Development of a 1.3 GHz NMR magnet with REBCO superconducting joints under the JST-Mirai Program

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Contents

- **Design overview of a 1.3 GHz NMR magnet featuring superconducting joints between REBCO tapes**

- **Key technical challenges in REBCO coils**
  - Strain dependence of long REBCO tapes and coil performance in high fields
  - Strategies for quench protection

Key concepts in magnet development

- Proof of concept (POC) on a 1.3 GHz (30.5 T) NMR magnet operated in the persistent-mode (10 ppb/h)

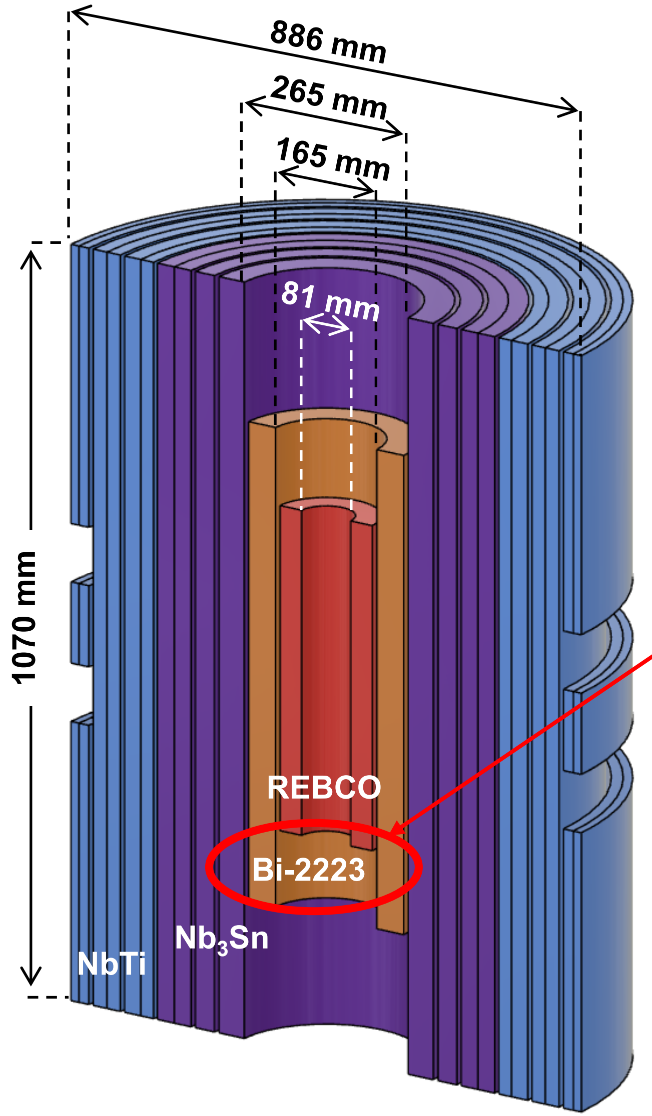
- Series connected LTS outer and HTS inner coils

- Superconducting joints between HTS tapes and low resistance joints between HTS tapes and LTS wires

- Layer-wound HTS coils with insulated REBCO tapes
  (LNI method is still under investigation in other projects)

Magnet design update

The design has been updated:
BSCCO is replaced by REBCO



Operating temperature (K)		4.2 (LHe)
Operating current (A)		231
Self-inductance (H)		988
Stored energy (MJ)		26.4
Weight of superconductors (ton)		3.9
Radial distance of 5 G line (m)		9.9
Main coils		HTS+LTS series
HTS inner coils	Layer-winding	REBCO / Bi-2223
Overall current density (A/mm^2)	REBCO / Bi-2223	205 / 137
Field contribution (T)	HTS (REBCO+Bi-2223) LTS	15.7 (8.7+7.0) 15.1
Conductor length for winding (km)	REBCO / Bi-2223 / LTS	5.2 / 11.0 / 154
Number of joints	RR / BB RL / BL (R: REBCO, B: Bi-2223, L: LTS)	16-32 / 30-45 several / several

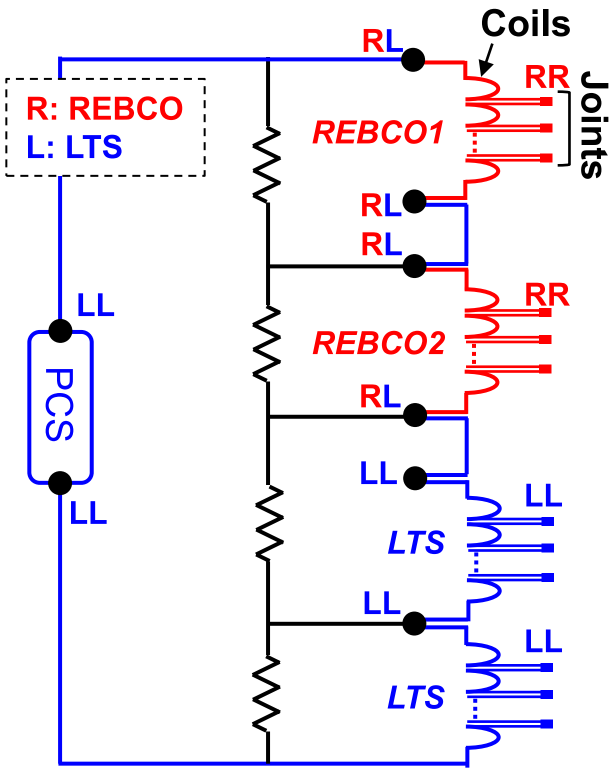
Related publication: Y. Yanagisawa *et al* 2022 *SuST* **35** 044006

Technical issues regarding the REBCO inner coils

- **Persistent-mode operation**
  - Superconducting joints ($<10^{-12}\ \Omega$) between REBCO tapes and low resistance joints ($10^{-10}\ \Omega$) between REBCO tapes and a LTS wires
  - Long REBCO tape characteristics (Ic)
- **Electromagnetic stresses**
  - Mechanical reinforcement for hoop and compressive stresses
  - Long REBCO tape characteristics (strain dependence)
- **Quench protection**
  - Avoiding an induced-quench on the REBCO coils due to an LTS coil quench

Persistent-mode circuit and requirements on joint resistance

Conceptual diagram of the main coil circuit



Inductance~1000 H

Target field drift rate: <10 ppb/h

$R_{circuit}$ < L/τ = 1000/(1/2.78e-12) => 2.8 nΩ

Joint	*Type*	*Number of joints*	*Resistance per joint*	*Total resistance*
RR	Superconducting	<77	<10^{-12} Ω	<77 x 10^{-12} Ω
RL	Low resistance	Several*	<10^{-10} Ω	<8 x 10^{-10} Ω
LL	Superconducting	~100	<10^{-12} Ω	<100 x 10^{-12} Ω

Coil (conductor)	*Total resistance*
REBCO1	<10^{-11} Ω
REBCO2	<10^{-11} Ω
LTS	<10^{-11} Ω

