Mechanical behavior of HTS coils in high field magnets

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百年兰大 Lanzhou University 1909 2009

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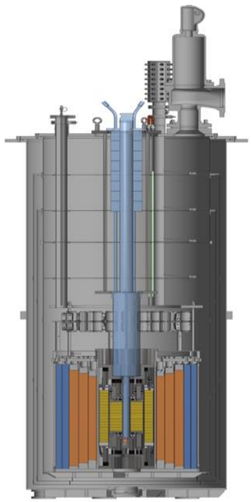
- **Future work**

Background

- **INS / NI REBCO magnets**

32 T magnet



https://nationalmaglab.org/

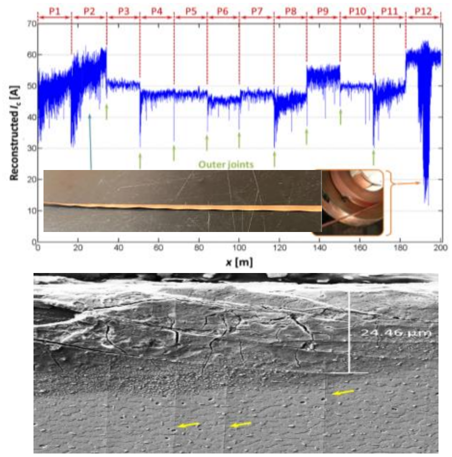
32.35 T magnet

Liu et al 2020 SUST 33: 03LT01

45.5 T LBC

Hahn et al 2019 Nature 570: 496

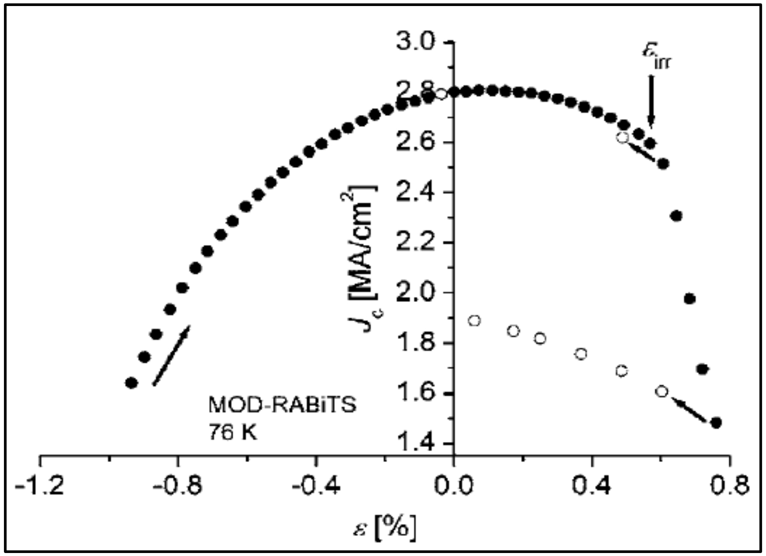
After high-field test



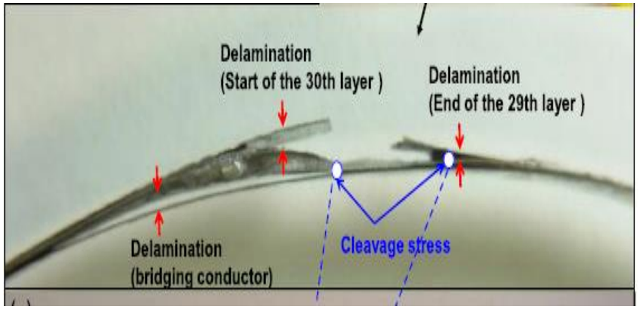
Hu et al 2020 SUST 33: 095012

- **The HTS coil is usually inserted in high field magnet**
- **The local critical current degradation is found in HTS coil under high Lorentz force**

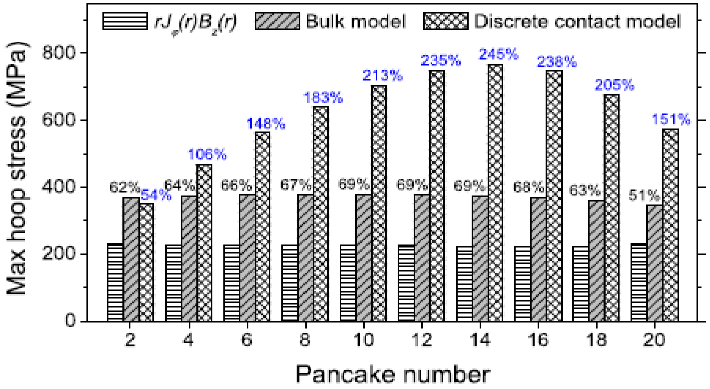
Background



van der Laan et al 2007 APL 90: 052506



Kajita et al 2016 IEEE Supercond 26: 4301106



Xia et al 2019 SUST 32: 095005

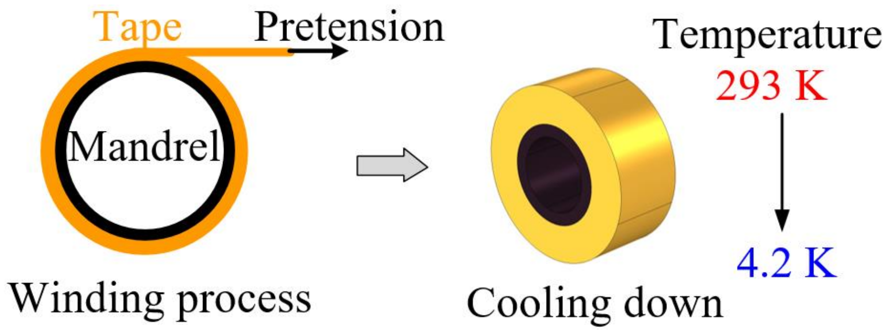
The mechanical stress or strain can affect the superconducting properties remarkably

