



TOHOKU
UNIVERSITY



26th International Conference on Magnet Technology (MT26)
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MT26 Special session
"Magnet Technology and Conductor for future High-Field Applications"

Status of High-field ReBCO Conductor

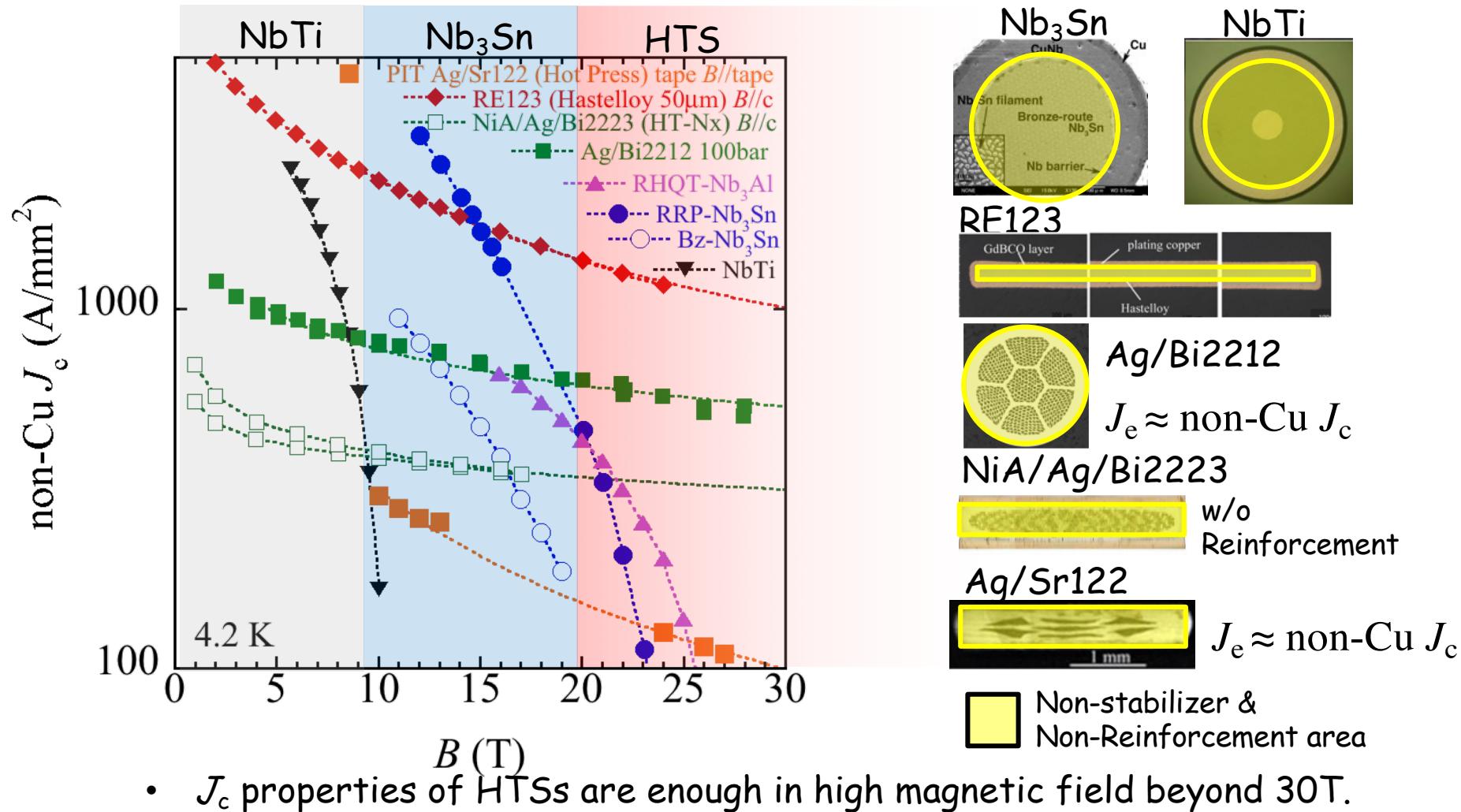
Satoshi Awaji

High Field Laboratory for Superconducting Materials
(HFLSM),

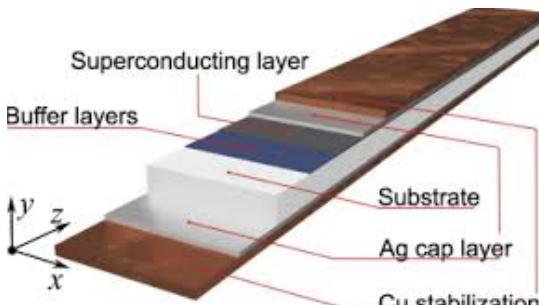
Institute for Materials Research, Tohoku University



Non-Cu J_c (non stabilizer J_c)



