

Temperature dependency of magnetic field drifts of HTS pancake coils for NMR/MRI applications

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(Received 20 November 2013; revised or reviewed 25 November 2013; accepted 26 November 2013)

Abstract

We had proposed a winding method so called “Wind-and-Flip”, which enables a persistent current operation of an HTS pancake coil without any electrical joint. In order to improve the magnetic field drift characteristics, a prototype HTS coil with the technique was fabricated, and tested under various temperatures. Because the coil doesn't have any electric terminals for current leads, an HTS background magnet was used to induce the persistent current in the coil by field cooling process. A conduction cooling system with a GM cryocooler was prepared to keep the operating temperatures of the prototype coil much below the 77 K. We investigated the magnetic field drift characteristics under the various operating temperatures by measuring the center magnetic field with a cryogenic Hall sensor. The persistent current mode operation at 20 ~ 50K showed a strong possibility of the winding technique for the application such as MRI or NMR.

Keywords : HTS Magnet, Magnetic Field Drift, Persistent Current, Wind-and-Flip

1. INTRODUCTION

HTS magnets have been widely developed recently because everybody agrees with the advantages of the higher operating temperature or the superior performance at lower operating temperature especially under the high magnetic field. Especially, a 2G HTS coated conductors (CC) has been one of the strong candidates for a material of hybrid high field magnet. As well agreed, adopting an HTS material is inevitable for these kinds of applications. However, using the HTS magnets as an insert coil of the NMR or MRI magnets has not been realized as a practical or commercial grade product because of the poor joint performances of the HTS wires, especially CC.

A new winding technique, so called wind-and-flip, had been proposed by the authors to realize an HTS coil with a perfect closed loop, which may enable to induce a persistent current in the coil [1-3]. Fig. 1 shows the concept of a double pancake coils by the wind-and-flip technique. First, a wide 2G HTS tape (a) is to be cut longitudinally along its center line but leaving both end parts not sliced (b). Second, each half width HTS tapes are wound on 2 separated bobbin as a pancake coil (c). Each coil should be connected with two incompletely sliced end parts. Because the directions of the magnetic fields from each coil would be opposite, one of the two coils should be “flipped” over to make magnetic fields from each pancake coils to have same directions. Through this process, we can build a double pancake coil with no electrical joints and have a possibility to introduce a persistent current mode in it [4].

We have fabricated a prototype of an HTS coil with the technique and tested the magnetic field drift of it under the condition of the field cooling. At the operating temperature of 77 K, which is the boiling temperature of the liquid nitrogen, we could have achieved a magnetic field drift of 1600 ppm/hour at the trap field of 163 mT after 72 hours of maintaining the induced current in the HTS prototype coil [5].

This result was not good enough for a magnet application such as MRI which requires guaranteed temporal stability of 0.1 ppm/hour. It should be improved by increasing inductance with large bore size and the number of turns or stacking coils, increasing index with lower operating temperature. In this paper, we tried to

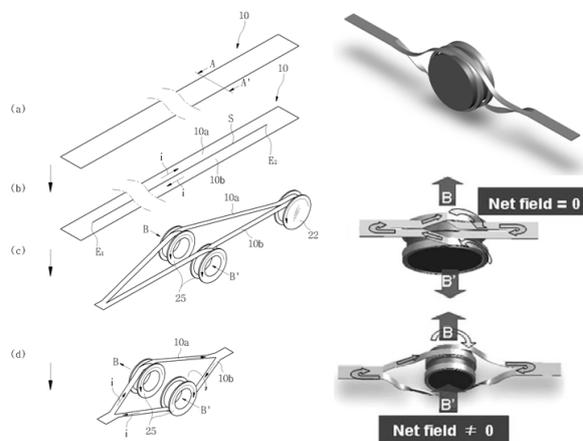


Fig. 1. Fabrication process of pancake coils for persistent mode operation by using “wind-and-flip” technique.

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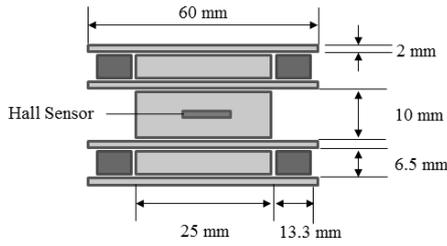


Fig. 2. Design of the prototype coil and the position of the Hall sensor.

