IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation 3-MO-PL2 given at EUCAS 2019, 01 - 05 September 2019, Glasgow (UK).

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EUCAS 2019 GLASGOW

14th European Conference on Applied Superconductivity
1st-5th September 2019, SEC, Glasgow

Superconductors in High Magnetic Fields - Now and the future -

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HFLSM Sendai

Research

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Furukawa-SuperPower:
S. Yamano, T. Fukushima

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KEK
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NIMS
G, Nishijima

Special Thanks

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Shanghai Supercond. Techn.: Y. Yamada

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Superconductors in High Magnetic Fields - Now and the future -

Contents

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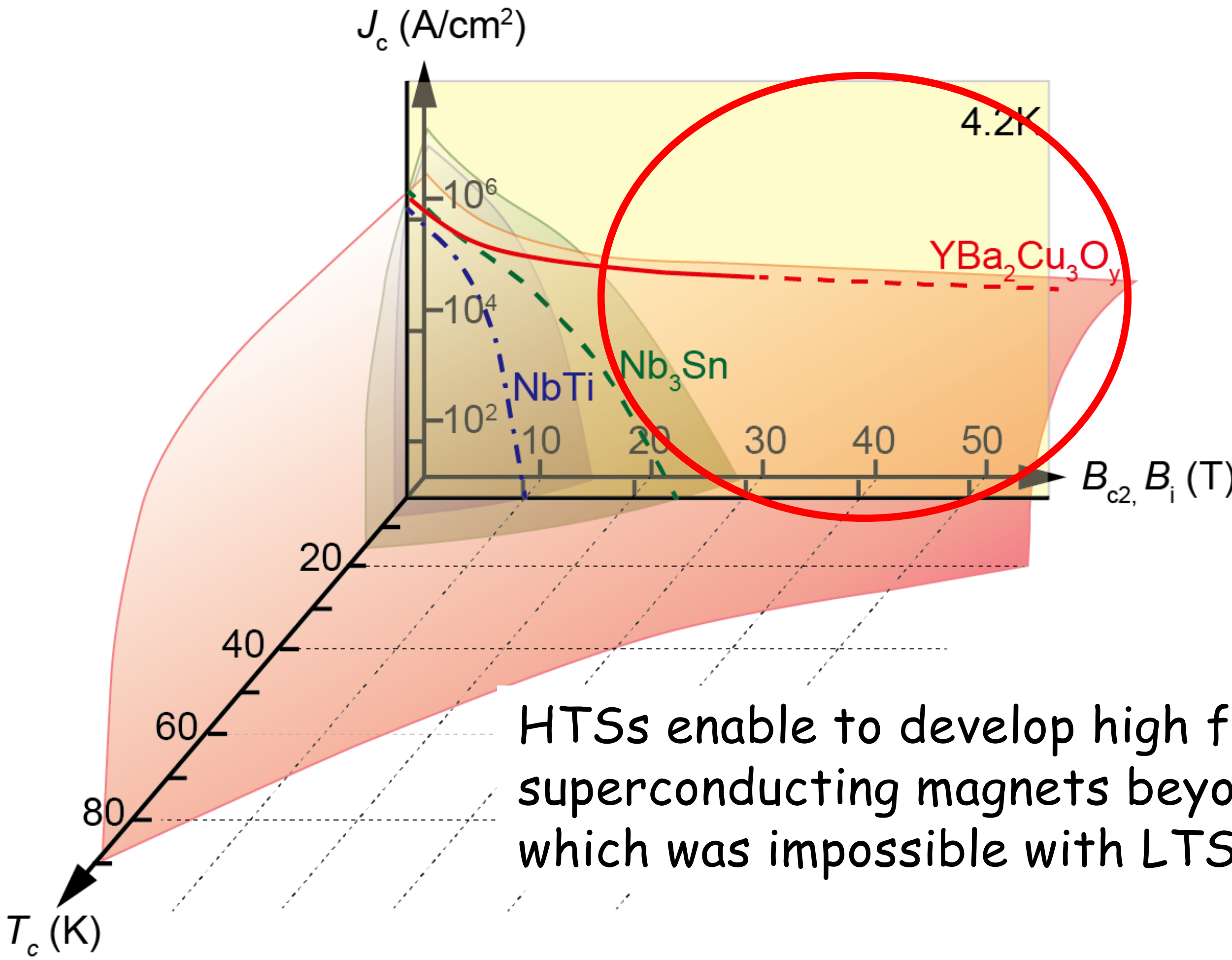
Research

Critical surface of practical SC

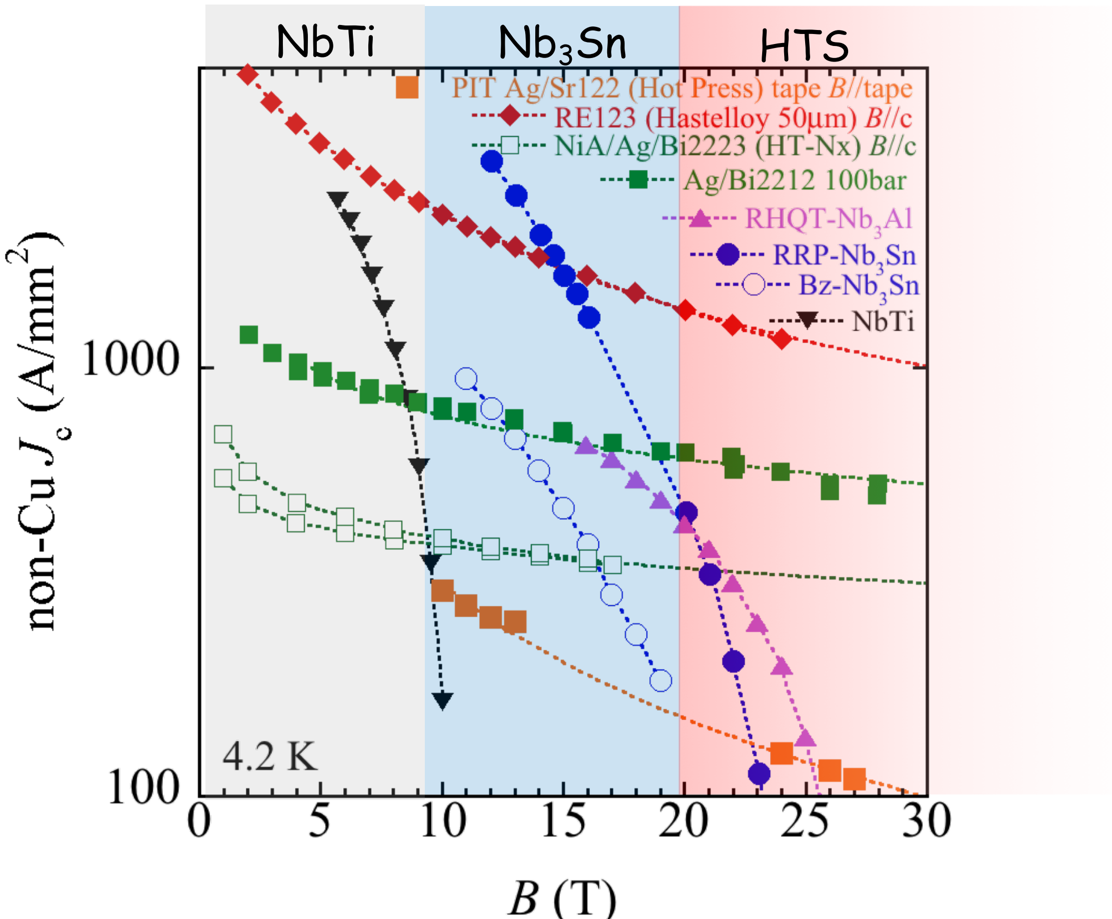


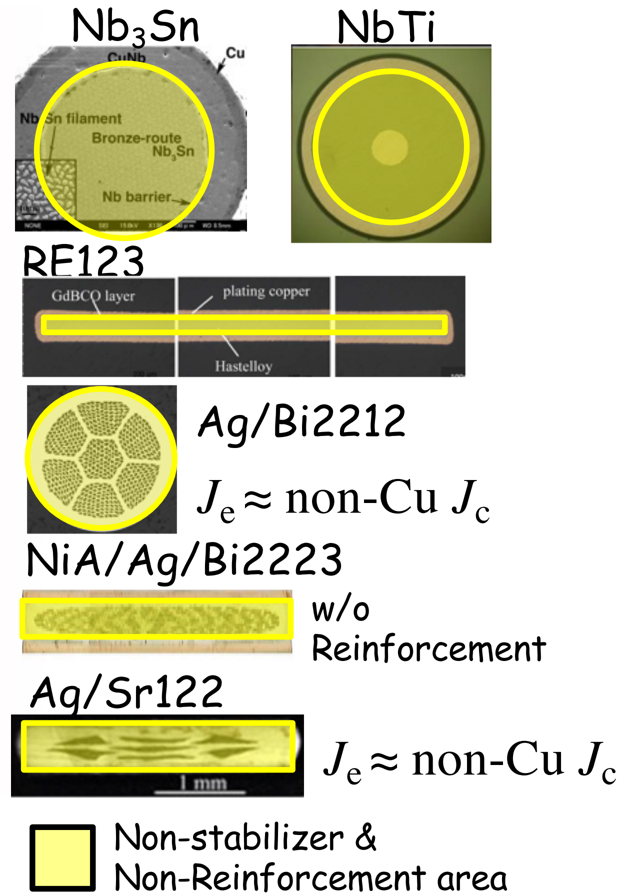
HTSs enable to develop high field superconducting magnets beyond 20 T, which was impossible with LTSs.

Key properties in High Field Superconductors

- Non-Cu J_c in high magnetic field
  - Introduction of flux pinning center to increase layer J_c
  - Increase volume fraction SC
- Stress/strain effect on J_c
  - Understand and control strain effects on J_c
  - Reinforcement with high strength materials.

Non-Cu J_c (non stabilizer J_c)

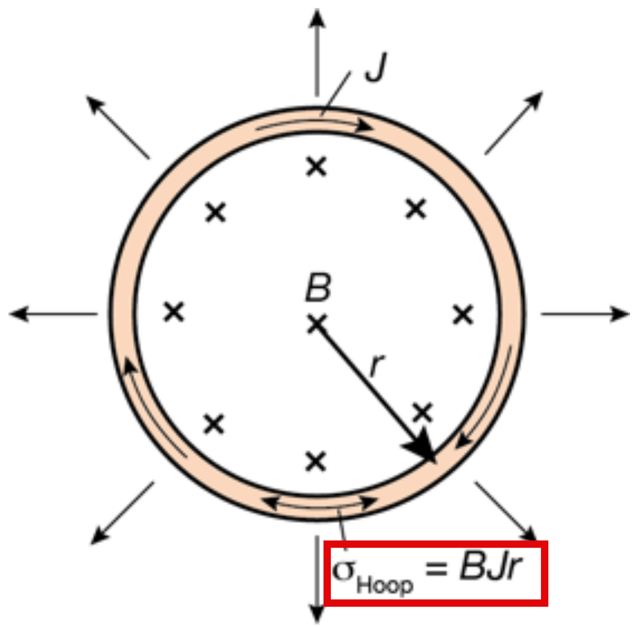




- J_c properties of HTSs are enough in high magnetic field beyond 30T.

