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A feasibility study on underground nuclear magnetic resonance detection using cooled coils and pre-polarization field

Tingting Lin
College of Instrumentation and Electrical Engineering, Jilin University, Changchun 130061, China
ttlin@jlu.edu.cn

Yi Zhang
Peter Grünberg Institute (PGI-8), Forschungszentrum Jülich (FZJ), D-52425 Jülich, Germany
y.zhang@fz-juelich.de

Yong-Ho Lee
Korea Research Institute of Standards and Science, Daejeon 305-340, South Korea
goodsquid@naver.com

Jun Lin
College of Instrumentation and Electrical Engineering, Jilin University, Changchun 130061, China
lin_jun@jlu.edu.cn

SUMMARY

Applying surface nuclear magnetic resonance (SNMR) principle to underground environment (UNMR), *e.g.* in tunnels and mines, one faces a major challenge of using small size of transmitter/receiver (Tx/Rx) without compromising sensitivity. In order to detect UNMR signals, we propose the use of a cooled Rx coil at 77 K to improve the receiver system sensitivity and the introduction of a pre-polarization field B_p with Tx to increase proton magnetization. A cooled Rx coil system was optimized and reached a field sensitivity of 2 fT/√Hz at Larmor frequency of the earth field (~0.05 mT), which is 3 times better compared to the sensitivity at 300 K. Applying B_p from 0.05 to 0.25 mT in the simulated realistic conditions, the amplitude of free induction decay, *i.e*, signal-to-noise ratios, could be enhanced proportionally to B_p. In addition, $B_p + B_{ac}$ (traditional alternating current pulse) in the shield room by using larger water volume have been tried. The forward and inversion modelling were performed concerning ac sequence to locate the water aquifer and evaluate the water volume. This feasibility study suggested that to use B_p(with or without B_{ac}) combined with a cooled coil enable the reliable acquisitions of UNMR signals in underground conditions, especially when the noise condition is unsatisfied.

Key words: Pre-polarization; Cooled coil; SQUIDs; UNMR; alternating current; *Q*-switch

INTRODUCTION

Surface nuclear magnetic resonance (SNMR) is a widely-used technique for the identification of shallow hydrogeological information using single or multi-channels. In usual SNMR measurements, one uses alternating current (ac) pulses emitted by a large-size Tx loop (typically 100-150m) at Larmor frequency (f_L~2 kHz). A tilt angle is therefore generated between the earth magnetic field (EMF), i.e., measurement field B_m of about 0.05mT, and the proton magnetization (M), thus starting the proton precession. Here, a free induction decay (FID) signal is induced across a coincident loop or separate receiver loops (Rx) due to a relaxation of the deflected hydrogen protons. Essential kernel functions for forward and inverse modeling are derived to interpret the recorded data. The water fraction can be estimated by the initial amplitude of the FID signal, while the size of the pores containing the water can be determined by the decay rate of FID signal in homogeneous (T_2*) and inhomogeneous (T_2) locations.

As the only established geophysical technique to detect and quantify ground water, the SNMR method can be very helpful for performing safe underground mining and tunneling operations. However, in the underground nuclear magnetic resonance sounding (UNMR), there are several technical issues to be considered: 1) the size of the Tx/Rx coils is can not be made large due to limited dimensions of the tunnel or mine, which are typically from 2 m (mine) to 6 m (tunnel) in diameter. Smaller size coils thus reduce the detection distance (D), which is proportional to the Tx/Rx diameter. 2) Low water content in fractured rock aquifers reduces the detected signal amplitude. 3) High environmental noise generated from the ongoing work activities further reduce the SNR. Until now, there is only one report about UNMR. Greben *et al.*,[2011] used a 3m × 3m coincident coil with 128 turns in tunnel environment. However, no signal was observed, because the real signal with low amplitude could not be separated from the noise.

To solve the problems in UNMR mentioned above, we refer to low measurement field (LF) (<1 mT) nuclear magnetic resonance (NMR), whose principle also can be applied to UNMR. In LF-NMR, a low f_L leads to a low induction voltage across the Rx loop according to Faraday's law of induction, thus reducing the signal-to-noise ratio (SNR) of measurements. A prepolarizing field B_p is needed to enhance M of the objects under test, *i.e.*, the SNR of the measurement. The FID signal is proportional to the strength of B_p at a certain f_L. Here, B_p should be perpendicular to B_m.

