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Title	Magnetic shield effect simulation of superconducting film shield covering directly coupled HTS dc-SQUID magnetometer
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Citation	Physica C: Superconductivity, 471(21-22), 1253-1257 https://doi.org/10.1016/j.physc.2011.05.172
Issue Date	2011-11
Doc URL	https://hdl.handle.net/2115/48041
Type	journal article
File Information	PhyC471-21-22_1253-1257.pdf



FDP-43/ISS2010

Submitted November 2, 2010

Magnetic shield effect simulation of superconducting film shield covering directly coupled HTS dc-SQUID magnetometer

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Abstract

An HTS SQUID is a high sensitive magnetic sensor. In recent years, the HTS SQUID is widely used in various applications. In some applications, high robustness with respect to magnetic noise is required to realize stable operation at outside of a magnetic shielding room. The target of this paper is a directly coupled HTS dc-SQUID magnetometer. To enhance the robustness of the SQUID magnetometer, use of a superconducting thin film shield has been proposed. The magnetic field directly penetrating the SQUID ring causes the change of the critical current of Josephson junction, and then the SQUID magnetometer transitions into inoperative state. In order to confirm the magnetic shield effect of the superconducting film shield,

electromagnetic field simulation with 3D edge finite element method was performed. To simulate the high temperature superconductor, E - J characteristics and c -axis anisotropy are considered. To evaluate the effect of the superconducting film shield, an external magnetic field which is supposed to be a magnetic noise is applied. From the simulation results, the time transition of the magnetic flux penetrating the SQUID ring is investigated and the effect of the superconducting film shield is confirmed. The amplitude of the magnetic flux penetrating the SQUID ring can be reduced to about one-sixth since the superconducting film shield prevents the magnetic noise from directly penetrating the SQUID ring.

PACS codes: 85.25.Am, 85.25.Dq

Keywords: SQUID; Superconducting film shield; Numerical analysis

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1. Introduction

High temperature superconducting quantum interference device (HTS SQUID) has been developed as a kind of extremely sensitive magnetic sensors. It can measure a very small amount of magnetic flux. The HTS SQUID is widely used in various fields such as non destructive examination (NDE), biomagnetic measurement and so on [1,2]. In many cases of the applications, the HTS SQUID is usually placed in a magnetic shielding room. Magnetic shielding is indispensable to reduce or cut off external magnetic noise such as the Earth's magnetic field. The reason is that the HTS SQUID often transitions into unstable state even if very small external magnetic noise is applied. Thus, high robustness with respect to magnetic noise is required to realize stable operation at outside of the magnetic shielding room.

In this study, the target is a directly coupled HTS dc-SQUID magnetometer. The external magnetic field affects a current induced on pick-up coils, and the induced current flows into SQUID ring. To enhance the robustness of the SQUID magnetometer, use of a high temperature superconducting thin film shield has been proposed [3]. The superconducting film shield is made of $\text{YBa}_2\text{Cu}_3\text{O}_x$ thin film. It can protect the SQUID magnetometer from the external magnetic noise by the Meissner effect. The magnetic field directly applying to the SQUID ring changes the critical current of the Josephson junction [3]. The change of the critical current puts the dc-SQUID into an inoperative state. The magnetic shield prevents the magnetic field

from directly penetrating the SQUID ring, but the current induced on the pick-up coils flow into the SQUID ring. The effect of the superconducting film shield has been already confirmed by the experiments [4]. In order to confirm the effect of the superconducting film shield by simulation, we performed electromagnetic field simulations by 3D edge finite element method (FEM). From the results of these simulations, the magnetic shield characteristics of the superconducting film shield were investigated. The characteristic investigation of the SQUID magnetometer is usually done by experiments. However, it takes a lot of costs to develop the device and to cool by using liquid nitrogen in the experiments. By using the electromagnetic field simulation, these costs can be reduced.

