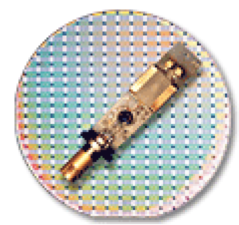
SQUID Instruments and Applications

- Basics
  - Types of SQUIDs
  - Input Circuits
  - Noise Reduction
  - Cryogenic Needs
  - Limitations



- Applications
  - Laboratory
  - Geophysical
  - Non-Destructive test and Evaluation
  - Biomedical

Robert L Fagaly

What is a SQUID?

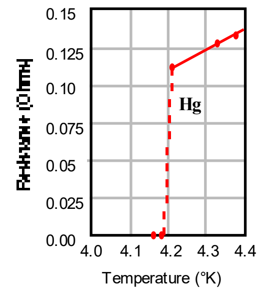
- A superconducting transducer that converts magnetic flux to voltage
- A simple input coil can transform this device into a current-to-voltage transducer
- Because of its superconducting nature, SQUIDs must operate at cryogenic temperatures
- What does SQUID stand for?
  - Superconducting QUantum Interference Device

Why Use a SQUID?

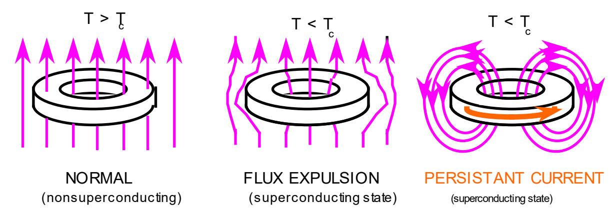
- Advantages of SQUIDs over other types of electromagnetic sensors
  - Sensitivity that approaches quantum limits ($< 10^{-30}$ J/Hz)
  - True dc frequency response
  - Ultra-wide bandwidth (> 10 GHz demonstrated)
  - Flat phase response
  - Large dynamic range: as much as 200 db
  - Excellent linearity: $> 1{:}10^7$
- Typical applications that need SQUIDs
  - Detection of gravitational waves in astrophysics
  - Measurements of changes in the Earth's magnetic field, *e.g.*, oil exploration
  - Non-Destructive Evaluation of cracks and flaws
  - Non-invasive detection of brain activity

Principles Behind SQUIDs

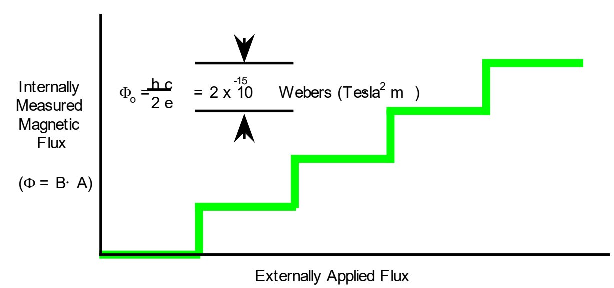
Superconductivity



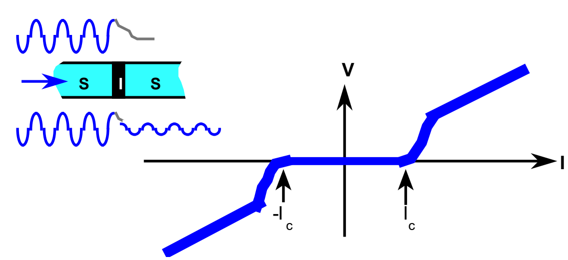
Meissner Effect



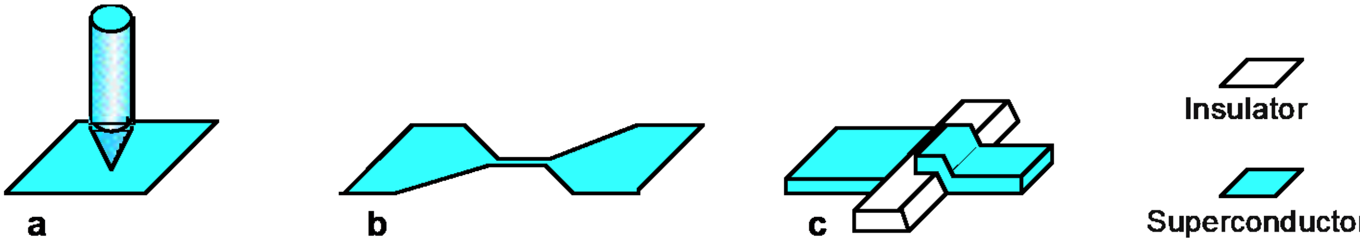
Flux Quantization



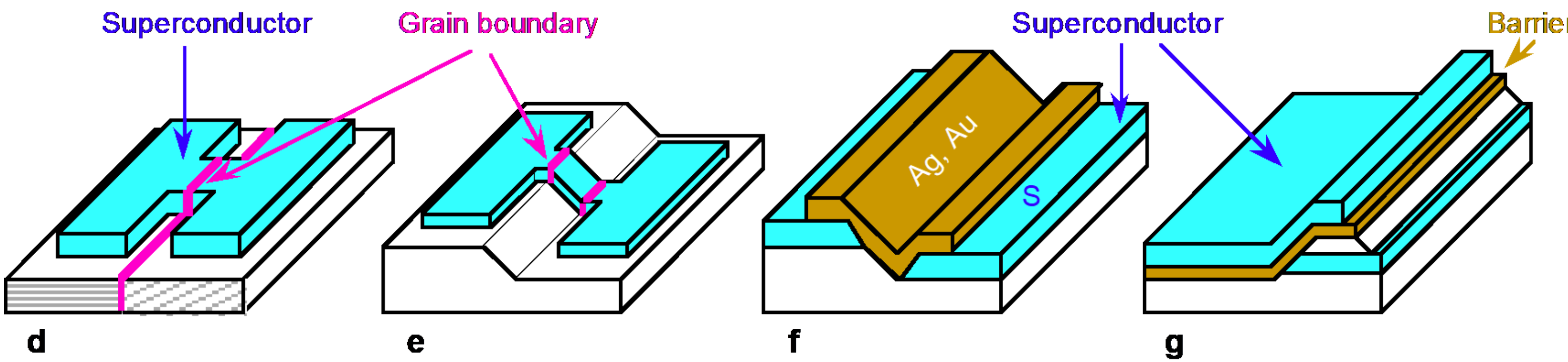
Josephson Effect



Junction Types



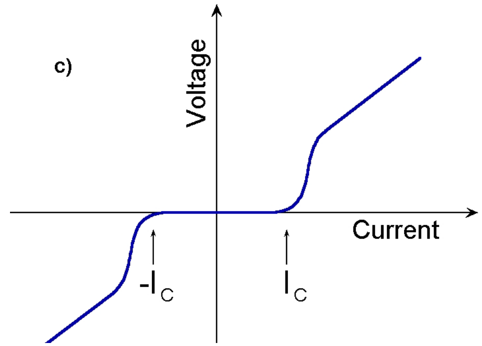
(a) point contact (b) microbridge (c) thin-film tunnel junction



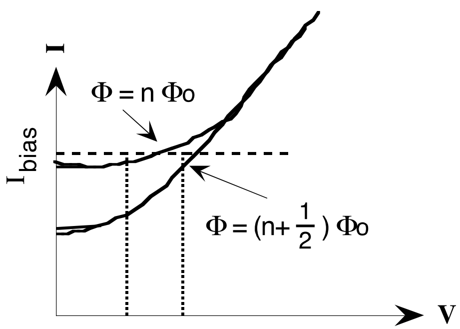
(d) bicrystal, (e) grain boundary, (f) step edge, (g) ramp edge

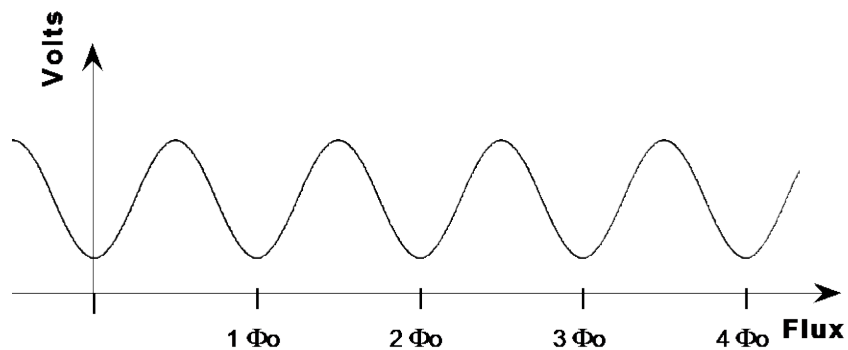
SQUID basics

- Bias current is at or just above I_c



- SQUID voltage is periodic with flux

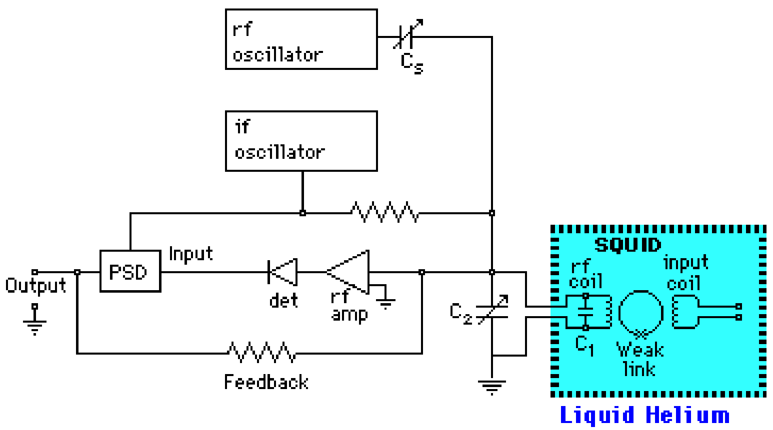




- dc – GHz device
  - electronics are limitation on bandwidth

Types of SQUIDs

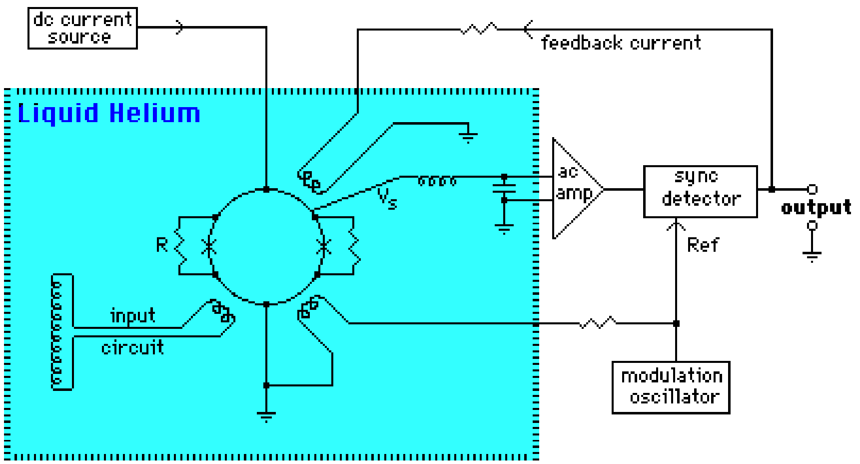
rf SQUID



Single Junction

rf current bias inductively coupled to the SQUID to measure its impedance

dc SQUID



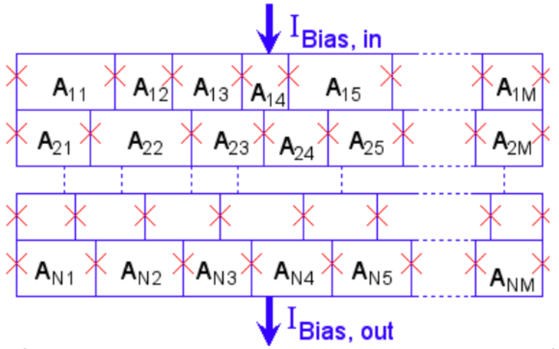
Double Junction

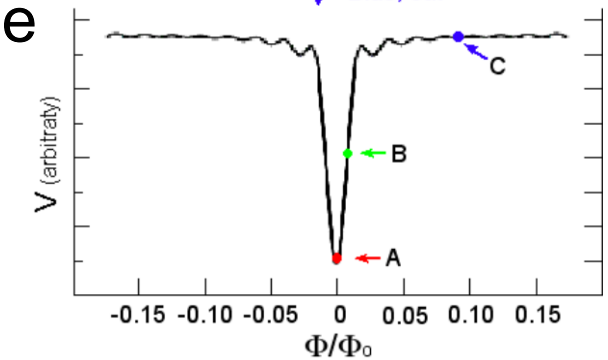
dc current applied directly to the SQUID to measure the loop impedance

Negative Feedback (closed loop operation) allows μΦ resolution

SQIFs/SQUID Arrays

- SQUIDs connected in series & parallel:
- Increased output voltage & dynamic range
- Highly non-linear V-Φ response which leads to high sensitivity
  - "B" is the ideal operation point





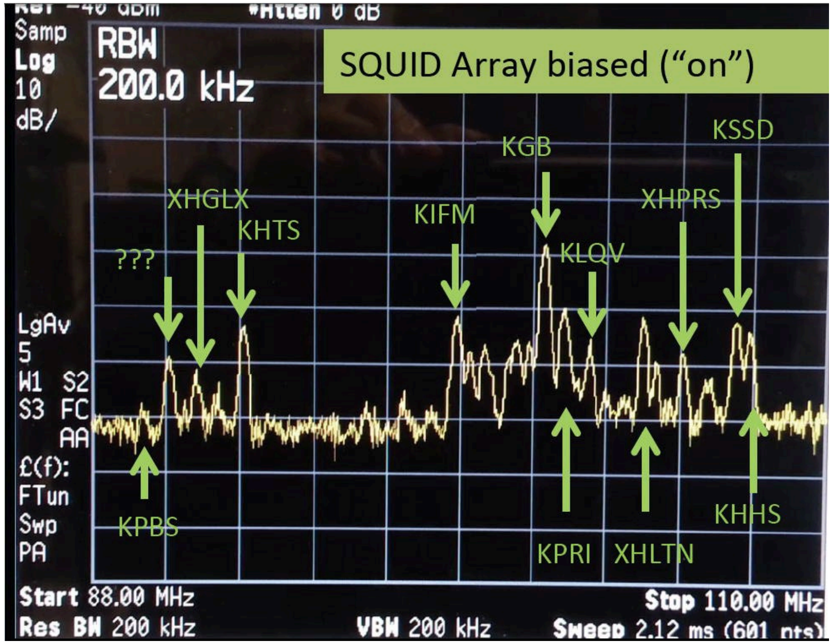
- SQIF properties scale with N parallel, M series loops:
  - Output voltage — M — *maximize*
  - Power gain — $M \times N$ — *maximize*
  - Signal-to-noise dynamic range — $M \times N$ — *maximize*
  - Spur-free dynamic range — $(M \times N)^{2/3}$ — *maximize*
  - Output resistance — M/N — target, *e.g.*, 50 Ω

2D 10,000 SQUID Array Chip: 5x5 mm

- HTS SQIF's with $>10^6$ elements have already been fab'd

SQIF Performance

- SQIFs are ultra-wideband receivers



IEEE TASC 2015

  - GHz bandwidths demonstrated

- Utilizing a small area SQIF in a magnetic microscope has the potential for non-destructive evaluation of IC's at operational frequencies

rf vs. dc SQUIDs

- rf SQUIDs
  - $E_{noise} = L_{input} I_{noise}^2 = \frac{\Phi_{noise}^2}{L_{input}} \sim \frac{1}{\sqrt{f_{pump}}}$ → 10^{-28} J/Hz sensitivity
    - 19 MHz pump frequency chosen in 1970 because of available components
    - QD 200 MHz pump frequency allowed E_N improvement of 10x (3x in B_N)
  - Simple cryogenic connections—only 2 leads needed
  - At 1 GHz, rf HTS may be quieter than dc HTS
- dc SQUIDs
  - $E_{noise} = 12 k_B T \sqrt{LC}$ → 10^{-31} J/Hz sensitivity for commercial devices
    - Research devices (no input coils) as low as 10^{-34} J/Hz (~ h)
  - SHE dc SQUID (1982)
    - 1st commercial dc SQUID, thin film tunnel junction with toroidal encapsulation
    - a-SiO_2 barrier allowed J_c of junctions within a few %
  - Present day devices are all thin film with AlO_x barriers

High Temperature Superconductivity

- Positives
  - Higher Operating Temperatures and Reduced Cooling Requirements
  - Device noise approaching LTS magnetometers (10^{-14} tesla/√Hz)
  - Simplified cryogenics
    - ratio of latent heats/unit volume (LN_2/LHe) ~ 50
    - single-stage closed cycle cooling possible
  - Reduced size and operating costs
- Negatives
  - Can't make flexible wires (no axial gradiometers)
  - Planar devices suitable only for:
    - Magnetometers: B_x (susceptible to environmental noise)
    - Intrinsic planar gradiometers (dB_Z/dx) possible, but not axial (dB_Z/dz)
  - Need $< 10^{-12}\ \Omega$ joint resistances for dc response

Types of SQUIDs (HTS & LTS)

