Screen current effects, experiencing with quenching REBCO tapes, and implications

Ye Yang[1], Tengming Shen[1], Ramesh Gupta[2], Toru Ogitsu[3]

1. Lawrence Berkeley National Lab
2. Brookhaven National Lab
3. KEK

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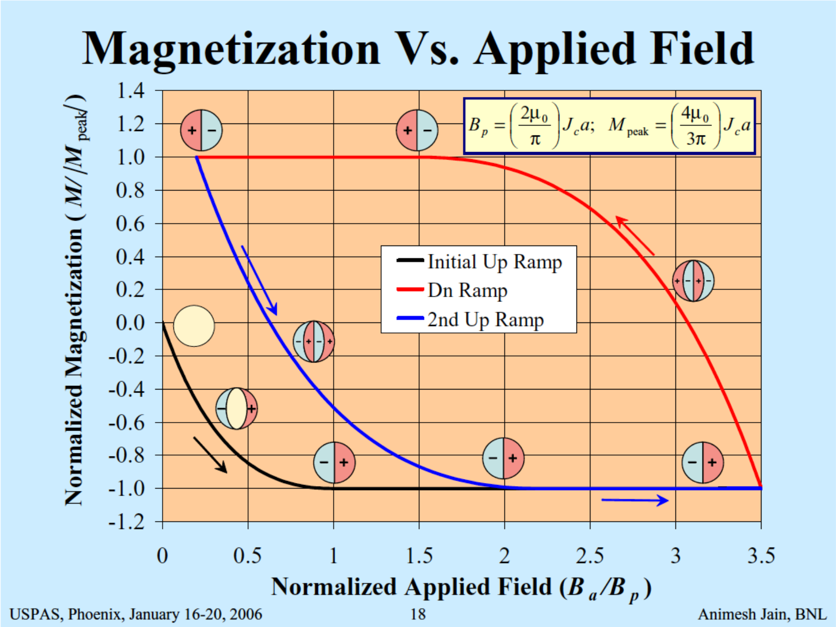
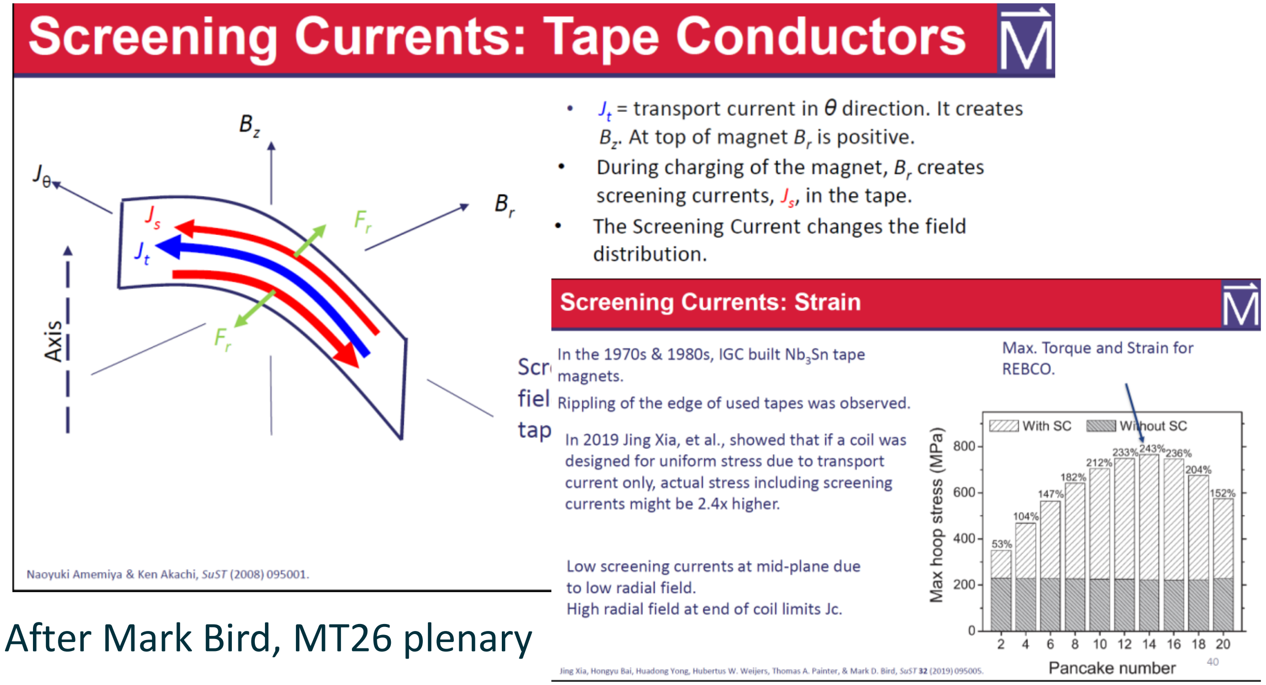
Outline and motivations

- Superconductor is a nonlinear magnetic material.
- Its magnetization also decays with time.



- $\Delta M \propto J_c \cdot D_{eff}$
- LHC Nb-Ti dipole wire, D_{eff}=6-7 μm.
- High-Lumi LHC Nb_3Sn wire, D_{eff}~50 μm.

- Large screen currents affect both field quality and the ability of REBCO magnets to survive high fields.
  - Results of FEM models of KEK REBCO coils in a BNL Nb_3Sn magnet
- Experience with quenching REBCO tapes



After Mark Bird, MT26 plenary

SCIF (screen current induced field) in a hybrid magnet – overall design

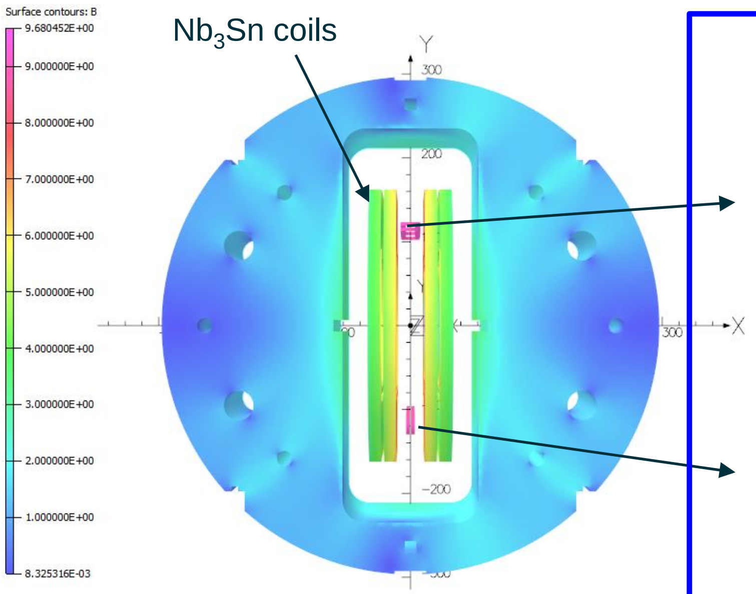
BNL Nb_3Sn magnet:

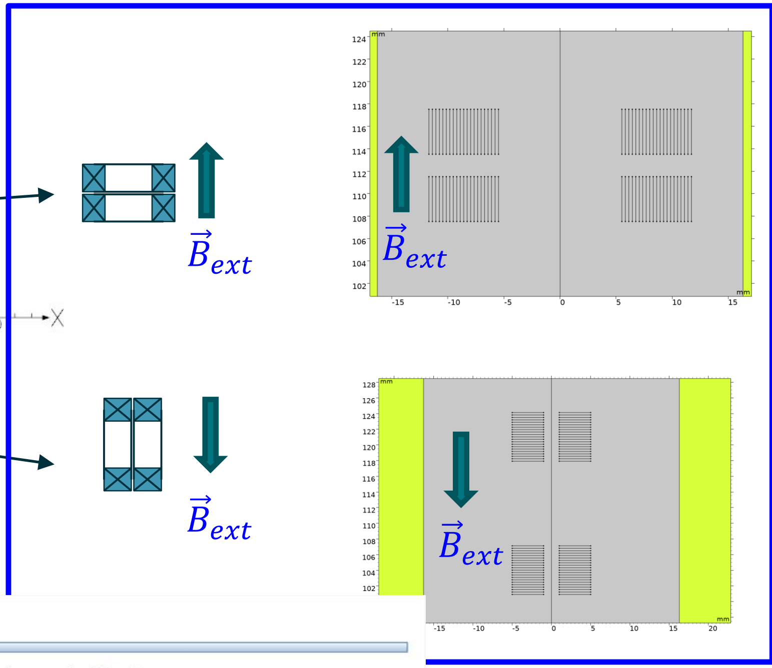
Item	Unit	Value
Magnet type	-	2-in-1
Horizontal aperture	mm	31
Vertical aperture	mm	338
Central field	T	8.7
Nominal current	A	8000
Nominal current density	A/mm^2	425

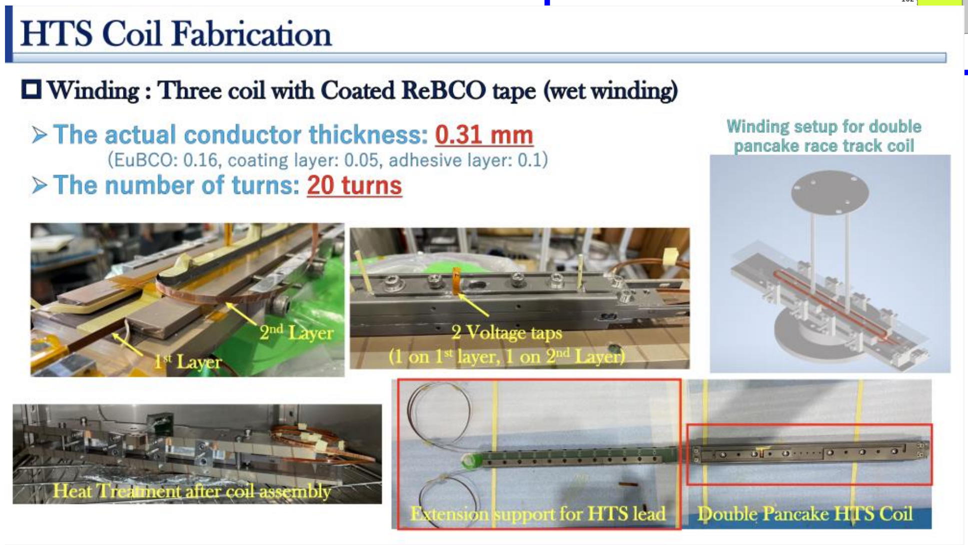
KEK HTS coils:

Item	Unit	Value
Number of HTS tape	-	20
HTS Tape width	mm	4
Thickness of HTS layer	μm	2.2
Thickness of HTS tape	μm	310
Current of HTS coil	A	500
Center field	T	0.8

REBCO (flat racetrack) coils







HTS coil construction led by Masami Iio, Mukesh DHAKARWAL from KEK and tests led by Febin Kurian, Piyush Joshi from BNL.

