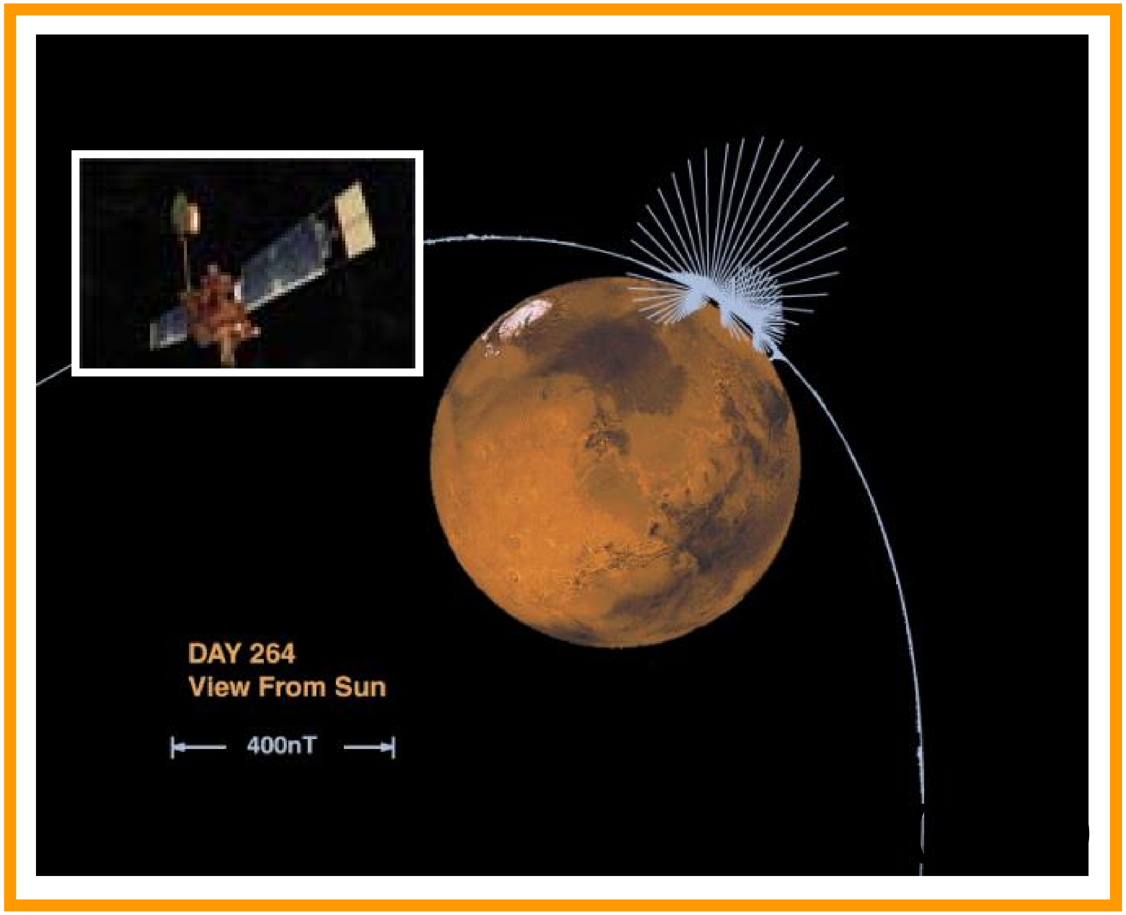
2003 Halloween magnetic storm



Applications

Mars Global Surveyor
Magnetic anomalies

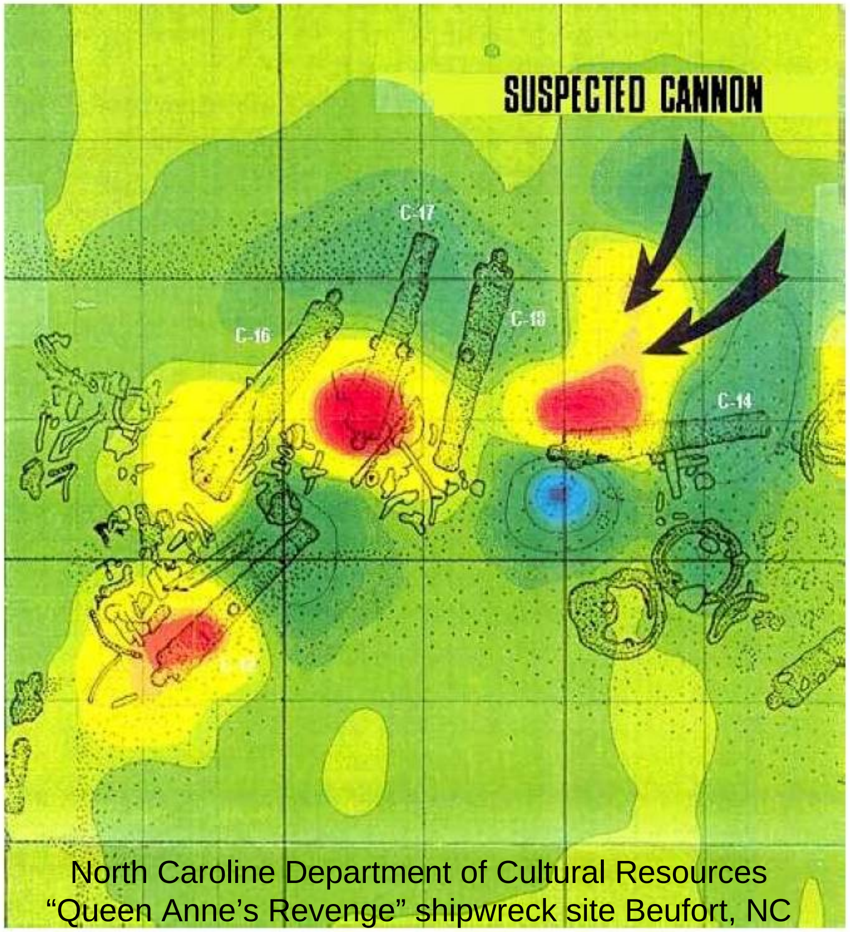
- Geophysical
- Astronomical
- Archeology
- Health Care
- Data storage



Applications

- Geophysical
- Astronomical
- Archeology
- Health Care
- Data storage

Blackbeard’s last stand

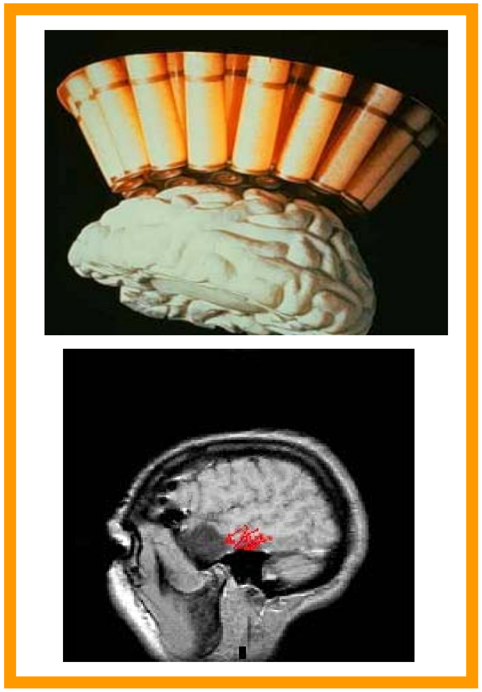


North Caroline Department of Cultural Resources
“Queen Anne’s Revenge” shipwreck site Beufort, NC

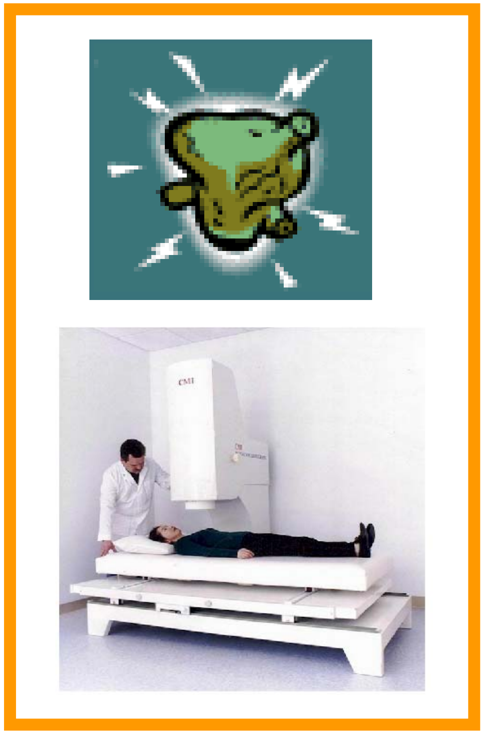
Applications

- Geophysical
- Astronomical
- Archeology
- Health Care
- Data storage

Magneto-encephalography



Magneto-
Cardiography



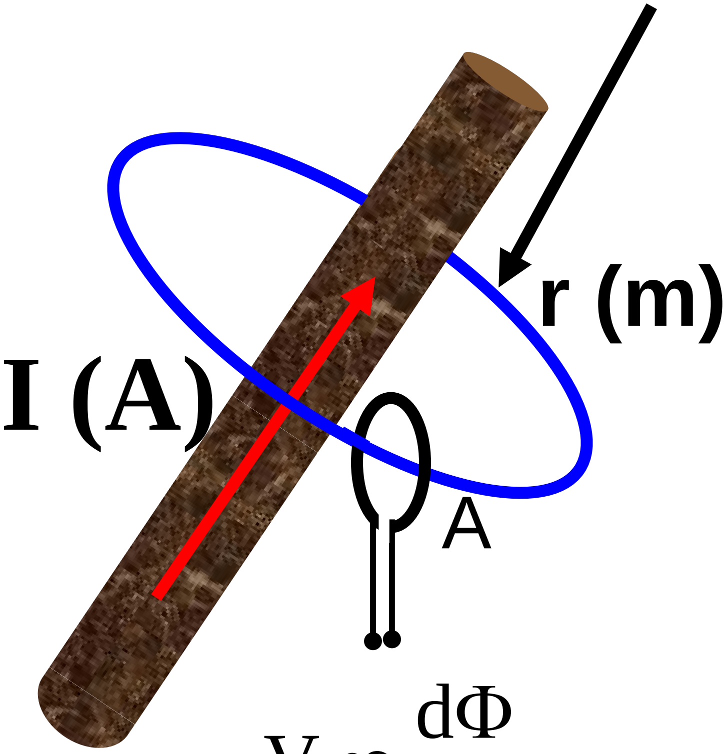
“Biomagnetism using SQUIDs: Status and Perspectives”
Sternickel, **Braginski**, Supercond. Sci. Technol. **19** S160–S171 (2006).

Applications

- Geophysical
- Astronomical
- Archeology
- Health Care
- Data storage

Hard disk drive

SI - *Le Système International d'Unitès*



H-field "Magnetic field intensity" ⇨ A/m

- What do we measure?

⇨B = flux density

= "Magnetic induction" field

= μH   includes medium

B-field ⇨ tesla (T)   kg/(As^2)

