Static magnetic field amplification in high-T_c superconducting flux transformer equipped with multi-turn coil prepared using REBCO tape conductor

Kazunori Komori[1]*, Shunichi Arisawa[1], Minoru Tachiki[1], Shuuichi Ooi[1], Tadayuki Hayashi[2], and Kazuhiro Endo[3]

[1]*National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan*

[2]*National Institute of Technology, Sendai College, Sendai, Miyagi 989-3128, Japan*

[3]*Kanazawa Institute of Technology, Nonoichi, Ishikawa 921-851, Japan*

E-mail: KOMORI.Kazunori@nims.go.jp

In this study, a high critical temperature (high-T_c) superconducting flux transformer is prepared using a commercially available $REBa_2Cu_3O_y$ (REBCO) high-T_c superconducting (HTS) tape conductor. The device configuration includes a 10 cm diameter pickup coil and a 3 cm diameter multi-turn input coil which are formed by the 'cut-and wind' method. The static magnetic field transfer efficiency between both coils has been estimated using inductance calculation of the multi-turn coils. The transfer efficiency measured is close to the calculation, and the field amplification of the transferred magnetic field compared to the applied field to the pickup coil is confirmed in the device which equipped with the multi-turn input coil. The magnitude of this magnetic field amplification has achieved to 125% of the applied field. This result suggests that the HTS flux transformer proposed in this study is effective in the sensitivity enhancement of the magnetometer for static magnetic fields.

1. Introduction

There has been several attempts to prepare superconducting flux transformers (SFTs) using a high-T_c superconductor (HTS) [1), 2)]. SFTs are conventionally used to detect weak magnetic fields in highly sensitive magnetic sensor instruments such as the superconducting quantum interference device (SQUID) [3)]. For stable instrument operation, SQUID is typically set in a magnetic shield of the instrument to ensure protect from magnetic disturbances. Magnetic flux guidance for observing magnetic signals to SQUID is provided by an SFT.

The SFT consists of two coils in one closed circuit: the pickup coil, which is the sensing area, and the input coil, which is the sensor interface. In addition, the SFT transfers magnetic flux from the pickup coil to the input coil[4)]. This property is due to the fact that the superconductive shielding current spontaneously generated by applying a static magnetic field to the pickup coil is transformed into a magnetic field signal generated by the input coil. The magnetic flux transfer due to the non-dissipative superconducting current in the SFT is considered more efficient than in other magnetic guides made of high permeability materials which involves magnetic flux dispersion. Furthermore, the flux transfer via conversion between current and magnetic field can amplify the magnetic field by condensation of the transferred flux in the coils, depending on the design ratio of the coil area and number of turns of each coil. Similar amplification and transfer of magnetic fields can be achieved by connecting two induction coils made of normal conductors in series. In this circuit, the applied alternating magnetic field induces a current in the source coil and the transferred current generates a magnetic field in the destination coil. However, as it operates on the principle of electromagnetic induction, the amplification and transfer of the magnetic field is limited to when an alternative magnetic field is applied. In contrast, an SFT function on the basis of spontaneous superconducting current induction due to the diamagnetic behavior of the superconducting closed circuit. Therefore, SFT can amplify the magnetic field with respect to the static magnetic field and are used for precise measurement of the static magnetic field signal. Conventional SFTs use low-T_c metallic superconducting wires and require liquid helium refrigeration for operation. In contrast, HTS wires can use liquid nitrogen cooling or small refrigerators during operation. Therefore, a high-T_c superconducting flux transformer (HTSFT) is considerable to be utilized as a magnetometer with non-cooling magneto sensors such as an anisotropic magneto resistive sensor or magneto impedance sensor[5)].