US Japan HEP collaboration on high temperature superconducting magnets for accelerator facilities

Tengming Shen (US PI), LBNL; Toru Ogitsu (Japan PI), KEK

Xiaorong Wang (US CO-PI), LBNL; Ramesh Gupta, (US CO-PI), BNL; Naoyuki Amemiya (Japan CO-PI, Kyoto University).

Modelling the Magnetization in HTS Tapes with FEM tool (COMSOL)

T-A formulation:

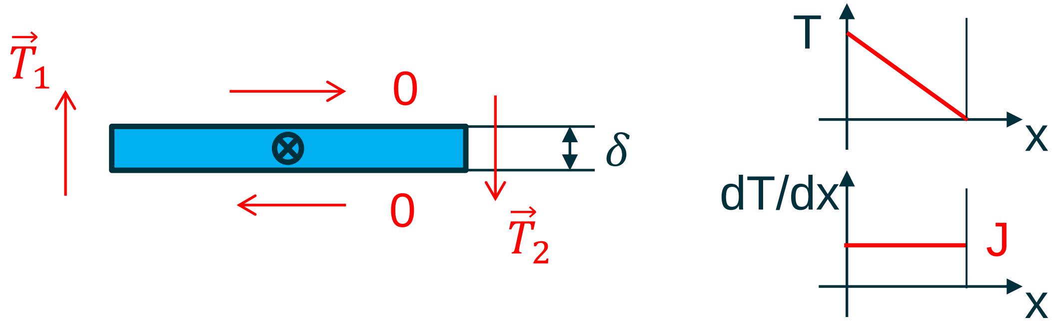
$$\begin{cases} \nabla \times \left(\rho_{HTS} \nabla \times \vec{T}\right) + \dfrac{\partial \vec{B}}{\partial t} = 0 & \text{HTS film} \\ \nabla \times \vec{B} - \mu_0 \vec{J} = 0 & \text{Entire domain} \end{cases}$$

$\vec{J} = \nabla \times \vec{T}$ HTS film

$\vec{B} = \nabla \times \vec{A}$ Other domains

Boundary condition:

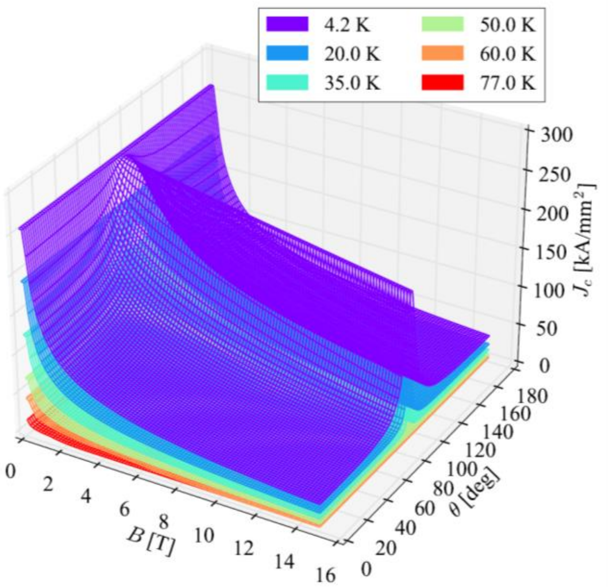
$$I_t = \int \vec{J}\, dA = \int \nabla \times \vec{T}\, dA = \oint \vec{T}\, dl = (\vec{T}_1 - \vec{T}_2)\delta$$



Resistivity of HTS film:

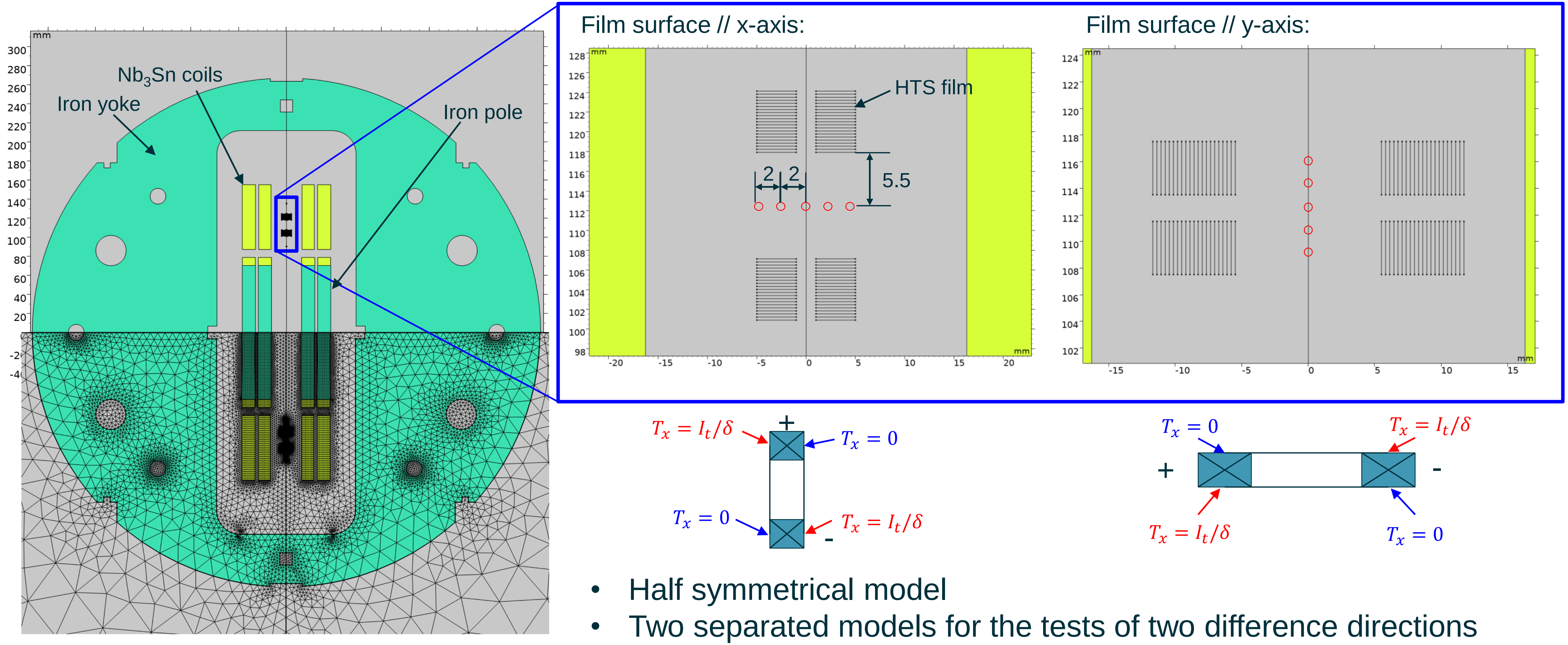
$$\rho_{HTS} = \frac{E_c}{J_c(T, B, \theta)} \left| \frac{\vec{J}}{J_c(T, B, \theta)} \right|^{n-1}$$

N value is fixed at 45



Critical surface for ReBCO tape:

Numerical Model – 2D infinitive FEM model



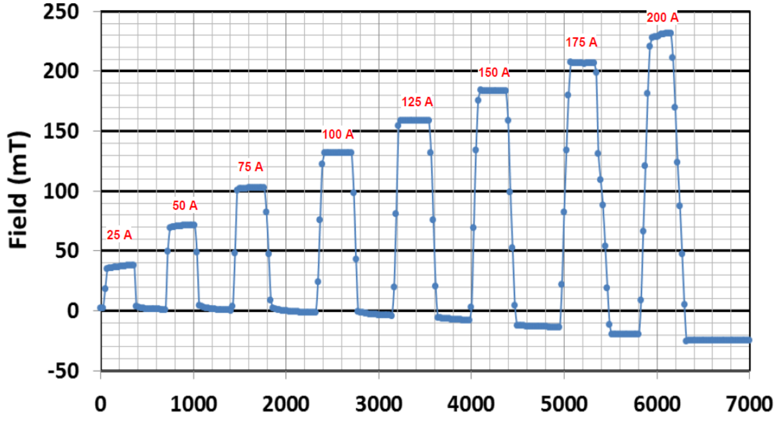
- Half symmetrical model
- Two separated models for the tests of two difference directions
- Hall sensor is set at the center of the HTS coil with the interval of 2mm

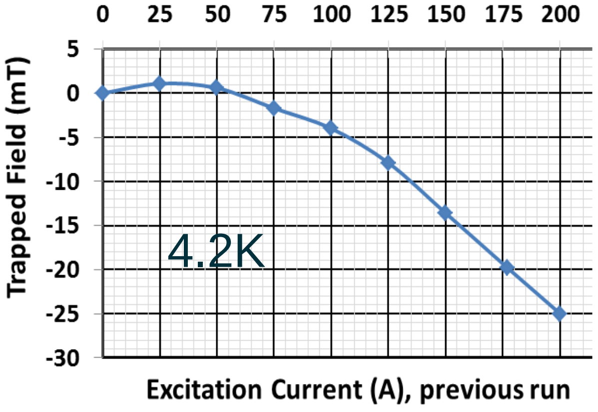
Validating the modeling technique: The benchmark case

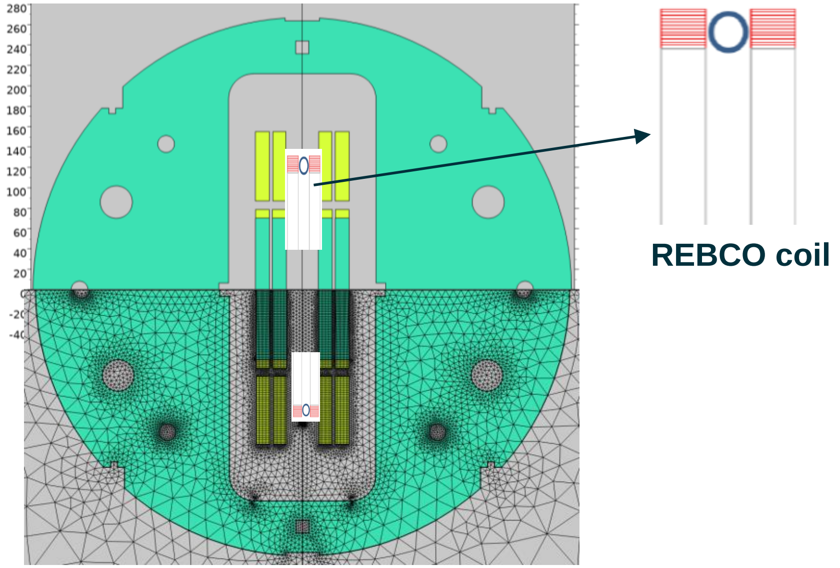
R. Gupta et al, Design, construction, and test of HTS/LTS hybrid dipole, *IEEE Transactions on Applied Superconductivity*, 28(3), 4002305, 2018
Coil construction and measurement financially supported by a SBIR award from US. DOE OHEP to Particle Beam Lasers, Inc. and BNL.

