LA-UR- 10-05122

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Author(s): Andrei N. Matlashov, Michelle A. Espy, Robert H. Kraus, Igor M. Savukov, Larry J. Schultz, Algis V. Urbaitis, Petr L. Volegov, Caroline J. Wurden

Intended for: Applied Superconductivity Conference 2010, Washington DC, August 1 - 6, 2010

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

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***Abstract*—Nuclear magnetic resonance (NMR) methods are widely used in medicine, chemistry and industry. One application area is magnetic resonance imaging or MRI. Recently it has become possible to perform NMR and MRI in ultra-low field (ULF) regime that requires measurement field strengths only of the order of 1 Gauss. These techniques exploit the advantages offered by superconducting quantum interference devices or SQUIDs. Our group at LANL has built SQUID based MRI systems for brain imaging and for liquid explosives detection at airports 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 provide enough sensitivity in the 3-10 kHz range and can be used for fast liquid explosives detection based on ULF NMR/MRI technique. We describe an experimental and computer simulation comparison of the world's first multichannel SQUID based and Faraday coils based instruments that are capable of performing ULF MRI for liquids identification.**

***Index Terms*— Inductive magnetometers, SQUID, Ultra-low field MRI, Ultra-low field NMR, liquid explosives detection.**

I. INTRODUCTION

RECENTLY it has become possible and practical to perform MR at magnetic fields from μT to mT, the so-called 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]. 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 [7]. 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 [8]. However, for all these applications the main draw-back of the method, the very low signal intensity, was mitigated by pre-polarization [9], [10] 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, and may even be acceptable in airports, such a system 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. In our experience designing a relaxometer for detection of liquid explosives, we have found that a practical sensitivity of 5 fT/√Hz is required for classification of threats. SQUIDs are sensitive to sub-fT magnetic fields, however all other noise sources associated with the ULF MRI hardware increase the background noise to 2-3 fT/√Hz. Based on this information, and some encouraging preliminary results we now believe that a practical ULF relaxometer based on very low-noise induction magnetometers can achieve this level of performance at frequencies 3 – 20 kHz. 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 [11]. 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 system would be suitable for deployment to theatres of war or emergency responders. A coil-based system, however, would be.

II. METHODS

The design of the MagViz instrumentation and the used

Manuscript received August 3, 2010. This work was supported by the US National Institutes of Health Grant R01-EB006456 and by the US Department of Energy OBER Grant KP150302, project ERWS115. The reported study was conducted in compliance with the regulations of the Los Alamos National Laboratory Institutional Review Board for research on human subjects, and informed consent was obtained.

The authors are with Los Alamos National Laboratory, Applied Modern Physics Group, MS D454, Los Alamos, NM 87545,USA (e-mail: matlachov@lanl.gov).

field pulse sequence are shown schematically in Fig. 1; these are similar to what has been described in [2, 6]. The MagViz system uses seven 2[nd] order wire-wound gradiometer pick-up coils, which are 90 mm in diameter; the baseline (coil separation along the gradiometer axis) is also 90mm. The arrangement of the gradiometers is shown in Fig. 1(A). 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 become normal with 350 Ohm resistance. The intrinsic noise of the gradiometers and the commercial cryostat is only about 0.3 fT/√Hz. However, external noise sources increase the total system noise at measurement frequency up to the 2-3 fT/√Hz level. Such noise sources include the gold-plated radio frequency interference shield around the cryostat, the measurement field and gradient electronics, a transient suppression feedback electronics etc.

