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Hoop stress concentration in an HTS tape coil under external magnetic fields

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JST-Mirai Program

Outline

1. Introduction: Degradation of REBCO coil performance

2. Hoop stress enhancement due to the screening current and the hysteresis effect

3. Effective remedies against stress concentration due to the screening current

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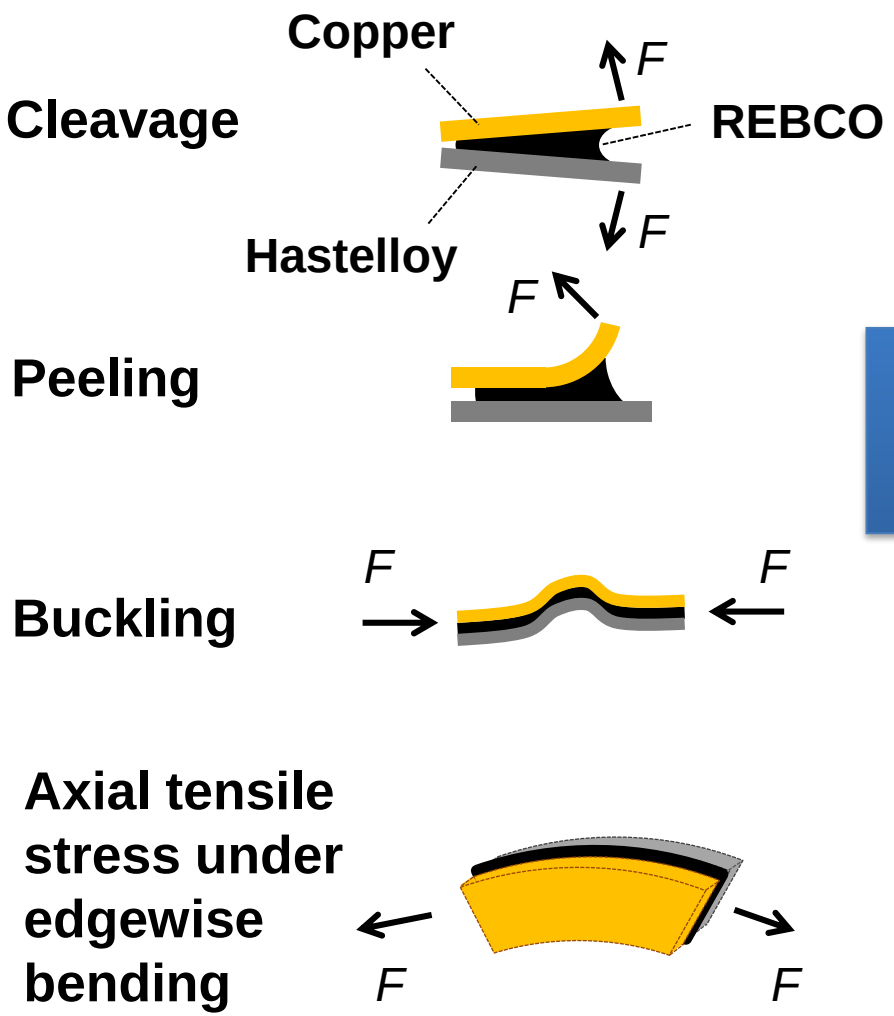
1. **Introduction: Degradation of REBCO coil performance**

2. **Hoop stress enhancement due to the screening current and the hysteresis effect**

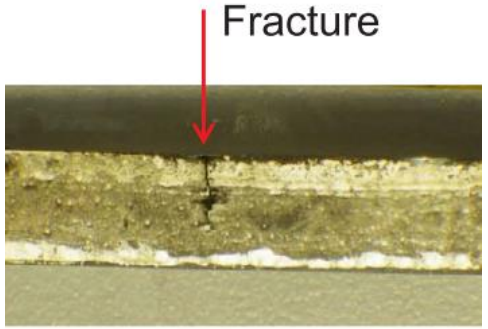
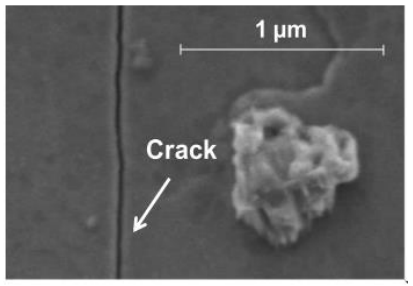
3. **Effective remedies against stress concentration due to the screening current**

Degradations of the REBCO conductor performance

Weak stress modes



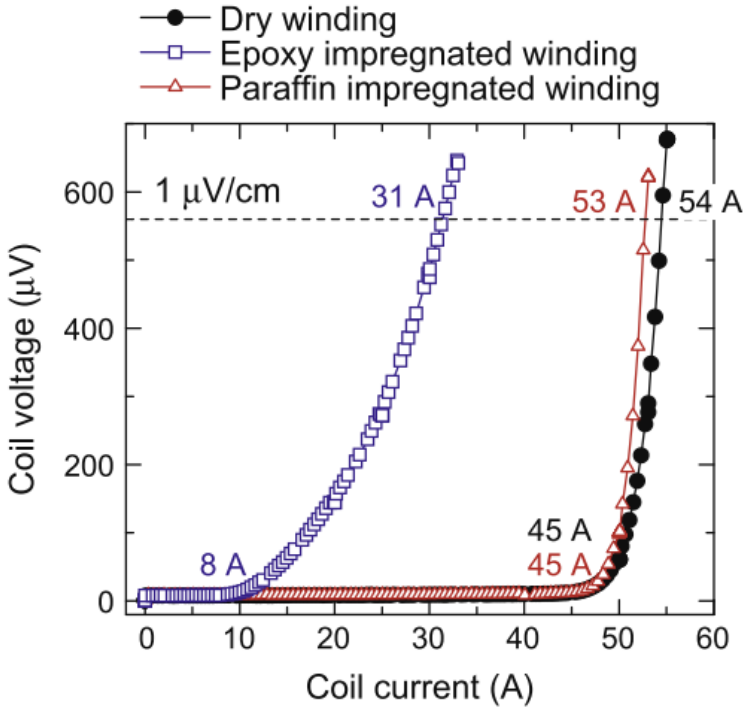
K. Kajita et al., *SuST*, **30** (2017) 074002

Delamination due to peeling	 K. Kajita et al., *IEEE TAS,* **26** (2016) 4301106
Macroscopic fractures	 T. Matsuda et al., *Cryogenics,* **90** (2018) 47–51
Microscopic hair cracks	 K. Kajita et al., *SuST*, **30** (2017) 074002

