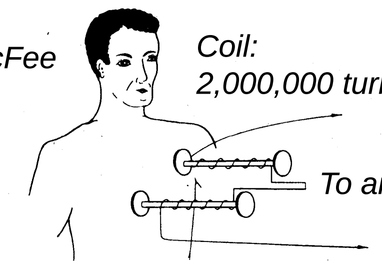
10. Biomagnetism

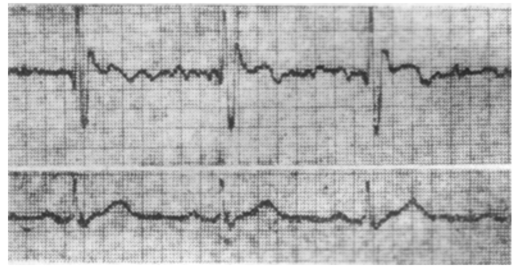
- *Biomagnetic sources*
- *Induction coil*
- *Fluxgate magnetometer*
- *SQUID magnetometer*
  - *Superconducting Quantum Interference Device*
  - *Magnetoencephalograph*
  - *Magnetocardiograph*

Magnetocardiogram (MCG)

Baule and McFee 1963



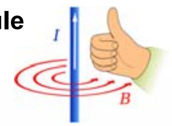
MCG



ECG

Current and Magnetic Density

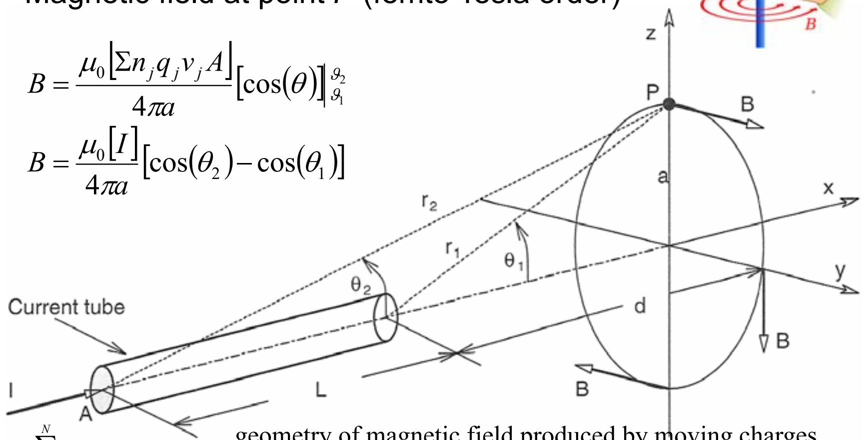
Right-hand rule



Magnetic field at point *P* (femto Tesla order)

$$B = \frac{\mu_0[\Sigma n_j q_j v_j A]}{4\pi a}[\cos(\theta)]_{\vartheta_1}^{\vartheta_2}$$

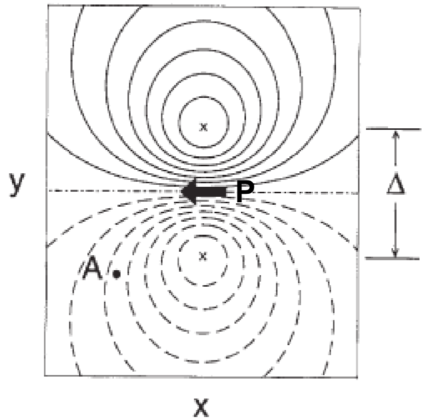
$$B = \frac{\mu_0[I]}{4\pi a}[\cos(\theta_2) - \cos(\theta_1)]$$



$$I = A\sum_{j=1}^{N} n_j q_j v_j$$

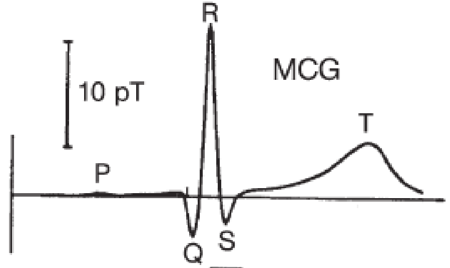
geometry of magnetic field produced by moving charges such as chloride, potassium and sodium ions in a solid tube

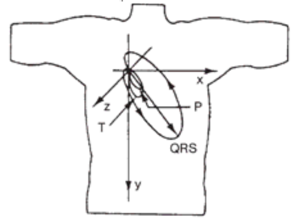
Current Dipole Magnetic Field and MCG



(a) Magnetic field distribution in x-y plane, due to a current dipole vector **P**

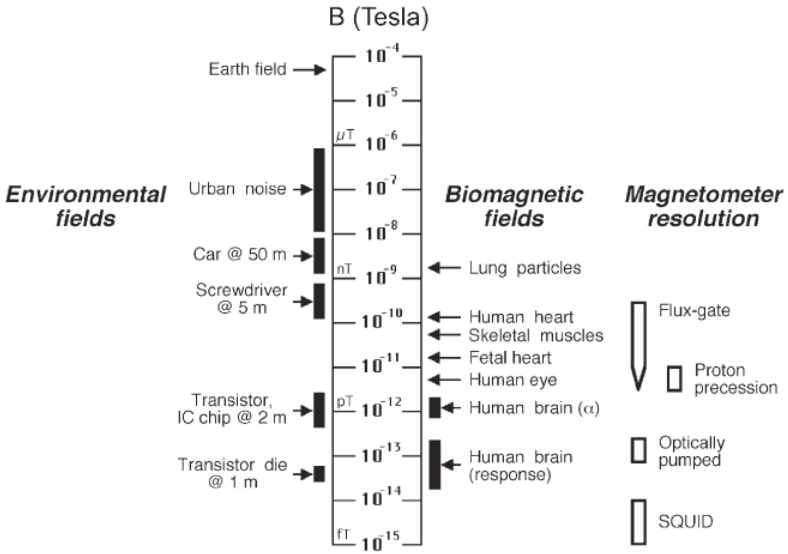
(c) MCG measured at point **A** when **P** follows locus of (b) during a cardiac cycle





(b) Locus of **P** during a cardiac cycle

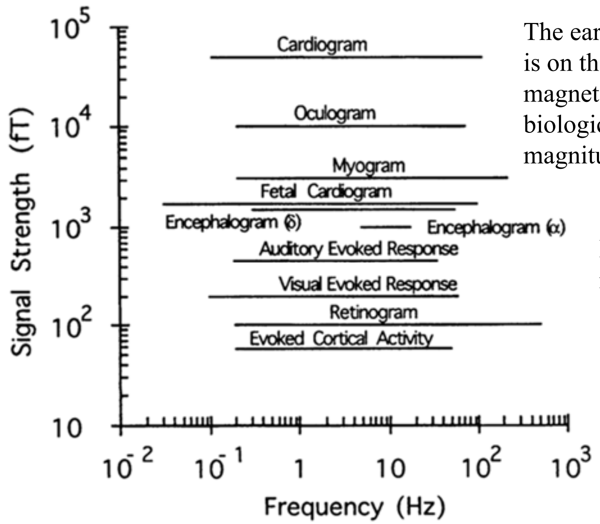
Ambient & Biological Magnetism



Magnetic Source and Measurement

Field source	$\mu_0 H$ [T]	Measuring principle	Detection limit [T]
Evoked human brain activity	$\leq 10^{-13}$	Atomic magnetometer	$\leq 10^{-15}$
		SQUID	10^{-15}
		Nuclear resonance	10^{-13}
		Optical pumping	
		Torsion magnetometer	
Spontaneous currents in the human brain	10^{-12}	Nuclear precision magnetometer	$\leq 10^{-11}$
Currents of the human heart	$\leq 10^{-10}$	Flux-gate	$\leq 10^{-11}$
		Rotating coil	10^{-11}
		Magnetoresistivity	10^{-10}
Contamination of lunge and stomach	$\leq 10^{-9}$	Hall sensor	10^{-9}
Liver iron	$\leq 10^{-8}$	Magneto-optical sensor	10^{-7}
Magnetic markers	$\leq 10^{-6}$	Magnetotransistor	$\leq 10^{-5}$
Earth's magnetic field	$\geq 10^{-5}$	Magnetodiode	10^{-5}