Use μ_0 = permeability of free space

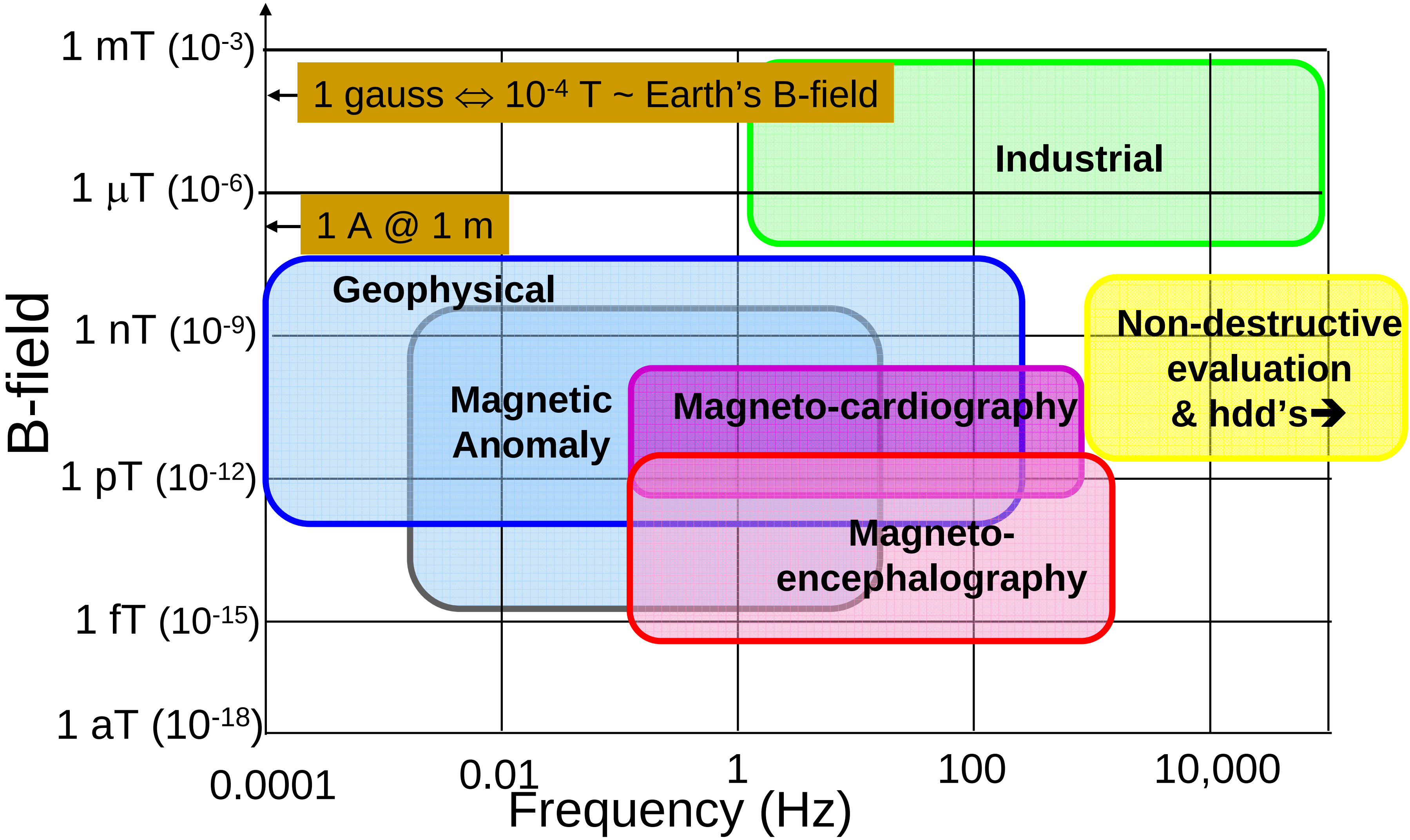
= $4\pi \times 10^{-6}$ Wb/Am

$$V \propto \frac{d\Phi}{dt}$$

$$\Phi = \mathbf{B \bullet A}$$

e.g. 1 A @ 1 m: **B = 2×10^{-7} T**

B-field Ranges & Frequencies



Adapted from "Magnetic Sensors and Magnetometers", P. Ripka, Artech, (2001)

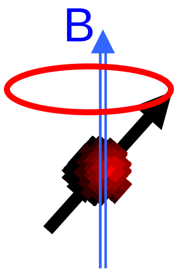
B-field effects

- **Induction (Faraday's Law)**
  - **Search Coil**
  - **Fluxgate**
  - **Giant magneto-impedance (+ skin effect)**

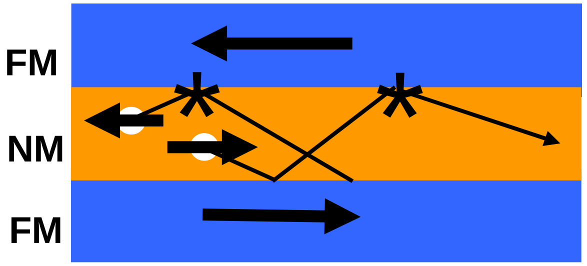
$$V \propto \frac{dB}{dt}$$

- **Torque -**
  - **Magnetic resonance (optical pumping)**
    - **Proton – f ~ 4 kHz/gauss**
    - **Electron – f ~ 3 MHz/gauss**
  - **Magneto-striction**

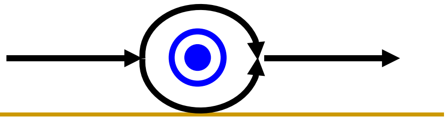
$$\vec{T} = \vec{m} \times \vec{B}$$



- **Scattering**
  - **Magneto-resistance (AMR)**
  - **Spintronics**
    - **Giant MR, Tunneling MR, Spin Xtor…**
  - **Hall Effect (Lorentz force)**
  - **Magneto-optical**



- **Wave function interference**
  - **Superconducting Quantum Interference Device (SQUID)**



State measurement

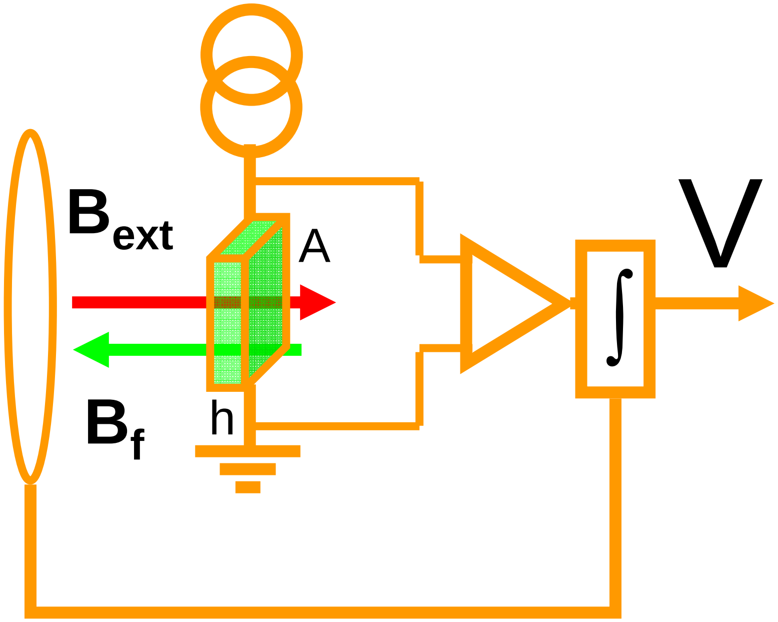
- Low noise excitation source -
  - Voltage, current, light, …
- Detector volume - Ω = A×h
- Sense state
  - e.g. sensitivity = V/T
- Flux feedback is typical

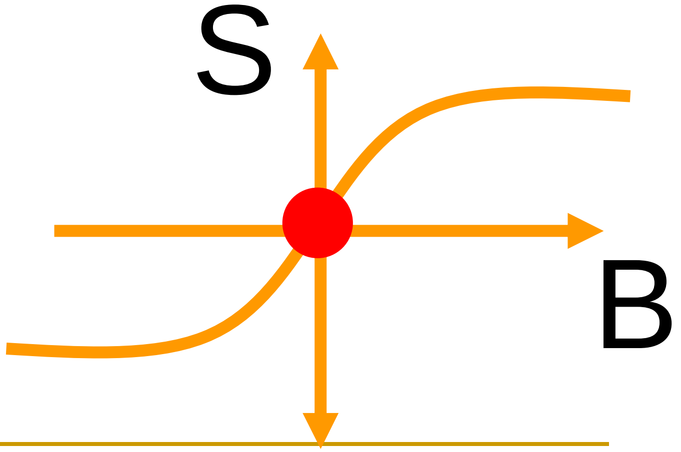
☑ Linearize

☑ Dynamic Range

☒ Complicated

☒ Limits slew rate & bandwidth

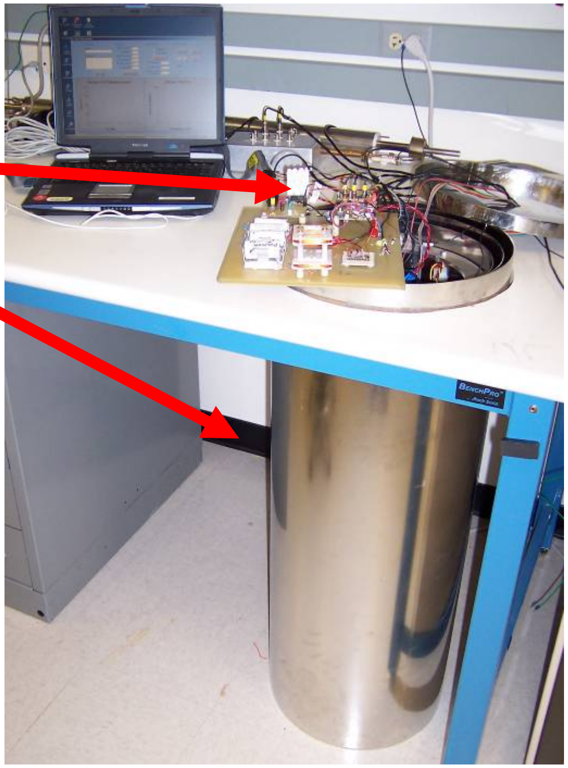




Noise metrology

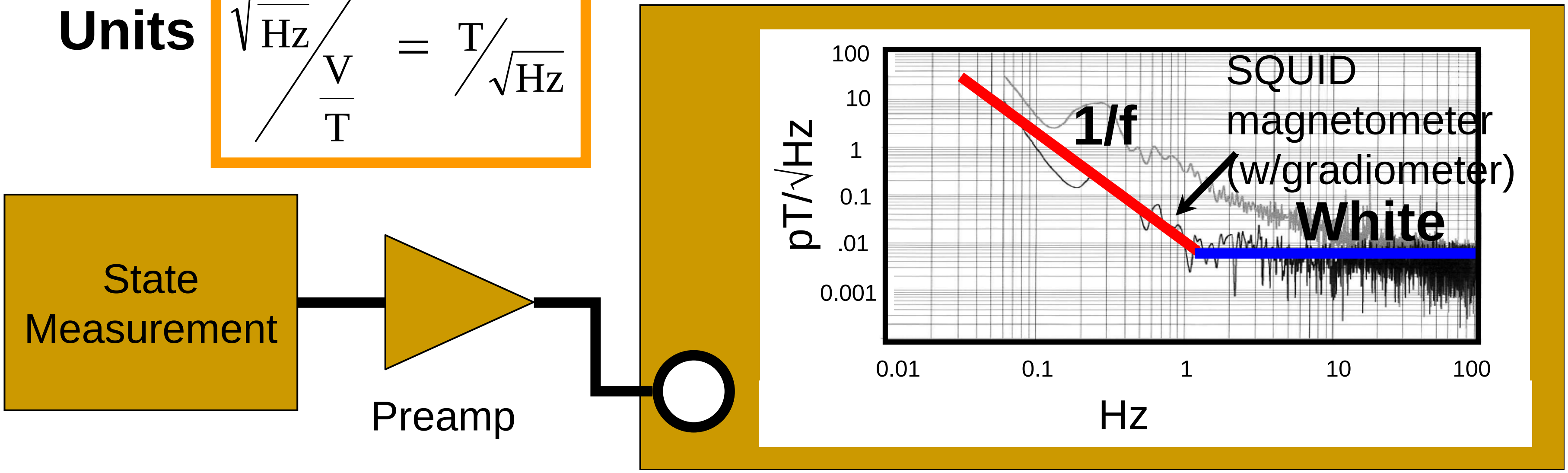
- Low noise preamplifiers
- Magnetically shielded container

  (or room)
- Spectrum analyzer
  - Noise power vs. frequency = V^2/Hz
  - field noise = √power / sensitivity



Units

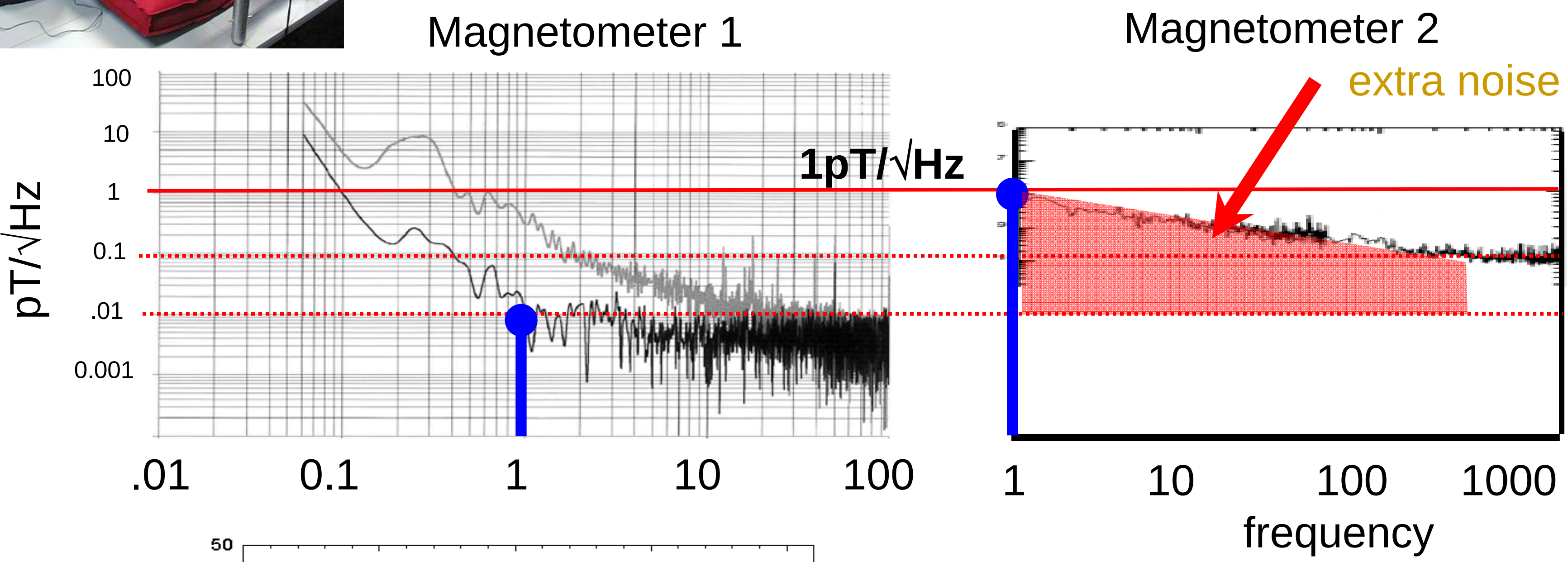
$$\frac{\sqrt{\frac{V^2}{Hz}}}{\frac{V}{T}} = \frac{T}{\sqrt{Hz}}$$