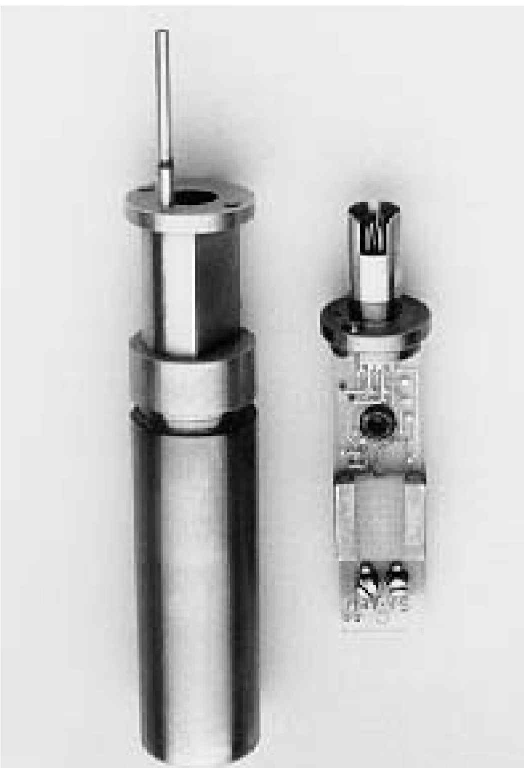
- Liquid Helium (LTS) SQUIDs
  - Niobium best material ($T_C \sim 9.3$ K)
    - only LTS device commercially produced
    - 4.2 K (~ ½ T_C)
    - $d\Phi/dT$, dI_C, dV_{mod}/dT small and consistent
  - lab demonstration of NbN devices ($T_C \sim 20$ K) many years ago
- Liquid Nitrogen (HTS) SQUIDs
  - YBCO has $T_C \sim 93$ K
    - 77 K 5/6 T_C
    - much larger $d\Phi/dT$, dI_C, dV_{mod}/dT
    - YBCO is only HTS device commercially available
  - BSCCO ($T_C \sim 110$ K)
  - lab demonstration of Thallium HTS SQUIDs ($T_C \sim 125$ K) many years ago
  - MgB_2 may have possibilities in future

Differences between LTS and HTS

- LTS isotropic, $\xi \sim 300$ Å; HTS anisotropic $\xi_{a,b} \sim 15$ Å; $\xi_c \sim 6$ Å
  - crossovers have larger dimensions than coherence length of YBCO in c-direction (MgB_2 is isotropic, but smaller: $\xi_c \sim 25$ Å , $\xi_{a,b} \sim 65$ Å)
  - Thus HTS crossovers have not been successfully fabricated
- LTS metallic, malleable; HTS ceramic
  - LTS can be wound in coils; HTS cannot
  - LTS coils can be remote from the SQUID sensor,
  - HTS coils are fabricated adjacent to the SQUID
- LTS coils can be operated in fields up to H_c
  - 9 tesla with NbTi, 20 tesla with Nb_3Sn
- HTS device performance degrades in magnetic fields
  - higher noise ($\propto \sqrt{H}$)
  - reduced slew rate
  - older devices hysteretic in μT ac fields

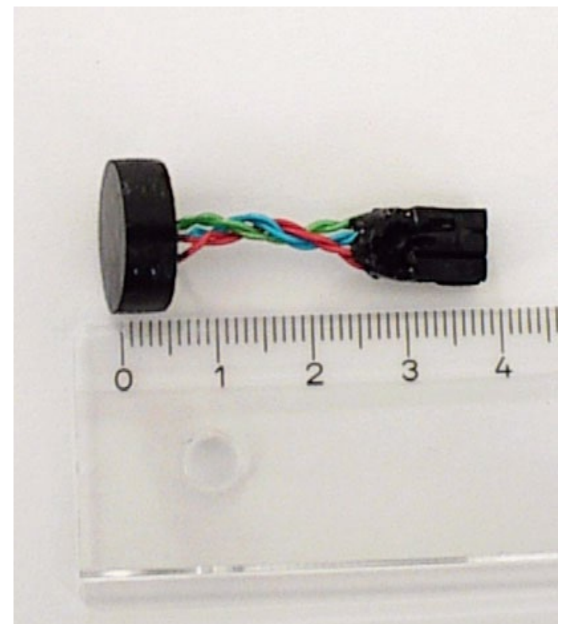
SQUID Sensors

LSQ/20 LTS dc SQUID



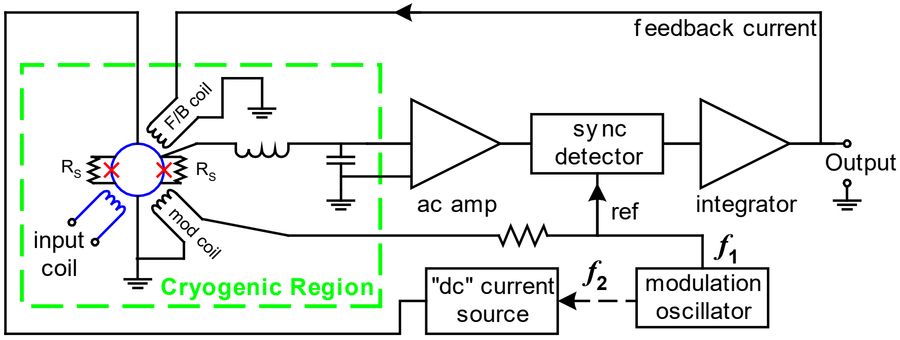
HTM-8 HTS SQUIDs
and detection coil

Sensing Element without Cold Electronics

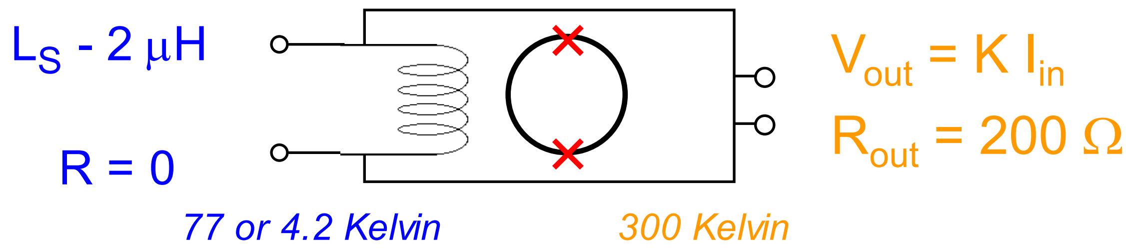


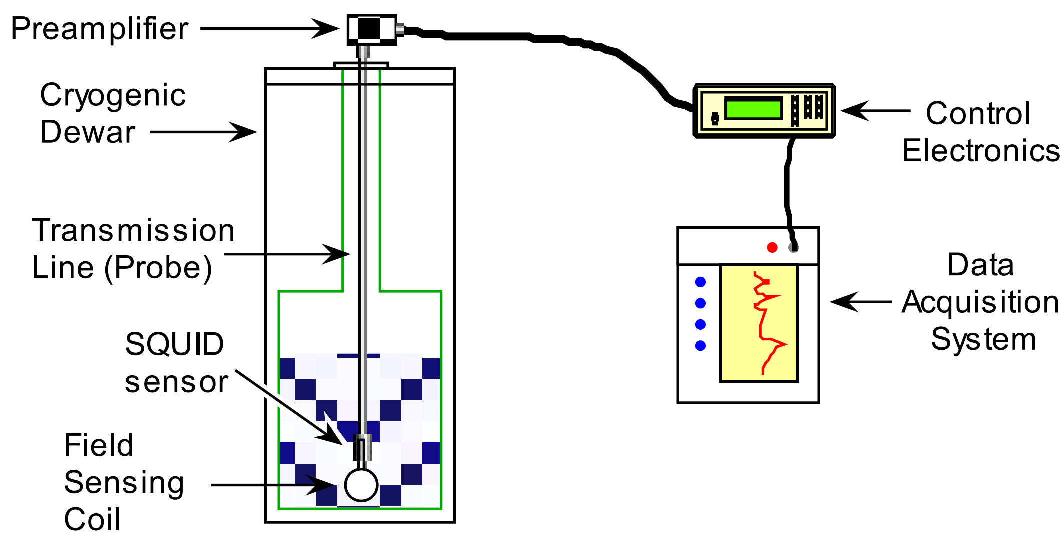
SQUID Electronics

- Analog Flux-Locked Loops
  - dc Biasing
  - ac Biasing
- Alternate schemes
  - APF
  - DSP
  - rf SQUID electronics
  - MHz electronics
  - GHz detection
  - Flux counters



The SQUID as a Black Box

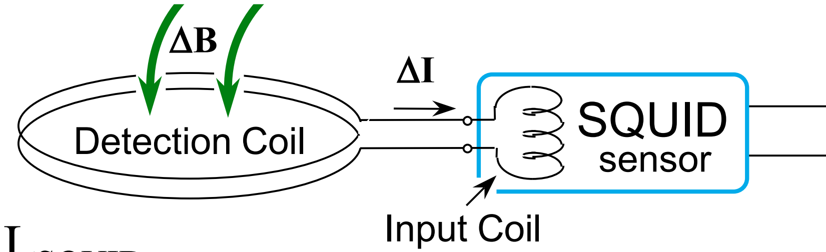




Detection coils need not be at same temperature as SQUID sensor

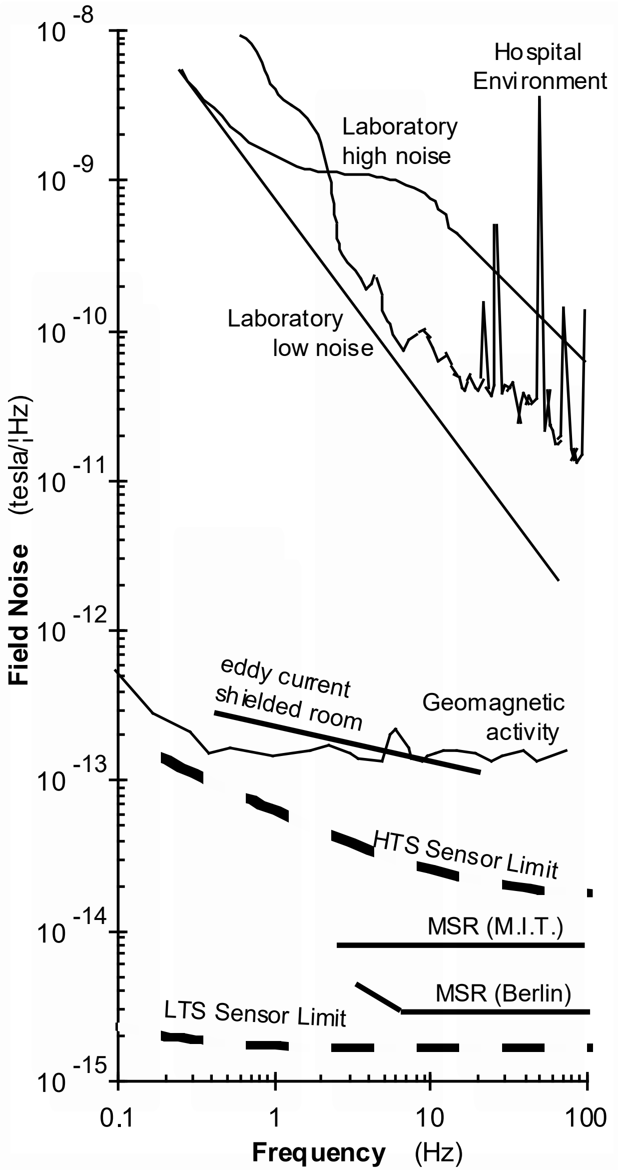
Input Circuits

- Sensitivity Calculations
  - $\Delta\Phi = N\ A\ \Delta B = (L_{Coil} + L_{SQUID})\ \Delta I$
  - $\Delta B = (L_{Coil} + L_{SQUID})\ \Delta I/NA$
  - Highest sensitivity occurs when $L_{Coil} = L_{SQUID}$



- Detection Coils
  - Magnetometers are highly sensitive
  - If object is close, gradiometer can reject distance noise sources
- For a pure magnetometer coil
  - $L_{Coil} = 4 \times 10^{-7} N^2 r_{coil} [\log_e (8\ r_{coil} / r_{wire}) - 2]\ \mu H$

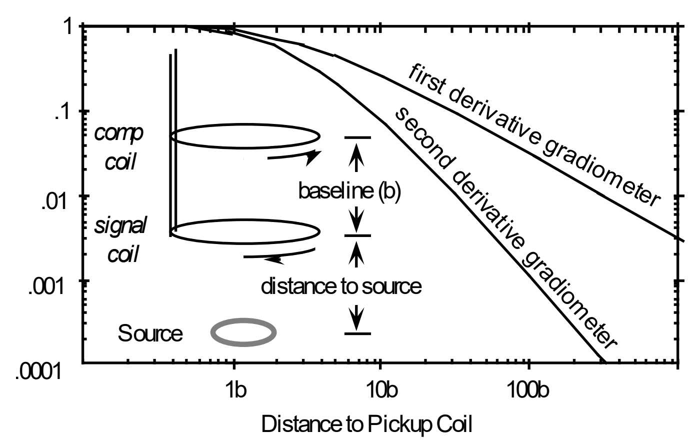
Environmental Noise



- Combination of
  - Geomagnetic activity (small)
  - 50/60 Hz Power line (large)
  - Moving Objects
  - Radiofrequency (rfi) interference
- Sensitivity of SQUIDS
  - < 10 fT/√Hz
- Result is
  - Noise can be 10^6 larger than Signal
- If Noise >> Signal
  - Noise Reduction Method Required
  - *e.g.*, gradiometers, shielding, etc.

Gradiometers for Noise Reduction

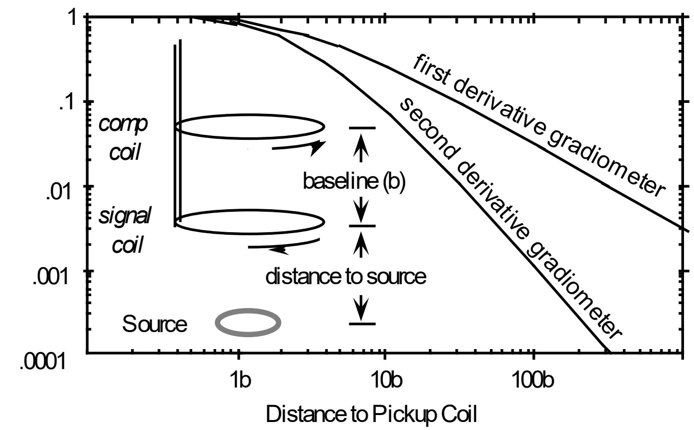
- Simple gradiometer is formed by two identical coils wound in opposite directions, separated by a baseline - b
- Distant sources couple equally well into both positive (→) and negative (←) sense coils of a gradiometer
- Distant sources close to the bottom coil couple much better into it than into the top coil
- For sources only a few baselines away, a gradiometer has essentially the same as a magnetometer
- Higher order gradiometers have better noise rejection, but poorer sensitivity

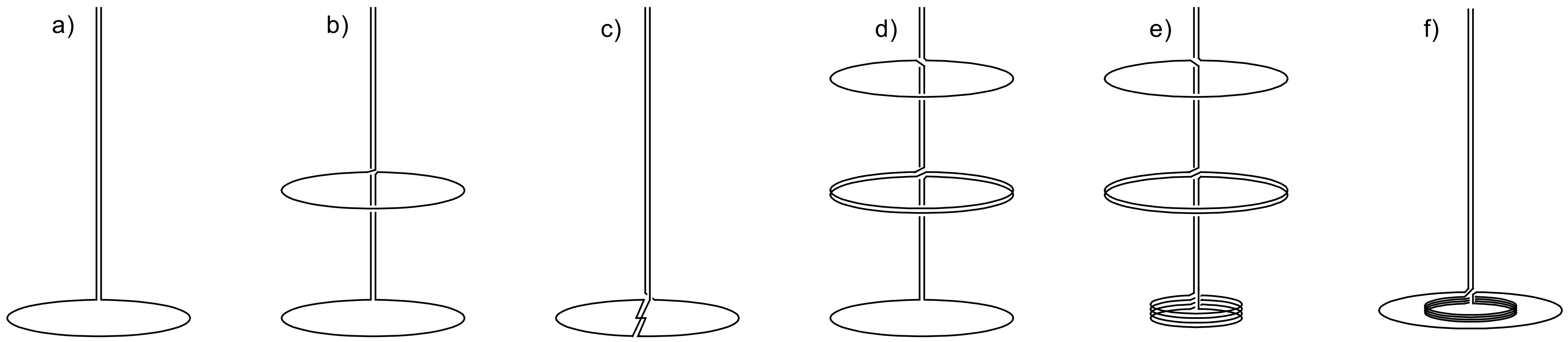


Response of gradient coils relative to magnetometer response ($1/z^3$ suppressed)

Gradiometers for Noise Reduction II

- The Imperfect Gradiometer
  - Superconducting Trim Tabs
  - Electronic Balance
- Coil Configurations
  - First (b), Second Derivative (d, e), etc
  - Symmetric (b, d) vs. Asymmetric (e)
  - Axial (b, d, e) vs. Planar (c) vs. Radial (f)



