Magnetic field measurements using very sensitive SQUIDs

V. Schultze(1), R. Stolz(2), V. Zakosarenko(2), A. Chwala(2), L. Fritzsch(2), R. IJsselsteijn(2), N. Oukhanski(2), M. Schulz(2), and H.-G. Meyer(2)

(1) Institute for Physical High Technology, Dept. of Quantum Electronics, http://www.cryo-jena.de, Winzerlaer Str.10, D-07745 Jena, Germany, E-mail: schultze@ipht-jena.de
(2) As (1) above, but E-mail: stolz@ipht-jena.de, zakosarenko@ipht-jena.de, chwala@ipht-jena.de, fritzsch@ipht-jena.de, ijsselsteijn@ipht-jena.de, ukhansky@ipht-jena.de, marco.schulz@ipht-jena.de, meyer@ipht-jena.de

ABSTRACT

SQUID systems, using either high temperature or low temperature superconductors, were developed for sensitive measurements in magnetically disturbed environments. They include the SQUIDs and fast SQUID electronics. Magnetometer SQUID systems are used for geophysical sounding, where they show superiority when compared to conventional induction coils for very deep sounding or fast measurement. Highly balanced 1st order gradiometer SQUID systems employed for the mapping of the earth's magnetic field can resolve archaeological sites with extremely high quality. By using gradiometers of 2nd order, even in normal laboratory environment, excellent human Magneto Cardiograms can be recorded.

INTRODUCTION

Superconducting Quantum Interference Devices (SQUIDs) are the most sensitive magnetic field sensors. The ultimate sensitivity is reached with low temperature superconductor (Low-T_c) SQUIDs working in liquid helium at a temperature of 4.2 K. However, because liquid nitrogen is the cheaper and more easily accessible and manageable coolant, for some applications it is also interesting to use high temperature superconductor (High-T_c) SQUIDs working at 77 K, especially when the intrinsic SQUID sensitivity is not a crucial parameter of the system.

Besides some exclusive applications, the main fields for SQUIDs are the detection of biomagnetic and geomagnetic signals and material inspection. Here, we report on the development of SQUID systems – both Low-T_c and High-T_c – at the Institute for Physical High Technology (IPHT) in Jena for measurements without magnetic shielding. This covers primarily geomagnetic prospection, but also biomagnetic measurements in realistic technical environments.

A big challenge of such applications is to make the SQUID systems robust against the many possible large disturbances whilst still retaining their ultimate sensitivity. This also applies to the very fast and low noise SQUID electronics with large dynamic range. When the magnetic field sources to be investigated are not too far away it is favourable to layout the SQUID sensors as gradiometers of first or second order instead of magnetometers. The gradiometer layout allows for a significant suppression of the interfering signals from distant magnetic sources. Here, the performance parameter is the gradiometer balance which depends on all system components. The layout of the complete SQUID system and the choice of either High-T_c or Low-T_c SQUIDs is dependent upon the particular application.

After a short description of the used SQUIDs we will report on some interesting applications of our SQUID systems.

SQUID SYSTEM COMPONENTS

High-T_c SQUIDs

The fabrication of High-T_C multilayer structures is still a challenge. Therefore, the highly sensitive SQUID sensors are often assembled from the SQUID itself and a flux transformer. They use different chips which are flipped together. The flux transformer consists of a large pickup loop for magnetic fields and an incorporated coupling coil. This coil is in the flip chip package positioned face to face against the SQUID.

The fabrication processes of single layer SQUIDs and multilayer flux transformers are described in detail elsewhere [1-3]. All SQUIDs are prepared on $SrTiO_3$ bicrystal substrates with 30° misorientation angle. The $YBa_2Cu_3O_{7-x}$ films are 200 nm thick. Josephson junction width is 2 µm. Multilayer flux transformers use two YBCO films isolated by a 100 nm $SrTiO_3$ film. The pickup loop area is 8 mm x 8 mm.

The SQUIDs are encapsulated together with a thick-film heater in order to expel any magnetic flux which may have penetrated the superconductor.

