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Construction and performance of small-sized coated conductor pancake coils for surgical applications

Y. Ge[a]*, R. Lewin[a], R. Cahill[b], N. Mortensen[b] and H. Jones[a]

[a]University of Oxford, Department of Physics, Clarendon Laboratory, Oxford OX1 3PU, UK
[b]John Radcliffe Hospital, Headley Way, Headington, Oxford OX3 9DU, UK

Abstract

With a view to applying small-sized superconducting coils for magnetic manipulation in surgery, three pancake coils have been built with commercially available (RE)BCO coated conductor using different impregnation methods and tested in liquid nitrogen and liquid helium. This paper presents the design and construction procedures of these pancake coils and subsequent test results including transport current characteristics in background fields are discussed.

Keywords: coated conductor; pancake coil; vacuum impregnation; critical current

1. Introduction

Since discovered, superconductivity has been believed to possess huge advantages in scientific and industrial applications, including producing high magnetic fields. A significant example is magnetic resonance imaging (MRI), which brought a revolution to medicine. As the prime candidate for the next revolution in surgery [1], natural orifice transluminal endoscopic surgery (NOTES) uses natural orifice on human body to access internal hollow viscera and then penetrate through the wall of the organ to gain entry into one of the closed internal cavities [2]. Small-sized superconducting magnets are expected to be employed in NOTES to achieve better manipulation. Pancake coils wound from second-generation high-

* Corresponding author.
E-mail address: y.ge1@physics.ox.ac.uk.

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temperature superconducting (2G HTS) wire, also known as the (RE)BCO coated conductor, were then considered. To investigate the impact of different impregnation procedures to the 2G HTS wire, three identical pancakes were built and impregnated with different methods (dry wound, resin impregnated and wax impregnated). Field-to-current ratio of each pancake coil was calculated and transport current characteristics including critical current and index of transition were measured in cryogens.

2. Coil construction

2.1. Wire and insulation

The wire used for winding the pancake coils was 4 mm wide (RE)BCO coated conductor SCS4050-AP supplied by SuperPower Inc. With a surrounding copper stabilizer, the total thickness of the wire is about 0.1 mm. According to the manufacturer, at 77K this wire has an average critical current of approximately 100 A under the criterion of 100 μV/m electric field and an average index of transition of around 28.

Meanwhile, a silk ribbon, sourced from doll-making industry, with a thickness of 0.08 mm and a slightly bigger width (about 4.1 mm) than the wire was used as the insulation layer for the pancake coil.

2.2. Coil former

Three identical formers were built for the coils. Characteristics of various materials, including common metals and composites, for fabricating coil formers had been previously discussed [3]. TUFNOL^{TM} 6F/45, a cotton-epoxy composite, was selected in this project for the following advantages: insulating, stable, cryogenically useable and excellent machinability.

As shown in Figure 1, the former was 10 mm thick and had a 4.2 mm wide winding area, which was slightly wider than the superconducting wire and the silk ribbon. The overall diameter was set to 38 mm, enabling the coil to fit into a standard 40 mm superconducting magnet bore. The inner diameter for winding was 29 mm, which should be fairly safe as the wire had a critical bend diameter of 11 mm according to the manufacturer. Two 1 mm thick slots with tapped holes were machined on the former for attaching the current leads. More small slots were drilled to guide the potential leads out from the wire. A step was machined in the centre bore to set a cryogenic Hall probe for field measurement. Openings on both sides of the former allowing cryogens to flow directly onto the superconducting wire as well as holes around the central bore were created on the former for better cooling efficiency.

