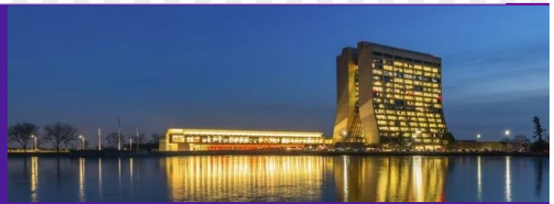
TOHOKU UNIVERSITY

Muon Cooling Demonstrator Workshop
October 30, 2024 to November 1, 2024
Fermilab - Wilson Hall



Magnet R&D in Japan

1. Cryogen-free superconducting magnet developments (TU)
2. 1.3GHz (30.5T) NMR magnet developments (RIKEN)

Satoshi Awaji

High Field Laboratory for Superconducting Materials (HFLSM),
Institute for Materials Research, Tohoku University, Sendai, JAPAN.

Special thanks to Yoshinori Yanagisawa (RIKEN)
for slides of 1.3GHz-NMR project

HFLSM Sendai

Research

Challenges of High field HTS magnets in the world (>20 T)

Name	Group	Purpose	B(T) (HTS/LTS)	HTS	J_{con} (A/mm^2)	Max Stress (MPa)	ID (mm)	T_{op} (K)	Winding	Impregnation	Status	Year	Insulation	Operation days
32T	IEE/CAS	User magnet	32.35 (17.35/15)	RE123	378	610	35	4.2 (LHe)	DP	Wax		2019	NI	
32T-SM	NHMFL	User magnet	32 (17/15)	RE123	193	378	40	4.2 (LHe)	DP	Dry	Open since 2021	2017	Insulated	
1.2GHz-NMR	Bruker	NMR	28.2	RE123				2.2? (LHe)			Persistent, stability <10 ppb, Commercial	2019	Insulated	
25T-CSM	Tohoku U.	User magnet	25.1 (11.1/14)	Bi2223	150	323	96	4-8	DP	Epoxy/ turn separation	Open since 2016	2016	Insulated	1100
20T-CSM	Tohoku U.	User magnet	20.1 (4.45/15.6)	Bi2223	118	212	90	4-6	DP	Epoxy/ turn separation	Open since 2013	2013	Insulated	1988
1020MHz-NMR	NIMS /RIKEN	NMR	24.2 (3.62/20.4)	Bi2223	150	194	78	1.8 (LHe)	Layer	Wax	Obtained NMR signal, Closed in 2017	2016	Insulated	End of operation
MIRAI	RIKEN	NMR magnet	23.8 (12.6/11.2)	Bi2223	225	291	78	4.2 (LHe)	Layer	Wax	1.01GHz	2019	Insulated	
MIRAI	RIKEN	NMR magnet	31.4 (14.2/17.2)	RE123/ Bi2223	723	513	17.6	4.2 (LHe)	Layer	Wax		2019	LNI	
24T RD	NIMS /RIKEN	Demo	24 (6.8/17.2)	RE123	428	408	50	4.2 (LHe)	Layer	Wax		2012	Insulated	
25T R&D NMR	U. Geneva	Demo	25 (4/21)	RE123	733	139	20	2.2	Layer	Epoxy		2019		
NOUGAT	LNCMI/CEA-Saclay	Demo	32..5 (14.5/18(RM))	RE123	717	716	50	4.2(LHe)	DP	Dry	32.5T under 18T by resistive magnet	2019	MI	
LBC	NHMFL	Demo	45.5 (14.4/31.1(RM))	RE123	1420	691	14	4.2 (LHe)	SP	Dry	Damaged at 45.5T	2017	NI	
28T Demo	RIKEN	Demo	27.7 (6.3/4.3/17.1)	RE123 /Bi2223	396/238		40	4.2 (LHe)	Layer	Wax	Quench and damaged at 27.7T	2016	Insulated	
30.5T	MIT	NMR	30.5 (18.8/11.7)	RE123	547		91	4.2 (LHe)	NI	Epoxy/ turn separation	NI, HTS coils damaged in test	2018	NI	
25T-CSM	Tohoku U.	User magnet	24 (10/14)	RE123	221	407	104	4-8	SP	Epoxy/ turn separation	Quench and damaged at 24T	2015	Insulated	
25T NI	SuNAM /MIT	Demo	26.4	RE123	404	286	35	4.2 (LHe)	NI-SP	Dry?	NI	2016	NI	
25T	IEE/CAS	Demo	25.7 (10.7/15)	RE123	100-306	382	36	4.2 (LHe)	NI-DP	Wax	NI, Quench at 25.7T	2017	NI	

Practical use　Demonstration　Damaged

May have left out. Apologize if so.

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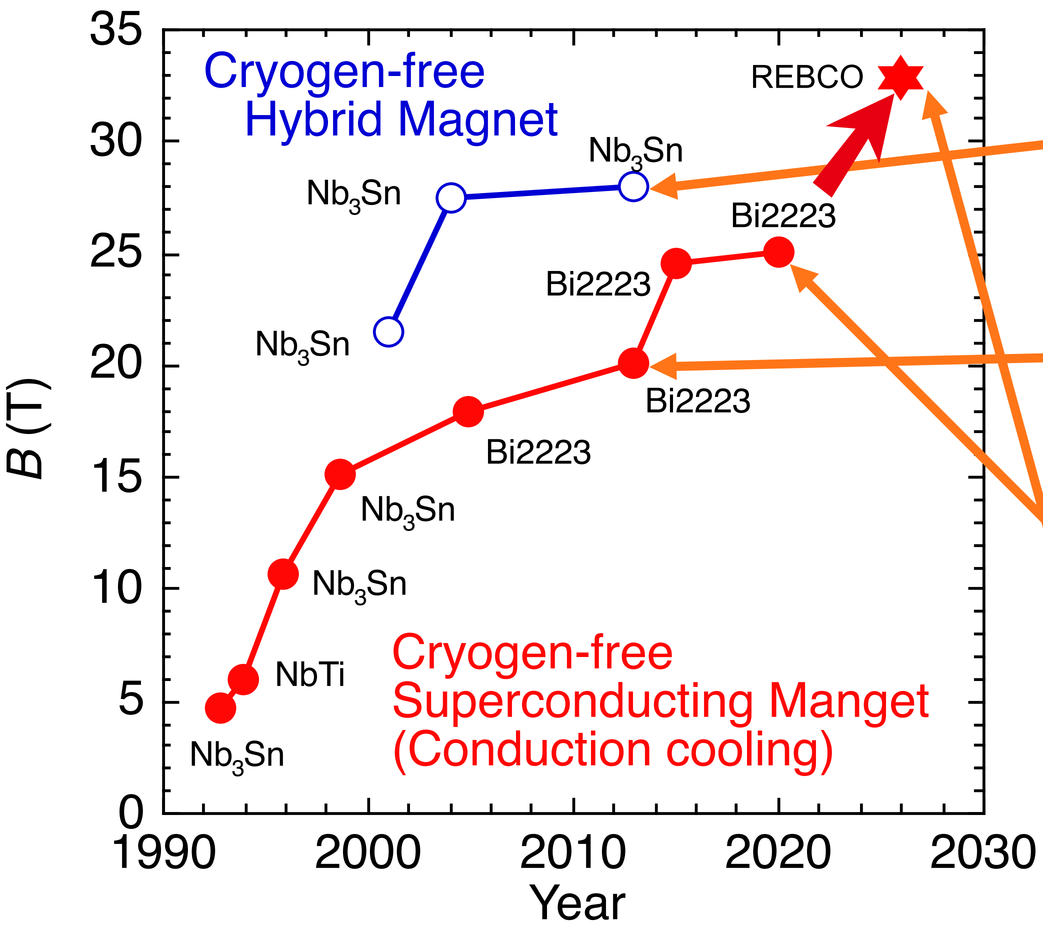
Cryogen-free superconducting magnet developments and operation at HFLSM

HFLSM Sendai

Research

Cryogen-free magnet developments at HFLSM, Sendai, Japan



28T-CHM (ϕ32RT)

ϕ360-9T-CSM
- CuNbTi/Nb_3Sn strand

ϕ32-19T-WM (8MW)
- Double Bitter

20T-CSM(ϕ52RT): 1988 days (18 years)

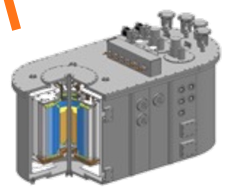
ϕ196-15.57T-LTS
- CuNbTi/Nb_3Sn, NbTi: 234 MPa

ϕ90-4.45T-HTS
- Cu-alloy/Ag/Bi2223 (SEI HT-CA): 212 MPa

25T-CSM(ϕ52RT): >1000 days (9 years)

ϕ300-14T-LTS
- CuNb/Nb_3Sn Rutherford, NbTi: 251 MPa

ϕ96-11T-HTS
- Ni-alloy/Ag/Bi2223 (SEI HT-Nx) : 323 MPa



33T-CSM(ϕ32RT): under construction

ϕ320-14T-LTS
- CuNb/Nb_3Sn Rutherford, NbTi:270 MPa

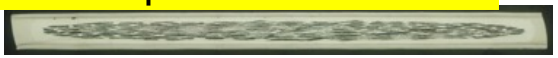
ϕ96-11T-HTS
- REBCO (Robust coil concept)

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

Insulated mono-tape winding

Magnets (HTS-Bi2223): 10.6T@188A

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

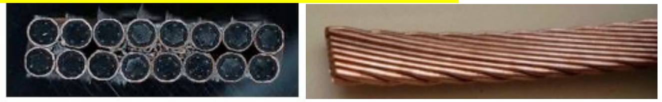


Magnet (HTS-REBCO): 10.5T@131A

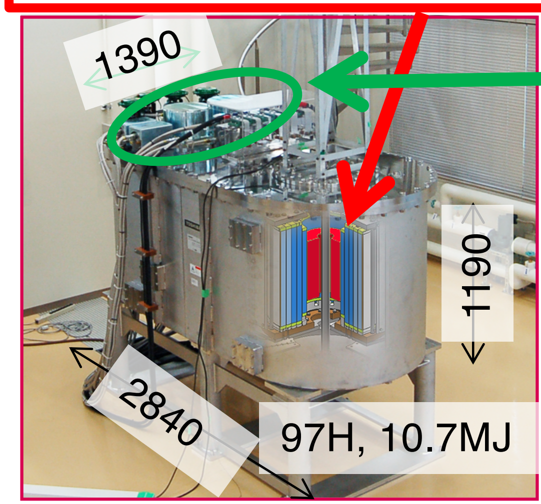
56 GdBCO single pancakes
ϕ104mm x ϕ263 mm x h336 mm
Max. hoop stress 366MPa

Magnets (LTS): 14T@854A

3 CuNb/Nb3Sn Rutherford solenoids
ϕ300 mm x ϕ539 mm x h628 mm
Max. hoop stress 252MPa



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 cryocoolers
- HTS: 2 x 4K-GM cryocoolers (3W@4.2K, 10W@8K)
- LTS: 2 x GM/JT cryocoolers (8.6W@4.3K)

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

9 years operation of 25T-CSM

Operation days per fiscal year of 25T-CSM

Fiscal year	Days of use
2016	31
2017	194
2018	246
2019	153
2020	99
2021	266
2022	112
2023	34
2024	125 (to Dec)
Total	1135 days

2015: Failed with REBCO insert but achieved 24.6T with the Bi2223 (HT-Nx)

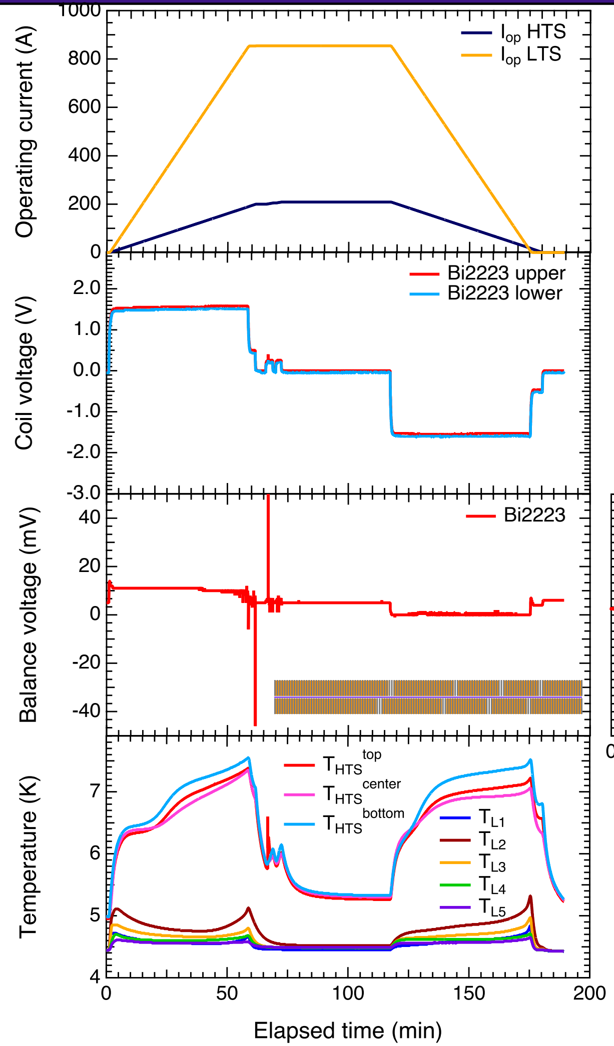
2016&2019: Short circuit between the Bi2223 pancakes due to not enough stiffness.
- slipping Bi2223 winding & touch to the next pancake.

2020: 25.1 T with replacement of the Bi2223 insert improvement of coil stiffness

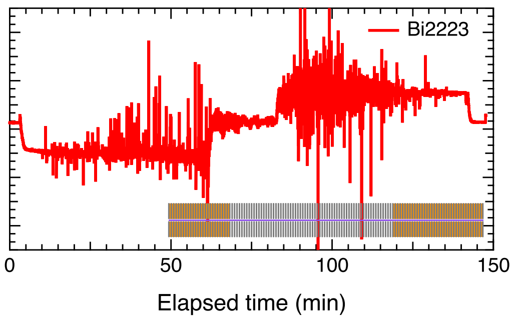
2022: Cold leak on the He line for HTS coil after a quench from 24 T at an earthquake.

K. Takahashi *et al.*, IEEE TAS, 34 (2024) 4601905

Achievement of 25.1 T by new Bi2223 coil

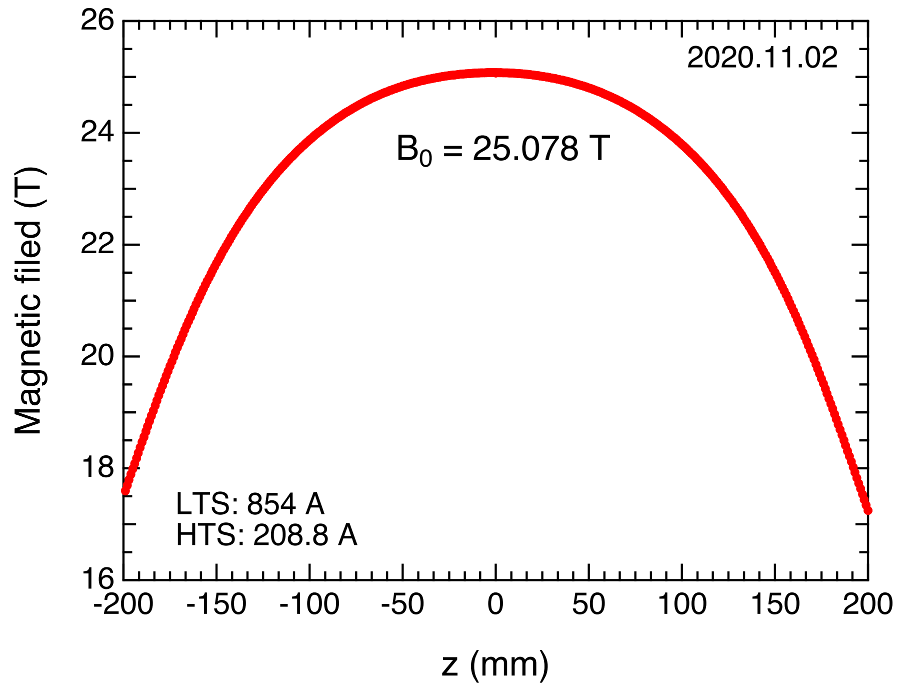


Ramping up & down in 60-min. mode



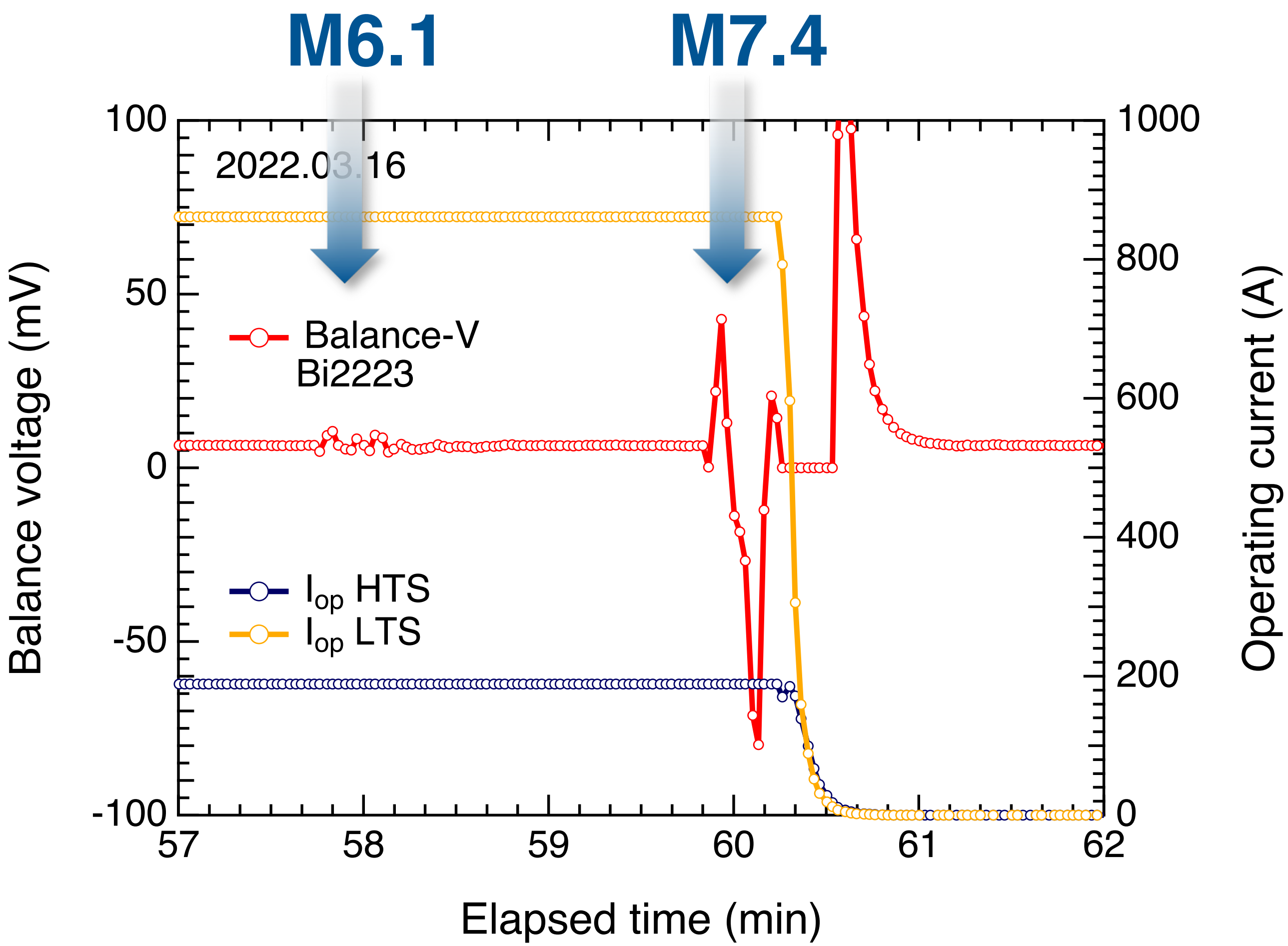
Balance voltage of the 1st coil

25.1 T @ I_{HTS} = 208.8 A, I_{LTS} = 854 A



- The improvement of coil stiffness enables the stable operation.
- Operated again as a user magnet up to 24 (25 T on request)

