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7-channel on-scalp MEG-system using high-T_c SQUID magnetometers

S. Ruffieux, C. Pfeiffer, M. Xie, E. Trabaldo, F. Lombardi, T. Bauch, A. Kalaboukhov and D. Winkler
Department of Microtechnology and Nanoscience – MC2, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

M. Chukharkin
Chalmers Industriteknik, SE-412 58 Gothenburg, Sweden

B. Riaz and J. F. Schneiderman
MedTech West and the Institute of Neuroscience and Physiology, University of Gothenburg, SE-405 30 Gothenburg, Sweden

L. M. Andersen, K. Westin, and D. Lundqvist
NatMEG, Department of Clinical Neuroscience, Karolinska Institutet, Nobels väg 9, SE-171 77, Stockholm, Sweden

***Abstract*— A seven-channel magnetoencephalography (MEG) system based on high-T_c Superconducting Quantum Interference Devices (SQUIDs) has been built, characterized, benchmarked against a commercial state-of-the-art full-head MEG system, and clinically evaluated. Compared to conventional MEG using low-T_c SQUIDs, we can decrease the sensor-to-head distance from about 20 mm to about 1 mm. This increases the signal significantly and makes it possible to increase the spatial resolution. To validate the technology, we have done comparative studies on the visual and somatosensory cortex and done a first clinical study on an epileptic patient. Superficially, the high-T_c MEG system performs essentially similarly to the commercial low-T_c based system, but the signals are stronger and of more complex nature.**

***Keywords*—MEG; high-T_c; SQUID; styling; insert (key words)**

I. INTRODUCTION

Magnetoencephalography (MEG), is a technique where neuronal processes in the brain can be studied with high temporal (milliseconds) and spatial (millimeters) resolution from the magnetic signal produced by the currents formed by large numbers of aligned neurons that are activated simultaneously. The technique is used both in neuroscience research as well as for clinical applications, where the most common one is presurgical mapping before brain surgery. Today, state-of-art systems contains hundreds of channels with Superconducting Quantum Interference Device (SQUID) gradiometers and/or magnetometers made in low-T_c superconducting material, which has to be cooled down to liquid helium temperatures (~4.2 K). This low temperature puts strict requirements on the cryogenic solutions, which, in turn, translates into fixed helmet sizes for full head coverage and large stand-off distances between the sensors and the head (typically 20-40 mm). With high-T_c SQUIDs, the cryogenic requirements can be relaxed and the sensors can be placed in very close proximity to the head [1]. This has coined the notion on-scalp MEG, where the sensors are place within millimeters of the head surface. Since the magnetic field decays rapidly with distance from the source, the sensors in an on-scalp MEG system can register stronger signals compared to sensors in a conventional MEG system [2] with a higher spatial resolution and hence provide a higher information capacity [3]. For this reason, less sensitive sensors could be used, while retaining an acceptable signal-to-noise-ratio (SNR). Here, we report on the design of, and measurements with, our seven-channel high-T_c MEG and benchmarking which have been done against a 306-channel full head MEG system (Elekta Neuromag® TRIUX), using phantoms, healthy human subjects, and an epilepsy patient. We compare, for example, the systems' relative sensitivities to the somatosensory, auditory and visual cortices, as well as to epileptic interictal spike activity.

II. THE 7-CHANNEL ON-SCALP MEG SYSTEM

A. 7-channel MEG cryostat

Our system is configured with a densely-packed set of seven 8.6 mm x 9.2 mm high-T_c bicrystal SQUID magnetometers positioned in a slightly concave hexagonal pattern, 2 mm apart, on a 44 mm diameter sapphire window (see Fig. 1). The window is in turn mounted on a 0.9 liter liquid nitrogen tank made from epoxy-reinforced glass fiber. The assembly is mounted in a vacuum jacket of the same material. To accommodate the sensors as close as possible to the head surface, a 0.4 mm thick concave window, with a concave-diameter of 16 cm fitting the curvature of the SQUID layout (as well as the average adult head), is mounted on the side of the end tail of the dewar and in front of the SQUID magnetometers. This brings the sensor-to-head stand-off distance down to about 1 mm while providing about 10 cm^2 head coverage. To minimize cross-talk between the sensors from individual feedback and to avoid bulky feedback coils, direct feedback injection to the SQUID loops was chosen [4].

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B. YBCO SQUID Magnetometers

Our single layer SQUID magnetometers were made from $YBa_2Cu_3O_{7-x}$ (YBCO) thin films fabricated by pulsed laser deposition on 10 mm by 10 mm bi-crystal $SrTiO_3$ (STO) substrates with a misorientation angle of 22.6°. The pick-up loop of 1 or 3 mm widths and outer dimensions of 8.6 mm by 9.2 mm were galvanically coupled to two hairpin SQUIDs on the same grain boundary for redundancy. The used SQUID-loop was directly coupled to the feedback of the SQUID electronics (3 units of the 3-channel Magnicon SEL-1 dc-SQUID electronics were used). One side of the substrate was manually polished to form a beveled edge to which all the electrical contacts to the SQUID chip were made in order not to compromise the stand-off distance.