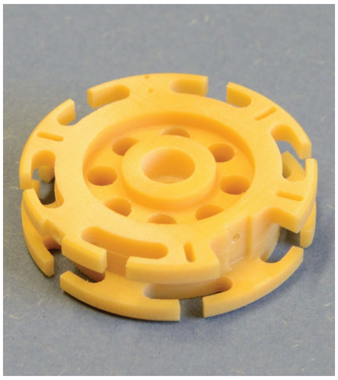

Figure 1. Coil former (ø 38 mm)

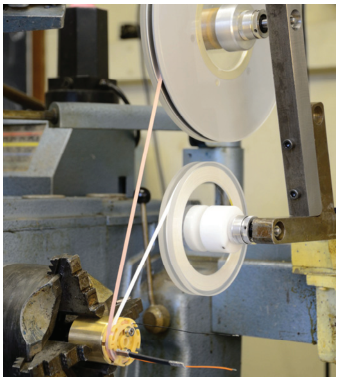

Figure 2. Winding process

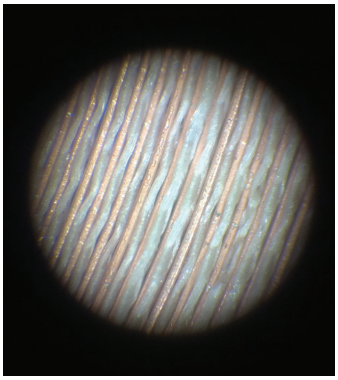

Figure 3. Winding structure

2.3. Winding process

Winding techniques for superconducting magnets have been exhaustively demonstrated by earlier publications [3-5]. However, special care must be taken when dealing with the 2G HTS wire, which is rather delicate due to the complex laminated structure. Localized critical current degradation can be easily caused by improper handling. To provide the maximum protection to the wire, indium-tin solder (52% In and 48% Sn alloy) with a melting point of 118 °C rather than regular lead-tin solder was used as the connecting medium and the tension applied during winding was kept relatively low. Besides, PVA gloves were necessary when handling the wire to avoid oxidation on the surface of the wire.

The winding process was carried out on a coil winding machine, where the wire spool, silk ribbon spool and the coil former were lined up (see Figure 2). The first and the last layers of the superconducting wire were soldered onto the inner and outer current leads respectively. Three potential taps were put on each pancake coil for future measurements, two at each end and one in the middle. It was important to keep a significant separation between the voltage and current contacts, normally a few centimetres, to avoid undesirable effects on voltage signals caused by temperature rise at the current leads [6].

2.4. Vacuum impregnation

Although the impregnation is not a compulsory procedure when winding a coil, it has always been an effective method to achieve a monolithic self-supporting structure especially for construction of high-field superconducting magnets, where the Lorentz force on the coil may cause self-destruction of a weak structure during operation. One of the most common impregnation methods is using a “pre-preg” material [7]. However, this technique is not practicable on pancake coils for their single-row winding geometry. Thus the alternative method, vacuum impregnation, was then applied in this case.

The resin impregnation was carried out in the apparatus with two separated chambers. The resin was heated in one vessel while the pancake coil was placed in the other, which had a heater jacket for uniform background temperature. Both chambers were pumped for enough time before the resin was transferred through a pipe to immerse the coil under vacuum. Pumping continued for a period and then nitrogen gas was admitted to the chamber to create a 10 bar overpressure. Finally, the coil was baked in a rotary oven for curing [7]. To minimize the possible damage to the superconducting wire, the temperature was kept no more than 75 °C for the whole process.

Compared with epoxy resin, the impregnation of paraffin wax was a simpler procedure. Granular paraffin wax together with the pancake coil was placed into a brass pot inside a vacuum furnace where the wax was heated until completely melted, heating and pumping continue for a period and then the temperature gradually lowered. For the same reason, the temperature was kept below 70 °C.

Figure 4, 5 and 6 show the completely constructed pancake coils. Their basic geometry data including coil inductance can be found in Table 1. It can be seen that the three coils’ parameters are, within very small errors, identical. This is a testament to how carefully the windings procedure was carried out.

Table 1. A comparison of the coils’ geometry

	Dry wound pancake	Resin impregnated pancake	Wax impregnated pancake
Inner radius(mm)	14.58	14.58	14.56
Outer radius (mm)	17.91	17.92	17.89
Total length of the wire (mm)	1774	1776	1769
Total turns	17.25	17.25	17.25
Coil inductance (μH)	14.6	14.6	14.6