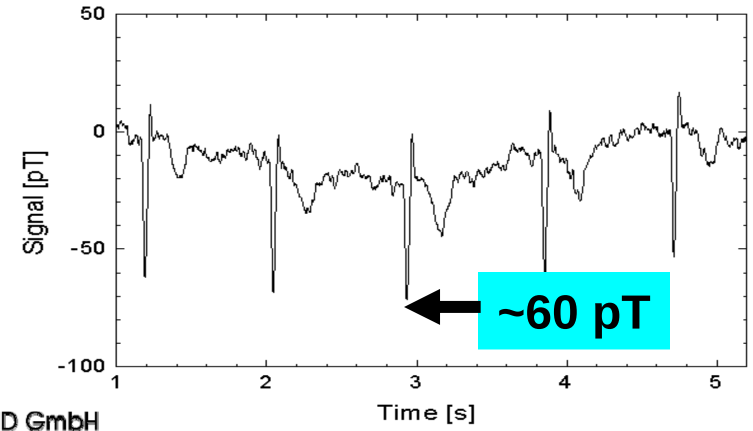


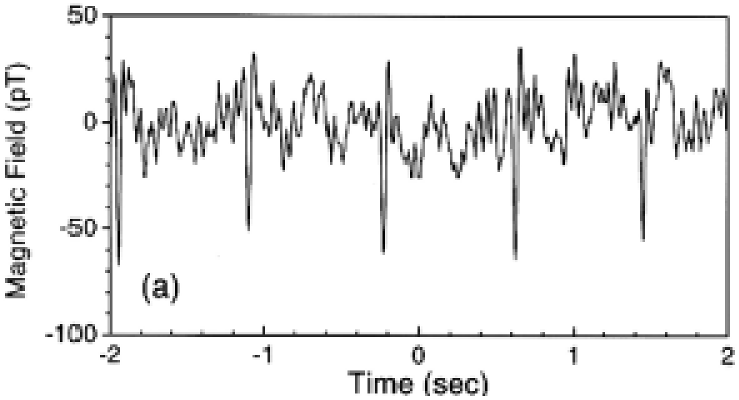
State Measurement

Preamp

e.g. Magneto-cardiography







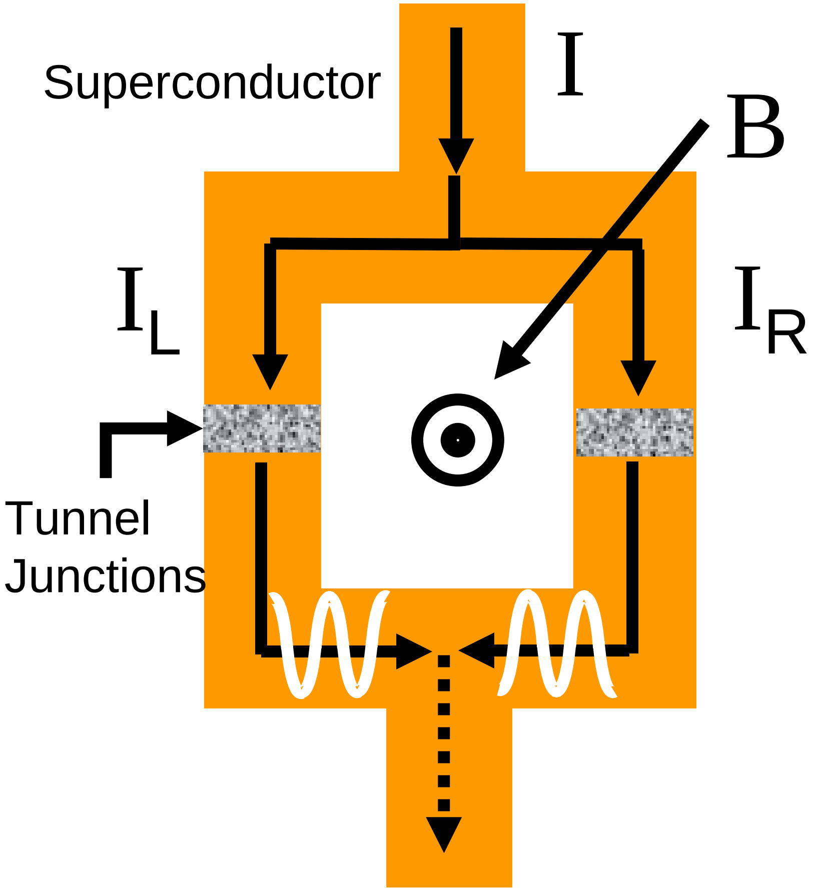
Jülicher SQUID GmbH
Sensortechnik

=> Use noise at lowest frequency in bandwidth as benchmark

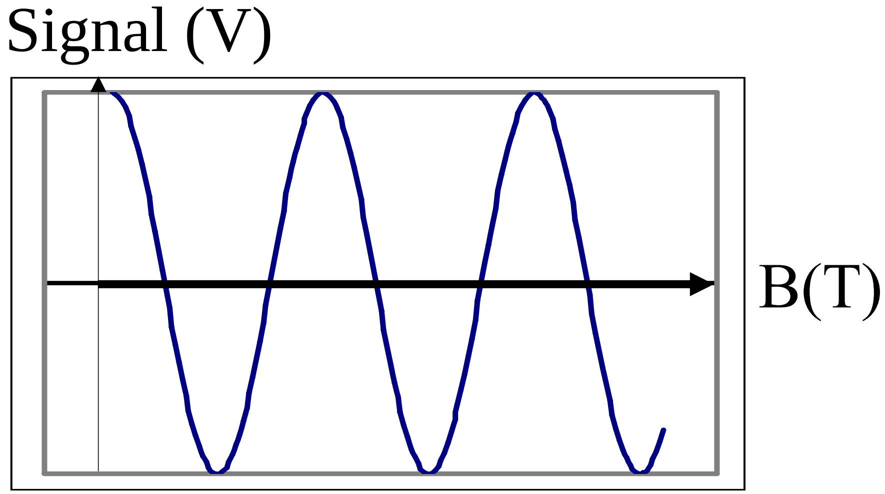
Benchmark properties:

State variable	**V, f, etc**
B-field measurement	**Vector/scalar**
B_{noise} - Noise @ 1 Hz	**pT/√Hz**
Detector volume (Ω)	**cm^3-mm^3**
Operating temperature, T	**Cryogenic/RT/heated**
Power – form factor	**Line/Battery**

Superconducting Quantum Interference Devices



Left-Right phase shifted by B



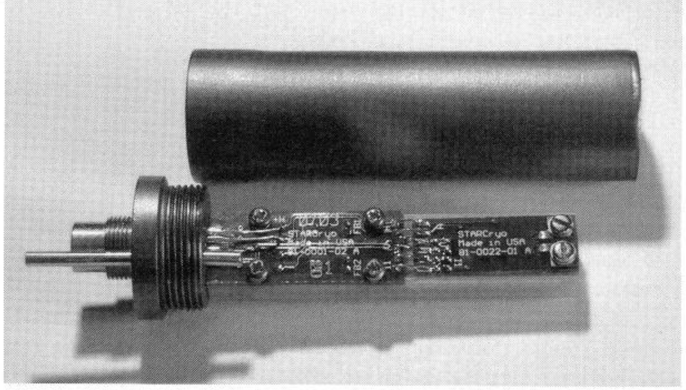
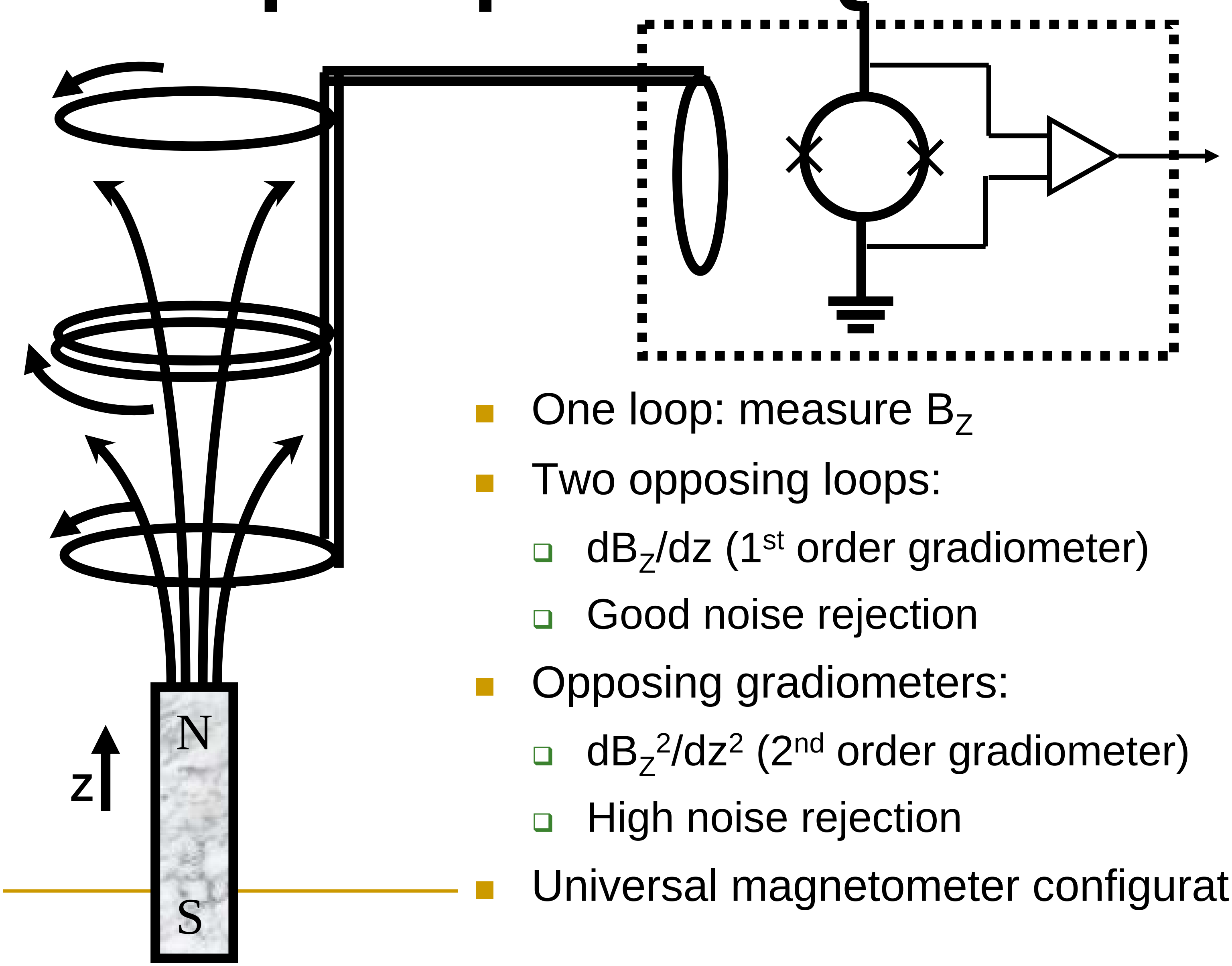


Fig. 5.12 A photograph of a packaged dc SQUID assembly with niobium shield.