Measurement:

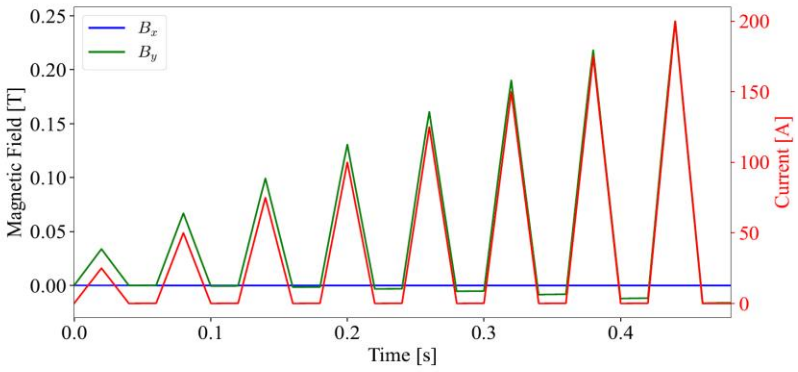
0 → 25 → 0 → 50 → 0 → 75 → 0, …

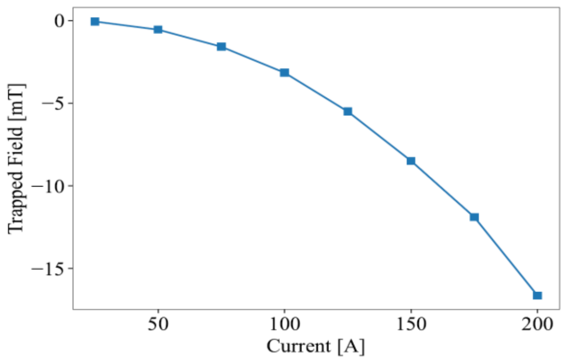






Simulation:





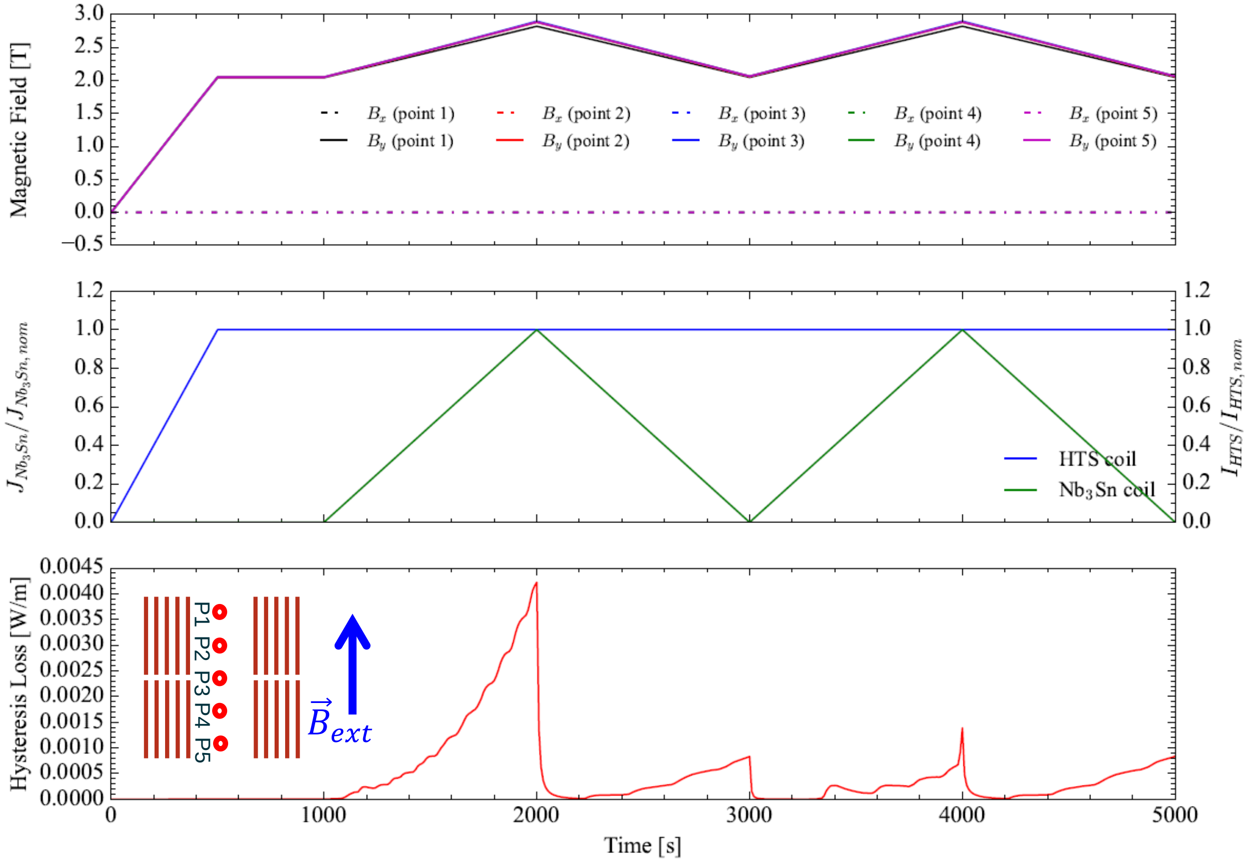
HTS Tape:

Manufacturer: **AMSC** 0.20 x 12.1 mm Tape
YBCO YBCO layer is 10 mm x 1.2 µm
Description : ***3R-174-1-37-38*** **Area (mm2):** 2.420 **Length:** 30 mm
SAMPLE # **1** **SC_Area (mm2):** 0.012
FIELD Dir. **PERP-H**

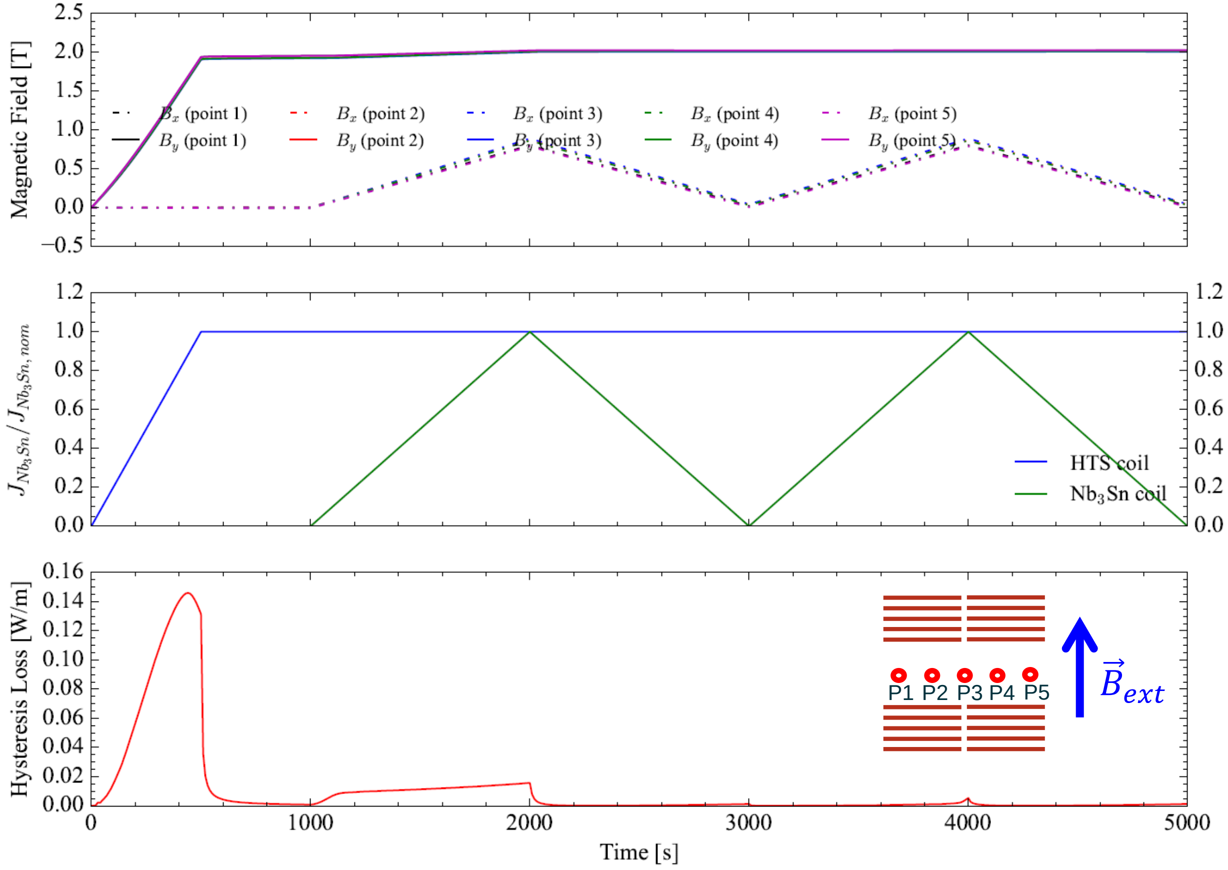
Thanks Ramesh for the information!

