

## **SQUIDS IN NEURO- AND CARDIOMAGNETISM**

**Olli V. Lounasmaa**

*Low Temperature Laboratory, Helsinki University of Technology, 02015 HUT, Finland*

**Heikki Seppä**

*Measurement Technology, VTT Automation, 02015 VTT, Finland*

**Keywords:** Brain, Cardiomagnetism, Current dipole, Flux transformer, Functional magnetic resonance imaging, Heart, Imaging techniques, Josephson junction, Magnetic field, Magnetic resonance imaging, Magnetic shielding, Magnetocardiography, Magnetoencephalography, Magnetometer, Multichannel instruments, Neuro-magnetism, Pick-up coil, SQUID, superconductors

### **Contents**

1. General comments
2. Magnetoencephalography and magnetocardiography
  - 2.1. Introduction
  - 2.2. The Human Brain
  - 2.3. Analysis of MEG and MCG measurements
  - 2.4. Magnetic Shielding
3. SQUIDS
  - 3.1. Properties of Superconductors
  - 3.2. The rf SQUID
  - 3.3. The dc SQUID
  - 3.4. The Pick-up Loop and the Flux Transformer
  - 3.5. Manufacturing Technology
  - 3.6. A Modern SQUID
    - 3.6.1. General Design Features
    - 3.6.2. Description of the VTT SQUID
    - 3.6.3. The Pick-up Loops
    - 3.6.4. Design Considerations
    - 3.6.5. The Readout System
  - 3.7. Other SQUID Designs
    - 3.7.1. The PTB Design
  - 3.8. High -T<sub>c</sub> SQUIDS
4. Multichannel instrumentation for MEG
  - 4.1. The Neuromag System
  - 4.2. The CTF Systems Neuromagnetometer
  - 4.3. The Neuromagnetometer of Biomagnetic Technologies
5. Examples of MEG studies
  - 5.1. Somatosensory Responses to Finger Stimuli
  - 5.2. Dynamic Brain Activation during Picture Naming
  - 5.3. Face-sensitive Areas in the Human Brain
  - 5.4. Action Viewing
  - 5.5. Increase of Cortical Representation with Use
  - 5.6. Clinical Applications

### 5.6.1.Epilepsy

### 5.6.2.Localization of Functionally Important Cortical Areas

## 6. Cardiomagnetic studies

### 6.1.The Human Heart

### 6.2.Methods and Instrumentation in Magnetocardiography

### 6.3.Detection of Heart Abnormalities

### 6.4.Estimation of Life-threatening Arrhythmia

### 6.5.Discussion on MCG

## 7. Comparisons of MEG, MCG, EEG, ECG, PET, and fMRI

## 8. Conclusions

## Acknowledgements

## Glossary

## Bibliography

## Biographical Sketches

## Summary

In this chapter, an adequate account of the theory and practice of SQUIDs and of magnetoencephalography (MEG) and magnetocardiography (MCG) is given. MEG and MCG are two completely non-invasive imaging techniques, suitable for basic and clinical studies of human subjects. Large SQUID arrays, operating at liquid helium temperatures, are employed for detecting and localizing the magnetically active regions, modeled by current dipoles, in the working brain or heart. The measurements are usually performed in magnetically shielded rooms. Time resolution of both methods is better than 1 ms and spatial uncertainty 5 ... 6 mm. The evoked brain signals are as small as 40 fT, one billionth of the earth's geomagnetic field. The dc SQUID is discussed with a detailed description of the ideas behind and construction of the modern VTT superconducting sensor. A shorted account is given on the PTB SQUID. Commercial multi-SQUID instruments, briefly described, are now available from three manufacturers. Seven examples of brain studies, including two clinical applications, are discussed. Cardiomagnetic instrumentation is described and the use of MCG in detecting heart abnormalities is presented with three examples. The advantages and drawbacks of modern imaging techniques, including MEG, MCG, MRI, fMRI, and PET, are compared and the future of MEG and MCG is discussed. Eventually, when it becomes feasible to use high- $T_C$  SQUIDs in MEG and MCG, the high cost of magnetic measurements can be reduced.

## 1. General Comments

Activity of the brain and heart involves small electrical currents which flow in the biological tissue. These currents, in turn, produce tiny magnetic fields which can be measured outside the body, using ultra-low-noise Superconducting QUantum Interference Devices (SQUIDs). Two related techniques, magnetoencephalography (MEG) and magnetocardiography (MCG) have emerged to enable non-invasive utilization of the magnetic data. Clinical applications of both methods have evolved and further developments are in progress. MEG is sometimes called magnetic source imaging (MSI).