Considering the amplification of the signal, both a large-diameter pickup coil and a small-diameter, multi-turn input coil are required to construct an SFT. Conventional SFTs use metal wires that are convenient for forming superconducting joints at the wire ends by soldering, cold pressing or welding[6)-9)]. Therefore, SFTs equipped with multi-turn coils can be easily fabricated. On the other hand, the joining techniques currently adopted for HTS wire[10)-12)] are not practical due to restrictions in terms of processing time, the shape of the joints and the superconductivity of the joints. For such reasons, HTSFT can be prepared by patterning HTS thin films on single-crystal substrates or tape conductors to create the essential superconducting closed circuits[1), 2)]. The limitations of using these methods to fabricate HTSFTs are that the coil diameter must be smaller than the substrate width, the coil configuration must be single-layer and single-turn, and the process to fabricate multi-layer junctions is complex.

To date, we have reported on the preparation of HTSFT[13)] using flexible monofilament superconducting tape formed by the "cut-and-wind" method[14)]. Hence, the preparation of a superconductive closed circuit operable above liquid nitrogen temperature is possible without jointing in the wire end. However, the magnetic field transferred by the HTSFT was only smaller than the applied field[13)]. From the viewpoint of a magnetic field amplifier for high-sensitivity magnetic measurement, this characteristic was insufficient. In order to realize static magnetic field transfer with amplification, we have modified the fabrication method to use multi-slitted tape and prepared HTSFTs with a larger aperture ratio of both coils and a multi-turn input coil. In this study, we report the preparation of HTSFT equipped with single-turn 10 cm bore pickup coil and multi-turn 3 cm bore input coil, and its magnetic field transfer property.

2. Experimental methods

2.1 Preparation of HTSFT using 2G-HTS tape

Monofilament $REBa_2Cu_3O_y$ (REBCO) second-generation HTS (2G-HTS) tape conductors (*SuperPower Inc.*) were used to prepare the HTSFT. The width of the tape was 12 mm. Figure 1 shows the preparation of the HTSFT used in this study: two through-slits at each end of the HTS tape were engraved with a 0.1 mm thick diamond wheel. A trench to connect the slits was also made in the substrate metal tape with removing a superconducting layer by chemical etching. The HTS tape consists of four layers: top copper layer (20 μm), protective silver layer (2 μm), REBCO superconducting layer (1 μm) and Hastelloy C-276 substrate with textured buffer layer (50 μm). The copper, silver and superconducting layers were chemically removed using 5% hydrochloric acid + 35% hydrogen peroxide water, 1% ammonia water + 35% hydrogen peroxide water and 1% hydrochloric acid, respectively. Thus, the HTS area surrounding the 'slit-trench-slit' forms a closed HTS circuit. The slit was then wound to form a loop, so that the HTSFT equipped with two loops in one closed HTS circuit were prepared by 'cut-and-wind' method.

Furthermore, our modified method using multi-slitted monofilament HTS tape improves on the 'cut-and-wind' method and allows the fabrication of multi-turn coils with any integer number of turns. HTSFTs with 1-, 2- and 3-turns coils have been fabricated using HTS tapes consisting of patterned trenches and 1, 3 and 5 slits. Figure 2 shows the fabrication process of these multi-turn input coils. In these HTSFTs, the diameters of the single-turn pickup coil and multi-turn input coil were 100 mm and 30 mm, respectively. The distance between the coils of the HTSFT was 280 mm.

2.2 Measurement efficiency of magnetic field transfer in HTSFTs

The static magnetic field transfer property of the HTSFTs was measured at a liquid nitrogen temperature (77 K). Figure 3 shows a schematic of the measurement system used in this study. A Helmholtz coil (308 mm in diameter) was used to apply a static magnetic field to the HTSFT pickup coil. In addition, the pickup coil was installed at the center of the Helmholtz coil, whereas the input coil was extended to the exterior of the Helmholtz coil. A magneto-impedance (MI) sensor (*Aichi Micro Intelligent Corp.* MGM-1DS) was surrounded by a thermal-insulating foamed polyethylene cylinder and installed at the center of the HTSFT input coil. The temperature of the MI sensor in the liquid nitrogen cooling bath was maintained at approximately room temperature via the thermal insulation cylinder so that the sensor works properly in the measurement system.

