Magnetic-field distribution generated by screening current flowing in YBCO coated conductor

Akihisa Miyazoe, Yasuaki Nakanishi, Masaki Sekino,
Hiroyuki Ohsaki, University of Tokyo, Japan
E-mail: miyazoe@ohsaki.k.u-tokyo.ac.jp

Tsukasa Kiyoshi
National Institute for Materials Science, Japan

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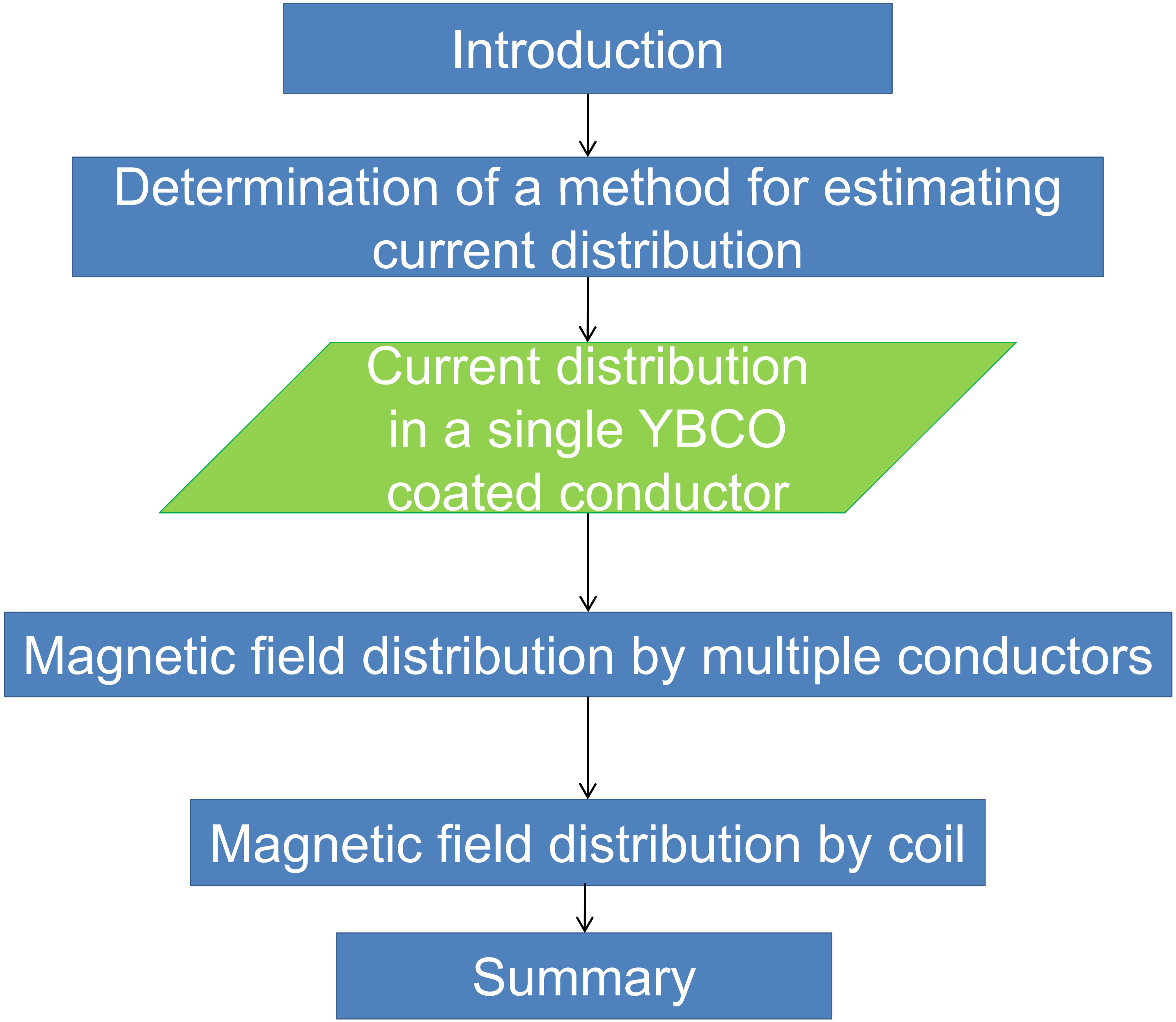
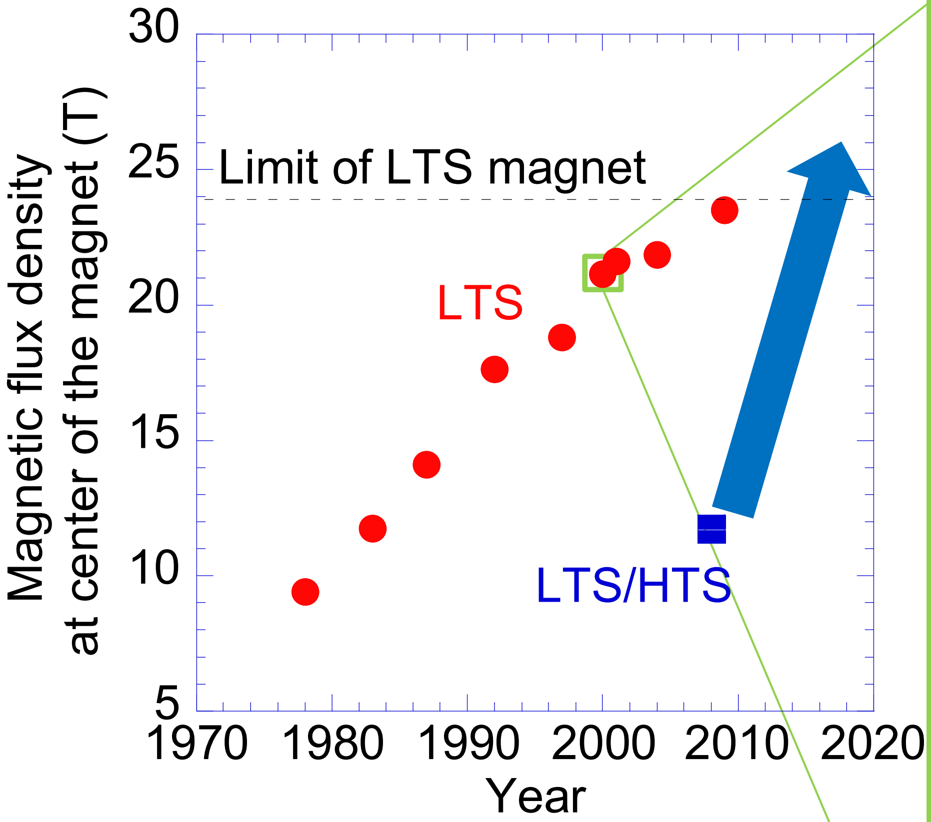

Introduction
Determination of a method for estimating current distribution
Current distribution in a single YBCO coated conductor
Magnetic field distribution by multiple conductors
Magnetic field distribution by coil
Summary

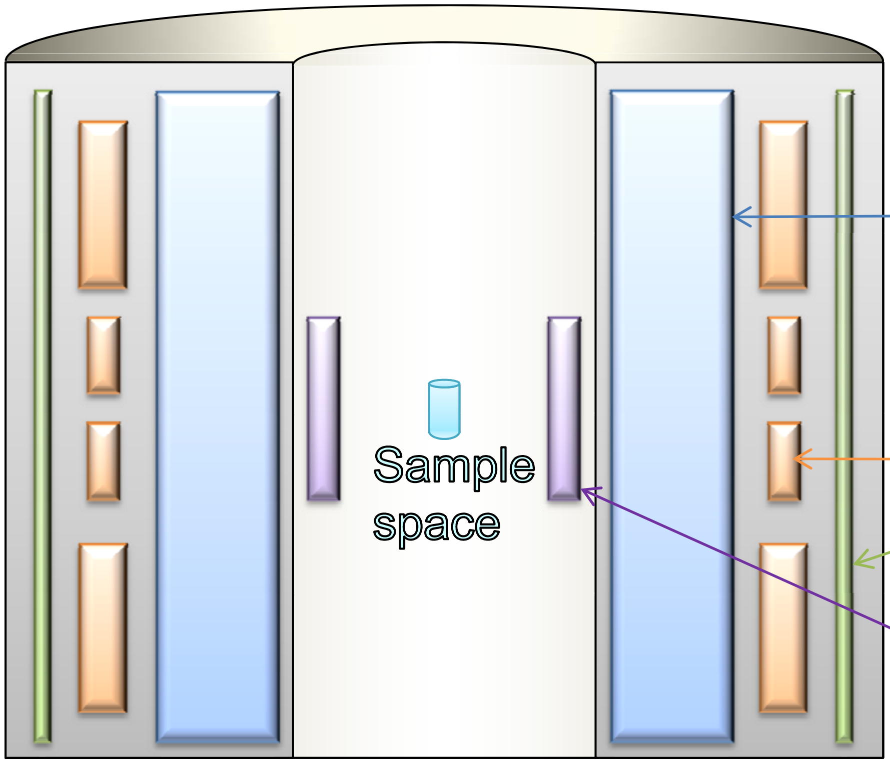
Advances in NMR superconducting magnet



21.6 T @ 1.8 K

920 MHz Nuclear Magnetic Resonance (NMR) spectrometer at Tsukuba magnet lab., Japan

Focus of this study



Superconducting magnet

< 2.4 μT/ sample space

< 0.24 μT/hour

✓ **Main coil**

ex) 50 ppm/sample space

3 ppm/sampling time

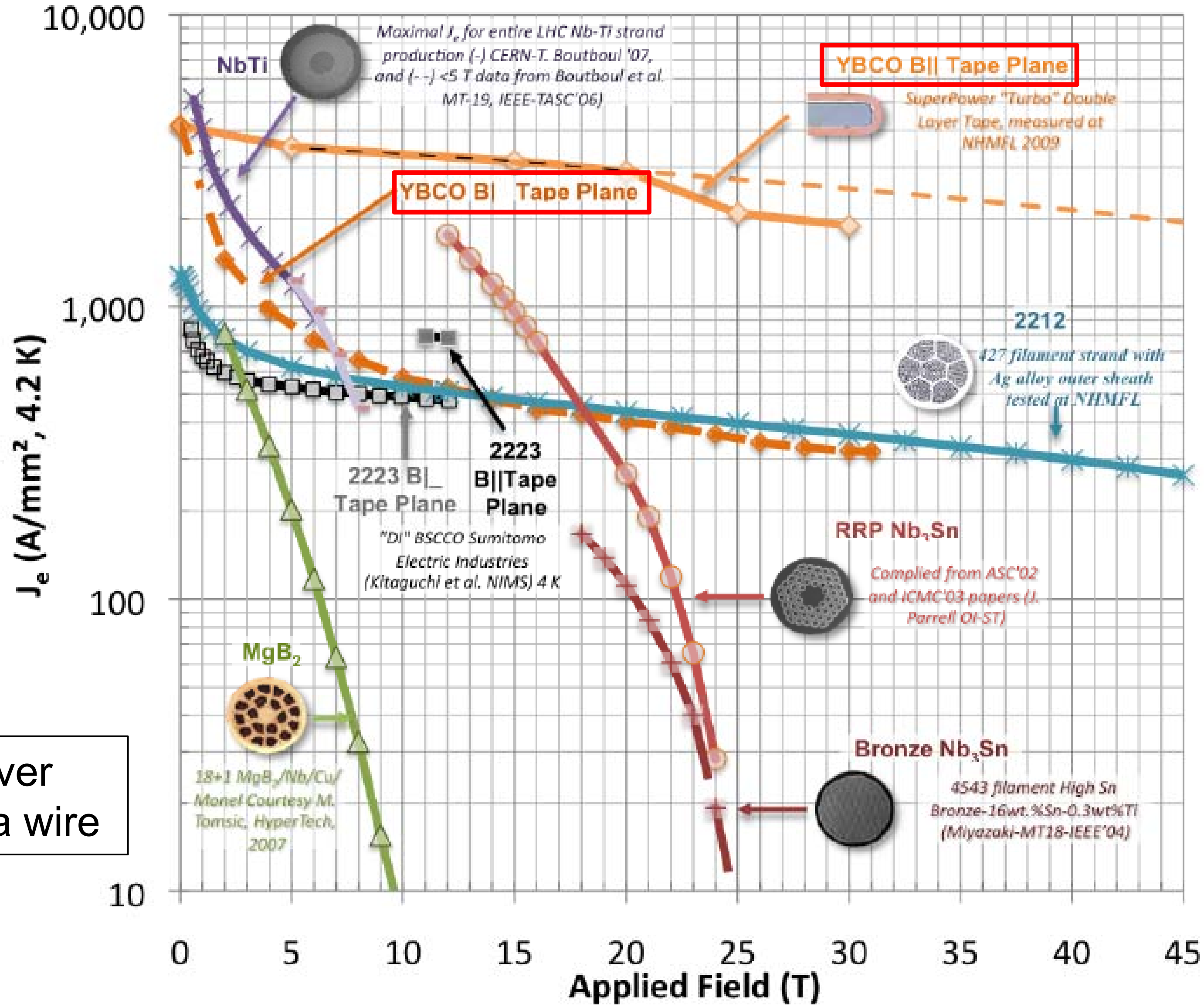
✓Correction coil

✓Shim coil

Room-temperature shim coil

Understanding of magnetic field distribution generated by **Main coil**

Why YBCO? -High critical current density versus magnetic field-



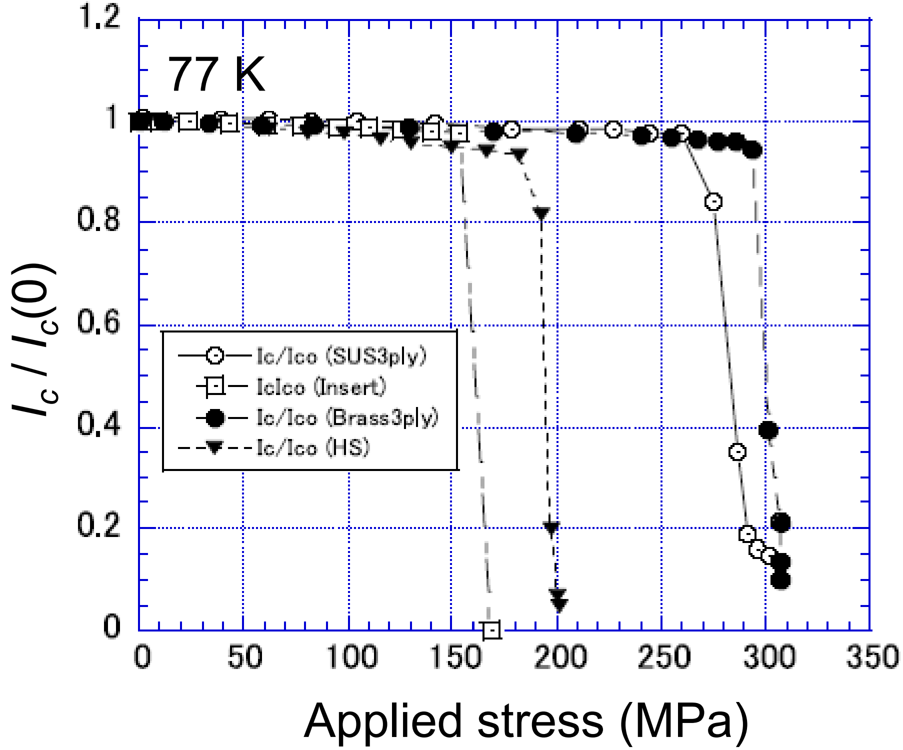
J_e: Critical current over cross section of a wire

Ref.: HE-LHC'10 AccNet Mini-Workshop on a "High Energy LHC." Reference No. ST262; Category 5, 6.

HTS have high J_e under high magnetic field.

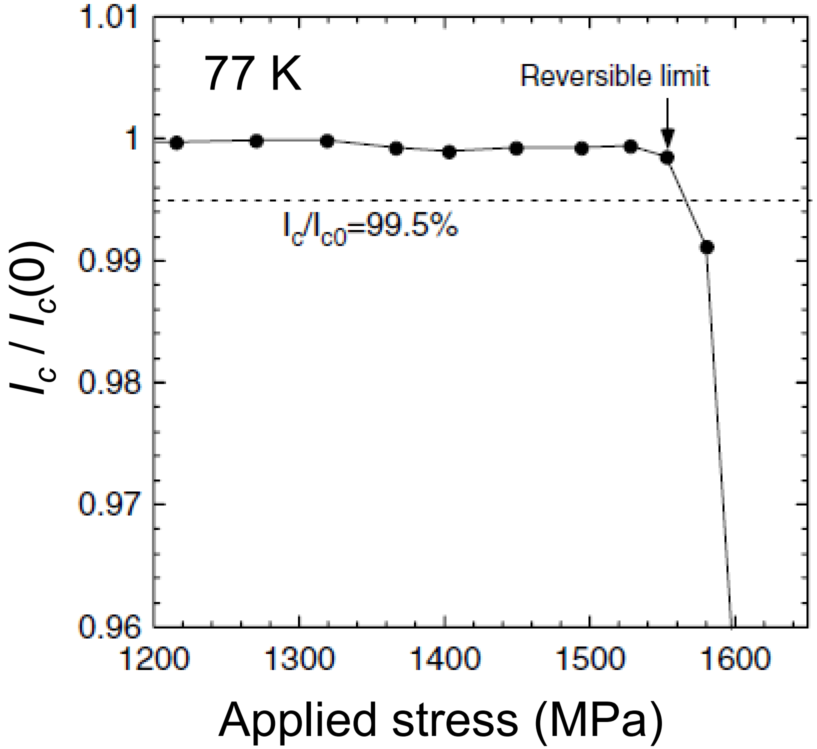
Why YBCO? –High tolerance to mechanical process-

