3MO2

Magnetic Microscopy for Magnetic Relaxation in RE-123 Coated Conductor with DC Transport Current and External Magnetic Field

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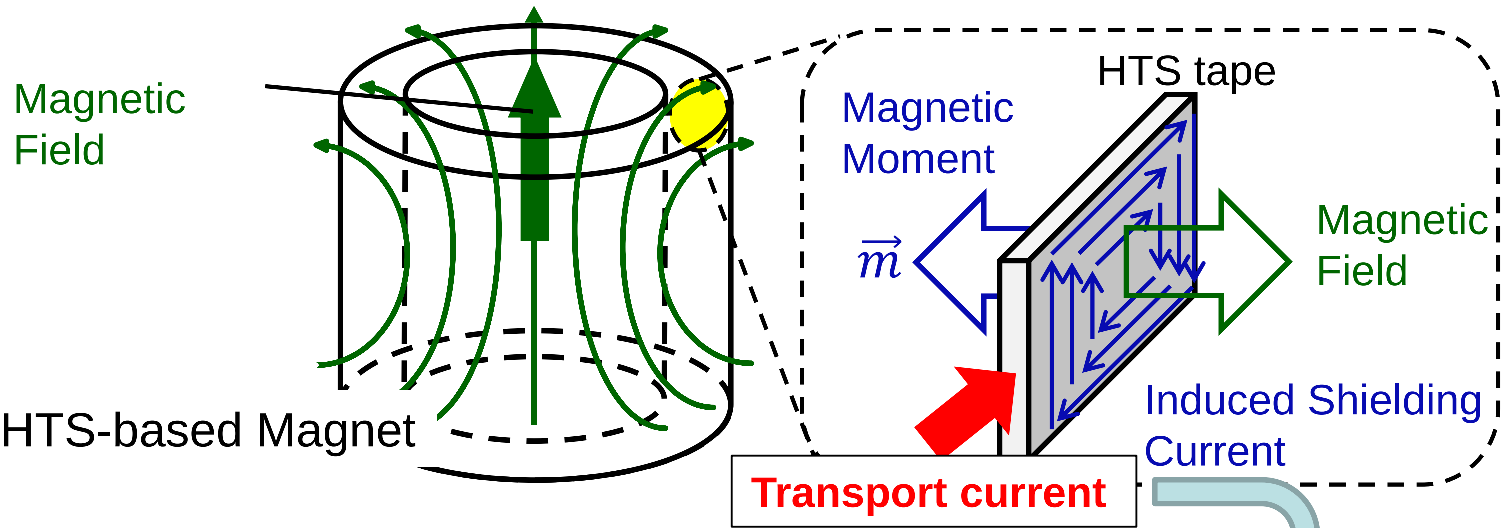
Introduction

HTS tapes

- Reduce cooling cost
- Improve high magnetic field

Magnet applications
(MRI/NMR)



Significant problems

- Large magnetization induced in the tape strand
- Magnetic moment relaxation

Disturb the field

- Spatial homogeneity
- Temporal stability

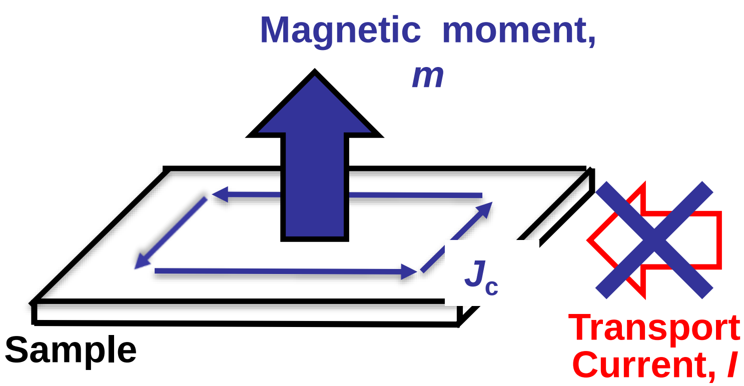
Understanding of magnetization properties is important issue

Magnetization Measurement

General method(MPMS)

Global measurement

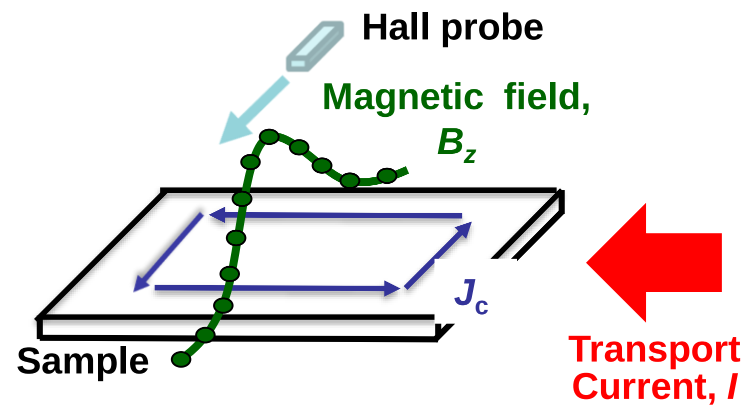
× Current influences



Magnetic microscopy(SHPM)

Spatially resolved measurement

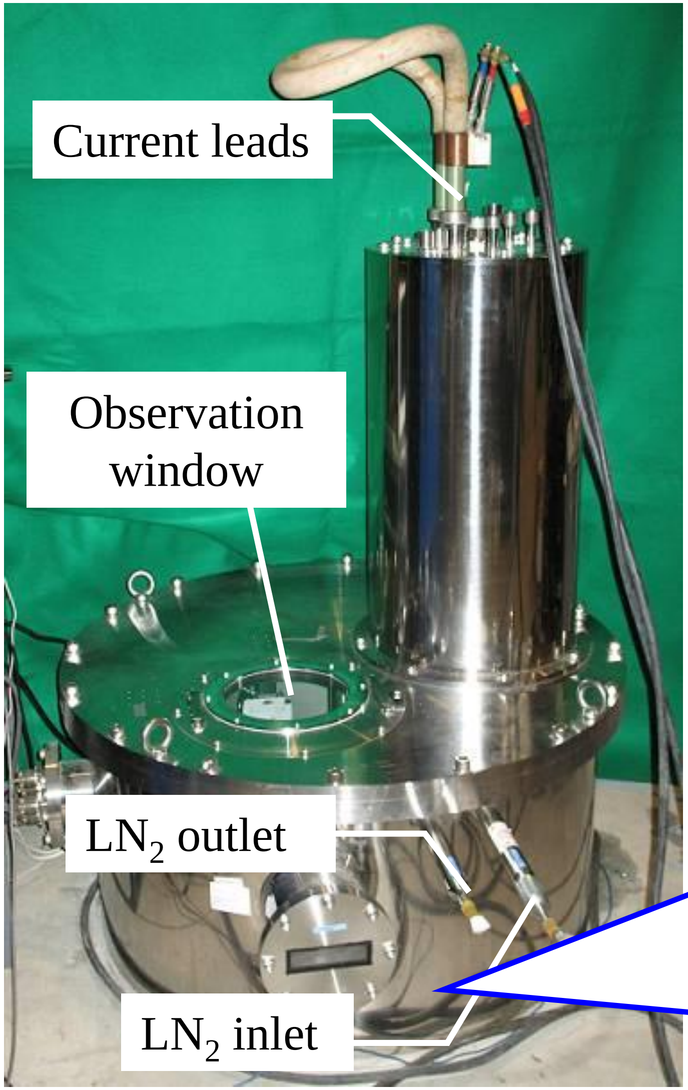
○ Current influences



Objectives

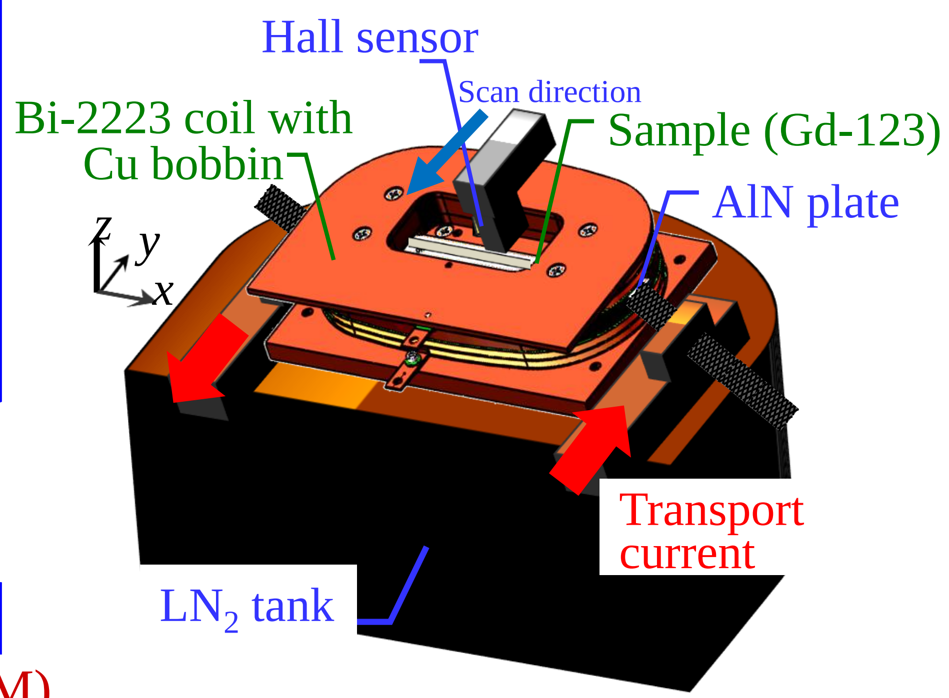
- Visualize the magnetization behavior including current influences
- Investigate the magnetic relaxation characteristics
  - ✓ Compare the local *E*-*J* properties for different current
  - ✓ Characterize the current and time dependence of magnetic moment