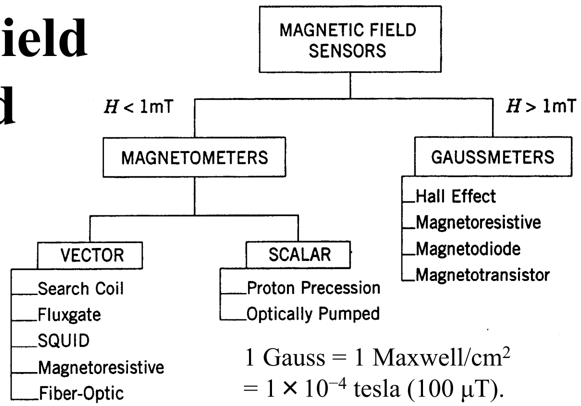
Biomagnetic Signals



The earth static magnetic field is on the order of 10^{-5} to 10^{-6}T. magnetic signal strength from biological organs is only a magnitude of 10^{-10}T.

Biomagnetism measurement demands special techniques.

Magnetic Field Sensors and Properties



strength and/or direction

Gaussmeter = A magnetometer whose scale is graduated in **Gauss** or **kGauss**, and usually measures only **the intensity** of the magnetic field.

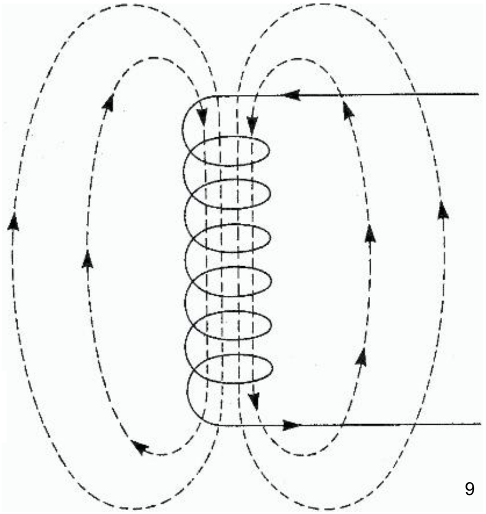
1 Gauss = 1 Maxwell/cm^2
= 1×10^{-4} tesla (100 μT).

Instrument	Range (mT)	Resolution (nT)	Bandwidth (Hz)	Comment
Induction coil	10^{-10} to 10^{6}	Variable	10^{-1} to 10^{6}	Cannot measure static fields
Fluxgate	10^{-4} to 0.5	0.1	dc to 2×10^{3}	General-purpose vector magnetometer
SQUID	10^{-9} to 0.1	10^{-4}	dc to 5	Highest sensitivity magnetometer
Hall effect	0.1 to 3×10^{4}	100	dc to 10^{8}	Best for fields above 1T
Magnetoresistance	10^{-3} to 5	10	dc to 10^{7}	Good for mid-range applications
Proton precession	0.02 to 0.1	0.05	dc to 2	General-purpose scalar magnetometer
Optically pumped	0.01 to 0.1	0.005	dc to 5	Highest resolution scalar magnetometer

Magnetic Field Inside and Outside a Coil

When an electric current passes through a long, hollow coil of wire there will be a strong magnetic field inside the coil and a weaker field outside it.
The lines of the magnetic field pattern run through the coil, spread out from the end, and go round the outside and in at the other end.

Where the field is strongest, the lines are most closely crowded.

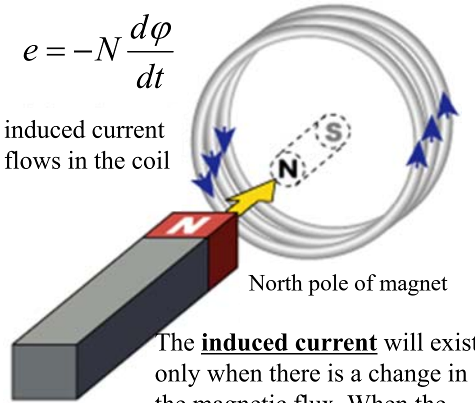


Induction Coil in a Changing Magnetic Field

Principle of electromagnetic induction

$$e = -N\frac{d\varphi}{dt}$$

induced current flows in the coil



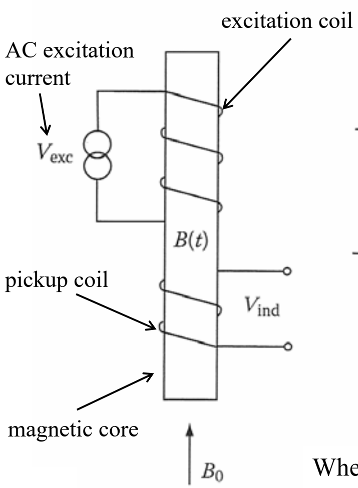
North pole of magnet

The **induced current** will exist only when there is a change in the magnetic flux. When the magnet bar stops moving, there is no change in flux and the induced current will disappear.

When a magnet rapidly approaches the coil, the magnetic flux through the coil will change, an induced EMF (**electromotive force**) will cause a current to flow in the coil.

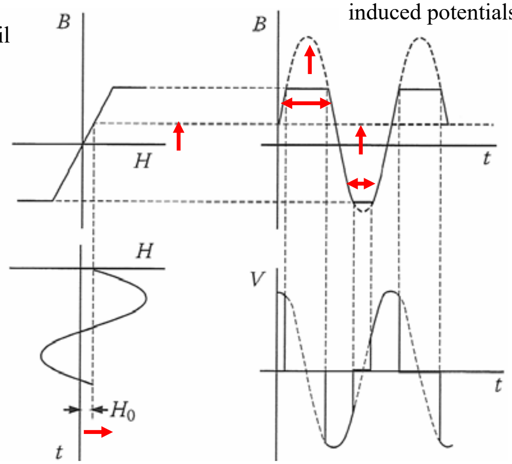
The induced current will flow in the direction so as to oppose the change that produces it.
When the north pole of the magnet moves towards the coil, the induced current will flow in an anti-clockwise direction to produce a magnetic field (north pole) which opposes the motion of the magnet (to repel the incoming magnet's north pole).

Principle of Fluxgate Magnetometer



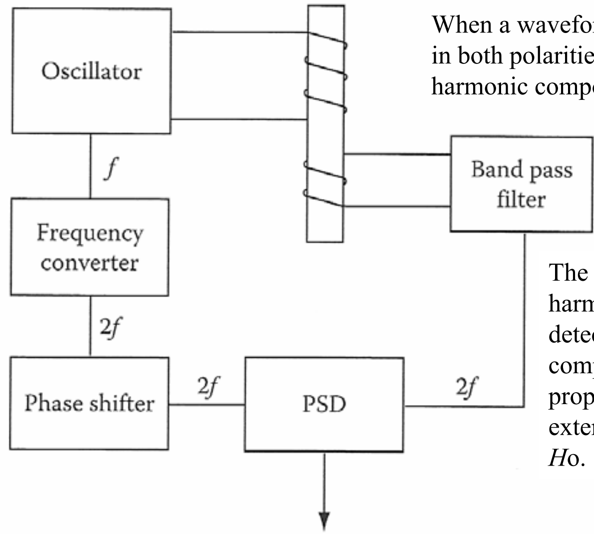
Sensor configuration

Excitation and induced potentials



When the external field *H*o is zero, the induced voltage is symmetric in both polarities. If *H*o is not zero, **asymmetric component** appears in induced voltage.

