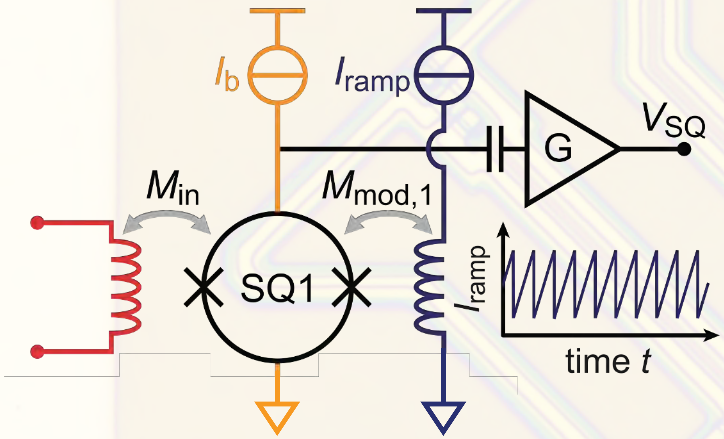
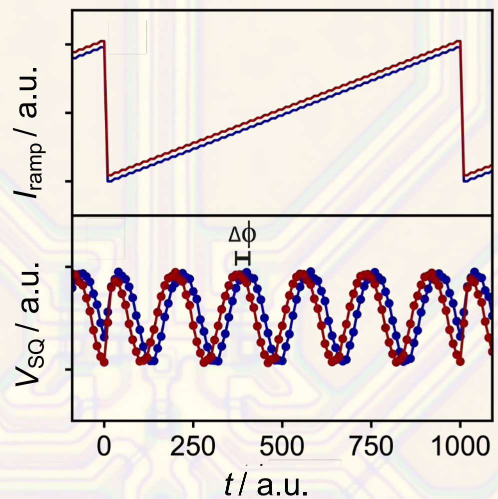
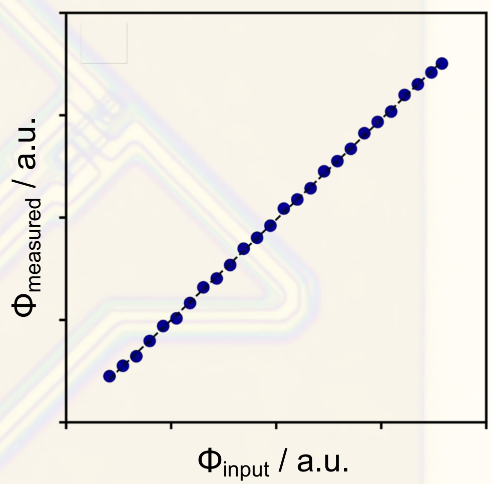
Flux-ramp modulation

