Investigation of power loss of Bi-2223 HTS tapes used for MRI gradient coil

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Introduction: Modern gradient coils are often required to provide high gradient strength and long continuous gradient rating. However, the higher gradient strength requires larger current, which brings the problem of coil heating and decreases the continuous gradient rating. This problem becomes more severe for MR microscopy. Therefore, gradient coil heating is a major barrier to achieve high spatial and temporal resolution images [1]. To reduce gradient heating effectively, normally the water-cooling system is necessary but it complicates the gradient construction. Furthermore, high-velocity water cooling may cause image artifacts of microphonic origin. Bi-2223 HTS tape is an ideal material to greatly reduce coil heating due to its zero resistance. In addition, its high critical current I_c can provide much higher gradient strength than copper wire. Investigation of power loss of HTS tape and its comparison with copper wire is very important for HTS gradient design to estimate thermal properties and power issues. However, normal gradients often works at several kilohertz, much higher than the frequencies interested in the traditional applications of HTS tape, therefore the power loss of HTS tape at these high frequencies should be studied.

Materials and method: I_c of the HTS tape is 80A at 77K and its cross section is 0.24 x 4.10mm. The experiment setup for power loss measurement is shown in Fig. 1, and the losses for HTS tape and copper wire were measured at 77 K in liquid nitrogen and 300K of room temperature respectively. To carry continuous high current, the copper wire requires about 20 times larger cross section than the tape. The measured power loss Q_t (per cycle per unit length) can be expressed by Eq. 1:

$$Q_t = I_t U_t / lf \tag{1}$$

where I_t and U_t are current and voltage respectively, l is the length of the tape and f is the working frequency.

Results and discussion: Measured power losses of the tape versus the current ratio i ($i=I_p/I_c$) are plotted in Fig. 2. Most of the losses fall between the Norris elliptical curve and strip curve. It indicates that hysteresis loss, rather than resistive loss, dominates the total losses [2, 3]. The comparisons of HTS tape loss with copper wire loss at 200Hz and 2000Hz are illustrated in Fig. 3. At 200Hz, the HTS tape shows a 3-order lower loss at low i and a 2-order lower loss at high i. At 2000Hz, the HTS tape still demonstrates much lower power loss than copper, which is 2-order lower at low i and 1-order lower at high i. Note that the copper wire has 20-fold larger cross section than the tape. It means the copper wire would generate about 200-fold to 20,000-fold more heat than the HTS tape if they have the same cross section.

For body-size gradient coils, the use of HTS tapes would greatly reduce the cross section, of conductor, which makes the coil more compact with the same gradient strength. HTS gradient may be possible to be placed into the cryostat for main magnet to simplify the construction. For small-size gradient coils, HTS gradient coils almost generate no heat and make possible of no cooling system, meanwhile can significantly increase continuous gradient rating.

Due to the inflexible property of HTS tapes, HTS tapes cannot be easily wound into any patterns as copper wire does, so solder joints are necessary for gradient coil fabrication. To estimate the effect of solder joints on the power loss, as example, we measured the loss of two segments of HTS tape (2 cm long) soldered with stannum solder. This loss is only about 5%-10% higher than the HTS tape of 4 cm. Therefore the solder joints would not greatly affect the gradient loss performance.

We also fabricated a prototype HTS gradient coil with Maxwell pair as axial gradient and Golay pairs as transverse gradients (Fig. 4). Its resistance in liquid nitrogen for X and Y pairs is about 5mΩ and for Z pair is 2 mΩ. It indicates that the resistive loss of the HTS gradient coil would be less than 5% of a normal copper gradient coil.

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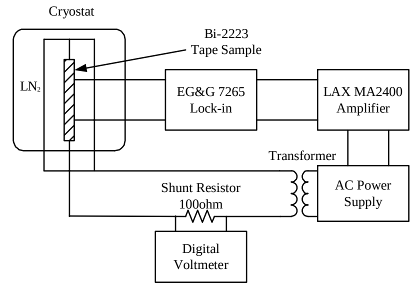

Fig. 1 A block diagram of the AC loss measurement setup

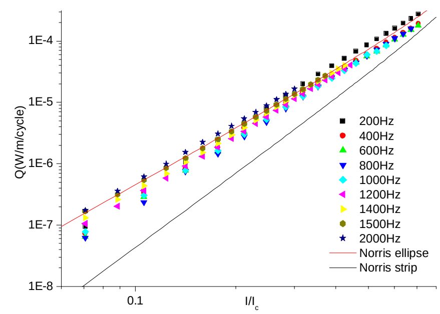

Fig. 2 HTS tape losses at different frequencies

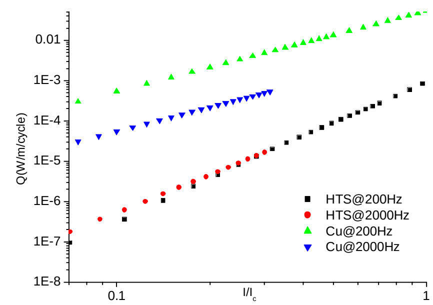

Fig. 3 Loss comparisons of HTS tape and copper wire at 200Hz and 2000Hz

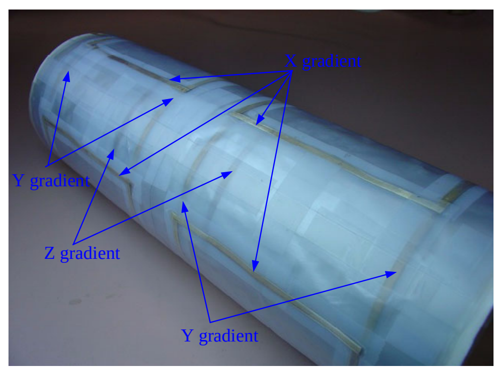

Fig. 4 A prototype HTS tape gradient