SQUIDs De-fluxing Using a Decaying AC Magnetic Field

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***Abstract*—Flux trapping is the Achilles' heel of all superconductor electronics. The most direct way to avoid flux trapping is a prevention of superconductor circuits from exposure to magnetic fields. Unfortunately this is not feasible if the circuits must be exposed to a strong DC magnetic field even for a short period of time. For example, such unavoidable exposures take place in superparamagnetic relaxation measurements (SPMR) and ultra-low field magnetic resonance imaging (ULF MRI) using unshielded thin-film SQUID-based gradiometers. Unshielded SQUIDs stop working after being exposed to DC magnetic fields of only a few Gauss in strength. In this paper we present experimental results with de-fluxing of planar thin-film LTS SQUID-based gradiometers using a strong decaying AC magnetic field. We used four commercial G136 gradiometers for SPMR measurements with up to a 10 mT magnetizing field. Strong 12.9 kHz decaying magnetic field pulses reliably return SQUIDs to normal operation 50 ms after zeroing the DC magnetizing field. This new AC de-fluxing method was also successfully tested with seven other different types of LTS SQUID sensors and has been shown to dissipate extremely low energy.**

***Keywords (Index Terms)* — SQUID, gradiometer, flux trapping, demagnetization, de-fluxing, alternating current de-fluxing, decaying magnetic field.**

I. INTRODUCTION

Since their first introduction in 1970, SQUID-based measuring instruments [1] became wide-spread science and technology tools, which in some areas cannot be replaced by any other types of magnetic field sensors. Currently, hybrid (two-chip) and single-chip gradiometers are recognized leaders in noise sensitivity of biomagnetic SQUID systems (see, for example, [2] and [3]). Due to variety of their sizes and designs such gradiometers cover practically all application areas, except those where magnetic sensors must be exposed to strong magnetic fields. Shielding could be a reasonable solution for two-chip gradiometers, if the SQUIDs are isolated from areas exposed to the magnetic field. This solution does not work for single-chip gradiometers where both pick-up coils and SQUIDs are placed in close proximity to each other. As a result, such gradiometers unavoidably trap magnetic fluxes and stop working.

This problem is critical for superparamagnetic relaxation measurements (SPMR) [4] and ultra-low field magnetic resonance imaging (ULF MRI) [5]. Thermal cycling provides the required SQUID demagnetization, but the required time could be unacceptable for SPMR and ULF MRI applications where it is expected that gradiometers recover a few milliseconds after the magnetization field is turned off.

In this paper we describe a new de-fluxing technique that has been successfully tested for sensors exposed to up to a 10 mT DC field. The technique is based on the exposure of SQUIDs to alternating current (AC) magnetic pulses with 5 – 50 ms duration and 3 kHz to 30 kHz carrier frequency. We didn't see obvious frequency dependence. Each de-fluxing AC pulse generates 3 – 30 mT decaying magnetic field on the chip. De-fluxing pulse energy dissipation is significantly less than the energy dissipation during thermal cycling which means that AC de-fluxing can be used with multiple SQUID sensors installed in dilution refrigerators, for instance, in the neutron-EDM experiments [6].

The method was thoroughly tested with commercial G136 first-order thin-film planar gradiometers from Star Cryoelectronics [7, 8]. A four-channel SPMR system using G136 gradiometers was built and is currently in operation. The AC de-fluxing technique was also tested with commercial SQUID sensors SQ180, SQ300, SQ600, SQ2600 and the single-chip magnetometer MAG8 from Star Cryoelectronics, also with the single-chip magnetometer SM7.5 from Supracon AG and with two-chip two-channel gradiometers from Neuromag-122 system manufactured in 1995. It successfully worked with all tested SQUID sensors, although an individual optimization of AC magnetic field strength and shape was needed for each case. In this paper we present experimental results recorded with the G136 planar gradiometers [8].

II. EXPERIMENTAL SETUP

Four G136 first-order planar gradiometers were placed in parallel in one plane (Figure 1), and positioned slightly above the bottom of a biomagnetic fiberglass cryostat model 607 from BTi. The gradiometers were connected to the commercial room-temperature SQUID PCI-1800 electronics from Star Cryoelectronics [7]. Four discs schematically show shapes and positions of the four individual AC de-fluxing coils.

