High field superconducting magnet development with HTS

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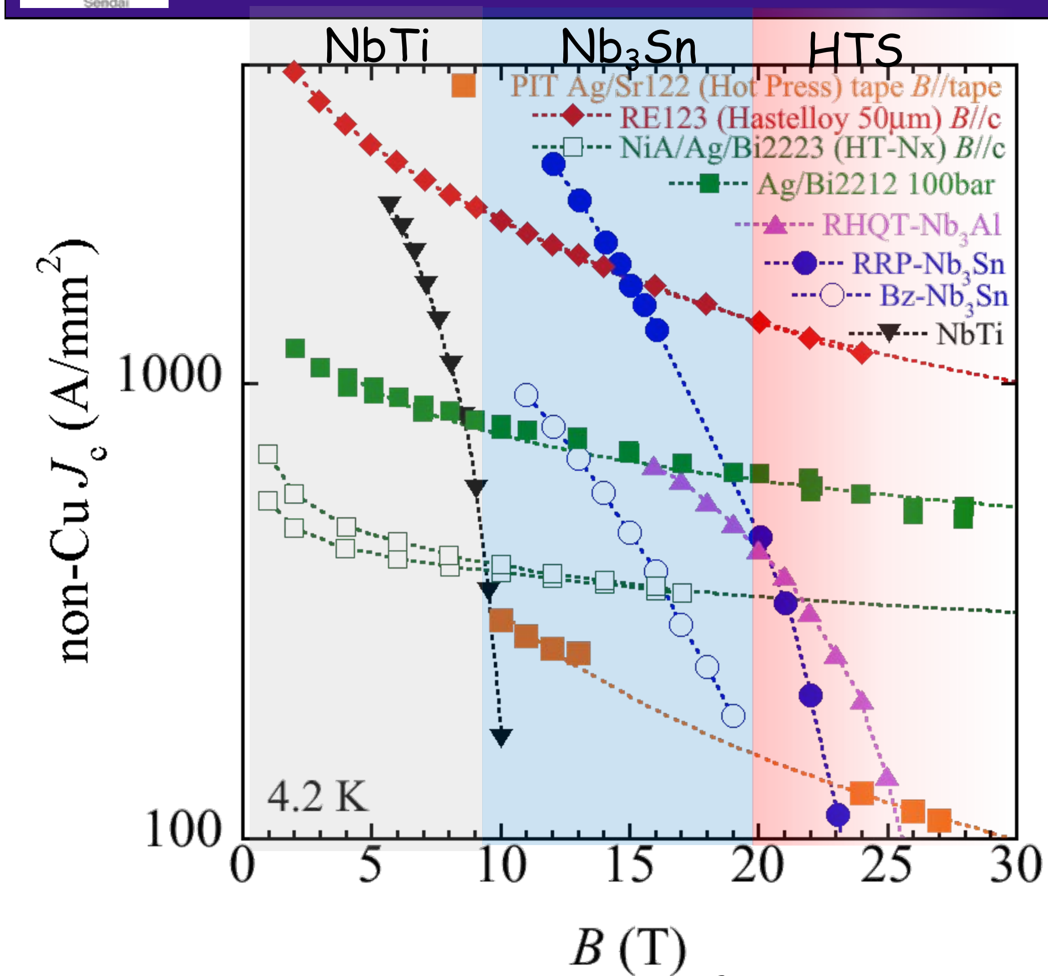
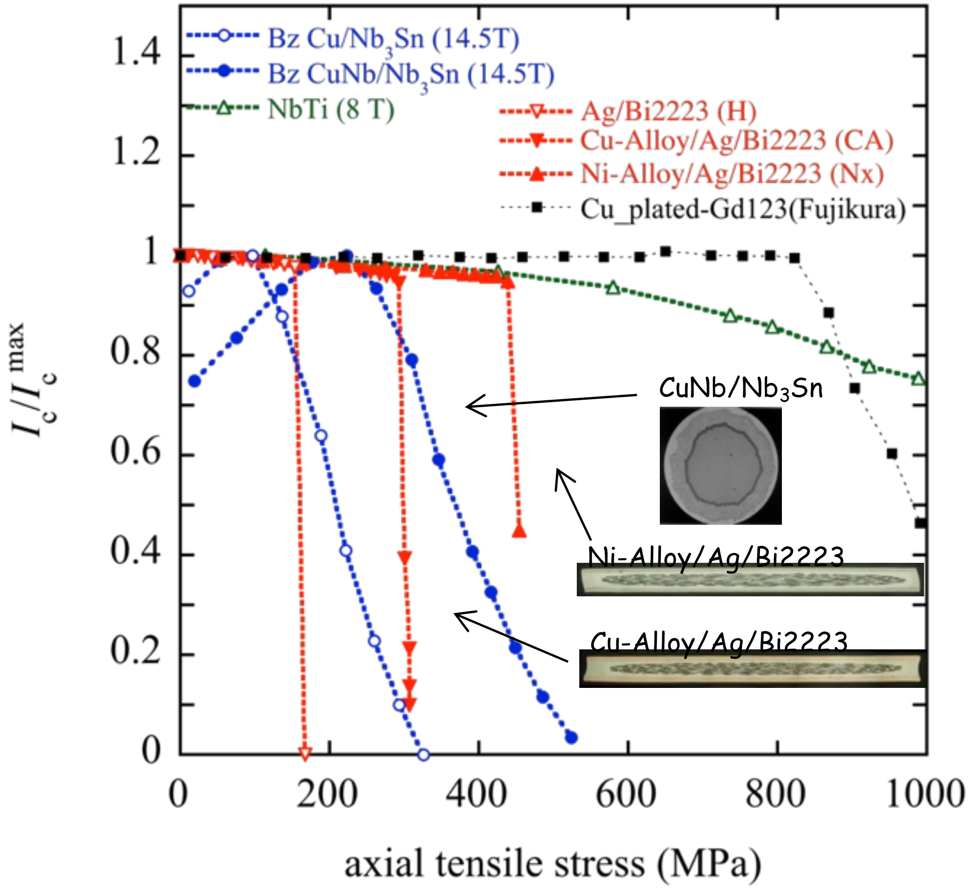
HFLSM Sendai

Research

J_c and electromechanical properties





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

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	NI	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	
MIRAI	RIKEN	NMR magnet	23.8 (12.6/11.2)	Bi2223	225	291	78	4.2 (LHe)	Layer	Wax	1.01GHz	2019	Insulated	
24T R&D	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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Practical high field superconducting magnets

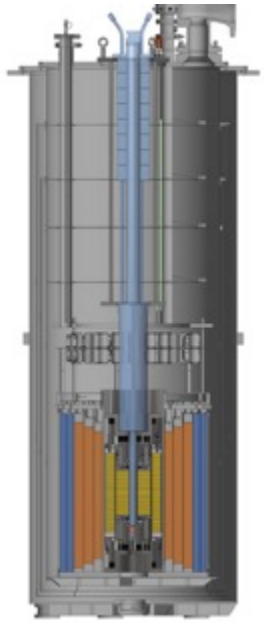
25.1 T (Bi2223) Cryogen-free

25.1T- 52 mm RT (HFLSM)
LTS: 300 mm -14 T
HTS: 96 mm-11.1 T
(Bi2223)
S. Awaji SuST , 30 (2017) 065001
K. Takahashi et al, under review

28.19 T (REBCO) LHe, Persistent

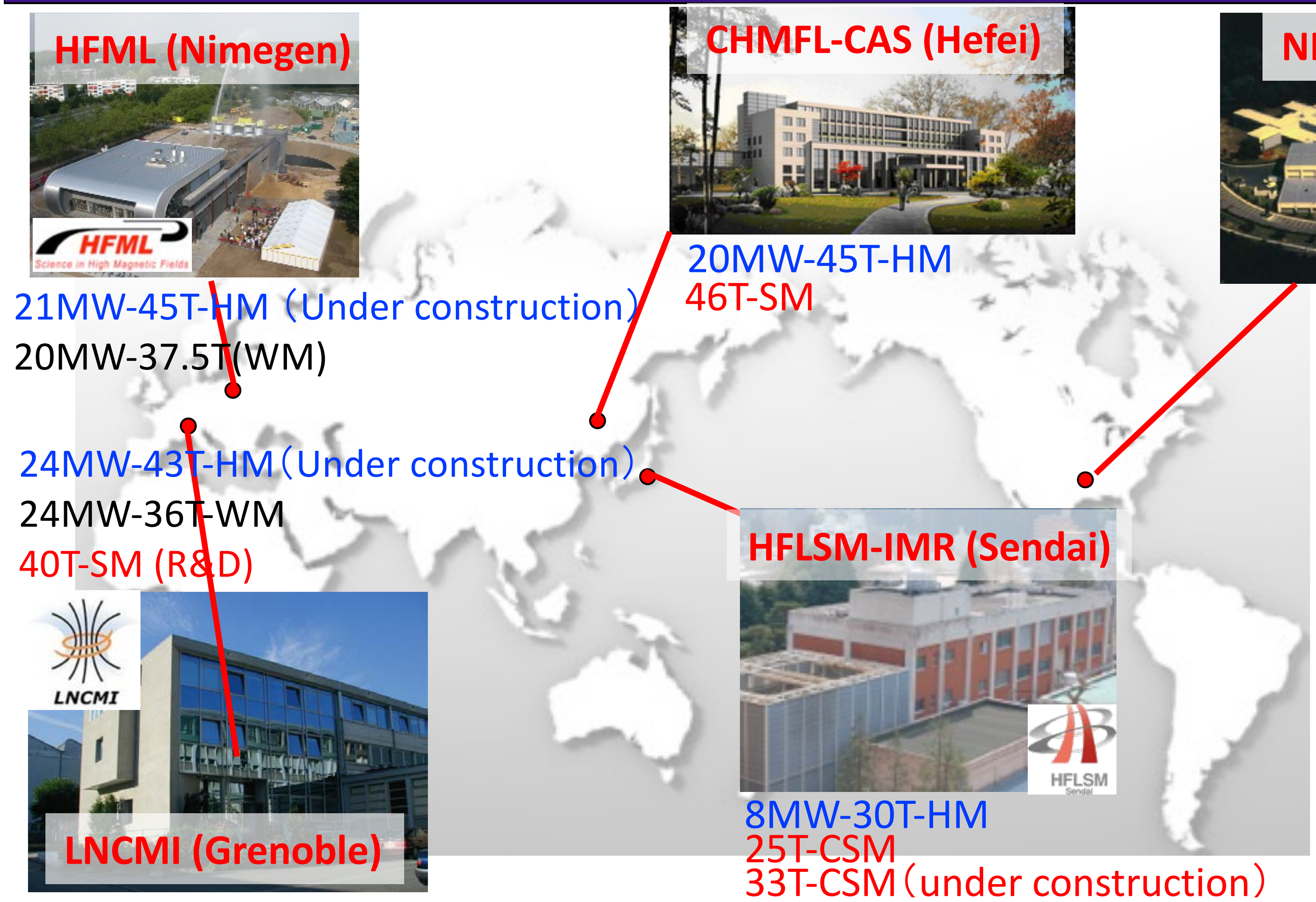
1.2 GHz-NMR Comercial (Bruker)
28.19 T – 54 mm RT
https://www.bruker.com/

32 T (REBCO) LHe



32T-32mm LT (NHMFL)
LTS: 250 mm -15 T
HTS: 32 mm-17 T
(REBCO)
H. Weijer, IEEE TAS. 24 (2014) 4301805

Steady High Magnetic Field Facilities in the world



HM: Hybrid magnet
WM: Water-cooled resistive magnet
SM: Superconducting magnet
CSM: Cryogen-free superconducting magnet

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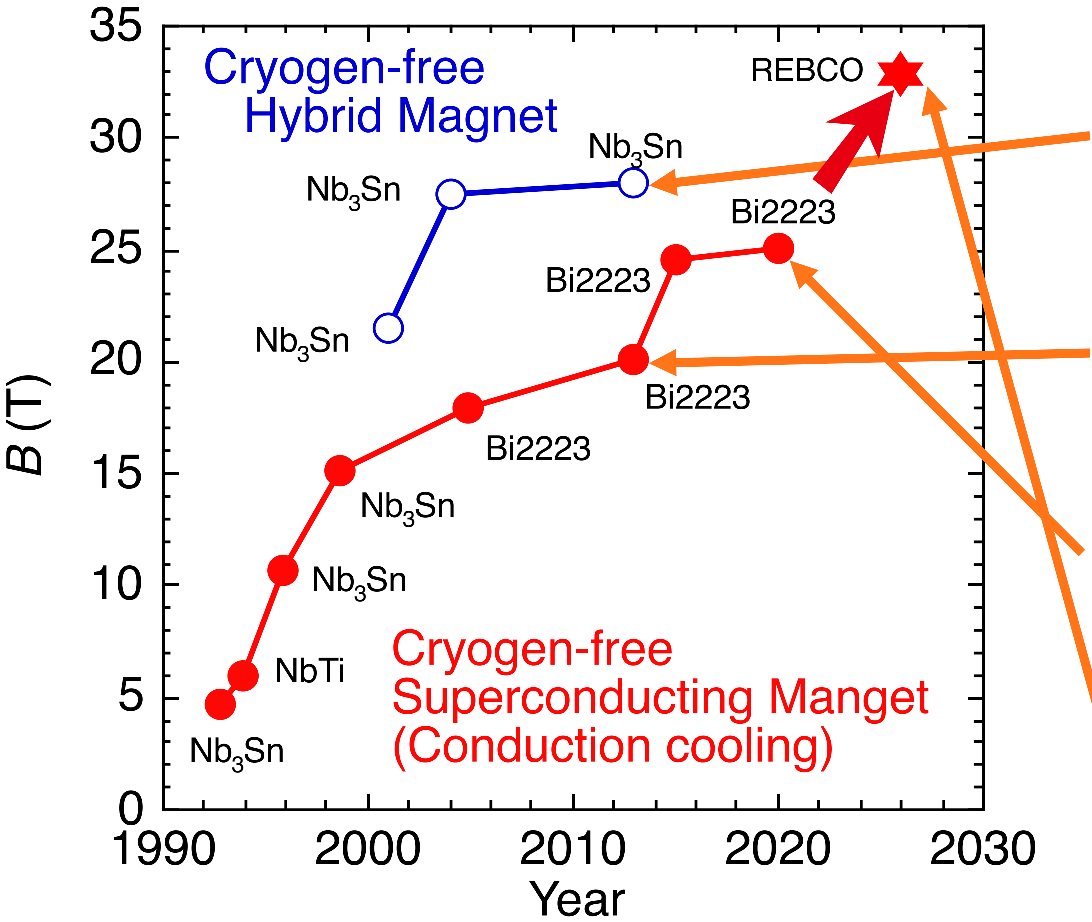
Cryogen-free magnet developments at HFLSM, Sendai, Japan



28T-CHM (ϕ32RT)

ϕ360-9T-CSM

- CuNbTi/Nb_3Sn strand

ϕ32-19T-WM (8MW)

- Double Bitter

20T-CSM(ϕ52RT)

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)

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)

ϕ320-14T-LTS

- CuNb/Nb_3Sn Rutherford, NbTi:267 MPa

ϕ96-11T-HTS

- REBCO (Robust coil concept)

We have many failures of REBCO coils behind these successes.