2. Simulation method

As electromagnetic field simulation, the 3D edge FEM is employed. The FEM is one of the most famous and widely used simulation methods. To simulate a space including the SQUID magnetometer covered with the superconducting film shield, the governing equations derived from the Maxwell's equations are

$$\text{rot}(\nu \text{rot} \mathbf{A}) = \mathbf{J}_0 + \mathbf{J}_{\text{sc}} \quad (1)$$

and

$$\text{div}(\mathbf{J}_0 + \mathbf{J}_{\text{sc}}) = 0 \quad (2)$$

where ν is the magnetic reluctivity, $\mathbf{A}$ is the magnetic vector potential, $\mathbf{J}_0$ is the bias current density of the SQUID magnetometer, and $\mathbf{J}_{\text{sc}}$ is the supercurrent density caused

by the Meissner effect in the SQUID magnetometer and the superconducting film shield. The governing equations are discretized with the Galerkin method. The backward difference method is employed to deal with the time derivative term. Therefore, the step-by-step method is employed in this simulation.

The supercurrent density is calculated from the following relations:

$$\mathbf{J}_{sc} = [\boldsymbol{\sigma}_{sc}] \mathbf{E}_{sc} = \begin{bmatrix} \sigma_{sc,a} & 0 & 0 \\ 0 & \sigma_{sc,b} & 0 \\ 0 & 0 & \sigma_{sc,c} \end{bmatrix} \mathbf{E}_{sc} \quad (3)$$

and

$$\mathbf{E}_{sc} = \frac{\partial \mathbf{A}}{\partial t} + \text{grad} \varphi \quad (4)$$

where $\sigma_{sc,a}$, $\sigma_{sc,b}$ and $\sigma_{sc,c}$ are a , b and c axis components of the equivalent electric conductivity of HTS, respectively. $\mathbf{E}_{sc}$ is the electric field that creates the supercurrent for shielding, φ is the electric scalar potential, and t is the time. To simulate the high temperature superconductor, the equivalent electric conductivity is adopted in order to consider the characteristic of that. The high temperature superconductor has a nonlinear characteristic which is called E - J characteristic [5]. The behavior of the superconductor changes drastically around the critical current density. It is much different from the Ohm's law. In this study, to express the E - J characteristic, n -value model is employed. The equation of n -value model is represented by

$$|\mathbf{E}| = |\mathbf{E}_0 + \mathbf{E}_{sc}| = E_c \left(\frac{|\mathbf{J}_0 + \mathbf{J}_{sc}|}{J_c} \right)^n \quad (5)$$

where $\mathbf{E}$ is the electric field, $\mathbf{E}_0$ is the electric field that creates the bias current of the

SQUID magnetometer, E_c is the electric field criterion, J_c is the critical current density that is defined by E_c , and n is the parameter that is concerned with the nonlinearity. The values of these parameters are set as follows; $J_c = 2.80 \times 10^{10} \text{ A/m}^2$, $E_c = 1.0 \times 10^{-3} \text{ V}$, and $n = 10$. It is also necessary to consider the anisotropy of the SQUID magnetometer and the superconducting film shield. In order to express this anisotropy, the equivalent electric conductivity parallel to the c -axis is set to an extremely small value, compared with that on the ab -plane. Considering the anisotropy, the equivalent electric conductivity is given by the following equations:

$$\sigma_{sc,x}, \sigma_{sc,y} = \frac{J_c}{|\mathbf{E}|} \left(\frac{|\mathbf{E}|}{E_c} \right)^{\frac{1}{n}} = \frac{J_c}{\sqrt{E_x^2 + E_y^2}} \left(\frac{\sqrt{E_x^2 + E_y^2}}{E_c} \right)^{\frac{1}{n}} \quad (6)$$

and

$$\sigma_{sc,z} = \text{constant} = 1.0 \times 10^{-10} \quad (7)$$

where $\sigma_{sc,x}$, $\sigma_{sc,y}$ and $\sigma_{sc,z}$ are the x , y and z direction components of the equivalent electric conductivity $[\sigma_{sc}]$, respectively. E_x and E_y are the x and y direction components of the electric field $\mathbf{E}$. Here, the a , b and c axes are corresponds to the x , y and z axes in the Cartesian coordinate, respectively. As shown in Eq. (6), to calculate the equivalent electric conductivity, the value of the electric field $\mathbf{E}$ is required. Here, the electric field $\mathbf{E}$ is given by the following equation

$$\mathbf{E} = \frac{\partial \mathbf{A}}{\partial t} + \text{grad}(\varphi + \varphi_0) \quad (8)$$

where φ_0 is the electric scalar potential which generates the bias current. The backward

difference is employed to deal with the time derivative term in Eq. (8). Thus, the equation derived from the backward difference is

$$\mathbf{E} = \frac{1}{\Delta t} (\mathbf{A}_{t+1} - \mathbf{A}_t) + \text{grad}(\varphi + \varphi_0) \quad (9)$$

where Δt is the time step, $\mathbf{A}_{t+1}$ and $\mathbf{A}_t$ are the magnetic vector potential at the time step $t+1$ and t , respectively. However, $\mathbf{A}_{t+1}$ is unknown variable when the simulation on time $t+1$ is performed. Therefore, the iterative calculation is done till the following condition is satisfied.