Exploration of the human brain is of utmost intellectual interest: The whole humanity depends on our minds. The human brain is the most complex "instrument" known in the universe. There are about  $10^{11}$  neurons in the cerebral cortex. These nerve cells are the active units in a complex network, consisting of about  $10^{14}$  interconnections or synapses. This is more than in the world's entire telephone system.

A great deal has been learned already about the cerebral anatomy and physiology, but the fundamental question of how the brain stores, retrieves, and processes information is still largely unknown. Neural computers are the future tools of designing and decision making. Recent developments in this new field of computing are one important source of inspiration to study the functional principles of the human brain, in addition to many interesting questions of basic and clinical neuroscience. For the first time it is now possible to investigate information processing in the living human brain, without philosophical speculations.

The heart is conceptually a much simpler device than the brain but, nevertheless, cardiology is a very important field of medical research. Heart diseases are the number-one cause of deaths in developed countries.

This chapter deals mainly with SQUIDS and their use in MEG studies. We naturally emphasize the MEG- and instrumentation work carried out under Riitta Hari and Olli Lounasmaa in the Low Temperature Laboratory of HUT, and the development of SQUIDS done under Heikki Seppä in VTT. A brief section towards the end describes the experimental arrangement and some results of MCG studies of the heart, emphasizing work carried out under Toivo Katila in the Laboratory of Biomedical Engineering of HUT and in the BioMag Laboratory jointly owned by HUCH and HUT.

## **2. Magnetoencephalography and Magnetocardiography**

### **2.1. Introduction**

The intracellular currents that flow through the brain's individual nerve cells (neurons) produce magnetic fields which are too small to be detected outside the head. However, when thousands of nearby cells act synchronously, the current is large enough so that the field it generates can be measured non-invasively by a SQUID magnetometer, placed outside the skull. Neuromagnetic fields are 50 ... 500 fT (femtotesla =  $10^{-15}$  T) in strength, *i.e.*, one part in  $10^9$  or  $10^8$  of the earth's geomagnetic field. Cardiac fields are about two orders of magnitude stronger.

From the measured field distribution it is possible, by making suitable assumptions, to calculate backwards the brain area which was activated by a sensory stimulus, such as a sound, a picture, or a touch. Spontaneous brain rhythms, like the 10-Hz  $\alpha$ -activity, can be investigated as well. Figure 1 shows a typical experimental situation during MEG recordings.

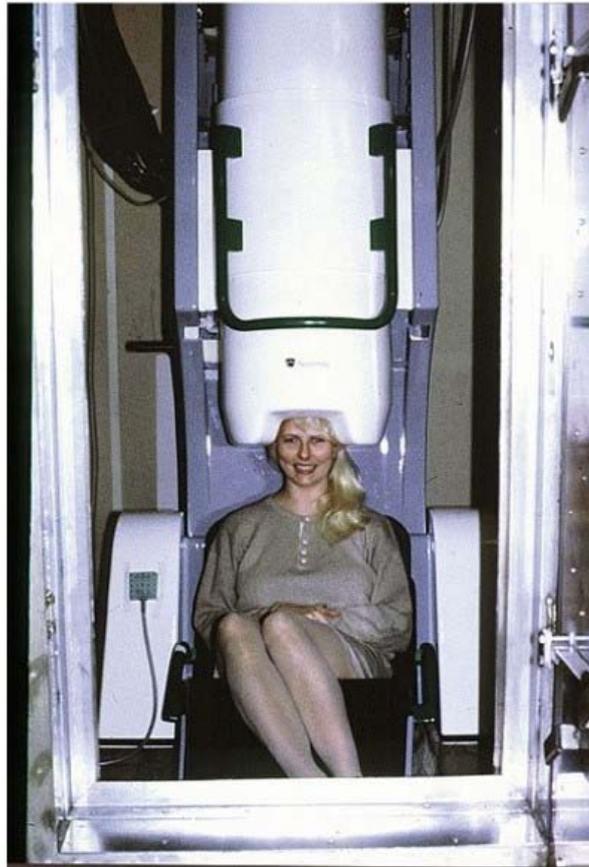


Figure 1. The first whole-head MEG instrument, installed to the Low Temperature Laboratory at HUT. During actual measurements the double doors to the shielded room must be tightly closed. The concave, helmet shaped bottom of the helium dewar, with the flux transformer coils near its tip, is brought as close as possible to the subject's head. The 122 SQUIDS in this prototype instrument were manufactured by the IBM Company of Yorktown Heights, NY.

