Screening-current-induced mechanical strains in REBCO insert coils

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Outline

Part 1 Introduction

Part 2 Modelling and Validation

Part 3 Discussion

- □ Over-banding
- □ Edge-bonding
- □ Full impregnation
- □ Conductor tilting limit

Part 4 Conclusion/Summary

Part 1 Introduction: UHF Magnet (ultra-high-field)

- DC field achieved/in development using REBCO materials (reported since 2017)

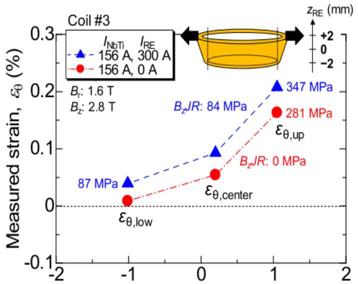
Leading Team	Magnetic Field	Configuration	Bore Size	Application
NHMFL	45.5 T	resistive magnet+ REBCO	i.d. 14 mm	R&D
CAS-IEE	32.35 T	LTS + REBCO	35 mm	NMR
CAS-IEE	30 T (design)	LTS + REBCO	35 mm	quantum oscillation application
CAS-IEE	27 T (design)	LTS + REBCO	50 mm	user magnet
CEA, LNCMI-CNRS	32.5 T	Resistive magnet + REBCO	38 mm	user magnet
KIT	26.5 T @1.8 K, 24.0 T @4.2 K	LTS + REBCO	68 mm	user magnet
MIT-FBML	30.5 T (design)	LTS + REBCO	54 mm	NMR
MIT-FBML	23.5 T (design)	(Extreme NI) REBCO	25 mm	benchtop NMR
NHMFL	32 T	LTS + REBCO	34 mm	user magnet, in commission
NHMFL	40 T (design)	LTS + REBCO	> 34 mm	user magnet
NHMFL	20 T (design)	REBCO	> 34 mm	user magnet
RIKEN	31.4 T	LTS + Bi2223 + (LNI) REBCO	i.d. 17.6 mm	R&D
RIKEN	30.5 T (design)	LTS + Bi2223 + REBCO	50-80 mm	persistent-mode NMR
SuNAM, SNU	18 T	REBCO	70 mm	axion haloscope experiment
SuNAM, MIT	26.4 T	REBCO	35 mm	user magnet
Tohoku U-HFLSM	25 T	LTS + Bi2223	52 mm	cryogen-free user magnet
Tohoku U-HFLSM	30 T (design)	LTS + REBCO	32 mm	cryogen-free user magnet

** ranked by name; may not be complete*

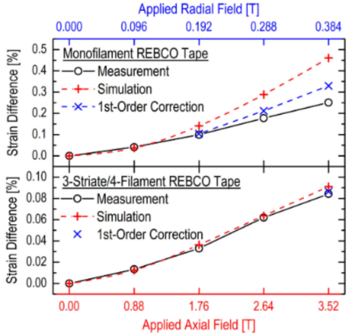
- Reevaluate the mechanical behaviors of CC in the magnet design

Part 1 Introduction: SCS (screening-current-induced stress/strain)

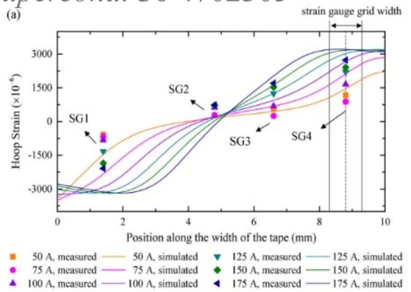
Observations



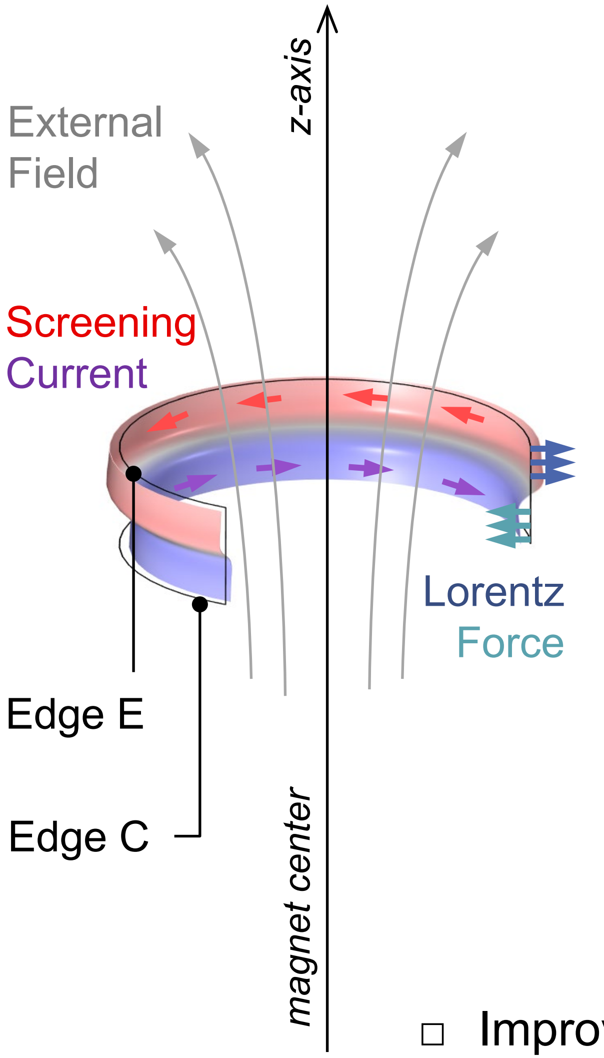
Takahashi S *et al* 2020 *IEEE Trans. Appl. Supercond.* **30** 4602607



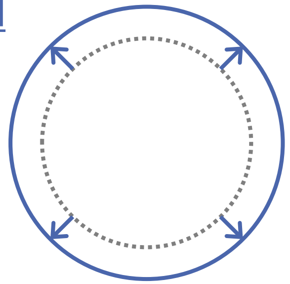
Li Y *et al* 2020 *IEEE Trans. Appl. Supercond.* **30** 4702305



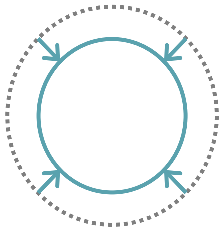
Yan Y *et al* 2020 *Supercond. Sci. Technol.* **33** 05LT02



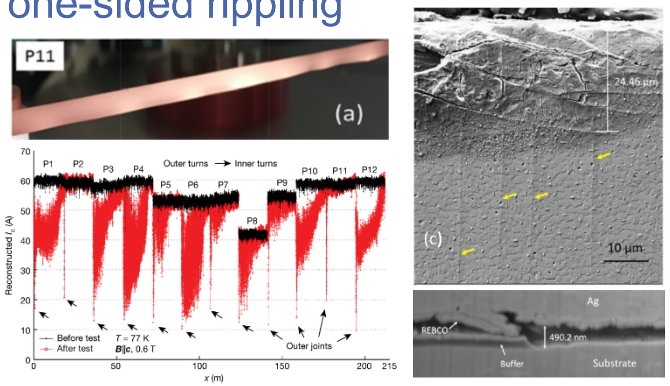
Edge E: expansive towards the magnet end