First, the entire HTSFT was cooled in a liquid nitrogen bath without a magnetic field, then a static magnetic field was applied to the pickup coil. The transferred static field in the input coil depending on the applied static field was measured using the MI sensor. As an evaluation of HTSFT performance, the transfer efficiency of the magnetic field was calculated as the ratio of the transfer field in the input coil to the applied field in the pickup coil of the HTSFT.

3. Results and discussion

3.1 Results

Recently we have reported about HTSFT preparation using 2G-HTS tape via the ‘cut-and-wind’ method, and its static magnetic field transfer property at liquid nitrogen temperature. However, the transferred field in the input coil of the HTSFT was smaller than the applied field in the pickup coil[13), this indicates that the magnetic field amplification has not been achieved. In this study, we attempted to increase the field transfer efficiency of newly designed HTSFTs by expanding the coil area of the pickup coil and miniaturization of the input coil diameter, and using the multi-turn input coil.

Figure 4 shows the measured field transfers of the HTSFTs discussed in this study. The transferred field in the input coil increased proportionally with the applied field in the pickup coil for each HTSFT design. In our previous work[13)], the efficiency of the HTSFT field transfer increased with the bore ratio of both coils in the HTSFT, and the maximum efficiency of the field transfer was 37.8 % of the applied field in the HTSFT equipped with a 1-turn 90 mm bore pickup coil and 1-turn 60 mm bore input coil. The HTSFT diameters used in this study were 100 mm for the pickup coil and 30 mm for the input coil; therefore the ratio between the diameters of both coils was enlarged. In this design, the field transfer efficiency significantly increased and reached 76.1 % for the 1-turn input coil configuration. Moreover, field transfer efficiencies of 118.2% and 124.9% were obtained for the 2-turns and 3-turns input coil configurations, respectively. This indicates that the field transfer efficiency of HTSFTs increase with the number of turns of the input coil. For the HTSFT design equipped with the multi-turn input coil, the transferred fields were larger than the applied field, hence the magnetic field transfer with field amplification owing to flux condensation were obtained.

3.2 Discussion

An HTSFT functions at liquid nitrogen temperature, therefore the HTSFT is probable to be used as a magnetic field amplifier for a generic magneto sensor and applicable to a portable instrument for environmental field measurement outside a magnetic shield room. To achieve this, the magnetic field amplification owing to flux condensation and efficient transfer of the magnetic signal to the sensor should be realized at the temperature achievable using the convenient cryogenic refrigerator. An SFT is a device that transfers magnetic flux between the coils via the induction of supercurrent by static field application. For the same magnetic flux, flux density is larger in a coil with a smaller cross-sectional area, resulting in a larger magnetic field in the coil. Adding to this, the largest flux transfer in an SFT is obtained with an SFT design in which the inductance of the each coils implemented is equal[15)]. Therefore, efficient magnetic field transfer can be achieved by using an SFT implementing an input coil with a small diameter and a large number of turns[16)]. In this study, we used both a 100 mm diameter pickup coil and a 30 mm diameter input coil in a design of HTSFT. Since the device geometry has a coil area ratio of approximately 0.1, it is estimated that the inductance of both coils would be about the same for a 3-turns input coil, excluding the shape effect. This is why we fabricated 1-turn, 2-turns, and 3-turns input coils and investigated the change in flux transfer efficiency.

The transferred field in the input coil of the HTSFT was expressed using the following formula:

$$B_s = N_i \cdot kI_s = kN_i \frac{\Phi_{ex}}{L_p + L_i} = \frac{kN_i N_p A_p B_{ex}}{L_p + L_i}, \qquad (1)$$

where B_s and B_{ex} are the transferred and applied fields, respectively. I_s is the supercurrent induced in the SFT. L_p and L_i are the self-inductances of the pickup and input coils, respectively. N_p and N_i are the number of turns of the pickup and input coils, respectively, and N_p =1. A_p is the area of the pickup coil. k is the coefficient between B_s and I_s. In formula (1), the field transfer efficiency in the HTSFT, B_s / B_{ex}, increases with A_p.