Detection of Asymmetric Component



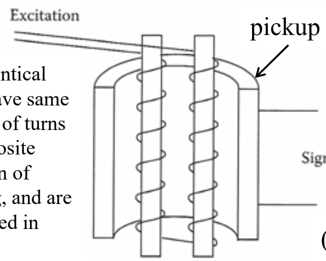
When a waveform is symmetric in both polarities, the 2nd harmonic component is zero.

The amplitude of the 2nd harmonics is used to detect the asymmetric component that is proportional to the external field strength *H*o.

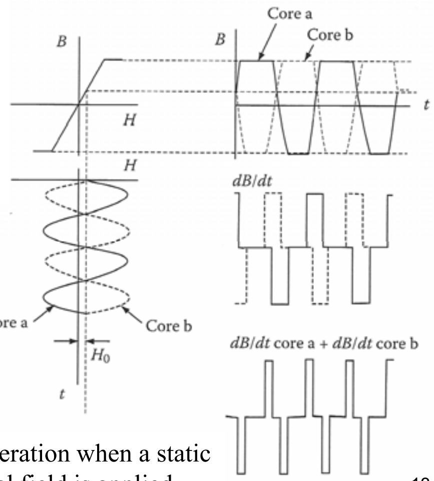
Vacquier Fluxgate Magnetometer

If the external field is zero, the induced fields in the two coils have the same amplitude in opposite polarity, but when an external field *Ho* is given, the time of transience in polarities is shifted, and the voltage induced in the pickup coil, which is proportional to the time derivative of the magnetic flux passing through the coil, has pulsatile components so that the pulse width is proportional to the external field strength.

Two identical cores have same number of turns but opposite direction of winding, and are connected in series.



(a) Sensor configuration

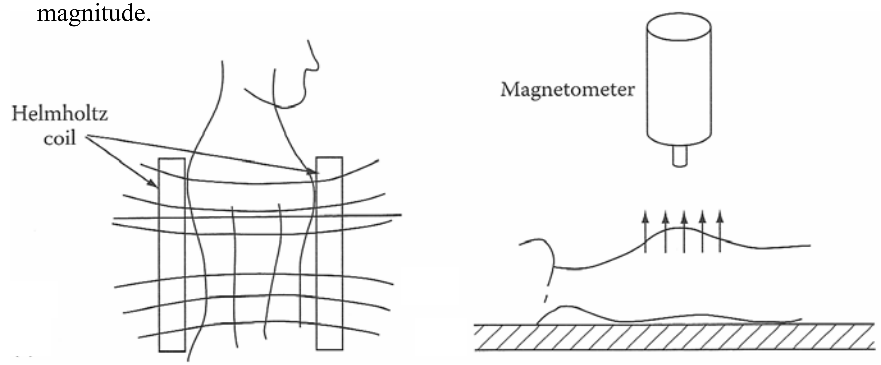


(b) Operation when a static external field is applied

Magnetopneumography

Magnetization and detection of magnetic particles in the lung

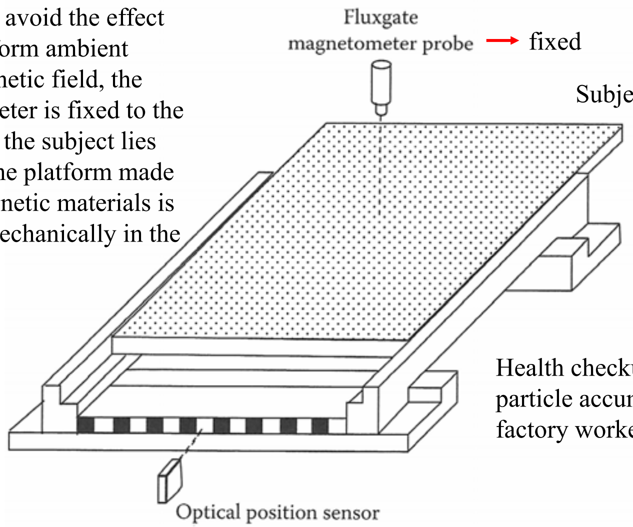
During the presence of a magnetic field (a few to 20 sec), the dust particles become magnetized and are aligned with the direction of the external magnetic field. The rate at which the dust particles align with the field is dependent on the magnitude.



(a) magnetization procedure (b) detection of magnetic particles in the lung

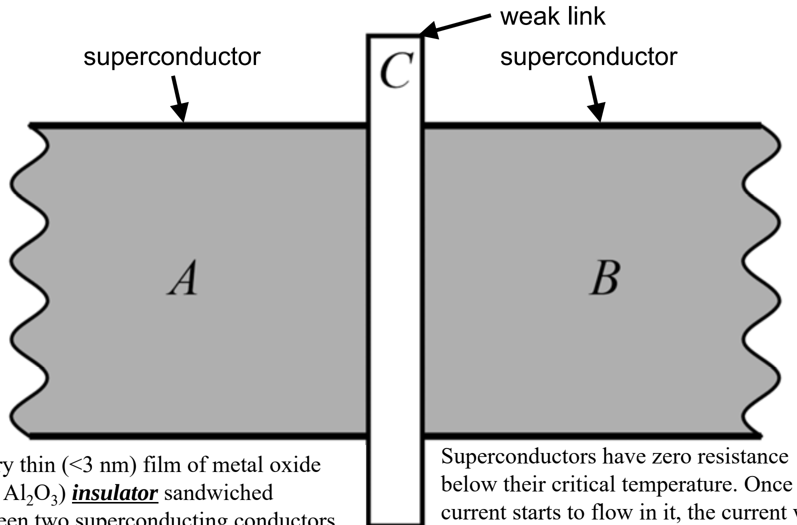
Magnetopneumograph System

In order to avoid the effect of nonuniform ambient static magnetic field, the magnetometer is fixed to the space, and the subject lies down on the platform made of nonmagnetic materials is scanned mechanically in the plane.



Hall probe (μT)
Flux gate sensors (nT)
SQUID (fT)

Josephson Junction

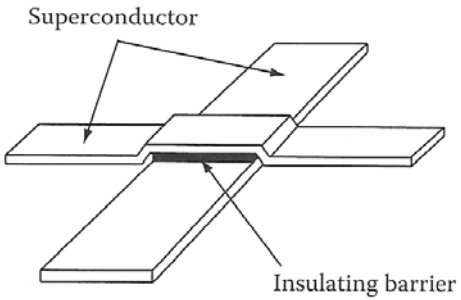


A very thin (<3 nm) film of metal oxide (e.g., Al_2O_3) ***insulator*** sandwiched between two superconducting conductors.

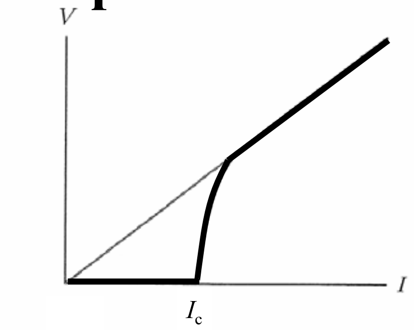
Superconductors have zero resistance below their critical temperature. Once a current starts to flow in it, the current will continue to flow even if left alone.

Super-current — a current that flows indefinitely long without any voltage applied — crosses a Josephson junction (JJ) — two superconductors coupled by a weak link — a thin insulating barrier, a short section of non-superconducting metal, or a physical constriction that weakens the superconductivity at the point of contact.