$$\frac{\left| \mathbf{E}_{t+1}^{m+1} \right| - \left| \mathbf{E}_{t+1}^m \right|}{\left| \mathbf{E}_{t+1}^m \right|} \leq \varepsilon \quad (10)$$

where $\mathbf{E}_{t+1}^m$ is the electric field at the m -th iteration on time $t+1$, and ε is the convergence criterion.

3. Analysis model

Fig. 1 shows the geometry of the SQUID magnetometer. The SQUID magnetometer was designed in Ref. [4]. The SQUID magnetometer is made of YBCO thin film with thickness of 200 nm. The kind of the SQUID magnetometer is called a directly coupled SQUID magnetometer. It has a multi-pickup-loop that is connected to the SQUID ring. The SQUID magnetometer is on a bicrystal STO substrate, but the substrate is not considered in the analysis. The sizes of the SQUID magnetometer and the SQUID ring with a very complex shape are $3 \text{ mm} \times 3 \text{ mm}$ and $44 \text{ } \mu\text{m} \times 86 \text{ } \mu\text{m}$, respectively. Fig. 2 shows the geometry of the superconducting film shield attached on the SQUID

magnetometer. The superconducting film shield is also made of an YBCO thin film. It can reduce or cut off the magnetic noise penetrating the SQUID ring. The size of the superconducting film shield is $1.6 \text{ mm} \times 1.6 \text{ mm}$. The thickness of the superconducting film shield is 200 nm, same as the SQUID magnetometer.

Two analysis models are prepared to confirm the effect of the superconducting film shield. One consists of the SQUID magnetometer without the superconducting film shield and the other the SQUID magnetometer with the superconducting film shield. The former is named as a non-shielding model, and the latter a shielding model. The overall view of the shielding model is shown in Fig. 3. The size of the analysis model is $15 \text{ mm} \times 15 \text{ mm} \times 7.5 \text{ mm}$ including the air region. The distance between the SQUID magnetometer and the superconducting film shield is $10 \text{ }\mu\text{m}$. The specifications of the analysis models are shown in Table 1. By the way, the AC magnetic field, which is supposed to be the magnetic noise, is applied to the SQUID magnetometer in the simulation. The AC magnetic field is sinusoidal, the amplitude is $1.5 \text{ }\mu\text{T}_{\text{p-p}}$, and the frequency is 100 Hz. The time step of the simulation is about 0.278 ms, it corresponds to 10 degrees. The bias current of the SQUID magnetometer is $16.6 \text{ }\mu\text{A}$.

4. Results and Discussions

From the simulation results, the amount of the magnetic flux penetrating the SQUID ring and the current density distribution are investigated. Fig. 4 shows the time

transition of the magnetic flux penetrating the SQUID ring. The amount of the magnetic flux penetrating the SQUID ring is calculated from adding the simulated magnetic flux on the elements of the air inside the SQUID ring. In this figure, the time transition of the AC magnetic field is also shown. From this figure, the magnetic flux penetrating the SQUID ring without the superconducting film shield changes in a little different phase compared with the AC magnetic field. On the other hand, the magnetic flux penetrating the SQUID ring with the superconducting film shield almost changes in the opposite phase. The reason is that the magnetic field generated by the shielding current in the superconducting film shield strongly affects to the SQUID ring.

The amplitude of the non-shielding model is 0.9265 fWb_{p-p} and the shielding model 0.1469 fWb_{p-p} . The amplitude of the latter is about one-sixth compared with the former. It is obvious that the difference of the amplitude is caused by the superconducting film shield. When the AC magnetic field is applied, the supercurrent flows in the SQUID magnetometer and the superconducting film shield to expel the magnetic flux. In the case of the non-shielding model, however, the magnetic flux is not completely expelled by the Meissner effect of the SQUID magnetometer. On the other hand, in the case of the shielding model, the amplitude of the magnetic flux penetrating the SQUID ring effectively decreased.

