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SQUIDs vs. Induction Coils for Ultra-Low Field Nuclear Magnetic Resonance: Experimental and Simulation Comparison

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Abstract

Nuclear magnetic resonance (NMR) is widely used in medicine, chemistry and industry. One application area is magnetic resonance imaging (MRI). Recently it has become possible to perform NMR and MRI in the ultra-low field (ULF) regime requiring measurement field strengths of the order of only 1 Gauss. This technique exploits the advantages offered by superconducting quantum interference devices or SQUIDs. Our group has built SQUID based MRI systems for brain imaging and for liquid explosives detection at airport security checkpoints. The requirement for liquid helium cooling limits potential applications of ULF MRI for liquid identification and security purposes. Our experimental comparative investigation shows that room temperature inductive magnetometers may provide enough sensitivity in the 3–10 kHz range and can be used for fast liquid explosives detection based on ULF NMR technique. We describe experimental and computer-simulation results comparing multichannel SQUID based and induction coils based instruments that are capable of performing ULF MRI for liquid identification.

Index Terms

Inductive magnetometers; liquid explosives detection; SQUID; ultra-low field MRI; ultra-low field NMR

I. Introduction

Recently it has become possible and practical to perform MR at magnetic fields from μT to mT, termed the "ultra-low field" (ULF) regime; see for example [1], [2]. This greatly reduces the cost and complexity associated with large magnetic fields, typically produced by superconducting magnets, and has enabled applications such as the determination of uranium enrichment fraction via relaxation and/or J-coupling [3], [4], the combination with functional brain imaging via MEG [5] and detection of liquid explosives via relaxometry [6], [7].

The simplified field generation allows flexibility in pulse sequences such as measurement field reversal and the ability to trivially change measurement field strength. In contrast to conventional MRI, relative homogeneity of the measurement field is not crucial, because μT-range magnetic fields of even modest relative homogeneity are highly homogeneous on the absolute scale [8].

There are numerous additional advantages to the ULF MR approach including imaging in the presence of metals, open system design, and enhanced T_1-weighted contrast [9]. However, for all these applications the main draw-back of the method, the very low signal intensity, was mitigated by pre-polarization [10], [11] and the use of ultra-sensitive detectors such as SQUIDs, which still require the use of cryogens. While the smaller amount of cryogens is a great reduction over the hundreds of liters used in conventional superconducting MRI systems, a system using cryogens will be unlikely for many locations. The cost and complexity of MR is the primary reason why applications of such a powerful technology are presently limited.

SQUIDs are sensitive to sub-femto-Tesla (10^{-15} T)magnetic fields, however all the other noise sources associated with the ULF MRI hardware may significantly increase the background noise. For instance, a recently built ULF MRI system for liquid explosives detection in airports, called MagViz (magnetic vision innovative prototype), has noise level about 2.5 fT/$\sqrt{\text{Hz}}$ [6]. Based on this information, and some encouraging preliminary results we believe that a practical ULF relaxometer based on very low-noise induction magnetometers may achieve this level of performance in the 3–10 kHz frequency range. This frequency range is important for many applications where imaging through metal (packaging or pipes) is important. This is a significant departure from previous work which seemed to indicate that the practical limit for coil-based MR systems was between 50–100 kHz [12]. It would represent a major step forward in ULF MR to be able to demonstrate that coil-based systems could operate at much lower magnetic fields, as that represents greatly simplified magnetic field generation. For example, there is presently no non-invasive high throughput method for identification of liquids inside closed containers. And many improvised explosive devices are based on liquid constituents (for example nitroglycerine and hydrogen peroxide have figured in several terrorist plots).

MR is a technology that has been demonstrated to be well-suited to such applications; however it is unlikely that a SQUID-based liquid explosives detection system would be suitable for deployment to theatres of war or emergency responders. For medical ULF MRI applications LT_C SQUIDs remains the only choice.