Josephson Effect



(a) Josephson Junction configuration



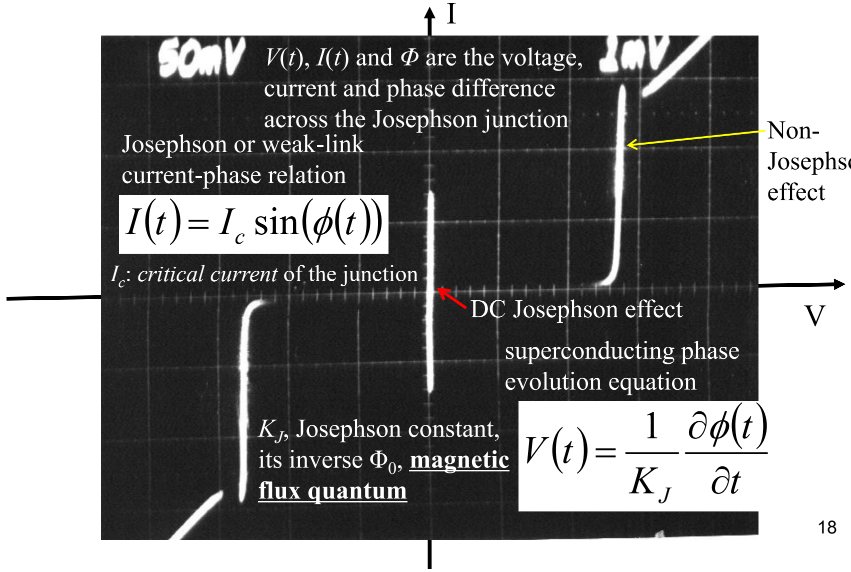
(b) Nonlinear current-voltage characteristics

Weak link is a resistive barrier that weakens the superconductivity at the point of contact. Electron tunneling happens between two superconducting regions that are separated by the weak link.
A current can penetrate the resistive barrier without causing a voltage drop.

When the current is lower than the critical current I_c, the voltage across the junction is zero. However, when the current is increased beyond I_c, the voltage across the junction appears abruptly

The basic equations governing the dynamics of the Josephson effect

Typical I-V Characteristic



DC and AC Josephson Effects

- DC Josephson effect $I(t) = I_c \sin(\phi(t))$
  - A DC current crossing from the insulator in the absence of any external electromagnetic field, owing to **tunneling**.
  - This DC **current** is proportional to the sine of the **phase difference across the insulator**, and may take values between $-I_C$ and I_C.
- AC Josephson effect
  - When a fixed **voltage** V_{DC} crosses the junctions, the phase will vary linearly with time, and the current will be an AC current with amplitude I_C and **frequency** $(2e/\hbar)V_{DC}$.
  - This means a Josephson junction can act as a perfect **voltage-to-frequency converter**. $f = \frac{2eV_{DC}}{\hbar}$

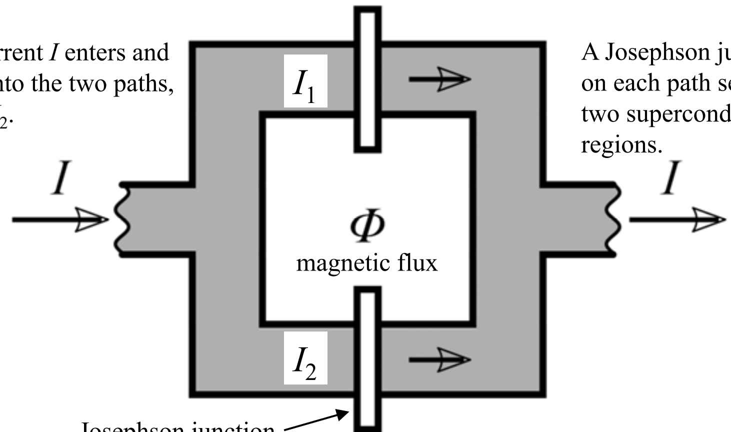
Superconducting QUantum Interference Device

SQUID Device

A **SQUID** is a low-noise ultra-high sensitive **magnetic field-to-voltage transducer** for measuring extremely subtle magnetic fields, based on superconducting loops containing Josephson junctions.

The current I enters and splits into the two paths, I_1 and I_2.

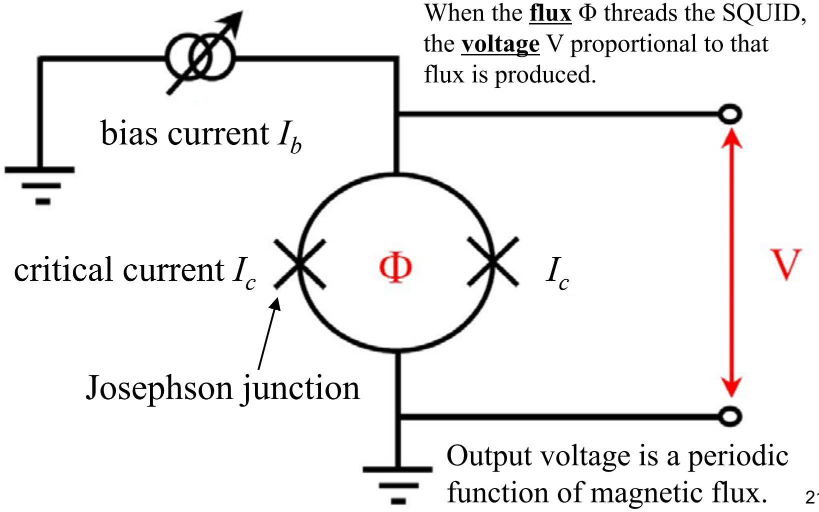
A Josephson junction on each path separates two superconducting regions.



Josephson junction

Electrical Schematic of a SQUID

When the **flux** Φ threads the SQUID, the **voltage** V proportional to that flux is produced.



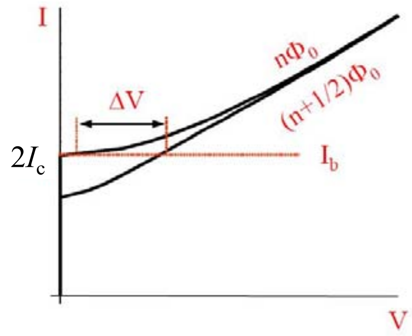
Output voltage is a periodic function of magnetic flux.

Magnetic flux quantum, physical constant, independent of the underlying superconductor material

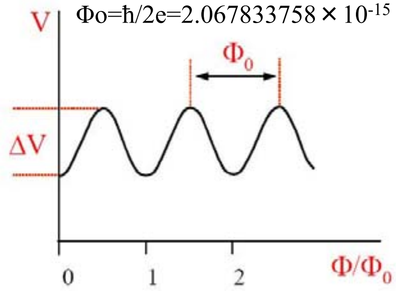
Φ Dependent I-V Property

ħ: Planck constant
e: elementary charge

$\Phi_o = \hbar/2e = 2.067833758 \times 10^{-15}$ Wb



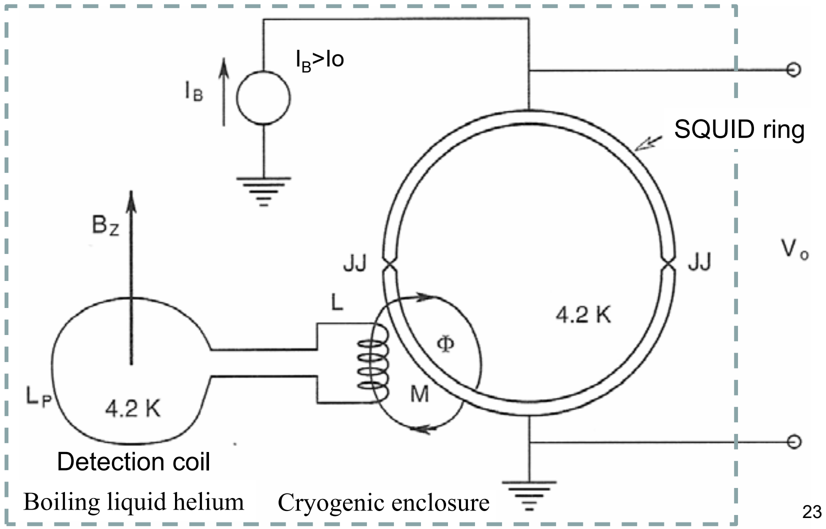
current vs. voltage for a SQUID.