***R*$_{circuit}$ <1.3 nΩ**

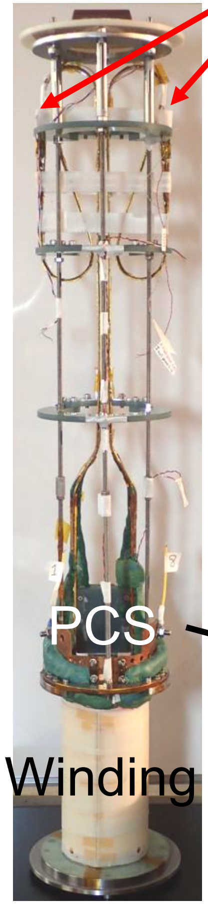
*Depending on protection circuit design

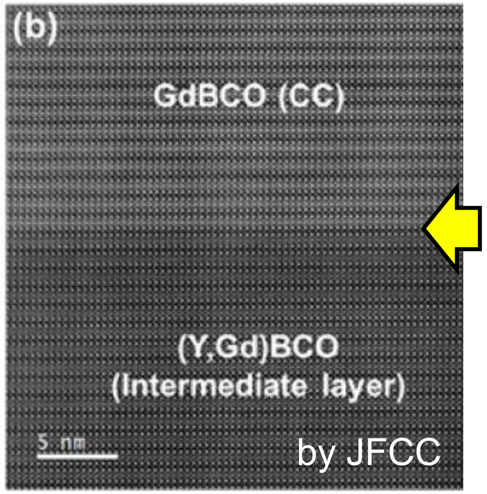
A persistent-mode demonstration on a 400 MHz magnet with superconducting joint between REBCO tapes

400 MHz (9.39 T) LTS/REBCO NMR magnet

REBCO inner coil

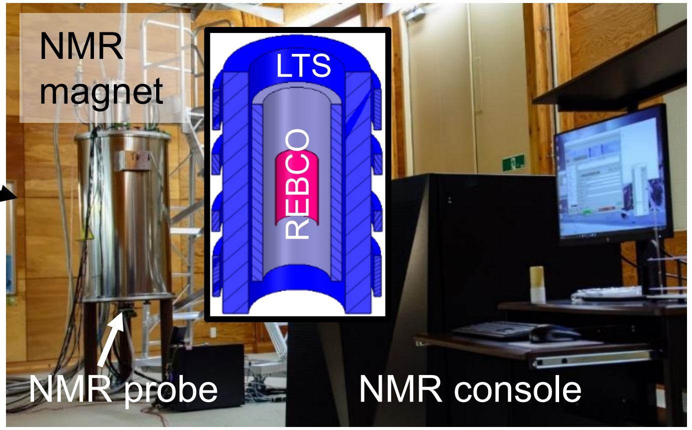
Joints between REBCO tapes (iGS joint)



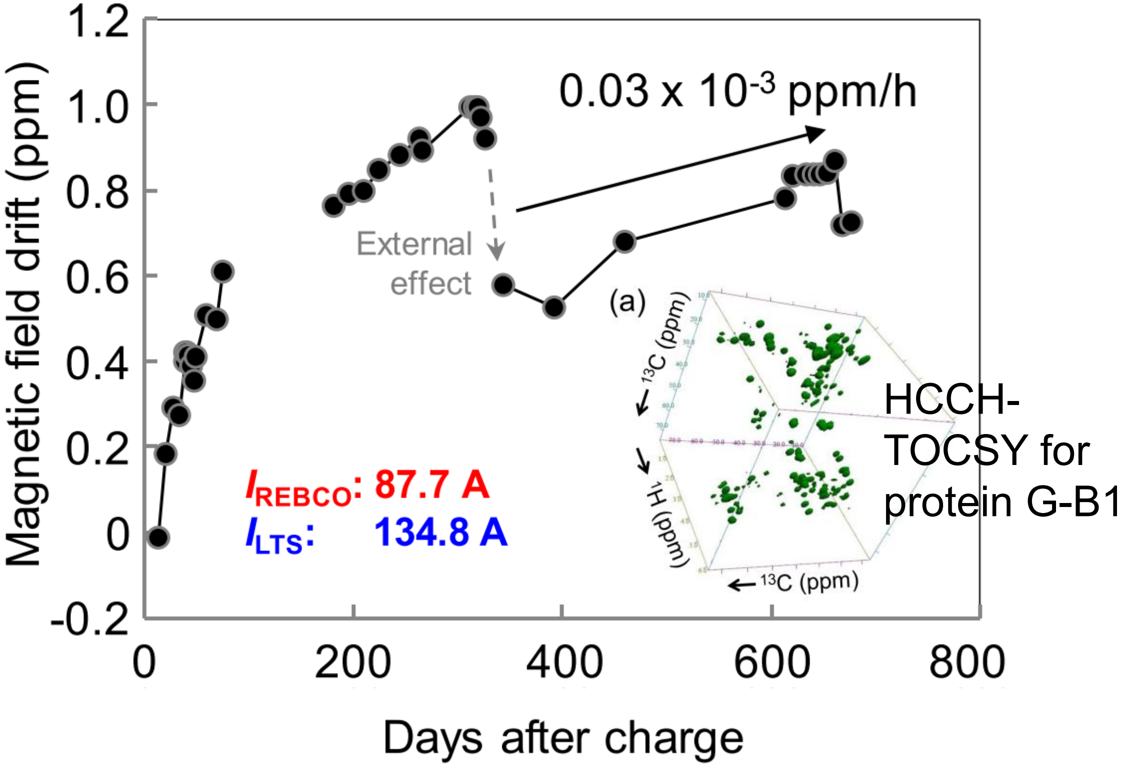


Joint boundary
(observed for a test short sample)

Typical Ic:
~160 A at 77 K
in self fields



Magnetic field drift for TWO YEARS:
Corresponding resistance <10^{-14} Ω



Practical superconducting joint technologies have been developed.

Related publications: K. Ohki *et al* 2017 *SuST* **30** 115017 ; T. Kato *et al* 2020 *SuST* **33** 105008 ; Y. Yanagisawa *et al* 2021 *SuST* **34** 15006