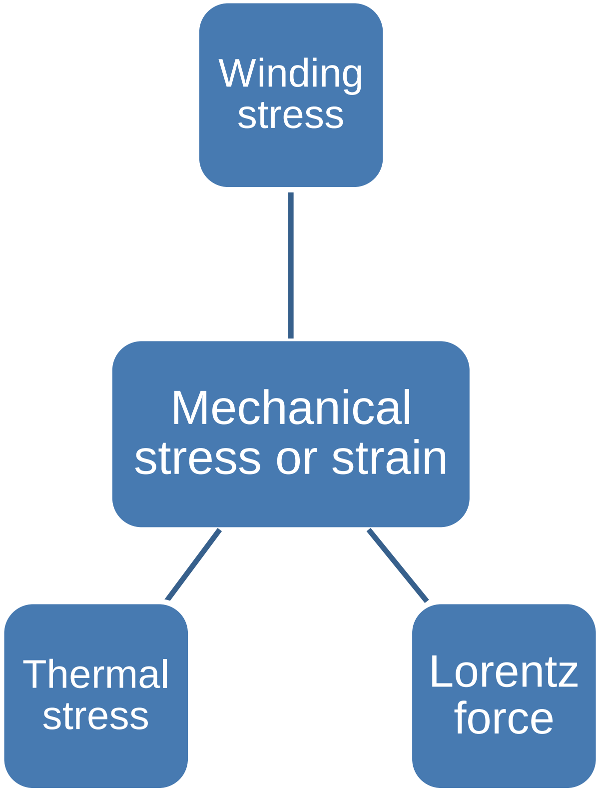
- **Degradation of critical current density with the strain**
- **Cracking or delamination is observed in the superconducting tape**
- **The discrete contact model should be used in the coil**

Background

The superconducting coil is subjected to the complicated stress or strain.

Firstly, the winding stress can be generated as the tape is under the pretension





Secondly, the thermal stress can be generated during the cooling process and quench

Thirdly, the Lorentz force can be improved with the increasing of critical current density and applied magnetic field

Background

The key points of numerical simulation of mechanical response

Highly nonlinear:

- E-J power law relationship
- Nonlinear plastic deformation
- Parameter are dependent on the temperature, such as thermal conductivity and heat capacity

Multi-field coupling:

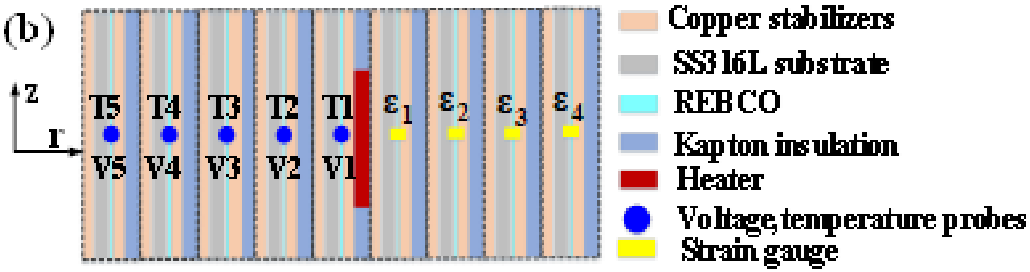
- The electric field and current can cause energy loss
- The critical current density is related to the temperature and magnetic field
- The superconductor is subjected to Lorentz force

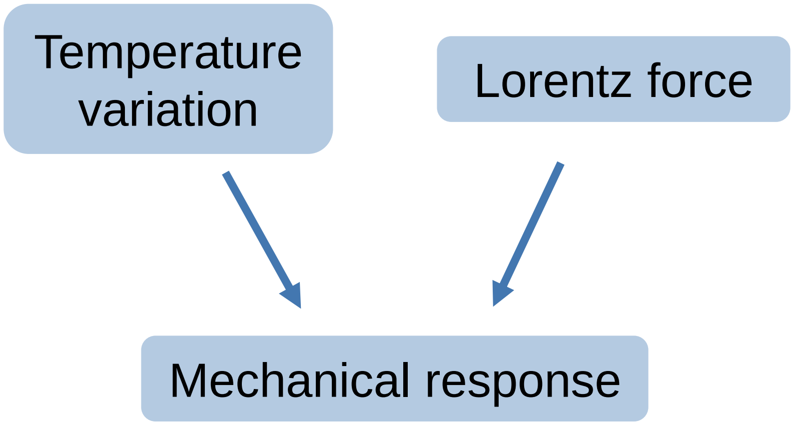
Multiscale modelling:

- The superconducting layer (μm) → magnet (m)

Case 1: Mechanical behaviors during quench

Simplified 2D-axisymmetric numerical model





H-formulation

$$\begin{bmatrix} \dfrac{\partial r\rho\times\left(\dfrac{\partial H_r}{\partial z}-\dfrac{\partial H_z}{\partial r}\right)}{\partial z} \\ -\dfrac{\partial r\rho\times\left(\dfrac{\partial H_r}{\partial z}-\dfrac{\partial H_z}{\partial r}\right)}{\partial r}\end{bmatrix} = \begin{bmatrix}\mu_0 r\dfrac{\partial H_r}{\partial t}\\ \mu_0 r \dfrac{\partial H_z}{\partial t}\end{bmatrix},$$

Mechanical equilibrium equations

$$\begin{cases} \dfrac{\partial \sigma_r}{\partial r}+\dfrac{\partial \tau_{zr}}{\partial z}+\dfrac{\sigma_r-\sigma_\varphi}{r}+f_r=0 \\ \dfrac{\partial \sigma_z}{\partial z}+\dfrac{\partial \tau_{rz}}{\partial r}+\dfrac{\tau_{rz}}{r}+f_z=0 \end{cases},$$