Mechanical stress in the magnet

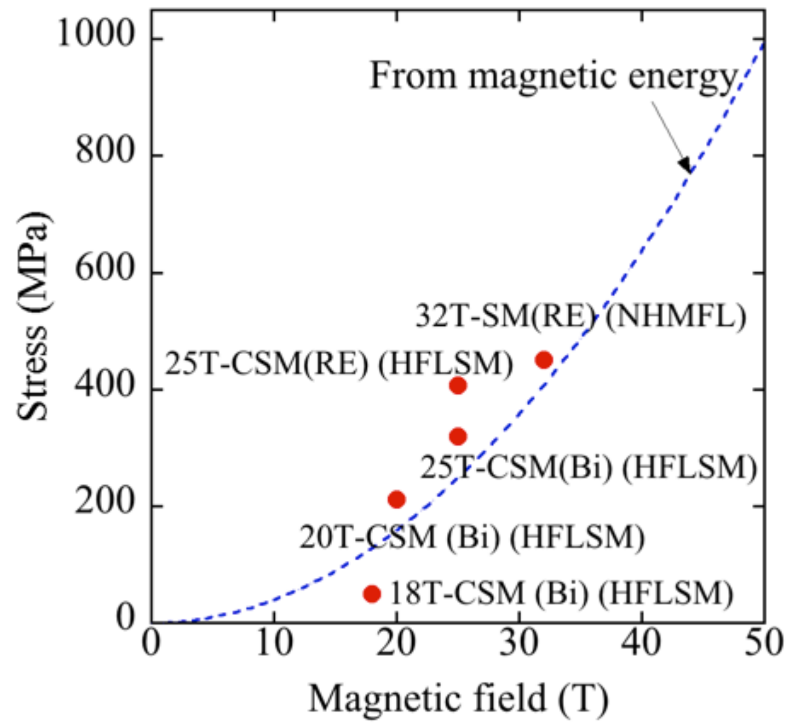
Hoop stress from electromagnetic forces



J. Ekin, Experimental Techniques for Low-Temperature Measurements, Oxford Univ. Press, 2006.

Equivalent stress from magnetic energy

$P_m = B^2/2\mu_0 = \sigma$



Electoromechnaical properties (stress/strain dependence of J_c) are important for high field magnets as well as in-field J_c.

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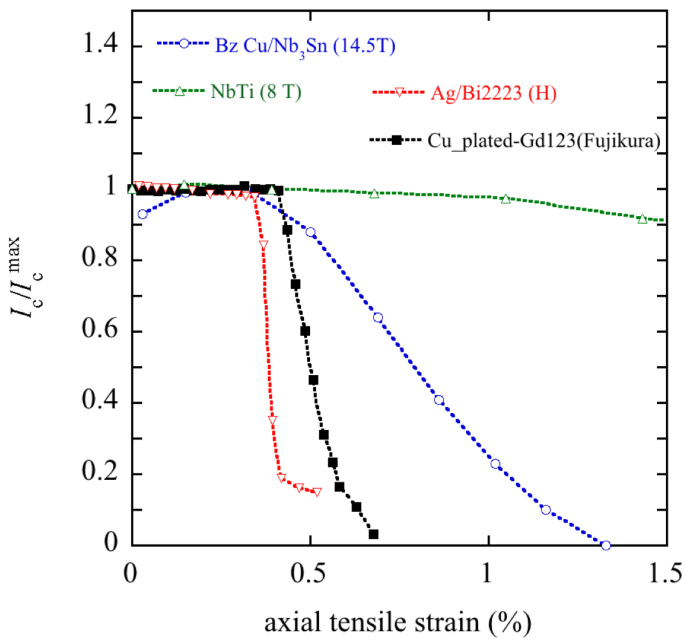
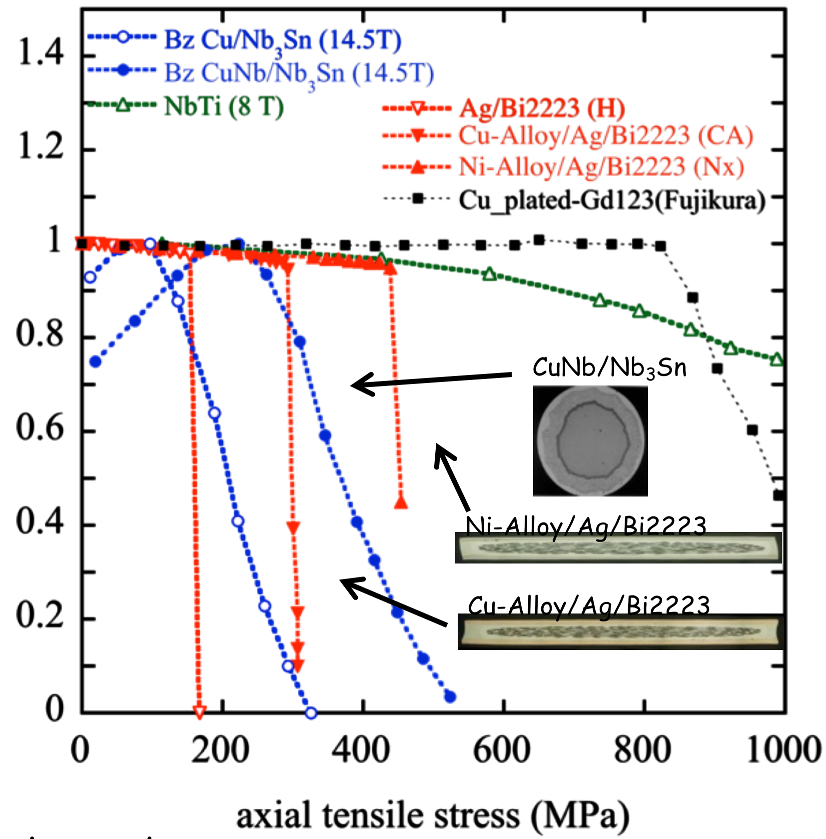
Importance of mechanical strength





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

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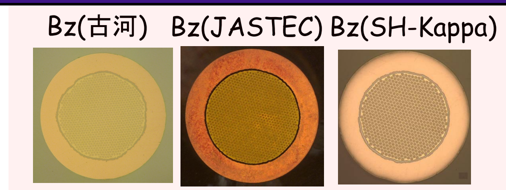
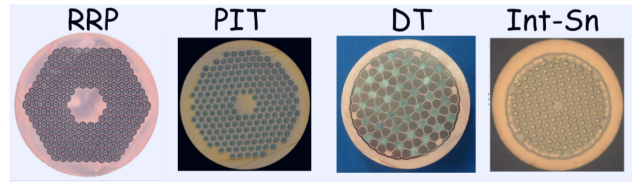
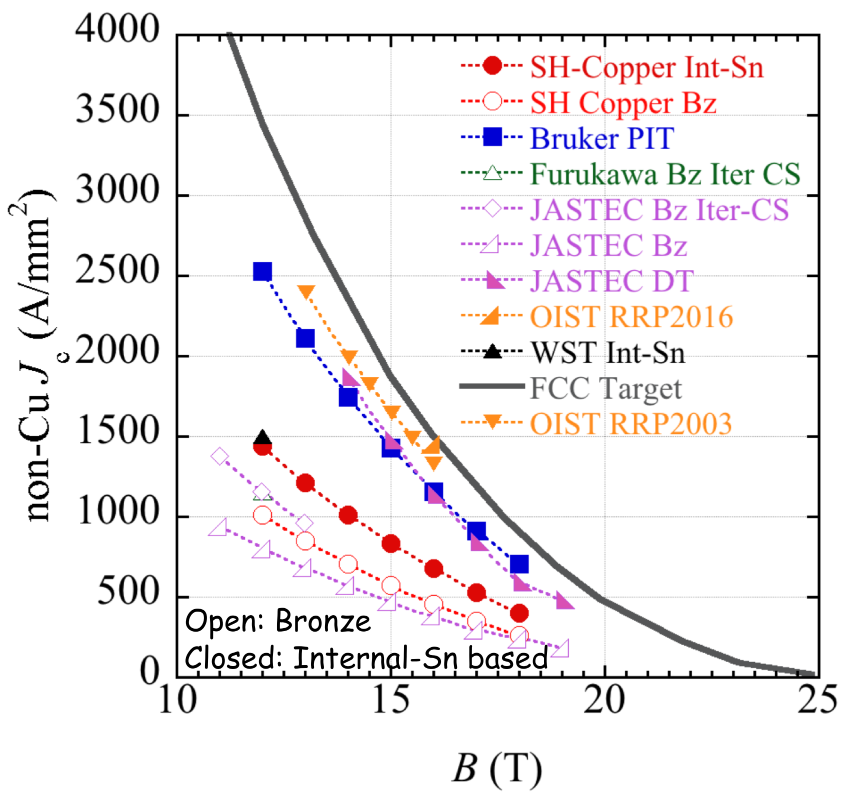
Practical Nb_3Sn wires







Bronze Nb_3Sn

- Thin filament > 3μm
  -> small ac-loss
  ->high stability
- Limitation of Sn content
  -> Lower non-Cu J_c
- Better mechanical property

Internal Sn/PIT Nb_3Sn

- Larger filament > 10μm
  ->larger ac-loss
  ->Magnetic instability
- Enough Sn->large non-Cu J_c

Flux pinning of Nb_3Sn - grain boundary -

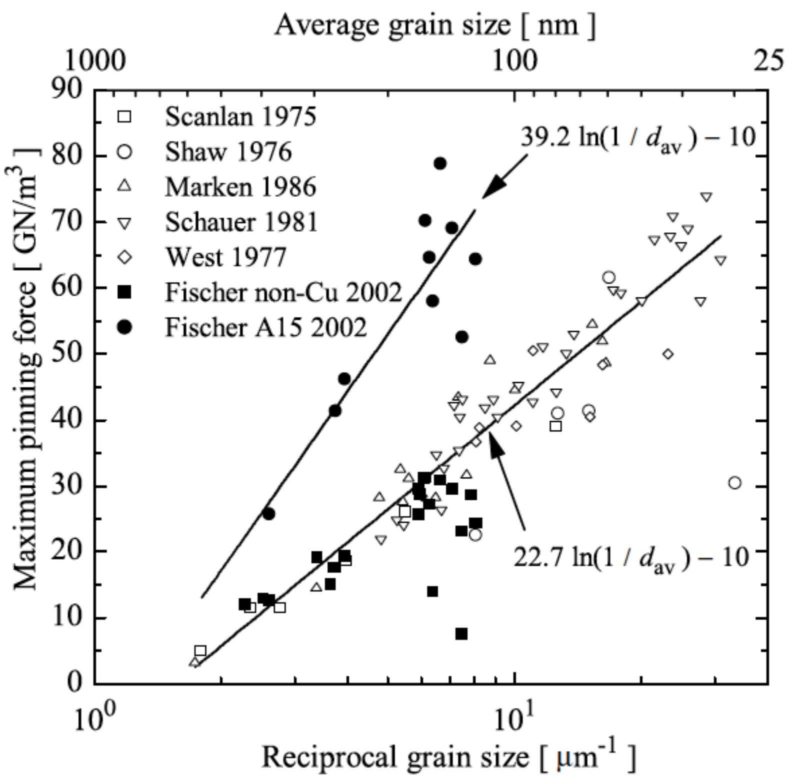
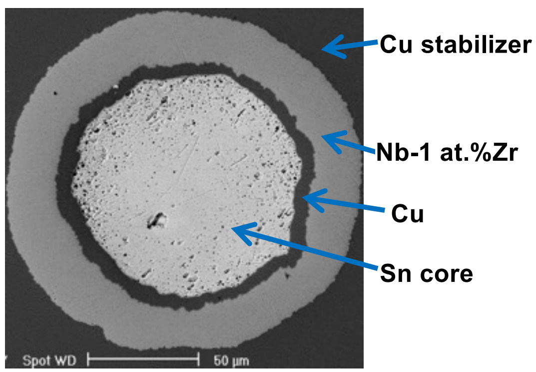


Figure 10. Maximum pinning force as function of reciprocal grain size, after Fischer [89]. (*Adapted with kind permission of C M Fischer*).