Bi2223 wire



Quoted by "K. Osamura et al, Supercond. Sci. Techonol. 21 (2008) 054010

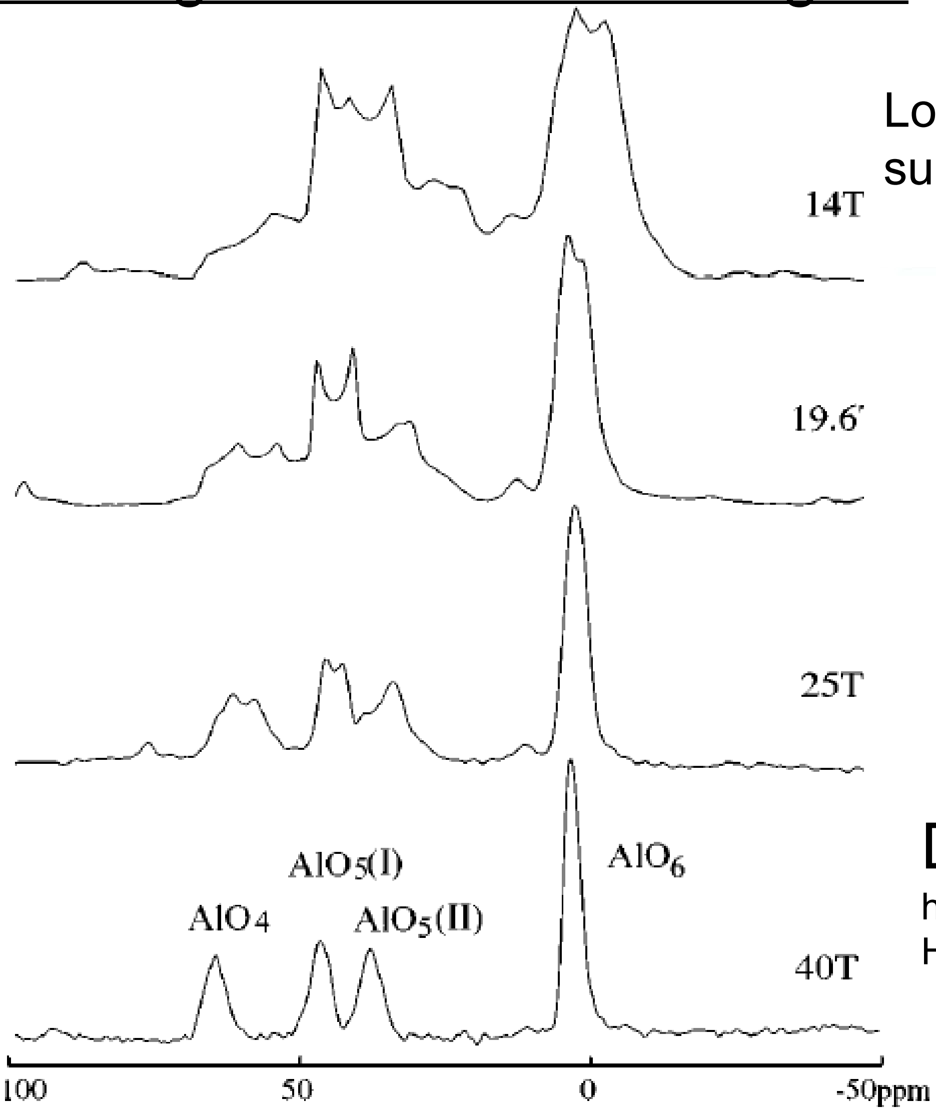
YBCO wire



Quoted by "M. Sugano et al, Supercond. Sci. Techonol. 21 (2008) 054006

Tolerant stress	Bi2223 wire < 300 MPa	YBCO wire < 1500 MPa

Advantage of YBCO NMR magnet

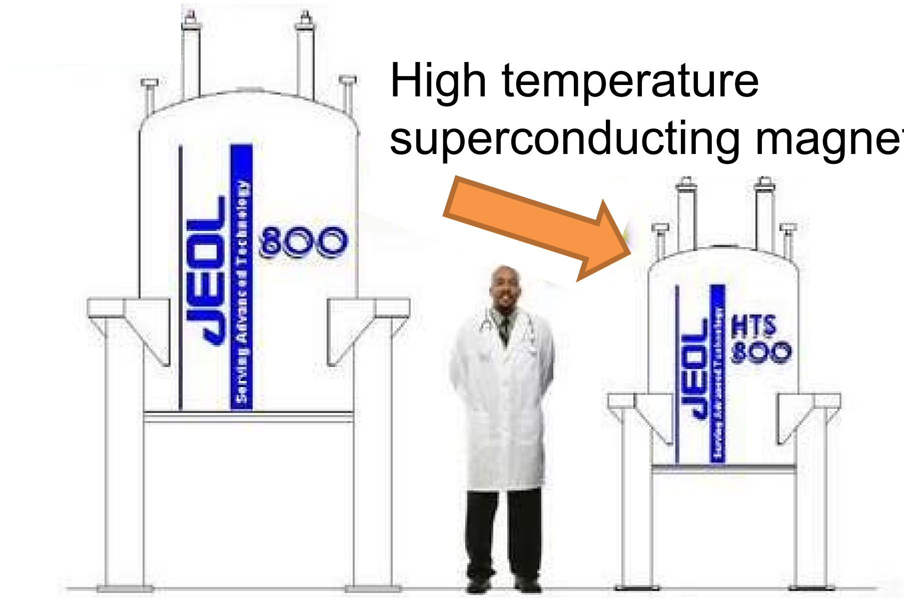


Upgrading of NMR spectrometer resolution

Quoted by "Z. Gan et al, J. Am. Chem. Soc. 124 (2002) 5634-5635

Low temperature superconducting magnet

High temperature superconducting magnet

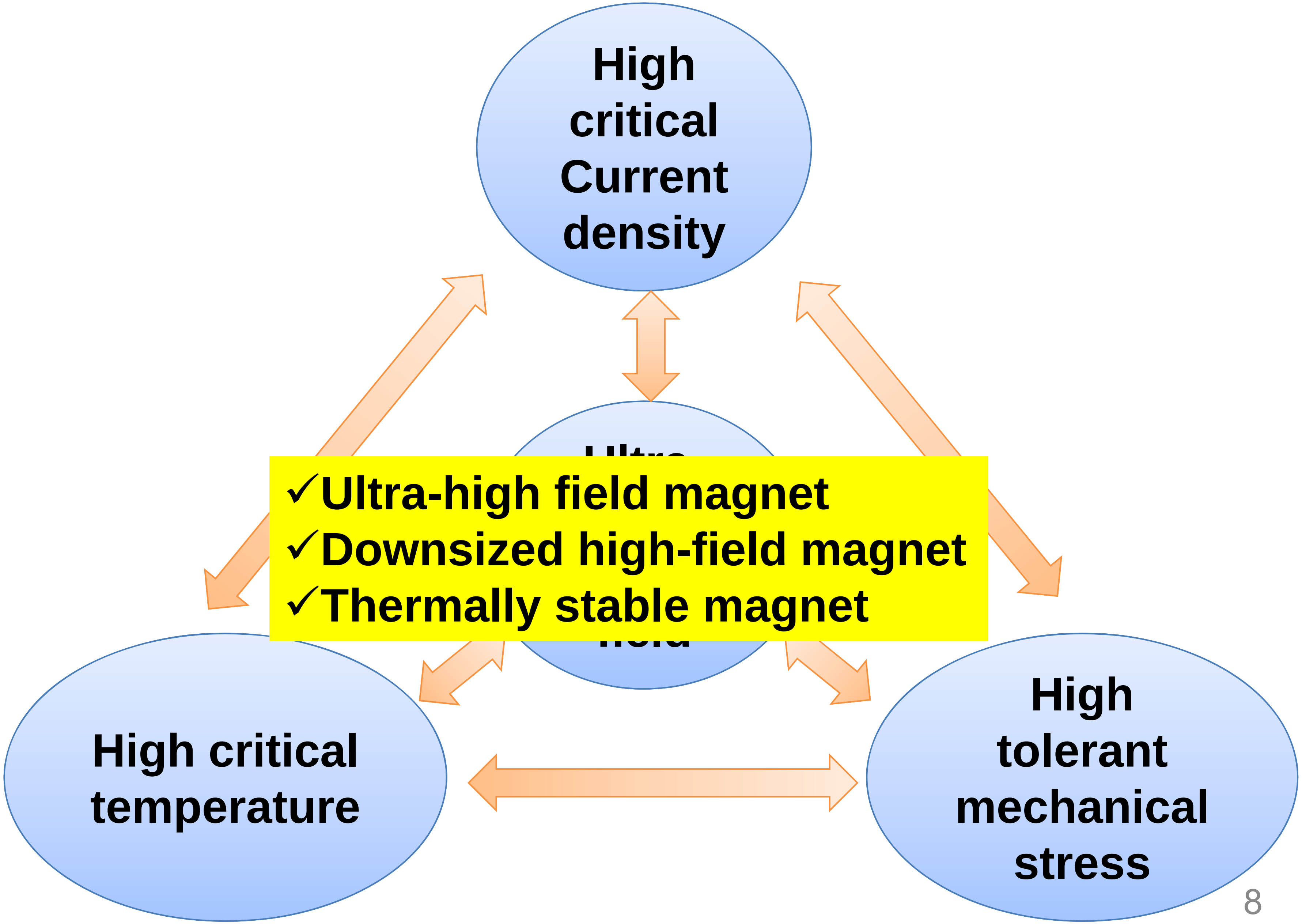


Downsized 18.8 T magnet

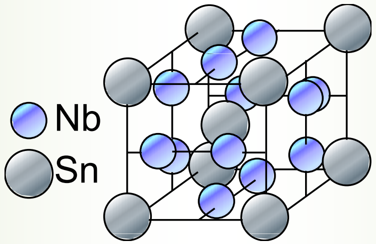
http://www.tsurumi.yokohamacu.ac.jp/damr/NMR/HTS/index.html

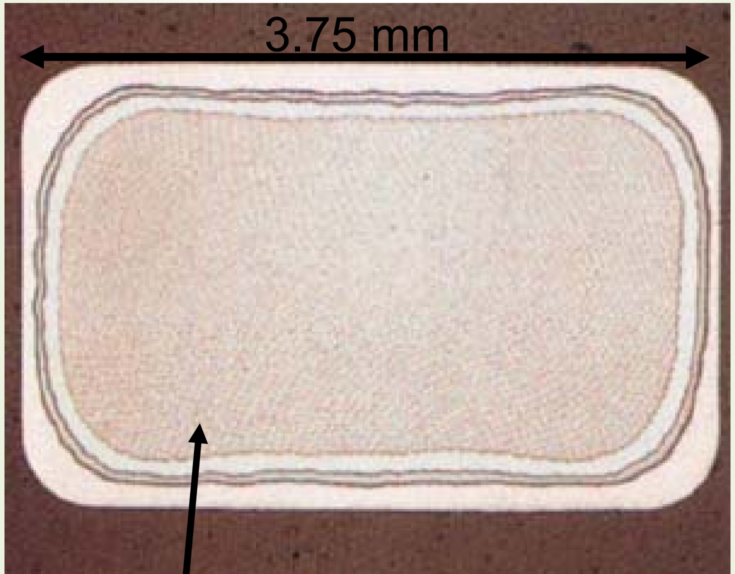
- ✓ Higher resolution
- ✓ Reduction of leak field

Advantage of YBCO magnet



Differences of shapes between conventional and YBCO wires

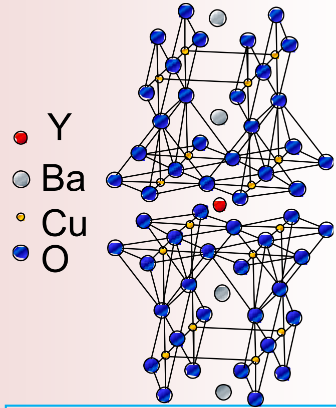


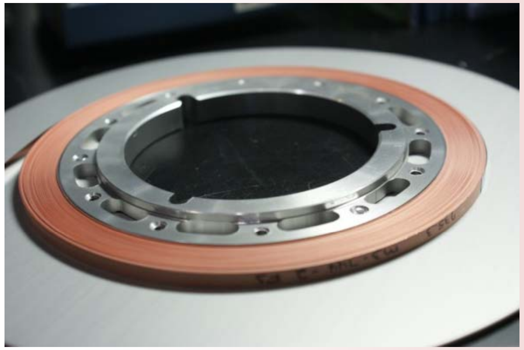


Nb_3Sn filament
Diameter: < a few μm

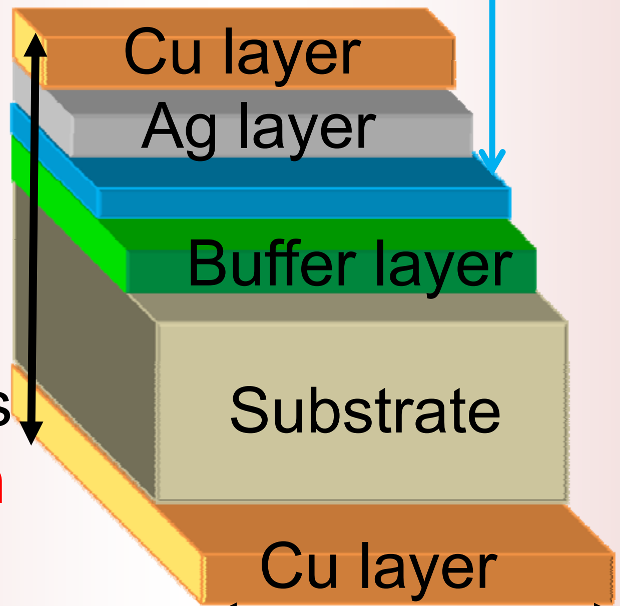
Nb_3Sn multi-filament wire
for 920 MHz NMR

T. Miyazaki, et.al., *IEEE Trans.Appl. Supercond.*, 9 (1999) p. 2505





YBCO superconducting layer
（Thickness：**1 μm**）

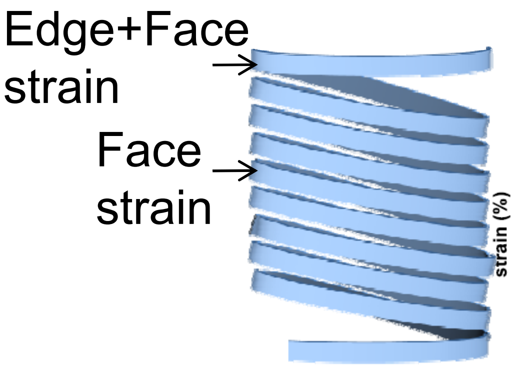


Thickness
～100 μm

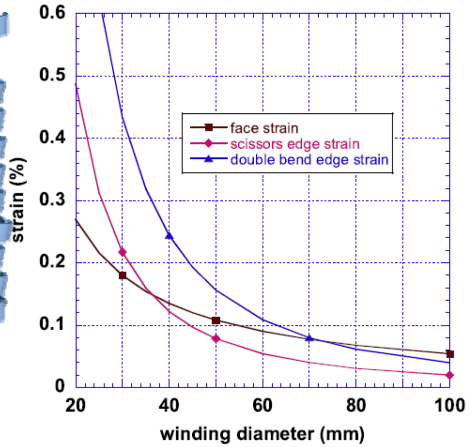
Width: **1～12 mm**

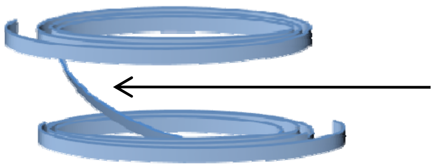
YBCO coated conductor (CC)

Challenges to construct YBCO superconducting coil

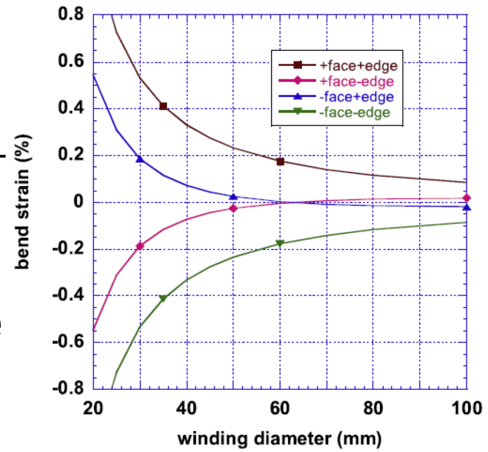


Layer wound



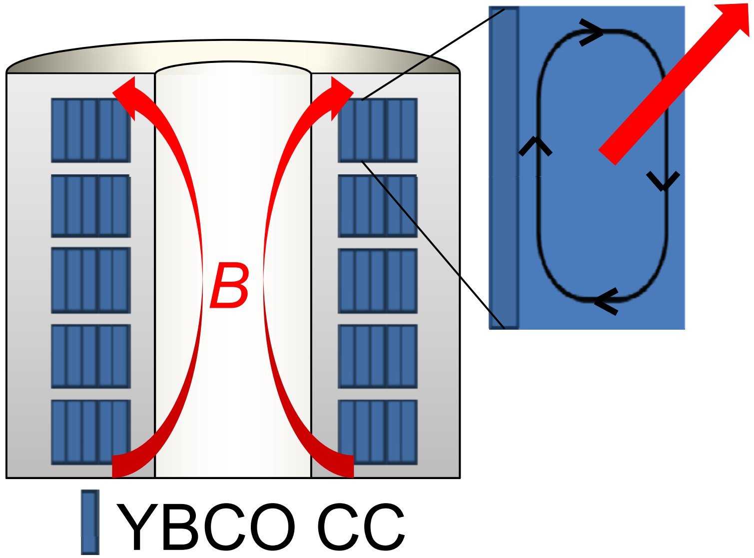


Double pancake



W. D. Markiewicz et.al., Superond. Sci. Techonol. 23 (2010)045017

Screening current



Tolerance strain < 0.5 – 0.9%

✓Method for winding YBCO CC
✓Screening current ⇦ Research topic

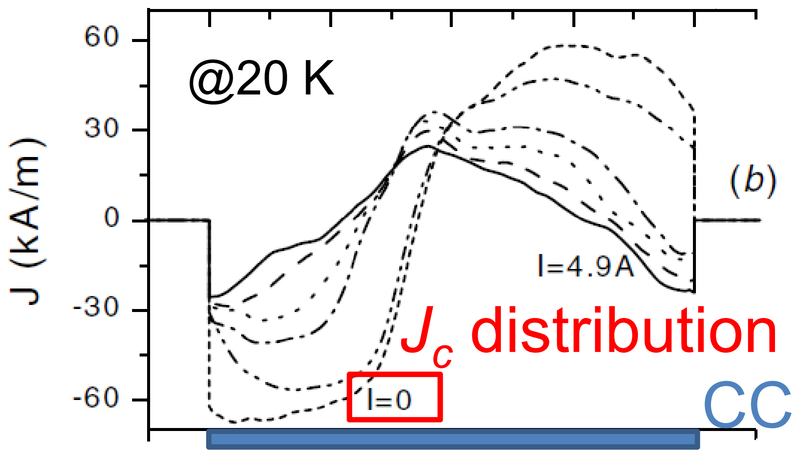
Screening current flowing in YBCO coated conductor

- Slow relaxation (due to flux creep)

$$J = A\left(1 - \frac{k_B T}{U_0^*}\log(Ct+1)\right)$$

J: Screening current density
A, C: constants
U_0^*: Apparent pin potential
k_B: Boltzman constant
T: temperature

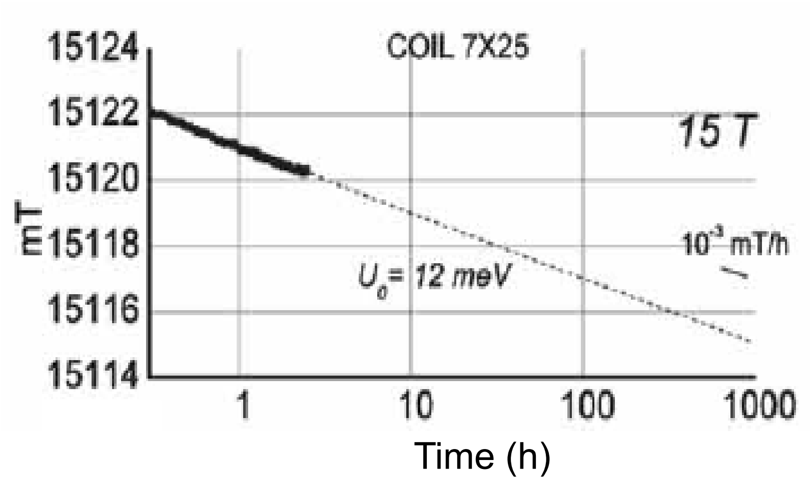
- Large screening current corresponding to I_c
- Inhomogeneity of current along width direction



Current density distribution in CC

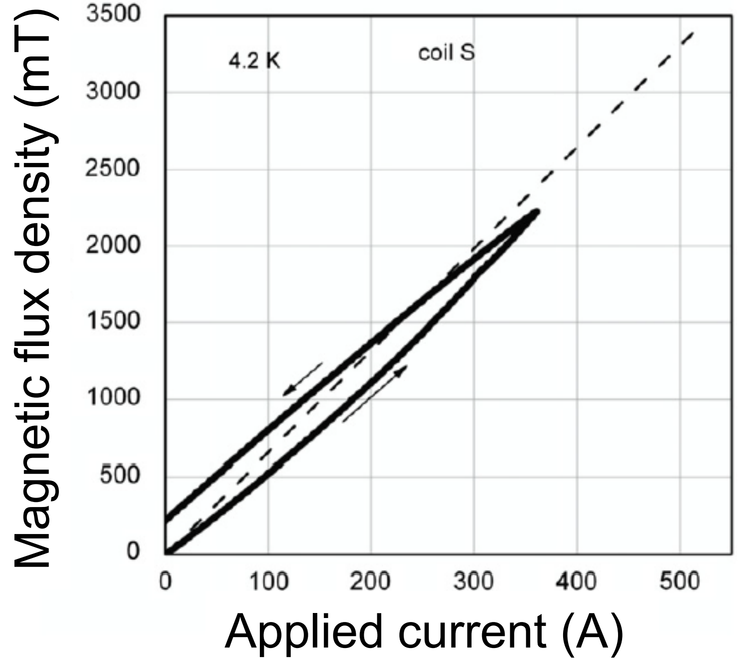
A. V. Bobyl et al, Supercond. Sci. Technol. 15 (2002) 82-89

Influence on generation magnetic field by screening current



Field decay for
down-sized YBCO coil

Uglietti et.al., *Abstracts of CSJ conference*, 80, pp. 22, 2009



Hysteresis of generation field at center position of small YBCO layer wound coil

Uglietti et. al., Supercond. Sci. Technol. 23 (2010) 115002

Understanding of current distribution in YBCO coated conductor under field at low temperature is required.

Purpose of this study

Understanding how current flows in YBCO coated conductor under a magnetic field at low temperature.

Current distribution in a straight single YBCO coated conductor

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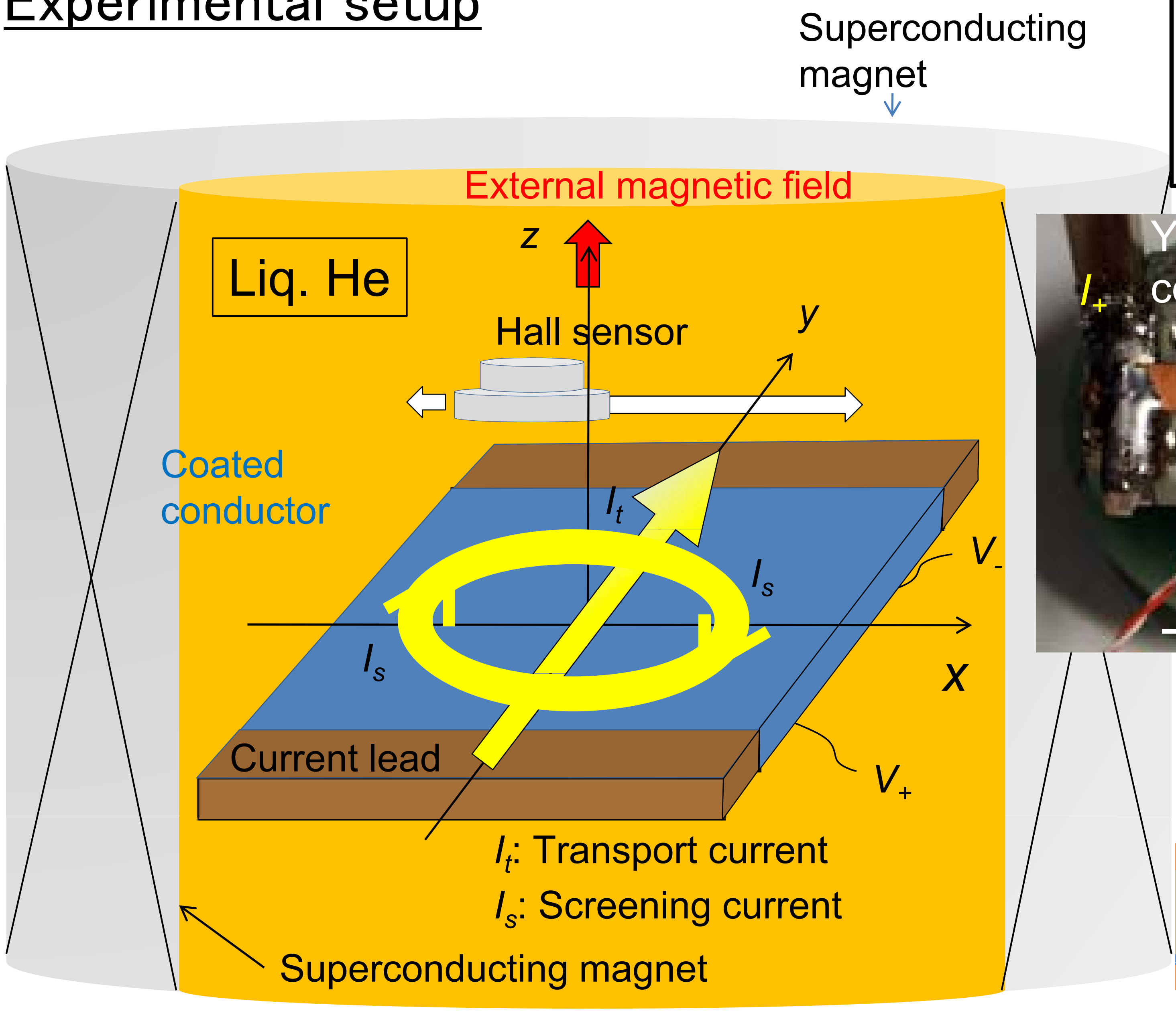
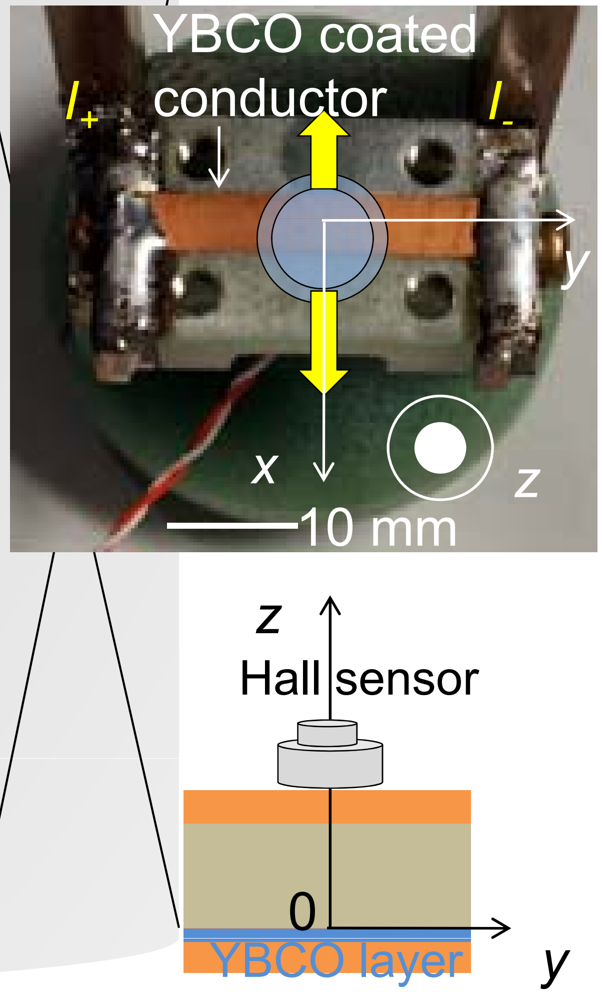
Magnetic-field distribution generated by a YBCO pancake coil taking into account screening current