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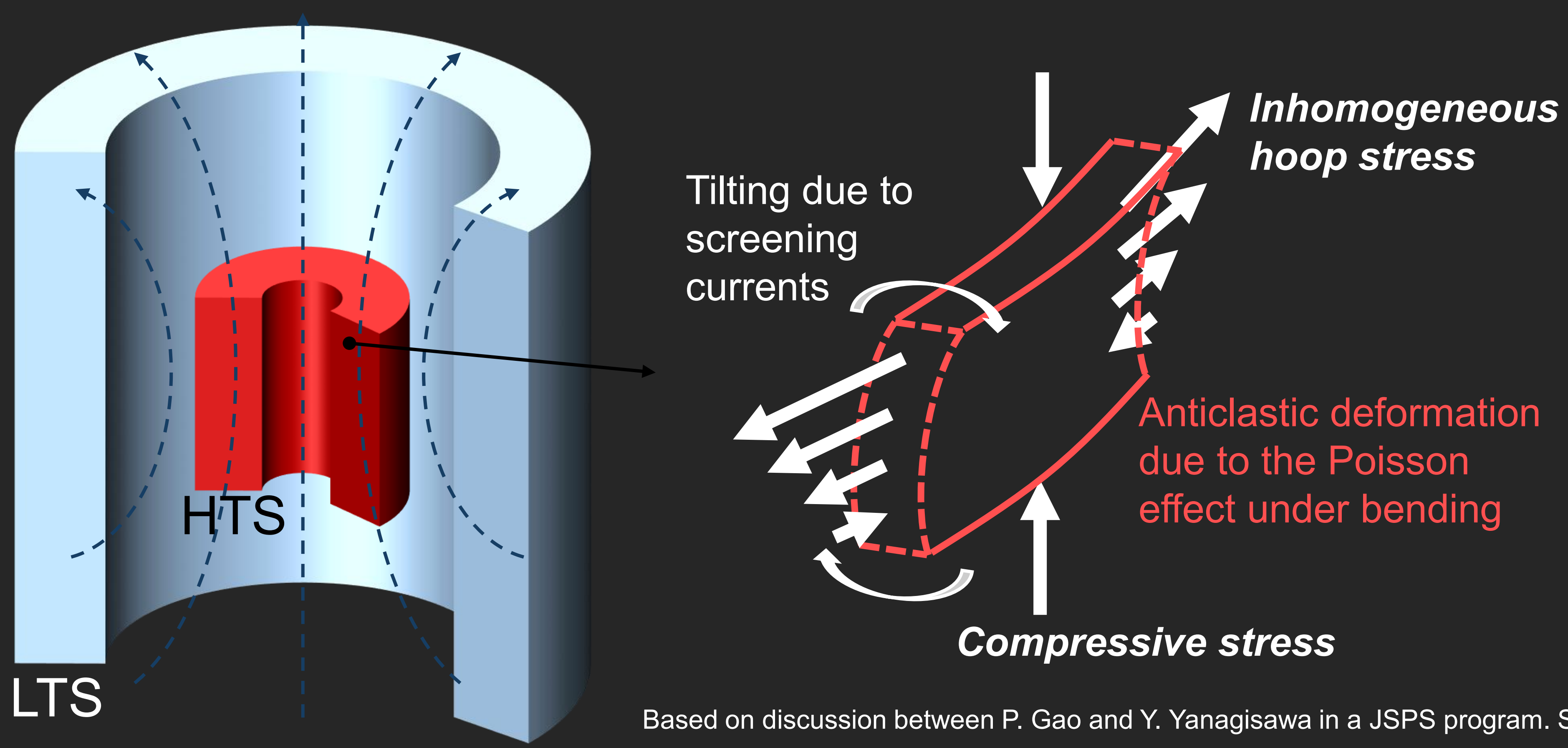
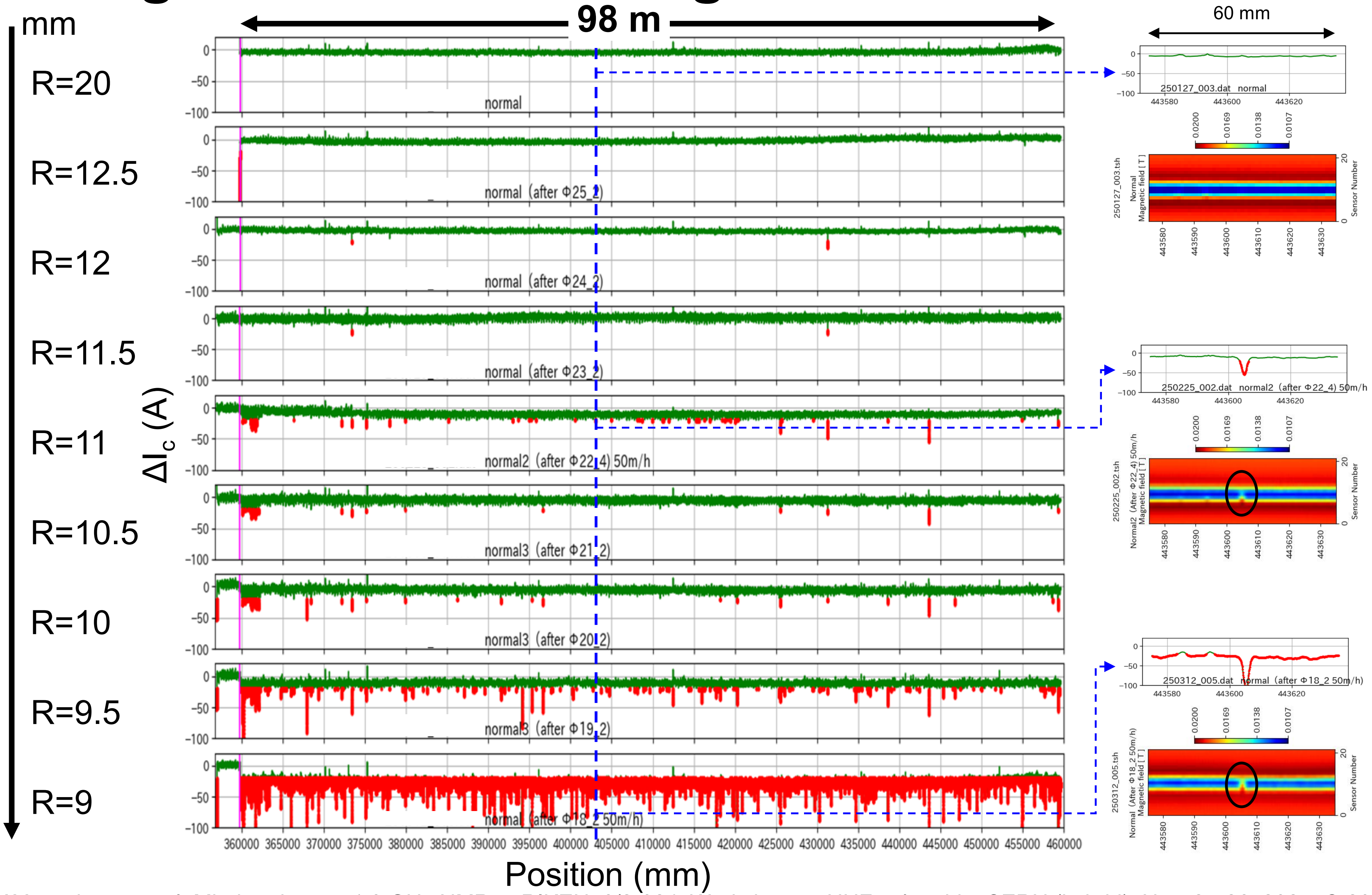
Stress and strain under bending and electromagnetic forces



Based on discussion between P. Gao and Y. Yanagisawa in a JSPS program. Submitted.

For persistent-mode operation, REBCO tapes require uniform strain dependence, and electromagnetic stresses and strains must be carefully managed within the coil structure.

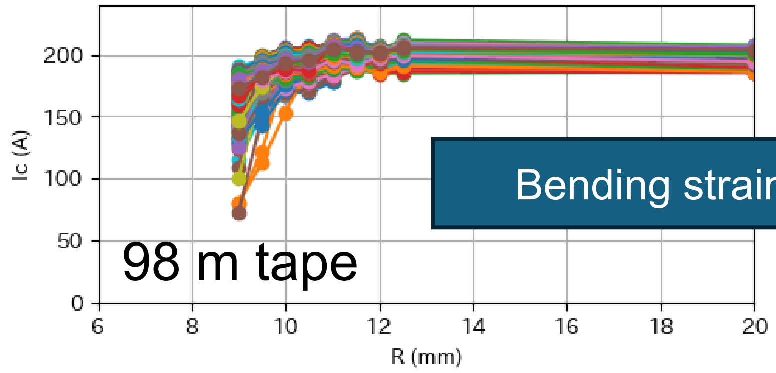
Ic degradation in bending test on a 100 m-class REBCO tape



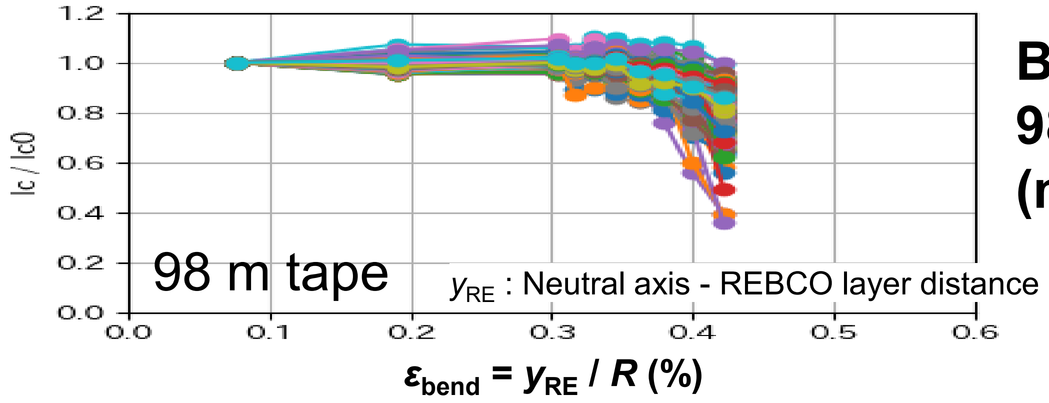
- **Bending tests (REBCO layer outward) at RT and Ic measurements with Tapestar at 77 K.**
- **Ic progressively degrades as the bending radius, R, becomes smaller.**
- **The entire length shows degradation at a bending radius of ~9 mm.**