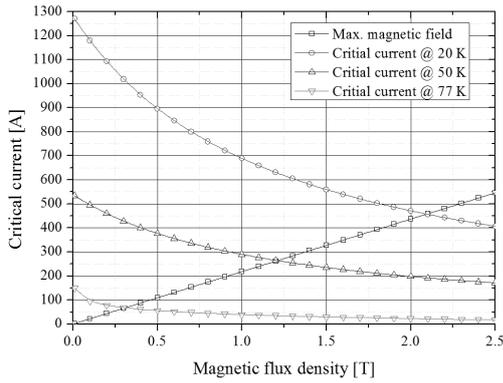


Fig. 3. Critical current according to the applied magnetic flux density on the CC of the prototype coil.

increase index of the HTS wires in the coils by lowering the operational temperature such as 50 K or even 20 K. Also, we carried out experiments under various temperatures to check out the temperature dependency of the magnetic field drift of the prototype coil.

2. EXPERIMENTAL SETUPS

2.1. Design of the prototype coil

Table I and Fig. 2 show the specifications of the prototype coil design. We prepared 2G HTS CC with the width of 12 mm and the length of 17.6 m. The total length of the coil should be double of the original wire because it is supposed to be cut into 2 parts for the wind-and-flip. The width of the wire becomes half of the original one. The total number of turns of the coil was 266 with the insulation layers of polyimide film for each turns. The calculated inductance of the coil is 1.693 mH. Fig. 3 shows the maximum normal magnetic flux density on the CC stacked with the degradation according to the magnetic flux density at the temperature of 20 K, 50 K, and 77 K.

2.2. Fabrication of the coil

The bobbin for the coil was made of oxygen free high thermal conductivity copper (OFHC) for the conduction cooling purpose. The coil consists of two pancake type coils and one of them was flipped after each winding. One Hall sensor was located at the center position in the middle of the two pancake coils. Fig. 4 shows the winding process and the thermal links attached to the upper surface of the copper bobbins for the conduction cooling.

TABLE I
SPECIFICATIONS OF THE PROTOTYPE COIL.

Quantity	Values
Conductor length	35.2 m (17.6 m @ 12 mm)
Conductor width	6 mm (12 mm slitting)
Number of turns	266
Outer diameter	51.6 mm
Inner diameter	25 mm
Insulation layers	Polyimide film
Insulation layer thickness	0.03 mm
Inductance	1.693 mH

2.3. Background magnet

Because the coil doesn't have a persistent current switch, a persistent current was supposed to be induced in the coil by the field cooling process with a background magnet. We prepared an HTS magnet which has a warm bore with 100 mm diameter. The maximum magnetic flux density at the center point was 3 T and the magnet has no insulation layers between turns. The operation temperature is 14 K with a conduction cooling cryogenic system. Fig. 5 shows the background magnet system and the installation-ready prototype coil which will be placed in the room temperature bore of the background magnet. The coil is supposed to be placed at the exact center of the background magnet.

For a field cooling process, the background magnet was supposed to be charged up first. The temperature of the coil should be kept way above the critical temperature. After the background magnet charged up, we turned on the cryocooler to cool the coil down to the operating temperature. Because of the slow response of the conduction cooling system, we should keep the operation temperature for two hours at least, so that we could guarantee the whole conductors in the coil would have the same temperature. Then we discharged the background magnet in a constant decreasing rate to induce a persistent current in the coil.

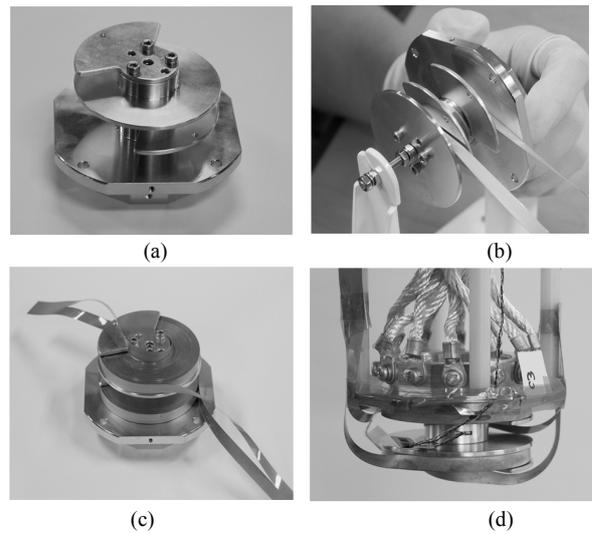


Fig. 4. Winding process of the wind-and-flip and adopting the thermal links for a conduction cooling; (a) copper bobbin, (b) winding process on each separated bobbins, (c) prototype coil, and (d) thermal links on the copper bobbin.

