Postmortem analysis of a failed liquid nitrogen-cooled prepolarization coil for SQUID sensor-based ultra-low field magnetic resonance

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Abstract

A liquid nitrogen-cooled prepolarization (B_p) coil made for ultra-low field nuclear magnetic resonance and magnetic resonance imaging (ULF-MR) designed to generate 7 mT/A was fabricated. However, with suspected internal insulation failure, the coil was investigated in order to find out the source of the failure. This paper reports detailed build of the failed B_p coil and a number of analysis methods utilized to figure out the source and the mode of failure. The analysis revealed that pyrolytic graphite sheet linings put on either sides of the coil for better thermal conduction acted as an electrical bridge between inner and outer layers of the coil to short out the coil whenever a moderately high voltage was applied across the coil. A simple model circuit simulation corroborated the analysis and further revealed that the failed insulation acted effectively as a damping resistor of $R_{d,eff} = 6 \Omega$ across the coil. This damping resistance produced a 50 ms-long voltage tail after the coil current was ramped down, making the coil not suitable for use in ULF-MR, which requires complete removal of magnetic field from B_p coil within milliseconds.

Keywords: ULF-NMR, ULF-MRI, magnetic resonance, prepolarization, SQUID, liquid nitrogen

1. INTRODUCTION

Ultra-low field nuclear magnetic resonance and magnetic resonance imaging (ULF-MR) utilizes a very weak magnetic field, in the order of μT , for its measurement field (B_m) that induces nuclear spin precession [1-4]. Such a low B_m requires (1) a magnetic sensor with a flat frequency response down to as low as 100 Hz or less and (2) a strong prepolarization field (B_p) which magnetizes the sample prior to magnetic resonance measurement to enhance magnetic resonance signal [3]. Using SQUID-based magnetic sensors satisfies the first requirement while the second requires a separate magnet subsystem that can produce a strong magnetic field in the order of 10 to 100 mT as well as completely remove the field in milliseconds so that resulting spin precession and its detection are not adversely affected by it [3].

An electromagnet paired with a current driver is most widely used to generate B_p [5, 6]. In order to generate a strong B_p , the electromagnet is usually built as a thick solenoid or a pancake coil with hundreds of turns or more. With a thick solenoid, the sample is placed either inside the barrel [2] or on top of the solenoid [3] while, with a pancake coil, the sample is placed on top of the coil [4]. The B_p coil can also be cooled below room temperature to increase current capacity and hence maximum B_p strength – we put our B_p coils inside small liquid nitrogen (LN) dewar to keep the coil at a low temperature.

Due to its structure, densely packed with fine conductors insulated from each other by thin enamel coatings, the B_p

Fig. 1. (a) Schematic diagram of ULF-MRI and LN-cooled prepolarization (B_p) coil. (b) Schematic sectional view of the B_p coil, with the section-plane parallel to the coil axis. The 52-layer coil contains strips of pyrolytic graphite sheets (vertical dashed lines) or bundles of enamel-insulated copper wire (vertical solid lines) between layers for better thermal conduction along each layer.

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coil is inherently prone to failure from broken insulation. The insulation can be broken from many reasons, including mechanical wear and compression during winding process, thermal shock from cool-down and warm-up cycles, voltage induction from rapidly changing current, *et cetera*. In many cases with coils of compromised insulation, the insulation failure can be easily detected by a simple measurement of its resistance and/or inductance with an LCR meter. However, in some cases, the break-down can be so subtle that such a simple measurement might not be able to conclusively reveal the failure.

Here, we report an investigation into a failed liquid nitrogen-cooled B_p coil, suspected of compromised insulation due to combination of mechanical wear and compression across insulation during winding process and voltage induction during current ramping exceeding the dielectric strength of compromised insulation. Coil current and voltage responses with the coil driven with a dedicated custom B_p coil driver [5] are presented and compared with those of an intact B_p coil. Also, an equivalent model circuit is proposed to suggest possible modes of failure. Analysis of the failed coil against the model circuit simulation revealed that at least one of the three methods applied in coil winding to facilitate cooling of the B_p coil core were to blame for the failed insulation.

2. METHODS

2.1. ULF-MR setup

The ULF-MR system was setup as shown in Fig. 1a. In short, the B_p coil was placed inside a liquid-nitrogen dewar designed to supply LN to cool the B_p coil while the evaporated N_2 gas was vented out of the dewar. B_p coil was placed just below the top of the dewar. The sample was then put on the B_p coil dewar. The SQUID sensor dewar was placed just above the sample.