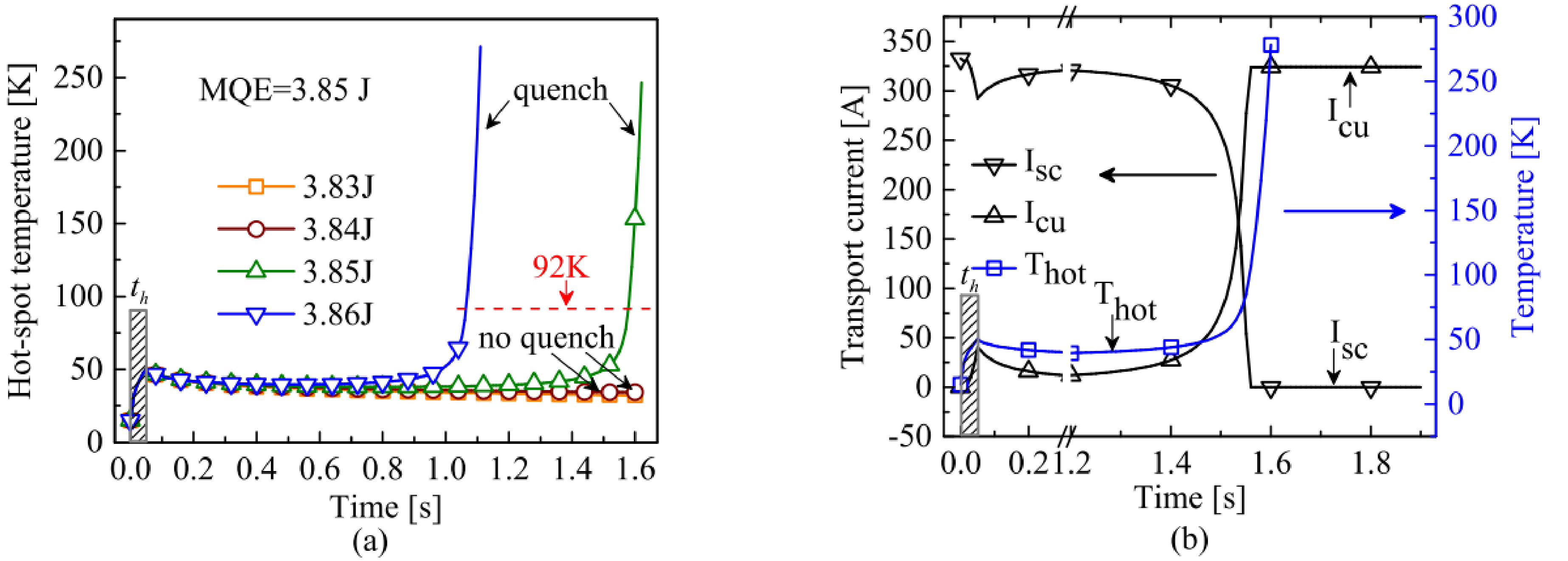
Heat diffusion equation

$$\upsilon C_p \frac{\partial T}{\partial t} = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\right]+Q_s+Q_c,$$

Niu et al, 2020, Appl. Math. Mech. -Engl. Ed. 42: 235-250

Mechanical behaviors during quench

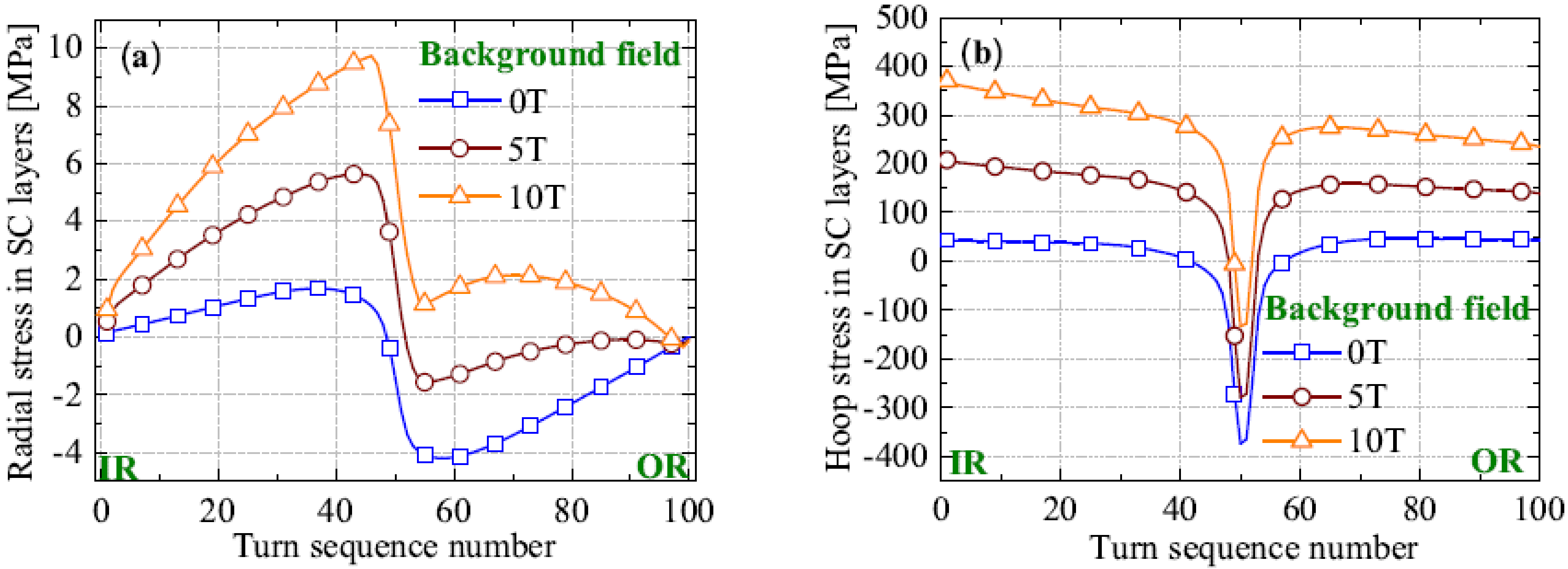
The hot-spot temperature and current distributions



- As the heating energy is larger than the MQE, the maximum temperature will increase quickly.
- The current will redistribute during the quench.

Mechanical behaviors during quench

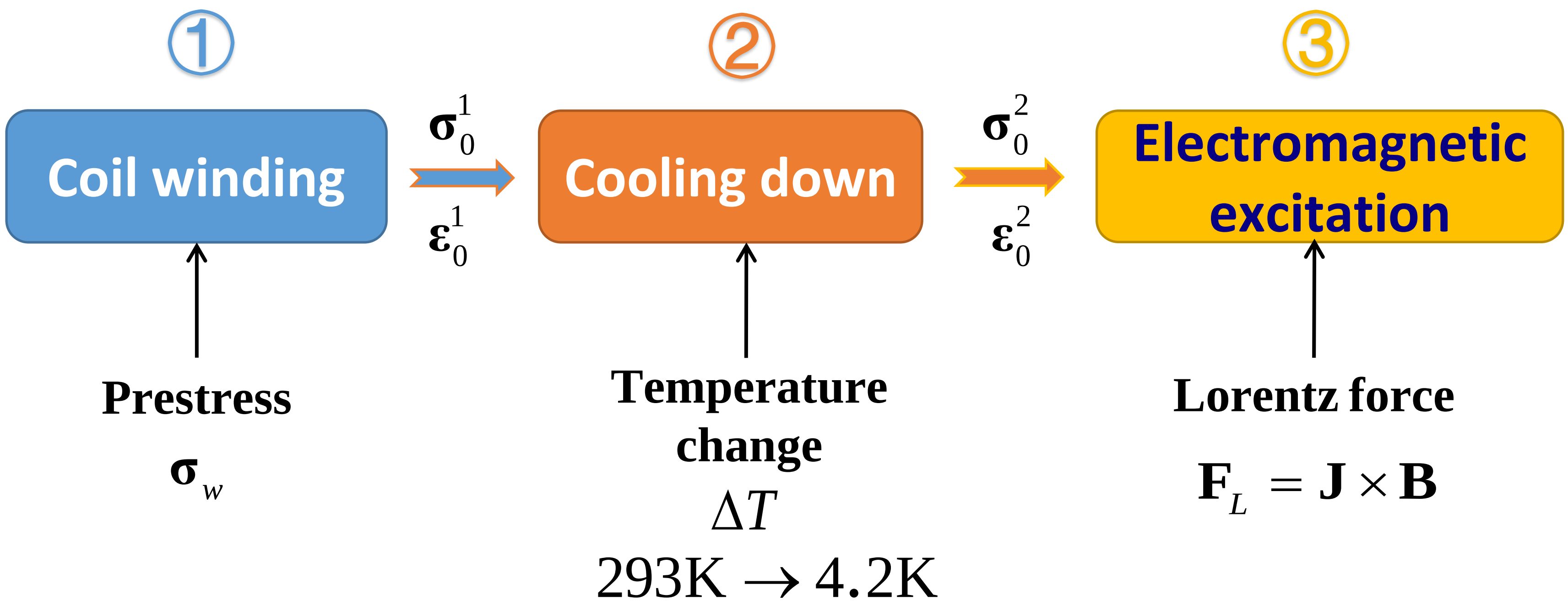
The radial and hoop stress distributions



