Biomagnetic measurements with an integrated $YBa_2Cu_3O_7$ magnetometer in a hand-held cryostat

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With low-noise magnetometers made from high-temperature superconductors, mobile applications of superconducting quantum interference device (SQUID) magnetometry become possible. Due to the high volume heat of evaporation of liquid nitrogen, a SQUID magnetometer can be operated in a small size cryostat for some hours. For the first time biomagnetic measurements are presented using an integrated $YBa_2Cu_3O_7$ magnetometer mounted in a hand-held cryostat with a content of 100 cm^3 of liquid nitrogen. These measurements and the noise properties are compared to those made in a conventional cryostat. The low-noise magnetometer consists of a multiloop pick-up coil coupled inductively to a dc SQUID based on ramp-type Josephson junctions with $PrBa_2Cu_3O_7$ barriers. © *1996 American Institute of Physics.* [S0003-6951(96)03544-9]

Biomagnetism is one of the most promising applications of magnetometers using superconducting quantum interference devices (SQUIDs). Aside from the well established use of low-temperature superconductors,[1] SQUIDs based on high-temperature superconductors (HTS) operating at 77 K are also used and biomagnetic measurements for magnetocardiography have already been demonstrated.[2–4] Relying on grain boundaries of bicrystal substrates as Josephson junctions, the HTS SQUIDs achieve very low magnetic flux density noise[2] down to below 10 $fT/\sqrt{Hz}$, and the use of ramp-type Josephson junctions with $PrBa_2Cu_3O_7$ barriers in low-noise integrated magnetometers recently has also been demonstrated.[5] Biomagnetic measurements are commonly made in magnetically shielded rooms in order to reduce the electromagnetic noise of the environment. Many new applications arise for SQUID operation in mobile, battery powered magnetometer systems, and mobile operation in an unshielded environment is desirable to simplify the handling and to reduce the costs. Sufficient reduction of external noise by electronic[6,7] or integrated[8] gradiometer arrangements has been demonstrated. When liquid nitrogen with its high volume heat of evaporation is used, the size of a cryostat for hand-held systems can be reduced significantly compared to liquid helium cooled ones for same operation time. We present biomagnetic measurements at 77 K with an integrated $YBa_2Cu_3O_7$ magnetometer mounted inside a hand-held cryostat. For comparison, these measurements were also performed in a conventional biomagnetic setup with the same magnetometer and flux-locked loop (FLL) electronics in a magnetically shielded environment.

In order to demonstrate the operation of HTS SQUIDs in a hand-held liquid nitrogen magnetometer system, we built a miniature cryostat that fits, together with batteries and the SQUID electronics, into a small hand-held case. The complete system is shown in Fig. 1. At the left-hand side, the SQUID electronics with its two 9 V batteries is shown. In the background a Dewar of 1000 cm^3 content to refill the cryostat, which suffices for 8h operation can be seen. The cryostat consists of two containers thermally insulated by vacuum and six layers of superinsulation foil in between. The magnetometer chip is mounted inside the vacuum avoiding contact to moisture. The inner part of the cryostat containing the liquid nitrogen is made of stainless steel which provides much better durability in mobile applications than glass-fiber epoxy. Because metal usually contributes to the SQUID noise by Johnson noise[9] and externally induced eddy currents, the chip is mounted on a ceramic cold finger 1 cm in distance from any massive metal part of the stainless steel container. For the same reason, the outer, room-temperature container is made from glass-fiber epoxy. Filled with 100 cm^3 liquid nitrogen, the magnetometer is cooled down to a temperature of 77 K. For about 1 h the temperature stays within ± 50 mK if the cryostat is not moved.[10] Moving reduces stability of both the temperature and operation time.

As a magnetometer chip we use an integrated multiloop pick-up coil (IMPUC) magnetometer that was recently demonstrated to operate at 77 K with low noise.[5] In this concept, a multiloop pick-up coil is inductively coupled to a dc SQUID of a small inductance resulting in a high output signal together with a good sensitivity for magnetic fields. The dc SQUID of the IMPUC magnetometer used here has an

FIG. 1. Hand-held SQUID magnetometer system used for biomagnetic measurements. The cryostat can be seen in an additional front part shown in the middle. The complete system is depicted at the right side.

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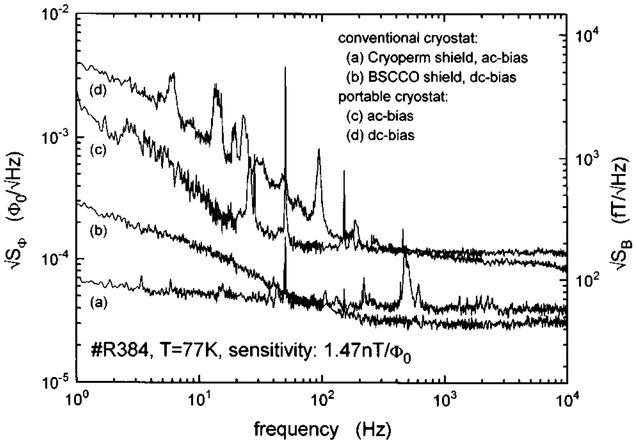

FIG. 2. FLL spectra of flux-density noise in an optimumly shielded environment measured in ac-bias (a) and dc-bias modes (b). Flux-density noise of the same magnetometer in the portable cryostat inside a magnetically shielded room measured in FLL mode in ac- (c) and dc-bias modes (d).