Return to the US-Japan case:
Field and AC loss during energization of the Nb_3Sn Magnet and HTS coils

B // Tape:

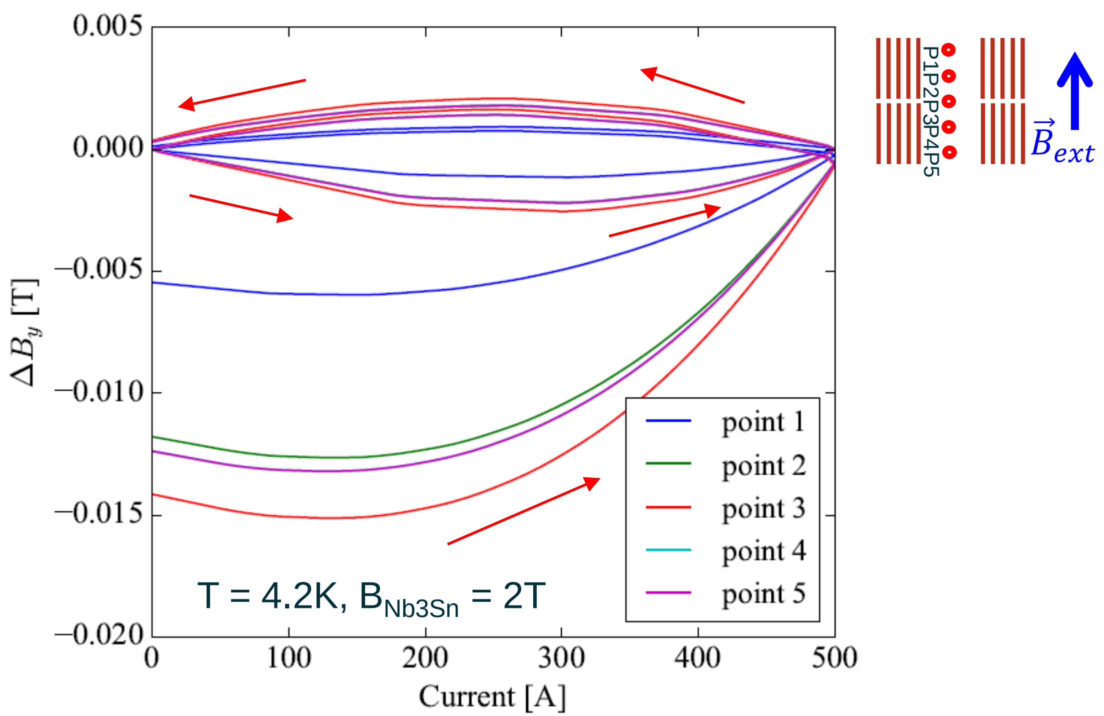


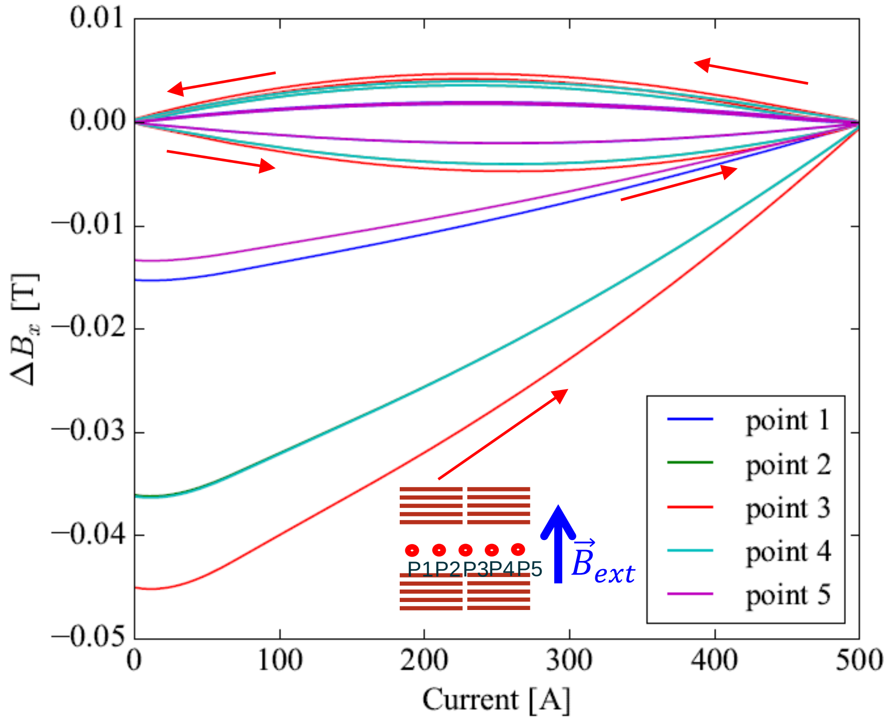
B ⊥Tape:



- Energized Nb_3Sn magnet first, then powered up the HTS coil with two cycles
- Bx and By are generated by the cases B//Tape and B⊥tape, respectively

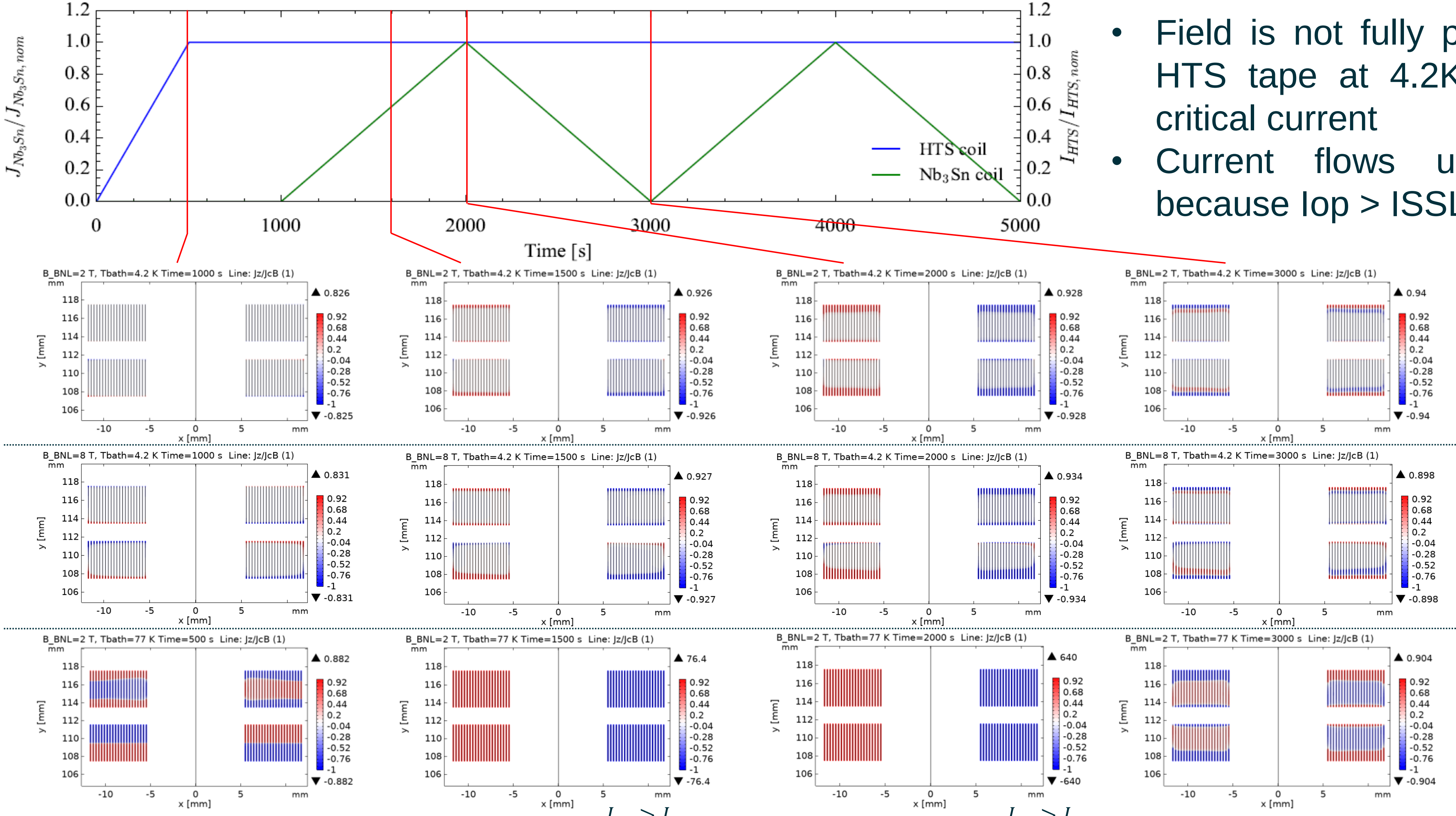
SCIF by HTS coils during energization with LTS magnet field removed





- Case of B // c has a large loop about dBx ~ 10 mT
- The loop for the case B // ab only has dBy ~ 5mT

Screening Current distribution (B // Tape case)



- Field is not fully penetrated into the HTS tape at 4.2K due to the high critical current
- Current flows uniformly at 77K because Iop > ISSL