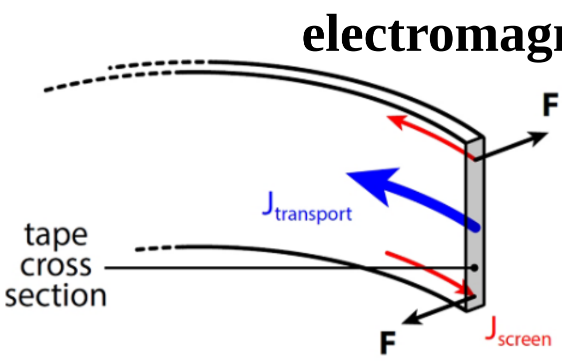
- The radial stress is much smaller than the hoop stress during quench.
- The stress or strain is remarkable at hot-spot region.

Case 2: Mechanical behaviors in REBCO coil

- **To reveal the stress-strain states of high-field REBCO magnets after excitation, we design the subsequetional FE models to include the winding and thermal stresses.**



Mechanical behaviors in REBCO coil



$$f_r = J_\varphi B_z$$

$$f_z = -J_\varphi B_r$$

- **Equilibrium equations**

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{zr}}{\partial z} + \frac{\sigma_r - \sigma_\varphi}{r} + f_r = 0$$

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} + f_z = 0$$

- **Boundary condition**

$\mathbf{u} \cdot \mathbf{n} = 0$ (at bottom edge)

- **Stress-strain relationship**

$$\begin{bmatrix} \varepsilon_r \\ \varepsilon_\varphi \\ \varepsilon_z \\ \gamma_{zr} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_r} & \frac{\nu_{r\varphi}}{E_\varphi} & \frac{\nu_{rz}}{E_z} & 0 \\ \frac{\nu_{\varphi r}}{E_r} & \frac{1}{E_\varphi} & \frac{\nu_{\varphi z}}{E_z} & 0 \\ \frac{\nu_{zr}}{E_r} & \frac{\nu_{z\varphi}}{E_\varphi} & \frac{1}{E_z} & 0 \\ 0 & 0 & 0 & \frac{1}{G_{zr}} \end{bmatrix} \begin{bmatrix} \sigma_r \\ \sigma_\varphi \\ \sigma_z \\ \tau_{zr} \end{bmatrix}$$ **(elastic stage)**

$$\text{if } \sigma_e = \sigma_{ys0}, \quad \sigma_{ys} = \sigma_{ys0} + \sigma_h(\varepsilon_{pe}) .$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_\mathbf{e} + \boldsymbol{\varepsilon}_\mathbf{p}$$ **(plastic stage)**

- **Contact behaviour**

$$T_n = \begin{cases} 0, & \text{if } gap > 0 \\ -p_n g_n, & \text{if } gap \le 0 \end{cases}$$

Mechanical behaviors in REBCO coil

- **Governing equations T-A formulation**

$$\begin{cases} \nabla\times\nabla\times\mathbf{A}=\mu\mathbf{J} & \text{(all domains)} \\ \nabla\cdot\mathbf{A}=0 & \text{(all domains)} \\ \nabla\times\rho_{HTS}\mathbf{J}=-\partial\mathbf{B}/\partial t & \text{(REBCO domains)} \end{cases}$$

Zhang et al 2017 SUST 30: 024005

- **E-J constitutive law**

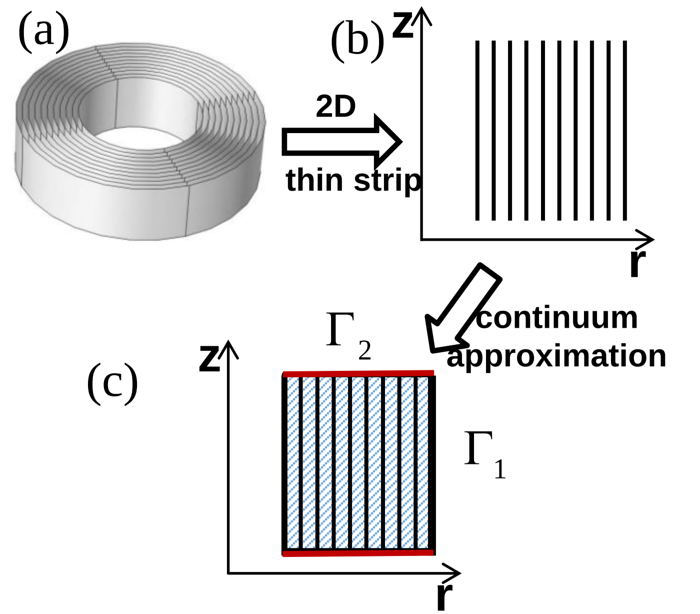
$$\rho_{HTS}=\frac{E_c}{J_c(B,\theta)}\left|\frac{J_\varphi}{J_c(B,\theta)}\right|^n$$

- **Magnetic field anisotropy of Ic**

$$I_c(B,\theta)=\frac{b_0}{(B+\beta_0)^{\alpha_0}}+\frac{b_1}{(B+\beta_1)^{\alpha_1}}\left[\varpi_1^2(B)\cos^2(\theta-\varphi_1)+\sin^2(\theta-\varphi_1)\right]^{-1/2}$$

$$w_1(B)=c_1\left[B+\left(\frac{1}{c_1}\right)^{1/\varepsilon_1}\right]^{\varepsilon_1}$$