Major two categories of degradations of the REBCO coil

Thermal stress

- **Thermal cycle (Epoxy impregnated coil)**

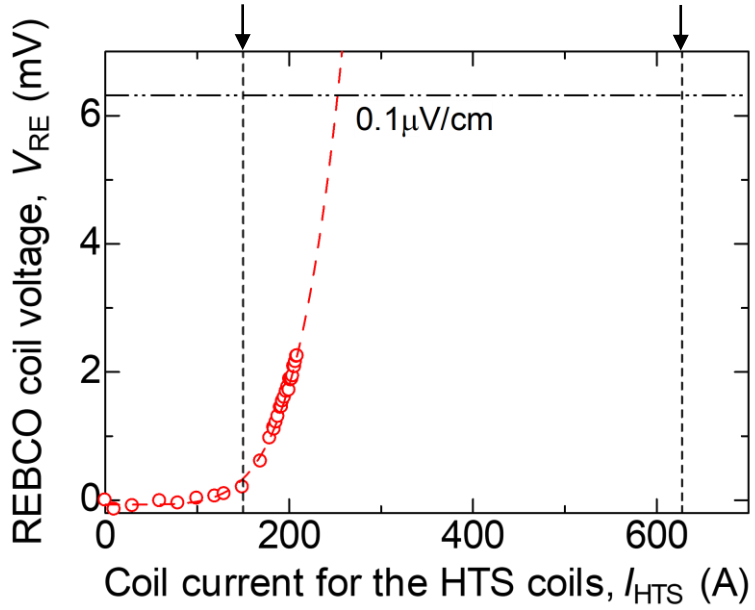


T. Takematsu et al., *Physica C*, **470** (2010) 674–677

Electromagnetic force

***BJR* = 141 MPa**

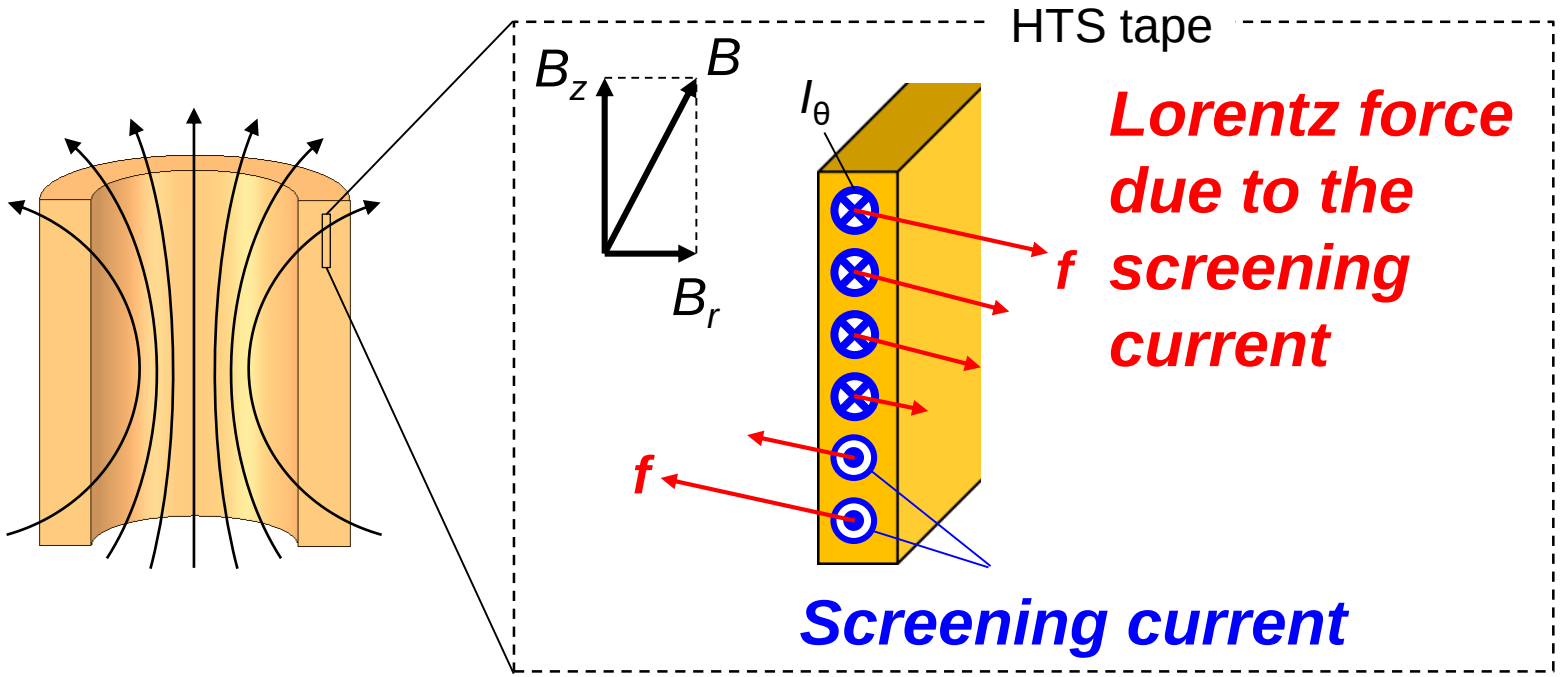
Tensile strength of the conductor > 500 MPa



It is possible that this type of degradation caused by screening current.

K. Kajita et al., *IEEE TAS,* **26** (2016) 4301106

Inhomogeneous Lorentz force distribution due to the screening current



Stress enhancement due to the screening current

Degradation in the coil performance

They are investigated by experiments and numerical simulations in this presentation

K. Kajita et al., *SuST*, **30** (2017) 074002
S. Hahn et al., *Nature*, **570** (2019) 496-499

Objectives

- Verifying inhomogeneous hoop stress distribution, or stress concentration, in a REBCO coil under external-magnetic fields.

- Finding remedies for decreasing the stress concentration and preventing the coil performance degradation.

Outline

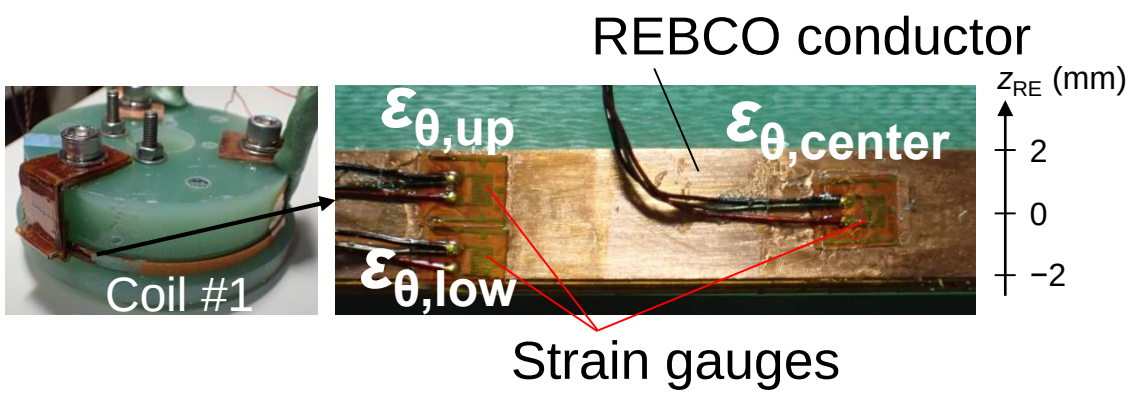
1. Introduction: Degradation of REBCO coil performance