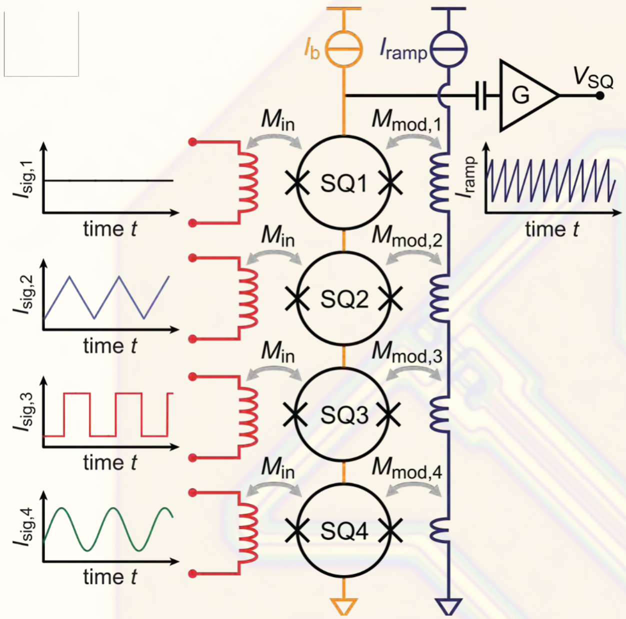


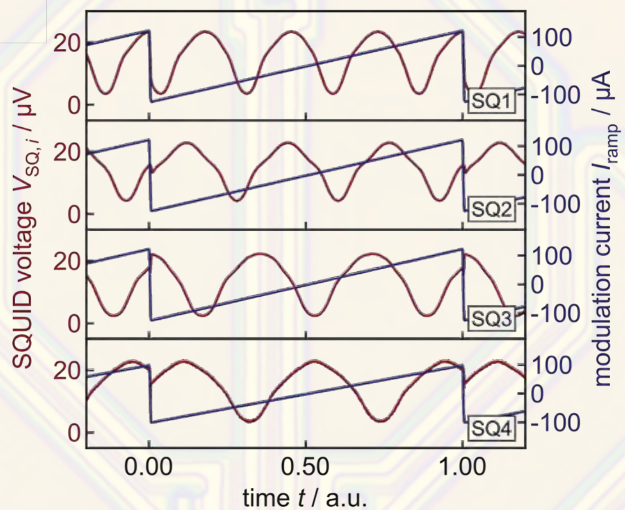


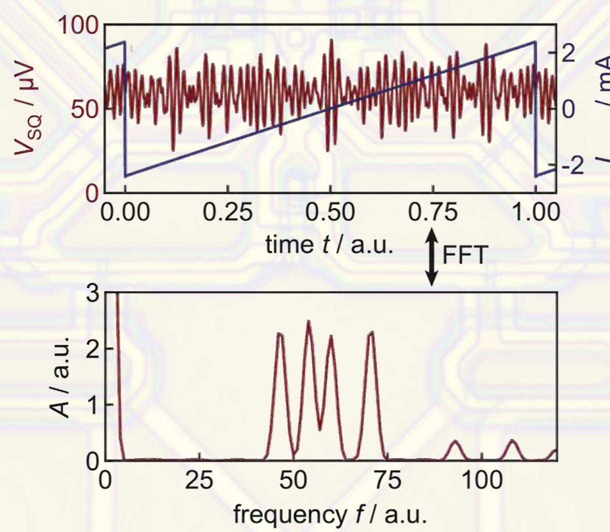


Flux-ramp modulation

multiplexing of arrays of SQUIDs

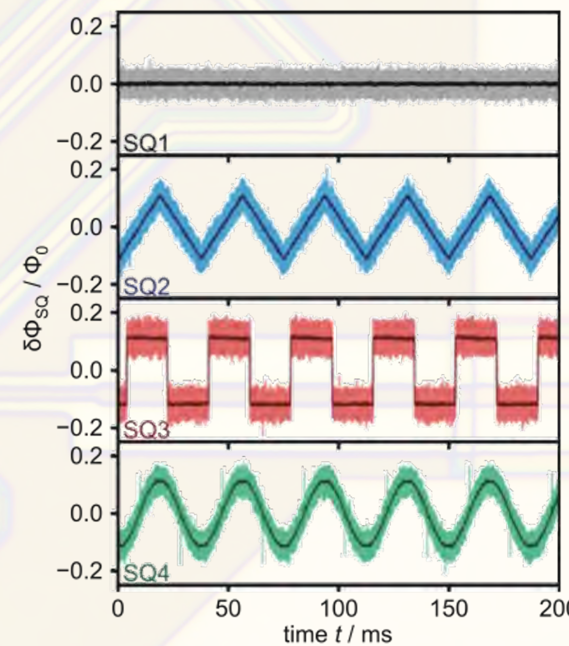






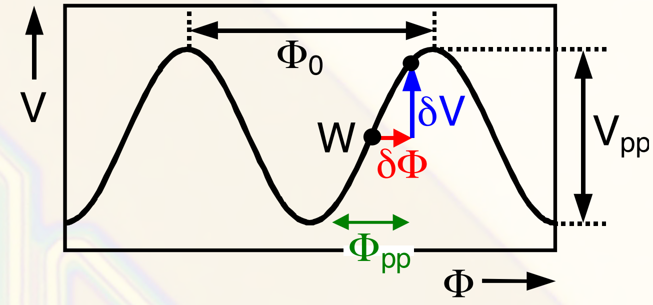
- flux changes from all SQUIDs are summed
- Fourier transform of output signal

- different flux ramp amplitudes to encode SQUID cannels
- different $V(\Phi)$ periods



dc-SQUID Readout

Summary



- transfer function should be linear

  problem: flux-to-voltage relation $\langle V\rangle(\Phi_{ext})$ is non-linear

  → linear input-output only for small signals

  possible solutions:

  operate SQUID as a null-detector for magnetic flux by using feedback } flux-locked loop (FLL)

  alternative: use flux ramp modulation → flux signal is transferred into a phase shift

- preamplifier noise should be kept below intrinsic SQUID

  problem: impedance of cold SQUID is low compared to room temperature electronics

  possible solutions:

  FLL with modulation and step-up-transformer: better impedance matching, but bandwidth limiting
  two-stage SQUID configuration: flux to flux amplification in the cold
  additional positive feedback: larger flux to voltage transfer

dc-SQUID Readout

- influence of intrinsic $1/f$ noise should be kept as small as possible

  problem: slow flux fluctuations dominate often the noise and thus the energy sensitivity

  possible solutions:
  reverse current biasing: slow in-phase fluctuations are canceled out
  flux-ramp modulation: signal is transferred into a higher frequency band

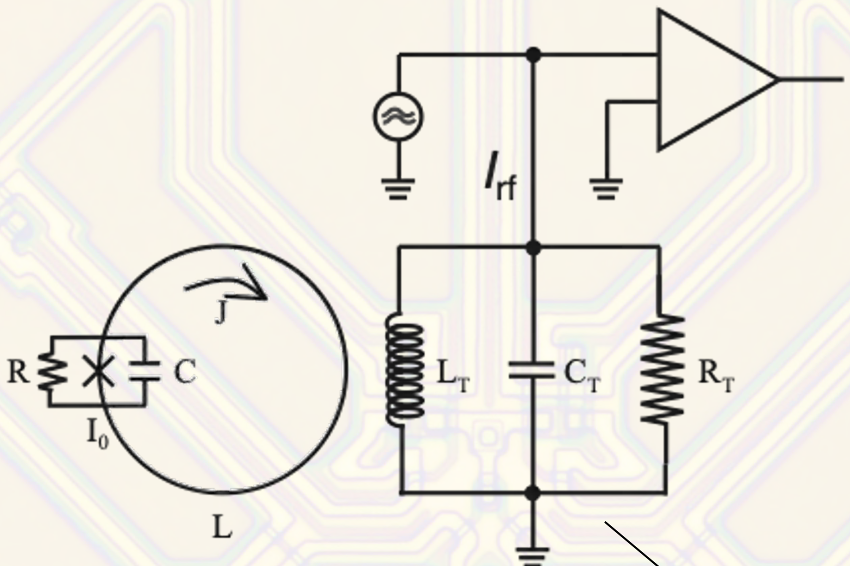
- readout of many SQUIDs with little complexity at low temperatures

  problem: individual readout has high wiring complexity, high costs and potentially increases parasitic heating

  possible solutions:

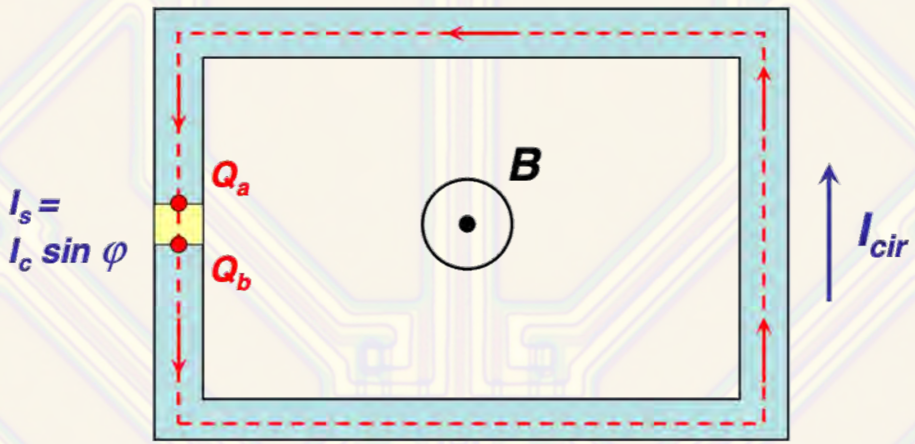
  flux-ramp modulation: flux change is transferred to a phase shift in characteristic curve, coupling of flux ramp can be adjusted at each SQUID and allows for encoding the SQUIDs → complexity is moved to room temperature.