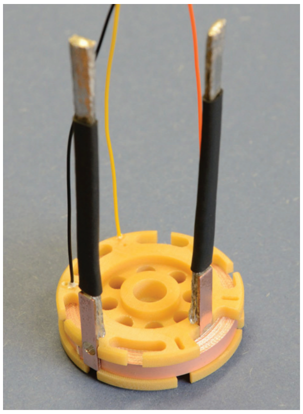

Figure 4. Dry wound coil

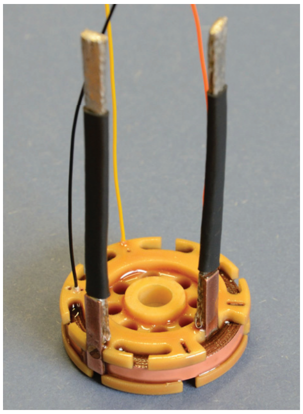

Figure 5. Resin impregnated coil

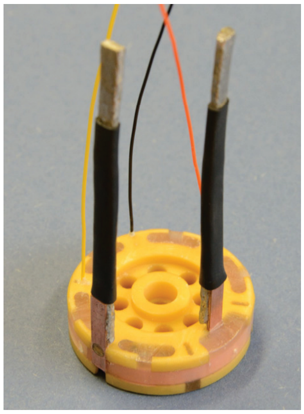

Figure 6. Wax impregnated coil

3. Coil performance

3.1. Field profile simulation

Finite element analysis software COMSOL Multiphysics was used to simulate the magnetic flux density. Figure 7 illustrates the field simulation when applying a 1 A current through the coil. Particularly, at the centre of the coil bore, the calculated field-to-current ratio was 0.66 mT/A.

3.2. Tests in liquid nitrogen

The initial tests were carried out in liquid nitrogen. The four-terminal method was employed to measure the transport critical current, and subsequently the index of transition. The experiment setting mainly involved a 500 A DC power supply, a data logger and a low-drift amplifier with a gain of 10^4 to enhance the potential signals (at μV level). Besides, a high-sensitivity cryogenic Hall probe was applied for magnetic field measurement and a copper electromagnet was used for field dependence measurement in low external fields. The experiment was monitored and controlled with NI LabVIEW.