Scanning Hall-probe Microscopy (SHPM)



External magnetic field: < 120 mT
Transport current: < 500 A
Typical stage temperature: 79 K
Active area of Hall sensor: 50 mm square
Spatial step: 1 mm in *x*, *y*, 0.25 mm in *z*

Sample: Gd-123 CC (width: 5 mm)
I_c at 10^{-4} V/m: 84 A



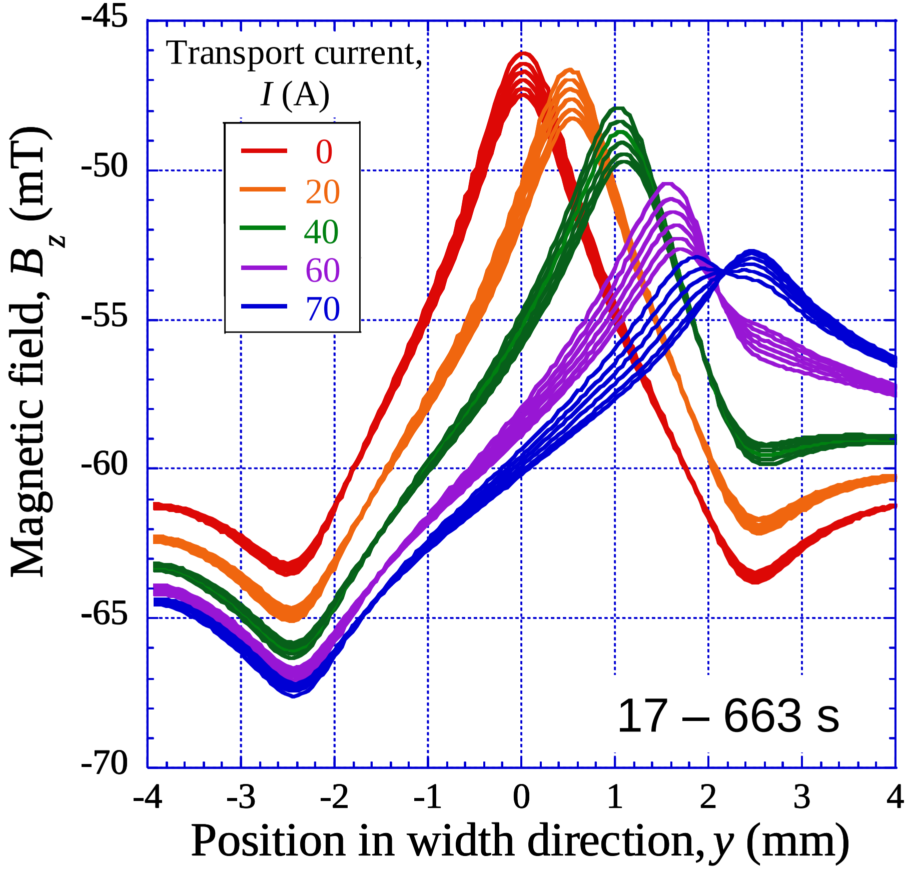
Scanning Hall-probe microscopy (SHPM)

Magnetic Relaxation Measurement by SHPM

Experiment Procedure

1. Apply transport current to the sample.
2. Apply constant external field (= -60 mT) to the sample and magnetize it.
3. Scan the Hall-probe in width direction of the tape to obtain magnetic field distributions.

Next to other current conditions (Transport current: *I* = 0 to 70 A).



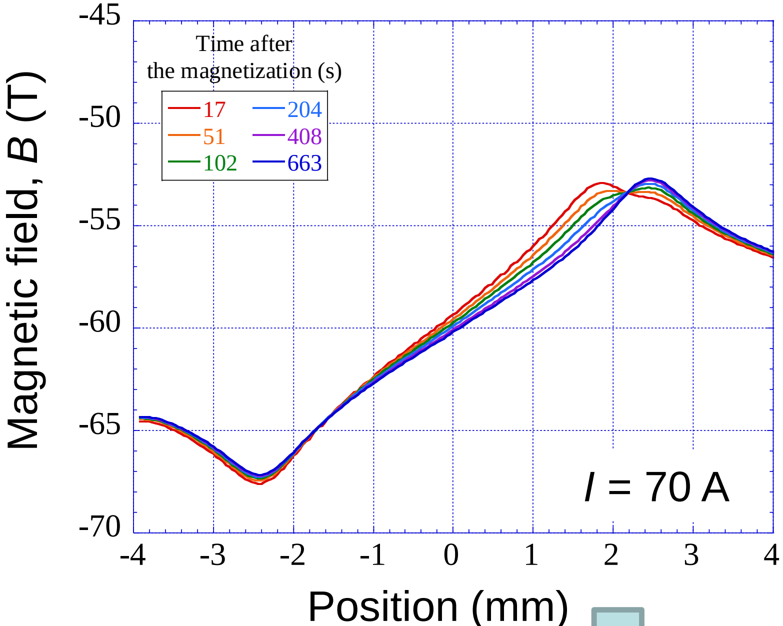
We have successfully measured the current-dependent behavior of magnetization in RE-123 CC