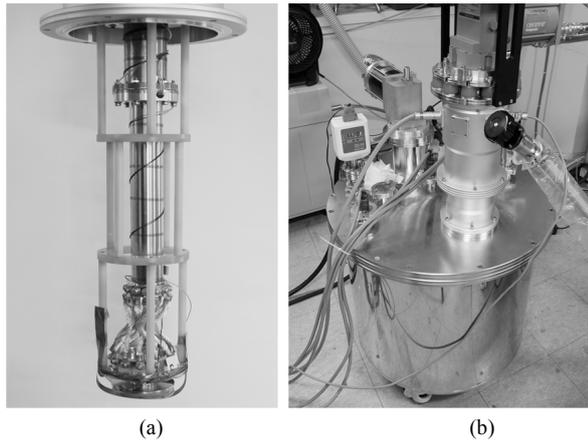


Fig. 5. Installation of the coil; (a) the coil with the thermal links attached on the cold head of a GM cryocooler, (b) 3T HTS background magnet.

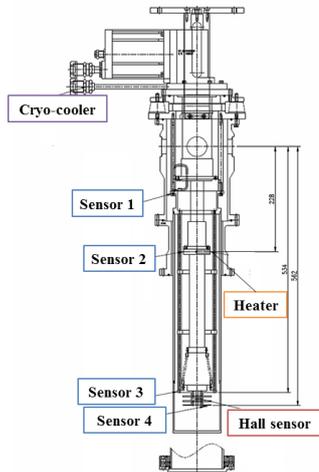


Fig. 6. Configuration of the cryogenic system for the coil and the location of the sensors and the heater.

2.4. Cryogenic system

A cryogenic system with a GM cryocooler had been made for keeping various operating temperature of the coil. Four temperature sensors and a heater were installed to measure and control the temperature. A Hall sensor was also installed to measure the magnetic flux density. Fig. 6 shows the configuration of the cryogenic system and the location of all the sensors and the heater. In order to prevent from traveling of the vibration from the cryocooler, 8 dampers were installed between the cold-head and the cryostat wall.

3. TEST RESULTS AND DISCUSSIONS

3.1. Field cooling test

A year ago, we had already fabricated the same coil with slightly different copper bobbin and a racetrack shape background magnet. We also had tested it in the liquid nitrogen bath and presented the result at *ASC conference*

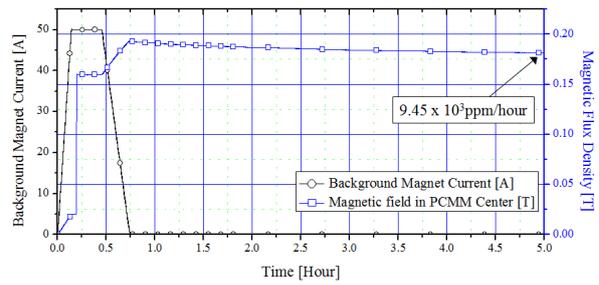


Fig. 7. Measured drift of the magnetic flux density at the center point of the prototype coil at 77.3 K. (LN2, result presented at ASC 2012).

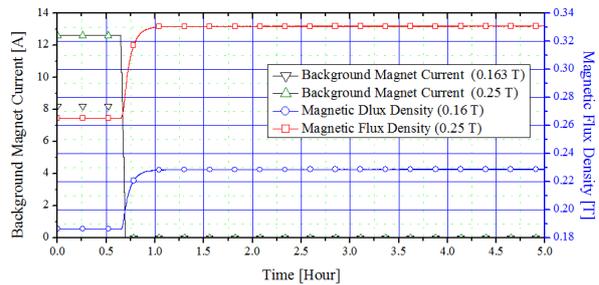


Fig. 8. Measured drifts of the magnetic flux density at the center point of the prototype coil at 20 K.

2012. The result of the measurement of the magnetic field drift at that time is shown in Fig. 7. At that time, the applied maximum magnetic flux density from the background magnet was 0.163 T. The measured magnetic field drift rate at 5 hours and 66 hours after inducing the persistent current in the coil was 9,450 ppm/hour and 1,578 ppm/hour, which had been still far above the criterion of the practical MRI applications, or 0.1 ppm/hour [5].

In order to compare to the previous results at 77.3 K, we tried to apply the same amount of the magnetic field before cool down the coil to the operating temperature of 20 K. Fig. 8 shows the results of this trial. When we applied the magnetic field of 0.164 T with the background magnet, the center magnetic field went up to 0.23 T during the discharging the background magnet. The coil kept the magnetic field for 4 hours and any detectable drift of magnetic field with a Hall sensor we used couldn't be found. Fig. 8 also shows the same result in case of the applied magnetic field of 0.25 T. Fig. 9 shows the results of the measurement of the drifts of the magnetic field of 0.65 T at 20 K, 30 K, and 50 K. In all cases, any change of the magnetic field couldn't be measured by the Hall sensor for 4 hours.