2.2. B_p coil construction

The B_p coil was constructed as a thick solenoid coil with inner diameter just large enough to accommodate a screw-type coil holder with a hole in the middle. Inner and outer diameters of the coil were 35 mm and 130 mm. Coil thickness was 30 mm. Total number of turns was 1144,

Fig. 2. (a) B_p coil. Bottom-side with cooling wires between coil layers leading downward is shown. (b) Winding an inner layer with pyrolytic graphite sheet between layers. (c) A middle layer with enamel-insulated copper wire bundles between layers.

composed of 52 layers with 21 to 23 turns per layer (Fig. 1b and Fig. 2a). The inside of the coil frame was lined with 30 μ m-thick pyrolytic graphite sheets to help spread heat across layers. Also, in order to facilitate heat conduction along each layer, small strips of the pyrolytic graphite sheet (Fig. 2b; for inner and outer layers) or bundles of fine insulated copper wires (Fig. 2c; for middle layers) was placed between layers. Litz wire, composed of 60 strands of enamel-insulated AWG 36 copper wires, was used for the main conductor of the B_p coil. The same Litz wire was used for strands of wires put between layers for heat conduction (Fig. 2c). Stycast 2850FT epoxy adhesive was applied between the last three layers to hold the coil together. Right after construction, the B_p coil measured at 7.09 Ω and 71.6 mH at room temperature. Submerged in LN, at 77 K, the DC resistance decreased to 0.908 Ω . When completely immersed in LN, it took 8 minutes to reach thermal equilibrium.

Magnetic field calculation with the B_p coil parameters showed that the coil would generate about 7 mT at sample space, 36 mm away from the center of the coil bore, per 1 A current driven through the coil, with up to 4.3% field variation in 15 cm $\times$ 15 cm $\times$ 2 cm sample space. Before failure, magnetic field measured with a gaussmeter at initial tests with slowly ramped DC current agreed with the calculated value of 7 mT/A.

A second B_p coil with the same geometry but without any heat conduction supplement was constructed after the failure of the first B_p coil, with 1199 total number of turns with 56 layers and 21 to 22 turns per layer (picture not shown). This coil measured at 7.54 Ω and 78.90 mH at room temperature and its DC resistance went down to 0.961 Ω at 77 K. The time required for thermal equilibrium after complete immersion into LN was 23 minutes, which is about 2.5 times that of the first B_p coil constructed with thermal conduction supplements.

2.3. B_p coil operation & measurement

In actual operation, the B_p coil was driven with a current driver specifically constructed for rapid current ramp-up and ramp-down of the high-inductance B_p coils [5]. Explaining briefly, a pair of IGBT (Insulated-Gate Bipolar Transistor) switches and diodes in bridge configuration, with the pairs placed across each other and a bank of capacitors placed inside the bridge, controls the current flow to the B_p coil. On current ramp-down, the inductive energy of the B_p coil charges the capacitor bank which is recycled on next current turn-on to rapidly ramp-up the B_p coil current. In this configuration, current ramp-down time becomes independent of the amount of current driven through the B_p coil [5, 6]:

$$\tau_{rd} \approx \frac{\pi}{2} \sqrt{L_c C_b} \quad (1)$$

Here, $C_b = 103 \mu$ F is capacitance of the coil driver capacitor bank. With coil inductance of $L_c = 70$ mH, expected ramp-down time is $\tau_{rd} \approx 4.2$ ms. During current ramp-down, maximum voltage induced across the B_p coil with current of I_c is [5, 6]:

$$V_{c,\max} \approx I_c \sqrt{\frac{L_c}{C_b}} \quad (2)$$

Eq. (2) indicates that the B_p coil would induce voltage spike of 26 V per 1 A of current driven to the B_p coil. The coil driver has a damping resistor of $R_d = 1 \text{ k}\Omega$ connected parallel to the B_p coil to damp out ringing after current ramp-down [5].

Fig. 3. B_p coil current (solid lines; units on left axes) and voltage across the coil (dot-dashed lines; units on right axes). (a) Normal B_p coil (Coil A) driven with 2 A current. (b) Failed B_p coil (Coil B) driven with 1 A current. (c) Voltage tail of the failed coil in (b). Irregular oscillations at current turn-on (before 0 ms for (a) and before 1 ms for (b)) are due to mechanical bouncing of the coil driver manual switch.

Fig. 4. A model circuit for the failed B_p coil. L_n and R_n represent each 21 to 23-turn layer and insulation resistance between the layers, respectively. $N=52$ is the total number of layers and R_{side} represents insulation resistance between the inner-most and the outer-most layers.