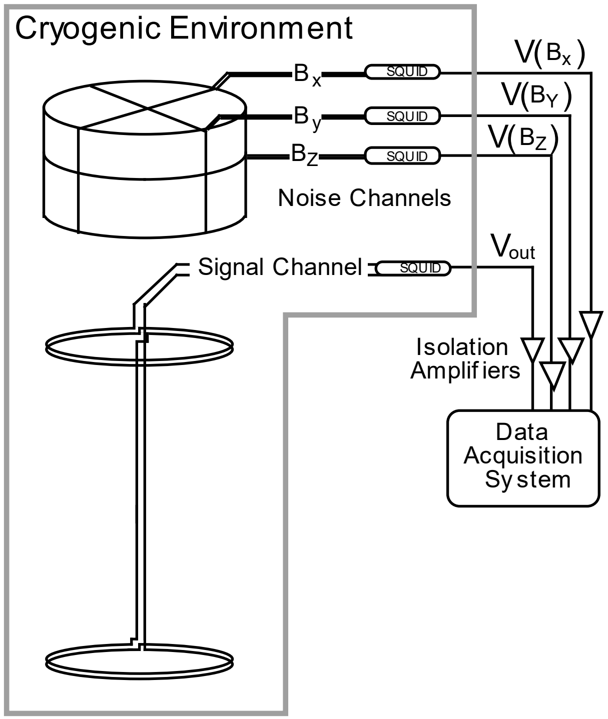


Electronic Noise Cancellation

- $G + \beta \mathbf{H} \propto V_{out} + b_1 V(B_X) + b_2 V(B_Y) + b_3 V(B_Z)$
  - Adjust gains (b_1, b_2, and b_3) to minimize $\beta \mathbf{H}$

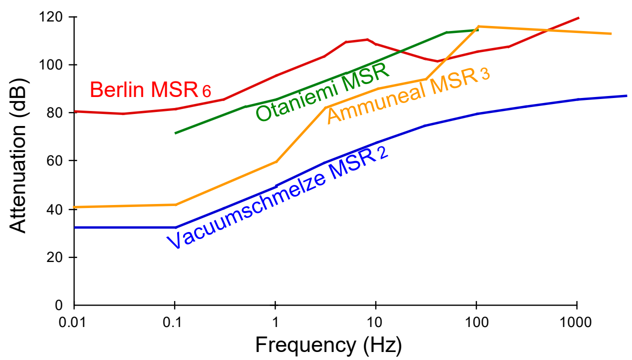
- Ideal reference is 8-element tensor

$$\begin{pmatrix} \frac{\partial B_x}{dx} & - & - \\ \frac{\partial B_x}{dy} & \frac{\partial B_y}{dy} & - \\ \frac{\partial B_x}{dz} & \frac{\partial B_y}{dz} & - \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{\partial B_x}{dx} & \frac{\partial B_y}{dx} & \frac{\partial B_z}{dx} \\ \frac{\partial B_x}{dy} & \frac{\partial B_y}{dy} & \frac{\partial B_z}{dy} \\ \frac{\partial B_x}{dz} & \frac{\partial B_y}{dz} & \frac{\partial B_z}{dz} \end{pmatrix}$$



Shielding for Noise Reduction

- Attenuation only!
  - 50/60 Hz is major offender
  - trains & subways also
- Passive
  - rf shielding
  - Magnetically Shielded Rooms - $$$
  - mu-metal & CryoPerm
    - *if it's not watertight, it's not really shielding*
    - 40 ~ 60 dB below 10 Hz
- Active
  - electronic noise cancellation
  - single frequency, single source
    - Comb filters
  - Adaptive filters

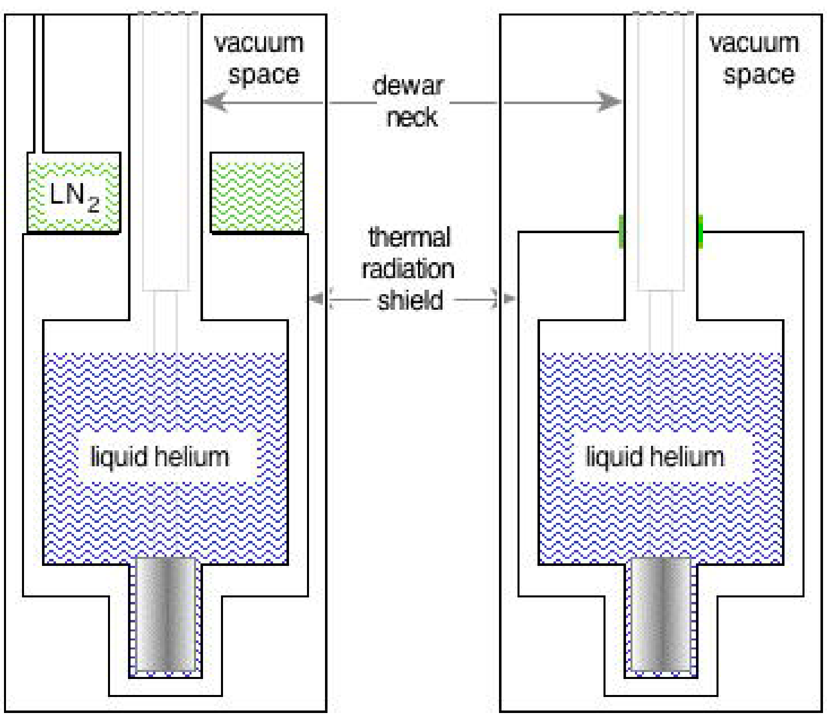


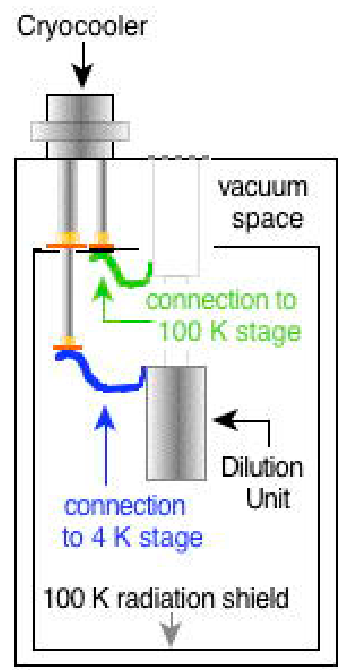
Limitations on SQUID Technology

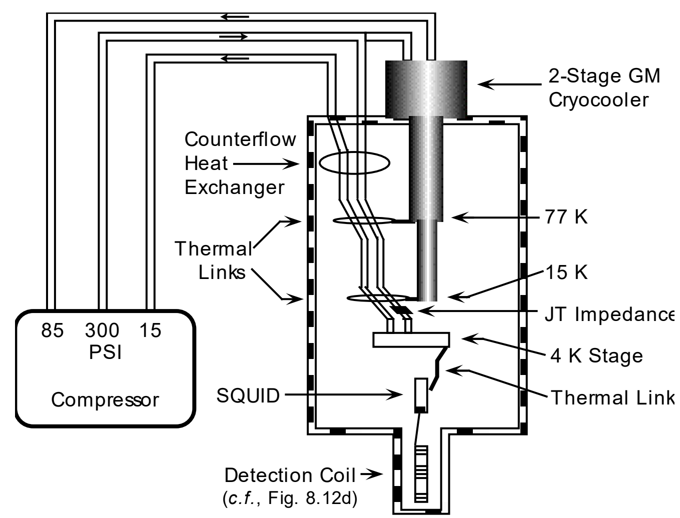
- SQUIDs are sensitive to relative (field or current) changes only
  - except for SQIFs
- Although the intrinsic bandwidth can be > 10 GHz
  - when operated with standard analog flux-locked loop electronics using ac flux modulation, the maximum bandwidth is typically 50 - 100 kHz.
  - MHz electronics commercially available, but not as user friendly
- Another limitation is the presence of $1/f$ noise
  - The use of ac modulation of the bias current for HTS SQUIDs limits the maximum bandwidth to less than half the bias reversal frequency, typically limiting bandwidth to many tens of kHz
- SQUID magnetometers are vector magnetometers
  - A sensitivity of 10 fT/√ Hz is equivalent to an angular resolution (in the Earth's magnetic field) of 0.001 seconds of arc.
  - Rapid rotation can rapidly exceed the system's slew rate if the sensor is a magnetometer
- Cryogenics needed

Refrigeration Considerations

- Cryogen Consumption
- Magnetic noise
- Warm-to-Cold Distances (tail gap)
- LN_2 vs. vapor shielded
- Dewar vs. Closed Cycle
- Cool Down Times
- Reliability
- Resistance to mechanical damage
- Safety

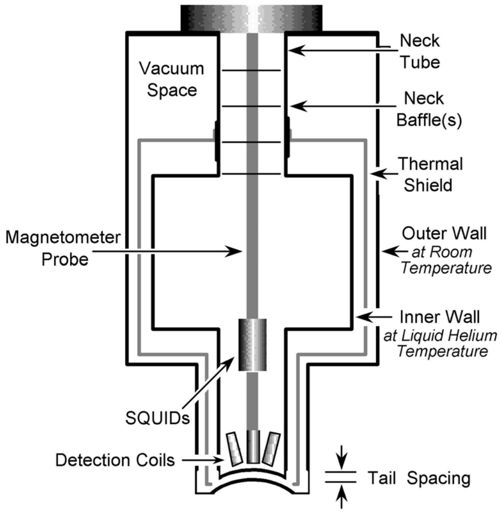




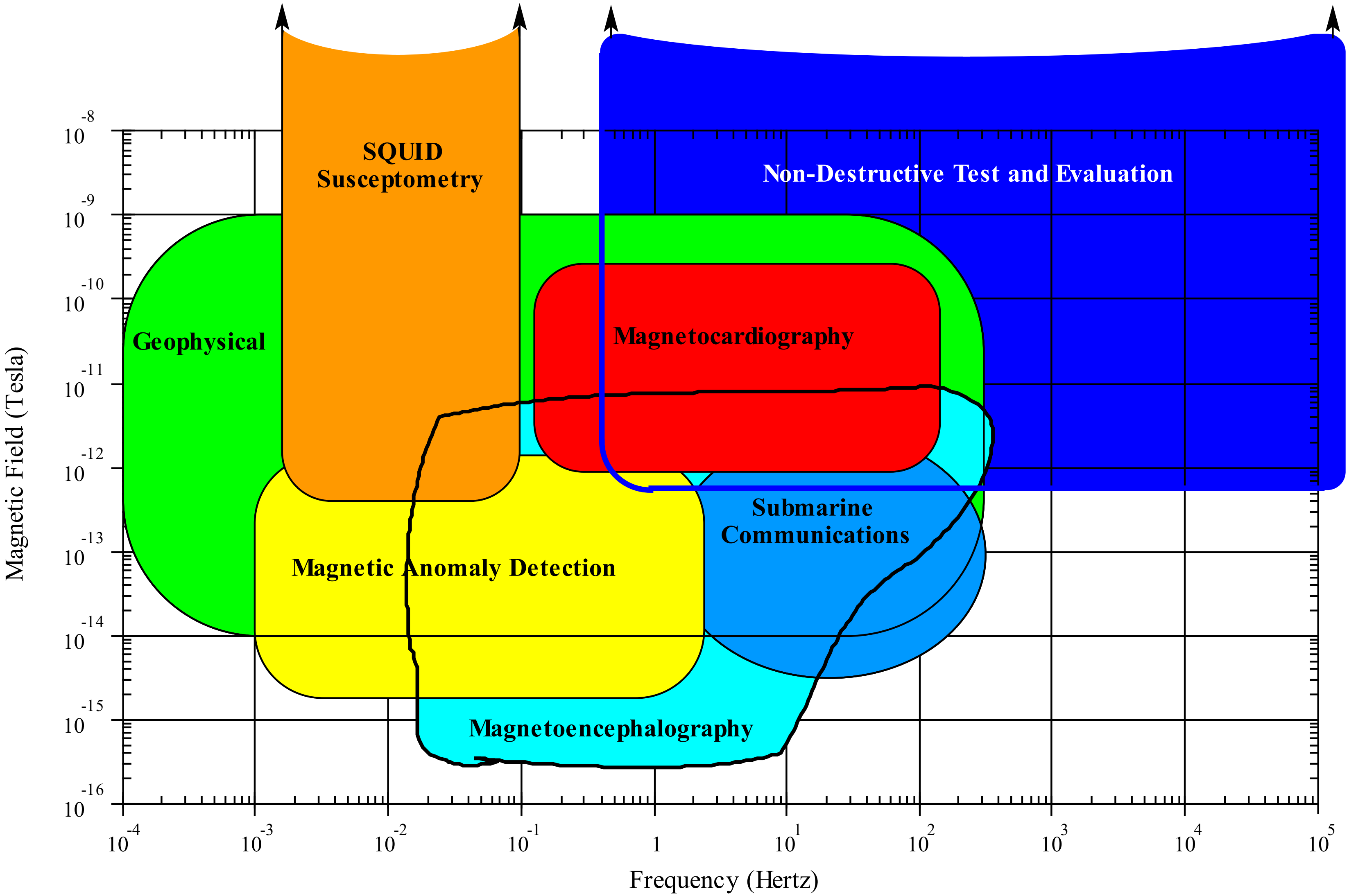


Dewar Construction

- Thermal Loads
  - Conduction
  - Convection
  - Radiation
- Vacuum Isolation
  - the dewar
- Mechanical Constraints
  - Proximity to Room Temperature
  - Physical Size
- Construction
  - metallic vs. magnetically transparent



What can I do with it?

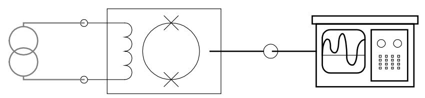


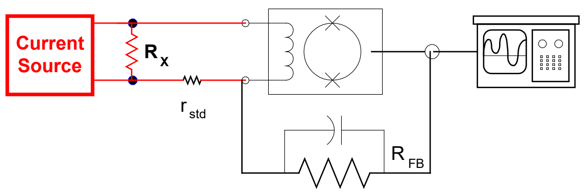
Laboratory Applications

- Ammeter: 10^{-13} ampere
- Voltmeter: 10^{-14} volt
- Ohmmeter: 10^{-12} Ω
- Mutual/Self Inductance: 10^{-12} henry
- Magnetic Susceptibility: 10^{-10} emu & single electron spins
- Magnetic Fields: 10^{-15} tesla
- Nuclear Magnetic Resonance
- Temperature: 10^{-12} kelvin
- Position: 10^{-10} meter
- Orientation: 10^{-10} radians

Probe Configurations

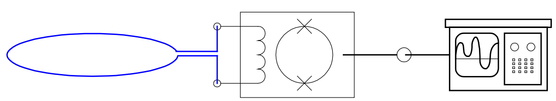
current

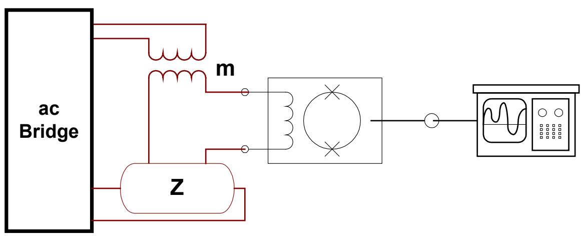




resistance

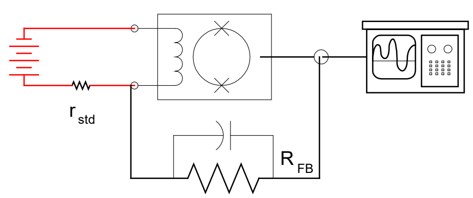
field

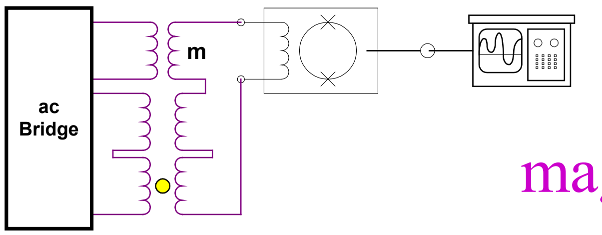




impedance

voltage





magnetization

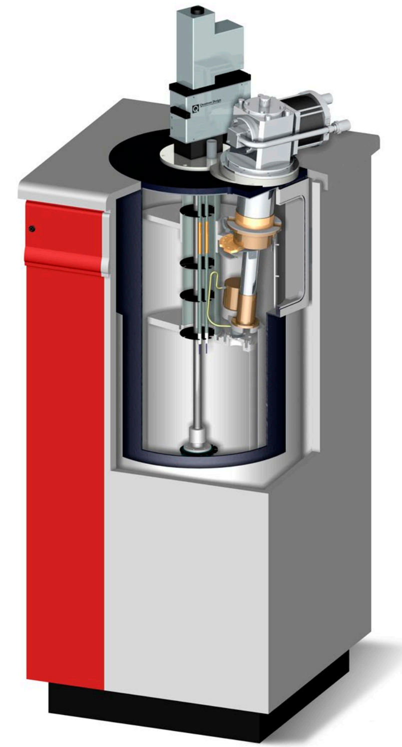
Exotic Applications

- Tests of Einstein's General Theory of Relativity
  - Gravity Probe B *experiment in orbit*
- Magnetic Monopole Searches
- Neutrino and Dark Matter Detection
  - SSC Weak Interactions
  - Cold Dark Matter
  - ßß decay in Sn, Tl, Mb
- Null Detector in Si bolometers
- Radiation Hardened Detectors
  - > 10,000 MRads
- Anti-proton Current Meter
- Quark (fractional charge) Searches