Periodic voltage responds to flux through a SQUID.
The voltage varies as a periodic function of Φ/Φ_0.
The periodicity is equal to one flux quantum, Φ_0

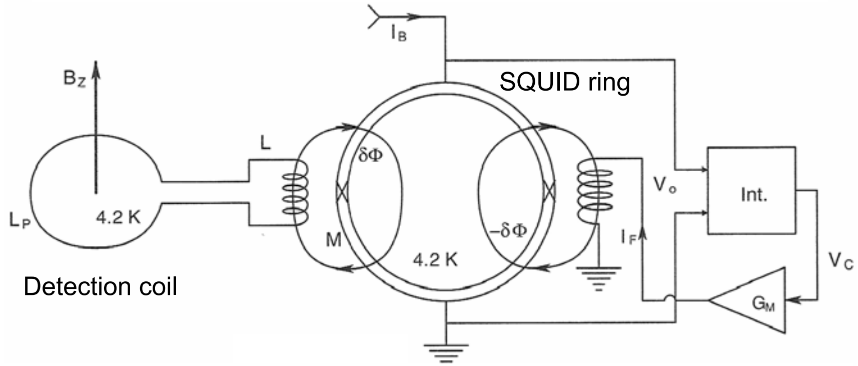
Basic SQUID

Two terminals are inputs for a DC bias current I_B.
Two terminals monitor the output voltage Vo.



Flux-locked SQUID

By adjusting I_B, the SQUID's operating point is located at one of the open circles in the Vo vs. $\Phi/\Phi o$ plot
By using a feedback null mode of operation, the SQUID is given a large linear dynamic range; the flux-locked SQUID output is now Vc = KΦi.



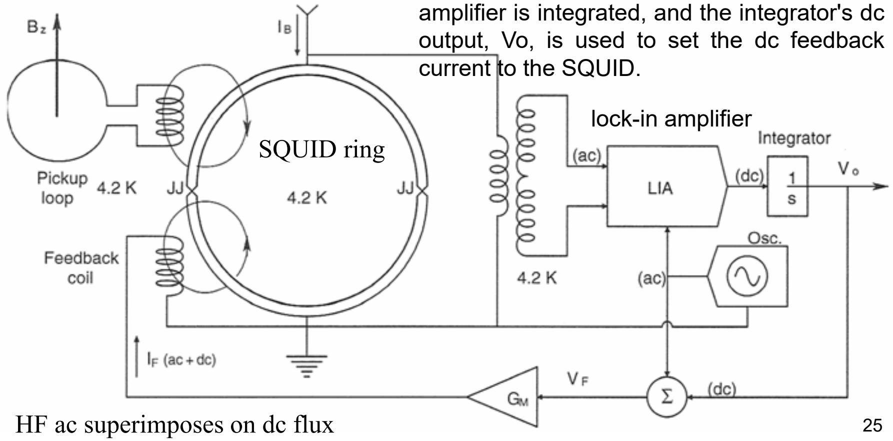
The voltage Vo is integrated, amplified, and used to control a V-I converter G_M.
The current I_F in the feedback coil produces a flux equal but opposite to the input flux Φi, nullifying Vo.

AC-modulated Flux-locked SQUID

I_B is set close to the critical current. The biomagnetic field is picked up by the detection coil and inductively coupled to the SQUID ring.

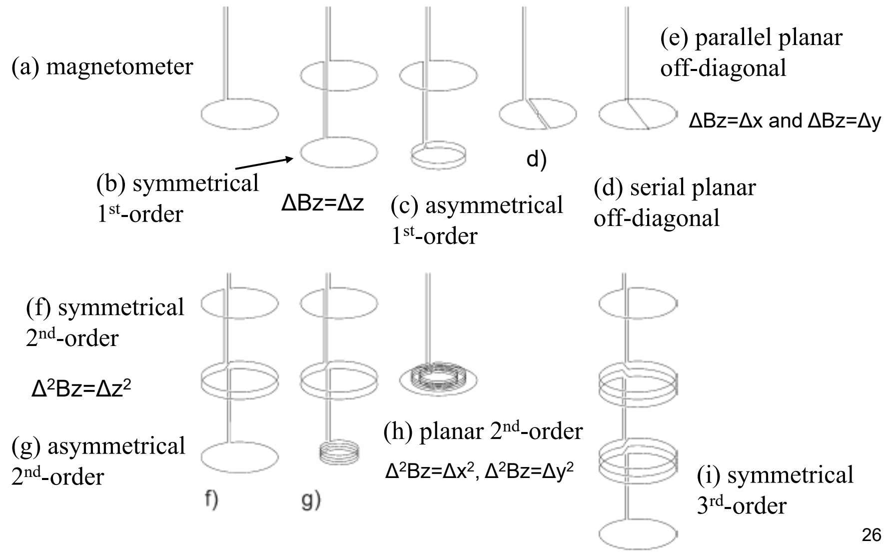
An ac flux is superimposed on the dc flux in SQUID ring. Any dc deviation from the null operating point produces an ac component in the SQUID's output voltage that is detected by a LIA. The dc output of the lock-in amplifier is integrated, and the integrator's dc output, Vo, is used to set the dc feedback current to the SQUID.

Detection coil



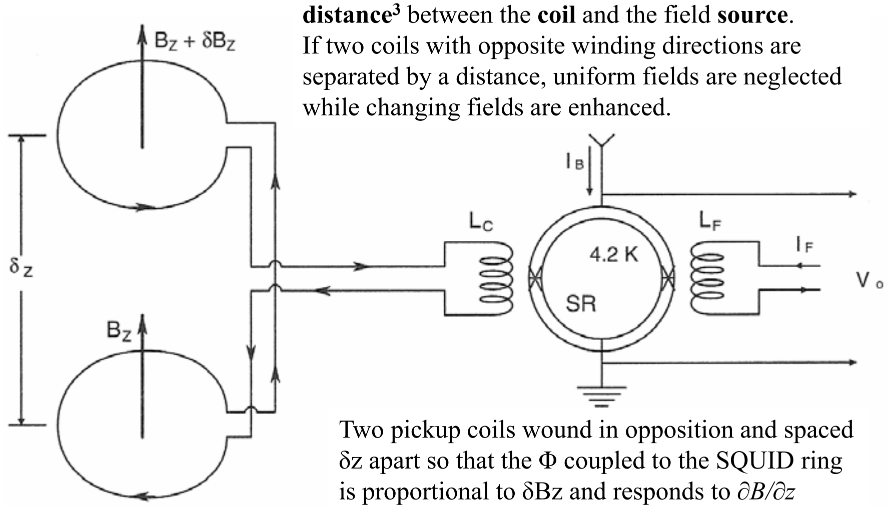
HF ac superimposes on dc flux

Various Pickup Coils



1st-order Gradiometer SQUID

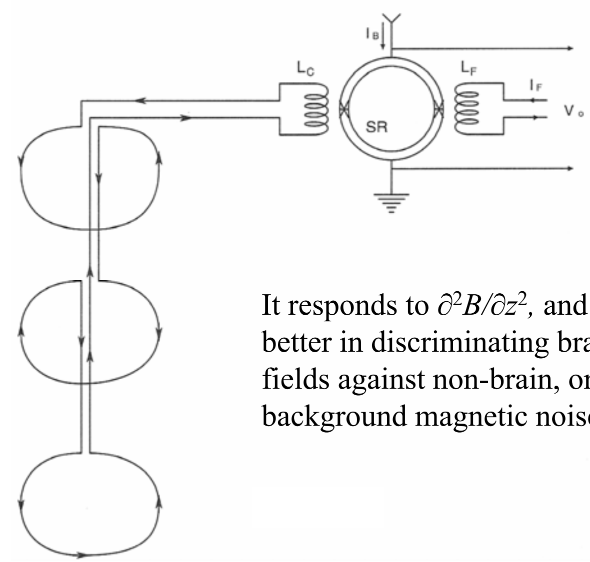
Magnetic strength is inversely proportional to the **distance**^{3} between the **coil** and the field **source**.
If two coils with opposite winding directions are separated by a distance, uniform fields are neglected while changing fields are enhanced.