Commercial REBCO tapes

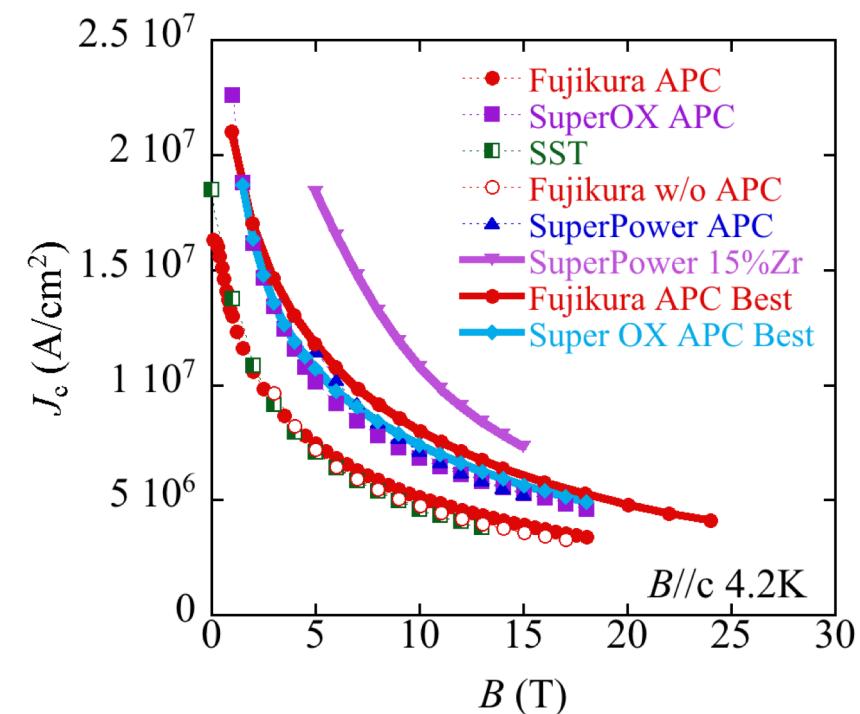
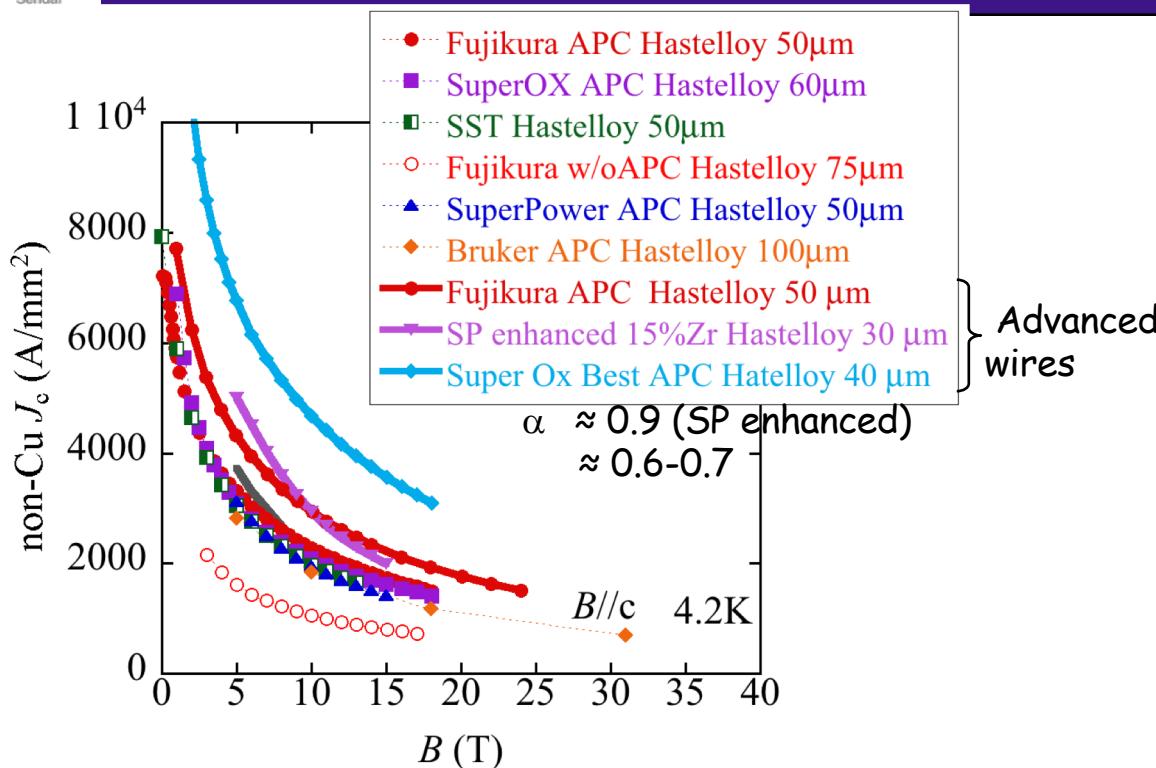


Solovyov et al, SuST 26 (2013) 115013



	RE	Method	t_{SC} (um)	APC	Template	Sub	t_{sub} (um)	Stabilizer	t_{stab} (um)
Fujikura	Gd	PLD	≈ 2	-	IBAD-MgO	Hastelloy	75	Cu plated	10-40 x 2
	Eu		≈ 2.5	Hf			50		
SuperPower	Y,Gd	CVD	≈ 1.5	Zr	IBAD-MgO	Hastelloy	(30), 50	Cu plated	20,40 x 2
SuNAM	Gd	RCE	1.3-1.8	-	IBAD-MgO	Hastelloy /SS	60	Cu plated	5-10 x 2
SuperOx	Gd	PLD	2.3-2.5	-	IBAD-MgO	Hastelloy	40, 60	Cu plated	1-50 x 2
	RE		2.3-2.7	Hf					
SST	RE	PLD	≈ 2.4	Not Open	IBAD-MgO	Hastelloy	30,50	Cu plated	5-10 x 2
Bruker	Y	PLD	1.5-1.7	Nano Rod	ABAD-YSZ	SS	100	Cu plated	40 x 2
AMSC	Y,Dy	MOD	0.8-1.2	Dy ₂ O ₃	RABiTS	NiW	≈ 100	Cu, Brass, SS laminated	50 x 2
THEVA	Gd	PVD (EB)	≈ 2.5	-	ISD-MgO	Hastelloy	50, 100	Cu PVD / laminated	30, 40, 100 (lamination) <20 x 2 (PVC)
STI	Y	RCE-CDR		-	IBAD-MgO	Hastelloy	100	Cu PVD	20 x 2
SEI	Gd	PLD	≈ 3	-	Textured-Cu	SS	100	Cu plated	20 x 2

