Moderately shielded high-$T_c$ SQUID system for rat MCG

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Abstract. Recently, we have developed a 5-channel high-$T_c$ SQUID system with one signal channel intended for rat magnetocardiography (MCG) in moderately shielded or “quiet” real environment. This system is an adapted version of a human MCG system which has been improved with respect to user-friendliness and stability. A dewar with a cold-warm distance of 7 mm and a refill cycle time of up to one week is utilized. The implemented high-$T_c$ SQUIDs are single-layer devices with grain boundary junctions fabricated at KRISS with laser ablation on 10 mm x 10 mm STO substrates. In order to cancel environmental magnetic noise, three of the five SQUIDs are arranged to build an axial software first-order or second-order gradiometer with a base line of 35 mm. The other two SQUIDs are used for balancing. To overcome previous system instabilities, we have implemented an Earth field compensation for each SQUID. For this, the SQUIDs were mounted in capsules containing integrated field compensation coils. The three Earth field components are measured with an additional triaxial fluxgate, and compensated at the SQUID locations using the low-noise current source of the SQUID readout electronics. This way, the SQUIDs can be cooled and operated in a low residual field that improves system stability and reduces low-frequency SQUID noise. It is even possible to slowly move the dewar in the Earth field (dynamic field compensation). Different noise cancellation procedures were optimized and compared employing a periodic signal source.

1. Introduction
Magnetocardiography (MCG) is a noninvasive method to measure the magnetic fields generated by cardiac activation currents. Compared to electrocardiography one of the most important advantages of MCG is the absence of electrodes which should enable high throughput measurements. In particular it could be an attractive diagnostic tool for monitoring the heart activity of small animal models in biomedical research [1, 2, 3].

2. Measurement setup
We have developed a single-channel high-$T_c$ SQUID system with a total of five magnetometers. This system is intended for rat MCG in moderately shielded or “quiet” unshielded environment.
2.1. Cryogenic setup

The cryogenic setup consists of the dewar and the probe stick, which contains the five capsuled high-T$_c$ SQUIDs. The dewar, originally built from ILK Dresden for tilted operation, was reconstructed at PTB in order to meet the requirements of animal MCG experiments. Now, the dewar features a flat nose, a cold warm distance of 7 mm, and a reservoir of 6 Liters, which results in a LN$_2$-hold time of up to one week.

The implemented high-T$_c$ SQUIDs, fabricated at KRISS with laser ablation on 10 mm x 10 mm STO bicrystal substrates, are single-layer devices with grain boundary junctions [4]. The noise of the SQUIDs, measured in the Berlin Magnetically Shielded Room (BMSR), is roughly 80 fT/Hz$^{1/2}$ at 10 Hz, and below 190 fT/Hz$^{1/2}$ at 1 Hz.

Three of the five SQUIDs are z-oriented (axial) and arranged in a distance of 35 mm, respectively. These magnetometers are used to build an axial software first-order or second-order gradiometer. The other two SQUIDs, measuring the x- and y-field components, are mounted into the space between the upper two z-SQUIDs (see figure 1). The x- and y-oriented magnetometers are used for balancing only. This arrangement enables effective environmental magnetic noise suppression.

![Figure 1. Probe stick with capsuled HT$_c$-SQUIDs.](image1)

![Figure 2. MCG system in rf shielded chamber -without any magnetic shielding.](image2)

To overcome system instabilities, each SQUID is housed in a capsule with an integrated Earth field compensation coil [5]. In combination with the low-noise current source of the readout electronics, compensation fields of up to ±71 μT can be produced with only 19 fT/Hz$^{1/2}$ excess noise above the 1/f corner at about 2 Hz. This feature allows one to compensate the background field as described in chapter 2.3.

Despite applying dynamical field compensation as described in chapter 2.3.2, sometimes the system becomes unstable in normal laboratory environment caused by switching operation of near-by power consumers, e.g. a coffee machine. To avoid such instabilities, the system was placed in an rf shielded chamber (see figure 2).
2.2. Room temperature setup
The animal under investigation can be placed beneath the cryostat by means of a supporting table connected to the tail of the dewar.

On top of the dewar, the two three-channel flux locked loop electronics with low-noise current sources (type SEL-1, Magnicon GbR) are located. The analog output signals of these electronics are acquired by a PXI system containing high resolution data acquisition devices (PXI-4461 and PXI-4461, National Instruments). This data acquisition system is operated outside the rf shielded chamber and not depicted in figure 2.

For measuring the Earth field components at the sensor position, an additional triaxial fluxgate (Stefan Mayer Instruments) is used, which is situated near the SQUIDs. The analog fluxgate data are converted by a low cost analog to digital converter (USB-6008, National Instruments), which is located also outside the chamber.