Bending strain dependence of a 100 m-class REBCO tape

98 m tape data with 1900 divisions

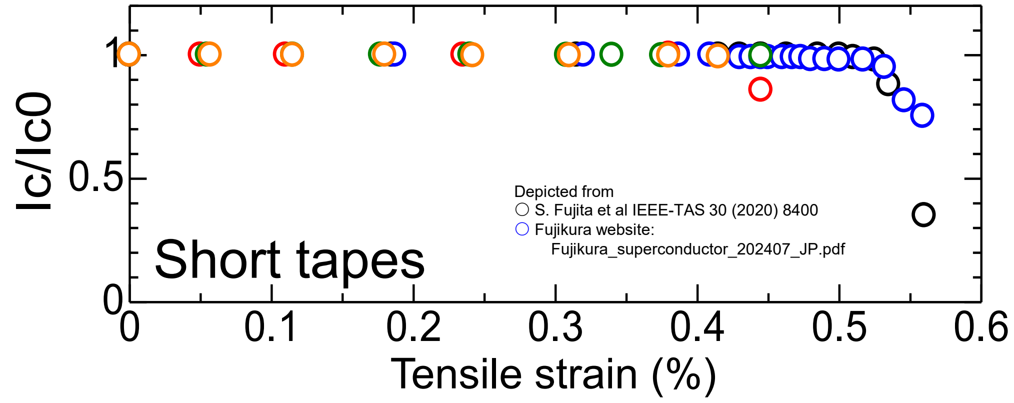


Bending strain



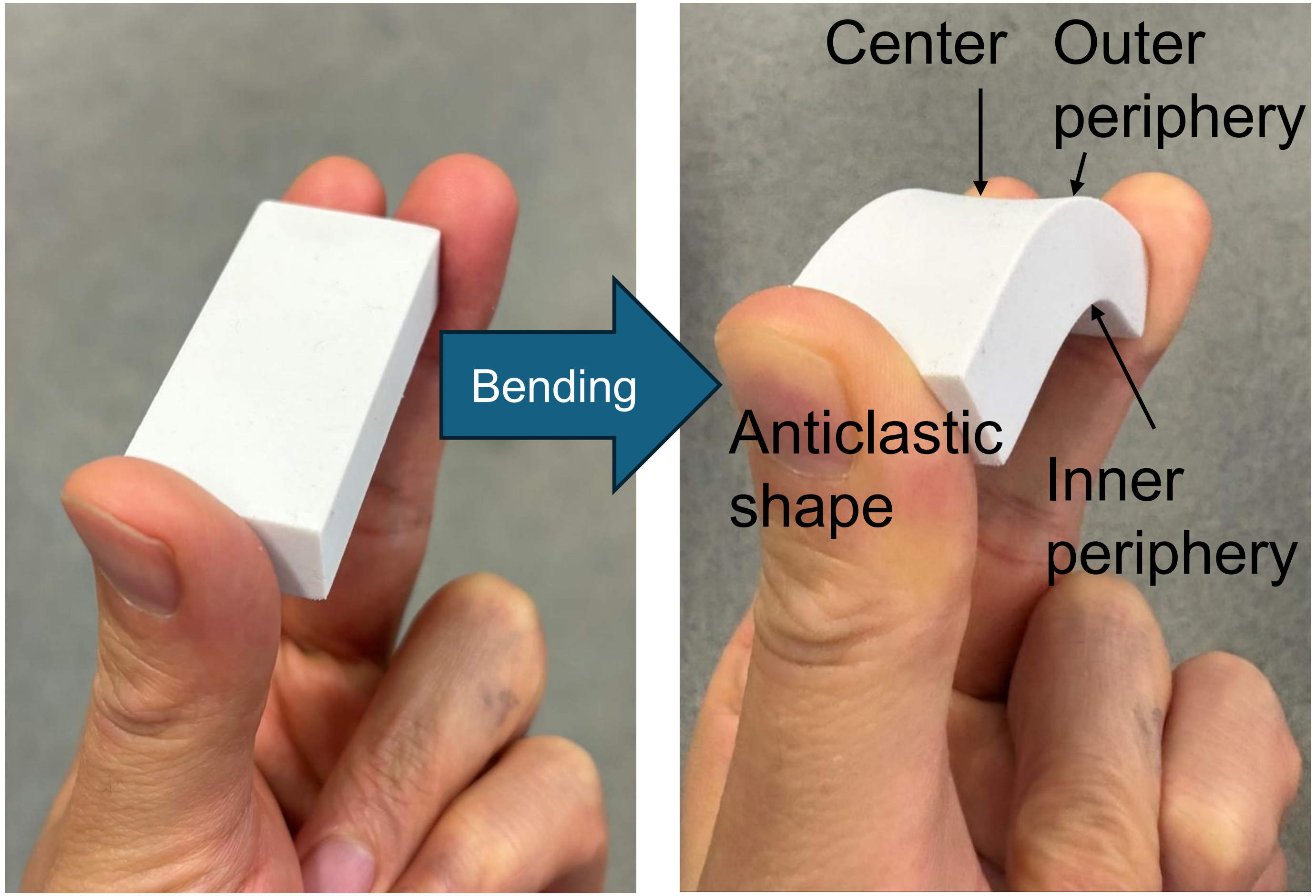
Bending test for a 98 m tape at RT (magnetization)

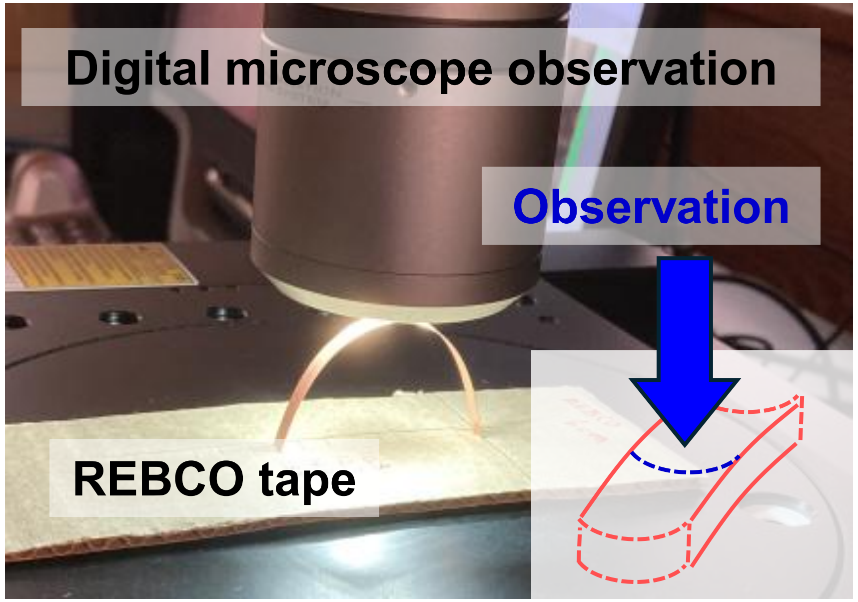
?