Figs. 5 and 6 show the current density distributions of the shielding model and the non-shielding model. In Fig. 5, without the superconducting film shield, the current in

the pick-up coils flow into the SQUID ring. Otherwise, in Fig. 6, the current in the pick-up coils is prevented from concentratively flowing into the SQUID ring by the superconducting film shield. Fig. 7 shows the current density distribution on the superconducting film shield. In Fig.7, the current mainly flow along the edges of the superconducting film shield. The supercurrent of the superconducting film shield can achieve to reduce the magnetic flux penetrating the SQUID ring.

In the SQUID magnetometer, the magnetic field is mainly measured at the pick-up coils. The current induced by the magnetic field penetrating the pick-up coil flows into the SQUID ring. The induced current generates the magnetic flux penetrating the SQUID ring. From the simulation results, the induced current flowing into the SQUID ring from the one pickup-coil is 0.509 mA in the non-shielding model and 0.526 mA in the shielding model at peak, respectively. The difference of the induced current is only 3.3%. Thus, the superconducting film shield has little influence on the induced current of the pick-up coils, but prevents the magnetic flux from directly penetrating the SQUID rings. It enhances the sensitivity of the SQUID magnetometer.

In this paper, the magnetic film shield covers a part of the pick-up coils, but it shouldn't cover. However, the simulation model was decided from the experiment model [4].

5. Conclusions

In this study, we have investigated the effect of the superconducting film shield. The

3D simulation of the SQUID magnetometer covered with the superconducting film shield has been executed. From the simulation results, it turns out that the influence of the external magnetic field can be reduced by the superconducting film shield. Consequently, it is obvious that the superconducting film shield enhances the robustness of the SQUID magnetometer.

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Tables

Table 1 Specifications of the analysis models.

Figure captions

Fig. 1. SQUID magnetometer.

(a) Geometry of the SQUID magnetometer. The size is $3\text{ mm} \times 3\text{ mm}$.

(b) Geometry of the SQUID ring. The size is $44\text{ }\mu\text{m} \times 86\text{ }\mu\text{m}$ with a hole of $4\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$.

Fig. 2. Geometry of the superconducting film shield covering the SQUID magnetometer. The size of superconducting film shield is $1.6\text{ mm} \times 1.6\text{ mm}$. The distance between the SQUID magnetometer and the superconducting film shield is $10\text{ }\mu\text{m}$.

Fig. 3. Overall view of the analysis model including the air region (shielding model).

Fig.4. Transition of magnetic flux penetrating the SQUID ring

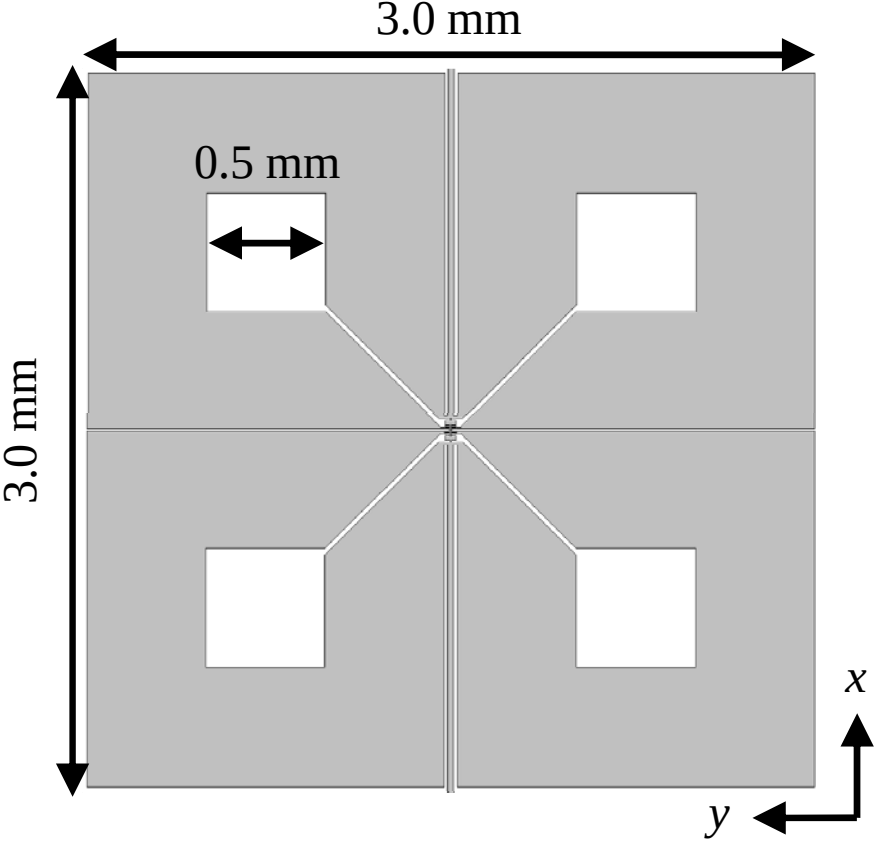
Fig. 5. Current density distributions without superconducting film shield. (a) Overall view. (b) Magnified view on one pick-up coil.