Magnetic Relaxation properties obtained by SHPM

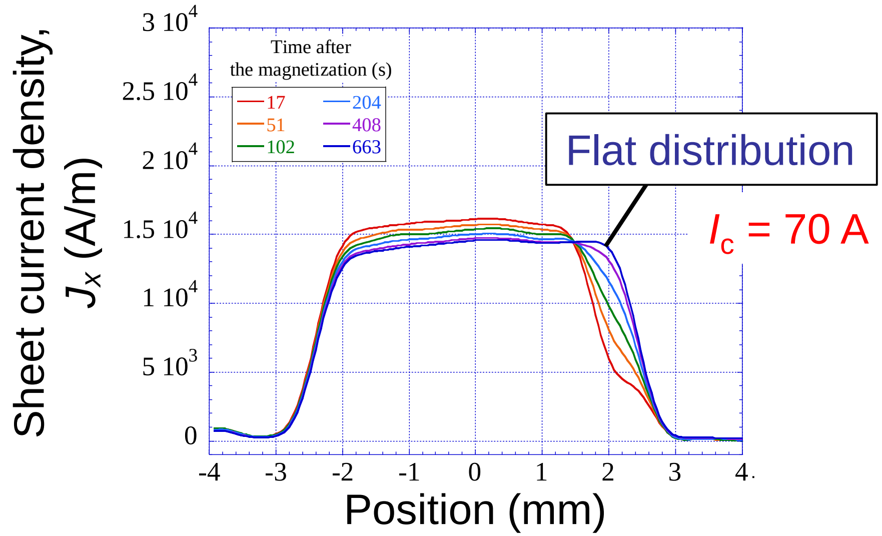
$B \rightarrow J$

Inversion of Biot-Sarvart law

Magnetic relaxation



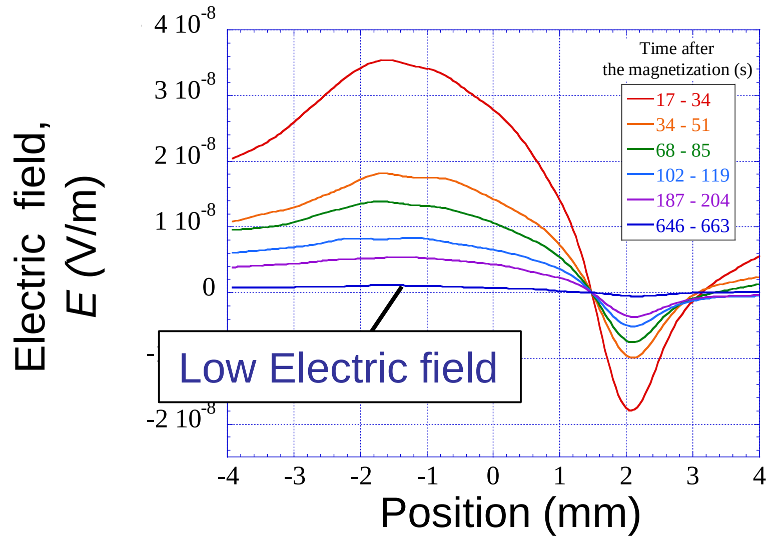
Sheet current density distribution



Faraday's law

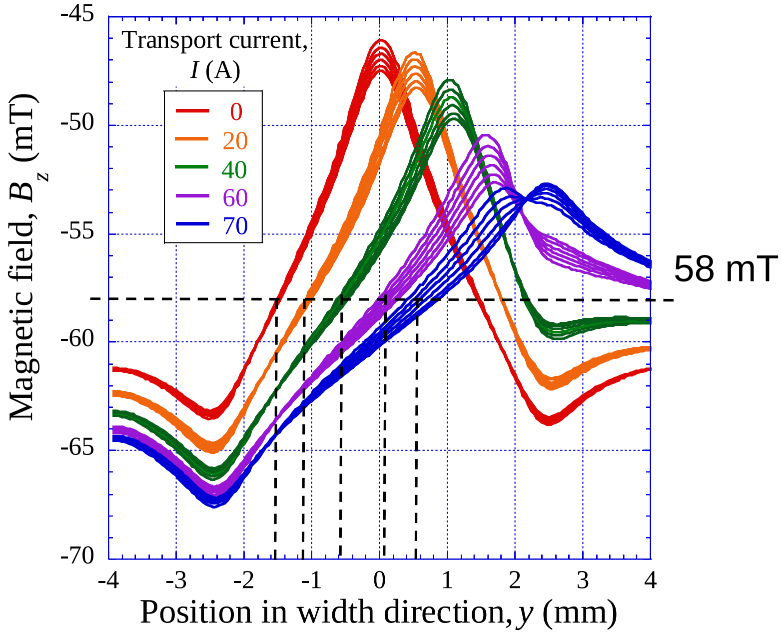
$$\frac{\partial B}{\partial t} \rightarrow E$$

Electric field distribution

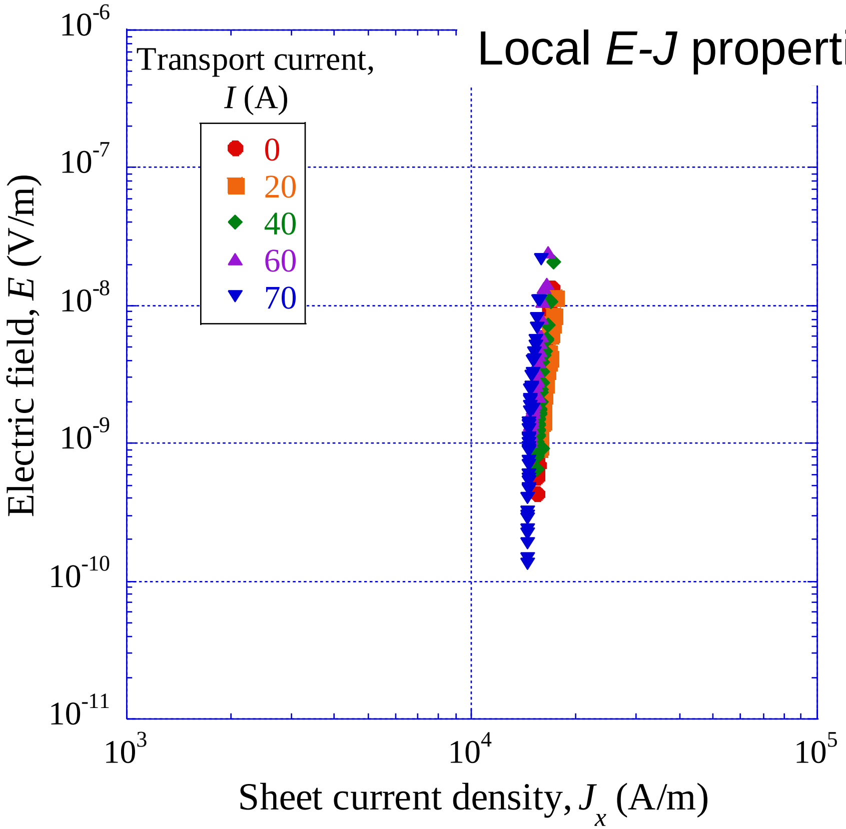


Local E-J properties for different Transport Currents

We extracted local E-J properties at the same B_z level (= -58 mT) due to the shift of external field by the self-field of transport current