Quench at 24.0 T in Mar. 2022 (by earthquake)

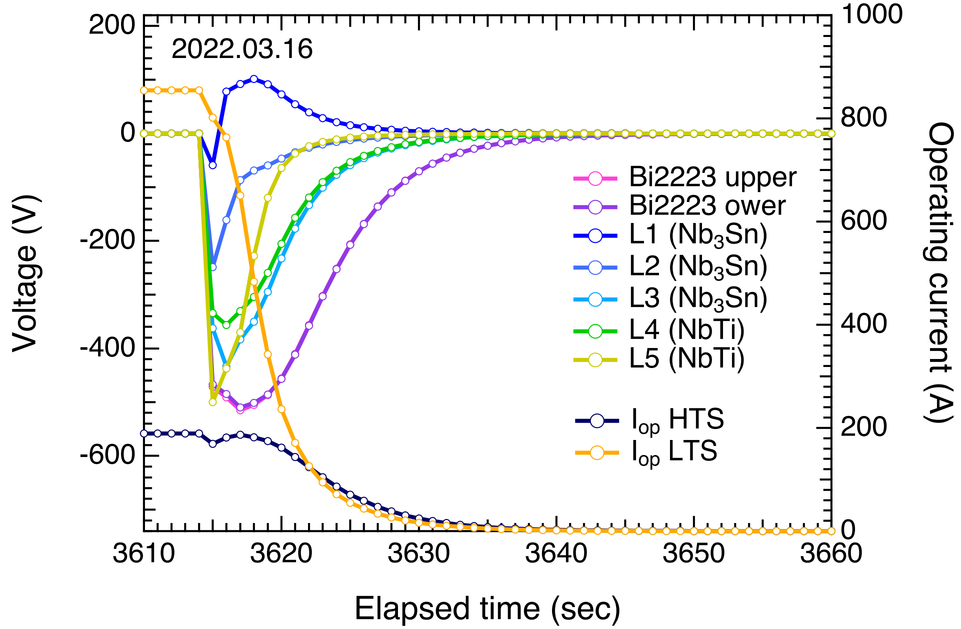


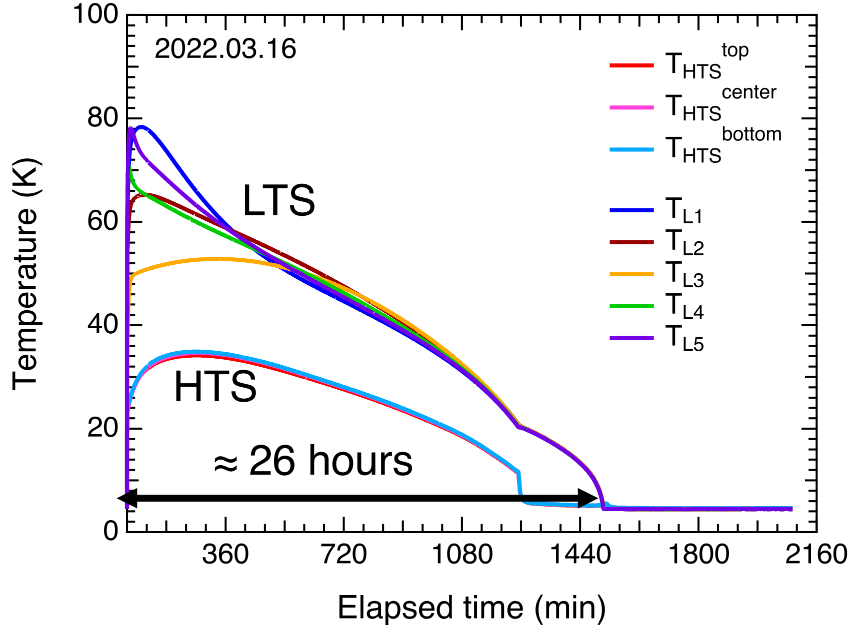
M7.4 earthquake @11:36 p.m.

M6.1 foreshock @11:34 p.m.

K. Takahashi *et al.*, IEEE TAS, 34 (2024) 4601905

Quench at 24.0 T in Mar. 2022 (by earthquake)





- No dissipation in the Bi2223 coil was observed.
- Normal zone propagated from the L1 coil

- Temperatures of all coils were less than 80 K.
- Temperatures reached the operating temperature after around 26 hours.

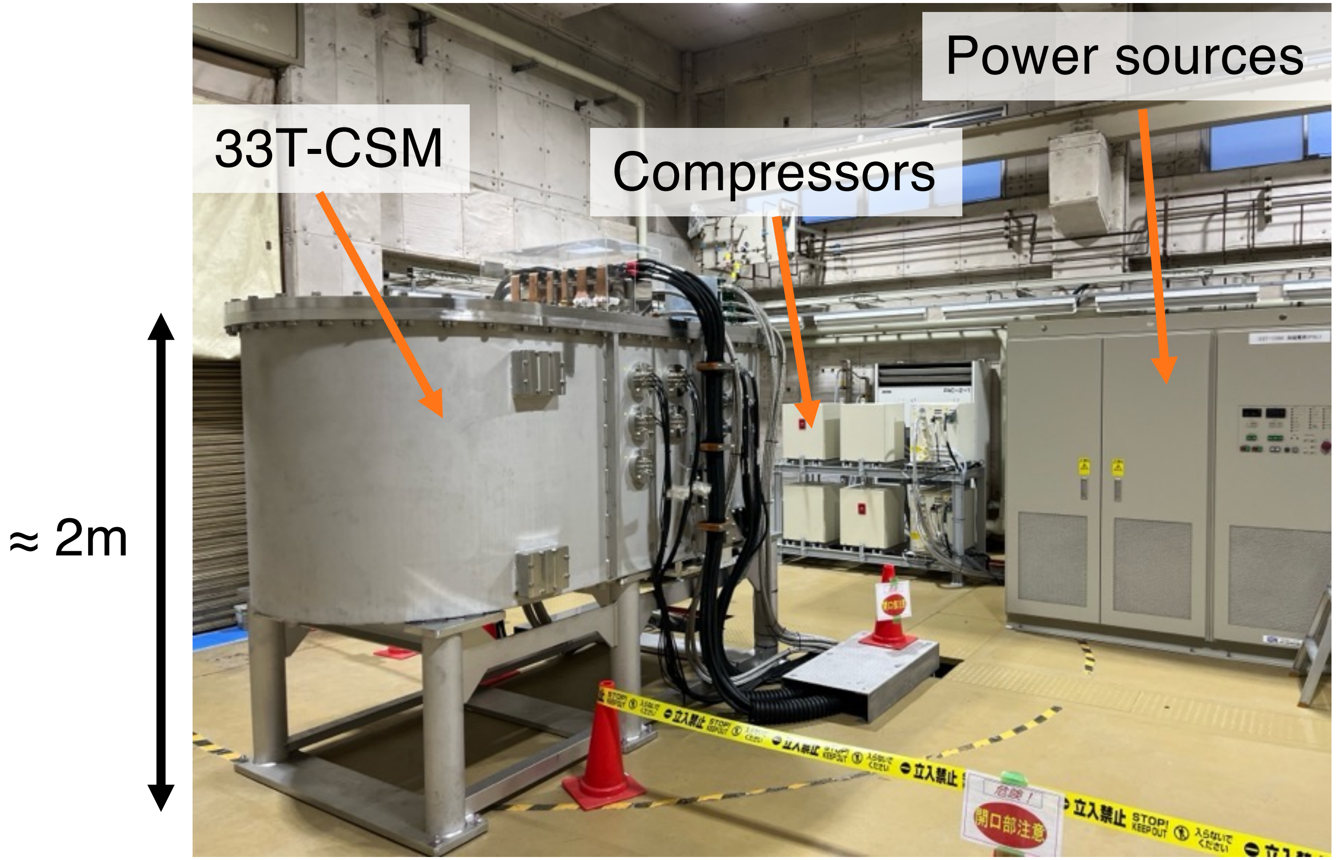
→ Most of stored energy was dissipated in the dump resistors.

K. Takahashi *et al.*, IEEE TAS, 34 (2024) 4601905

Installation of 33T-CSM (w/o HTS insert)

2022 : The project was budgeted.

2024 March: Whole system of 33T-CSM was installed without a 19 T-REBCO insert.



Overview of 33T-CSM

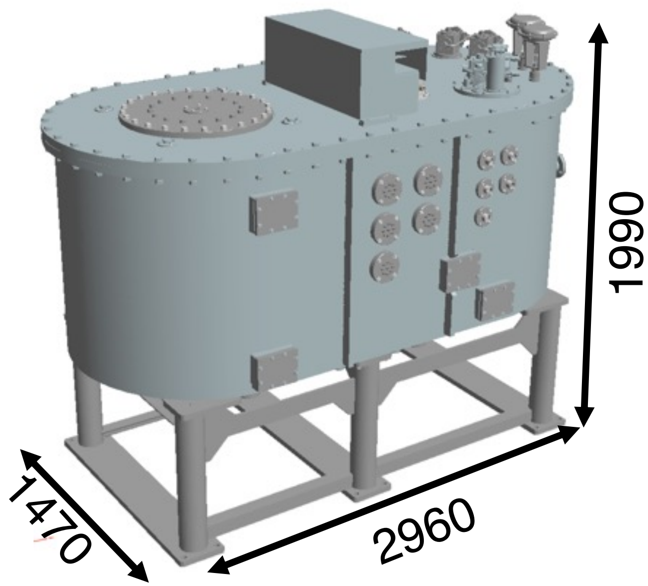
LTS outsert
- 14 T-ϕ320 mm layer wound impregnated coil with Rutherford Cables

HTS insert
- 19 T- ϕ68 mm (ϕ32mm RT bore)
- Impregnated two REBCO tape co-wound insulation coil

Cooling system
- Conduction cooling with He circulation
- 4 x 4K-GM cryocooler for HTS coils (4 x 1.5W@4.2K)
- 1 x GM/JT cryocooler for LTS coils (9W@4.2K)
- Thermally separated LTS and HTS coils

Protection
- Passible protection with a dump resistor

Others
- < 90min ramping
- Magnetic field monitor



Concept of Robust REBCO coil

Two tape bundle winding with a face-to-back configuration

Current share at local damaged area.

Reduce amount of insulation (Increase J_{space}).

Abe *et al*,, IEEE TAS, 32 (2022) 4603306

Edge impregnation
Thin FRP plate glued on coil & Impregnation

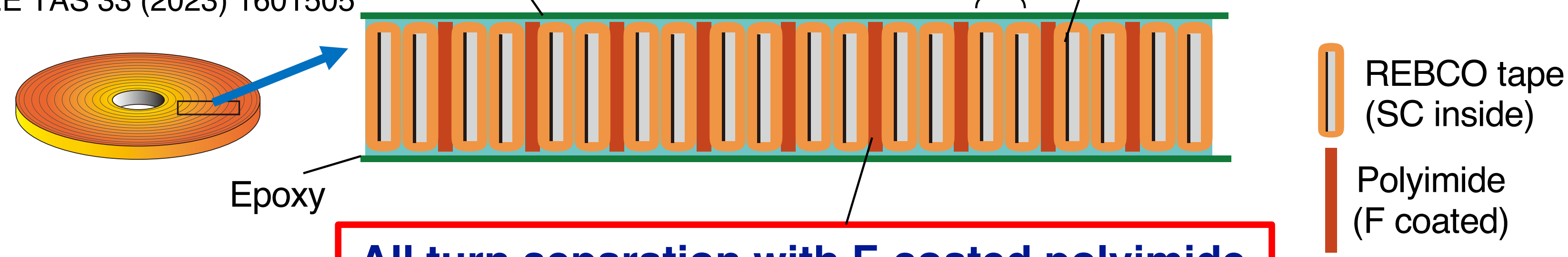
(Improve coil stiffness, optimize stress distribution, reduce screening current induced stress)

A. Badel et al., IEEE TAS 33 (2023) 1601505

40 mm Cu stabilizer

(Reduce hot-spot temp & delamination strength.)

Muto et al., IEEE TAS 28 (2018) 6601004 .



All turn separation with F-coated polyimide

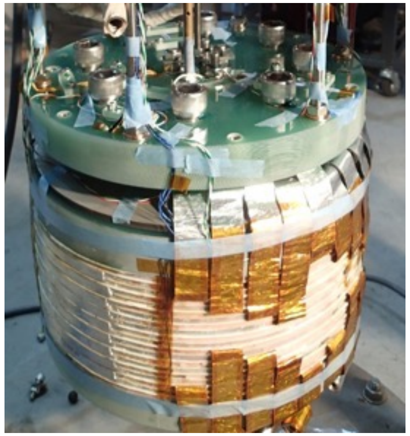
(Reduce delamination force on REBCO tape)

Miyazaki et al., IEEE TAS 24 (2013) 4600905

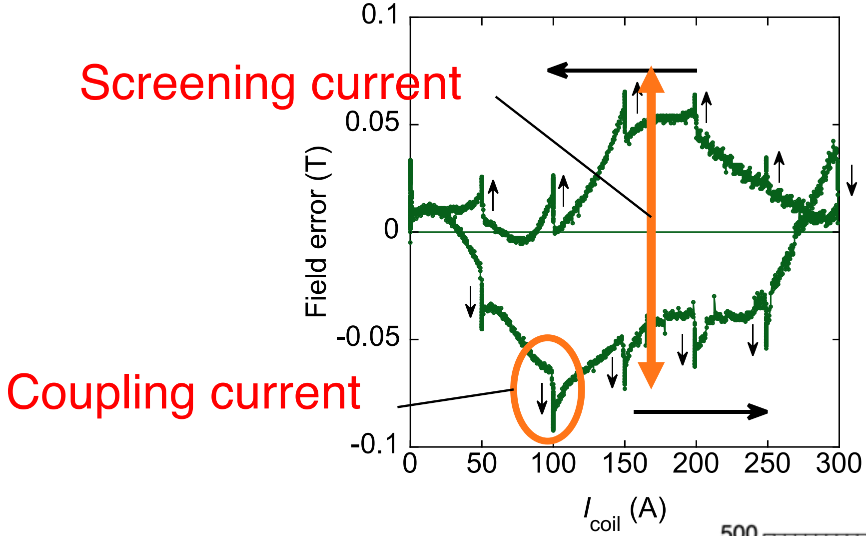
S. Awaji IEEE TAS 31 (2021) 4300105

Large-scale prototype REBCO coil (20 stacked)

K. Takahashi et al., IEEE TAS, 33 (2023) 4601405
A. Badel et al., IEEE TAS, 33, (2023) 4601505



20-stacked Coil	
No. of bundled tapes	2
Inner diameter (mm)	68
Outer diameter (mm)	266
Height of coil (mm)	120
No. of turns / PCs	271-294
I_c of pancake	121-174
n-value of pancake	22-27
No. of pancakes	20

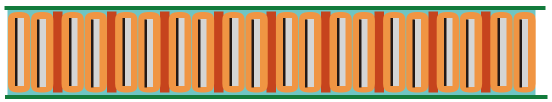


25T was achieved under B_{BG}=14 T @NIMS

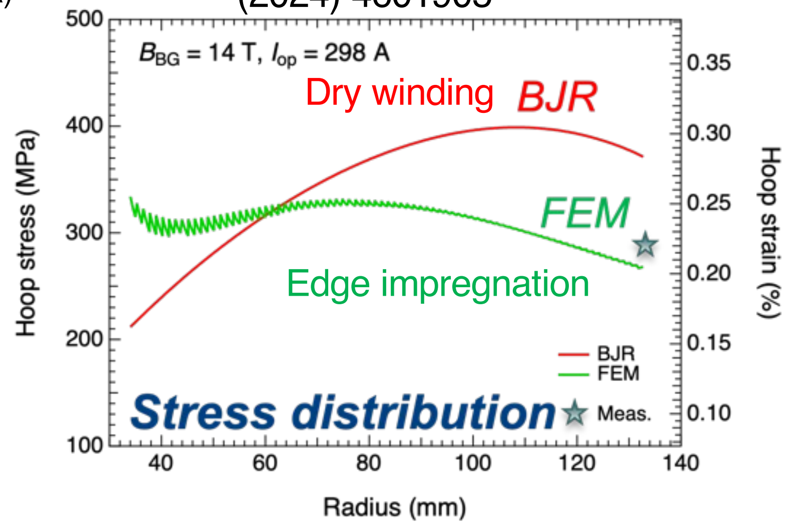
Screening current induced field B_{SCIF} and coupling induced field B_{CCIF} appear.