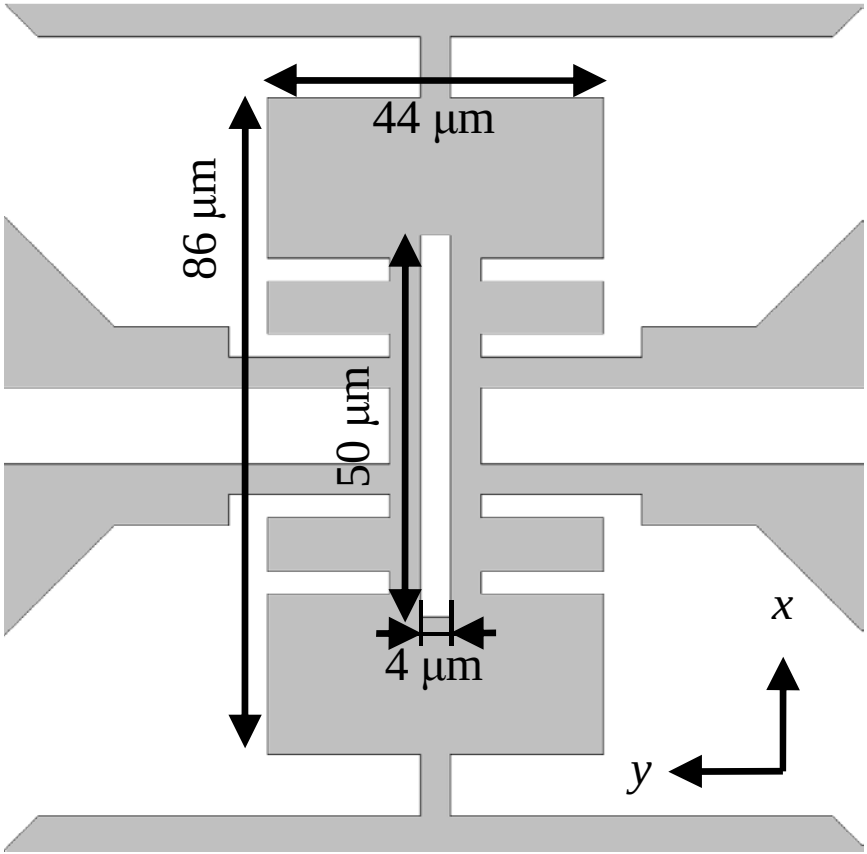
Fig. 6. Current density distributions with superconducting film shield. (a) Overall view.