2. Hoop stress enhancement due to the screening current and the hysteresis effect

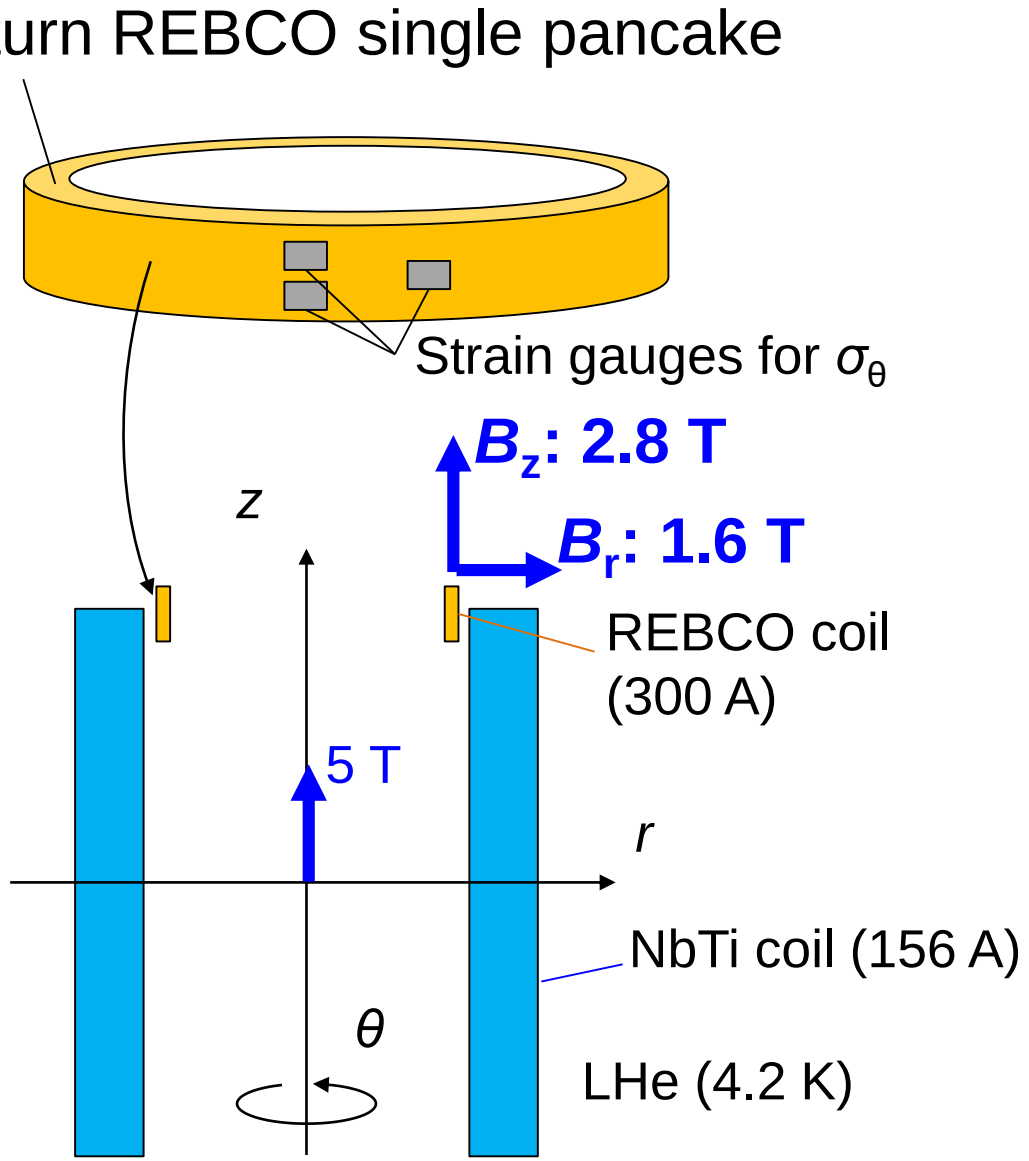
3. Effective remedies against stress concentration due to the screening current