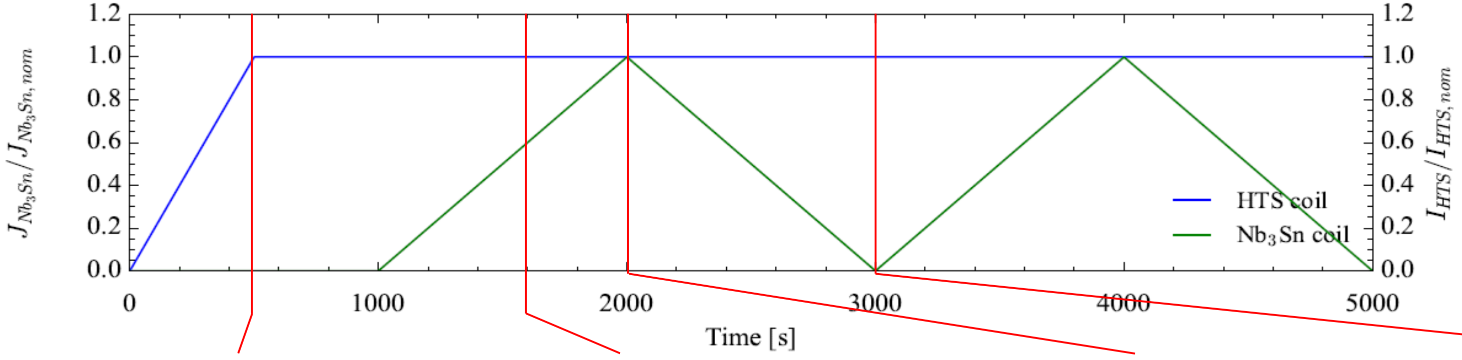
B = 2T, T = 4.2K

B = 8T, T = 4.2K

B = 2T, T = 77K

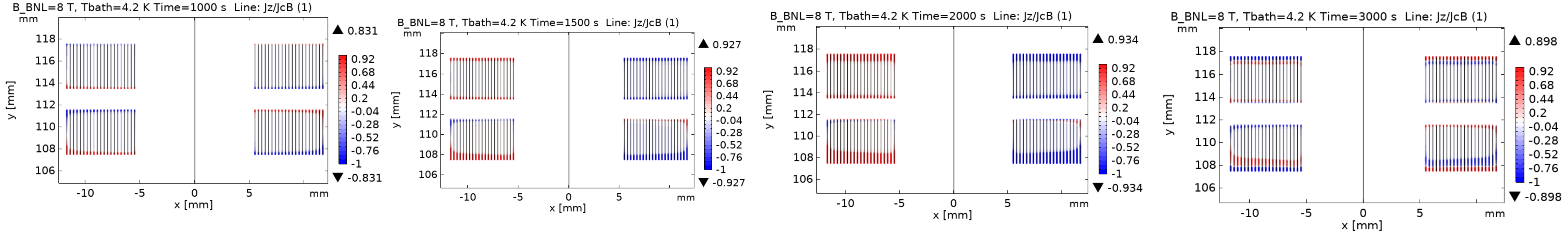
$I_{op} > I_{SSL}$ $I_{op} > I_{SSL}$

Screening Current distribution (B // Tape case)

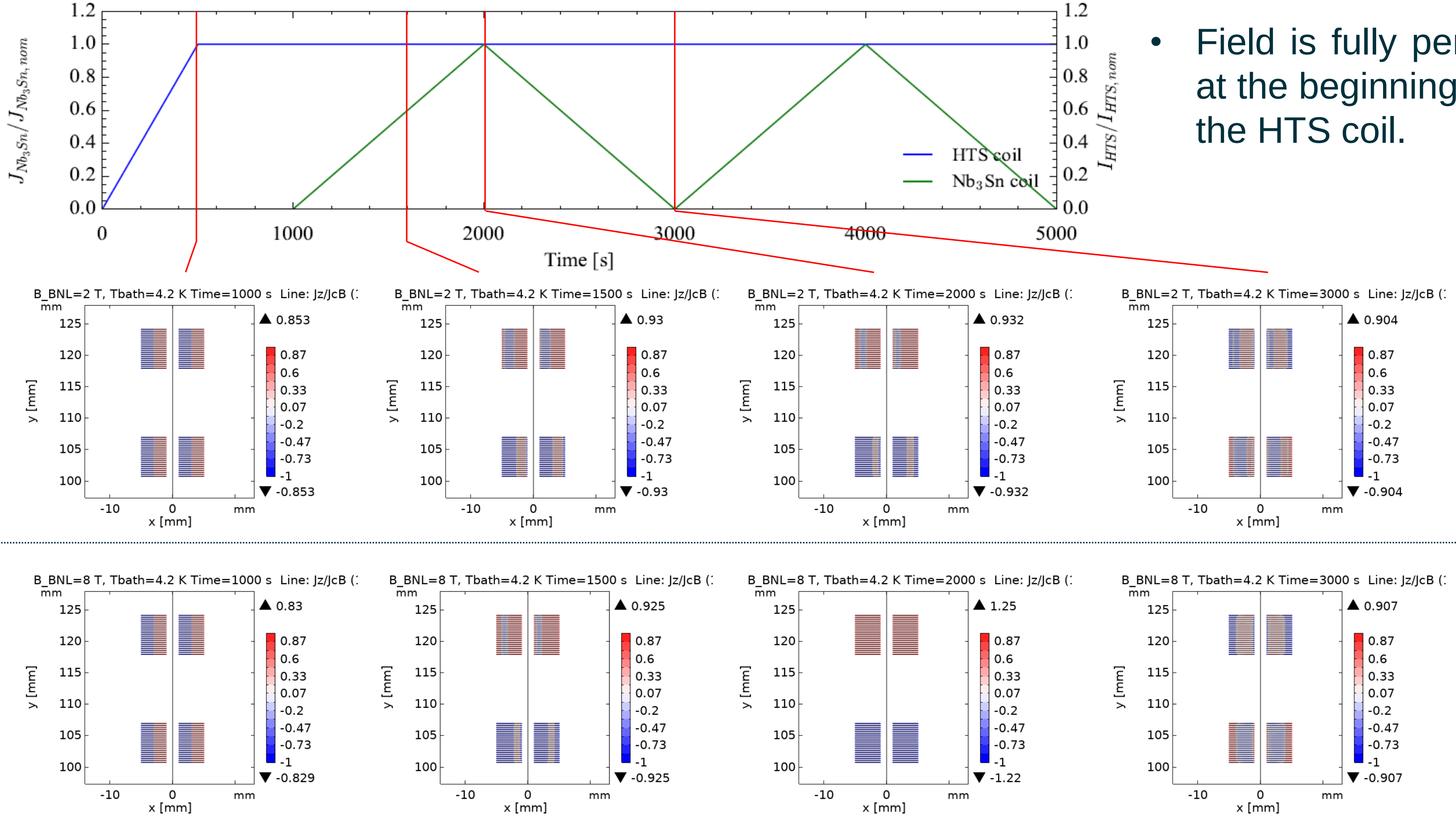


- Field is not fully penetrated into the HTS tape at 4.2K due to the high critical current
- Current flows uniformly at 77K because Iop > ISSL

B = 8T, T = 4.2K



Screening Current (B ⊥ Tape case)



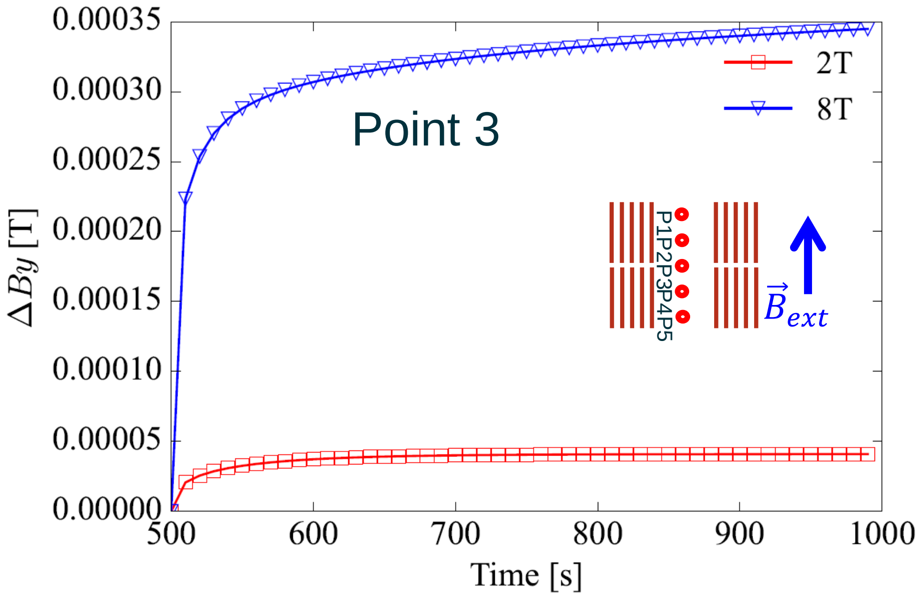
- Field is fully penetrated into the tape at the beginning of the energization of the HTS coil.