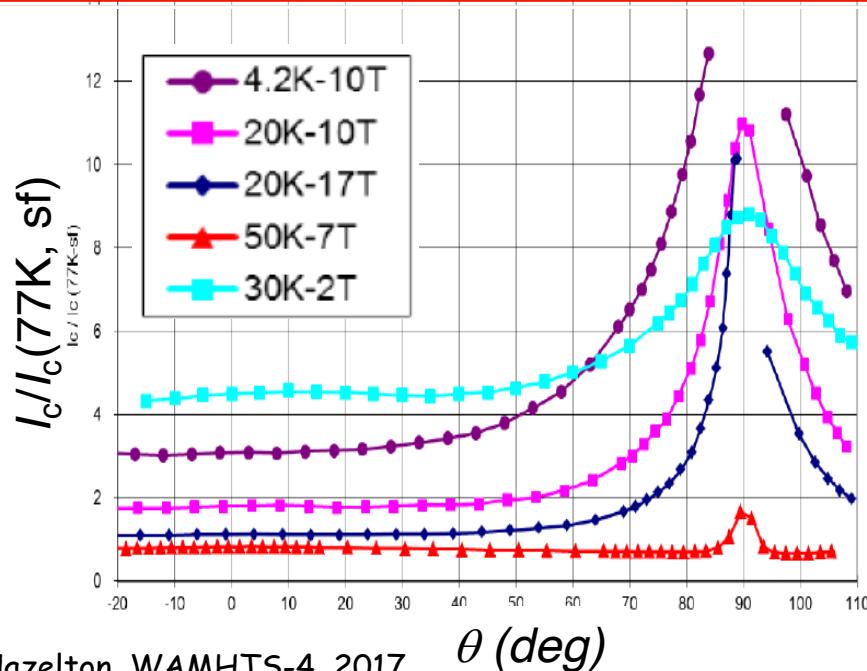
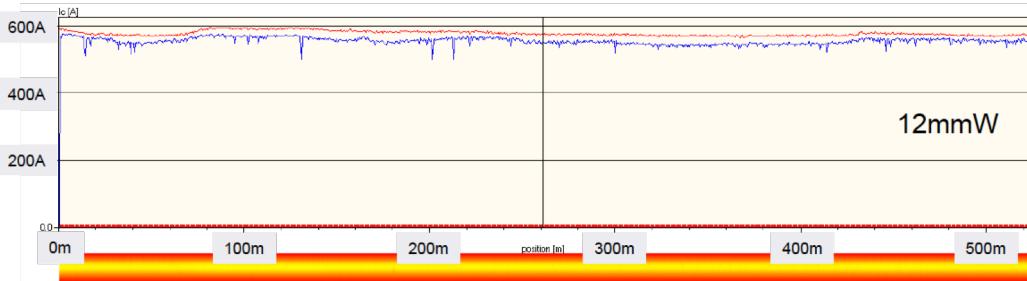
Non-Cu J_c of REBCO commercial tapes



- APC is effective even in low temperatures and high fields.
- Many vendors introduce APC.
- Non-Cu J_c increases with a reduction of substrate thickness and an increase of REBCO thickness.
- Increase REBCO thickness is effective to increase non-Cu J_c but may increase cost and delamination risk.

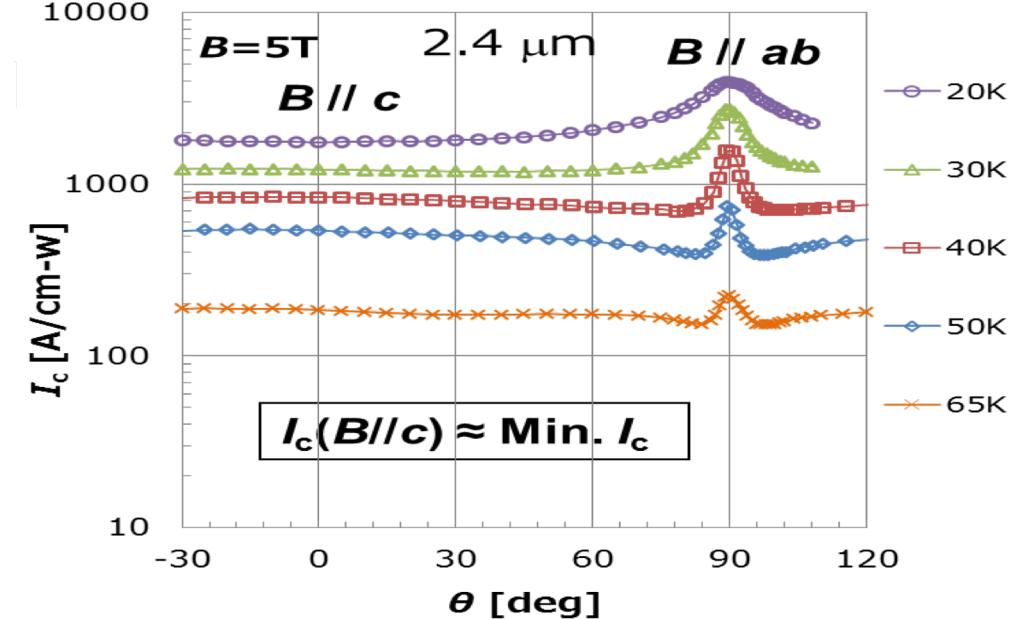
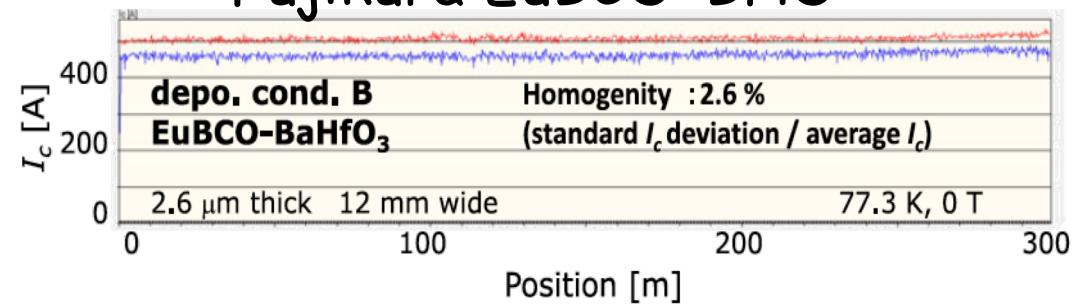
Homogeneity and Typical angular dependence of J_c for REBCO tapes with APC

