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14. ABSTRACT

Recent collaborative work with the Naval Research Laboratory (NRL) to improve explosive detection using nuclear quadrupole resonance (NQR) is summarized. The work includes studies of the effects of imperfections in gradiometer coil design on radio-frequency (RF) interference mitigation and preliminary work on the use of cooled and superconducting coils for explosive detection. Additional studies involving slowly rotating NQR measurements were also pursued.

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Scientific Support for NQR Explosive Detection Development

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Scientific Support for NQR Explosive Detection Development

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This is the final report for the grant N00173-04-1-G011 which was based on a proposal submitted in response to NRL Broad Agency Announcement BAA 61-03-04, "Innovative Applications of Magnetic Resonance." This grant is for work related to the development of better explosive detection methods and techniques using nuclear quadrupole resonance (NQR), done in collaboration with Garroway's (now Miller's) group at NRL. The two-year grant start date is recorded as 8 March 2004. Only partial funding for the second year was received.

Three specific projects were proposed for study at MTU: Three-dimensional (3D) modeling of coil designs, two-photon NQR theory, and an investigation into the prospects for the use of High-T_c superconducting coils for explosive detection. We have also reexamined some previous NQR work done on rotating samples.

The vast majority of this work has already been communicated to the NRL group and is only summarized here.

3D RF Coil Modeling

One of the major problems which has been impeding the routine implementation of NQR for land mine detection has been high levels of omnipresent radio frequency interference (RFI) present in the field. This RFI can be addressed by keeping it out of the system in the first place through the development of RFI-immune NQR coils and/or through the use of signal processing later in the receiver chain. Due to the large magnitude of the interference, an appropriate solution will undoubtedly involve a combination of these techniques. We have concentrated on developing RFI-immune NQR coils.

We have used Ansoft's 3D modeling package (available through MTU's Electrical Engineering Department) to investigate imperfections in coils. In particularly, we have looked at small symmetry-breaking effects for axial gradiometer coils. The work was done with very simple coil configurations (e.g. a single driven loop) which can be compared with known results, and then proceeded with more complicated configurations (e.g. gradiometers) over soil.

Figure 1 shows graphically the results of calculations for a simple 2-coil gradiometer (an anti-Helmholtz arrangement) to estimate the changes in the sensitivity of the coil for far-field interference reception in the presence of small imperfections in the coil. The far field pattern was computed and the worst case direction of propagation was chosen to estimate the potential for interference reception. This value represents the worst-case potential interference pick-up (in practice one does not know if there will be a source of noise in that direction). One can see that even a very small imperfection can cause a 30 dB change in potential interference pick-up.

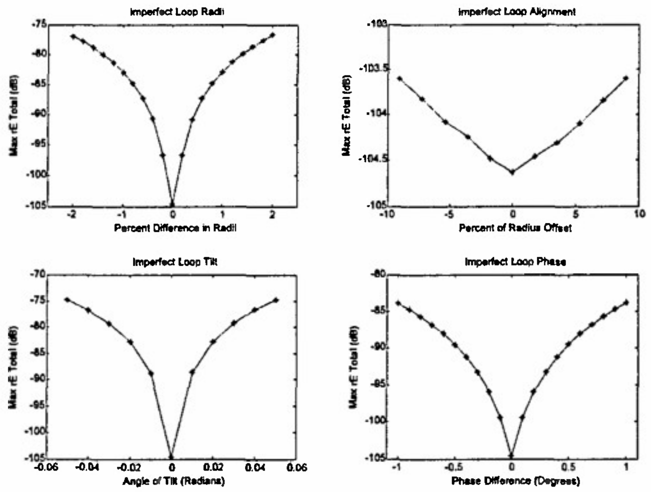

Figure 1 - The relative far-field sensitivity changes (Vertical Axis) for different imperfections of the anti-Helmholtz gradiometer. Determined using Ansoft's 3D software. Upper Left: Coil radii differ, Upper Right: a horizontal translation of one coil relative to the other, Lower Left: planes of coils are not parallel, Lower Right: an electrical phase difference between the currents in the two coils.

