TOHOKU
UNIVERSITY

Workshop on Advanced Superconducting Materials and Magnets

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Design concept and R&D studies for upgrading of 25T cryogen-free superconducting magnet

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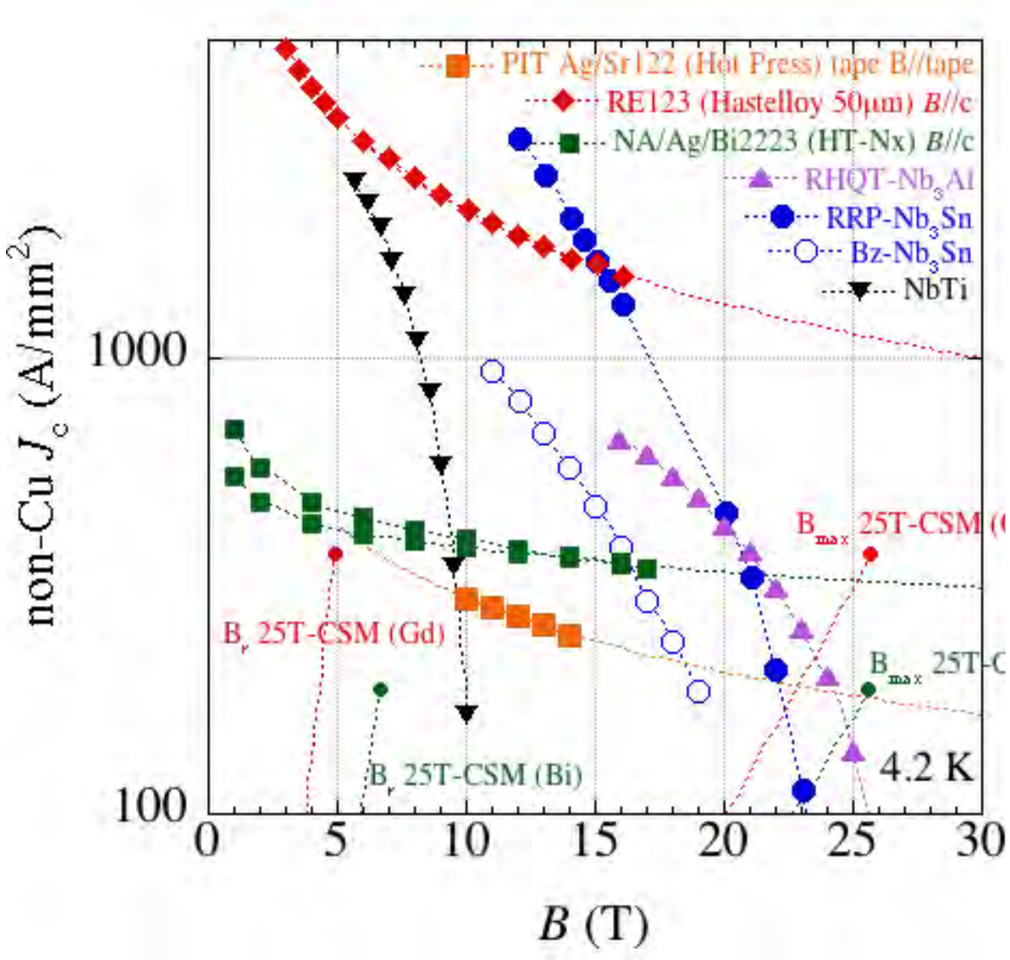
Sendai

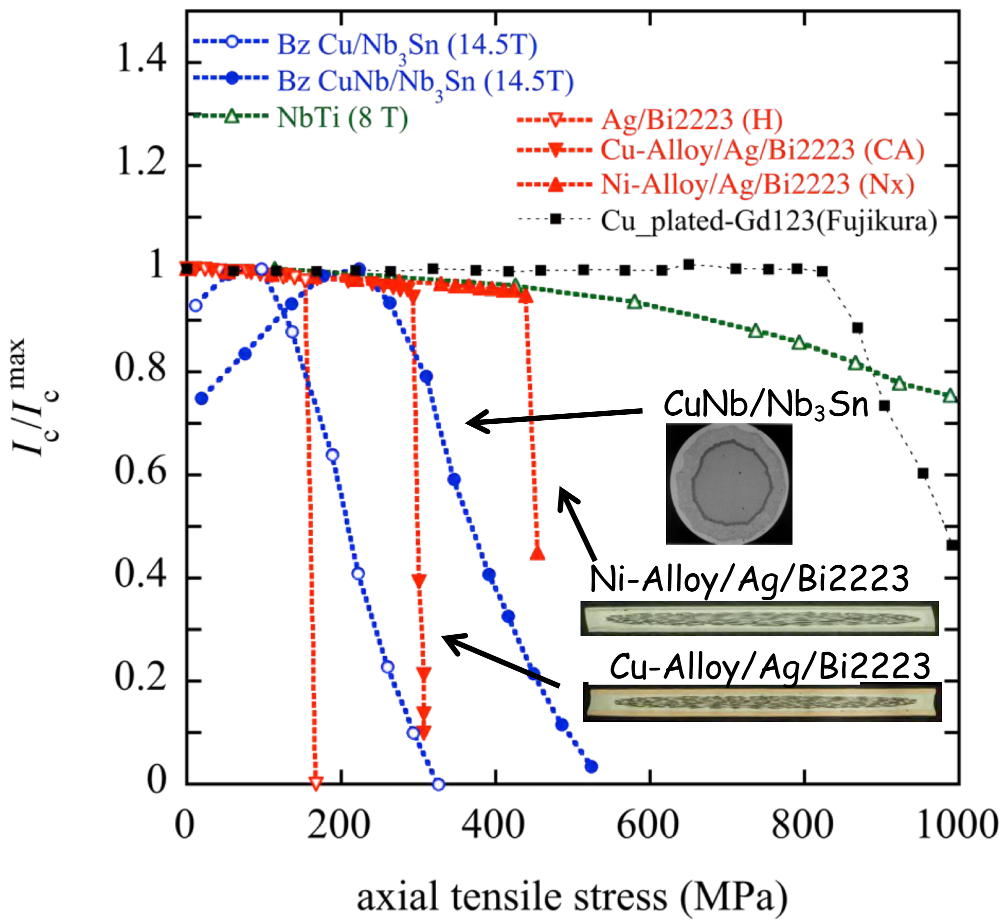
Research

Acknowledgements to collaborators

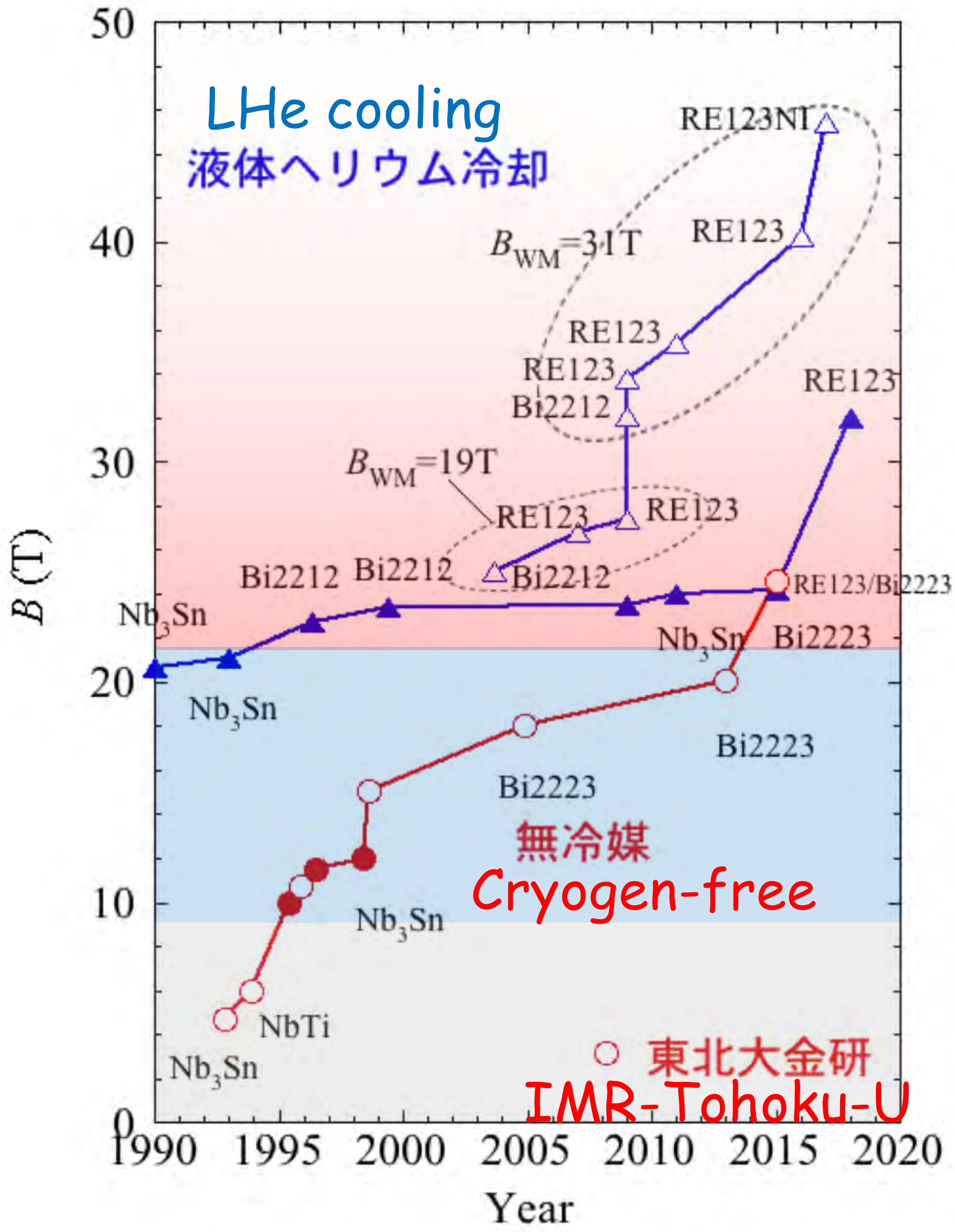
HFLSM, IMR, Tohoku Univ.	T. Okada, K. Takahashi, A. Badel
Toshiba (Magnet system)	H. Miyazaki, S. Hanai, S. Ioka
Fujikura (Gd123 tapes)	S. Fujita, H. Iijima, M. Daibo
Furukawa (LTS cables)	M. Sugimoto, H. Tsubouchi
NIMS(R&D)	G. Nishijima,
Kyusyu-U (AC-loss)	K. Kajikawa