2.3. Field Compensation
Two different types of field compensation modes are implemented. The static field compensation is used for setting up the system. The dynamic field compensation is required for operation in environments with very large low-frequency field fluctuations or if the system is intended to be slowly moved in the Earth field.

2.3.1. Static field compensation (SFC). Before the SQUID system is ready to operate, the three Earth field components are measured with the triaxial fluxgate and read out by the USB-6008 device. The current needed to compensate the Earth field component perpendicular to the magnetometer pickup coils is calculated from the dc field components. After setting the coil currents provided by the low-noise current source of the readout electronics, the SQUIDs are sequentially heated up above the critical temperature in the low residual field to remove trapped flux. Now, the SQUID working point adjustment can be performed.

2.3.2. Dynamic field compensation (DFC). Normally, after the initial procedure described above, one can switch over directly from static to dynamic field compensation. The DFC changes the compensation field automatically, if the preselected dynamic range of the flux locked loop is exceeded. This feature allows to move the system slowly in the Earth field without loss in noise performance, which could be important for portable systems. Counting the number of DFC steps enables the recalculation of the field components.

3. Measurements

3.1. Crosstalk between a SQUID and the compensation coil of an adjacent SQUID
In order to ascertain the influence of the compensation coil of a particular SQUID to the adjacent SQUID, we fed the compensation coil of a capsule with low-frequency currents corresponding to a peak-to-peak field of up to 13.9 μT, and measured the signal at the adjacent SQUID under different arrangements.

Crosstalk levels below 0.27% and about 0.86 % have been obtained for an orthogonal and a parallel configuration, respectively, related to a baseline of 35 mm (see figure 3). The overall uncertainty of the measurement is dominated by other properties, e.g. misorientation of the magnetometers rather than by the influence of the compensation coils.
3.2. System in shielded operation
To demonstrate the potential of the SQUID magnetometers, we have measured the heart signals of two rats with a single sensor inside the BMSR. The body weight of the rats was 480 g (Rat#1) and 497 g (Rat#2), respectively. Rat#1 was healthy, Rat#2 was hypertrophy (heart enlargement). The rats were in the anesthetized condition during the MCG measurements. Each rat was in supine position so that the distance between the SQUID and the body could be aligned to less than 1 cm. The average heart beat of the rat was about 7 Hz, the averaged Q-peak about 14 pT. Missing beats and significant variations in the heart beat rate could be clearly detected.

All measurements were approved by the local ethics committee and performed according to the German Animal Welfare Law.

3.3. System in magnetically unshielded operation
In unshielded operation, the quality of a MCG system depends on the residual noise after noise cancellation. For balancing of the first- and second-order gradiometers, a time-domain noise cancellation algorithm as described in [6] has been applied. With this procedure, we achieved a noise suppression for the second-order gradiometer signal of up to 20000 at 50 Hz (see figure 4). That is fifty times higher than obtained with a former human MCG system of a similar sensor configuration (described in [7]) with time-domain balancing and eight times higher than obtained with the frequency-domain balancing procedure.
Figure 4. Magnetic noise of the bottom magnetometer (ZB) and the balanced second-order gradiometer (GRAD2), in magnetically unshielded operation. The dotted line represents the ratio between both signals (right scale).

For system optimization an artificial signal source instead of an animal has been used. A small coil was mounted directly underneath the tail of the dewar. It was driven by the analog output of the PXI-4461 device providing an MCG-like signal. The signal form and frequency were taken from the measured MCG patterns of Rat#1. Applying our noise cancellation procedure, we could detect periodic, heart-like signals with a peak-to-peak value of a few 10 pT in real-time mode. Figure 5 shows the averaged second-order gradiometer signal at different 50 Hz power line suppression factors (numbers 500 up to 20000). In this experiment, the peak-to-peak value of the current through the coil was 2.5 µA, or twice that value (5 µA).

Figure 5. (a) signal form of coil current provided by PXI-4461, (b) measured averaged second-order gradiometer signal, the peak-to-peak coil current was set to 2.5 µA, (c) measured averaged second-order gradiometer signal, the peak-to-peak coil current was set to 5 µA.
Recording such small signals, we had to implement a wide-band notch filter (40-60 Hz) and a relatively wide high-pass filter against drifts (cut-off frequency 3 Hz). For higher signals and higher suppression factors, one can apply a notch filter with a smaller bandwidth (48 Hz-52 Hz, labeled with * in figure 5). In case of high power line noise suppression, the measurement is limited by noise rather than by the 50 Hz suppression.

4. Summary
A high-T_c SQUID system with a second-order software gradiometer and with an Earth field compensation at the position of each individual SQUID magnetometer has been presented. Noise suppression of power line disturbances in the order of $10^4$ could be demonstrated. Whereas the SQUID magnetometers have been already used for real rat MCG measurements in shielded environment, such measurements with the system described will be performed in the next future.

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