論文内容の要旨

論文題目 Study on current distribution in $YBa_2Cu_3O_{7-x}$ superconducting wire for NMR magnet design

（NMR 用マグネット設計の指針となるイットリウム系超電導線材内の電流分布に関する研究）

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1. Introduction

Superconducting magnets generating higher magnetic fields than conventional ones are required in Nuclear Magnetic Resonance (NMR) spectrometers and Magnetic Resonance Imaging (MRI) devices. Magnets generating magnetic fields over 30 T have been studied in NMR [1]. In MRI, a 11.7 T-magnet with a large room temperature bore, 900 mm, have been designed [2]. The increases of magnetic fields result in enhancement of nuclide identifications. A lot of superconductors have been discovered, but only a few of them are usable for magnets. Practical superconducting magnets consist of Nb-based low-temperature superconducting (LTS) wires and/or Bi-based high-temperature superconducting (HTS) wires, which are called first generation (1G) HTS wires. One kilometer-long $YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors (CCs), second generation (2G) HTS wires, with a critical current (I_c) over 200 A/cm-width at 77.3 K and self field have been developed [3]. Nb_3Sn superconducting wires, which are one of LTS wires, are used as a material of high field magnets. LTS magnets cannot generate static fields over 25 T due to the upper critical magnetic field (B_{c2}) of Nb_3Sn [4]. Compared with 1G HTS wires, CCs have high I_c under high fields [5] and advantages for high stress applications [6]. The properties of CCs give rise to the possibility of constructing high field magnets with the advent of several kilometers long CCs.

Magnets for NMR spectrometers and MRI devices should generate magnetic fields with high homogeneities and stabilities. In contrast with multi-filamentary LTS wires, HTS wires have tape shape with high aspect ratios. Experiments and calculations [7], [8], [9] have showed that a 1G HTS magnet inserted concentrically into a LTS magnet generates inhomogeneous and unstable fields due to screening currents flowing on the 1G HTS wires. Uglietti *et al.* [10] have reported that magnetic fields generated by a downsized coil consisting of a CC have inhomogeneities and instabilities as well due to a screening current on the tape-shaped CCs. Magnetic fields component perpendicular to the tape surface induces screening currents. The magnetic fields consist of self field and external fields. It is not known well how the total currents consisting of screening and transport currents flow in CC at 4.2 K under high field. Further investigations regarding relation between the screening and transport currents were carried out in this thesis. The further investigations bring simplification of calculation in electromagnetic design of YBCO magnet and optimization of operating conditions of the magnet.

The purpose of this work is to understand relations between the screening and transport currents at 4.2 K under high field and to suggest a method of electromagnetic design taking screening current into consideration. The following evaluations were performed:

- The current distribution flowing in a YBCO CC was estimated from magnetic field distribution.
- Magnetic field distributions induced by screening currents flowing in YBCO CCs and the interaction between the screening currents in CCs were evaluated.
- Temporal variations of the SCF were measured.
- An electromagnetic design method for fabricating a YBCO coil taking the current distribution, temporal variations and the interaction of the screening current between the CCs into consideration was suggested.

2. Current distribution in a single coated conductor

Current distributions were estimated from actual magnetic field distributions generated by transport and screening currents. As shown in Fig. 1, a Hall sensor was scanned in liquid helium under external magnetic field in order to the magnetic field distributions.

Models of total currents consisting of screening and transport currents flowing in a short CC with a short length were examined. Observations of magnetic flux densities above the center of the CC under external magnetic field gave a macroscopic view of the screening current flowing one-dimensionally even in the CC with the short length. Magnetic field dependences of macroscopic critical current estimated from transport measurement expressed external magnetic field dependences of screening-current-induced magnetic field (SCF). This result verifies that the screening current corresponds to the critical current. This may be helpful when considering intensity of magnetic flux density, angular dependence of magnetic field and operation temperature in a magnet design

Assuming that current flows one-dimensionally, a model and a solution using the Tikhonov regularization were described. The distribution of sheet current density was calculated from the distribution of actual magnetic field. Using the distributions of sheet current density, magnetic field distributions at different positions were calculated and then were compared with the actual distributions. The calculation and experimental results agreed well and the validity

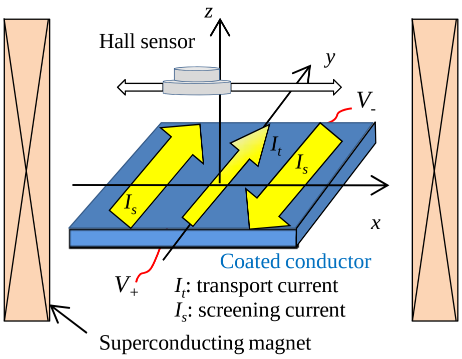

Fig. 1: Schematic diagram of measurements of magnetic flux densities above a coated conductor under external magnetic field and transport currents.