The self-inductance of the input coil was calculated using the following formula:

$$L_i = k_N \frac{\mu A_i N_i^2}{l}, \qquad (2)$$

where N_i, l, A_i, k_N, and μ represent the number of turns, coil length, coil area, Nagaoka coefficient[17] of the input coil, and magnetic permeability of the coil, respectively. In equations (1) and (2), the magnetic field transfer efficiency B_s / B_{ex} varies with N_i to have a maximum value. However, for a 1-turn coil, the inductance cannot be calculated using equation (2) because the turn density cannot be defined. Therefore, assuming a round wire conductor with the same cross-sectional area of the HTS tape, the inductance of the pickup coil and 1-turn input coil can be estimated from the inductance calculation formula for 1-turn coils as 450 nH and 110 nH, respectively. The self-inductance of the planar 1-turn coil was calculated using the following formula[18]:

$$\mathrm{L} = \mu_0 r \left\{ \ln\left(\frac{8r}{a}\right) - 2 \right\}, \qquad (3)$$

where L, r and a are the inductance of planar coil, the coil radius and the radius of the round wire. We confirmed that the calculated inductances of a closed HTS coil were reasonable compared to the measured values of an open coil of the same geometry prepared using thin copper tape. Using this calculation, the inductance of a multi-turn coil is determined using equation (3), taking into account the increase in the number of turns, the change in coil length, and the change in the Nagaoka coefficient. The coil length of a multi-turn coil must be determined by considering the wire width and gap. For example, the coil length of a 1-turn coil is considered to be 6mm, same as the wire width which is half of the tape width. In the case of a multi-turn coil, the wire width and gap must be taken into account to determine the coil length. Therefore, for a 3-turns coil, the coil length is calculated to be 10 mm when the wire width and gap are considered. As a result, the Nagaoka coefficient and inductance of the input coil vary[18]. Considering this change in inductance, the increases in magnetic field transfer efficiency of the device with 2-turns coil and the device with 3-turns coil were calculated to be 1.65 and 1.81 times higher, respectively, than that of the 1-turn coil device. The measured values for the device with 2-turns coil and the device with 3-turns coil were 1.56 and 1.65 times higher, respectively, than for the device with 1-turn coil. These calculated values of the increase in magnetic field transfer efficiency are close to the measured values.

In this study, the maximum value of magnetic field amplification was 125% of the applied magnetic field. Moreover, larger magnetic field amplification is probably obtained with an HTSFT implementing an input coil with a small diameter, long coil length, large number of turns, and large inductance comparable large inductance of a pickup coil with a large area. The modified 'cut-and-wind' method enables to fabricate the HTSFT equipped with a small bore and large inductance input coil and a highly sensible magnetometer that uses a generic magneto sensor enhanced by the HTSFT would be probable. Although coils with a large number of turns are difficult to fabricate owing to smaller line width of the circuit, it may be possible to achieve higher inductance by stacking or insertion with multiple coils prepared to multi-turn configuration.

4. Conclusions

In this study, high-T_c superconducting flux transformers (HTSFTs) equipped with a large bore pickup coil and multi-turn input coil were prepared via the 'cut-and-wind' method using commercial REBCO 2G-HTS tapes. Magnetic field transfer between the pickup coil and input coil of the HTSFT was estimated at liquid nitrogen temperature (77K). The transferred static field in the input coil was larger than the applied field in the pickup coil for the HTSFT with a 2-turns input coil, furthermore, the field transfer efficiency was achieved to 125% of the applied field for the HTSFT with a 3-turns input coil. This indicates that the HTSFT is applicable to magnetic field amplifiers in enhancing the sensitivity of a generic magneto sensor. For the HTSFTs implementing the multi-turn input coil fabricated in this study, it is possible to estimate the field transfer efficiency of the static magnetic field from the device geometry.