B_p coil current was measured with a Hall-type current probe and voltage across the coil was measured with two $10\times$ voltage probes on both ends of the B_p coil, all connected to a single 4-channel digital oscilloscope.

3. RESULTS AND ANALYSIS

Fig. 3a shows a set of current and voltage responses with the normal 1199-turn B_p coil (Coil A) driven with 2 A current. Fig. 3b shows the same set of responses with the failed 1144-turn B_p coil (Coil B) driven with 1 A.

Coil A (Fig. 3a) exhibited current ramping time of 4.2 ms and voltage spikes of 50 V at both current ramp-up and ramp-down, as expected of a normal B_p coil. It was capable of being driven with 25 A of current, resulting in a voltage spike of 660 V, without any indication of insulation break-down. Current and voltage responses were basically the same as Fig. 3a except for their magnitude (not shown). No current higher than 25 A was tried. Coil B (Fig. 3b), on the other hand, exhibited a more complex current ramp-up behavior. At turn-on, the coil current quickly rose to 56% of the desired current and then rapidly fell to about 27%, all within 2 ms. The voltage across the coil followed suit, displaying mostly resistive response with an equivalent resistance of 6Ω . The coil current then rose slowly to full 1 A with a time constant of 51 ms. At turn-off, the current fell down to zero quickly in 1.6 ms, followed by a long voltage tail with a time constant of 13 ms (Fig. 3c).

Fig. 4 shows an equivalent model circuit for the failed B_p coil to facilitate analysis of the failed coil B. In this model circuit, L_1 to L_N represent individual layers of the B_p coil composed of 21 to 23 turns. Insulation resistances between neighboring layers were modeled as R_1 to R_N . R_{side} models insulation between the inner and outer-most layers and the pyrolytic graphite sheet linings on either side of the B_p coil frame.

The mostly resistive behavior at current turn-on indicates that effective inductance of the coil B was very small during the initial few milliseconds, suggesting that insulation between the inner-most and the outer-most layers through the graphite sheet linings broke down due to the sudden voltage spike applied to the coil from the stored energy of the coil driver capacitor bank (C_b), $R_{side} = 6 \Omega$. Alternative explanation is that the insulations between all layer-pairs have broken down ($\sum R_N = 6 \Omega$), which is much less persuasive. With the stored energy from C_b dissipated

via resistive heating through the broken insulation and current reduced to a level where the voltage across the broken insulation was not enough to maintain conduction, the insulation could have been restored to allow current conduction through the entire coil. The time constant for the increasing coil current, 51 ms, was close enough to the time constant calculated from the resistance and the inductance of the pre-failure coil B, $71.6 \text{ mH} / 0.908 \Omega = 79 \text{ ms}$, to plausibly suggest recovery of the coil insulation.

The argument for the coil insulation recovery is further supported from the detailed analysis of the coil current and voltage during the slow current ramp-up. Between 3 ms and 6 ms, I_c rose from 266 mA to 308 mA, with $dI_c/dt = 14 \text{ A/s}$. Voltage across the coil during the same time period was 1.31 V on average. At 205 ms, just before current ramp-down, the coil voltage reached 0.88 V with a stable 1.00 A current, which is in line with the measured coil resistance of 0.908Ω . Therefore, between 3 ms and 6 ms, coil voltage contribution can be divided into two parts, (1) Ohmic voltage from DC current and (2) inductive voltage due to increasing current. Average current between 3 ms and 6 ms was 287 mA, which translates into an Ohmic voltage of $0.88 \text{ V/A} \times 287 \text{ mA} = 0.255 \text{ V}$. This leaves 1.055 V to the inductive voltage, leading to an effective inductance of $L_{\text{eff}} = 1.055 \text{ V} / 14 \text{ A/s} = 75 \text{ mH}$ through Eq. (3), which agrees with the inductance of Coil B measured right after construction, 71.6 mH.

$$L_{\text{eff}} = V_{\text{ind}} / \frac{dI_c}{dt} \quad (3)$$

Fig. 5. Current ramp-down transients of (a) Coil A from Fig. 4a and (b) Coil B from Fig. 4b. On the right are equivalent circuit models for current ramp-down from inductive energy of the coil (L_c) charging the driver capacitor bank (C_b) and voltage tail after current ramp-down due to the damping resistor (R_d) and the coil inductance (L_c).