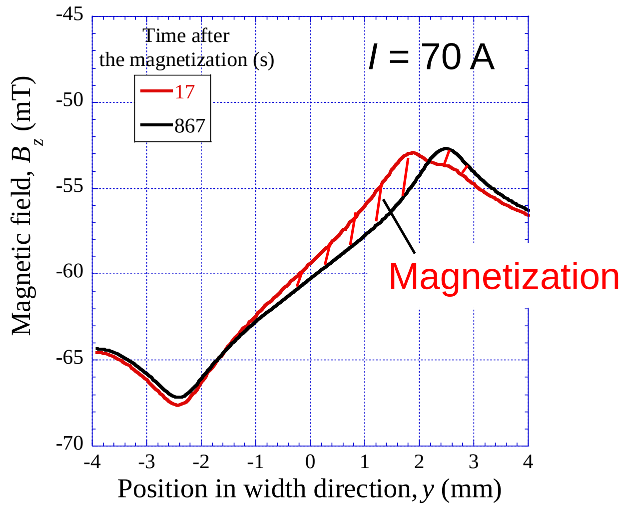
Local E-J properties



local E-J properties were consistent even for different current conditions

Local properties obey the E-J properties of RE-123 CC

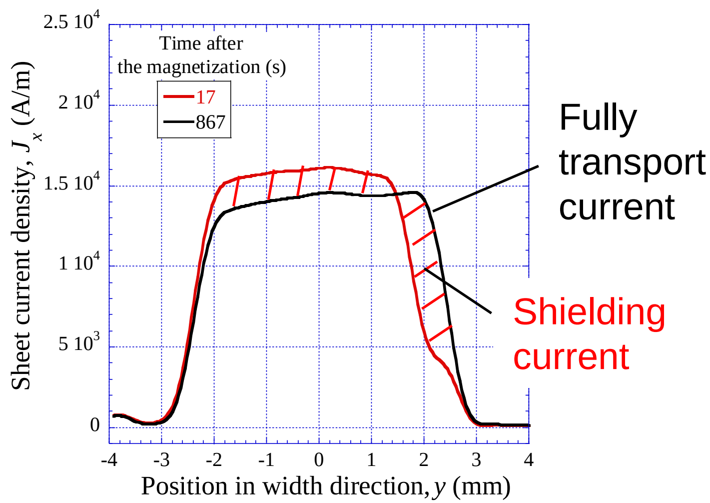
Extraction of Shielding Current

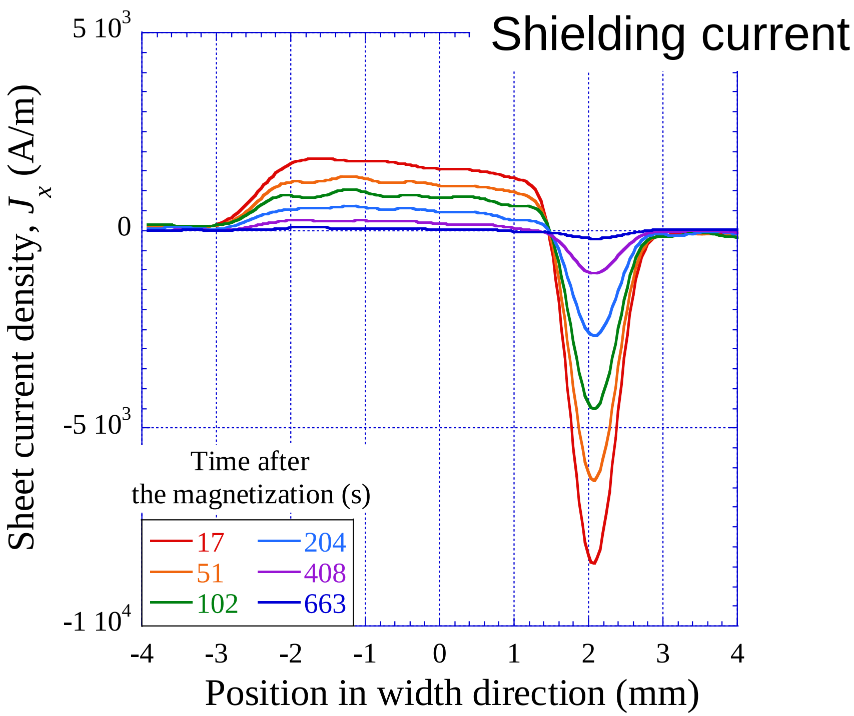


Difference between the Bz distributions

= Magnetization

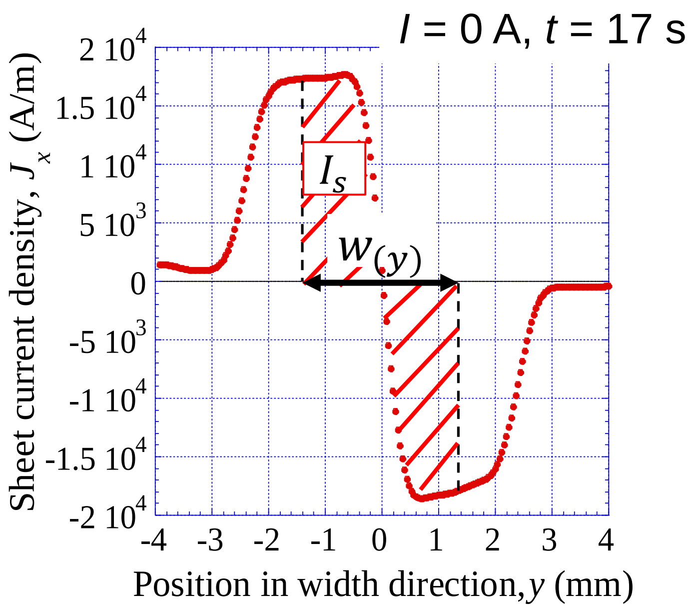
Shielding current can be extracted

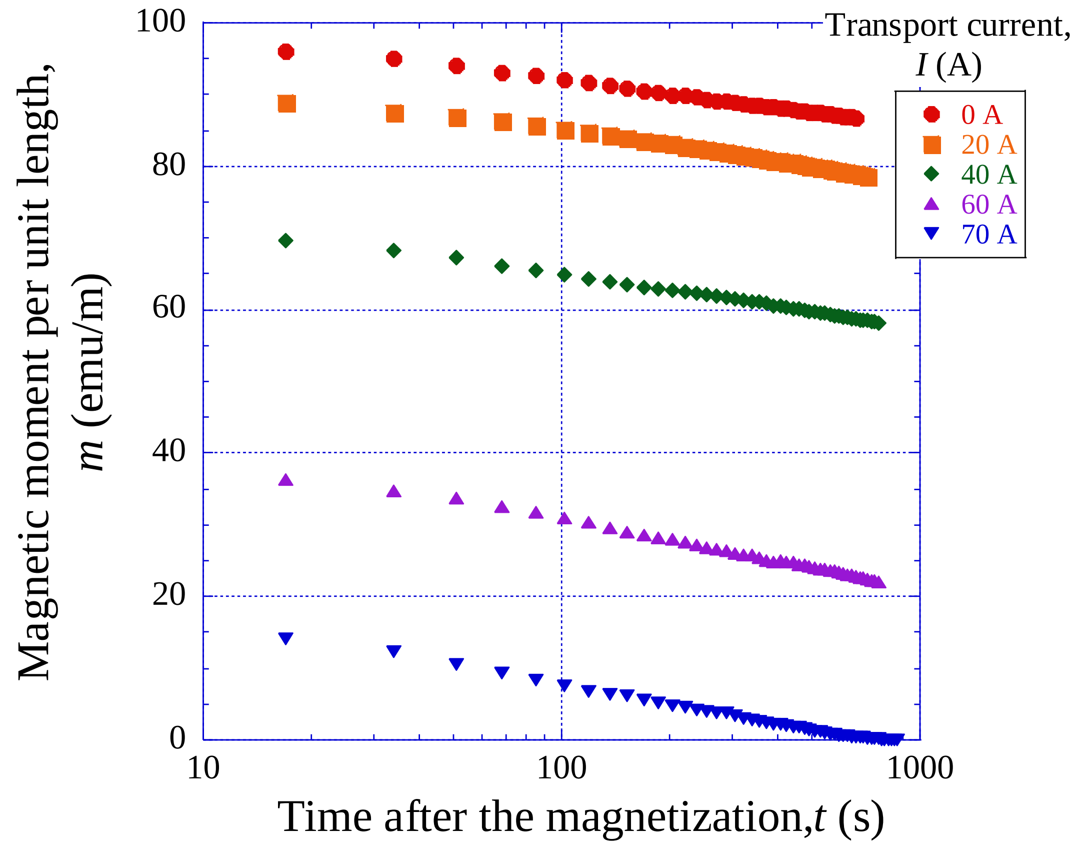




Magnetic moment can be determined by integration of the distribution.

Time Dependence of Magnetic Moment





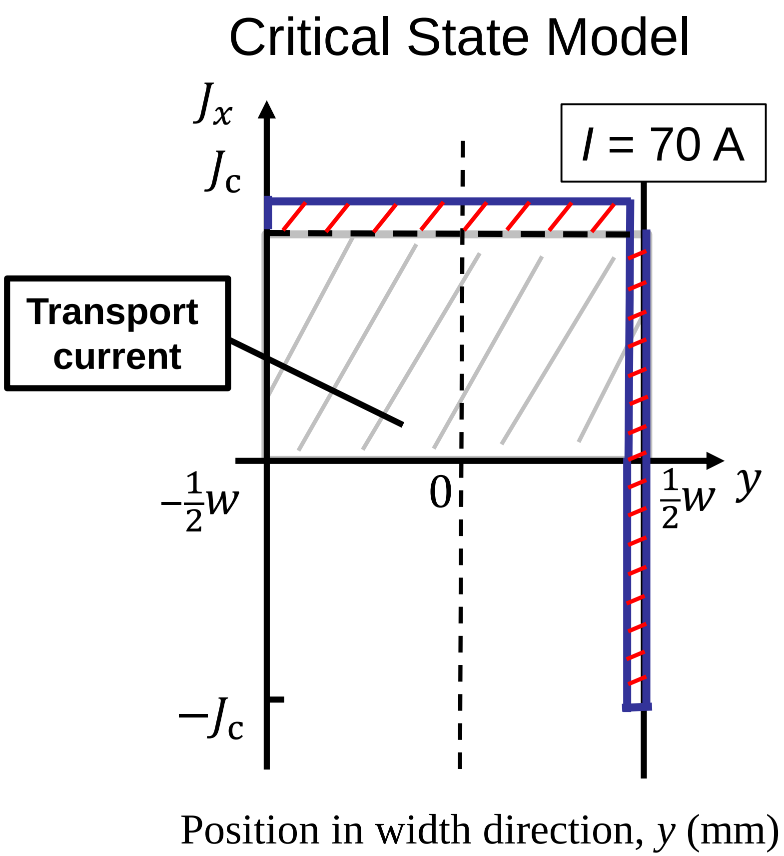
Magnetic moment per unit length

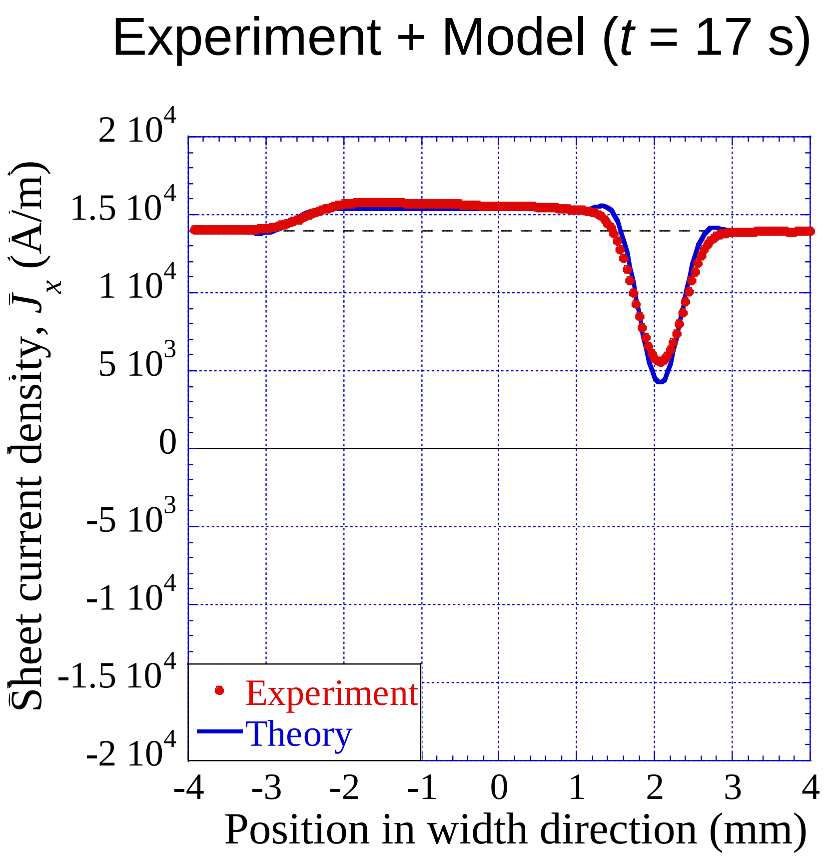
$$m = \underbrace{\sum J_x dy}_{I_s} w_{(y)}$$