II. Method

A typical ULF MRI instrument includes pre-polarization coils, a coil set to produce uniform measurement field, three magnetic gradient coil sets, and SQUID-based receivers [2]. A receiver can be designed as a gradiometer that decreases ambient noise and makes it also more robust to radiofrequency interference (RFI). Gradiometer coils and SQUID sensors are placed inside a liquid helium fiberglass cryostat. The pre-polarization field should be as strong as practical. Its uniformity is not important, for instance, 30% non-uniformity usually is good enough that makes such coils inexpensive. The relative non-uniformity of the measurement field should be about 0.1% or better. The measurement field is usually oriented perpendicular to the pre-polarizing field. Three coil sets generate encoding gradients similar to conventional MRI systems. One or more SQUID gradiometers inside a liquid helium cryostat are placed in close proximity to a region of interest. The gradiometer design is very similar to that used for biomagnetic applications with one difference—a protection circuit may be needed to suppress transients from pulsing fields and changing gradients. The ULF MRI system can be placed inside a large magnetic shield to decrease the Earth's magnetic field and ambient magnetic noise. Alternatively, 3D compensation coils can be used.

III. SQUID-Based System

The design of the MagViz instrumentation and the used field pulse sequence are similar to what has been described in [6], [7]. The MagViz system uses seven axial 2nd order wire-wound gradiometer pick-up coils. Each gradiometer is 90 mm in diameter; the baseline (coil separation along the gradiometer axis) is also 90 mm. The gradiometer coils are connected to commercial CE2Blue SQUID sensors via cryogenic switches SW1 from Supracon. Cryogenic switches are activated during pre-polarization time and switching periods becoming normal with 350 Ohm resistance. The intrinsic noise of the gradiometers and the commercial cryostat is below 0.5 fT/√Hz. However, the field resolution of such system becomes worse due to additional external noise sources. When MagViz system is working in complete operational mode, its field resolution is about 2.5 fT/√Hz.

Additional noise comes from a few different sources. For instance, RFI shield made of gold-plated Mylar surrounds a dewar and produces 1 fT/√Hz noise although gold plating thickness is only 90 nm. More noise comes from electronics that provide current to coils generating measurement field and gradients during detection time. These increase the noise up to about 2 fT/√Hz. Another unavoidable noise source comes from switching transients and additional feedback circuits for transient suppression. This feedback consists of integrators that take signals from each output and provide strong negative feedback to SQUID sensors at low frequencies [12]. It increases dynamic range of each channel and suppresses low-frequency signals including transients.

IV. Inductive Coil Magnetometers

We have built the first prototype of a coil-based sensor system for MagViz and tested it in exactly the same measuring conditions as used for SQUID-based sensor system. The coil sensor system consists of seven identical induction coils and has the same footprint as SQUID gradiometers. Each coil has 90 mm outer diameter, 20 mm inner diameter and 14 mm height. It consists of 1400 turns of AWG24 ø0.51 mm) copper wire. Its inductance is 70 mH and resistance 20 Ohm. The field transfer coefficient is about 70 V/mT at 3.3 kHz. We used instrumentation amplifiers INA217 as the first stage. It has input voltage and current noise of 1.2 nV/√Hz and 0.8 pA/√Hz, respectively. Such induction magnetometers have magnetic field resolution about 20 fT/√Hz at 3.3 kHz.

In experiments we determined that accurately designed coil magnetometers could reach signal to noise ratio (SNR) up to 30 when SQUID gradiometers have SNR about 100 using exactly same conditions and very close form-factors. For our experimental comparison we used pre-polarization and measurement fields 50 mT and 0.078 mT respectively. Although the intrinsic noise of SQUID sensor is about 40 times lower than coil sensor noise, this difference is not as dramatically large in the real environment when additional external noise is very difficult or sometimes impossible to avoid. Fig. 1 shows power spectrum densities (PSD) graphs for signal recorded using SQUIDs and coils.