SuperPower (Y, Gd)BCO+7.5%Zr



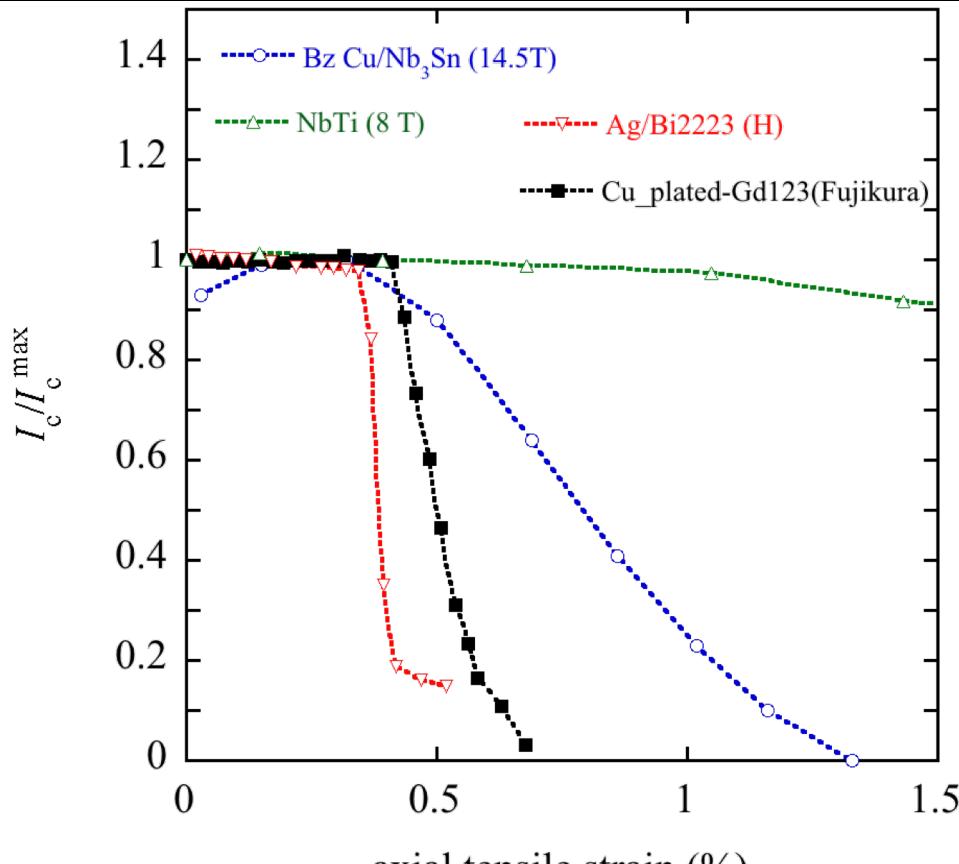
D. Hazelton. WAMHTS-4, 2017

Fujikura EuBCO+BHO



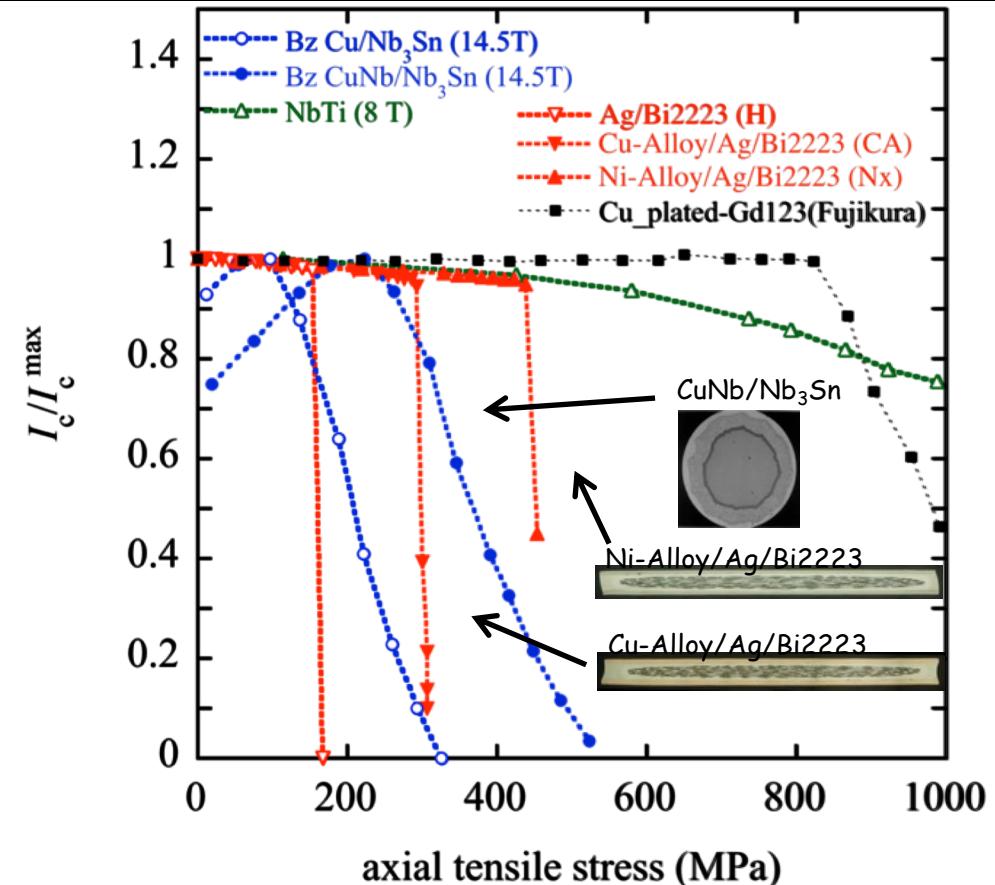
Iijima et al., IEEE TAS 27 (2017) 6602804,
Fujita et al, IEEE TAS 28 (2018) 6600604.