Performance of practical SC wires

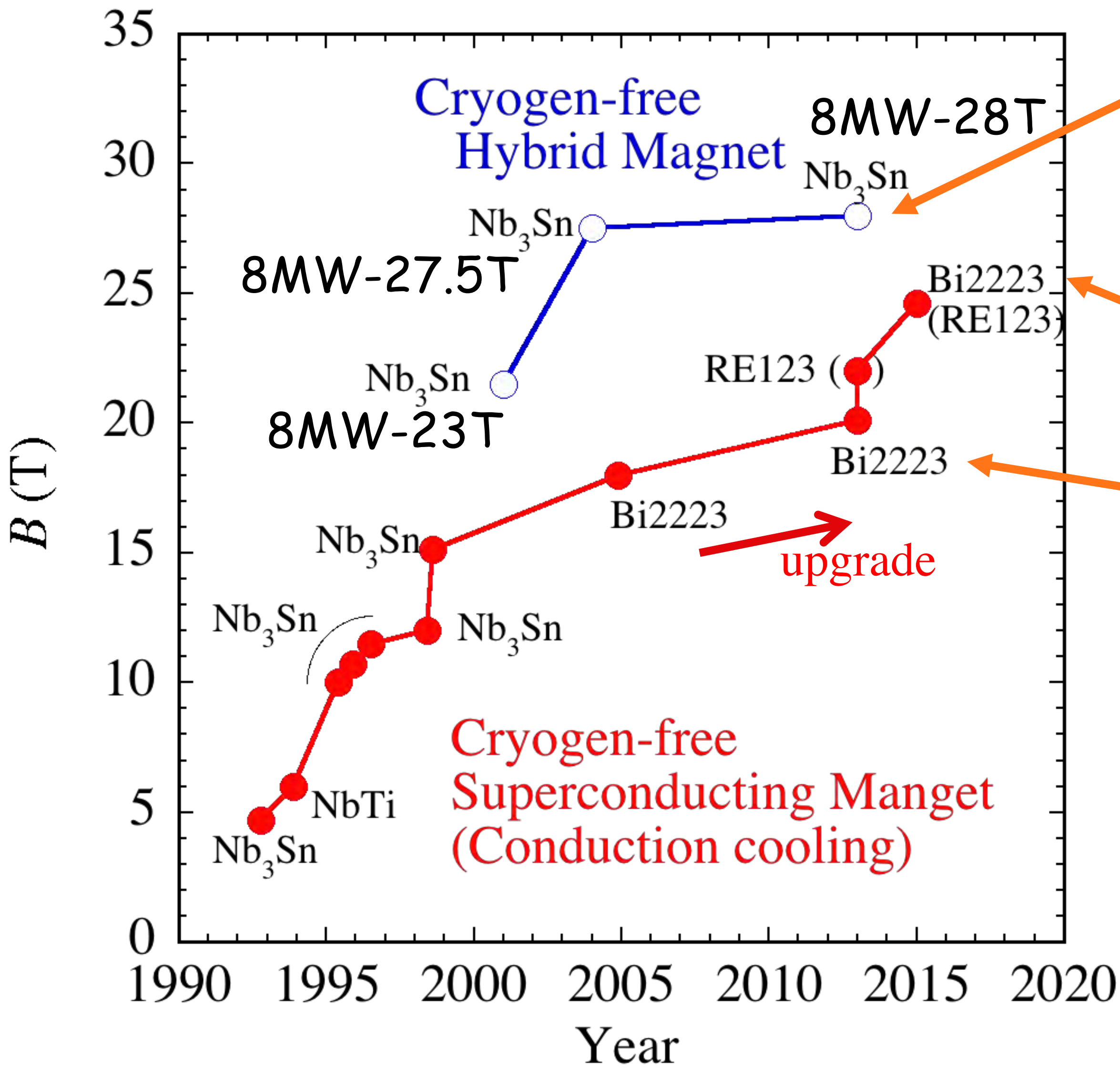




Present status of HF magnets



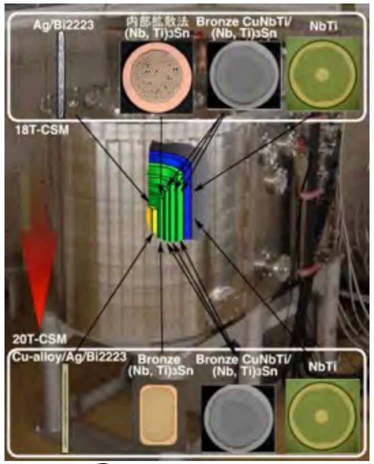
Progress of Cryogen-free Magnets at HFLSM, Sendai



28T-CHM (ϕ32RT)

ϕ360-9T-CSM
+ ϕ32-19T-WM

20T-CSM(ϕ52RT)



Bi2223

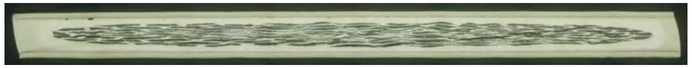
25T-CSM(ϕ52RT)

Gd123, Bi2223

25T Cryogen-free Superconducting Magnet (25T-CSM)

Magnets (HTS): 10.6T@188A

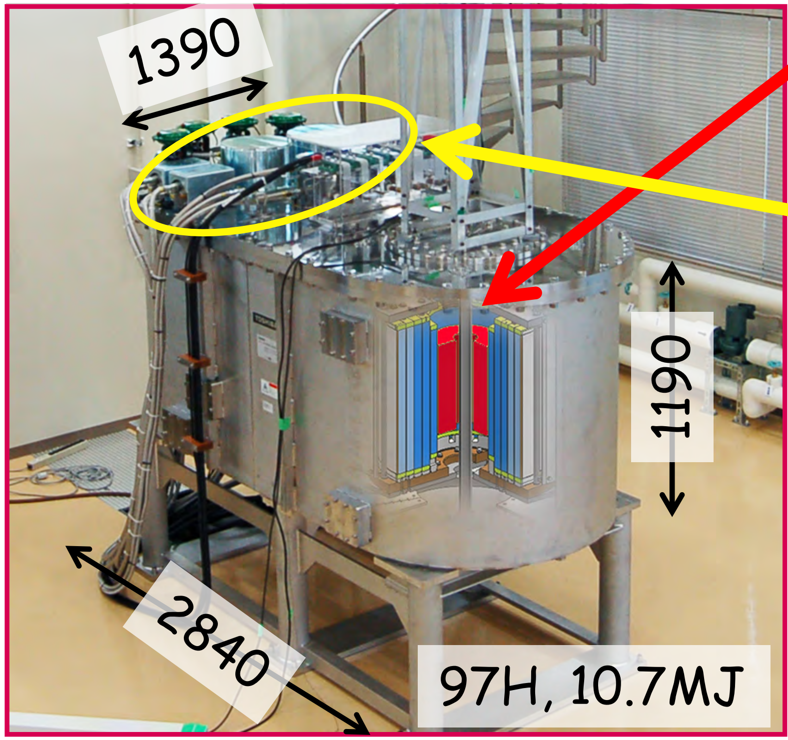
38 Ni-alloy/Bi2223 double pancakes
φ96mm x φ280 mm x h390 mm
Max. hoop stress 323 MPa



Magnets (LTS): 14T@854A

3 CuNb/Nb3Sn Rutherford solenoids
φ300 mm x φ539 mm x h628 mm
Max. hoop stress 251MPa

3 NbTi Rutherford solenoids
φ545 mm x φ712 mm x h628 mm
Max. hoop stress 138 MPa



Cooling system

Conduction cooling using He circulation
Shield: 2 x 1 stg GM cryocooler
HTS: 2 x 4K-GM cryocooler (3W@4.2K, 10W@8K)
LTS: 2 x GM/JT cryocooler (8.6W@4.3K)

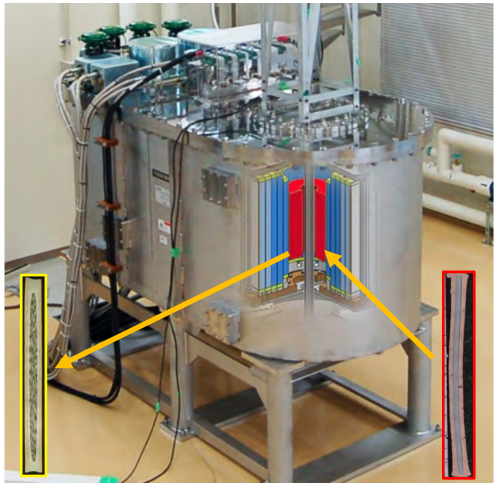
Awaji *et al.*, SuST. **30** (2017) 065001

Scenario beyond 30T-CSM

Upgrade of 25T-CSM replacing Bi2223 to REBCO insert (3-4 years) to 30T-CSM

- Low cost but many limtted factors
- Small margin (expect improvement of REBCO tapes)