The MagViz system [6] characterizes liquids by making measurements of MR relaxation properties at both the pre-polarization and measurement fields. We used a large water phantom to compare coils and SQUIDs using the same NMR measurement protocol. Gradiometer pick-up coils were placed about 30 mm above the water sample (they cannot be placed closer because of dewar warm-cold gap). We recorded NMR echo signals with signal-to-noise ratio (SNR) of 100 in frequency domain at 3–3.6 kHz frequency range. The induction coils were placed right on-top of a water phantom (30 cm diameter and 8 cm height) and showed SNR about 30 at the same conditions. This SNR is good enough to use the coils as an NMR signal detector for liquid identification. We ran a threat detection protocol using MagViz standard hardware and software with the SQUID sensor system replaced with the induction coils sensor system. Fig. 2 shows first results of threat detection using induction magnetometers.

V. Computer Simulations

Significant flexibility is available in coil size, 3D shape, position, etc. and geometry may be optimized for any particular experiment. To assist in design exploration we developed a computer simulation, validated against our experimental data, to predict sensitivity for various configurations.

Fig. 3 shows simulated results indicating the potential for dramatically improved signal detection using induction coils in MagViz or similar applications. Although coils have a shallower sensitivity distribution in comparison with gradiometers, by placing two coils above and below a region of interest we can enhance the signal from deeper sources.

Analytical descriptions of different designs of induction coils can be found in [14]. It includes equations that show that the SNR of coils does not depend on wire diameter. But this is true only for a coil itself without considering other noise sources contributed by electronic amplifiers and AC active losses in pick-up coils at 3–10 kHz frequency range. If we consider a coil and an amplifier together, the optimization process becomes much more complicated. AC active losses can be decreased by using litz wire and optimized winding pattern but results depends on many technical and technological factors that difficult to predict or simulate.

Our estimations show that using the best available amplifiers and better optimized pick-up coils further improvements of magnetometer coils are possible. Assuming that one can build an amplifier with input voltage and current noise of 1 $nV/\sqrt{Hz}$ and 0.02 $pA/\sqrt{Hz}$, respectively, we expect the SNR in MagViz standard scanning mode well above 100. This may allow us replace SQUIDs with room temperature coils for this particular application.

VI. Discussion

While we are enthusiastic about the potential of MagViz-like systems for airport security, we believe the real potential of ULF MRI may extend greatly beyond this application. A simple, mobile, inexpensive MRI system could open up many new markets for MRI. For example, because of the large cost of conventional MRI magnets, many people in resource-poor locations do not have access to MRI. Moreover, the ULF MR approach may provide open MRI systems for emergency rooms and field hospitals. Without any hardware modification at all, the MagViz system has already shown itself to be a capable imaging device [6]. While the spatial resolution remains below that of conventional MRI scanners, we expect this to improve as we increase the pre-polarization field and reduce system noise. For medical imaging applications, it appears clear that field resolution on the order of 1 $fT/\sqrt{Hz}$ (or even better) will be required. Such sensitivity will never be reached by room temperature induction coils at 3–10 kHz range, because of the thermal noise.