Xia et al 2019 SUST 32: 095005



Schematic diagram

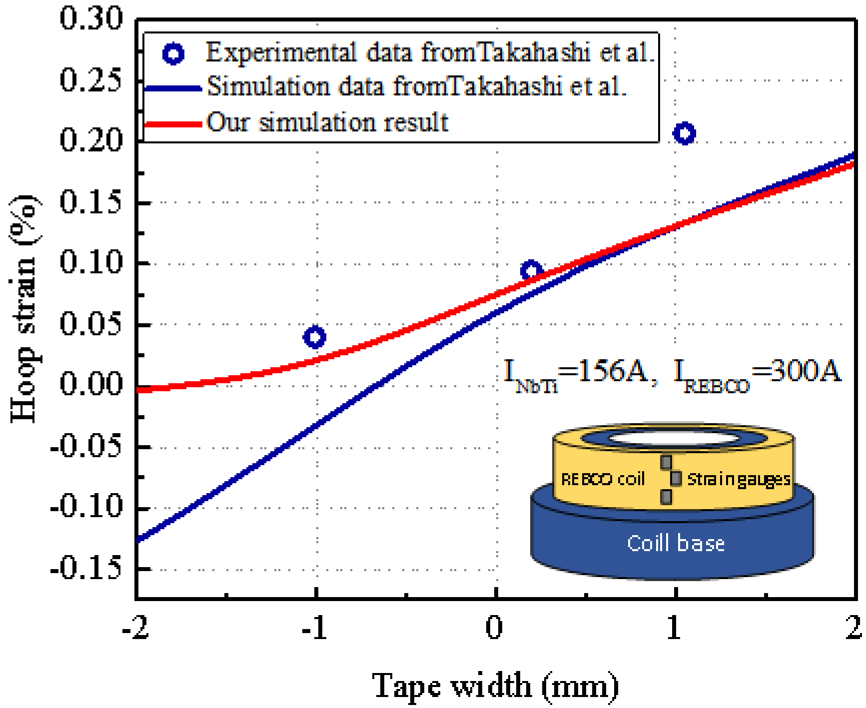
Berrospe-Juarez et al 2019 SUST 32 065003

- **Boundary conditions**

$$\begin{cases} \partial T_n/\partial n=0 & (\text{on } \Gamma_1) \\ \int_{\Gamma_2} T_n dl = I_0 & (\text{on } \Gamma_2) \end{cases}$$

Mechanical behaviors in REBCO coil

Comparison between simulation and experimental results for 5-turn REBCO coil



Coil parameters

	REBCO coil	NbTi coil
Inner/Outer Radius (mm)	39.75/40.65	47.5/52.5
Height (mm)	4.2	160
Turns number	5	
Transport current (A)	300	156
Conductor width/thickness (mm)	4.0/0.1	
Critical current (A)	912	
n-index	24	

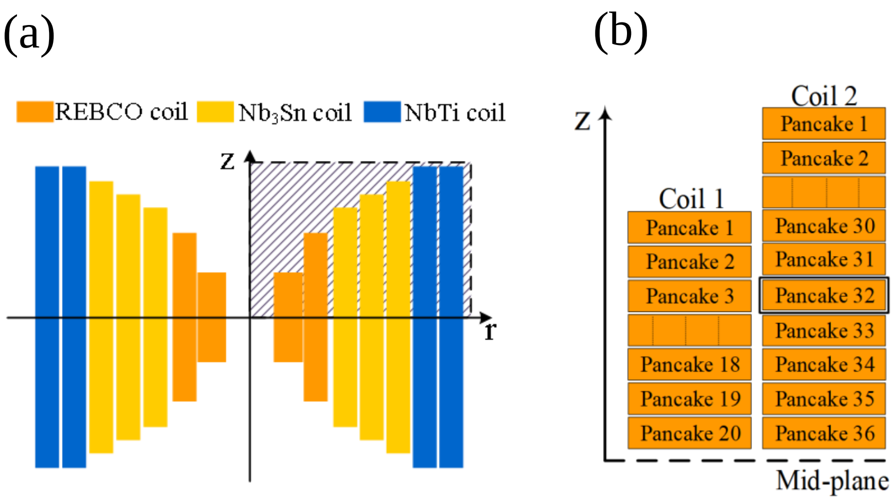
Elastic constants

	Young's Modulus (GPa)	Poisson's ratio
Copper	98	0.34
REBCO	157	0.3
Hastelloy	228	0.307
Polyimide	3.4	0.34

Takahashi et al, 2020, IEEE supercond 30: 4602607

Mechanical behaviors in REBCO coil

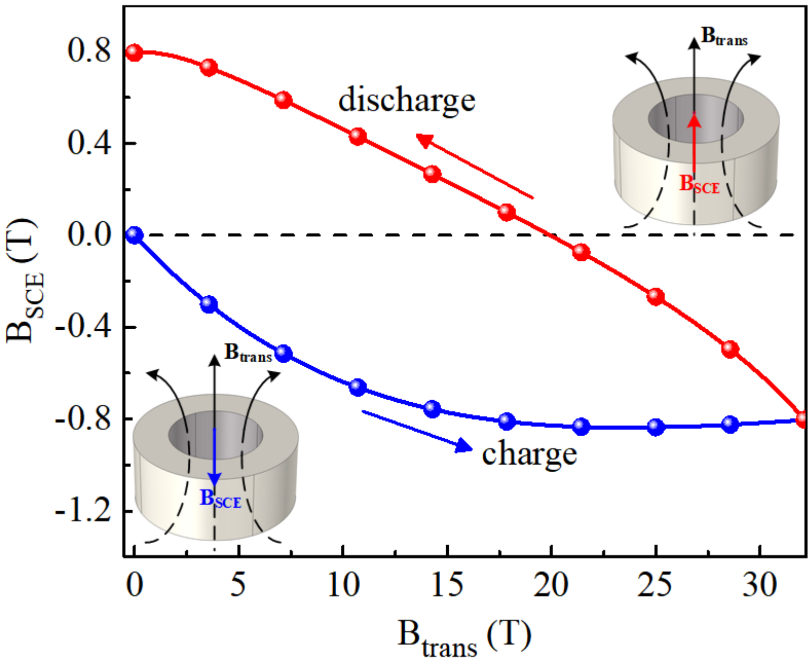
- Large-scale REBCO magnet



✓ **Screening current reduces the total field at the fully charged state, and results in the remanent field of ~0.8 T.**