Zampa: 3LOr2E-04
K. Takahashi et al., IEEE TAS34 (2024) 4601905

Robust coil structure reduces maximum stress and optimizes its distribution in coil.



Edge impregnation



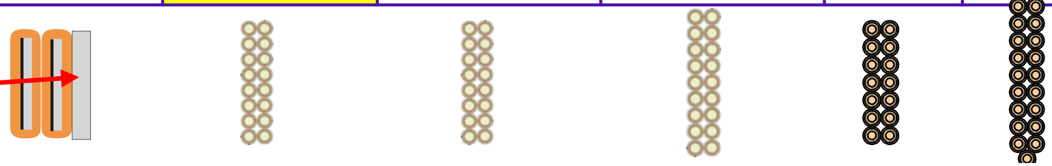
Primitive design of 33T-CSM

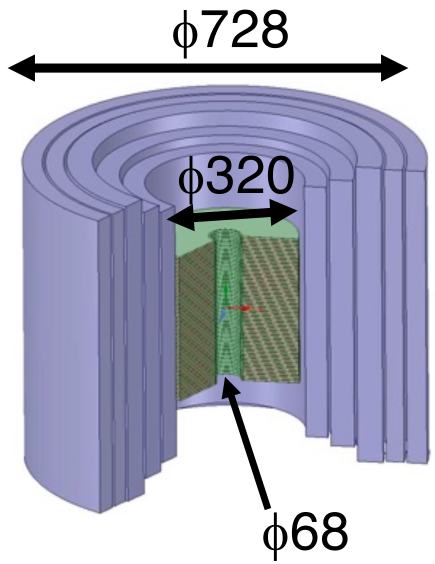
		HTS	NS1	NS2	NS3	NT1	NT2
Strand		REBCO	CuNb/Nb_3Sn			Cu/NbTi	
Iop	A	361	879				
Rin	mm	34	162.3	210.3	264.2	321.7	356.1
Rout	mm	147.2	205.5	259.4	317.1	362.1	410
Height	mm	324.5	537.6	571.2	632.5	632	632
No of PCs	-	64					
No of layer	-		24	26	28	20	22
Bmax	T	33.27	13.97	10.48	8.06	6.16	5.32
B0	T	19.1	3.22	3.26	2.99	1.91	2.63
Strand size	mm	4.1 x 0.15	ϕ0.8				
No of strands		2	16	16	18	16	19
Ic @4.2K	A		> 2192[*1]	> 2064[*1]	> 2322[*1]	> 6300[*2]	> 8550[*2]
Reinforcement		1 x 0.1 mm	-	-	-	-	-
Insulation thick	mm	0.06	0.075				
Jcon	A/mm^2	220.1	109.3	109.3	97.2	92.0	124.9
Jcoil	A/mm^2	154.8	71.8	69.2	61.5	55.0	72.7
Tcs	K	—	6.92	9.7	11.9	6.4	6.68
Axial stress	MPa	-51	-51	-50	-48	-38	-43
Hoop stress	MPa		275	251	165	82	-28

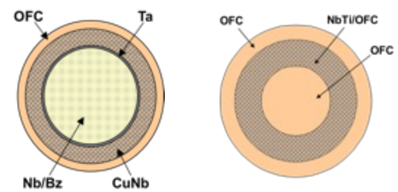
High stress

[*1] 12 T, [*2] 5 T

reinforcement







CuNb/Nb_3Sn Cu/NbTi

Concept of Robust REBCO coil (modified)

Two tape bundle winding with a face-to-back configuration
Current share at local damaged area.
Reduce amount of insulation (Increase J_{space}).

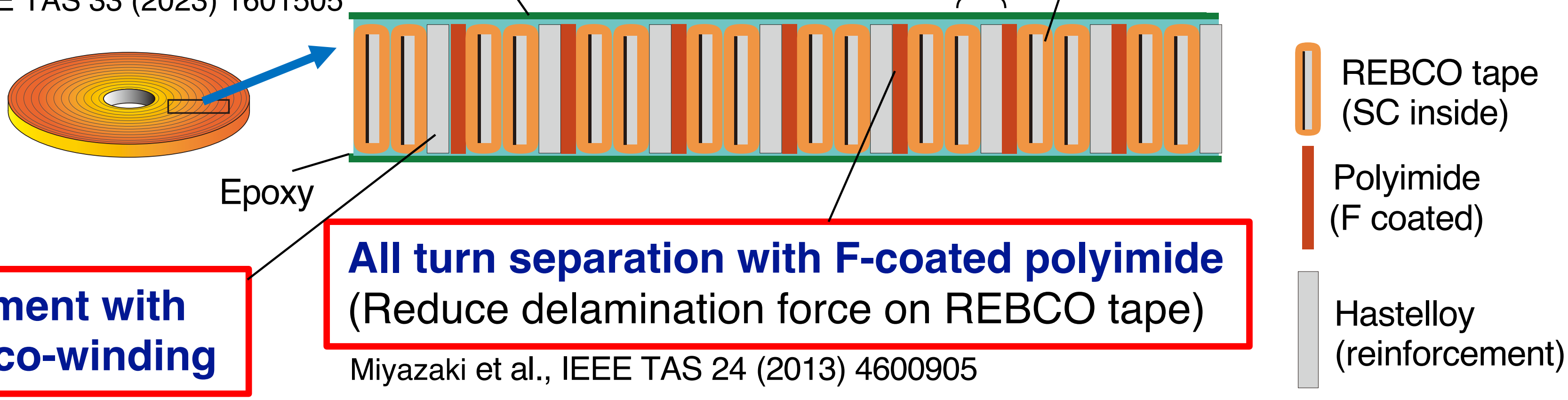
Abe *et al*,, IEEE TAS, 32 (2022) 4603306

Edge impregnation
Thin FRP plate glued on coil & Impregnation
(Improve coil stiffness, optimize stress distribution, reduce screening current induced stress)

A. Badel et al., IEEE TAS 33 (2023) 1601505

40 mm Cu stabilizer
(Reduce hot-spot temp & delamination strength.)

Muto et al., IEEE TAS 28 (2018) 6601004 .



Reinforcement with Hastelloy co-winding

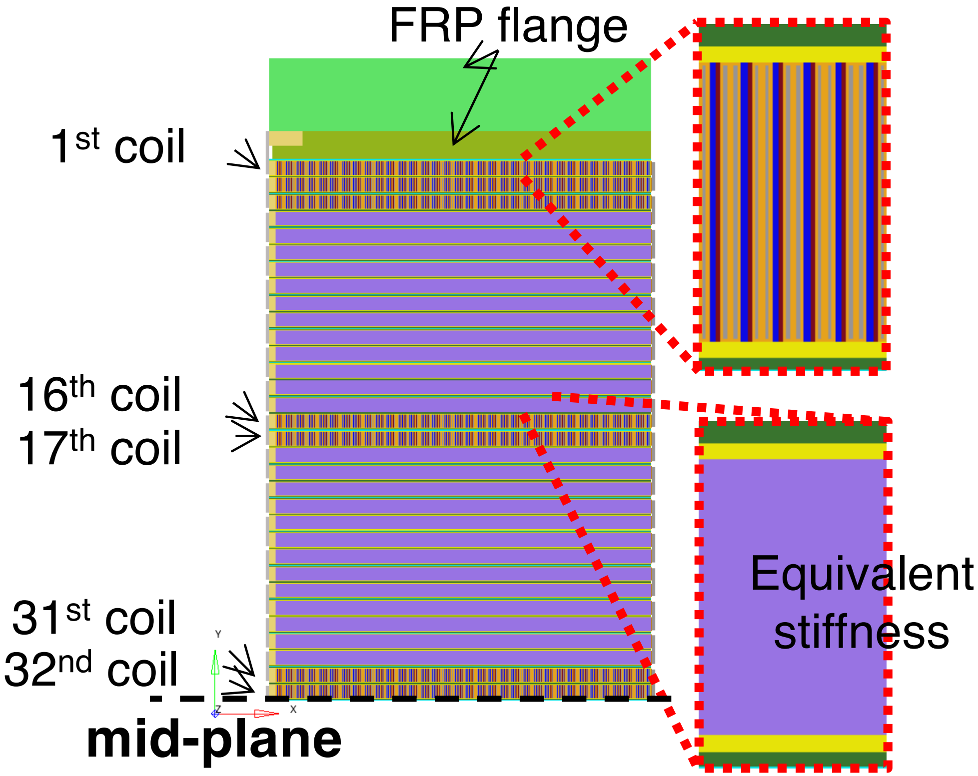
All turn separation with F-coated polyimide
(Reduce delamination force on REBCO tape)

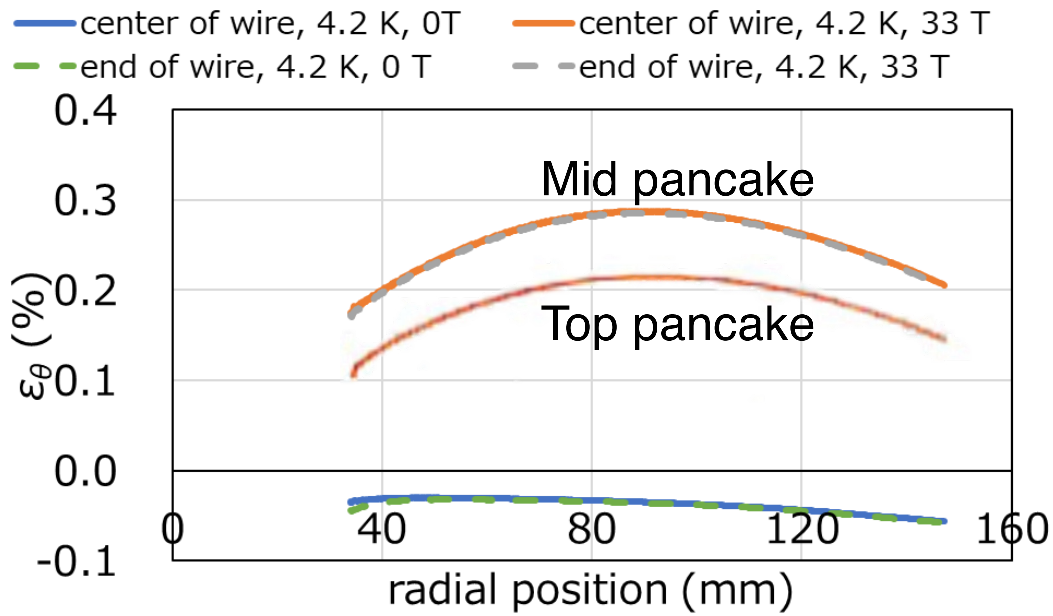
Miyazaki et al., IEEE TAS 24 (2013) 4600905

A. Badel et al., IEEE TAS 34 (2024) 4301205
Uto: 2LPo1B-04

S. Awaji IEEE TAS 31 (2021) 4300105

2D FEM analysis in the pancake coil



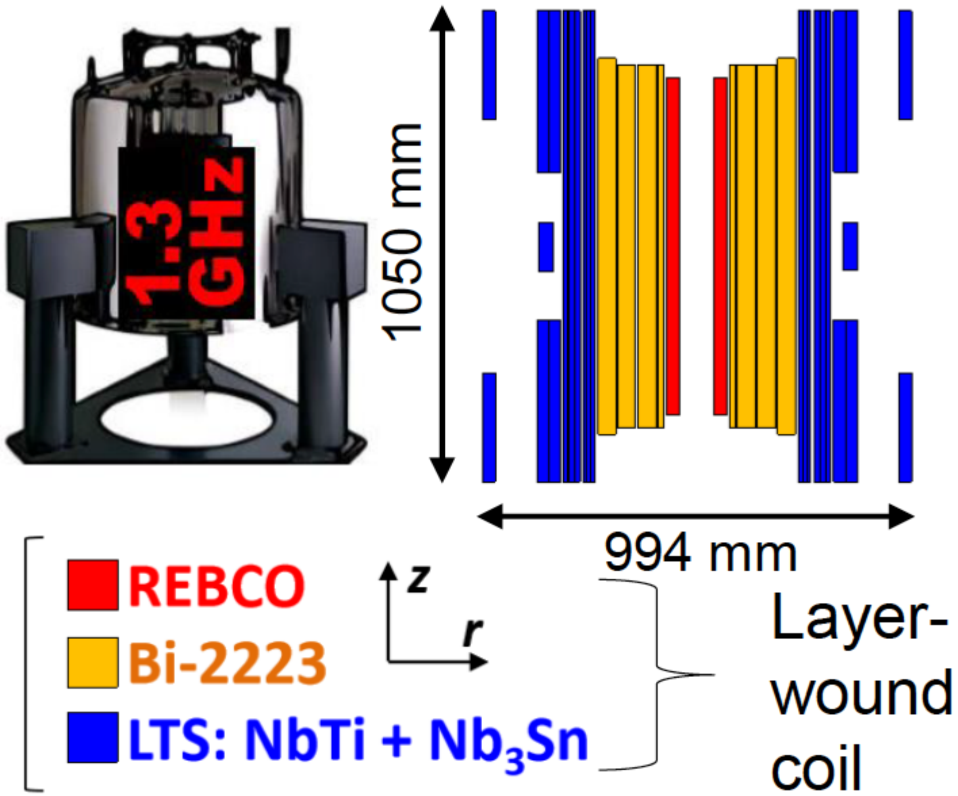


- Maximum hoop strains are about 0.29% for the mid pancake and 0.21% for the top pancake.
- Screening current induced stress/strain should be considered. It is about 10% and negligible in the mid coil.

Uto: 2LPo1B-04

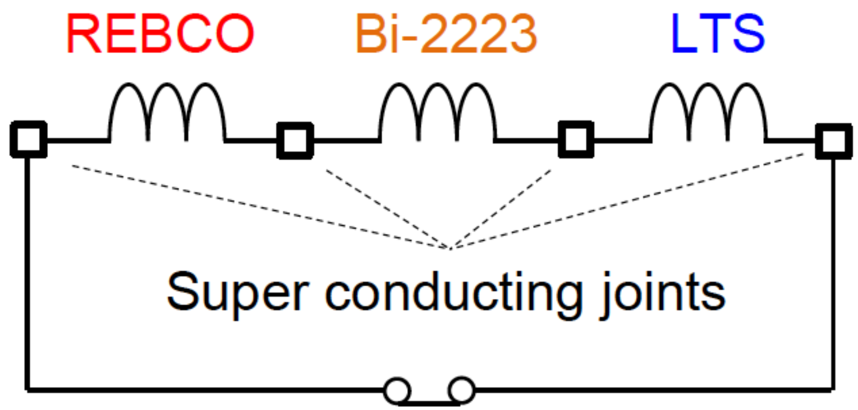
MIRAI project (Riken)
Persistent mode 1.3 GHz NMR magnet

MIRAI project (Riken): Persistent mode 1.3 GHz NMR magnet



Primitive designs by Hamada, JASTEC

H. Maeda., IEEE TAS, 29, 5 (2019)



Requirements

- **30.5 T** generation by LTS / Bi-2223 / REBCO **layer-wound** coils.

etc.

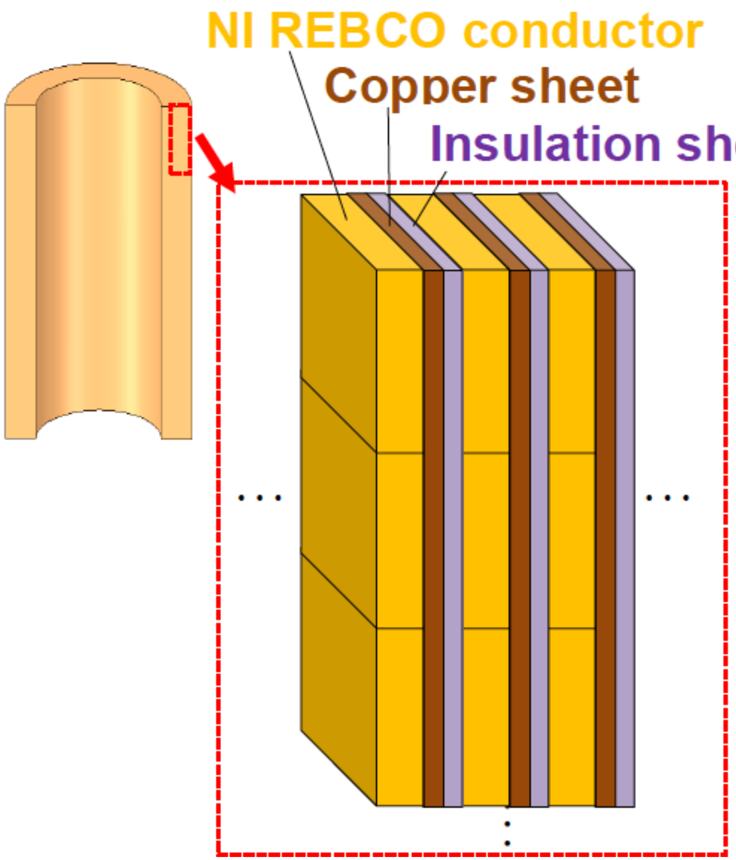
Courtesy of Yanagisawa (RIKEN)

MIRAI project (Riken): 30 T model test coil

Yu Suetomi, SuST. 34 (2021) 064003

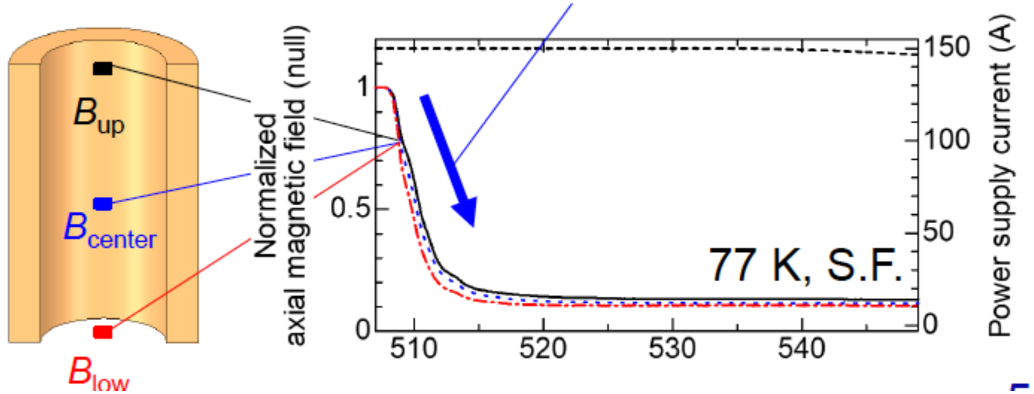
Possible protection method for a REBCO layer-wound coil :
"intra-Layer No-Insulation (LNI)" method