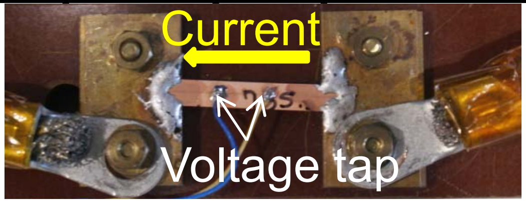
Experimental setup

YBCO CC
Length: 20-26 mm
Width: 4.1 mm
(SuperPower)

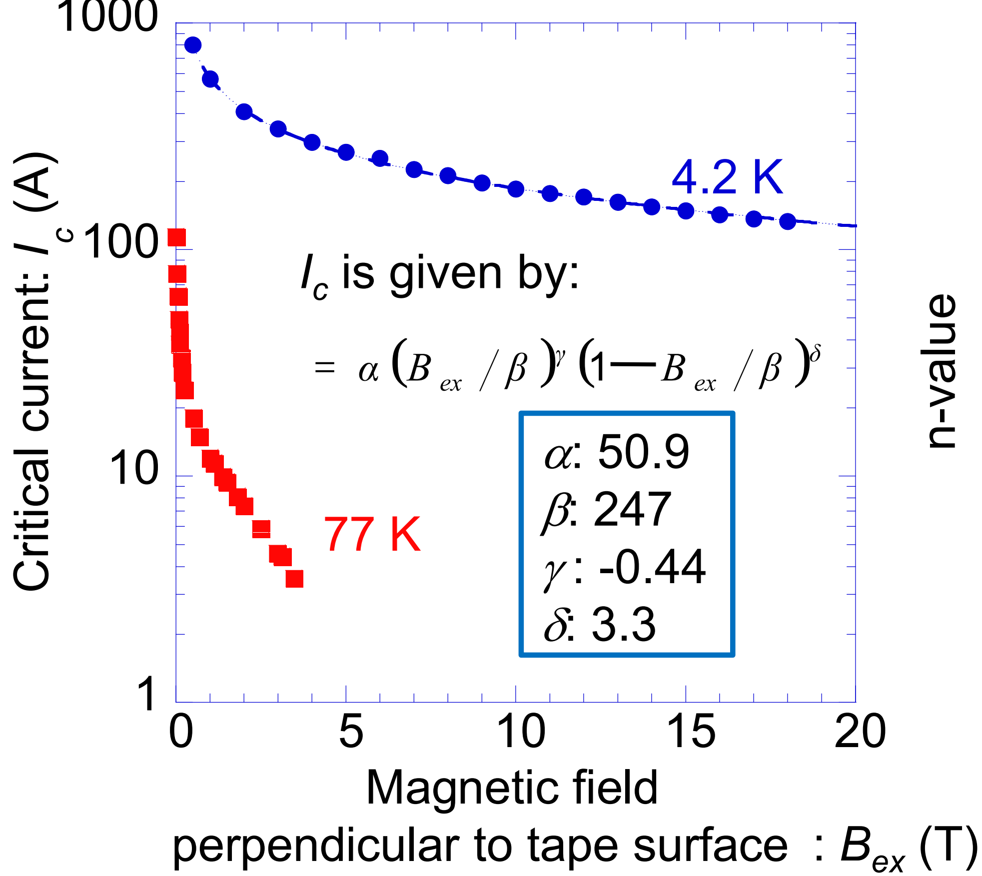


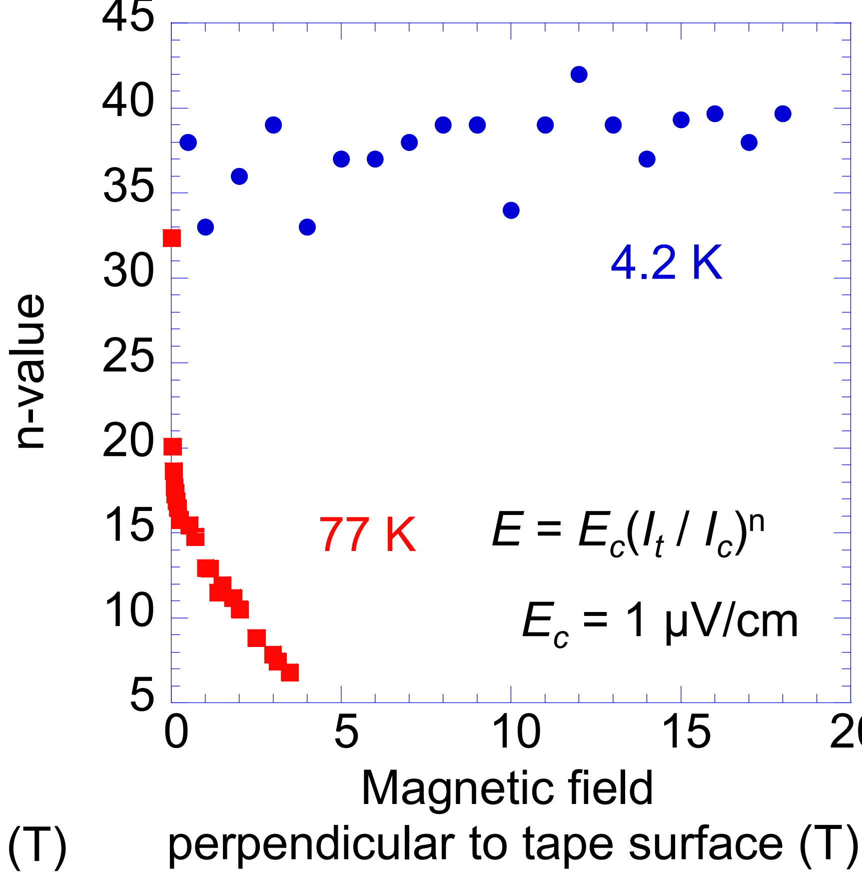


Measurement of I_c –Transport properties of CC-



Setup of I_c measurement





Low n-value shows variation in I_c.

Determination of a method for estimating current distribution flowing in a straight single coated conductor.

Simple model of screening current

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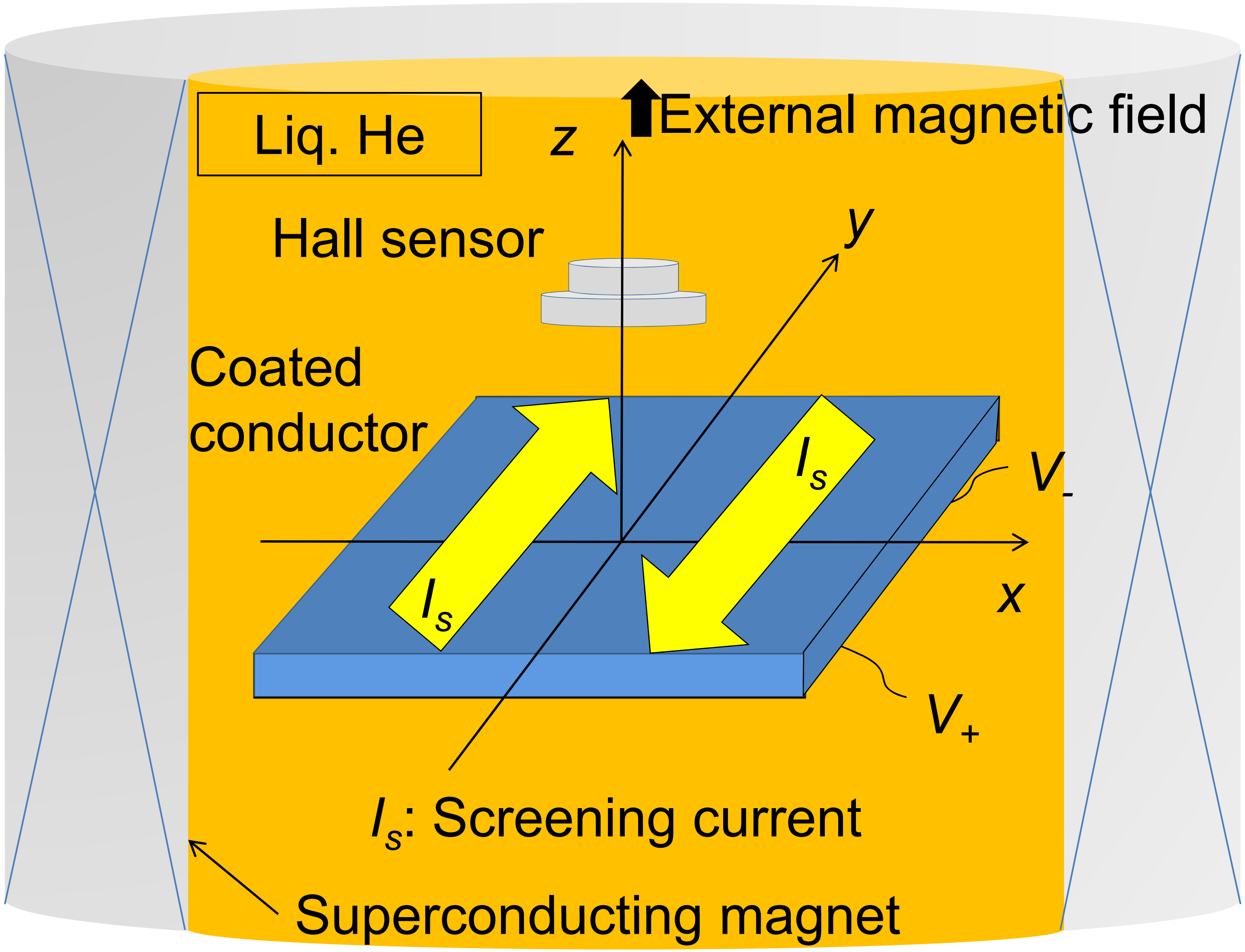
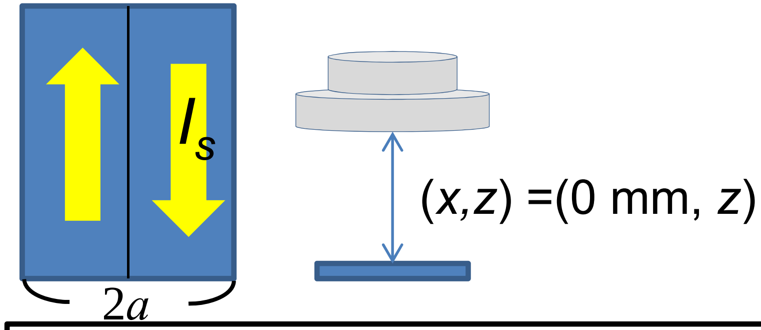
Model of current distribution as one dimensional inverse problem

Experimental setup and symmetric current model



Determination of dimension of screening current

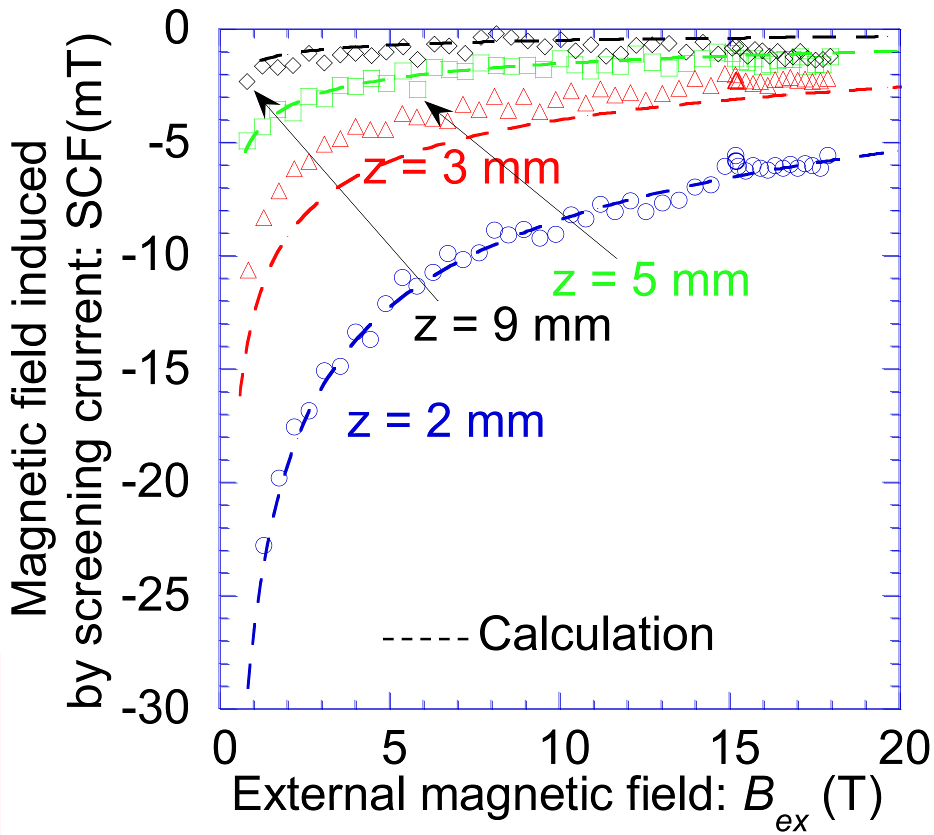


$$B_z(z) = \frac{\mu_0 I}{\pi a}\log\frac{\sqrt{a^2+z^2}}{z}$$

Superconducting critical current

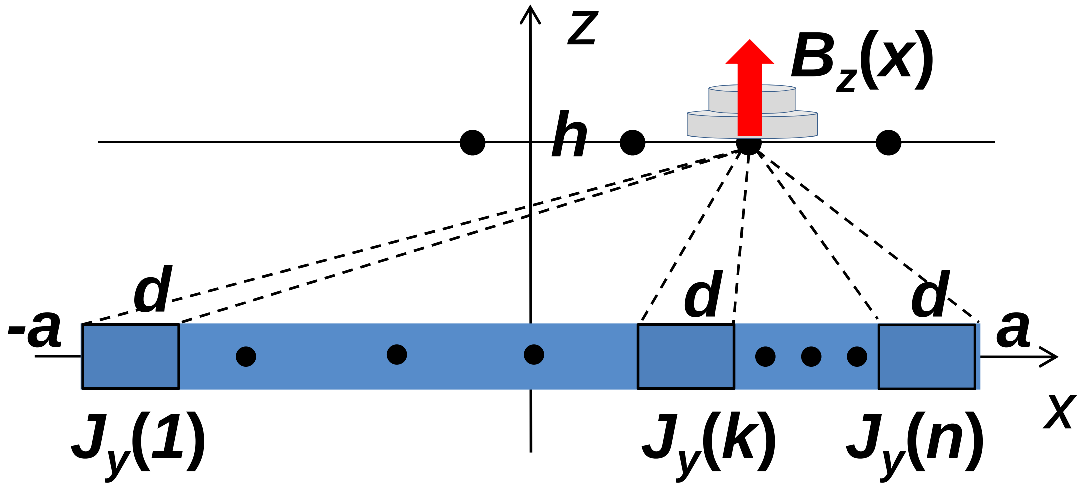
I_c is given by:

$$= 50.9\left(B_{ex}/247\right)^{-0.444}\left(1-B_{ex}/247\right)^{3.33}$$



One-dimensional screening currents give SCFs.

Solution of one dimensional inverse problem



$J_y(k)$: uniform sheet current density

The B_z on $z = h$ is described by Biot-Savart's law:

$$B_z(x, h) = B_{ex} + (\mu_0/4\pi) \bullet \sum_{k=1} J_y(k) \log \frac{(x + a - (k-1)d)^2 + h^2}{(x+a-kd)^2 + h^2}$$

ΔB_z: Magnetic fields generated by currents flowing in a CC.

$$\Delta B = AJ$$

$\Delta B \equiv [\Delta B_z(x_1, h), \ldots, \Delta B_z(x_m, h)]$, $J \equiv [J_y(1), \ldots, J_y(n)]$, A: A matrix m × n

Tikhonov regularization

J : obtainable by minimizing the function *f*: $f = \|\mathbf{AJ} - \mathbf{B}\|^2 + \lambda\|\mathbf{J}\|^2$

λ: parameter to minimize *f*

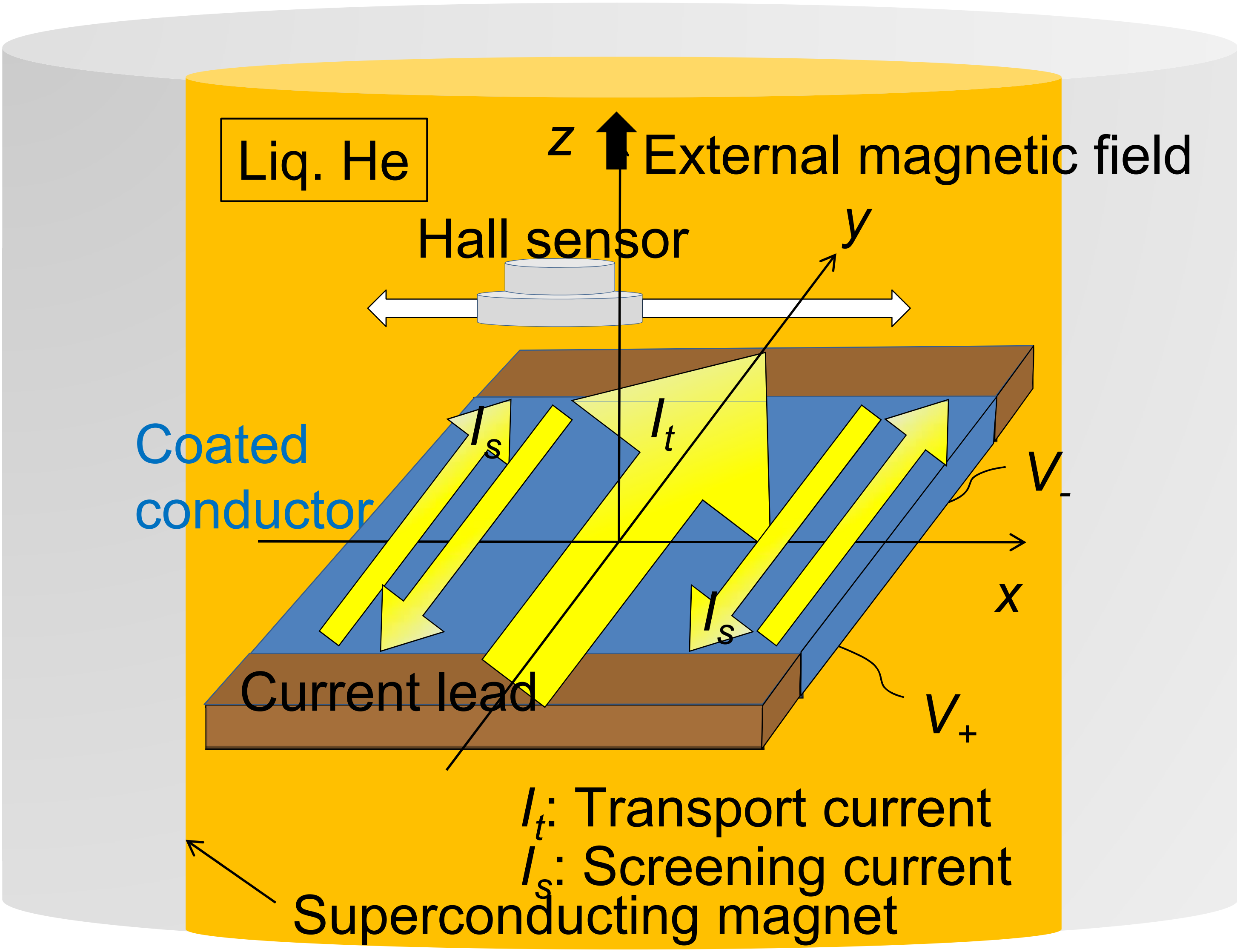
Experimental error

Determination of a method for estimating current distribution flowing in a straight single coated conductor.

