$YBa_2Cu_3O_7$ thin film SQUID gradiometer for biomagnetic measurements

Y. Tavrin,[a] Y. Zhang, M. Mück, A. I. Braginski, and C. Heiden
Institut für Schicht und Ionentechnik (ISI), Forschungszentrum Jülich (KFA), Postfach 1913, D-W5170 Jülich, Germany

(Received 12 August 1992; accepted for publication 9 February 1993)

Low-noise rf SQUID washers fabricated from $YBa_2Cu_3O_7$ epitaxial thin films have been used to construct a first-order electronic gradiometer operating at 77 K and suitable for biomagnetic measurements. Mechanical adjustment of the two-SQUID gradiometric setup made it possible to attenuate signals due to far magnetic field sources by three orders of magnitude. A magnetic field resolution of $\leqslant 280$ fT/Hz$^{1/2}$ above 2 Hz was attained through the use of large flux focusers. The fine structure of human heart magnetocardiograms was recorded in unshielded space. In a shielded room, magnetoencephalograms were obtained. The system was used to obtain new data on auditory evoked cortical response.

We have developed a first-order superconducting quantum interference device (SQUID) gradiometer operating in liquid nitrogen, i.e., at 77 K, and capable of detecting weak biomagnetic signals in an unshielded or weakly shielded environment. A first order gradiometer is insensitive only to far-magnetic field sources which are uniform in space, such as the dc earth field. To exclude closer, nonuniform noise fields, a higher order gradiometer is necessary. However, a first-order device is sufficient for testing a specific gradiometer design concept.

To achieve a high magnetic field sensitivity, one needs to effectively couple the external flux to a low-noise SQUID sensor. In liquid-helium-cooled devices, the conventional solution is to use a flux transformer with a superconducting wire-wound pickup coil. A common first-order gradiometric geometry used in biomagnetic SQUID instrumentation consists of two pickup coils connected in opposite series. The coils are separated by the base distance d along the vertical symmetry axis. The lower coil is positioned as close as possible to the measured signal source.

Unfortunately, no suitable low-noise high-temperature superconductor wire exists for use at 77 K. Multilevel thin-film coils and flux transformers usable in a planar, i.e., horizontal, gradiometer geometry[1] are still in their infancy. However, an ultimately less effective but simple alternative to a flux transformer is a planar flux focuser consisting of a large thin-film SQUID washer. Low-noise, high-tank frequency (150 MHz) rf SQUIDs with $YBa_2Cu_3O_7$ (YBCO) step-edge junctions and large washers were recently demonstrated.[2] By using a 8×8 mm^2 square YBCO washer chip, a magnetic field resolution $B_N \leqslant 200$ fTHz$^{1/2}$ at 1 Hz and 77 K could be attained.[3] We employed a magnetometer with such a SQUID chip to record human heart and brain signals inside a magnetically shielded clinical room.[3]

An alternative to a gradiometer pickup-coil arrangement is an electronic gradiometer where two separate SQUIDs are disposed in parallel planes separated by d along the vertical symmetry axis. Their in-phase signals A and B are electronically balanced to obtain the (A-B) output. Such electronic balancing was first introduced in some multi- and single-channel SQUID systems operating in liquid helium.[4,5] The same approach was then used with bulk, ceramic YBCO SQUIDs to obtain first, at a SQUID temperature of 77 K, recordings of human heartbeat traces in a weakly shielded environment.[6] However, the $1/f$ low frequency noise in the ceramic SQUID sensors was too high to clearly observe the fine structure of cardiac signals.

In this letter, we report on the construction and performance of an electronic first-order gradiometer with two similar large washer thin-film rf SQUID chips of Ref. 3. Table I summarizes the parameters of these chips measured at a tank frequency of 100 MHz. The large value of the SQUID inductance, $L_s=380$ pH, was not optimal but rather dictated by the availability of two sufficiently similar chips.

Additional bulk flux concentrators were also used.[7]

TABLE I. Parameters of two rf SQUIDs measured at 77 K, $\beta_L=2\pi I_c L/\Phi_0\approx 1$, tank frequency $f_T=100$ MHz.

SQUID chip	1	2
Inductance, L_s, pH	380	380
Hole area, μm^2	300×300	300×300
Washer area, mm^2	6×6	6×6
Transfer function $dV/d\Phi$, $\mu V/\Phi_0$	23	30
Noise, $S_\Phi^{1/2}$, Φ_0/Hz$^{1/2}$ at 1 Hz	4.0×10^{-4}	2.6×10^{-4}
Crossover frequency, (to white noise)	2	1
Noise, $S_\Phi^{1/2}$, Φ_0/Hz$^{1/2}$ (white)	2.0×10^{-4}	2.6×10^{-4}
Magnetic field gain:[a]	14	14
Field/flux transformation coefficient nT/Φ_0	1.7	1.7
Field resolution B_N, fT/Hz$^{1/2}$ at 2 Hz	340	440

[a]Ratio of effective to geometrical loop area.

[a]Permanent address: Institute of Low-Temperature Physics and Engineering, Ukrainian Academy of Science, Khar'kov, Ukraina.