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)

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33T-CSM(ϕ32RT)

ϕ320-14T-LTS
- CuNb/Nb_3Sn Rutherford, NbTi:267 MPa

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

Failures

50 REBCO Pancakes for upgrading to 22 T (Insulation & Impregnation)
- ϕ96mm x ϕ177mm, J = 217 A/mm^2, σ = 297 MPa
- Degradation in the outer windings after cooling down due to axial thermal shrink in large-scale coil.

56 REBCO Pancakes (Insulation & Impregnation)
- ϕ104mm x ϕ262mm, J = 130 A/mm2, σ = 407 MPa
- Quenched at 24 T due to a local degradation and damaged.

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

Insulated mono-tape winding

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

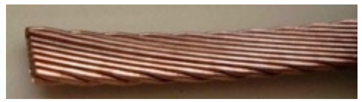
38 Ni-alloy/Bi2223 double pancakes
ϕ96mm x ϕ280 mm x h390 mm
Max. hoop stress 323 MPa

Magnet (HTS-RE123): 10.5T@131A

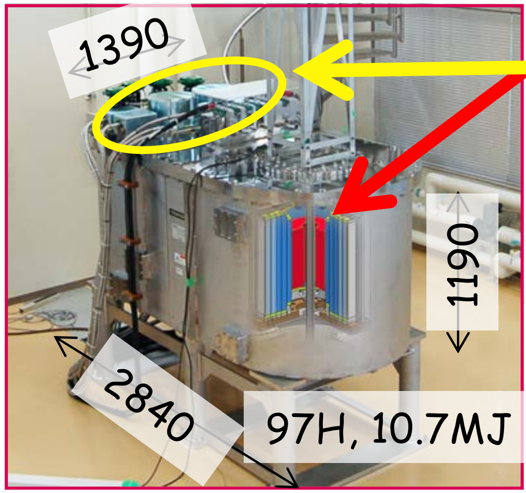
56 GdBCO single pancakes
ϕ104mm x ϕ263 mm x h336 mm
Max. hoop stress 366MPa

Magnets (LTS): 14T@854A

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



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



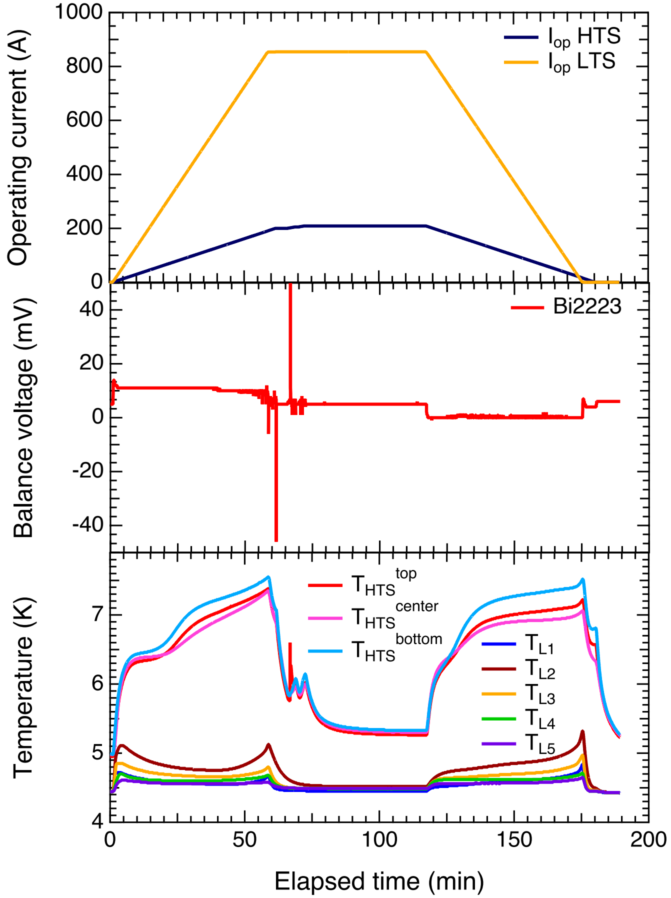
Cooling system

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

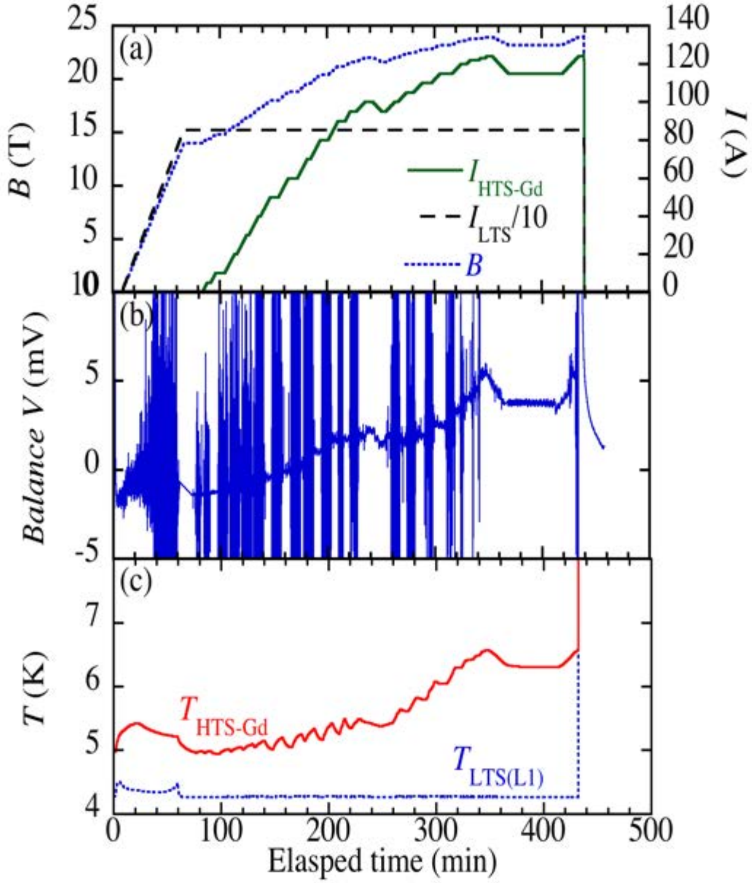
Performance of 25 T-CSM

Bi2223 insert



B_{cal} = 25.1 T was achieved!

RE123 insert



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

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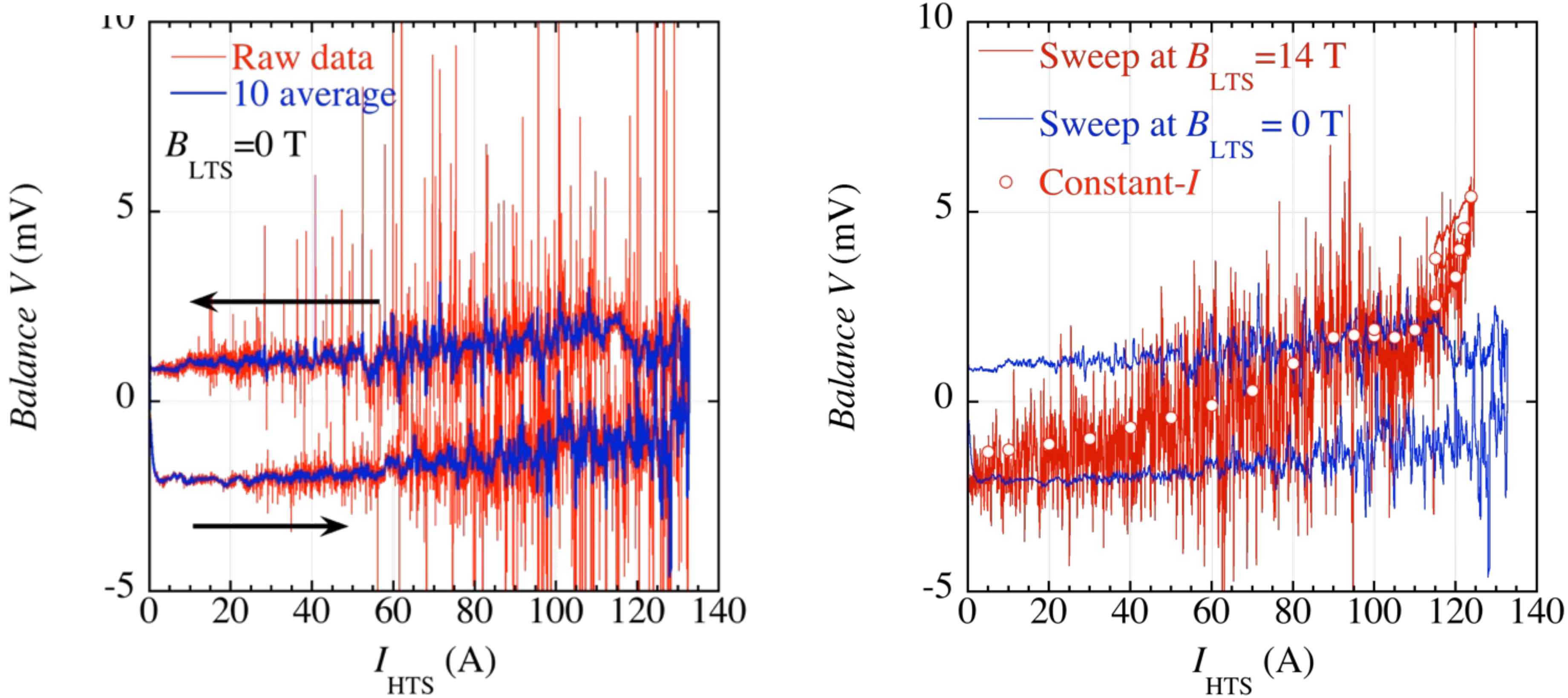
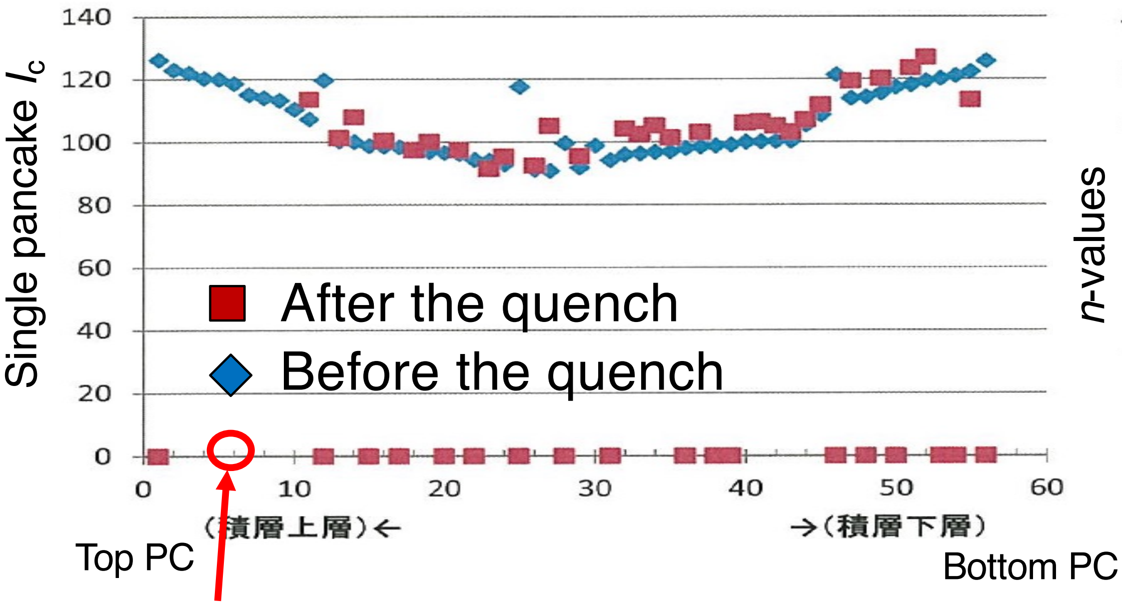
IV property of REBCO coil for 25T-CSM



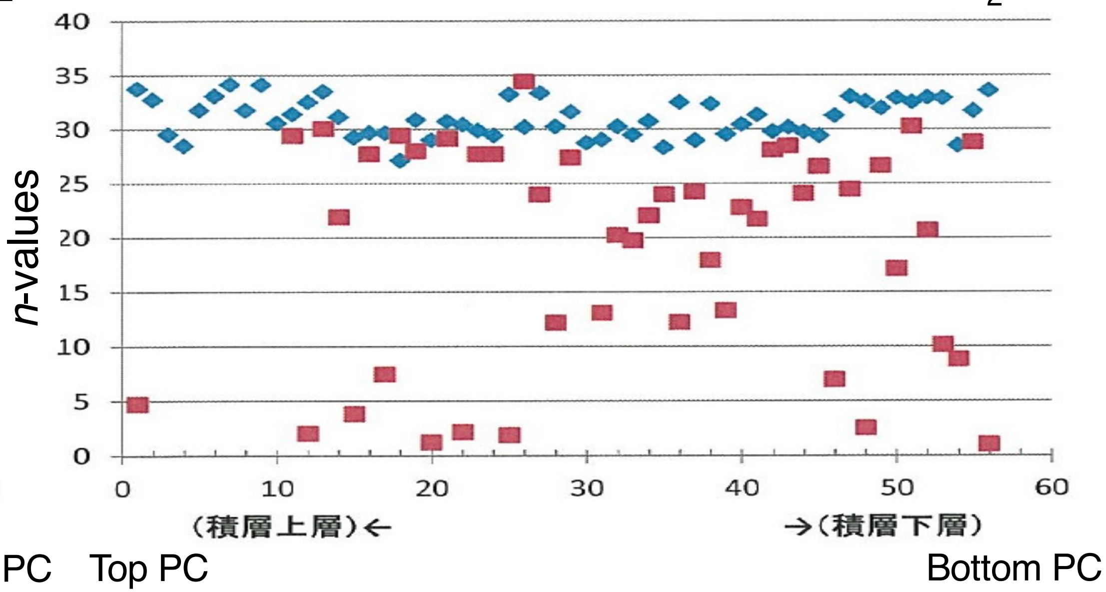
- REBCO insert achieved 10 T with 125 A in the stand-alone test but deteriorated from an initial state in the background field of 14 T.
- Broad *IV* properties (small *n*-value) was observed under 14 T.