Edge C: compressive towards the magnet center



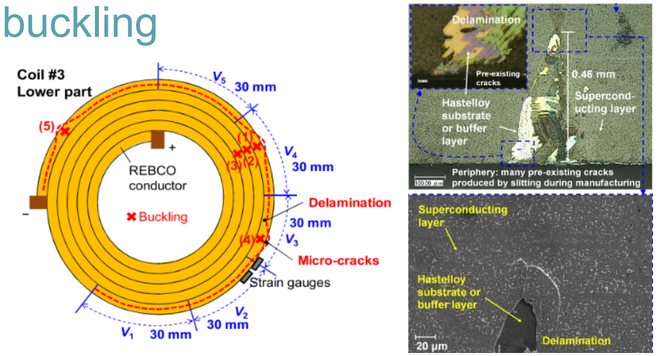
one-sided rippling



Hahn S et al 2019 *Nature* **570** 496–9

Hu X *et al* 2020 *Supercond. Sci. Technol.* **33** 095012

buckling



Takahashi S *et al* 2020 *IEEE Trans. Appl. Supercond.* **30** 4602607

Degradation (micro-cracks, delamination…)

- ☐ Improve the accuracy of the numerical models
- ☐ Increase the scale & complexity of the studies

⇒ UHF magnet

Part 2 Modelling and Validation

T-A formulation

thin-strip approximation $J_\phi = -\dfrac{\partial T}{\partial z}$

$$\frac{\partial B_n}{\partial t} = \frac{\partial E_\phi(J_\phi)}{\partial z}$$

power law $E(J) = \dfrac{E_0}{J_c}\left(\dfrac{|J|}{J_c}\right)^{n-1} J$

domain $\nabla \times \nabla \times \boldsymbol{A} = \mu_0 \boldsymbol{J}$

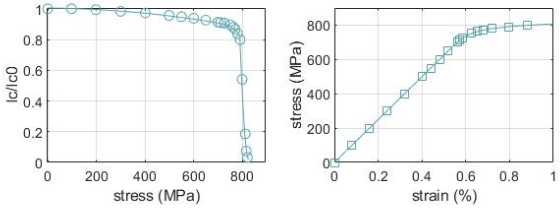
$\boldsymbol{B} = \nabla \times \boldsymbol{A}$

sequential-discrete | coupled-discrete | block

SCIF and the 32-T all SC Magnet
Kolb-Bond D *et al* 2021 *Supercond. Sci. Technol.* **34** 095004

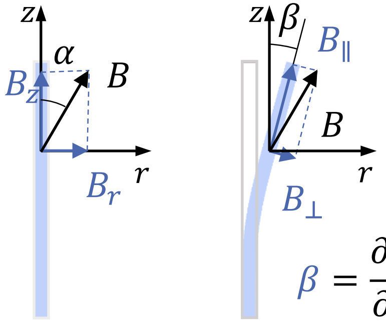
distributed force
$\boldsymbol{f} = J_\phi \times \boldsymbol{B}$

in-situ strain-I_c
$J_c = k(\varepsilon_1) \cdot J_c(|\boldsymbol{B}|, \alpha - \beta)$



Zhang Y et al 2016 *IEEE Trans. Appl. Supercond.* **26** 8400406

conductor tilting



$\beta = \dfrac{\partial u}{\partial z}$

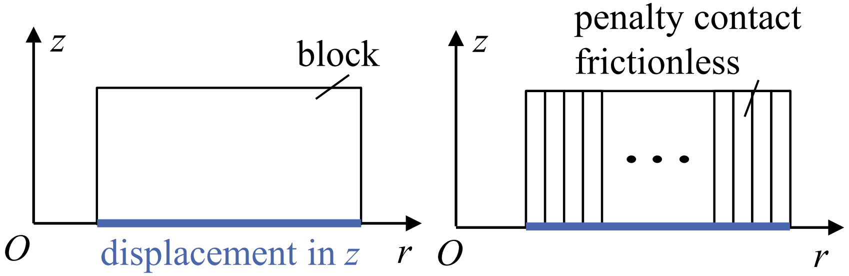
Displacement Field

$$\begin{cases} \dfrac{\partial \sigma_{rr}}{\partial r} + \dfrac{\partial \tau_{rz}}{\partial z} + \dfrac{\sigma_{rr} - \sigma_{\theta\theta}}{r} + \bar{f}_r = 0 \\ \dfrac{\partial \sigma_{zz}}{\partial z} + \dfrac{\partial \tau_{rz}}{\partial r} + \dfrac{\tau_{rz}}{r} + \bar{f}_z = 0 \end{cases}$$

$$\begin{cases} \varepsilon_{rr} = \dfrac{\partial u}{\partial r}, \varepsilon_{\theta\theta} = \dfrac{u}{r}, \varepsilon_{zz} = \dfrac{\partial w}{\partial z} \\ \gamma_{rz} = \dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial r} \end{cases}$$

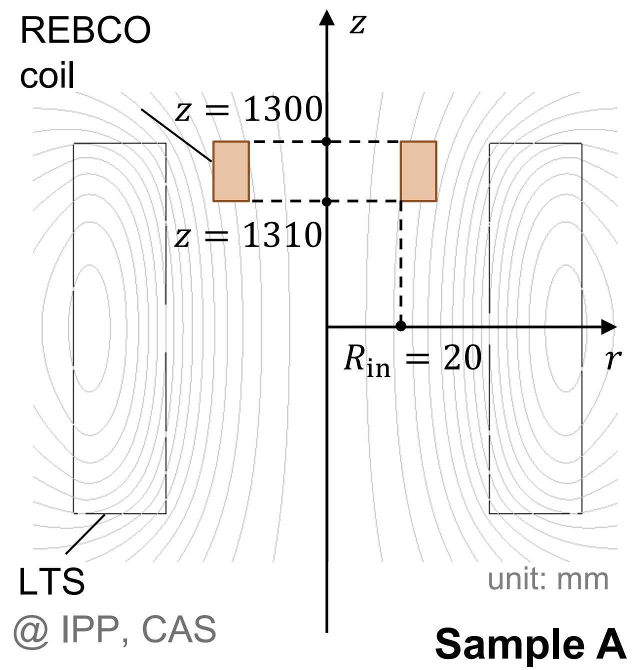
u, w

Geometry (Structural)