->Artificial pinning centers

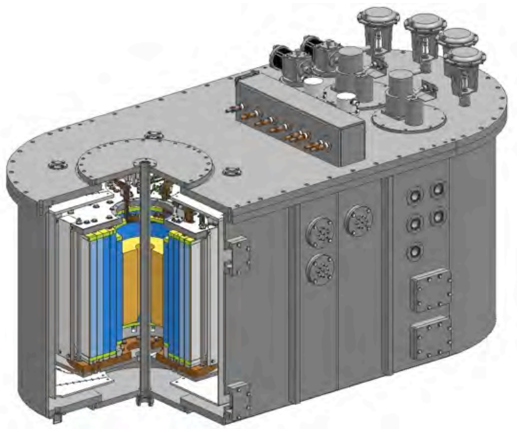


Next

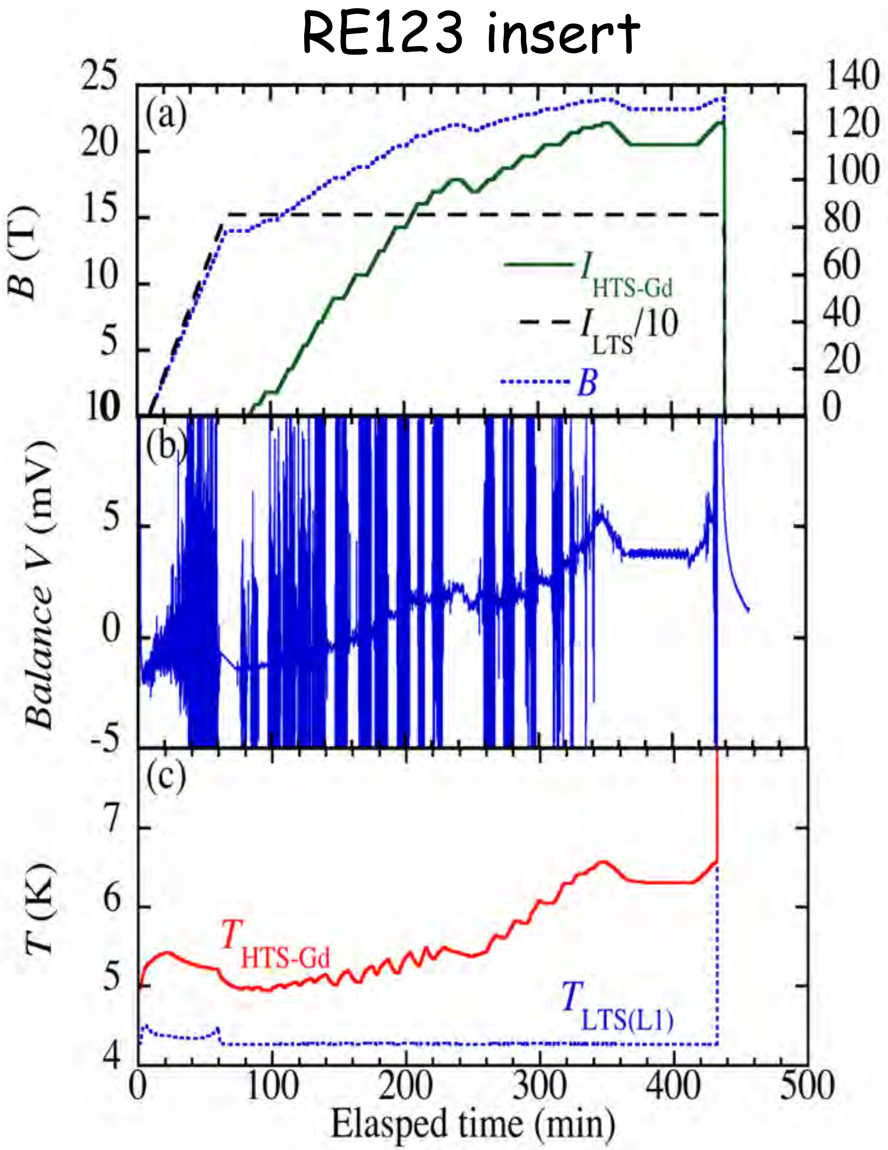
Beyond 30T-CSM (3-4 years)

- Consideration of 40 T in design

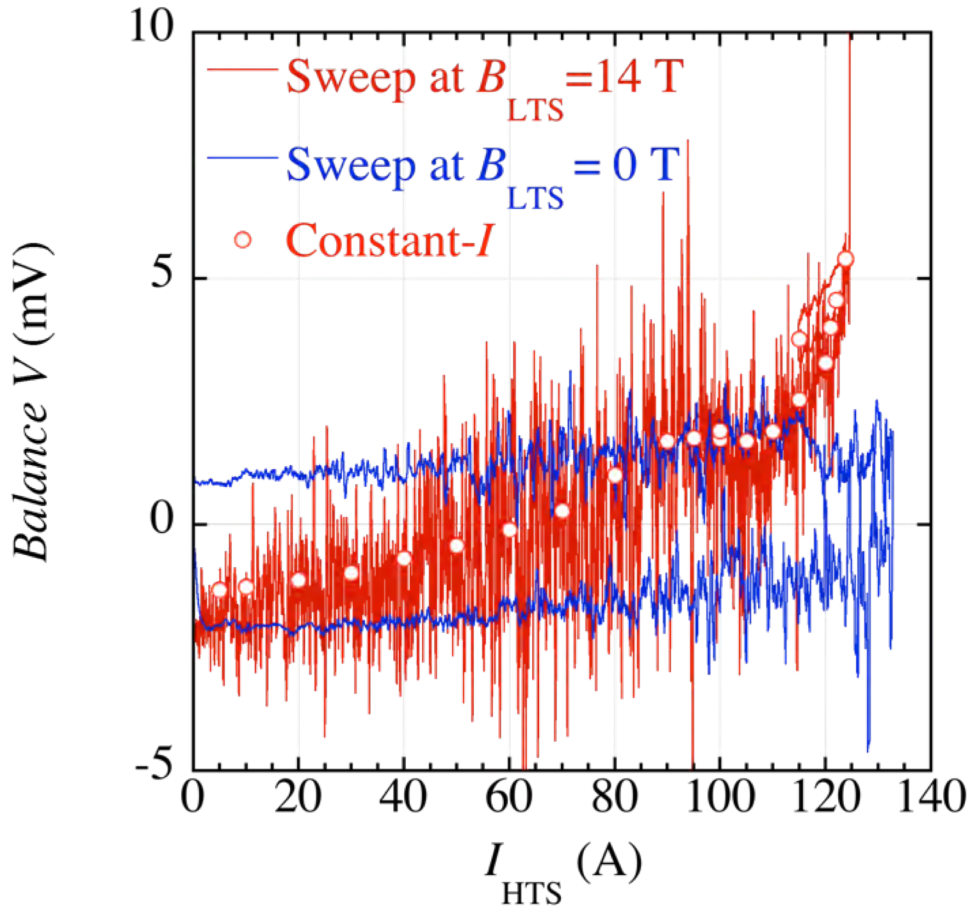
-> Improvement of mechanical strength of Nb_3Sn conductors are needed as well



Performance of RE123 insert for 25 T-CSM



Quench at B_{cal} = 24.01 T (124.6A)



The quench data was obtained!

Awaji *et al.*, SuST. **30** (2017) 065001

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Toward 30T-CSM

- REBCO is only solution, because of its high strength (800MPa). More high strength of Bi2223 tape is expected.
- Reliability of REBCO tapes
  - Improve **reliability** against local degradation.

  -> Current sharing with bundled tapes
- Quench protection
  - Against **local degradation** (REBCO)

  -> Dumping before burn-out with mV-scale detection.
  - Against quench of LTS coil

  -> Conventional dump resistance can be used.
- Mechanical reinforcement
  - 500 MPa for 30 T

Strategy of upgrading design

- ✓ The additional high strength tapes are co-wound as the reinforcement to introduce a compressive radial stress in order to reduce a risk of degradation. An adequate tension would be added only in the reinforced tape if possible.

  → Reduce a risk of degradation

- ✓ More than two tapes are co-wound without an insulation in between the co-wound two tapes to share a current if the local degradation would occur.

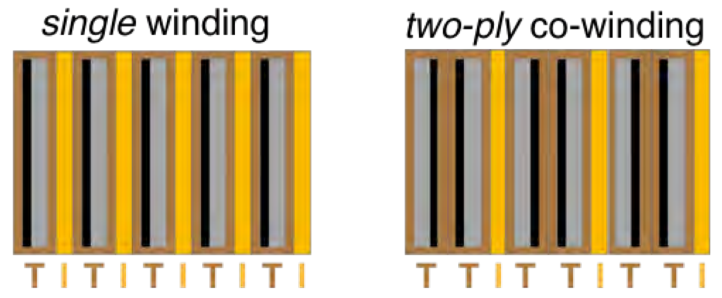
  → Improve reliability

- ✓ A quench detection with a few mV is considered to protect the coil from the hot-spot. The balance voltage is used for the quench detection with a bridge circuit.

  → Protection from hot-spot

Primitive upgrading design of RE123 insert for 30T-CSM

	Case 1	Case 2	Case 3
Wire (mm)	RE123 w4.1 x t0.11 x 2		
Thickness of Hastelloy (mm)	0.05		
Thickness of Cu stabilizer (mm)	0.02 (circumference)		
RT bore (mm)	32		
Inner x Outer diameters (mm)	68.0 x 274.0		
Coil height (mm)	290.9		
No. of turns/pancake	339	288	250
No of pancakes	56		
Operation current (A)	229	271	312
Total No of turns	19000	16128	14000
B_{max} (T)	30.2		
B_r^{max} (T)	5.7	5.7	5.7
Central field (T)	16.0		
Self inductance (H)	21.2	15.1	11.4
Insulator thickness (mm)	0.06		
Reinforced tape thickness (mm)	0	0.05	0.1
Hight of pancake coil (mm)	4.9		
Thickness of cooling plate (mm)	0.3		
Space current density (A/mm²)	157	157	157
Conductor current density (A/mm²)	255	245	238
Maximum hoop stress in conductor (2 x RE123 + Hastelloy) *BJR* (MPa)	499.4	482.2	468.2
Maximum hoop strain (%)	0.36	0.31	0.28



- Increase a packing factor
- Current share for a local degradation

30T design was achieved by...

- two REBCO tape co-wound
- reinforced by co-wound Hastelloy

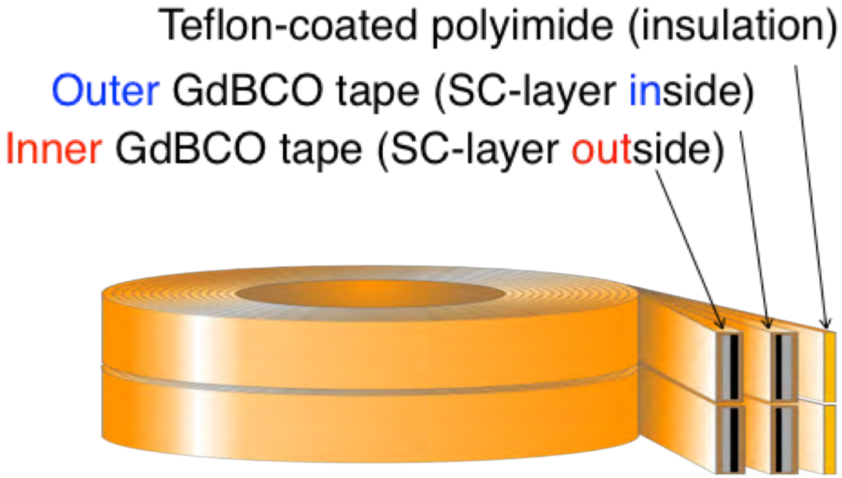
under the limited condition.
(I_{op} < 300A & size limit)

More improvement of design is under consideration!