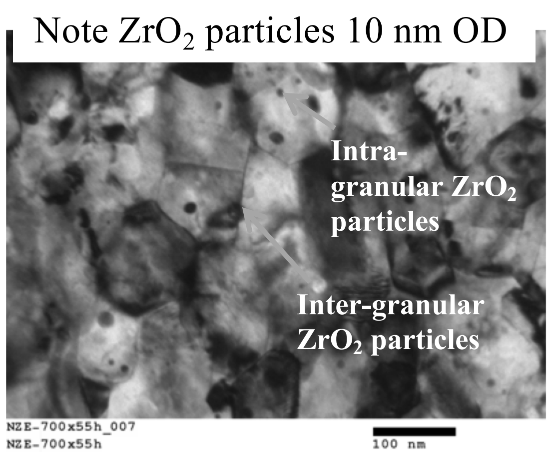
Godeke, SuST 19 (2006) R68

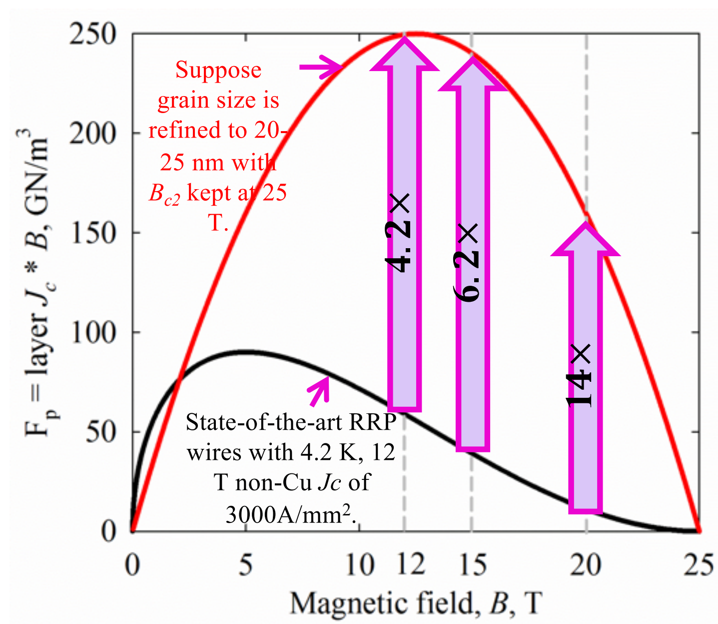
Dominant flux pinning center in Nb_3Sn wires is grain boundary!

Improve flux pinning in Nb_3Sn wires



X. Xu et al., Appl. Phys. lett. **104**, 082602



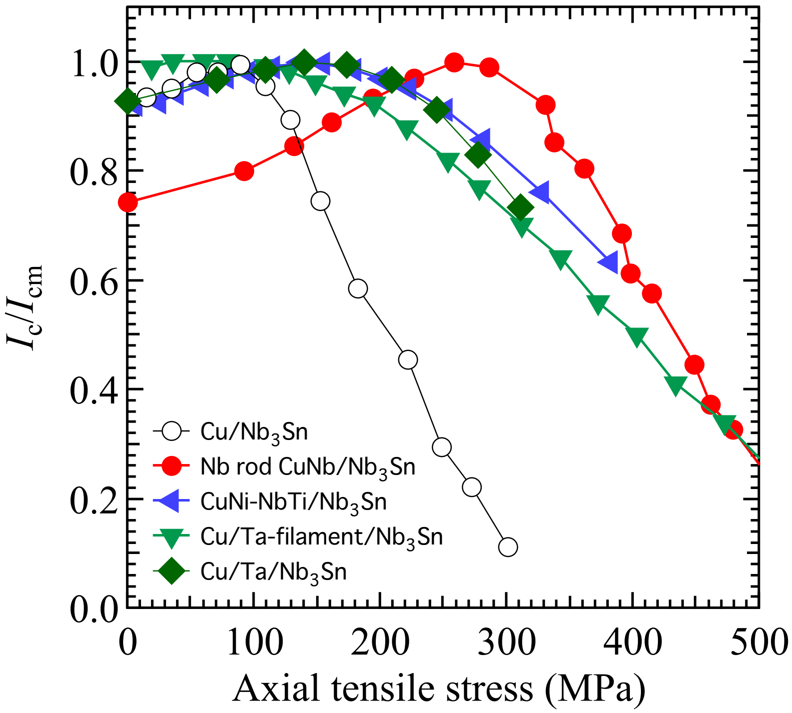


How do ZrO_2 particles refine Nb_3Sn grain size?

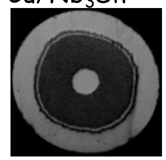
- **Impede Grains coarsening:** distinct gradients in grain size.
- **Be nucleation centers:** newly-formed grains in the internal oxidation samples are smaller.

M. Sumption, FCC week 2016 slides

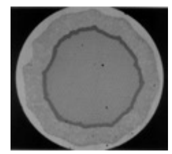
High strength Nb_3Sn



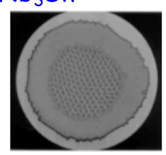
Cu/Nb_3Sn



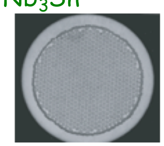
$CuNb/Nb_3Sn$



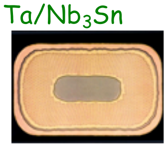
$CuNi$-$NbTi/Nb_3Sn$

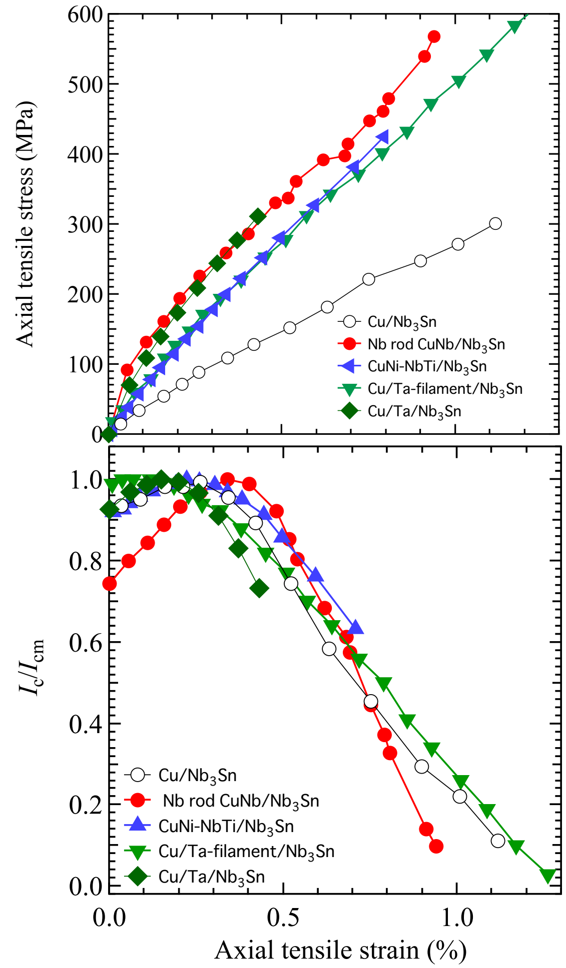


Ta-filament/ Nb_3Sn



Ta/Nb_3Sn



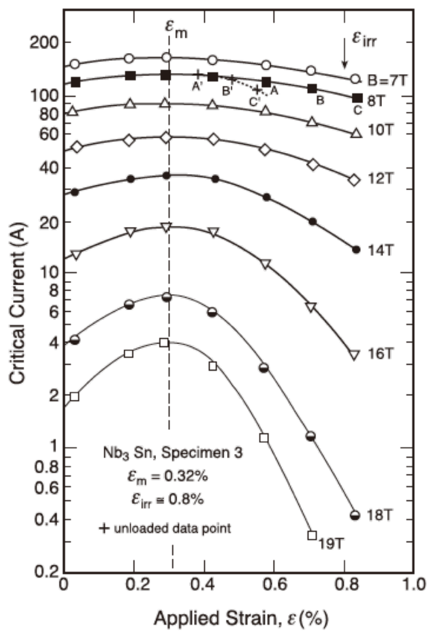


- From application view point,
  Stress is important.
- From material view point,
  Strain controls property.
- Steep SS curve reduces strain

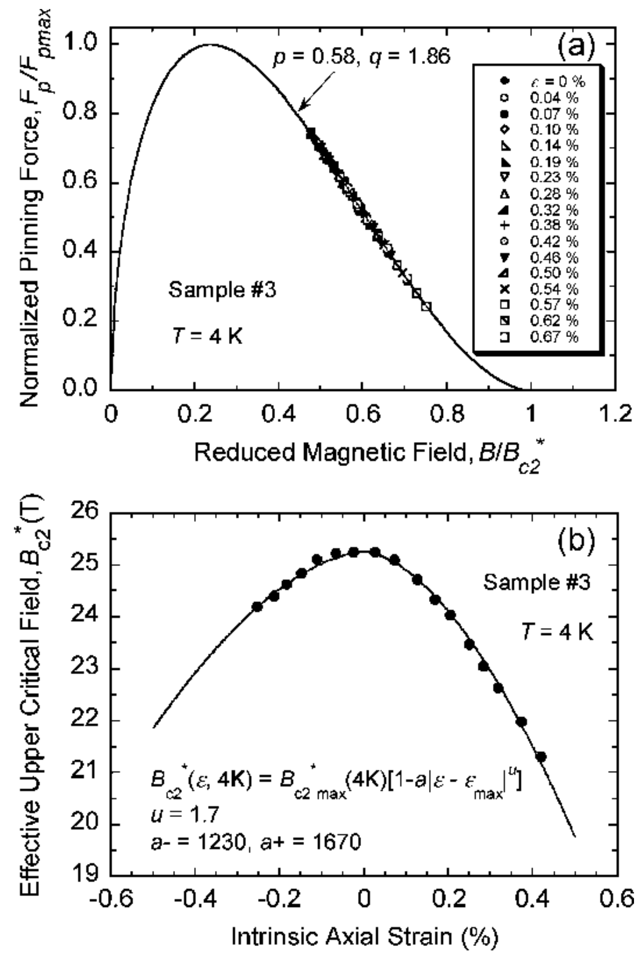
Strain dependence of Nb_3Sn

- Thermal strain due to the composite
- J_c peak at thermal strain
- Scaling of $J_c\,(\varepsilon)$ curves by $B_{c2}(\varepsilon)$

$$\frac{J_c}{J_{cm}} = \left[\frac{B^*_{c2}(\varepsilon)}{B^*_{c2m}}\right]^{n-q}\left[\frac{1-B/B^*_{c2}(\varepsilon)}{1-B/B^*_{c2m}}\right]^{q}$$



J. Ekin SuST 23 (2010) 083001.



N. Cheggor, DOI:10.1109/tasc.2007.897819

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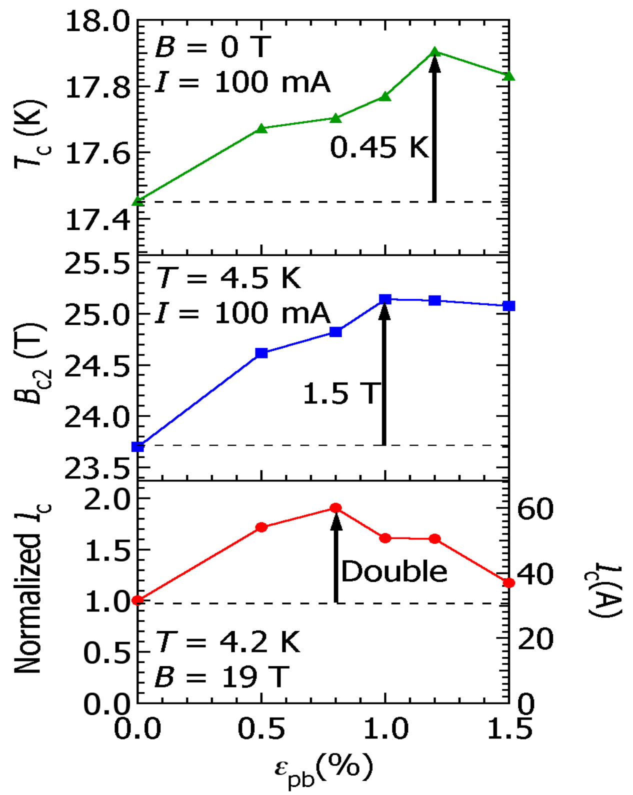
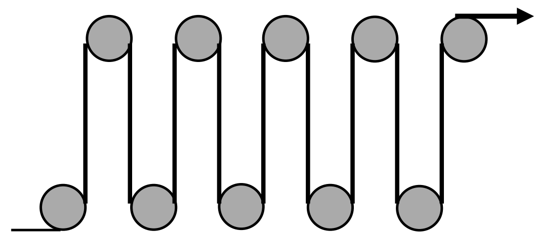
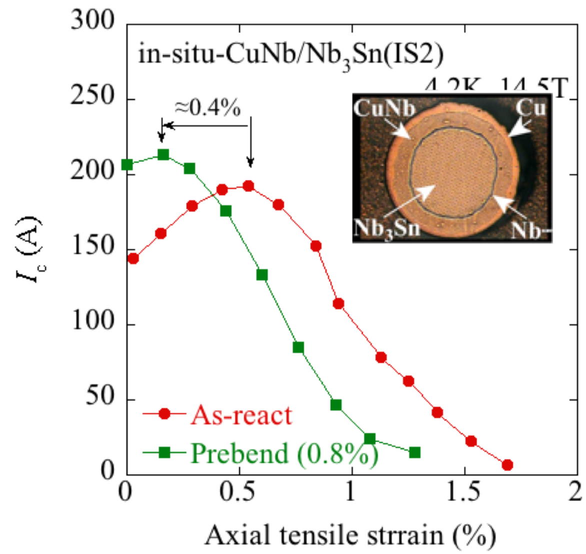
Effect of internal strains
—pre-bending treatment—







Prebending (repeated bending) improves all superconducting parameters because of a change of residual strain state.