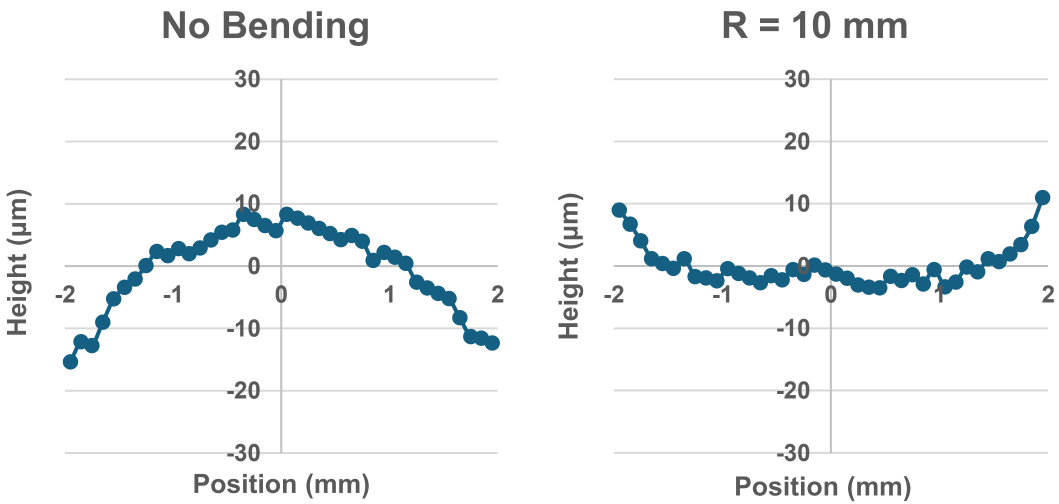


Tensile test for short tapes at 77 K (four-terminal)

Poisson effect in bending

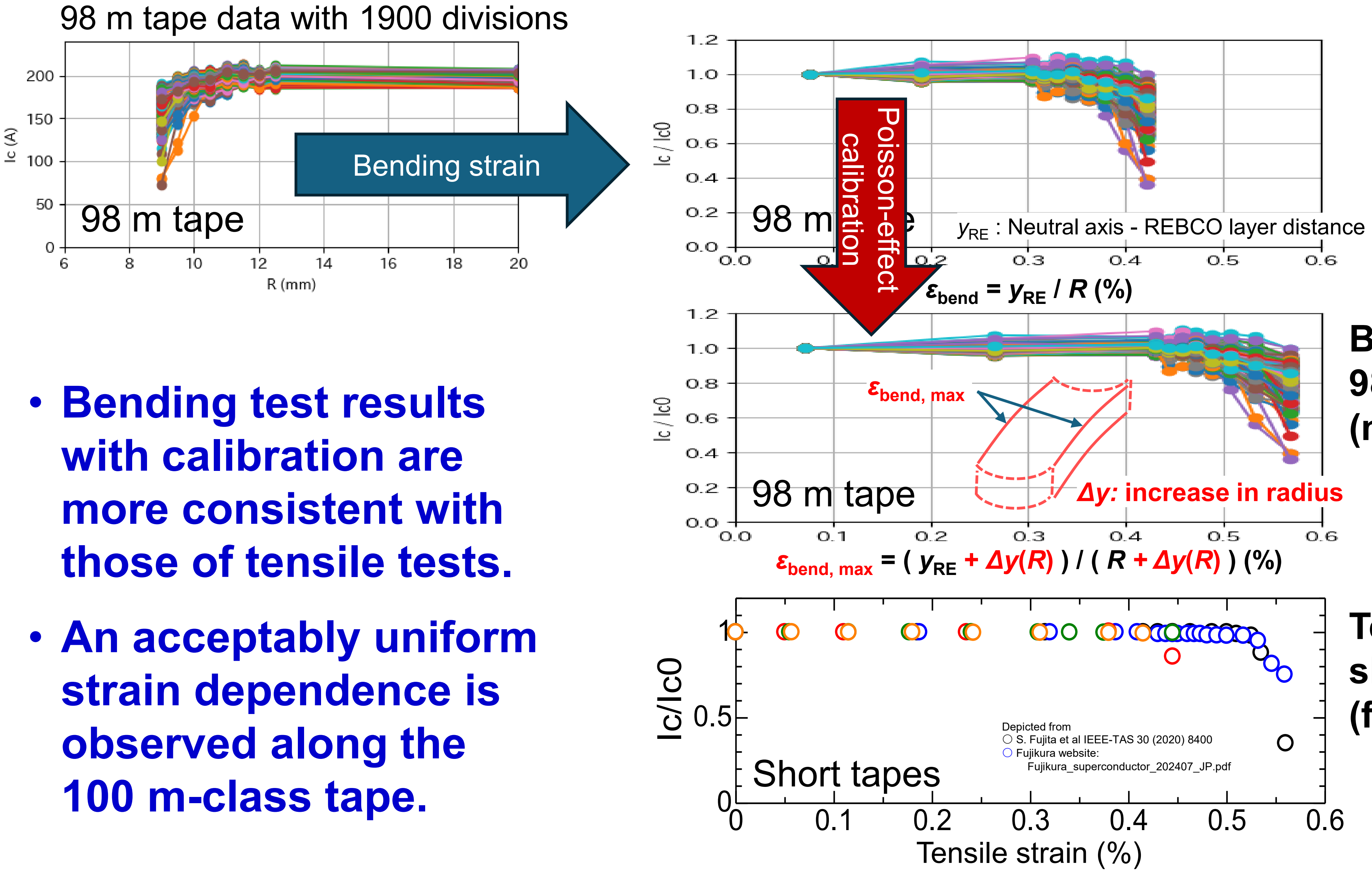






References:
- Y. Pan and P. Gao, *SuST* **36** (2023) 045006
- Private communication with P. Gao

Bending strain dependence of a 100 m-class REBCO tape



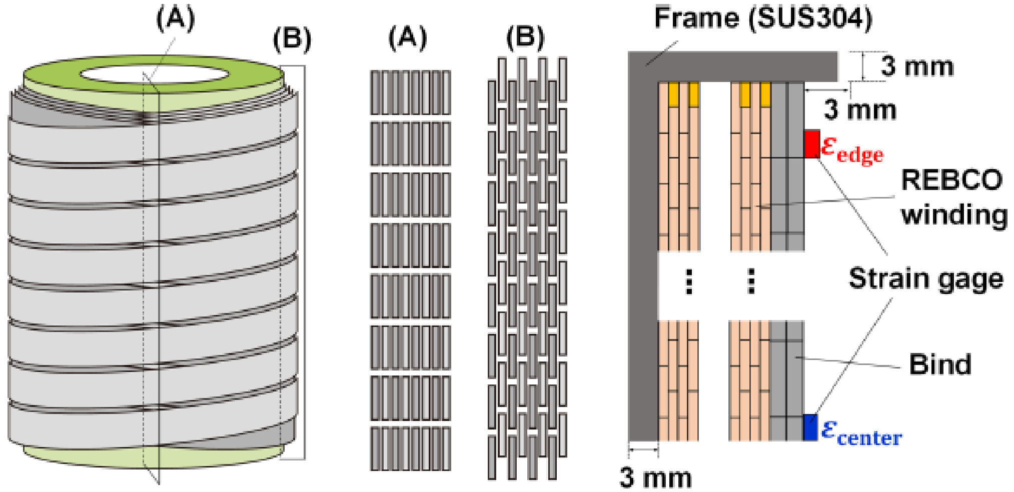
Bending test for a 98 m tape at RT (magnetization)

Similar dependence

Tensile test for short tapes at 77 K (four-terminal)