Experimental and results

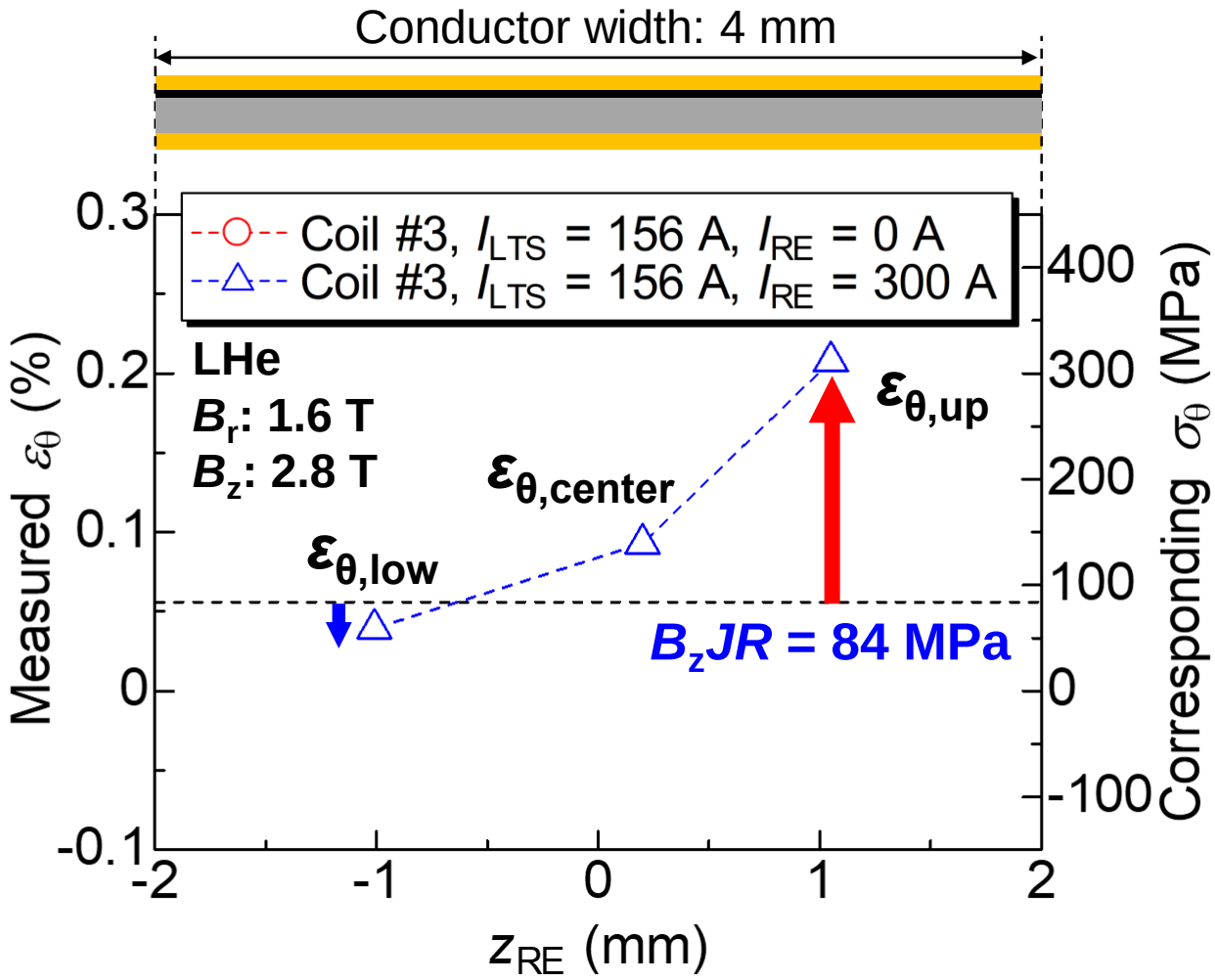
Experimental

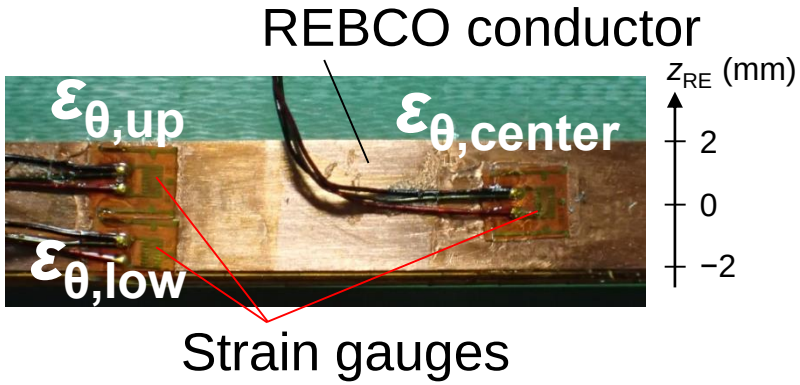


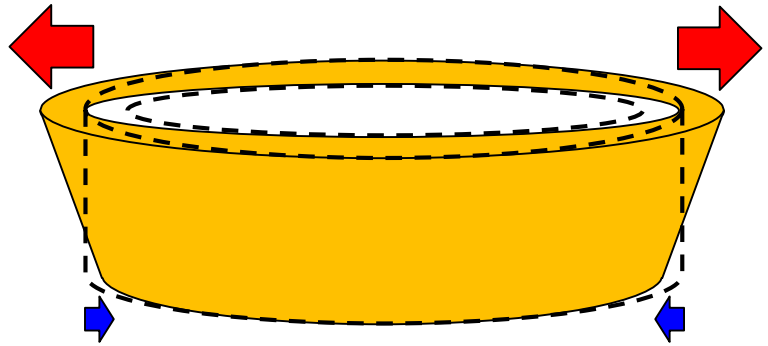
	REBCO coil #1~3	NbTi coil
Conductor	SuperPower SCS4050	NbTi
Conductor width / thickness (mm)	4.0 / 0.1	-
Winding	Single pancake	Layer-wound
Coil ID / OD / height (mm)	79.5 / 81.3 / 4.2	95.0 / 105.0 / 160
Number of turns	5	-
Operating current (A)	300	156
$I_{c,coil}$ at 4.2 K in 5 T (A)	912	-
B_0 (T)	0.024	5
B_zJR (MPa)	84	-



Circumferential strain distribution along the width direction

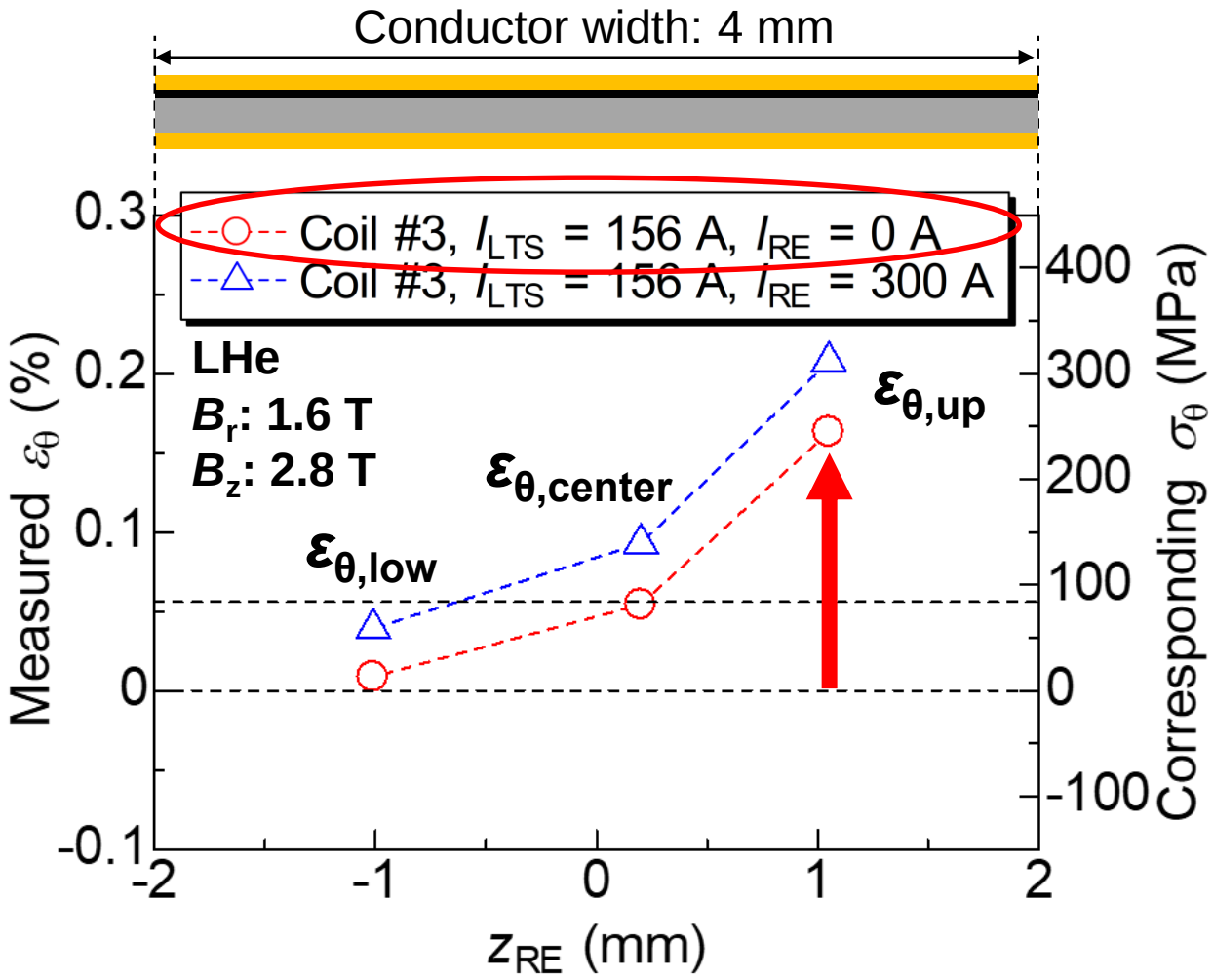


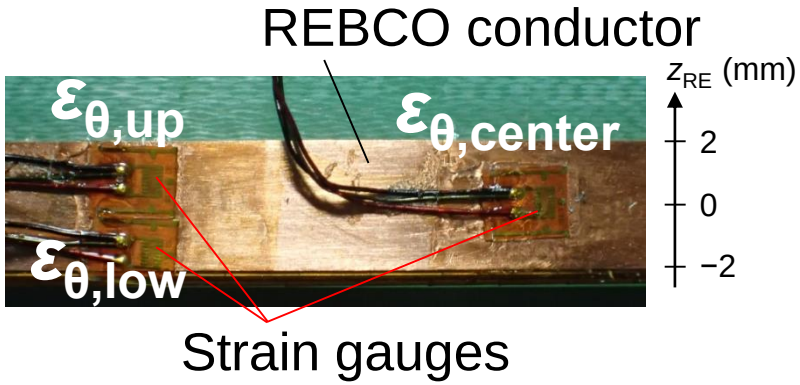




- Inhomogeneous distribution of the hoop strain and stress along the width direction
- Hoop stress concentration factor, $\alpha = \sigma_{\theta,max} / B_zJR > 4.0$

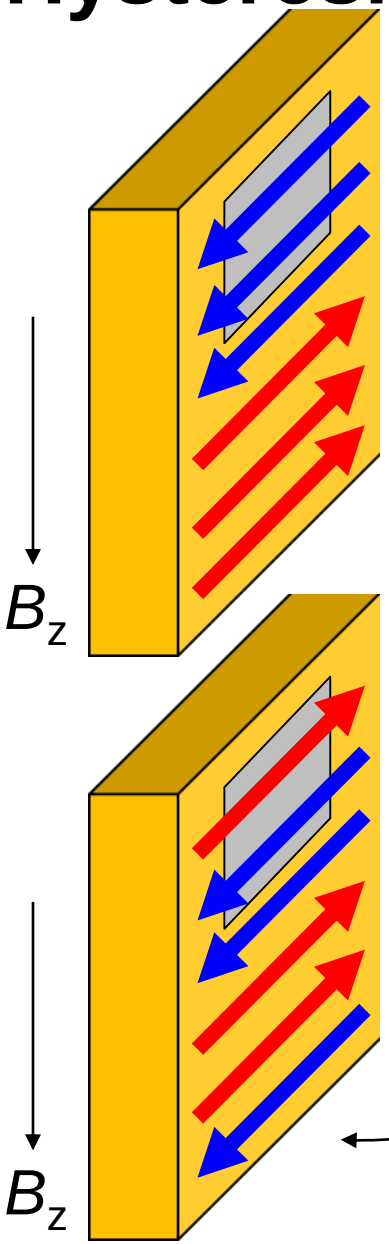
Circumferential strain distribution along the width direction