Another way to improve the SNR of LF-NMR measurement is to increase the sensitivity of pickup sensors. High- critical temperature (high-T_c) superconducting quantum interference devices (SQUIDs) with a sensitivity of 40 fT/Hz$^{1/2}$, and low-Tc SQUIDs with a few fT/Hz1/2 were used. Recently, low-Tc SQUIDs were employed as receiver sensors for a SNMR experiment. Owing to its high field sensitivity, SQUIDs (pickup area < 0.4 mm^2) could detect the SNMR signals down to 20 meters, when a 50-m diameter circular loop was used as the ac Tx loop. This work is expected to open up a new field for the application of SQUIDs to SNMR technology.

In this paper, we describe a feasibility study for UNMR using an additional B_p and a liquid nitrogen cooled coil as an Rx, whose sensitivity is comparable to the low-T_c SQUIDs at f_L ≈ 2 kHz.

2 Considerations for UNMR

Fig.1 shows a possible working condition for UNMR. Fissure water near the drilling forefront is the main threat to the safety of underground mining and tunneling operations. Similar to SNMR arrangement, a Tx coil with large size inside the mine or tunnel, and an Rx array with a smaller coil diameter is required to get 2D or 3D information of the invisible aquifer. Therefore, achieving high field sensitivity with the small-size

Rx is important. To amplify UNMR signals, the Rx coil is connected to a capacitor to form a resonant circuit at f_L. Its quality factor (Q) is an important parameter for the Rx's sensitivity. An effective method to improve sensitivity is cooling the Rx coil, thus reducing its resistance, i.e., enhancing Q ($Q = \omega L/R_s$). Here, ω represents Larmor frequency; L and Rs are the inductance and dc resistance of the coil, respectively.
Next, we discuss a possibility to introduce B_p to a Tx coil in order to increase the magnetization of the proton. Based on the typical parameters of the portable SNMR instruments, we assume that our Tx coil resistance is 6.6 Ω and the excitation current is 150 A. The maximal diameter of the Tx coil is then about 2 m with 45 turns in a mine, and about 6 m with 15 turns in a tunnel, both for a wire diameter of 2 mm.
Now, we discuss the relation between the amplitude of B_p, diameter of the Tx and detection distance D, as shown in Fig. 2. At D = 2 m, B_p reaches 0.75 mT (15 times of EMF) and 0.2 mT (4 times) for Tx diameter of 2 m and 6 m, respectively. At D = 5 m, B_p decreases to 0.1 mT (2 times) for both coils. When B_p < 0.1 mT, SNR does not increase appreciably with the application of B_p. Obviously, the Tx with 2 m diameter can generate larger B_p than that with 6 m diameter within 5 m distance. When B_p is applied with 1 m diameter Tx (90 turns), it reduces rapidly with D. For example, at D=4 m, B_p decreases to 2 times of EMF. Considering both the detection distance and signal strength, a Tx coil of 2-m diameter seems to be optimum. Thus, the B_p vs. D curve of the 2-m diameter Tx was used as the basic data for our following feasibility study. For applying B_p in the following feasibility study to simulate a 2-m diameter Tx coil conditions, B_p = 0.25 mT (D=3.5 m) and B_p = 0.125 mT (D=4.5 m) will be used.