Angular dependence of internal strain (CuNb/Nb_3Sn)

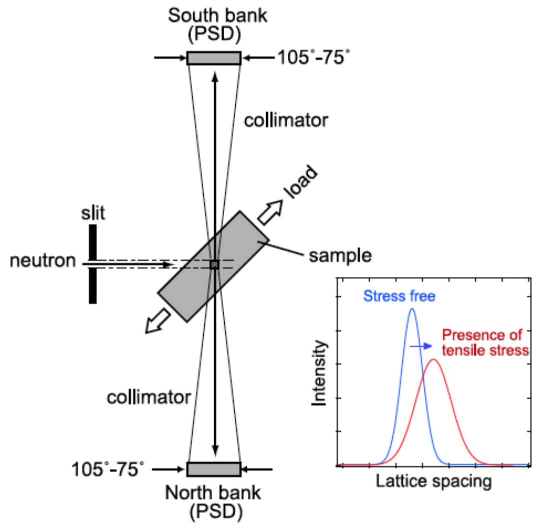


Figure 5. Experimental setup for the TOF diffraction at TAKUMI [6].

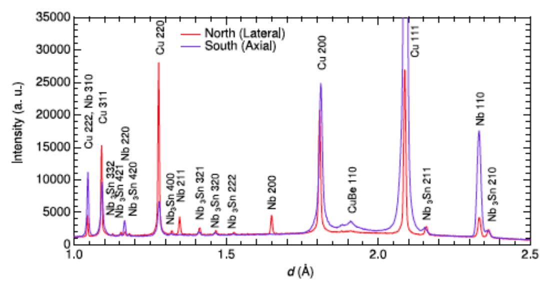
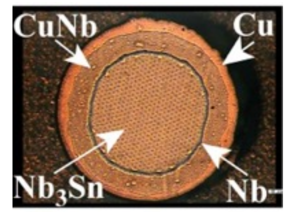
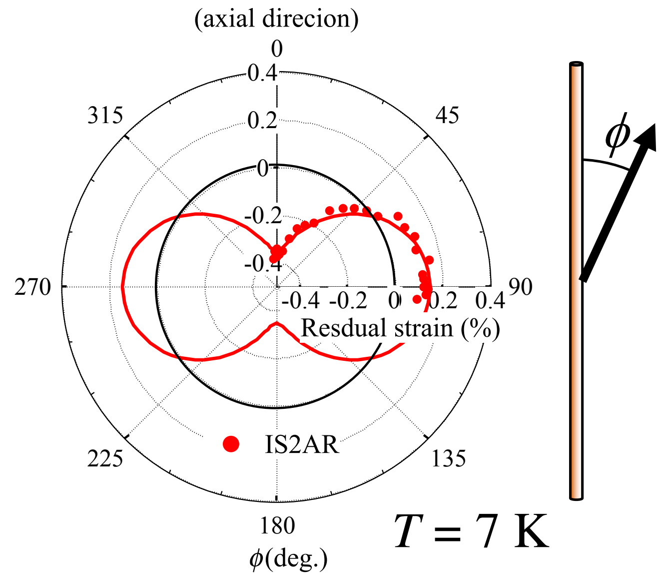


Figure 6. Typical diffraction pattern of Cu20%Nb/(Nb, Ti)$_3$Sn wires measured by the TOF method at TAKUMI.



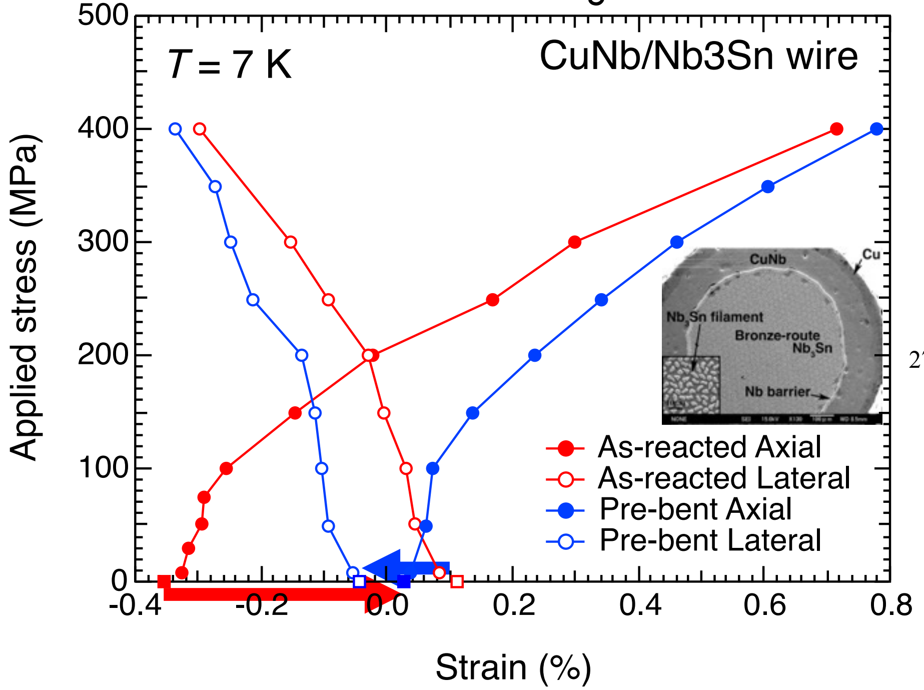


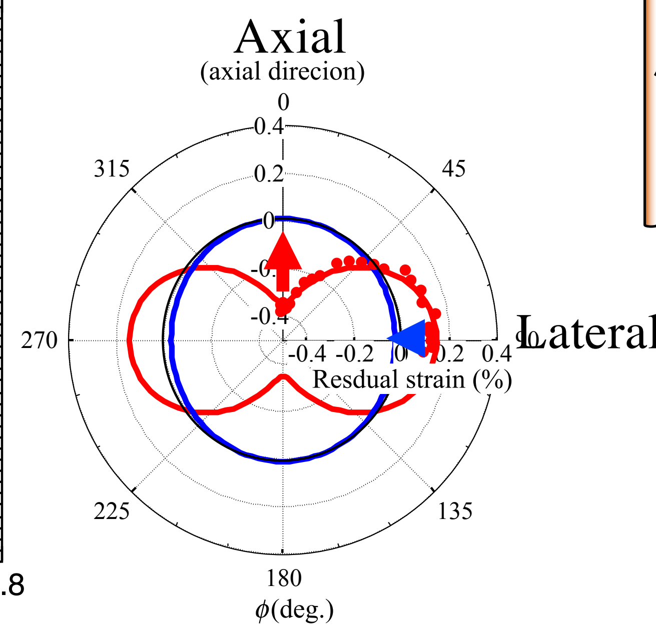
$$\varepsilon(\theta) = \sqrt{(1+\varepsilon_z)^2 \sin^2\theta + (1+\varepsilon_r)^2 \cos^2\theta} - 1$$

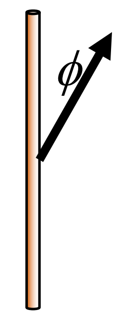
S. Awaji et al, SuST 23 (2010) 105010, SuST 26 (2013)073001.

Effect of prebending

CuNb/Nb_3Sn wire







- ✓ Improve J_c and mechanical property by pre-bending process due to the plastic deformation and work hardening of CuNb.
- ✓ Improve J_c^{max} due to the change of 3D strain

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Advanced technology of Nb_3Sn conductor for 25T-CSM

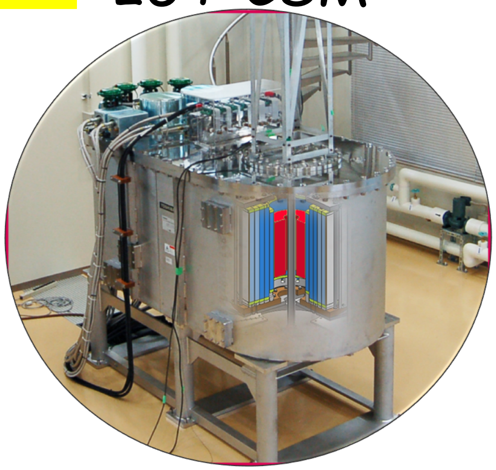
High strength (CuNb/Nb_3Sn)

Oguro et al., SuST. 26 (2013) 094002.

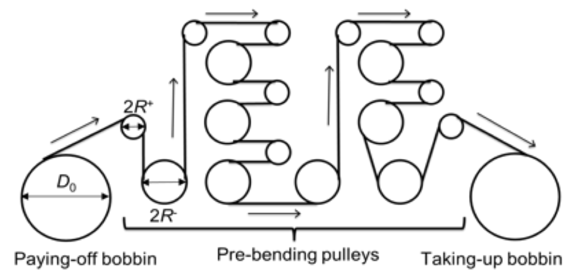
Rutherford cable

Sugimoto et al., IEEE TAS., 25 (2015) 6000605.

25T-CSM



Pre-bending (0.5%)



React & Wind (Strain management)

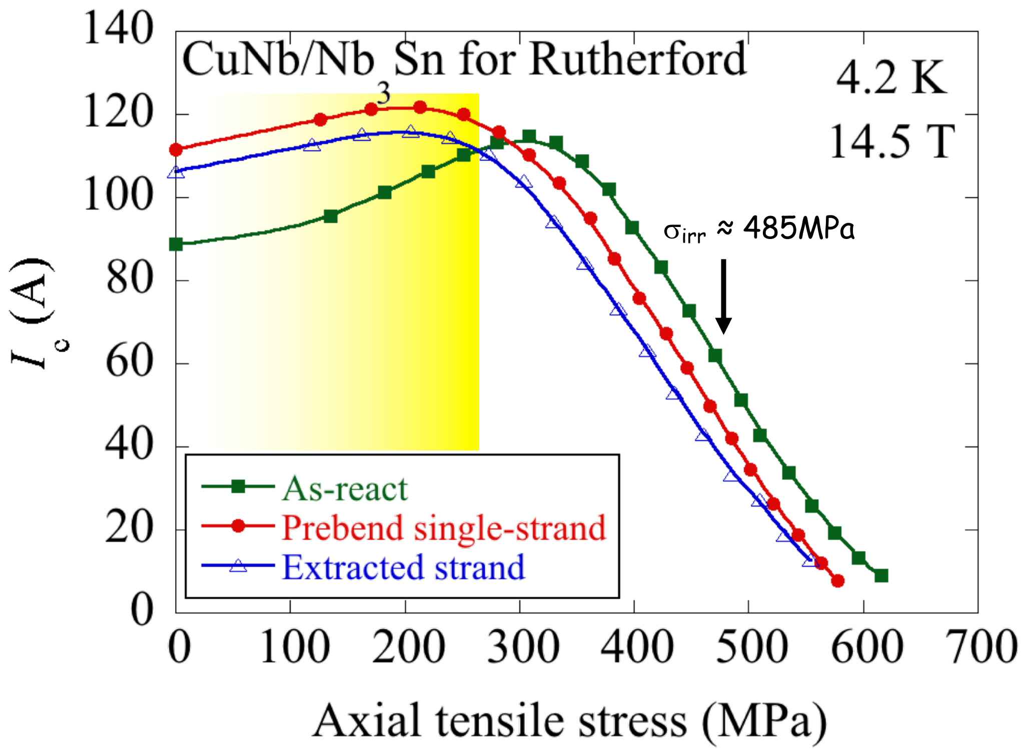
Oguro et al., SuST. 29 (2016) 084004.