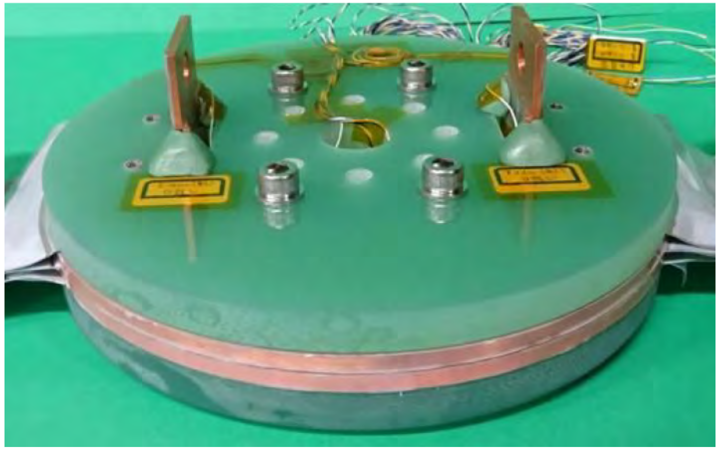
Double pancake R&D coil

Tape	
Tape	RE123 tapes (Fujikura)
Tape width	4.1 mm
Tape thickness	0.13 mm
No of bundles tape	2
Thickness of Hastelloy	75 μm
Stabilizer	20 μm electroplated Cu
Coil	
Inner diameter	100 mm
Outer diameter	168.5 mm
Coil height	100 mm
No. of turns/pancake	107
No of pancakes	2
Impregnation	Epoxy

L = 7.9mH



Epoxy impregnation



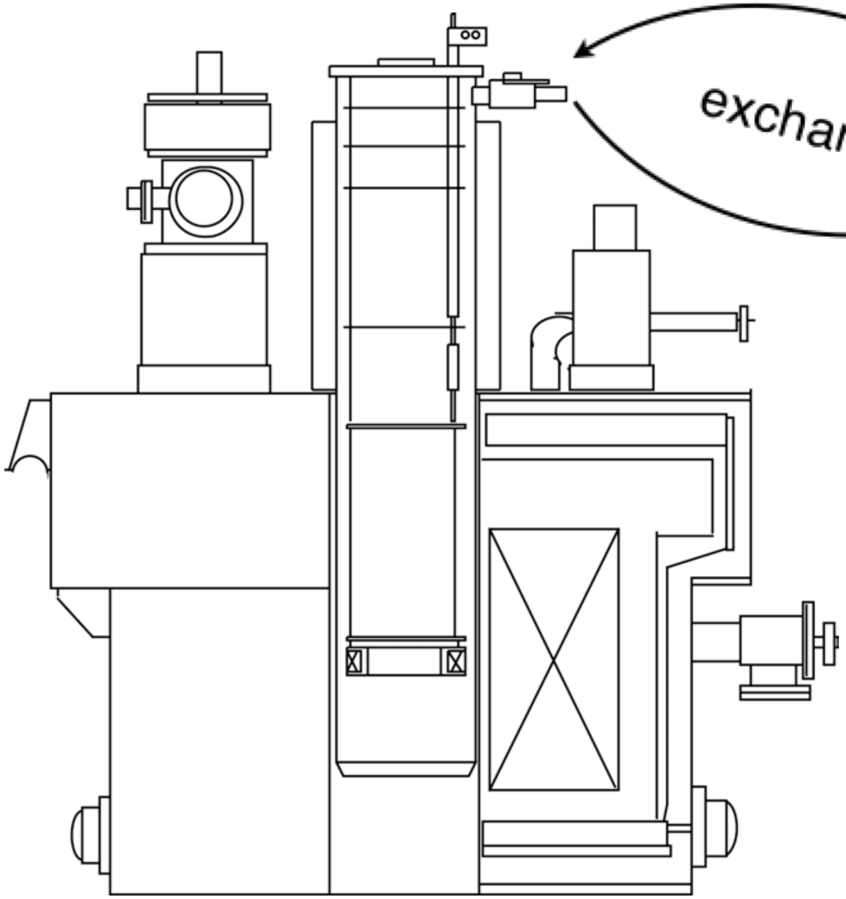
Performance test of R&D coil under electromagnetic stress

①Hoop-stress test @4.2 K(LHe)

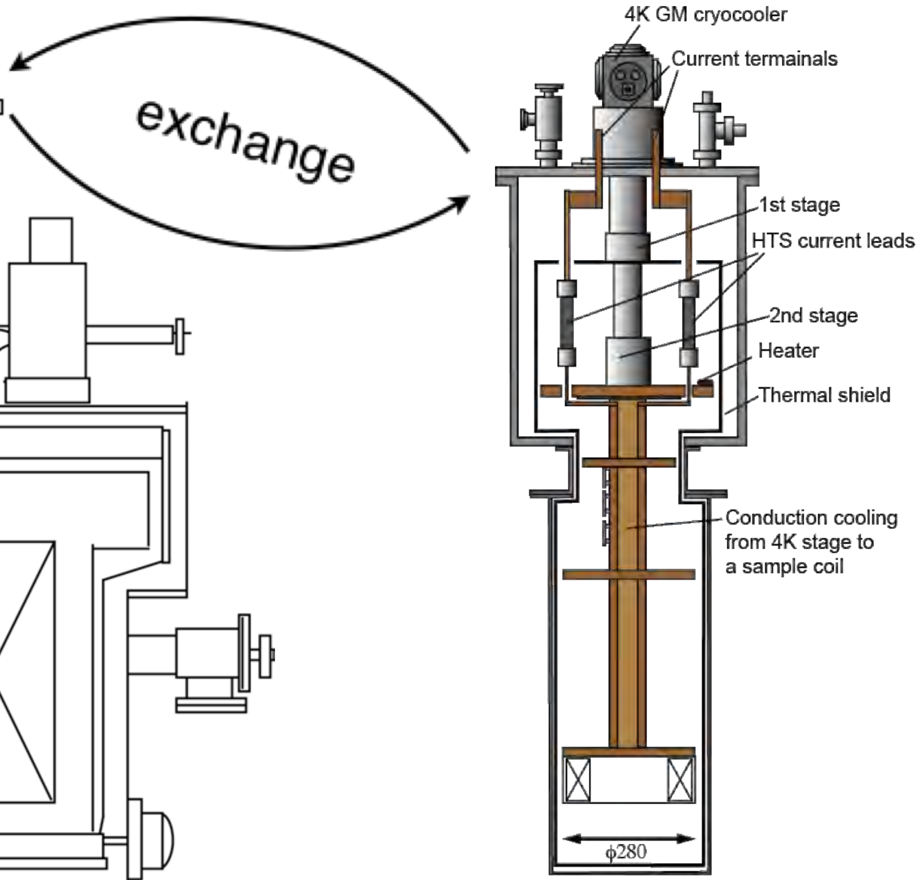
Large bore LHe Cryostat (<1500A)

②Magnetic field measurement @10~30 K

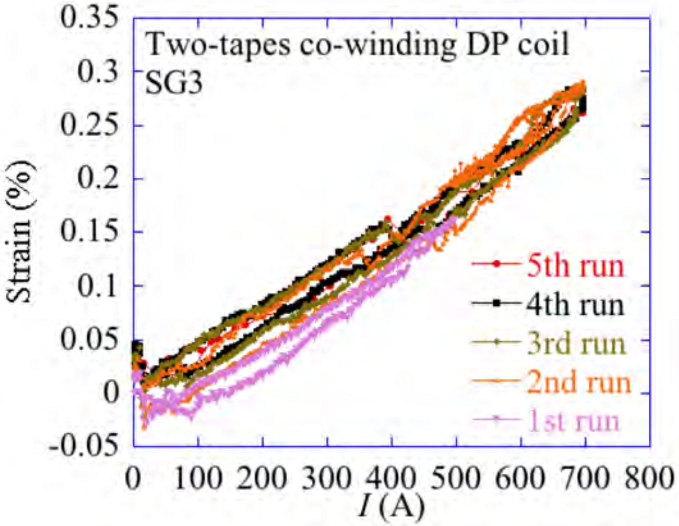
Large bore Conduction-cooled Cryostat (<500A)