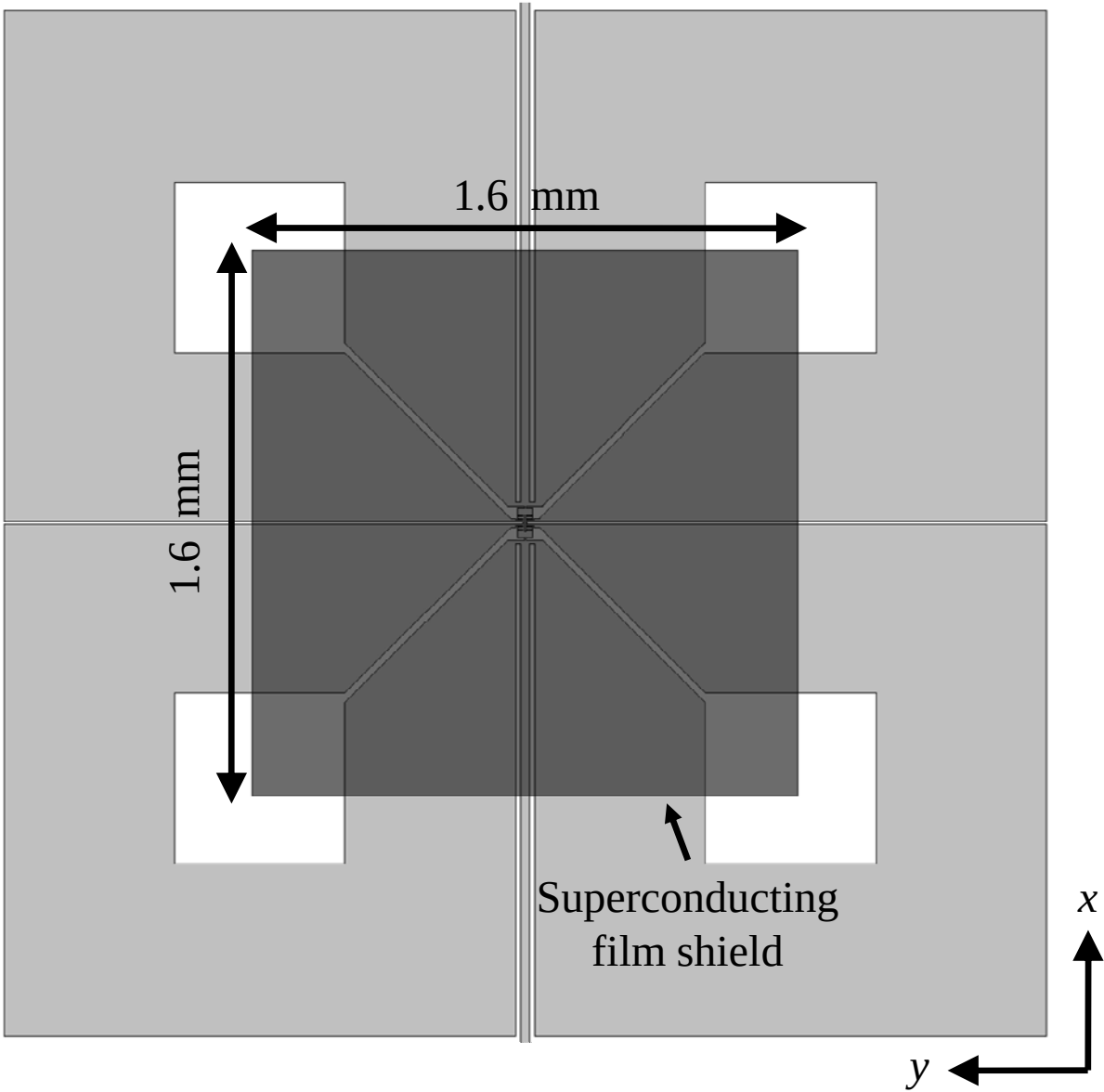
(b) Magnified view on one pick-up coil.

