# Towards the Integration of Graphoepitaxial High-$T_c$ SQUIDs into Multichannel MEG Systems

**M. I. Faley[1], I. A. Gerasimov[2], O. M. Faley[3], H. Chocholacs[1], J. Dammers[1], E. Eich[1], F. Boers[1], N. J. Shah[1], A.S.Sobolev[2,4], V. Yu. Slobodchikov[4], Yu. V. Maslennikov[4], V. P. Koshelets[4], and R. E. Dunin-Borkowski[1,5]**

[1] Peter Grünberg Institut-5, Forschungszentrum Jülich, Germany
[2] Moscow Institute of Physics and Technology, Moscow, Russia
[3] II. Institute of Physics, RWTH Aachen University, Germany
[4] The Kotel'nikov Institute of Radio Engineering & Electronics RAS, Moscow, Russia
[5] Ernst Ruska-Centrum für Mikroskopie und Spektroskopie mit Elektronen, Forschungszentrum Jülich, Germany

**We have assessed the possibility to construct multichannel magnetoencephalography (MEG) systems based on high-$T_c$ direct current superconducting quantum interference devices (DC SQUIDs) with graphoepitaxial step-edge Josephson junctions [1]. A new layout of multilayer high-$T_c$ superconducting flux transformers was tested and a new type of high-$T_c$ DC SQUID magnetometer intended for MEG systems was realized. These magnetometers have vacuum-tight capsules of outer diameter 24 mm and a magnetic field resolution of ~ 4 fT/√Hz at 77 K. Crosstalk between adjacent sensors was estimated and measured for in-plane and axial configurations. The vibration-free cooling of sensors, minimization of the sensor-to-object distance, optimization of the sensor positions and gantry design are discussed. Our findings have implications for the next generation of non-invasive imaging techniques that may be used to understand human brain function.**

The importance of developing a new generation of non-invasive imaging techniques that can be used to understand human brain function is reflected, for example, in the "Human Brain Project" (EU) and the "BRAIN Initiative" (USA). Multichannel MEG systems that are based on low temperature SQUIDs are well developed and used routinely for the non-invasive investigation of multiple time-dependent sources of weak magnetic field generated by the human brain. MEG systems that are based on sensitive high-$T_c$ SQUIDs promise to improve signal-to-noise ratio and to provide better source characterization by reducing the SQUID-to-scalp separation [2]. A single-channel MEG system based on high-$T_c$ DC SQUID flip-chip magnetometers with a 16 mm x 16 mm multilayer flux transformer has achieved a magnetic field resolution of ~ 4 fT/√Hz at 77.4 K [3], which is similar to the magnetic field resolution of individual channels in commercial MEG systems based on 28 mm x 28 mm low-$T_c$ SQUIDs (Elekta Neuromag). The first source localization of brain activity using a single channel high-$T_c$ system for MEG was demonstrated recently [4].

We have prepared high-$T_c$ DC SQUIDs by high oxygen pressure magnetron sputtering and deep-UV photolithography of YBCO-$SrTiO_3$ heterostructures. Oxygen transport through epitaxial $SrTiO_3$ insulating films is important for resistive switching devices and for oxygenation of the bottom superconducting layer in multilayer high-$T_c$ superconducting flux transformers. The current development of high-$T_c$ SQUIDs is partially supported by the rapid development of metal-oxide heterostructures for applications such as room temperature resistive switching devices. We have observed large bipolar resistive switching in heterostructures that contain YBCO-$SrTiO_3$ interfaces [5]. A resistance switching ratio over $10^3$ and a stable operational endurance over 5000 cycles were observed at room temperature.

The low capacitance of high-$T_c$ Josephson junctions is advantageous for lowering the intrinsic flux noise of high-$T_c$ DC SQUIDs:

$$S_\Phi \approx 32 k_B T L \left( LC / \beta_C \right)^{1/2}, \quad (1)$$

where $\beta_C = 2\pi I_C R_n^2 / \Phi_0 \approx 0.4$ is the McCumber parameter and $\Phi_0 = 2.07 \cdot 10^{-15}$ T·m$^2$ is the magnetic flux quantum. The lower operating temperatures of low-$T_c$ SQUIDs are almost compensated by the typically much higher capacitance of their Josephson junctions (~1 pF). This property can explain the comparably high sensitivities of high-$T_c$ and low-$T_c$ SQUIDs, in spite of the much higher operating temperature of high-$T_c$ SQUIDs.

In MEG systems, near-optimal sensitivity of SQUIDs to magnetic fields of ~ 4 fT/√Hz at 77.4 K can be provided by a superconducting flux transformer with a 14-turn input coil and a pick-up loop with an outer diameter of 20 mm. Figure 1 shows a photograph of such a flux transformer and a vacuum-tight encapsulated high-$T_c$ magnetometer intended for assembly into a multichannel

MEG system. It encloses a flip-chip high-$T_c$ DC SQUID magnetometer, a feedback coil and a heater.