Magnetoencephalography and magnetocardiography are fully based on the SQUID which is a superconducting ring interrupted by one or two Josephson junctions. Phase coherence of charge carriers in a superconductor gives rise to flux quantization in the SQUID ring. Owing to the smallness of the flux quantum, about  $2.07 \text{ fWb}$ , the SQUID can be made into a very sensitive parametric amplifier.

Pioneers in the MEG field are James Zimmerman, the inventor of the practical SQUID in 1970, David Cohen who, with Zimmerman, first detected magnetic brain signals, and Samuel Williamson whose group did much of the earlier work. At present, about 100 laboratories worldwide are engaged in magnetoencephalographic studies of the human brain; some of the interdisciplinary teams consist of a dozen or more researchers, including physiologists, physicists, psychologists, linguists, and information scientists. Comprehensive reviews of the MEG technique and of experimental data are available (see Bibliography). The state-of-the-art in biomagnetism is reflected in the proceedings of the biennial International Conferences on Biomagnetism.

## 2.2. The Human Brain

In MEG, one is usually concerned with the uppermost layer of the brain, the cerebral cortex, which is a 2 ... 4 mm thick sheet of gray tissue, consisting of complexly interwoven neuronal networks. Both hemispheres of the brain, the left and the right, are subdivided by deep fissures into four lobes: frontal, parietal, temporal, and occipital (see Figure 2).

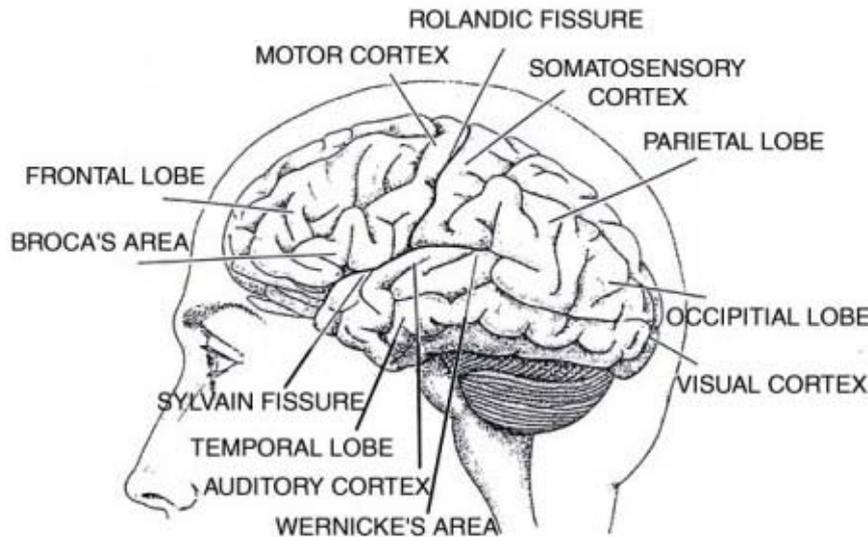


Figure 2. Illustration of the cerebral cortex from the left side.

Most regions of the cerebral cortex have been mapped functionally in animals and also in man during brain surgery. The area just in front of the nearly vertical Rolandic (= central) fissure, in the frontal lobe, is the motor cortex, concerned with control and integration of muscular activity. Behind this fissure, in the parietal lobe, the primary somatic sensory cortex is located. This structure is involved with the reception and analysis of information from the skin, joints, and muscles. The left and right auditory cortices, in the temporal lobes, are largely buried within the Sylvian fissures. The primary visual cortex is in the occipital lobe at the back of the head. Wernicke's and Broca's areas, which are important for the analysis and production of speech, are also indicated in Figure 2. Most of the remaining cortical regions are known as association areas where inputs from several sensory modalities are integrated.

Signals in the brain are processed by neurons, which communicate with each other via weak electrical impulses. The neurons are able to generate so-called action potentials, which are voltage pulses of about 100 mV that last for about 1 ms. Action potentials travel along axons, the long branches of individual neurons. When the pulse reaches a synapse where two neurons meet, it causes the release of chemical neurotransmitters that trigger a postsynaptic current in the next neuron. This allows transmission of inter-neuronal currents to continue through the brain.