3 Measurement setup

The UNMR feasibility study was performed inside a magnetically shielded room. The measurement arrangement is schematically shown in Fig.3. It consists of three parts: (I) a Helmholtz coil pair for the generation of the B_m; (II) a cooled Rx coil for FID signal; and (III) a solenoid coil surrounding the water sample for applying B_P. The sensing directions of cooled Rx coil, B_m and B_p are perpendicular to each other. The Helmholtz coil pair with1 m diameter provides a B_m of 48.85 μT (EMF), which determines the Larmor frequency f_L=2.075 kHz. The volume of the water sample and the size of Rx are scaled down for this feasibility study, as compared to the real UNMR dimensions shown in Fig.1. Two-liters of tap water inside a cylindrical container with a diameter of 13 cm and a length of 20 cm are located in the center of the Helmholtz coil pair. The Rx coil is cooled to liquid nitrogen temperature (77 K) using a styrofoam container. A one-layer solenoid coil (wire diameter 0.4 mm, inductance 7.2 mH) is employed to generate a B_p of 3 mT A^{-1}.
Fig.4 shows the measurement sequence: each measurement starts by polarizing the sample in a B_p field for t_1=4s. When B_p is switched off, a transient ringing effect is encountered due to the large inductance of the Rx coil. To damp the ringing, we used a Q-switch circuit which the preamplifier from the resonance circuit for a short period of time [*Dong et al.*, 2009]. After a delay of a dead-time Δt, in which the ringing is completely suppressed, the sample is left in measurement field B_m and starts procession. Subsequently, the FID signal is detected by the cooled Rx and recorded with a dynamic signal analyzer HP35670A. To improve SNR, the sequence of the measurement can be repeated, and the acquired FID signals are averaged. A transient alternating current (B_{ac}) pulse for recovering the FID signal can also be applied through the Tx coil, see Discussion section.

Figures and Tables

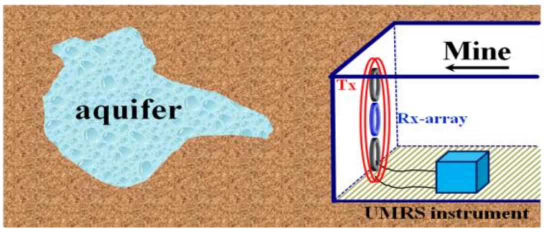


Fig.1 Illustration for UNMR working environment for detecting fissure aquifer in mine; the Rx coils were shown as array configurations

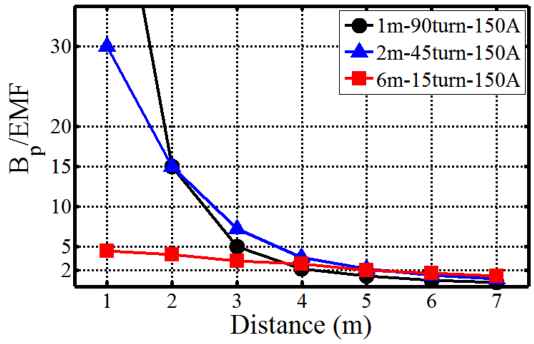


Fig.2 the amplitude of B_p *vs*. detection distance (D) using Tx coils with a diameter of 1 m, 2 m and 6 m, respectively. B_p is in unit of EMF.

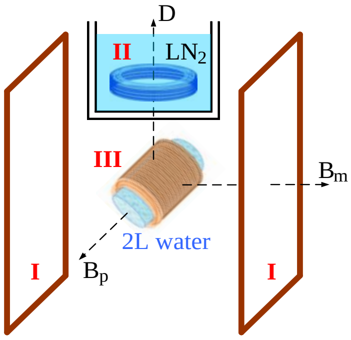


Fig.3 measurement setup for our down scaled UNMR model

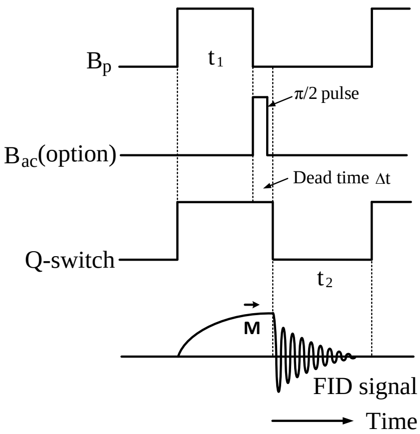
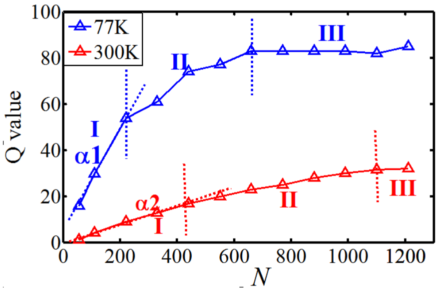