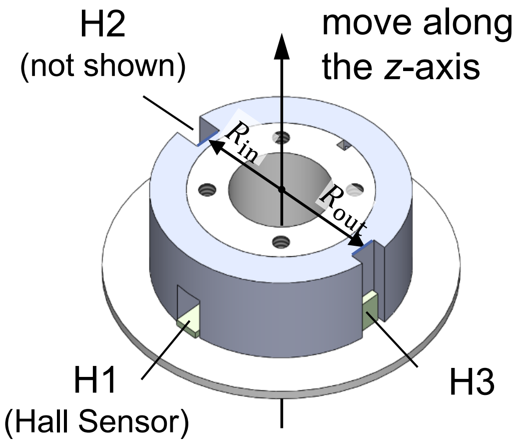


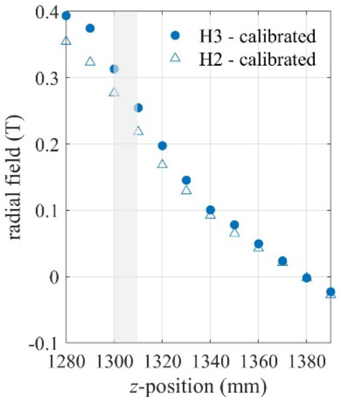
displacement in z
$w = 0$

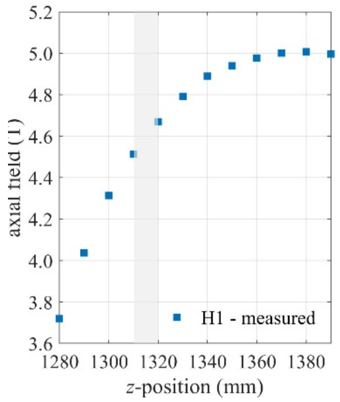
Part 2 Modelling and Validation: Experimental Setup