- Screening current induced field

$$B_{SCE} = B_{tot} - B_{trans}$$



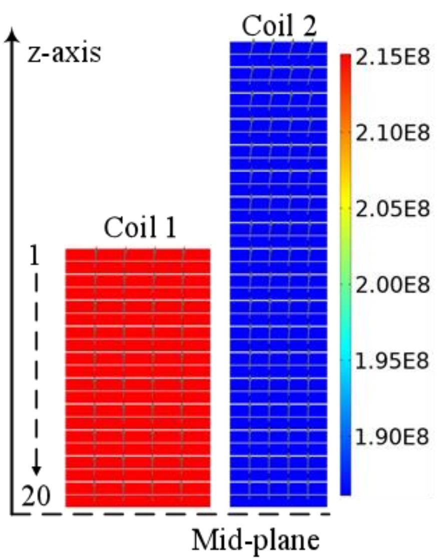
Some parameters of coil are given in Berrospe-Juarez et al 2020 IEEE supercond 30: 4600705

Mechanical behaviors in REBCO coil

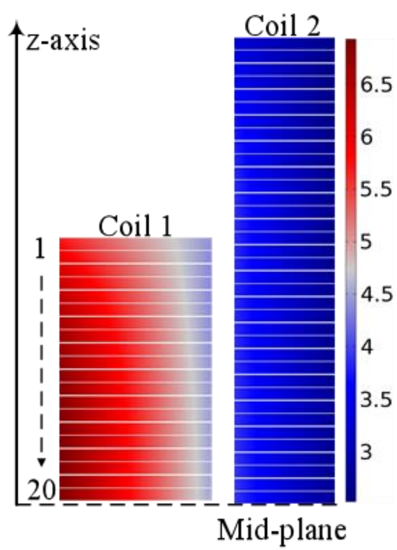
➢ Current and electromagnetic force after fully charged

- Screening current significantly changes the distribution of total current and Lorentz force.
- The maximum radial Lorentz force is increased almost 400% by screening current effect.

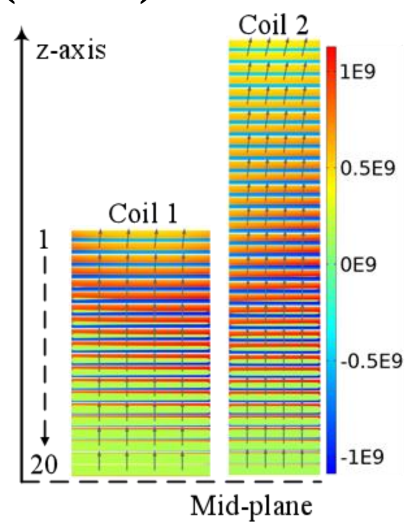
Transport current (A/m^2)



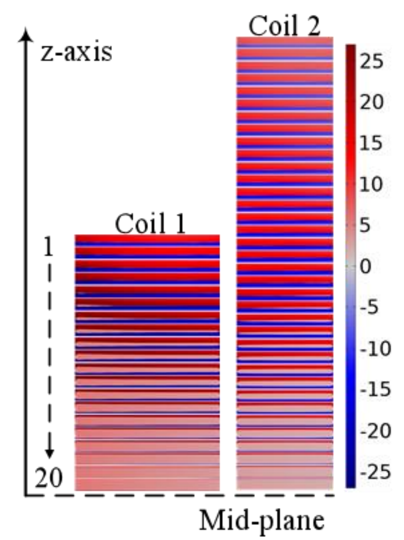
Lorentz force(N/mm ^3)



Screening current + Transport current (A/m^2)



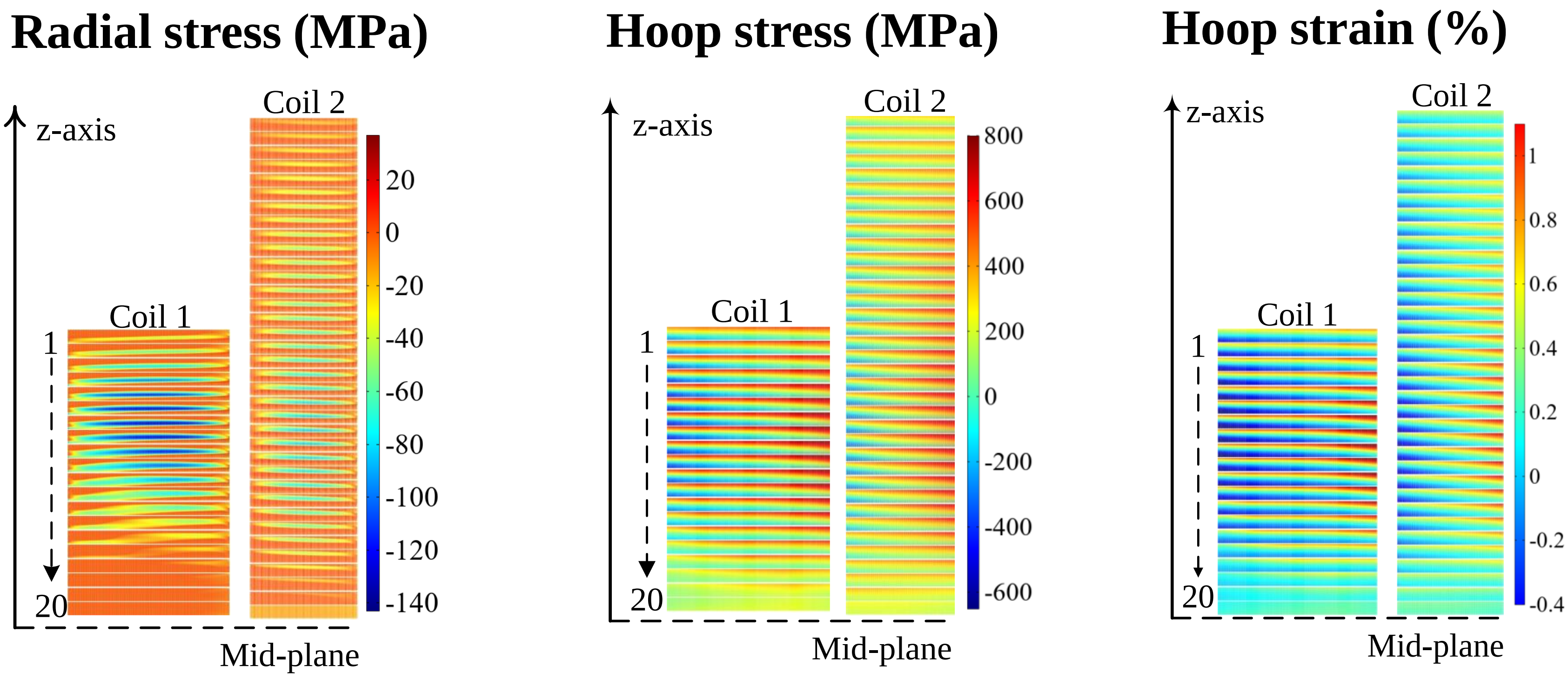
Lorentz force(N/mm ^3)