Acknowledgments

We are thankful to Prof. Gen Uehara and Prof. Yoshiaki Adachi from the Kanazawa Institute of Technology for their helpful discussions during this study.

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Figure Captions

Fig. 1. Preparation of HTSFT shaped by the "cut-and-wind" method using a 2G-HTS tape monofilament conductor.

Fig. 2. Preparation of multi-turn input coils via the modified "cut-and-wind" method. Fabrication of multi-slits in the HTS tape and alternative winding of each line enables the preparation of the multi-turn coil for an arbitrary integer number.

Fig. 3. Schematic of a magnetic field transfer measurement system for the HTSFTs.

Fig. 4. Transferred magnetic fields in the HTSFT input coil for the applied field in the pickup coil. Three HTSFT designs implementing input coils of 1-, 2- and 3- turns were estimated at 77K. Dashed line shows 100% of field transfer efficiency (transferred field B_i =applied field B_p).
Transferred field in the HTSFT designed with smaller bore ratio (reference 13) was also indicated.

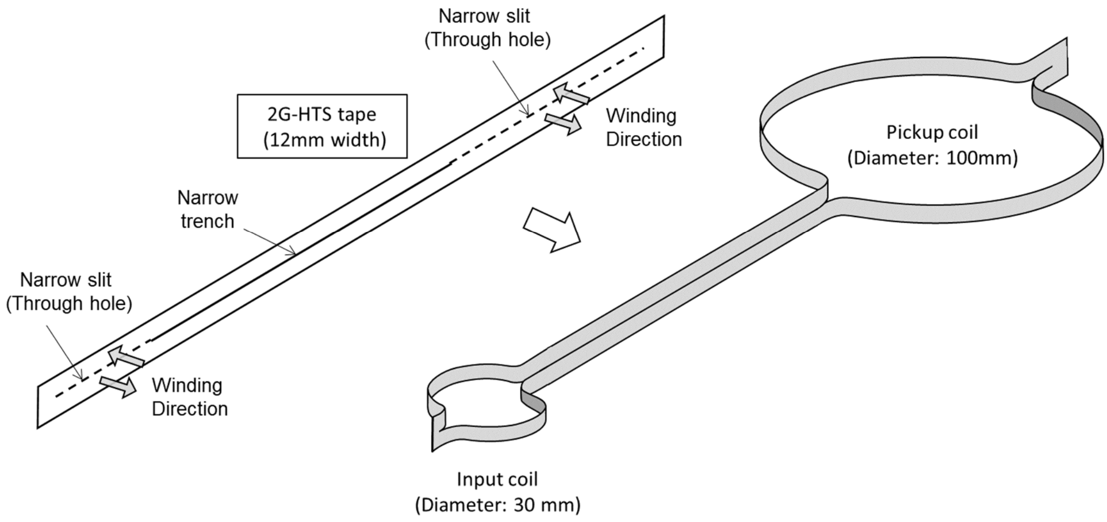
Narrow slit
(Through hole)
2G-HTS tape
(12mm width)
Winding
Direction
Narrow
trench
Narrow slit
(Through hole)
Winding
Direction
Pickup coil
(Diameter: 100mm)
Input coil
(Diameter: 30 mm)

Fig.1.