Laboratory Systems

iMAG® components

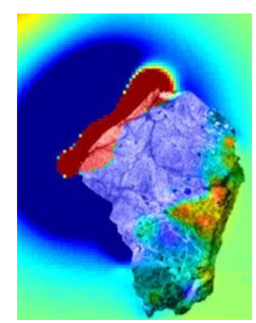
LTS Measurement
System



MPMS
Susceptometer

Geophysical Applications

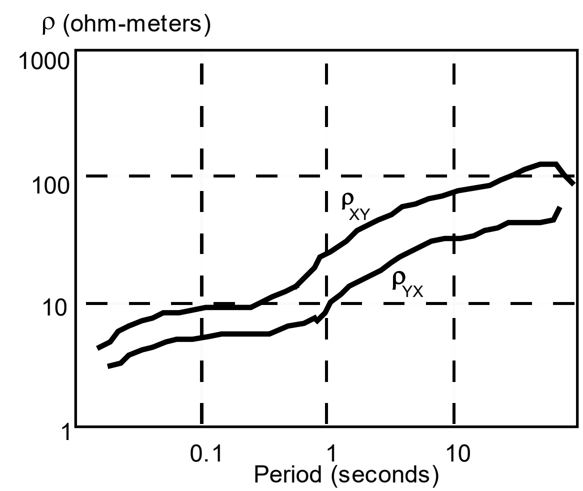
- Oil Exploration
  - MagnetoTellurics; Well Cracking
  - Core samples/Rock Magnetometers
- Borehole Exploration
  - mineral searches to few hundred meter depths
  - petroleum searches to 15 km depths (200° C, 2 kpsi)
  - contaminants to 500 meters
- Airborne Exploration Systems
  - Buried Structures and Minerals
- Controlled Source ElectroMagnetics
  - used for finding minerals; usually done by aircraft
- Oceanographic Measurements
- Geophysical monitoring
  - Earthquakes; Volcano flow
- Paleoarcheology

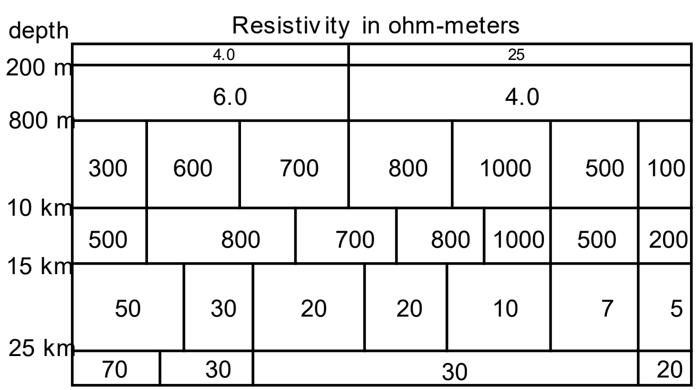


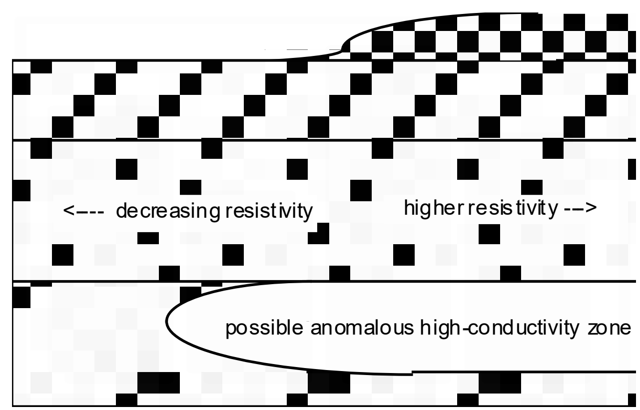
MagnetoTellurics

$$E(\omega) = \mathbf{Z}\, H(\omega)$$
$$E_x(\omega) = Z_{xx}\, H_x(\omega) + Z_{xy}\, H_y(\omega)$$
$$Ey(\omega) = Z_{yx}\, H_x(\omega) + Z_{yy}\, H_y(\omega)$$
$$\rho_{ij} = 0.2\, \left|Z_{ij}\right|^2 \tau$$
$$\delta = 0.5\sqrt{\rho\tau}$$

- MagnetoTellurics
  - used in oil exploration
  - requires 10^{-12} T/√Hz sensitivities
    - initially used LTS sensors (early 80's)
    - HTS technology adequate
    - existing room temperature technology (very large copper coils) adequate
- First "Industrial" application of SQUIDs

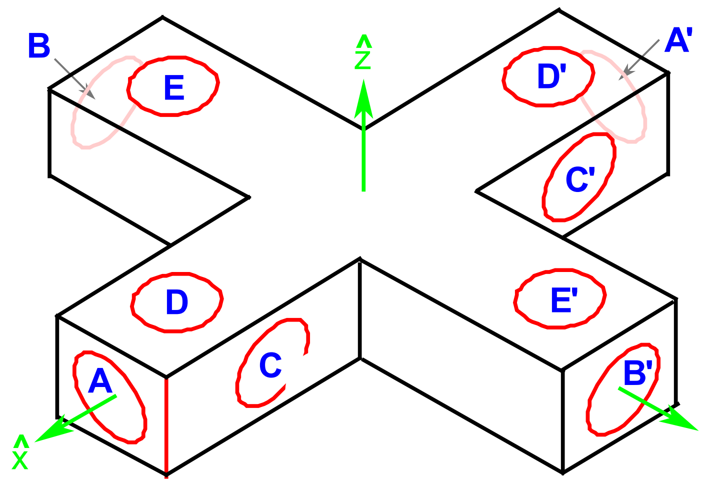






Magnetic Anomaly Detection

- Mineral Surveys
  - Airborne
  - Induced Polarization
- Mine Detection
  - Unexploded Ordinance **(UXO)**
  - Buried or underwater



$$\frac{\partial H_x}{\partial x} \propto A - A'$$

$$\frac{\partial H_y}{\partial y} \propto B - B'$$

$$\frac{\partial H_y}{\partial x} \propto C - C'$$

$$\frac{\partial H_z}{\partial x} \propto D - D'$$

$$\frac{\partial H_z}{\partial y} \propto E - E'$$

$$H_x = \frac{1}{2}(A + A')$$

$$H_y = \frac{1}{2}(B + B')$$

$$H_z = \frac{1}{2}(D + D')$$

$$\begin{pmatrix} \frac{\partial H_x}{\partial x} & & \\ \frac{\partial H_y}{\partial x} & \frac{\partial H_y}{\partial y} & \\ \frac{\partial H_z}{\partial x} & \frac{\partial H_z}{\partial y} & \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{\partial H_x}{\partial x} & \frac{\partial H_x}{\partial y} & \frac{\partial H_x}{\partial z} \\ \frac{\partial H_y}{\partial x} & \frac{\partial H_y}{\partial y} & \frac{\partial H_y}{\partial z} \\ \frac{\partial H_z}{\partial x} & \frac{\partial H_z}{\partial y} & \frac{\partial H_z}{\partial z} \end{pmatrix}$$

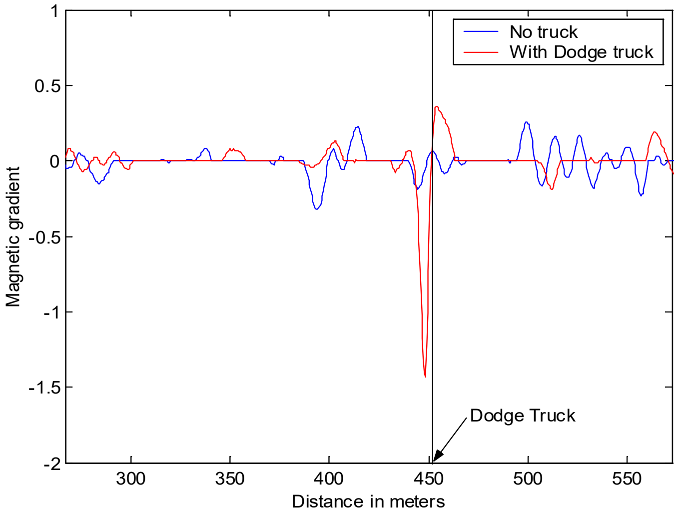
$$X = \frac{-3H_x \frac{\partial H_z}{\partial x}}{\frac{\partial H_z}{\partial x} + \frac{\partial H_z}{\partial y}} \quad and \quad Y = \frac{-3H_y \frac{\partial H_z}{\partial y}}{\frac{\partial H_z}{\partial y} + \frac{\partial H_z}{\partial x}}$$

position of magnetic anomaly

Technical Challenges in MAD

- Sensitivity
- Vector Motion
- Refrigeration
- Pressure

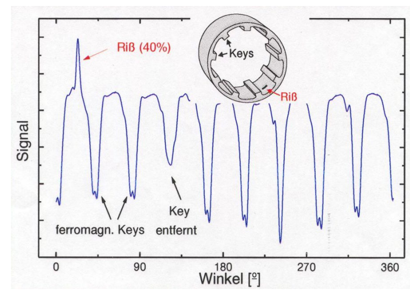
Tristan Model 703 HTS SQUID Gradiometer System in flight

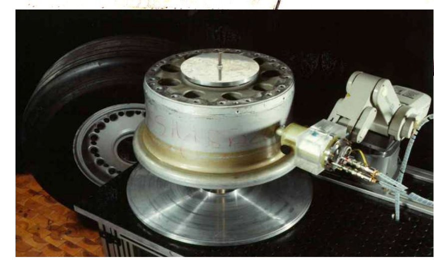


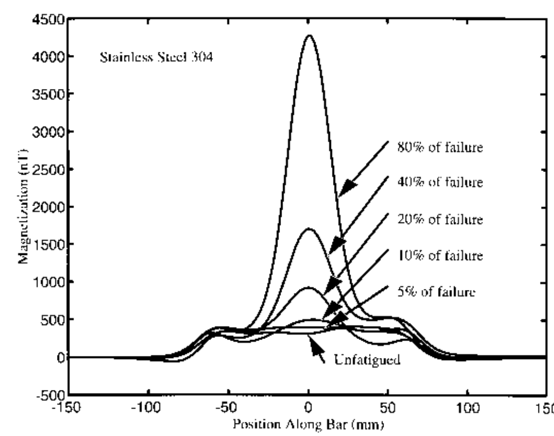
- Flight over a Dodge Truck

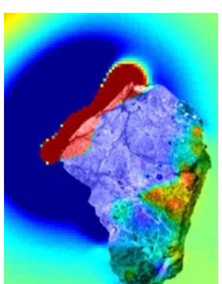
Non-Destructive Test & Evaluation

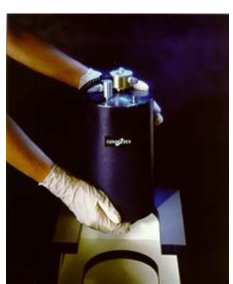
- **Defect Detection in Ferrous and Non-Ferrous Metals**
  - Cracks, Voids, Weld inspection
  - Stress, Strain, Corrosion
- **Insulating Material Analysis**
  - Flaw features < 150 µm
- **Bridges, Runways, Buildings**
  - Corrosion in reinforcing rods
  - Embedded sensors
- **Aerospace**
  - Cracks in wheels and turbine blades
  - Skin corrosion
  - Embedded sensors in composite structures
- **Biotech related**
  - Food Processing Nanoparticle Detection
  - Pharmaceutical Manufacturing
  - Magnetoimmunoassay (MIA)
- **Paleoarcheology**



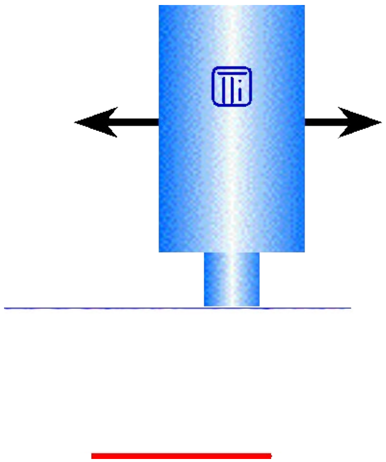






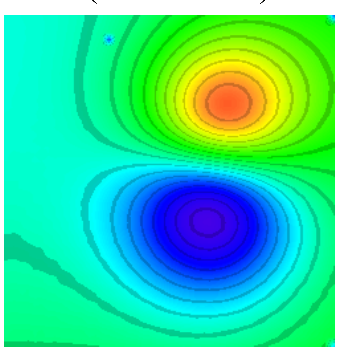


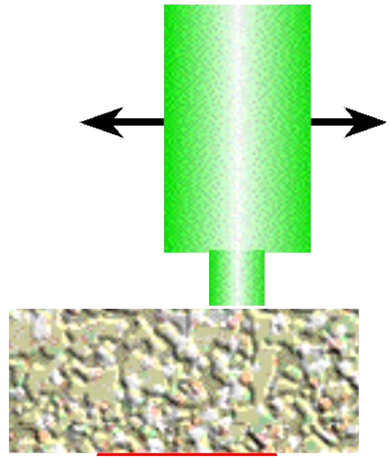
SQUID Detection through Concrete



A

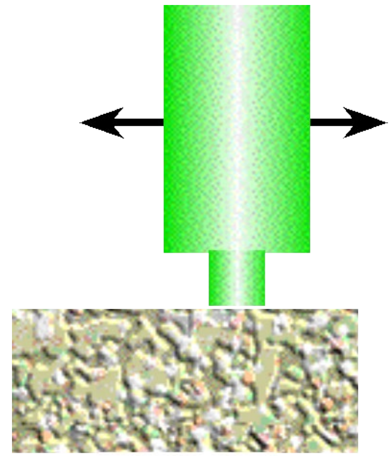
Bare Sensor at 4 cm
(25% strain)





B

Sensor under 4 cm Concrete



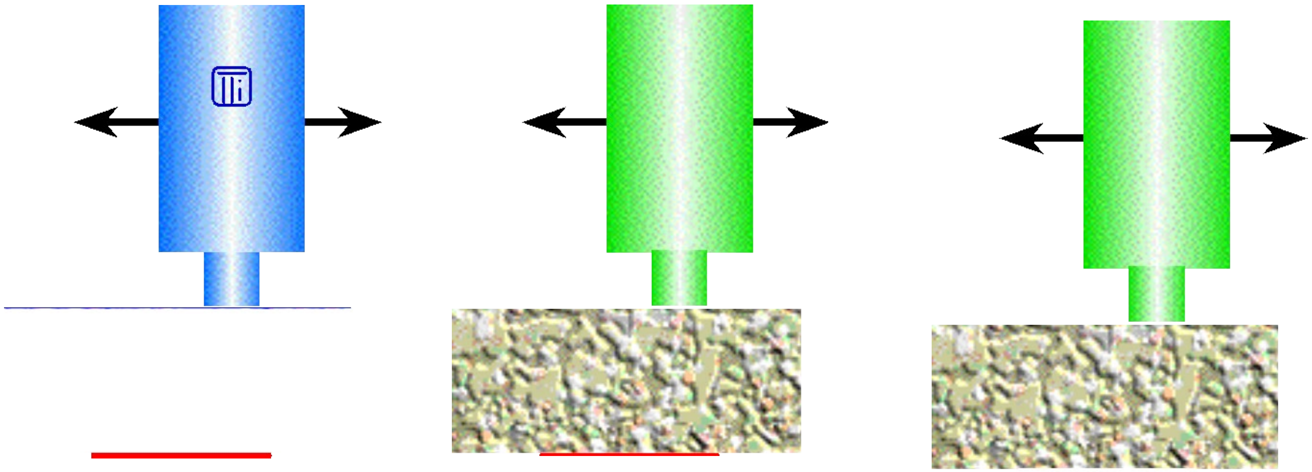
C

Concrete

D

B - C

SQUID Detection through Concrete

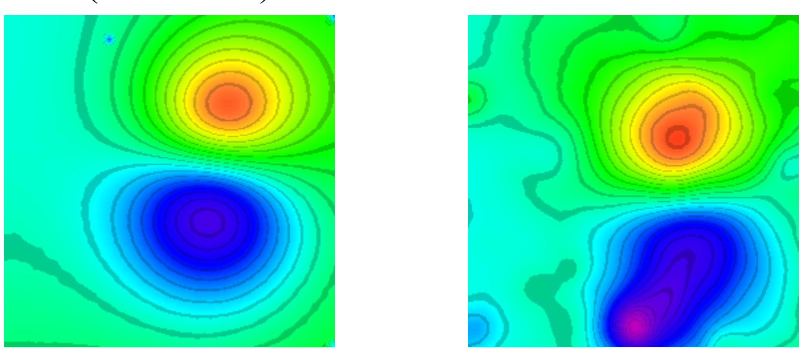


A — Bare Sensor at 4 cm (25% strain)