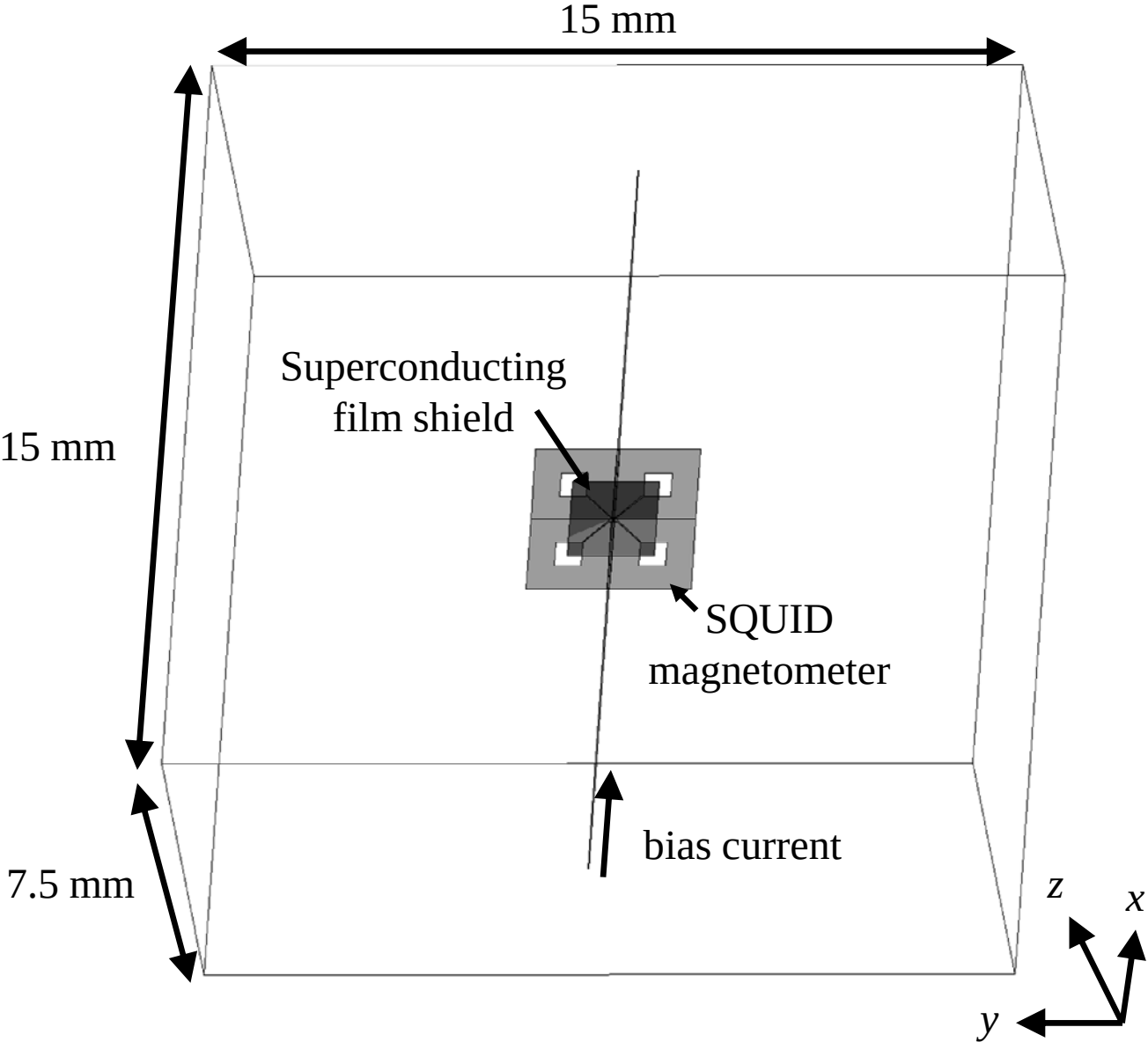
Fig. 7. Current density distribution on the superconducting film shield