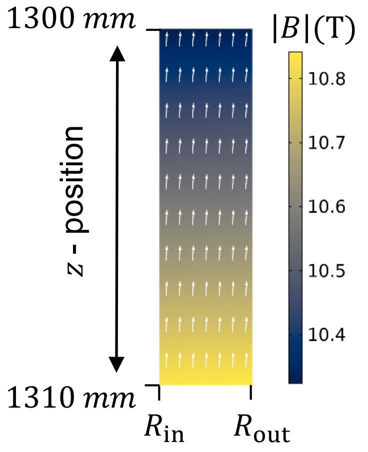


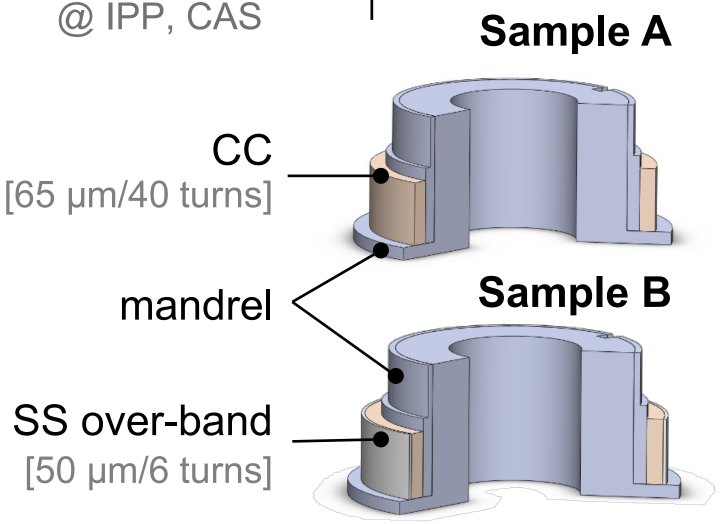
Field Mapping

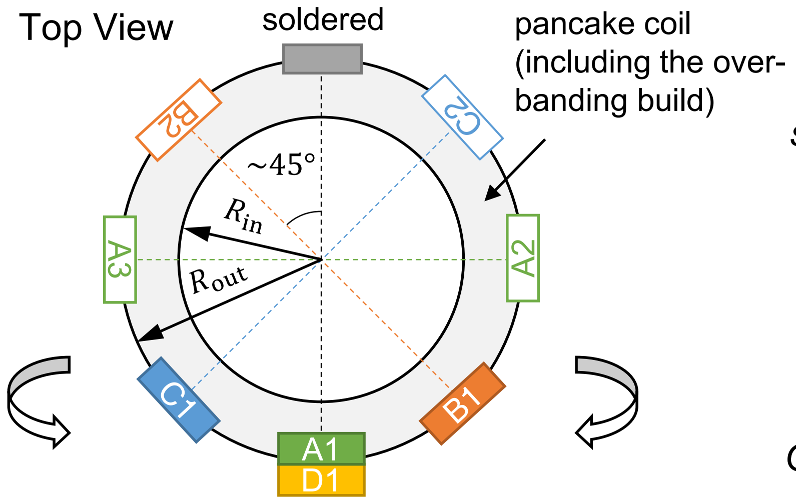




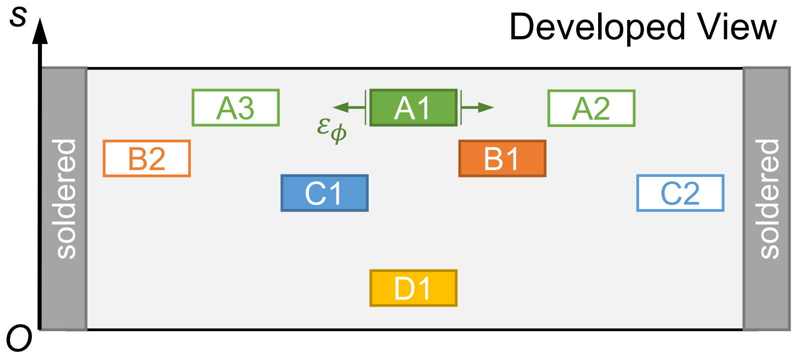






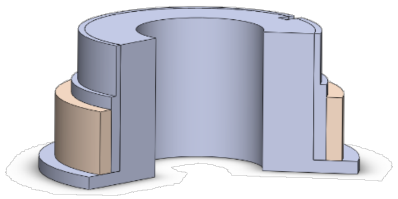


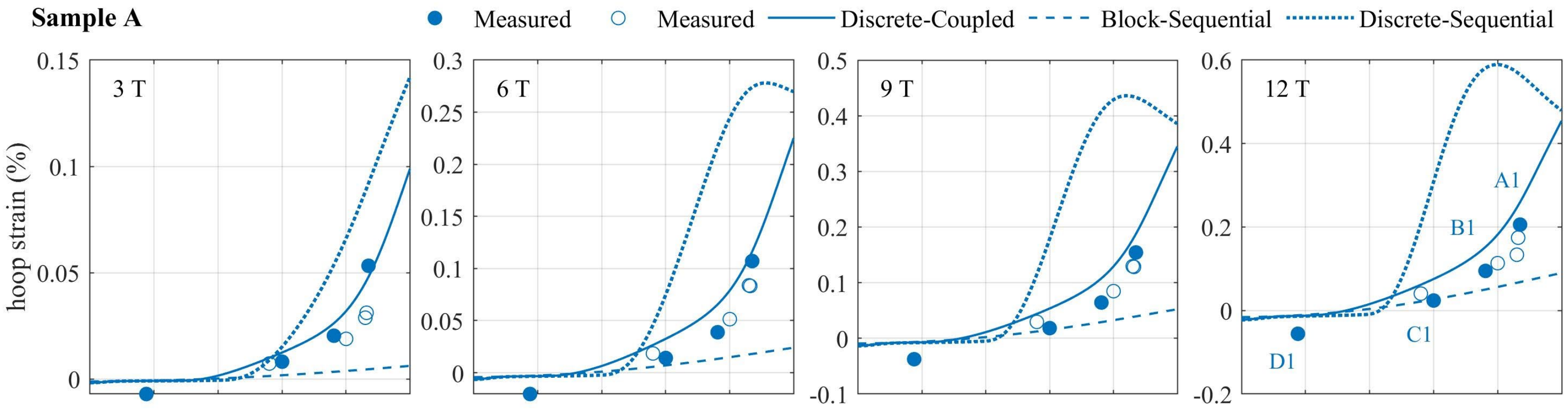
Strain Gauges



Part 2 Modelling and Validation: Results

Sample A



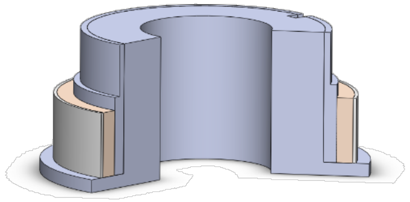


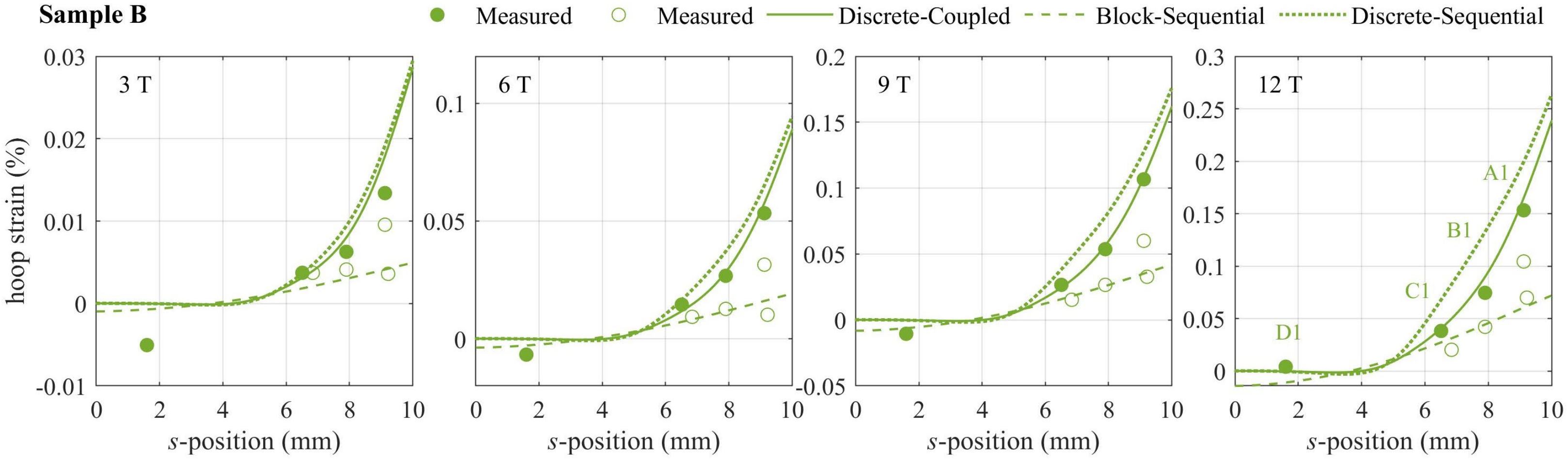
discrete-sequential

discrete-coupled

block

Sample B





discrete-sequential

discrete-coupled

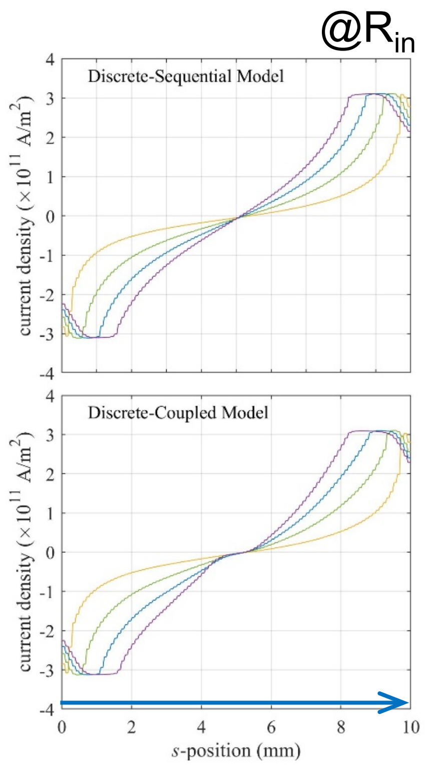
block

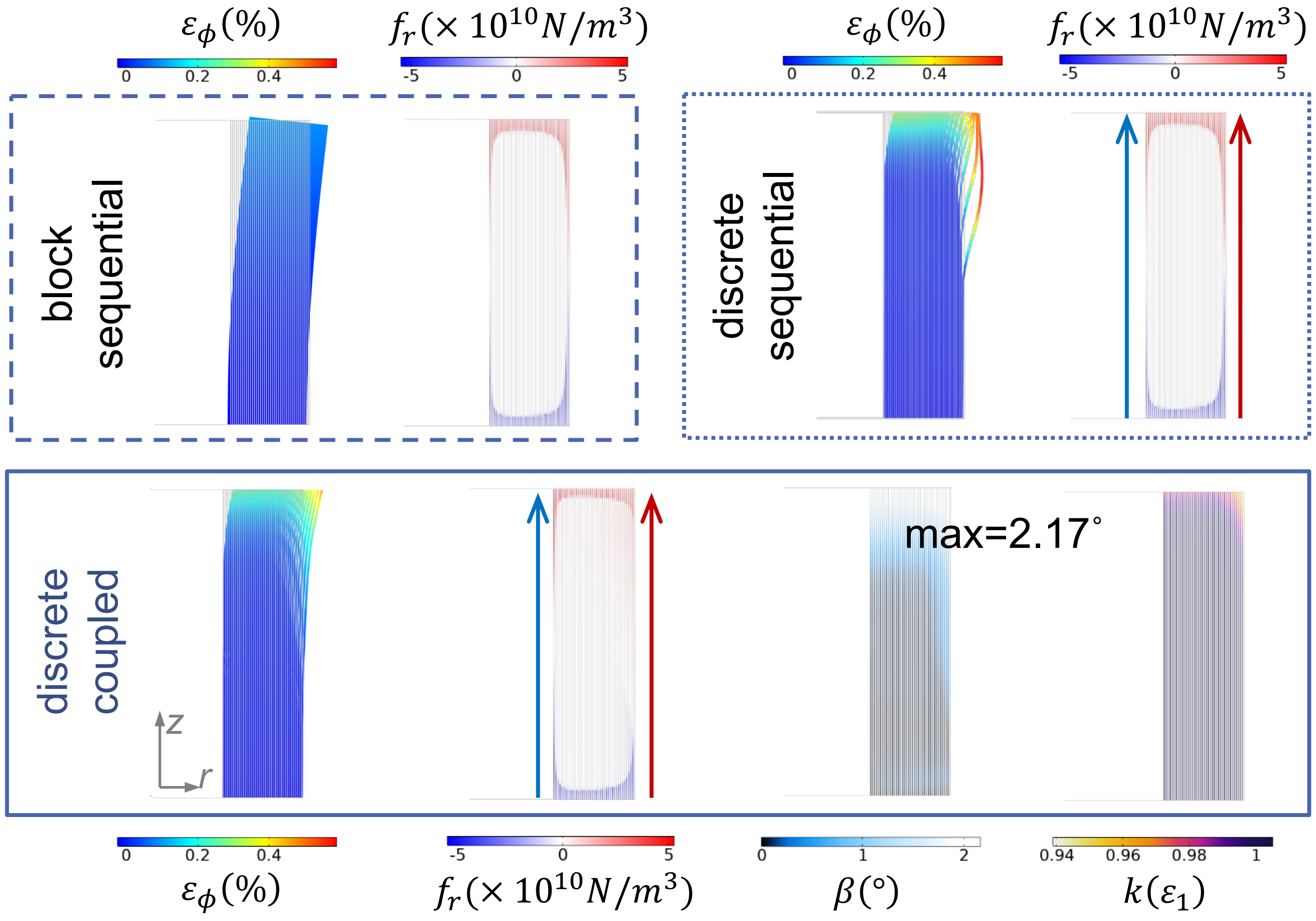
hollow dots: closer to the soldered joint