The noise limited magnetic field resolution of these magnetometer SQUIDs outside any shielding is 30 fT/√Hz in the white noise range. Below about 1 kHz the noise rises and reaches about 1 pT/√Hz at 1 Hz.

Low-T$_c$ SQUIDs

The Low-T$_c$ family of the IPHT covers a wide spectrum of magnetometers and gradiometers. They are produced with a nine-layer Nb/AlO$_x$/Nb technology. The technology and SQUID configurations are described elsewhere [4,5].
The basic component is a current sensor that measures the current of any external source. The current resolution can be < 1 pA/√Hz. In most cases the measured current is generated in pickup loops with various configurations. For example, a SQUID magnetometer with an on chip pickup loop of 7.5 mm x 7.5 mm shows a noise limited magnetic field resolution of less than 2 fT/√Hz down to frequencies below 1 Hz.
The integration of gradiometer pickup loops and a current-sensor SQUID on one large substrate results in good field gradient resolution and a high gradiometer balance. Here, the SQUID itself is made as a symmetrical structure, insensitive to external homogeneous magnetic fields. Therefore, the sensitivity is determined only by the pickup loop configuration. A gradiometer with two pickup loops of 2 cm x 2 cm on a substrate of 2 cm x 6 cm (a base length of 4 cm) shows a field gradient resolution of better than 50 fT/(m·√Hz) in the white noise range. The onset of low frequency noise is below 1 Hz.

SQUID Electronics

In order to take advantage of the ultimate sensitivity of the SQUIDs even in the presence of large and fast disturbances it is necessary to have a fast SQUID electronics with low noise and large dynamic range. This electronics is described in [6]. In particular it uses a specially designed preamplifier with extremely low thermal drift (30 nV/K) and low input noise (0.33 nV/√Hz). For magnetically unshielded SQUID operation a large bandwidth (6 MHz), large dynamic range (> 150 dB), and high slew-rate (3 MΦ_0/s) are crucial.

APPLICATIONS

Geomagnetic Prospection

We set up a SQUID system with High-T$_c$ SQUIDs for geophysical sounding. In the method used – the Transient Electromagnetics (TEM) - a bipolar square wave current in a large transmitter loop, laying on the surface of the earth, generates a primary field with an amplitude of about 100 nT perpendicular to the soil. The fast switching off of the primary field generates eddy currents in the ground. Their decay depends on the earth's conductivity, which can be used to detect minerals in the ground. During the current-off periods the weak secondary fields down to some pT or below, generated by the eddy currents, are measured.

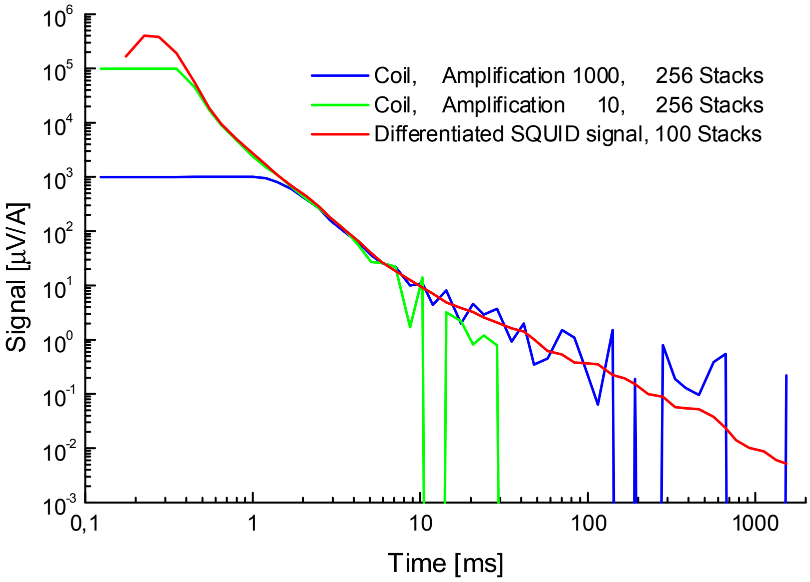

Fig. 1. Secondary field of a TEM transient measured with coil and SQUID, respectively. For the purpose of comparison, the SQUID signal is differentiated.