rf-SQUIDs

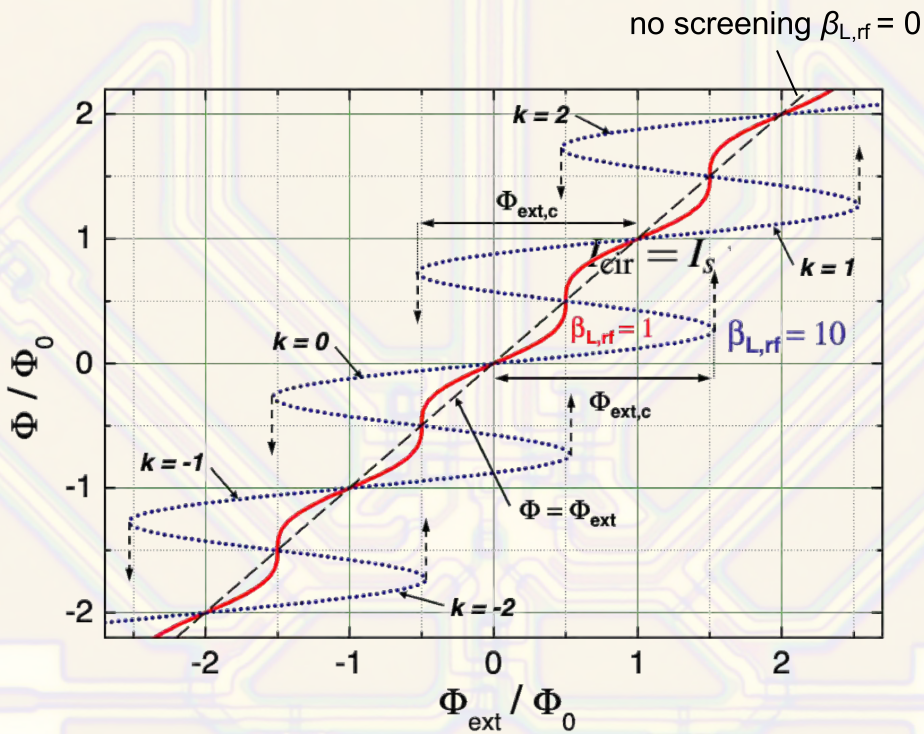


LC resonator (tank circuit)

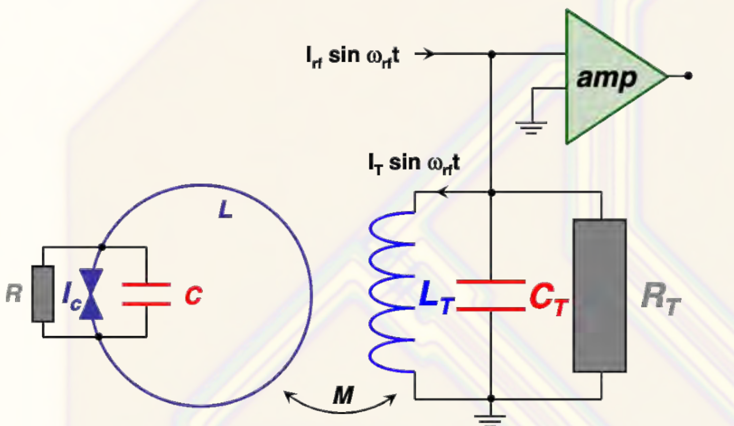
4.2 rf-SQUIDs



4.2 rf-SQUIDs


no screening $\beta_{L,rf} = 0$
$k = 2$
$k = 1$
$k = 0$
$k = -1$
$k = -2$
$\Phi_{ext,c}$
$\Phi_{ext,c}$
$I_{cir} = I_s$
$\beta_{L,rf} = 1$
$\beta_{L,rf} = 10$
$\Phi = \Phi_{ext}$
Φ / Φ_0
Φ_{ext} / Φ_0
2
1
0
-1
-2