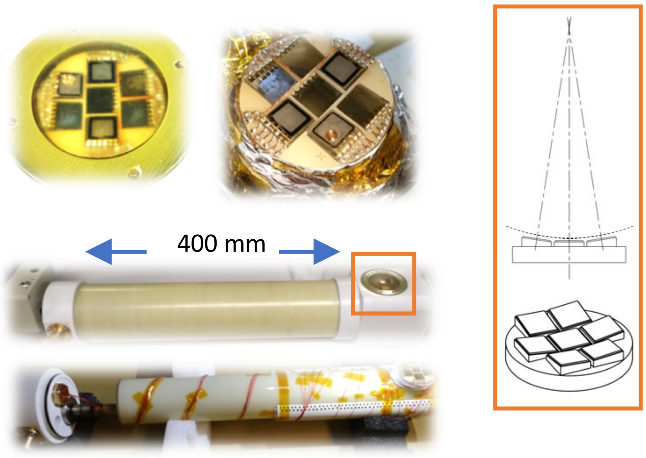

Fig. 1. The 7-channel on-scalp high-T_c MEG system. Top part shows the layout of the 7 SQUID magnetometers on the sapphire window with and without the outer jacket window. Lower figures show the assembled system and the disassembled inner liquid nitrogen container with the sapphire window to the right.

III. RESULTS

A. Cryostat

The base temperature of the sapphire window reaches around 80 K. By pumping on the nitrogen bath to a pressure of ~150 mbar, the temperature on the widow comes down to about 70 K. The hold time without pumping is 19 hours and 16 hours when pumping. This has been sufficient for all the MEG studies that we have performed so far.

B. Sensors

The SQUID magnetometers were operated with dc-SQUID electronics using ac bias reversal. They have field white-noise levels between 50 fT and 130 fT down to 6 – 10 Hz (see Fig. 2). The sensor-to-sensor cross-talk was less than 0.6 %, most of which can be attributed to the twisted wire pairs making electrical contacts to the SQUID chips.

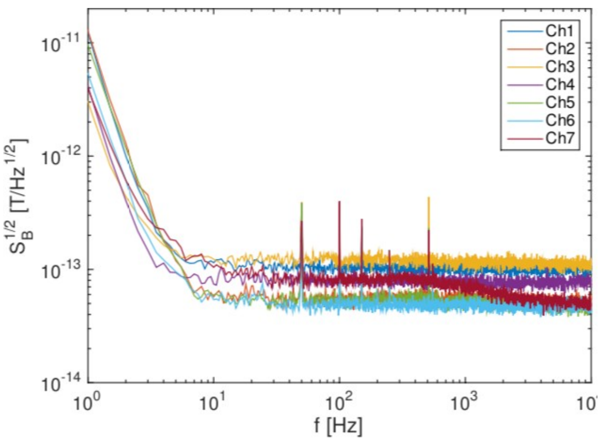

Fig. 2. Equivalent magnetic field noise spectra recorded in the 7-channel system inside the MSR.

C. MEG measurements – validation

Several different measurement paradigms have been tested with the on-scalp 7-channel MEG system to validate its performance. Induced alpha, evoked auditory and somatosensory measurements have been done at Chalmers in Gothenburg in a 3-layer magnetically screened room (MSR). Similar and additional measurements have been done at the NatMEG facility at Karolinska Institutet in Solna, where also benchmarking has been done against the commercially available 306 channel Elekta TRIUX system (Elekta Neuromag Oy) inside a similar, but larger MSR [2, 5]. The 7-channel on-scalp system was also used in a session with a patient with refractory focal epilepsy [6]. Tests were also done using an interactive dual MEG measurement set-up with the Elekta system measuring one subject and the on-scalp system measuring another subject.

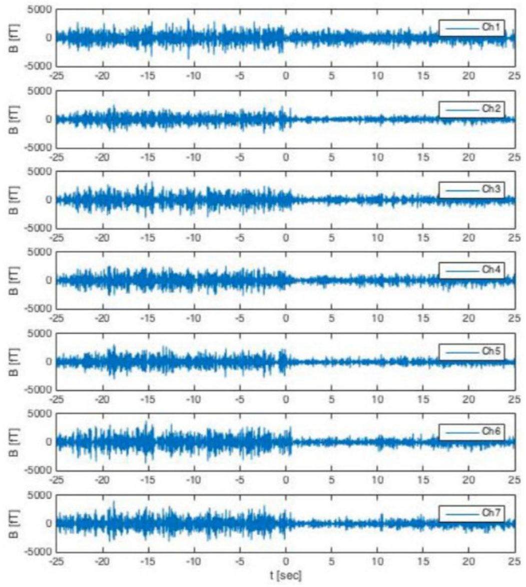

Fig. 3. Single trial of alpha suppression (bandpass filtered between 5 and 15 Hz). The signal is attenuated after the subject opens the eyes (at t=0).