Each first-order planar gradiometer consists of a dc SQUID and gradiometer pick-up coils deposited on a 12×48 mm^2 silicon substrate. The substrate is glued and bonded to 16×58 mm^2 printed-circuit board, and is covered by a fiberglass protection cup. The four de-fluxing coils are connected in series and together with capacitor C_0 they serve as an LC-resonator with resonant frequency f_0 = 12.9 kHz (Figure 2). One applied de-fluxing pulse works for all four gradiometers at once.

Coil L_5 is coaxially placed on top of coil L_1 and used to generate the excitation AC pulse by external electronics. All coils $L_1 – L_5$ have a pancake shape with 15 mm outer diameters. AC current pulse I_{AC} is applied to coil L_5 and stimulates ringing of the LC-resonator. The excitation AC current is measured using a 1 Ohm reference resistor. One-turn 10 mm diameter coil L_6 is coaxially placed under coil L_4 and used to read out the AC voltage that allows calculating the de-fluxing magnetic field strength in its plane.

Figure 3 shows AC current pulse in coil L_5 (orange) and AC output voltage (blue) from coil L_6. The AC excitation current pulse is applied to coil L_5 for 5 ms. It's carrier frequency is tuned close to the resonance frequency of the LC-resonator, f_0 = 12.9 kHz. The output voltage of approximately 100 mV from coil L_6 on this screenshot corresponds to a 16 mT (peak-peak) AC de-fluxing magnetic field.

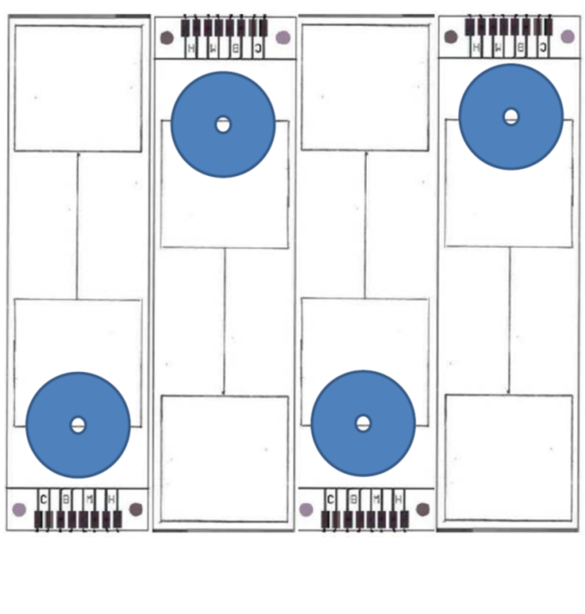

Fig.1. Four G136 gradiometers placed in parallel in one plane on the bottom of a bio-magnetic fiberglass cryostat model 607 from BTi; the four blue discs illustrate the shape and size of the de-fluxing coils placed right above the DC SQUIDs.

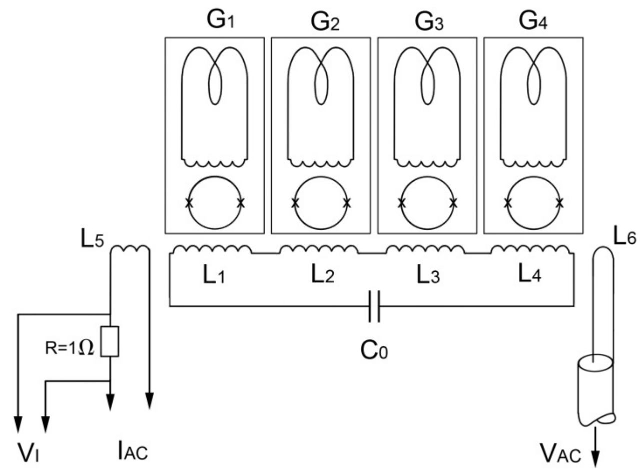

Fig.2. Schematic of the AC de-fluxing setup: a DC SQUID and pick-up coils are patterned on a 12×48 mm^2 silicon substrate; AC de-fluxing magnetic field is generated by $L_1 - L_4$; together with C_0 they form an LC-resonator with $Q \approx 100$ at f_0 = 12.9 kHz; AC current pulse in L_5 rings the LC-resonator; one-turn Ø10 mm L_6 is used to read out the strength of the AC de-fluxing magnetic field.