PU loop

Pickup loops for SQUIDS



- One loop: measure B_Z
- Two opposing loops:
  - dB_Z/dz (1st order gradiometer)
  - Good noise rejection
- Opposing gradiometers:
  - dB_Z^2/dz^2 (2nd order gradiometer)
  - High noise rejection
- Universal magnetometer configurations

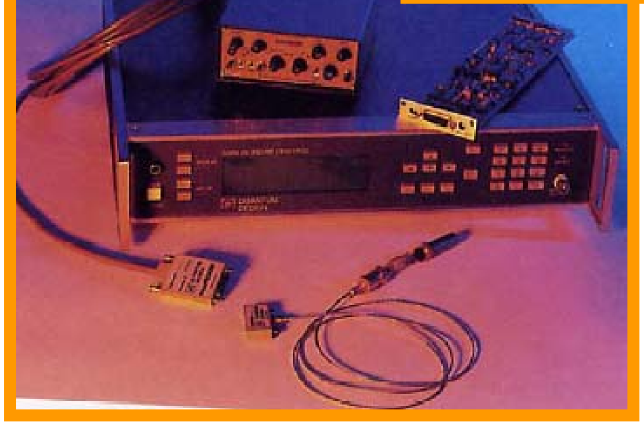
SQUID Magnetometer

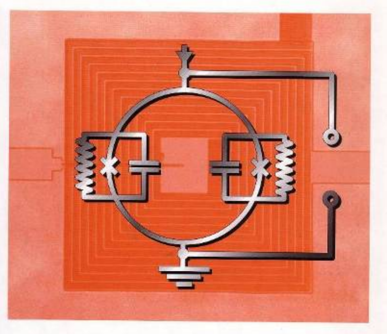
Integrated Systems

State variable	**Voltage (10's μV)**
B-field	**Vector, gradients**
B_{noise} @ 1 Hz sources	**<u>0.001 - .010 pT/√Hz</u>** **Shunt resistors** **Shielding eddy currents**
Ω - Volume	**~ 10 cm^3 coil**
Operating T	**cryogenic**
Power	**Line**

Commercial: 10 – 100's k$

Discrete components





"The SQUID Handbook,"
Clarke & Braginski, Wiley-VCH 2004

SQUID detected Magnetic Resonance Image

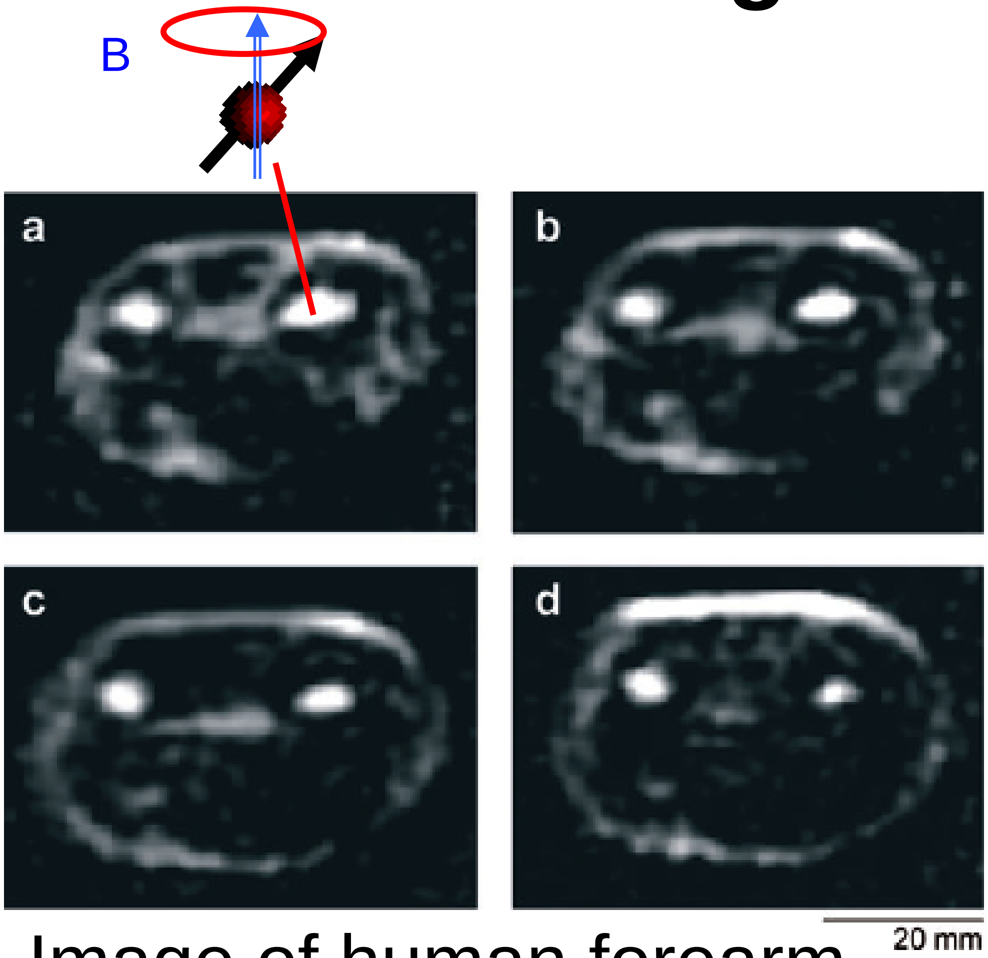


Image of human forearm

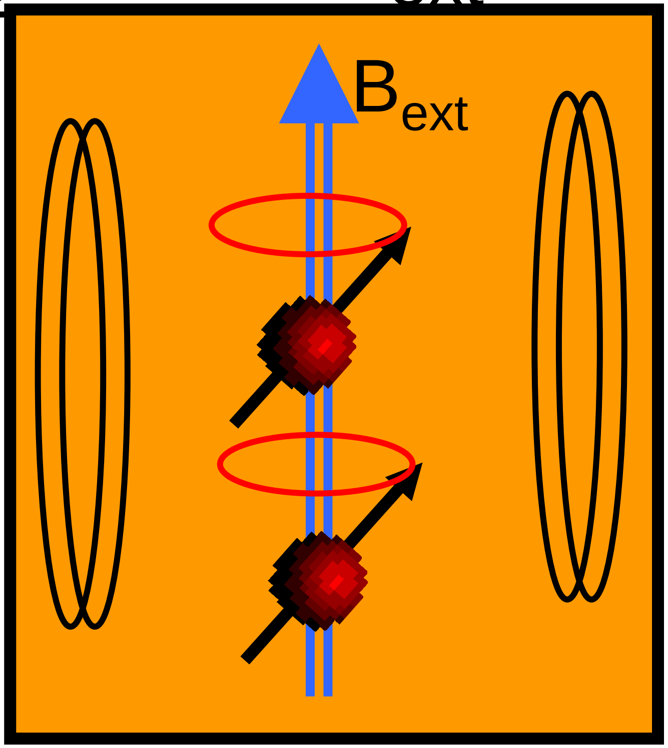
- Low polarizing B-field
  - 60 mT
- Low precession field
  - 132 μT
- Low resonance f
  - ~ 6 kHz
- Don’t need superconducting magnets

Clarke, et. al, ANRV 317-BE09-02 (2007)

Resonance magnetometers

- Proton Nuclear spin resonance
  - f = 43 MHz/T
    - Water, methanol, kerosene
    - Overhauser effect
      - Transfer e^- spin to protons
      - He^3, Tempone

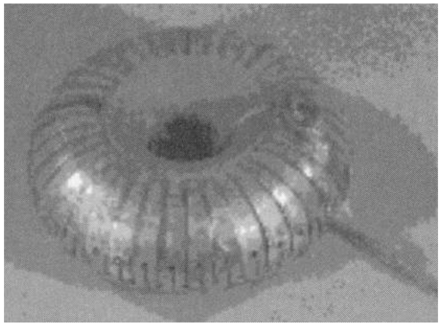
$f \propto B_{ext}$



Proton magnetometer

State variable	Frequency ~ kHz
B-field	Scalar
B_{noise} @ 1 Hz sources	<u>~10 pT/√Hz</u> depolarization
Ω - Volume	1 cm^3 cell
Operating T	-20 => 50 ^oC
Power	Battery

Commercial: 5 k$



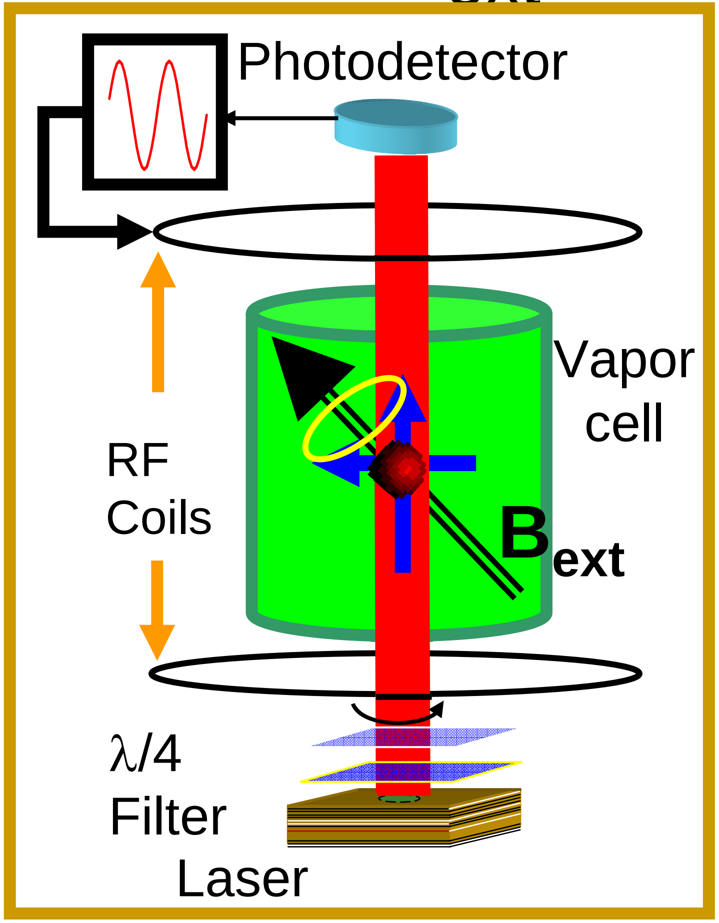
- Kerosene cell
- Toroidal excitation & pickup

Olsen, et. al (1976)
From Ripka, (2001)

Resonance magnetometers

- Electron spin resonance
  - f = 28 GHz/T
  - He^4: 2^3S_1 - optical pumping
  - Alkali metals (Na, K, Rb)

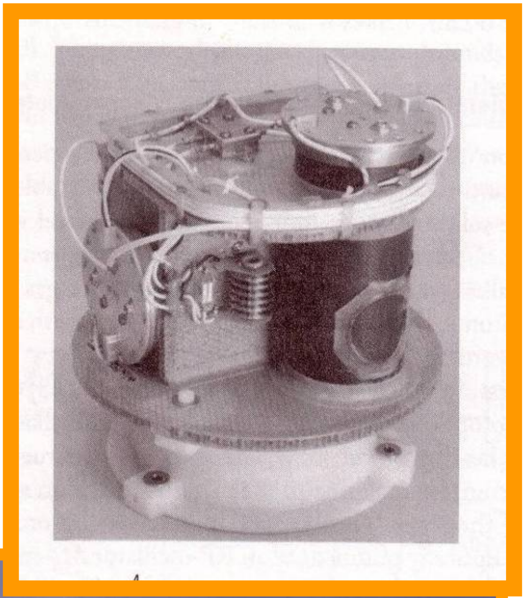
$$f \propto B_{ext}$$



Proton

He^4 e$^-$-spin magnetometer

State variable	Frequency
B-field	scalar
B_{noise} @ 1 Hz sources	<u>1 pT/√Hz</u> Depolarization e.g., precession & collisions w/walls
Ω - Volume	~10 cm^3 cell
Operating T	ambient
Power	battery



JPL - SAC-C mission Nov. (2000)

Smith, et al (1991) from Ripka (2001)

e^--spin magnetometer Spin-exchange relaxation free

State variable	Frequency
B-field	Vector
B_{noise} @ 1 Hz	<u>0.0005 pT/√Hz</u>
Ω - Volume	~ 3 cm^3
Operating T	180 ^oC
Power	line

K metal vapor

Low field, high density of atoms

Line narrowing effect

All-optical excitation & pickup

=>Optimized for high sensitivity

Solid state

Kominis, et. al, Nature 422, 596 (2003)

Solid state magnetometers

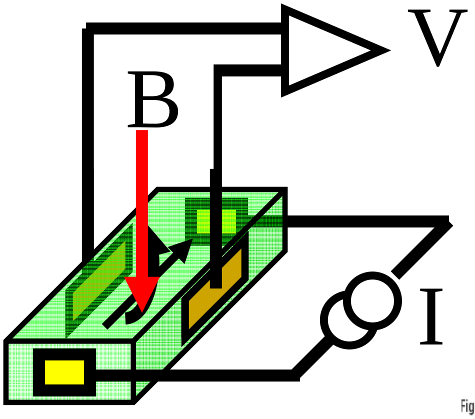
- Semi-conductors
  - Hall effect
- Ferromagnetic based:
  - Magneto-resistive
  - AMR – Anisotropic MR
  - Spintronic
    - GMR – Giant MR, TMR – Tunneling M
  - Fluxgate
  - Giant magneto-impedance
- Disruptive technologies
  - Hybrid superconductor/solid state
  - Colossal magneto-resistance
  - Magneto-electric
  - Spin Transistors

Hall

Hall Effect

State variable	Voltage
B-field	Vector
B_{noise} @ 1 Hz **problems**	<u>300,000 pT/√Hz</u> Resistive noise + Small signal – need high electron mobility
Ω - Volume	0.001 mm^3
Operating T	RT
Power	battery