The method, our setup and results are described in more detail in [7-9]. Comparisons of our highly compact SQUID TEM system with conventional ones, using induction coils as magnetic field sensors, showed a clear superiority of the SQUIDs at low frequencies (or for large elapsed times). There are three big advantages of SQUIDs. Firstly, the decay of the field transient directly measured by the SQUID is slower than the voltage decay across a receiving coil detecting the time derivative of the magnetic field . Secondly, SQUIDs have a higher field resolution in the low frequency region. Therefore, – most importantly – the noise of the SQUID system is much lower for a large elapsed time, as shown in Fig. 1. Because these late times (or low frequencies) are connected to large depths via the skin effect, it is possible to increase the investigation depth by a factor of more than 3. Or in other words, for the same quality of averaged data as that measured with conventional coils, it is possible to reduce the measurement duration by a factor of 25-100 as compared to conventional coils.

And thirdly, because of the slower decay of the transient the SQUIDs need less dynamic range. Thus, the SQUID systems can cover the full time scale (see Fig. 1), whereas coils need two different amplifications.

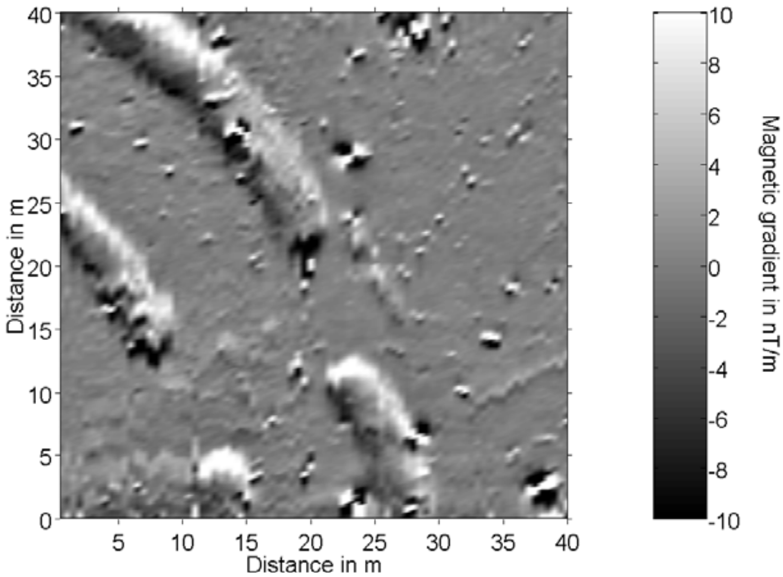

Fig. 2. Mapping of a part of a Neolithic double-ring ditch with a gate in Niederzimmern near Weimar, Germany. The horizontal line spacing is 0.5 m. Vertically the points are separated by 20 cm.

Archaeometry

In geomagnetic archaeometry anomalies of the earth's magnetic field caused by magnetic materials are of interest. Archaeologically interesting objects lie about 0.5-2 m beneath the soil. The mapping of the earth's magnetic field near the surface is a proven method in archaeometry. Currently, caesium vapour magnetometers are widely used, which show good magnetic field resolution, but have a limited sampling frequency which hinders the mapping of large areas in a reasonable time. Therefore, SQUID systems with large bandwidth are of great interest. They are described in [10].

Because the magnetic field sources are not so deep, a first order gradiometer is preferable. This is also necessary for the suppression of the large disturbances caused by the movement of the SQUID system in the earth's homogeneous magnetic field. An integration of gradiometer pickup loop with the low-T_c current-sensor SQUID together on one large substrate gives extremely good field gradient resolution. Because of the highly symmetrical layout this gradiometer has already an intrinsic balance of 5×10^4. This balance was further enhanced by two orders of magnitude by electronically subtracting the weighted signals of three orthogonal SQUID magnetometers. This good balance in connection with the high sensitivity makes it possible to detect archaeological structures with a much better resolution than ever before possible. In Fig. 2 a measurement is shown; a part of a Neolithic double ring ditch. What can be seen are the residues of rotten organic materials which fills the ancient structures, which have slightly different magnetization than the surrounding.