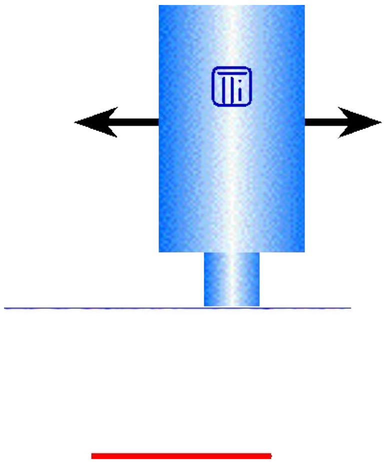
B — Sensor under 4 cm Concrete

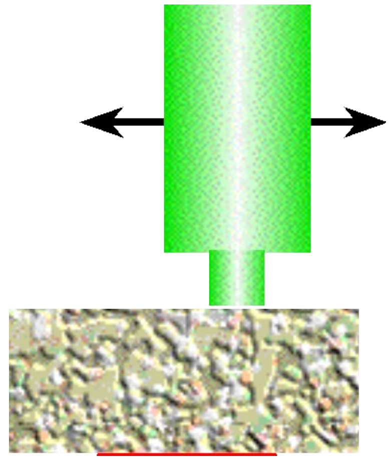
C — Concrete

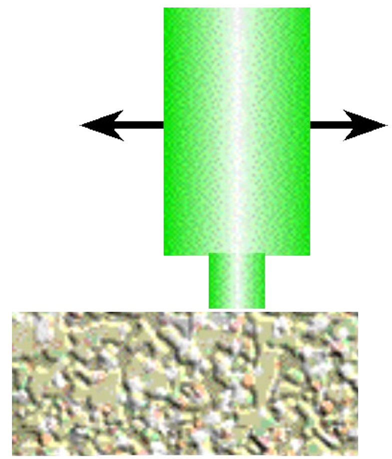
D — B - C



SQUID Detection through Concrete







A

Bare Sensor at 4 cm
(25% strain)

B

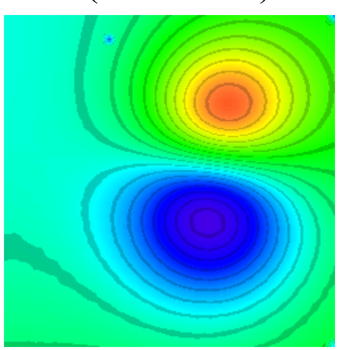
Sensor under 4 cm Concrete

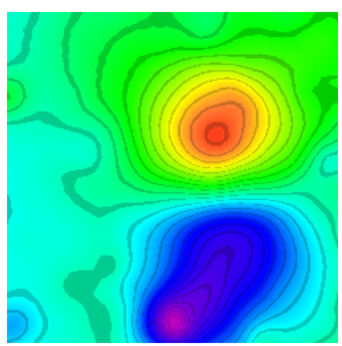
C

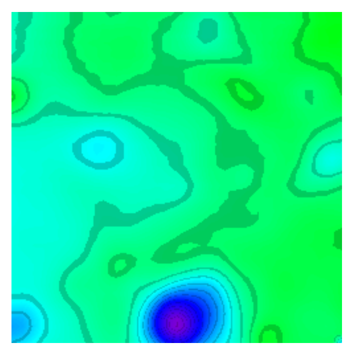
Concrete

D

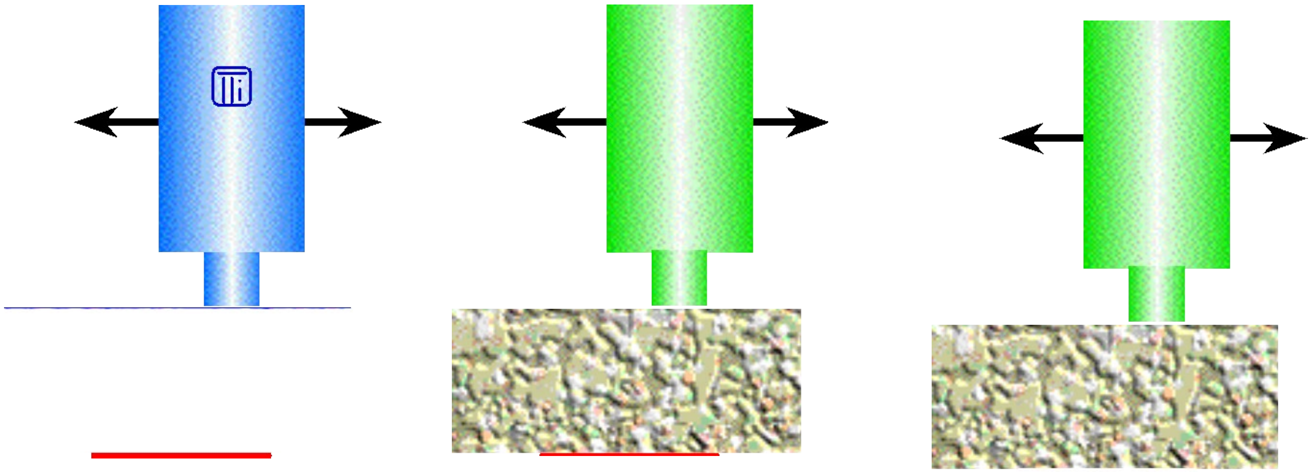
B - C



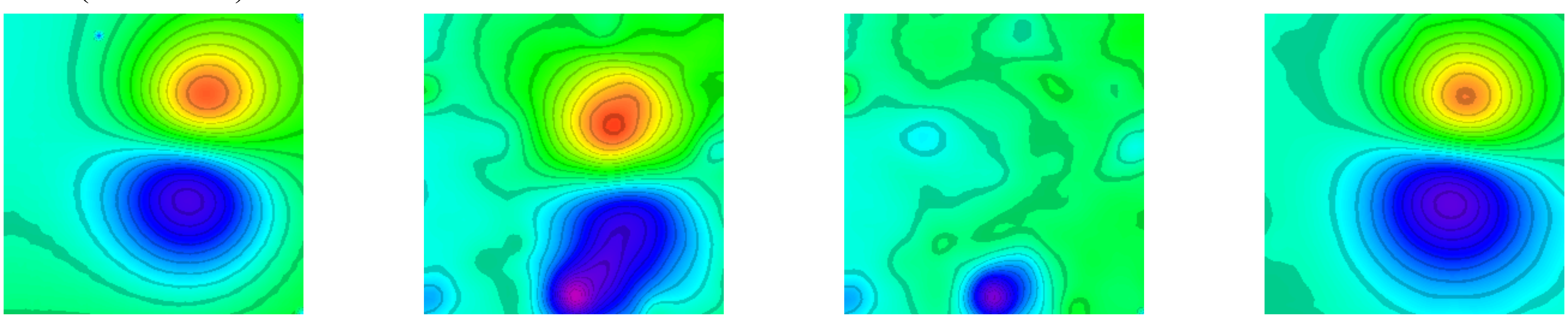




SQUID Detection through Concrete

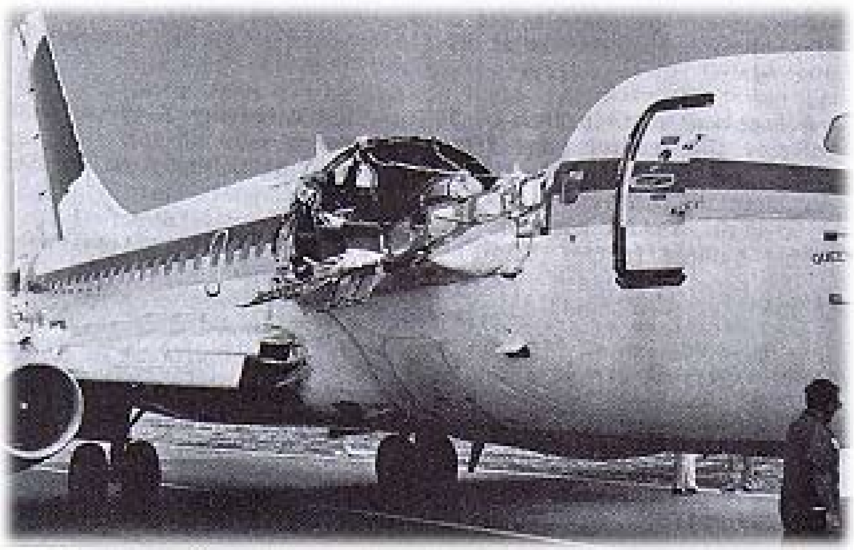


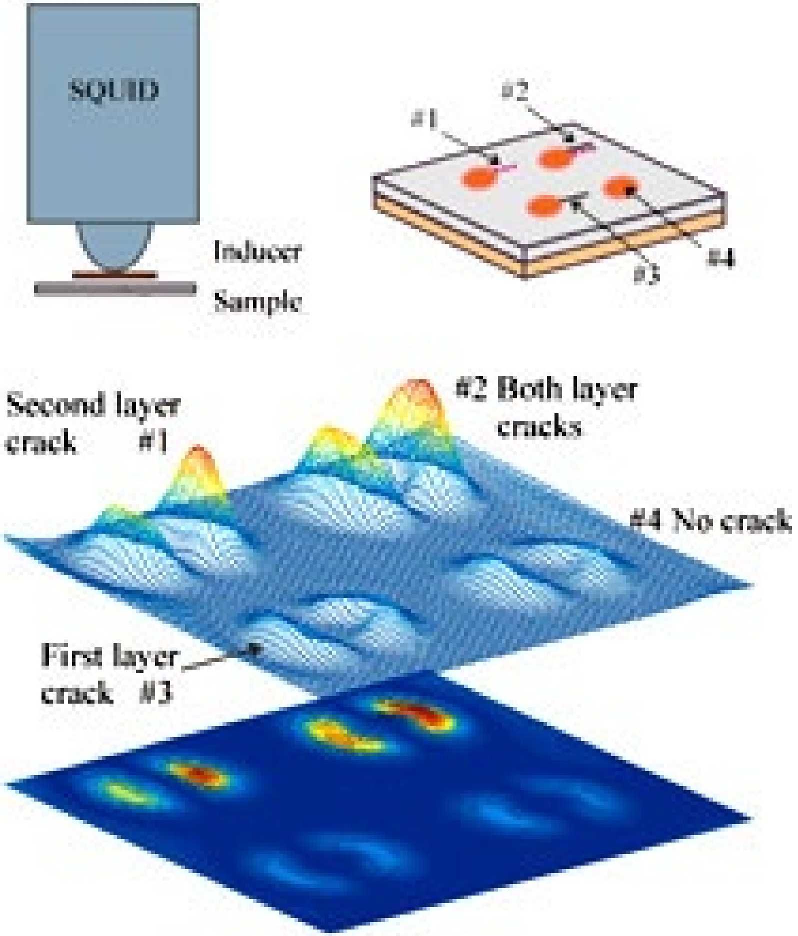
A	B	C	D
Bare Sensor at 4 cm (25% strain)	Sensor under 4 cm Concrete	Concrete	B - C



Second Layer Measurements

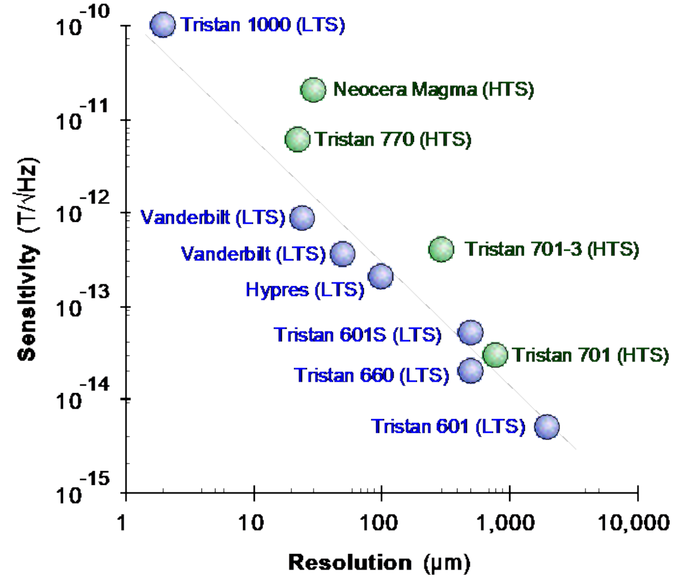
- Looking through top layers to find hidden corrosion is of great interest to DoD and the aircraft industry

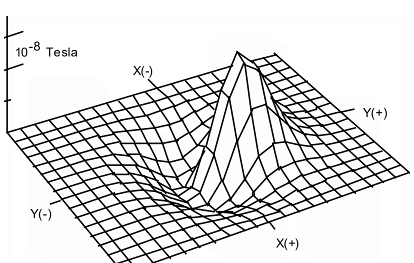




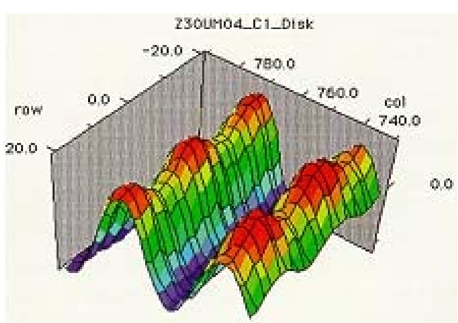
Electronic Applications

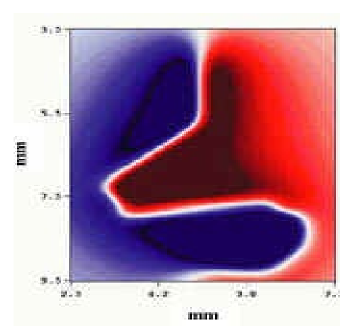
- Magnetic Microscopes
  - micron resolution
  - MHz bandwidths (GHz with SQIFs)
  - non-contact
- Magnetic Structure Mapping
  - Circuit Boards
  - Integrated Circuits
  - Disc Drives
  - Currency
- Process Control
  - thickness monitoring
  - Metrology and QA

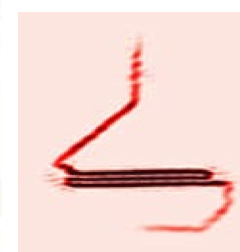




First magnetic microscope image
IEEE Trans Mag 1989



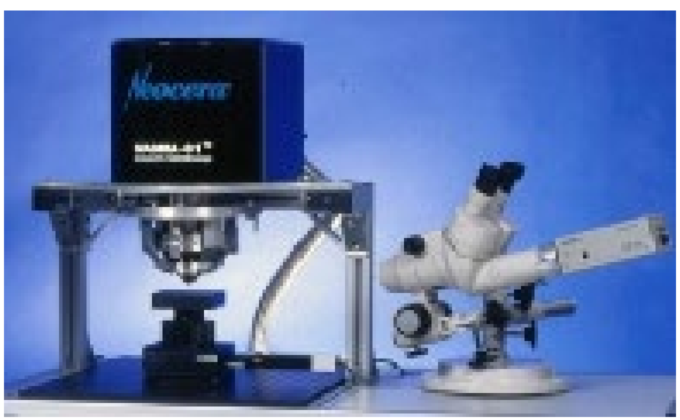




Commercial SQUID Microscopes

Neocera Magma

- LN_2 cooled 1-channel HTS
- 50 μm diam. coil
- <15 pT/√Hz sensitivity
- 50 μm lift-off

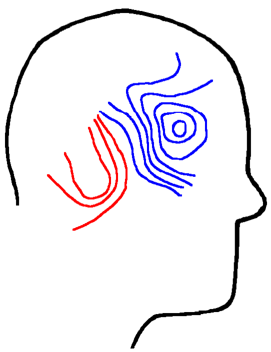


Tristan Inverted LTS

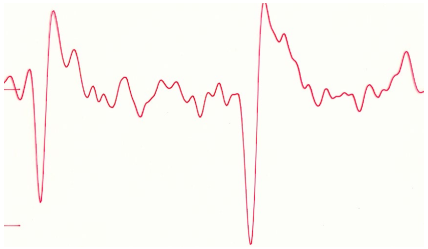
- Cryocooled 8-channel LTS
- 600 μm diam. coils
- <70 fT/√Hz sensitivity
- 200 μm lift-off

Biomagnetic Measurements

- **Studies of the Brain—Neuromagnetism (MEG)**
  - Epilepsy
  - Presurgical Cortical Function Mapping
  - Drug Development and Testing
  - Stroke and Alzheimer's
  - Neuromuscular Disorders
  - Prenatal Brain Disorders
  - Brain Injury



- **Studies of the Heart—Magnetocardiography (MCG)**
  - Arrhythmia
  - Cardiac Ischemia
  - Heart Injury Currents
  - Fetal Cardiography



- **Other Medical Applications**
  - Spinal Cord, Peripheral and Single Nerve Studies
  - Non-invasive in-vivo Magnetic Liver Biopsies (Ferritometry)
  - Studies of the Stomach—Gastroenterology and Intestinal Ischemia
  - Lung Function and Clearance Studies—Magnetopneumography
  - Organ Transplant Rejection Risk
  - Blood Flow Disorders
- **Animal Research**