Y Suetomi et al., SuST, 32, 045003 (2019)



- **Short field delay**
- **Self-protection**

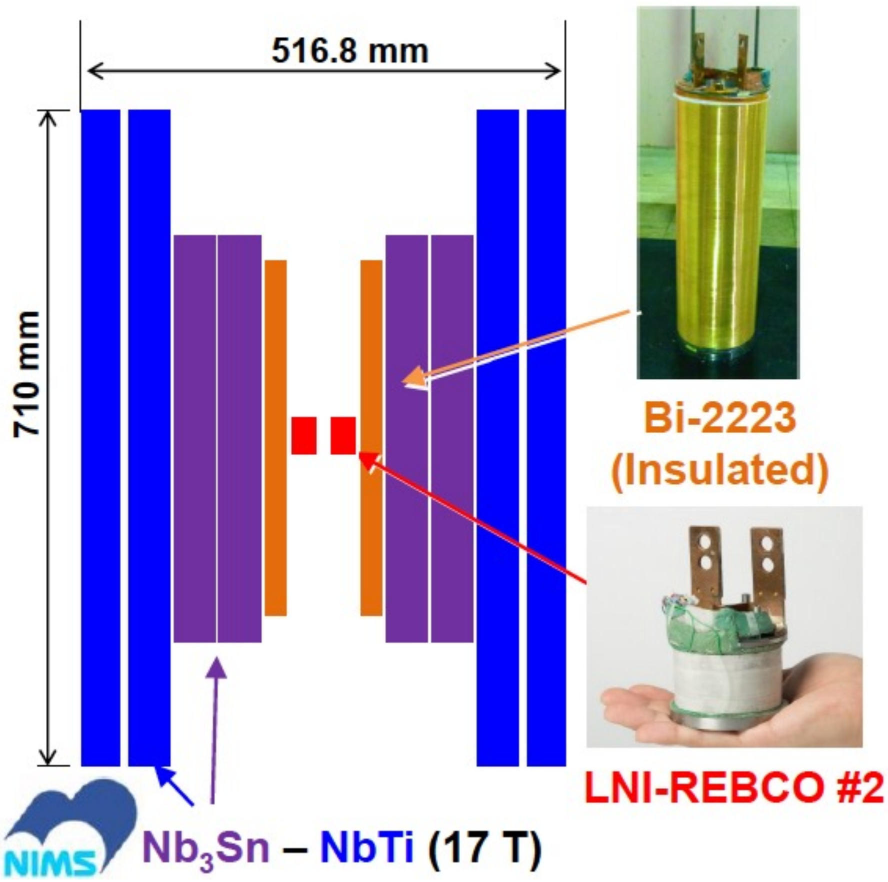
Homogeneous field decay in the axial direction during quench.



MIRAI project (Riken): 30 T model test coil

Yu Suetomi, SuST. 34 (2021) 064003

30 T model test coil



Parameters	REBCO coil	Bi-2223 coil
Conductor Type	SuperPower Inc. SCS4050	SEI, Ltd. HT-NX
Winding	LNI	Layer-wound
Inter-layer material	Cu+PET sheet (26 μm)	-
Impregnation	Paraffin wax	Paraffin wax
Over-band material / Over-band thickness	Ni-alloy tape / 2.1 mm	Brass round wire / 0.9 mm
Coil I.D. / O.D. (mm)	17.6 / 66.95	81.1 / 125
Coil height (mm)	40.1	384
Number of turns	1604 (~9 ×180)	4640 (~80×58)
Number of joints	0	3
Iop (A)	265	
Iop / Ic	0.56	0.51
Magnetic field (T)	9.3	4.0
Self-inductance (mH)	47.7	450

13 T

Center magnetic field : 13 T + 17 T = 30 T

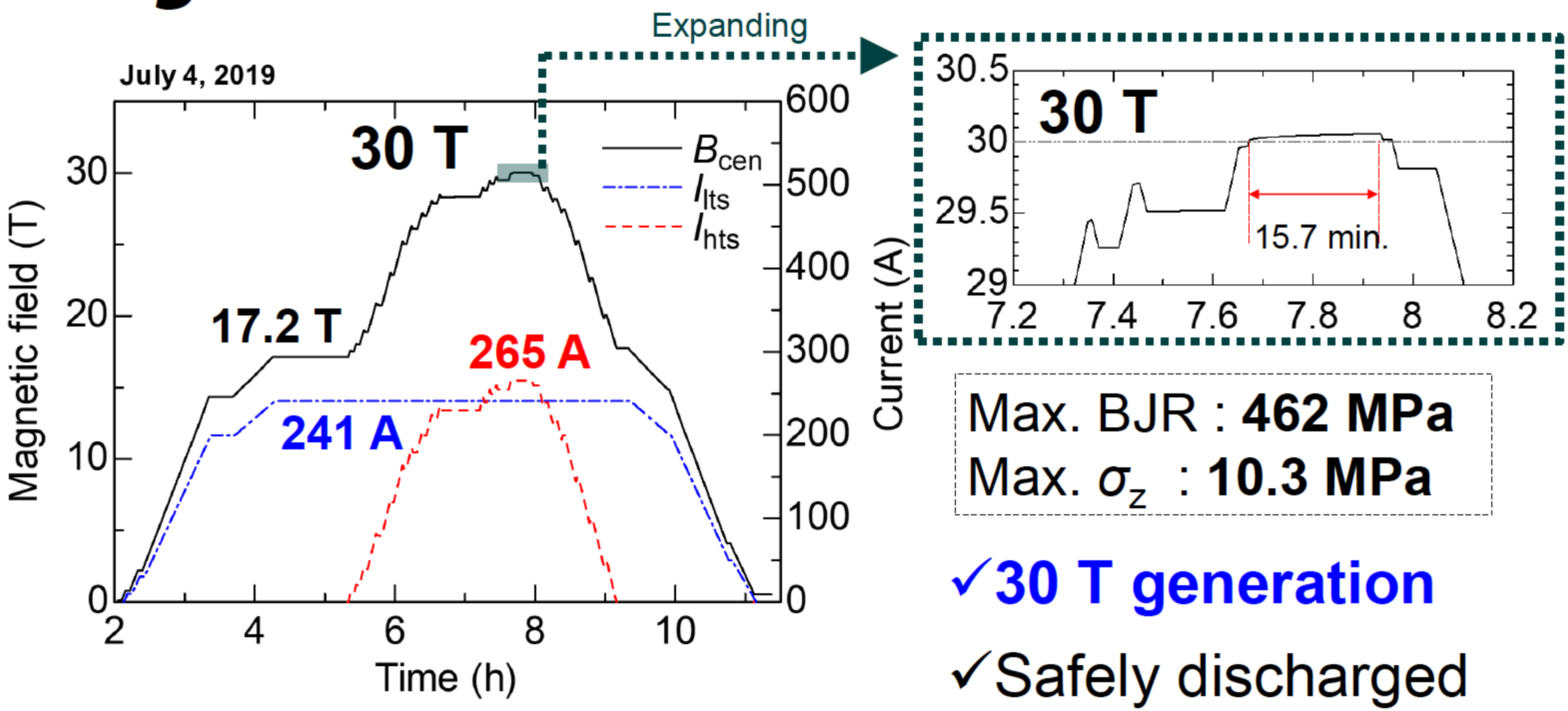
Yu Suetomi, Fri-Mo-Or27-02 MT26 (Sep. 27. 2019)

MIRAI project (Riken): 30 T generation

Yu Suetomi, SuST. 34 (2021) 064003

30 T generation

Yu Suetomi, Fri-Mo-Or27-02 MT26 (Sep. 27. 2019)



Max. BJR : **462 MPa**

Max. σ_z : **10.3 MPa**

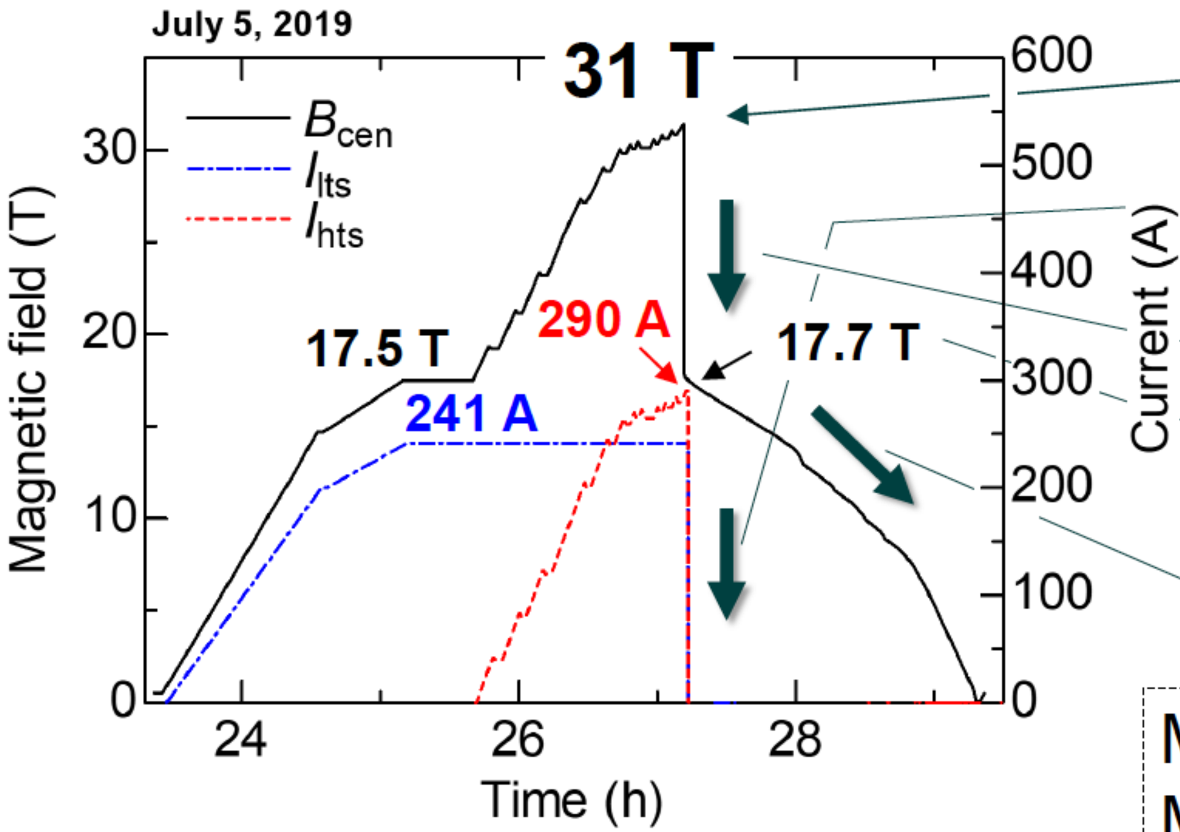
✓**30 T generation**

✓Safely discharged

MIRAI project (Riken): Quench at 31 T

Yu Suetomi, SuST. 34 (2021) 064003

31 T generation ➡ REBCO coil Quench



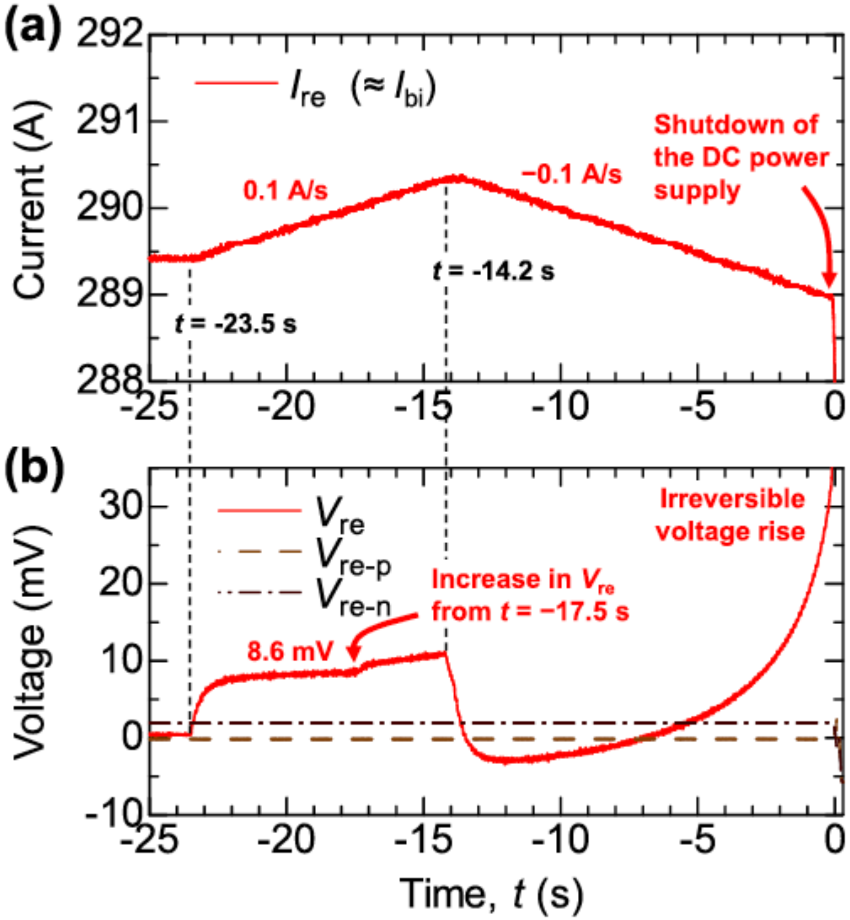
Yu Suetomi, Fri-Mo-Or27-02 MT26 (Sep. 27. 2019)

1. **Quench occurred in the LNI-REBCO coil**
2. **Power supplies were shut down**
3. **HTS fields vanished**
4. **No quench in the LTS coil**
5. **Diode discharge**

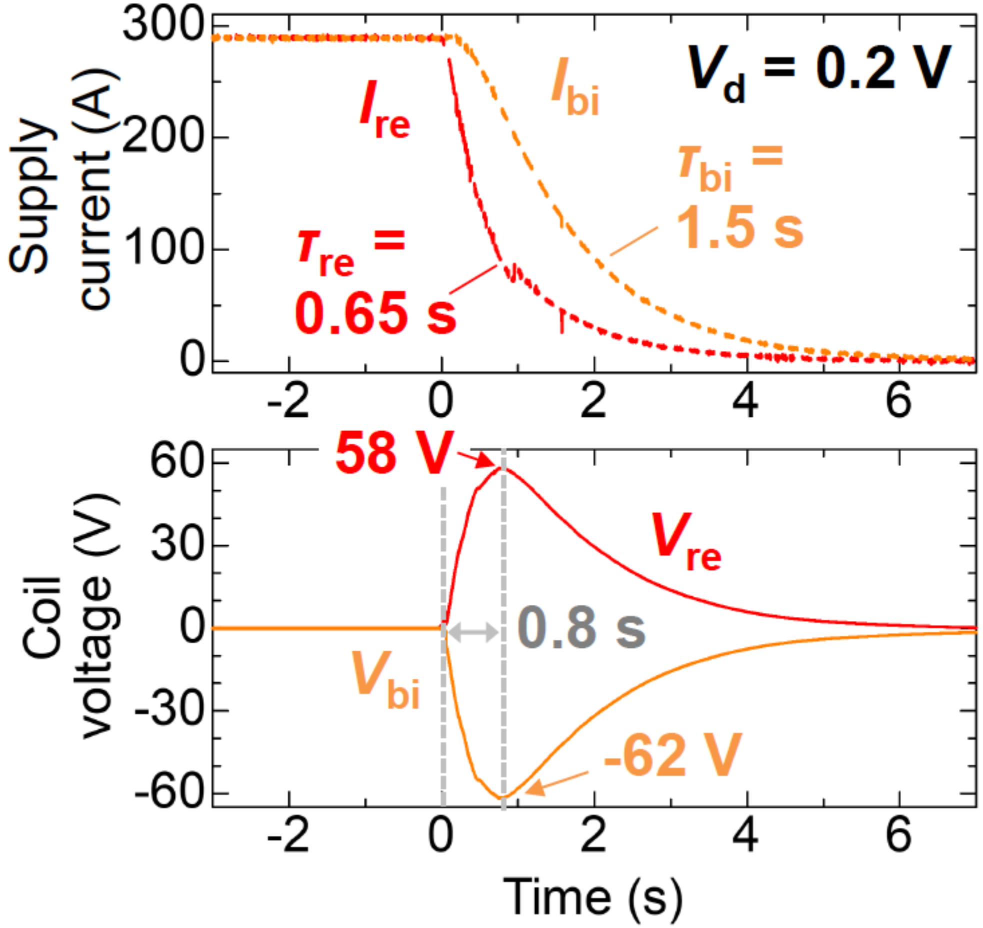
Max. BJR : **513 MPa**
Max. σ_z : **12.9 MPa**

MIRAI project (Riken): Quench at 31 T

Yu Suetomi, SuST. 34 (2021) 064003



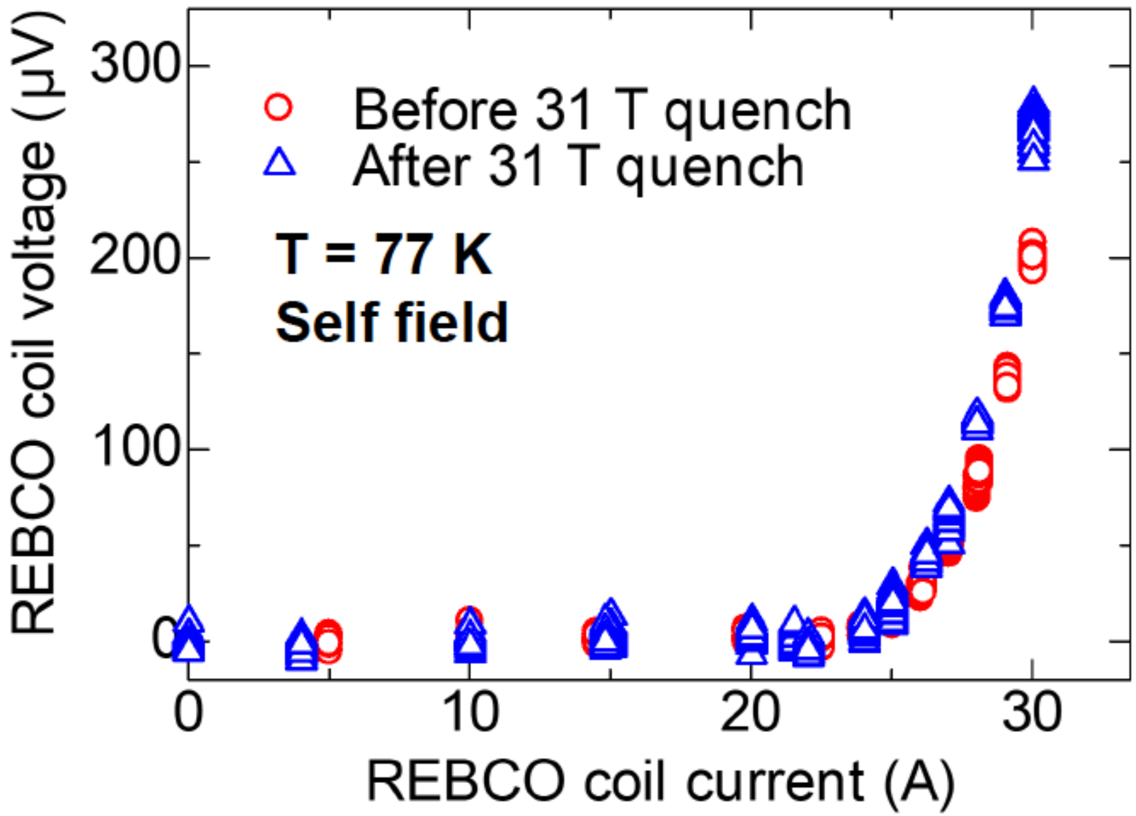
Initiation of quench & thermal runaway in REBCO coil



No dissipation in Bi2223 coil

MIRAI project (Riken): Quench at 31 T

Yu Suetomi, SuST. 34 (2021) 064003



✓**No degradation**

Degradations due to unbalanced electromagnetic forces as seen in the case of NI DP coils didn't occur.