Fig. 6. (a) Circuit model for Coil B. $V = 880 \text{ mV}$, $C_b = 103 \mu\text{F}$, $L_c = 78 \text{ mH}$, $R_c = 1.05 \Omega$, and $R_d = 5.5 \Omega$. (b) Coil voltage and (c) Coil current of the model (dot-dashed lines) and Coil B (solid lines).

At current turn-off, again the current and voltage responses from Coil B differ from the normal Coil A. In contrast to Coil A, where the current was ramped down in 4.2 ms and the voltage tail lasted only a fraction of a millisecond, the current ramp-down lasted only 1.6 ms for Coil B while the voltage tail lasted significantly longer, with a time constant of 13 ms.

For Coil A, the voltage tail after current ramp-down had a time constant of 0.16 ms, which was twice that of the expected time constant of $L_c/R_d = 78.9 \text{ mH} / 1 \text{ k}\Omega = 0.08 \text{ ms}$. Coil B, however, had a much longer time constant of 13 ms, which translates to an effective damping resistance of $R_{d,\text{eff}} = 6.1 \Omega$ with coil inductance of $L_c = 78.9 \text{ mH}$.

To better understand Fig. 5b, a model circuit for Coil B has been constructed and simulated (Fig. 6a). This simple model circuit has an SPDT (single-pole double-throw) switch (SW) that connects the model coil to a DC voltage source (turn-on) or to a capacitor C_b (turn-off). Through trial-and-error, optimal parameters for the model circuit that could best emulate the current and voltage data for Coil B during current ramp-down have been determined as: $V = 880 \text{ mV}$, $C_b = 103 \mu\text{F}$, $L_c = 78 \text{ mH}$, $R_c = 1.05 \Omega$, and $R_d = 5.5 \Omega$. These parameters agree with the previous analysis that insulation break-down occurred through the pyrolytic graphite linings on the coil frame side.

4. DISCUSSION AND SUMMARY

We have compared the coil current and voltage responses of Coil B, with internal thermal conduction supplements, and Coil A, without them. We showed that Coil B suffered conditional electrical insulation break-down that prevented it from operating normally. Specifically, (1) it failed to utilize stored energy in the driver capacitor bank for rapid current ramp-up, (2) it showed abnormally short current ramp-down time and significantly reduced voltage spike at current ramp-down,

and most devastating for a B_p coil to be used in ULF-MR operation, (3) there was a voltage tail that persisted up to 50 ms after current ramp-down. All of the analysis performed with the acquired data indicates that, among possible points of insulation failure, the pyrolytic graphite sheet linings put the inside surface the coil frame are the most likely suspect. Any weakness on the wire insulation, cracked insulation from thermal cycling, thinned insulation from mechanical compress or wear during winding process, *et cetera*, if happened to be present where the wire was pressed into the graphite sheet could form an electrical pathway into the electrically conducting graphite sheet with a low dielectric strength, significantly lowering maximum voltage rating of the entire coil. The analysis indicates that this insulation failure, when conducting, acted as a damping resistor of $R_d = 6 \Omega$.

The analysis above implicates one of the three thermal conduction supplements, pyrolytic graphite sheet side linings, as the culprit of the insulation failure. The other two, namely strips of pyrolytic graphite sheets and bundles of Litz wire placed between layers, across current-carrying wires, were not implicated as causes of the failed insulation. However, placing the wire between layers put the cooling wires, across current-carrying wires, which are then compressed very tightly together during winding process, carries a significantly increased chance of insulation thinning and wear-out. Strips of pyrolytic graphite sheet are significantly better in this regard, since they are of a soft material and can also act as lubricant between layers. However, high electrical conductivity of graphite leaves room for local insulation failure as wires with compromised insulation can come in direct contact with it. The safest method for better internal thermal conduction of the B_p coil therefore would be placing strips of pyrolytic graphite sheet, with thin insulating linings on both sides, between coil layers.

In summary, we have presented current and voltage responses of two B_p coils, one with intact internal electrical insulation, and the other with compromised internal electrical insulation, driven with a current driver specifically designed for driving B_p coils [5]. A number of methods have been introduced to analyze the coil responses and investigate the source of insulation failure. It has been revealed that pyrolytic graphite sheet linings on either sides of the coil acted as an electrical bridge between inner and outer layers of the coil and shorted the coil whenever a high voltage is applied across the coil. A simple model circuit has been simulated to show that the failed insulation acted as a damping resistor of $R_d = 6 \Omega$ across the coil. This damping resistance produced a 50 ms-long voltage tail after current was ramped down, making the coil not suitable for use for ULF-MR.

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