Advantages of Biomagnetism

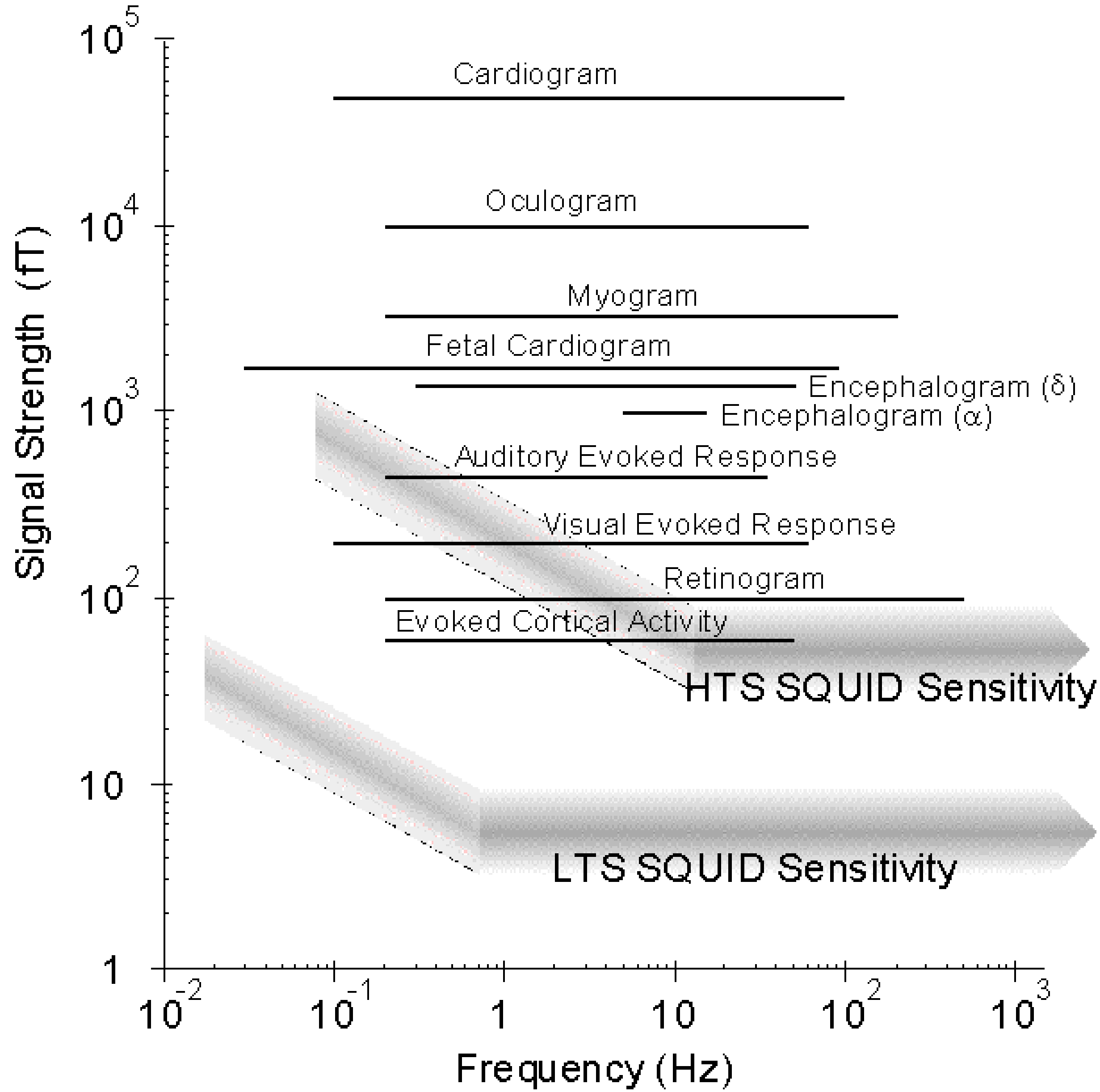
Useful in identifying electrophysiological activity
- measures functional activity

Biomagnetism has significant advantages over electrical recordings
- Non-Invasive
  - *e.g.*, fetal cardiography
- Measures a vector quantity—magnetic field, rather than a scalar quantity—voltage

Many magnetic analogs to electrical activity
- Magnetocardiogram (MCG) - Baule & McFee
- Magnetoencephalogram (MEG) - Cohen
- Magnetoenterogram (MENG)- Wikswo

There are also biomagnetic signals that have no electrical analogs
- Biomagnetic Liver Susceptometry (Ferritometry)
- Magnetopneumography

Strengths of Biomagnetic Signals

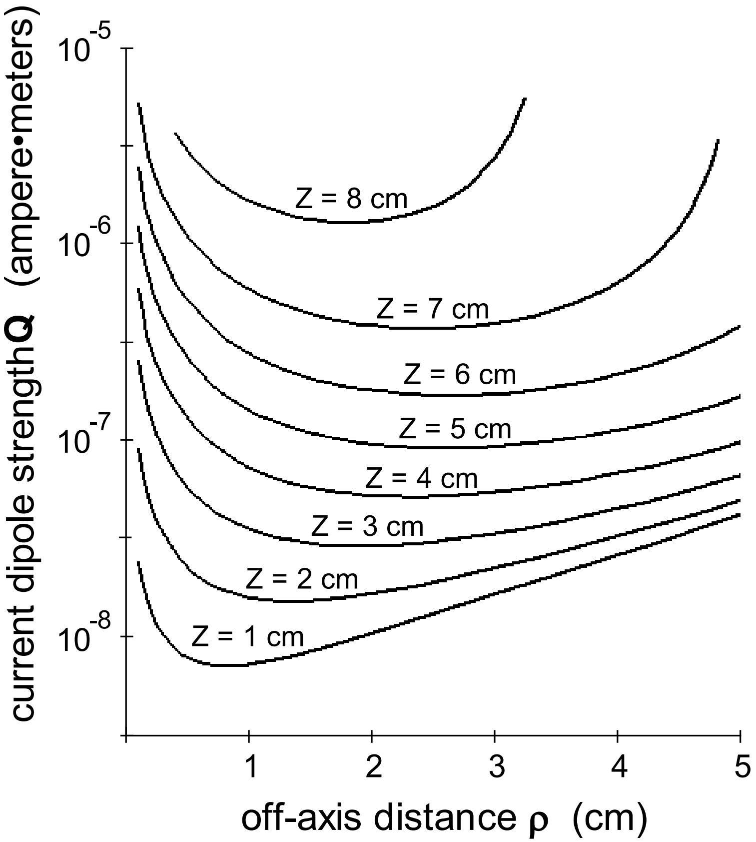


Sensitivity to Actual Signals

- Field Sensitivity
  - measured in tesla/√Hz
  - on-axis response goes as $1/z^3$
  - best suited for magnetic dipoles
- Current Dipole Sensitivity
  - describes neural activity
  - measured in A m/√Hz
  - magnetometer response goes as

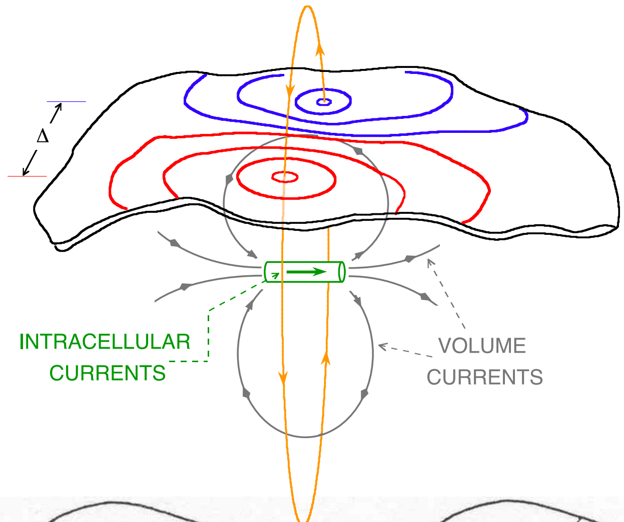
$$Q = \frac{\pi \Phi \sqrt{m}}{\mu_o \sqrt{\frac{r}{\rho}} \left\{ \left(1 - \frac{m}{2}\right) K(m) - E(m) \right\}};$$

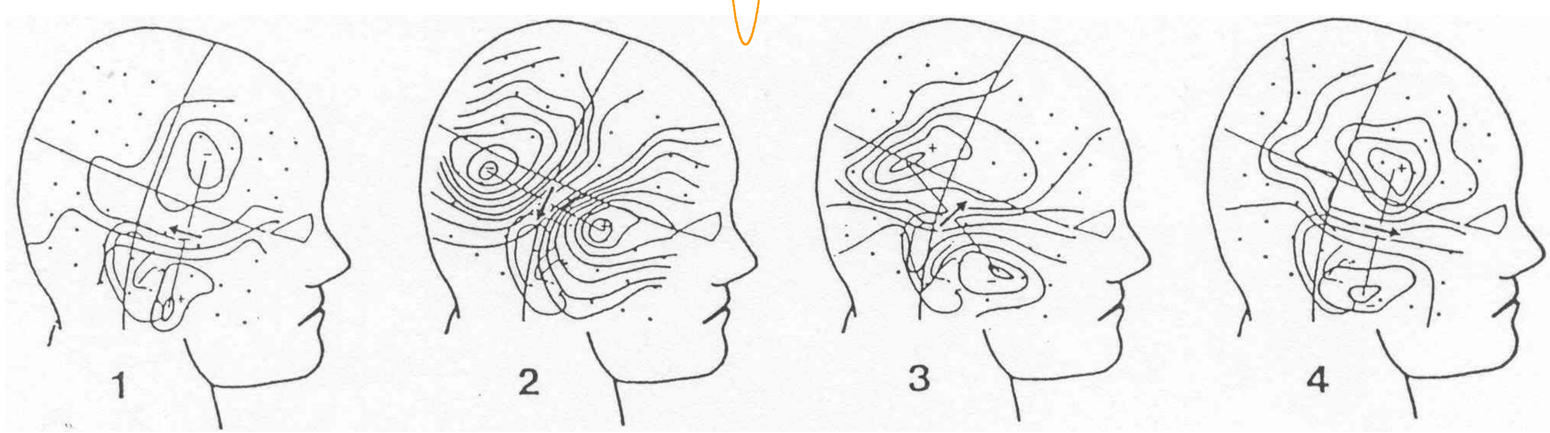
$$where \qquad m = \frac{4 r \rho}{(r+\rho)^2 + z^2}$$



Magnetoencephalography (MEG)

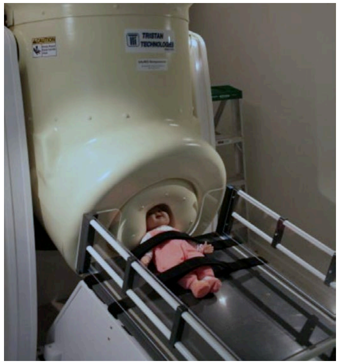
- Dipole mapping of electrical brain activity
  - Neuromagnetic patterns of a patient with a partial epileptic seizure disorder measured at intervals of approximately 20 msec.





MEG Systems

- Whole Head Systems
  - > 150 detection channels
  - Magnetic Shielded Rooms (MSR)
  - Electronic Noise Cancellation
  - Sophisticated Imaging Software
  - $2,000,000+ price tags
- Unique Systems
  - fetal MEG
  - babySQUID®
- Custom Research Systems
  - Limited capabilities
    - Channel number can vary from one to dozens
    - Limitations usually due to budget limitations
  - Different Features
    - *e.g.*, vector channels (B_X, B_Y)



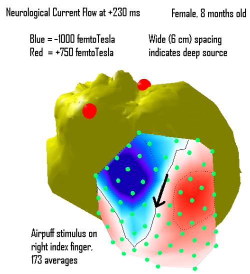
MEG vs. Other Functional Imaging

Methods based on metabolic processes

- **Functional Magnetic Resonance Imaging (fMRI)**
  - Measures blood oxygenation associated with neural activity, rather than electrophysiology.
  - Does not allow for millisecond time resolution.
    - Does not allow for spontaneous measurements of Alpha rhythms etc.
- **Positron Emission Tomography (PET)**
  - Measures metabolism of oxygen or sugar, rather than electrophysiology.
  - Does not allow for millisecond time resolution.
    - Does not allow for spontaneous measurements of Alpha rhythms etc.
  - Possible hazard, especially to children or pregnant women, due to ionizing radiation from ingested radionuclides.
    - Cannot be repeated, after annual maximum dose is reached (generally one examination)

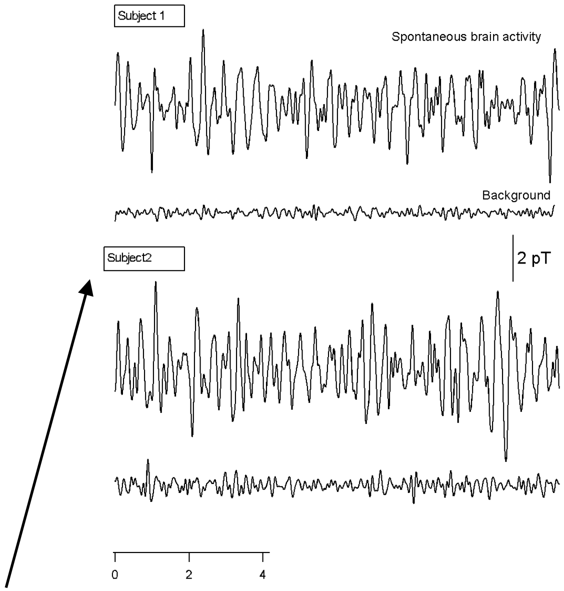
Methods based directly on neural electric activity

- **Electroencephalography (EEG)**
  - Measures electrophysiology of extracellular and volume currents.
  - Localization accuracy is impaired by distortions created by the conductivity of the scalp and inhomogeneous tissue conductivity.
  - Time consuming to place and localize large numbers of electrodes.



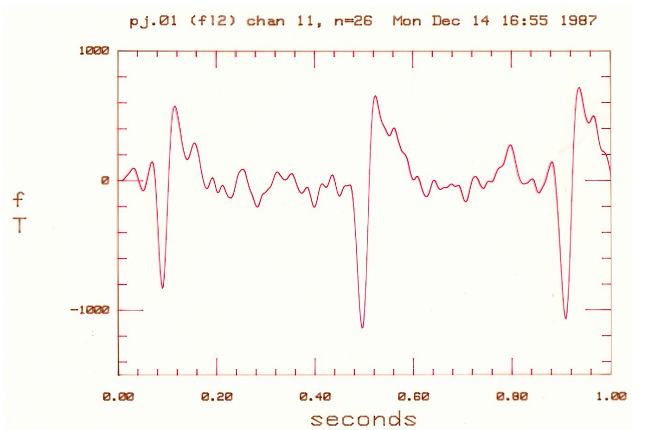
BabySQUID®

- Evaluation of neurological impairments of preterm and term infants
  - Uses superconducting magnetic sensing (magnetoencephalography - MEG) to map the sites and dynamics of sensory functions
- Operates outside large shielded rooms needed for adult MEG
- Sensing elements ~ 5**x** closer to infant skull than adult MEG
  - Greater detection capability (strength $\propto 1/\text{distance}^2$)
  - Spatial resolution is 4x greater than adult MEG sensors
- Completely non-invasive
  - Rapid setup
  - No gluing and attaching leads
  - No contrast agents
- Fast measurement time
  - 2 – 20 minutes
  - Mapping system tracks infant movements
- Portable and Accessible
  - movable into elevators, obstetric suites and neonate ICUs

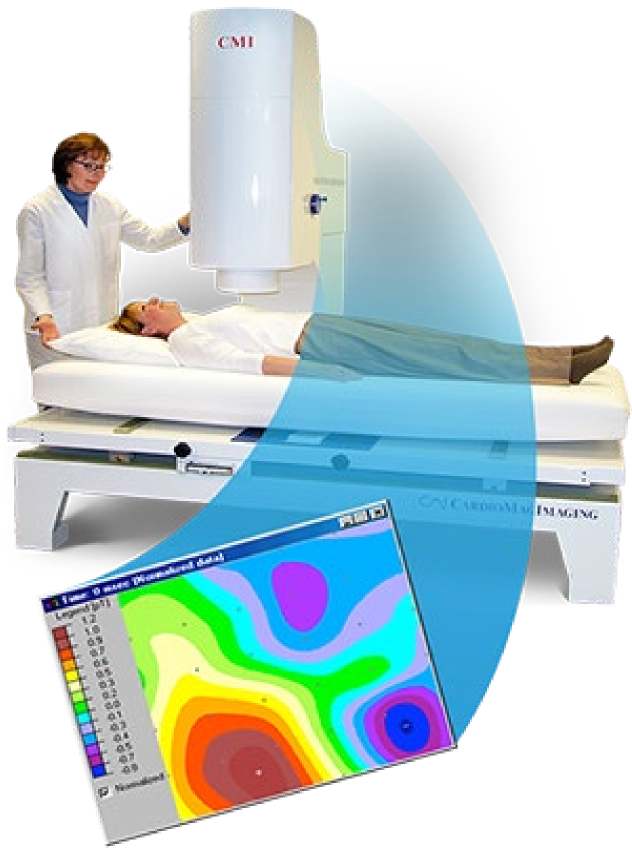


- Operational
  - Spontaneous activity obtained from two infants in an unshielded hospital room.