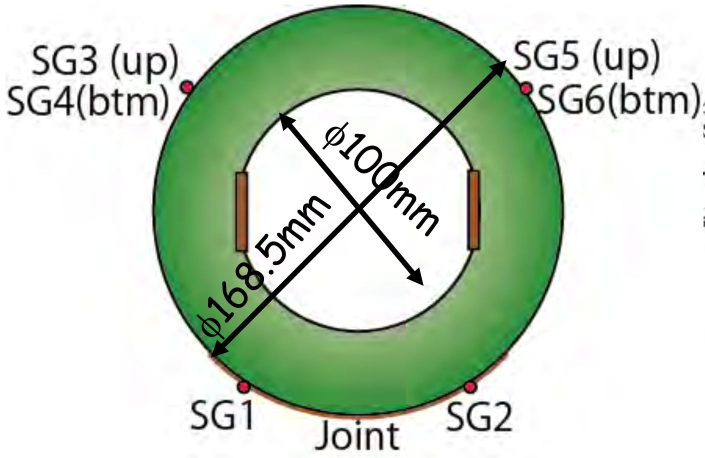


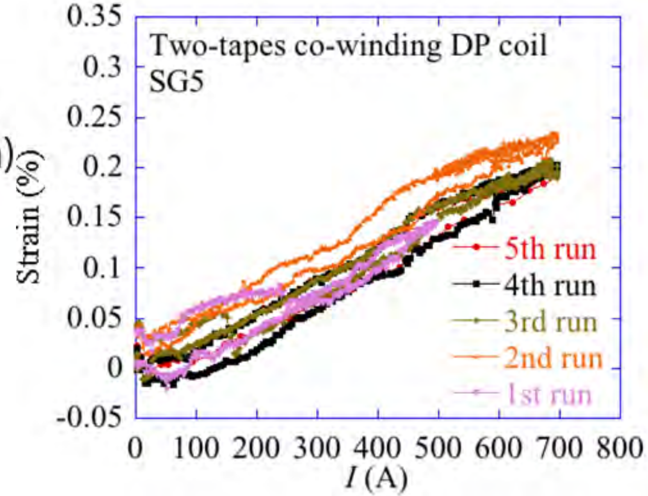
φ360mm-12T SM@HFLSM

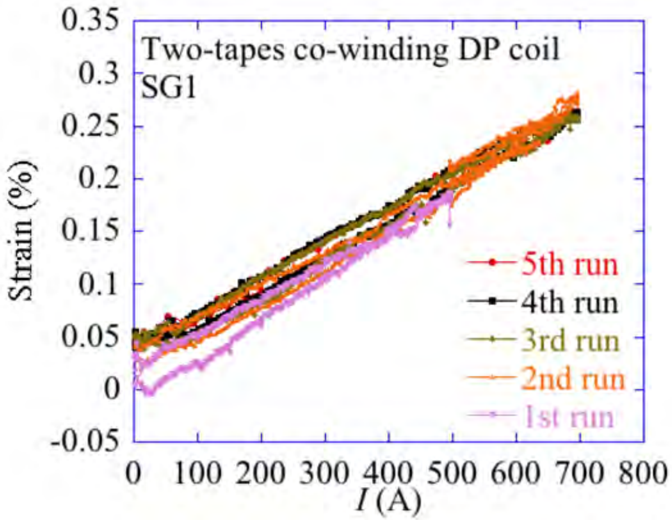


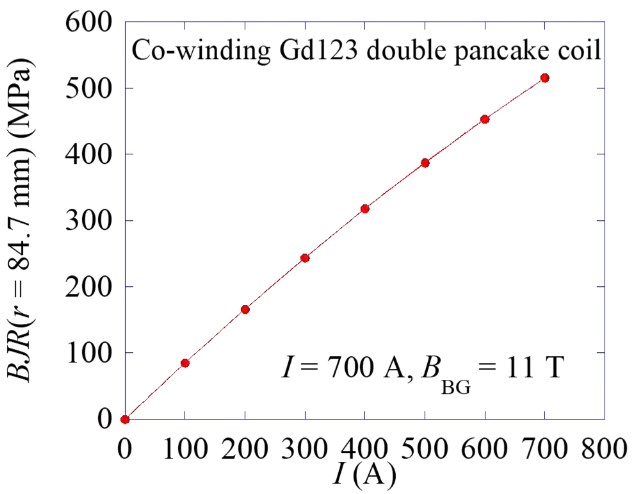
Deformation of coil by hoop stress

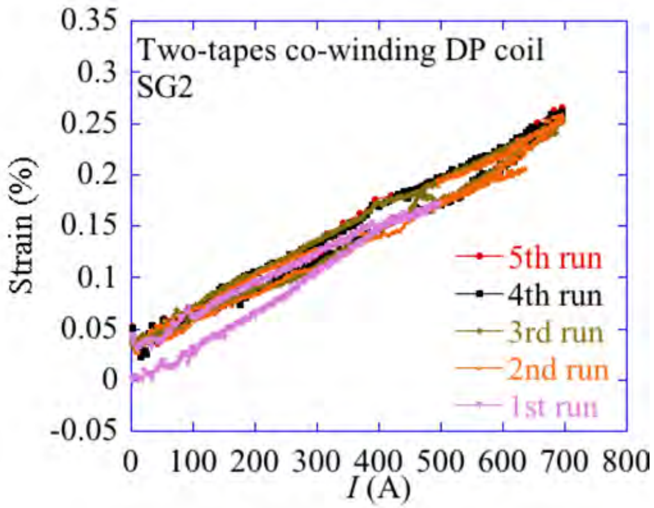




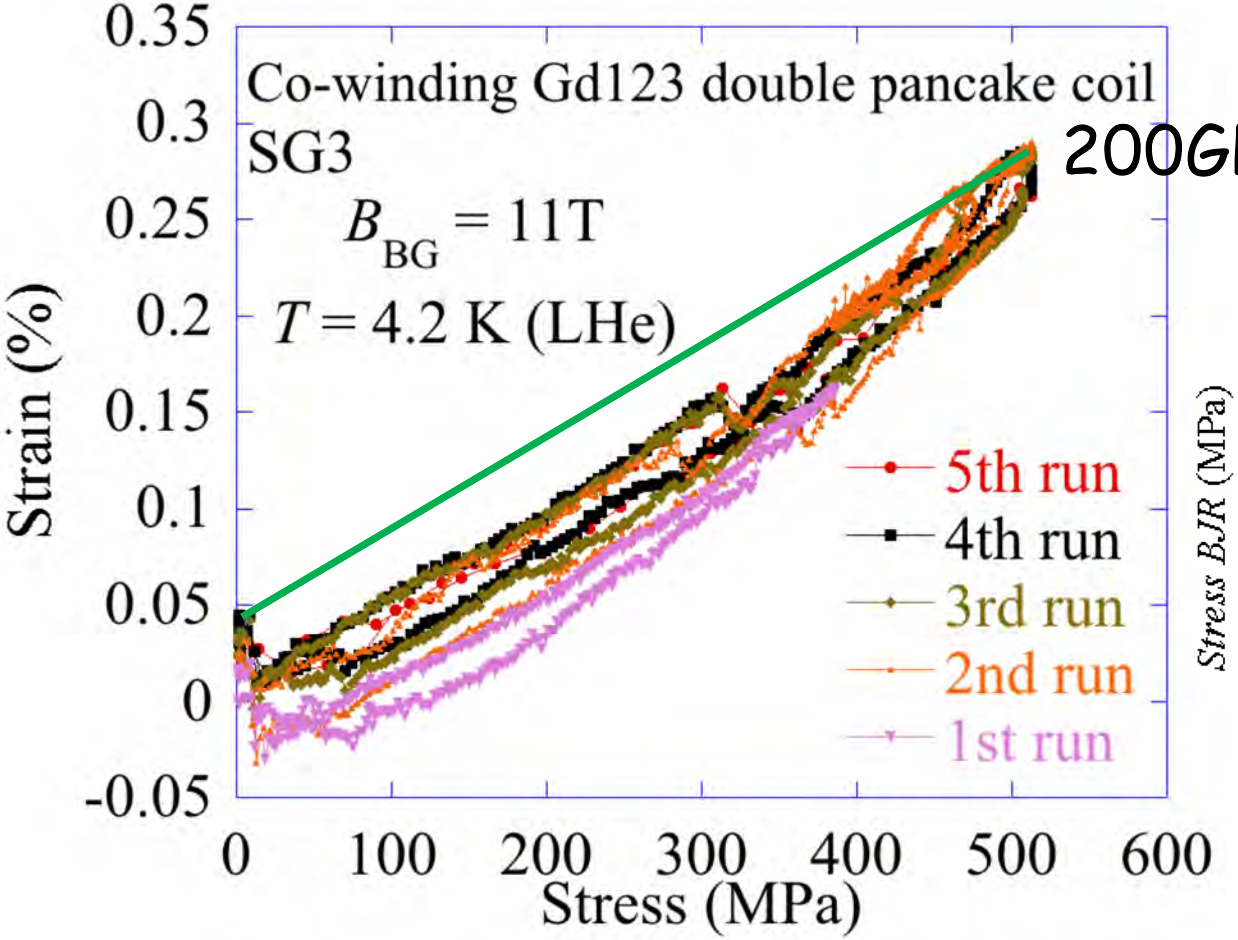


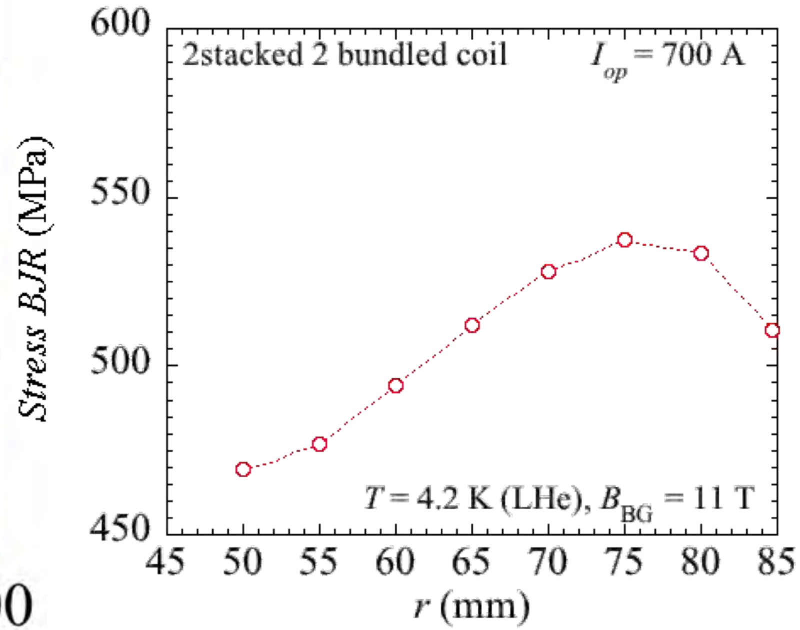






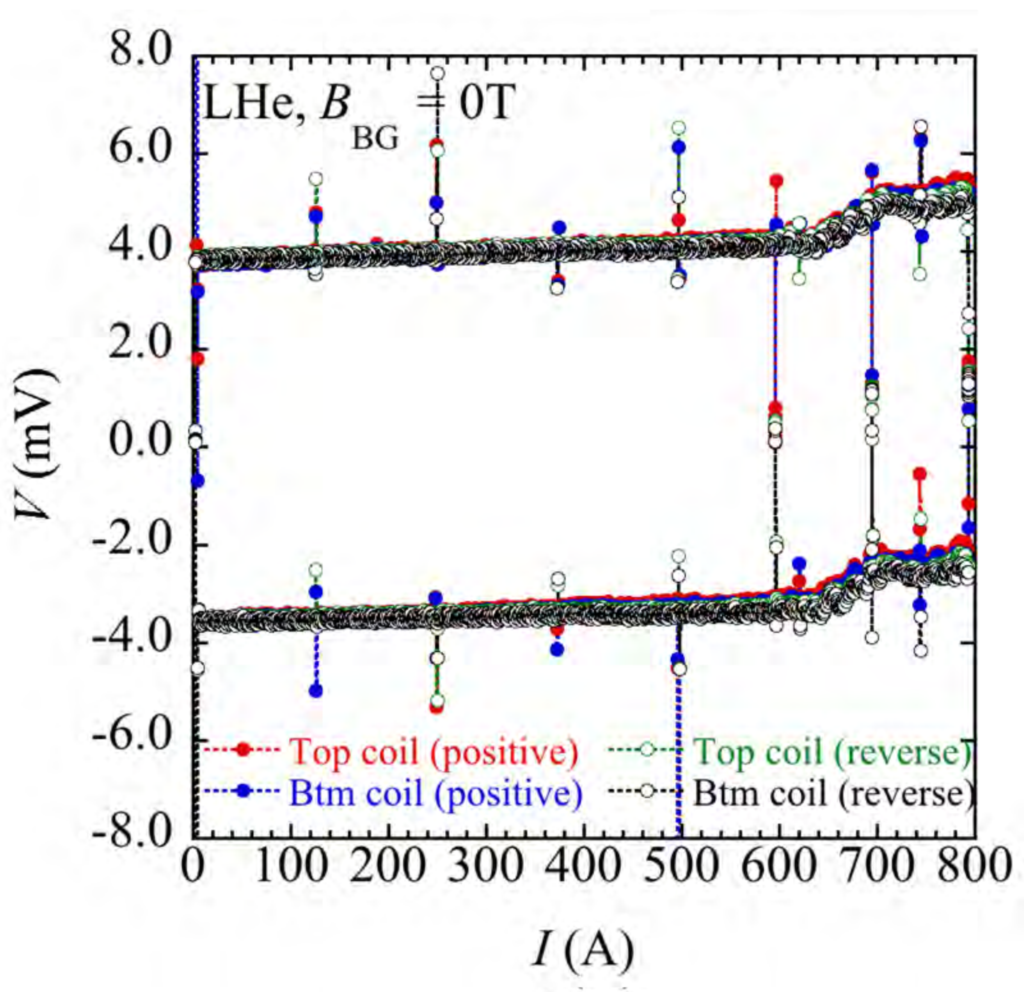
Deformation of coil

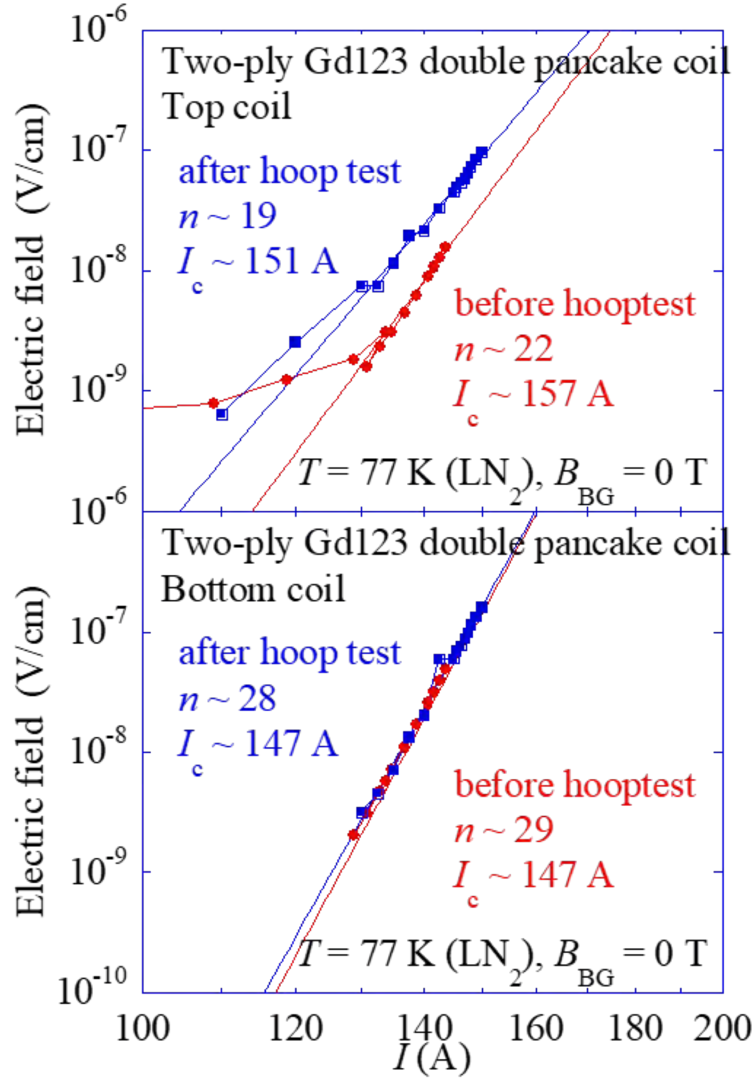




- ✓ The strain of the coil was about 2.5% at 500MPa.