Magnetic relaxation $\propto$ log *t* ⇨ Flux creep

Transport current ↑ ⇨ Magnetization ↓

Current Estimation based on CSM





When magnetized until the flux full penetration,
Assume "transport current = uniform NC current",

Current dependence of magnetization can be modeled

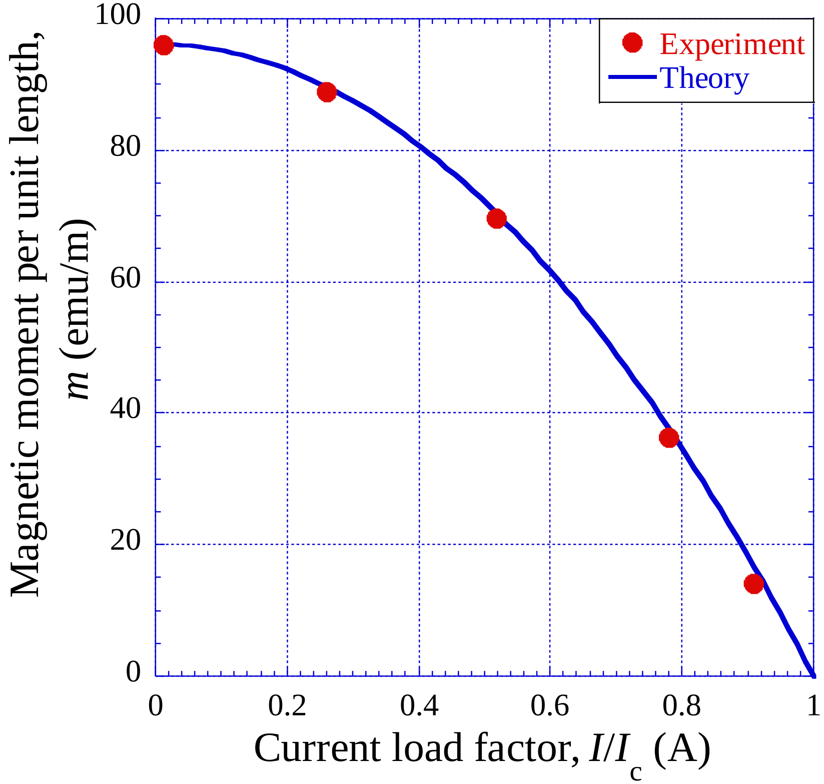
Current Dependence of Magnetic Moment

From the current estimation,
Theoretical equation of magnetic moment is derived as follows,

$$m = m_c \left\{ 1 - \left(\frac{I}{I_c} \right)^2 \right\}$$

Fitting to $m_c = m_{I=0}$,
Model curve of current dependence of magnetic moment can be described.

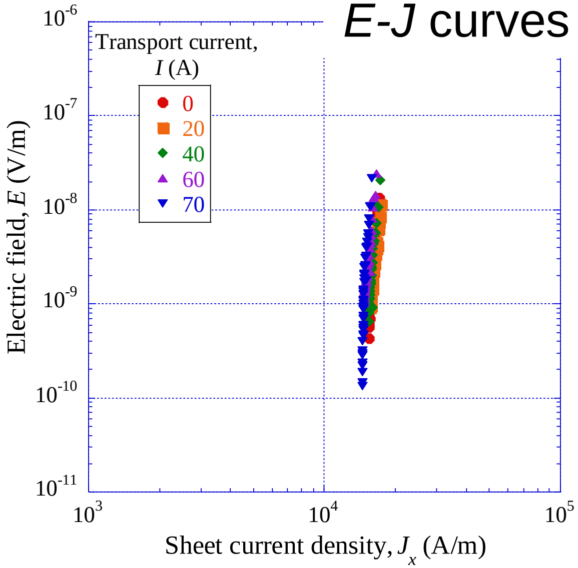
Experimental data and Model curve were agreed well to the high current load.



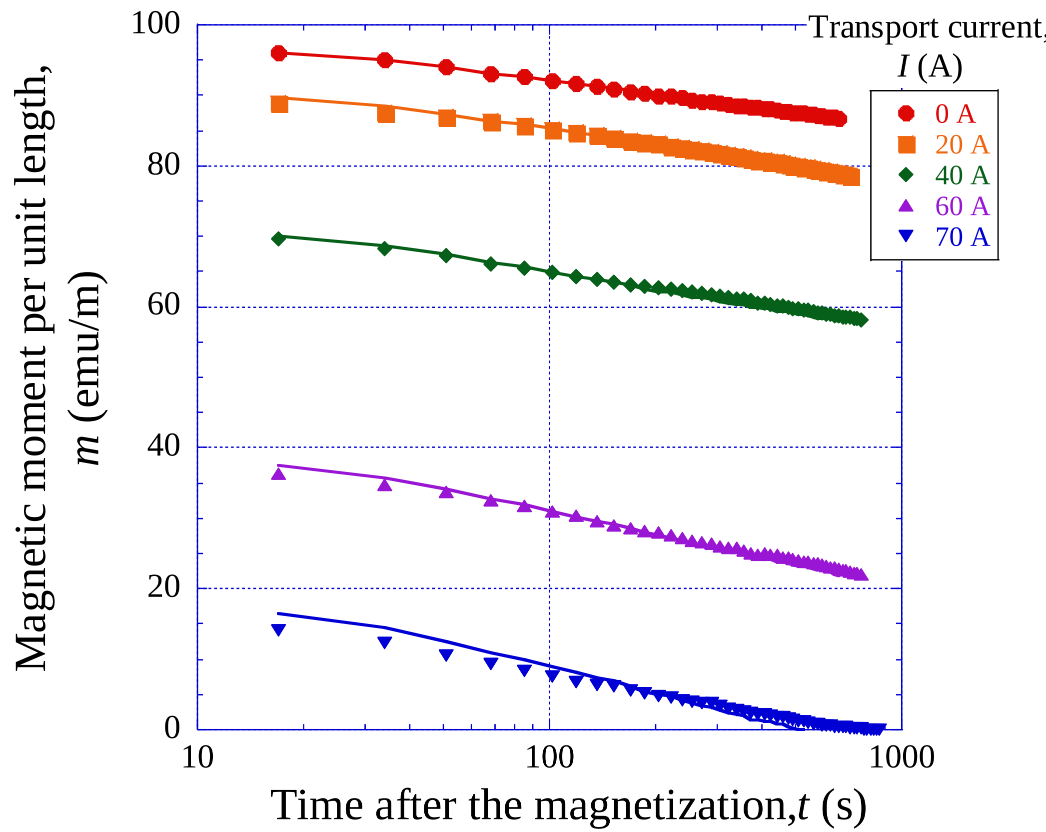
Succeeded in Modeling the Magnetization in RE-123 CC, when both transport current and external field are applied.

Characterization of Magnetic Relaxation

E-*J* curves



Experiment(dot) + Theory(solid)



Relaxation = *E* dropping

⇨ Temporal decay of I_c

Magnetic relaxation characteristics can be modeled by inserting a time term in the current, $I_c(t)$.