Two pickup coils wound in opposition and spaced δz apart so that the Φ coupled to the SQUID ring is proportional to δBz and responds to $\partial B/\partial z$

Bz: skull surface magnetic field

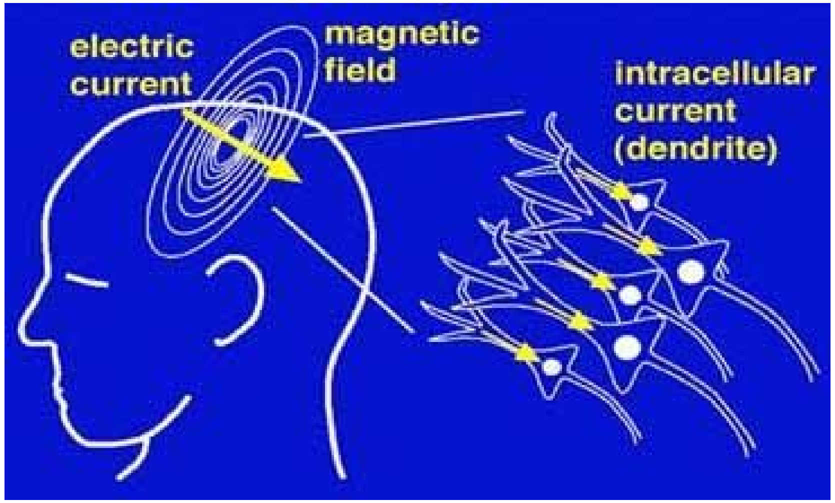
2nd-order Gradiometer SQUID



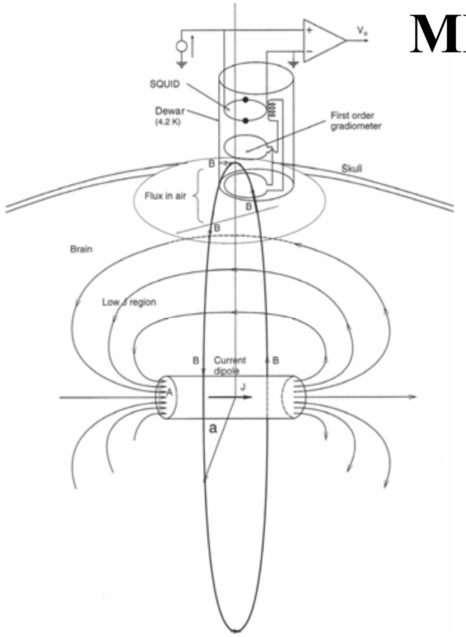
It responds to $\partial^2 B/\partial z^2$, and is better in discriminating brain fields against non-brain, or background magnetic noise.

Brain Magnetic Field

By measuring the brain magnetic fields created by the electric current flowing within the neurons, various brain functions are evaluated with mm spatial accuracy.

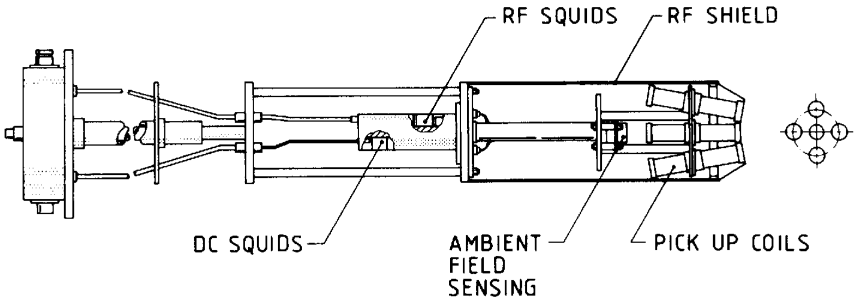


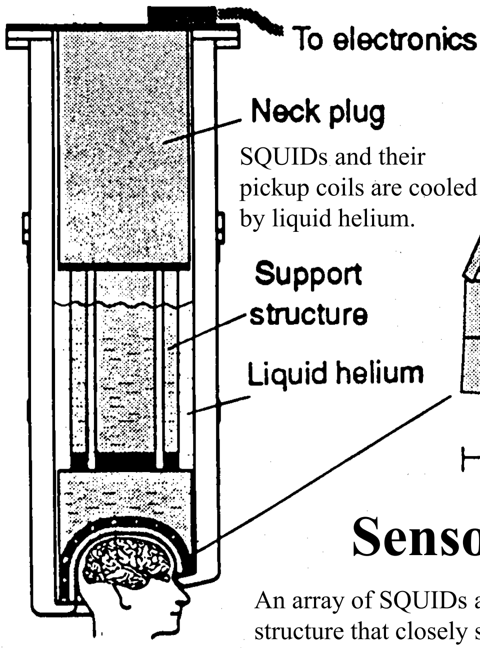
MEG Measurement



The circle of constant ***B*** of radius ***a*** provides more flux to the gradiometer coil closest to the skull, hence produces a SQUID output.
Flux cutting both coils **equally**, such as from the Earth's magnetic field, produces no output.
There can be millions of current dipoles active at once, and because of the way the cortex is folded, some can be parallel to the surface of the skull, and others may be directed radially.
B from the radial dipoles will only be sensed weakly with SQUID coils that are parallel to the skull surface.

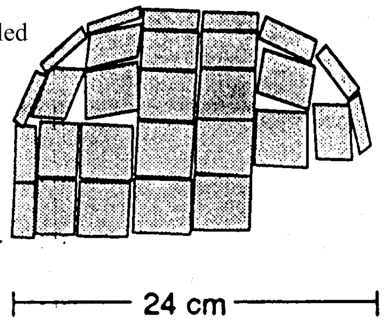
SQUID Gradiometer Probe





SQUIDs and their pickup coils are cooled by liquid helium.

148-sensor array

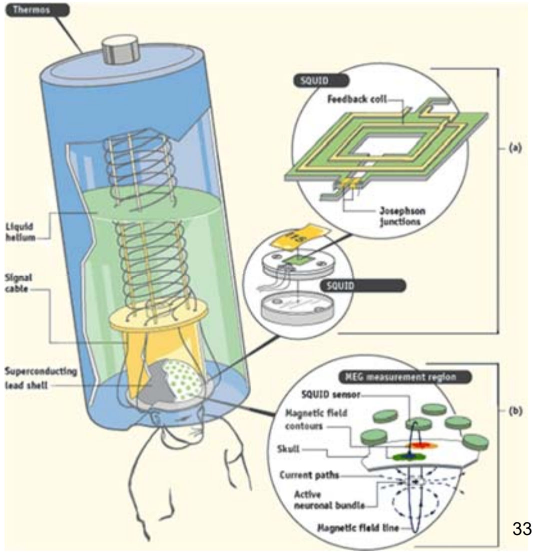


Sensor and Helmet

An array of SQUIDs are configured in a helmet-like structure that closely surrounds the subject's head.