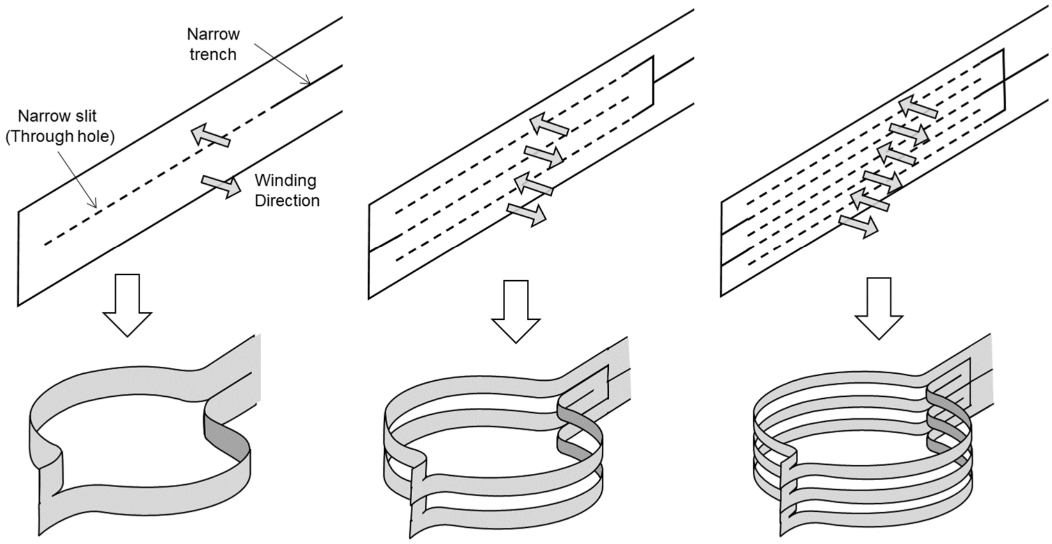

Fig. 2.

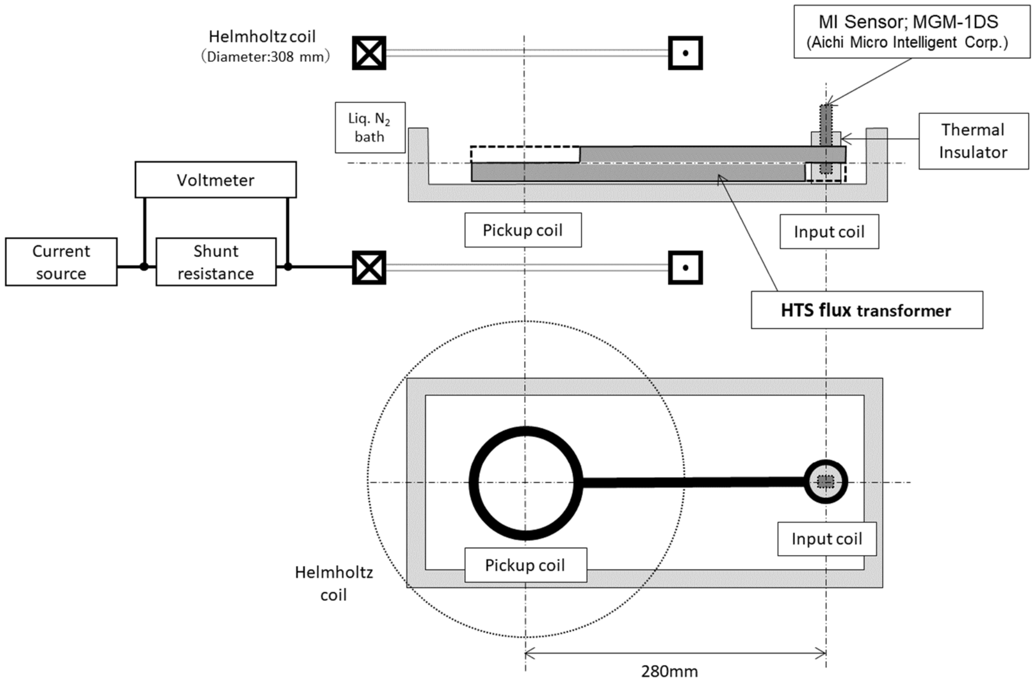
Helmholtz coil
(Diameter:308 mm)
MI Sensor; MGM-1DS
(Aichi Micro Intelligent Corp.)
Liq. N_2 bath
Thermal Insulator
Voltmeter
Current source
Shunt resistance
Pickup coil
Input coil
HTS flux transformer
Pickup coil
Input coil
Helmholtz coil
280mm

Fig. 3.