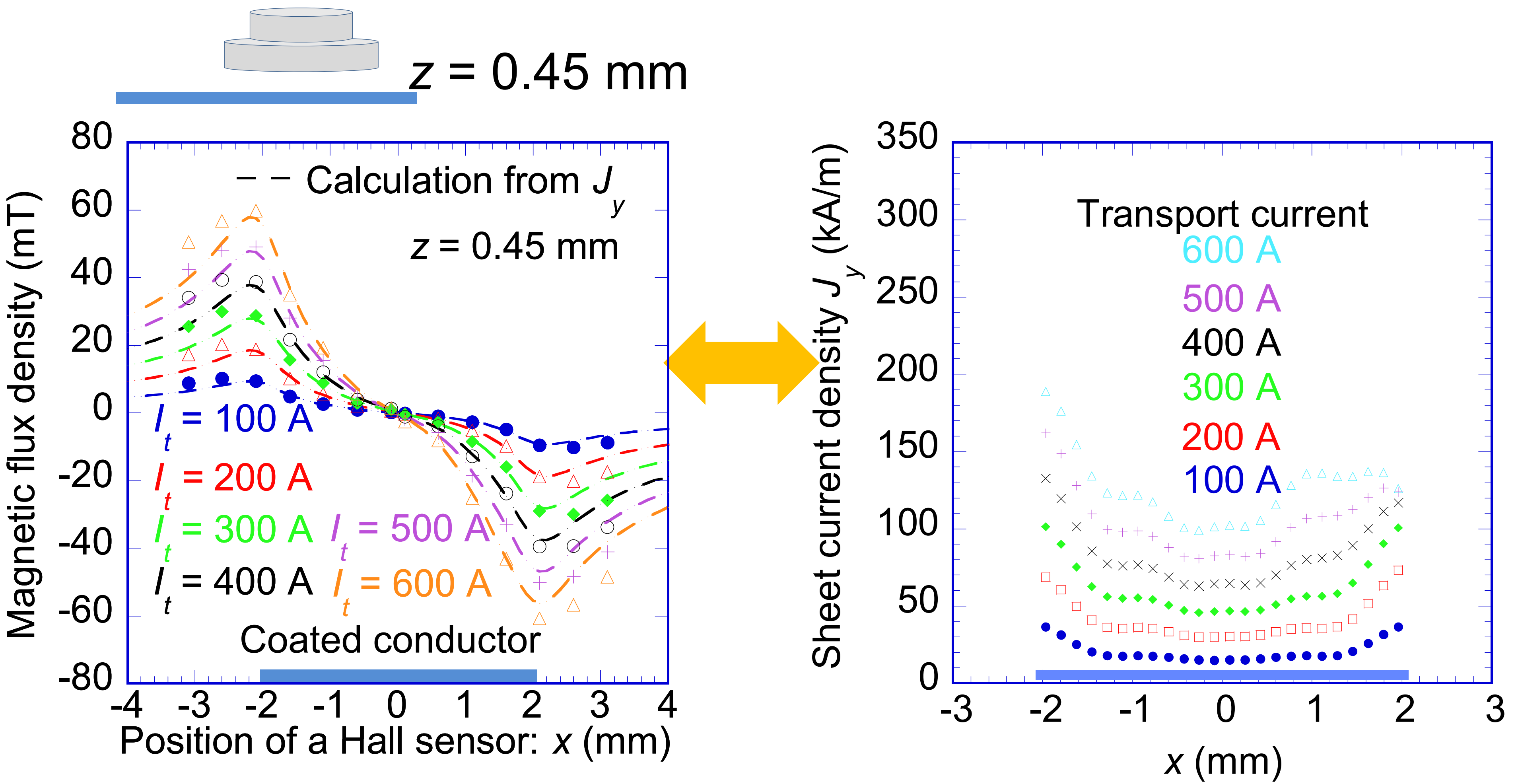
Magnetic-field and current distributions under self-field

✓Verification of current distribution

Experimental setup for measurement of self field distribution

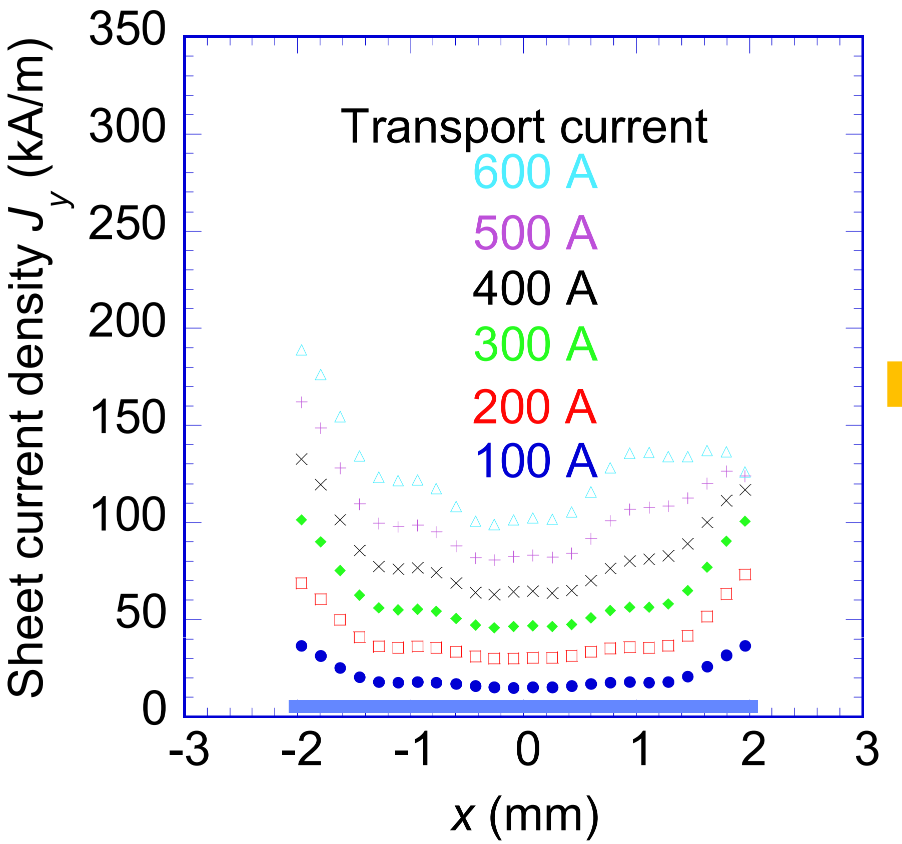


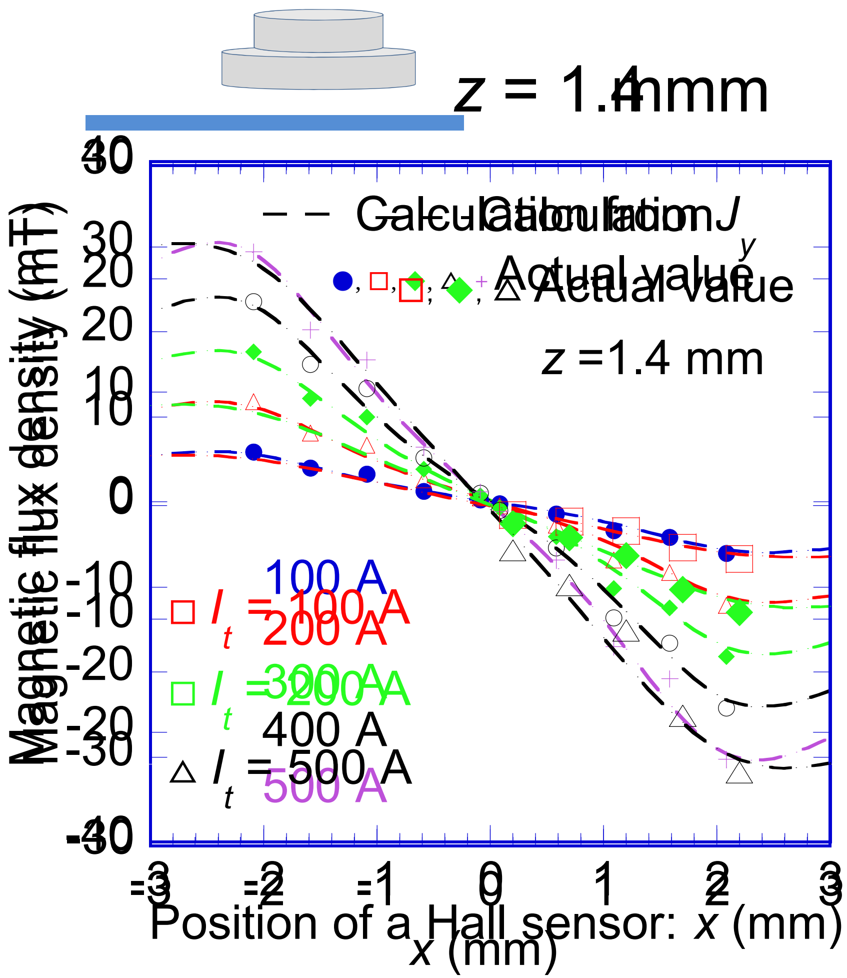
Magnetic field and current distributions under self-field



As transport current increases, symmetry of sheet current becomes low.

Verification of the current distribution





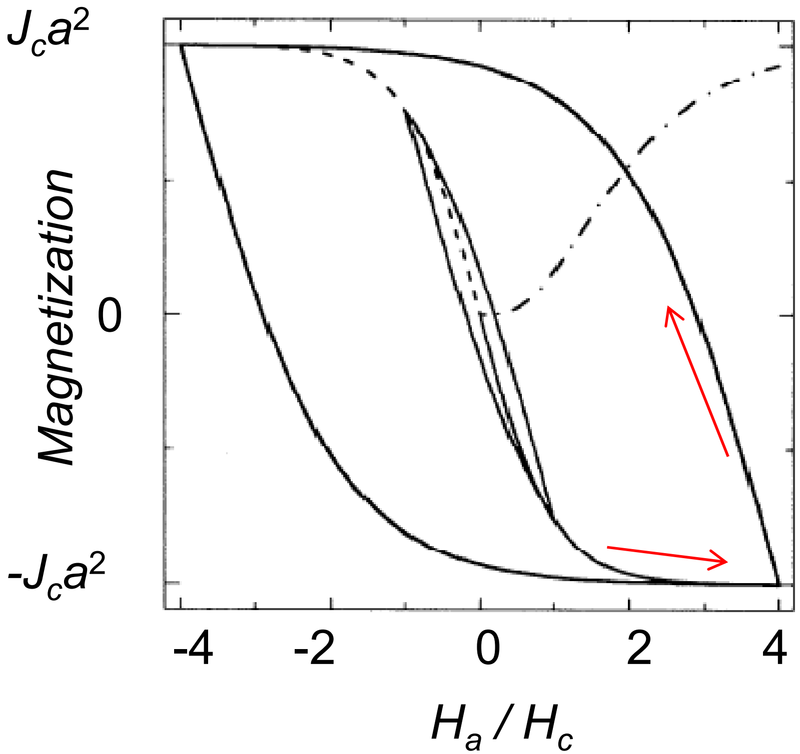
Magnetic field distributions estimated from the sheet current densities agrees well.

→ **Verification of sheet current density distribution**

Magnetic-field and current distributions under a low magnetic field

✓Comparison of magnetic field and current distributions between experimental and calculation results

Bean model for thin superconducting films



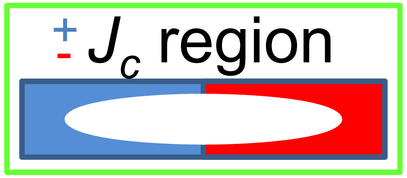
Magnetization curve of a thin superconducting film based on the Bean model

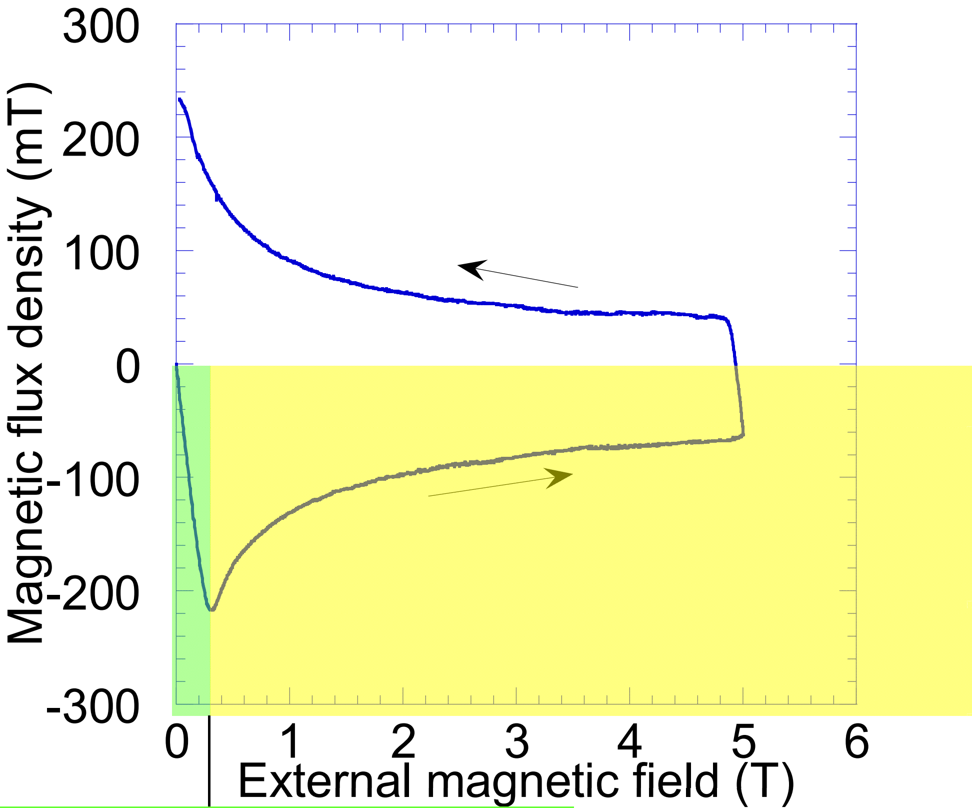
E. H. Brandt et. al., Phys. Rev. B 48 (1993) 12893

J_c: constant under any magnetic field
Amount of Magnetic flux: increasing

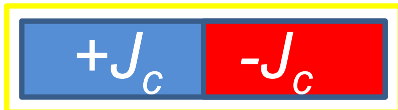
SCF at (x, z) = (0.2 mm, 0.4 mm)

Cross section of a CC



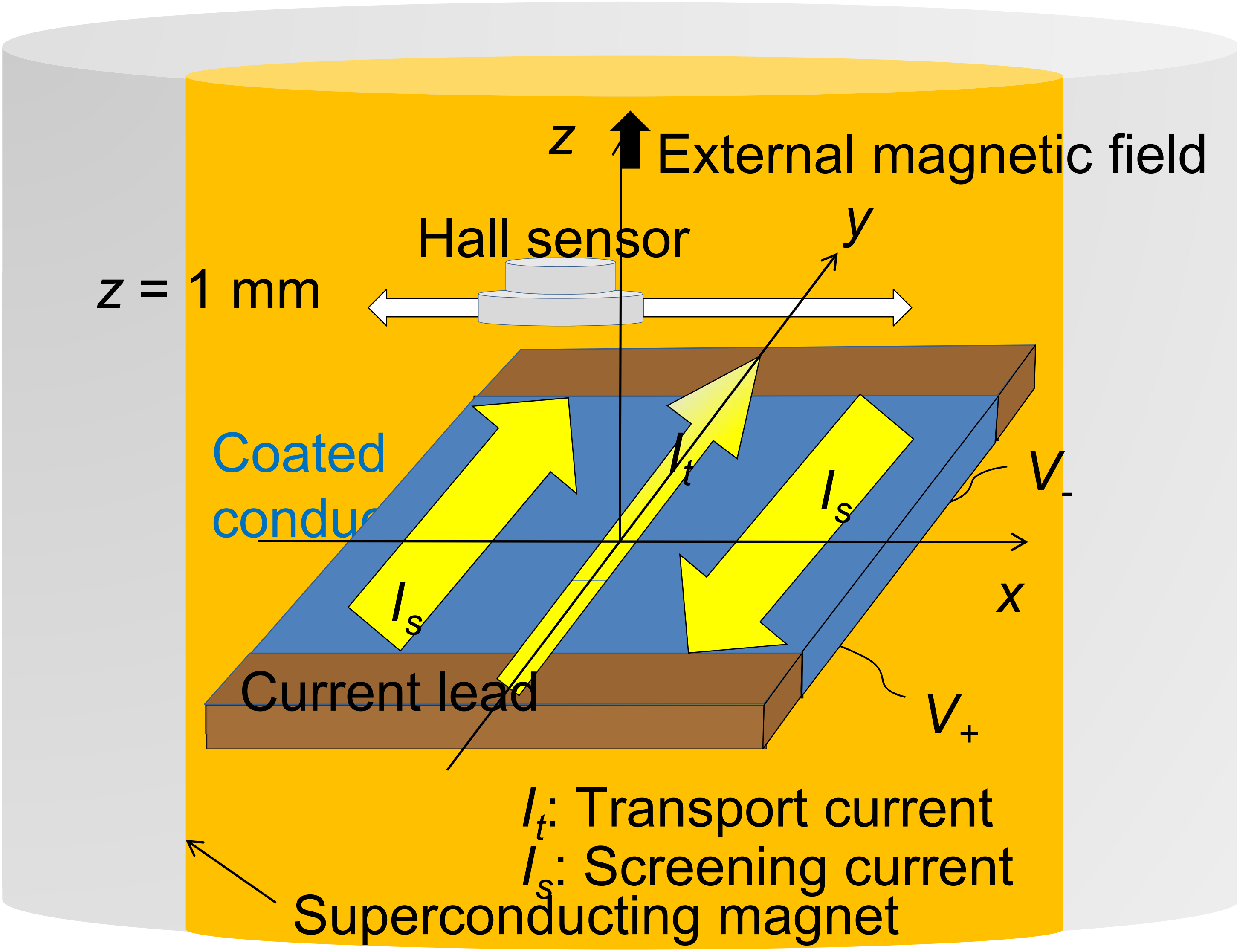


Magnetic flux going to the width of CC

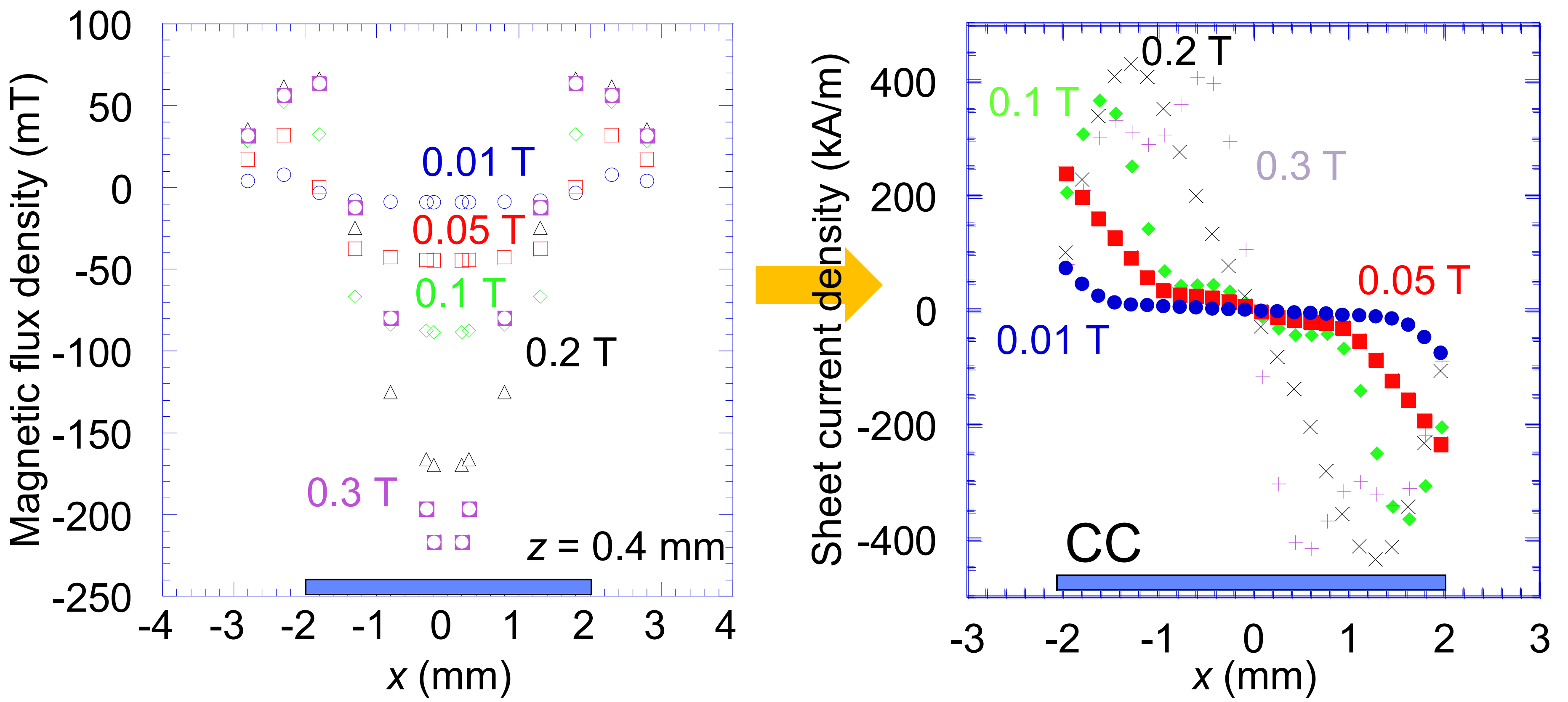


Magnetic flux over the entire width of CC

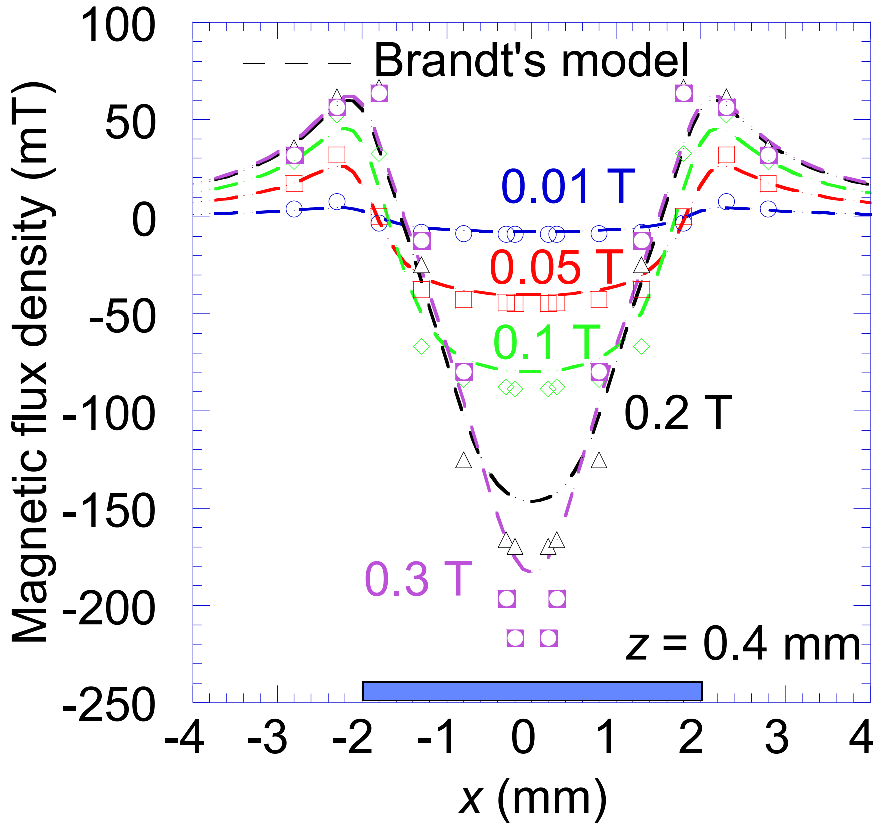
Experimental setup for measurement of total fields distribution