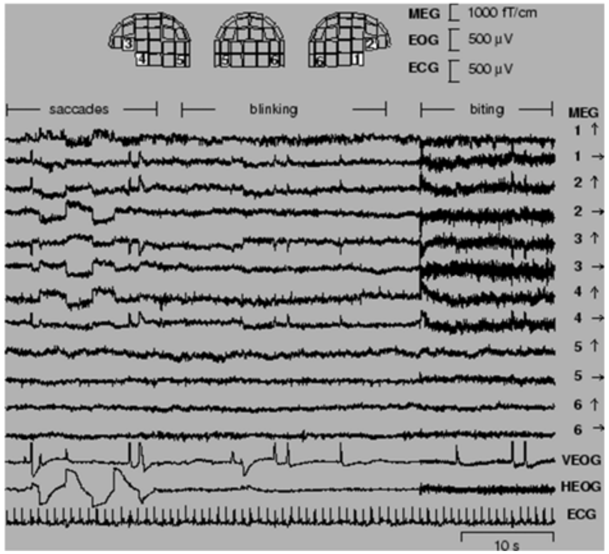
Brain Magnetic Measurement

Both **spontaneous brain function** and **evoked brain activity** can be measured.
The outputs localize the source of the brain activity within mm, and are overlaid on a MRI.



Spontaneous MEG

artifacts produced by blinking, saccades, biting and cardiac cycle.

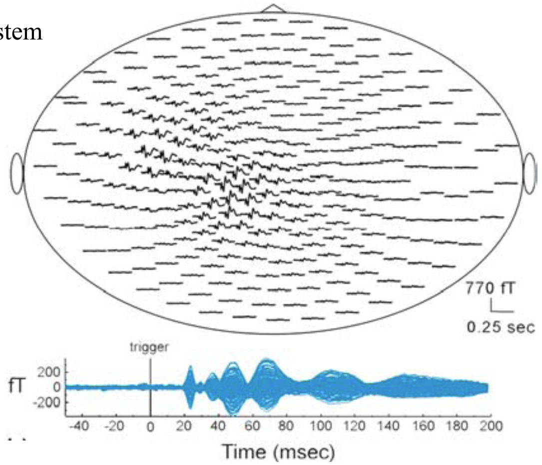


six positions

two orthogonal directions of each position

Evoked MEG

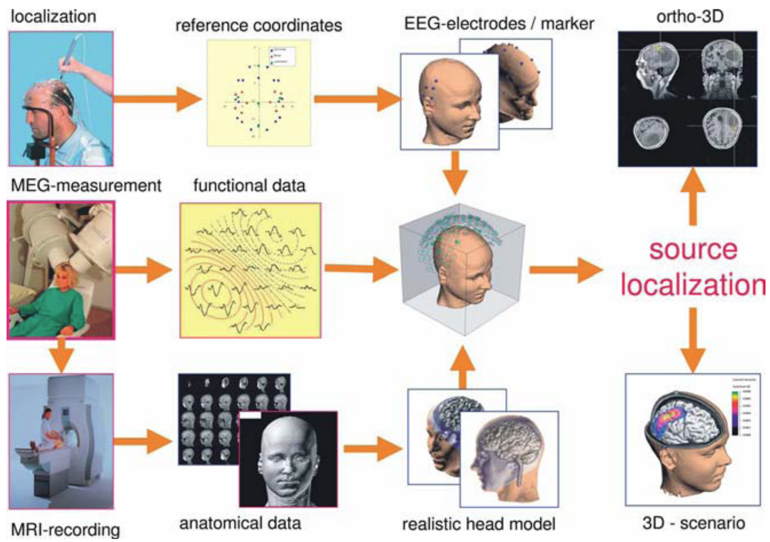
(a) Cortical 275-channel MEG System



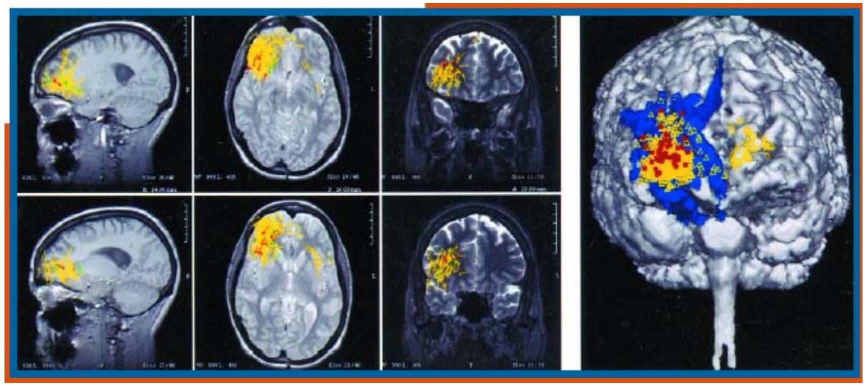
(b) Somatosensory-evoked MEG recorded by (a) (DC to 300 Hz bandwidth, 628 averages and 3rd order gradiometer)

Magnetic Source Imaging

MSI = localization of the magnetic source using biomagnetic measurement and MRI



Source Localization in Epilepsy



MEG localization superimposed on surface-rendered MRI images: Blue, subdural electrodes; Yellow, interictal localizations; Red, ictal localizations; Green, spread pattern.

MCG-recording

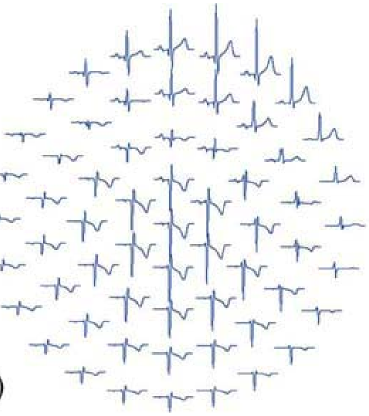
62ch twin **Dewar** (2 × 31ch) biomagnetometer (Philips).

The double-dewar construction allows measurements to be performed over both hemispheres of the head for magnetoencephalogram, such as auditory and somatosensory-evoked responses, presurgical mapping, fetal MEG, spontaneous brain activity, or over the chest for magnetocardiogram.

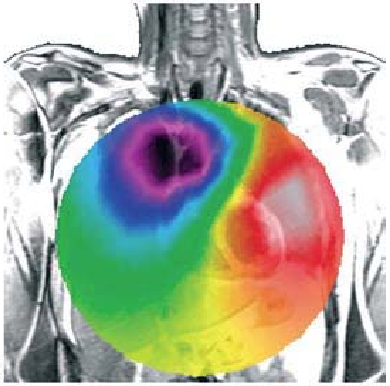
MCG in a Healthy Subject

The different measures are based on the morphology and the time interval of the MCG signal, the reconstruction of magnetic field maps, the estimation of current density and current source.

a)



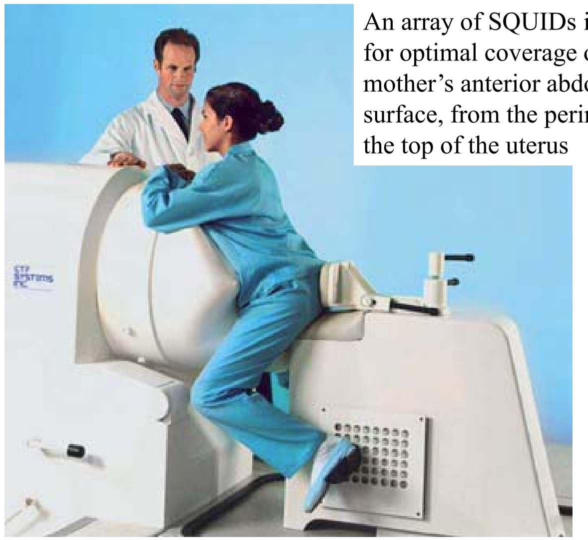
b)