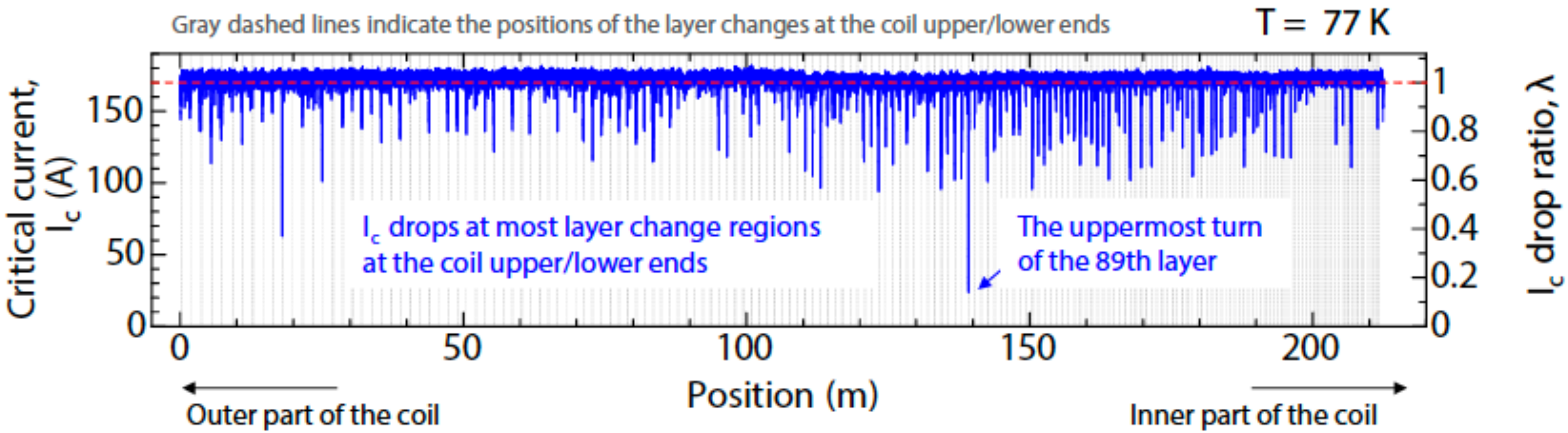
✓**LNI-REBCO coil was protected from very high-field quench.**

Yu Suetomi, Fri-Mo-Or27-02 MT26 (Sep. 27. 2019)

MIRAI project (Riken): Quench at 31 T

Yu Suetomi, SuST. 34 (2021) 064003

Ic distribution after the quench



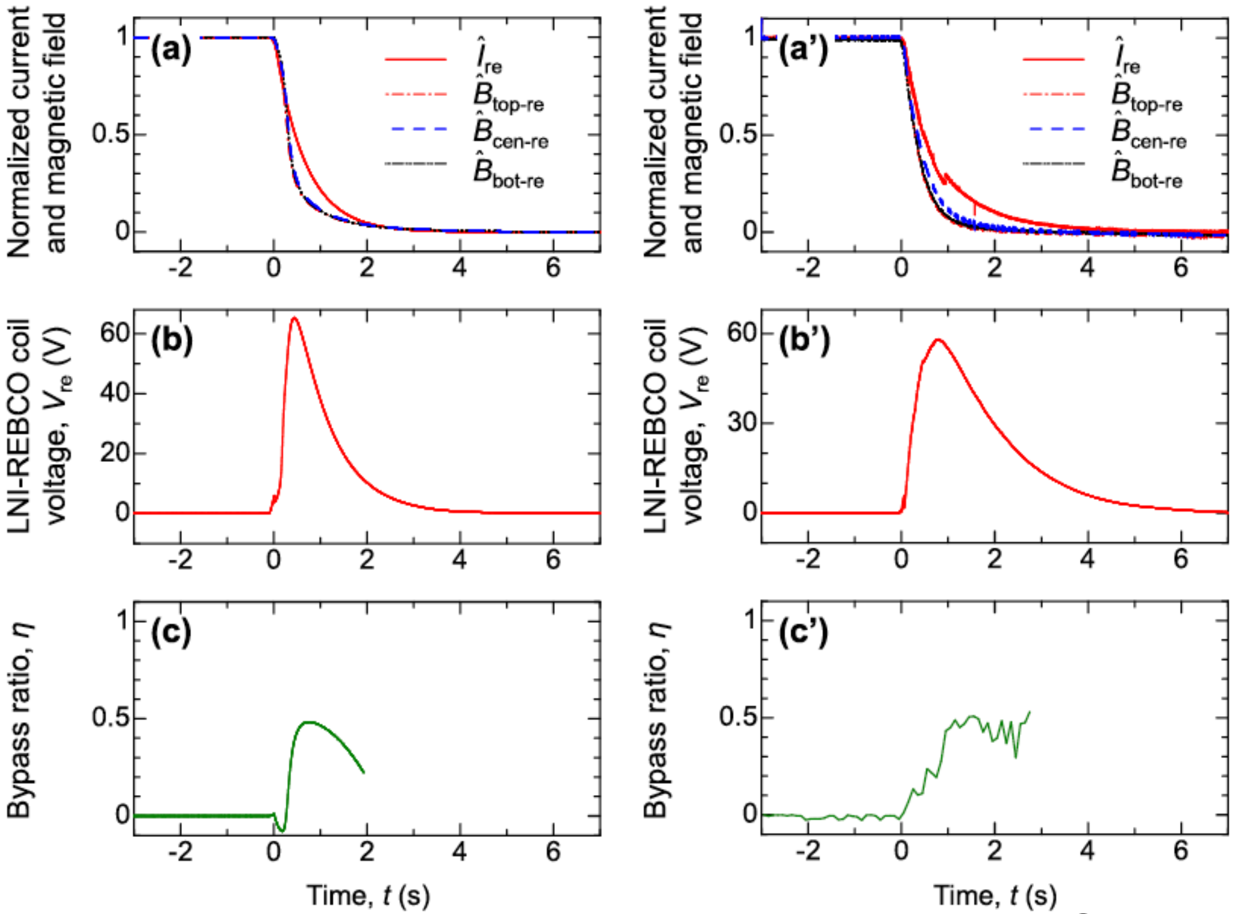
A quench initiation from the top of 89th layer is considered.

Yu Suetomi, Fri-Mo-Or27-02 MT26 (Sep. 27. 2019)

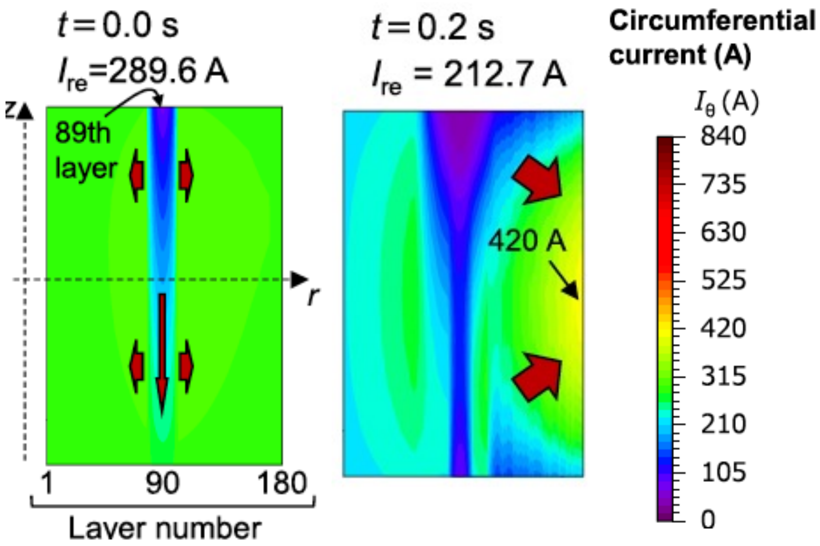
MIRAI project (Riken): Quench simulation

Yu Suetomi, SuST. 34 (2021) 064003

Simulation Experiment



ρ_{ct}=10 mΩcm^2



Circumferential current is induced.

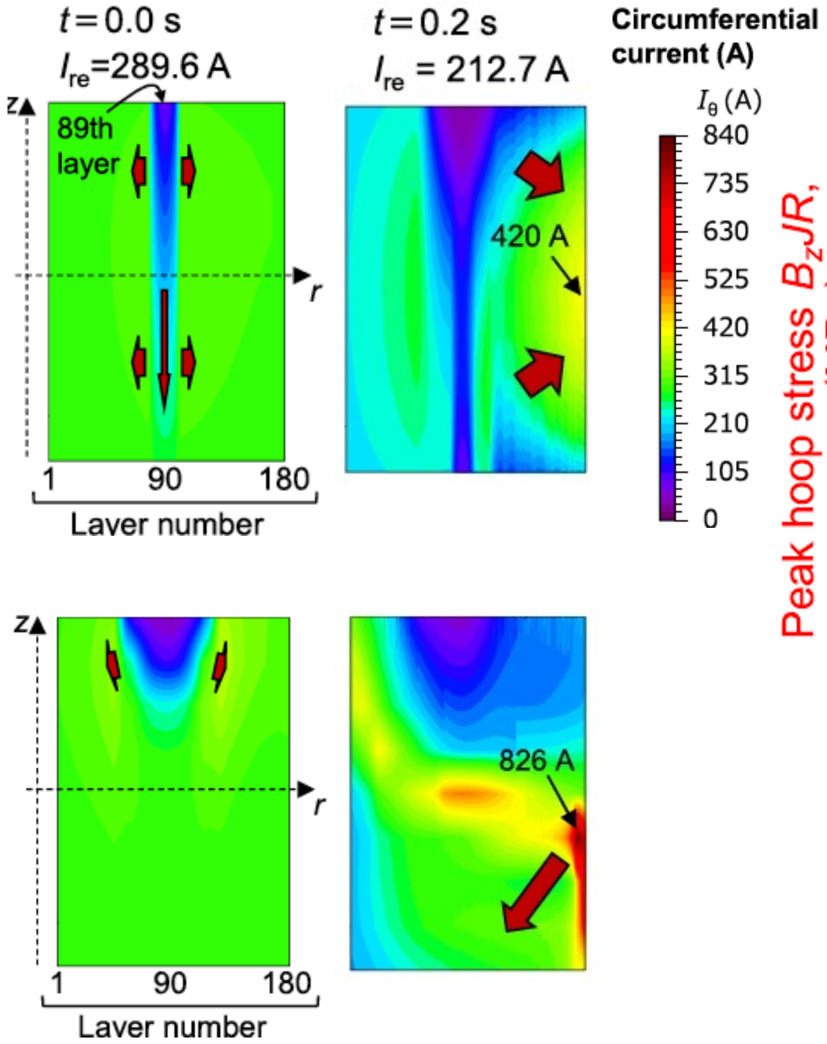
Yu Suetomi, Fri-Mo-Or27-02 MT26 (Sep. 27. 2019)

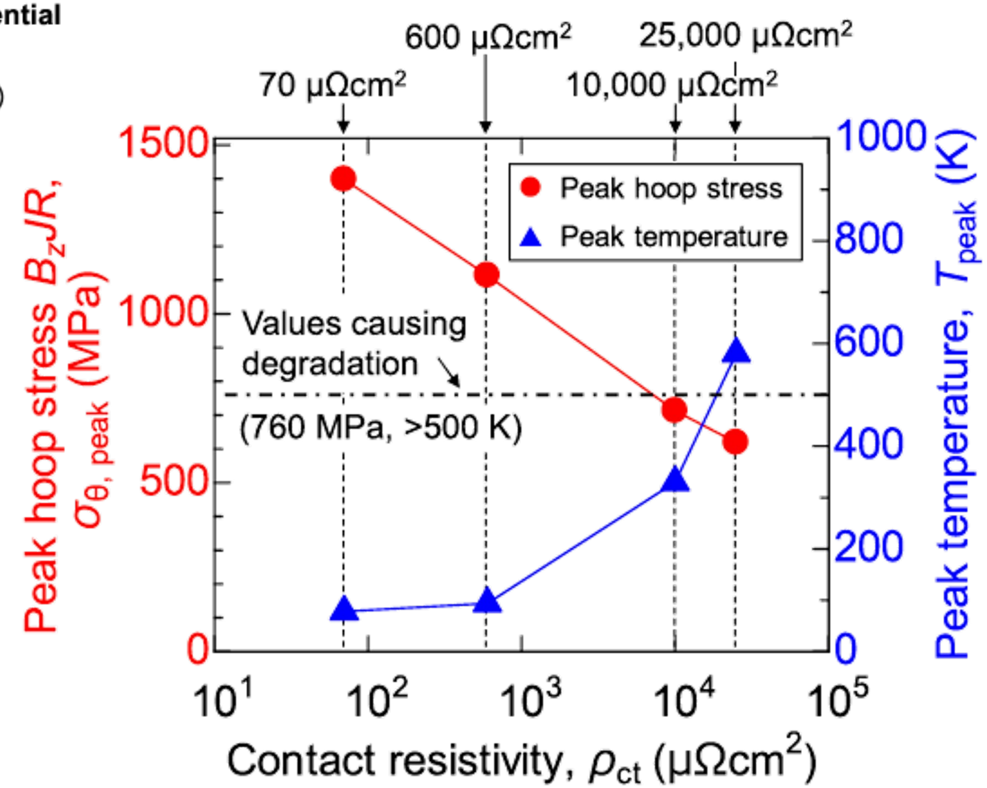
MIRAI project (Riken): effect of contact resistance

Yu Suetomi, SuST. 34 (2021) 064003

ρ_{ct}=10 mΩcm²

ρ_{ct}=70 μΩcm²



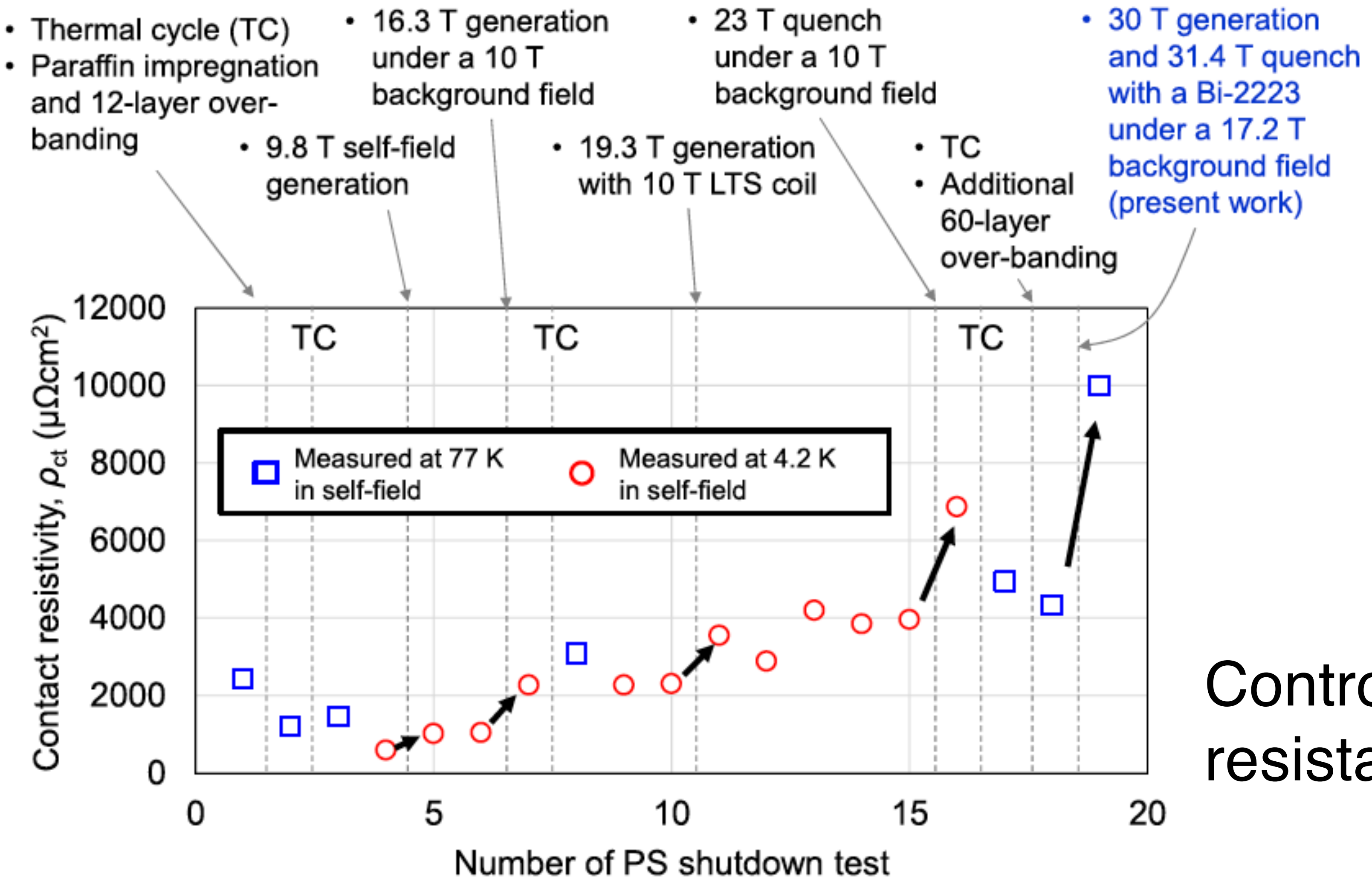


Control of ρ_{ct} is essential.