Five parameters are employed to characterize the current dipole that is used to explain MEG data: three for the dipole's position in 3-D space, one for its orientation, and one for its strength. Just one parameter is needed to characterize the orientation, because

only currents that are tangential to the nearest point on the surface of the brain produce external magnetic fields. Contributions from all other currents cancel each other out because the brain is approximately spherically symmetric. This means that MEG signals arise mainly from the walls of the fissures in the cortex, where the neurons are aligned in such a way that currents through them are parallel to the nearest surface of the head. Typical dipole moments (current  $\times$  length of the dipole) encountered after sound stimuli, for example, are on the order of 5 ... 50 nAm. Since the effective current only flows over a distance of about 1 mm in the cortex, these dipole strengths are associated with currents of about 10  $\mu$ A.

### 2.3. Analysis of MEG and MCG measurements

Owing to spontaneous brain activity and incoherent "noise", individual signals resulting from 20 to 500 successive sensory stimuli are usually averaged. In this way the evoked response, for example after "beeps" of sound, emerges from the background. To collect enough data for calculating the magnetic field distribution, measurements must be made at many, typically at 50 to 100 different locations. In earlier MEG experiments this was done sequentially, over one or a few sites at a time. This was a slow procedure which also endangered the reliability of the data: The subject could not be expected to remain in the same state of vigilance throughout a long measurement session. Now this "human" problem has been overcome by the use of neuromagnetometers covering simultaneously the whole head (see section 4).

Figure 3 shows, at left, a typical magnetic signal evoked in the auditory cortex by 50-ms tones presented to the subject's left ear. The field gradient, in fT/cm, is plotted as a function of time. By combining such signals from many locations, a computer can calculate the magnetic field distribution shown at right. The active region in the brain, underneath the center of the red arrow, may be determined from this type of data. The field pattern varies with time because the activated region in the cortex changes.

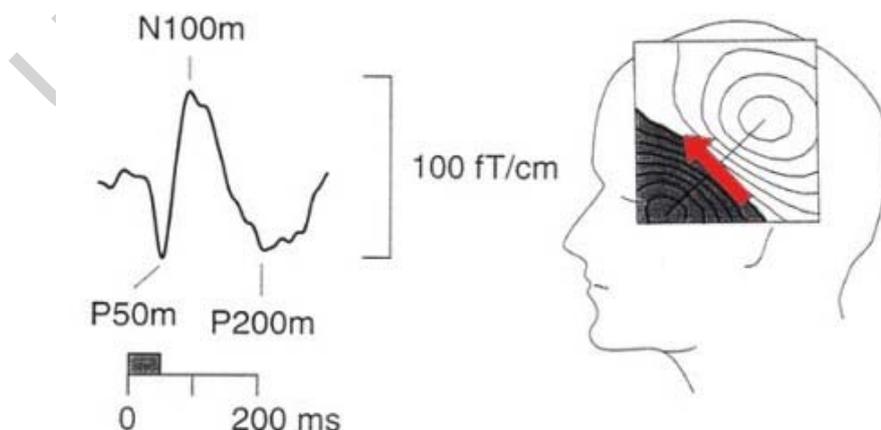


Figure 3. *Left:* Typical magnetic response from the brain as a function of time; the N- and P-numbers refer to latencies in milliseconds after the stimulus was given. *Right:* Topographic map of the magnetic field gradient from which the active cortical area (center of the red arrow) can be determined. Gray indicates field out of the head and white into.

In interpreting MEG data, one is dealing with the electromagnetic inverse problem, *i.e.*, with the calculation of the source currents responsible for the externally measured magnetic field. The inverse problem has no unique solution. One must, therefore, use a suitable source model to interpret the data. When the neural currents are confined to a small region in the cortex one may assume that, looking from the outside, the source is a current dipole. The magnitude, direction, and position of the active brain area can then be deduced unambiguously with a least-squares fit of the experimental data as shown on the right side of Figure 3. The dipole lies in the middle of the two field extrema, at a 90° angle to the line joining them.

## 2.4. Magnetic Shielding

Since biomagnetic signals are small, rejection of all external disturbances is of extreme importance. Other body parts also generate signals. For example, the heart's magnetic field on the chest is two to three orders of magnitude larger than the brain signals just outside the head. The vulnerability of the system to external magnetic noise can be reduced greatly by a gradiometric design of the superconducting flux transformer which gathers the magnetic signal and transmits it to the SQUID. Two configurations are in common use (see Section 3.4): a flat figure-of-eight geometry and two axial but oppositely wound coils in series. Both loop systems are insensitive to spatially uniform background fields but respond to changes in an inhomogeneous field as generated by the nearby brain.