Niu, Xia, Yong, Submitted for publication

Mechanical behaviors in REBCO coil

➢ Stress-strain states at the fully charged state of REBCO magnet

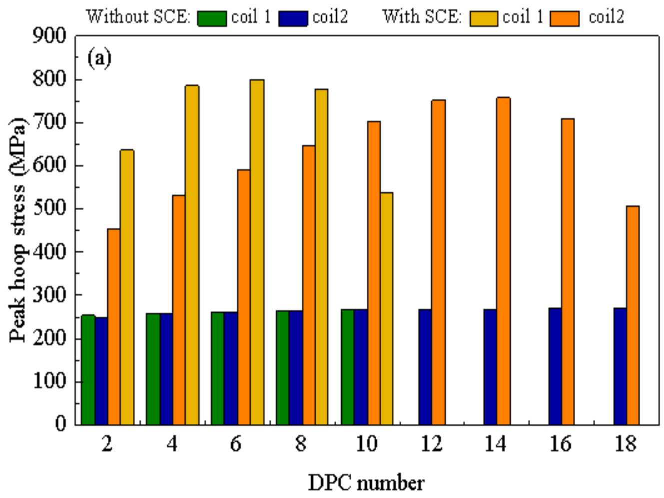


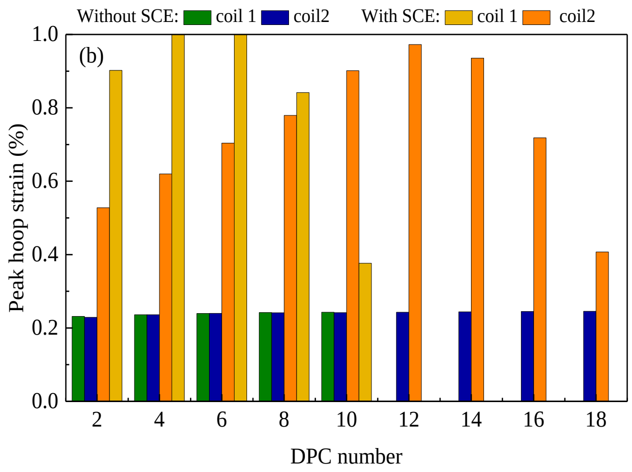
- The maximum tensile hoop stress appears at the outer tapes of pancakes 9 and 10 for REBCO coil 1.
- The calculated maximum stress is high enough to cause the plastic deformation of local conductor, which correlates well with the practical observation in the test REBCO coils.

Mechanical behaviors in REBCO coil

➤ **Peak stress and strain in REBCO magnets (only Lorentz force)**

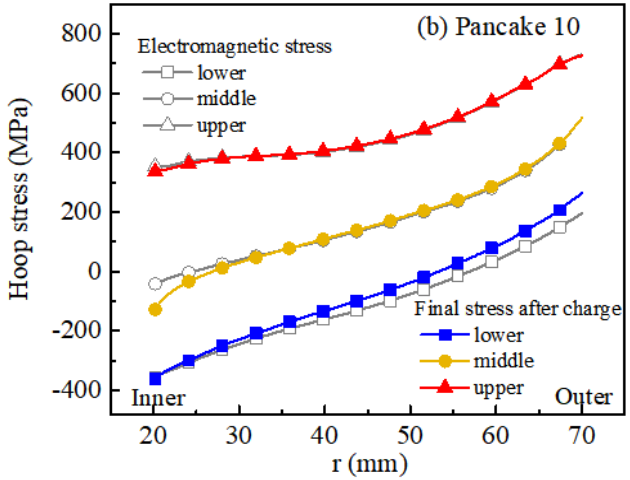
Maximum stress increment factor of ~3.1 (=800/260)