ρ_{ct}: contact resistance

MIRAI project (Riken): contact resistance

Yu Suetomi, SuST. 34 (2021) 064003



Control of contact resistance is difficult!

Summary

- High field cryogen-free superconducting magnets at Tohoku University
  - 25T-CSM is operated for 9 years as user magnet.
    - The high stress operation of with the pre-bent R&W LTS coils was demonstrated.
    - The coil stiffness is important especially for the high stress operation in the HTS coil.
  - The 33T-CSM system without HTS insert was installed in March 2024.
    - The test including the LTS coil has been confirmed successfully.
    - The “Robust coil concept” consisting a edge impregnation, two bundle co-winding REBCO tapes, all turn separation was proposed.
    - Various tests with the large-scale prototype coil was carried out without any problems.
      (First discharge, operation at various temperatures , magnetic field stability, electromagnetic tests)
- 1.3 GHz (30.5T) NMR project at Riken
  - 30T was achieved with small REBCO layer NI coil, Bi2223 insulated layer would coil and 17T LTS coils.
  - The intra Leyer NI looks good because of no inhomogeneous bypass current along the longitudinal axis.
  - The contact resistance between turns is essential for the protection but it is difficult to be control.

Thank you for your kind attention!

TOHOKU UNIVERSITY

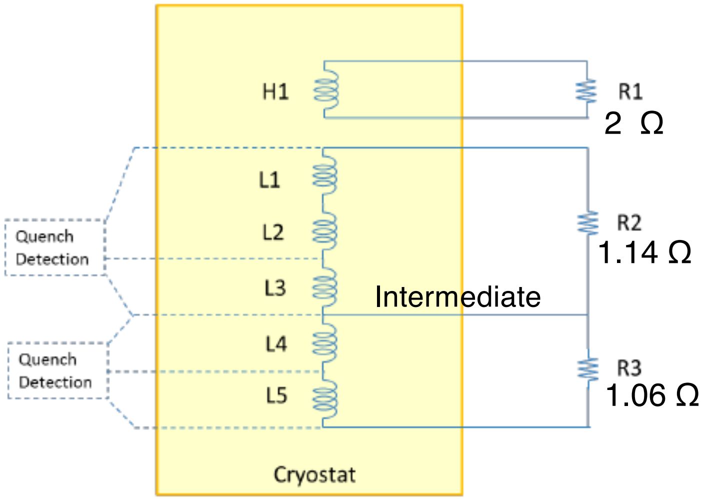
Backup slides

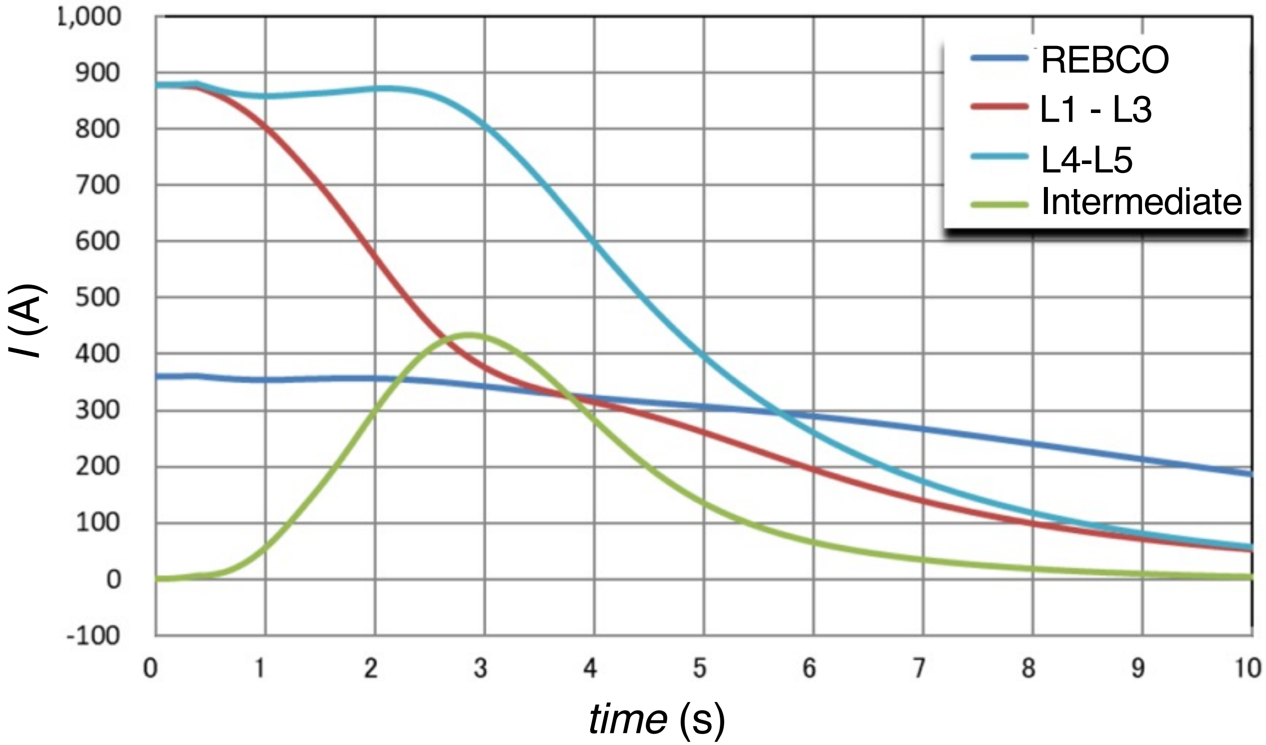
HFLSM Sendai

Research

Discharging behavior for L1 quench

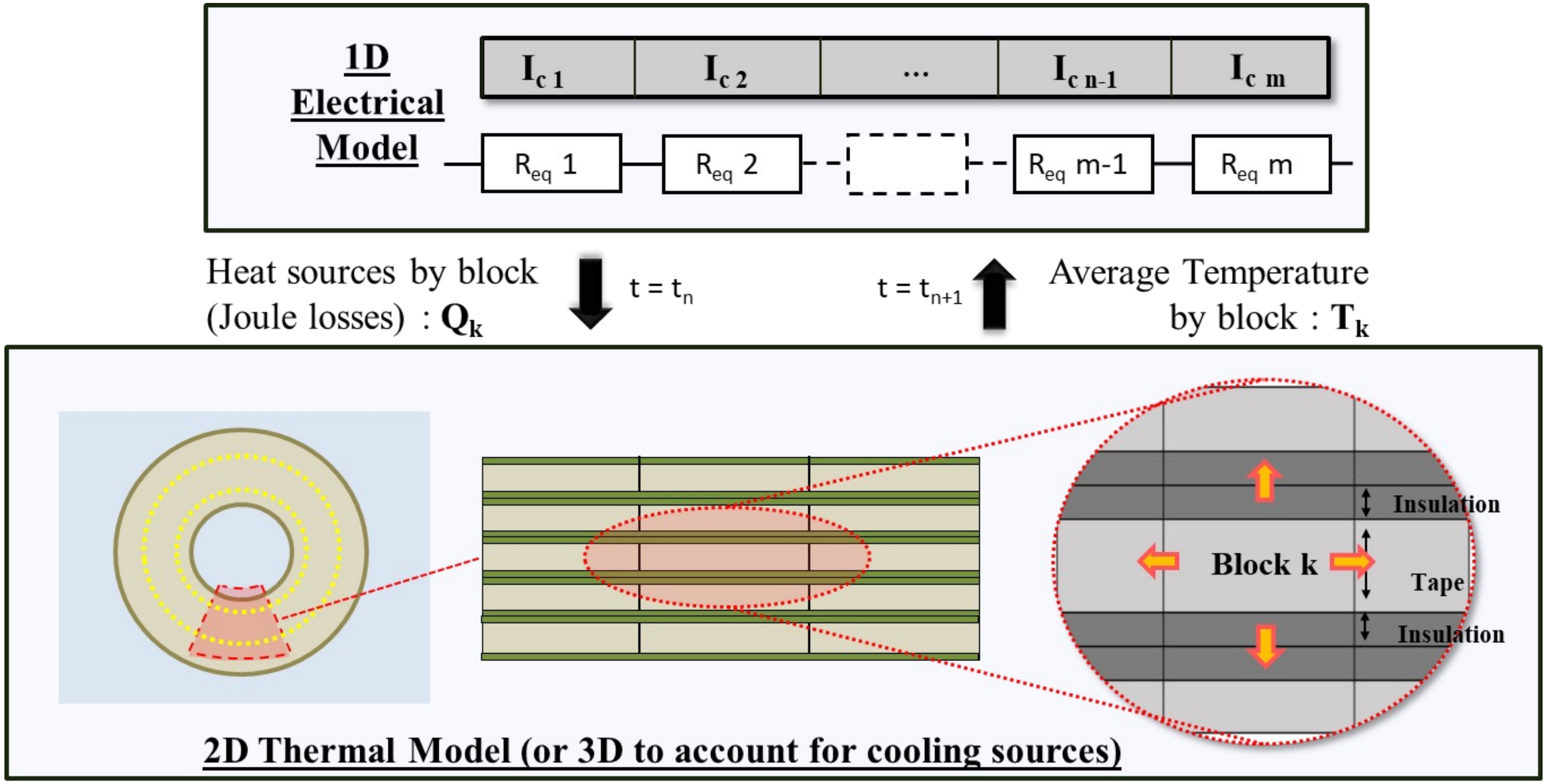
Protection circuit





- Operation current of REBCO (H1) coil is not over the I_c after quench.
  -> No dissipation appears in the REBCO coil if no local degradation exists.

Thermal runaway : Modelling for REBCO HTS Magnets



Badel 2019 *SuST: DOI* 10.1088/1361-6668/ab181f

Quench analysis of REBCO insert in 33T-CSM

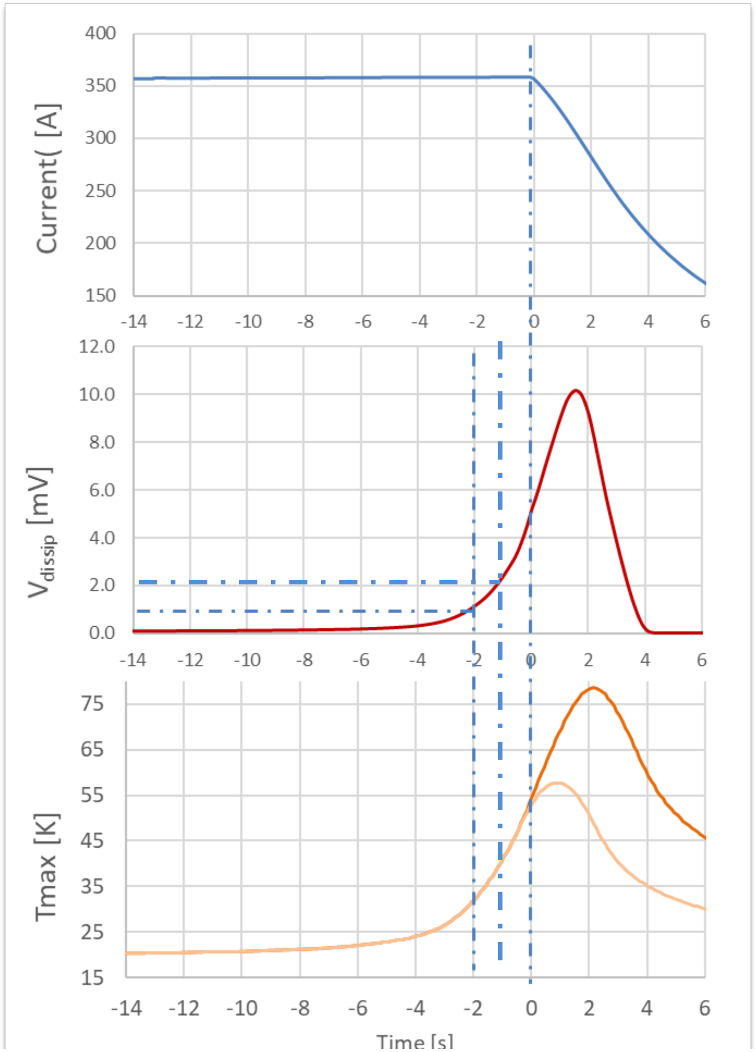
Assumption : 50 % I_c reduction over 1.6 cm
(Damaged one tape in two tapes)

Operation at 358 A -> J_{tape} = 290 A / mm²

No delay achieved with 4 mV threshold
1 s delay achieved with 2 mV threshold

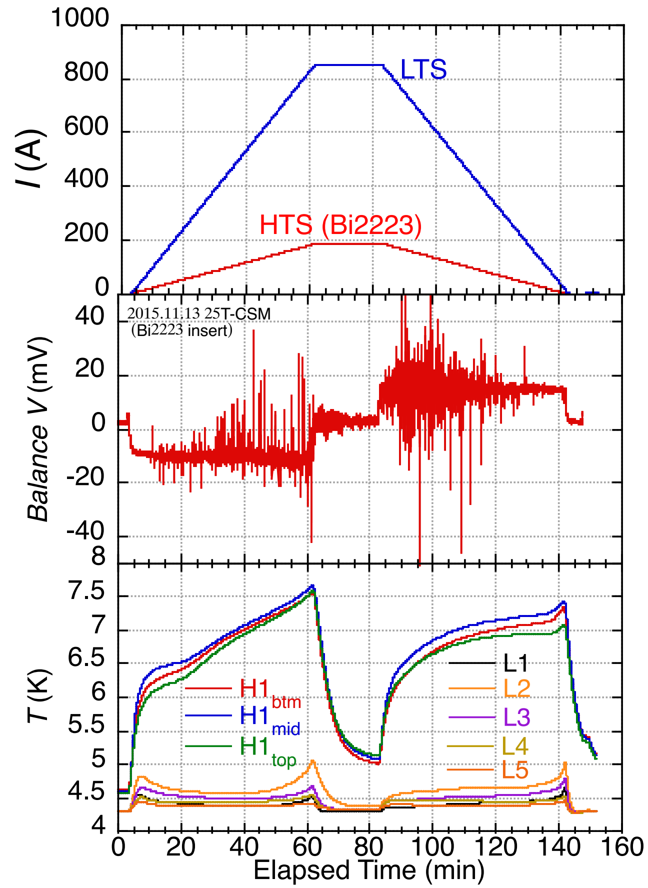
Sensitive thermal runaway detection still feasible even if the local damage in one tape may take place

More detail consideration for detection is needed!



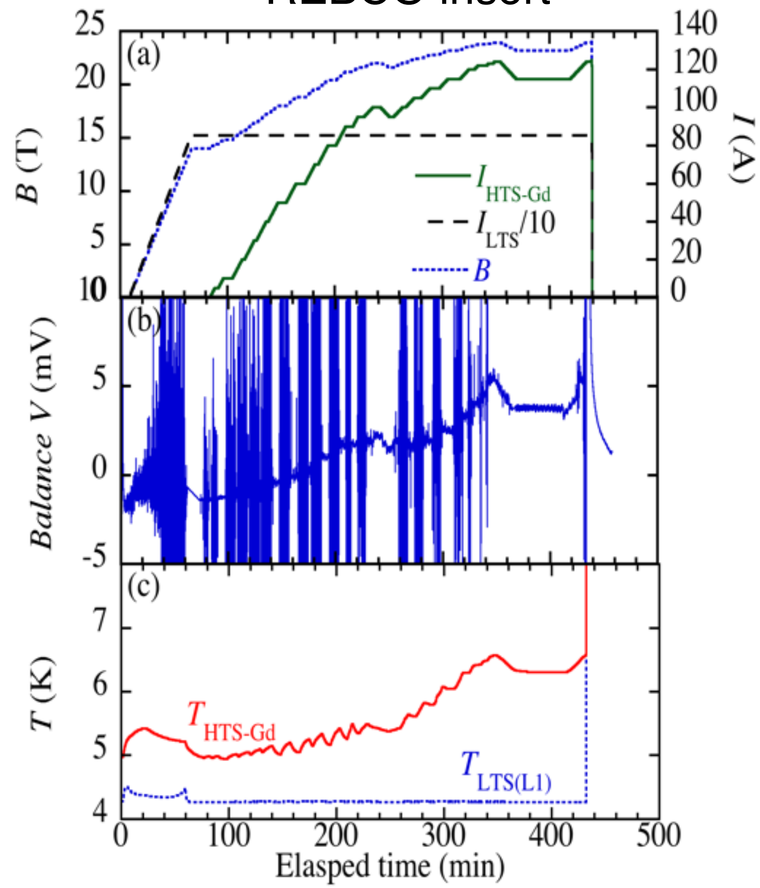
Performance of 25 T-CSM in 2015

Bi2223 insert



B_{cal} = 24.6 T was achieved!