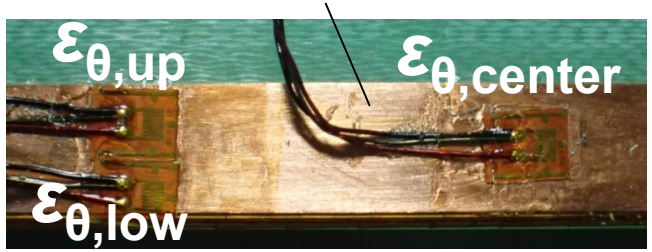


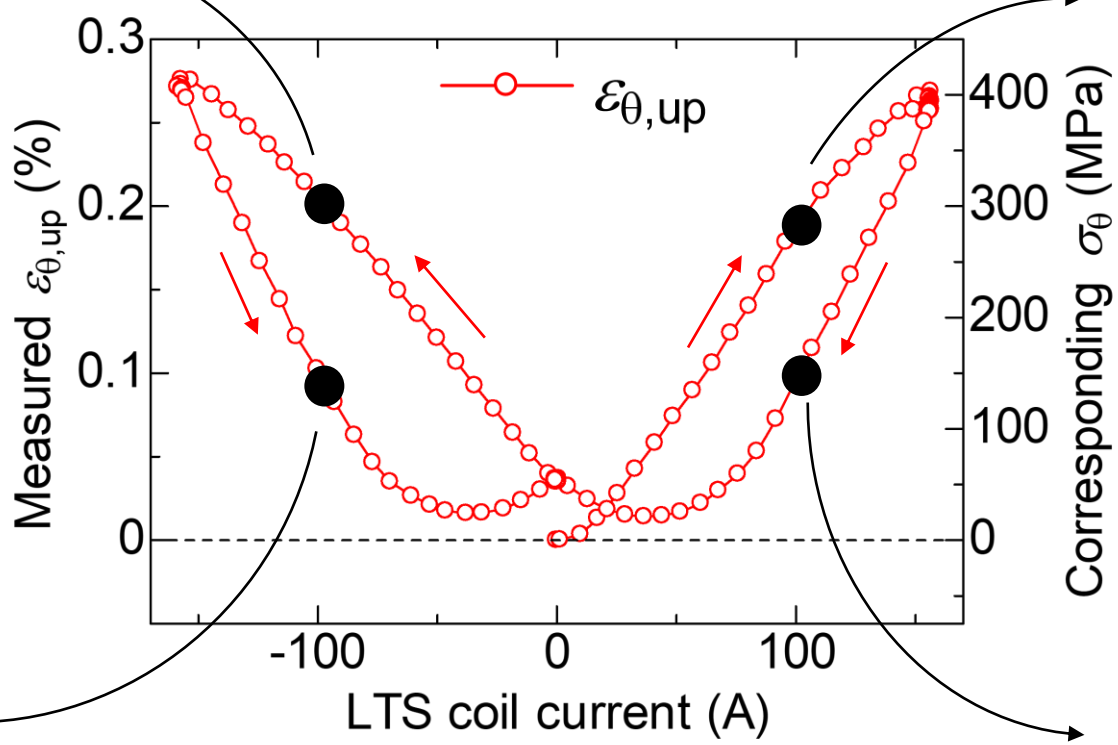
- Even if the REBCO is not charged, a substantial inhomogeneous hoop stress is generated only by charging the LTS coil.
- This result clearly shows that the screening current dominates the inhomogeneous hoop stress.

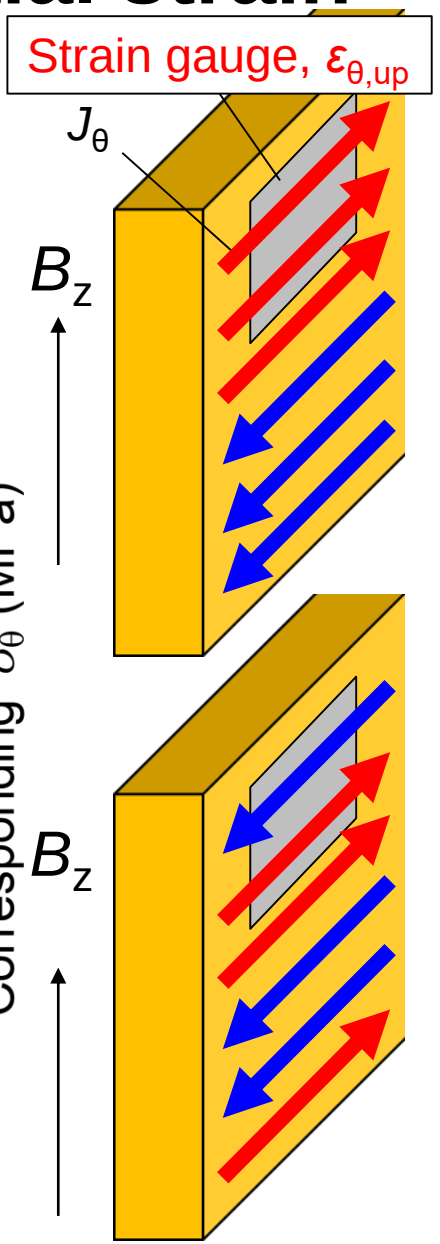
Hysteresis effect of the circumferential strain