III. EXPERIMENTATION

For evaluation of the AC de-fluxing technique, we used a SPMR system built by Senior Scientific, LLC [4, 9]. We replaced its standard seven-channel axial gradiometer probe with the four channel planar gradiometer probe. In this system the cryostat is positioned in vertical direction along an axis of a square-shaped magnetizing Helmholtz coil with side size 80 cm. The cryostat tail is placed a little bit above the coil geometrical center. The uniform magnetizing field is oriented perpendicular to the gradiometers plane.

All four planar gradiometers become non-functional when the DC magnetizing field of 5 – 10 mT is applied for 750 ms. The critical currents of all SQUIDs become very small and the voltage-flux signals, also called the $V\Phi$ curves, practically disappear. To avoid influence of the SQUID electronics on SQUID sensors during the de-fluxing process we set all signals coming to SQUIDs from the SQUID electronics to zero during both magnetization and AC de-fluxing periods.

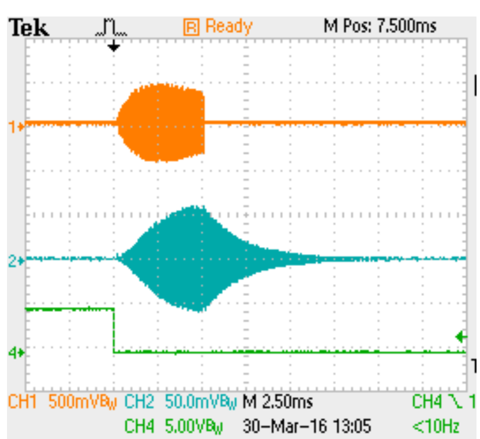

Fig.3. Oscilloscope screenshot: orange signal – AC current pulse in coil L_5 measured on 1 Ohm reference resistor; blue signal – AC output voltage from coil L_6; green signal – TTL control signal that starts the AC de-fluxing sequence.

One AC de-fluxing pulse is applied right after the magnetizing field is turned off, and 40 ms after the de-fluxing pulse the SQUID control software automatically starts searching the working currents *(I_W)* of all four gradiometers. The working current corresponds to the first maximal amplitude of the voltage-flux signal as the bias current is increased from zero μA. Working currents of G136 gradiometers are normally a little bit above their upper critical currents, $I_W \approx 1.05\times I_C$. This measurement procedure was repeated 10 times for each of 30 amplitudes of the applied AC de-fluxing fields. Figure 4 shows the dependence of the working currents vs. the de-fluxing field strength (left graph) and the working currents corresponding to the voltage-flux signals amplitudes (right graph) for the first gradiometer *(G_1)* that is coupled to the de-fluxing coil L_1 and also parasitically to the ringing excitation coil L_5.

When the AC de-fluxing magnetic field strength is below approximately 3 mT the working currents never reach the maximal value I_{Wmax} = 27.3 μA, rather they reach random values in the 5 – 10 μA range. With increasing strength of the de-fluxing magnetic field, the working currents range moves up toward the maximal value that corresponds to a truly thermally cycled SQUID. At the de-fluxing field strength of 4 – 6 mT, the SQUID becomes fully functional with almost maximal V-Φ amplitude and low intrinsic noise level after each de-fluxing pulse. Such gradiometers can be used for high-resolution measurements. Fine tuning of the working current is not required as I_W varies by approximately 5 μA with the volt-flux signal V-Φ amplitude in the 2.5 – 3.0 V range.

At a high enough strength of the AC de-fluxing magnetic field, all four gradiometers become completely functional shortly after each pulse. In our particular settings the dead time after the de-fluxing pulse was set to 40 ms, at which point the de-fluxing magnetic field decays below the level of interference with the SQUIDs. This dead time can be significantly decreased with higher AC frequency or lower Q-factor of the LC-resonator. In our experiments we were able to decrease it to below 10 ms.