Fig.4 Recommended pulse sequence for UNMR model

For the Rx coils, enameled copper wire with 0.4 mm diameter was selected. For this wire diameter, the skin depth effect at 2 kHz can be neglected. Uniformly wound and layered coils with an average diameter of 12 cm and height of 2.2 cm were used. The number of coil layers was varied from 1~22, corresponding to a change of N from 55~1210 (55 turns /layer). Q *vs*. N is shown in Fig.5a for two different temperatures. As we expected, Q values at 77 K are higher than those at 300 K at each N. For clearly show the Q performances, we divided the result to three range: I) a linear range ($Q = \omega L/R_s$), in which Q increases rapidly with increasing N. II) transition range ($Q < \omega L/R_s$), in which Q increases non-linearly with N. III) saturation range **(**$Q << \omega L/R_s$), where Q remains almost constant, because the parasitic capacitance of the coil becomes large. The maximum Q value at 77 K is about 83 when $N > 660$, as compared to about 33 at 300 K when $N > 1100$.

To optimize the combination of coil parameter and preamplifier, we investigated system noise contribution from different preamplifiers (the calculation details can be referred to our recent publications, *Lin* et al. 2014). Fig. 5b shows a comparison of the calculated and measured system sensitivity B_n. The measured data at 77 K and 300 K using preamplifier OPA124. We see that a discrepancy exists for $N \geq 440$ at 77K and ≥ 990 at 300 K. The minimum B_n is about 2 fT/Hz$^{1/2}$ at 2 kHz at 77 K, while it increases to 6 fT/Hz$^{1/2}$ at 300 K. These sensitivities are comparable to the sensitivity of low-T_c SQUIDs, though the coil pickup area is larger than that of the SQUIDs.

(a)



(b)

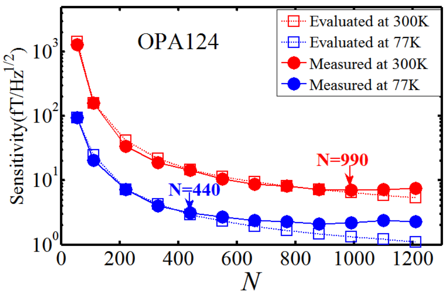
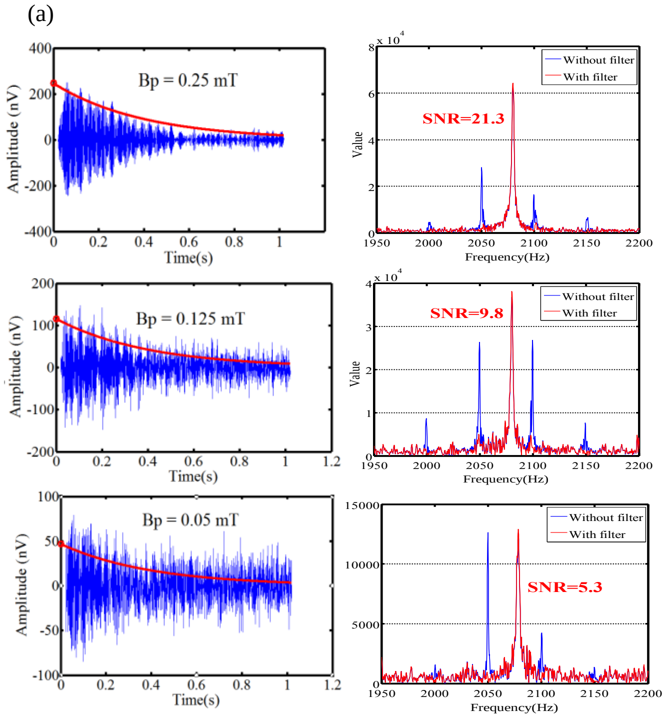


Fig.5, measured and evaluated data using a liquid-nitrogen cooled coil with a diameter of 12 cm. (a) measured Q *vs*. N at 77 K and 300K; (b) system sensitivity comparisons between evaluated value and measured data at 77 K and 300 K with OPA124.