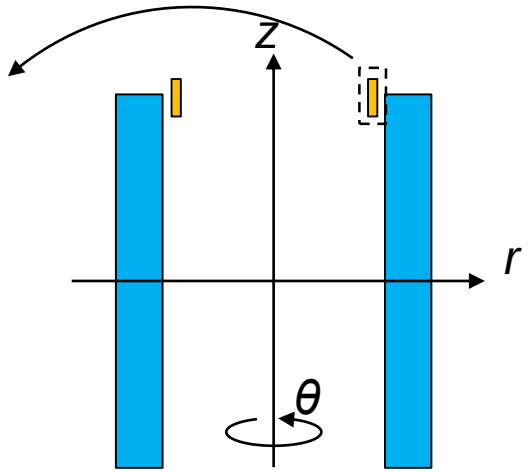


Coil #2
LHe
I_{RE}: 0 A









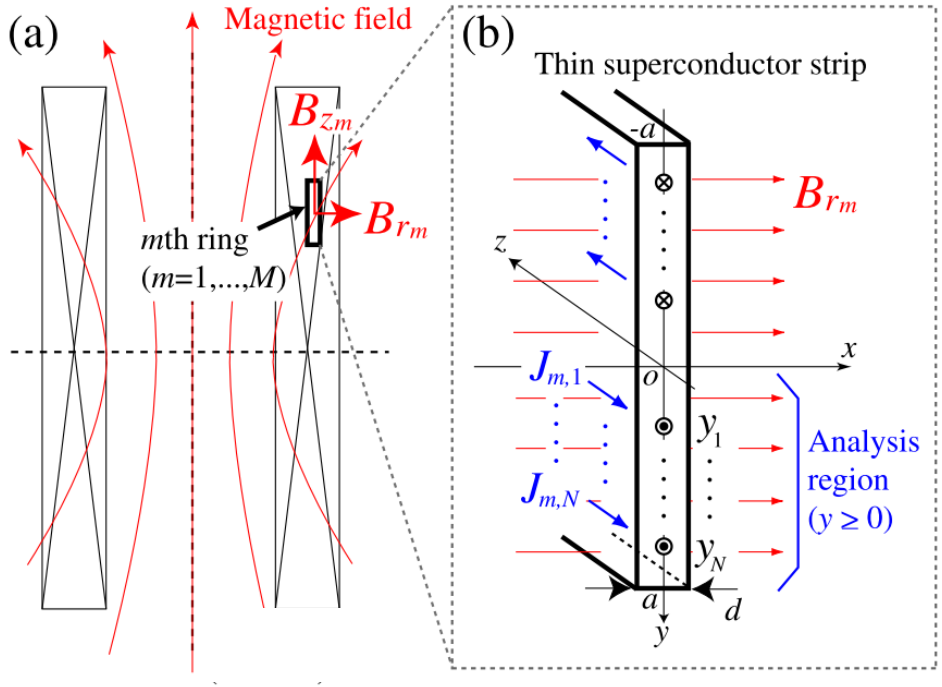
Hysteresis effect of the circumferential strain due to the screening current

Numerical simulations

Numerical simulation of the screening current

Screening current simulation → Finite element structural analysis

Thin superconductor strip model



Y. Yanagisawa et al., *Physica C*, **469** (2009) 1996-1999

$$J_{m,i}(t+\Delta t) = J_{m,i}(t) + \frac{2\pi\Delta t}{\mu_0 d}\sum_{j=1}^{N} K_{ij}^{-1}\left[E_{m,j}(t) - y_j \dot{B}_{rm}(t)\right]$$

	unit	value
Superconductor layer thickness, d_{RE}	μm	1.0
Tape width, w	mm	4.0
Operating current, I_{RE}	A	300
Critical current, I_c	A	912
n-value	-	24
External radial magnetic field, B_r	T	1.6
External axial magnetic field, B_z	T	2.8

⇒ J_θ and B_r distribution

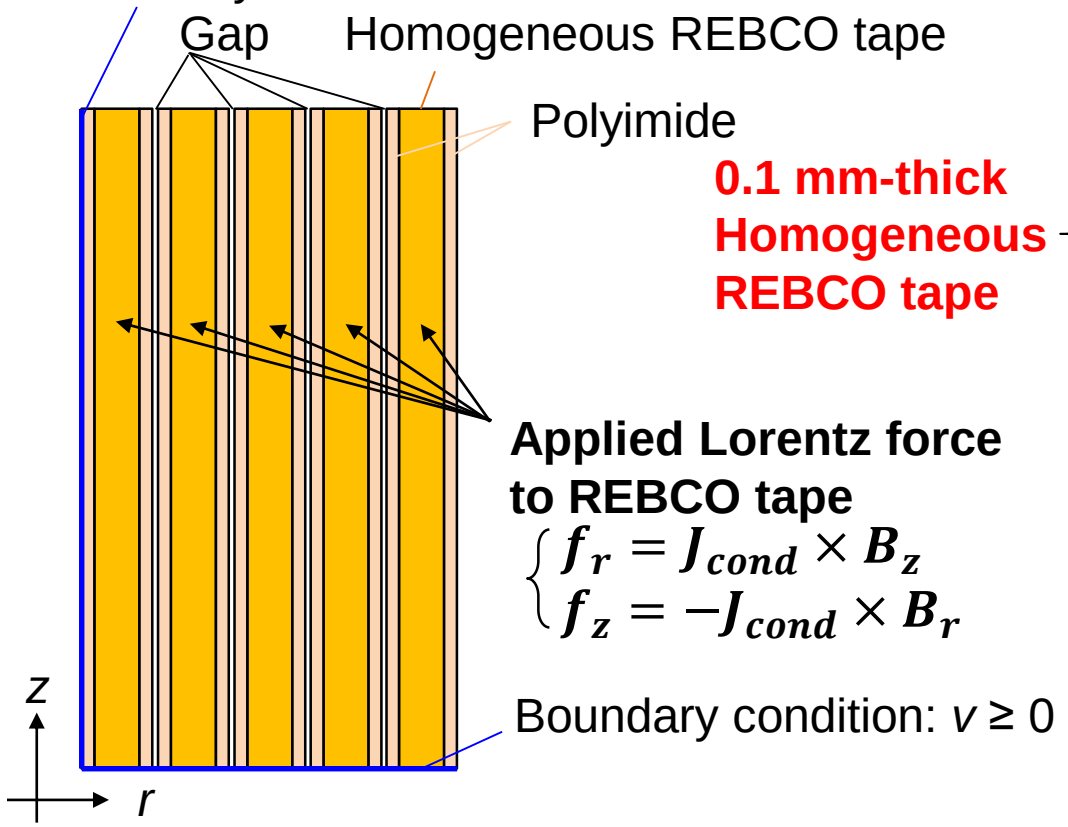
Structural analysis using FEA

Screening current simulation → Finite element structural analysis

2D axisymmetric model

➢ **Cross section of the model coil**

Boundary condition: $u \geq 0$



0.1 mm-thick Homogeneous REBCO tape

Applied Lorentz force to REBCO tape

$$\begin{cases} f_r = J_{cond} \times B_z \\ f_z = -J_{cond} \times B_r \end{cases}$$