LTS:ϕ300mm-14T@854A

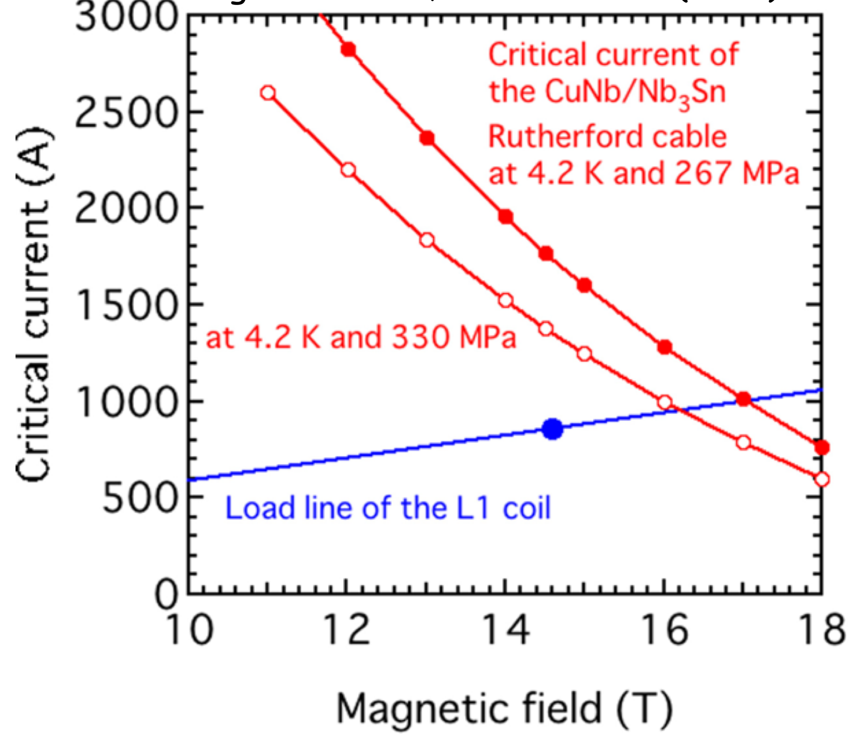
Coil	L1	L2	L3
Inner Dia. (mm)	150	185.9	229.2
Height (mm)	540	628	628
I_{po}(A)		854	
B_{max} (T)	13.8 (14.6)*	11.3	8.37
T_{cs} (K)	6.76	8.39	9.95
Trans. stress (MPa)	-38	-49	-48
Hoop stress (MPa)	251 (267)*	243	200

*( ) w/o energizing the HTS insert

CuNb/Nb_3Sn Rutherford Cable for 25T-CSM

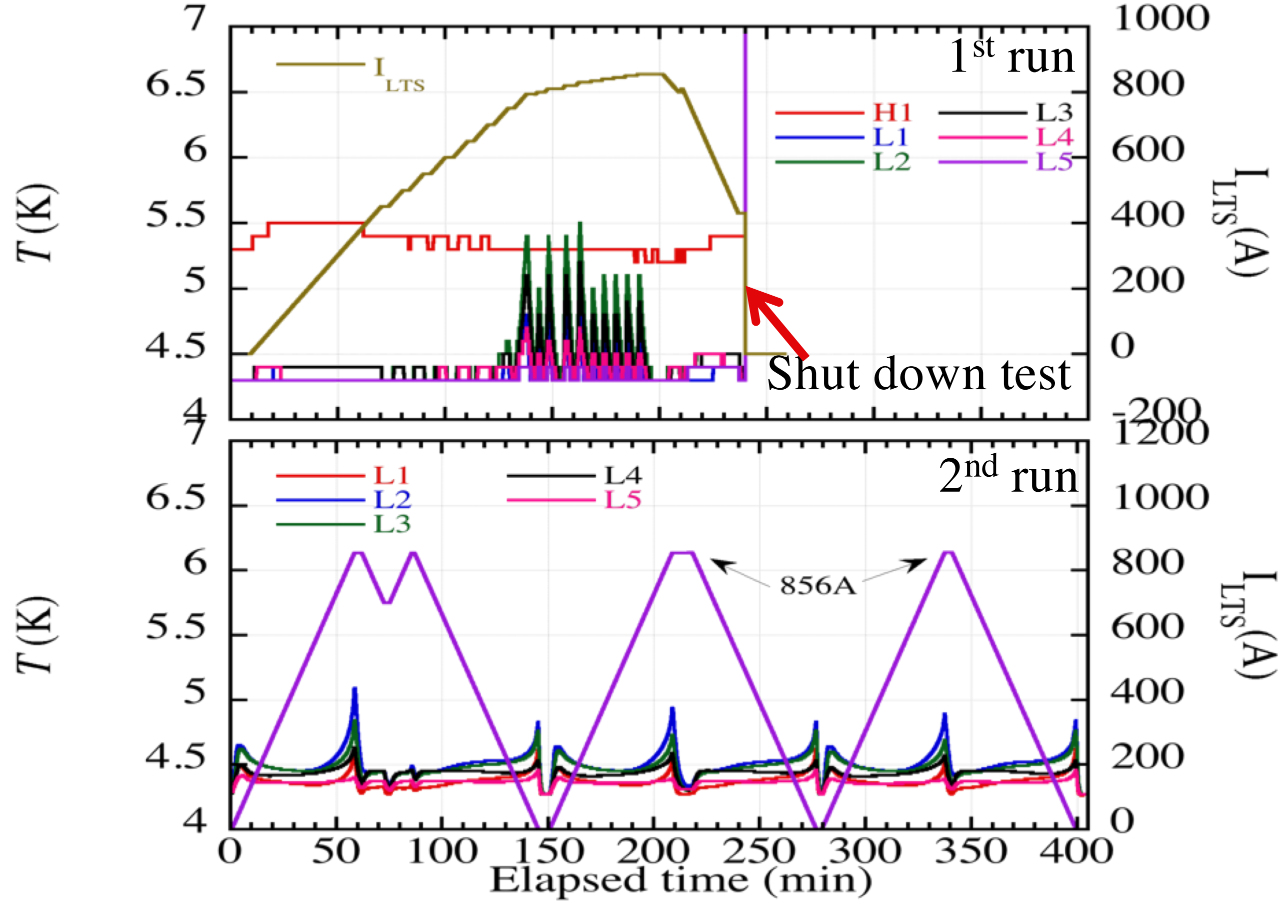


Sugimoto et al., IEEE TAS 25 (2015) 6000605



- ✓ The Nb_3Sn Rutherford cable optimized by reinforcement and strain control (prebending) is operated in high stress state below 251 MPa (267 MPa in stand-alone operation).

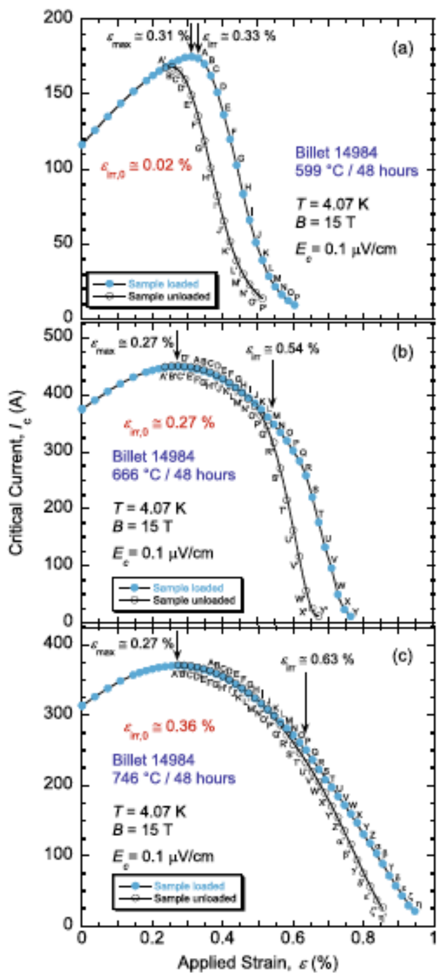
LTS coil for 25T-CSM



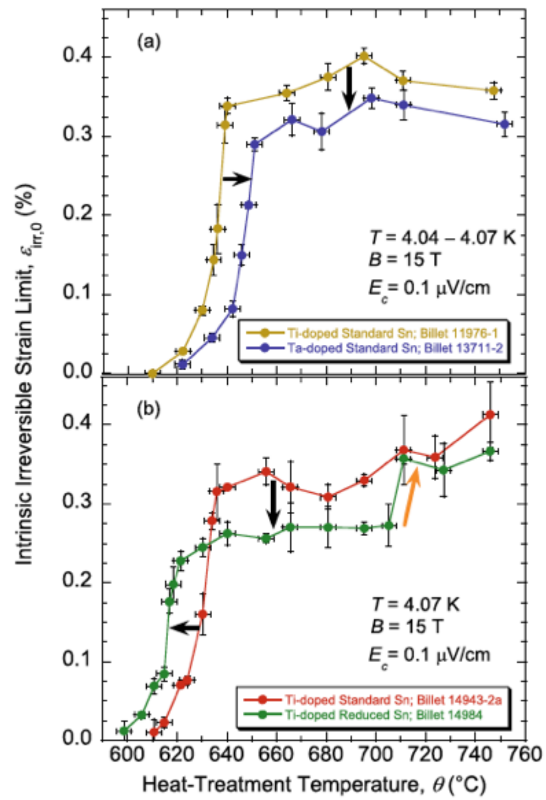
No training quench!

Oguro et al, SuST 29 (2016) 084004

Irreversible strain Cliff in RRP Nb_3Sn wires



N. Chegour et al, Sci. Rep. 9 (2019)9466.



Strain limit (irreversible strain) strongly depends on the HT temperature.