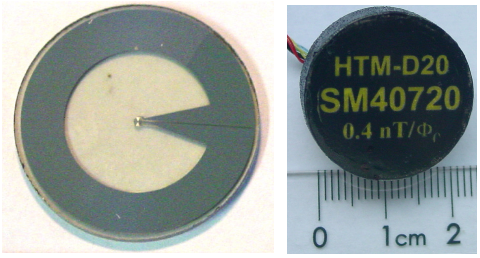


*FIG. 1: A multilayer high-$T_c$ superconducting flux transformer with a 20 mm pick-up loop and a 14-turn input coil (left photograph) and an encapsulated DC SQUID containing such a flux transformer (right photograph).*

In multi-channel SQUID systems, an important requirement is the prevention of crosstalk between channels. Linearization of the output signal of each SQUID in a multichannel system is provided by feedback signal to each SQUID from its feedback coil. Parasitic inductive coupling between the feedback coil and the pick-up loop of neighbouring sensors should be minimized. Such coupling can be expressed in terms of crosstalk between the SQUID sensors using the ratio between the flux induced by the feedback coil in a test sensor $\Phi_1$ by a nearby inducing sensor and the flux read by the inducing sensor $\Phi_2$:

$$\frac{\Phi_1}{\Phi_2} \approx \frac{\mu_0 m}{4\pi\Phi_2} \int_{y_0-R}^{y_0+R} \int_{-\sqrt{R^2-(y-y_0)^2}}^{\sqrt{R^2-(y-y_0)^2}} \frac{2x_0^2 - y^2 - z^2}{\left(x_0^2 + y^2 + z^2\right)^{5/2}} dz dy, \quad (2)$$

where R = 1 cm is the radius of the pick-up loop of the neighbouring magnetometer. The flux $\Phi_2$ induced by the feedback coil in the pick-up loop of the inducing SQUID is:

$$\Phi_2 \approx \frac{\mu_0 m r^2}{2\left(r^2 + x_0^2\right)^{3/2}} \quad . \quad (3)$$

The results of the calculation of Eqs. (2) and (3) are shown in Figure 2, while experimentally measured data for $\Phi_1/\Phi_2$ are shown in Figure 3.

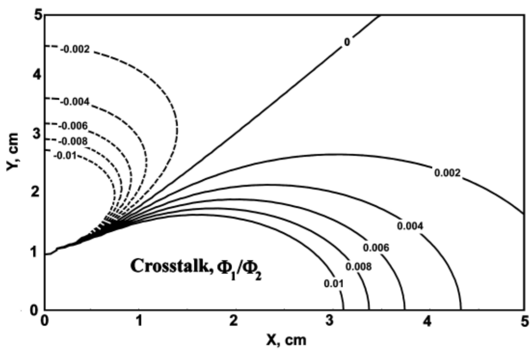


*FIG. 2: Crosstalk calculation according to Eqs.(2) and (3).*

A crosstalk of below 1 % was achieved at distances of more than 30 mm in both orientations. This measurement confirms the possibility to build close-packed arrays of high-$T_c$ SQUID magnetometers with the proposed configuration of feedback coil.

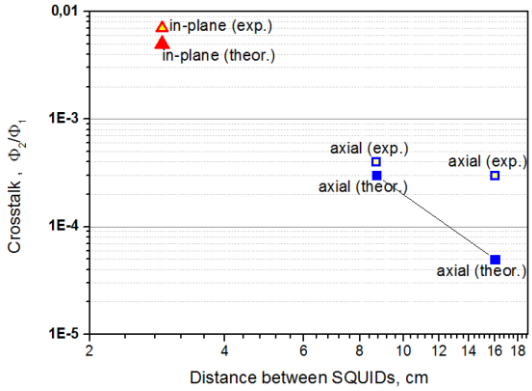


*FIG. 3: Experimentally measured crosstalk for different positions of neighbouring sensors and corresponding estimations: (△, ▲) for a coplanar orientation and (□, ■) for an axial orientation.*

In order to take full advantage of high-$T_c$ DC SQUIDs, they should be placed in a dense array as close as possible to the scalp and to neighbouring sensors. More than 100 encapsulated high-$T_c$ DC SQUID magnetometers can be arranged around the head of an adult human. The problem is the variety of individual sizes of heads that should be accommodated in a mechanically adjustable MEG system to maintain close proximity of the sensors to the scalp.

The high-$T_c$ sensors may be placed very close (< 3 mm) to the scalp by locating them in the vacuum space of the cryostat. In this case, the sensors are fixed inside thermal conducting sockets and cooled sidewards, for example with the help of vacuum grease. The thermal radiation shields can be placed between the sensors and the warm wall. Alternatively, the sensors can be placed inside individual dimples on the other side of the cold wall, preferably immersed in liquid nitrogen.

When constructing the cryostat holder or gantry for a multichannel high-$T_c$ MEG system, one should take into account the fact that the density of liquid nitrogen (~0.8 kg/liter) is much higher than that of liquid helium (~0.128 kg/liter). A typical 50 liter cryostat for MEG would be ~33 kg heavier if it would be filled with liquid nitrogen. This may require modifications of contemporary gantries for low-$T_c$ MEG systems.

In conclusion, we have developed high-$T_c$ DC SQUID magnetometers, which can be implemented in multichannel measurement systems for MEG, but construction of a cryostat of high-$T_c$ MEG systems is still an issue.

[1] M.I.Faley *et al.*, IEEE Trans. Appl. Supercond. **25**, No.3, 1601605 (2015).

[2] F.Öisjöen *et al.*, Appl. Phys. Lett. **100**, 132601 (2012).

[3] M.I.Faley *et al.*, IEEE Trans. Appl. Supercond. **23**, Issue 3, 1600705(5) (2013).

[4] J.Dammers *et al.*, Appl. Phys. Lett. **104**, 213705 (2014).

[5] M.I.Faley *et al.*, in “Superconductors - new developments”, InTech; 73 (2015).