3.2. Long-term test

After the experiment under the condition of 0.65 T and 50 K for 4 hours, we tried to keep the temperature for 48 hours to measure the long-term magnetic field drift. Fig. 10 shows the result of measurement, and we couldn't get any detectable magnetic field drift rate either.

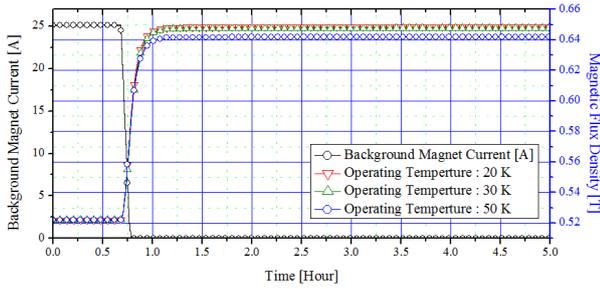


Fig. 9. Measured drifts of the magnetic flux density at the center point of the prototype coil at 20 K, 30 K, and 50 K.

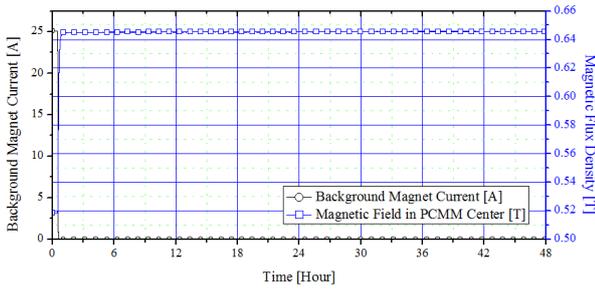


Fig. 10. Measured long-term drift of the magnetic flux density at the center point of the prototype coil at 50 K.

3.3. Temperature dependency

In order to investigate a temperature dependency on the magnetic field drift, we tried to elevate the operating temperature starting from 20 K while the coil maintained the trapped magnetic field of 0.63 T. Each time we increase the temperature with a step of 10 K, it seemed that the trapped magnetic field dropped slightly but it was caused by the dependency of the voltage from the Hall sensor. The trapped magnetic field of 0.63 T had been maintained without any detectable change until the temperature went up to 50 K. When the temperature reached up to 60 K, the magnetic field suddenly started to drop and approached around 0.5 T. The measured drift rate was 2,430 ppm/hour after 15 hours from the beginning of the initial drop.

4. CONCLUSION

We investigated the temperature dependency of the magnetic field drift by inducing the persistent current in an HTS coil fabricated by the technique so-called “wind-and-flip”. At the 50 K or below, we didn’t see any detectable change of the magnetic field at the center point of the coil during the elapsed time of the experiment. It seemed like ‘perfect closed loop’ at least under the condition of 0.65 T or below. Poor resolution of the Hall sensor we used may cause no magnetic field drift during 48 hours. If we measured the magnetic field with more sensitive device, such as NMR probe, we might be able to find a meaningful numbers. Or if we maintain the measurement for very long time, like a couple of months, small drift rate might be measure even with a Hall sensor.

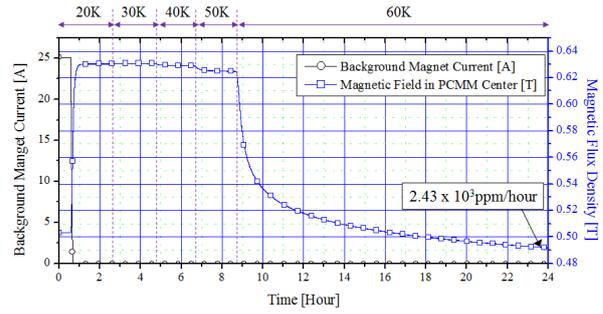


Fig. 11. Temperature dependency of the drift of the magnetic flux density at the center point of the prototype coil at 20 K, 30 K, and 50 K.

Nonetheless, the experimental results showed a remarkable improvement and a strong possibility of using the technique for practical applications such as MRI or NMR. Relatively low magnetic field could be one of the reasons. Apparently, higher trapped field would show a meaningful drift rate. At this moment, we didn’t want to raise the trapped magnetic field way above 0.5 T because we worried about the Lorentz force. Modification of the coil structure is now in progress in order to endure stronger electromagnetic force so that we will be able to apply much higher magnetic field.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(2012R1A1A2009554), Republic of Korea.

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