Magnetocardiography (MCG)

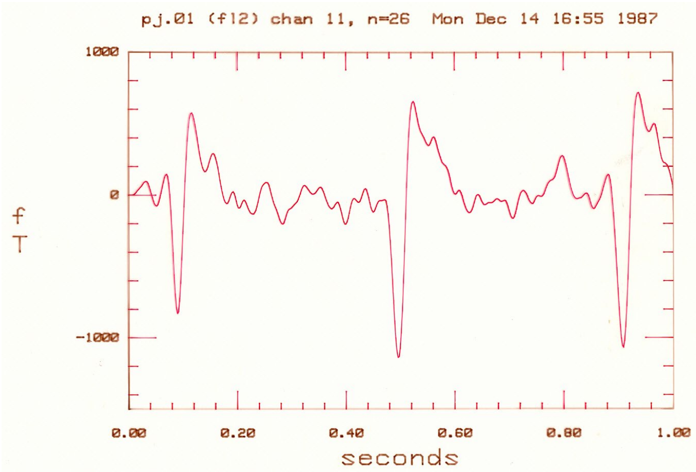


- Rapid - Non-Contact Scans
- Yields Vector Information
  - rather than scalar voltage from ECG
- Allows Non-Invasive Measurement of Fetal Cardiac Signals ↑
  - not possible with electrical methods
- Allows Mapping of Cardiac Injury Currents
- Interest in Detection of Ischemia
  - insufficient blood supply to the heart
  - arrhythmogenic foci localization
- Unshielded operation with HTS Sensors
  - Development underway



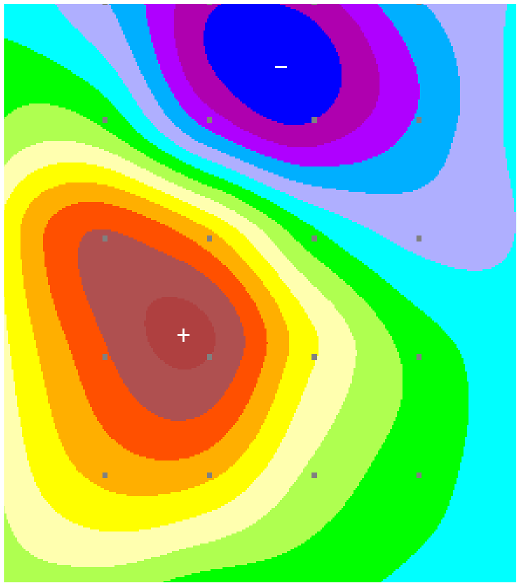
Magnetocardiography

- Time series data
  - Fetal heart beat →

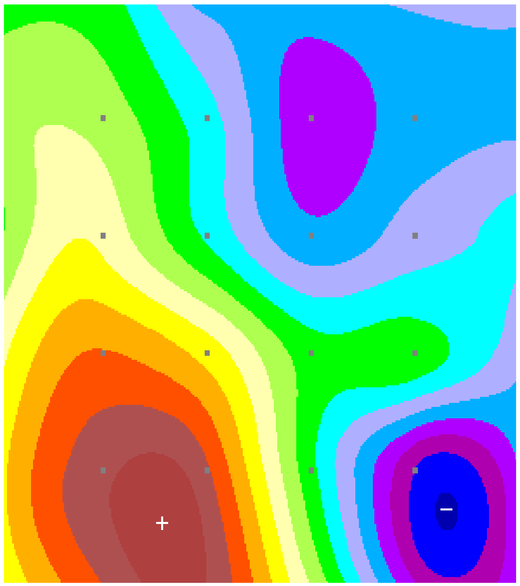


- Dipole mapping

Normal heart

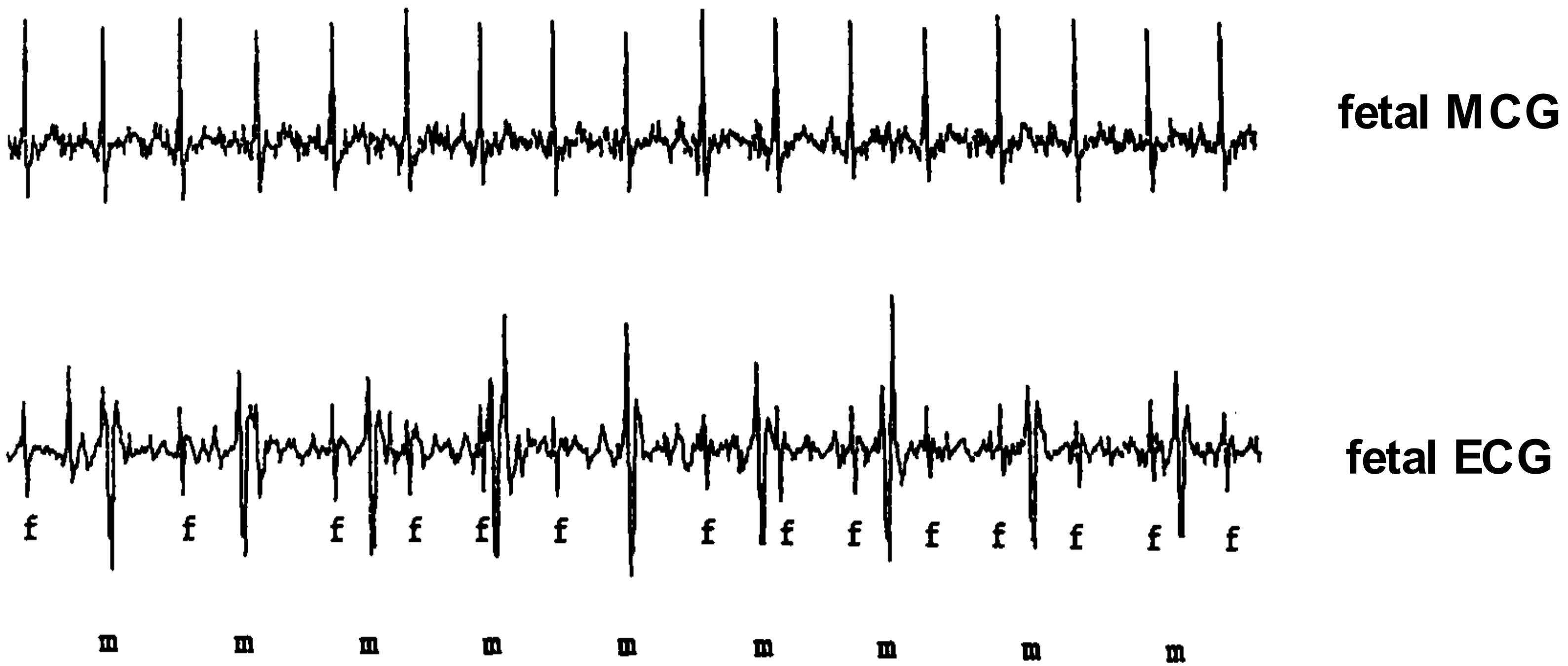


Possibly ischemic heart



Fetal MagnetoCardiography (fMCG)

- Capacity to measure fetal heart rhythms
  - Signal is not mixed with mother’s heartbeat



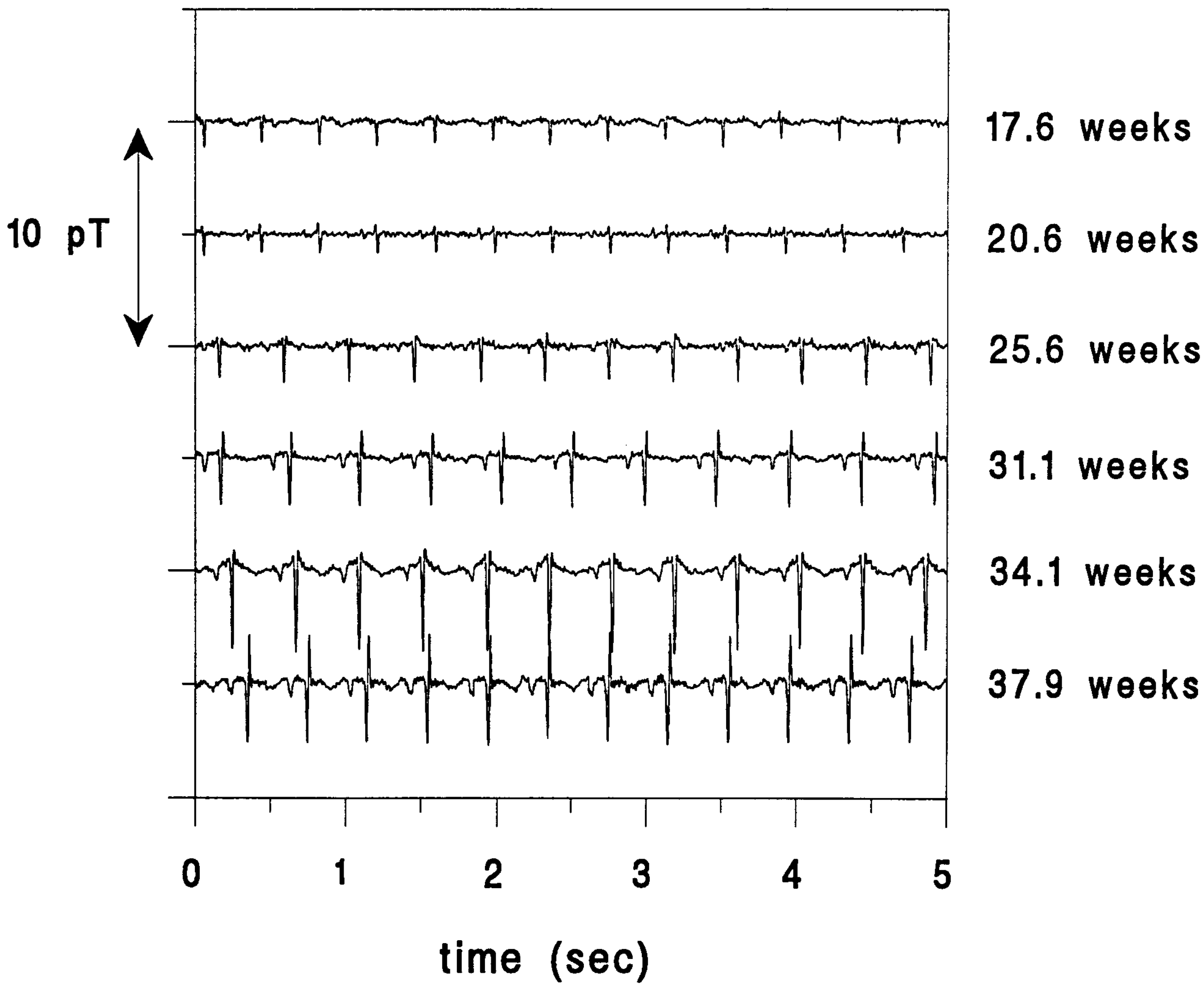
- Fetal ECG (bottom)– weak fetal signal (f) and mother’s heartbeat (m) is mixed in

experimental clinical data from Dr. Wakai at University of Wisconsin

The Need for fMCG

- In the US alone …
  - 35,000 infants stillborn; 40,000 die before age one
  - 150,000 born with severe deficits
- Fetal Heart Rate monitoring needed
  - … for all high risk pregnancies (~20%)
  - Congenital heart disease has an incidence of 7/1000 liveborn infants
- Heart rhythm irregularities are predictive
  - Fetal surgical treatments exist

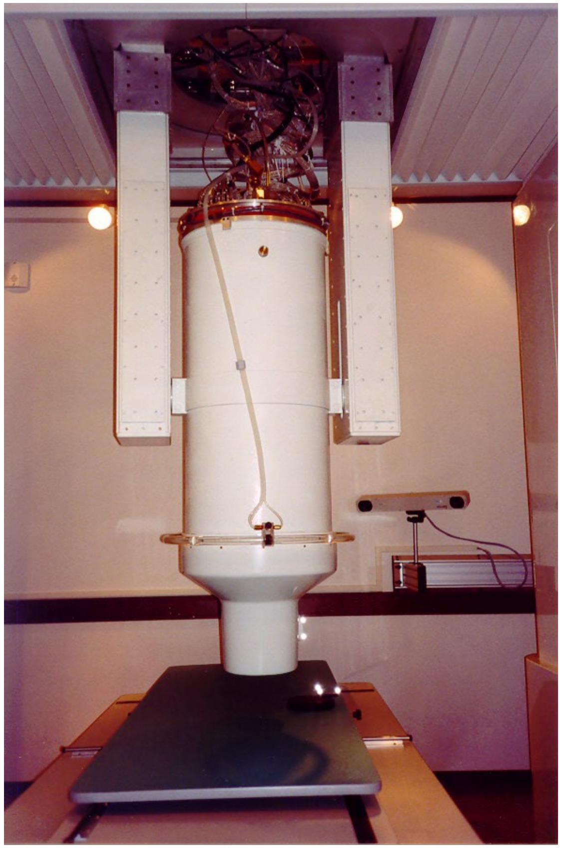
fMCG: early detection …



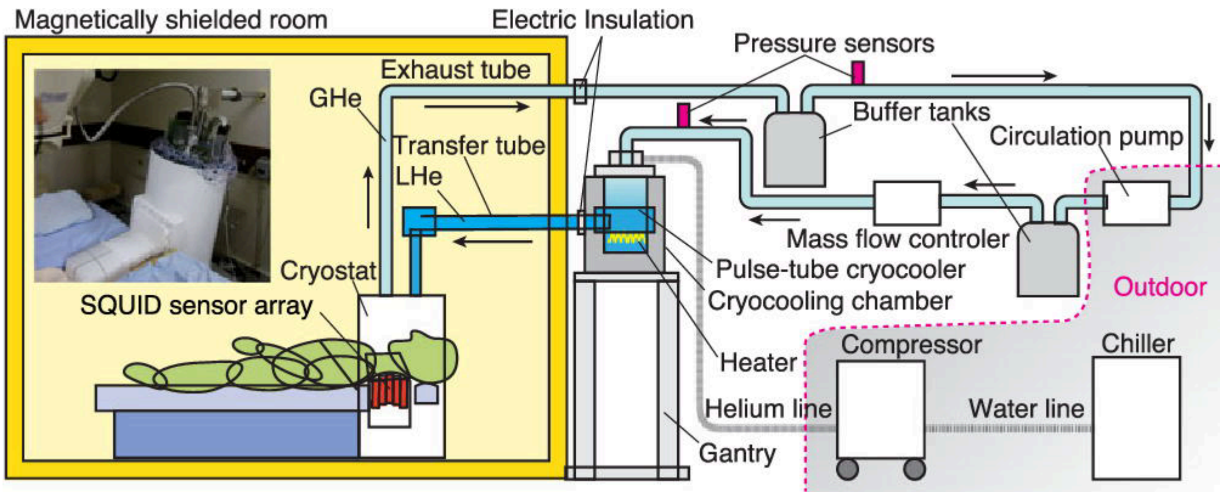
Tristan Technologies

Magnetospinography

- Spatial Characteristics
  - Signal is quasi-one dimensional problem
  - Summated action potentials
  - Rapid events
- Temporal Characteristics
  - Higher data rates (than MEG) needed
    - Brain events typically on 10 msec time scale
    - Spine events typically on 1 msec (or faster) time scale
- Sensor Geometry
  - Moderate spatial resolution with large coverage area
    - high channel count
  - Higher spatial resolutions require microSQUID™ systems
    - Smaller coils, denser packing