Electromechanical properties

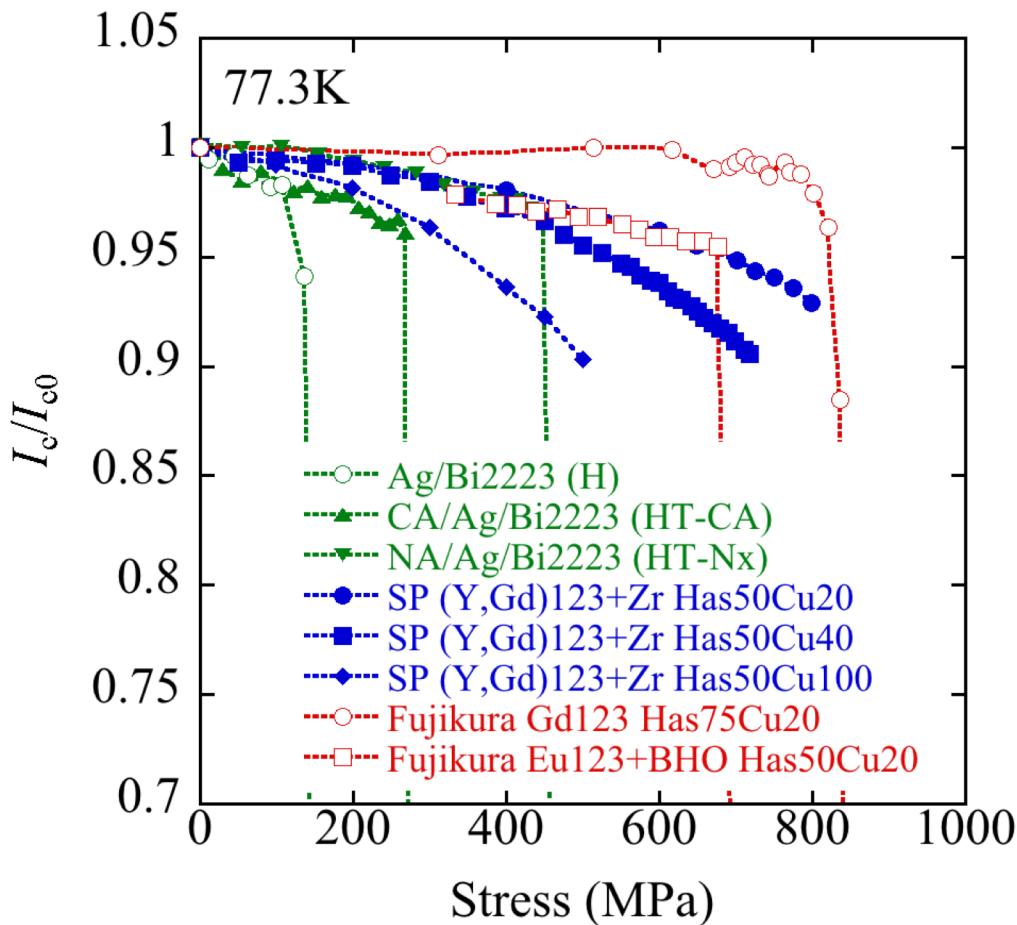


axial tensile strain (%)

- Alloy SC NbTi has broad strain dependence.
- Strain limits of most superconductors are 0.3-0.5%.
- Reinforcement is necessary for high field magnet.



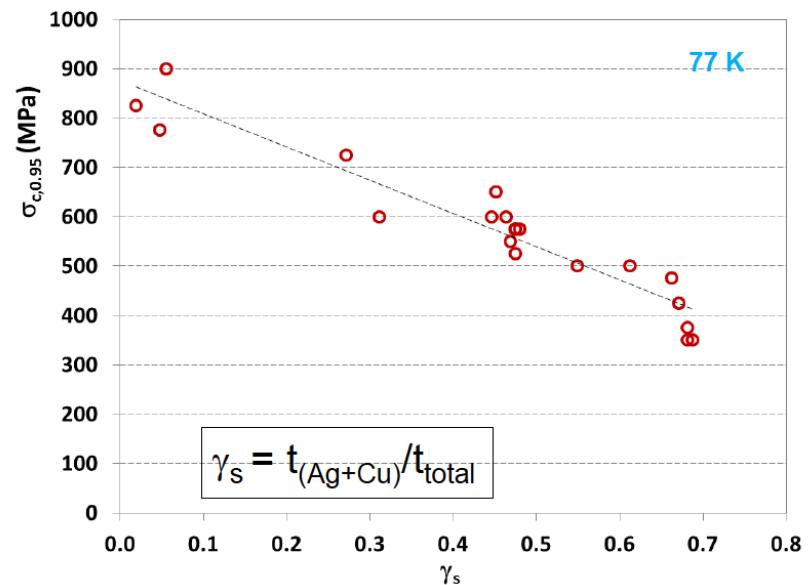
Electromechanical properties



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

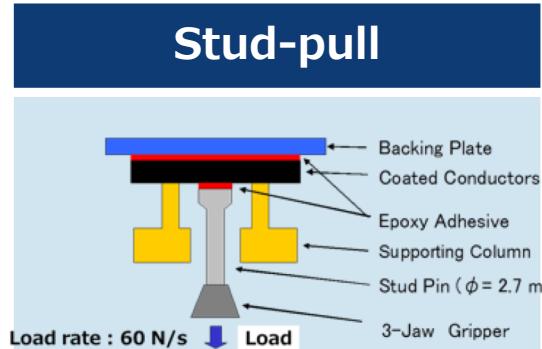
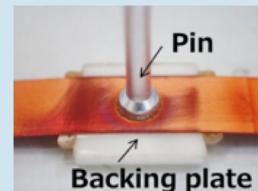
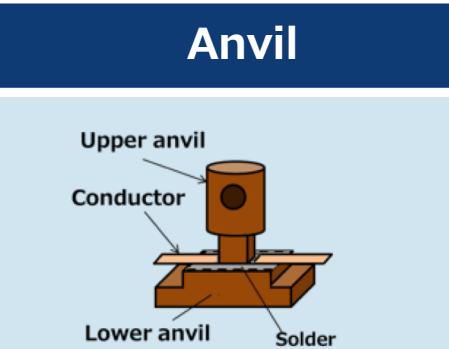
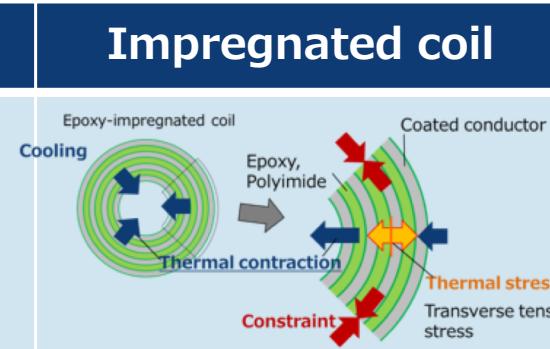
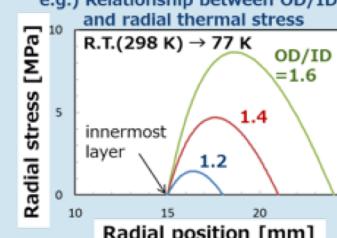
Stress tolerance of REBCO decreases with decreasing a volume fraction of Hastelloy.