Commercial: ~$ 0.1 ⇨ 1



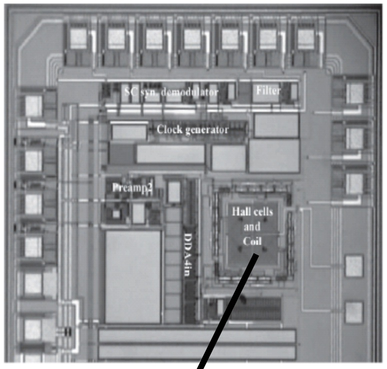


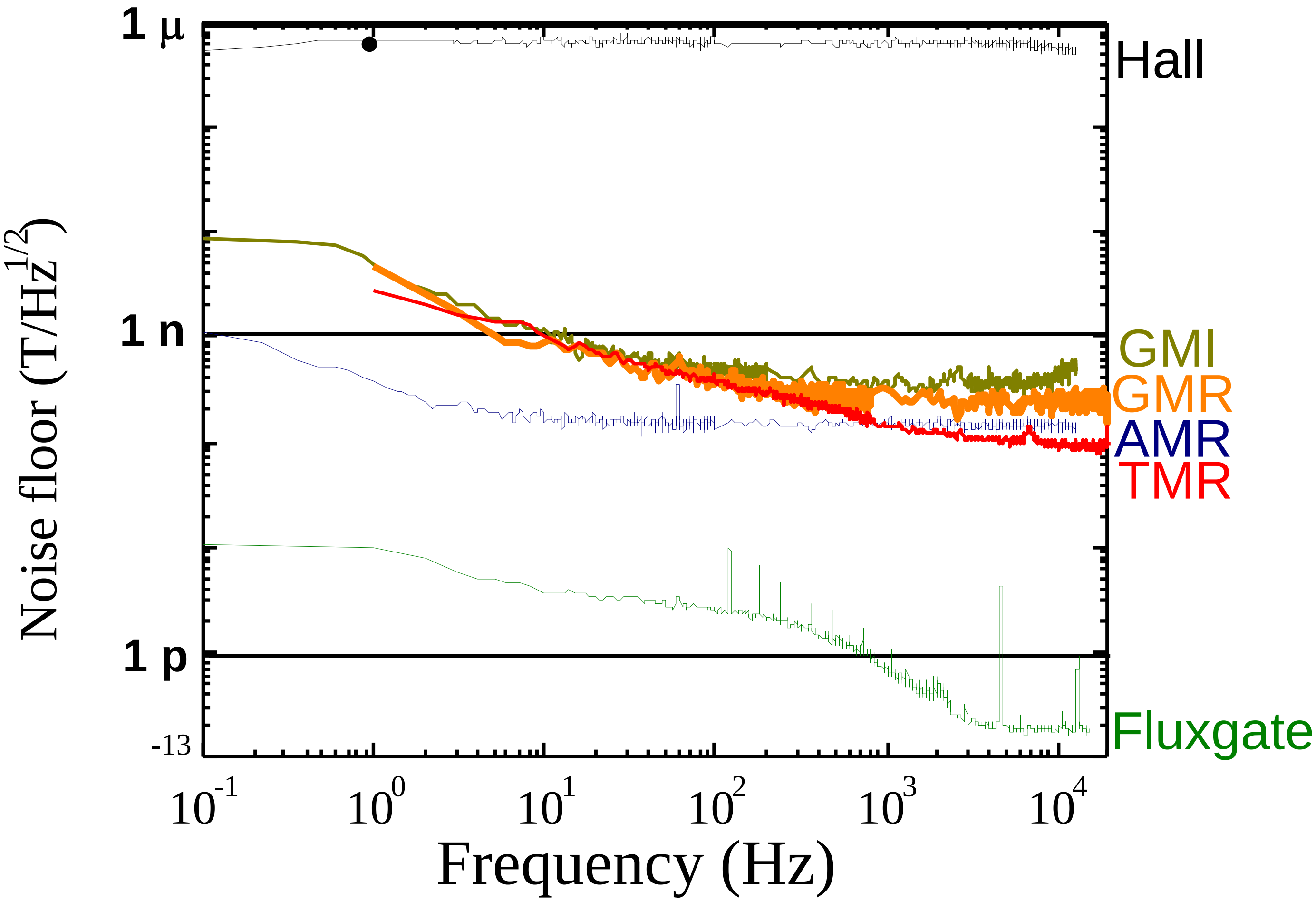
Figure 16.3.7: Die micrograph of integrated hall sensor array microsystem.

- In-line with CMOS
- <u>Applications</u>
  - Keyboard switches
  - Brushless DC motors
  - Tachometers
  - Flowmeters
  - etc.

Fruounchi, Demiere, Radjelovic, Popovic, ISSC (2001)

noise

Spectral noise measurements



Stutzke, Russek, Pappas, and Tondra, J. Appl. Phys. **97**, 10Q107 (2005)
Yuan, Halloran, da Silva, Pappas, J. Appl. Phys. submitted (2007)

Magneto-resistive (MR) sensors

- AMR - Anisotropic MR
  - Single ferromagnetic film NiFe
  - 2% change in resistance
- Spintronic:
  - GMR trilayer w/NM spacer
    - 60% $\Delta R/R_{min}$ Co/Cu/Co
    - “Spin Valve”
  - TMR – Insulator spacer
    - 500% $\Delta R/R_{min}$ at R.T.
    - CoFeB/MgO/CoFeB
    - Hayakawa, APL (2006)

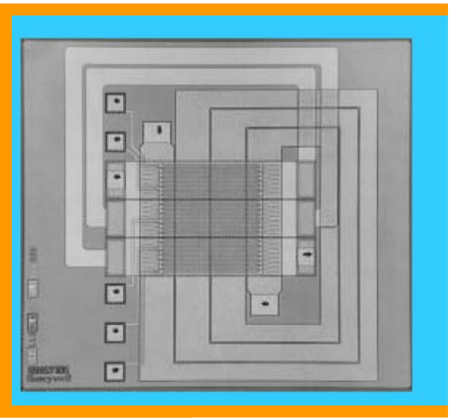
“Thin Film Magneto-resistive Sensors
S. Tumanski, IOP (2001).

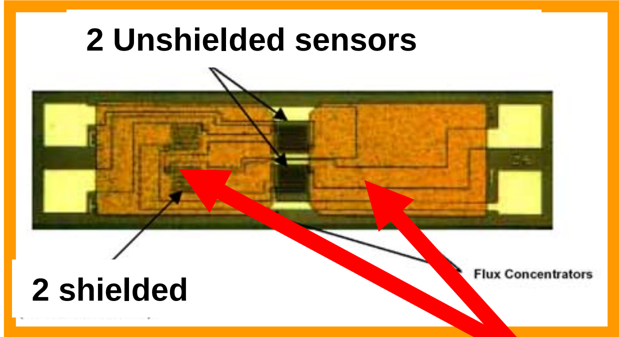
Low field

MR as low field sensors

State variable	Resistance
B-field	Vector
B_{noise} @ 1 Hz sources	~200 pT/√Hz 1/f mag noise Temp fluct. M Johnson/Shot Perming
Ω - Volume	0.001 mm^3 film
Operating T	RT
Power	battery

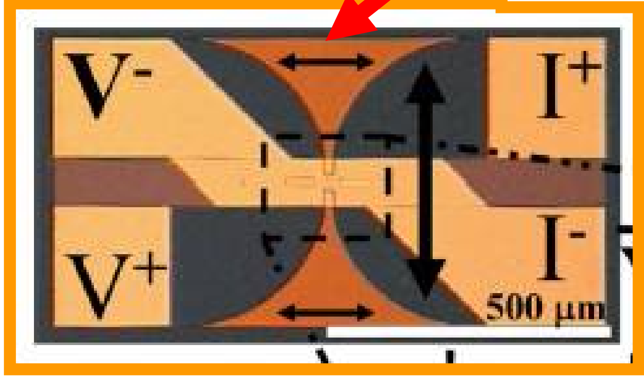
AMR
Large area films





GMR
Small
sensors

Flux
concentrators



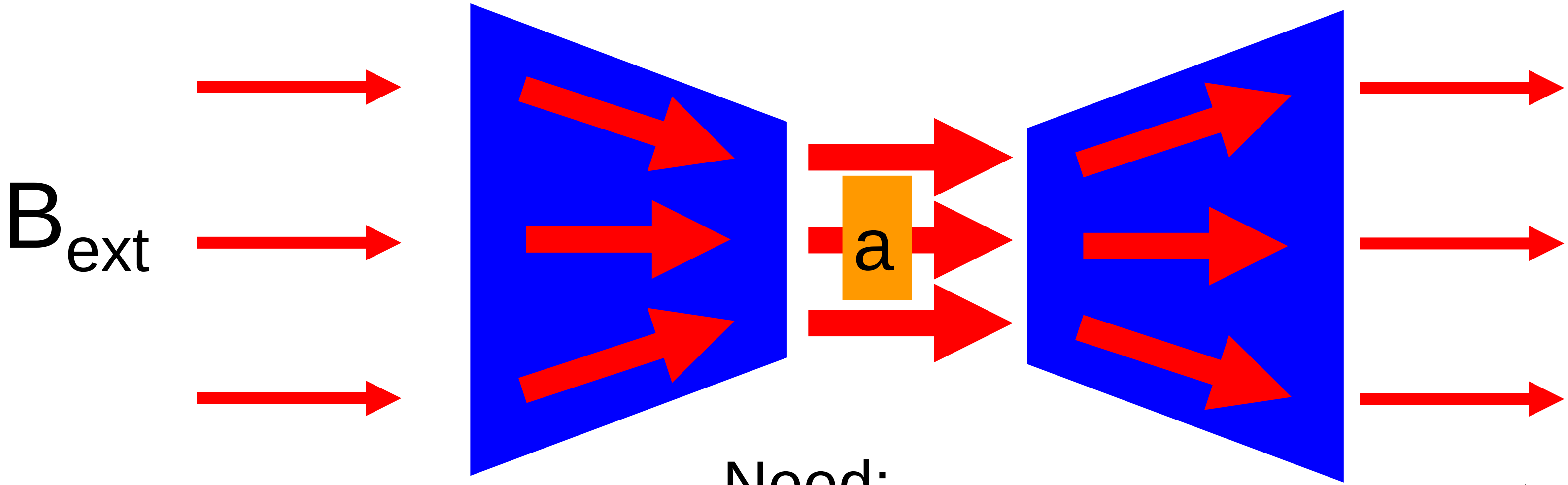
TMR

Commercial: ~ 1$

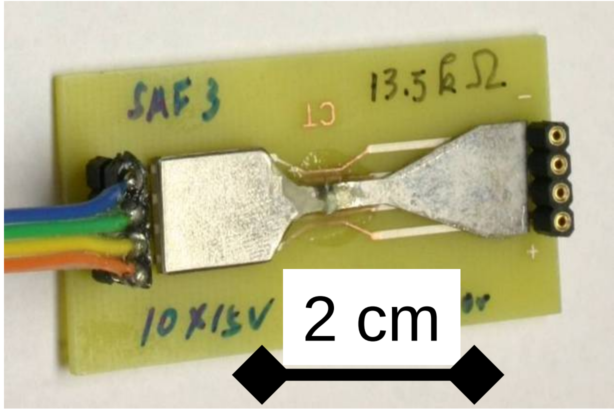
"Low frequency picotesla field detection…"
Chavez, et. al, APL 91, 102504 (2007)**.**

F.C.

Application of flux concentrators



TMR with F.C.