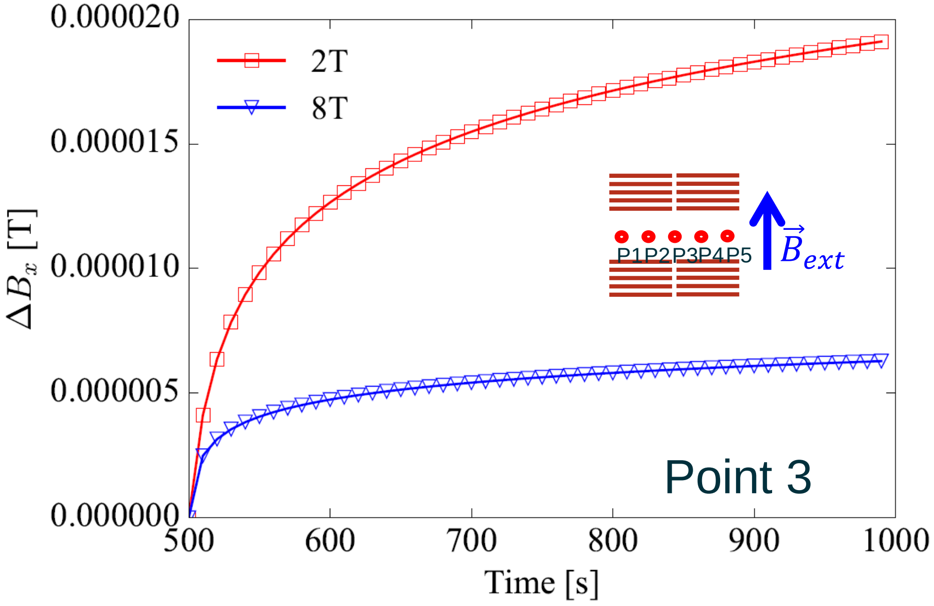
B = 2T, T = 4.2K

B = 8T, T = 4.2K

$I_{op} > I_{SSL}$

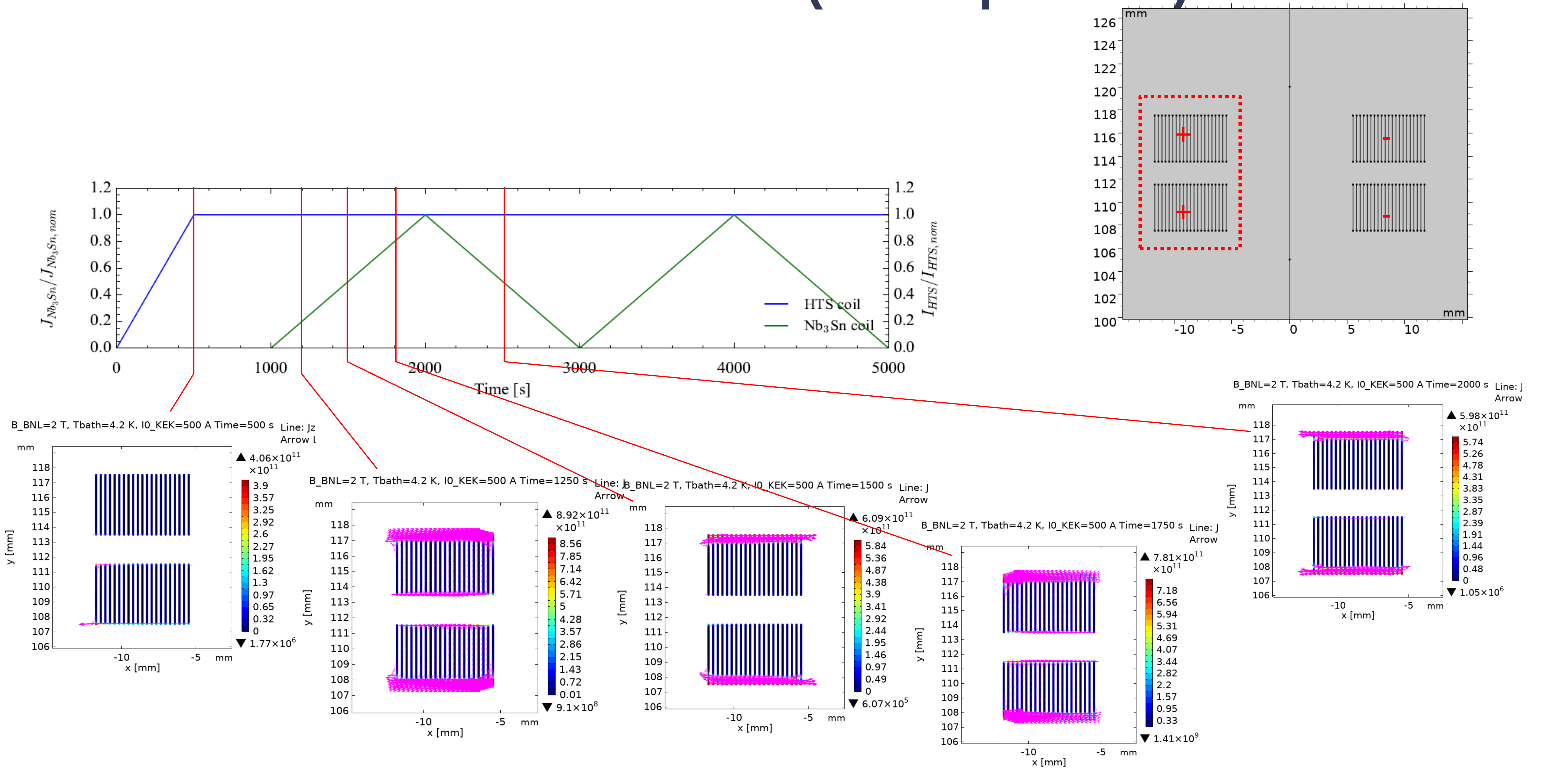
Decay of SCIF after Ramping Nb_3Sn Magnet



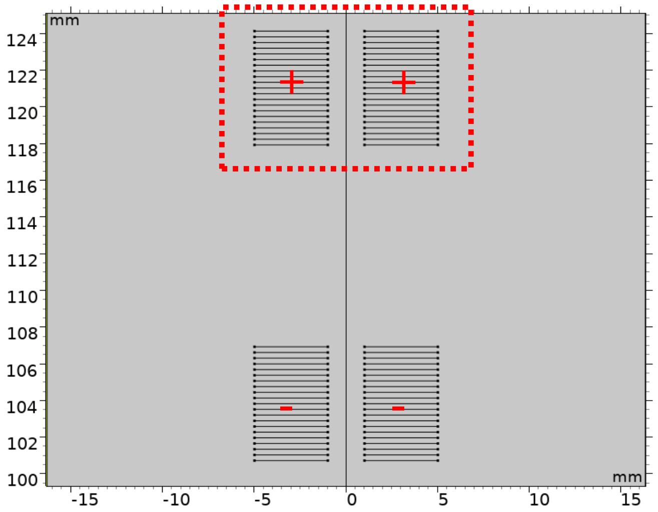


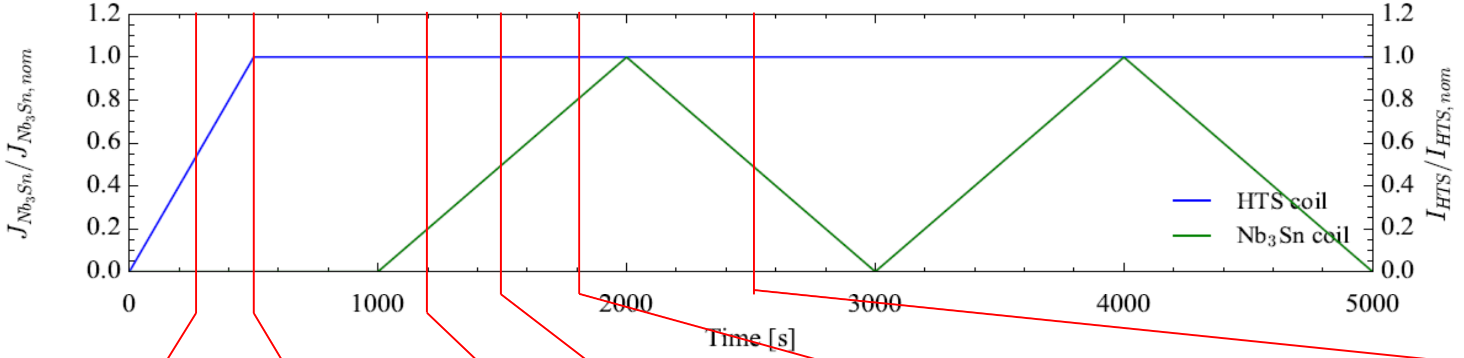
- Field decays as a function of time due to the resistivity of flux flowing
- Field increases because the shielding field is decreased
- Field decay at 2T background field for the case B // c seems faster that at 8T
- For the case B//ab, the field decay is faster at 8T

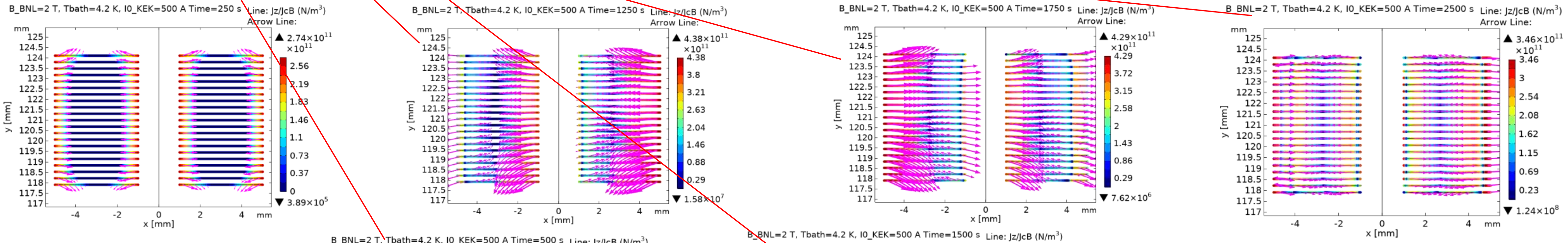
Lorentz Force at the HTS Film (B // Tape case)

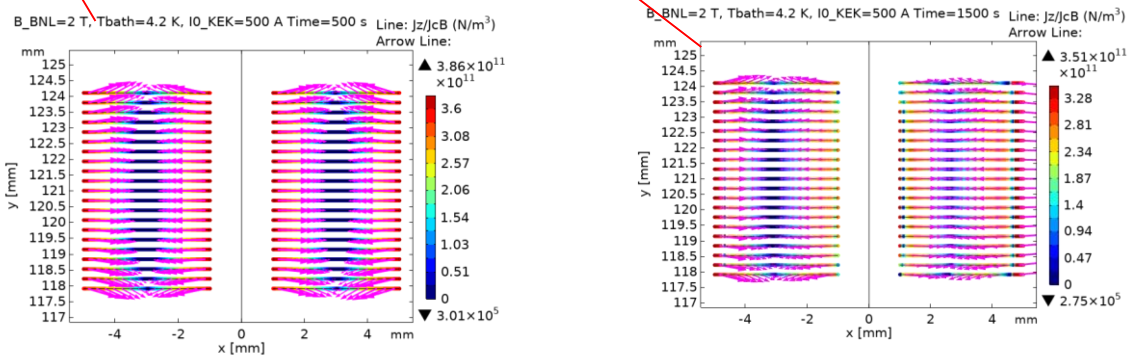


Lorentz Force at the HTS Film (B ⊥ Tape case)