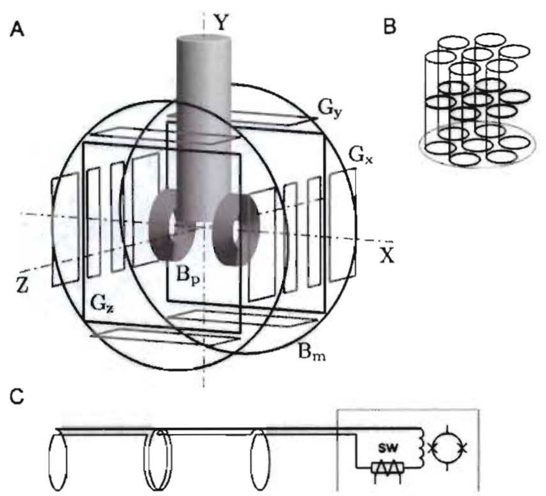

Fig. 1. SQUID-based instrumentation for microtesla MRI and MEG.
(A) General view of the system. (B) Seven second-order gradiometers inside the cryostat. (C) Schematic of one SQUID channel.

The Fig. 2 shows the arrangement of magnetic field generation coils. The pre-polarization coil, generating the field B_p, is cooled by a fluorine-based industrial coolant, Fluorinert™, allowing continuous running without substantial heating. Fluorine was chosen instead of water for cooling to avoid hydrogen background. We do see the 19F signal from the coil itself, but this appears at a frequency removed from our area of interest (γ = 42.6 MHz/T for protons and 40.0 MHz/T for 19F). The B_p coil has 0.34 H inductance and it is capable of attaining pre-polarization fields as high as 50 mT in a sample volume at 35 A current. After some pre-polarization time (ranging from 1-3 seconds) the B_p field is turned off non-adiabatically (with a ramp-down time of 10 milliseconds) and the much weaker measurement field, B_m, is applied perpendicular to B_p to start precession. The intensity of B_m typically ranges from 50 to100 μT (proton Larmor frequencies from ~2kHz to 4kHz). A measurement field echo technique is used to reduce the effects of measuring magnetic field inhomogeneity. The measuring field and gradient sequence is shown in Fig. 2.

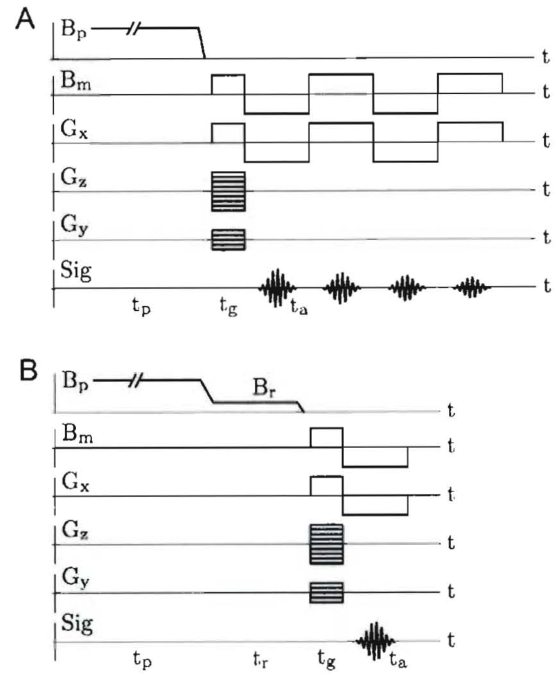

Fig. 2. Experimental procedures for 3D ULF MRI of the human brain. A) Protocol for T_2 measurements. B) Protocol for T_1 measurements (see text).

Such a sequence would be impossible with a conventional MRI system where the measurement field is generated by large permanent or superconducting magnets with fixed field orientations. Gradient field echoes in the *x*-direction are also used. The encoding scheme is based on the 3D Fourier protocol with a frequency encoding gradient $G_x = dB_z/dx$ and two phase encoding gradients, $G_z = dB_z/dz$ and $G_y = dB_z/dy$.

The following imaging parameters were used in the present work: $G_x = \pm 60$ μT/m, $|G_z| \leq 24$ μT/m, 9 encoding steps, $|G_y| \leq$ 7 μT/m, 3 steps, polarization time t_p = 1 s and 3 s, gradient encoding t_g = 50 ms, and acquisition t_a = 85 ms The lowest sequence is that of the NMR echo signal. The actual MagViz hardware is shown in Figure 2. From the sequence described above we determine T_2 and a low- resolution image, 5 mm x 10 mm x 30 mm, is produced. The measurement of T_2 is performed at the lower field value B_m. However, T_1 is determined by repeating the pulse sequence shown in Fig. 2 for two differing polarization times, t_p. The spins are allowed to reach their thermal equilibrium distribution in the polarization field for $t_p \sim 1$ s in the first sequence applied, and then the entire procedure it is repeated with $t_p \sim 3$ s.