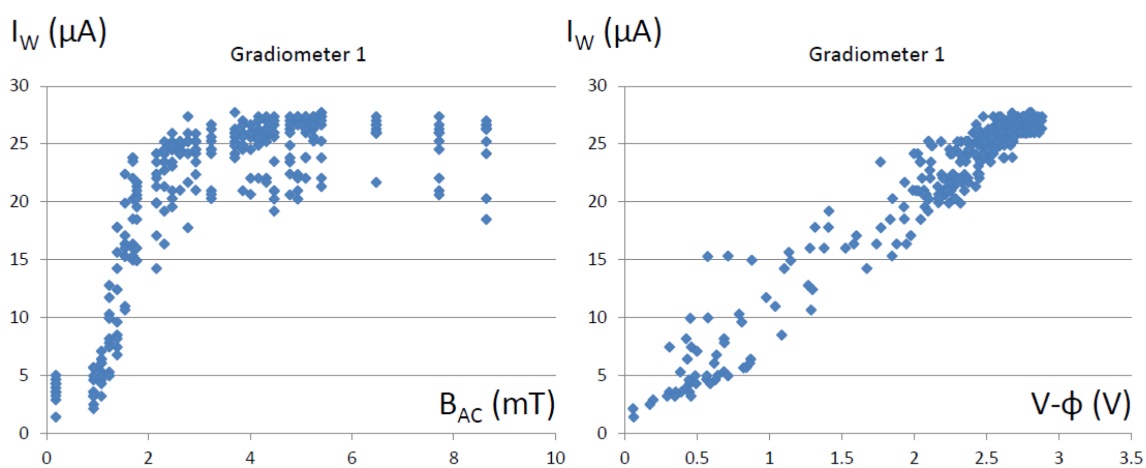

Fig.4. Dependence of working currents I_W (μA) vs. the de-fluxing field B_{AC} (mT) (left graph) and working currents corresponding to voltage-flux signals amplitudes V-Φ *(V)* (right graph) for the first gradiometer coupled to the de-fluxing coil L_1 and also parasitically to the ringing excitation coil L_5.

De-fluxing graphs for the first gradiometer look significantly different from similar graphs for the three other gradiometers. On Figure 5 the upper graphs show the dependence of working currents vs. the de-fluxing field strength (left) and working currents corresponding to voltage-flux signals amplitudes (right) for the second gradiometer *(G_2)*.