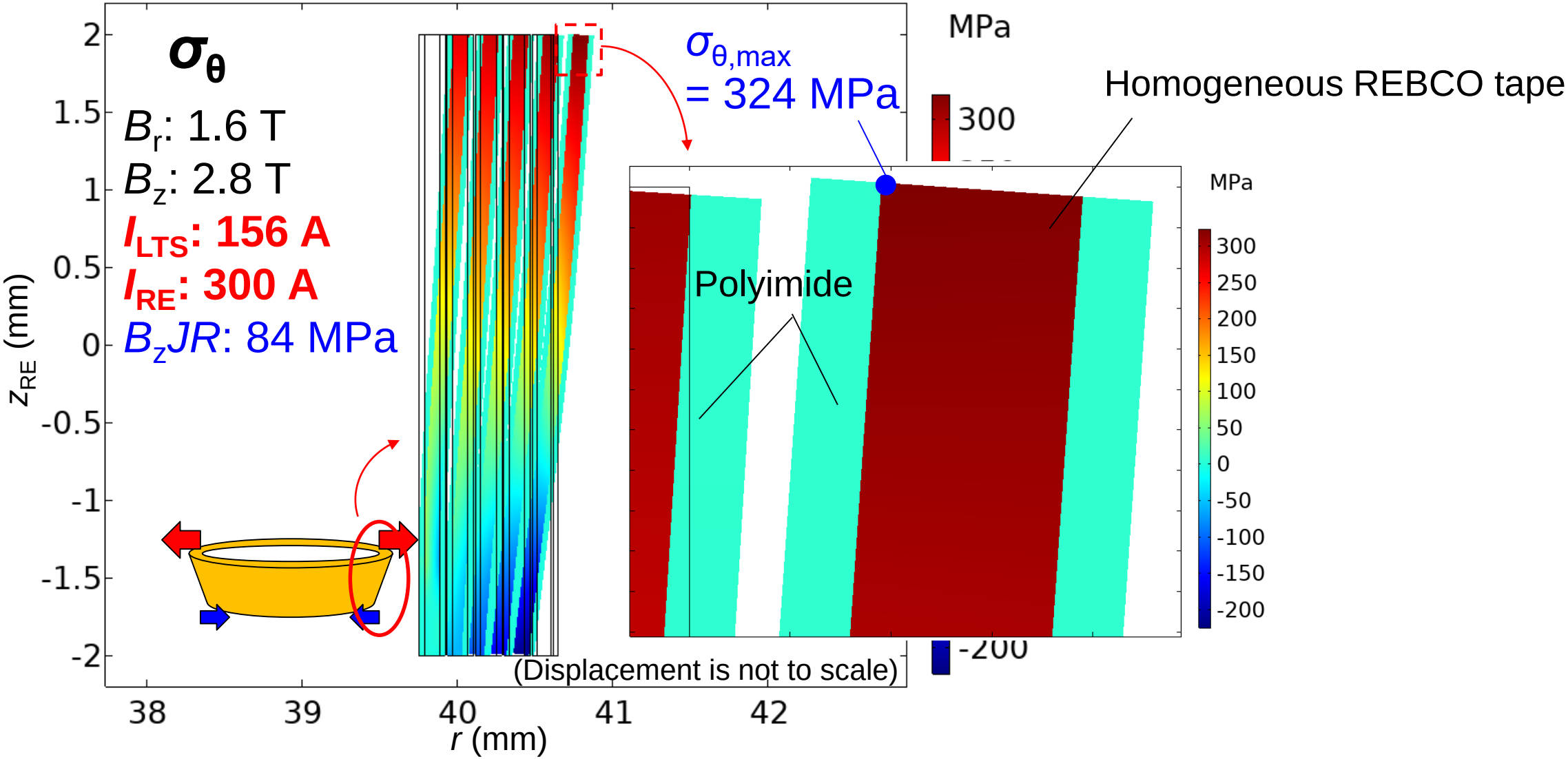
Boundary condition: $v \geq 0$

	Thickness (μm)	Young's modulus (GPa)	Poisson's ratio
REBCO layer	1	157	0.3
Copper stabilizer	40	98	0.34
Hastelloy substrate	50	228	0.307
Polyimide	70	3.4	0.34

Y. Yang et al., *J. Appl. Phys.* **124** (2018) 073902

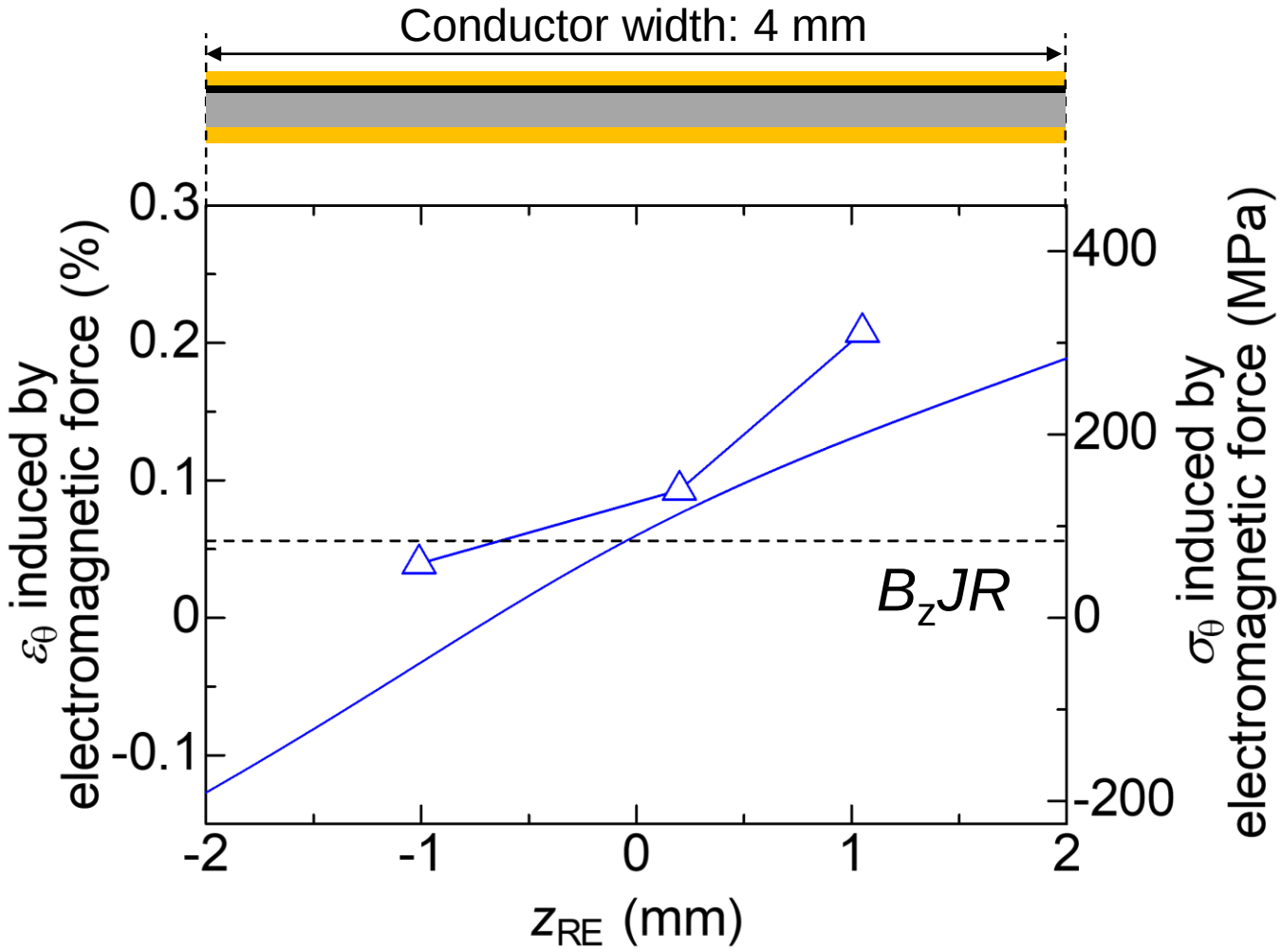
⇒ Structural analysis by using Solid Mechanics interface of the commercial FEA software COMSOL Multiphysics

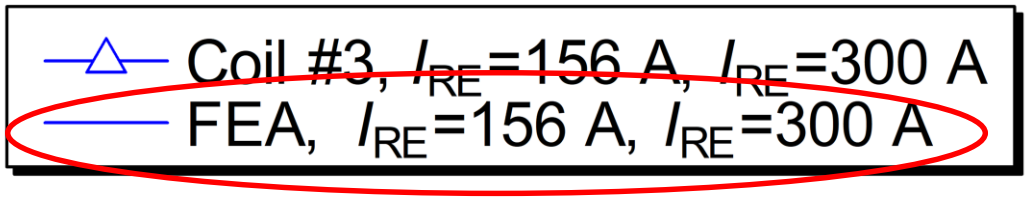
Stress distribution under an external magnetic field