Conclusion

We done a local measurement of magnetization properties in RE-123 CC with both transport current and external magnetic field applied,

- ✓ Successfully visualized the current-dependent behavior of magnetization
  - ⇨ Current dependence of magnetization can be expressed by CSM
- ✓ Local properties just obeyed the *E*-*J* properties of RE-123 CC
- ✓ Magnetic relaxation is caused by the flux creep even apply the currents
  - ⇨ Relaxation properties can be modeled with time function, $I_c(t)$

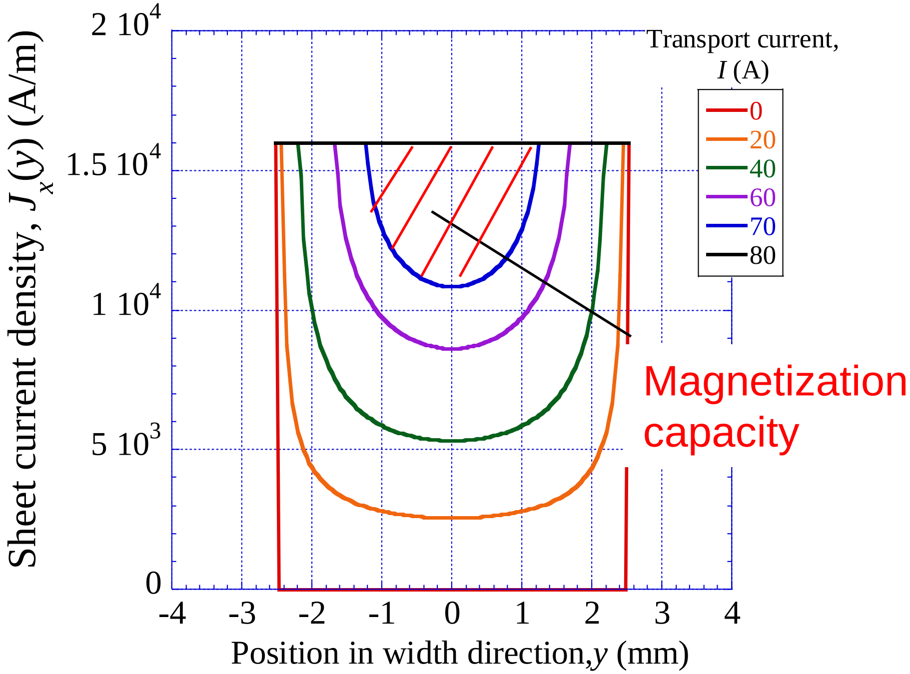
Succeeded in modeling the magnetization characteristics

⇨ Effective feedback on design of magnet applications

These findings could be obtained only by a local measurement

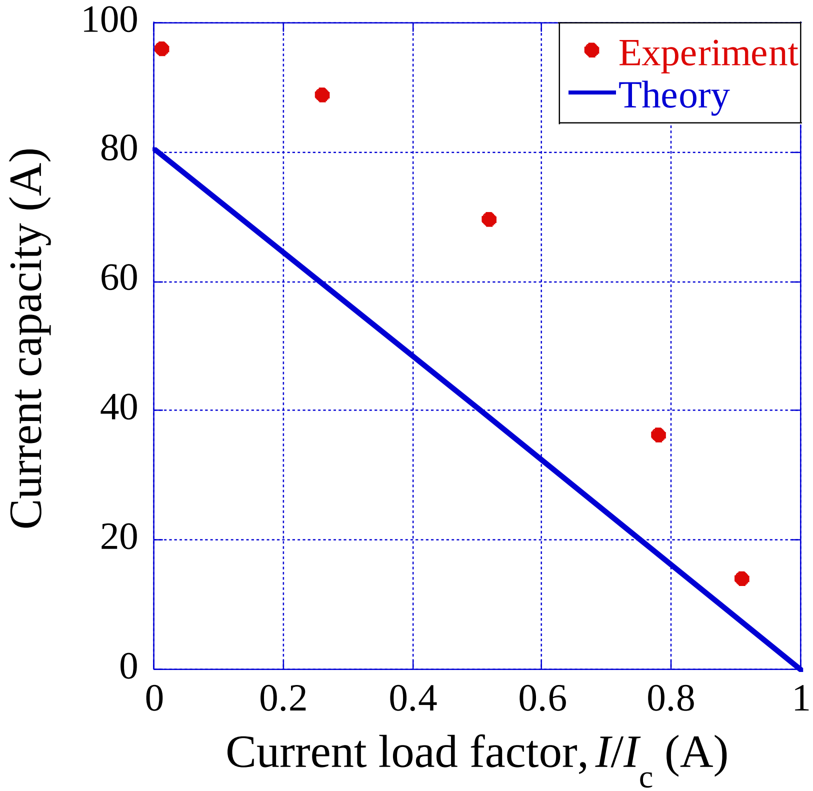
Current Penetration & Magnetization based on CSM

Current distribution



*"Type-II-superconductor strip with current in a perpendicular magnetic field", E. H. Brandt, 1993