The difference in the measured signal amplitude between the two polarizing times, t_p, is then used to determine the value of T_1. Thus we are actually measuring the value of T_1 in the higher (50 mT) pre-polarization field. Such combination of relaxation parameters provides robust parameter space for classification of liquids. To minimize effects of the residual fields and non-uniformity of the measurement field, polarity of the both fields (*i.e.*, of the polarization field and measurement field) is alternated from scan to scan, and the measurement field from echo to echo. To minimize the measurement time the SENSE technique is used [12].

Thus far the MagViz project has focused on high concentration hydrogen peroxide, which is an oxidizer commonly used for improvised liquid explosives. Hydrogen peroxide is a substance expected to be difficult to detect since the chemical structure (H_2O_2) is very close to that of water. Now that the proof-of-concept has been demonstrated, a major objective of the project is to add other materials to the database. The Department of Homeland Security maintains a list of nearly 100 items including oxidzers, fuels, and mixtures that should be excluded from airplanes. These all need to be measured and characterized. Preliminary results indicate that MagViz can also distinguish certain fuels; however this needs to be investigated further. Moreover, we have only scanned between 100 and 200 items from streams of commerce. While the false-positive rate presently is acceptably low (less than a few percent), obviously there are many more types of items carried aboard aircraft. Although we have not observed any significant effect of bottle shape or configuration of bottles on accuracy (other than those related to signal-to-noise for very small bottles or bottles at a depth greater than 100 mm) we need to rigorously study possible effects.

III. Inductive Coil Magnetometers

ULF NMR techniques exploit the advantages offered by superconducting quantum interference devices or SQUIDs. The MagViz system utilizes many of the advantages of ULF MR, in particular exploiting the power of relaxometry to fingerprint materials, the relatively simple MRI instrumentation suitable for a public setting, and the ability to image through non-ferrous metal foils and cans. While relaxometry is used to classify materials as "threat" or "benign", a low-resolution ULF MRI allows multiple bottles to be examined simultaneously and without opening. The requirement of liquid Helium cooling for SQUID gradiometers limits potential applications of ULF NMR for liquid identification in public places. This is why we experimentally tested induction coil sensors at room temperature for recording NMR signals at exactly the same conditions as SQUID gradiometers work in MagViz system.

Accurately designed coil sensors could reach signal to noise ratio (SNR) up to 40 when SQUID gradiometers have SNR about 100. The pre-polarization and measurement fields were 50 mT and 0.078 mT respectively. Although intrinsic noise of SQUID sensor is about 30 times lower than coil sensor noise, this difference becomes not so dramatically large in real environment when additional external noise very difficult or sometimes impossible to avoid. Thus, induction coil sensor with field resolution about 15-20 $fT/Hz^{1/2}$ at 3.3 kHz may become good enough as NMR signal detector used for liquid identification at airport security points using ULF NMR technology. For medical applications of ULF MRI technology SQUID sensors remain the best choice.

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 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 homemade amplifiers with INA217 instrumentation amplifier 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. The system 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 and showed SNR about 35 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. 4 shows first results of threat detection using induction magnetometers.