- ✓ The maximum hoop stress; 540 MPa was applied by I_{op} = 700 A at 4.2 K and 11 T.
- ✓ The young modulus of coil is E = 200-220 GPa, which is slightly higher than tape.

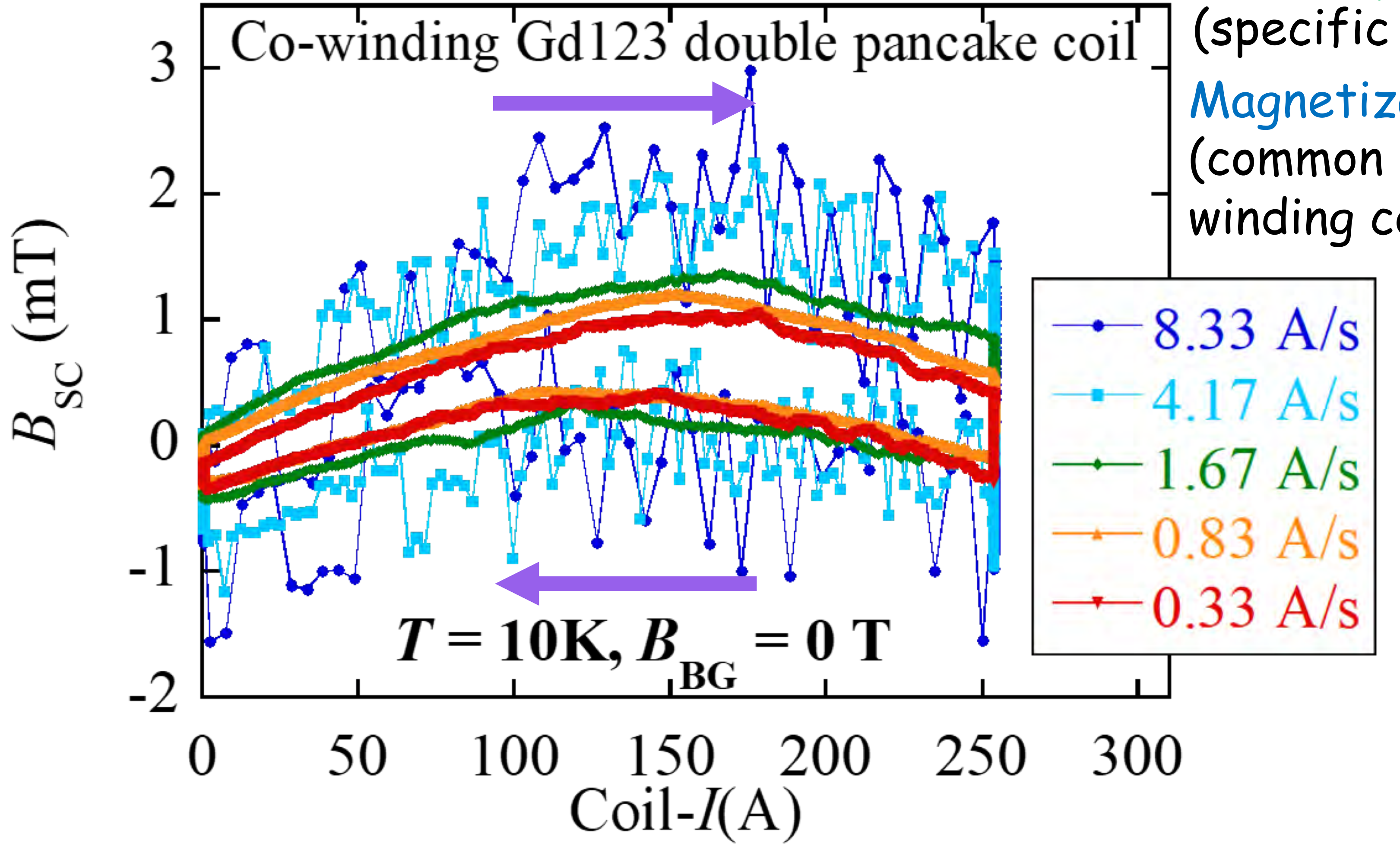
Transport properties





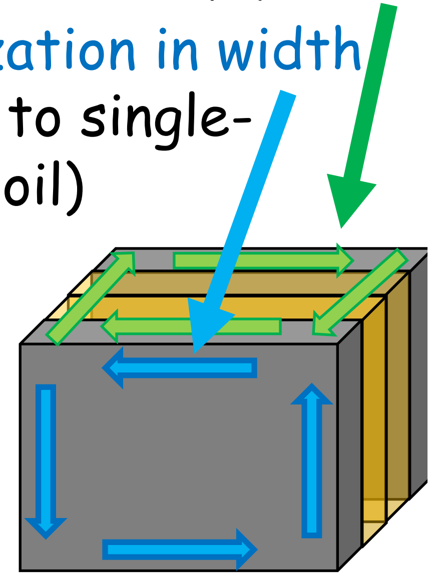
- ✓ Inductive voltage ≈ 4mV for 1A/s (L=0.39 H)
- ✓ Slight decrease of voltage can be seen . It is probably not ohmic resistance.
- ✓ Top coil was slightly deteriorated. But the degradation is not serious (due to current share?)