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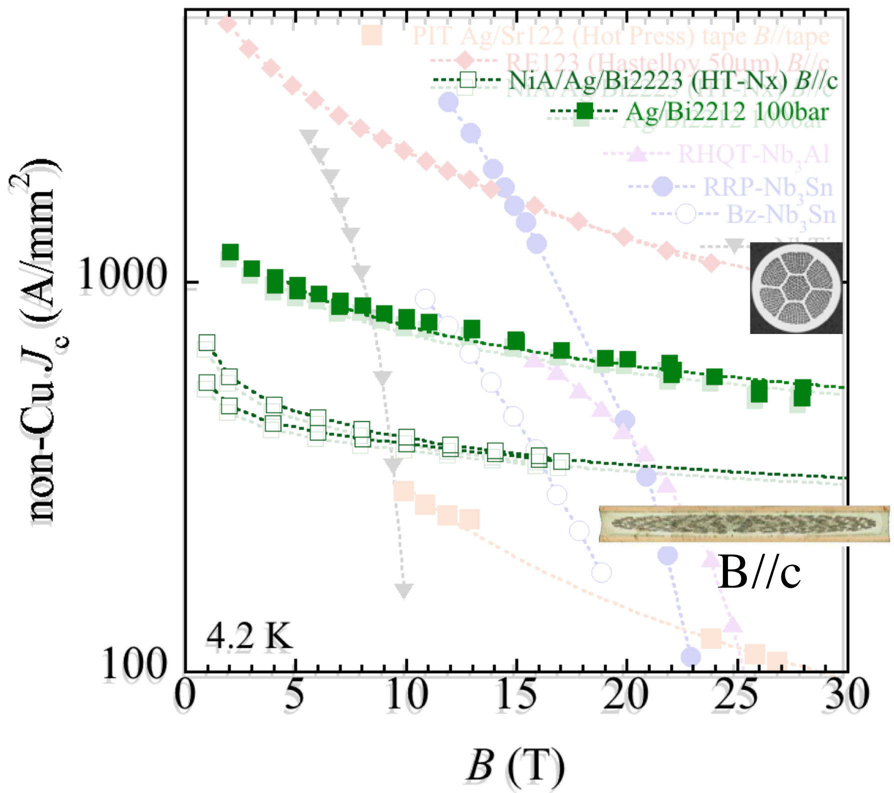
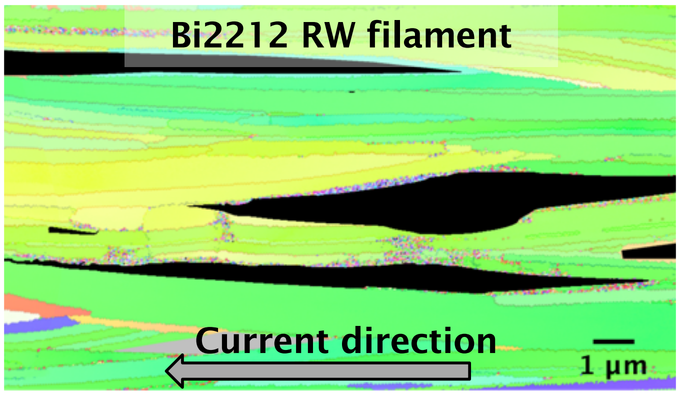
Bi-Sr-Ca-Cu-O

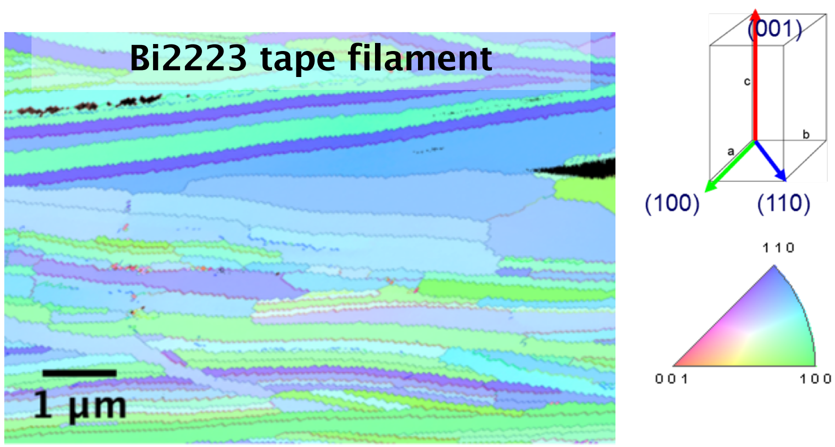
HFLSM Sendai

Research

BSCCO







- Both of Bi2212 and Bi2223 have strong c-acis orientation.
- In-plain alighment can be seen only in Bi2212.

Kametani et al., SR 5 (2015) 8285.

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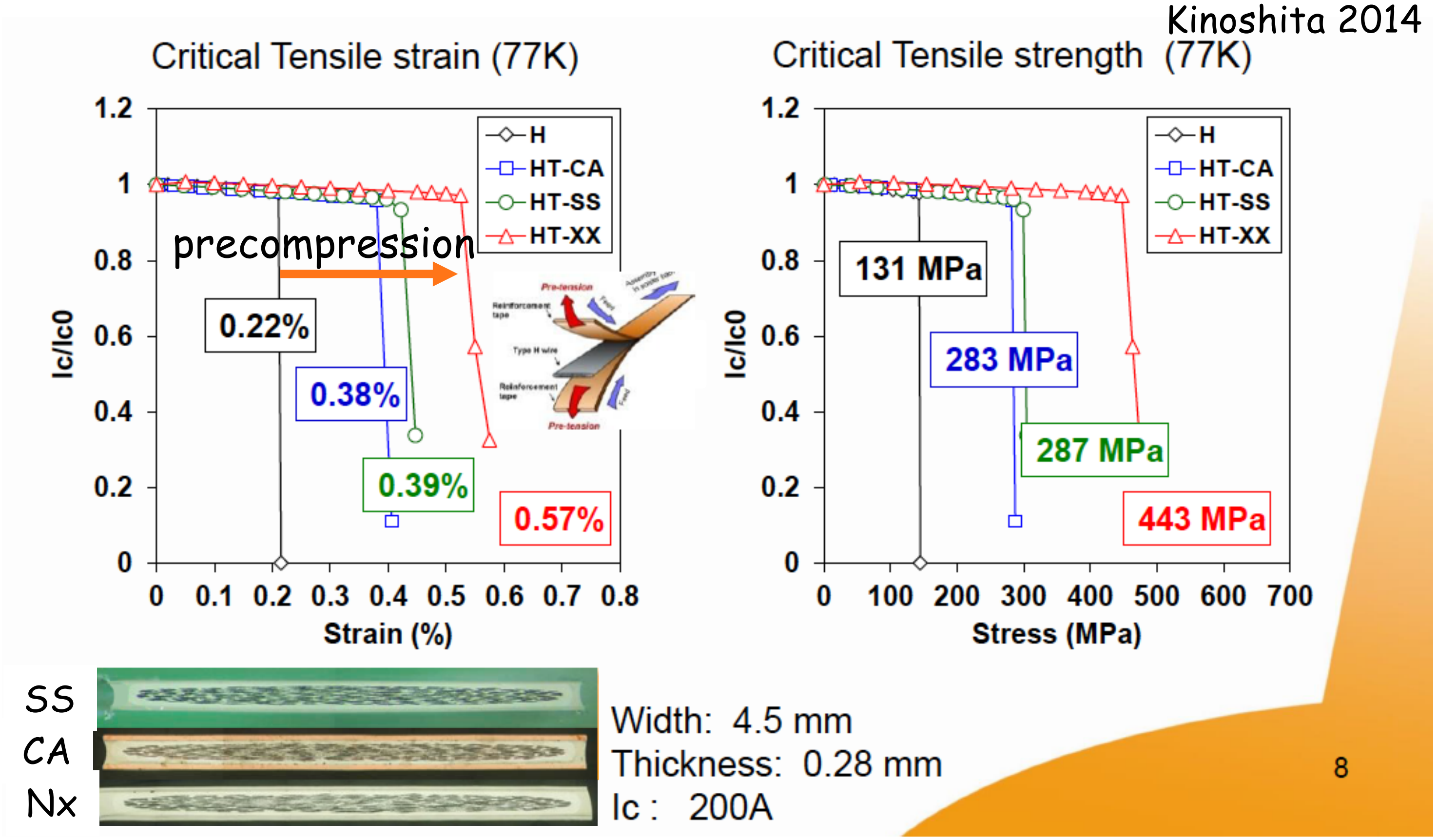
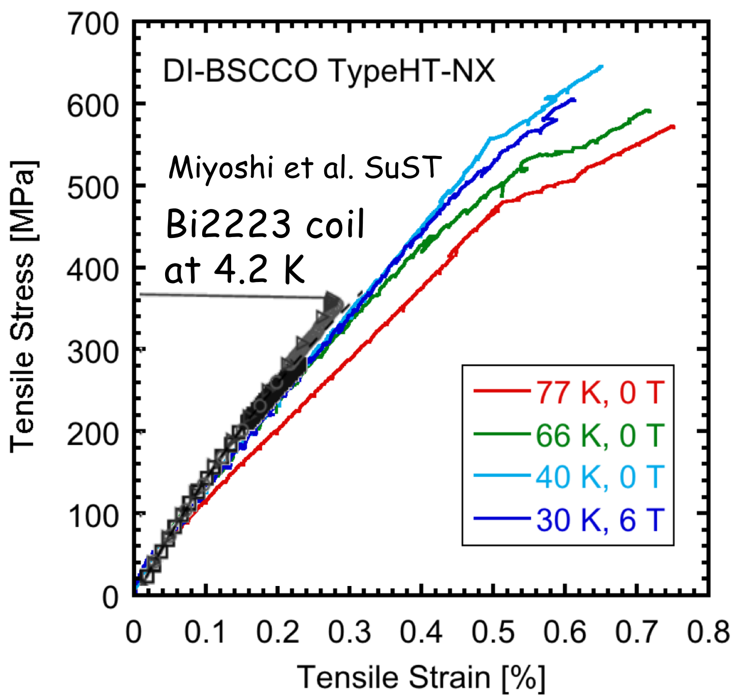
High strength Bi2223 tapes by SEI

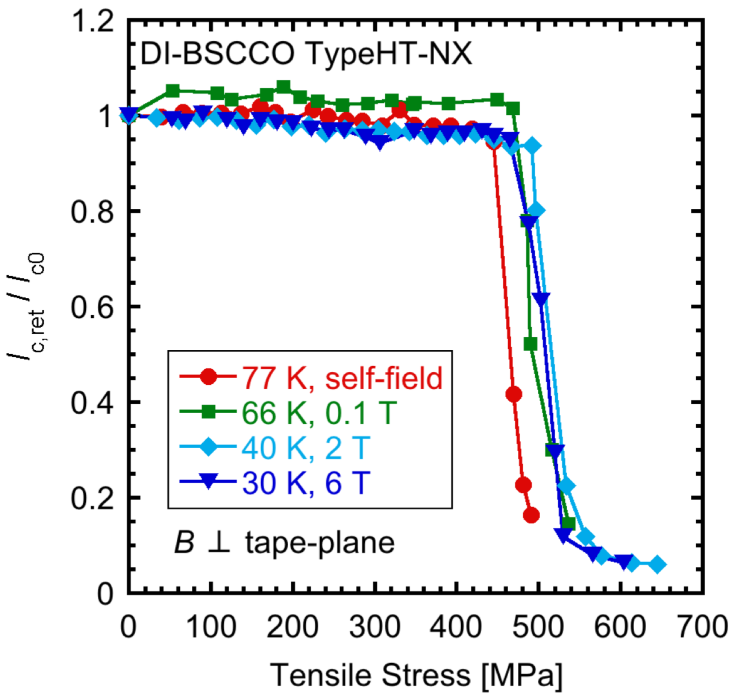
Kinoshita 2014



- High strength due to the pre-strain (<0.35%) and reinforcement.
- Improvement of strength is expected with thicker reinforcement.

Mechanical Properties at low temps.





- Stress-strain curves become slightly steeper with temperature decreasing and close to the result of coil at 4K.
- Stress limit more than 400 MPa is not so different with temperature.