In addition, MEG experiments are usually carried out inside a magnetically shielded room, which in the LTL at HUT employs for noise reduction two layers of aluminum, that attenuate very effectively the high frequency band of the external magnetic disturbances, and two layers of mu-metal for rejection of noise at low frequencies. In addition, the magnetic field entering the outer mu-metal shield is detected by demagnetization coils. A controller and Helmholtz-type feedback coils outside the room are employed to compensate for low frequency magnetic fields. There is also a special feedback circuit to cancel the 50 Hz magnetic field.

## 3. SQUIDS

Since the late 1960's, SQUIDS have been familiar devices in most low temperature laboratories. Multi-SQUID applications, however, have materialized only after 1980, owing to the slow progress in fabrication technology and small demand. Today, reliable and stable thin-film Josephson circuits can be manufactured in large quantities. The cost of one complete sensor unit, including the dc SQUID and the pick-up loop, is about \$ 150, but the price will be reduced to \$ 50 if production is markedly increased.

### 3.1. Properties of Superconductors

Phase coherence of charge carriers in a superconductor gives rise to quantization in the SQUID ring: the total magnetic flux threading the loop must be an integral multiple of the so-called flux quantum,  $\Phi_0 = h/2e = 2.07$  fWb. Owing to the smallness of  $\Phi_0$ , the SQUID can be made into a very sensitive device for measuring magnetic fields. A flux

noise below  $10^{-5} \Phi_0 \text{Hz}^{-1/2}$  in the frequency band of interest is necessary for a dc SQUID to be used in a state-of-the-art neuromagnetometer. Moreover, a flat noise spectrum down to well below 1 Hz, *i.e.*, a low  $1/f$  noise, is required for recordings of brain signals.

If two superconducting electrodes are put within tunneling distance from each other, separated by an insulating layer, a supercurrent can flow through the barrier without voltage generation. The Josephson junction is characterized by a critical current  $I_c$ , which is the highest current that does not produce a voltage drop across the junction. Brian Josephson showed in 1962 that the current through a weak junction is a periodic function of the phase shift between the quantum mechanical wave functions on both sides of the barrier. By interrupting a superconducting loop with one or two such junctions, the quantum phase shift and thus the maximum voltageless current can be controlled by the magnetic field threading the loop.

There are several ways to accomplish a flux detector based on Josephson junctions, but only the rf and dc SQUIDS will be discussed here.

### 3.2. The rf SQUID

The first practical rf SQUID magnetometer, consisting of one Josephson junction, was introduced in the late 1960's by James Zimmerman. The dc SQUID is a superconducting ring interrupted by two Josephson junctions. For operation, the sensors are kept at 4.2 K, the boiling point of liquid helium. SQUIDS made of high- $T_c$  materials work at liquid nitrogen temperatures.

When a radio frequency flux is superimposed, via a tank circuit, on the low frequency flux threading the superconducting ring, dissipation in the system becomes proportional to the signal flux. This is because the phase of the sinusoidal pump signal, at the moment when the Josephson junction is switched to its resistive state, depends on the low frequency flux. By monitoring the amplitude of the rf signal across the tank circuit, the applied flux can be measured. Since the change in the voltage amplitude of the tank circuit is reasonably high, several hundreds of microvolts per flux quantum, this so called hysteretic rf SQUID became the first practical SQUID magnetometer. Owing to its complicated readout electronics the rf SQUID is no longer used in commercial neuromagnetometers.

(see *Magnetic Fields*)

### 3.3. The dc SQUID

Two Josephson junctions set in parallel via a small superconducting ring double the critical current  $I_c$ . An external magnetic flux generates a phase shift in the macroscopic wave function in the ring portion connecting the junctions. The total phase shift along the closed path around the ring has to be a multiple of  $2\pi$ , and thus the flux in the ring modifies the phase shift across the two junctions and the critical currents accordingly. If a current bias is set just above  $2I_c$ , the voltage across the junctions is close to zero in a fluxless ring, but an increasing flux decreases the effective critical current and thus also

the voltage. By imposing a small voltage across the junctions, the current through the device varies from zero to  $2I_c$  while the flux is increased.

The interference pattern in a ring with two junctions was first demonstrated in 1965. As an example, Figure 4a shows the current-voltage characteristics of a dc SQUID for three different applied fluxes. The current in a voltage biased SQUID, as a function of the external magnetic field, is illustrated in Figure 4b.

