Ultra-low Field MRI for the Detection of Liquid Explosives Using SQUIDs

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Abstract – **Recently it has become both possible and practical to perform MR at magnetic fields from μT to mT, the so-called ultra-low field (ULF) regime. SQUID sensor technology allows for ultra-sensitive detection while pulsed pre-polarizing fields greatly enhance signal. The instrumentation allows for unprecedented flexibility in signal acquisition sequences and simplified MRI instrumentation. Here we present the results for a new application of ULF MRI and relaxometry for the detection and characterization of liquids. We briefly describe the motivation and advantages of the ULF MR approach. We then present recent results from a 7-channel ULF MRI/relaxometer system constructed to non-invasively inspect liquids at a security check-point for the presence of hazardous material. The instrument was fielded to the Albuquerque International Airport in December, 2008, and results from that endeavor are also presented.**

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I. INTRODUCTION

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) are ubiquitous tools in science and medicine, providing powerful probes of local and macromolecular chemical structure and dynamics, as well as tomographic imaging. Because signal scales with magnetic field strength, the technological trend has been to higher and higher magnetic fields with Larmor precession frequencies of hundreds of MHz. Although high fields enhance magnetic resonance (MR) signal strength and many forms of image and spectral contrast, they also preclude or place significant restrictions on many potentially important applications. Recently it has become possible and practical to perform MR at much lower fields (from microtesla to millitesla), the so-called ultra-low field (ULF) regime; see for example [1], [2]. The draw-back of the method, the very low signal intensity can be mitigated by pre-polarization [3], [4] and the use of ultra-sensitive detectors such as SQUIDs. The simplified field generation allows flexibility in pulse sequences such as measurement field reversal and the ability to trivially change field strength. In contrast to conventional MRI, relative homogeneity of the measurement field is not crucial, because microtesla-range magnetic fields of even modest relative homogeneity are highly homogeneous on the absolute scale [5]. Improvements in SQUID sensor technology allow ultra-sensitive detection in a pulsed field environment [6]. There are numerous additional advantages to the ULF MR approach including imaging in the presence of metals, open system design, enhanced T_1-weighted contrast [7] and strong magnetic relaxation dispersion exhibited by tissues in the μT – mT field range [8].

We have recently developed several applications of ULF MR including 46 μT imaging of the human brain concurrent with magnetoencephalography [9] [10]), possible ways for direct tomographic imaging of neural currents [11], and preliminary work in the determination of uranium enrichment fraction via relaxation and/or *J*-coupling [12], [13].

II. AIRPORT SECURITY APLICATION: SCREENING

In airport security checkpoints, there is a strong desire to know the chemical content of materials being carried on board aircraft, but this determination must be made quickly and non-invasively. Since 2006, there has been increased concern about the threat of liquid explosives being carried on to aircraft, which has prompted costly and onerous travel restrictions on the volume of liquids passengers are allowed to carry on board.

Presently there are numerous screening technologies deployed and being tested at airport security check-points. However, most of these are looking for hidden weapons (x-ray and millimeter wave) or the presence of material residue from making bombs (mass spectrometry) and most of these methods focus on solids. X-ray is excellent for rapid and non-invasive screening of structure. Recently very sophisticated x-ray machines, such as [14], have been deployed that are able to distinguish liquids from solids. There is evidence that this approach might also be able to identify at least some threat liquids. However, accurate determination of a variety of threat liquids remains speculative. X-ray methods rely not on detection of chemical signature but on density and atomic number, which is more indirect. Moreover, the approach may have difficulties achieving sufficiently low alarm rates in case of complicated bottle shapes.

Mass spectrometry, which does give chemical structure, presently relies on either opening bottles up in the case of liquids, or swiping surfaces. Raman scattering, in which the frequencies and intensities of Raman-scattered photons reflect the conformation and electronic states of the probed molecule, can also provide a chemical signature. Electromagnetic methods based on multi-frequency microwave evanescent field sensors [15] measure the conductivity and dielectric relaxation of liquids, to provide a chemical fingerprint in a very short amount of time (~ 1 s). However, liquids in metal and metalized containers cannot be inspected by this technique. These approaches are all limited to single bottles, which makes luggage screening impractical. Single bottle approaches are more suitable for random checks. NQR or "zero field" NMR has been investigated for the detection of solid explosives, including SQUID-based approaches; see for example [16-20]. Thus far, none of these approaches has been widely fielded.

An important benefit of the MR approach is the ability to probe chemical structure. Indeed, MR spectroscopy is an ideal technology for screening liquids. However, conventional instrumentation, employing magnetic fields > 1T, presents an unacceptably large risk to the public. Presently, owing to lack of another screening technology, airport rules require that all of a passenger's carry-on liquids be contained in 3-ounce bottles and that all of the bottles be placed in a single one-quart, zip-lock bag.

In this paper we present a ULF MR imager and relaxometer [21] known as "MagViz" that was designed for the non-invasive inspection of liquids at an airport security checkpoint. 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. We show examples of performance, and report on this system's demonstration at the Albuquerque International Airport.

III. PRINCIPLE AND APPROACH

Magnetic resonance imaging is an imaging modality used to construct images based on the NMR signal from the spin-polarized nuclei in an object. In medical MRI, radiologists are most interested in looking at the NMR signal from water and fat, the major hydrogen containing components of the human body. In the case of MagViz, we have also focused on the hydrogen in liquids, thus measuring the proton resonance. However, because the SQUIDs are operated as untuned detectors, other nuclei can be detected as well. The principle behind all magnetic resonance imaging is the resonance equation, which shows that the Larmor (resonance) frequency v of a spin is proportional to the magnetic field, B_o, it is experiencing:

$$v = \gamma B_o .$$

The use of gradients allows for spatial encoding of the spins to produce an image; see for example [22]. In addition to imaging the bottles, MagViz must make a chemical identification of the material inside. At ULF it is not possible to resolve different spectral components in the frequency domain by chemical shift, and thus the technique exploits information in the time domain. Our approach to ULF spectroscopy relies on measurement of the relaxation parameters, T_1 and T_2, to provide information on the physical and chemical properties of the sample, an approach known as relaxometry. Relaxometry at low fields, ~ 0.1 T is frequently used in industrial applications where the instrumentation can be made quite simple with permanent magnets. MagViz operates as a ULF relaxometer for chemical identification. While the detectors are more complicated, due to the cryogenic cooling of the SQUIDs, the instrument has the advantages of very simple magnetic field generation hardware, low magnetic fields, low Larmor frequencies (at which signals can penetrate through metal cans, pipes, foil packaging), and enhanced contrast as described above.

Local magnetic field fluctuations, *e.g.*, due to particle motion, matching the spin Larmor frequency cause relaxation. The longitudinal or spin-lattice relaxation, T_1, involves redistributing the populations of the nuclear spin states to reach the thermal equilibrium distribution by energy exchange with their surroundings. The transverse or spin-spin relaxation, T_2, corresponds to decoherence of the transverse nuclear spin magnetization caused by random fluctuations of the local magnetic field [23]. The T_1