Degradation Gd123 insert of 25T-CSM after quench

Single pancake I_c LN$_2$



n-values LN$_2$



Initiation of quench from PC#3-5

- Quench was initiated from the pancakes #3-5 by the observations of damage.
- Many pancakes were deteriorated seriously because of arc discharge.

->The risk of local degradation should be taken into account in design at the moment.

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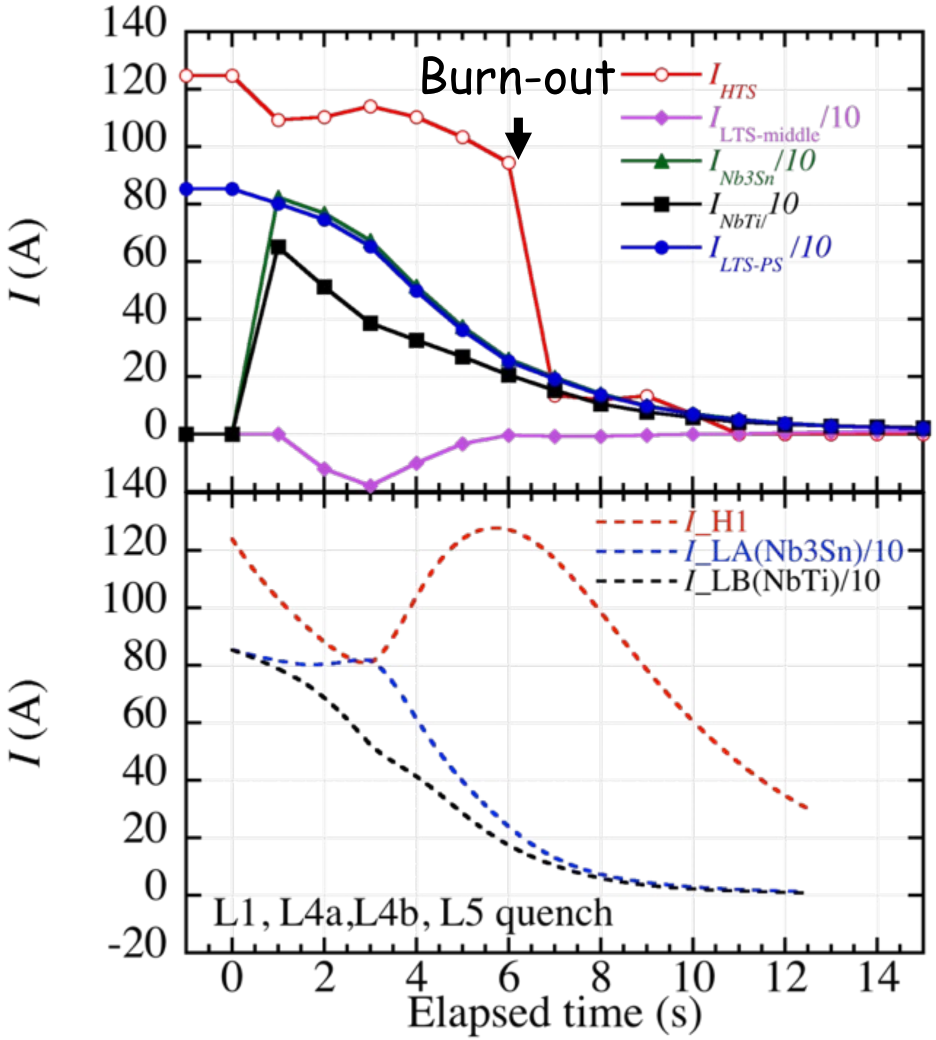
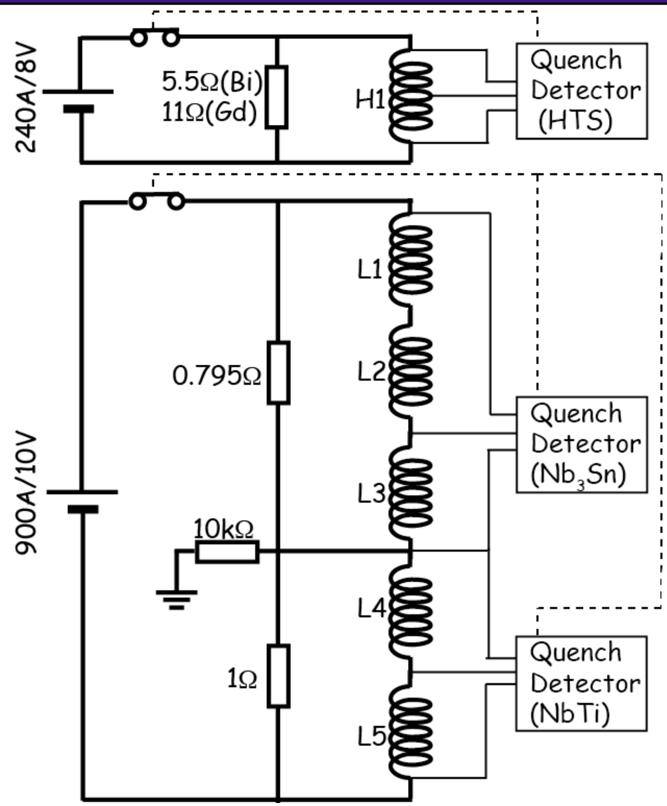
Quench behavior of 25T-CSM with REBCO





The quench protection looks well at least for 6 s after the quench?

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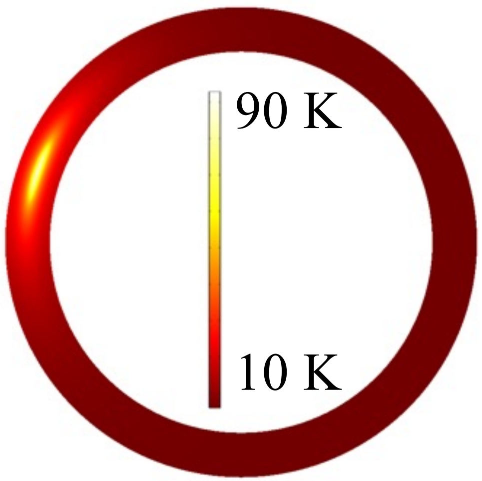
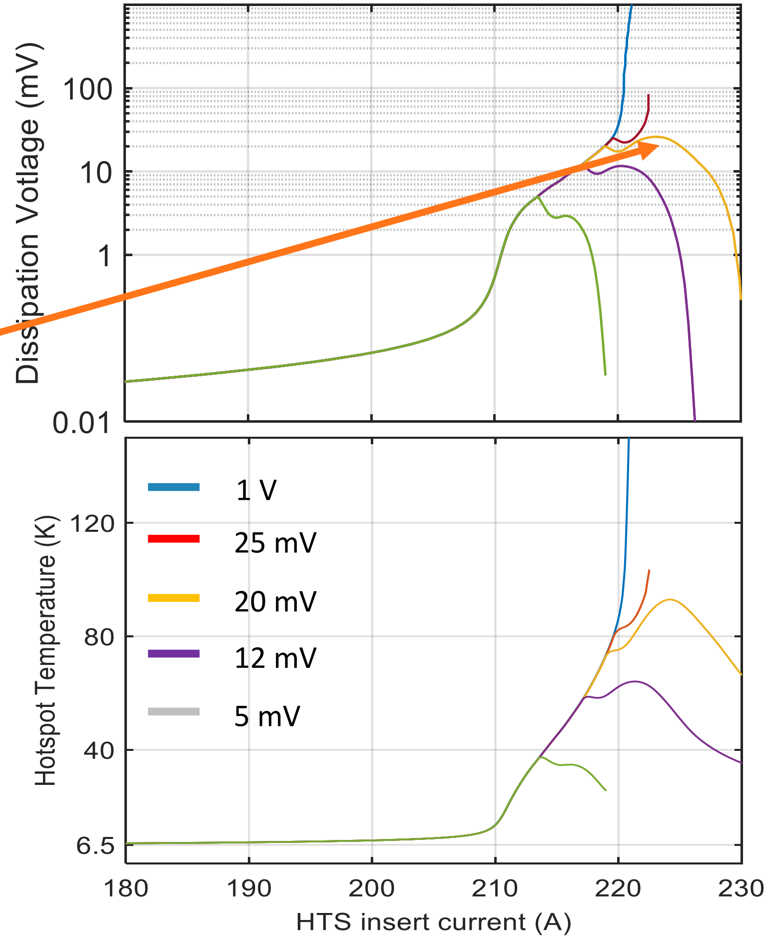
Simulation results of the quench

Single 2 cm defect at 18.8 % of Ic

Detection less than 20 mV would have enable magnet protection



the maximum temperature with 20 mV detection



A. Badel et al, IEEE TAS

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.

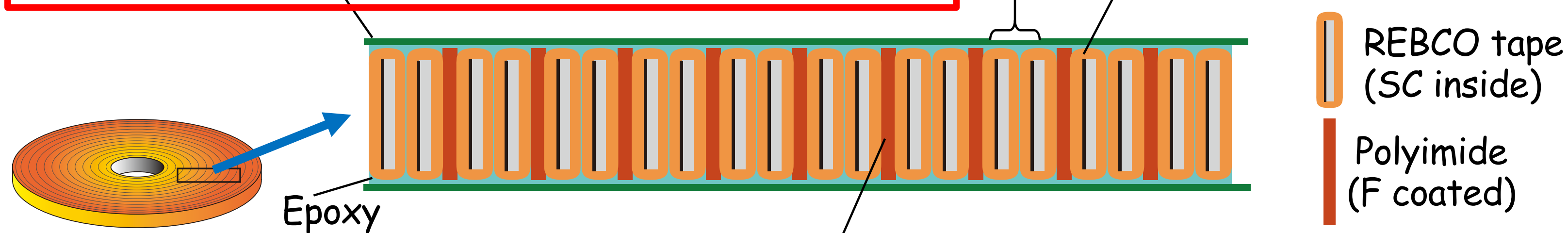
→ Early detection of thermal runaway is one of solution

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}).

Edge impregnation
Thin FRP plate glued on coil & Impregnation
(Improve coil stiffness)

40 μm Cu stabilizer
(Reduce hot-spot temp.)



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

S. Awaji IEEE TAS 31 (2021) 4300105

Robust against local degradation:

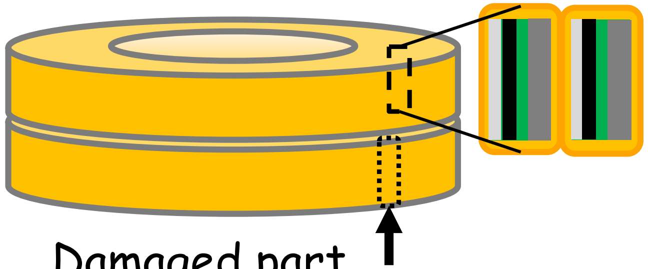
Two bundle insulated double pancake coil with a damaged area

EuBCO tape with BHO	
Width	4 mm
full thickness	0.11 mm
REBCO thickness	2.5 μm
Hastelloy® thickness	50 μm
Cu thickness	20 μm
I_c (4mm, 77 K, s.f.)	213.5 A

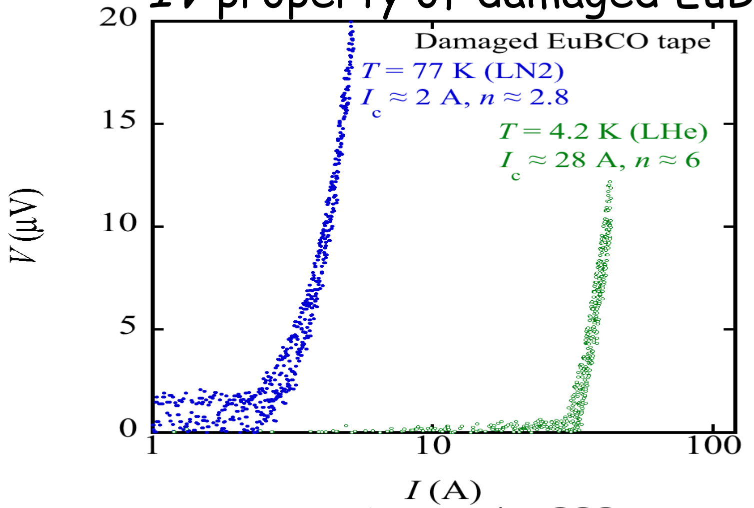
Double pancake coil	
tape	EuBCO+BHO
Turn number	101 turn × 2 layer
Inner diameter	40.0 mm
Outer diameter	94.0 mm
Position of damage*	55 turn of bottom coil, outer tape
Coil constant	3.87×10^{-3} T/A

*Damage was introduced by double bending with ϕ12 mm bending dia.