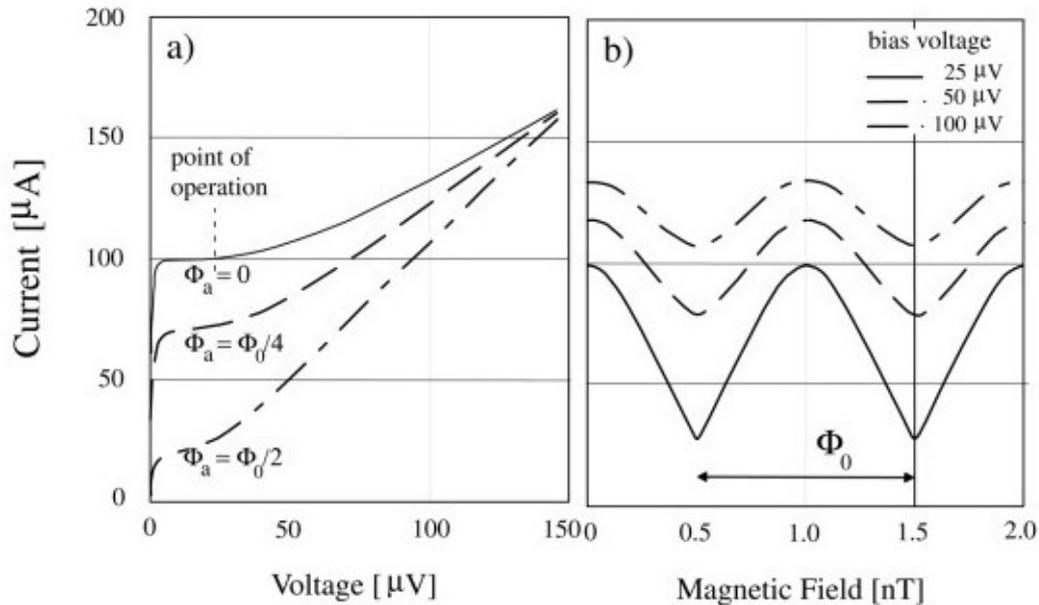


Figure 4. (a) Current-voltage characteristics of a dc SQUID for three different applied fluxes. The solid line represents the external flux value  $\Phi_a = 0$ ; the dashed line,  $\Phi_a = \Phi_0/4$ ; and the dash-dotted line,  $\Phi_a = \Phi_0/2$ . (b) SQUID's output current as a function of the external magnetic field for three different bias voltages. The solid line indicates the periodic response for the optimal point of operation ( $U = 25 \mu\text{V}$ ). The dashed line represents the voltage value,  $U = 50 \mu\text{V}$ , and the dash-dotted line,  $U = 100 \mu\text{V}$ . In this example, 1 nT corresponds to one flux quantum and thus the maximum sensitivity of the magnetometer is  $200 \mu\text{A/nT}$ .

Noise in a SQUID is related to the thermal noise from shunt resistors set in parallel with the Josephson junctions; the resistors are needed in order to stabilize the system. The optimization of the energy resolution and the intrinsic flux noise leads to an extremely low loop inductance. Therefore, in a practical low noise SQUID, the loop sizes range from  $4 \mu\text{m}^2$  to  $25 \mu\text{m}^2$ . Such a tiny loop is too small for detecting weak magnetic fields and thus flux transformers must be used to pick-up the signal from a much larger area. (see *Application of Measurements and Instrumentation*) (see section 3.4)

### 3.4. The Pick-up Loop and the Flux Transformer

Owing to quantization of the flux in a superconducting ring, a closed loop can be used to pick-up the magnetic field from a large area, close to signal sources, and to transfer it into the SQUID ring. A multiloop signal coil wound around the SQUID compresses the

magnetic field into the SQUID ring. The supercurrent induced by the applied field is inversely proportional to the inductance of the flux transformer and thus the signal coil inductance, *i.e.*, the number of turns, should be as small as possible. On the contrary, high mutual inductance between the signal coil and the SQUID ring maximizes the flux threading the SQUID ring and thus a compromise is necessary. A simple calculation shows that inductance matching between the pick-up loop and the signal coil maximizes the transfer efficiency to convert magnetic field to flux in the SQUID ring.

There is variety of ways to accomplish a pick-up loop. High inductance is realized by using a multiloop configuration but connecting the loops in parallel leads to low inductance. Since the SQUID inductance is very small, the signal coil is made of several turns in series, in order to secure a high signal coil inductance.

