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Development of magnetic particle imaging modules using high-Tc superconducting coils

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Abstract

Magnetic particle imaging (MPI), in which harmonic magnetization signals from magnetic nanoparticles are detected to image diseased regions with high sensitivity, is attracting attention. In MPI, the spatial resolution of the image is mainly determined by the DC magnetic field gradient of the scanner, and MPI scanners only for small animal size were commercialized at the present stage. In this work, we developed magnetic particle imaging modules with 120 mm bore diameter using yttrium barium copper oxide (YBCO) high temperature superconducting (HTS) tape as a selection field coil. The gradient field of 0.63 T/m is realized with the developed YBCO HTS coil cooled with liquid nitrogen (LN). The power consumption and the mass of the HTS selection field coil could be reduced compared with a Cu coil and it indicates that utilizing a HTS selection field coil is one of the best options toward the realization of human-body-sized MPI scanner.

I. Introduction

Magnetic particle imaging (MPI) is a new modality for the imaging of the spatial distribution of magnetic nanoparticles (MNPs), especially for in-vivo diagnostics [1]. To extend the application of MPI to clinical applications, some large scale (brain-sized) MPI scanners have been developed [2]-[6]. One of the challenges to overcome for large scale MPI scanner is to develop a low power consumption and lightweight selection field coil with large magnetic gradient field strength, which is required to achieve a high spatial resolution of the image. One of the solutions is to utilize superconductors as a selection field coil, and Le et al. developed a brain-sized MPI system using low temperature superconductor (LTS) [6].

In this work, we are developing a MPI modules with 120 mm bore diameter using yttrium barium copper oxide (YBCO) high temperature superconducting (HTS) tape as a selection field coil. Liquid nitrogen (LN) can be used as a refrigerant for YBCO HTS coil, which is an advantage compared with using LTS coil.

II. Material and method

Figure 1 shows the schematic of the developed MPI modules, which is composed of drive field, selection field, and detection coils. Note that since a shift coil, which is used for moving the field-free-point (FFP), is not designed and installed at this stage, mechanical scanning is needed to obtain an MPI image.

II.I. Drive field coil

We developed a drive field coil made of Cu Litz-wire, which is composed of twisted multi-filamentary wires. The diameter and the number of element filaments were 0.1 mm and 600, respectively. The field coil and its resonant capacitance were designed so that the ac excitation field amplitude and frequency become 12 mT and 15 kHz, respectively. Figure 2 and Table 1 represent the photo of the developed drive field coil and its specifications. The drive field coil is composed of 25 sub coils with 7 turns. The 25 sub coils and 25 resonant capacitances are

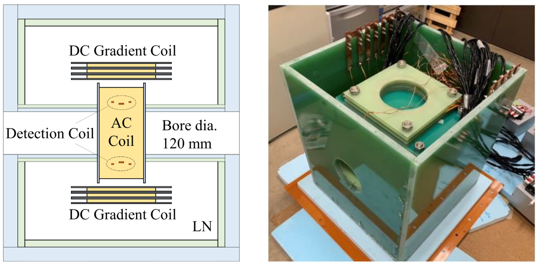

Figure 1: Schematic and photo of a developed MPI modules.

Figure 2: Drive field coil made of Cu Lits-wire.

connected in series alternately to suppress the voltages across any two terminals of the coils and resonant capacitances. Note that if the drive field coil is composed of single 175 turns coil and its resonant capacitance, the voltage across the coil exceeds 5 kV.

II.II. Selection field coil

A selection field coil was developed using YBCO HTS tape (SCS4050-APi, Super Power) having a width of 4 mm and a thickness of approximately 0.15 mm. The HTS film, whose thickness is approximately 1.6 mm, was coated by a thick Cu stabilizing film. As shown in Fig. 1, three pairs of Maxwell-type coil, which are composed of six coil frames wound with HTS tape, were connected in series with solder, to generate the gradient field. Figure 3 and Table 2 represent the photo of the developed one coil frame wound with HTS tape and its specifications.

III. Results and discussion

We measured the I-V characteristics of the developed six HTS coils by 4-terminal-method to investigate their critical currents (I_c). The I-V characteristics of each HTS coil cooled at 77 K with LN are shown in Fig. 4. The I_c was defined as the current at the critical electric field of 0.1 mV / m. Since the length of one HTS coil is 112 m, I_c is derived as the current at the voltage of 11.2 mV. As shown in Fig. 4, I_c for the six HTS coils were 56.4, 58.2,

Table 1: Specifications of Drive field coil.