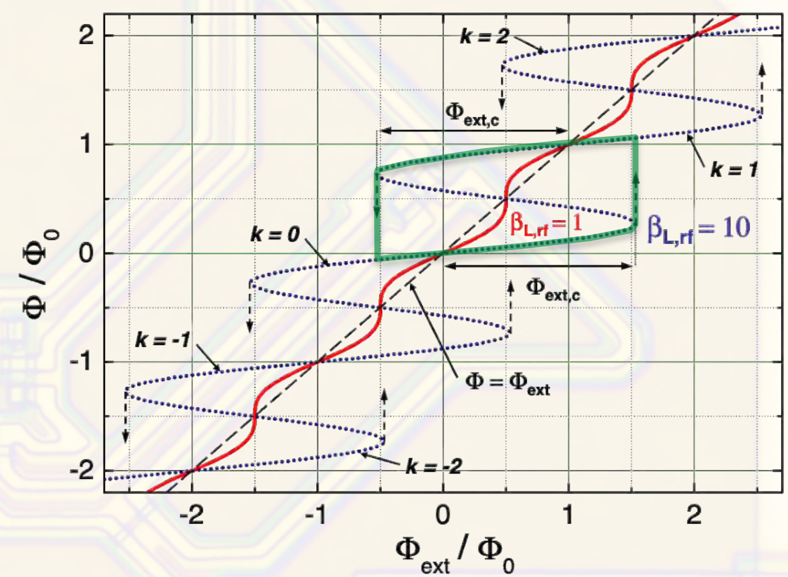
Operation and performance of rf-SQUID



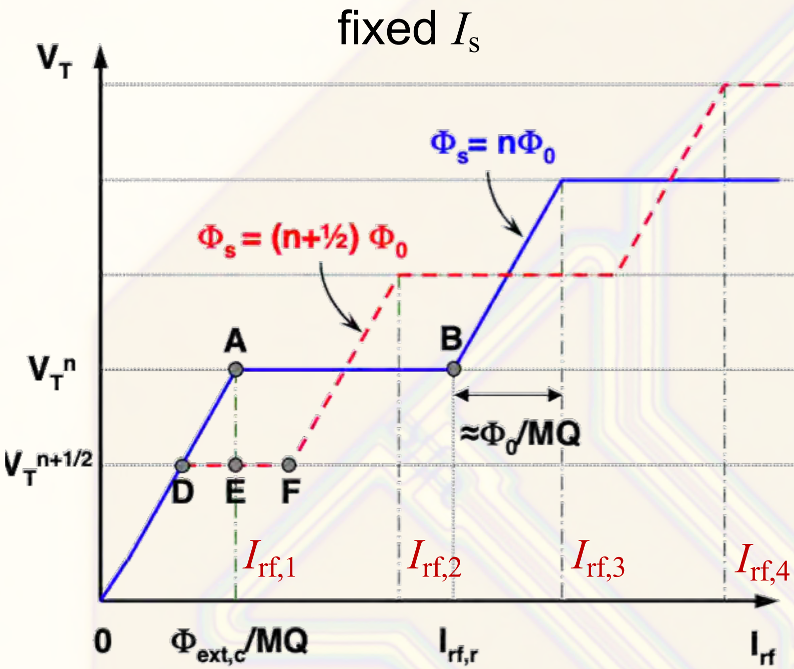
tank circuit

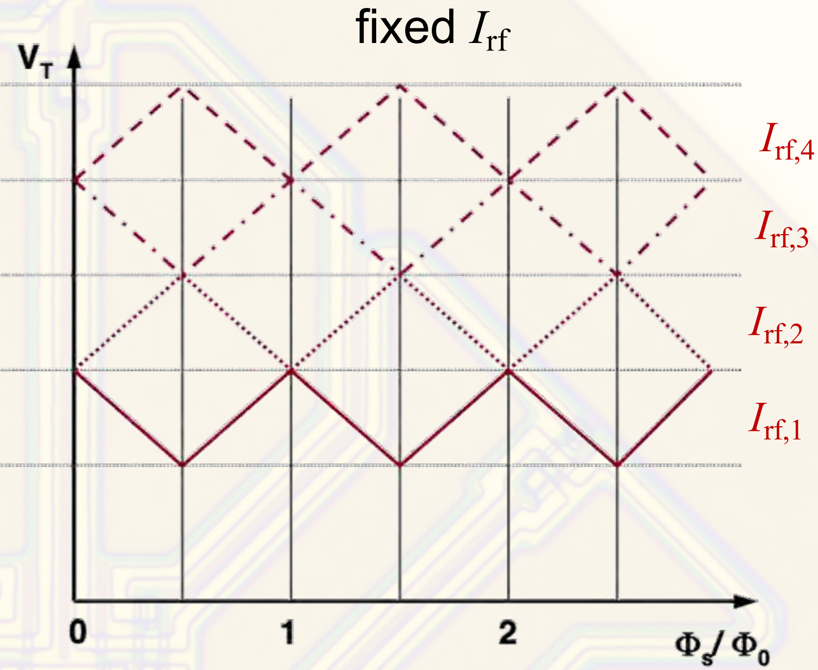
quality factor $Q = R_T/\omega_{rf}L_T$

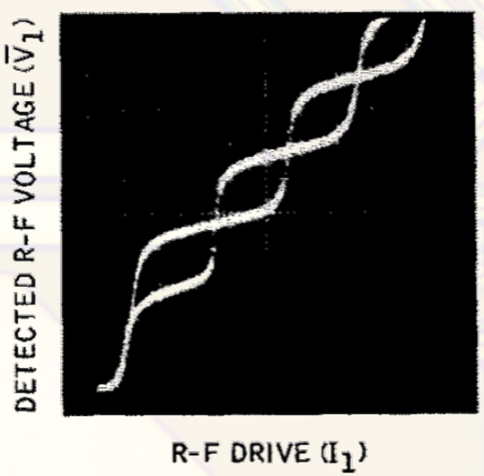
resonance frequency $\omega_{rf} = 1/\sqrt{L_T C_T}$

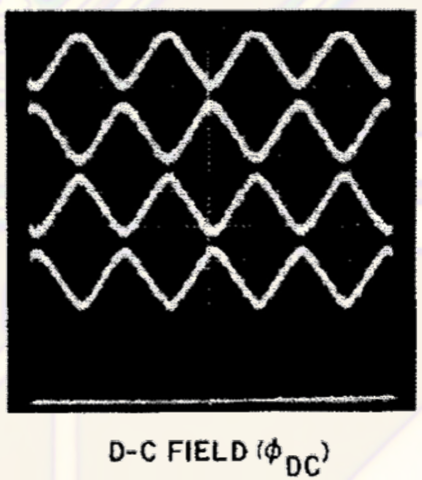


4.2 rf-SQUIDs


fixed I_s
V_T
V_T^n
$V_T^{n+1/2}$
$\Phi_s = n\Phi_0$
$\Phi_s = (n+½)\, \Phi_0$
A
B
D
E
F
$\approx\Phi_0/MQ$
$I_{rf,1}$
$I_{rf,2}$
$I_{rf,3}$
$I_{rf,4}$
0
$\Phi_{ext,c}/MQ$
$I_{rf,r}$
I_{rf}


fixed I_{rf}
V_T
$I_{rf,4}$
$I_{rf,3}$
$I_{rf,2}$
$I_{rf,1}$
0
1
2
Φ_s / Φ_0


DETECTED R-F VOLTAGE ($\bar{V}_1$)
R-F DRIVE (I_1)


D-C FIELD (ϕ_{DC})

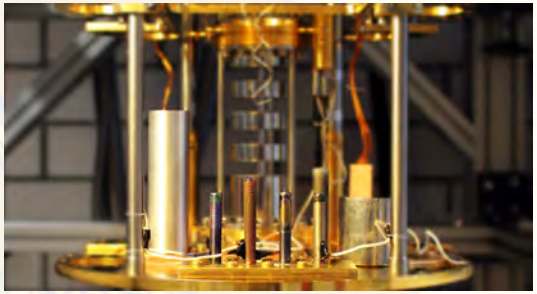
4.3 SQUID Applications

Overview of applications:

- Biomagnetism and medical applications
- Thermometry
- Displacement sensors
- Particle detection
- Geophysical applications
- Archeology
- Non-destructive Evaluation of Materials
- Gravity and Motion Sensors
- Metrology *I*, R, V, *T*
- …