<u>Need:</u>

Soft ferromagnet

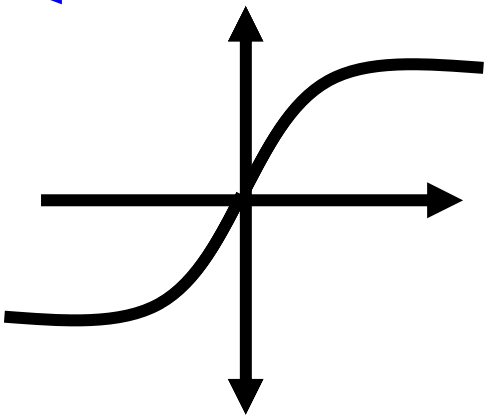
High M = χH

No hysterisis

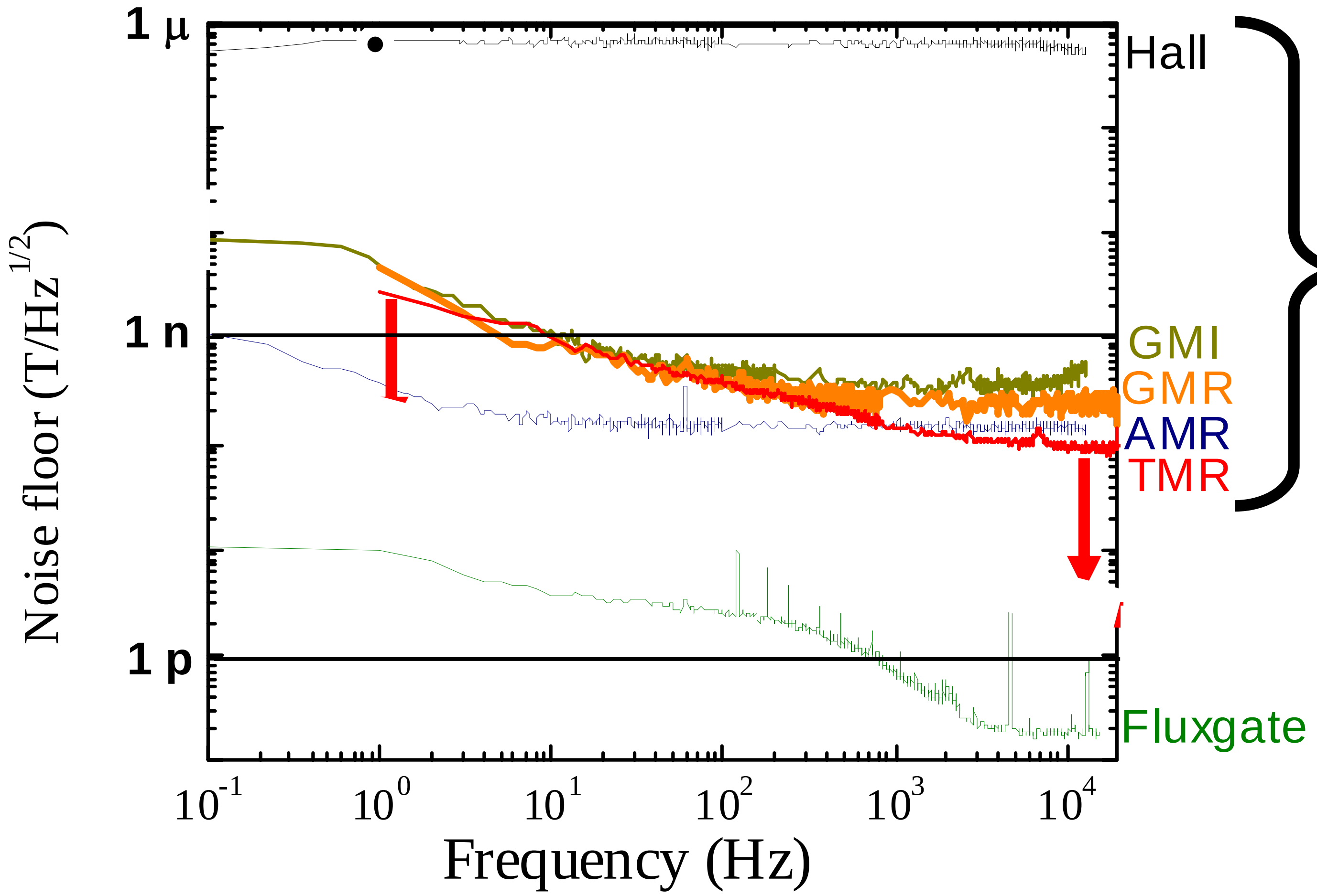
⇒ Gain up to ~50

⇒ No increase in noise

☹ Increase in volume

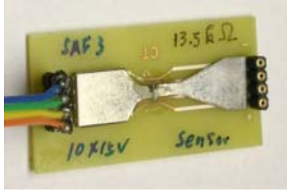


Spectral noise measurements



without flux concentrator

with external flux concentrator



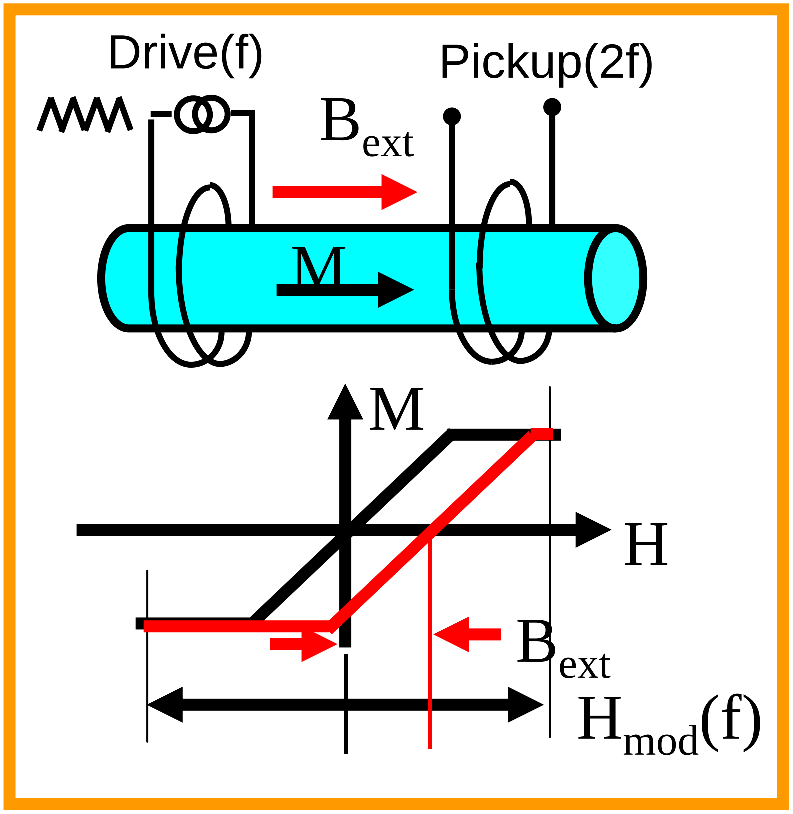
Stutzke, Russek, Pappas, and Tondra, J. Appl. Phys. **97**, 10Q107 (2005)
Yuan, Halloran, da Silva, Pappas, J. Appl. Phys. submitted (2007)

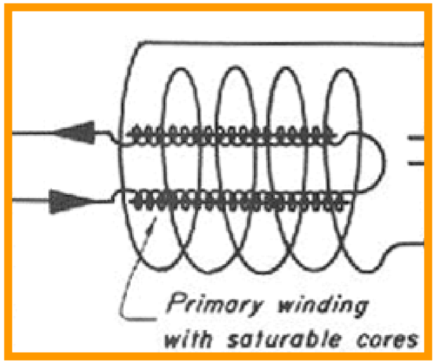
fluxgate

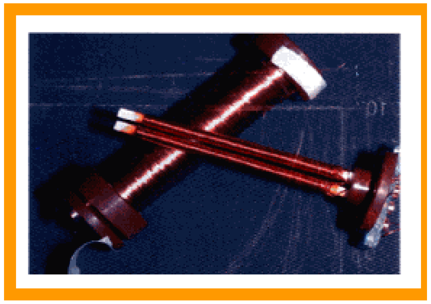
Fluxgate

State variable	Inductive 2f
B-field	Vector
B_{noise} @ 1 Hz Sources	10 pT/√Hz Thermal magnetic Johnson Perming
Ω - Volume	~1 cm³
Operating T	RT
Power	battery

Commercial: ~1 k$

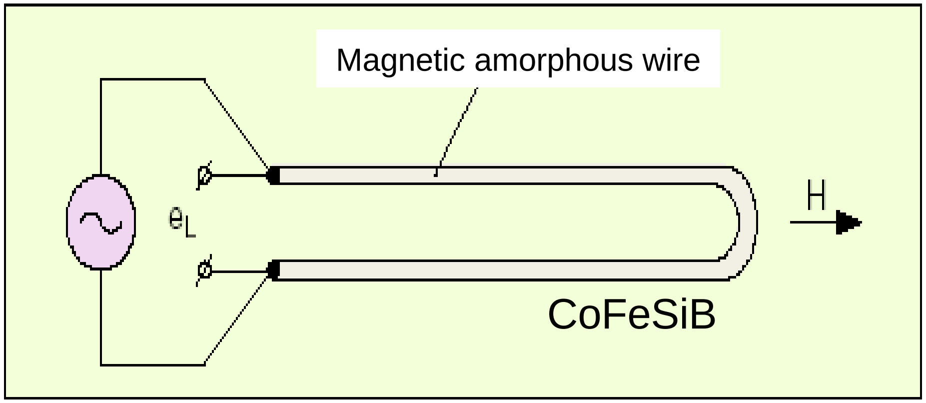


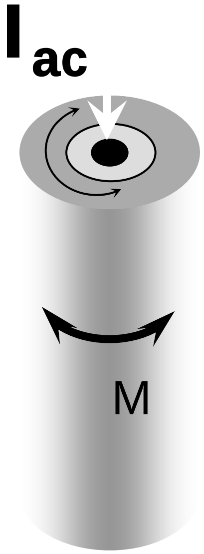




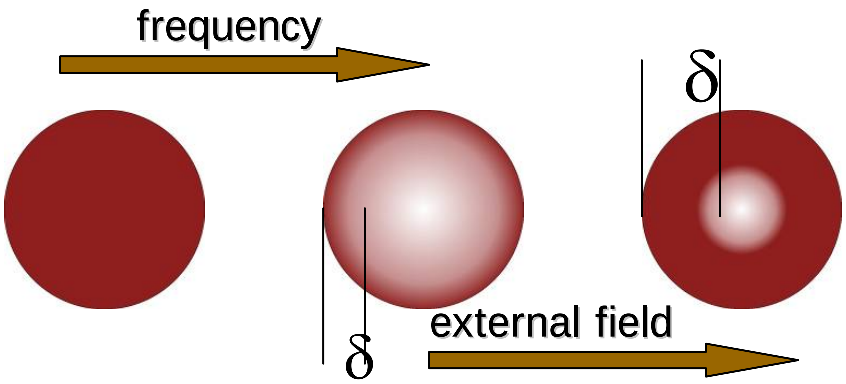
"Magnetic Sensors and Magnetometers" P. Ripka, Artech, 2001

Giant Magneto-impedance (GMI)





Enhanced skin effect in magnetic wire

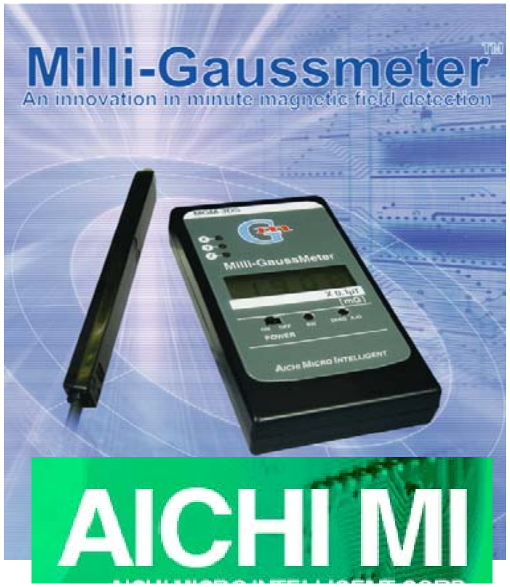


$$\frac{Z(\sim 1\,\mathrm{MHz})}{R_{DC}} \sim 400\%$$

“Giant magneto-impedance and its applications”
Tannous C., Gieraltowski, Jour Mat. Sci: Mater. in Electronics, V15(3) pp 125-133 (2004)

GMI specifications

State variable	Z @ MHz
B-field	Vector
B_{noise} @ 1 Hz sources	~3000 pT/√Hz 1/f mag noise Temp fluct. M Johnson Perming
Ω - Volume	0.01 mm^3 (wire)
Operating T	RT
Power	Batter

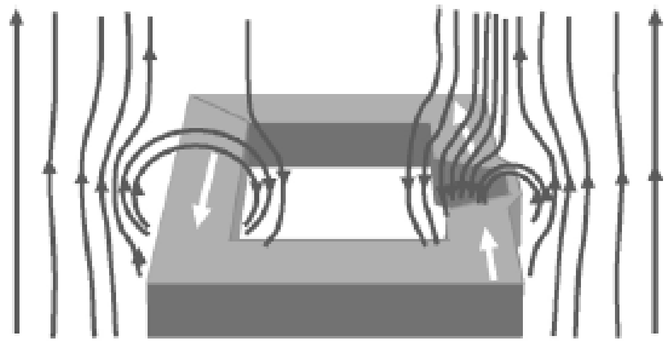


Commercial: ~100 $

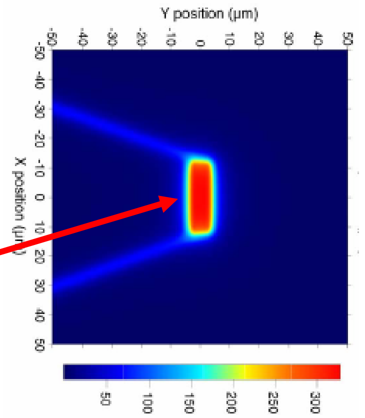
Disruptive technologies? Superconducting flux concentrator

State variable	GMR voltage
B-field	Vector
B_{noise} @ 1 Hz sources	**.03 pT/√Hz** **Sensor noise**
Ω - Volume	$0.1\ cm^3$
Operating T	cryogenic
Power	line

Hybrid S.C./GMR



Field Gain
Nb ~ 500
YBCO ~2000

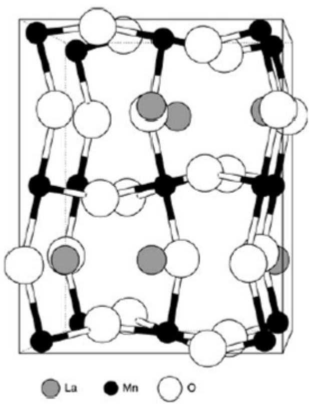


Sensor

"…An Alternative to SQUIDs"
Pannetier**, et. al, IEEE Trans SuperCond** 15(2), 892 (2005)

Colossal Magneto-resistance

- Manganite materials
  - $La_{1-x}M_xMnO_3$
  - Phase transition – Jahn-Teller distortion
    - Low T – Ferromagnetic
    - High T – Paramagnetic semiconductor

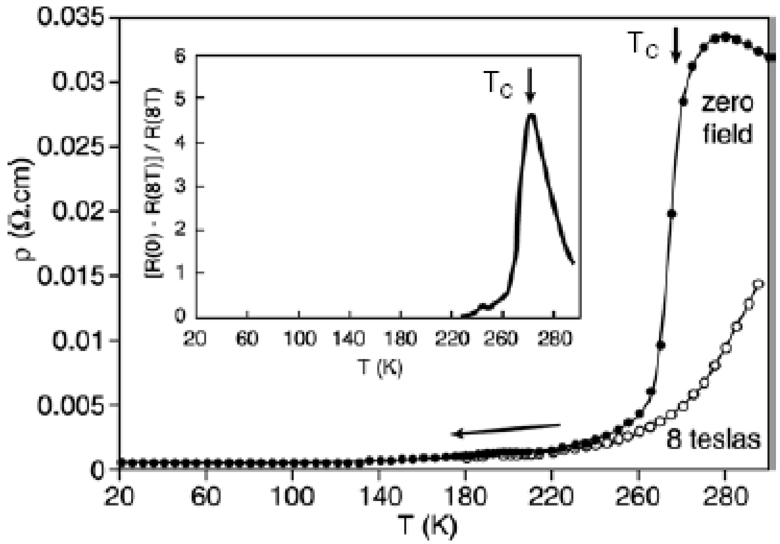


re 2. Crystallographic structure of $LaMnO_3$ (after [26]).