In the induced alpha measurements, the subject was instructed to keep his/her eyes closed during 30 s and then keep them open for another 30 s. A time trace for each of the channels is shown in Fig. 3. Another example of auditory N100m response is shown in Fig. 4 where the subject was listening to 1 kHz tones for 400 ms once a second.

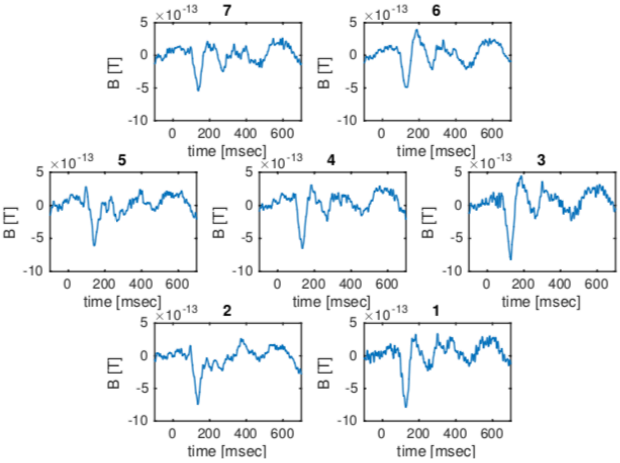

Fig. 4. Time-locked averages of auditory evoked fields with the 7-channel on-scalp MEG system. All seven channels show typical auditory N100m response.

D. *MEG measurements - benchmarking*

The benchmarking recordings were designed to build upon previous work in which we target specific neural activations with both the low-T_c and high-T_c MEG systems in order to explore the similarities and differences in the way the systems sample the brain [2, 5].

The activations we studied include:

- the N20m component and high-frequency oscillations induced by somatosensory (median nerve) stimulations.
- visual gamma-band neural oscillations modulated by viewing circular high-contrast gratings that drift towards the center of the field of view at different motion velocities.
- spontaneous interictal spike activity in an epileptic patient.
- the N16, P23 and P60 components following tactile stimulations to five different phalange of the hand.
- the somatosensory responses representing prediction, production and processing of tactile stimulations to the phalange during a 2-person interactive MEG set up with simultaneous on-scalp and conventional MEG measurements.

IV. CONCLUSIONS

We have developed a 7-channel HTS MEG system with a dense (2 mm edge-to-edge), head-aligned sensor array covering about 10 cm^2. The system employs seven high-T_c single layer SQUID magnetometers that exhibit low noise (50-130 fT/Hz$^{1/2}$) down to about 10 Hz as well as low crosstalk. We tested feasibility in recordings of alpha and auditory evoked activity and benchmarked it against a state-of-the-art full-head system.

Preliminary results suggest our high-T_c system in many cases detects higher signal levels with more details and, perhaps more importantly, complementary activations, as compared to the low-T_c MEG system.

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REFERENCES

[1] F. Öisjöen, J. F. Schneiderman, G. Figueras, M. Chukharkin, A. Kalabukhov, A. Hedström, M. Elam, and D. Winkler, “High-T_c superconducting quantum interference device recordings of spontaneous brain activity: Towards high-T_c magnetoencephalography,” Appl. Phys. Lett., vol. 100, no. 13, p. 132601, 2012.

[2] M. Xie, J. F. Schneiderman, M. L. Chukharkin, A. Kalabukhov, B. Riaz, D. Lundqvist, et al., “Benchmarking for on-scalp MEG sensors,” IEEE Trans. Biomed. Eng., vol. 64, no. 6, pp. 1270–1276, 2017.

[3] J. F. Schneiderman, “Information content with low- vs. high-T_c SQUID arrays in MEG recordings: The case for high-T_c SQUID-based MEG,” J. Neurosci. Methods, vol. 222, pp. 42–46, 2014.

[4] S. Ruffieux, M. Xie, M. Chukharkin, C. Pfeiffer, A. Kalabukhov, D. Winkler, and J. Schneiderman, “Feedback solutions for low crosstalk in dense arrays of high-T_c SQUIDs for on-scalp MEG,” Supercond. Sci. Technol., vol. 30, no. 5, p. 054006, apr 2017.

[5] Andersen LM, Oostenveld R, Pfeiffer C, Ruffieux S, Jousmäki V, Hämäläinen M, Schneiderman JF, Lundqvist D. “Similarities and differences between on-scalp and conventional in-helmet magnetoencephalography recordings”. PLoS One. 2017 Jul 24;12(7):e0178602. doi: 10.1371/journal.pone.0178602. eCollection 2017.

[6] K. Westin, C. Pfeiffer, L. M. Andersen, S. Ruffieux, G. Cooray, A. Kalabukhov, D. Winkler, M. Ingvar, J.F. Schneiderman, & D. Lundqvist “Detection of interictal epileptiform discharges (IEDs): A comparison of on-scalp MEG and conventional MEG measurements. Unpublished.