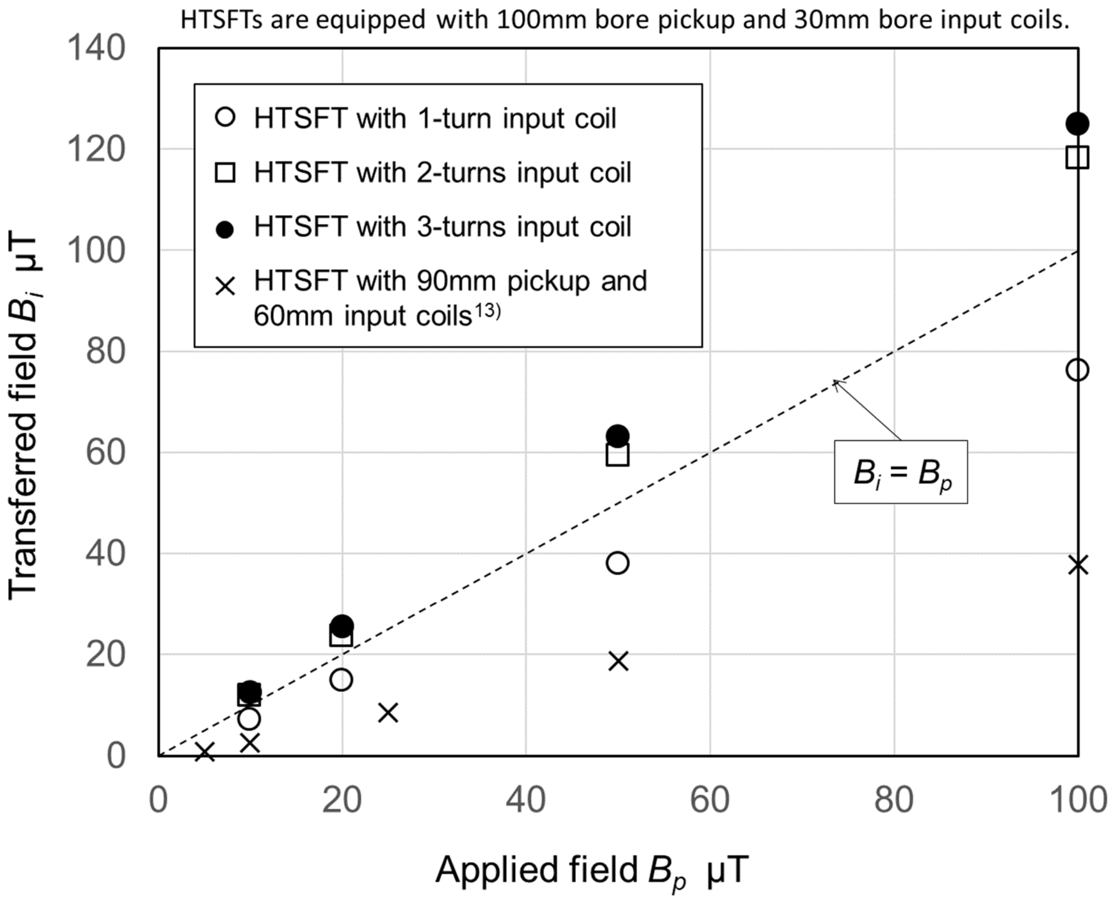
HTSFTs are equipped with 100mm bore pickup and 30mm bore input coils.
140
120
100
80
60
40
20
0
0
20
40
60
80
100
Transferred field B_i μT
Applied field B_p μT
HTSFT with 1-turn input coil
HTSFT with 2-turns input coil
HTSFT with 3-turns input coil
HTSFT with 90mm pickup and 60mm input coils[13)]
$B_i = B_p$

Fig. 4.