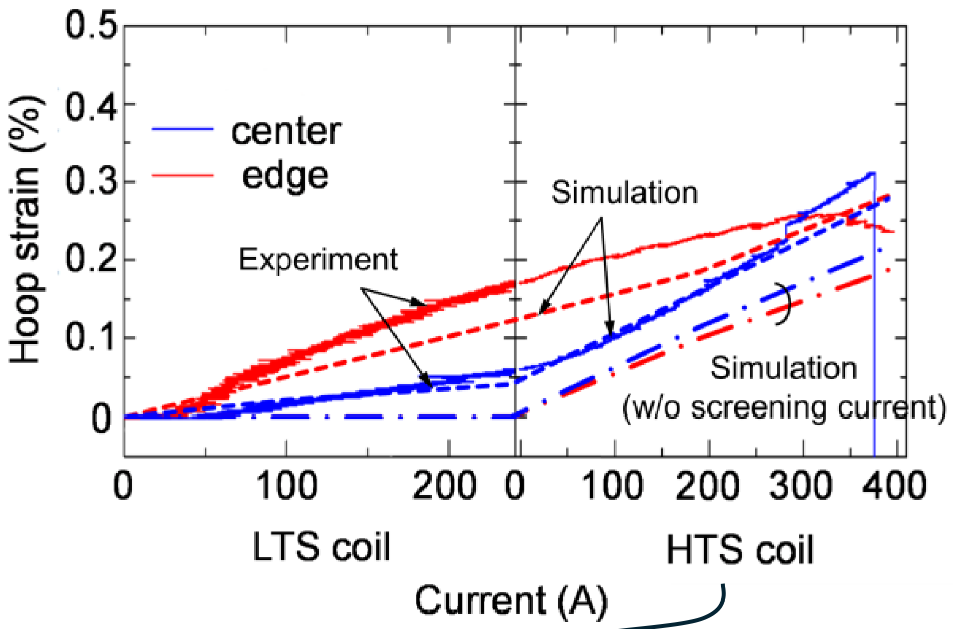
- **Bending test results with calibration are more consistent with those of tensile tests.**
- **An acceptably uniform strain dependence is observed along the 100 m-class tape.**

Coil test under high hoop and compressive stresses

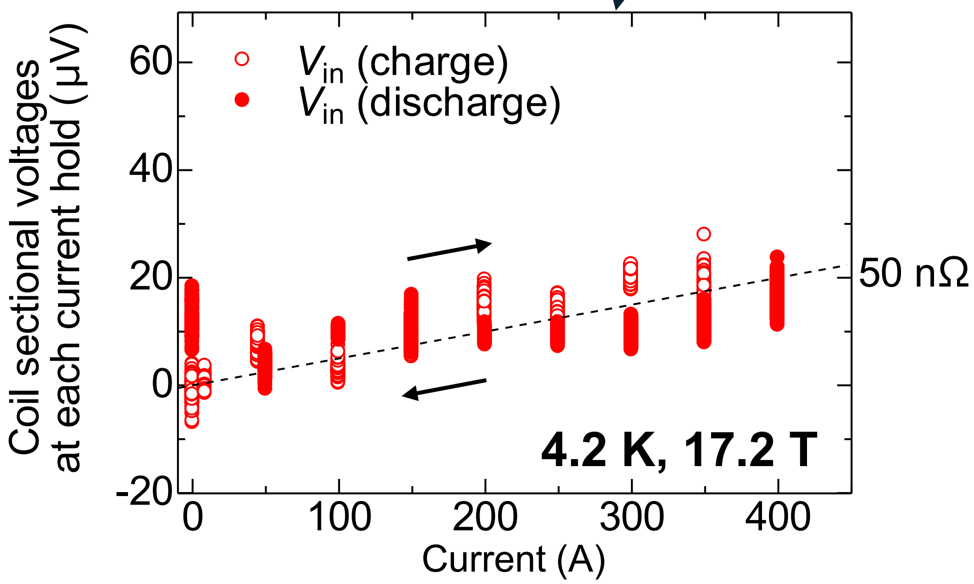


Parameter	Values
ID / OD / length	118 / 122 / 374 mm
Layers	8
Turn / layer	90
Total tape length	272 m
I	400 A
B_0	0.922 T
Background field	17.2 T
Maximum *BJR*	434 MPa
Compressive stress	38.9 MPa

Ref: K. Naito *et al* 2023 *IEEE-TAS* **33** 4300805



Measured strains are reproduced by a simulation that includes screening currents.



No normal voltage appears under high hoop and compressive stresses.

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Basic strategy for quench protection

- **Quench from HTS coils**

  Detect a small normal voltage during current pause

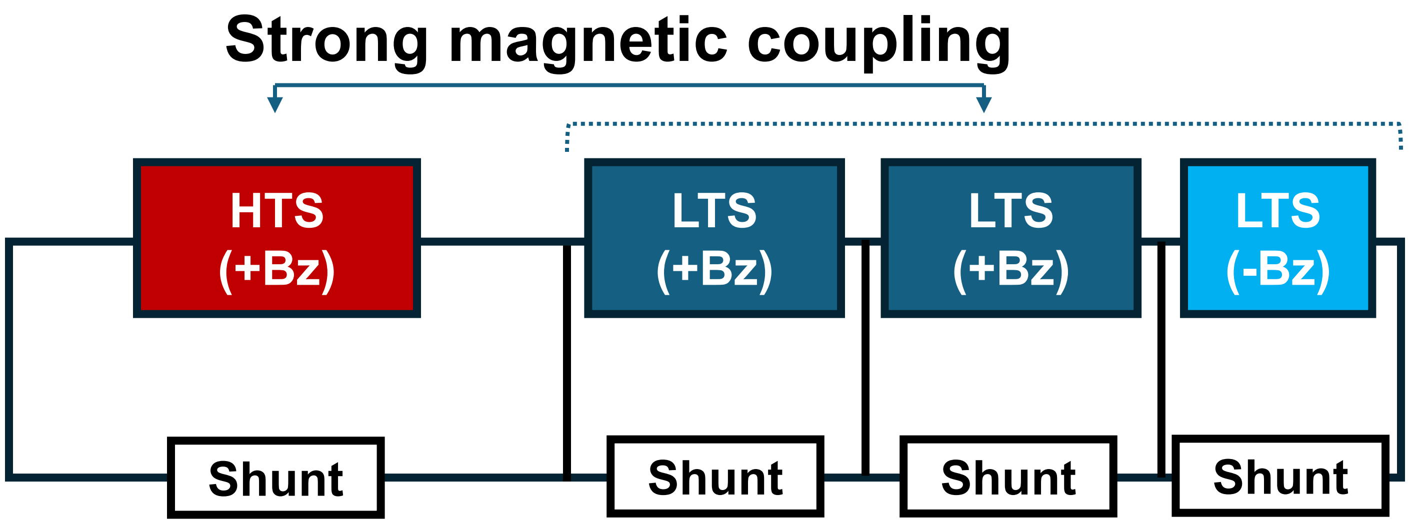
  => Stop charging => Repair or replace coil

- **Quench from LTS coils**

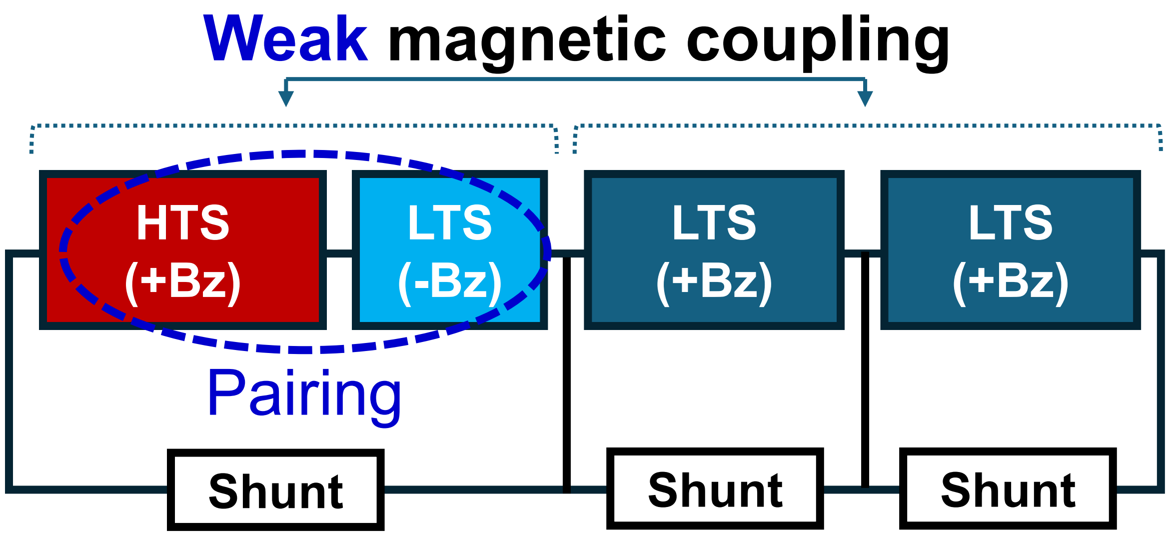
  Induced quench in REBCO coil

  => Catastrophic (burnout) => Must be strictly avoided

How to prevent induced-quench on REBCO coils?