The pick-up coil can be a single loop sensing homogenous magnetic field or it may comprise of two or more loops in series but in opposite directions sensing thus only gradients of the field. Gradiometers are easier to operate in a noisy environment, because the rapid decay of the gradient field as a function of distance makes the sensor most sensitive to nearby source currents, provided that the gradiometers are balanced sufficiently well. Immunity to external noise sources can further be improved by using a pick-up unit comprising of three separate coils. This arrangement leads to a second order gradiometer which is insensitive not only to the homogenous field but also to its gradient. Higher order gradiometers are employed in biomagnetic studies which are performed in unshielded environments. Magnetometers, on the other hand, are good for extracting information about deep sources but they unavoidably respond to distant noise sources, too.

Several possibilities of arranging magnetometers and first order gradiometers are shown in Figure 5. The tangential and planar gradiometers can be integrated on a silicon chip but the axial configuration requires a flexible board or it can be made of a superconducting wire.

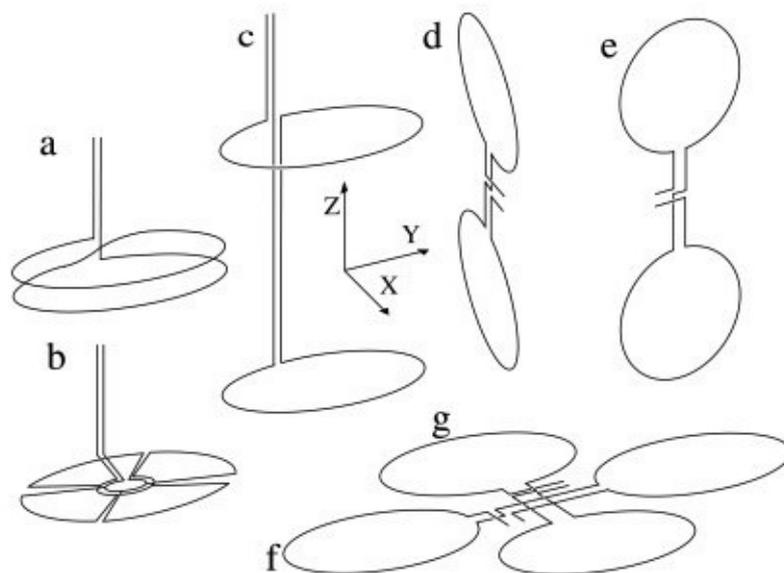


Figure 5. Different types of pick-up coils. (a) Simple multi-turn pick-up loop with high output inductance and sensitive to the homogenous magnetic field  $B_z$ . (b) Magnetometer with low output inductance composed of several sub-loops set in parallel. (c) Axial gradiometer which measures  $\partial B_z / \partial z$ . (d and e) Two tangential gradiometers that measure the vertical gradient of the magnetic field,  $\partial B_y / \partial z$  and  $\partial B_x / \partial z$ , respectively. (f and g) Planar gradiometers responding to two gradients of the field,  $\partial B_z / \partial y$  and  $\partial B_z / \partial x$ , respectively. In gradiometric sensing coils the distance between the loops (baseline) should be close to that from the source but is smaller in practice, at least in integrated gradiometers.

TO ACCESS ALL THE 37 PAGES OF THIS CHAPTER,  
Visit: <http://www.eolss.net/Eolss-sampleAllChapter.aspx>

### Bibliography

Andrä W. and Nowak H., Editors (1998). *Magnetism in Medicine*. 511 pp. Berlin: Wiley-VCH. [Discusses all uses of magnetism in medical practice and research, including SQUIDS, MEG, MCG, MRI and fMRI]

Hämäläinen M., Hari R., Ilmoniemi R.J., Knuutila J. and Lounasmaa O.V. (1993). *Magnetoencephalography – Theory, Instrumentation and Applications to Noninvasive Studies of the Working Human Brain*. *Reviews of Modern Physics* **65**, 413-497. [A comprehensive treatment of MEG]

Hämäläinen M. and Nenonen J. (1999). *Magnetic Source Imaging*. *Encyclopedia of Electrical Engineering* **12**. Webster, J., Editor. 133-148 pp. New York: Wiley and Sons [A recent overview of source imaging techniques in MEG and MCG].