Shielding current induced field B_{sc}



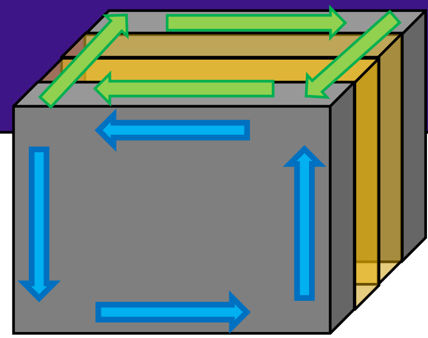
inter-tape coupling (specific to two-ply coil)

Magnetization in width (common to single-winding coil)

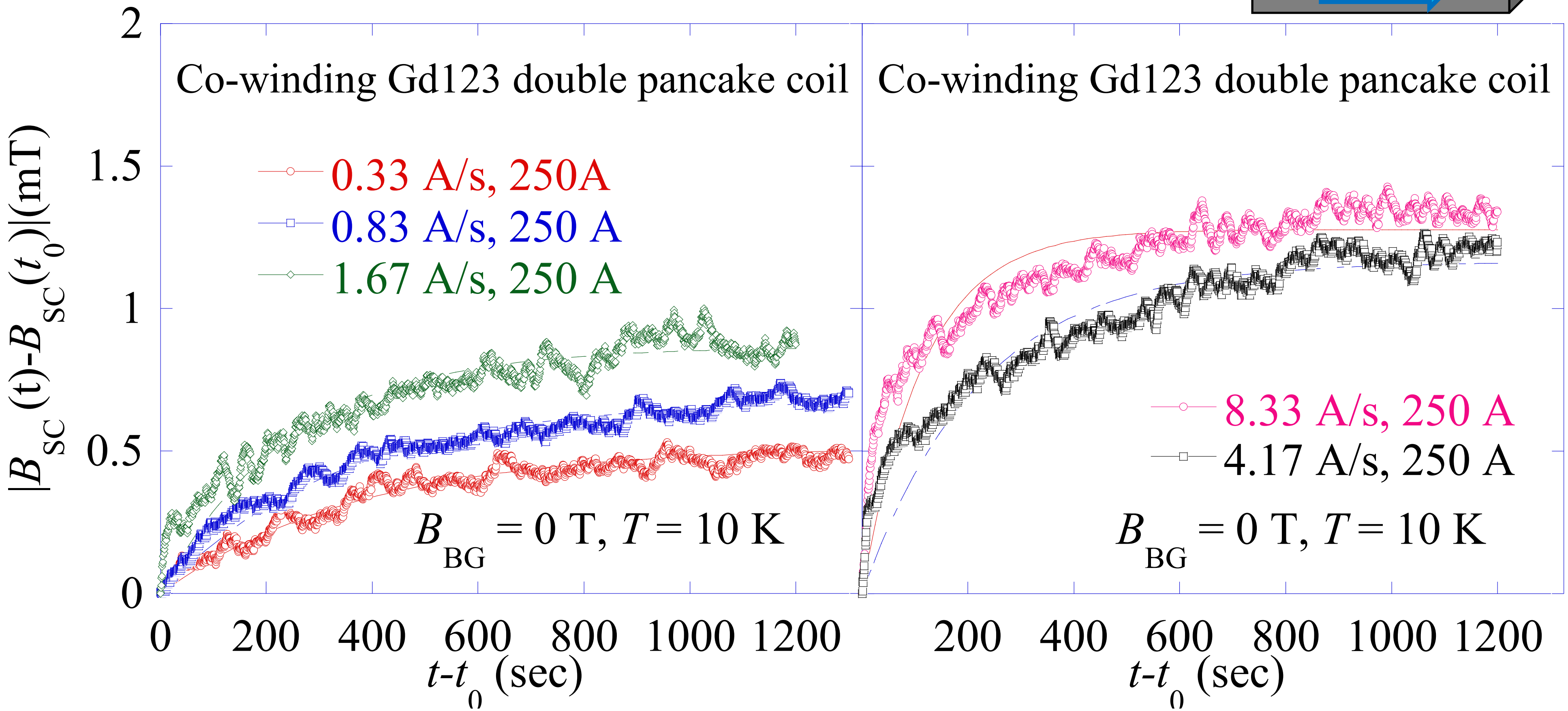


- ✓ Hysteresis of B_{sc} is opposite to that for single tape wound coil.
  -> The coupling of two Gd123 tapes are dominant for B_{sc}.
- ✓ The hysteresis width of B_{sc} increases with increasing ramp rate.

Relaxation of B_{sc}



$$|B_{SC}(t) - B_{SC}(t_0)| = \delta B\left[1 - \exp\left(-\frac{t - t_0}{\tau}\right)\right]$$

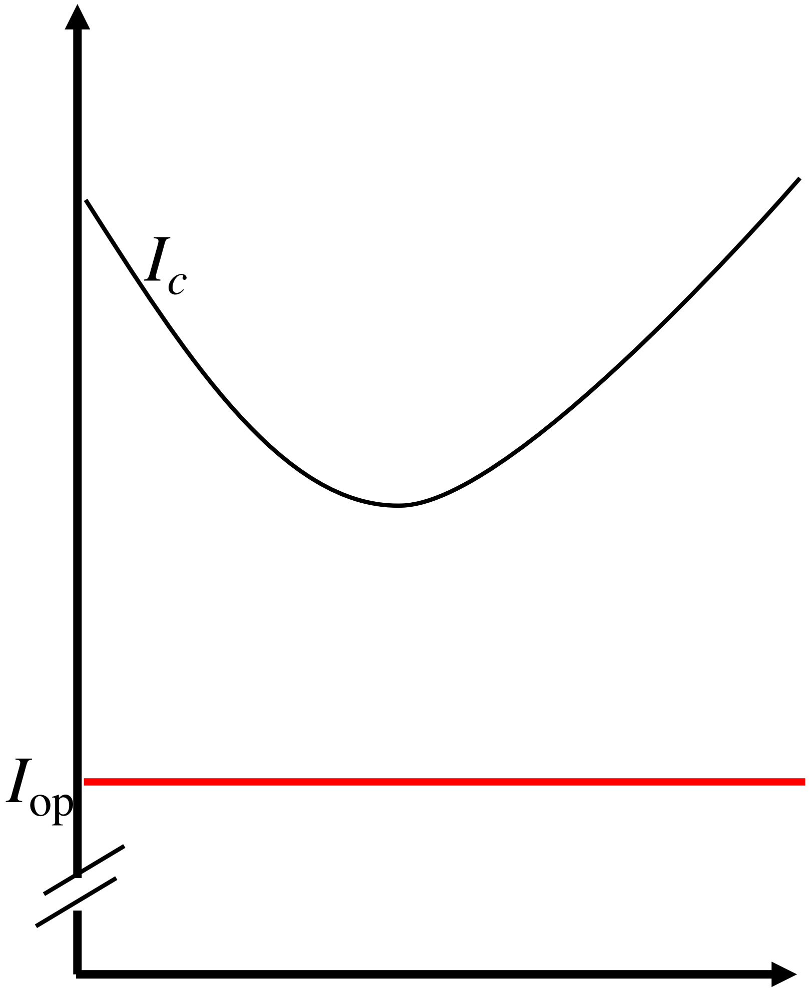


✓ Relaxation of B_{sc} can be fitted well for slow ramp rate but cannot for fast ramp rate.-> Different contributions should be considered like inter-coupling and magnetization in tape width.

Further study is needed.

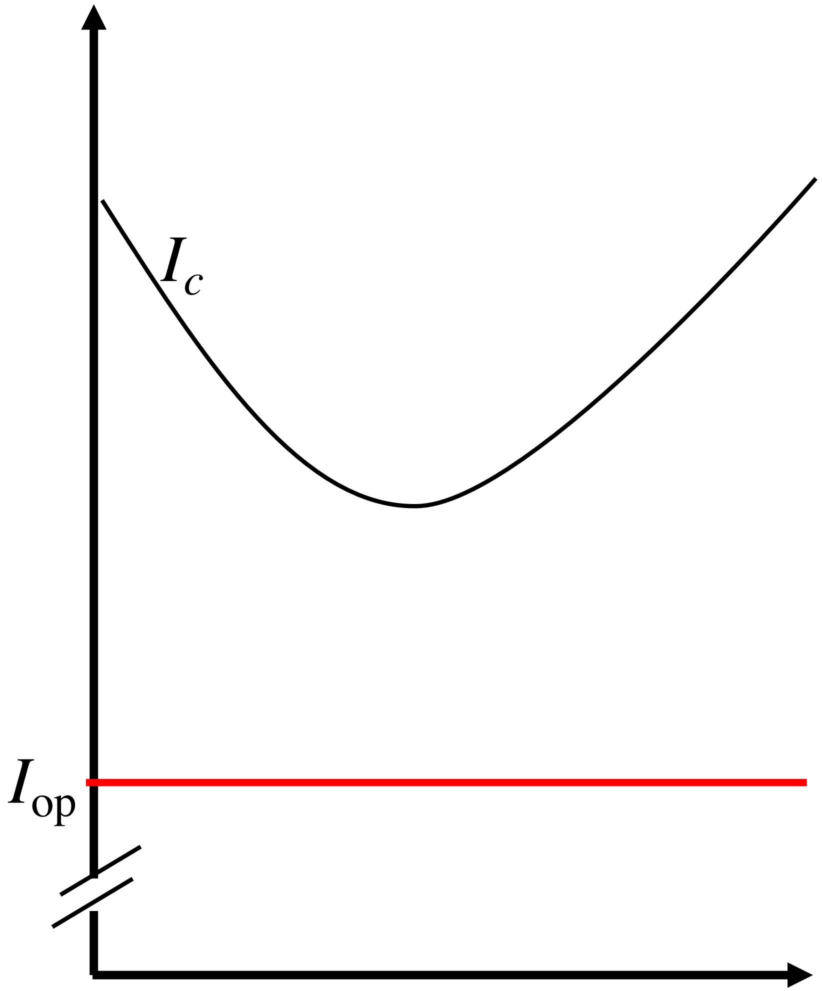
Quench protection for REBCO w/o local degradation

Passive protection (HFLSM)



Energy is dissipated in damp resistor.

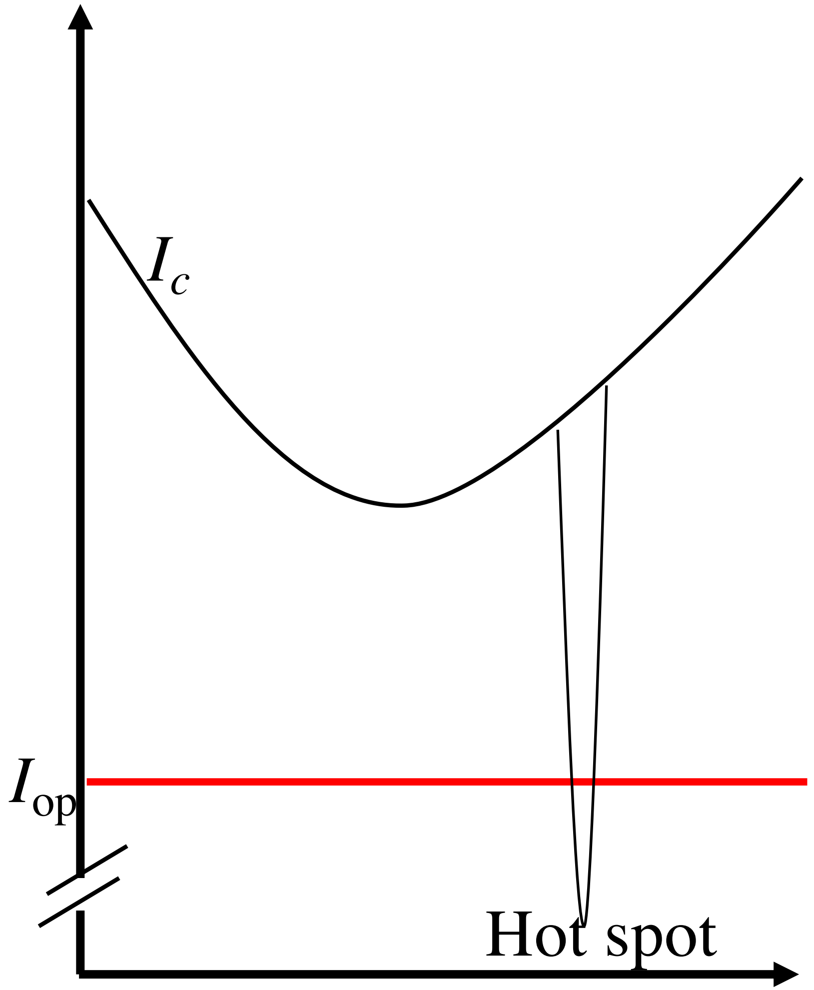
Active protection (NHMFL)



Energy is dissipated in whole coil and resitor.

