Elimination of $1/f$ Noise in Gradiometers for SQUID-based Ultra-Low Field Nuclear Magnetic Resonance

Andrei Matlashov*, Per Magnelind, Peter Volegov, Michelle Espy

Department of Physics, Applied Modern Physics Group
Los Alamos National Laboratory
Los Alamos, USA
matlach@lanl.gov

Abstract—Superconducting wire may trap magnetic flux after being exposed to strong magnetic fields, for example when used as gradiometer material in a SQUID-based ultra-low field nuclear magnetic resonance system. In this work we investigated noise caused by the dynamics of trapped flux in superconducting gradiometers made from different materials. Niobium (Nb), niobium-titanium (NbTi), and tantalum (Ta) wires were tested. Small wire-wound gradiometers were connected to a SQUID sensor. Nb and NbTi wires showed increasing $1/f$ noise after exposure to magnetic fields of 5 mT and above. A larger second-order gradiometer made of Ta wire was tested inside a magnetically shielded room. A heating wire was placed on the outside of the Ta wire. Thermo-cycling of the Ta gradiometer significantly decreased the $1/f$ noise caused by its exposure to a magnetic field.

Keywords—Ta, thermo-cycling, pulsed-field, flux-trapping

I. INTRODUCTION

Ultra-low field Magnetic Resonance Imaging (ULF MRI) was pioneered and developed at Berkeley at the beginning of the 2000s [1]. Using SQUIDs, both magnetoencephalography (MEG) and magnetic resonance imaging (MRI) signals of the brain can be detected [2]. In the ultra-low field (ULF) regime the Larmor frequency can overlap and interact with frequencies of neuronal activity that can lead to a direct functional imaging modality of neuronal currents [3]. ULF NMR is based on a field cycling technique, in which a magnetic field in the 0.1–0.3 T range pre-polarizes an object. The superconducting gradiometer pick-up coil is also exposed to the applied pre-polarization field. Typical choices of gradiometer wire material are Nb or NbTi. Both of these type-II superconductors trap magnetic flux during the pre-polarization time and generate flux jumps during the subsequent measurement time. This significantly increases the low-frequency noise with a typical $1/f$ -shaped spectrum [4, 5]. We have observed significant $1/f$ noise below 6 kHz after niobium gradiometers were exposed to a 0.1 T field [6]. NbTi wire traps even more flux at lower magnetizing field and thus is impractical for ULF MRI systems. In this work we investigated $1/f$ noise of small Nb, NbTi and Ta wire-wound gradiometers exposed to magnetic fields from 5 mT to 82 mT. We also constructed a large gradiometer with tantalum wire placed in parallel with high resistive heating wire to investigate efficiency and timing of tantalum wire thermo-cycling after it was exposed to a 0.1 T field.

II. METHODS

A. Small gradiometers of NbTi, Nb, and Ta

We tested three small gradiometers made of NbTi, Nb and Ta in up to 82 mT magnetizing field. Each gradiometer was wound on 2.4 mm fiberglass rod forming the first-order axial gradiometer with +7 and −7 turns and 12 mm baseline. Each gradiometer was placed inside a solenoid along its axis. The solenoid was 14 mm OD, 6.4 mm ID and 20 mm long. It was wound using litz wire with 25 insulated copper 0.1 mm diameter wires that reduce thermal Johnson noise from the wire. The solenoid generates a 38.4 mT field along its axis at 1 A current. Each gradiometer was connected to CE2SBlue SQUID sensor (with a cryogenic switch) [7] completely covered by a small lead shield. This shield was placed inside a larger lead shield 100 mm away from the solenoid. The large lead shield is 25 mm diameter and 180 mm long. Lead has a critical field of about 80 mT that ultimately limited the magnetic field of the solenoid we could apply during these tests to avoid trapped flux in the lead shield. The SQUID sensor itself does not sense magnetic field generated by the solenoid. The probe was immersed in liquid helium with a temperature of 4.0 K.

B. Large Ta gradiometer with heater wire

The large second-order gradiometer has 86 mm diameter and 90 mm baseline. It was wound on a fiberglass cylinder and has one bottom, two middle and one upper turns of 0.125 mm diameter tantalum wire. It was connected to CE2SBlue SQUID sensor by 140 mm long twisted Ta wire. The SQUID sensor was placed inside a small lead shield located 120 mm above the upper gradiometer turn. We used a heater made of 0.125 mm diameter phosphor bronze wire. The phosphor bronze wire was twisted to significantly decrease its own magnetic field and current switching transients. It was placed in the same groove in parallel with Ta wire and ran along it all the way from the bottom gradiometer turn, along all 4 turns to the SQUID sensor including all areas where the Ta wire was twisted. Thin foam plastic strips were placed above the grooves with wires providing thermal insulation from liquid helium. The heater resistance was about 26 Ohm at 4.0 K.

The tantalum gradiometer was tested by recording ULF MRI of a water phantom. The phantom consisted of seven 20 mm diameter and 24 mm tall cylinders with pure water

---

The authors gratefully acknowledge the support from the Los Alamos National Laboratory LDRD office through grants 20130625ER and 20130121DR

Fig. 1. Noise spectra recorded for niobium (left), niobium-titanium (center) and tantalum (right) small gradiometers after magnetization in magnetic field from 5 mT to 82 mT.

located on hexagonal corners with one cylinder in the center. The distance between their centers was 35 mm.