We have also looked at the effects of the soil. We have found, not surprisingly, that as conductivity is varied there is a transition from "vacuum-like" behavior to "perfect conductor - like" behavior. Figures 2 and 3 show this for a range of ground dielectric constants, ε. With larger dielectric constants we clearly see the formation of the ground wave mode of propagation and a shift in the transition region. The fact that soil has a relatively large dielectric constant (5 to 10) is turning out to be of significant consequence. The transition region occurs for

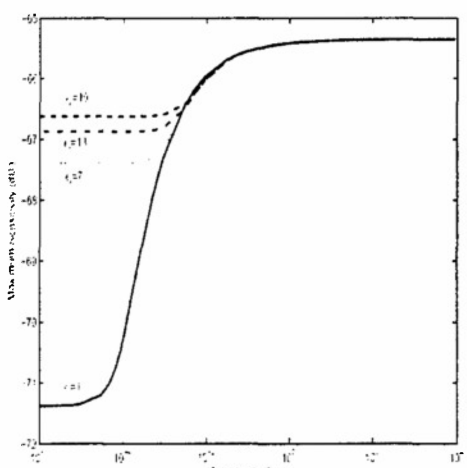

Figure 2 - The maximum sensitivity to far-field signals of a simple gradiometer for different soil conditions.

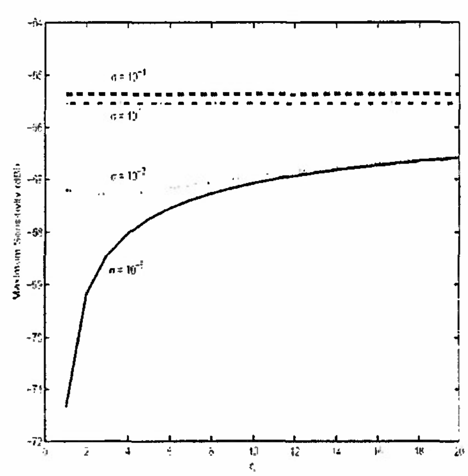

Figure 3 - The maximum sensitivity to far-field signals of a simple gradiometer for different soil conditions.

combinations of soil conductivity and dielectric constant which are "typical" for soils. That is, the reception of far-field interference can be expected to depend strongly on the soil type.

We also investigated the need for the full 3-D calculation for the far-field results for a gradiometer over soil. It appears that quite adequate results are obtained using combinations of magnetic dipoles to model the coils and complex image theory to include the ground effects. The full 3-D technique may still be needed to obtain accurate results very near the coil, but they do not seem necessary for far-field results.

The 3-D modeling work is summarized in more detail in the Master's thesis of Adam J. Webb (MS Physics, MTU, Fall 2005). A copy of his thesis was sent to the NRL group and is also available through the Michigan Technological University Library.

Two-photon NQR Excitation

This work was to be coordinated with an NRL post-doc who was to perform experiments. That position was not filled and so the this theory work was put "on hold." We note that some recent work with cross-coil detection of spin-3/2 NQR was recently reported by Eles and Michal.[1]

Superconducting Coils

A major concern for the design of a receiving coil for NQR is the coil's quality factor, Q, since the signal to noise ratio (SNR) of the NQR signal scales proportional to $Q^{1/2}$. The Q of the coil is determined by the ratio of the inductive impedance of the coil to its resistive impedance. Superconducting coils will have a very low resistive impedance and hence can be expected to have a very high Q. With the development of high temperature (High-T_c) superconducting wires ("tapes") which can be cooled quite cheaply using liquid nitrogen, it is appropriate to investigate the practicality of using a coil designed using High-T_c materials for the detection of NQR signals. There are, however, some significant practical disadvantages of such a coil as well.

A number of groups have used High-T_c wire materials to make magnetic resonance coils. In some cases they achieved a surprisingly *small* increase in Q (up to only about 1000 at 5 to 10 MHz).[2] It is not clear why this may happen, though in all cases they used a solder connection to a capacitor, which could limit the Q. In addition, in at least one case the coil was unshielded. An unshielded coil can interact with its surroundings in a way which can dramatically decrease the coil's Q. For comparison, Shiano, *et al.*, has been able to achieve a Q of over 100,000 at ~3 MHz with a self-resonant High-T_c coil made by deposition on a substrate.[3,4] (Note that NQR results have now been obtained using these High-T_c coils and are reported in ref. 3).