- ~ 500% change of resistance

- Barriers to commercialization
  - Optimal $\Delta R/R$ at ~260 K
  - High fields
  - Single crystal materials
  - High growth temperatures

- Can integrate with superconducting flux concentrators

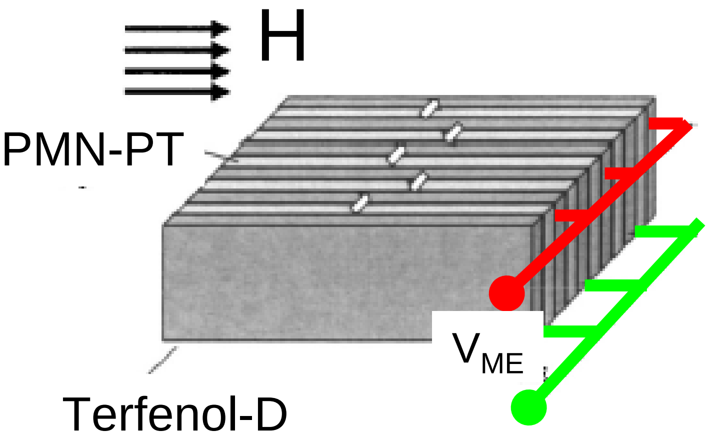


Haghiri-Gosnet, **Renard,** J. Phys. D: Appl. Phys. **36** (2003) R127–R150

Magneto-electric

State variable	Piezo voltage
B-field	Vector
B_{noise} @ 1 Hz sources	**100 pT/√Hz** **pyro/static**
Ω - Volume	1 mm^3
Operating T	-40 to 150°C
Power	0

Magnetostrictive
+
piezo-electric
multilayer



Disruptive
No power required
Two terminal device
High impedance output

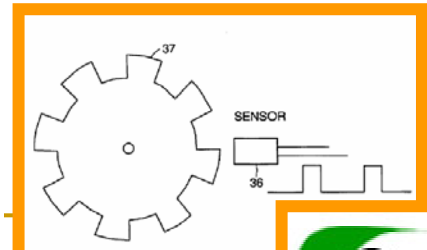
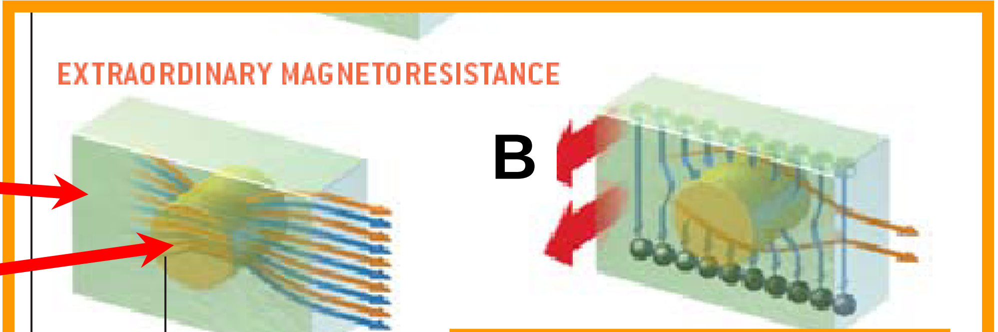


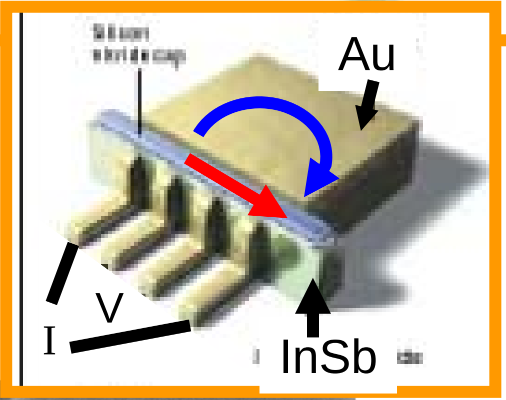
FIG. 15

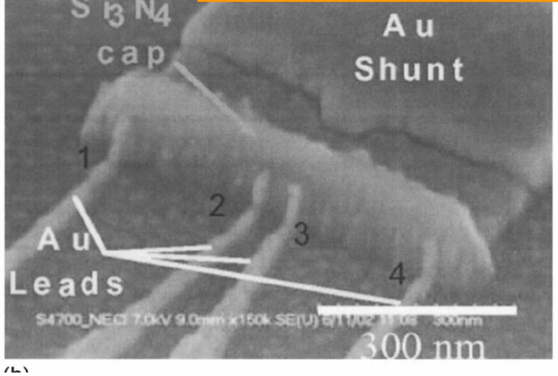
Spinix
Spinix Corporation

Zhai, Li, Viehland, Bichuin, JAP (2007)
Dong, et. al APL V86, 102901 (2005).

Extraordinary MR (EMR)







- Hall effect with metal impurity
  - Based on 10^6 MR in van der Pauw disks
- Non-magnetic materials
- Mesoscopic devices
- ΔR/R ~ 35% in field
- Replacement for GMR in hdds?
  - Can't compete with TMR in MgO
  - May scale better at small sizes

"Magnetic Field Nanosensors, Solin, Scientific American **V291**, 71 (2004)

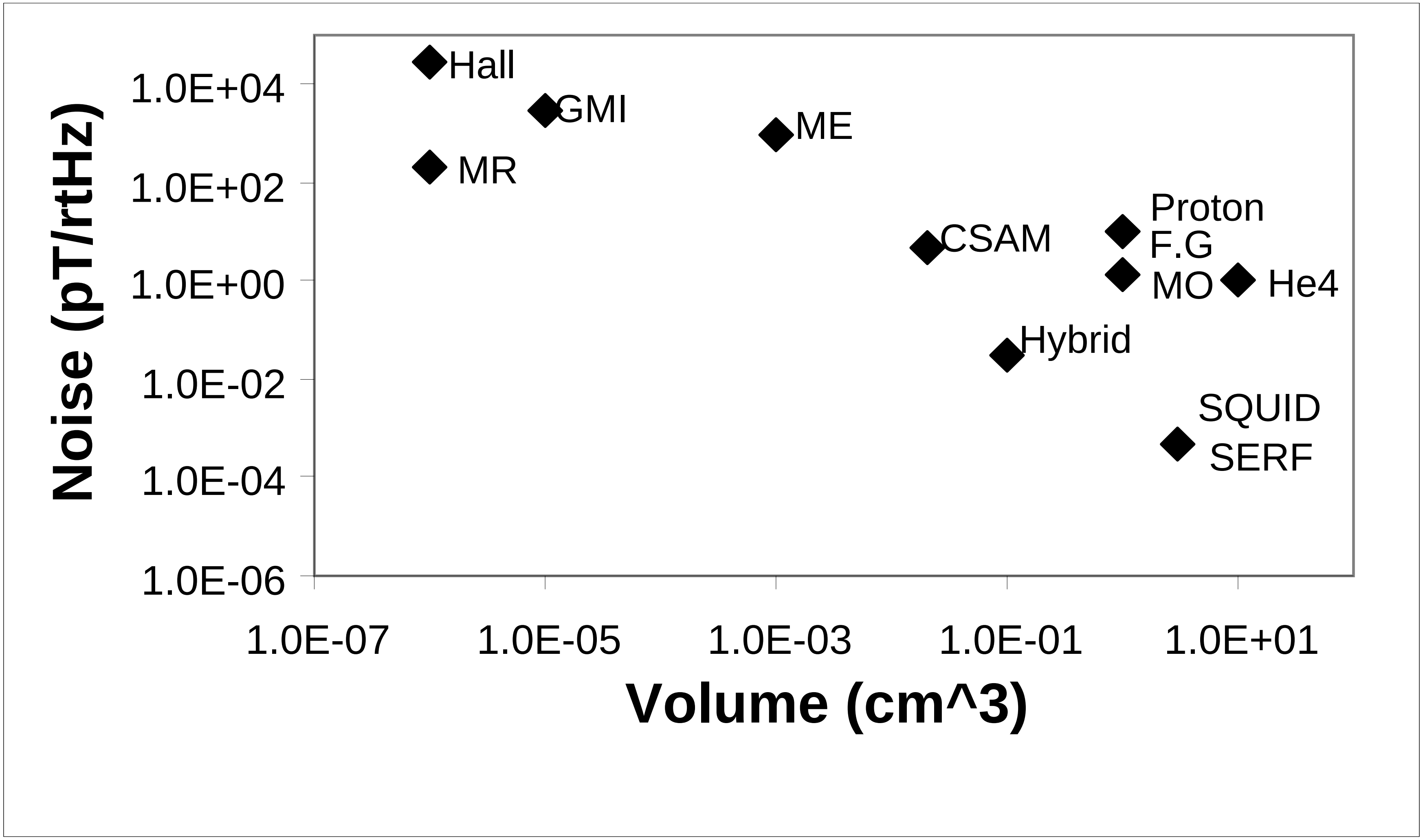
Compilation

Sensor	$\vec{B}$	B_n (pT/√Hz @ 1 Hz)	Volume	Power
SQUID	**v**	0.001	3 cm^3	Line
e^- - SERF	**v**	0.001	3 cm^3	Battery-line
Hybrid GMR/SC	**v**	**0.032**	**0.1 cm^3**	**line**
Proton	**s**	1	10 cm^3	battery
e^{-} - He^4	**s**	1	1 cm^3	Battery-line
Magneto-optic	v	1.4	1 cm^3	line
Fluxgate	**v**	10	1 cm^3	battery
ME	**v**	**100**	**1 mm^3**	**0**
MR	**v**	200	0.001 mm^3	battery
GMI	**v**	3000	0.01 mm^3	battery
Hall	**v**	**30,000**	**0.001 mm^3**	**battery**

Bn vs. V

Trend: Noise increases as Volume decreases

B_{noise} vs. Volume



Volumetric energy

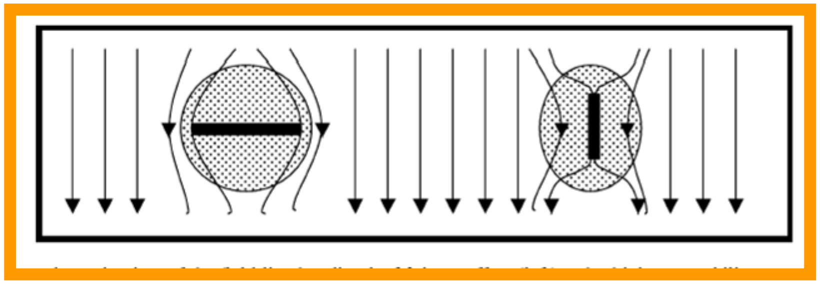
Compare sensors based on volumetric energy resolution

- Energy resolution ∝ Noise Power × Volume

$$e \approx \frac{B_n^2}{2\mu_0}\Omega$$

Ω

S.C. F.M



Device	Energy Resolution e(J/Hz)
SQUID w/pickup	3×10^{-29}
SERF	3×10^{-29}
Hybrid GMR/SC	4×10^{-29}
GMI	6×10^{-28}
AMR	7×10^{-26}
CSAM	2×10^{-25}
He4	4×10^{-24}
Fluxgate	3×10^{-23}
GMR w/feedback	4×10^{-23}
Hall	5×10^{-23}
Magnetoelectric	5×10^{-23}
TMR w/FC	1×10^{-19}

D. Robbes / Sensors and Actuators A 129 (2006) 86–93

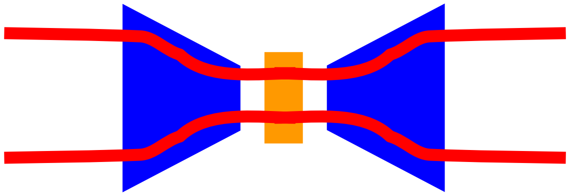
Conclusions

- High sensitivity magnetometers research very active
- Many advances to be made in conventional devices
  - Potentially disruptive technologies
  - Move to smaller, lower power, nano-fabrication
- Noise floor decreases with volume
- Can look at intrinsic energy resolution of sensor
- Also need to evaluate high sensitivity against many other parameters:
  - Spatial resolution
  - bandwidth
  - dynamic range
  - cost, …

Pick the right tool for the job!