(a) Signal-averaged traces from a 61-channel prethoracic acquisition

(b) Magnetic field map at Q onset schematically superimposed on an MRI

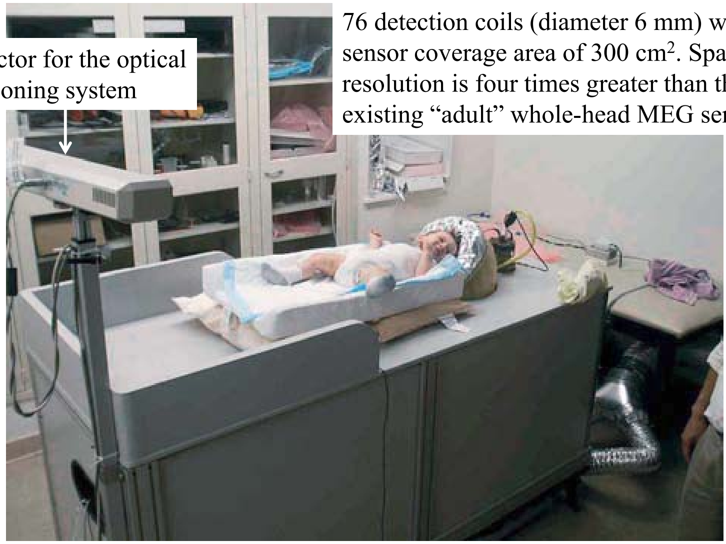
Fetal MEG



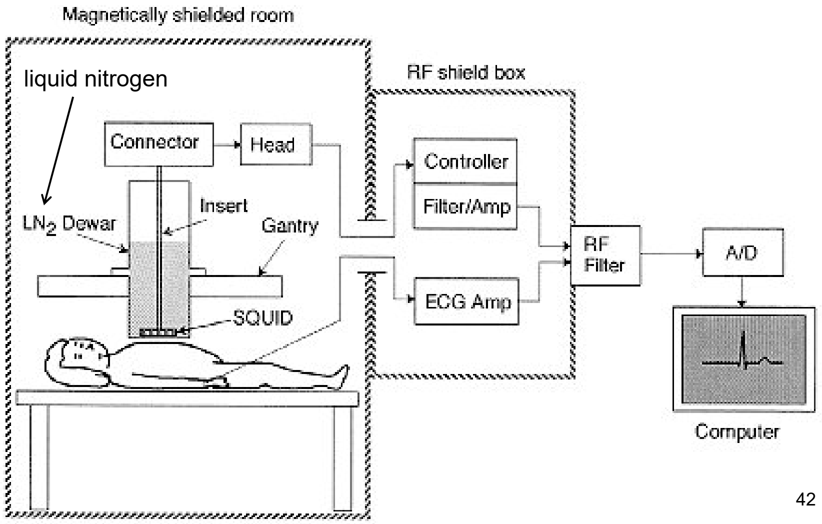
An array of SQUIDs is arranged for optimal coverage of the mother's anterior abdominal surface, from the perineum to the top of the uterus

Baby MEG

76 detection coils (diameter 6 mm) with a sensor coverage area of 300 cm^2. Spatial resolution is four times greater than that of existing "adult" whole-head MEG sensors.

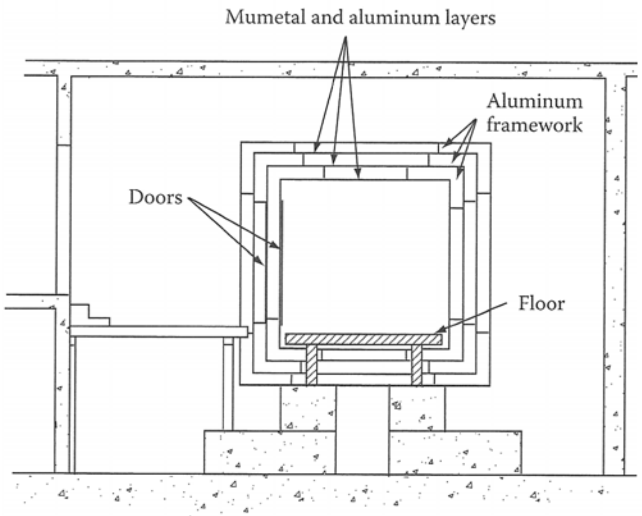


MCG Measurement System



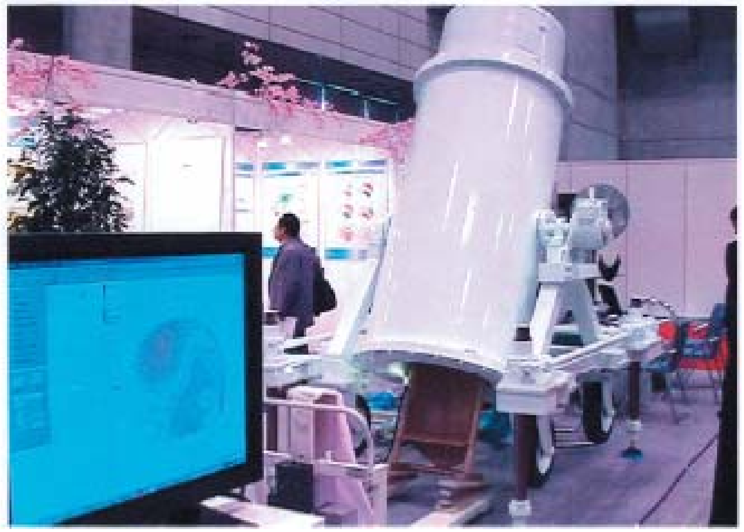
Magnetically Shielded Room

Alloy (Ni 80%) with exceptionally high magnetic permeability, very low coercive force, very low core losses, and low remanence



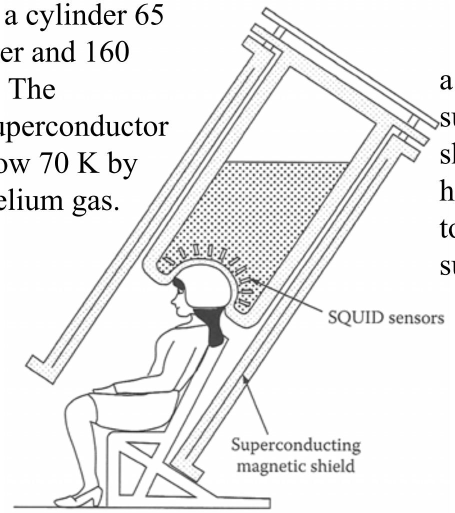
DC magnetic field of the earth is close to 50 uT, which is about 1 million times greater than the magnetic field of the heart. The brain signals are about two orders of magnitude lower than the heart. Noise in lab buildings is of the magnitude 1-10 $nT/Hz^{1/2}$ at 1 Hz. Part of the noise can be eliminated by using gradiometer coils in the SQUID equipment, such as 2^{nd} or 3^{rd} order gradiometers.

Mobile SQUID System



Superconducting Magnetic Shield

It consists of a cylinder 65 cm in diameter and 160 cm in length. The cylindrical superconductor was kept below 70 K by circulating helium gas.



a partly covered superconducting shield for a whole head SQUID system to reduce the surrounding noise.