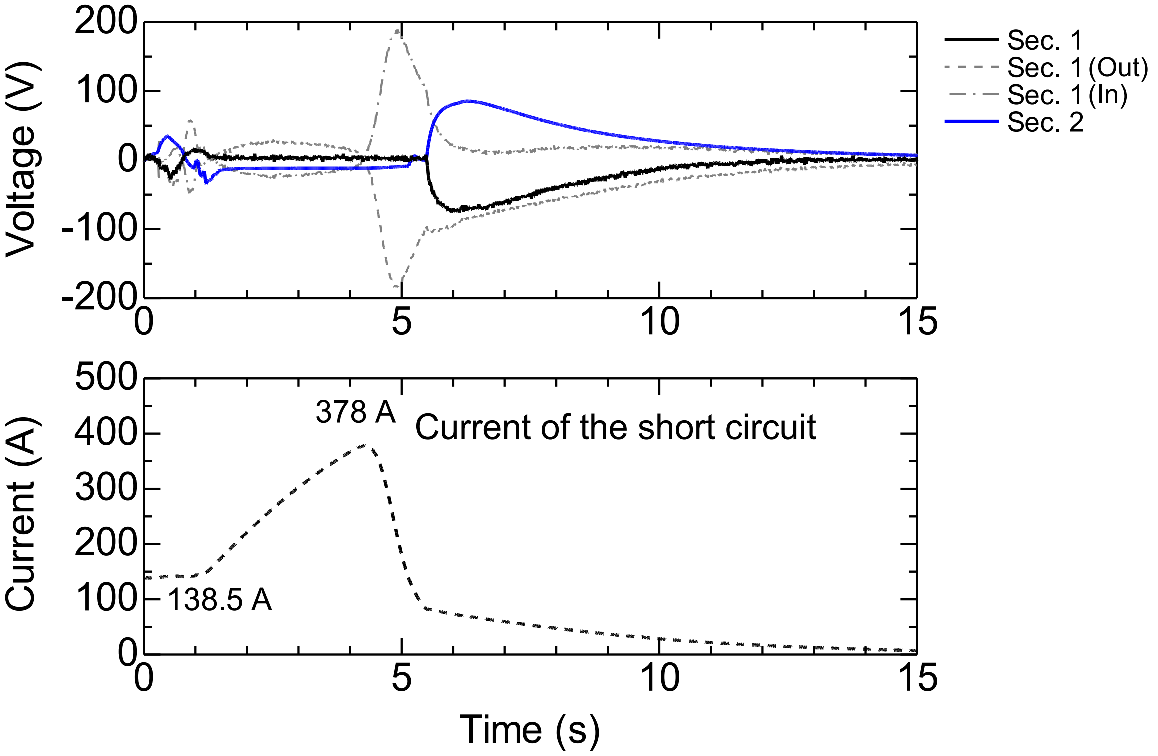
Strong coupling between the HTS and LTS sections can trigger an induced quench in the HTS coil during an LTS coil quench.



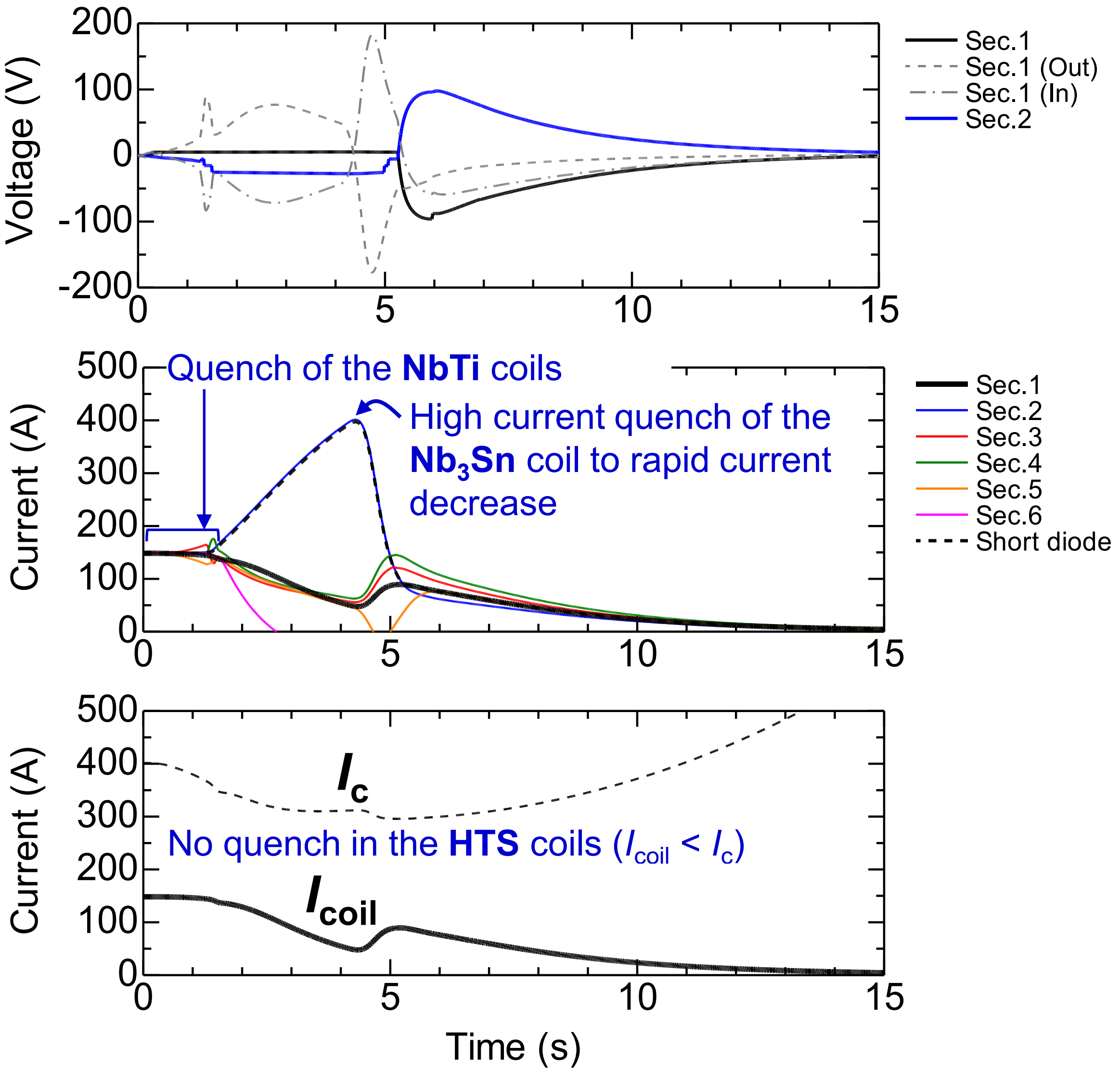
Pairing the HTS coil with negative-field coils reduces magnetic coupling and helps prevent induced quenches.