Our first attempts to make a superconducting RF coil from superconducting tape failed. The tape we obtained was from American Superconductor and reportedly has a Ag (or Ag alloy) sheath. In order to use these coils at radio frequencies (RF) the sheath has to be (mostly) removed. The procedure outlined by Grasso, et al.,[5] was tried, however even after several hours, the sheath was not removed. According to the description the process should have taken only a few minutes. After substantial searching, we found an alternate technique involving a pre-treatment with nitric acid. That method was originally intended to remove the sheath in order to make superconducting joints between such wires, discussed by Huang, et al.,[6,7] and not to make magnetic resonance coils. The most detailed description of the technique we have been able to find is within US Patent 5,882,536, "Method and etchant to join ag-clad BSSCO superconducting tape." This involves a pre-treatment with concentrated (~ 30%) nitric acid followed by an etch made with roughly equal mixtures of concentrated Ammonia (~30%), Hydrogen Peroxide (~30%), and water.

We have acquired the chemicals to try this with our superconducting tape and are awaiting the availability of an appropriate fume hood. Due to some building construction, this has been delayed. The fume hood should be available later this summer (2006).

Several test coils have been made using copper ribbon of almost the same dimensions as the superconducting tape. The idea is to mimic the spiral coils made by deposition[8] using a spiral of ribbon and adding small capacitors which help to lower the frequency and at the same time provide support. The first batch included a spiral coil with six turns, i.d. 21 cm, o.d. 26 cm, with 1500 pF surface mount capacitors (Murata 2000V Monolythic Ceramic Chip Capacitors from Mouser Electronics) every 10 cm along the wire (a total of 36 capacitors). At room temperature his coil resonated at 985 kHz with a Q of just under 60. With the outer turn removed, the frequency went only up to 1080 kHz, a surprisingly small increase, with a Q of about 55. When this coil was placed in liquid nitrogen, no clear resonance could be seen. This suggests that the capacitors used here do not behave well when cold. The change in the capacitors seems to be reversible upon warming, however they are clearly unsuited for use with the superconducting material. Clearly, the effect of the capacitors will become very important for this application.

We have also spend some effort trying to understand earlier experimental results of Garroway using our simple copper coil immersed in liquid nitrogen. He observed that in practice, the increase in signal to noise upon cooling was significantly less than one expects based on simple arguments. One possible source which was identified was the tuned circuit used for transmit/receive switching. Since that circuit is typically optimized for signal rejection during transmit rather than maximum signal transmission during receive, it is easy to lose ca. 1 dB of signal at that point. Since we were unable to identify the particular circuit used, we could not test this for the previous measurements, however using a tunable pi-network it was found that a signal loss of ca. 1 dB could certainly be present in such a case. The signal loss in this case is best described as being due to impedance mismatch (i.e. inefficient coupling) rather than resistive loss, but the net effect is the same – a loss in signal relative to noise.

NQR of Rotating Samples

We also reexamined some older NQR data taken while the NQR sample was rotating at slow rates (~ 1 Hz). The experimcnts are the "reverse" of those done by Hill and Yesinowski[9] in that Hill and Yesinowski used a situation with a nuclear electric quadrupole perturbation of a large Zeeman interaction whereas our measurements were for a Zeeman perturbation of a large nuclear quadrupole interaction. These are spin echo experiments using spin 3/2 nuclei. When the sample is in a small magnetic field (10-100 G) there are significant changes in the spin echo amplitude even for very small rotation rates. Since the sample has moved very little during the measurement (~ 1°) similar results can be expected for other motions, such as for transverse vibrations, which appear similar to a 1° rotation on the time scale of the measurement. These results may be significant for NQR imaging (or "localization") schemes and to some signal enhancement schemes which use magnetic fields, when those schemes are applied to moving samples.

This work was presented as a poster at the 2005 Rocky Mountain Conference and was recently accepted for publication in Journal of Magnetic Resonance (currently listed as "in press," copies are available online). We noticed that this technique may also be useful to help determine the asymmetry parameter for spin 3/2 nuclei in powder (polycrystalline) samples. The underlying physics will be somewhat different for spin 1 nuclei, such as those used for (most) explosives detection, and this might be a subject to pursue in the future.

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