 0003-6951/93/151824-03$06.00

These nearly octagonal concentrators were glued together from two blocks of polished, 85% dense YBCO ceramics. Glued interfaces provided for two slits in the loop. The concentrator dimensions were: outer diameter (of an equivalent circle) OD=22 mm, internal hole 5×5 mm and thickness of 3.5 mm. The OD was determined by the diameter of the existing gradiometric fixture (see below). Other dimensions were chosen arbitrarily. Measurements with and without concentrators have shown that they increased the field/flux transformation coefficient of the system by a factor of approximately 3.

The gradiometric fixture holding two planar SQUIDs with concentrators (A,B) had a base $d=6$ cm. With such a long base, a vertical gradiometer can measure essentially the local biomagnetic field rather than that field's gradient. A cardanic x-y mount of the upper chip permits one to adjust the plane of the upper SQUID for a parallel alignment with the lower chip and the resulting best rejection of the common mode signal. Any slack in the position control is removed by spring loading. The additional advantage of this fixture is a significant damping of external vibrations. The fixture, having an outer diameter of 5 cm, is rigidly mounted inside a low self-noise fiberglass-reinforced epoxy dewar filled with liquid nitrogen. The dewar holds 5 liters of liquid and permits one to operate at 77 K for a period of four days. The lower SQUID (A) is positioned at a distance of $\geqslant 10$ mm from the external boundary of the dewar bottom wall. In biomagnetic measurements, this wall is adjacent to the chest or skull of the investigated human subject.

To determine the attainable degree of balancing out the external dc field, the dewar containing the operating gradiometer was slowly oscillated along different geographic (radial) directions in the absence of any shielding. The amplitude of the resulting signal oscillations was measured simultaneously as the magnetometric output A and the gradiometric output (A-B) while the balancing ratio (A-B)/A was being optimized by adjusting the x and y axis of the cardanic mount. We obtained $(A-B)/A=6.7\times10^{-4}$ to 2.0×10^{-3}, depending upon the direction of oscillations.

The rf SQUIDs have been operated with a tank frequency of 100 MHz. Two identical rf SQUID readout electronics sets, of a rather conventional design, are used in the A and B channels.[8] The high-frequency units, each including a preamplifier having 1.5 nV/Hz$^{1/2}$ noise voltage (referred to the input), are mounted on top of the dewar. The low frequency control and flux locking loop units are connected with the hf units by 4 m long shielded cables. The modulation frequency is 50 kHz. The signals from two output (buffer) amplifiers are substracted and balanced using potentiometer controls to obtain the gradiometric output (A-B). An additional band pass filter (0.3–30 Hz) is optionally connected to the output.

The performance of the system is summarized in Table II. Only the gradiometric output signal (A-B) is characterized. The system noise spectra were determined in our unshielded laboratory space. The spectra were measured repeatedly over short periods of time. The B_N value of Table II is based on ten successive spectra, each averaged five times over 20 s and recorded when no nearby magnetic objects such as cars, metallic office furniture, etc. were in motion.

TABLE II. Parameters and performance of the gradiometer system in unshielded space.

Parameter	Value
Field-flux transformation coeff., T/Φ_0	5.0×10^{-10}
Peak-to-peak noise, T [the (A-B) output, bandwidth: 0.3–30 Hz]	$\leqslant 4.5\times10^{-12}$
Magnetic field resolution B_N, fT/Hz$^{1/2}$ [the (A-B) output, bandwidth: 2–30 Hz]	$\leqslant 280$
Slewing rate, Φ_0/s	4×10^4
Maximum measurable dc field, Φ_0	±1000

To further characterize the unshielded environment noise and its rejection by the gradiometer, time-domain measurements have been made. A typical example is shown in Fig. 1. In the absence of moving magnetic objects, the ambient field background, at the system location in our relatively "quiet" laboratory, has been dominated by 50 Hz sources. The peak-to-peak amplitude of the unfiltered background signal was measured with a single SQUID channel (A) to vary, typically, between 1 and 20 nT, as shown in the trace of Fig. 1(a). The fast switching between noise levels, seen in the trace, is a common occurrence. At the filtered (A-B) output, a simultaneous recording of a human heart signal was made and is shown in Fig. 1(b). It can be seen that fast switching events produce only minor noise spikes in the recording. The slight delay in their occurrence is due to the filter.

In the bandwidth of 30 Hz, the gradiometer permitted us to record comparable heart signal traces, both in the magnetically shielded room[9] and without any shielding. Two real-time heart signal traces recorded, with and without shielding, at nearly the same chest position of a human subject are compared in Fig. 2. The fine structure of the cardiac signal could be equally well resolved in both cases. In the shielded room, and with signal averaging, an earlier version of the system (without bulk flux concentrators) was also used to record the auditory evoked cortex re-

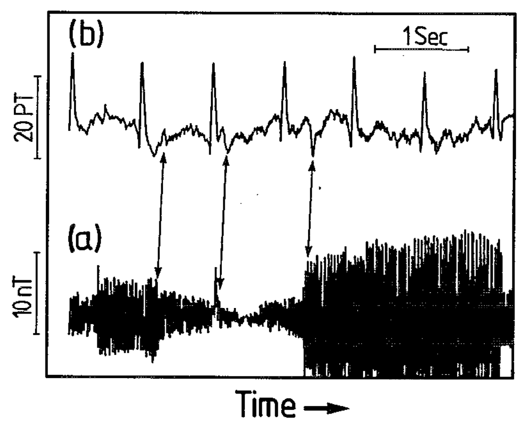

FIG. 1. Time domain signal traces in the absence of shielding: (a) unfiltered single channel (A)—background signal output; (b) simultaneous recording of human heart signal.