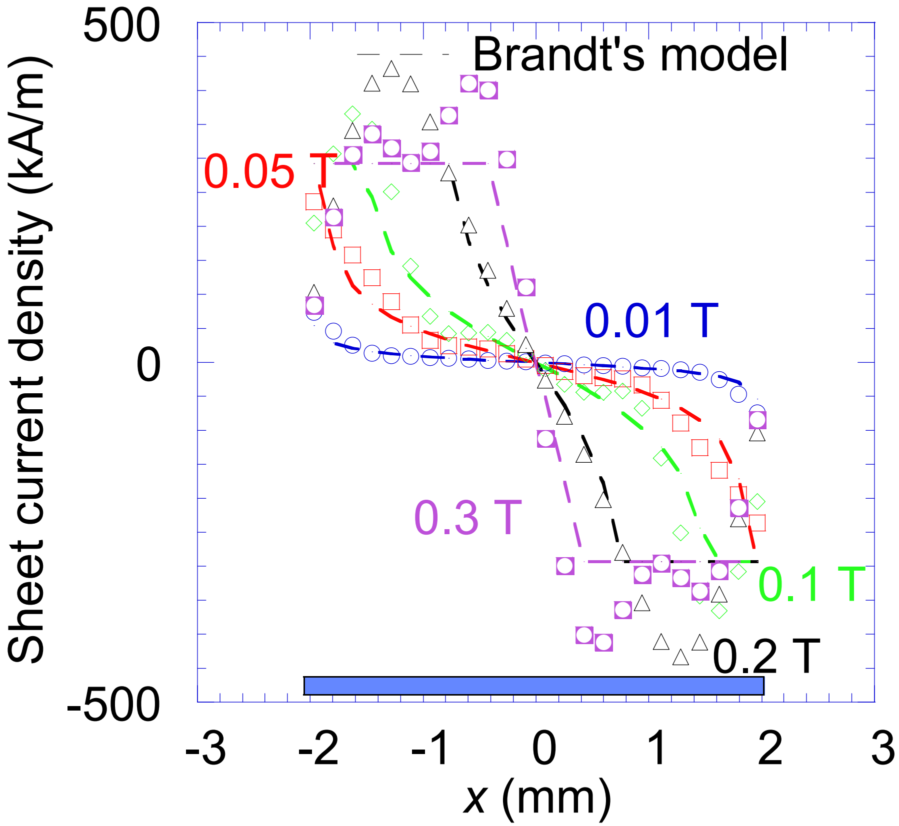


SCF under a low external filed where magnetic flux is going to the width



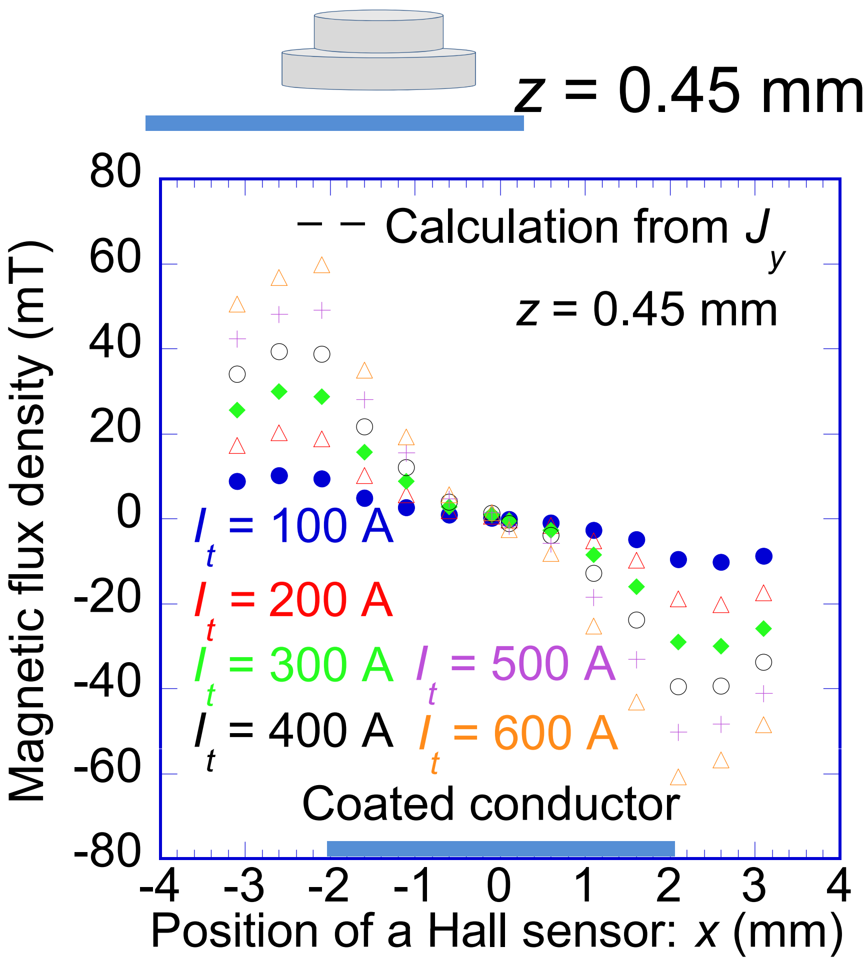
Comparison of SCF under a low external field with the Brandt's model

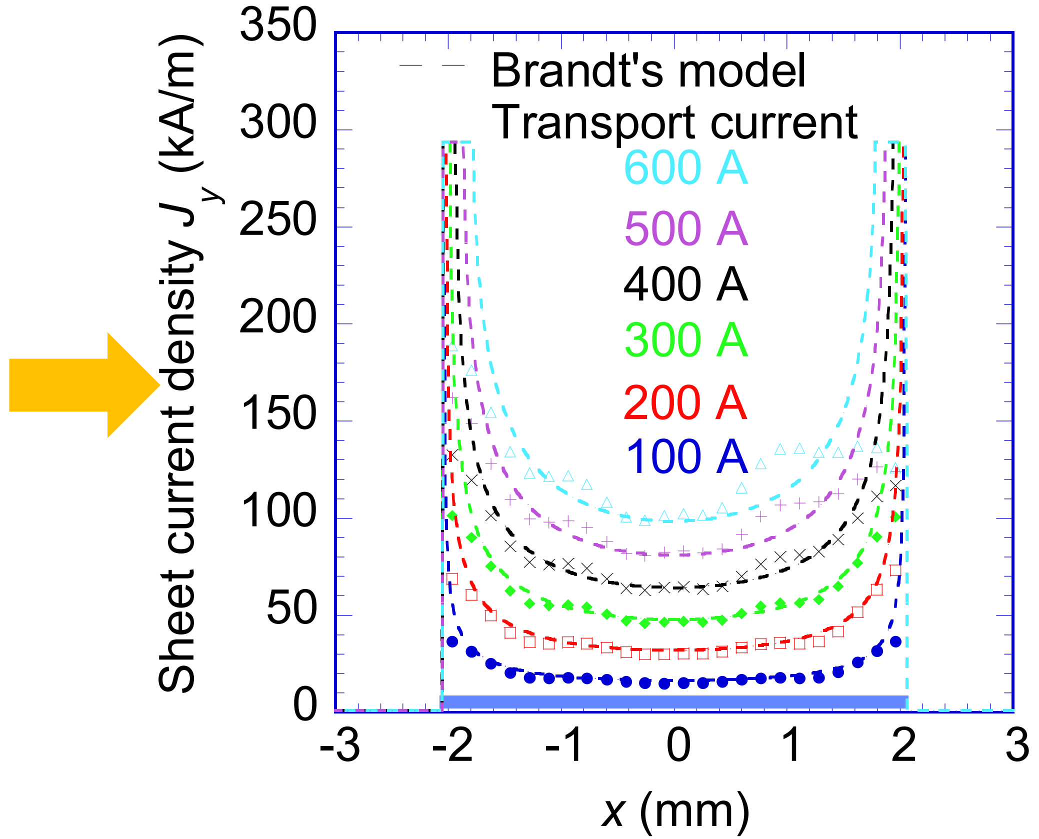




Calculation and experimental results agree well under low external field.

Magnetic field and current distributions under self-field



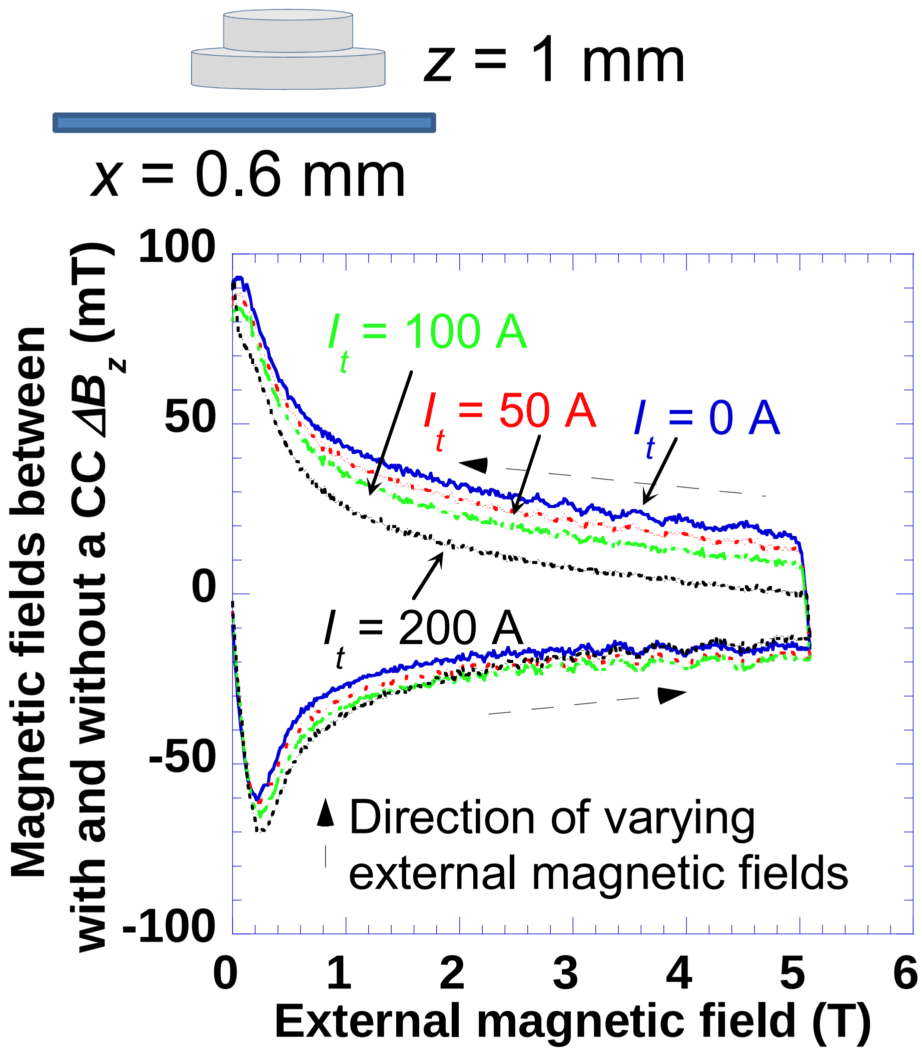


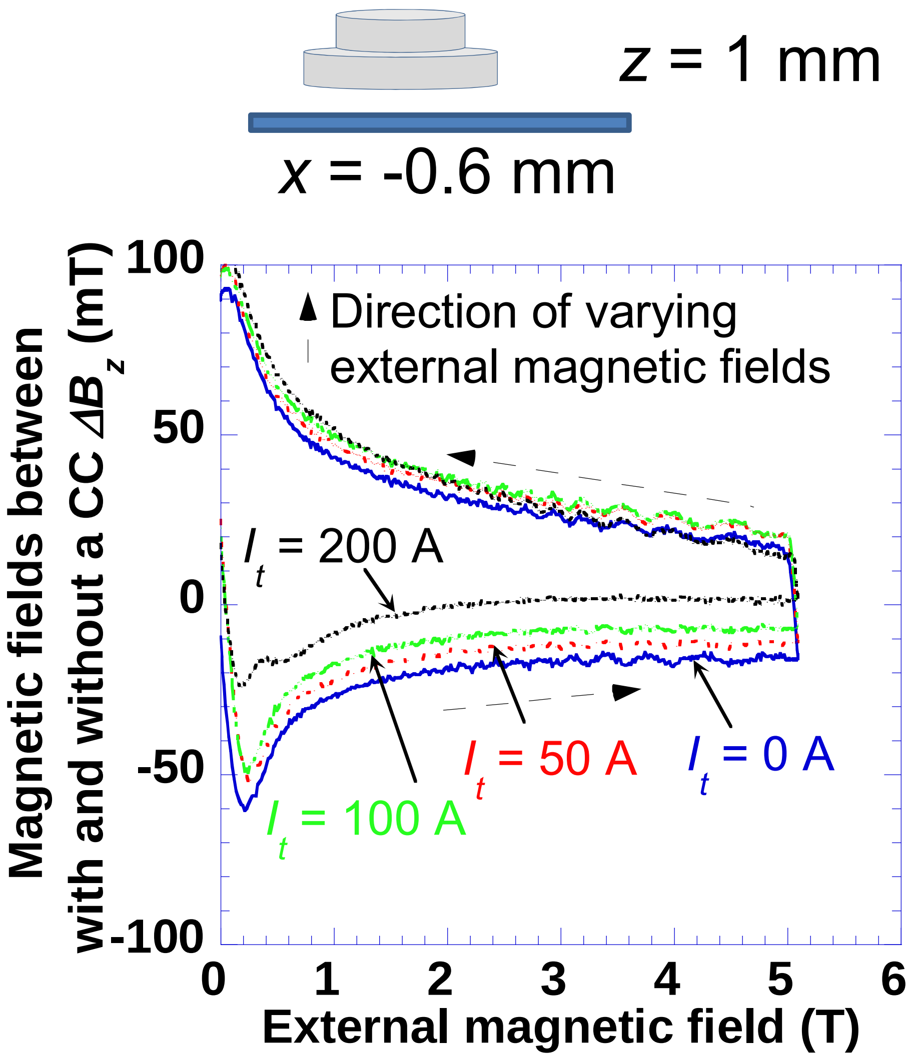
When I_t / I_c is small, the Brandt's model describes the current distribution.

Magnetic-field and current distributions under self field and a high external magnetic field

✓Acquisition of current distributions flowing in a coated conductor under self field and external magnetic field.

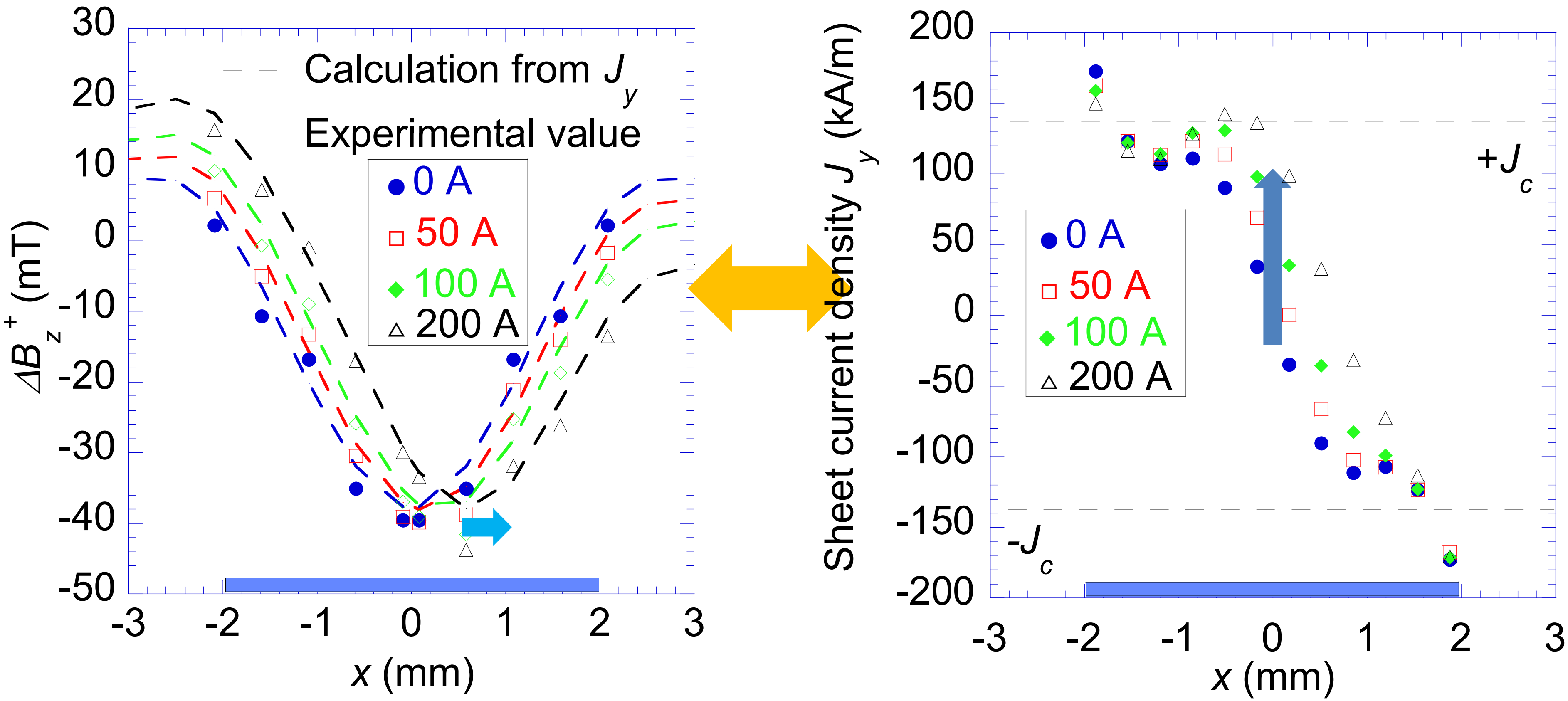
Variations of hysteresis at symmetric positions





Hysteresis shrinks in same ways and shifts in opposite directions at symmetric positions.