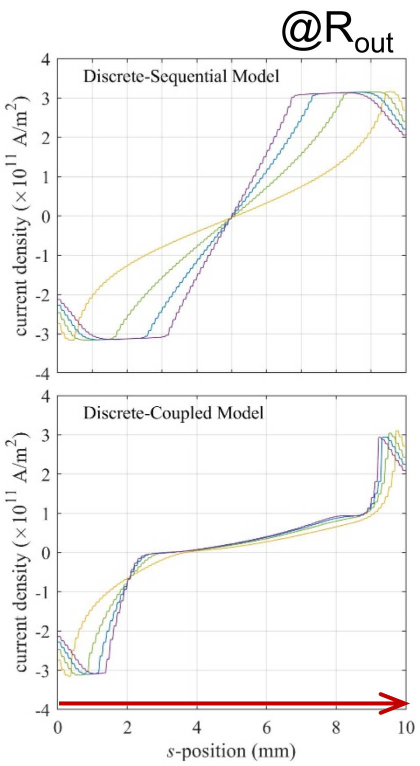
0 T→12 T
stay for 90 s per 1 T
sampling rate @10 Hz

- Near the soldered joint: between estimations from the block model and the discrete-coupled model
- In general: discrete-coupled model shows better agreement with the measured hoop strains

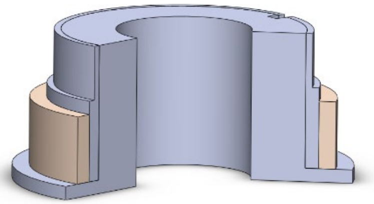
Part 2 Modelling and Validation: Results





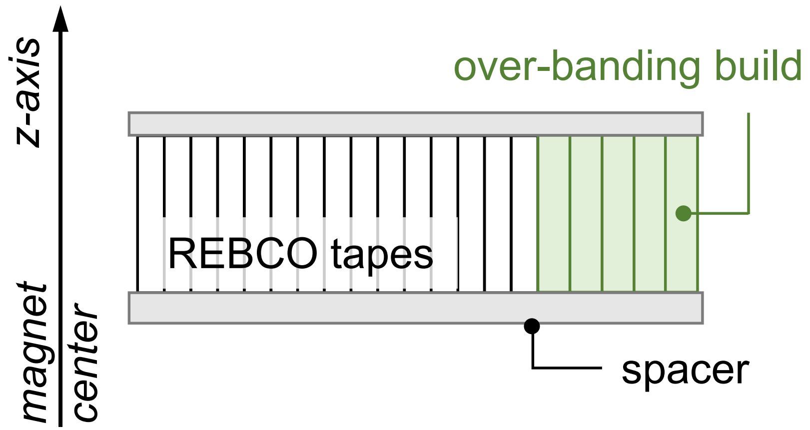


Sample A

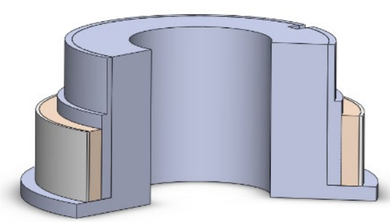


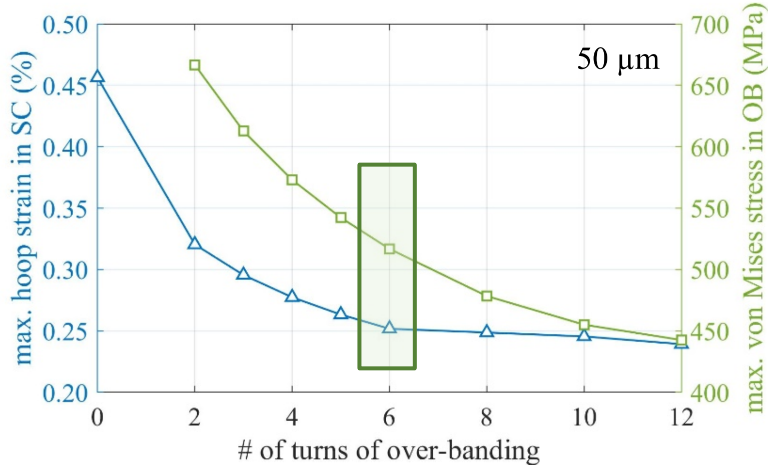
- Tendency to lean towards the external field (2.8-4.2°)
- Delaying field penetration→modification of the current/strain distribution (~R_{out})