ϕ40 x ϕ94, 101 x 2 turns/pc



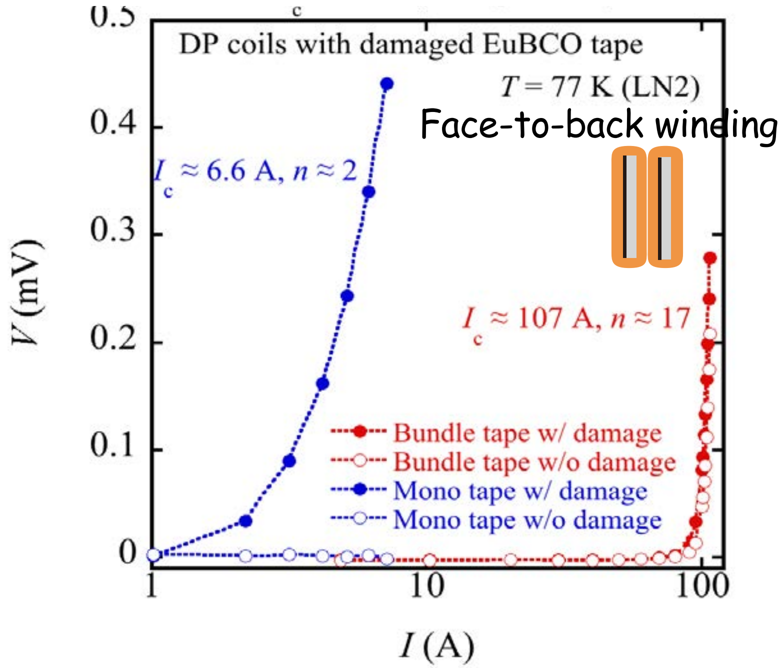
IV property of damaged EuBCO

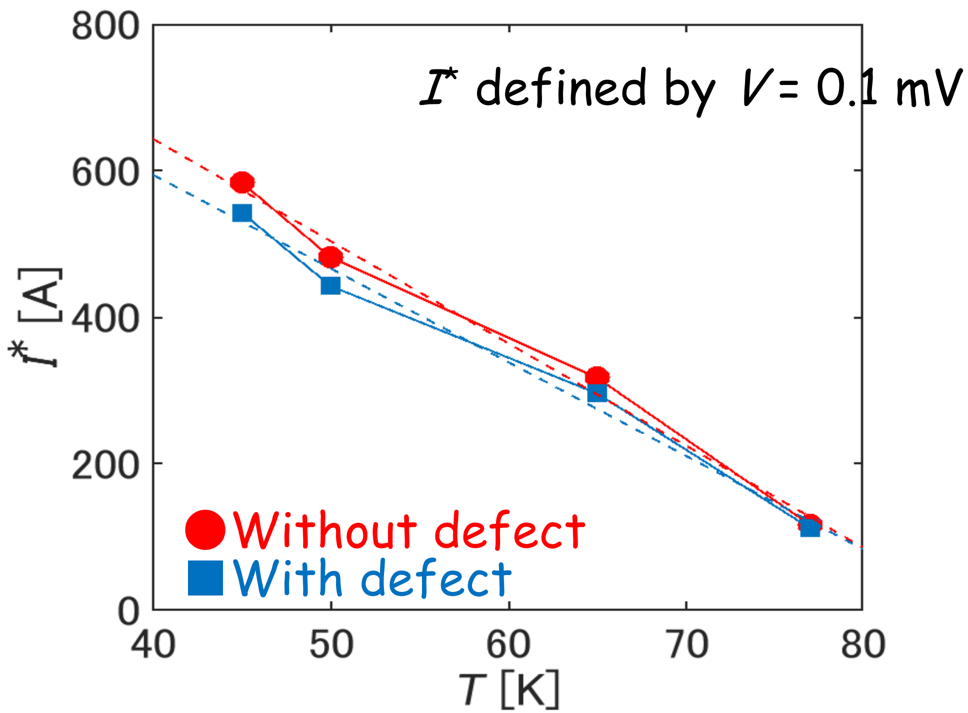


Abe *et al.*, IEEE TAS, 32 (2022) 4603306

Robust against local degradation:
Two bundle insulated double pancake coil with a damaged area

Bundle winding ϕ40 x ϕ94 (101 turns x 2)
Mono tape winding ϕ40 x ϕ99 (198 turns)





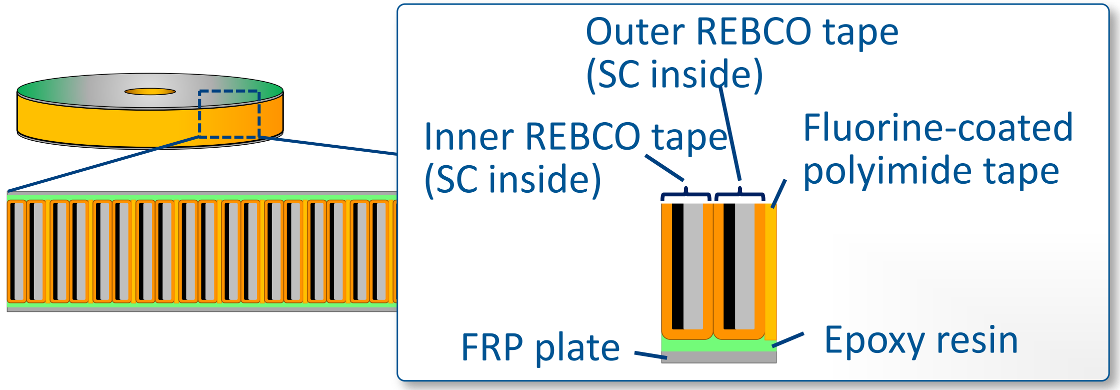
- Monotape coil with a damage shows low performance.
- Bundle tape coil with damage shows similar performance to that without a damage at 77K and slightly lower with decreasing temperature.
- Ic difference may be related to Ic distribution in the coil.

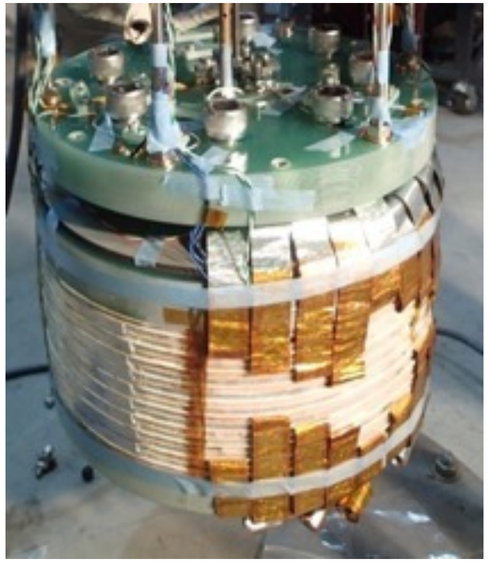
⇨ Bundle winding is effective!

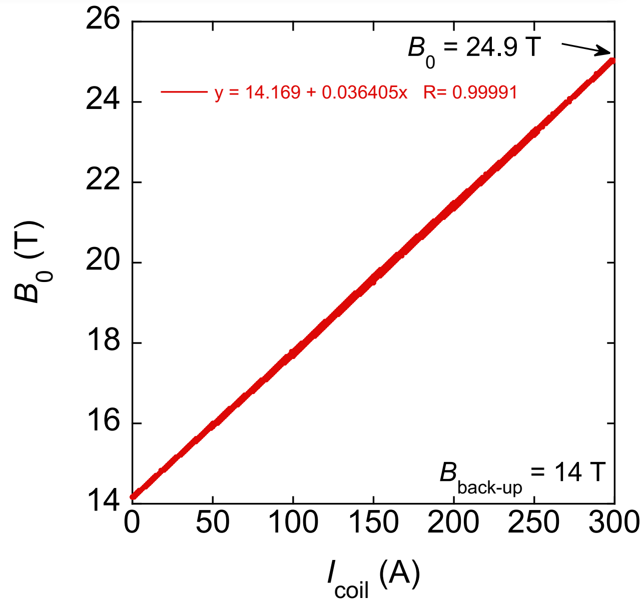
Abe *et al.*, IEEE TAS, 32 (2022) 4603306

20 stacked REBCO pancake coil

20-stacked Coil	
No. of bundled tapes	2
Tape stacking configuration	face-to-back
Inter bundle insulation	fluorine-coated polyimide tape
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



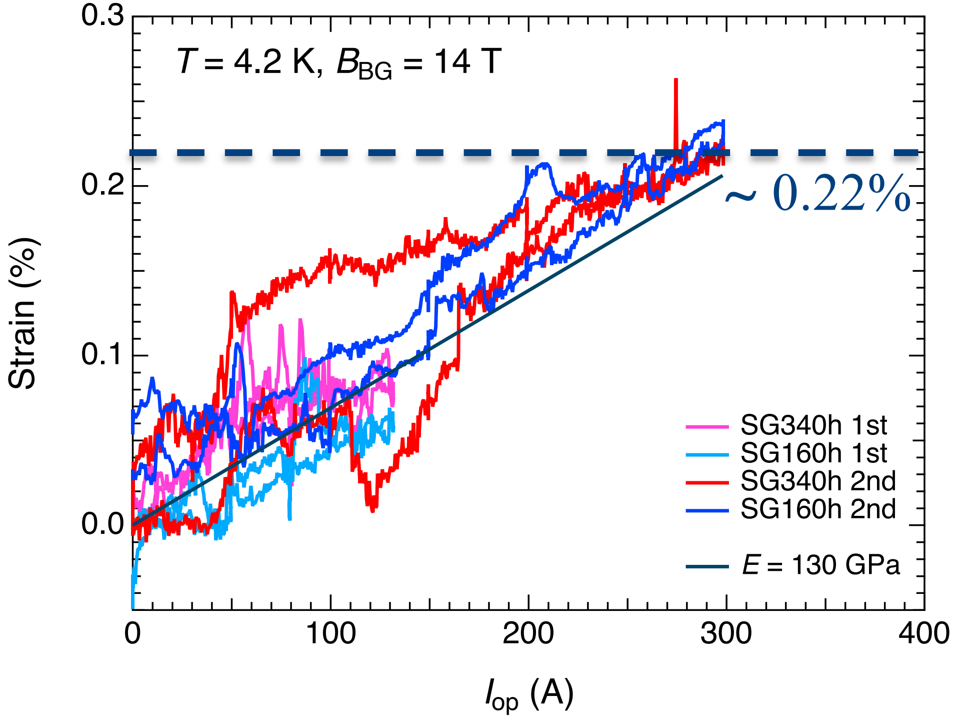


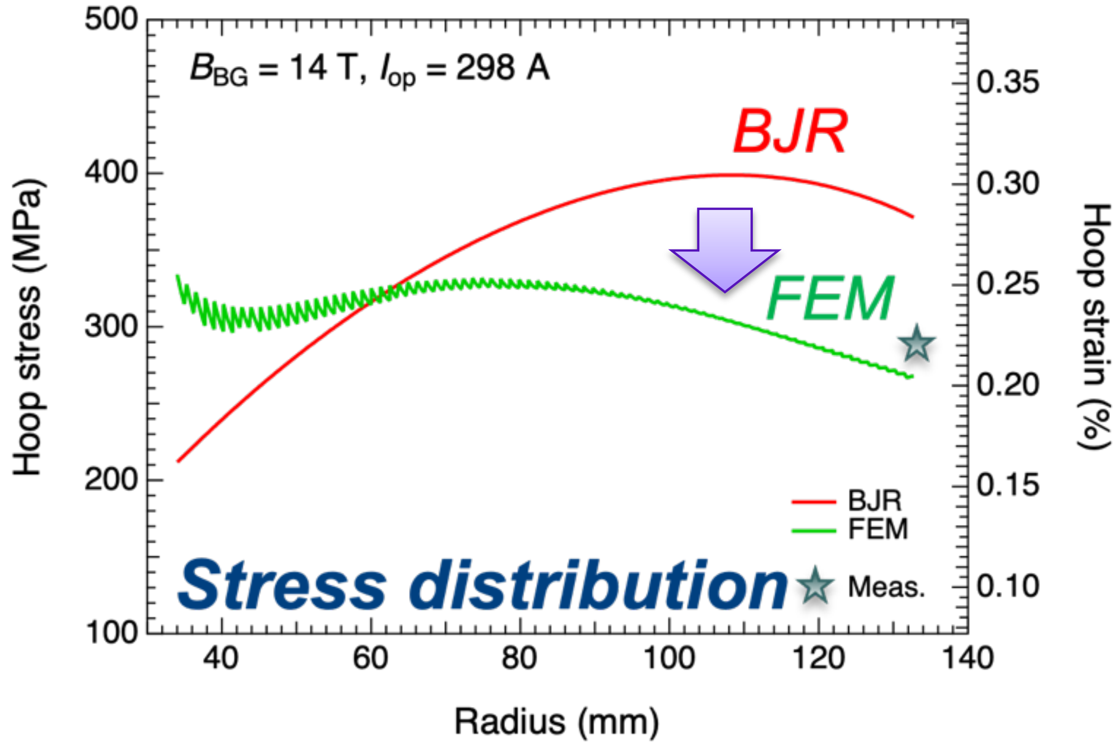


K. Takahashi *et al*, IEEE TAS (2023) 4601405, A. Badel *et al*, IEEE TAS (2023) 4601505, A. Zampa *et al*, IEEE TAS under review.