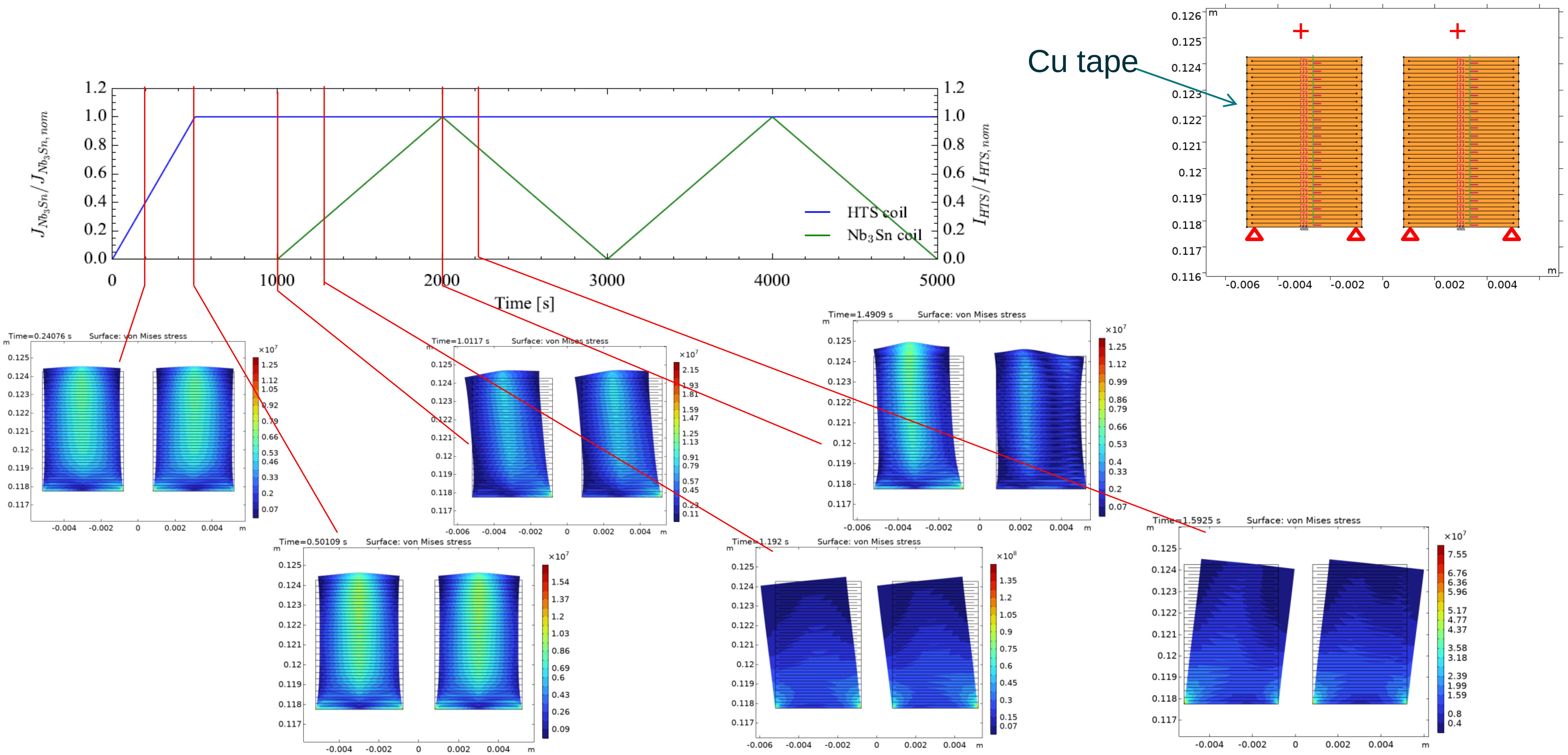




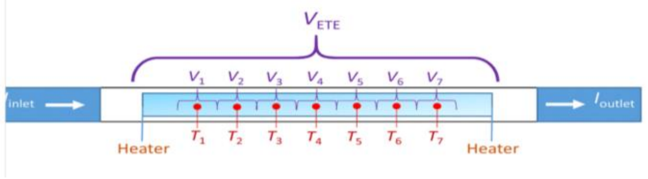


- Once the transport current is applied, the Lorentz force distribution is not balanced

Deformation during the energization (B ⊥ Tape case)



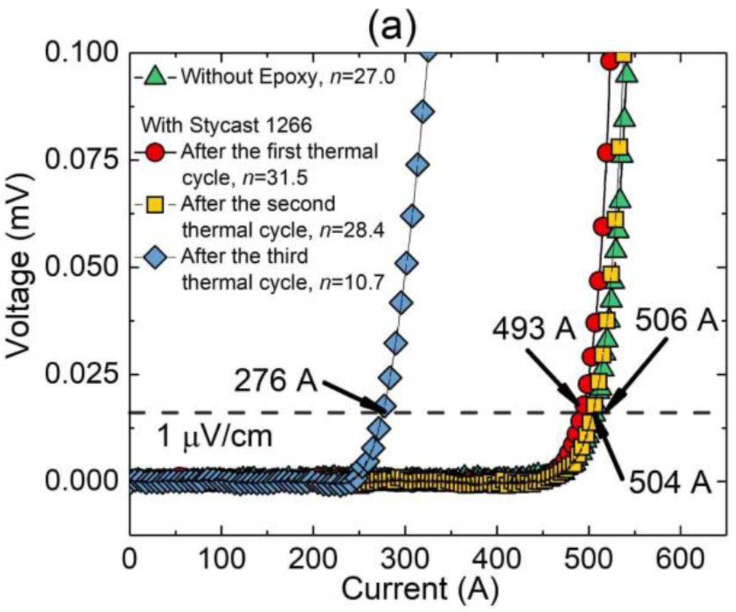
Experience with impregnating and quenching REBCO tapes



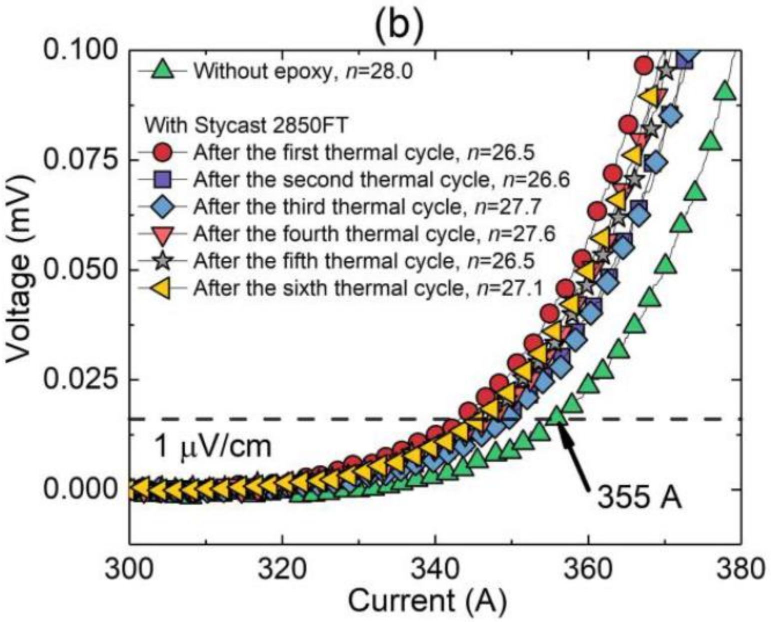
S. Yin et al., Degradation of REBCO coated conductors due to a combination of epoxy impregnation, thermal cycles, and quench: Characteristics and a method of alleviation, J. Appli. Phys. 128, 173903 (2020)

Uncertainty with maximum allowable temperature during a quench

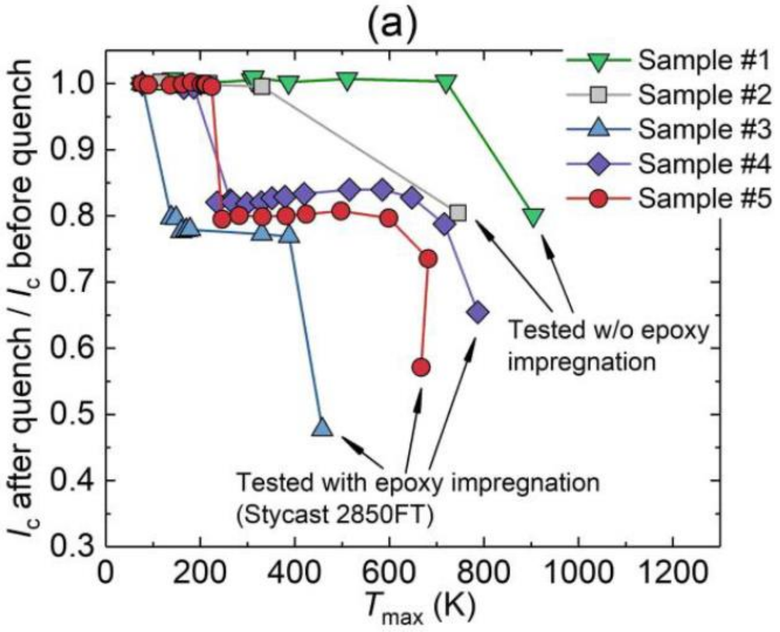
REBCO tape + Stycast1266



REBCO tape + Stycast2850 (filled resin)



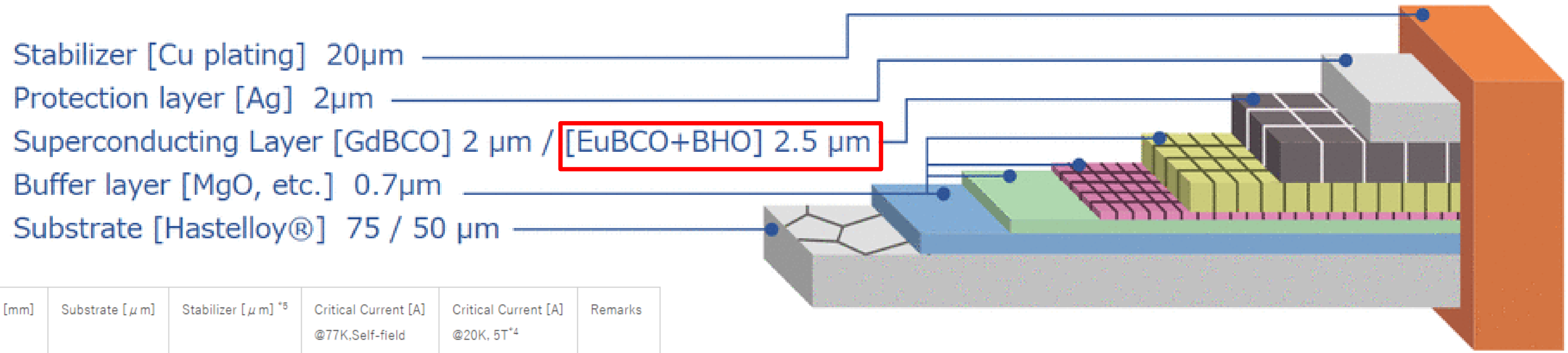
REBCO tape + Stycast2850 + quench



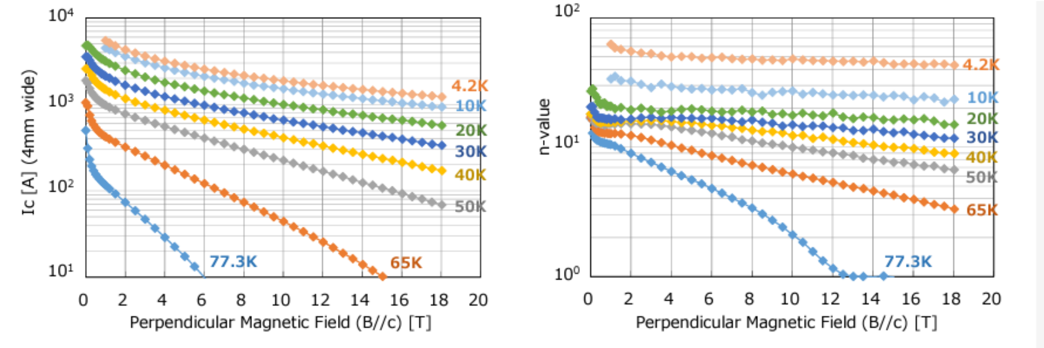
Concluding remarks

- **A tool developed for predicting SCIF for the upcoming US-Japan collaboration's test of KEK HTS coils at BNL.**
  - **Screening currents in HTS coils calculated by solving the T-A formulation.**
  - **The model was benchmarked with earlier measurement data at BNL.**
  - **Strong mechanical consequences.**
- **Experience with impregnating and quenching REBCO tapes**
  - **Further work needed to access the conductor limits.**