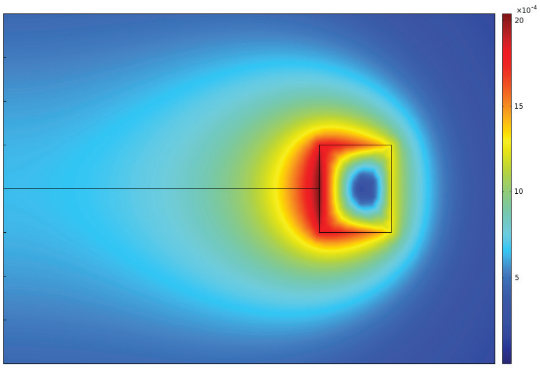

Figure 7. Field profile when applying a 1 A current

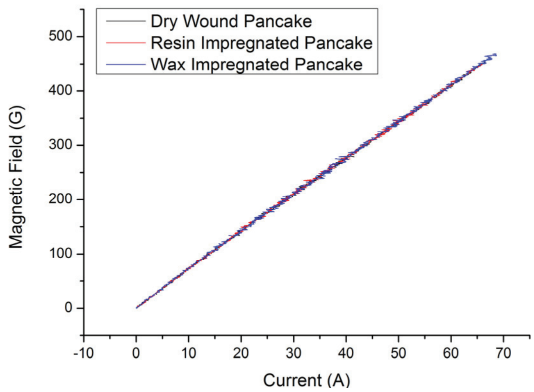

Figure 8. Field-to-current ratio of the three coils

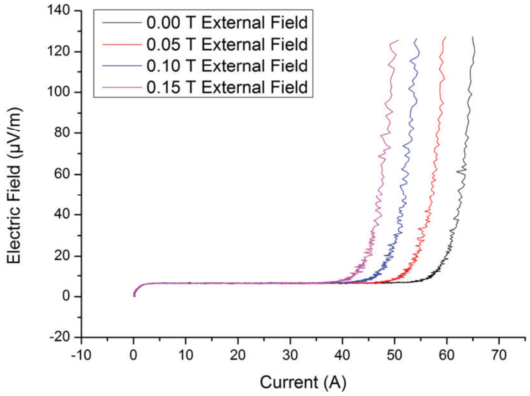

Figure 9. Field dependence data at 77 K

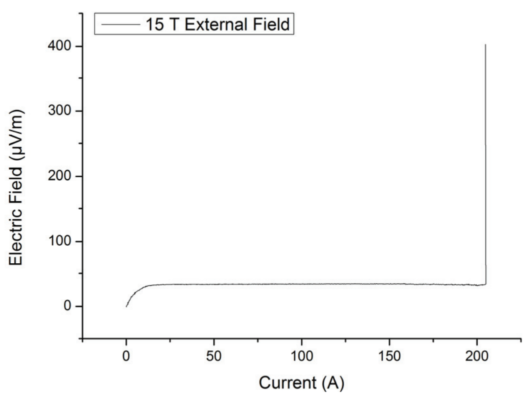

Figure 10. Transition in 15 T background field at 4.2 K

Table 2. A comparison of the coils' performance at 77 K

	Dry wound pancake	Resin impregnated pancake	Wax impregnated pancake
Ic and index of transition at 0 T	65 A / 16	64 A / 25	67 A / 26
Ic and index of transition at 0.05 T	59 A / 16	58 A / 24	61 A / 22
Ic and index of transition at 0.10 T	53 A / 16	53 A / 22	55 A / 21
Ic and index of transition at 0.15 T	50 A / 16	49 A / 21	50 A / 20
Average field-to-current ratio	0.68 mT/A	0.68 mT/A	0.68 mT/A

3.3. Tests in liquid helium

The resin impregnated pancake was next tested in the bore of a superconducting magnet in liquid helium but we encountered problems. To begin with, at 5 T, there was no transition at over 400 A. A series of spurious quenches of the magnet forced us to abort the tests pending investigation of the problem. However, we present the result at 15 T in Figure 10.

4. Discussion

Repetitive tests proved that the performance and behaviour of the three pancake coils are similar and stable, which indicates impregnation up to 75 °C would not degrade the wire's performance. However, the wax seems to be easy to crack, especially when surrounding temperature changes rapidly.

Figure 8 shows the field-to-current ratios of the three coils are almost the same, the average value is 0.68 mT/A while the computer simulation gives a similar result of 0.66 mT/A. Figure 9 shows the magnetic field dependence data of the resin impregnated coil at 77 K. As expected, the external field significantly lowers the critical current of the superconducting wire. Table 2 gives a more detailed data of the transport current characteristics of the three pancake coils. Although one could possibly draw the conclusion from the field dependence data (especially of the two impregnated pancakes) in Table 2 that stronger external field may decrease the index of transition of the superconducting pancake coils, further experiments involving much higher external field need to be performed to provide more conclusive evidence on this.

There is an unexpected result from the tests. Normally one would imagine the index of transition of the two impregnated pancakes to be equal to or even smaller than the dry wound pancake, as the high temperature during impregnation might cause a possible damage on the wire. As shown in Table 2, index of transition of the dry wound pancake is actually smaller. We have basically two possible explanations of this "abnormal" phenomenon. One is simply that the wire for the dry wound pancake was damaged before or during the winding even though great care was taken. As this pancake was wound from the wire at the outer end of the packaging spool, there is a possibility that it was damaged and did not behave as the wires from other parts. The other explanation is that when the dry wound pancake was injected with a current, the Lorenz force managed to move the winding away from its original position and somehow caused a decrease of index of transition. Since the other two pancakes were impregnated, the wingdings were kept where they were by resin or wax and the decrease of index of transition is avoided. To prove any of the explanations, a new dry wound pancake will be built and tested. After tests, it will be impregnated, then be tested again. That hopefully should give an answer to this question.

As for the tests at 4.2 K, the E-I characteristic in Figure 10 is symptomatic of a quench moving in from outside the potential taps. We speculate the followings. The soldered current contacts are about 0.1 cm^2. At a heat transfer of ≥ 1 W/cm^2, film boiling takes place [8]. At around 200 A, this would occur if the contact resistance was only 2.5 $\mu\Omega$. At this field level, we think the high contact temperature initiated a quench that propagated into the rest of the windings. We will pursue further tests in due course.

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