Acknowledgement.

Acknowledgements



- Fabio da Silva
- Sean Halloran
- Lu Yuan
- Jeff Kline
- Steve Russek
- Bill Egelhoff
- John Unguris
- Mike Donahue
- John Kitching

Noise vs. volume in magnetic sensors

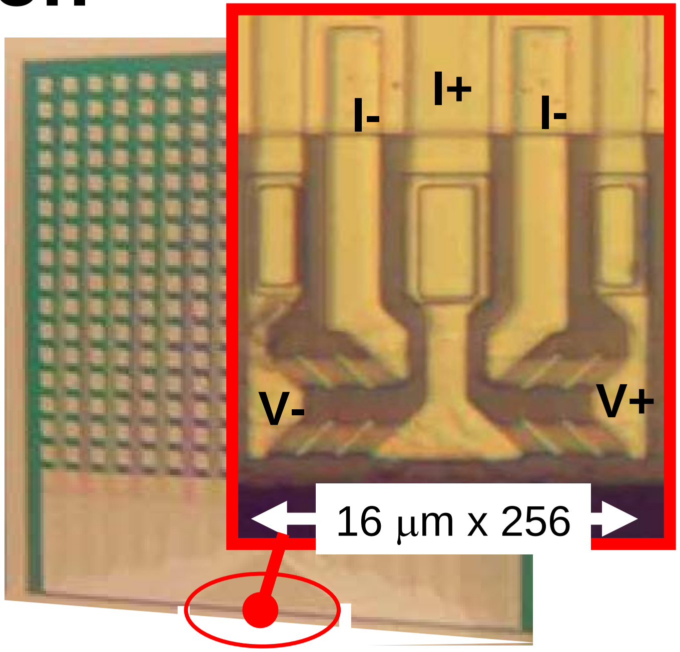
$$\boxed{B_{n,mag} \propto \frac{T\chi''}{\Omega}}$$

- Fluxgate magnetometers
    - Increase volume (Ω) & decrease loss (χ'')
- AMR – make up for low $\Delta R/R$ by:
    - Large arrays of elements (volume)
    - good magnetic properties (reduce χ'')
- Flux concentrators
    - Increase volume
    - Softer, low hysterisis to reduce χ''

"Fundamental limits of fluxgate magnetometers…"
Koch et al, APL V75, 3862 (1999)

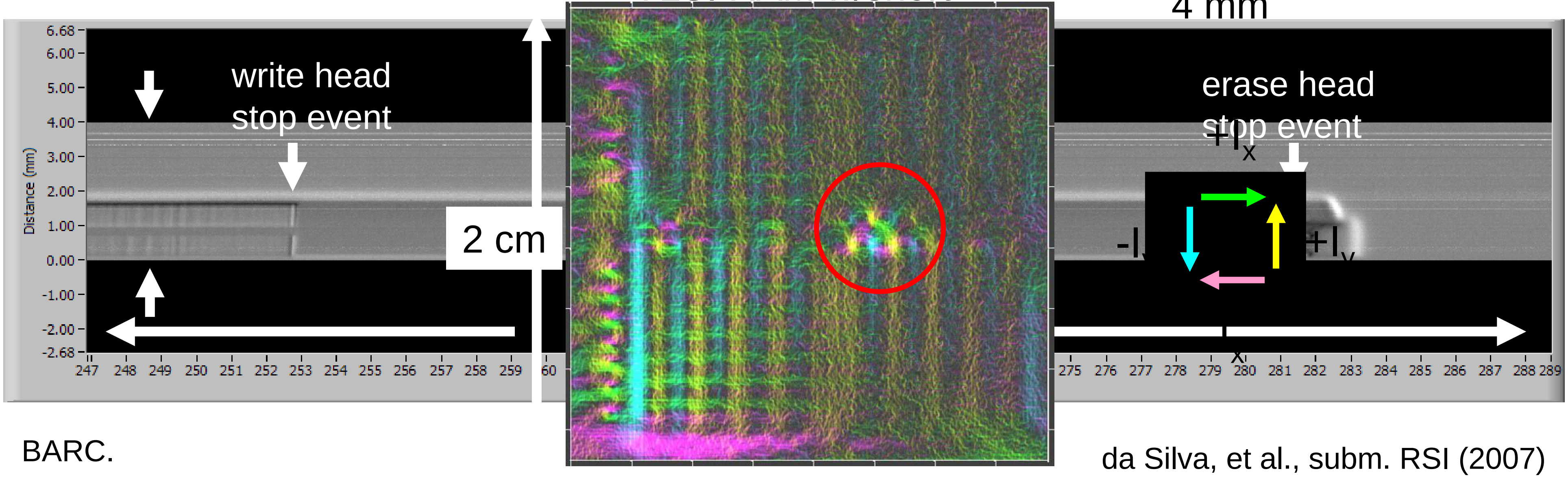
MR Sensors – spatial resolution

- 256 element AMR linear array
- Thermally balanced bridges
- High speed magnetic tape imaging – forensics, archival
- NDE imaging



4 mm

Current flow in VLSI RAM w/short



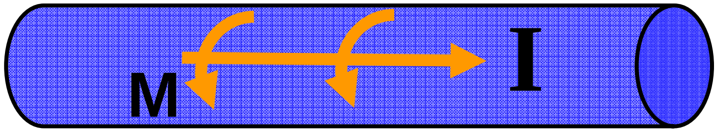
BARC.

da Silva, et al., subm. RSI (2007)

Innovations in Fluxgate technology

Circumferential Magnetization

- Apply current in core

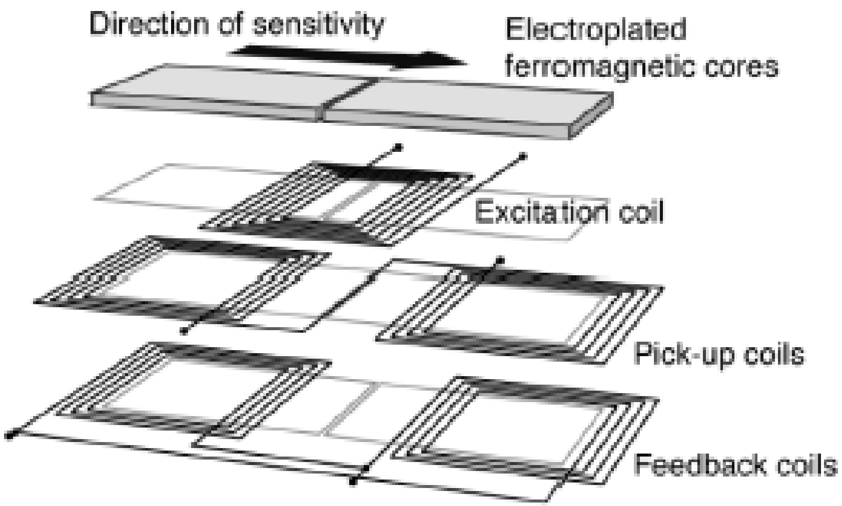


- Single domain rotation
- <u>1 pT/√Hz @ 1 Hz</u>

Koch, Rosen, APL 78(13) 1897 (2001)

Micro-fluxgates

- Planar fabrication
- <u>80 pT/√Hz @ 1 Hz</u>



Kawahito S., IEEE J. Solid State Circuits 34(12), 1843 (1999)

e^--spin magnetometer

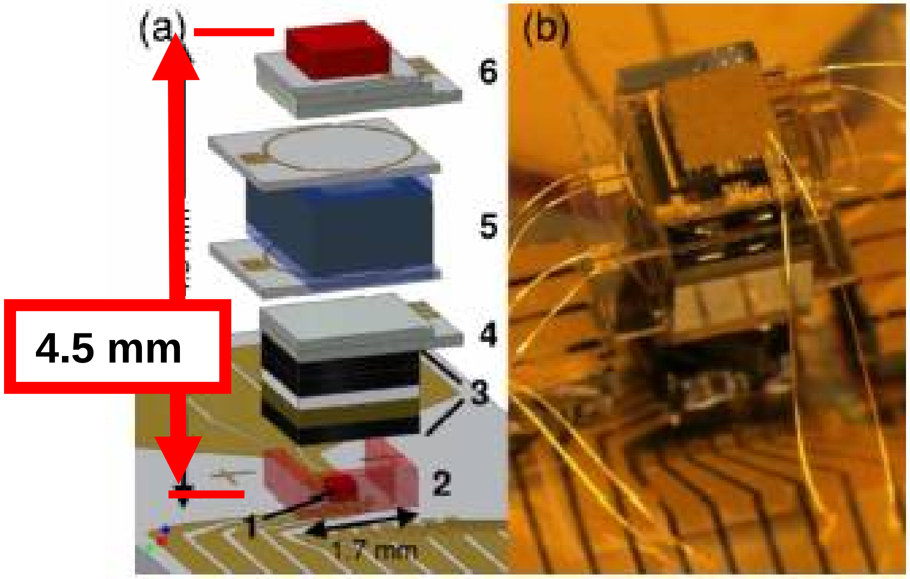
Chip scale atomic magnetometer

State variable	Frequency
B-field	Scalar
B_{noise} @ 1 Hz	5 pT/√Hz
Ω - Volume	20 mm^3
Operating T	110 ^{o}C
Power	Small battery

Rb metal vapor

Optimized for low power

Very small form factor

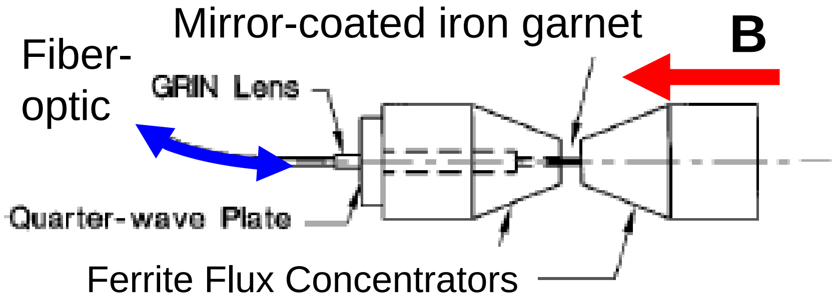


P. D. D. Schwindt, et al.
***APL* 90, 081102 (2007).**

Magneto-optic

State variable	Light intensity
B-field	Vector
B_{noise} @ 1 Hz	1.4 pT/√Hz
Ω - Volume	1 cm^3
Operating T	ambient
Power	line

Magnetometer head



- Light polarization changes in garnet
- Rotation ∝ B-field (Faraday effect)
- Sensed with interferometer

<u>Disruptive</u>

- **Light not affected by B**
  - **Remote sensors**
- **High speed**
- **<u>Imaging capability (light)</u>**
  - **NDE**

Deeter, et. al Electronics Letters, V29(11), p 993 **(1993).**

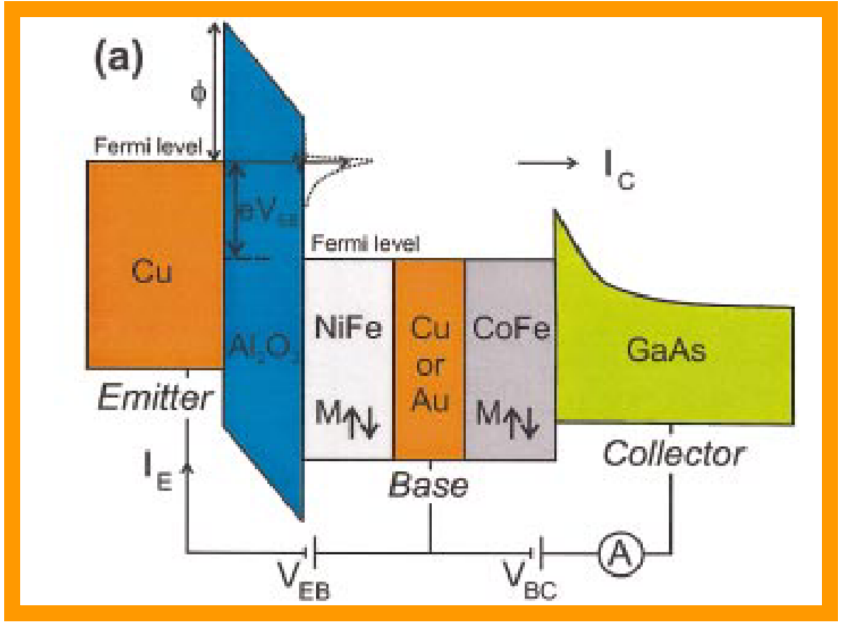
Youber, Pinassaud, Sensors and Actuators A129, 126 **(2006).**

Spin transistors

- Tunnel junction based devices

  Spin dependent hot e- transmission

  - Cu⇨Tunnel Barrier⇨Spin Valve⇨Schottky barrier
- 3400% magneto-conductance at 77 K
- Relatively low currents (10 μA)



van Dijken, et. al, APL V83(5) 951 (2003)