20 stacked REBCO pancake coil
- mechanical property -

Outer surface strain of the coil





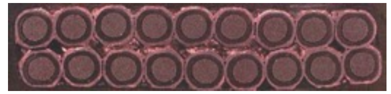
Robust coil structure reduces the maximum stress and optimizes its distribution in coil.

K. Takahashi *et al*, IEEE TAS (2023) 4601405, A. Badel *et al*, IEEE TAS (2023) 4601505, A. Zampa *et al*, IEEE TAS under review.

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

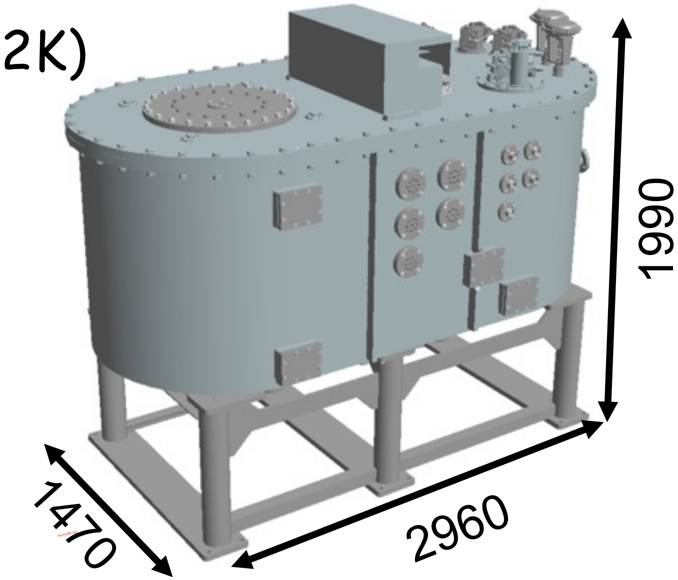
- Conduction cooling with He circulation
- 4 x 4K-GM cryocooler for HTS coils (4 x 1.5W@4.2K)
- 1 x GM/JT cryocooler for LTS coils (8W@4.2K)
- Thermally separated LTS and HTS coils

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}).

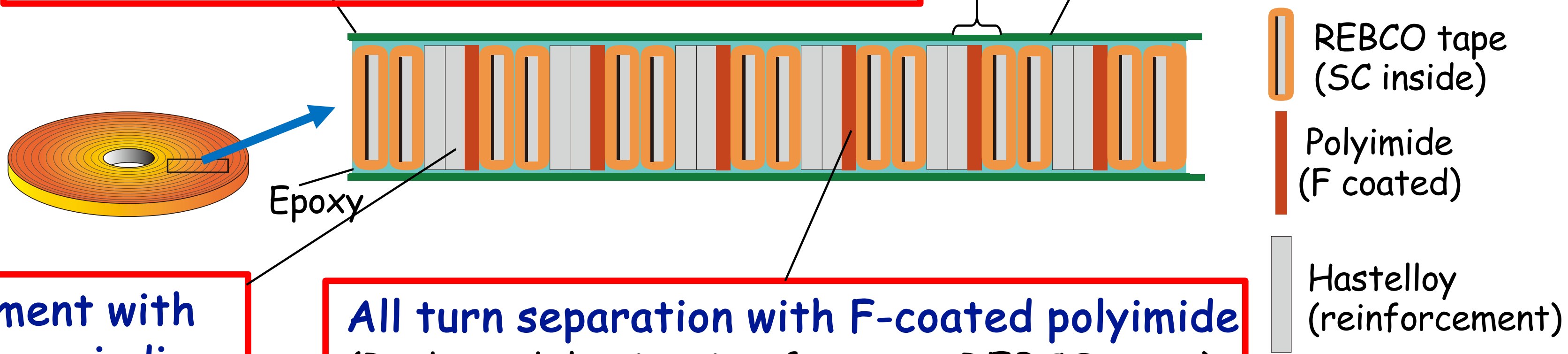
Edge impregnation

Thin FRP plate glued on coil & Impregnation

(Improve coil stiffness)

40 μm Cu stabilizer

(Reduce hot-spot temp.)



Reinforcement with Hastelloy co-winding

All turn separation with F-coated polyimide

(Reduce delamination force on REBCO tape)

S. Awaji IEEE TAS 31 (2021) 4300105

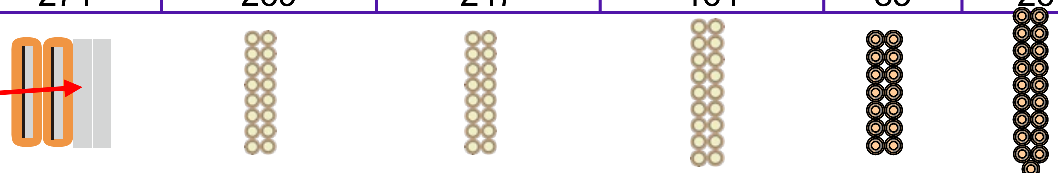
Primitive design of 33T-CSM

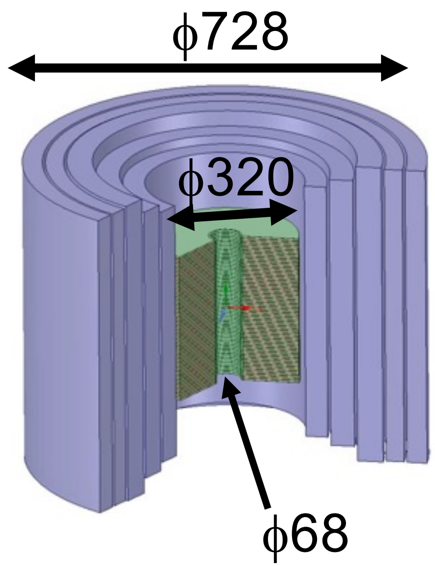
		HTS	NS1	NS2	NS3	NT1	NT2
Strand		REBCO	CuNb/Nb_3Sn			Cu/NbTi	
Iop	A	438	867				
Rin	mm	34	160	210.2	264	321.5	363.9
Rout	mm	147.2	204.2	258	315.5	357.9	404
Height	mm	325	537.6	571.2	632.5	626.9	627.8
No of PCs	-	64					
No of layer	-		24	26	28	20	22
Bmax	T	33.27	13.97	10.48	8.06	6.16	5.32
B0	T	19.2	3.22	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		2 x 0.1 mm	-	-	-	-	-
Insulation thick	mm	0.06	0.075				
Jcon	A/mm²	220.1	107.8	107.8	95.8	90.8	123.2
Jcoil	A/mm²	154.8	70.1	70.1	62.6	61.5	82.7
Tcs	K	—	6.97	9.74	11.5	6.4	6.69
Axial stress	MPa	-51	-50	-50	-49	-43	-49
Hoop stress	MPa	271	269	247	164	83	-26

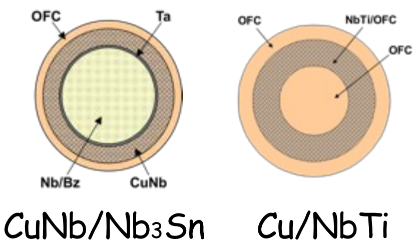
High stress

*1 12 T, *2 5 T

reinforcement







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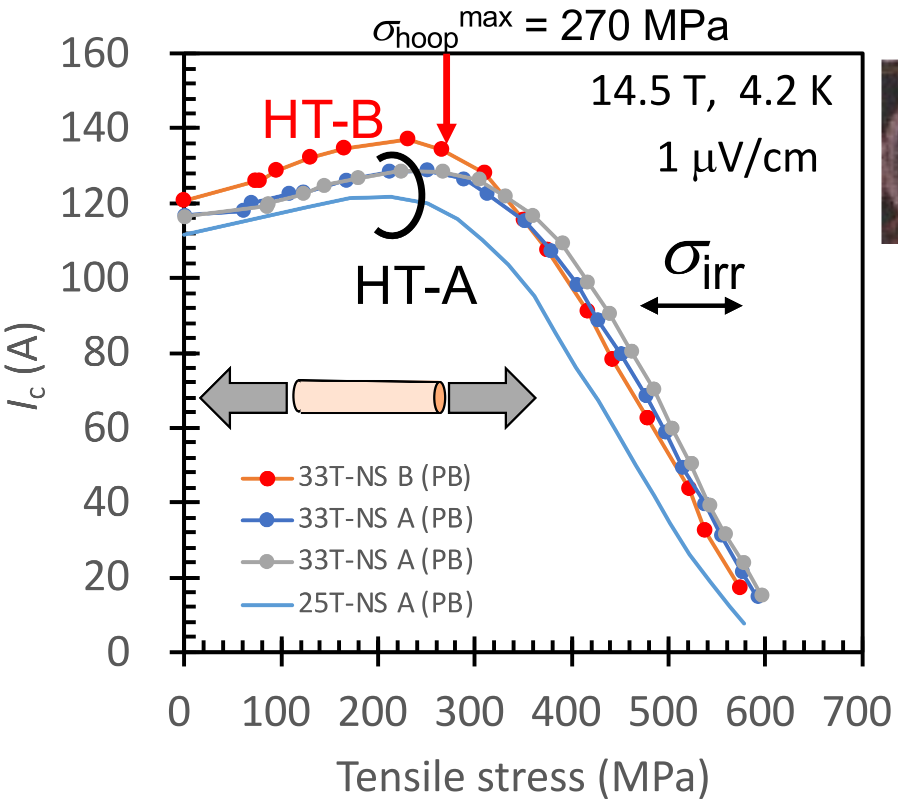
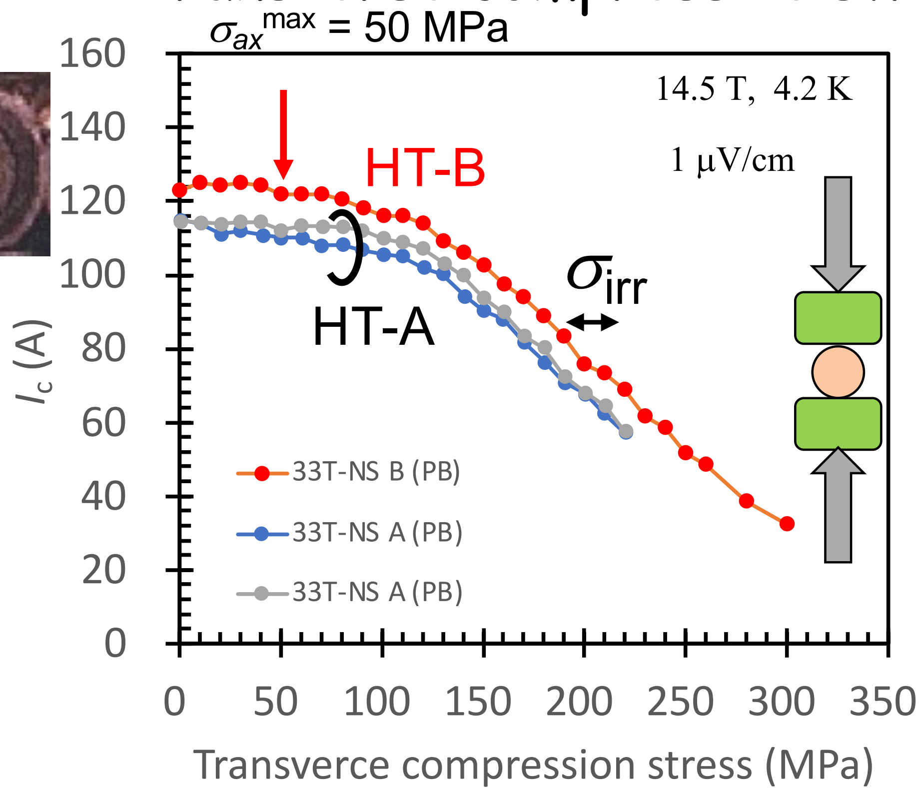
I_c under mechanical stresses

Axial tensile stress



Transverse compressive stress



- Improvement of elctoromechanical and I_c properties with "pre-bending".
- Strands with HT-A has higher I_c than with HT-B.
- Success of the improvement for 33T-CSM

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High Field Magnet Development at HFLSM
- Road map -

2015

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

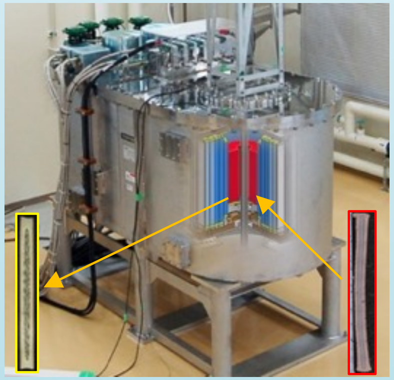
- 25.1 T in a 52 mm RT bore with 1 hour ramping
- Advanced high strength Nb_3Sn technologies and high strength Bi2223 (Type HT-Nx (SEI))
- World highest field in CSM
- Open for users since 2016 (250 days operation in 2018)
- Long time, high precision experiments.

S. Awaji SuST 30 (2017) 065001.

2018-2022

Upgrade to 30T-CSM (JSPS project)

Plan changed



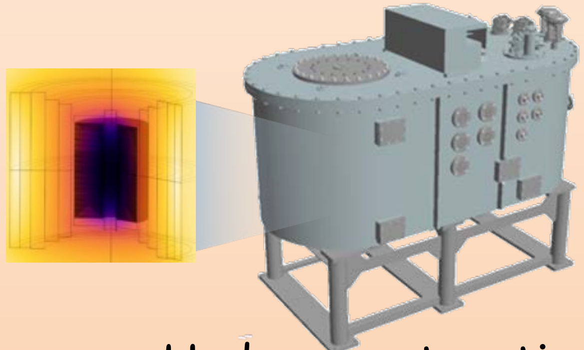
- Replace from Bi2223 insert to REBCO one.
- 25 T under B_{BG} = 14 T with "Robust REBCO coil"

S. Awaji IEEE TAS 31 (2021) 4300105

2022-

NEW 33T-CSM

- High strength Nb_3Sn Rutherford Cable
- Robust REBCO coil technol.



