A prototype Bi-2223 HTS tape gradient coil for MRI

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Introduction: Coil heating is one of the most important engineering issues for MRI gradient coils. It is the primary limit on duty cycle of the gradient coils [1]. Coil heating is directly related to the resistance of the conductor and it becomes more severe when high current is required to obtain high gradient strength. To remove heat effectively, forced air cooling or water-cooling are usually necessary for normal gradient coils. The cooling systems not only complicate the experimental setup and reduce reliability, but also sometimes result in image artifacts. High Temperature Superconductor is ideal material to greatly reduce coil heating due to its almost zero resistance. Its resistance can be expressed by Eq. 1: [2]

$$R = \frac{lE_0}{I_c}\left(\frac{I}{I_c}\right)^{n-1} \qquad \text{where } E_0 = 1\mu V/cm,\ \text{n} = 10 \sim 15 \quad (1)$$

where l is the tape length and I_c is the critical current. The resistance of HTS tape is about 4 orders lower than the copper wire with the same length and cross section when the applied current equals the critical current. The high critical current enables HTS tapes to provide strong gradient field. We have investigated the power loss of HTS tape compared with copper wire from 200Hz to 2KHz, and the results have showed that the tape demonstrates 2-4 orders lower loss than copper wires with the same length and cross section. To verify the feasibility of HTS gradient coil, a prototype gradient coil made by Bi-2223 HTS tapes was designed and fabricated.

Materials and method: Multi-filamentary Bi-2223 tapes used in the HTS gradient have the critical current of 80A and cross section of 0.24*4.10mm. A PVC cylinder with inner diameter of 100mm is used as the gradient bore. To simply the fabrication, conventional Maxwell pair is used for z-gradient and Golay pairs are used for transverse gradients. Fiberglass material is used for insulation layers between x, y, z gradients. First, HTS tapes are soldered together to obtain the 2-D coil pattern required, and then fix the pattern onto the fiberglass layer. After that, the fiberglass layer is wrapped onto the cylinder to obtain the 3-D coil pattern. The HTS gradient coil is connected to the gradient amplifier by AWG-4 copper wires to minimize the effect of copper resistive loss to the total gradient coil. A homemade simple cryostat is fabricated and liquid nitrogen is used as cryogen.

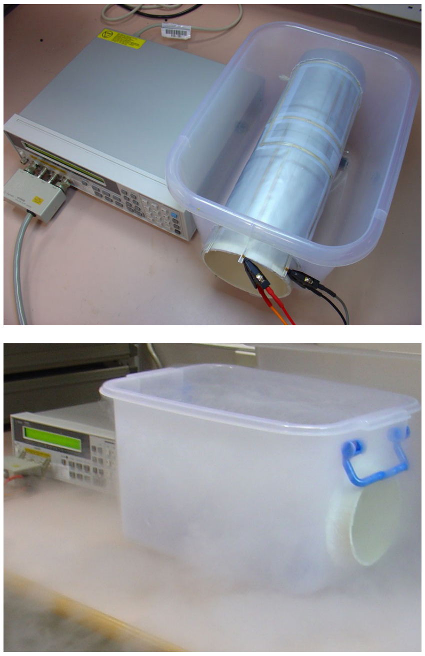

Fig 1. Resistance measurement of the HTS gradient coil in (a) room temperature and (b) liquid nitrogen

Results and discussion: The prototype HTS gradient coil and its inductance and resistance measurement are shown in Fig 1. The specifications of the prototype HTS gradient coil at 77K in liquid nitrogen and those of a typical copper gradient with the same pattern are illustrated in Table 1. The gradient strength along the X or Z axis is plotted in Fig 2. The applied current of 60A is lower than the critical current due to the presence of solder joints. According to Eq. 1, the tape resistance would increase rapidly if the applied current exceeds the critical current. To provide higher gradient strength, HTS tapes can be stacked together to carry higher current. Multi-circle fingerprint pattern can also greatly increase gradient efficiency. The use of fingerprint or other novel patterns will be helpful for improving gradient homogeneity and enlarging DSV value.

	Inner Diameter (mm)	Conductor cross section	Total Conductor Length (m)	Gradient Strength (mT/m)	Current (A)	Inductance (μH)(x,y,z)	Resistance (mΩ)	Heat 100% duty (W)	DSV (mm)
HTS	103	0.24*4.10mm	5.2	25, 25, 20	60	~7, 7, 5	~7	25	~50
Copper	103	AWG-17	5.2	25, 25, 20	60	~7, 7, 5	~86	308	~50

Note that most of the resistance in the HTS gradient coil comes from solder connections, and these connections can be further improved to reduce resistance. The application of HTS tape for gradient coils may be restricted by its mechanical properties. Because the existing commercial HTS tape is inflexible and very brittle, it could not be wounded easily into any coil patterns like copper wires. Curves with small curvature radius in some novel patterns are hard to approach by soldering HTS tapes together. Cryostat design is another important issue for HTS gradient coil applications. However, this issue would be much easy to deal with, if this design could be integrating into the superconducting main magnet chamber.

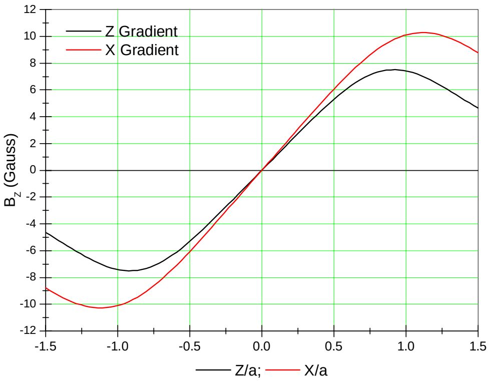

Fig 2. Gradient strength along X or Z axis

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