Effect of stabilizer thickness ratio on critical stress under uniaxial tension



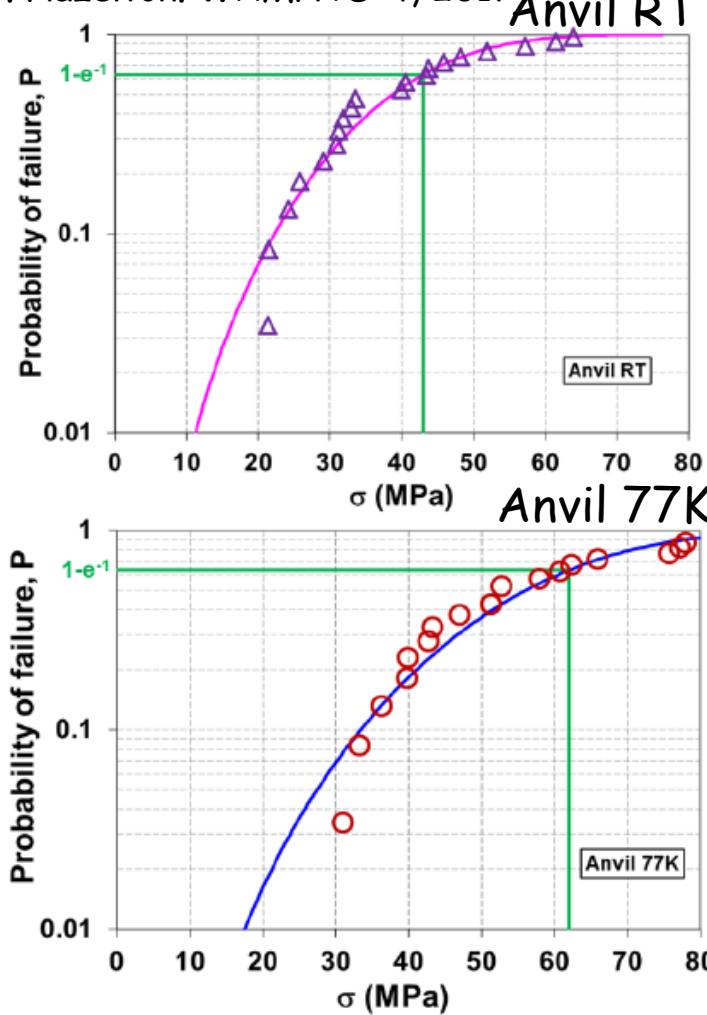
Y. Zhang 2018 IAS-HEP Hong Kong January 18,

Delamination in REBCO tapes

Stud-pull	Anvil	Impregnated coil
  <p>Test area : 5.7 mm² (φ2.7 mm pin) Strength : ~ 40 MPa</p> <p>T. Oyama, et al., Journal of The Surface Finishing Society of Japan, 58 (2007) P. 292</p>	  <p>Test area : 32 mm² (4×8 mm anvil) Strength : ~ 10MPa</p> <p>H. Shin, et.al., SuST, 27 (2014) 025001</p>	 <p>e.g.) Relationship between OD/ID and radial thermal stress</p>  <p>OD/ID: The ratio of outer diameter to inner diameter</p> <p>Test area : 16000 mm² (4 mm^w×4 m coil) Strength : ~ 5 MPa</p> <p>H. Miyazaki et al., IEEE TAS, 25 (2015) 6602305</p>