Under construction!

Upgrade to 40 T

50T Superconducting magnet

Under "High Magnetic Field Collaboratory Japan" project

HFLSM Sendai

Summary

- Many high field superconducting magnet developments with HTS are on-going in the world.
- We have serious issues for REBCO especially complicated mechanical stress/strain.
- Local degradation due to mechanical stress looks unavoidable for high field superconducting magnet.
- Multi-tapes such as co-winding, cables are necessary at the moment.
- From R&D studies for REBCO tapes, we reached the "robust REBCO coil concept" consisting of two tape co-winding and edge impregnation.
  - Two tape co-winding can reduce the risk of hot-spot due to the local degradation.
  - Edge impregnation can reduce the maximum hoop stress by the optimization of stress distribution, and screening current induced stress.

Thank you!

Field monitor for 25T-CSM

Cu coil for field monitor

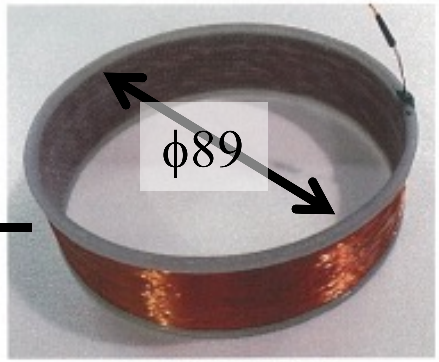
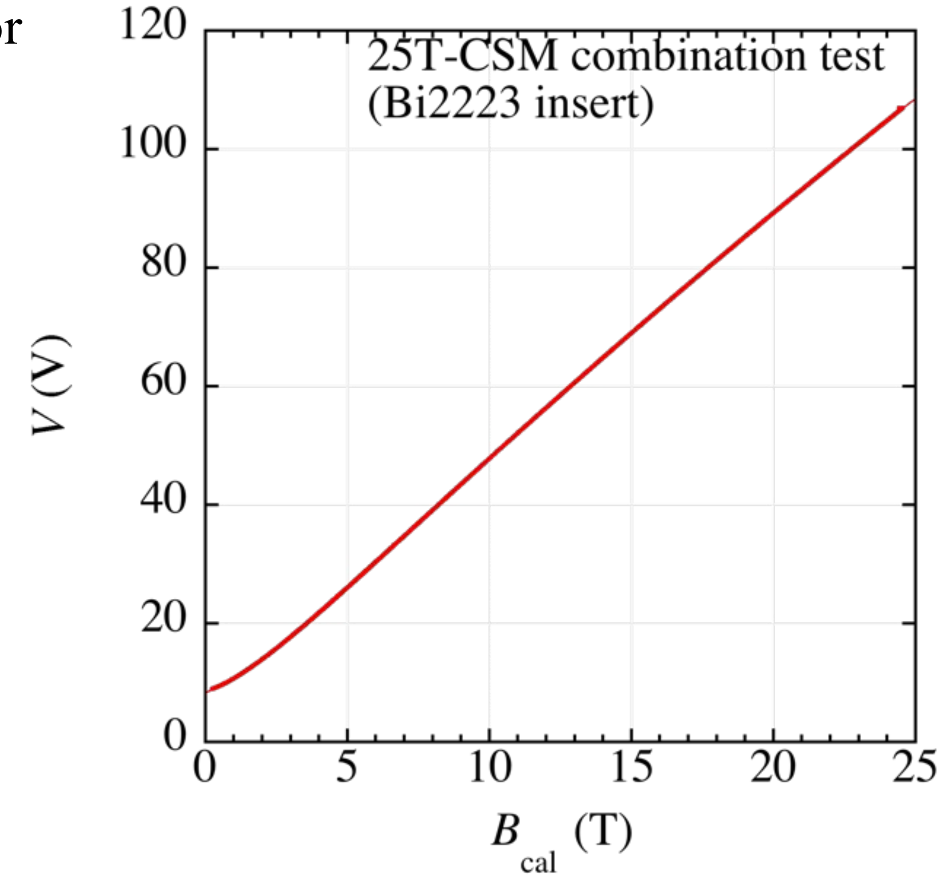


図6　磁場モニタコイル外観



Field monitor with a magnetoresistance of Cu works very well!

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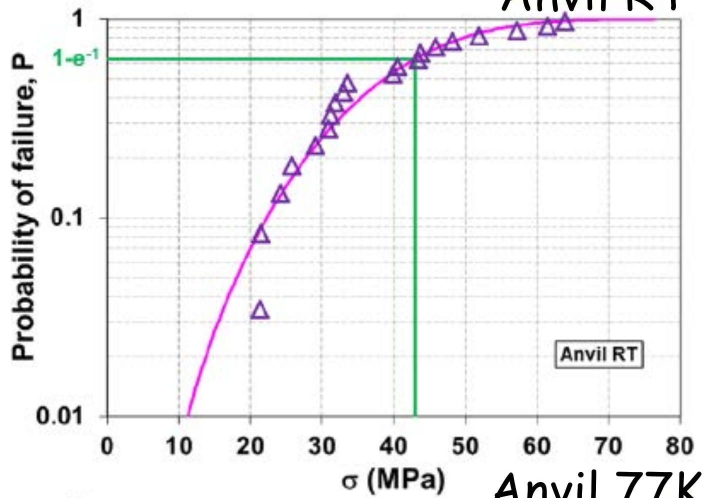
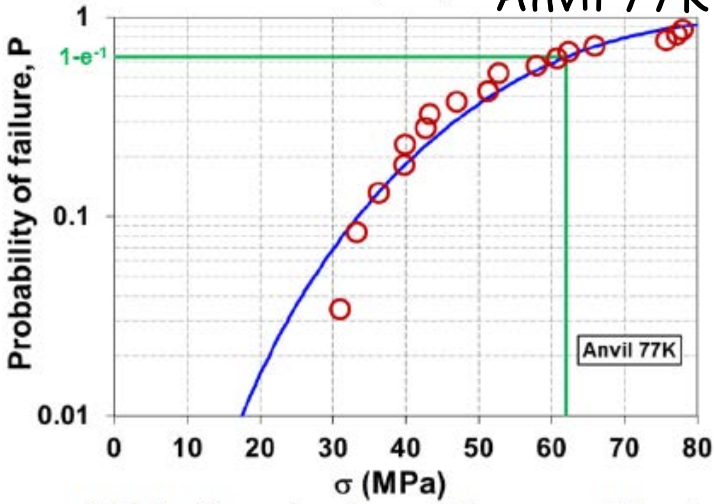
Weibull analysis on delamination strength

D. Hazelton. WAMHTS-4, 2017

Anvil RT



Anvil 77K

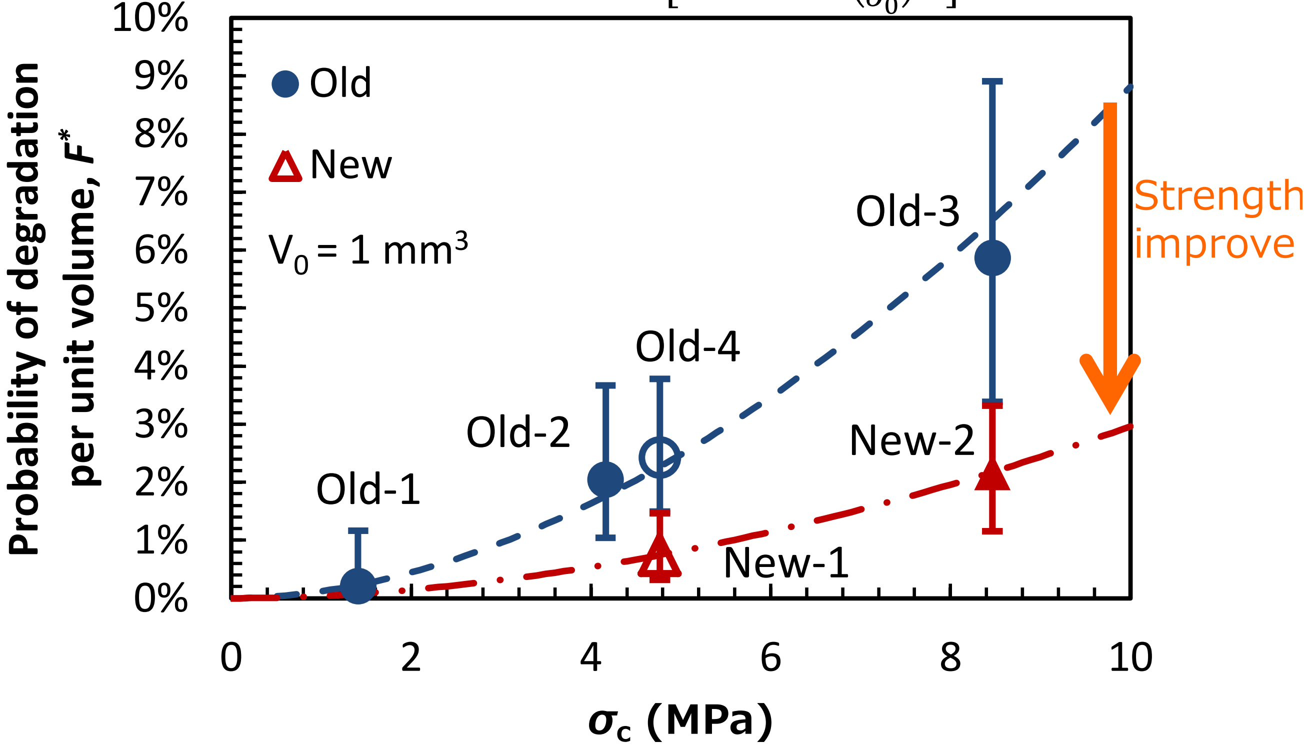


Muto et al., IEEE TAS 28 (2018) 6601004

Open symbol : 2.6 m
Closed symbol : 4.2 m

$$F(\sigma_c, V) = 1 - \exp\left[-V_E(m, V)\left(\frac{\sigma_c}{\sigma_0}\right)^m\right]$$

Coil 77K



Delamination strength as a function of volume-> depending on thickness
The local degradation is unavoidable.
-> Need strategy for the local degradation in REBCO magnet.

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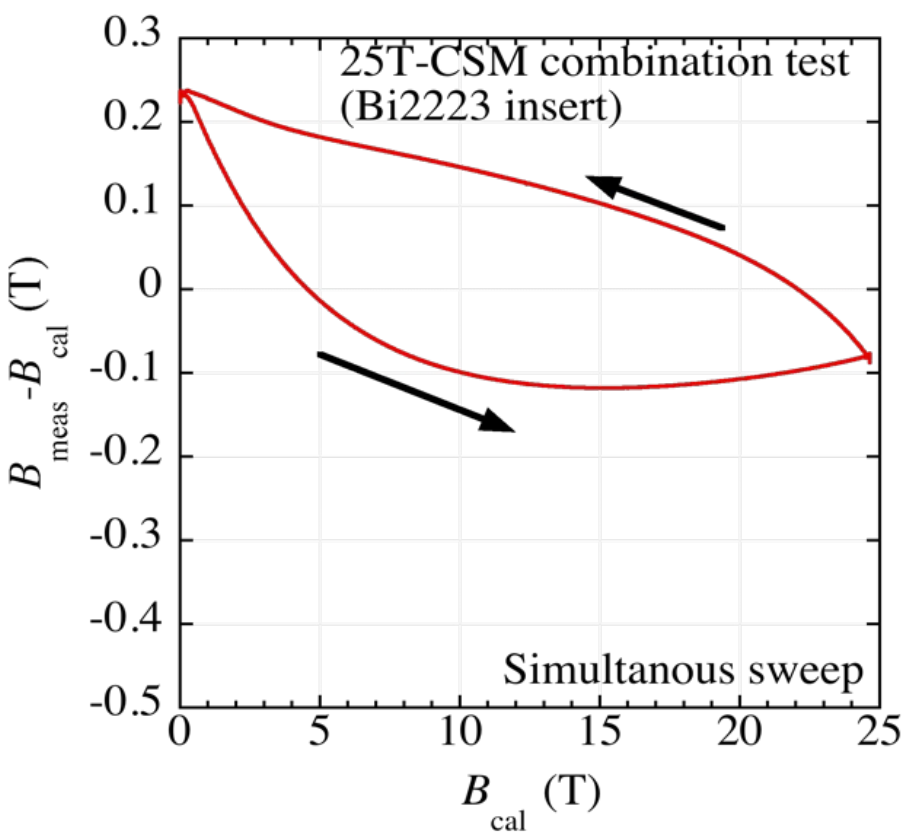
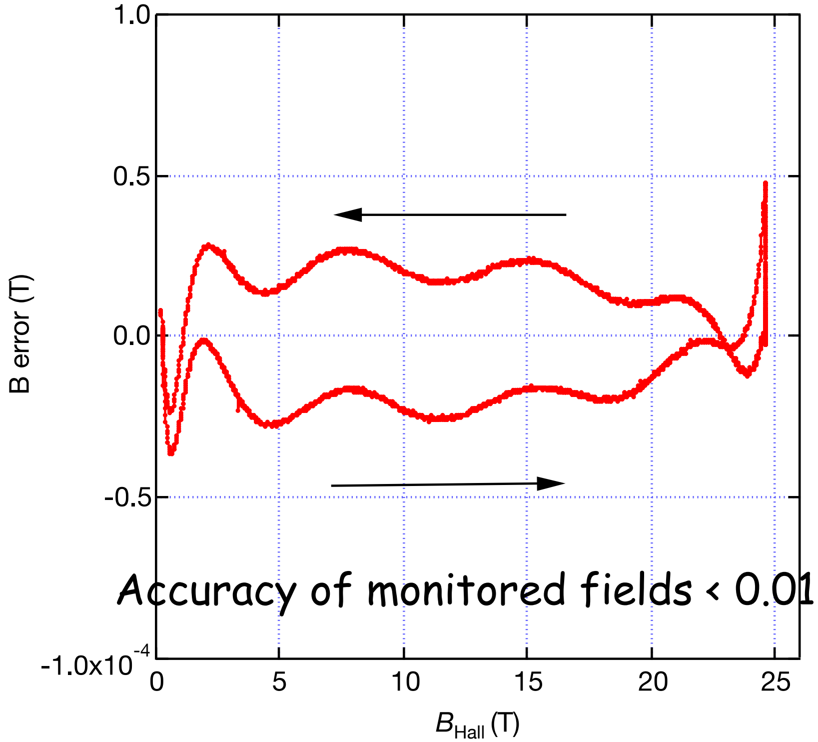
Magnetic field monitor with Cu bifilar coil (25T-CSM)





Accuracy of monitored fields < 0.01%

Although large hysteresis appears, the magnetic field can be monitored all the time.