Magnetic moment

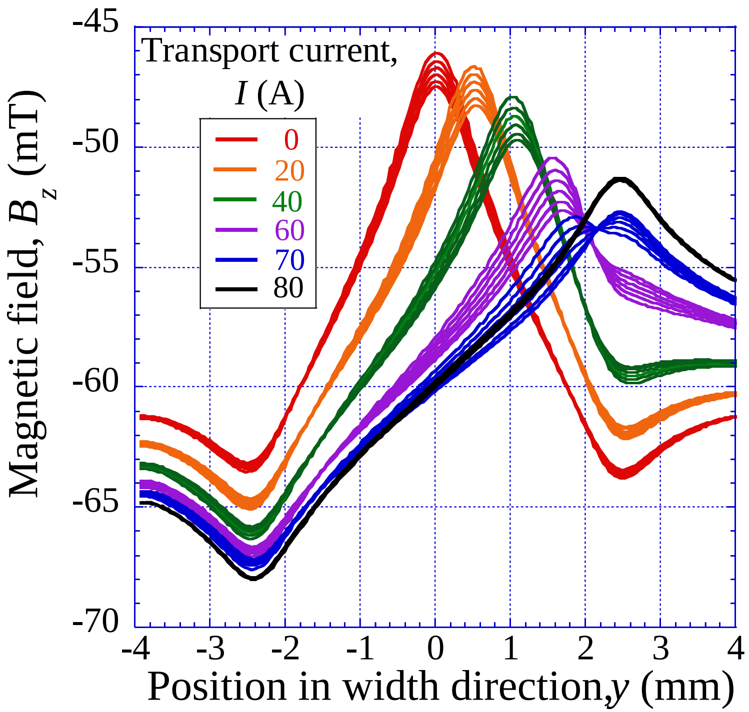


Magnetic moment decreases linearly with respect to current load

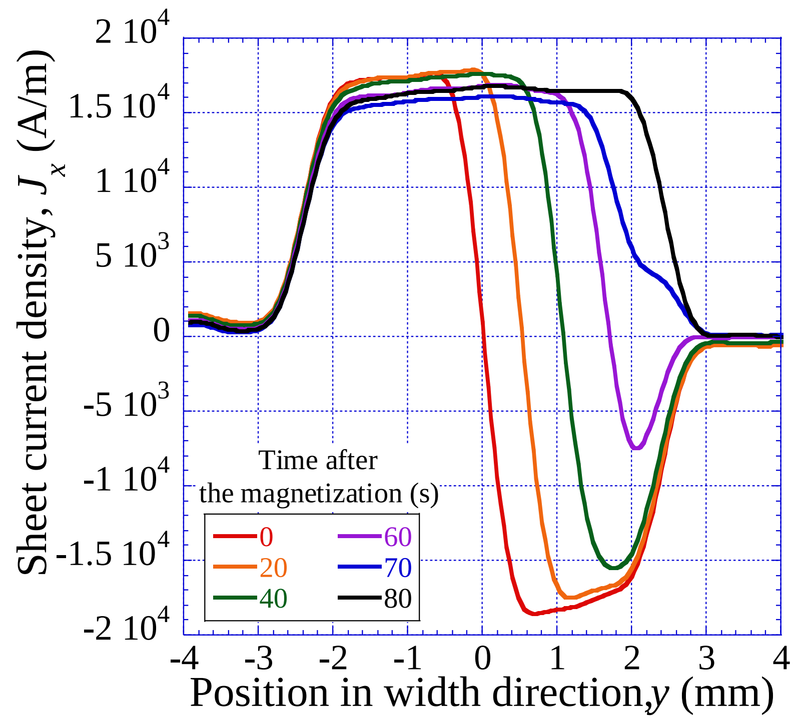
⇒ Disagree with experimental result

Including 80 A Measurement

Magnetic field



Current density

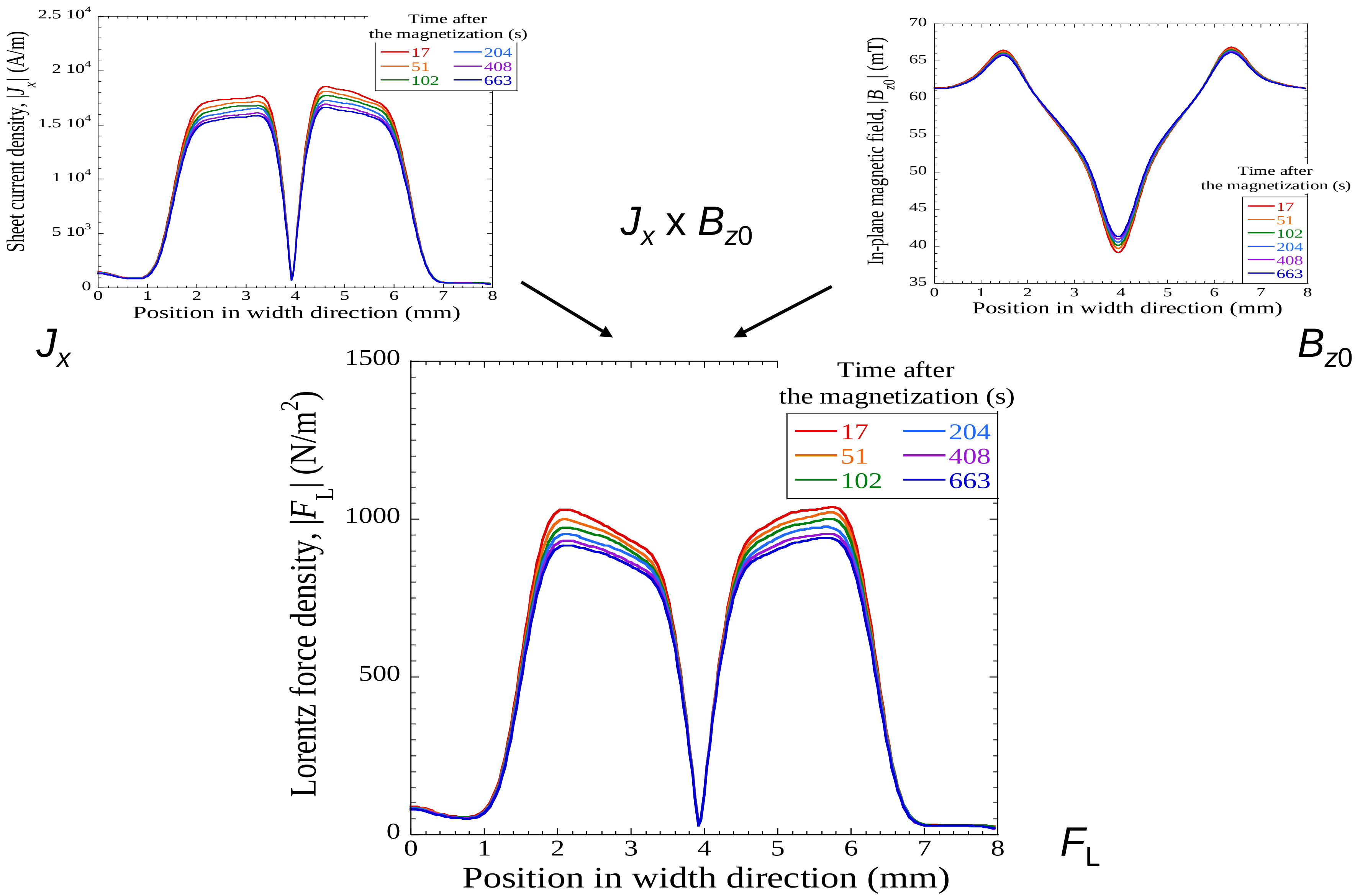


No relaxation in 80 A

J_x over 1st data of 70A

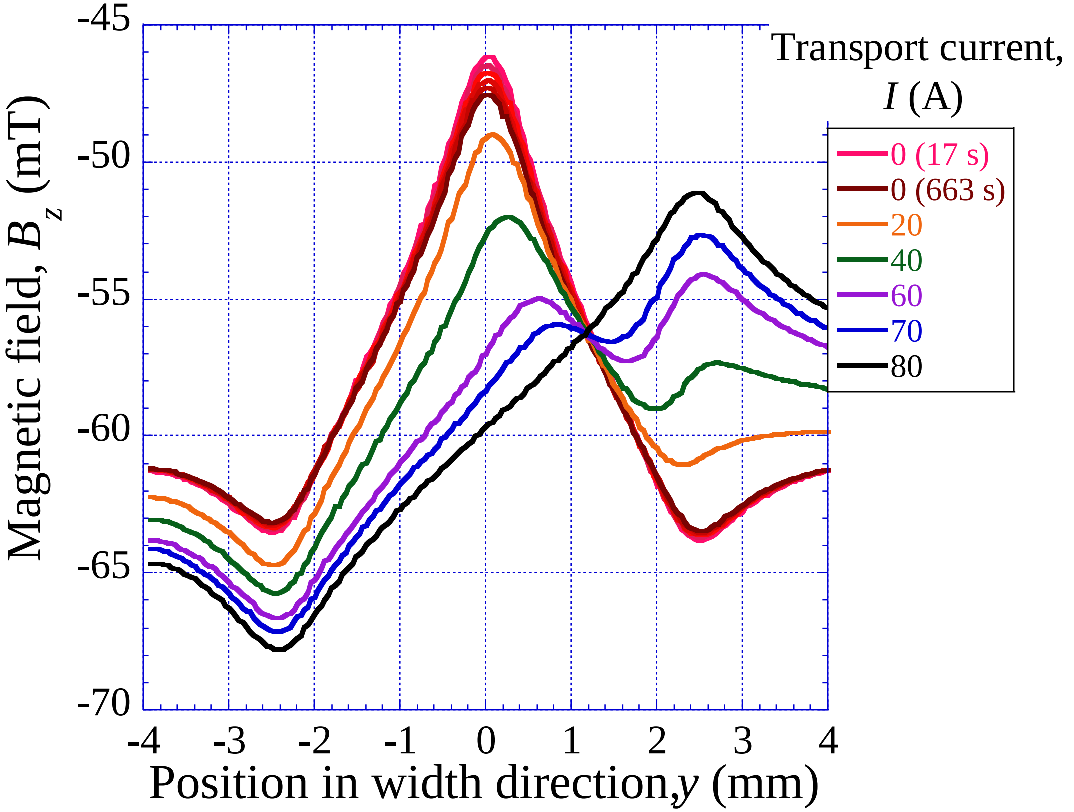
High E region dominated by resistive component

Lorentz force density



1st Magnetize → 2nd Energize Measurement

After the 0 A relaxation measurement, increased the current up to 80 A



Historical characteristics can be seen

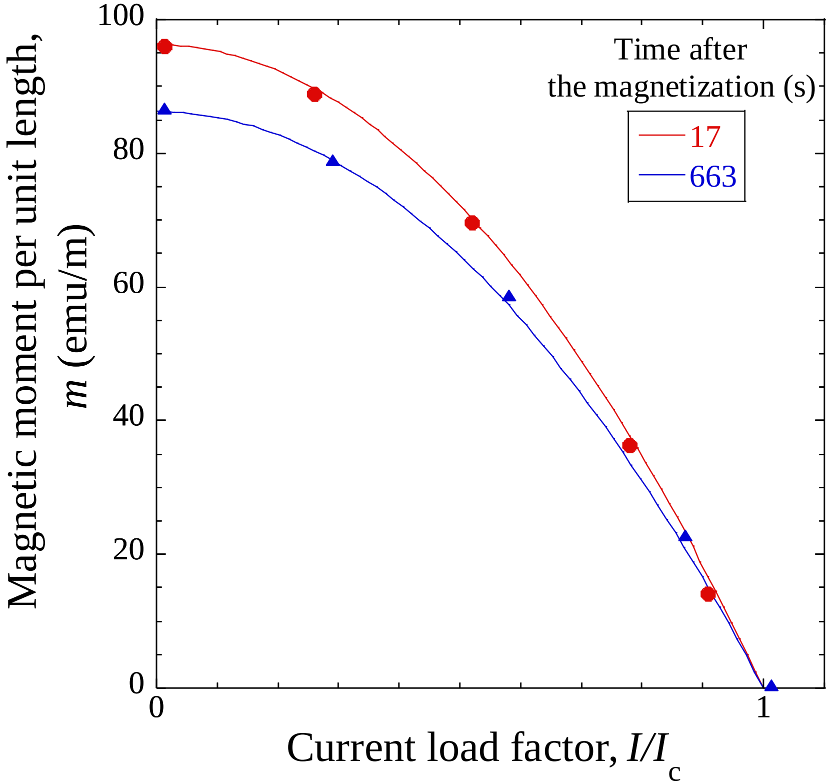
Time dependence of magnetic moments

Even if sufficient time passed,
the experimental and the theoretical moments were in good agreement.

Magnetization characteristics of RE-123 CC can be estimated based on CSM, even though J_c has time dependence caused by flux creep.