Biomagnetism

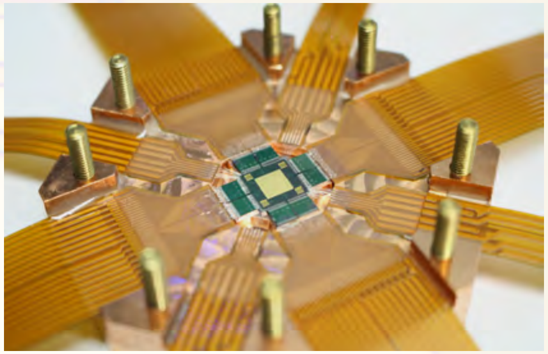
Thermometry



Archeology

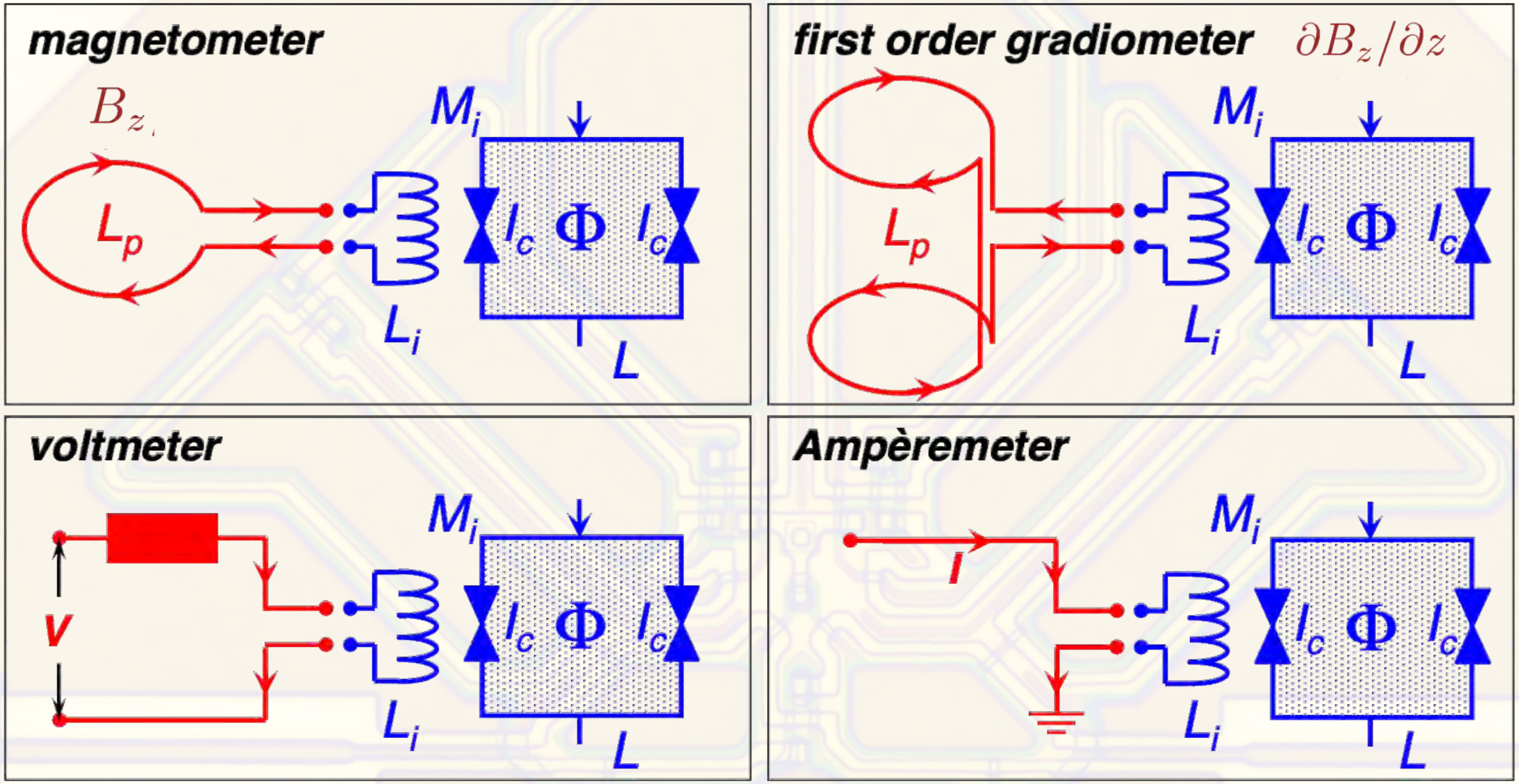
Geophysical applications

Particle detection

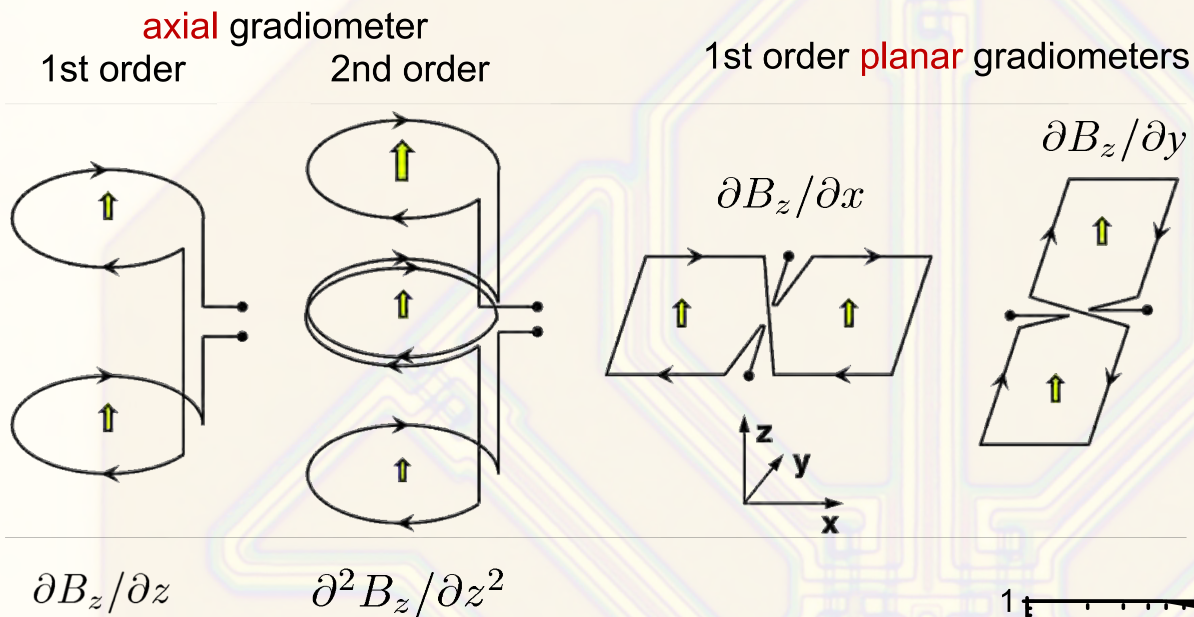


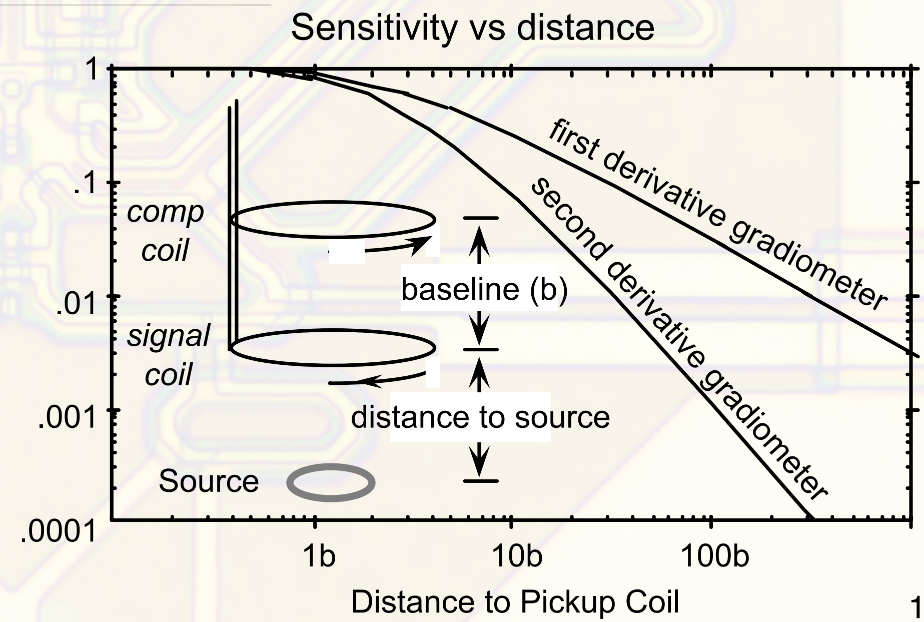
4.3 SQUID Applications

Basic SQUID configurations for different applications:



Different gradiometers

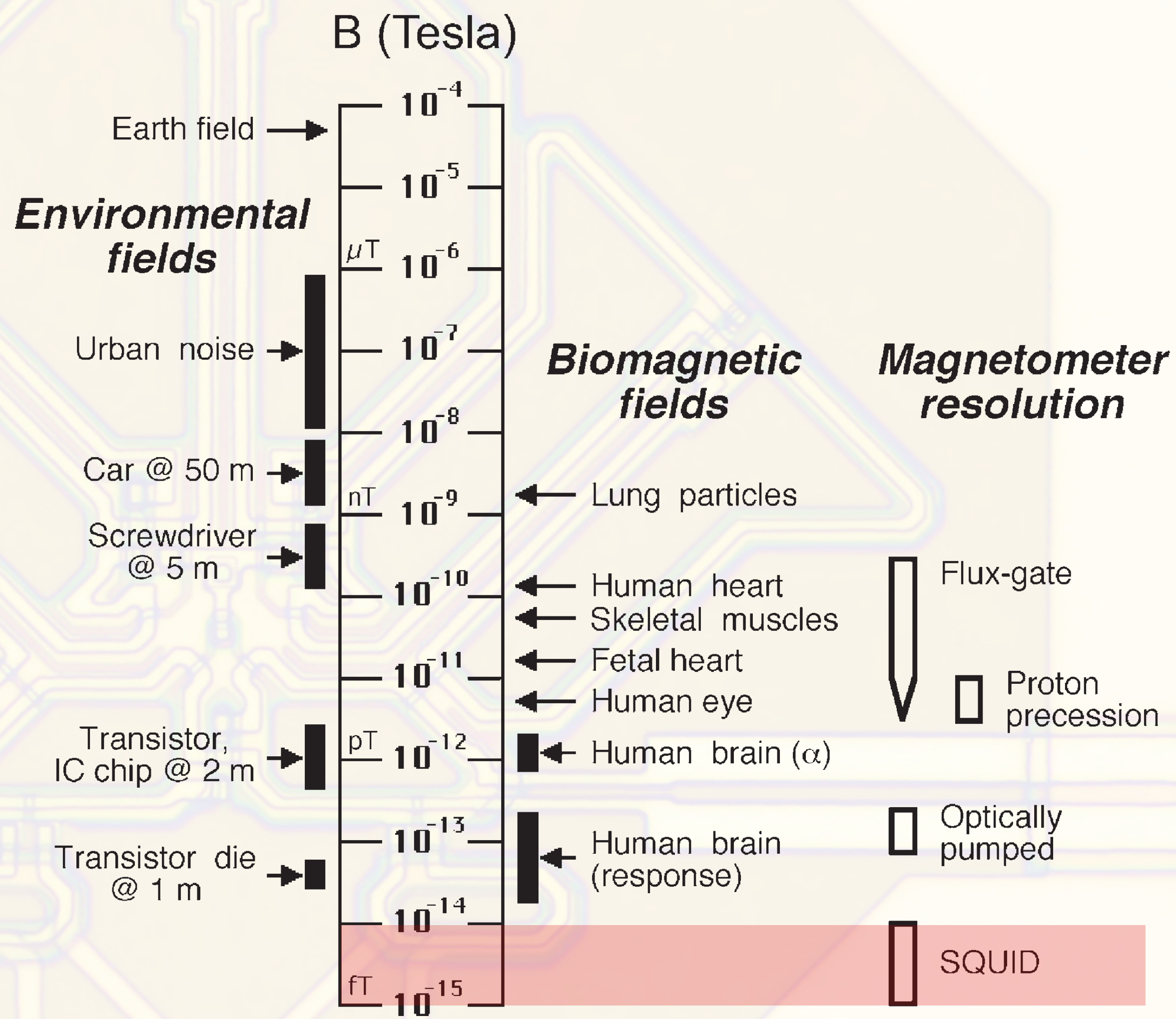




- gradiometers suppress homogeneous fields
- gradiometers can be used to construct vectors
- loops need to be identical
- stability is a very important aspect

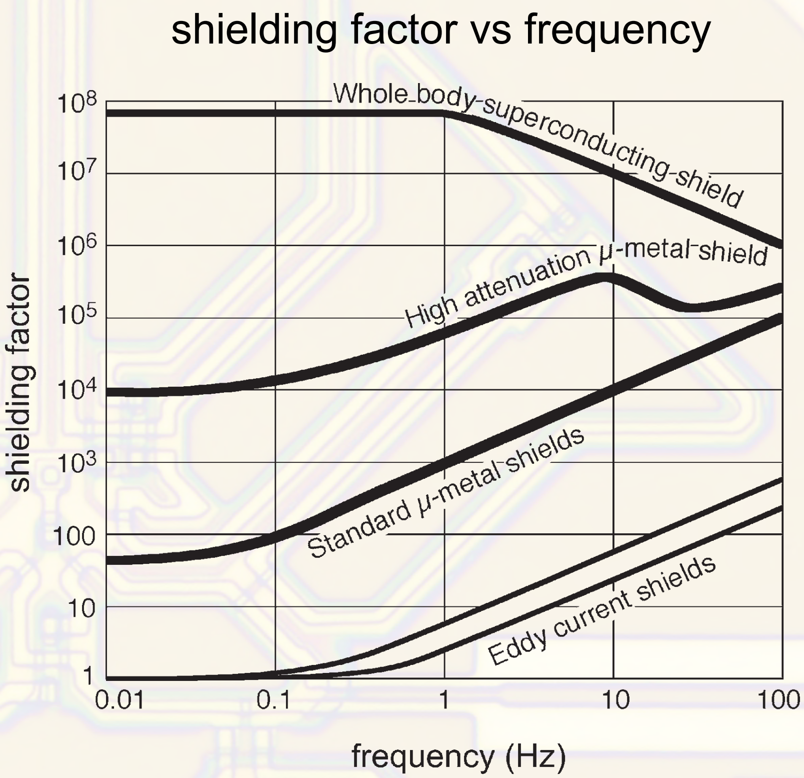
Biomagnetism and Medical Applications

- Magnetoencephalography MEG
- Magnetocardiography MCG
- Magnetooculogram (MOG)
- Magnetogastrogram (MGG)
- Magnetoneurogram (MNG)
- Liver iron susceptometry
- Magnetic marker monitoring
- …