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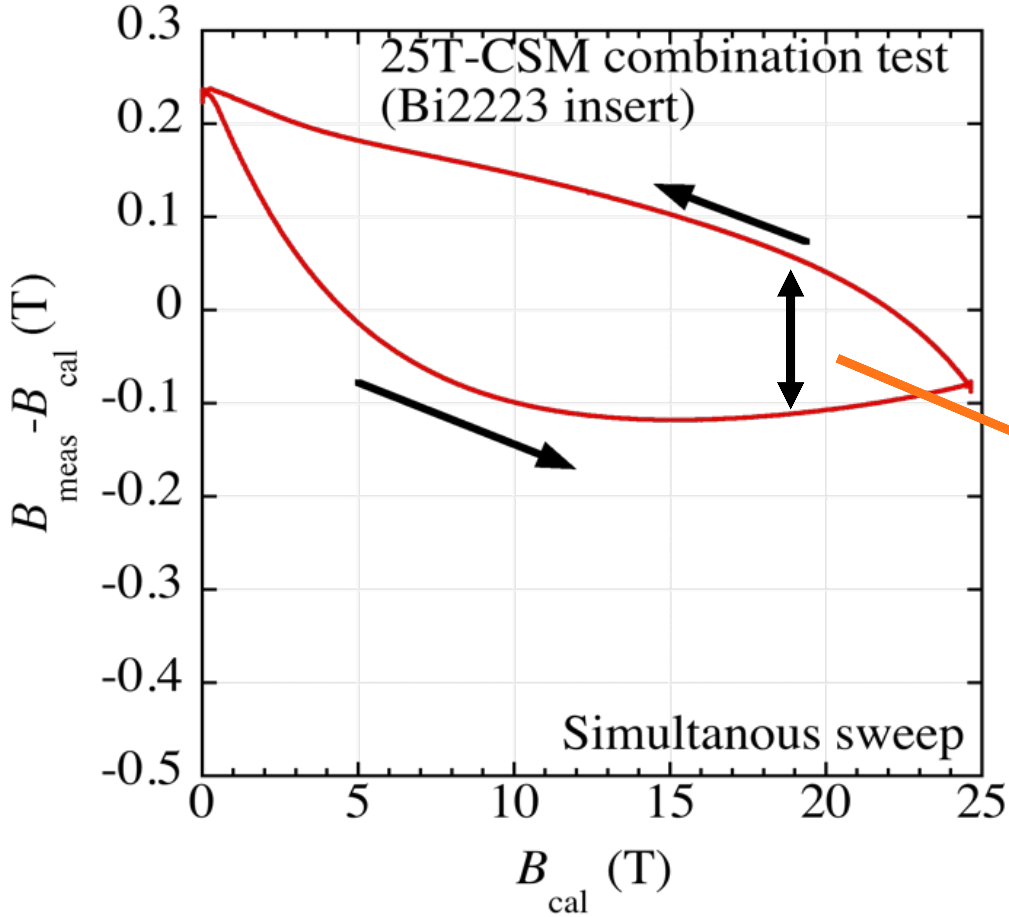
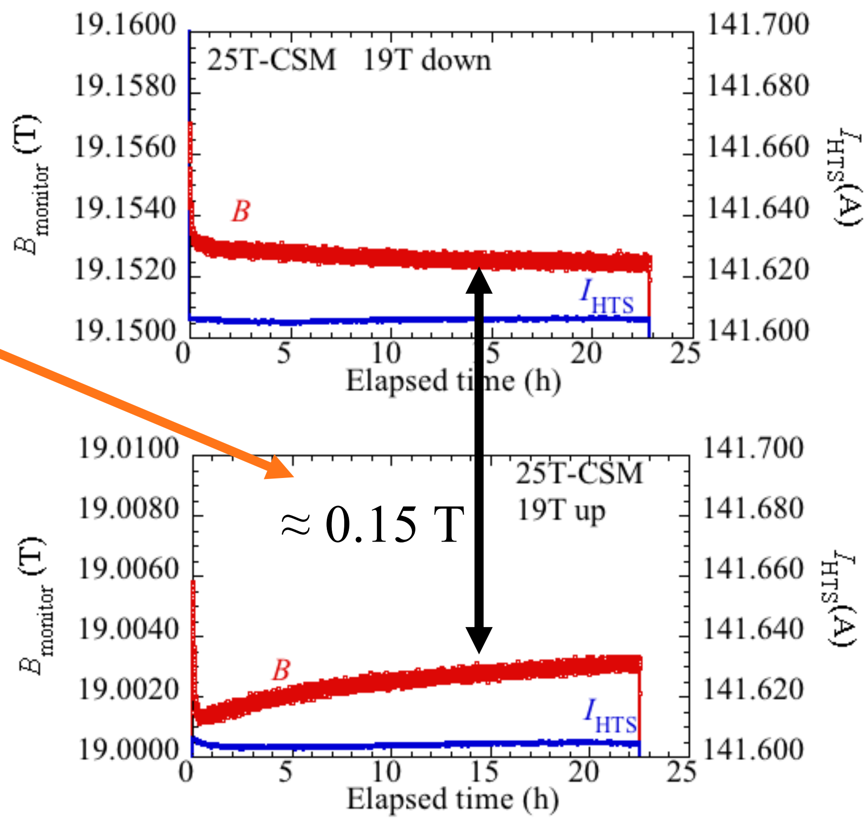
Magnetic field stability of the 25T-CSM (Bi2223)

S. Awaji et al., **IEEE TAS, 29 (2019) 4300305.**



Magnetic filed was measured by the field monitor.



In case of REBCO with higher J_c, better field stability is expected.

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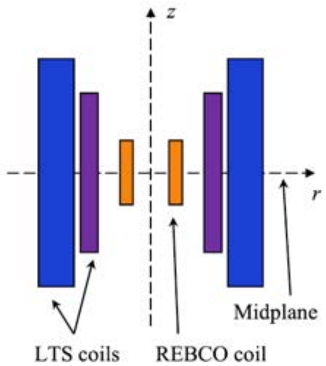
Screening current induced stress - effect of impregnation -



REBCO insert for 32T-SM
(B_{LTS}=15T, B_{HTS}=10.7T)

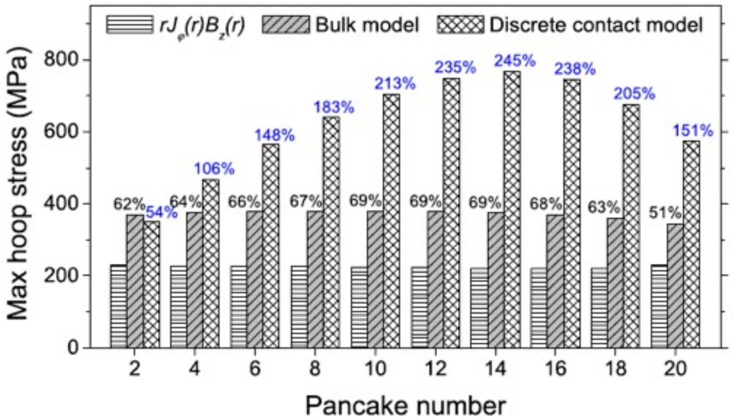
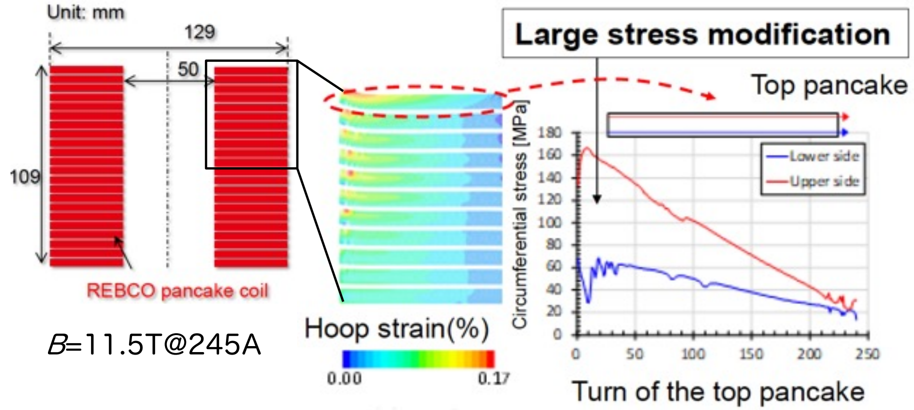
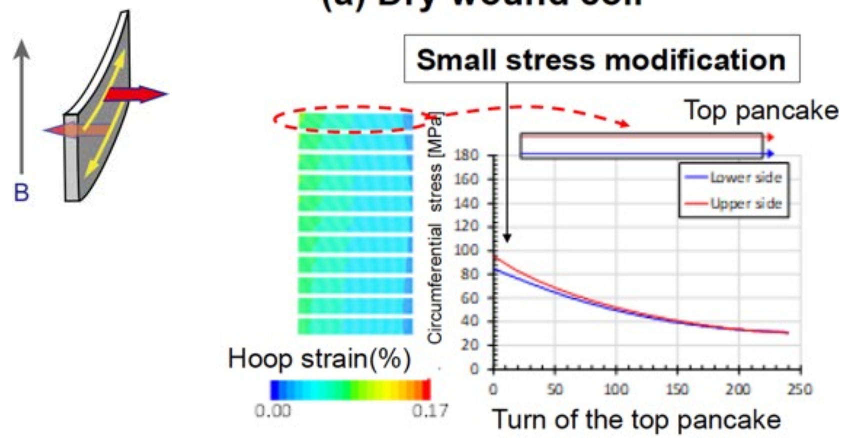


Figure 15. Maximum local hoop stresses in pancakes based on the classic formula (without SC), bulk model (with SC) and discrete contact model (with SC), respectively.

Xia et al, SuST, 32 (2019) 095005



(a) Dry wound coil



(b) Epoxy impregnated coil

H. Maeda, ASC2020 Wk2LOr2A-2, Ueda et al, to be published.

Impregnation –>reduce the screening current induced stress.

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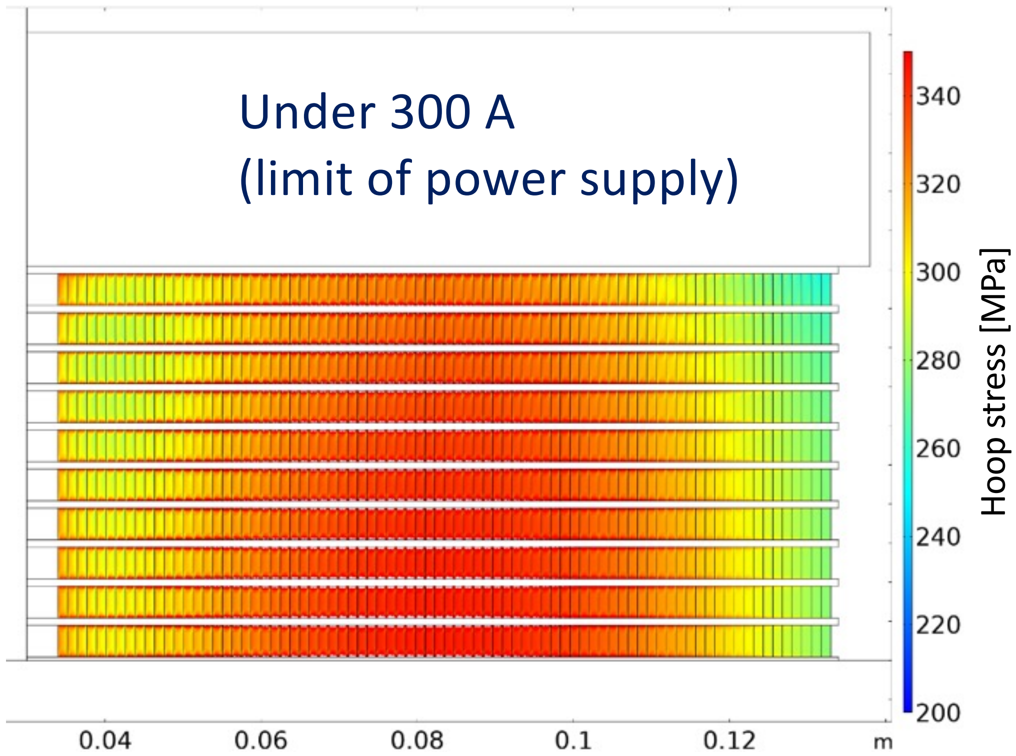
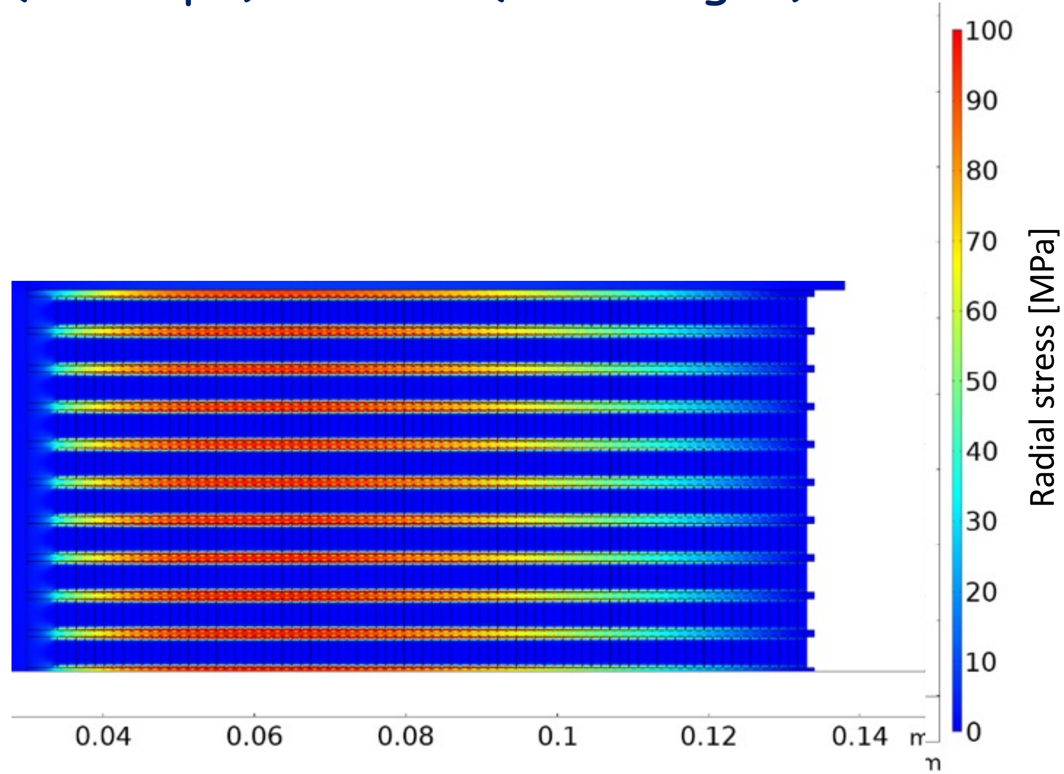
FEM modelling of 20 pancake coil under 14 T