REBCO insert



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

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

Design concept of CuNb/Nb_3Sn strands

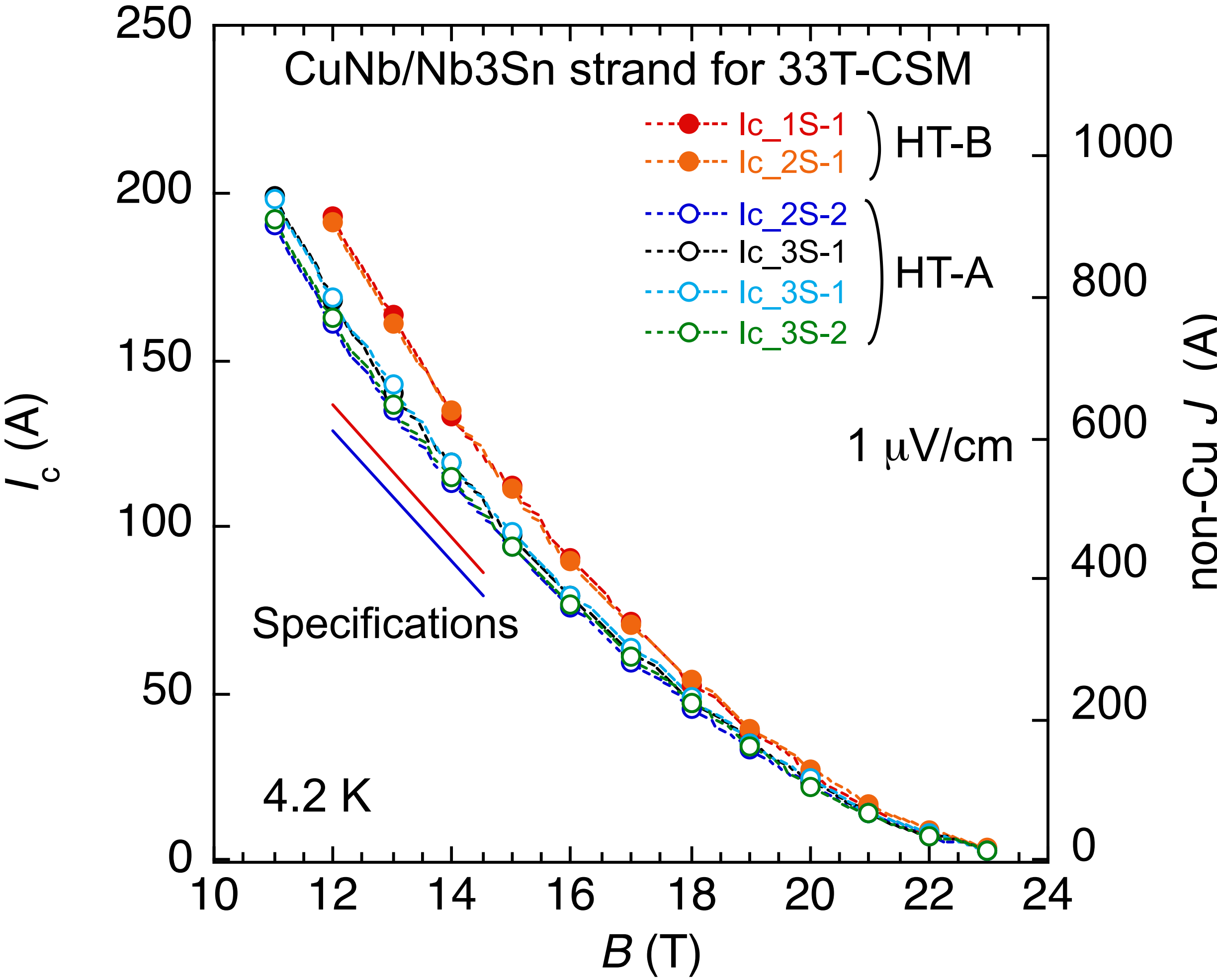
	25T-CSM	33T-NS-A	33T-NS-B
Cu/Cu-Nb/non-Cu (%)	20/30/45	20/38/42	
Nb in Cu-Nb (vol%)	20	25	
Bronze	Cu-14wt%Sn-0.2wt%Ti	Cu-15.7wt%Sn-0.3wt%Ti	
Wire dia.(mm)	0.8		
Filament dia. (mm)	3.3	3.2	
Pre-bending strain (%)	±0.5	±0.5	
Heat Treatment	670℃×96H	670℃×96H	575×100H +670℃×50H
I_c @4.2 K, 12 T	150-160 (> 119)	≈150 (> 127)	≈ 160 (> 137)

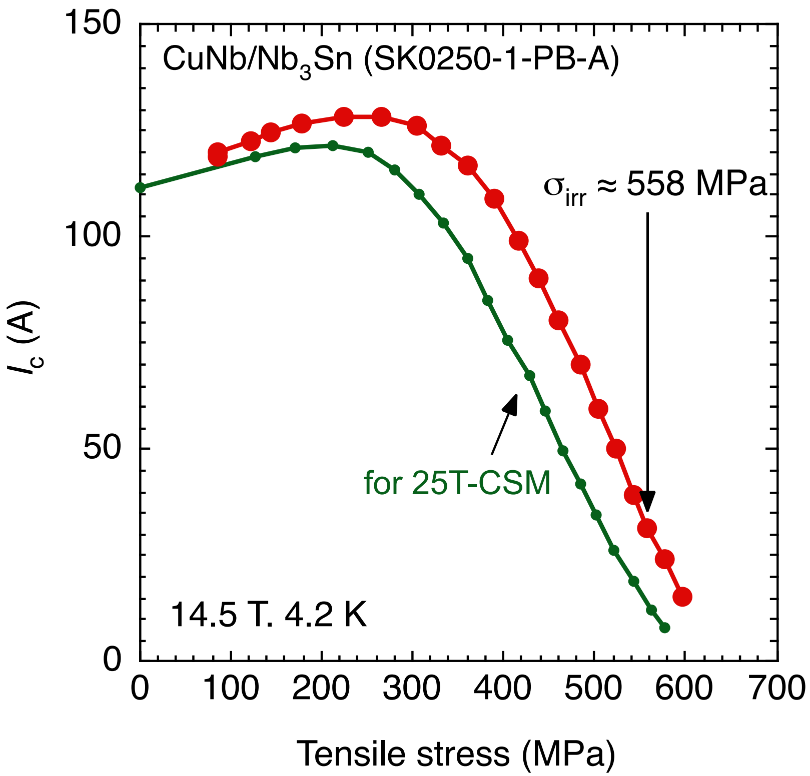
Improve strength

Improve non-Cu Jc

Sugimoto et al, IEEE TAS, 30 (2020) 6000905

High strength CuNb/Nb_3Sn strands for 33T-CSM



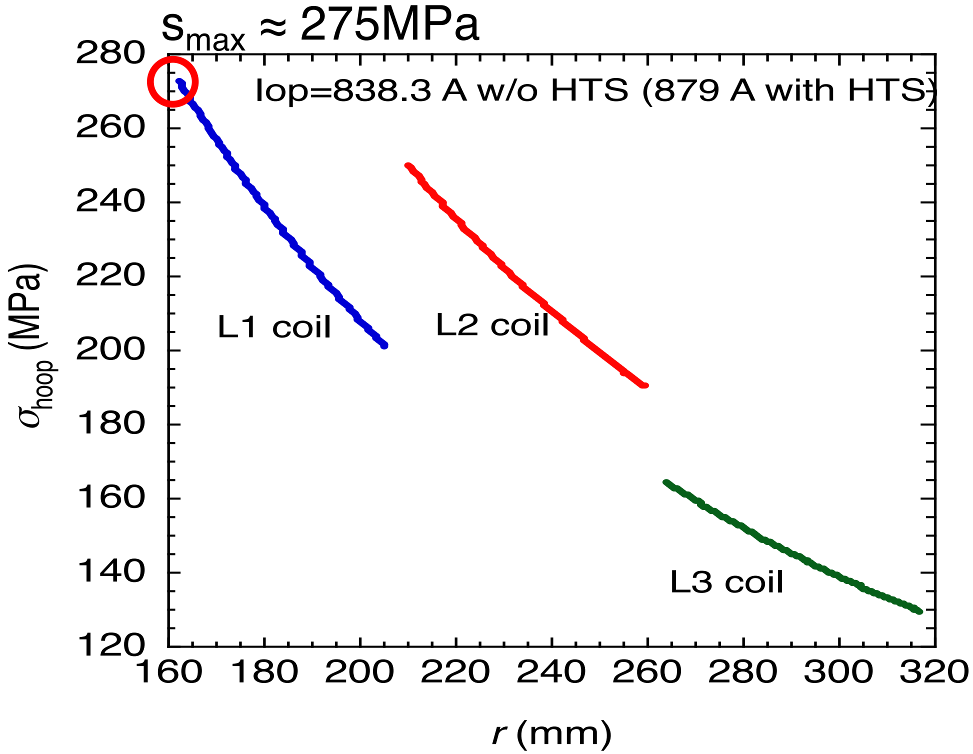


1245 days operation for 9 yrs (2016-2024FY) with high stress of 251 MPa in 25T-CSM

CuNb/Nb3Sn for 33T, Taniguchi 2MPo2A-09

CuNb/Nb3Sn for Fusion, Sugimoto, 2MPo2A-02

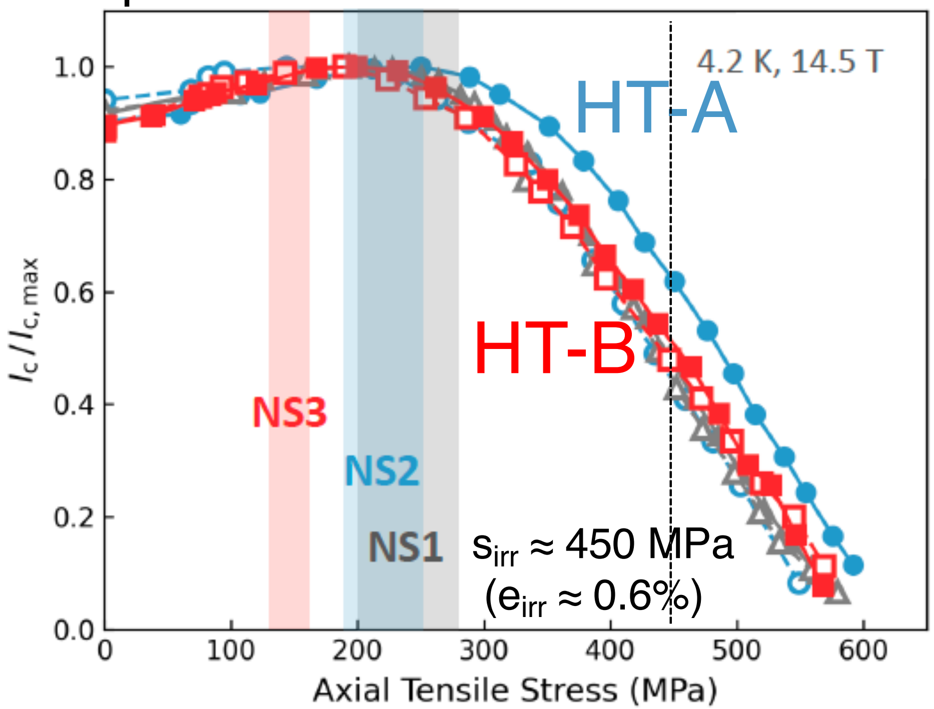
Stress/Strain in the coil



Closed: strands

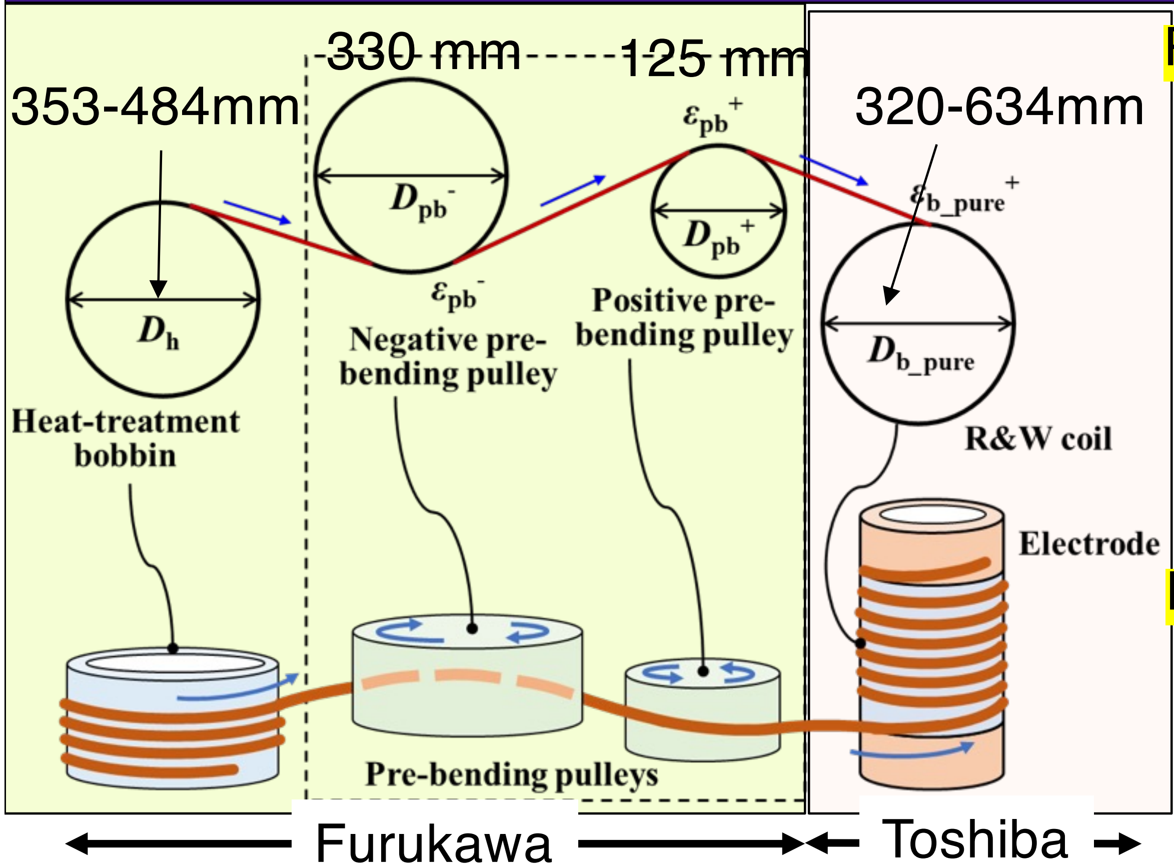
Open: extracted from cable

Taniguchi 2MPo2A-09



- The LTS coils were layer wound impregnated insulation coils.
- Hoop stress is distributed from 110 MPa to 275 MPa without bending strain.

Strain management in the pre-bending and winding process



Winding dia. on HT bobbin: D_h=353-484mm

Winding dia. on coil: $D_{h,\ pure}$ = 320-634mm

Pre-bending: experienced strain

$$\varepsilon_{pb} = d_{non-Cu}\left(\pm\frac{1}{D_{pb}} - \frac{1}{D_h}\right)$$

$$\varepsilon_{pb}^{max} = +0.3\% \text{ (Inner most)}$$
$$-0.31\% \text{ (outer most)}$$

Pure bending: permanent strain

$$\varepsilon_{b\_pure} = d_{non-Cu}\left(\pm\frac{1}{D_{b\_pure}} - \frac{1}{D_h}\right)$$

$$\varepsilon_{b\_pure}^{max} = +0.03\% \text{ (inner most)}$$
$$-0.07\% \text{ (outer most)}$$

Cooling system（LTS)