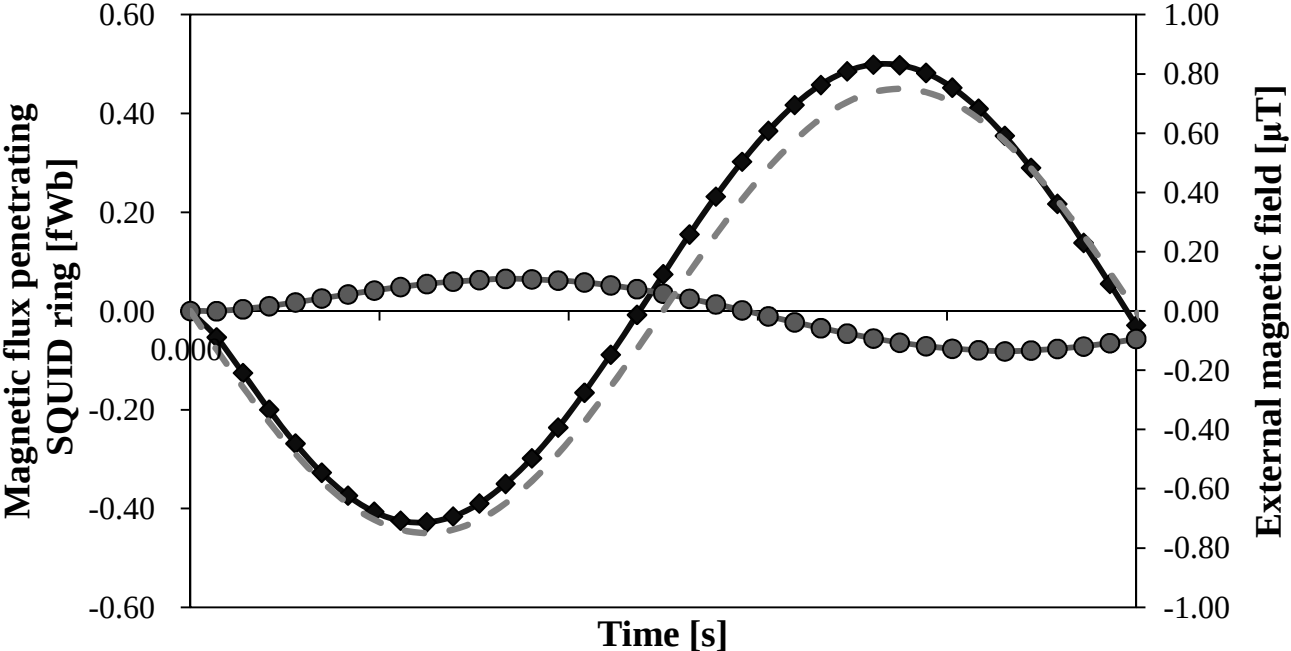
	Non shielding	Shielding
Number of nodes	525,813	796,009
Number of	3,098,852	4,503,179
Number of edges	3,629,542	5,304,065

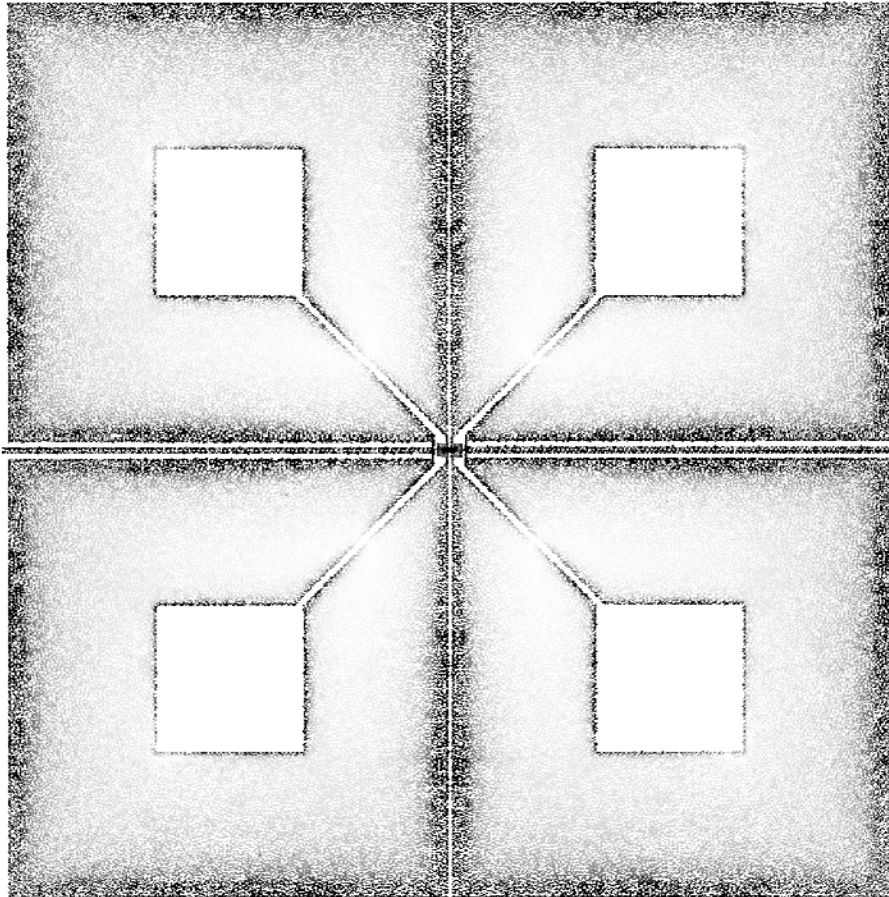












4.00×10^7

3.20×10^7

2.40×10^7

1.61×10^7

8.08×10^6

1.00×10^5

[A/m²]