Hari R. and Salmelin R. (1997). *Human Cortical Oscillations: A Neuromagnetic View through the Skull*. *Trends in Neuroscience* **20**, 44-49. [Review of MEG measurements on rhythmic oscillations generated in the human brain]

Lounasmaa O.V. (1996). *Medical Applications of SQUIDS in Neuro- and Cardiomagnetism*. *Physica Scripta* **T66**, 70-79; Lounasmaa O.V., Hämäläinen M., Hari R. and Salmelin, R. (1996). *Information Processing in the Human Brain: Magnetoencephalographic Approach*. *Proceedings of the National Academy of Sciences of the USA* **93**, 8809-8815; Hari R. and Lounasmaa O.V. (2000). *Neuromagnetism: Tracking the Dynamics of the Brain*. *Physics World* **13**, 33-38. [The present paper uses liberally material from these publications]

Nenonen J., Montonen, J. and Mäkijärvi M. (2000). *Principles of Magnetocardiographic Mapping. Cardiac Mapping*, Shenasa M., Borggreffe M. and Breithardt G., Editors. Mount Kisco, NY: Futura Publishing Co. [Short review of MCG mapping to be published in 2000]

Nicholls J.G., Martin A.R. and Wallace B.G. (1992). *From Neuron to Brain*. 805 pp. Sunderland: Sinauer Associates. [An excellent text on the human brain]

Ryhänen T., Seppä H., Ilmoniemi R. and Knuutila, J. (1989). *SQUID Magnetometers for Low Frequency Applications*. *Journal of Low Temperature Physics* **76**, 287-386. [Comprehensive review of SQUIDS]

describing their fabrication, electronics and operation, as well as the use of SQUIDS in several applications]

Williamson S.J., Romani G.-L., Kaufman L. and Modena I., Editors (1983). *Biomagnetism – An Interdisciplinary Approach*. 706 pp. New York: Plenum Press. [This book treats in detail all basic aspects of biomagnetism but is now partly outdated]

Yoshimoto, T., Kotani, M., Kuriki, S., Karibe, H. and Nakasato, N. (1999). *Recent Advances in Biomagnetism – Proceedings of the 11th International Conference in Biomagnetism*. 1161 pp. Sendai: Tohoku University Press. [Short papers on recent advances in MEG and MCG]

### **Biographical Sketches**

**Olli Viktor Lounasmaa** (OVL) obtained his D.Phil. degree at the University of Oxford in 1958. He then worked four years at the Argonne National Laboratory in the US. In 1965 he was appointed Professor of Technical Physics at the Helsinki University of Technology (HUT) where he founded the Low Temperature Laboratory (LTL). In 1970 he was appointed Professor of the Academy of Finland but continued his work at HUT until his retirement in January 1996. In the LTL, his research has been on superfluid  $^3\text{He}$  in the millikelvin region and on nuclear ordering in several metals at positive and negative temperatures in the nano- and picokelvin regions of temperature. SQUIDS were developed and used extensively in the LTL for thermometry at ultralow temperatures. Brain research, especially the development of multichannel instrumentation, has been OVL's secondary field of interest since 1980. In 1987, a 7-channel neuromagnetometer became ready for MEG measurements in the LTL. Studies of evoked responses to acoustic, somatosensory, and visual stimuli were then made under Academy Professor Riitta Hari, MD; later her work was extended to investigations of cognitive brain functions and clinical applications. OVL participated in some of this research. In 1982 the first neuromagnetometer covering the whole scalp became available with 122 SQUID sensors. In 1998, the Finnish company Neuromag Ltd. inaugurated its Vectorview<sup>TM</sup> instrument with 306 sensors, constructed in collaboration with the LTL. Twelve of these neuromagnetometers had been sold abroad by mid-2000. OVL is a Foreign Member of the Royal Swedish Academy of Sciences and of the National Academy of Sciences of the USA. He is also the recipient of the Kapitza Gold Medal of the Russian Academy of Sciences and of numerous domestic and international prizes. He has an Honorary Degree of Medicine from the University of Helsinki.

**Heikki Seppä** obtained his Ph.D. degree in technology from the Helsinki University of Technology (Espoo, Finland) in 1989. From 1976 to 1979, he was an assistant at HUT, working in the area of electrical metrology. He joined the Technical Research Centre of Finland (VTT) in 1979 and since 1989 he has been working there as a Research Professor. In 1994 he was appointed Head of the Measurement Technology Laboratory which is part of VTT Automation. During 1996 ... 98 he was acting as the Director of VTT Automation. Besides his research work, Heikki Seppä has developed several measurement apparatuses and sensors for industry, e.g., dc SQUIDS and readout electronics used by Neuromag Ltd in the Vectorview<sup>TM</sup> system. He is the recipient of several domestic prizes and has discovered numerous patented inventions. He has done research work on electrical metrology, in general, and on superconducting devices for measurement applications, in particular. Heikki Seppä has developed most of the standards used to realise and maintain electrical units in Finland. He is currently doing and directing research on dc SQUIDS, Josephson circuits, quantized Hall effect, and rf instruments. Recently, his work has been focused on mesoscopic systems and micromechanical devices.