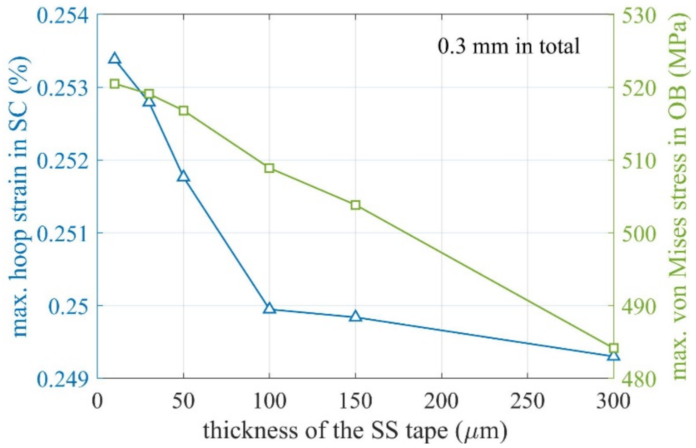
Part 3 Discussion: Over-Banding

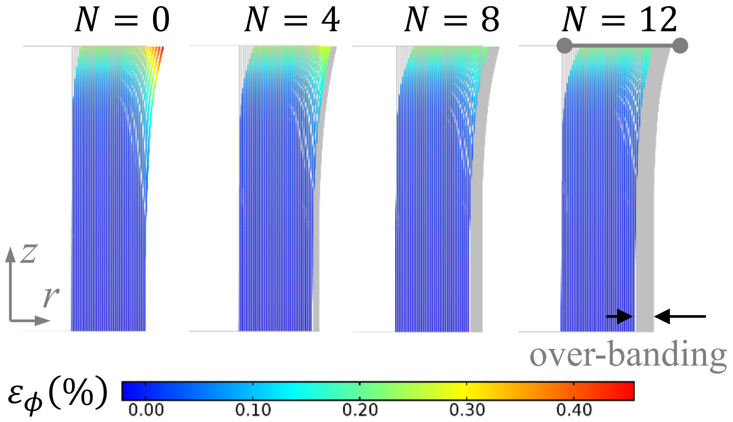


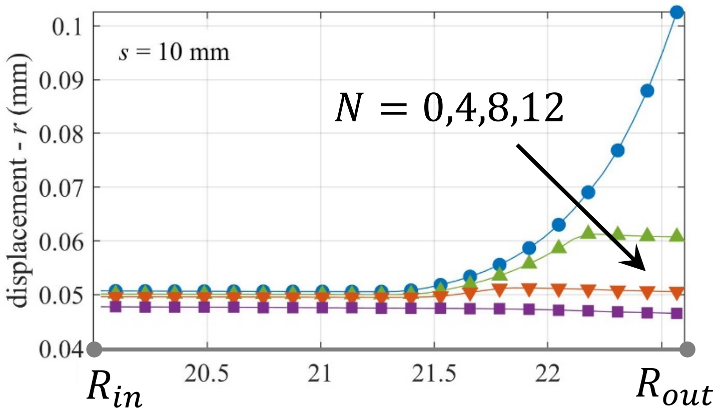
Sample B







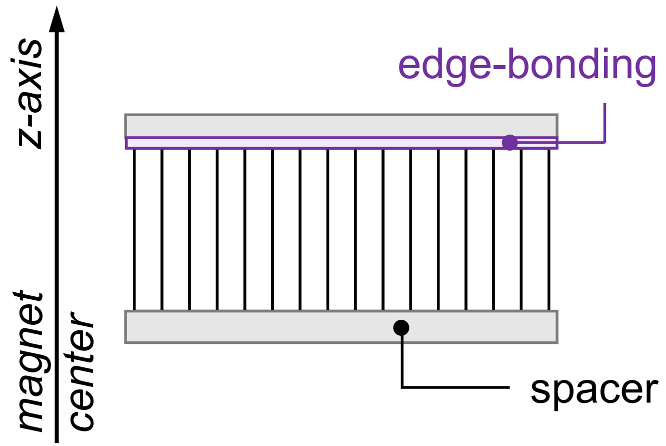


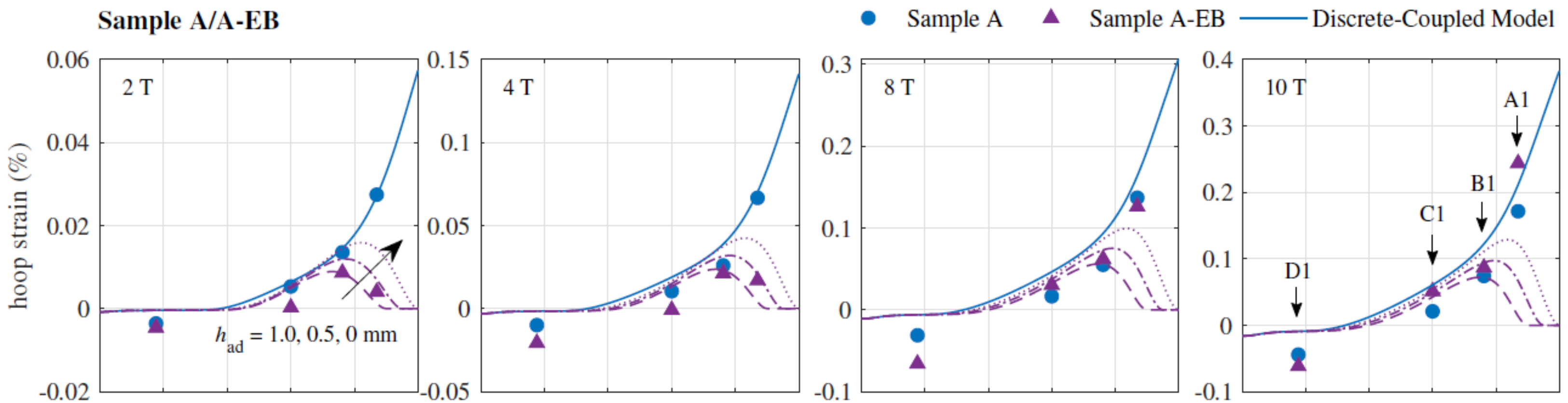


* *backup slide*

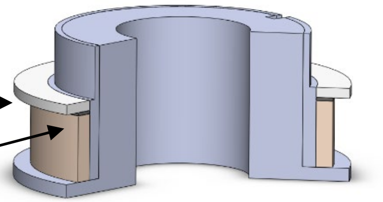
- ☐ Strong influence on the compactness of dry-wound coils
- ☐ ‘Saturation’ trend in its effectiveness
- ☐ ‘Torque’ type of force: thickness of the OB SS tape matters (with pancake configuration)