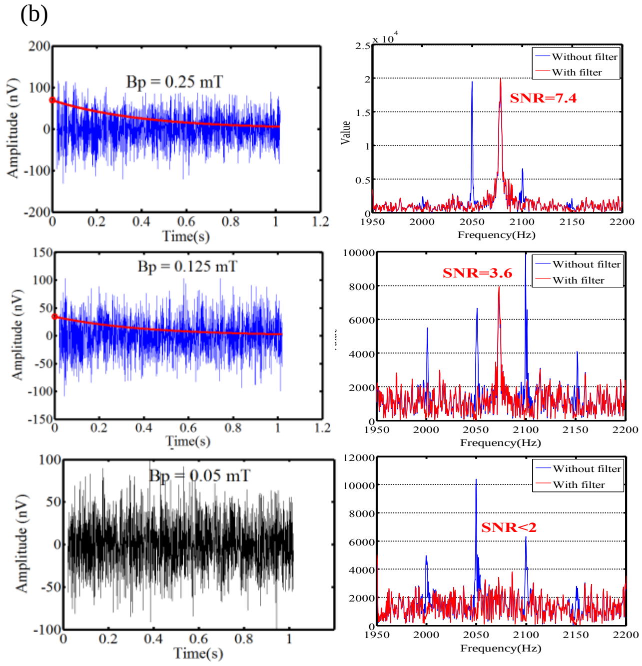
4 Results

We observed FID signals and its spectra at different B_p and different D at 77 K and 300 K. Firstly, we kept D= 10 cm and Rx at 77 K while the B_p was changed by three different values ranged from 0.05~0.25 mT (see Fig. 6a) to demonstrate the initial amplitudes changes with B_p. At B_p =0.25 mT, a clear FID with high SNR of 21.3 was observed in the spectrum. An initial amplitude of E_0 = 249 nV and T_2*=533 ms were fitted after de-noising process [*Müller-Petke et al.*, 2012], respectively. The shorter T_2* value can be attributed to the inhomogeneity of the Helmholtz field. With the reduction of the B_p field, E_0 of the FID signal decreased proportionally, *i.e.* leading to a SNR of 10 in spectra at B_P= 0.125 mT to 5 at B_P= 0.05 mT.

(a)



(b)



Both the E_0 and SNR at 300K (Fig. 6b) decreased about 3 times as compared to the results of Fig. 6a at 77 K. It should be noticed that the SNR reduction is due to the 3 times higher system noise. Furthermore, the FID signal at B_p = 0.05 mT was is quite noisy, leading to a SNR < 2. In SNMR, one generally accepts that data with SNR $\geq$ 2 are reliable.

(c)

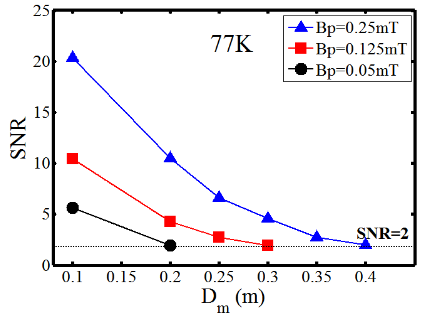


Fig.6, measured FID signal (*left column*) and its corresponding spectra (*right column*) applied for three different B_p at 77K (a) and 300 K (b). All data were averaged 32 times, f_L= 2075 Hz. The red curves in spectra were de-noised by using a notch filter and a digital band-pass filter (200 Hz off f_L). (c) Dependence of SNR on the measurement distance (D_m) for different values of B_p.

Secondly, we varied D from 0.1 to 0.4 m using three different B_p as above (Fig. 6 c). It is demonstrated that the measureable distance D_m with SNR ≥ 2 could be augmented with increasing B_p. At B_p =0.25 mT, D_m increased to 0.4 m, which is twice of the coil diameter. At B_p =0.05 mT, D_m reduced to 0.2 m (Rx diameter). Thus, application of B_p for detecting larger D_m is verified. Because the inhomogeneity of the Helmholtz field in laboratory environment is inevitable, the D_m is expected to increase in field applications, in which the EMF is more homogeneous.