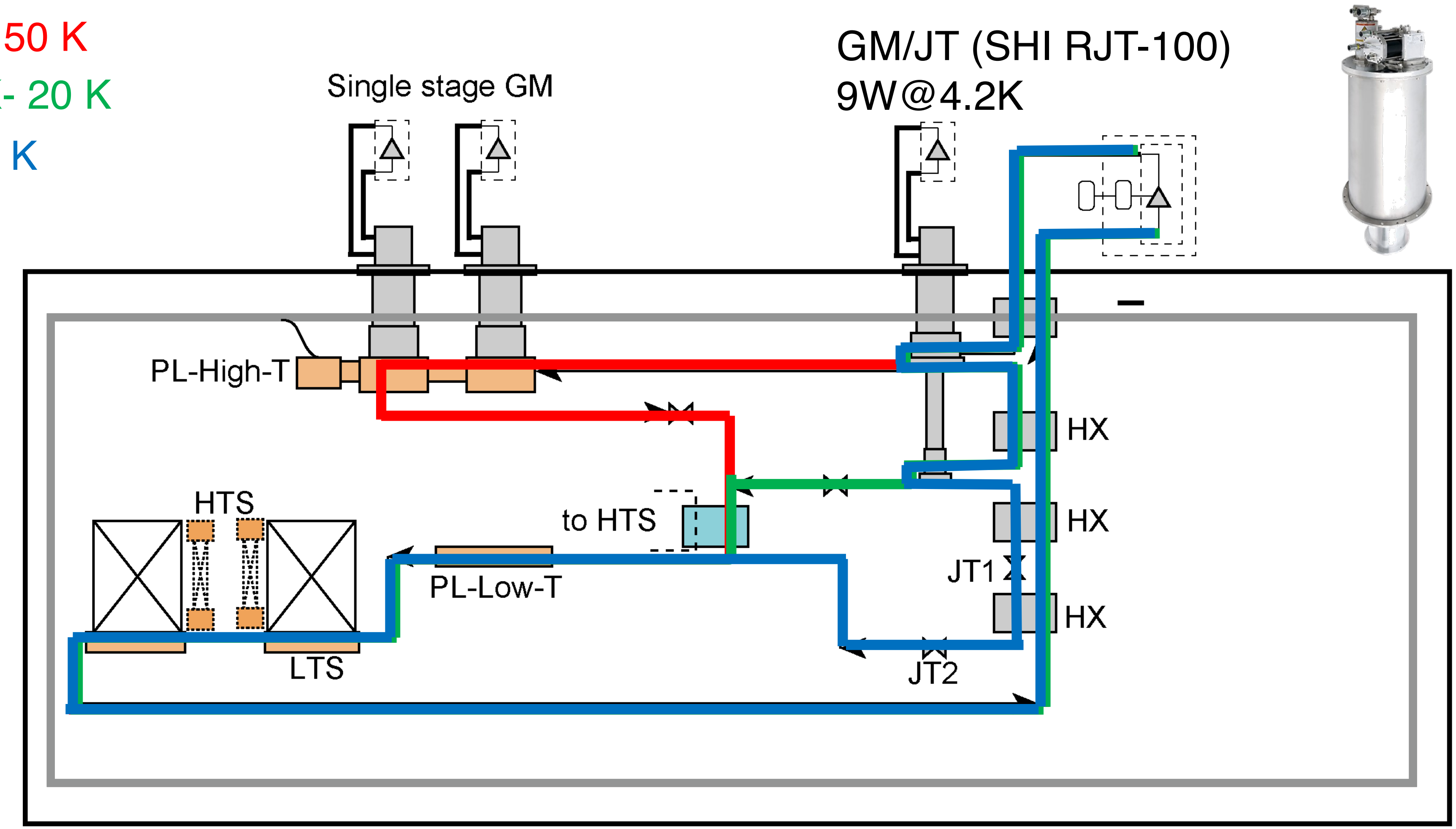
RT - 50 K

50 K- 20 K

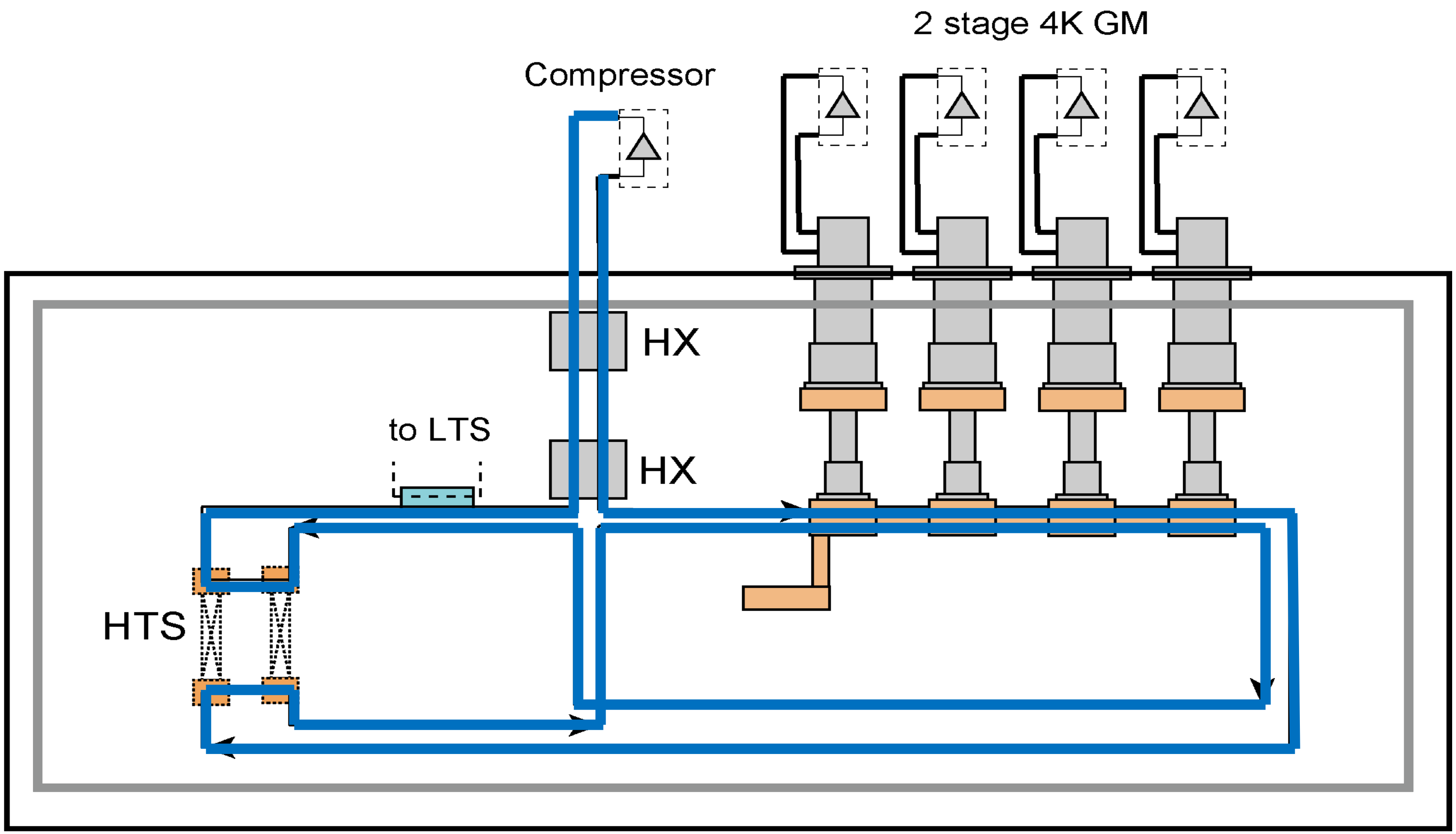
< 20 K

Single stage GM

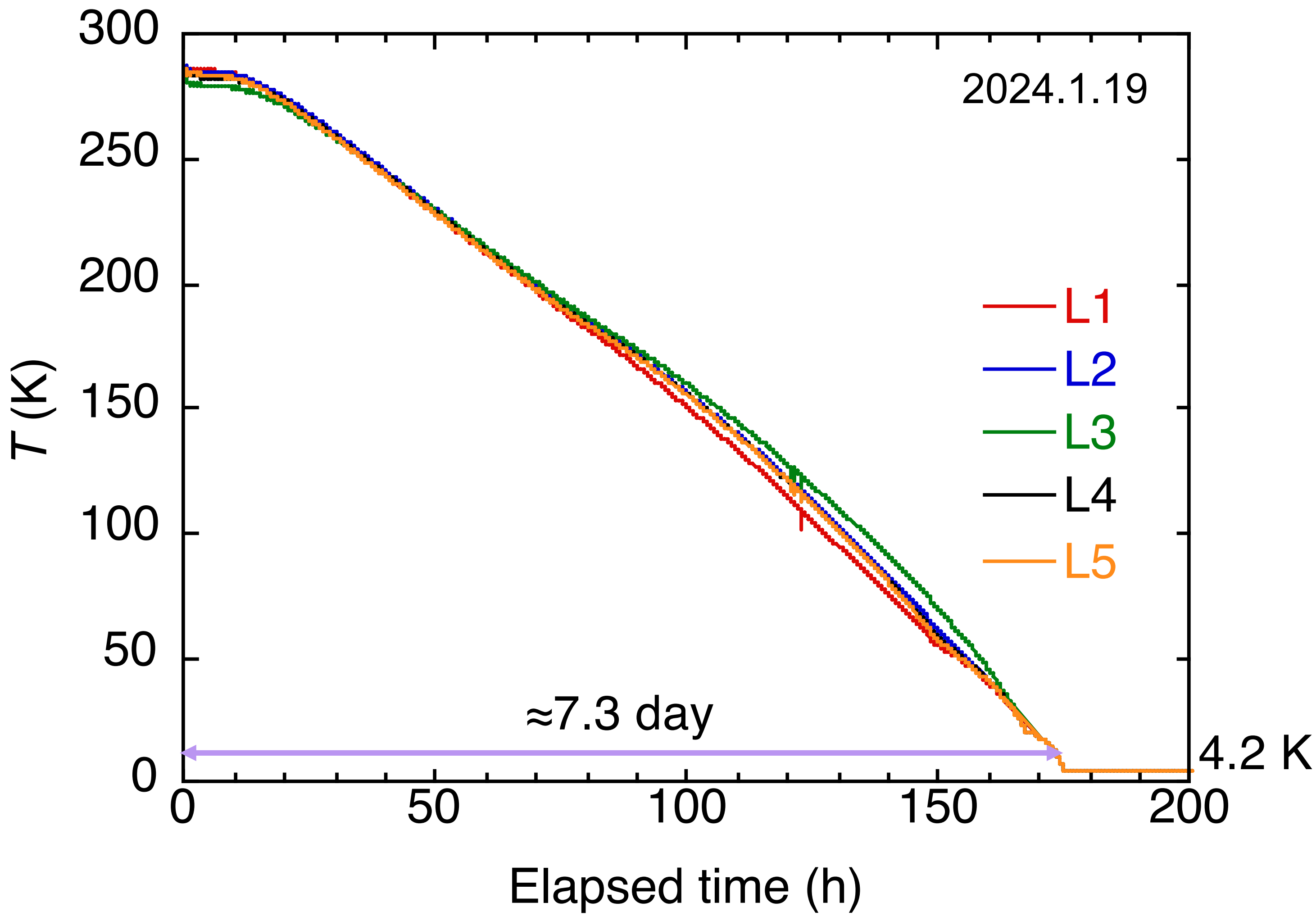
GM/JT (SHI RJT-100)
9W@4.2K



Cooling system（HTS)



Initial cooling of 33T-CSM



Lessens learned from failures of REBCO high field coils (insulated and impregnated coils)

✓ A risk of local degradation should be taken into account in design at the moment.

➔Two tape co-winding for current shearing in order to mitigate and reduce hotspot temperature

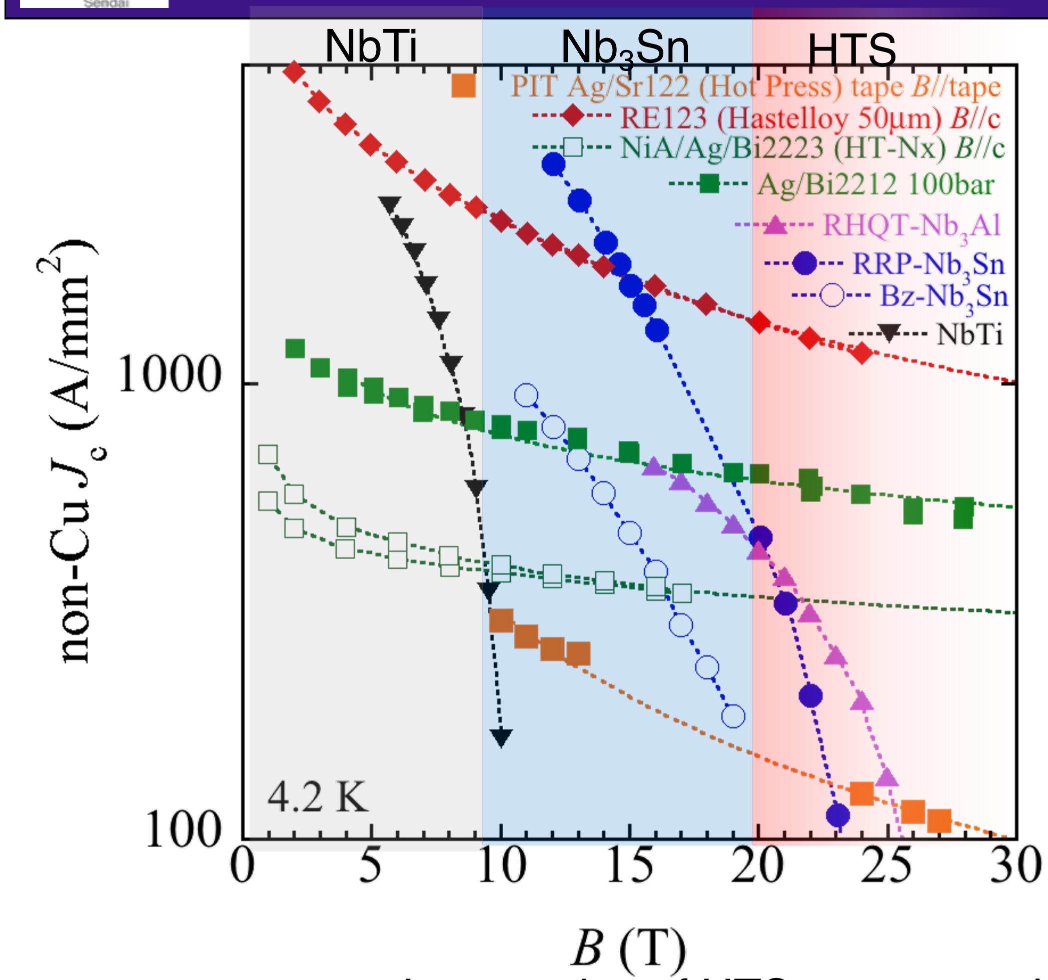
✓ Broad *IV* property in case of a local degradation and not too short time to burn-out after thermal runaway

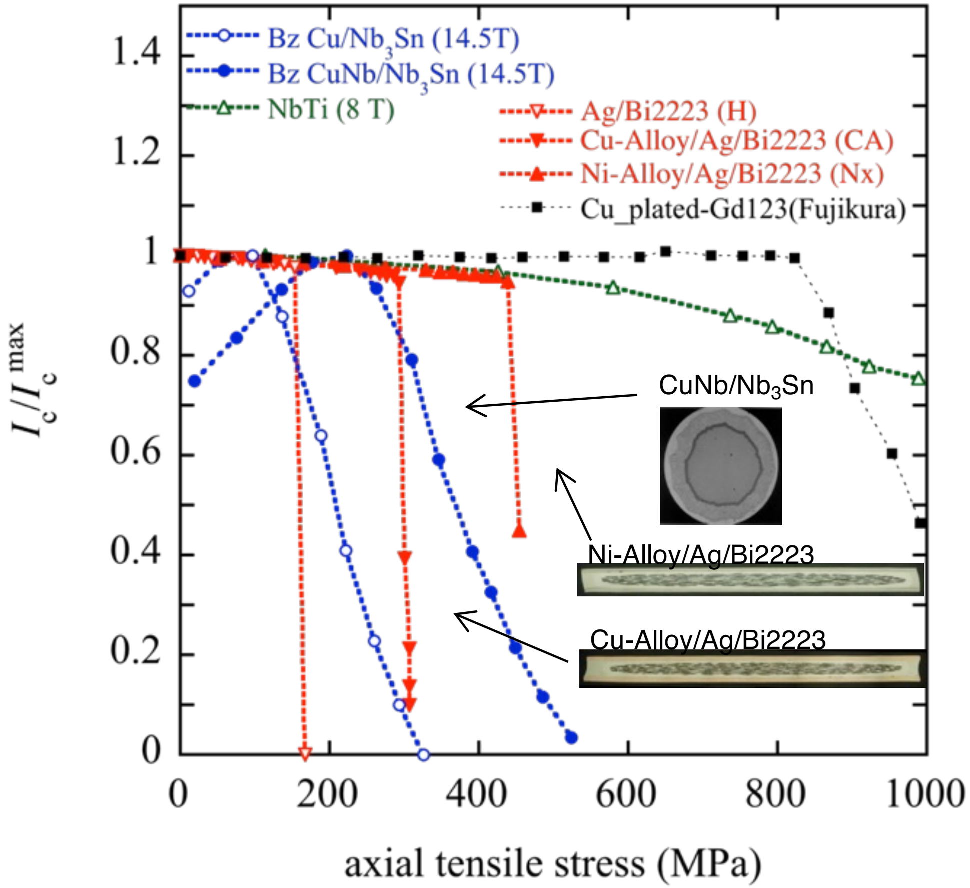
➔Protection is possible if we set adequate threshold in balance voltage.

✓ Protection for the hot-spot related to local degradation and inhomogeneity is crucial.

➔Early detection of thermal runaway is one of solutions.

J_c and electromechanical properties

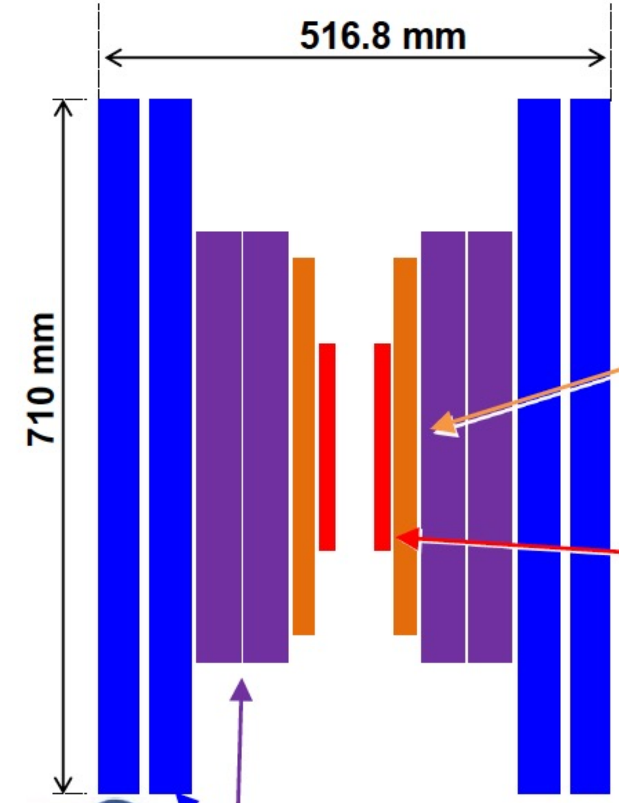




- J_c properties of HTSs are enough in high magnetic field beyond 20T.
- Excellent electromechanical properties in REBCO and Bi2223

MIRAI project (Riken): 27.6T generation by layer would coils

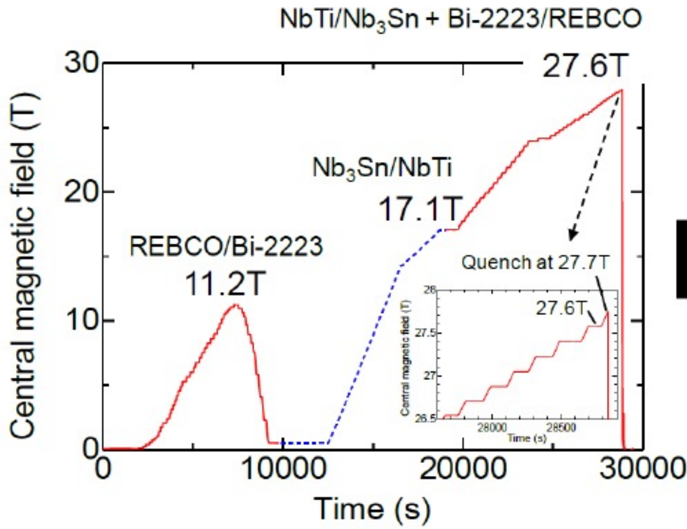
27.6 T generation by LTS / Bi-2223 / REBCO layer-wound coils



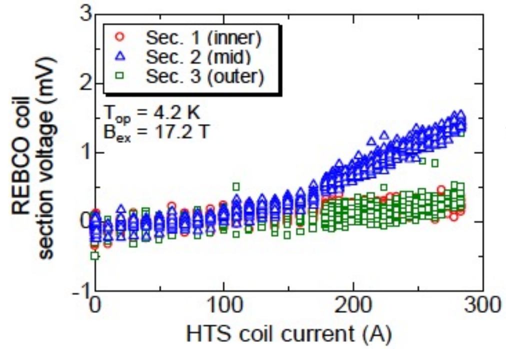
Bi-2223 (Insulated)

REBCO (Insulated)

Nb_3Sn – NbTi (17 T)



Burnout on the REBCO coil



Degradation in the middle section of the REBCO coil

Y. Yanagisawa et al., IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (Global Edition), 21(6), 3599-3602, (2016)