Magnet applications with Bi2223

Bi2223 (HT-Nx)

24.6T- 52mm(HFLSM)

$\sigma_{max} \approx 323$ MPa

Open for users since 2016
250 days/year operation

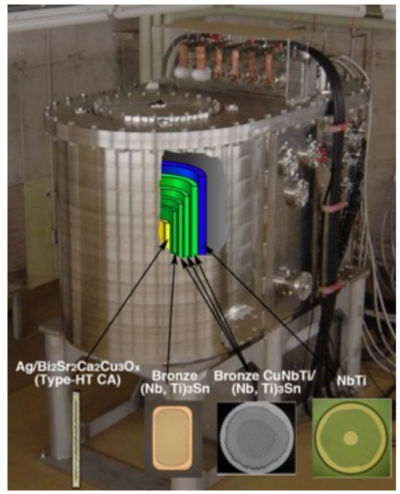
Bi2223 (HT-CA)

24.2T-53mm (NIMS)
1.02GHz-NMR

$\sigma_{max} \approx 198$ MPa

NMR with 1.02 GHz

20.1T- 52mm(HFLSM)



$\sigma_{max} \approx 118$ MPa

Open for users since 2013
>250 days/year operation

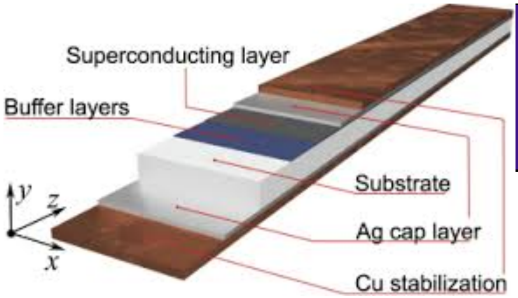
TOHOKU UNIVERSITY

$REBa_2Cu_3O_y$

HFLSM Sendai

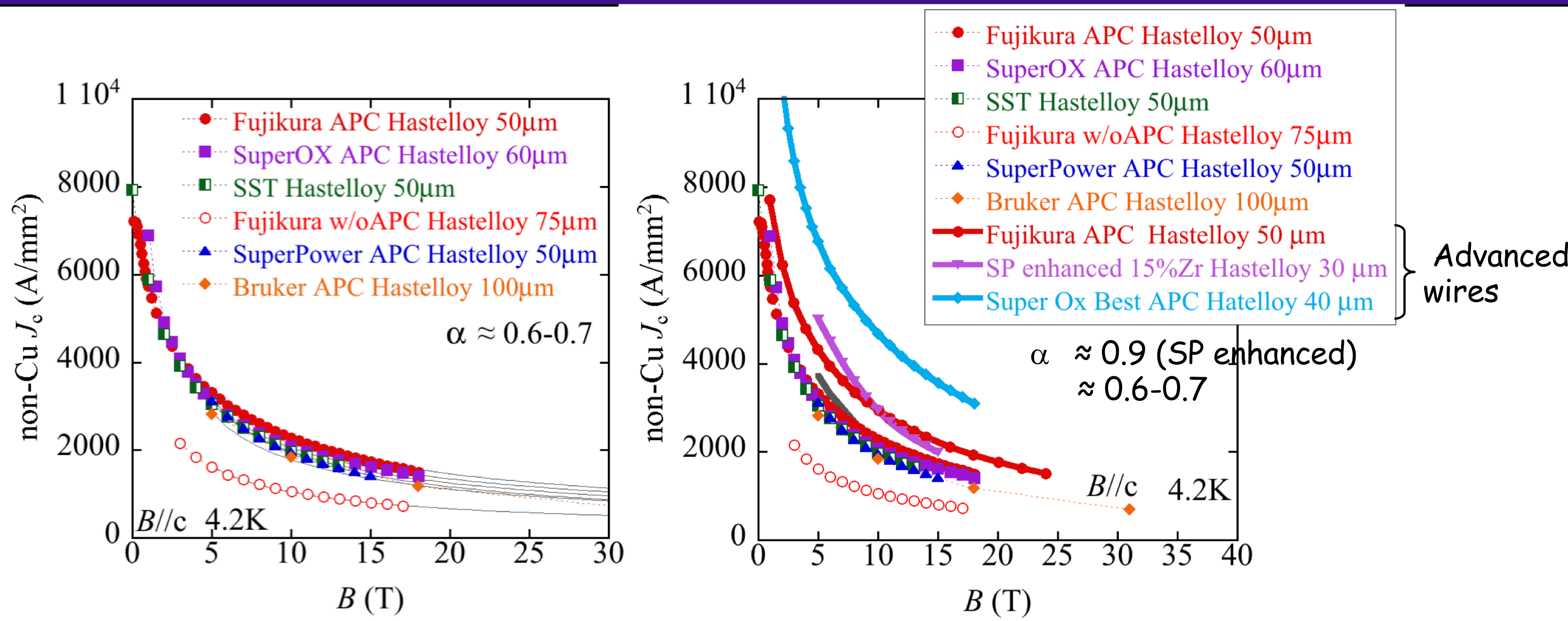
Research

Commercial REBCO tapes



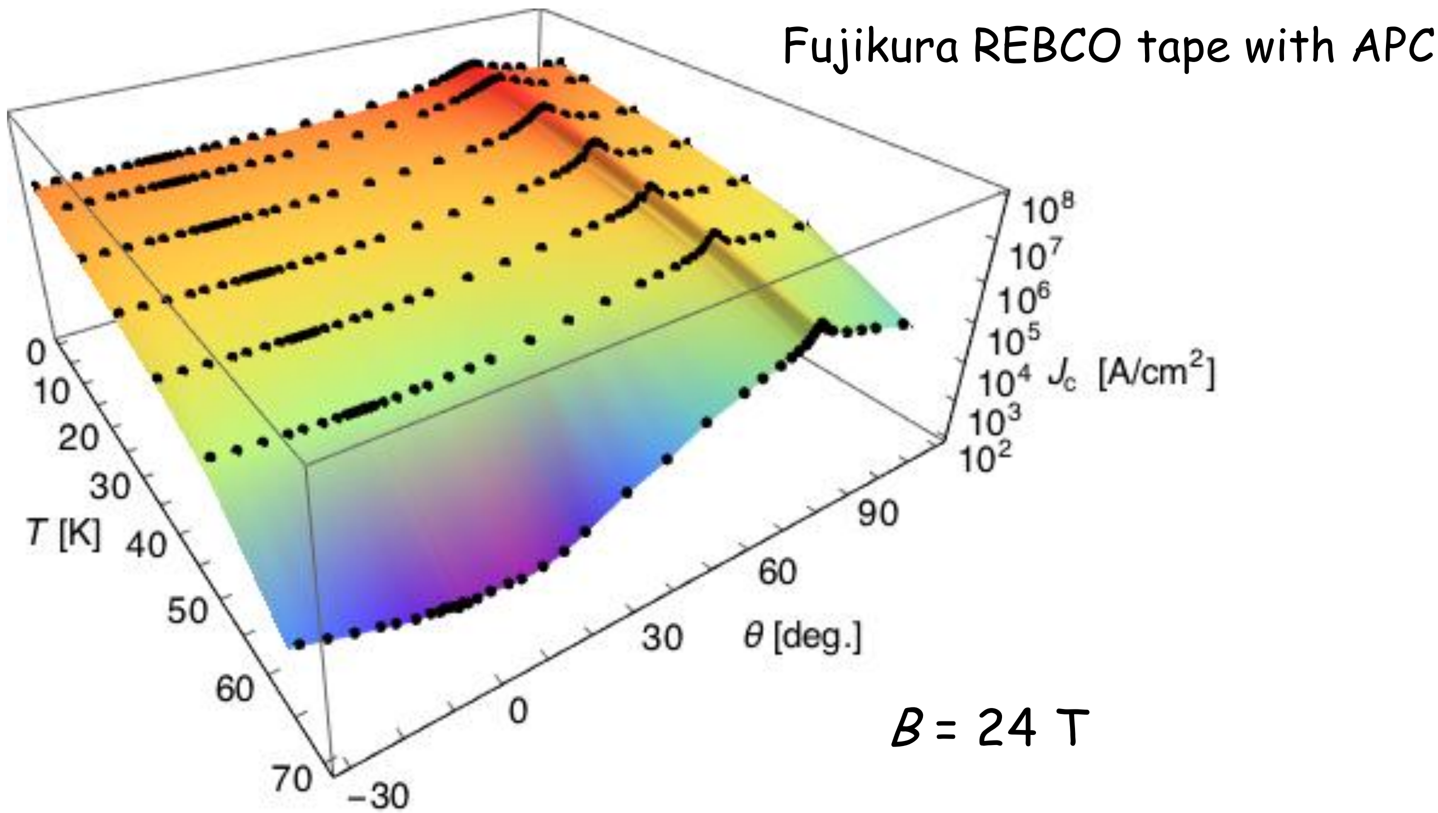
	RE	Method	t_SC (um)	APC	Template	Sub	t_sub (um)	Stabilizer	t_stab (um)
Fujikura	Gd	PLD	≈2	-	IBAD-MgO	Hastelloy	75	Cu plated	10-40 x 2
	Eu		≈2.5	Hf			50		
SuperPower	Y,Gd	CVD	≈1.5	Zr	IBAD-MgO	Hastelloy	(30), 50	Cu plated	20,40 x 2
SuNAM	Gd	RCE	1.3-1.8	-	IBAD-MgO	Hastelloy /SS	60	Cu plated	5-10 x 2
SuperOx	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_2O_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		-	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 venders 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.

Typical angular dependence of J_c for REBCO tapes



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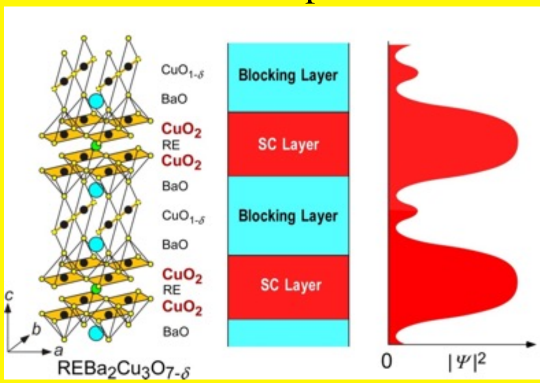
Flux pinning centers in REBCO