Our concept of adding B_p and a cooled Rx coil, can enhance SNR in UNMR measurements with an improvement ratio (R_I):

$$R_I = \frac{SNR_{(77K)}}{SNR_{(300K)}} = \frac{B_{n(77K)}}{B_{n(300K)}} \times \frac{B_p}{EMF} \qquad (1)$$

Where $SNR_{(77K)}$, $SNR_{(300K)}$, $B_{n(77K)}$ and $B_{n(300K)}$ are the UNMR detection SNRs and system sensitivities at these temperatures. Indeed, R_I >10 is demonstrated in our feasibility study.

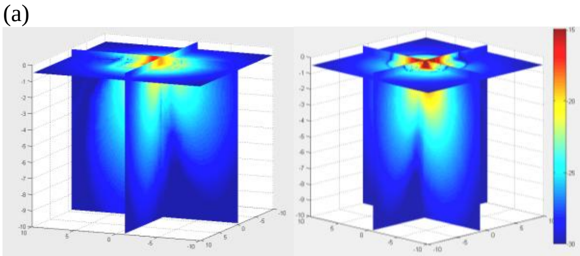
5 Discussion and Conclusion

From Fig. 6, it is clearly showed that B_p will allow for enhancement of SNR and larger distance D. Therefore, the main UNMR difficulties of using small size coil for longer detections and acquiring low SNR for the fissure water could be solved simultaneously. Also, B_p could enable the signal detection for UNMR especially when the environmental noise is dominated. Based on our assumption that the maximum current and voltage for the instrument is 150 A and 1000 V, we can anticipate advanced detection in 4.5 m for UNMR, when the advanced water volumes are scaled up. If the instrument transmitting capacity could increase to 400 A and 4000 V, detected FID signal within 15 m by using effective B_p (B_p≥2 times of EMF) is also possible.

By successfully developed the down scaled UNMR system, we showed the receiver system optimization way for both of the 77 K and 300 K coils. For reducing the total system noise by cooling the Rx coil, we can benefit from the following aspects: 1) the 3 times lower system noise for detect FID signal is achieved when the external environmental noise is low enough; 2) higher system sensitivity of 77 K can be reached at fewer N, *i.e.*, less inductance L, thus leading to the reduced dead-time Δt. As a result, the capacity for UNMR system to detect silt-bound water for shorter dead-time can be easily at 77 K, which could be helpful for preventing the mud and sand gushing disasters.

Due to the inclination angle of the earth field against the measurement surface, B_p is not necessarily perpendicular with EMF in the field measurement. This can make the magnetization M of the sample start to process with a reduced initial tilt angle after B_p is switched off, thus reducing both E_0 and T_2* significantly. To recover the signal, an ac pulse can be applied to increase the initial tilt angle (see the option of Fig. 4). Furthermore, to get depth information of the water distribution in UNMR, we can apply the typical ac scheme of SNMR. *i.e.*, numbered acquisitions pulse moment defined by ac current multiplied by duration time. As a result, water content (E_0) and T_2* for each layer are acquired, which is expected to improve the aquifer localization and characterizations. When ac and B_p working schemes are combined, new kernel forward models and inverse algorithms for UNMR need to be established (Fig.7).

(a)



(b)

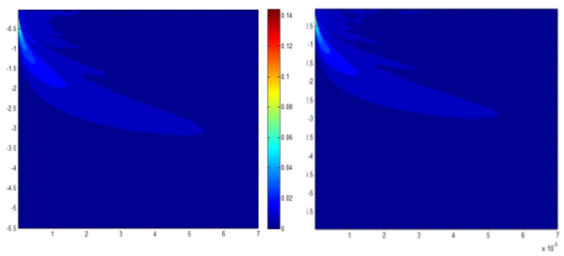


Fig.7 3D (a) and 1D (b) kernel functions of *B*ac pulse without (*left column*) and with (*right column*) B_p. By setting up this model, we assume to use 0.5 m Tx/Rx loop, 60 turns. The maximum current is 30 A for B_p.

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