HTS Tape



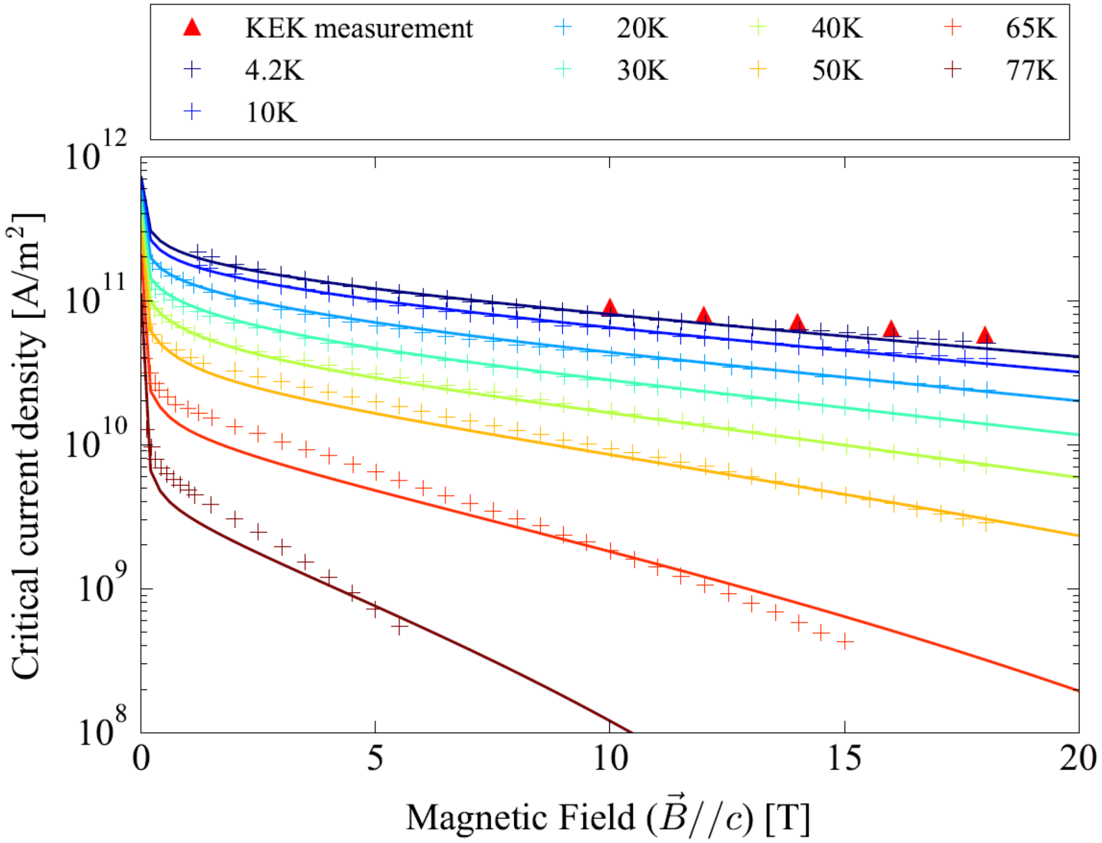
Products	Width [mm]	Thickness [mm]	Substrate [μm]	Stabilizer [μm] [*5]	Critical Current [A] @77K,Self-field	Critical Current [A] @20K, 5T [*4]	Remarks
FYSC-SCH04	4	0.13	75	20	≥ 165	368	Non-AP [*2]
FYSC-SCH12	12	0.13	75	20	≥ 550	1,104	Non-AP [*2]
FYSC-S12 [*1]	12	0.08	75	-	≥ 550	-	Non-AP [*2]
FESC-SCH02	2	0.11	50	20	≥ 30	257	AP [*3]
FESC-SCH03	3	0.11	50	20	≥ 63	497	AP [*3]
FESC-SCH04	4	0.11	50	20	≥ 85	663	AP [*3]
FESC-SCH04(05)	4	0.07	50	5	≥ 85	663	AP [*3]
FESC-SCH12	12	0.11	50	20	≥ 250	1,990	AP [*3]
FESC-S12 [*1]	12	0.06	50	-	≥ 250	-	AP [*3]

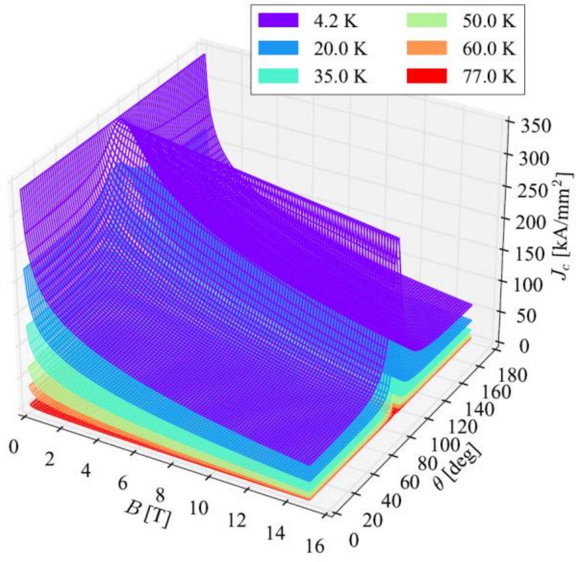


Sample:

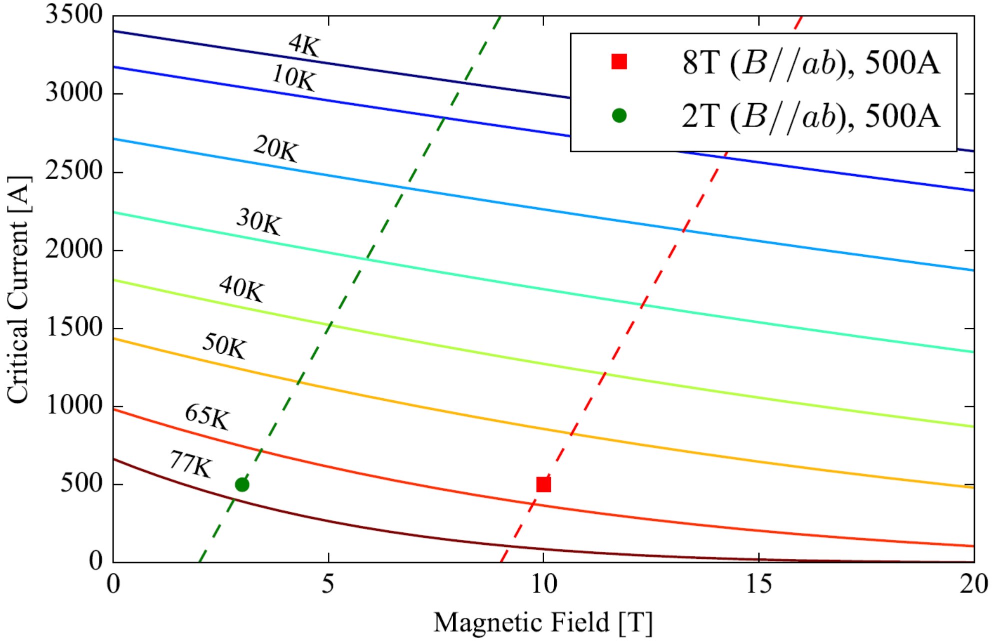
- Width: 10 mm, thickness: 2.4 um

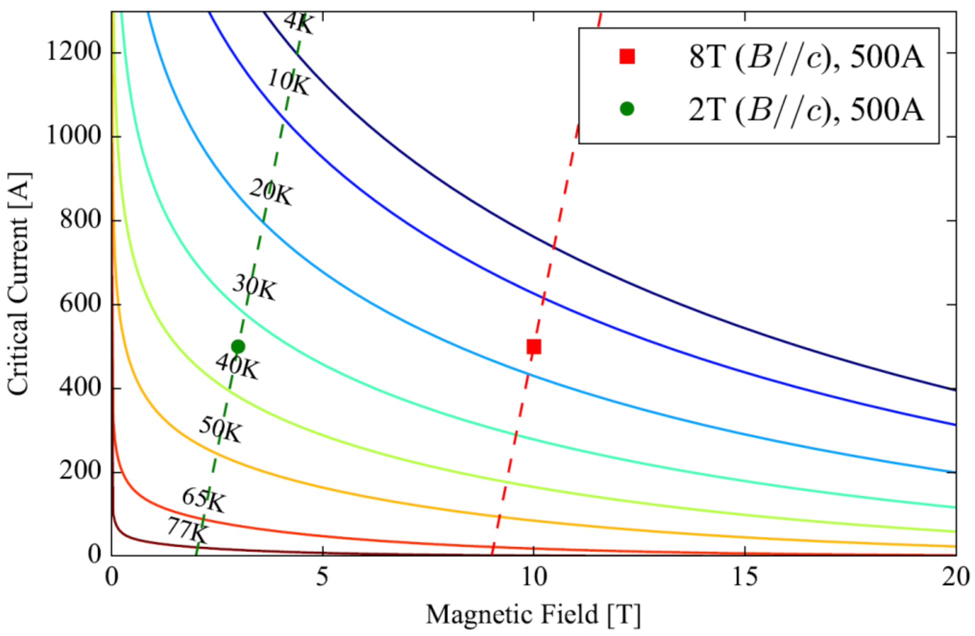
Fujikura measurements





Short Sample Limit





- Still can test the HTS coil in the background field of 2T at 77T with 200A (B//ab)

Thank You