Distributions of total current consisting of transport and screening currents at 1 T

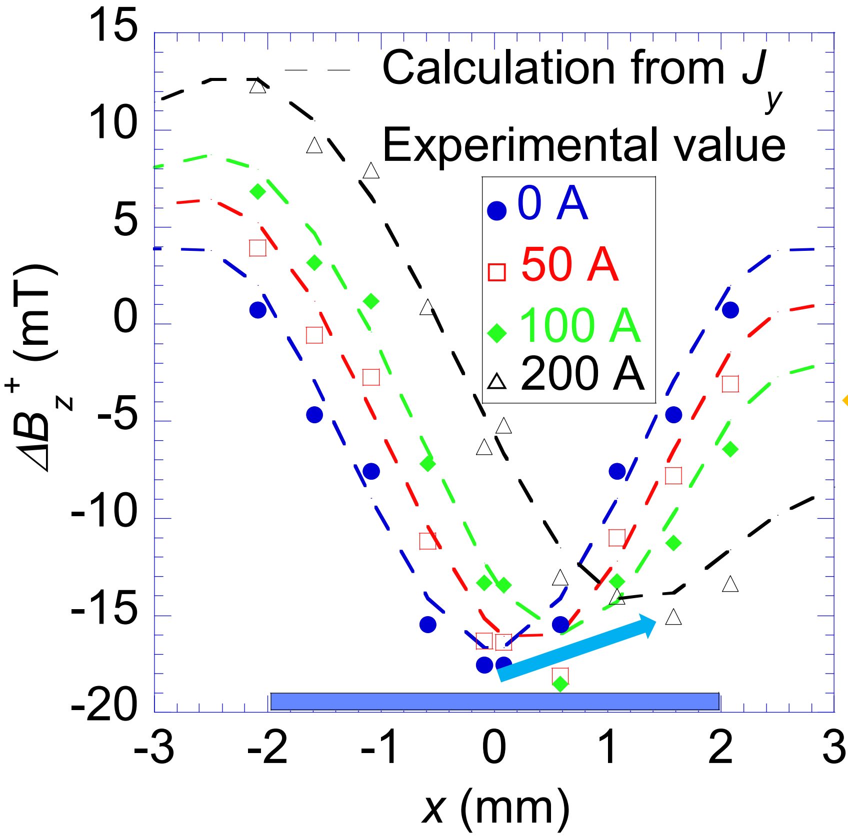


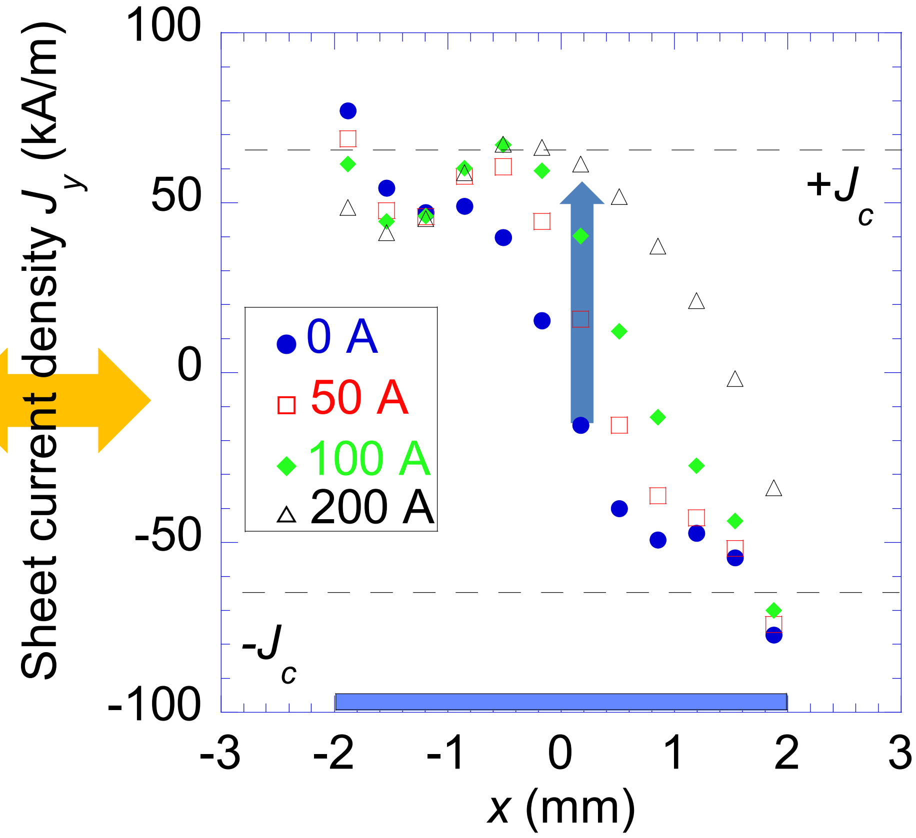
ΔB_z^+: magnetic fields generated by screening and transport currents under charging external fields

50 A: 9% of I_c
100 A: 18%
200 A: 35%

Bottom positions of ΔB_Z^+ shift in positive direction.

Distributions of total current consisting of transport and screening current at 5 T



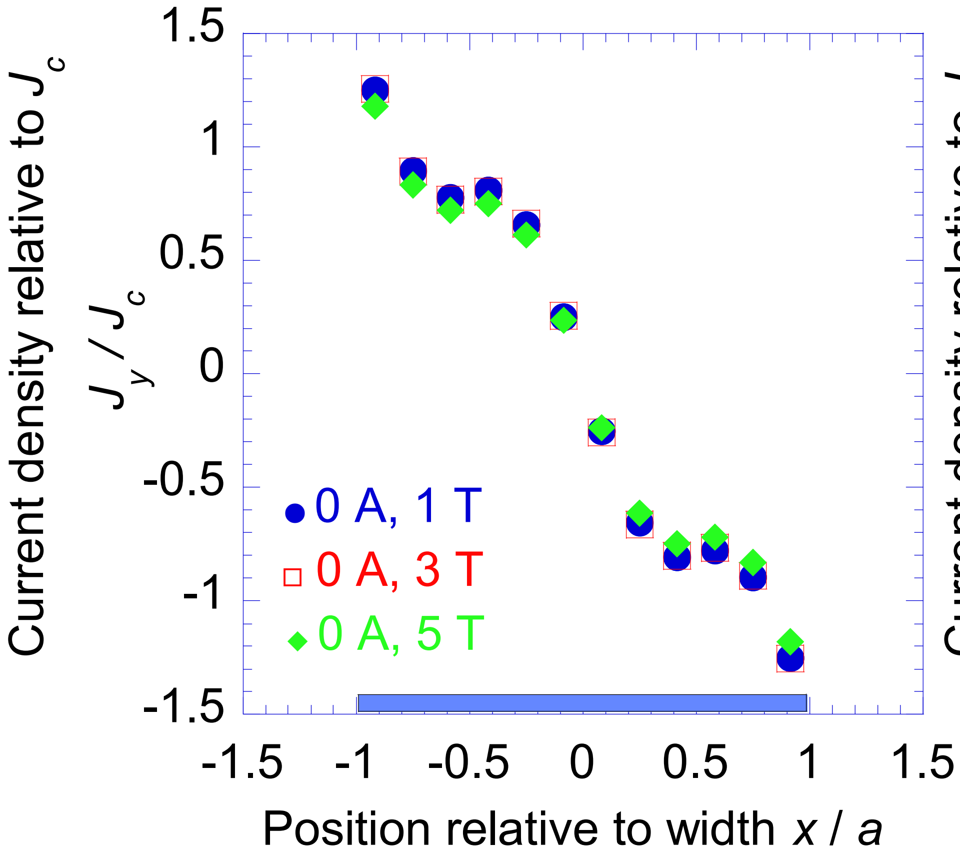


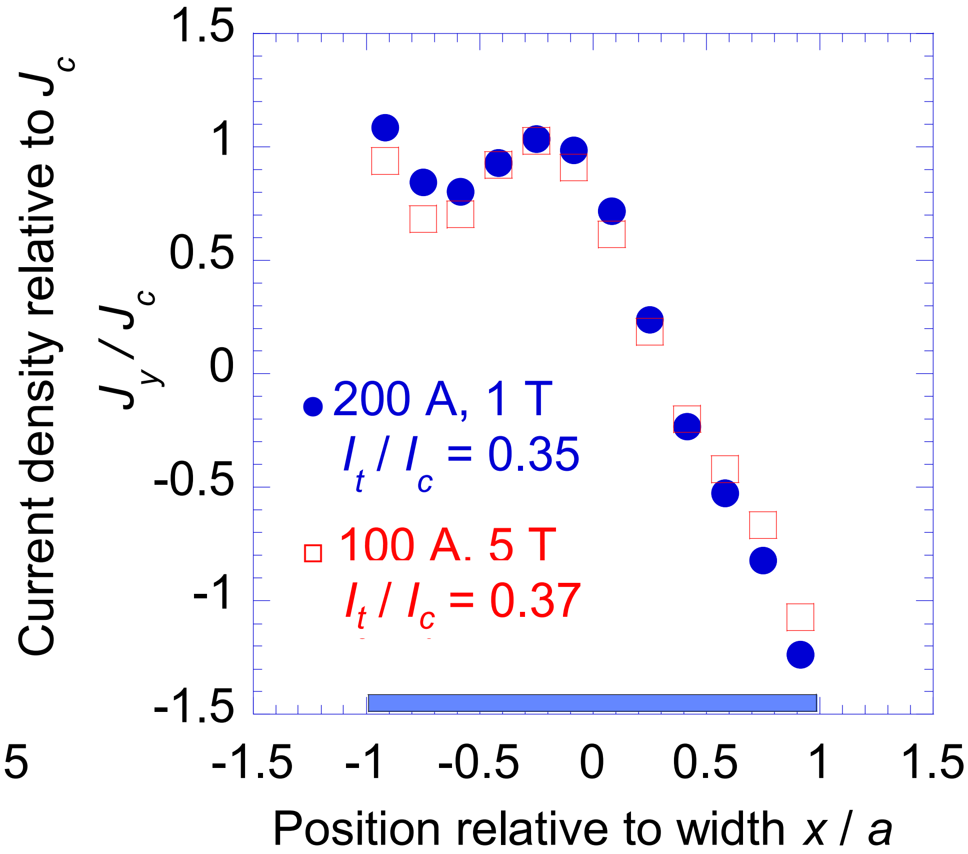
ΔB_z^+: magnetic fields generated by screening and transport currents under charging external fields

The shift of bottom positions are larger than those at 1 T.

50 A: 19% of I_c
100 A: 37%
200 A: 75%

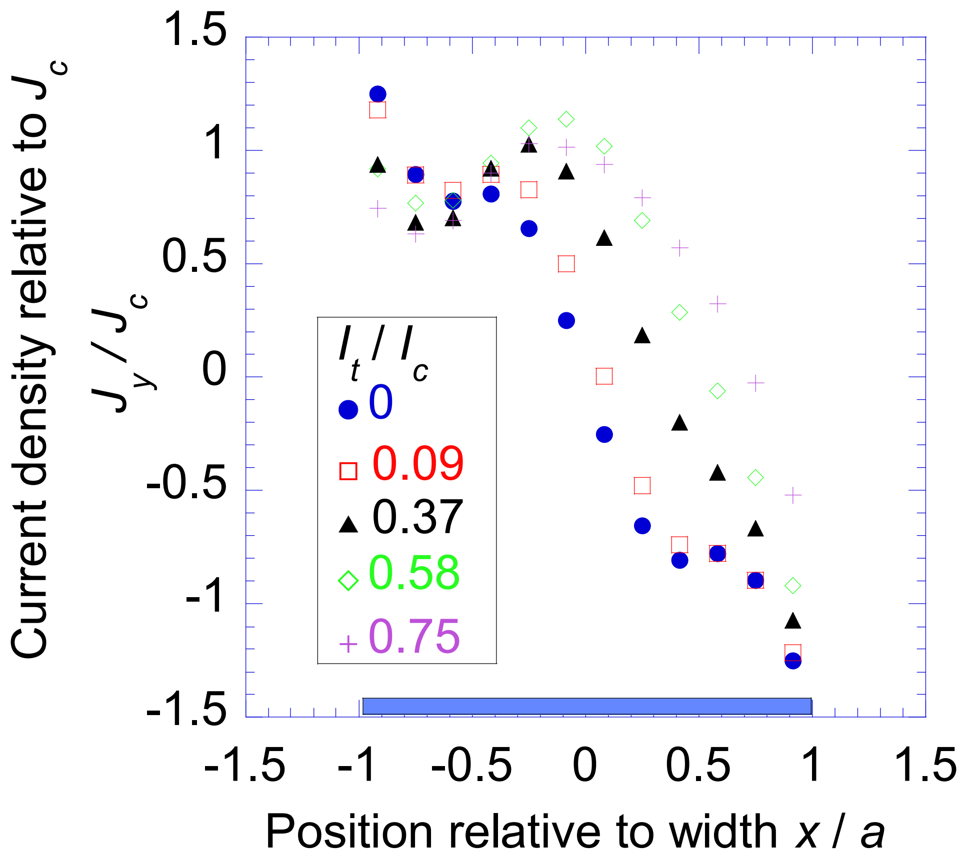
Normalization by J_c





Variations of current distributions are determined by I_t / I_c.

Variations of J_y / J_c as functions of I_t / I_c



As I_t / I_c increase, sheet current densities over the width approach J_c.

$I_t / I_c(B_{ex})$  **Current distribution**

Current distribution in a straight single YBCO coated conductor

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Interaction between coated conductors?

↓

How is the calculation carried out based on the current distribution?

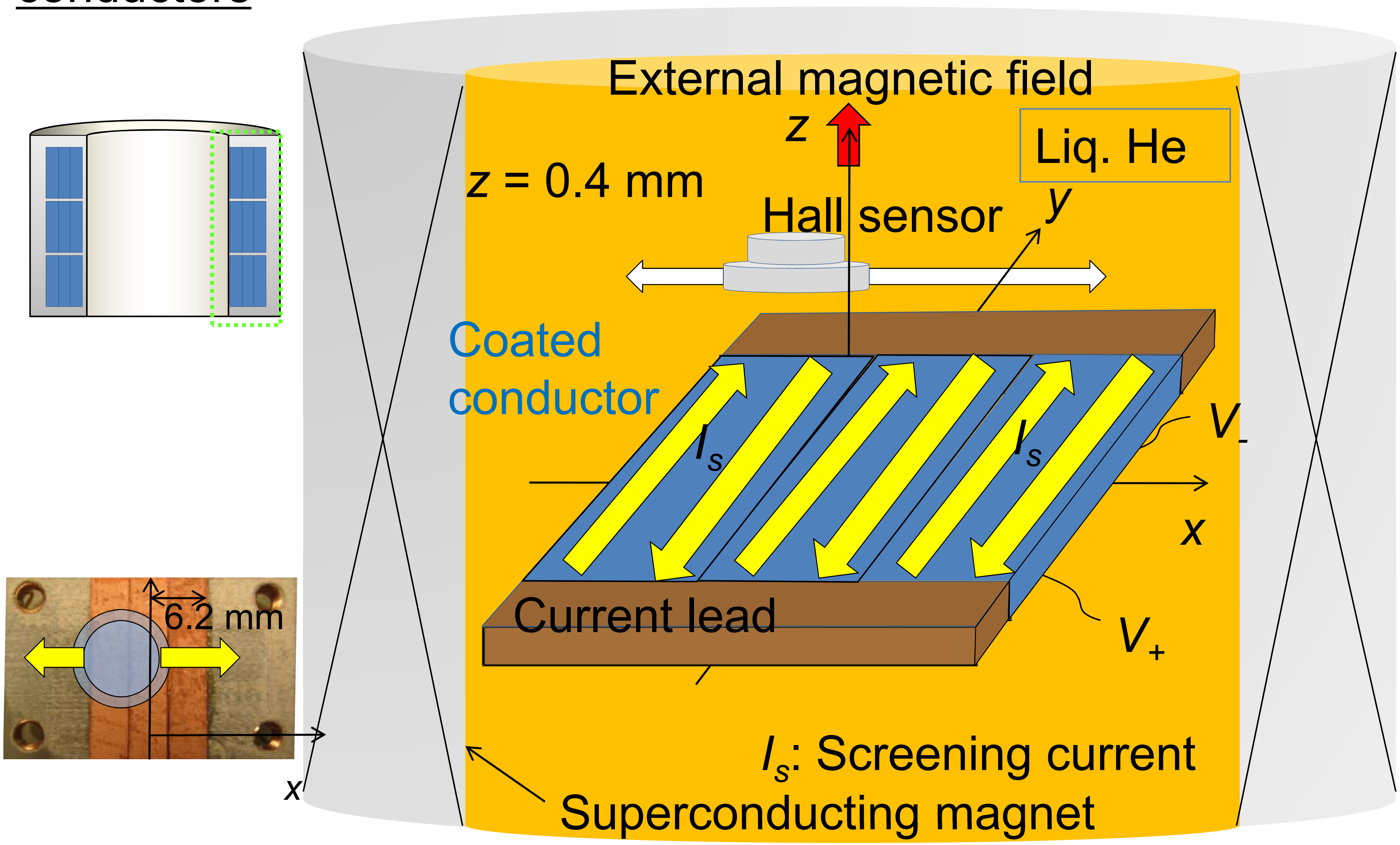
↓

Calculation of magnetic-field distribution generated by a YBCO pancake coil

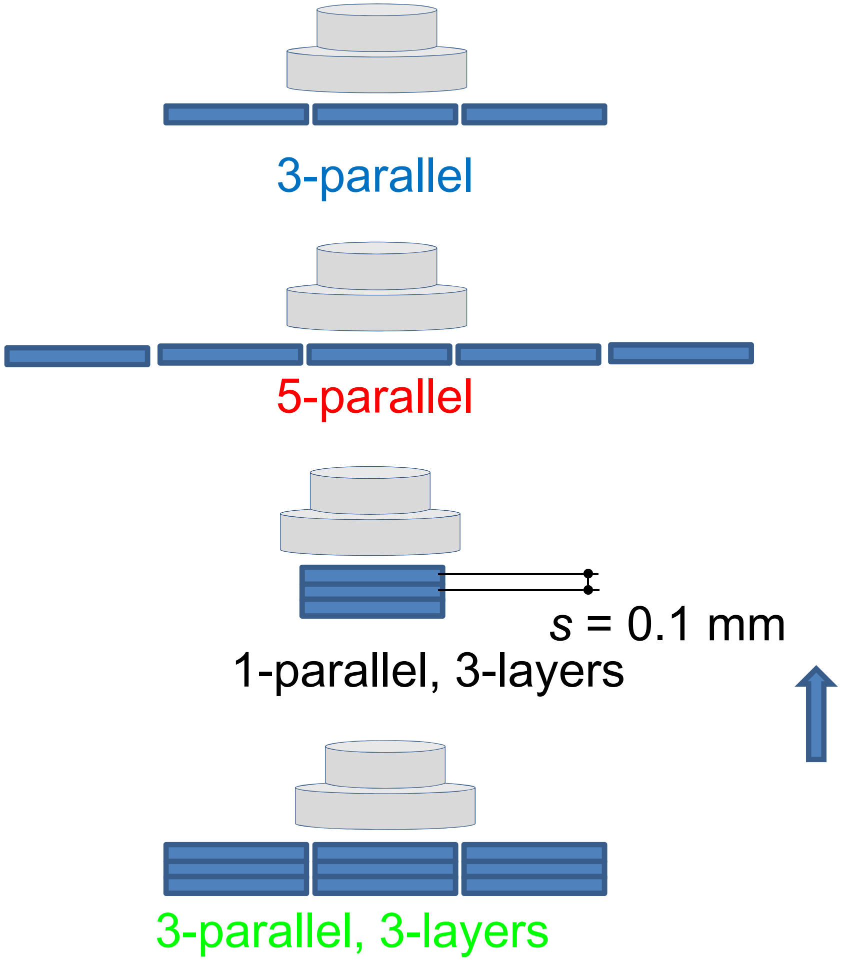
Magnetic field distributions generated by multiple YBCO coated conductors

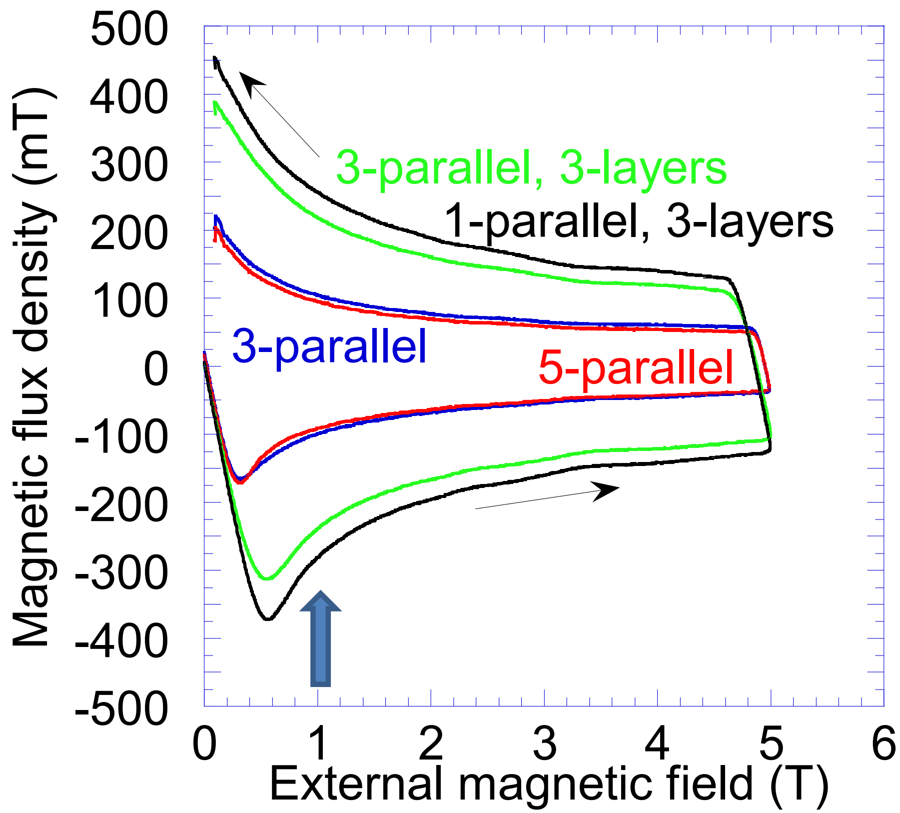
✓Calculation method of magnetic field distribution generated by multiple coated conductors under background magnetic filed.
✓Understanding how a screening current flows in each coated conductor arranged and/or superimposed.