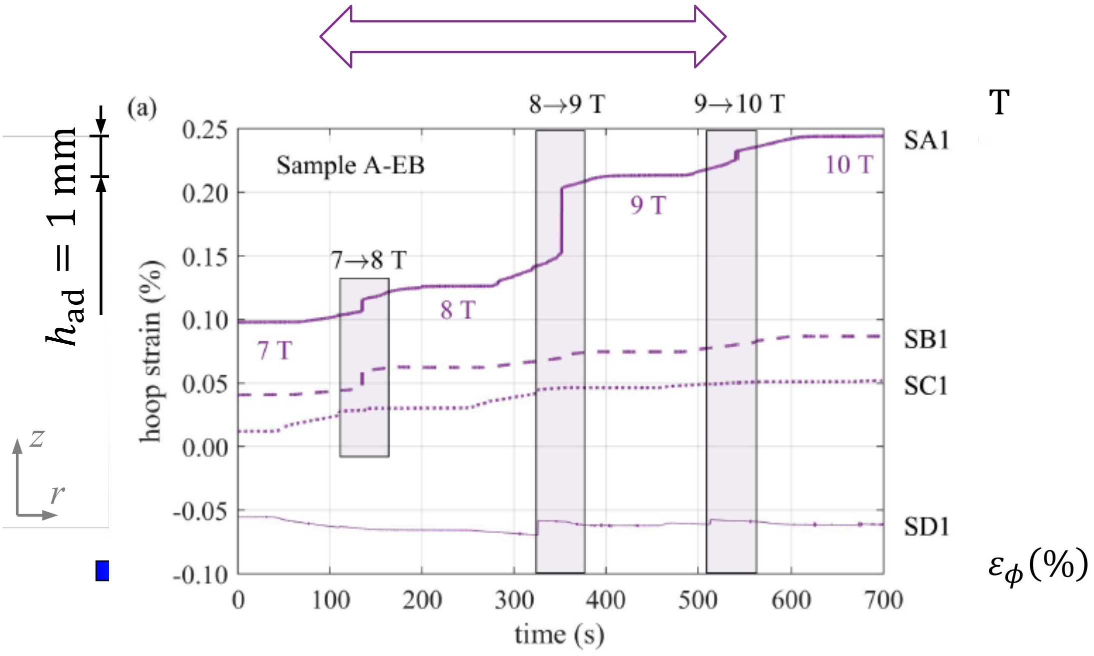
Part 3 Discussion: Edge-Bonding





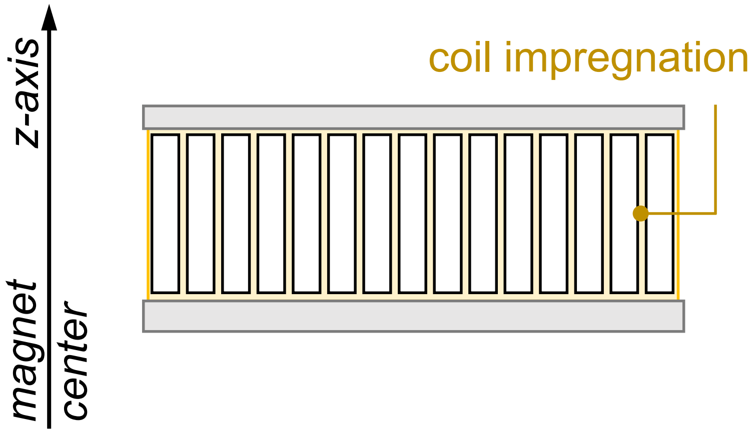
Sample A-EB

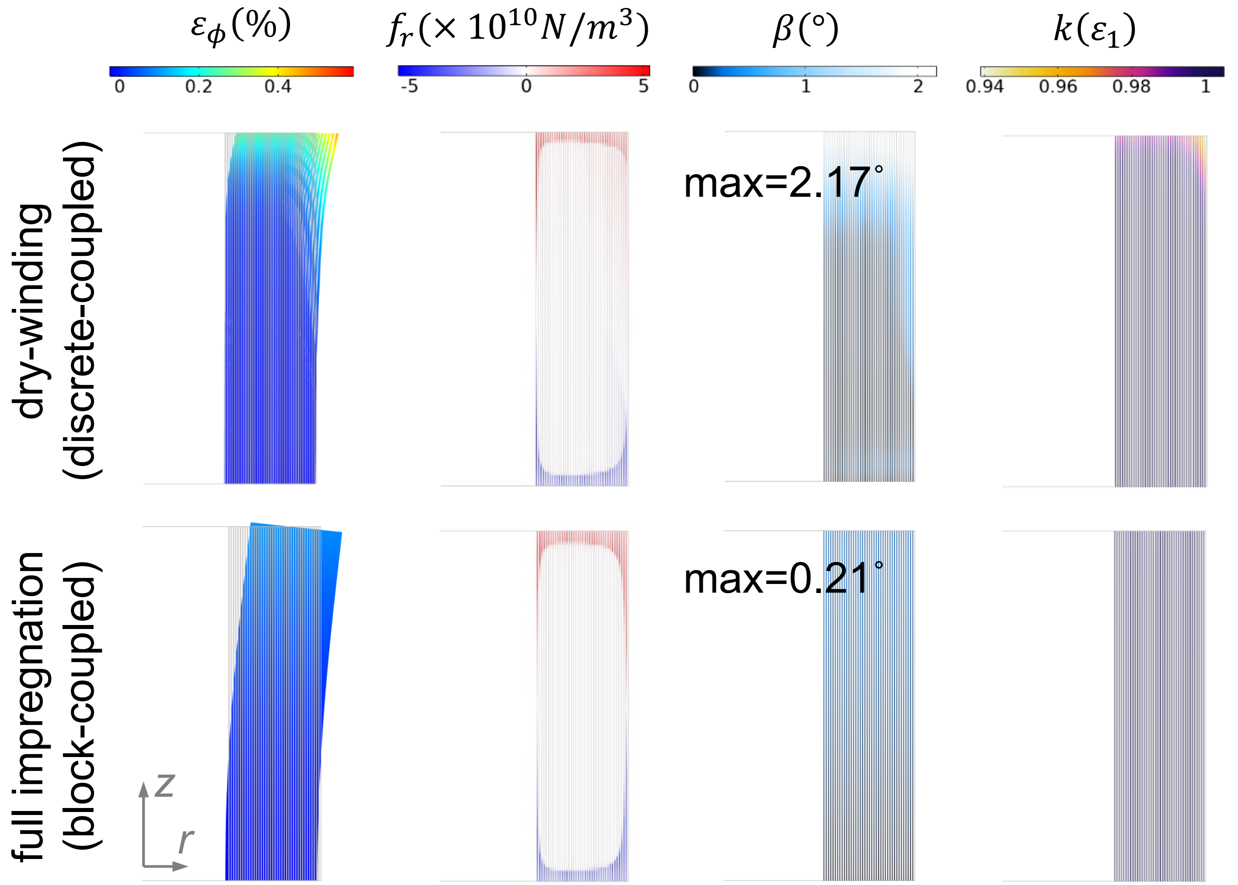




- Enhance the spacer(SS)-to-pancake bonding against the concentrated force
- Unfortunately failed with increasing external field
- Optimization of the bonding method and combination with other reinforcements required

Part 3 Discussion: Full Impregnation





□ Extremely effective by inhibiting the overall conductor movement, in spite of the concentrated force

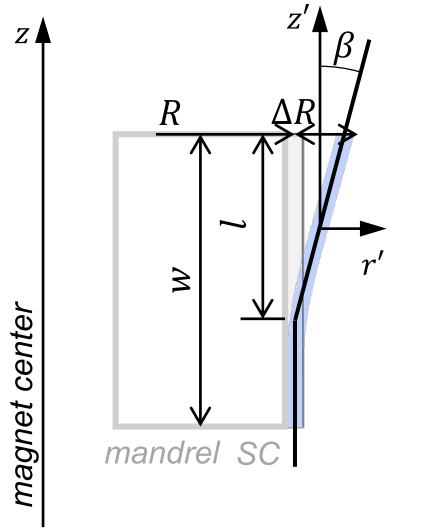
□ Calibration of the stress calculation with the SC-induced Lorentz force in mind

□ Compatibility with NI/MI technique?