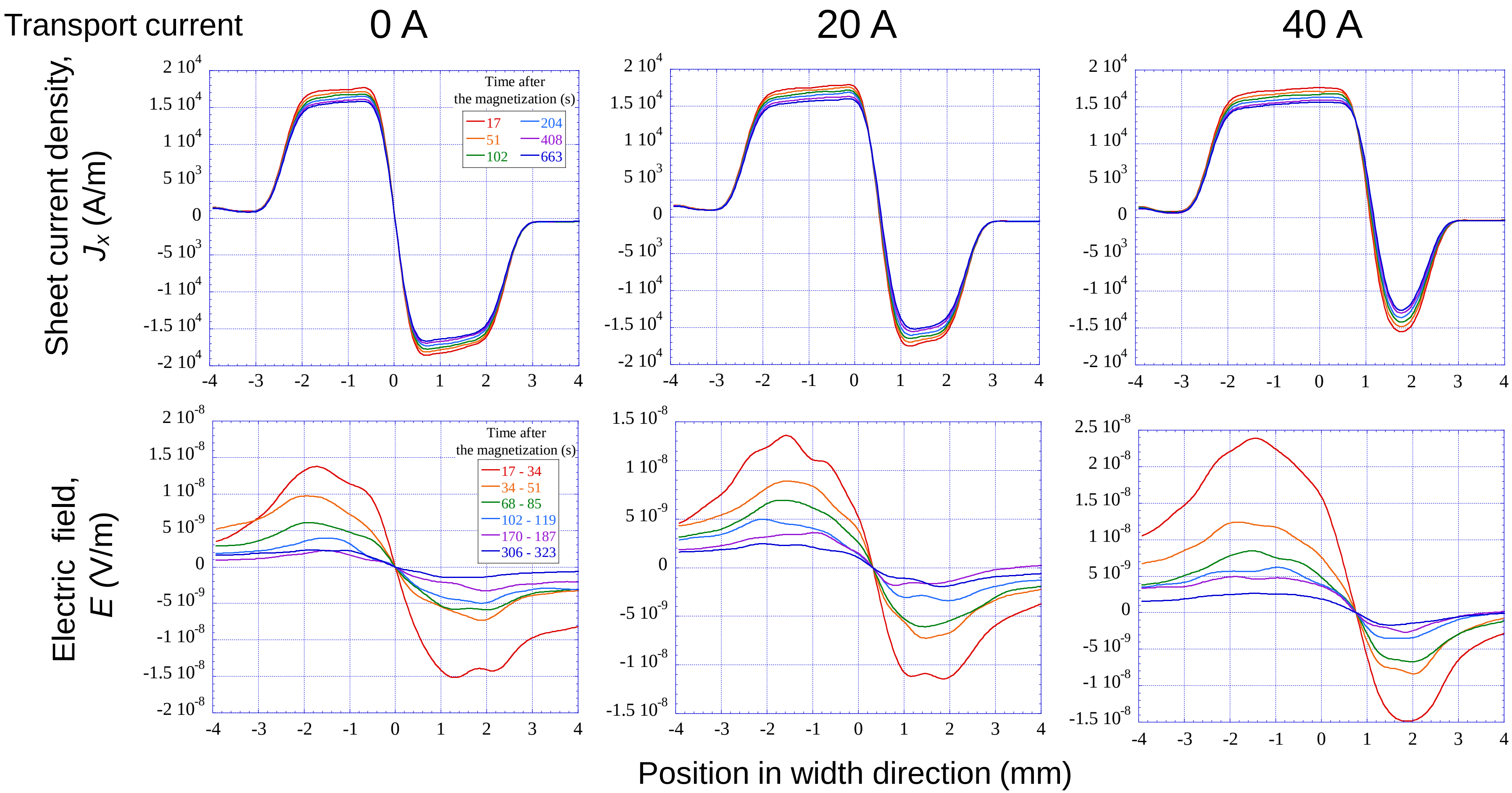
The Estimated I_c based on CSM,

$$I_c = \begin{cases} 77\ \text{A}\ \ (t = 17\ \text{s}) \\ 69\ \text{A}\ \ (t = 663\ \text{s}) \end{cases}$$



These are reasonable considering the difference in electric field criterion.
(4-probe method: $E_c = 10^{-4}$ V/m, SHPM: $E_c \sim 10^{-8}$ V/m)

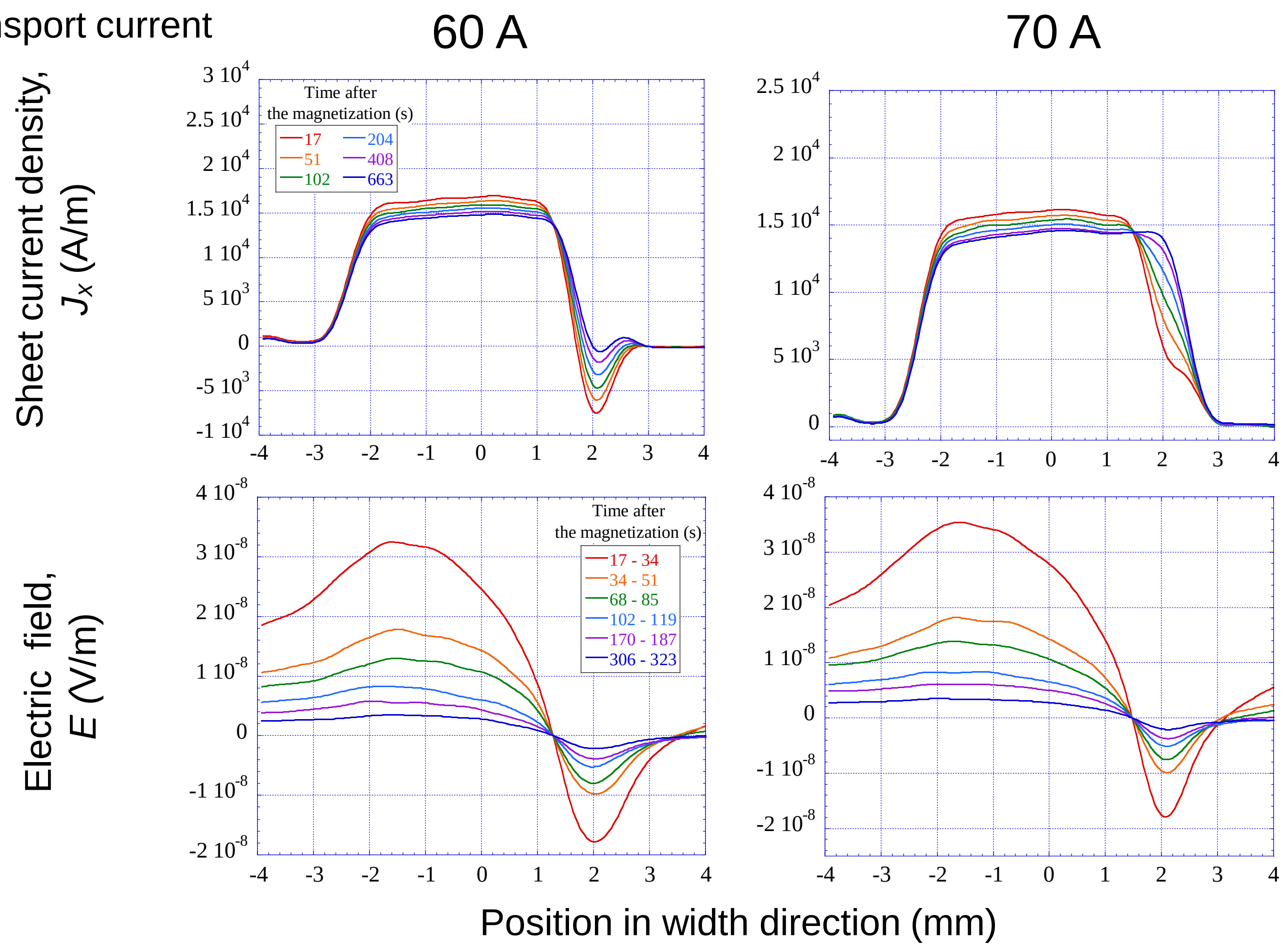
J_x and E distributions with I = 0, 20, 40 A



- Magnetization capacity became smaller due to the increase of transport current
- Peak values of J_x distributions do not depend on the currents

⇨ Magnetization properties follow the Critical State Model ($J_x = \pm J_c$)

J_x and E distributions with I = 60, 70 A



At 663 s in J_x with 70 A can be seen flat distribution that indicates the end of the relaxation ⇨ I_c became 70 A at low E

Succeeded in visualization of complicated behavior of the magnetic relaxation