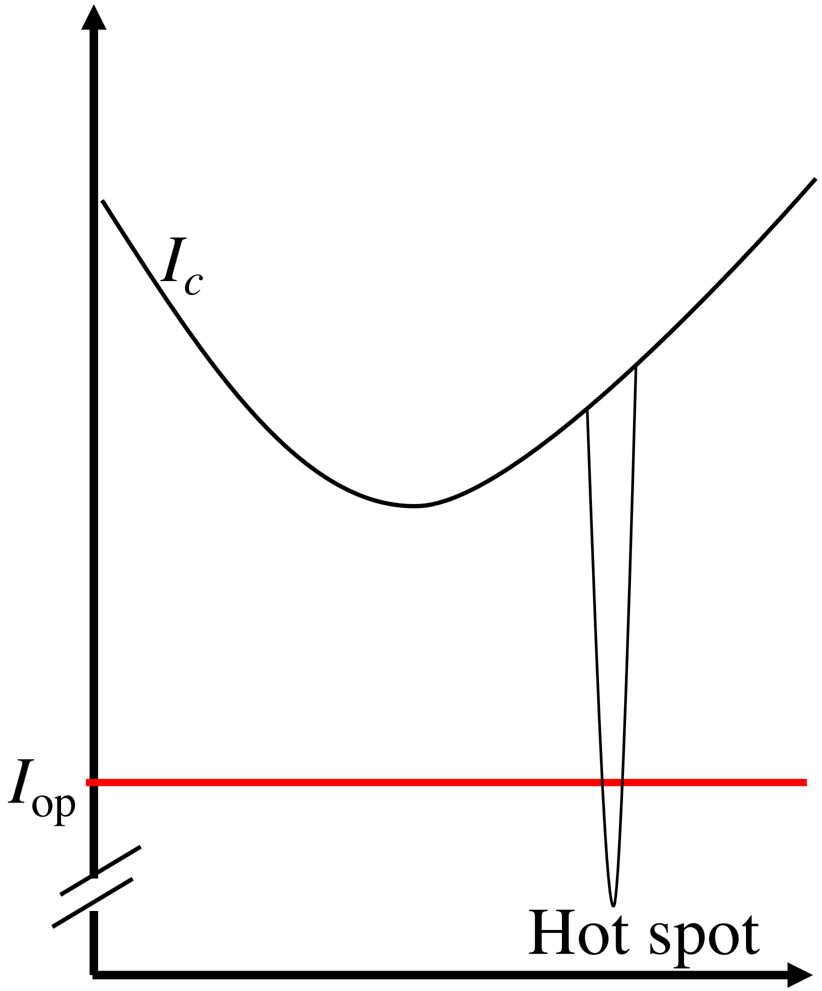
Quench protection for REBCO w/ local degradation

Passive protection (HFLSM)



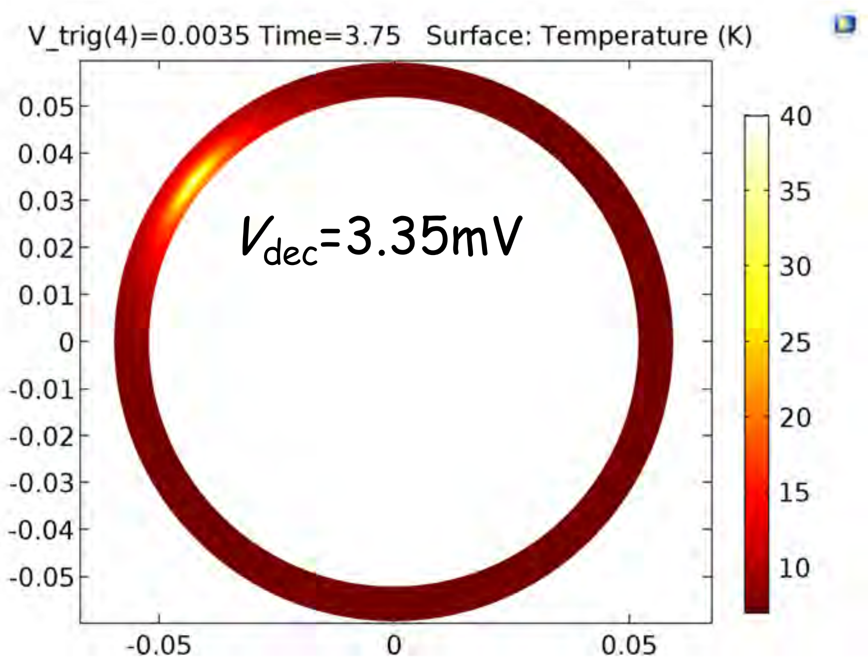
Most energy is dissipated in hot spot

Active protection (NHMFL)

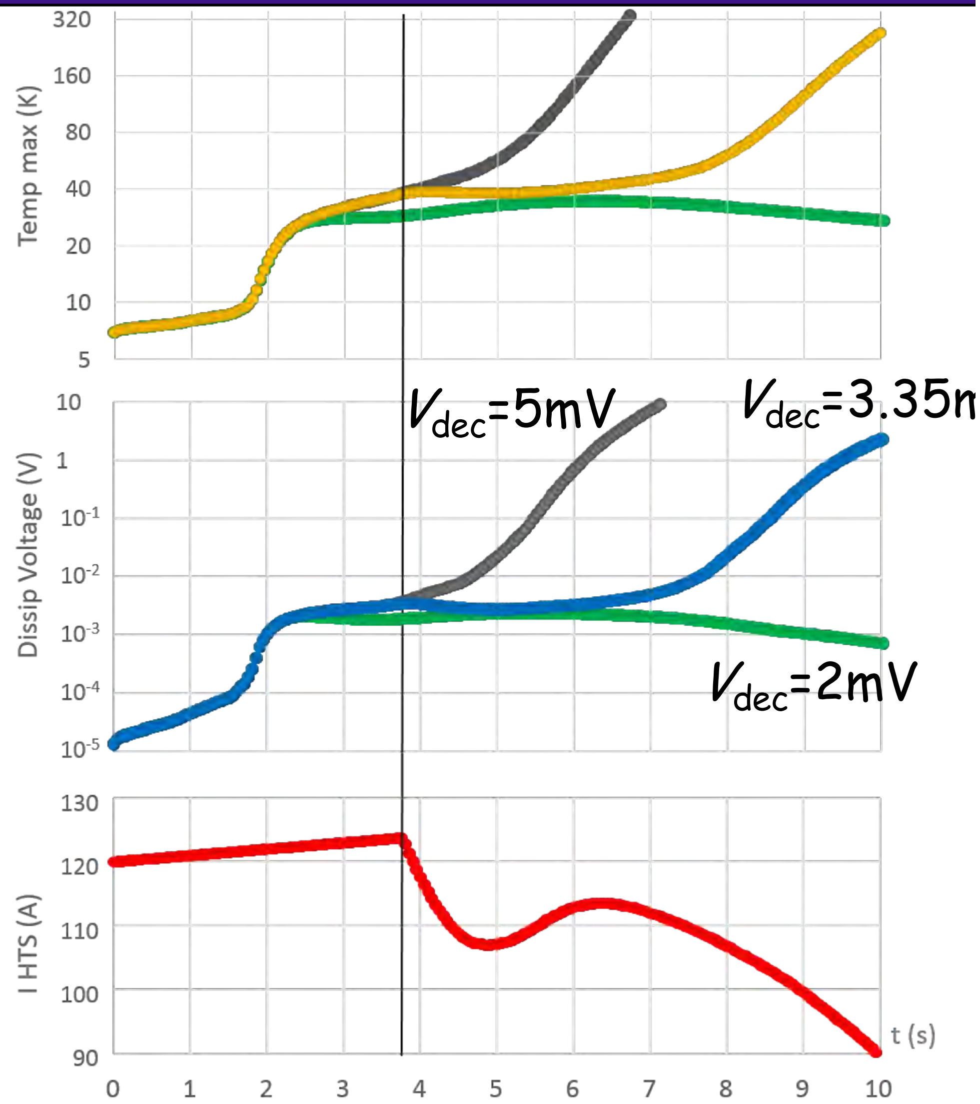


Energy is dissipated in whole coil and resistor.

Simulation of HTS Insert quench in 25T-CSM



- Upper pancake 40 inner turns, modelled using COMSOL FEM turns discretized in around 2000 5mm-long blocks
- Both tape (130 µm) and Isolation layers (55 µm) modelled
- Nominal Critical current with randomized ± 15 % distribution
- Lift factor variation with temperature, field and orientation
- 1 damaged block (22 % of nominal value)
- Input : current variation after threshold detection



A. BADEL, presented EUCAS2017
And ASC2018

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Summary

Thank you !

- ✓ Upgrading project of 25T-CSM to 30T is on going. In addition, the design work of CSM beyond 30T is just started.
- ✓ For an achievement of 30T by upgrading of 25T-CSM, we performed test of **twoply Gd123 double pancake coils** under hoop stress.
- ✓ The stable operation of two-ply Gd123 double pancake coil in high stress states up to 540 MPa.
- ✓ The multiple tape winding (similar to PI technique) may be effective to **improve the reliability of Gd123 coil.**
- ✓ The inter-tape coupling of two Gd123 tapes is dominant in screening current induced field and maybe ac-losses.
- ✓ The passive protection is possible if we detect adequate voltage (above a few mV).