Weibull analysis on delamination strength

D. Hazelton. WAMHTS-4, 2017

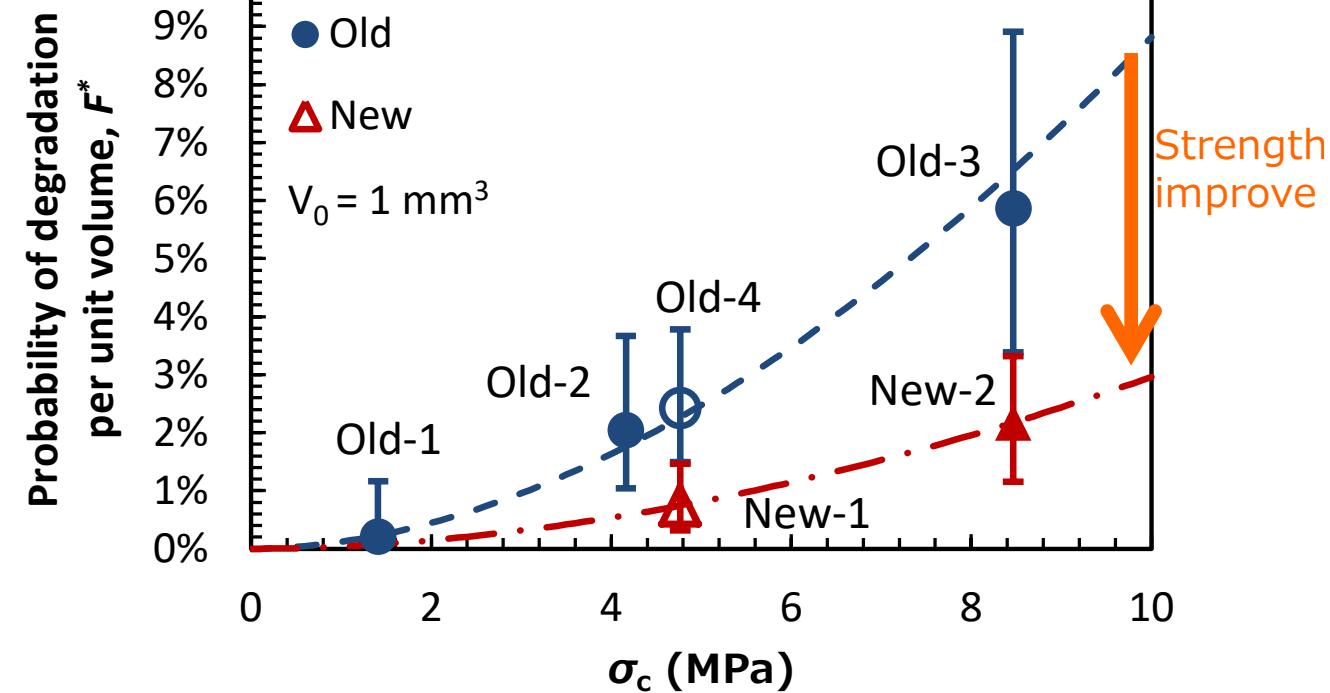


Muto et al., IEEE TAS 28 (2018) 6601004

Open symbol : 2.6 m
Closed symbol : 4.2 m

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

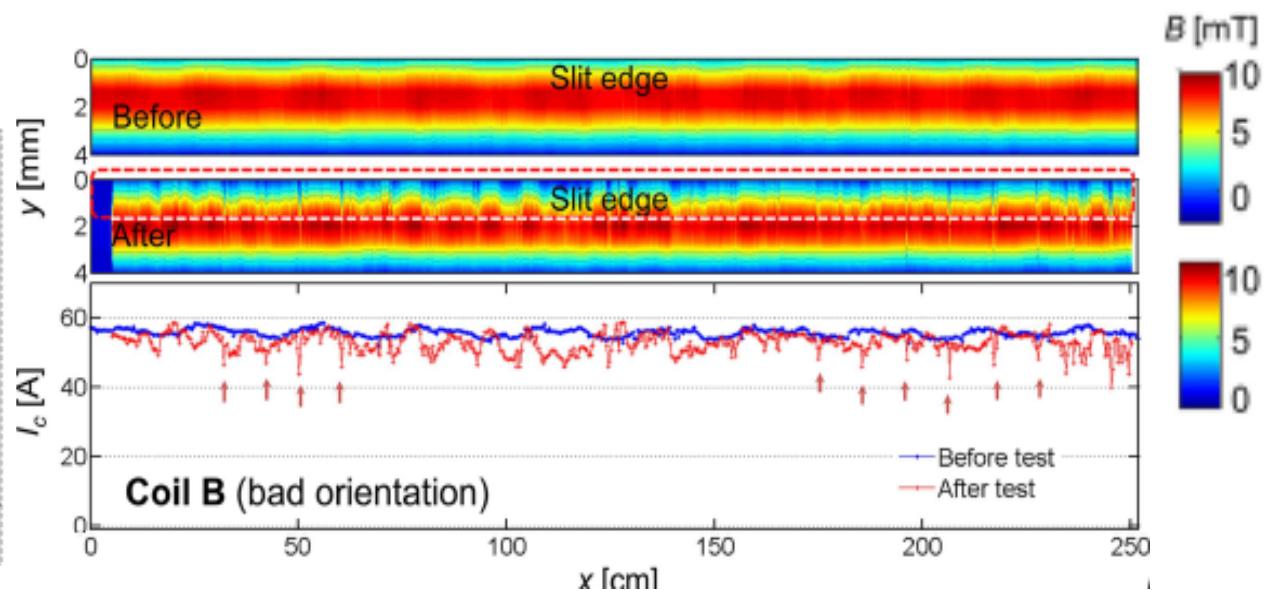
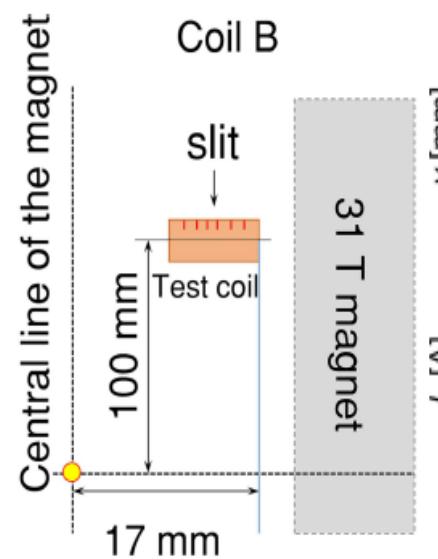
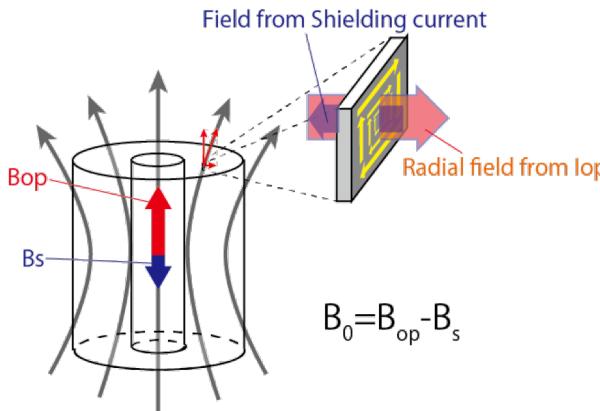
Coil 77K



Delamination strength as a function of volume \rightarrow depending on thickness
The local degradation is unavoidable.

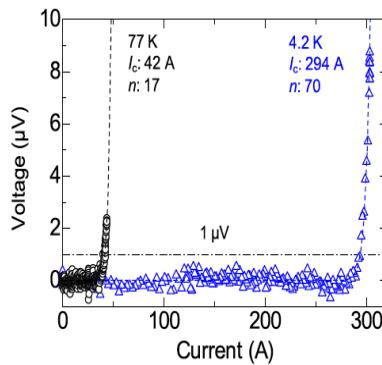
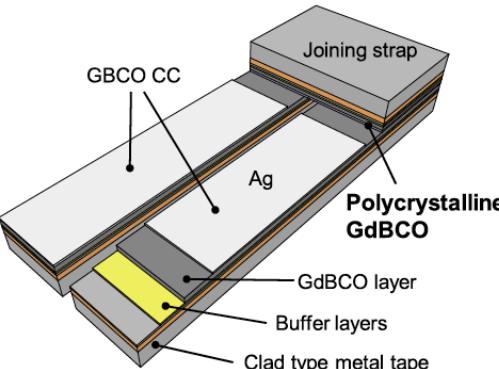
\rightarrow Need strategy for the local degradation in REBCO magnet.