The tantalum gradiometer was tested inside a two-layer magnetically shielded room that eliminated ambient low-frequency noise. The external magnetic field was applied using a pancake shaped coil 300 mm diameter that generated 100 mT field at the bottom gradiometer turn. Its ramp down time was 7.5 ms. A 52 mA heating current was applied 0.5 s before ramping down the magnetization field and it was switched off 7.5 ms after zeroing the field. The time $t = 0$ s corresponds to a moment when the command is sent to switch off the heater current. Data acquisition started 15 ms after switching off the heater current. The total heating time is about 0.5 s for 35 mJ total heat energy dissipation. It evaporates about 1.2 cm^3 of liquid helium after 100 heating cycles. The total dead time from starting ramping down the magnetization field is about 30 ms.

The 2D MRI sequence consisted of 2.5 s pre-polarization followed by a gradient echo sequence with 28 ms encoding time using 33 steps with a maximum phase-encoding gradient of 5.73 Hz/mm. The frequency-encoding gradient was $\pm 6.57 \text{ Hz/mm}$ and the Larmor frequency was 4 kHz.

III. RESULTS AND DISCUSSION

A. Noise of small gradiometers in pulsed fields

We investigated the low-frequency noise of three small gradiometers after applying magnetizing fields from 5 mT to 82 mT along their axis. Gradiometer signals were recorded for 2 s with a delay time of 4 ms after zeroing the magnetizing field. Fig. 1 shows the noise spectra for gradiometers at different magnetizing field strengths. Experiments with these small gradiometers show that Nb and NbTi wires trap flux even at small magnetizing fields and NbTi wire traps even more flux than Nb wire. Ta wire traps significant flux at magnetizing field above 20 mT field. This field is still about 10-fold smaller than the pre-polarization field needed for ULF MRI applications, thus leaving Ta wire unsuitable. At the same time it has a critical temperature 4.5 K that is very close to liquid Helium boiling temperature 4.2 K at sea level or 4.0 K in Los Alamos, New Mexico (2200 m above sea level). This means that heating up Ta wire by only 0.5 K will release trapped flux. To test this idea we decided to build a large size gradiometer using Ta wire with a heater.

Fig. 2. Standard deviation of the SQUID signal, σ_s , recorded with 12 different delays after pre-polarization pulse without heating (upper) and with heating (lower). Data is from 2D imaging sequences and the echoes show up as increased σ_s , at least when the heater was used (lower panel).

Fig. 3. Ultra-low field 2D images corresponding to the 8-th delay in Fig. 2 with the echo centered at 427 ms after pre-polarization pulse with heating (left) and without heating (right).

B. ULF MRI using a Ta gradiometer with heater wire

We recorded 2D magnetic resonance images of a water phantom at a Larmor frequency of 4 kHz using the tantalum gradiometer with and without wire heating. Fig. 2 shows the standard deviation of the SQUID signal during 2D MRI acquisition recorded with 12 different delays between the end of the pre-polarization pulse and the beginning of the encoding period. The spins were relaxing in the transverse plane during the delay. Each echo shows up as five extrema in the standard deviation of the SQUID signal, and is seen most pronounced in the bottom panel. Flux jumps lead to increased variation in the signal and are seen as spikes in the graphs. The upper panel shows the signal without wire heating and the bottom figure with heating. The number of flux jumps decreased significantly after heating. The tantalum wire thermal cycling did not eliminate all trapped fluxes but it significantly decreased their number especially after 200 ms. We believe this is explained by the fact that in our first tantalum gradiometer prototype the heating wire is not fully attached to tantalum wire along its total length about 160 cm.

Fig. 3 shows two 2D images corresponding to the 8-th delay in Fig. 2 with the echo centered at 427 ms after the pre-polarization pulse. The left and the right images were recorded with and without heating. The thermal cycling of tantalum gradiometer significantly decreases the number of jumps and improves the quality of the MRI.

IV. CONCLUSION

Fast thermal cycling of tantalum gradiometers significantly eliminates low-frequency noise caused by flux jumps in the

gradiometer wire. The increase in liquid helium evaporation is very minor even in the case of a large size gradiometer with a total wire length exceeding 1.5 m. We believe that an improved heater design can completely expel trapped fluxes. For instance, more effective heater design can be made using thin film technology. This in turn will lead to the development of low-noise gradiometers working at very low Larmor frequencies, significantly below 1 kHz, even after applying a strong pre-polarizing field significantly above 100 mT.

REFERENCES

- [1] J. Clarke, M. Hatridge, M. MöBle, "SQUID-detected magnetic resonance imaging at microtesla fields," *Annu. Rev. Biomed. Eng.*, vol. 9, pp. 389–413 2007.
- [2] V. Zotev, et al., "Microtesla MRI of the human brain combined with MEG," *J. Magn. Reson.*, vol. 194, pp. 115–120, 2008.
- [3] R. H. Kraus, Jr, et al. "Toward direct neural current imaging by resonant mechanisms at ultra-low field," *NeuroImage*, vol. 39, pp. 310–317, 2008.
- [4] I. Hilschenz, et al., "Magnetic resonance imaging at frequencies below 1 kHz," *Magn. Reson. Imaging*, vol. 31, pp. 171–177, 2013.
- [5] S.-m. Hwang, et al., "Type-I superconducting pick-up coil in SQUID-based ultra-low field nuclear magnetic resonance," *Appl. Phys. Lett.*, vol. 104, 062602, 2014.
- [6] M. Espy, et al., "Progress toward a deployable SQUID-based ultra-low field MRI system for anatomical imaging," *IEEE Trans. Appl. Supercond.*, vol. 25, 1601705, 2015.
- [7] <http://www.supracon.com/en/sensors.html>