Parameter	Value
Inner diameter (mm)	196
Outer diameter (mm)	256
Width (mm)	124
Number of Turns	7×25

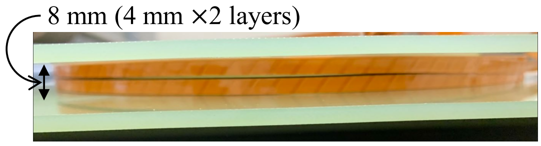

Figure 3: One coil frame wound with YBCO HTS tape for selection field coil.

60.2, 61.5, 57.7, and 54.8 A, respectively. According to the technical data sheet, I_c of the straight HTS tape is 100 A. The degradation of the I_c was caused by bending and torsion of the HTS tape wound in a coil shape. If the operated current of the selection field coil is set to 50 A, which is approximately 80-90% of each I_c, the gradient field of 0.63 T/m can be expected for z axis. Note that a gradient field of stronger than 1 T/m can be obtained if the HTS selection field coil is optimally designed.

Next, we discuss the advantages of using HTS tape against Cu wire as a selection field coil. The voltage across the selection field coil was 8.17 mV at 50 A (the mean value of single HTS coil was 1.36 mV at 50 A as shown in Fig. 4), indicating the total power consumption of the HTS selection field coil was only 68 mW. The power consumption of the selection field coil made of Cu wire, on the other hand, is roughly estimated as follows. Assuming that the current density of the Cu wire is J A/mm^2, and the current, number of turns, the total length of Cu wire are the same for HTS tape, i.e., 50 A, 90×2×6 turns, and 672 m, respectively, the Cu wire with $50/J$ cross-sectional area is required. In this case, the resistance R_c, power consumption P_c, and mass M_c of the 672 m Cu selection field coil at room temperature are estimated as $0.227J$ W, $568J$ W, and $300/J$ kg, respectively. This indicates that the P_c, and M_c are in the relation of trade-off. In the case J is set to 20 (A/mm^2), for example, P_c and M_c are calculated as 11.36 kW and 15 kg, respectively. Compared with the power consumption using HTS tape (68 mW), the P_c becomes larger by a factor of more than 5 orders. We note that though the R_c is reduced to 1/7 if the Cu selection field coil is used at 77 K, the P_c is still much larger. In the case J is set to small value, on the one hand the P_c can be decreased, the M_c becomes large on the other hand. Note that the mass of the HTS selection field coil is 3.6 kg. The P_c and M_c are estimated as 568 W and 300 kg, respectively, if J is set to 1 (A/mm^2) as an example.

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Table 2: Specifications of one coil wound with YBCO HTS tape for selection field coil.

Parameter	Value
Inner diameter (mm)	180
Outer diameter (mm)	207
Width (mm)	8
Number of Turns	90×2

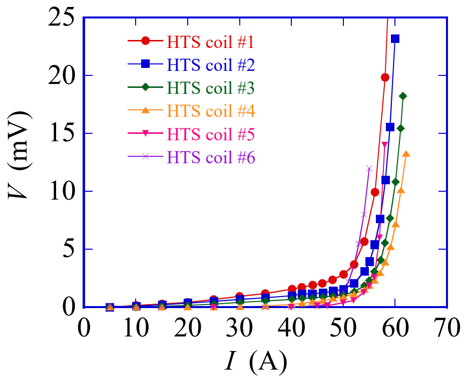

Figure 4: I-V characteristics of YBCO HTS coils cooled at 77 K with liquid nitrogen.

IV. Conclusions

In this work, we designed MPI modules with 120 mm bore diameter and developed the drive field coil made of Cu Litz-wire and selection field coil made of YBCO HTS tape. The gradient field of 0.63 T/m was realized with the developed YBCO HTS coil cooled with LN. It was shown that, the power consumption and the mass of the selection field coil can be dramatically reduced by using HTS tape compared with those made of Cu wire. For the realization of human-body-sized MPI scanner, a HTS selection field coil will be one of the best options to achieve both low power consumption and lightweight.

Acknowledgments

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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