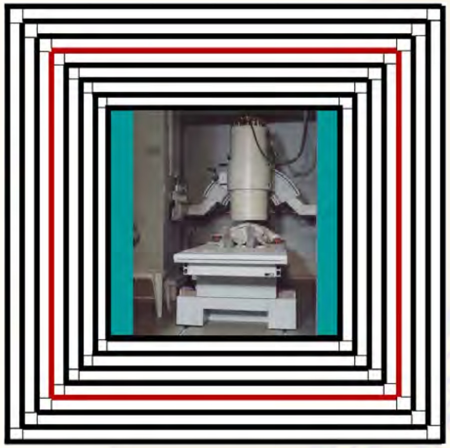
Shielding

magnetically shielded room:

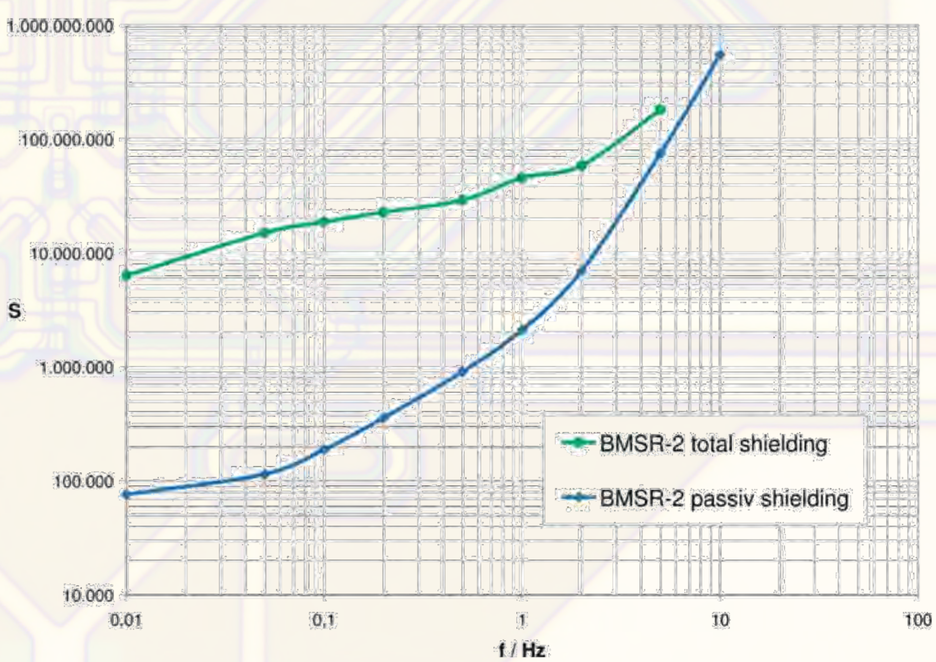


BMSR-2

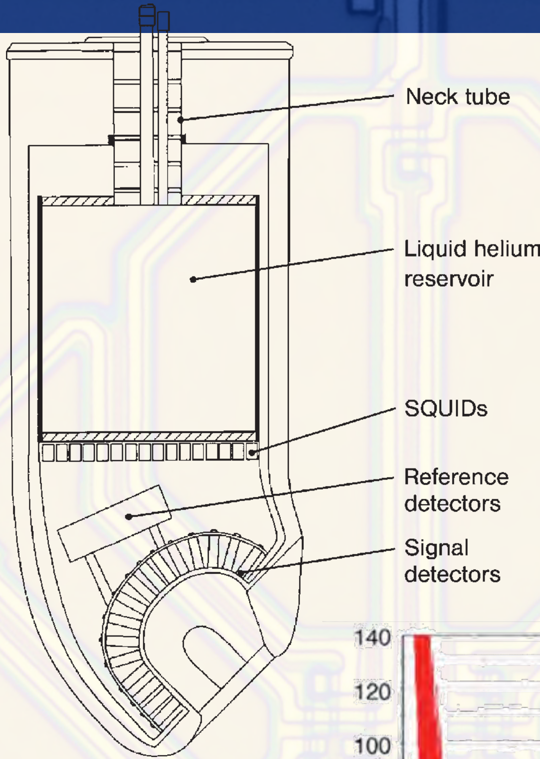
BMSR-2: best magnetically shielded room, which one can enter