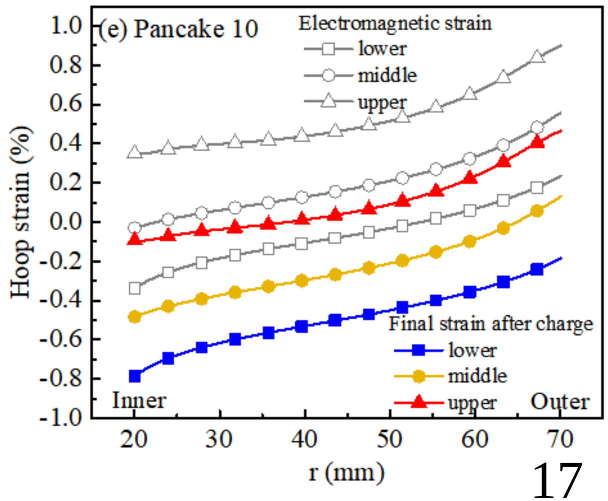




➤ **Stress-strain states considering winding, cooling and excitation**

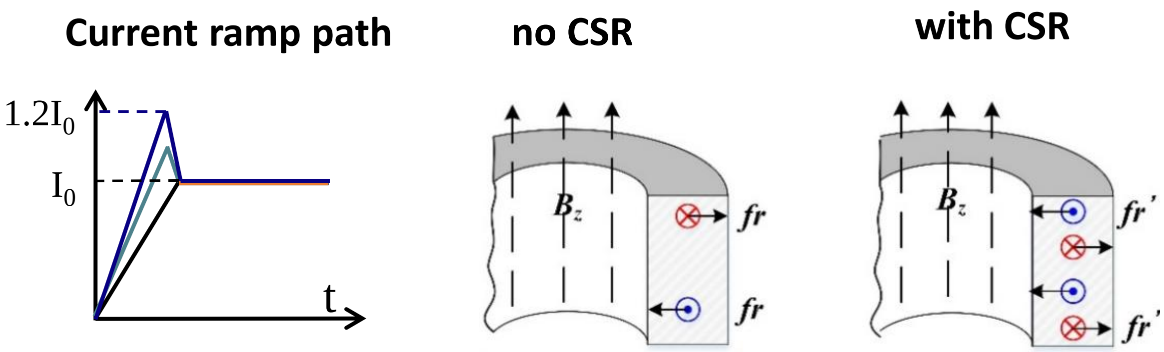
Overlarge local stress of ~800 MPa





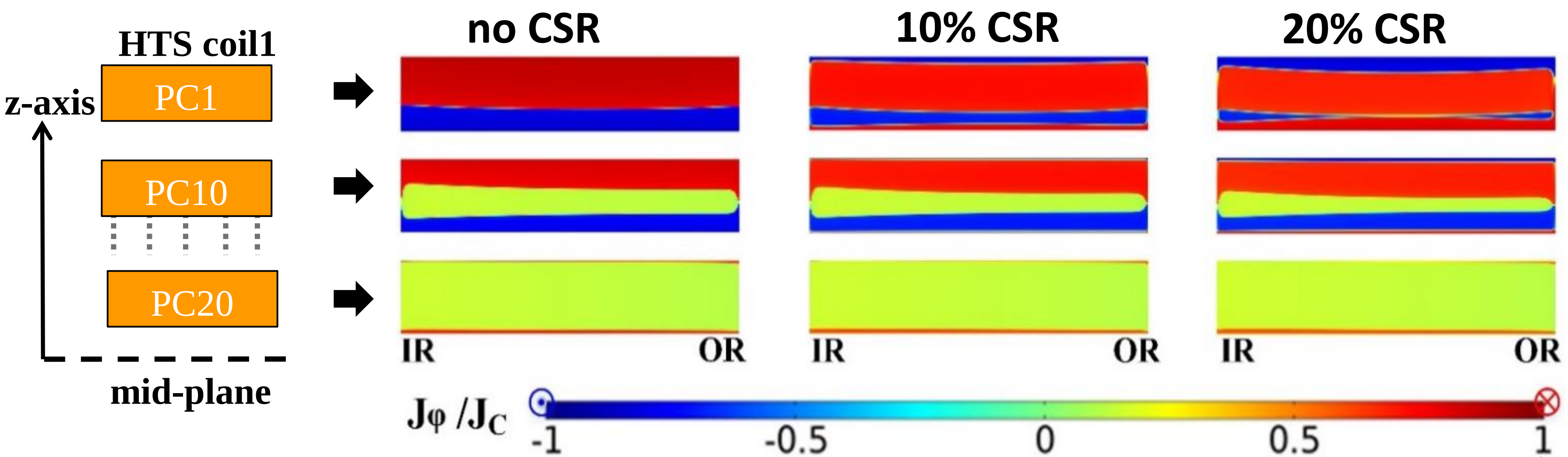
Mechanical behaviors in REBCO coil

➢ Current sweep reversal (CSR)



- ✓ Opposite screening currents appear in the ends of tape.
- ✓ Penetration depth increase with the increase of overshooting current

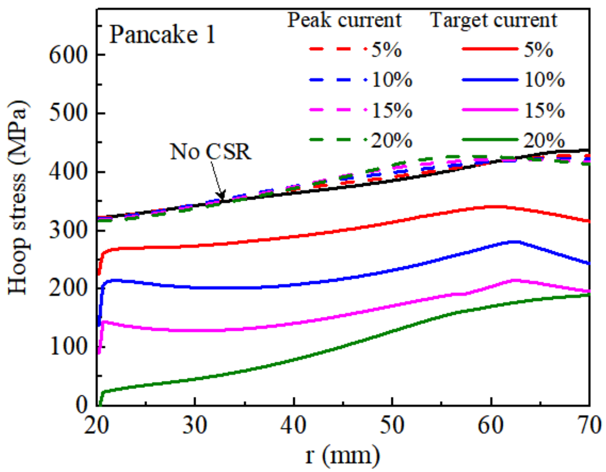
➢ Current distribution



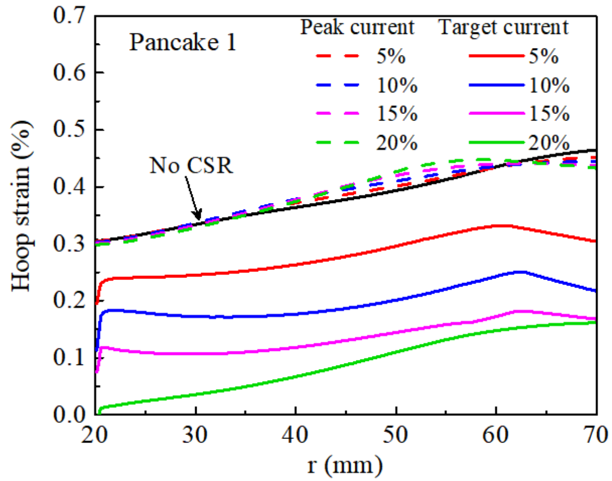
Mechanical behaviors in REBCO coil

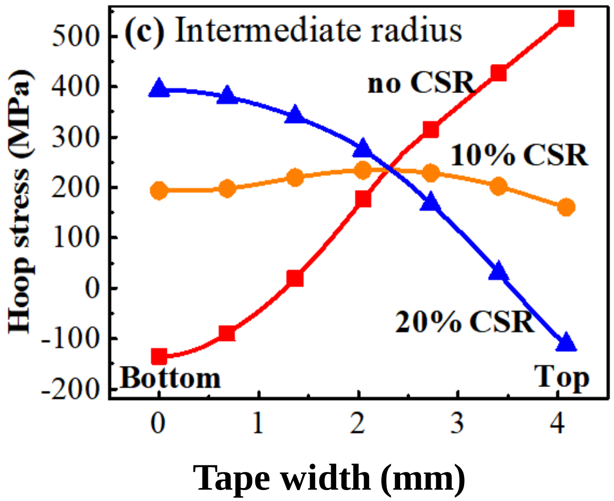
➢ Changes of hoop stress and strain using CSR

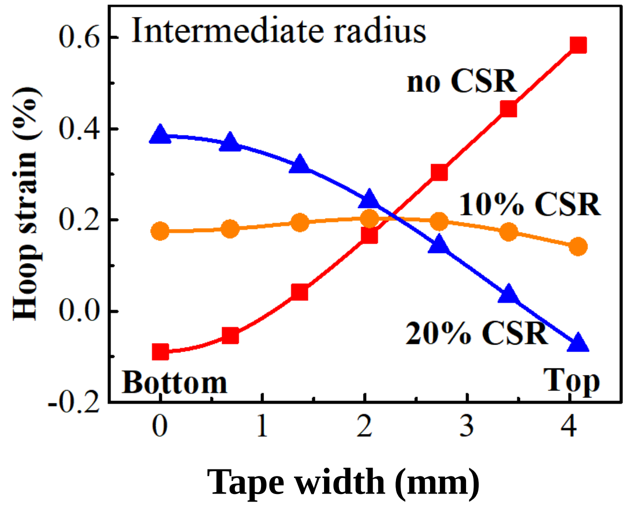
Hoop stress (MPa)



Hoop strain (%)







Future work

1. Numerical simulation of 3D magnet structure

2. Fully coupled simulation

3. Complicated mechanical response, such as plastic deformation, delamination, buckling and cracking

4. Dynamic mechanical response……

Thank you for your attention!