Tristan Model 661 Spinal Cord System

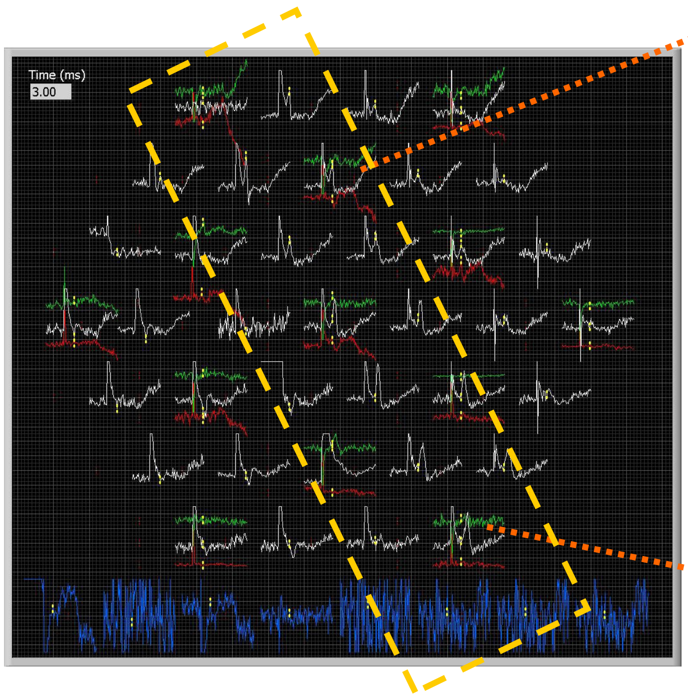


Adachi *et al*, *IEEE TASC* 2017

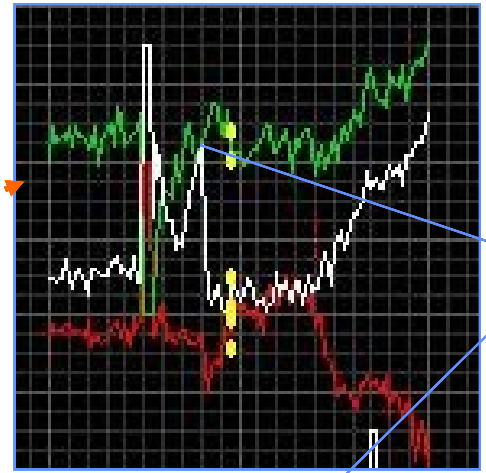
Peripheral Nerve – Human Data

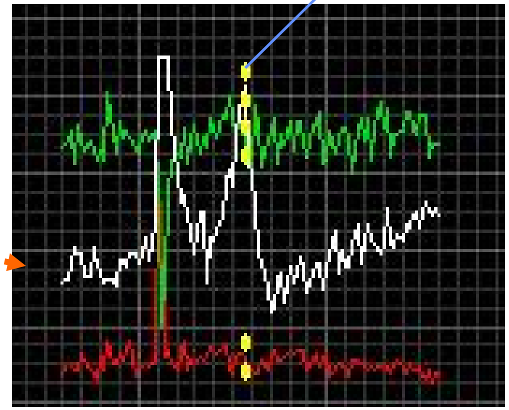
- Forearm stimulated by electrical shock at median nerve

Sensor layout display



Physical location of arm



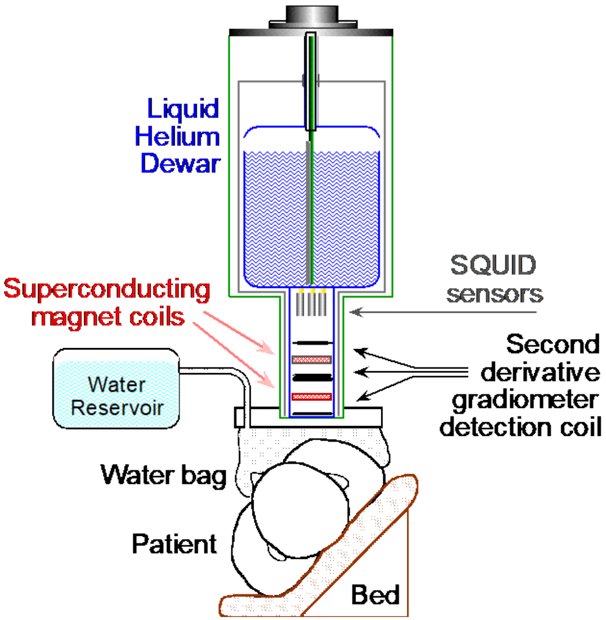


…Peak (B_Z) of neural signal has moved by ~ 5 cm in ~ 2 msec

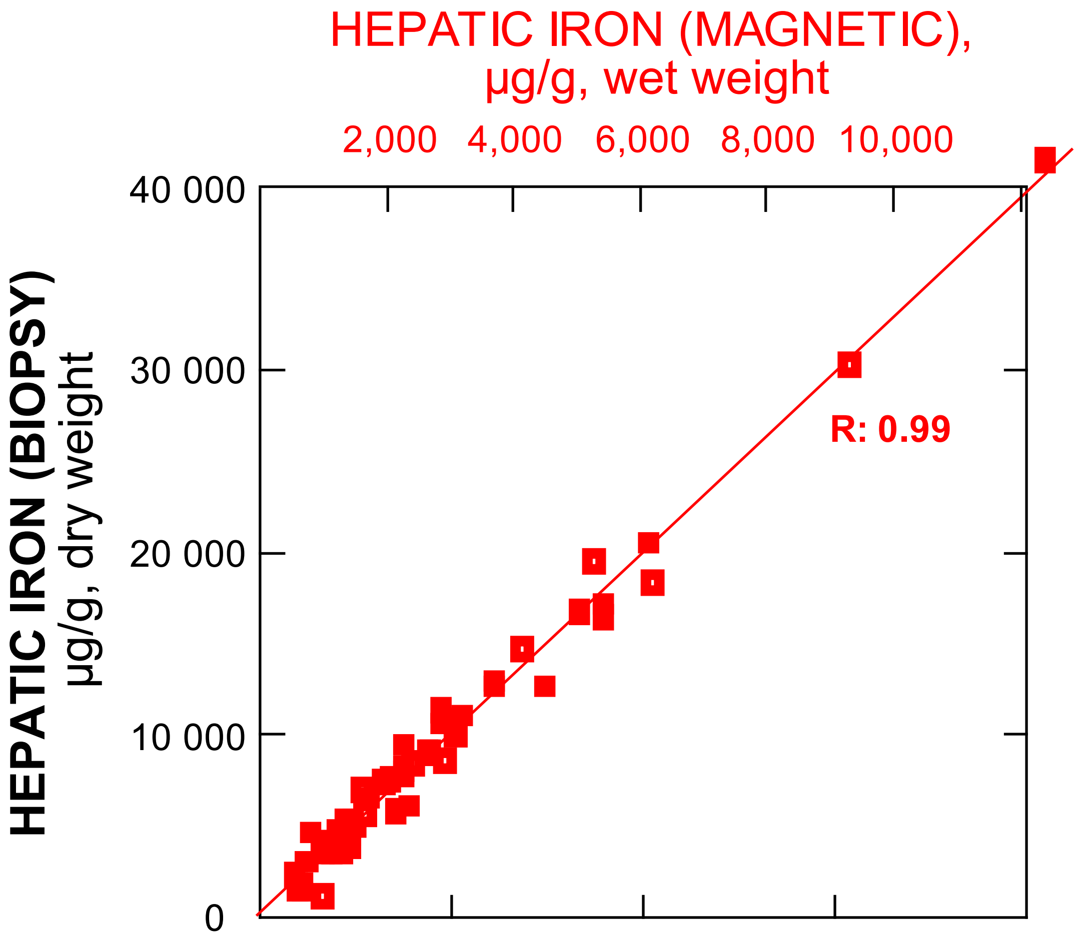
First (vertical) peak is the stimulus artifact

Clinical Assessment of Liver Iron Stores

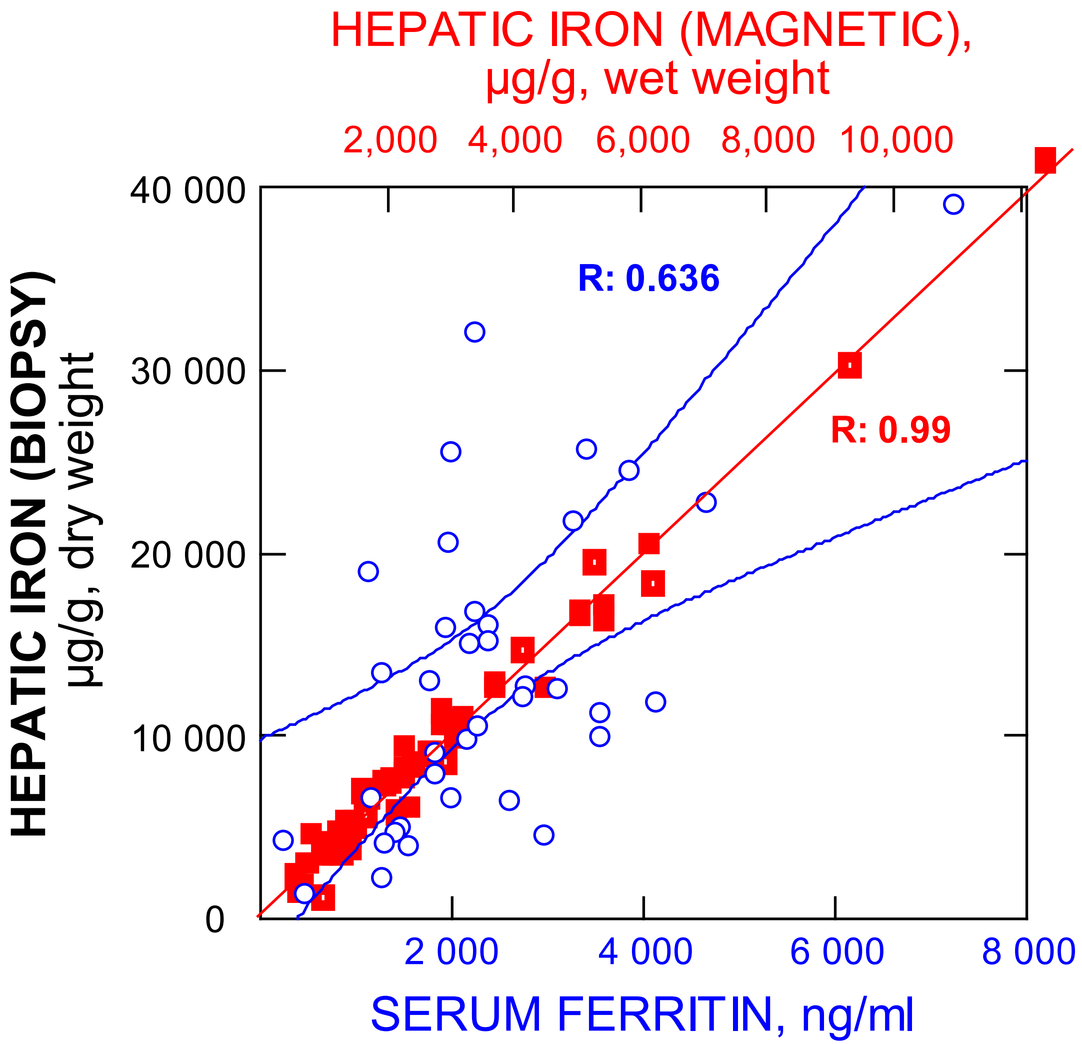
- **Iron Overload**
  - While not common in the US, iron overload has fatal consequences if not treated.
  - Monitoring is either inaccurate (Serum Ferritin) or painful and risky (Needle Biopsy)
- **The Ferritometer® is a Non-Invasive alternative**
  - Uses SQUID to measure susceptibility
- **Very Reliable**
  - Fundamental technology dates to 1970
  - 30 year operational history as measurement of iron stores
    - Repeatability better than 5%
    - Allows serial measurements
    - Allows pediatric measurements
  - Rapid Results
    - Measurement time (including ultrasound) < 30 minutes
- **Clinical Sites in Germany, Italy and US**



Clinical Results

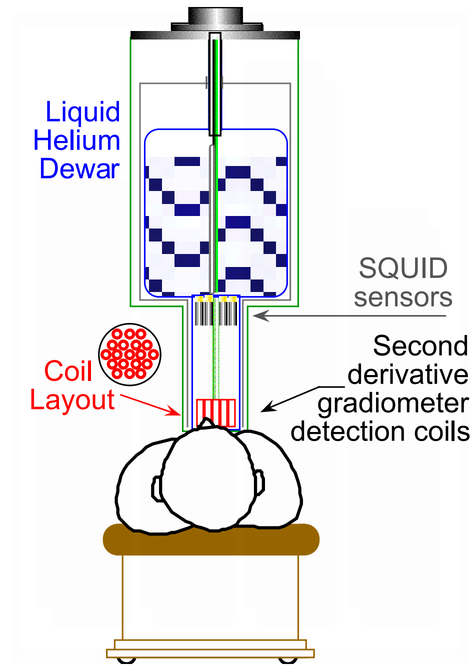


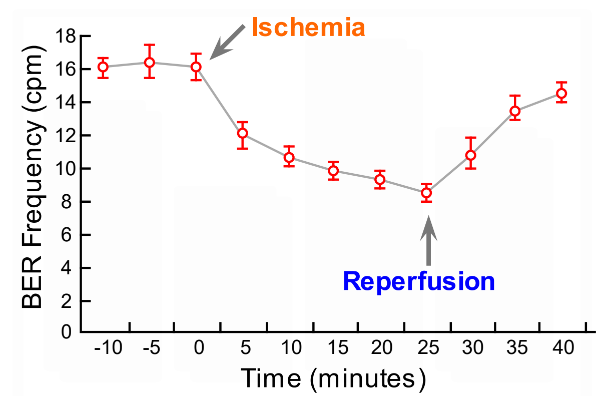
Comparison Against Serum Ferritin



Intestinal Ischemia

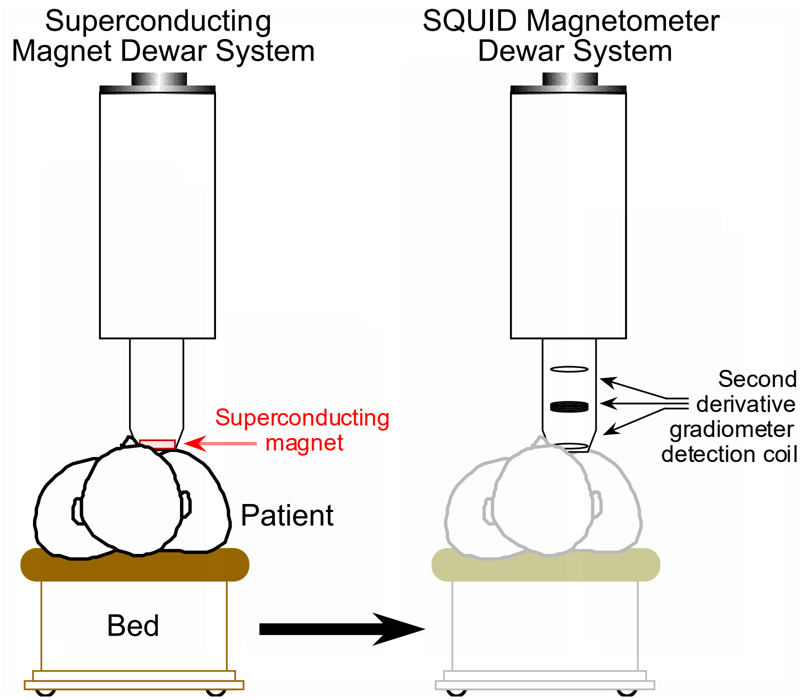
- Mesenteric arteries carry blood to the stomach, small and large intestine
  - Blockage of the blood flow (ischemia) can lead to intestinal necrosis
- Treatment requires surgical intervention
  - if intestinal tissue is necrotic, segment(s) must be removed or bypassed
  - if diagnosis delayed, mortality rate can exceed 50%
- Statistically significant frequency shift may permit diagnosis
- Gastrointestinal (GI) tract exhibits two types of electrical activity
  - high frequency spiking (muscle contraction)
  - Low frequency oscillations known as electric activity or BER
    - Human gastric BER: 3.2 ± 0.1 CPM
    - Small intestine BER: 11.3 ± 0.1 CPM
    - duodenum BER: 12 CPM
    - terminal ileum BER: 8 CPM





Magnetopneumography

- Body is normally diamagnetic or paramagnetic
  - no naturally occurring ferro- or ferrimagnetic constituents
- Ferrimagnetic materials associated with particulate contaminates
  - dust in lungs of coal miners, welders, asbestos workers
  - magnetite dust tracer for lung clearance studies
- Allows lung clearance studies
  - $\mathbf{M} = \mathbf{m}_S\,(1 - e^{-3\,\mathbf{H}/Q})$
  - 70 mT (5 sec) $\Rightarrow$ 90% saturation of ferrimagnetic particles
  - $\mathbf{M}_{H = \text{constant}} = \mathbf{m}_S\,(1 - e^{-t/\tau_H})$
  - $\tau_{\text{ferrimagnetism}}$ as short as minutes
- Example of a Research Application rather than a Clinical Application



- Magnetize lung
  - –H ~ 100 mT 9 cm below magnet
- Move subject beneath magnetometer
- Scan magnetometer for remnant magnetism
  - – 500 picogram/cc sensitivity 1 μgram total particulates
  - – $\Delta t \geq 10$ seconds

Animal Systems

- Animal Brains smaller than Humans
  - Requires higher spatial resolution
    - Smaller diameter coils packed closer together
  - Requires closer spacing
- Wide Variety of Systems

7-channel microSQUID™ system →

- Adjustable Tail Dewars Useful
  - coil-to-room temperature spacings < 2 mm →

  - closer spacing means later detected signals
    - Current dipole signal strength $\propto 1/z^2$

Summary

- SQUIDs have been a key factor in the development and commercialization of ultrasensitive electric and magnetic measurement systems.
- SQUID Instruments offer:
  - High dynamic range and excellent linearity with noise levels approaching quantum limits
  - True dc response, ultra-wide bandwidths and zero phase distortion
- SQUIDs have a wide variety of uses
  - Electromagnetic and materials property measurements
  - Geology and Magnetic Anomaly Detection
  - Non-Destructive Testing and Magnetic Microscopy
  - Medicine
- In many cases, SQUID instrumentation offers the ability to make measurements where no other methodology is possible.