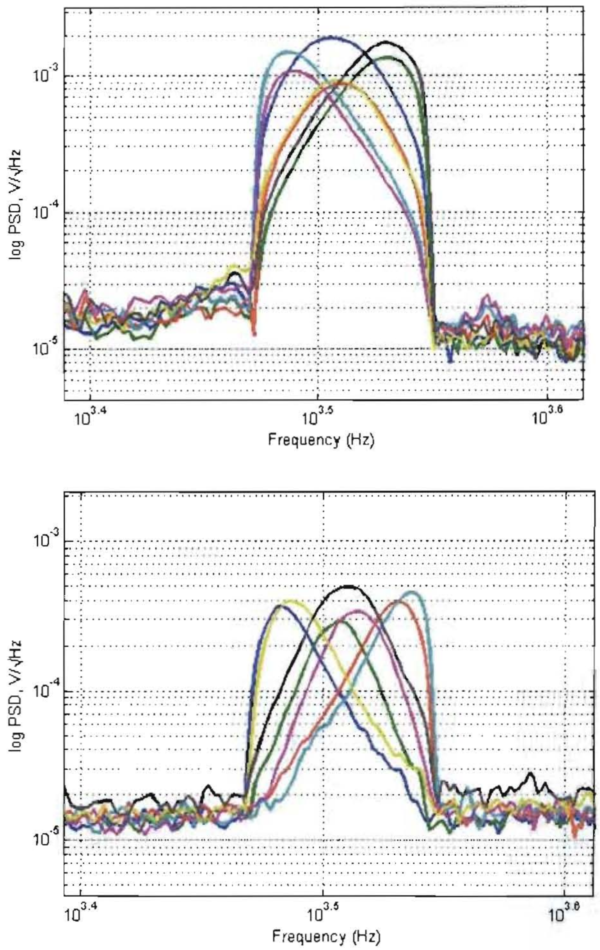

Fig. 3 Power spectrum density of the first echo signal recorded using the seven SQUID sensor system (above) and the seven induction coils array (below) at the same conditions using a large water phantom. SNR is about 100 for SQUIDs and 30 for coils.

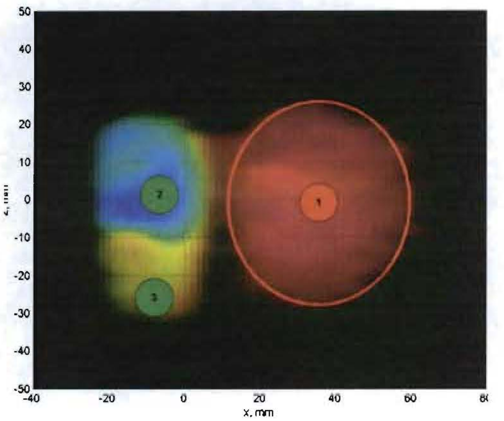

Fig. 4 Photograph of items (above) and 2D MR image (below) with threat detection and benign liquids (green). Red dot and circle indicate 40% of hydrogen peroxide inside a bottle. NMR echo signals recorded using the induction coil sensor system and MagViz standard hardware and software.

Fig. 5 shows our first preliminary simulations indicating the potential for dramatically improved signal detection using induction coils in MagViz. By placing coils above and below a region of interest we can detect signals from deeper sources.

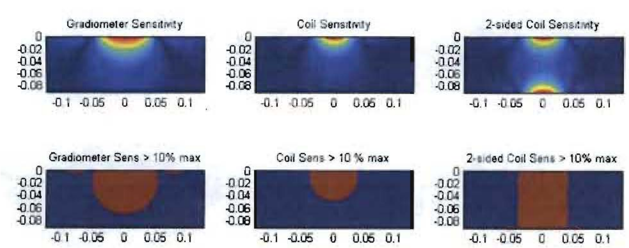

Fig. 5 Computer simulation of sensitivity distribution of a SQUID gradiometer and one-coil (center) and two-coil (right) sensor systems (x and y scales in meters). A gradiometer has better sensitivity than one coil, but two-coils on both sides can beat a gradiometer. Such geometry is practically impossible for SQUID-based gradiometers.

IV. Conclusion

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. 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. The real potential of ULF MRI as a medical research tool is yet to be determined.

Acknowledgment

The authors gratefully acknowledge the support of the U.S. Department of Energy, the U.S. National Institutes of Health and the U.S. Department of Homeland Security for this work. We also thank the members of the SQUID Team as well as the Engineering Team at LANL who contributed to the design and manufacturing of the ULF MRI instruments.

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