Magnetic field distribution generated by multiple coated conductors

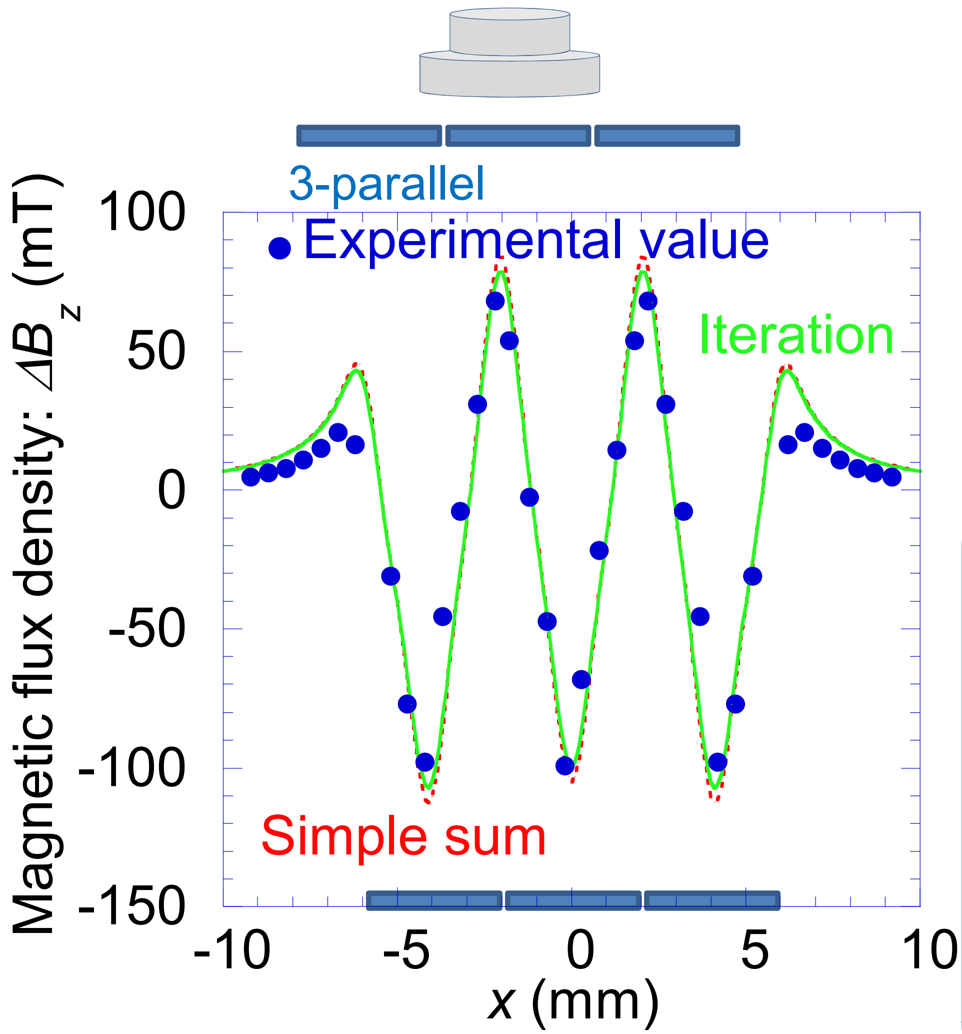


SCF at (*x*, *z*) = (0.2 mm, 0.4 mm) generated by multiple coated conductors

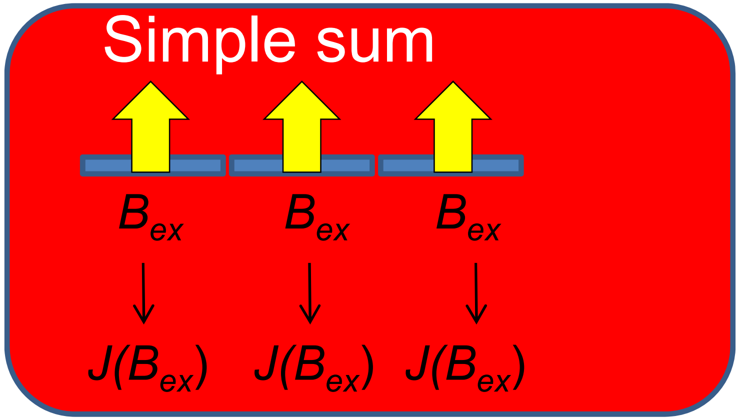


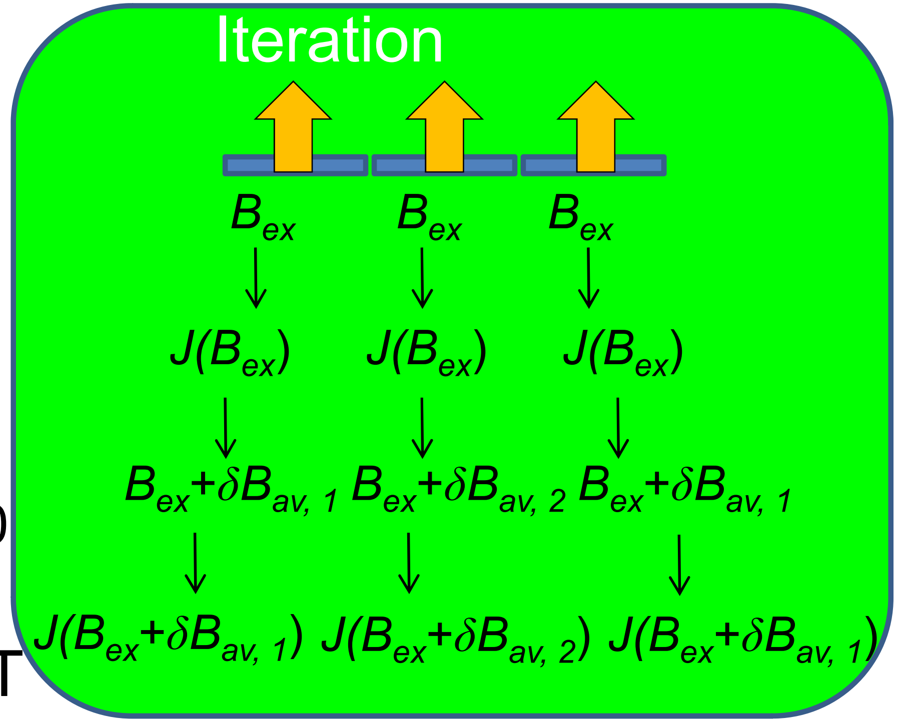


Distribution of SCF generated by multiple coated conductors

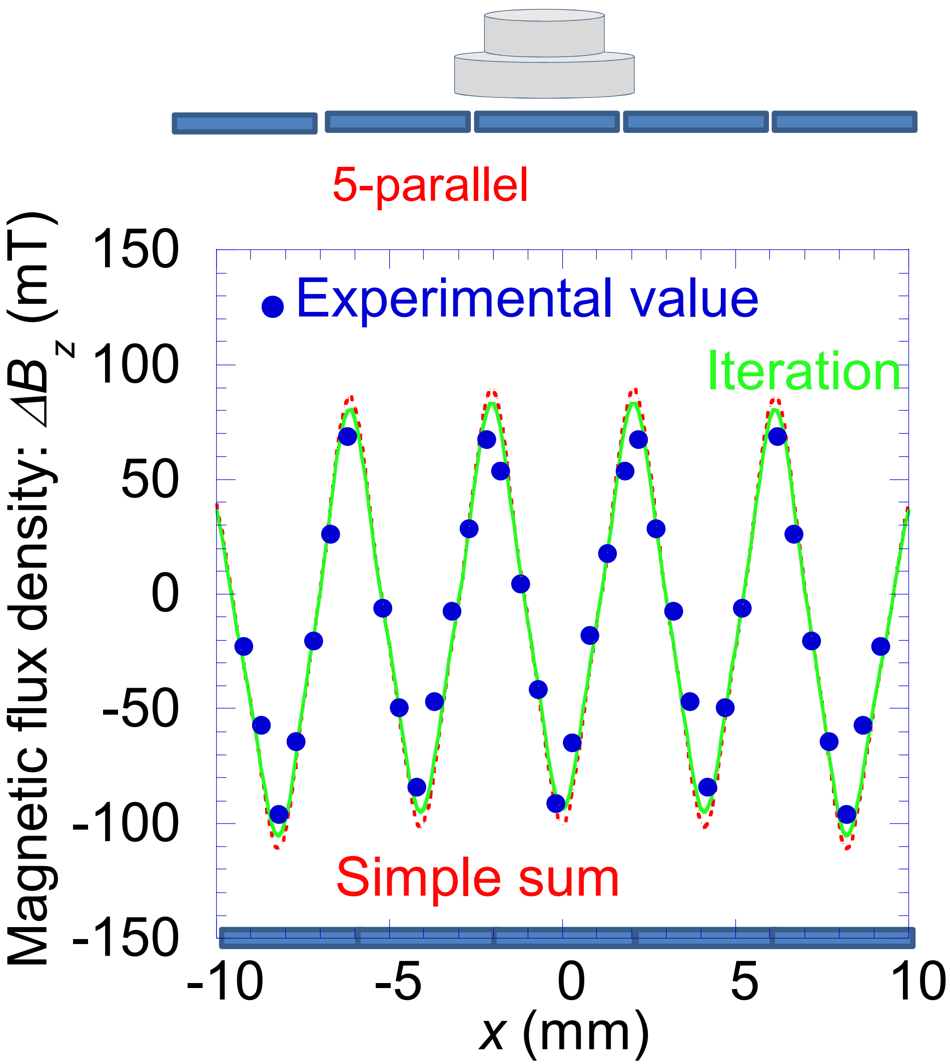


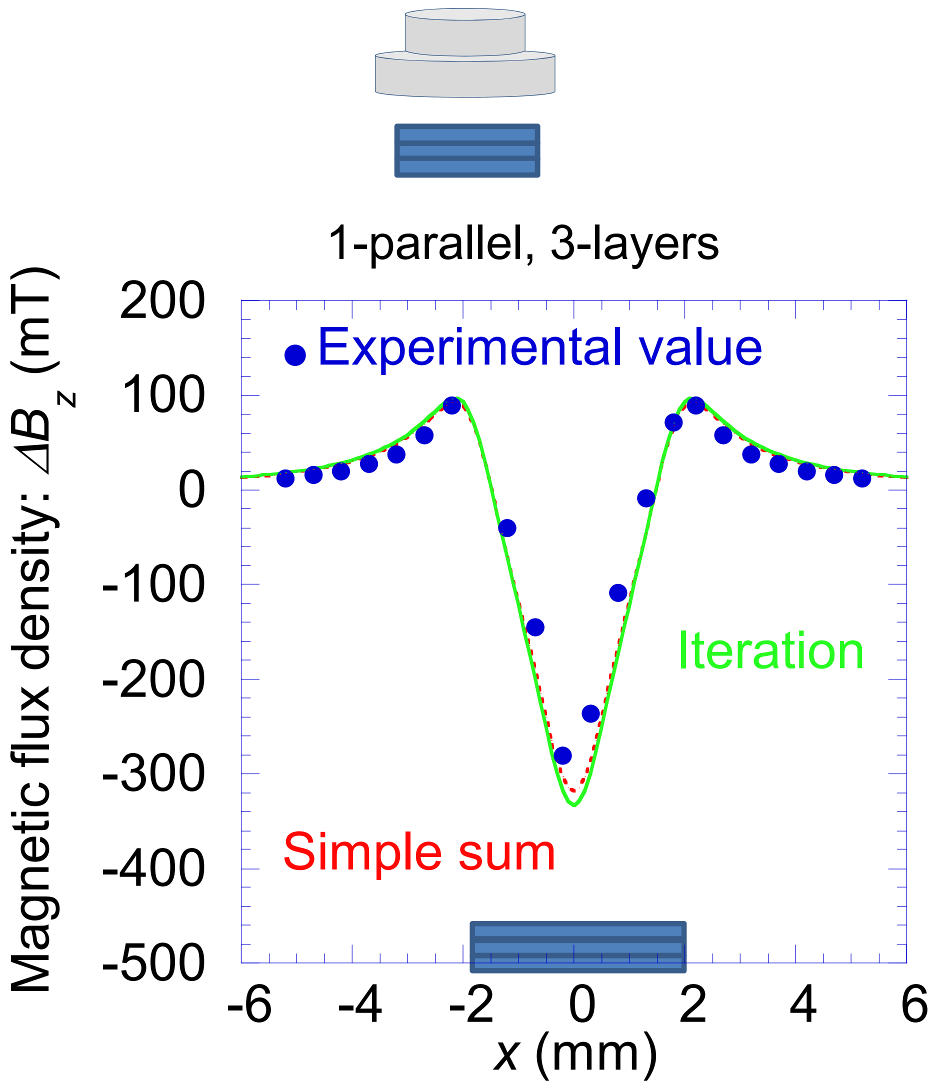
External magnetic field: B_{ex} = 1.0 T



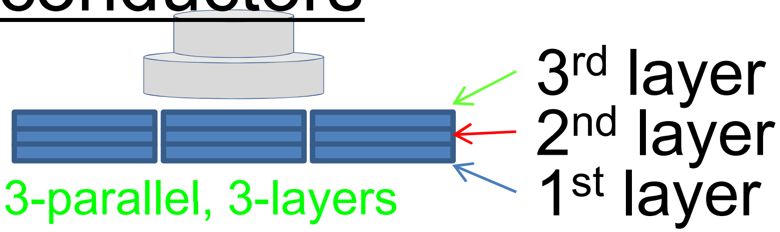


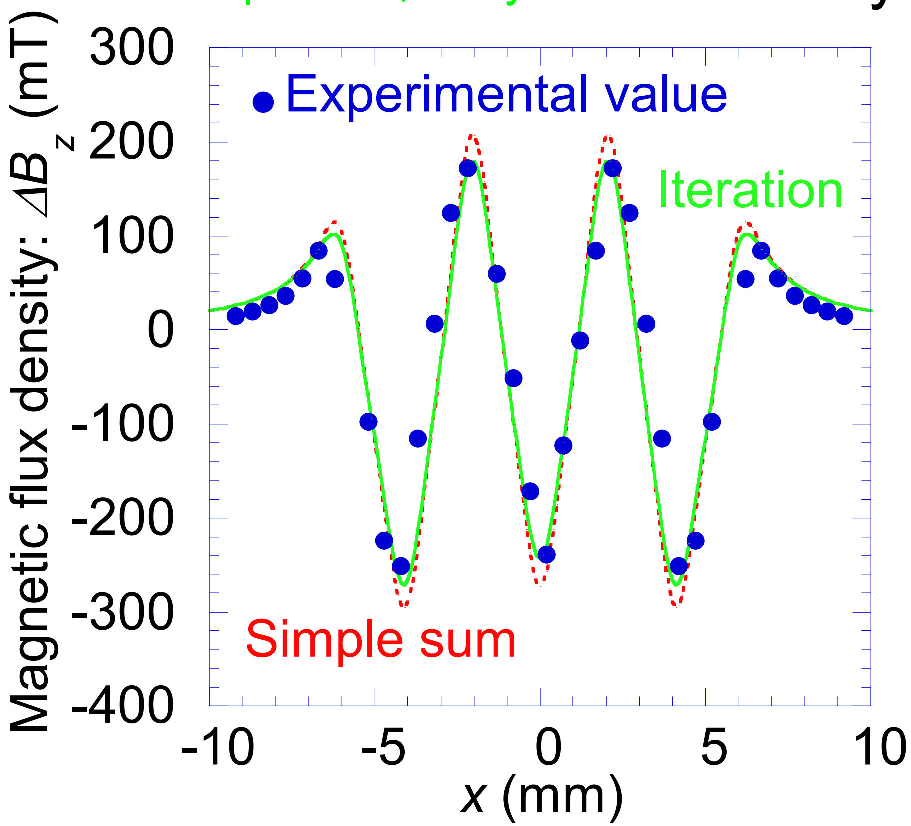
Distribution of SCF generated by multiple coated conductors

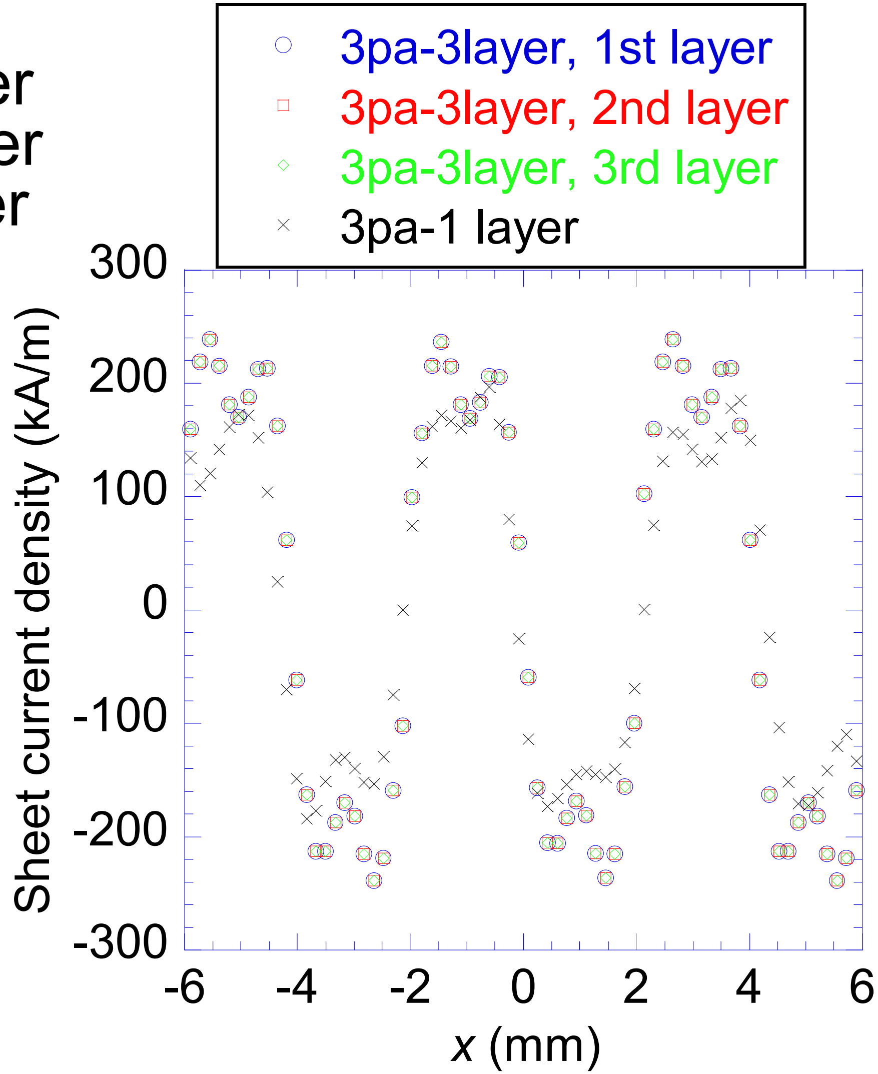




Current distribution in arranged and superimposed coated conductors







External magnetic field: B_{ex} = 1.0 T

The current distribution in each layer is almost same.

Current distribution in a straight single YBCO coated conductor

Interaction between coated conductors.

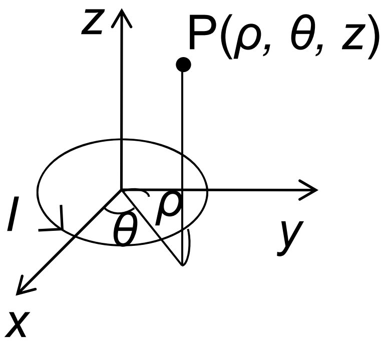
How is the calculation carried out based on the current distribution?

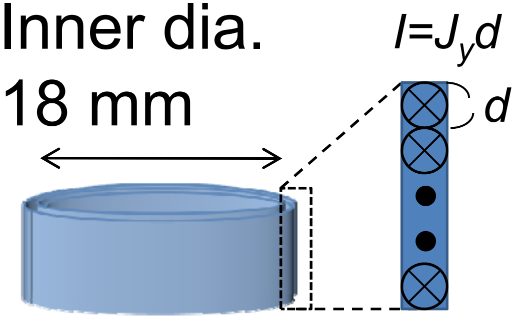
Calculation of magnetic-field distribution generated by a YBCO pancake coil

Magnetic-field distribution generated by a current flowing
in a YBCO pancake coil

✓Calculation method of magnetic-field distribution generated by pancake coils under background magnetic filed.
✓Difference in magnetic-field distribution due to a difference of a current distribution

A calculation model of magnetic field generated by actual current distribution in a pancake coil





Single-pancake coil

Magnetic vector potential

$$A_\theta = \frac{\mu I}{\pi k}\sqrt{\frac{a}{\rho}}\left\{\left(1-\frac{k^2}{2}\right)K(k)-E(k)\right\}$$