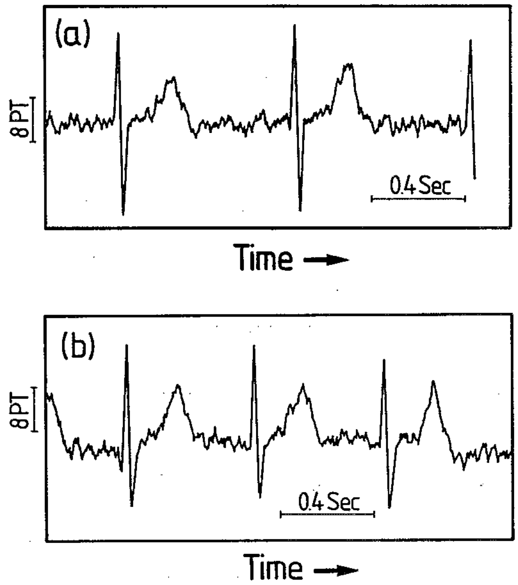

FIG. 2. Real-time magnetocardiograms recorded in: (a) the shielded room (bandwidth 1–30 Hz) and (b) without shielding (bandwidth 0.3–30 Hz).

sponse of many human subjects[10] and produced new biomagnetic information.[11]

In conclusion, we have shown that the use of (1) low-noise, YBCO thin-film rf SQUIDs with large thin film and bulk YBCO focusers and (2) the mechanical balancing of SQUIDs has resulted in a practical first-order electronic SQUID gradiometer system operating at 77 K and suitable for many biomagnetic measurements. A further improvement in the magnetic field resolution is expected. The developed system concept is extendable to a second-order gradiometer.

At the Wilhelms University Münster, we benefited from the collaboration of Professor T. Elbert, and Dr. C. Pantev who directed the magnetoencephalographic measurements. S. Hampson conducted the digital data acquisition and processing. At ISI-KFA, we were greatly helped by Dr. J. Schubert and W. Zander who laser-deposited the YBCO films and Dr. Y. Xu who fabricated the bulk ceramic concentrator parts. This work was supported, in part, by the BMFT Consortium "First Applications of High Temperature Superconductors in Micro- and Cryoelectronics."

[1] W. Eidelloth, B. Oh, R. P. Robertazzi, W. J. Gallagher, and R. H. Koch, Appl. Phys. Lett. **59**, 3473 (1991); and references therein.
[2] Y. Zhang, H.-M. Mück, K. Herrmann, J. Schubert, W. Zander, A. Braginski, and C. Heiden, Appl. Phys. Lett. **60**, 645 (1992).
[3] Y. Zhang, Y. Tavrin, M. Mück, A. I. Braginski, C. Heiden, T. Elbert, and S. Hampson, Physiol. Meas. (to be published).
[4] S. J. Williamson, M. Pelizzone, Y. Okada, L. Kaufman, D. B. Crum, and J. R. Marsden, in *Biomagnetism: Application and Theory*, edited by H. Weiberg, G. Stroink, and T. Katila (Pergamon, New York, 1985), p. 46.
[5] M. Nakanishi, M. Koyanagi, H. Kado, N. Kasai, and T. Endo, in *Biomagnetism '87*, edited by K. Atsumi, M. Kotani, S. Ueno, T. Katila, and S. J. Williamson (Tokyo Denki University Press, Tokyo, 1988), p. 446.
[6] A. G. Likhachev, V. N. Polushkin, S. V. Uchaikin, and B. V. Vasiliev, Supercond. Sci. Technol. **3**, 148 (1990).
[7] A. N. Matlashov, V. P. Koshelets, P. V. Kalashnikov, Yu. E. Zhuravlev, V. Yu. Slobodchikov, S. A. Kovtonyuk, and L. V. Filippenko, IEEE Trans. Magn. **27**, 2963 (1991).
[8] P. P. Pavlov, Y. A. Tavrin, A. S. Linnik, V. V. Ryabovol, and V. V. Kartsovnik, Instr. Geophys. Research **90**, 3 (1989) (in Russian).
[9] Institute of Experimental Audiology, Univ. of Münster, D-4400 Münster, Germany.
[10] Y. Zhang, Y. Tavrin, M. Mück, A. I. Braginski, C. Heiden, S. Hampson, C. Pantev, and T. Elbert, J. Brain Topography (to be published).
[11] T. Elbert, C. Pantev, S. Hampson, and M. Hoke (unpublished).