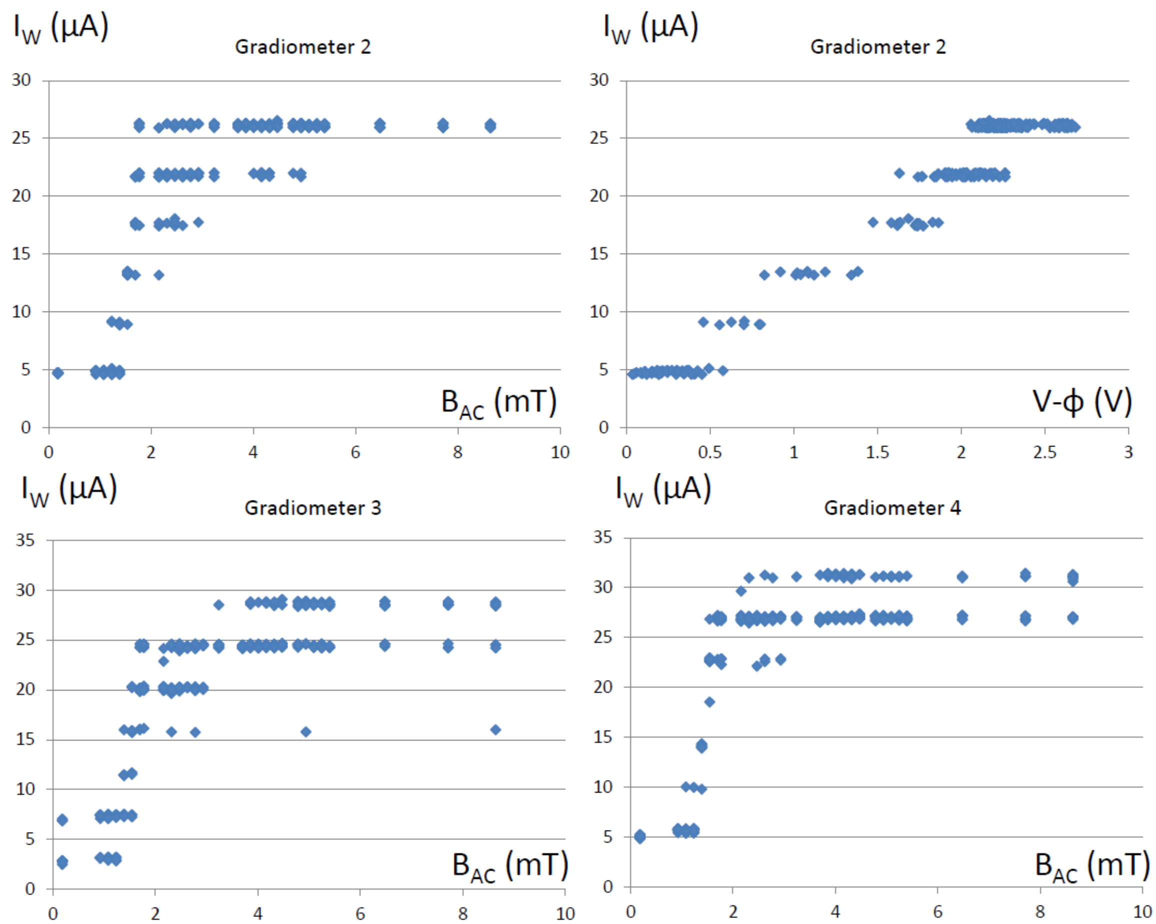

Fig.5. Upper two graphs: dependence of working currents I_W (μA) vs. the de-fluxing field B_{AC} (mT) (left) and working currents corresponding to voltage-flux signals amplitudes V-Φ (V) (right) for the second gradiometer. Bottom graphs: dependences I_W (μA) vs. B_{AC} (mT) for the third and the forth gradiometers.

The third and the fourth gradiometers (G_3 and G_4) behaved virtually identically with the second one. Their dependence of working currents vs. the de-fluxing field is shown on the two bottom graphs. They have a few equidistant discrete working current levels. The accurately measured discrete levels steps are equal to 4.26 μA, 4.30 μA and 4.33 μA for the second, third and fourth gradiometers respectively. All data was collected from the four gradiometers with exactly the same conditions using exactly the same hardware and software. The only obvious difference between the first gradiometer and the other three gradiometers is that the first gradiometer is coupled to the pulse ringing coil L_5 that stays connected to a room-temperature de-fluxing electronics all the time. This coupling may cause additional external noise, and therefore blur or destroy the discrete behavior of the SQUID during de-fluxing process. The discrete current levels also disappear, and all I_W vs. B_{AC} dependences look similar to the first gradiometer on Figure 4, if signals coming to SQUIDs from the electronics are not zeroed during the AC de-fluxing pulse.

The AC de-fluxing technique has extremely low energy dissipation. Each de-fluxing coil, L_1 – L_4, has inductance of 2×10^{-4} H. During the decaying process, it dissipates all energy stored at the highest strength of the de-fluxing magnetic field. The total magnetic flux measured by the L_6 coil is about 2×10^{-6} Wb when the de-fluxing field strength is estimated to be $B_0 = 10^{-2}$ T. It gives the total stored energy in each coil about 10^{-8} J per every de-fluxing pulse. The ringing coil L_5 does not dissipate energy at all, if it is made of superconducting wire. In comparison, each thermal cycle of G136 gradiometer dissipates about 0.5 J of energy.

IV. CONCLUSION

The thin-film SQUID sensors and gradiometers trap magnetic flux and stop operating after being exposed to a strong DC magnetic field. We proposed the new de-fluxing technique that can quickly return such SQUID sensors back to normal operation with significantly lower recovery time and energy dissipation than conventional thermal cycling. This technique is based on applying strong enough decaying AC magnetic field. This method was thoroughly tested with the commercial first-order thin-film planar gradiometers G136 using decaying 12.9 kHz AC magnetic field with strength up to 10 mT. There is no obvious frequency dependence. Equidistant discrete working current levels after de-fluxing pulses were observed in three gradiometers. It was not the case for the first gradiometer that stayed coupled to room-temperature electronics during the de-fluxing process. The four-channel SPMR system using G136 gradiometers was built and is currently in operation using up to a 10 mT DC magnetizing field. This de-fluxing technique has extremely low energy dissipation and can be used with multiple SQUID sensors installed in dilution refrigerators, for instance, in the neutron-EDM experiments. It was successfully tested with seven different niobium thin-film SQUID sensors produced at different times using different schematics and technologies by three independent manufacturers. The further experimental results and possible theoretical models of the AC de-fluxing mechanism will be presented at Applied Superconductivity Conference 2016 [10, 11].

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