Stress induced from screening current



Joints

- Superconducting joints are developed under the MIRAI project in Japan and by a few private companies.
- $R_{\text{joint}} \approx 50 \text{n}\Omega/\text{cm}^2$ can be achieved by a solder.
- Good superconducting joints of REBCO tapes and persistent current operation are achieved.



Ohki *et al*, SuST 30
(2017)115017.

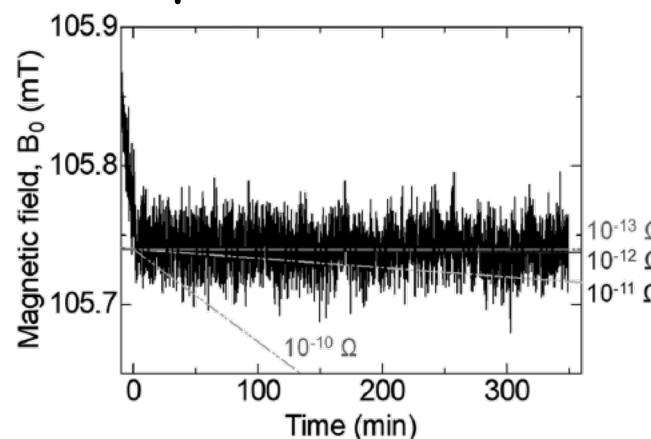


Fig.1 Measured magnetic field in a persistent current operation at 4.2 K at 100 A.

Yanagisawa *et al*, Abst. CSSJ conf. 96 (2018)83.

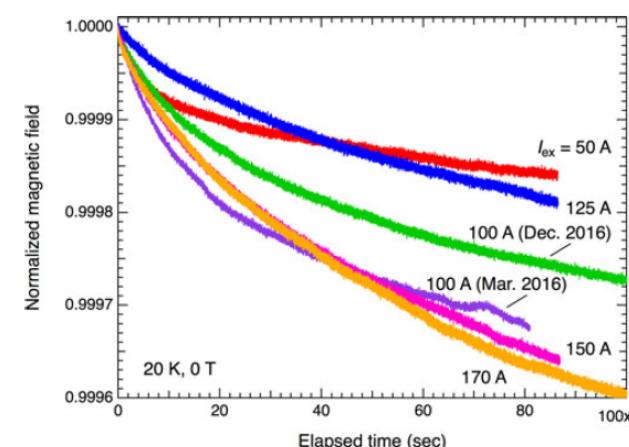


Fig.4. Magnetic field decay of the REBCO coil in persistent current operation of various excitation currents at 20 K in zero external magnetic field.

0 T		
B_0 (T)	Decay rate after 1day (ppm/h)	
50 A	0.175	1.9
75 A	—	—
100 A	0.348	3.1
125 A	0.434	4.8
150 A	0.521	8.1
170 A	0.590	6.0

Takahashi *et al*, IEEE TAS 28 (2018) 4600104.



High Field HTS Magnets (All SC magnet)

S. Awaji, School Textbook "High Temperature Superconductors (in Japanese) vol. 2", JSAP, 2019 in press

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	Ref	
32T-SM	NHMFL	User magnet	32 (17/15)	RE123	193	378	40	4.2 (LHe)	DP	Dry	Open soon	2017	[1]	Insulated
25T-CSM	Tohoku U.	User magnet	24.6 (10.6/14)	Bi2223	150	323	96	4-8	DP	Epoxy/ turn separation	Open since 2016	2016	[2]	Insulated
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	[3]	Insulated
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	[4]	Insulated
Fly-wheel	Furukawa	300kW FW	3.4	RE123	130		120	30-50	DP	Dry	Operate since 2015 as FW (4ton)	2015	[5]	Insulated
5T R&D	Fujikura	Demo	5	RE123	83	150	260	25	SP	Epoxy	Use at Fujikura	2013	[6]	Insulated
24T R&D	NIMS /RIKEN	Demo	24 (6.8/17.2)	RE123	428	408	50	4.2 (LHe)	Layer	Wax		2012	[7]	Insulated
25T R&D NMR	U. Geneva	Demo	25 (4/21)	RE123	733	139	20	2.2	Layer	Epoxy		2019	[8]	
3T-MRI	Mitsubishi	MRI	3	RE123	257		320	7	DP	Epoxy/ turn separation	Obtained MRI Image	2017	[9]	Insulated
9.4T-CSM	Toshiba	Demo	13.5	RE123	375	255	50	10	SP	Epoxy		2016	[10]	Insulated
NOUGAT	LNCMI/CEA -Saclay	Demo	14.5	RE123	717	(454@30T)	50	4.2(LHe)	DP	Dry	32.5T under 18T by resistive magnet	2019	[11]	MI
LBC	NHMFL	Demo	14.5	RE123	1420	691	14	4.2K(LHe)	SP	Dry	Damaged at 45.5T under 31T by resistive magnet	2017	[12]	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	[13]	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	[14]	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	[2]	Insulated
25T NI	SuNAM /MIT	Demo	26.4	RE123	404	286	35	4.2 (LHe)	NI-SP	Dry?	NI	2016	[15]	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	[16]	NI
27T	IEE/CAS	Demo	27.2	RE123	389		36	4.2 (LHe)	NI-DP	Wax	NI	2019	[17]	NI
3T-MRI	NIMS /SEI	MRI	3	Bi2223	114	137	514 (RT bore)	14	DP	Epoxy	MRI image at 1.5T, damaged in test	2013	[18]	Insulated

Practical use

Demonstration

Damaged

Summary and issues of commercial REBCO CC tapes

- ✓ **Excellent in-field J_c and electromechanical properties.**
 - ✓ Stress tolerance decreases with decreasing volume fraction of Hastelloy
- ✓ APC is effective to improve in-field J_c properties.
 - ✓ Angular dependence of J_c is not complicated below 20 K even for REBCO with APC.

Issues

- ✓ **Delamination** and the local degradation.
 - ✓ Current share is a key to overcome the hotspot.
- ✓ **Piece length**: typically 100m, 2-300m (high cost), Is 1km possible?,
- ✓ **Cost**: $\approx \$50/m$ (4mm-width), Need less than $\$10/m$?
- ✓ **Protection** from the hot-spot is critical.
 - ✓ 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.
 - ✓ Dump resistor (Passive protection) -> need detection and quick dump before burn-out



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