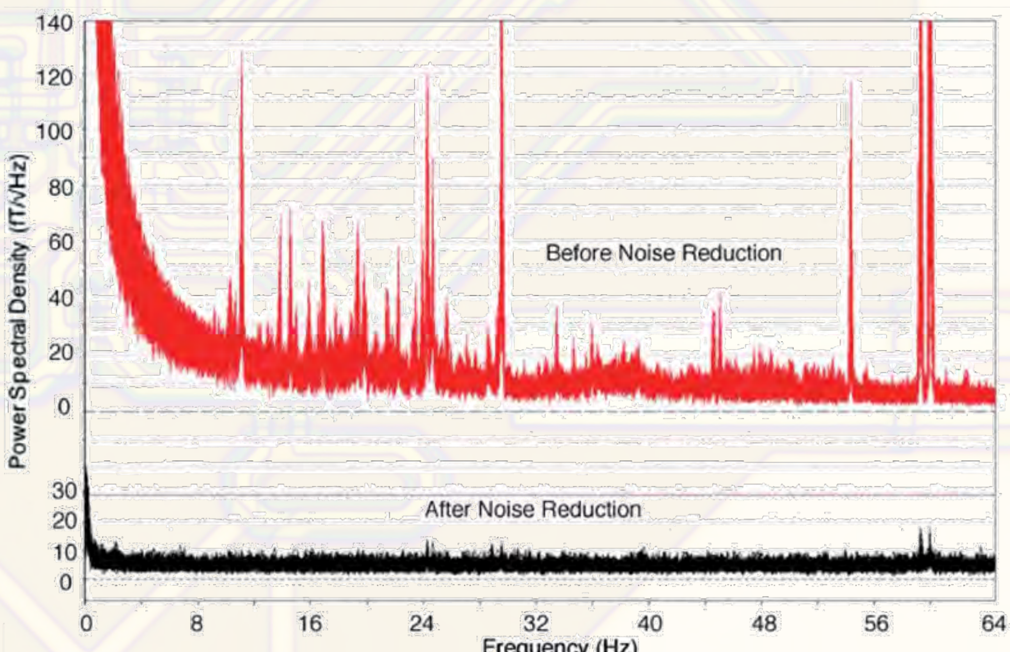


- 7 μ-metal shields
- 1 aluminum layer (rf-shield)
- additional active shielding



Magnetoencephalography MEG

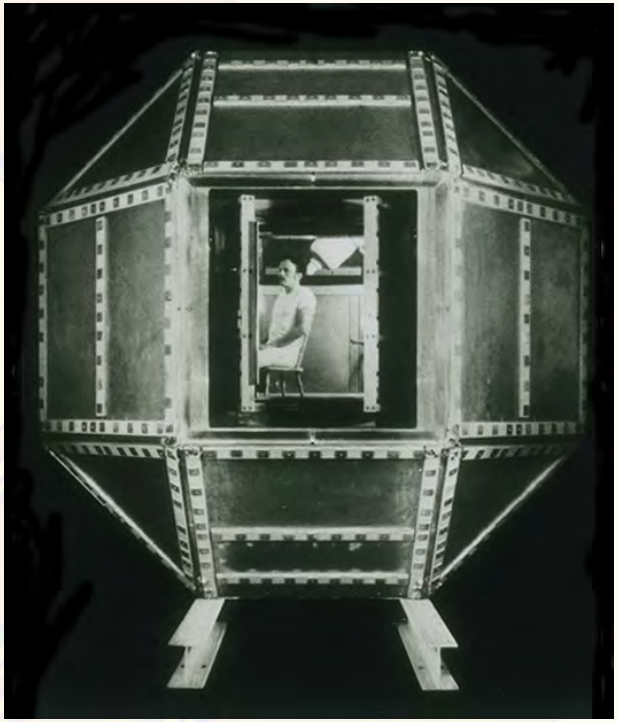




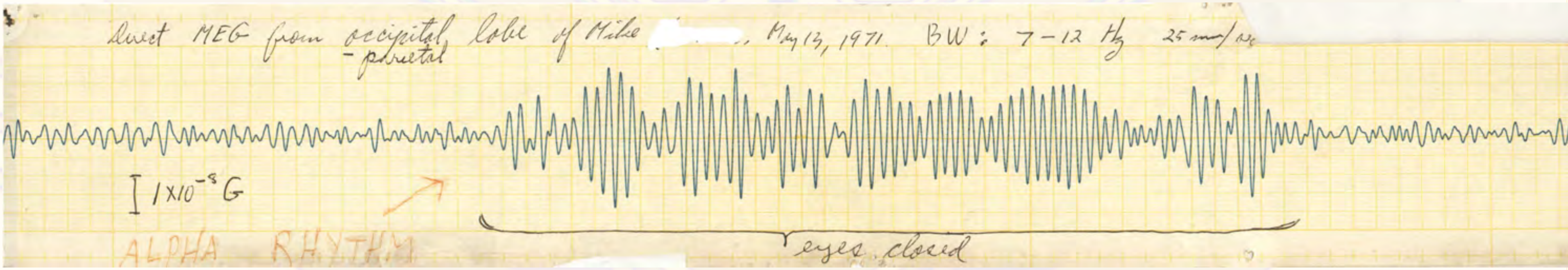
Magnetoencephalography MEG

First measurements of brain currents with a SQUID 1971 at MIT

early days for SQUID applications

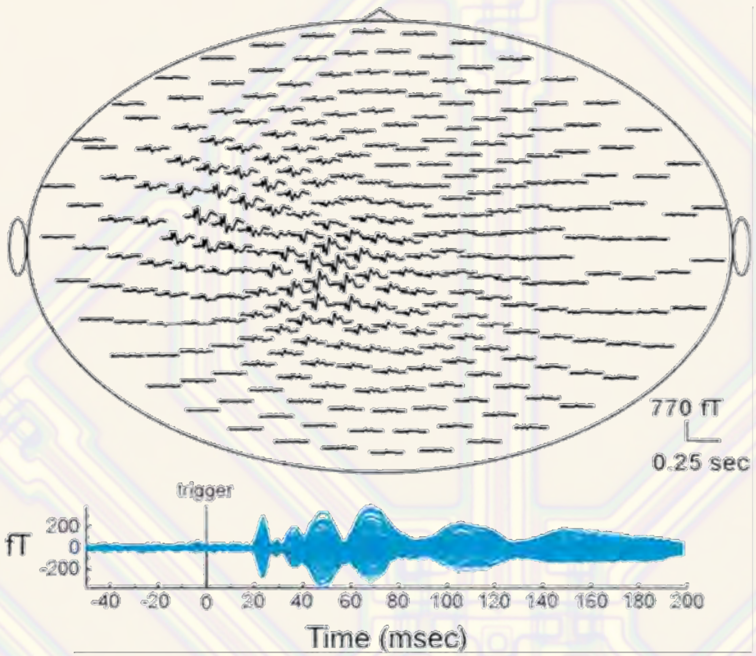


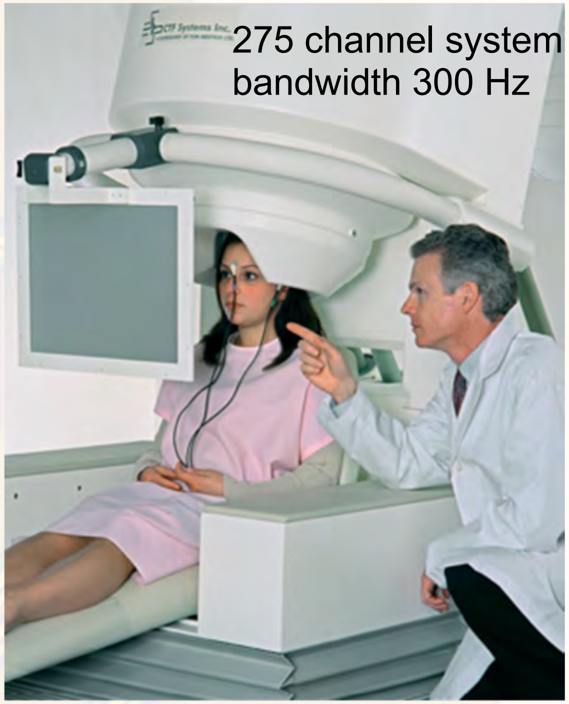
first recording



Magnetoencephalography MEG

Typical measurement





4–7 $fT/\sqrt{Hz}$ above 1 Hz

Signal reconstruction

- brain currents have caused the measured fields
- it is not possible to uniquely calculate the brain current distribution from a given field distribution
- this is known as the inverse problem of electromagnetism
- physiological model assumptions are needed to solve this problem