Long Time Magnetic Field Measurements

A long measurement was performed in the Laboratoire Souterrain á Bas Bruit (LSBB) in France near Avignon [11]. The main capsule where the measurements were performed is a Faraday cage of soft iron formed as a tube with an 8 m diameter and a 28 m length, located 1500 m inside and 450 m below the top of a mountain. In this case, the low-T_c SQUID system consisted of three orthogonal magnetometers with sensitivity better than $2.5\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ and one of the above described planar first order gradiometers. Because of their ultimate sensitivity maintained also in the earth's magnetic field, during these measurements an earthquake in India, transformed into a magnetic signal by the shaking of the 20 tonne measurement capsule, was detected.

Biomagnetic Measurements

A quite promising application of SQUID gradiometers with high balance is the measurement of magnetic fields of a human body, *e.g.* Magneto Cardiograms (MCGs), in normal clinical environments, without the need for large and expensive magnetic shielding chambers. In such technical environments with many electrical devices the disturbances are relatively close to the SQUID system, thus producing disturbing magnetic fields as well as gradients. Therefore, these interfering signals have strong 1^{st} order gradients, which are detected by our gradiometer (see Fig. 3 upper part). A setup with two first order SQUID gradiometers, as described above, forming a second order gradiometer solved this problem (middle part of Fig. 3). Now MCGs with a relatively good resolution, showing all details, could be recorded in a technical environment even on-line, i.e. without averaging. A three axis magnetometer was used for software balance improvement. Averaging of course still can be used to improve the quality further (Fig. 3 lower part).

SUMMARY

Complete SQUID systems consisting of highly sensitive SQUID magnetometers and gradiometers, adapted to operating with large disturbances, and fast SQUID electronics with large dynamic range, were developed. They are well suited to sensitive measurements outside magnetic shielding, for example biomagnetic measurements, geomagnetic prospection for the detection of mineral resources, or the mapping of the earth's magnetic field for archaeometry.

REFERENCES

[1] R. IJsselsteijn, H. Elsner, W. Morgenroth, V. Schultze, and H. G. Meyer, "Bicrystal submicrometer Josephson junctions and dc SQUIDs," *IEEE Trans. Appl. Supercond.,* vol. 9, pp. 3933-3936, 1999.

[2] J. Ramos, A. Chwala, R. IJsselsteijn, R. Stolz, V. Zakosarenko, V. Schultze, H. E. Hoenig, H. G. Meyer, J. Beyer, and D. Drung, "Low-noise Y-Ba-Cu-O flip-chip dc SQUID magnetometers," *IEEE Trans. Appl. Supercond.,* vol. 9, pp. 3392-3395, 1999.

[3] J. Ramos, V. Zakosarenko, R. IJsselsteijn, V. Schultze, and H. G. Meyer, "Mutual inductance and noise of high-T-c SQUIDS with flip- chip and integrated input coils,". *IEEE Trans. Appl. Supercond.,* vol. 11, pp. 1118-1121, 2001.

[4] R. Stolz, L. Fritzsch, and H. G. Meyer, "LTS SQUID sensor with a new configuration," *Supercond. Sci. Technol.,* vol. 12, pp. 806-808, 1999.

[5] R. Stolz, V. M. Zakosarenko, L. Fritzsch, N. Oukhanski, and H. G. Meyer, "Long baseline thin film SQUID gradiometers," *IEEE Trans. Appl. Supercond,.* Vol. 11, pp. 1257-1260, 2001.

[6] N. Oukhanski, R. Stolz, V. Zakosarenko, and H. G. Meyer, "Low-drift broadband directly coupled dc SQUID read-out electronics," *Physica C,* vol. 368, pp. 166-170, 2002.

[7] A. Chwala, R. Stolz, J. Ramos, V. Schultze, H. G. Meyer, and D. Kretzschmar, "An HTS dc SQUID system for geomagnetic prospection," *Supercond. Sci. Technol.,* vol. 12, pp. 1036-1038, 1999.