Stress concentration factor, $\alpha = \sigma_{\theta,max} / B_zJR = 3.9$

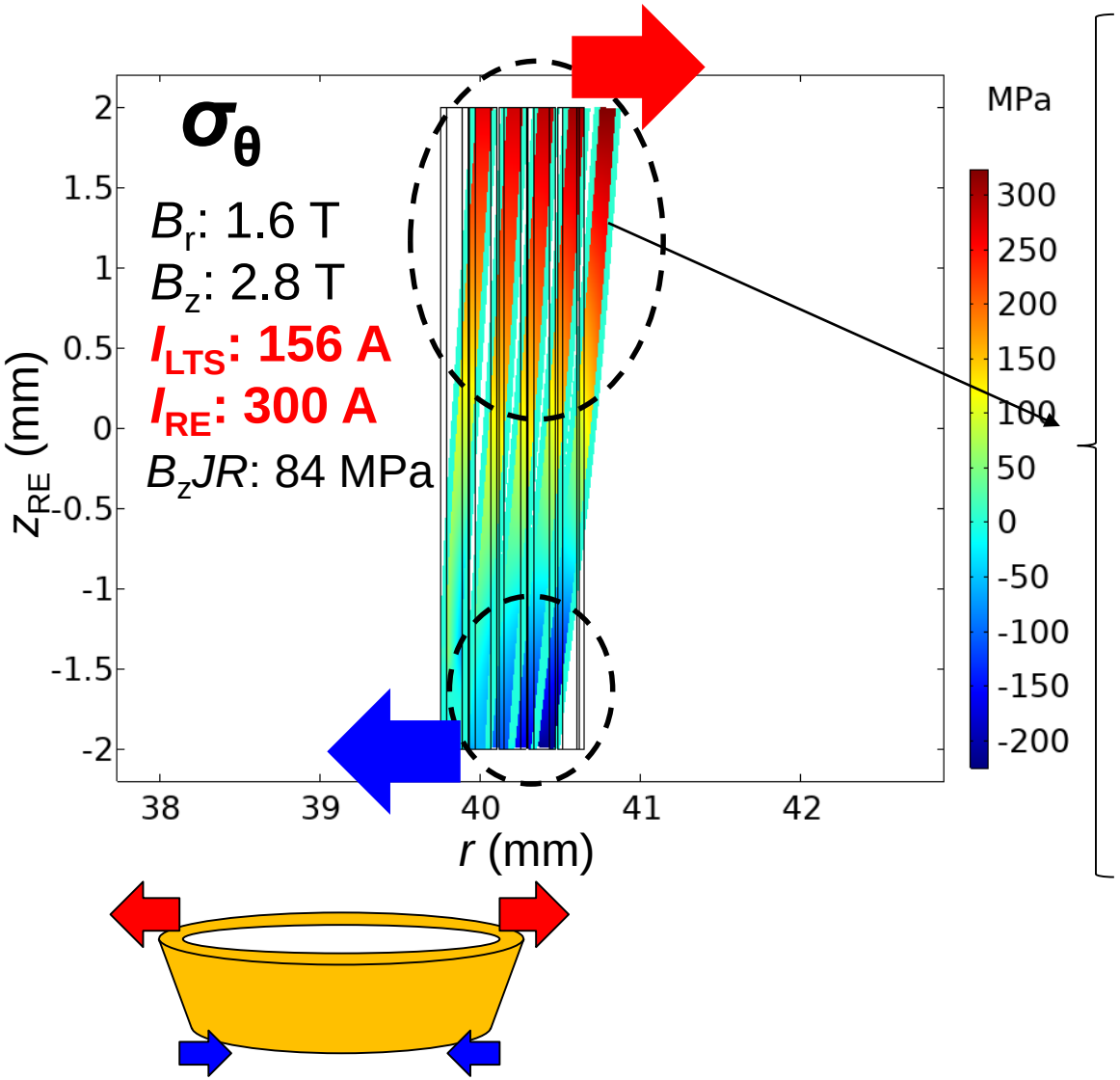
Comparison between the experimental result and the simulated result

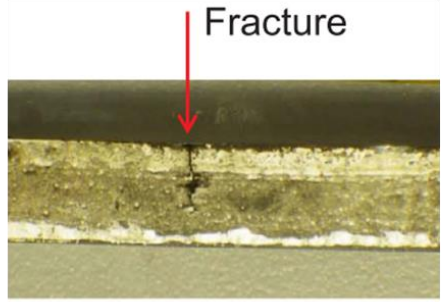
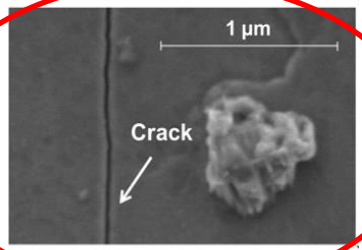




- **The simulated result agrees well with the experimental result**

Possible degradation modes



Delamination due to peeling	
Macroscopic fractures	
Microscopic hair cracks	

Most probable degradation mode

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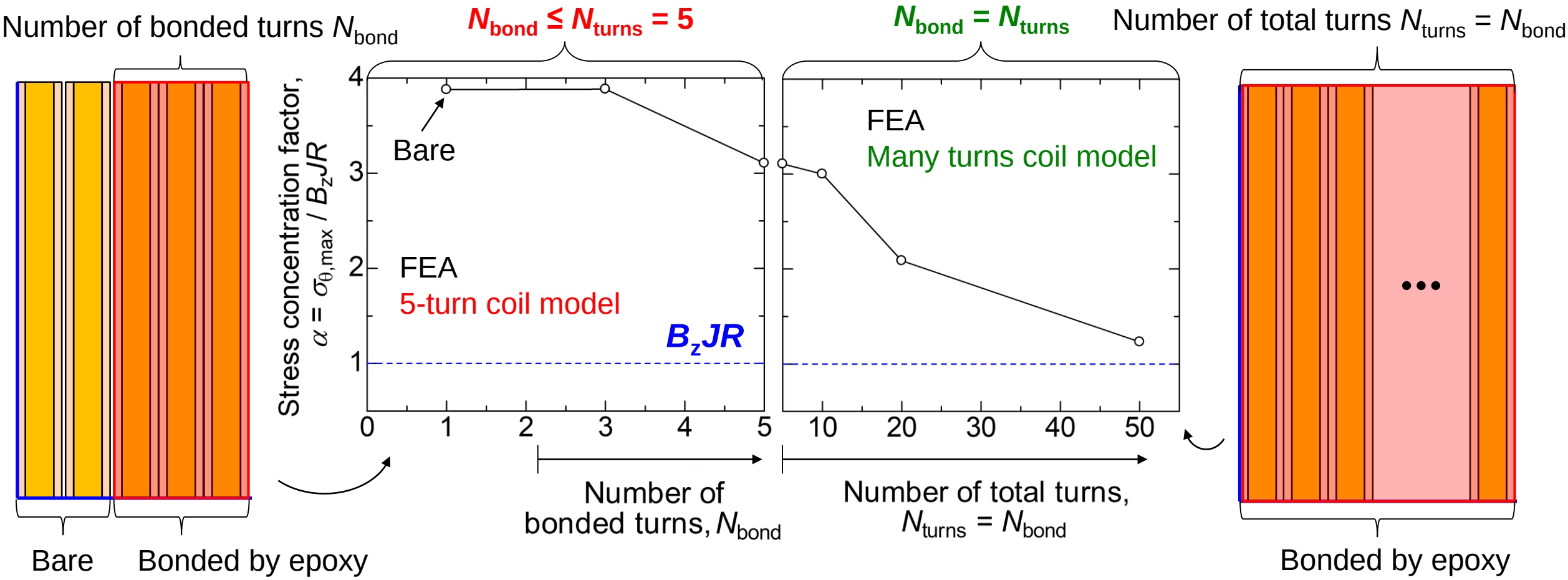
Reduction in stress concentration by bonding turns

5-turn coil model

Many turns coil model



- Stress concentration is reduced, if some tape conductors are bonded together by epoxy resin, as it increases the bending rigidity

Summary

- We experimentally demonstrated an inhomogeneous hoop stress in a REBCO coil caused by the screening current, which gives a substantial enhancement of the hoop stress.

- The stress inhomogeneity is dominated by the screening current and therefore shows hysteresis.

- Epoxy bonding between turns increases the bending rigidity of the winding, resulting in the decrease in the stress concentration factor.

Thank you very much
for your kind attention.