** electromagnetic force only*

Part 3 Discussion: Conductor Tilting Limit

- □ Rule-of-thumb estimation of the conductor tilting limit
- □ Case study: single-turn, $w = 10\ \mathrm{mm}$, $R = 20\ \mathrm{mm}$, $J_c(B_\perp, \varepsilon_1)$, with SS mandrel

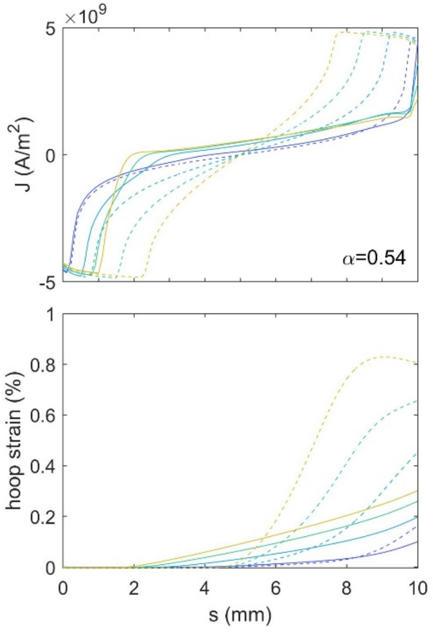


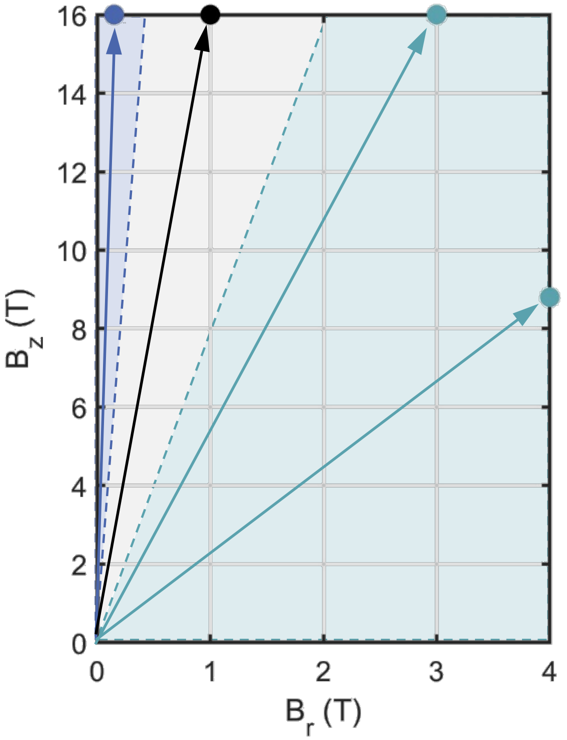
$$\varepsilon_0 = \frac{\Delta R}{R} \approx \frac{\beta l}{R} \to \varepsilon_c$$

$$\beta \to \frac{0.55\% \times 20}{(5\sim10)} = 0.63\sim1.26$$

ε_c : critical strain 0.45%~0.65%, electro-mechanical property

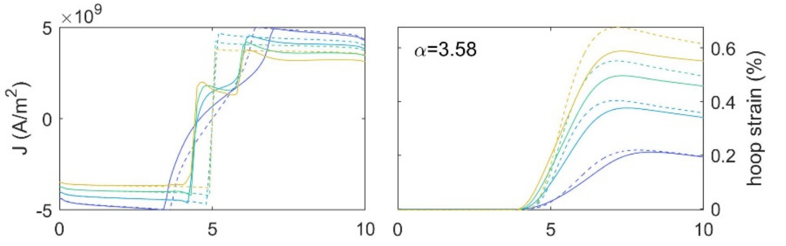
● conductor tilting dominated



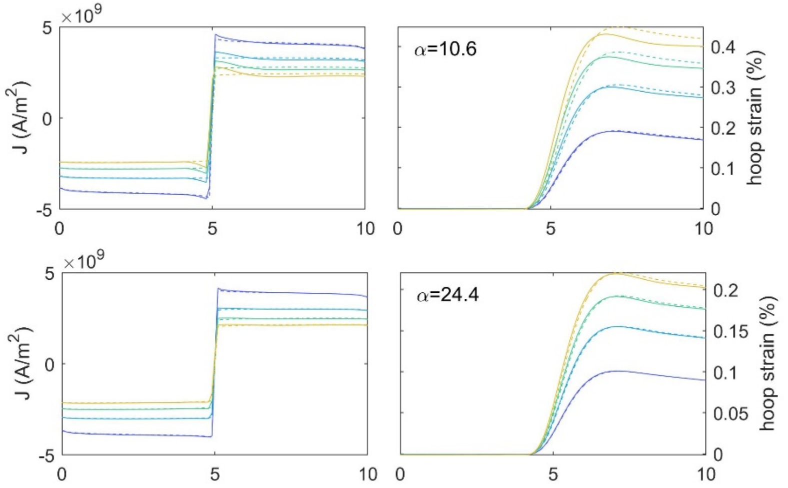


increase monotonically & simultaneously

● mixed



● $B_z J_c$ dominated



Part 4 Conclusion/Summary

- Development of a 'coupled' electromagnetic-mechanical model for SCS calculation
- Validation with hoop strain measurements
- Preliminary discussions about various reinforcement methods
  - Over-banding (Experimental & Theoretical)
  - Edge-bonding (Experimental & Theoretical)
  - Full impregnation (Theoretical)
- Conductor tilting limit with a case study of a single-turn insert

Thank you!

Contact: Yufan Yan
PhD candidate, Tsinghua University
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- Related publications:

Y. Yan, P. Song, C. Xin, M. Guan, Y. Li, H. Liu and T. Qu, "Screening-current-induced mechanical strains in REBCO insert coils," *Supercond. Sci. Technol.*, vol 34, no. 8, 2021, Art. no. 085012.

Y. Yan, Y. Li, and T. Qu, "Screening current induced magnetic field and stress in ultra-high-field magnets using REBCO coated conductors," *Supercond. Sci. Technol.*, 2021, *accepted*. (review paper, url: doi.org/10.1088/1361-6668/ac392b)

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