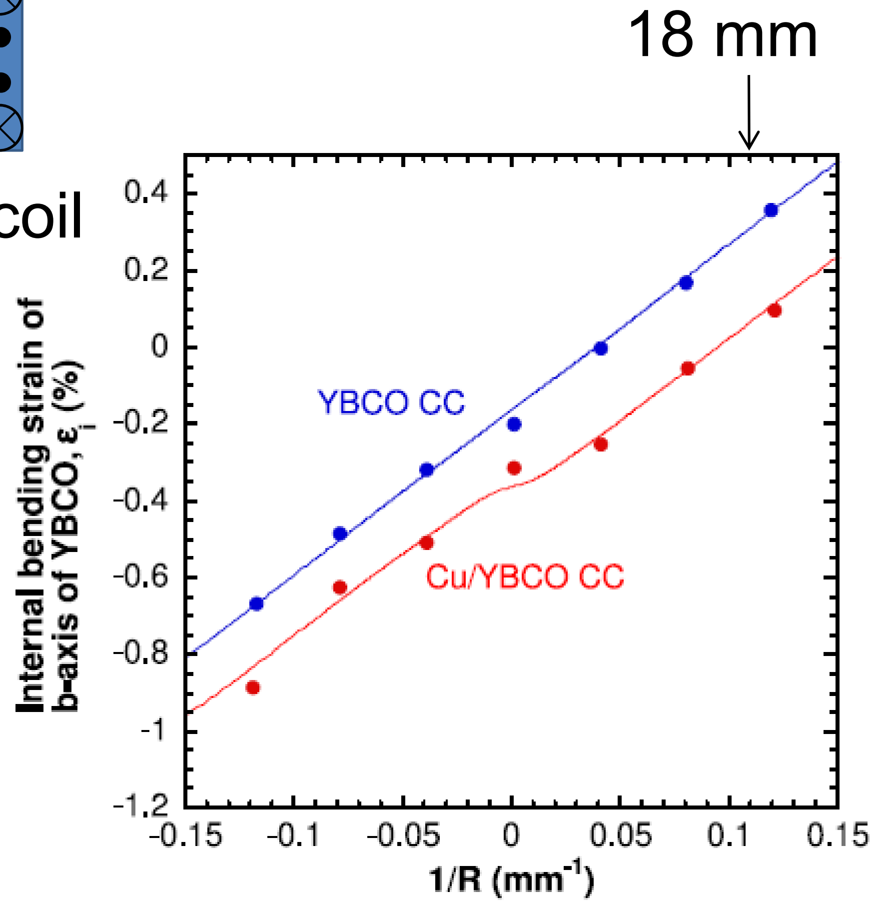
$$K(k)=\int_0^{\pi/2}\frac{d\theta}{\sqrt{1-k^2\sin^2\theta}}$$

$$k^2=\frac{4a\rho}{(a+\rho)^2+z^2}$$

$$E(k)=\int_0^{\pi/2}\sqrt{1-k^2\sin^2\theta}\,d\theta$$

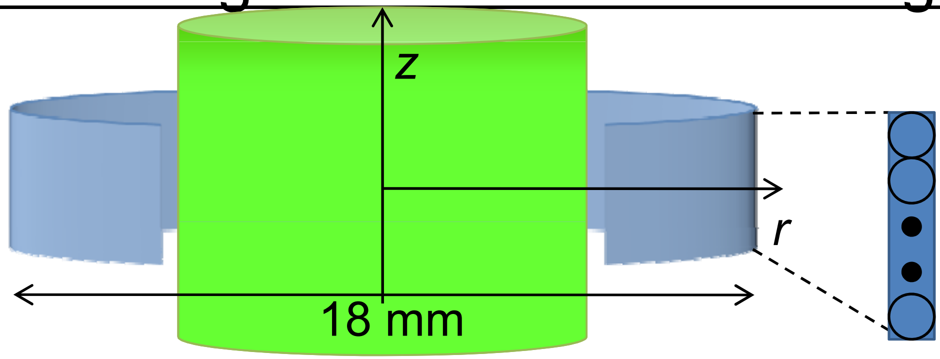
Magnetic flux density

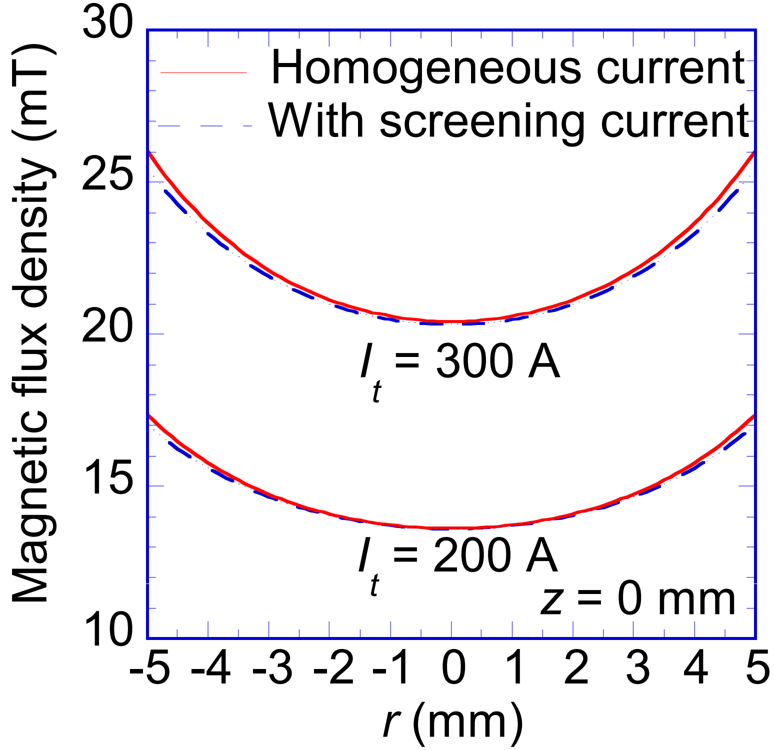
$$B=\nabla\times A$$

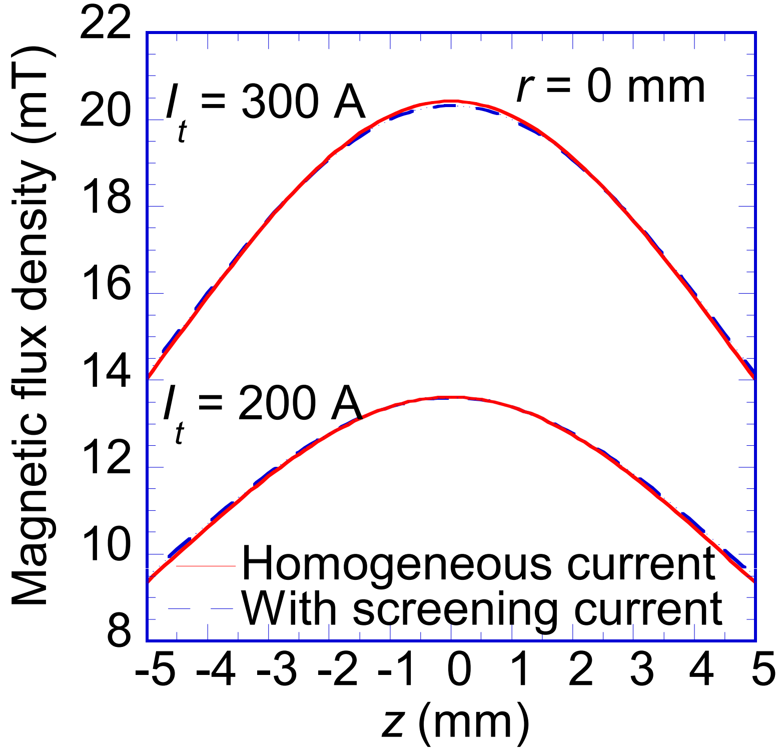


M. Sugano et al., *Supercond., Sci., Technol.*, 075019, 2011

A calculation of magnetic field distribution using Brandt's model and homogeneous current in a single-turn coil under self field

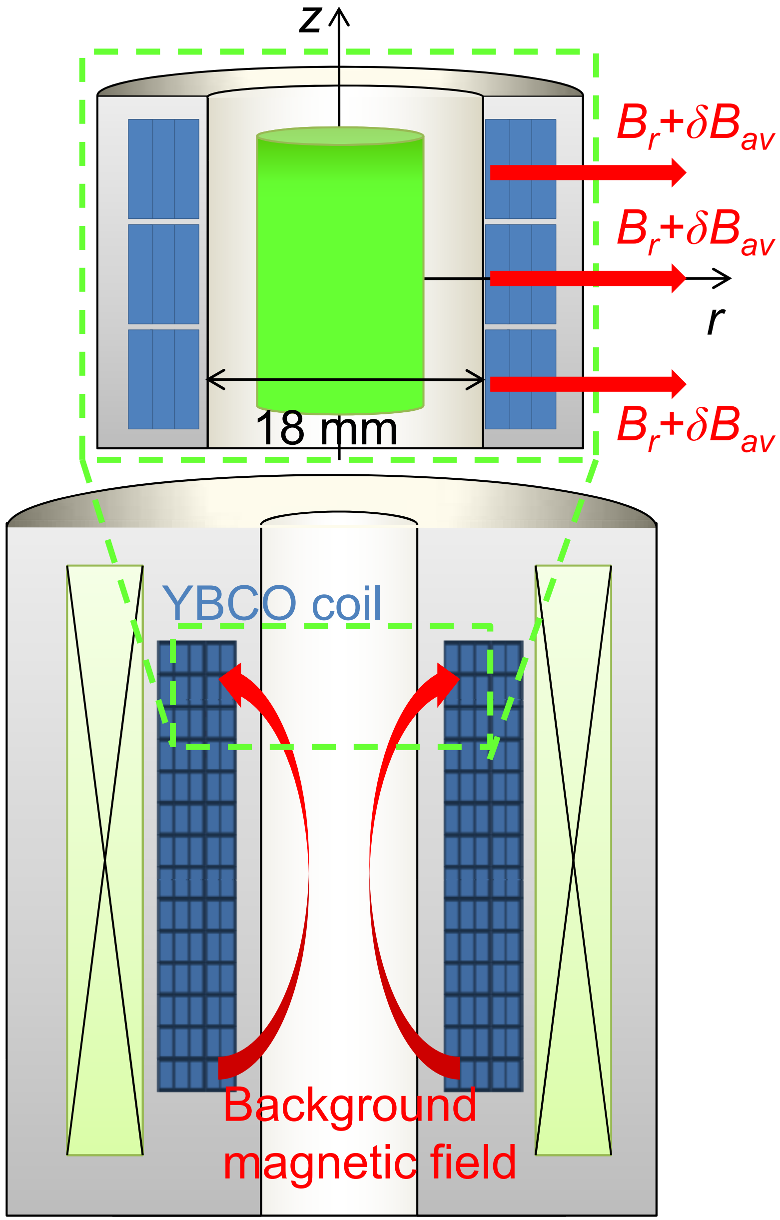


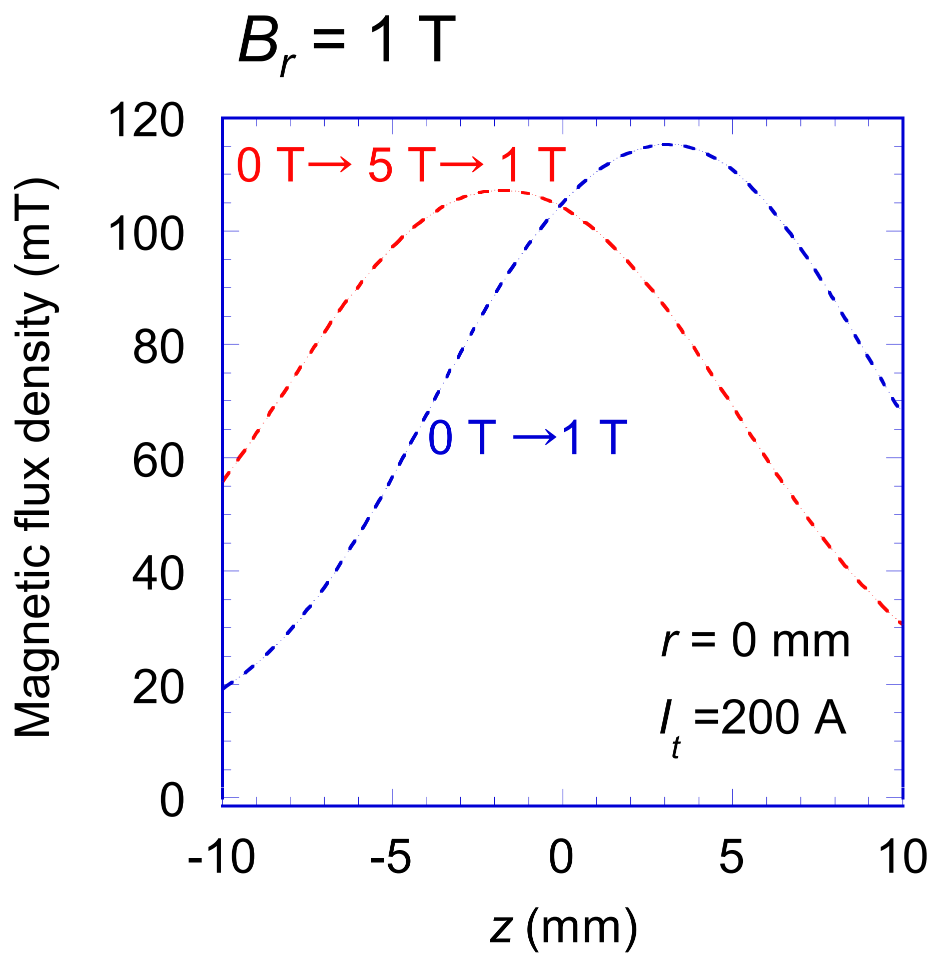




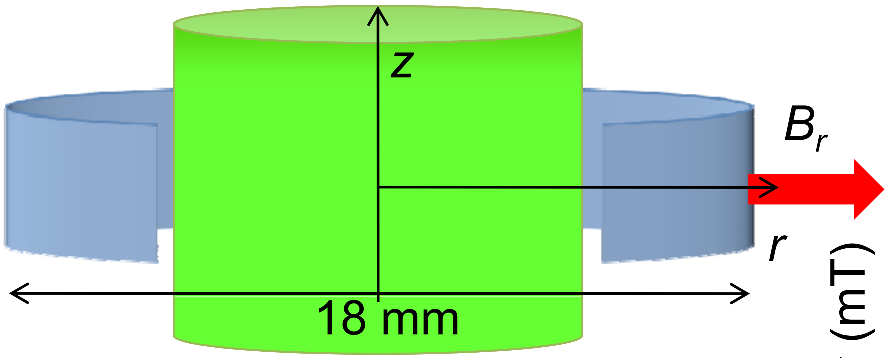
Differences of magnetic flux density at the center:
0.01 mT (I_t = 200 A) , 0.10 mT (I_t = 300 A)

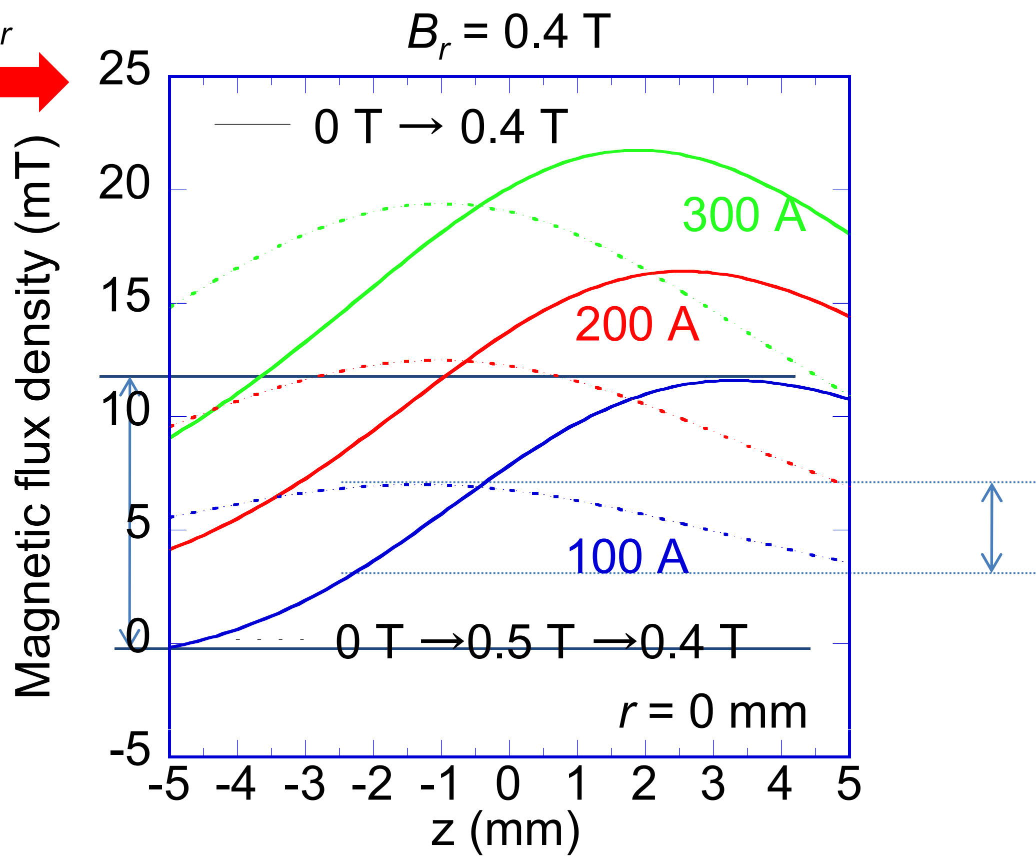
Magnetic field distribution generated by a multi-turn and multi-layered pancake coil





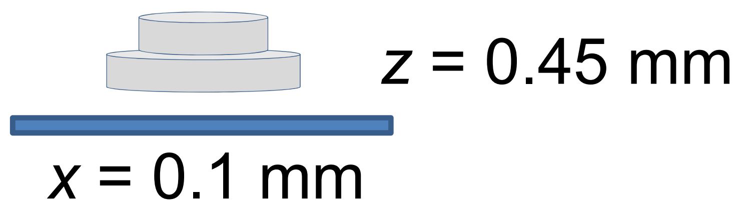
A reduction of influence of screening current on magnetic field generated by a single-turn coil

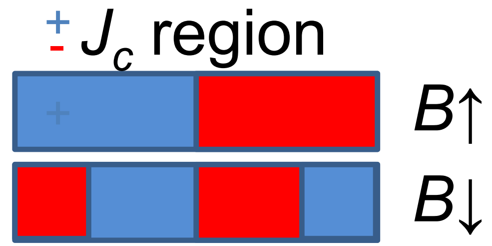


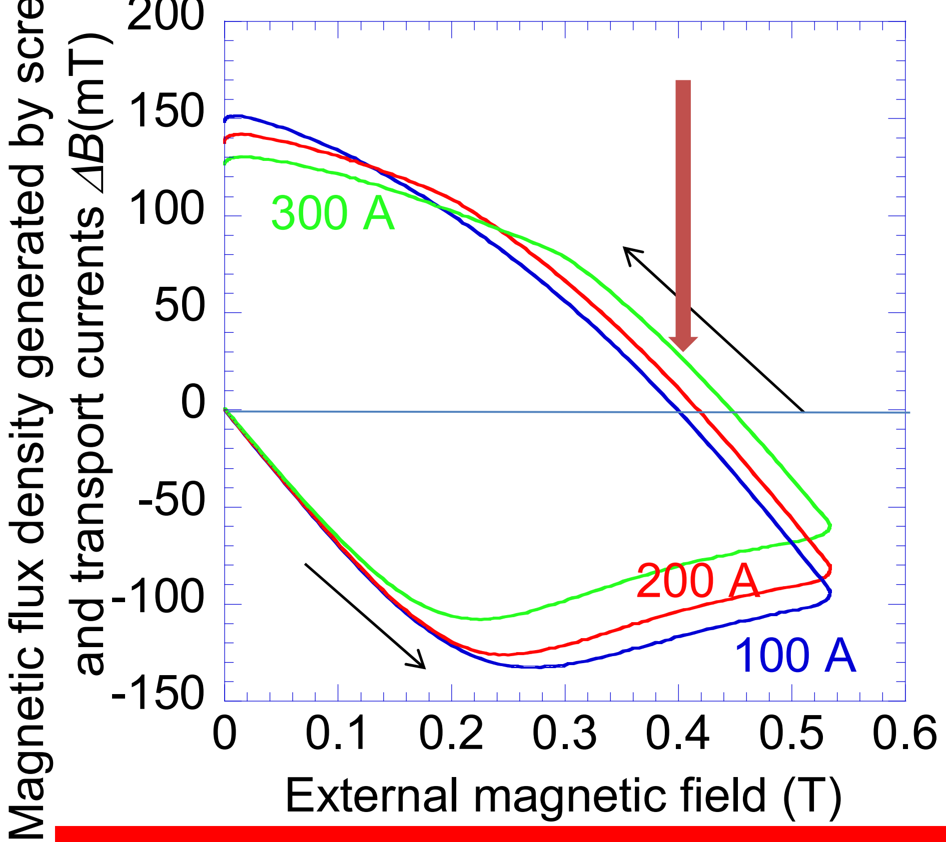


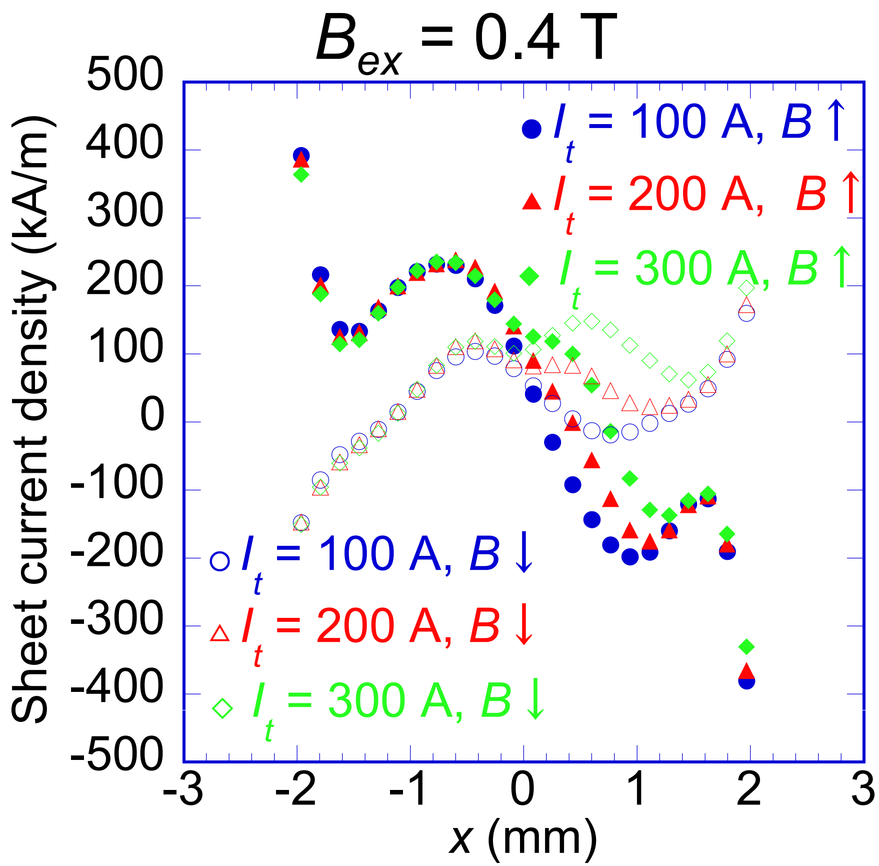
It is important how coils charge in order to reduce influence of the screening current on the magnetic field.

Differences of current distributions between history of background magnetic field









Control of current distribution enable reduction of SCF.

Summary

- The current distribution flowing in a coated conductor under low magnetic field follows Brandt's model (J_c constant).
- Variations of current distribution consisting of screening and transport currents are determined by ratio of transport current relative to critical current under high field.
- Brief calculations of magnetic-field distributions generated by YBCO pancake coils taking into account screening current were carried out.
- It is very important to control current distributions in coated conductors and reduce SCFs for YBCO NMR magnet.

Future work

•Optimal design of YBCO NMR magnet including operating conditions