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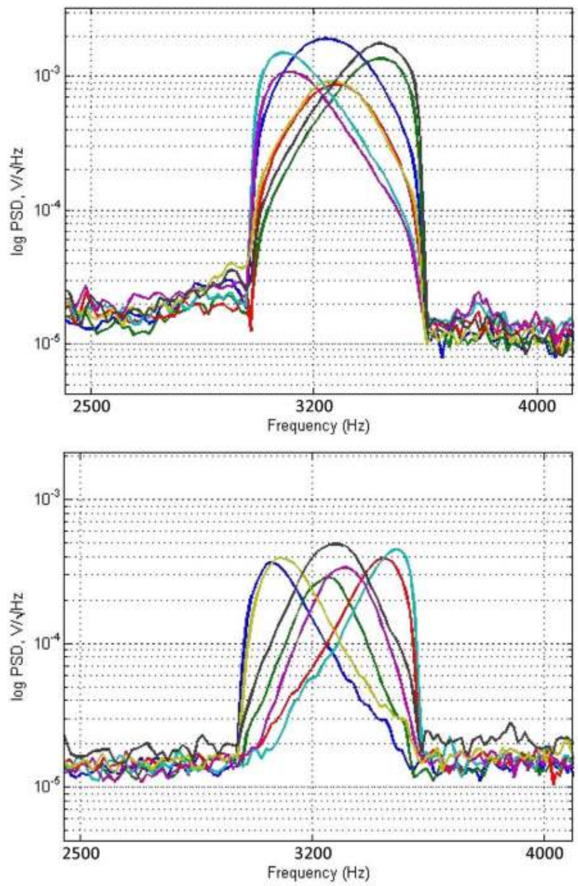

Fig. 1.
Power spectrum density of the first echo signal recorded using the seven SQUID sensor system (above) and the seven induction coils array (below) at the same conditions using a large water phantom (30 cm diameter, 8 cm deep). SNR is about 100 for SQUIDs and 30 for coils.

Fig. 2.

Photograph of items (above) and 2D MR image (below) with threat detection (circle with number 1) and benign liquids (numbers 2 and 3). The circle indicates 40% of hydrogen peroxide inside a bottle. NMR echo signals recorded using the induction coil sensor system and MagViz standard hardware and software.

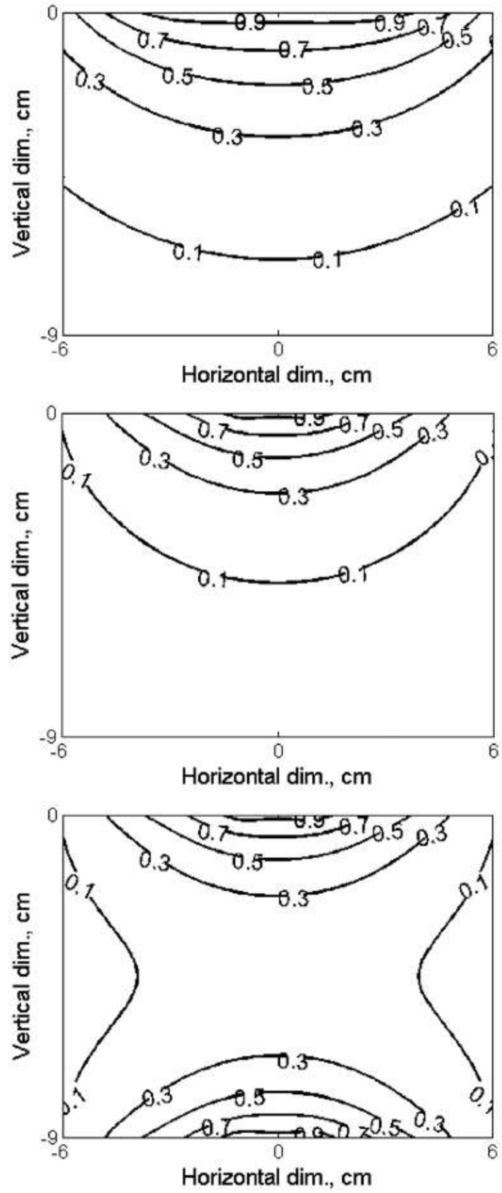

Fig. 3.

Analysis of sensitivity distribution of a SQUID gradiometer (upper figure) and one-coil (center figure) and two-coil (lower figure) sensor systems assuming static permittivity. Contours show fraction of maximum sensitivity. A gradiometer has better sensitivity than one coil, but two-coils on both sides can beat a gradiometer. Such geometry is practically impossible for SQUID-based gradiometers.