Quench measurements at 600 MHz on a model magnet

Measurements

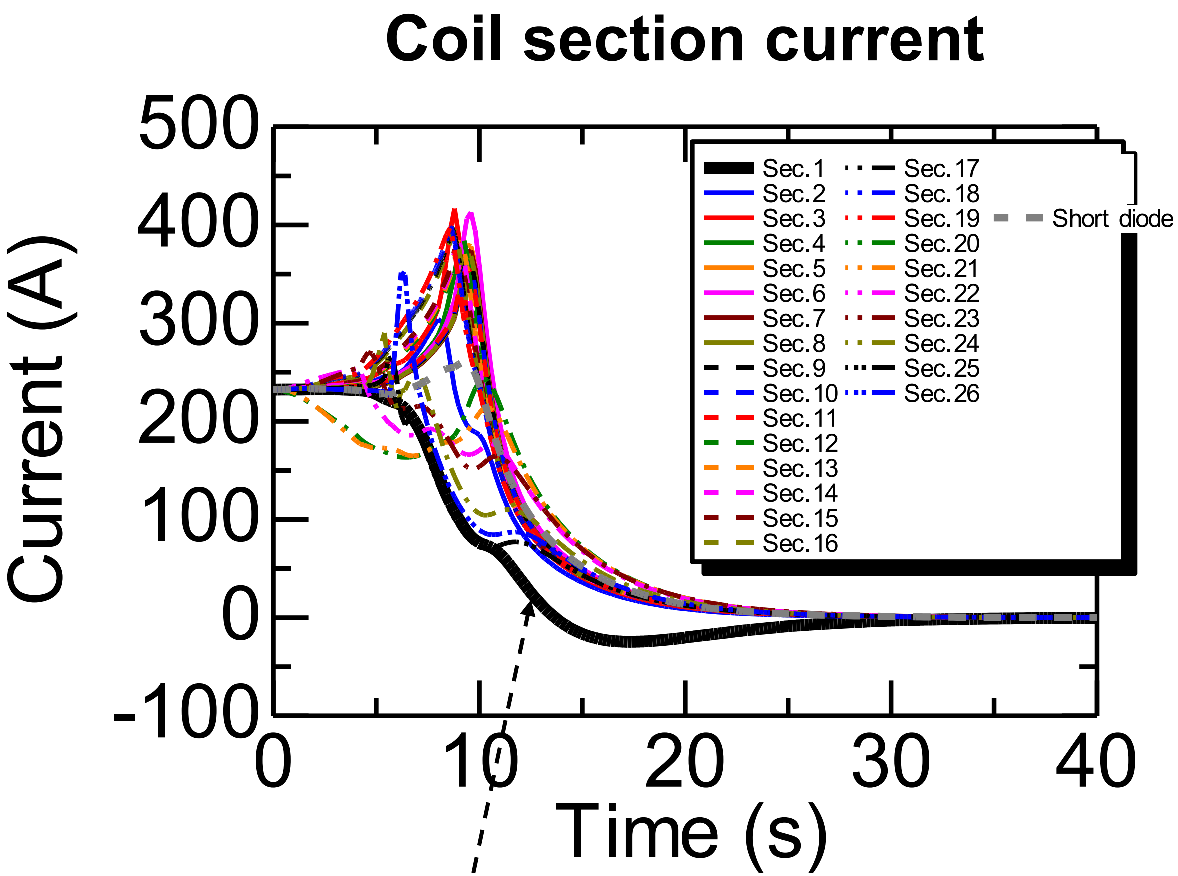


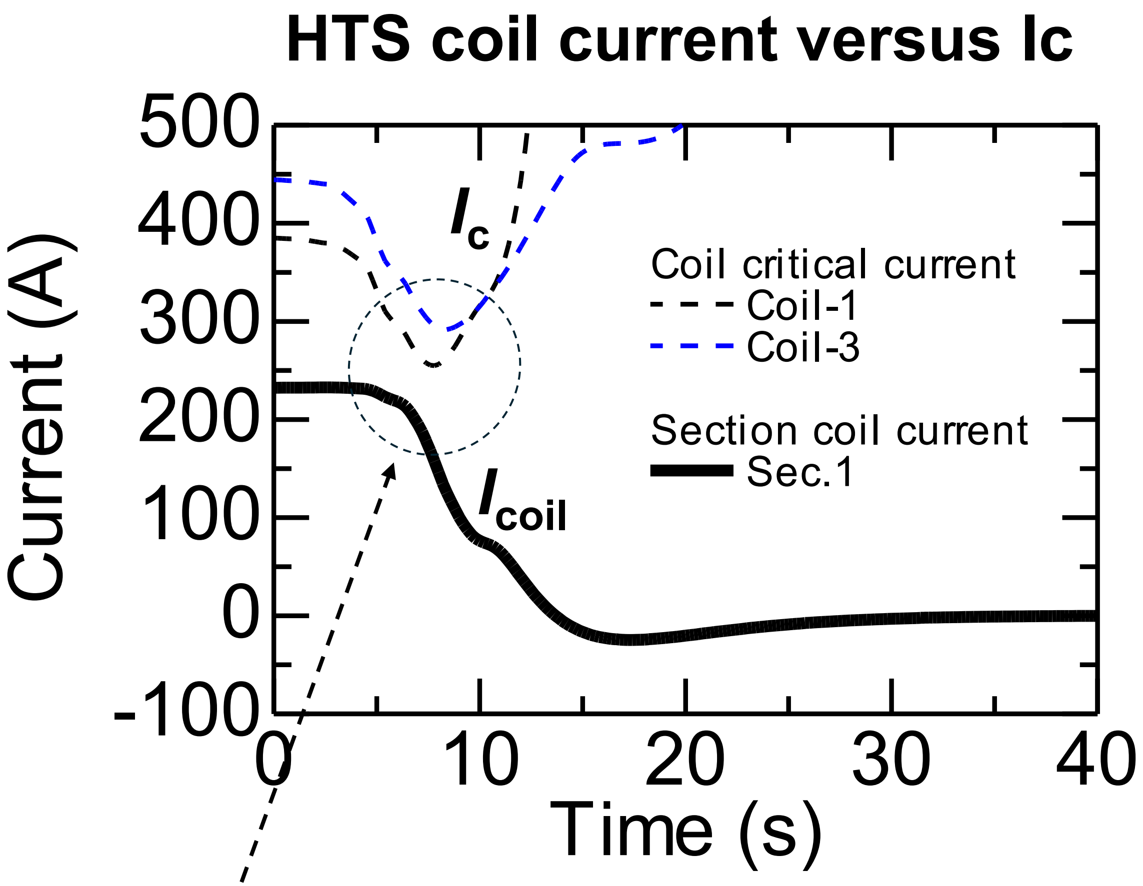
Simulation



- NbTi coils rapidly quenched <1.5 s; Nb_3Sn: quenched at a high current at ~4.5 s.
- Simulation reproduces the experiment.
- HTS coil: no quench ($I_{coil} < I_c$) even during the rapid current decay of the Nb_3Sn coil, owing to weak magnetic coupling.

Quench simulation on the 1.3 GHz magnet





- While the LTS-coil current shows large fluctuations, the HTS-coil current decreases rapidly and monotonically due to the weak magnetic coupling.
- It stays below the critical current, preventing the HTS coil from quenching.

Conclusions

- A series connected 1.3 GHz (30.5 T) LTS/HTS persistent-mode magnet incorporating REBCO superconducting joints
- The design has been updated: BSSCO has been replaced by REBCO.
- The strain dependence of REBCO tapes is uniformly acceptable, and coil tests under high stress have demonstrated excellent performance.
- A critical protection requirement is to prevent REBCO coil quenching during an LTS coil quench.
- The magnet is currently under construction.