[8] A. Chwala, V. Schultze, R. Stolz, J. Ramos, R. IJsselsteijn, H. G. Meyer, and D. Kretzschmar, "An HTS dc SQUID system in competition with induction coils for TEM applications," *Physica C,* vol. 354, pp. 45-48, 2001.

[9] V. Zakosarenko, A. Chwala, J. Ramos, R. Stolz, V. Schultze, H. Lütjen, J. Blume, T. Schüler, and H. G. Meyer, "HTS dc SQUID systems for geophysical prospection," *IEEE Trans. Appl. Supercond,.* vol. 11, pp. 896-899, 2001.

[10] A. Chwala, R. Stolz, R. IJsselsteijn, V. Schultze, N. Ukhansky, H. G. Meyer, and T. Schüler, "SQUID gradiometers for archaeometry," *Supercond. Sci. Technol.,* vol. 14, pp. 1111-1114, 2001.

[11] http://geoazur.unice.fr/PERSO/lsbb/

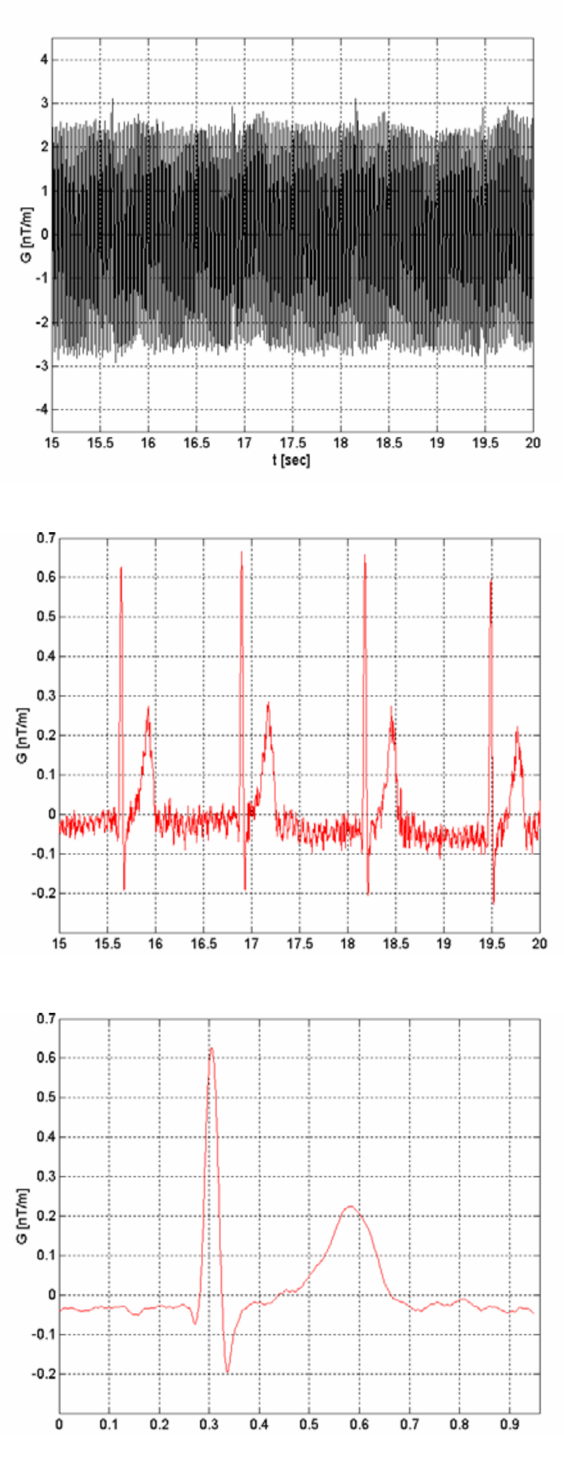

Fig. 3. MCG recorded with a Low-T_c SQUID gradiometer system, without magnetic shielding in the Lab. Top: Raw real-time data taken with a first-order gradiometer; Middle: Real-time data taken with a second-order gradiometer and with adaptive filtering; Bottom: Data from the middle Figure averaged 26 times.