Modelling assumption : Homogenous J
turn to turn separation as soft elastic interface
Elastic regime: Young modulus 130 GPa (for tape), 30 GPa (for flanges)



Estimated hoop stress up to 346 MPa



Estimated radial stress up to 100 MPa in flanges

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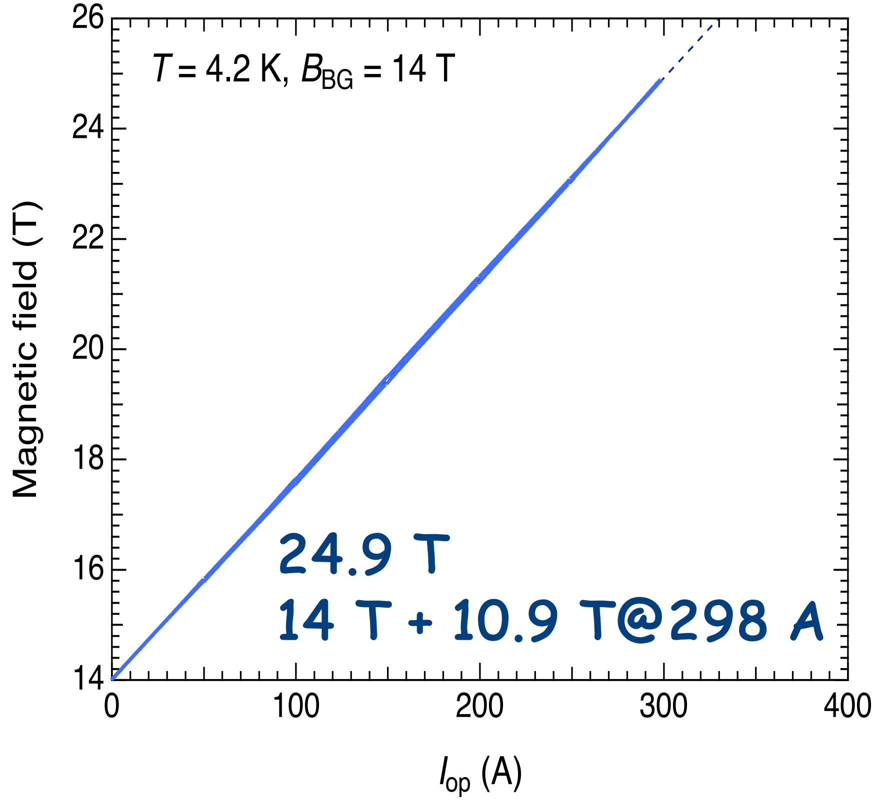
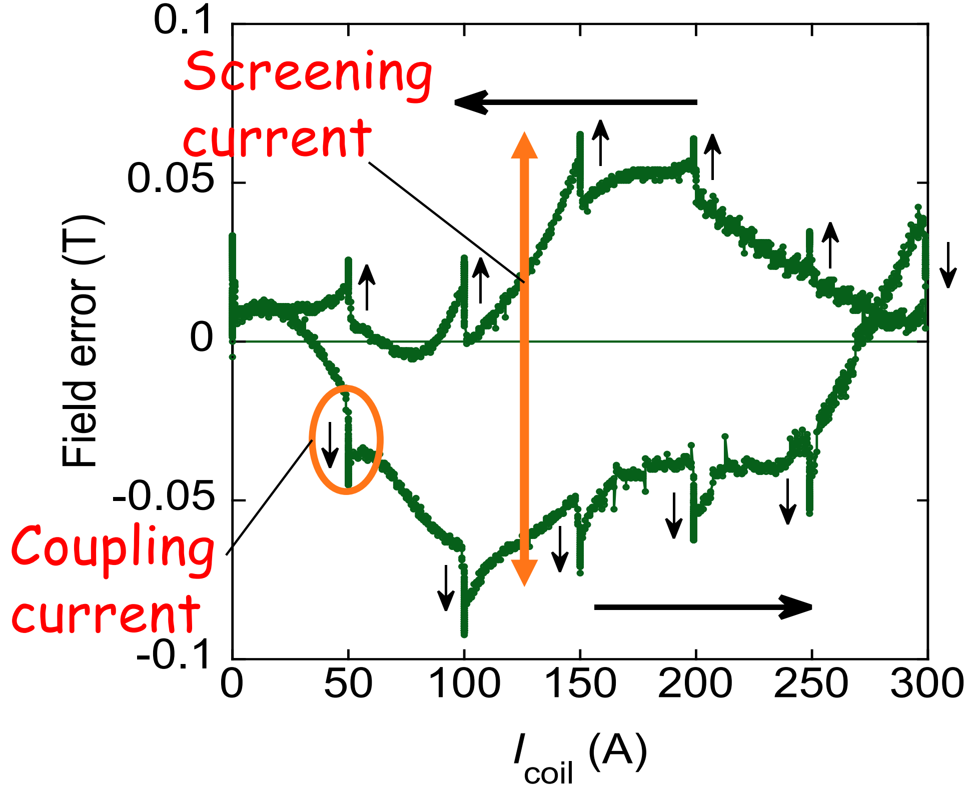
20 stacked REBCO pancake coil





25T was achieved combined with B_{BG}=14 T
Although screening current is dominant on field error, relaxation of coupling current appears first.

ASC2022, 1LPo2K-11: K. Takahashi, 4LOr1A-01: A. Badel

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 March 2024.
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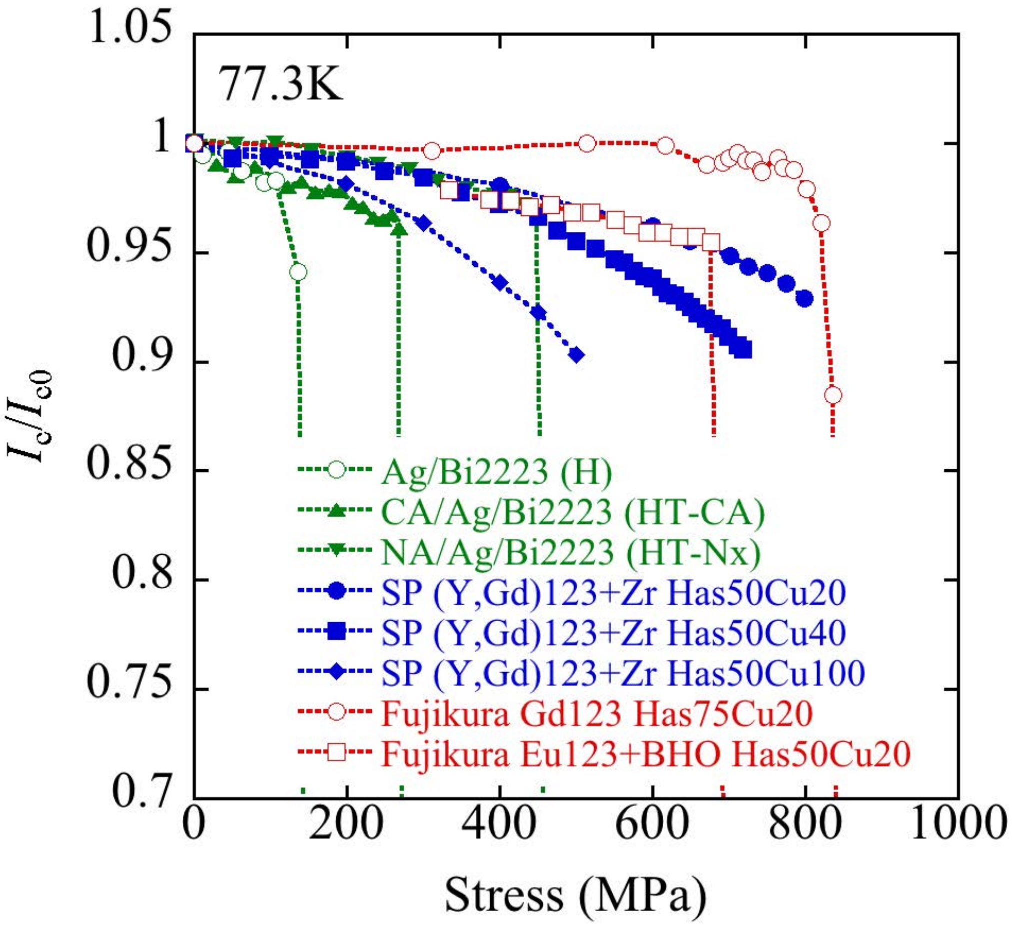
Issues and strategies of HTS coil for high field magnet

- ✓ Local degradation (maybe due to a local unexpected stress) should be considered.
  - -> All turns separation to make a delamination stress minimum
  - -> mitigate a possibility of local degradations as small as possible. (stiffness of pancakes)
  - -> more than two tape bundle conductor (two tape co-wind) in order to mitigate a hotspot.
- ✓ Screening current induced magnetic field
  - -> magnetic field monitor works well if its hysteresis is accepted
- ✓ Screening current induced stress
  - -> high stiffness of coil can reduce it (edge impregnation)
  - -> reduce a volume of polyimide in coils may be more effective (hopefully replace to ceramic insulation)
- ✓ Inhomogeneity and different grade in critical currents
  - -> quality analysis by performances of pancakes
- ✓ Large stress operation
  - -> optimization of stress distribution and reinforcement (edge impregnation)
- ✓ Protection for the hot-spot related to local degradation and inhomogeneity is crucial.
  - ✓ Dump resistor (Passive protection) -> need detection and quick dump before burn-out
  - ✓ No-insulation (self-protection)-> delay of magnetic field and heating are issues.
  - ✓ Quench heater (Active protection) -> need huge power in quench heater with short time

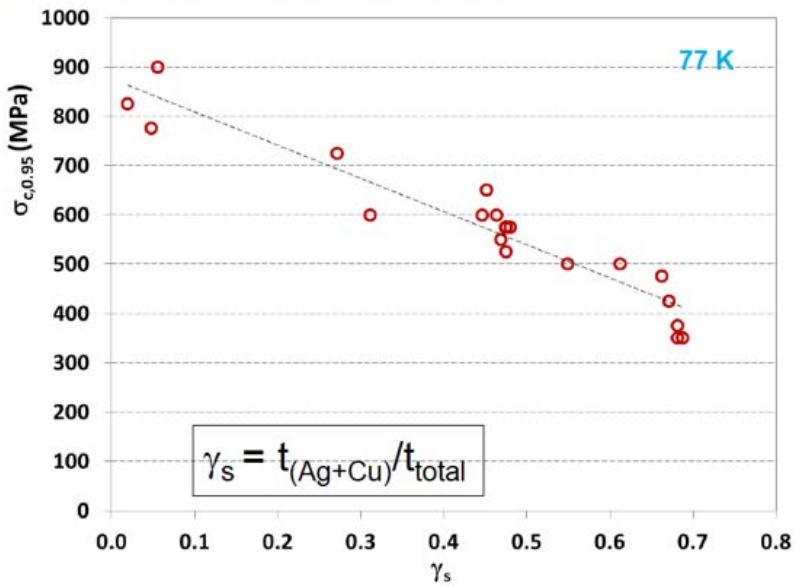
Electromechanical properties - effect of Cu stabilizer -



S. Fujita et al., Presented at MT26, Tue-Mo-Po2.09-02
Y. Zhang et al., IEEE TAS 26 (2016)8400406.

Stress tolerance of REBCO decreases with decreasing a volume fraction of Hastelloy.

Effect of stabilizer thickness ratio on critical stress under uniaxial tension



Y. Zhang 2018 IAS-HEP Hong Kong January 18,