inductance of 90 pH, a critical current of 20 μA and a normal state resistance of 2.5 Ω, and a maximum flux-to-voltage modulation of 2.8 μV. The effective area of the complete IMPUC magnetometer is 1.4 mm^2. The preparation relies on a multilayer process using KrF-excimer laser deposition of $YBa_2Cu_3O_7$, $PrBa_2Cu_3O_7$, and $SrTiO_3$ films that are all patterned by conventional photolithography and argon-ion etching.[11] The Josephson junctions of the dc SQUIDs are realized in ramp-type geometry with $PrBa_2Cu_3O_7$ barriers.[12] For electrical insulation in the crossovers, epitaxial $SrTiO_3$ films are employed.[13]

The noise properties of the IMPUC magnetometer were characterized at 77 K in an optimally shielded environment.[5] Operated in a FLL mode, we used a ceramic, superconducting $Bi_2Sr_2CaCu_2O_8$ (BSCCO) cylinder for the static bias current mode (dc bias) and a double cryoperm shield for additional bias current modulation (ac bias).[14] Both ac- and dc-bias measurements were made inside a magnetically shielded room in a large commercial liquid nitrogen tank at 77 K. The two flux density noise spectra are depicted in Figs. 2(a) and 2(b), respectively. Here, values of $\sqrt{S_B}(1\,\mathrm{Hz}) = 100$ fT/$\sqrt{\mathrm{Hz}}$ and $\sqrt{S_B}(1\,\mathrm{kHz}) = 44$ fT/$\sqrt{\mathrm{Hz}}$ in the white noise region are found. We assume these values to be the intrinsic noise level of the magnetometer.

For comparison, we mounted the same magnetometer chip No. R384 inside the portable cryostat and operated it attached to a stand in a fixed position. It should be noted that even refilling of liquid nitrogen does not affect the stable FLL operation of the IMPUC magnetometer. Magnetic flux density noise spectra measured in ac- and dc-bias modes are shown in Figs. 2(c) and 2(d), respectively. For operation in the same magnetically shielded room without further magnetic shielding by cryoperm or HTS ceramics, we find in the white noise regime a flux density noise of $\sqrt{S_B}(77\text{ K}, 1\text{ kHz}) = 150$ fT/$\sqrt{\mathrm{Hz}}$ measured in dc-bias mode. At low frequencies, a strong increase of the flux density noise is observed. This noise was only partly suppressed by operation in the ac-bias mode where a value of $\sqrt{S_B}(1\,\mathrm{Hz}) = 3.1$ pT/$\sqrt{\mathrm{Hz}}$ was obtained. Furthermore, discrete peaks in the noise spectra were observed especially in this low-frequency region. These peaks were found to be time dependent and are most probably caused by external disturbances penetrating the chamber.

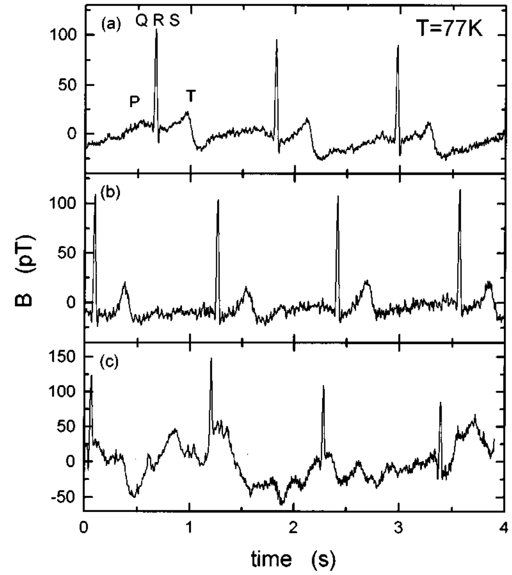

FIG. 3. Biomagnetic measurements of the human heart beat using the IMPUC magnetometer in ac-bias mode at liquid nitrogen temperature. (a) Measured in a conventional setup using a large conventional glass-fiber epoxy cryostat. (b) Measured with the portable SQUID magnetometer system mounted in a stand. (c) Hand-held measurement with the portable SQUID magnetometer system.

Using the IMPUC magnetometer, we performed biomagnetic measurements in a large conventional glass-fiber epoxy cryostat at 77 K. The magnetic human heart signals were recorded in ac-bias mode. An unfiltered and unaveraged trace measured is shown in Fig. 3(a). The maximum *R*-peak intensity is about 100 pT while the peak-to-peak noise level of about 8 pT for a measuring bandwidth of 200 Hz is dominated by the 50 Hz signal from the power line. This gives a signal-to-noise ratio of 12.5. The human heart signal of the same person was recorded using the portable SQUID magnetometer system, as depicted in Fig. 3(b). Here, the maximum intensity of the *R* peak is about 120 pT due to a smaller distance of the magnetometer to the heart. The peak-to-peak noise level for the same measuring bandwidth was determined to about 13 pT resulting in a signal-to-noise ratio of 9.2 which is smaller compared to the conventional cryostat. The performance is somehow degraded, but we believe that the main noise contribution is the again the 50 Hz signal of the power line. Finally, in Figs. 3(c) a real-time trace of the heart signal is depicted where the portable cryostat system was freely handheld over the chest of the person investigated. The FLL operation was observed to be stable but the movement of the cryostat in residual magnetic fields leads to a drift of the zero signal in the same order of magnitude as the intensity of the *R* peak. The use of two magnetometers in the same cryostat system as the electronic gradiometer is being worked on and it should reduce this drift.

In conclusion we have performed biomagnetic measurements with a low-noise IMPUC magnetometer prepared from $YBa_2Cu_3O_7$ with ramp-type Josephson junctions containing $PrBa_2Cu_3O_7$ barriers. Using a hand-held cryostat for recording human heart traces, we have successfully demonstrated SQUID magnetometer operation in a very small and mobile liquid nitrogen system. This clears the way for new future applications. A further crucial task, operation in a magnetically unshielded environment, is under investigation.

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