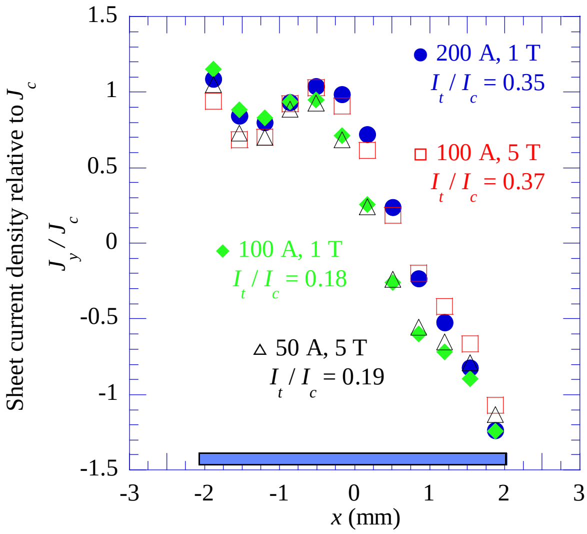

Fig. 2: Profiles of sheet current density J_y relative to critical sheet current density J_c unified by the transport current relative to critical current I_t/I_c.

of the model and solution were confirmed. On condition of low external magnetic field and low transport current, the sheet current density given by actual magnetic field distributions and the Brandt's critical state model [11] agreed well. Therefore, the agreement enhances the validity of the solution of the sheet current density.

It turned out that the transport current relative to critical current depending on external magnetic field determines distribution of the sheet current density under high field shown in Fig. 2. On the other hand, the measurement and analysis reveals that variations of external magnetic field are dominant to the distributions of sheet current density under the low magnetic field, where magnetic flux is not at the center of the CC.

3. Magnetic field distributions generated by multiple YBCO coated conductors

Distributions of SCF generated by arranged and/or superimposed CCs are examined and then the calculation method for estimating the distributions from sheet current densities in a single CC is suggested. The calculation results give the accordance with the experimental values as shown in Fig. 3. As a result, it was verified that distributions of SCF and current density for arranged- and/or superimposed-CCs could estimate current distribution in a single CC.

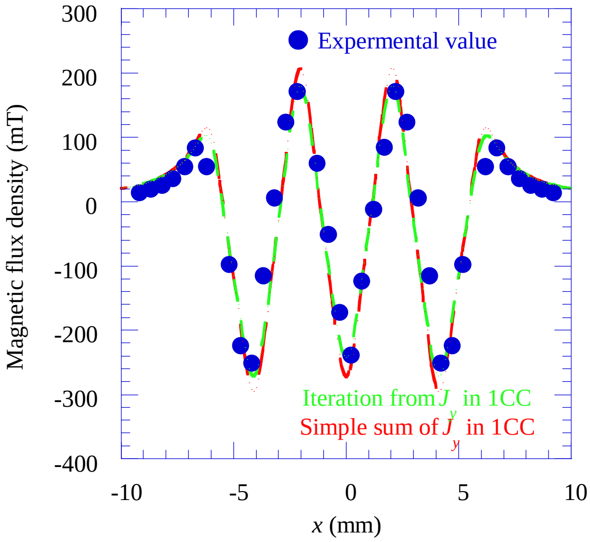

Fig. 3: Distributions of SCF for 3-parallel, 3-layers CCs at external field with magnetic flux of 1 T. The blue circles show experimental values. Green and red lines were calculated using the iteration and the simple sum method, respectively. Distributions of SCF for 3-parallel, 3-layers CCs at external field with magnetic flux of 1 T. The blue circles show experimental values. Green and red lines were calculated using the iteration and the simple sum method, respectively.

4. Temporal variations of the SCF

Temporal variations of the SCF generated by arranged- and/or superimposed-CCs were observed. The result shows that the variations are determined by amount of magnetic flux in the multiple CCs and temperature

5. An electromagnetic design method for fabricating a YBCO coil taking the current distribution and the interaction of the screening current between the CCs into consideration

An electromagnetic design method for calculating magnetic field generated by the multi-turn and multi-layer YBCO coil from the sheet current density in a CC was suggested. As an example, Fig. 4 shows distributions of

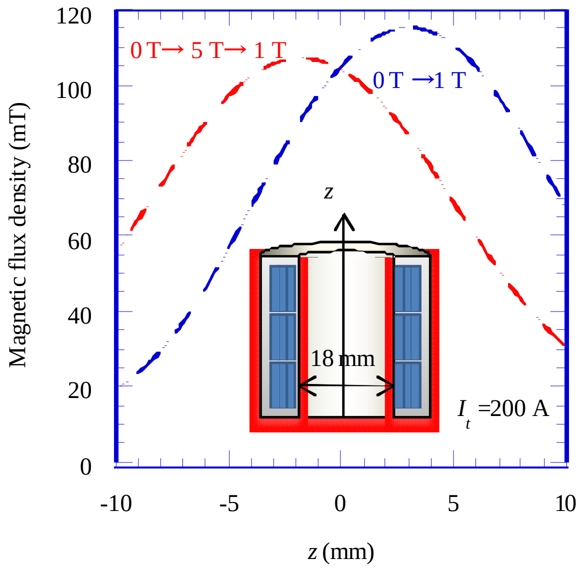

Fig. 4: Distribution of z-component of magnetic flux densities along z-axis

z-component of magnetic flux densities along z-axis generated by a YBCO coil with a diameter of 18 mm. The transport current supplied to the YBCO pancake coil is 200 A. The blue line shows distributions of magnetic flux density along *z*-axis at instant when background magnetic field goes from 0 T to 1 T. The red line shows distributions of the magnetic flux density at 1 T during a reduction of background magnetic field. The difference between red and blue profile shows that the calculation model takes screening current into considerations.

6. Conclusion

This thesis reveals a relation between screening and transport currents in a coated conductor and then, a coil design taking screening current into consideration became possible. This design method may promote a construction of YBCO magnet.

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