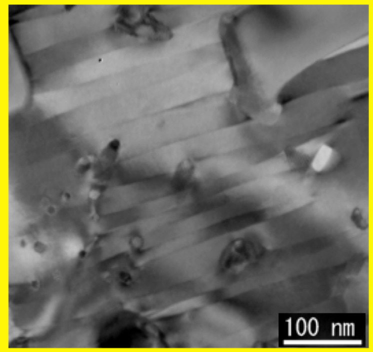
Natural pinning centers

Intrinsic pin

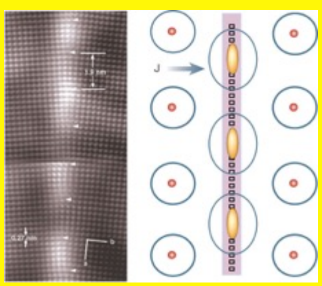


Courtesy of Prof. Shimoyama

Twin boundaries



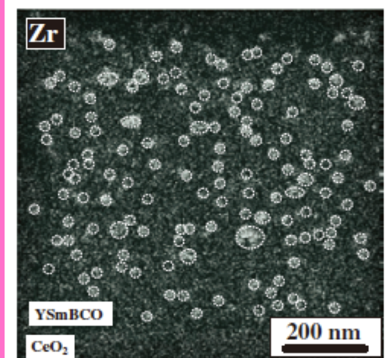
Edge dislocations at GB



D. Larbalestier, Nature 414(2001)368

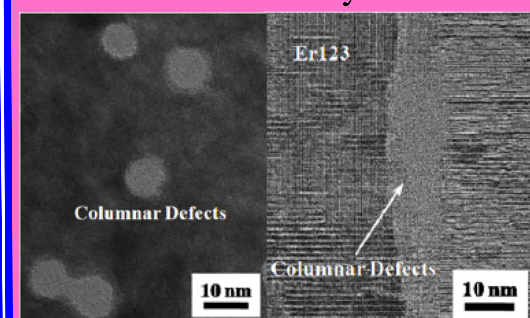
Artifical pinning centers

Nano particles

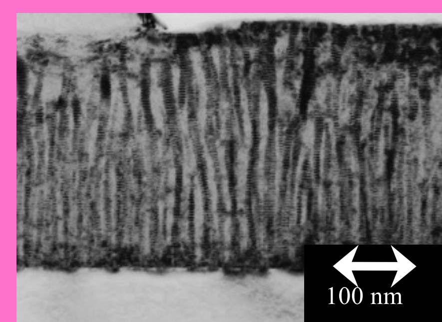


Miura et al., APEX 2009

Columnar defects by irradiation

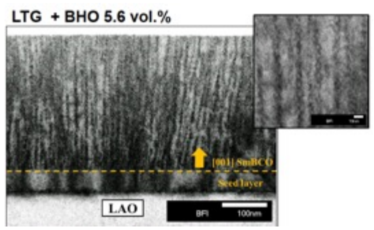


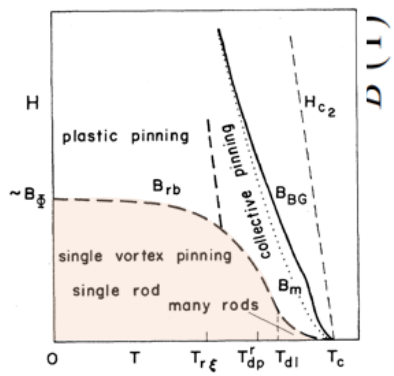
Nano rods



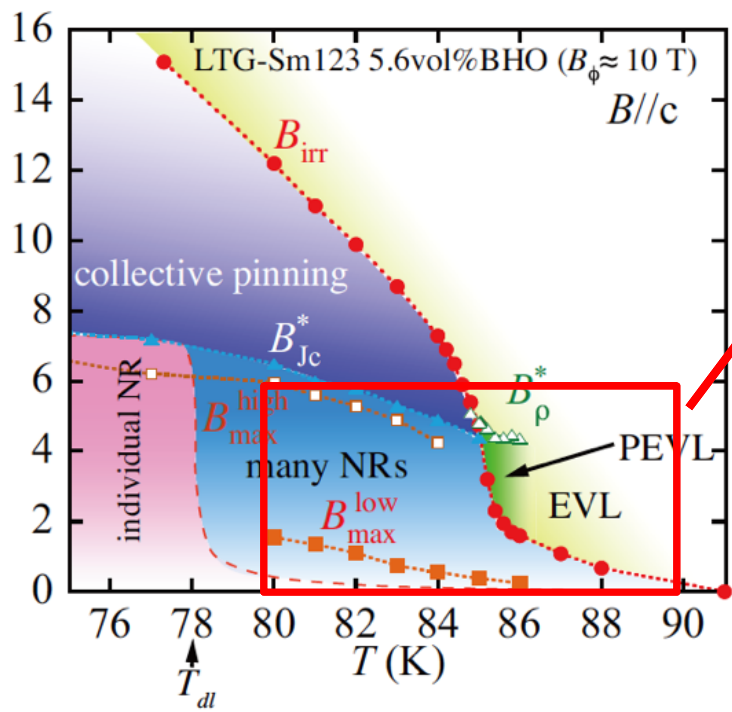
Flux pinning phase diagram (High Temperature)

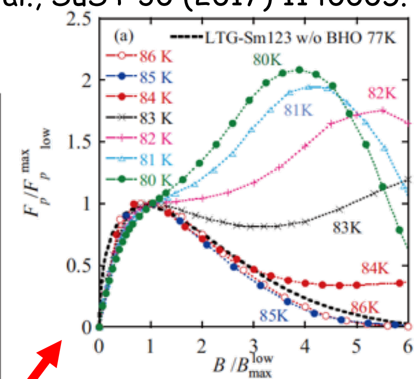
Awaji et al., SuST 30 (2017) 1140005.

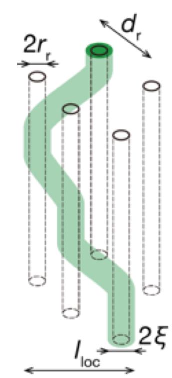




G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).



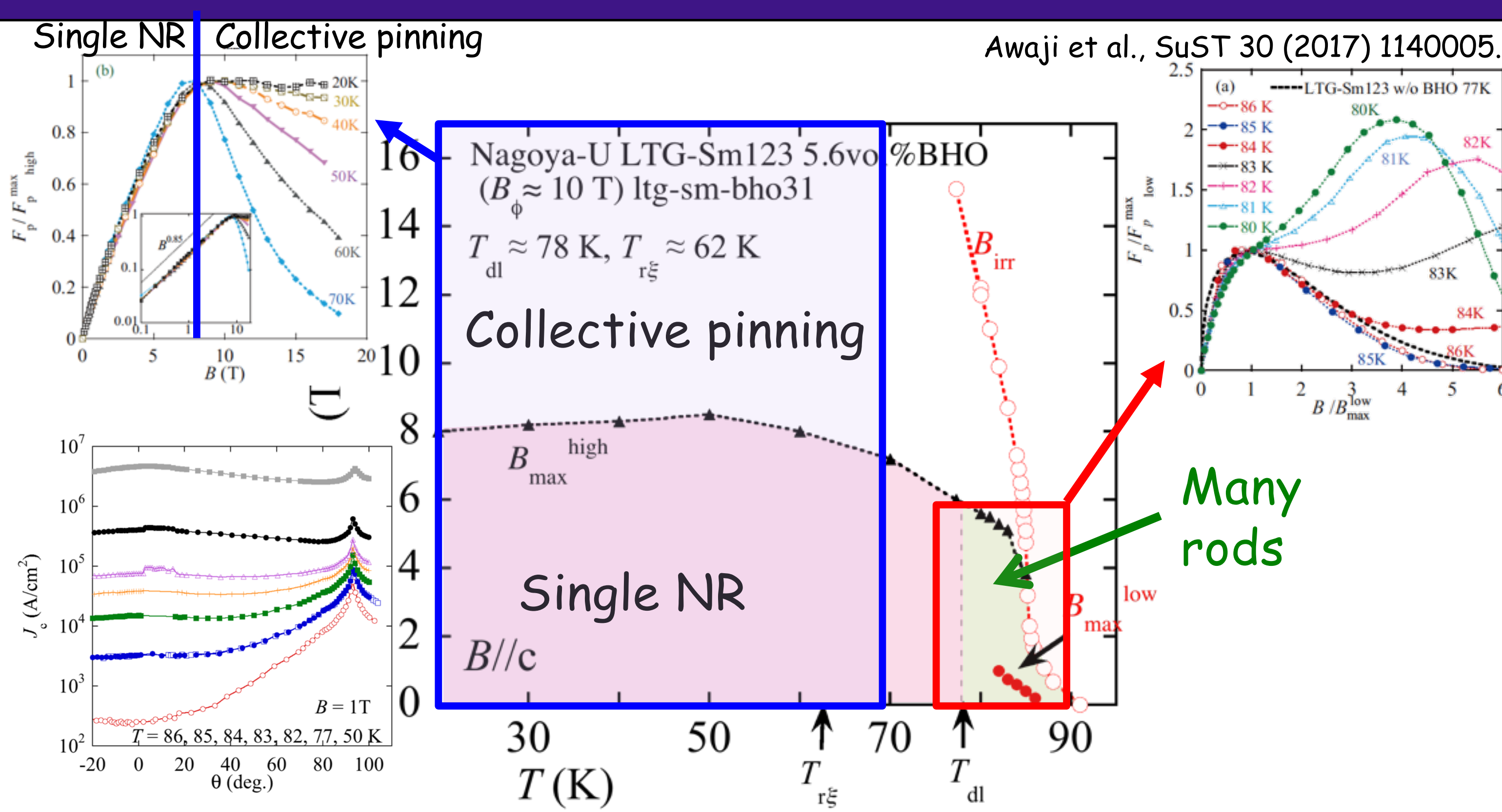




The correlated pinning strength in many NRs shrinking rapidly with increasing T toward to T_{dl}. The random and correlated pins competed in HT. The correlated pinning becomes dominant below T_{dl} and B_ϕ.

Flux pinning phase diagram

Awaji et al., SuST 30 (2017) 1140005.

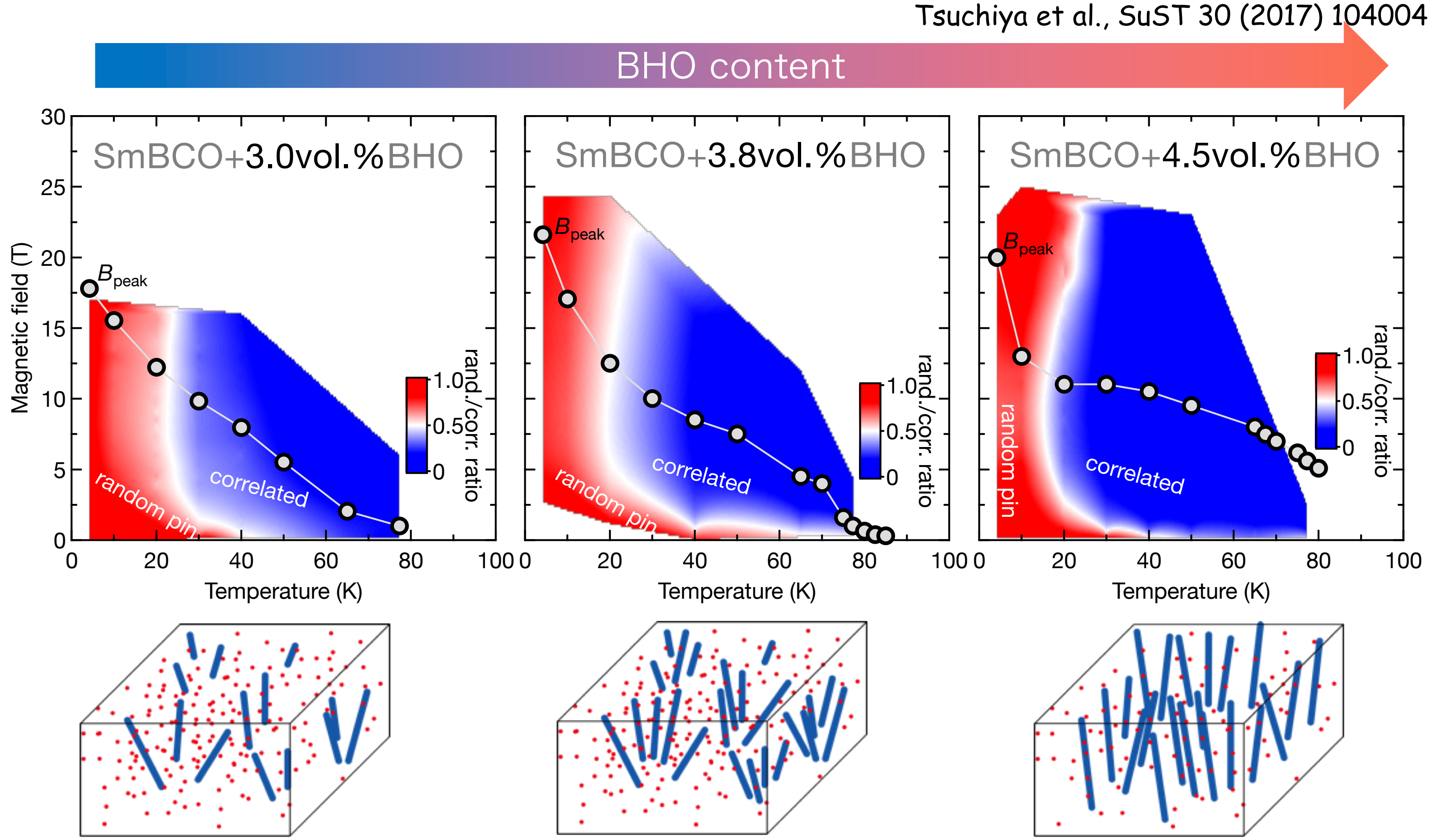


The correlated pinning strength in many NRs increases rapidly with T-decreasing toward to T_{dl}. The random and correlated pins competed in HT. The correlated pinning becomes dominant below T_{dl} and B_{ϕ}.

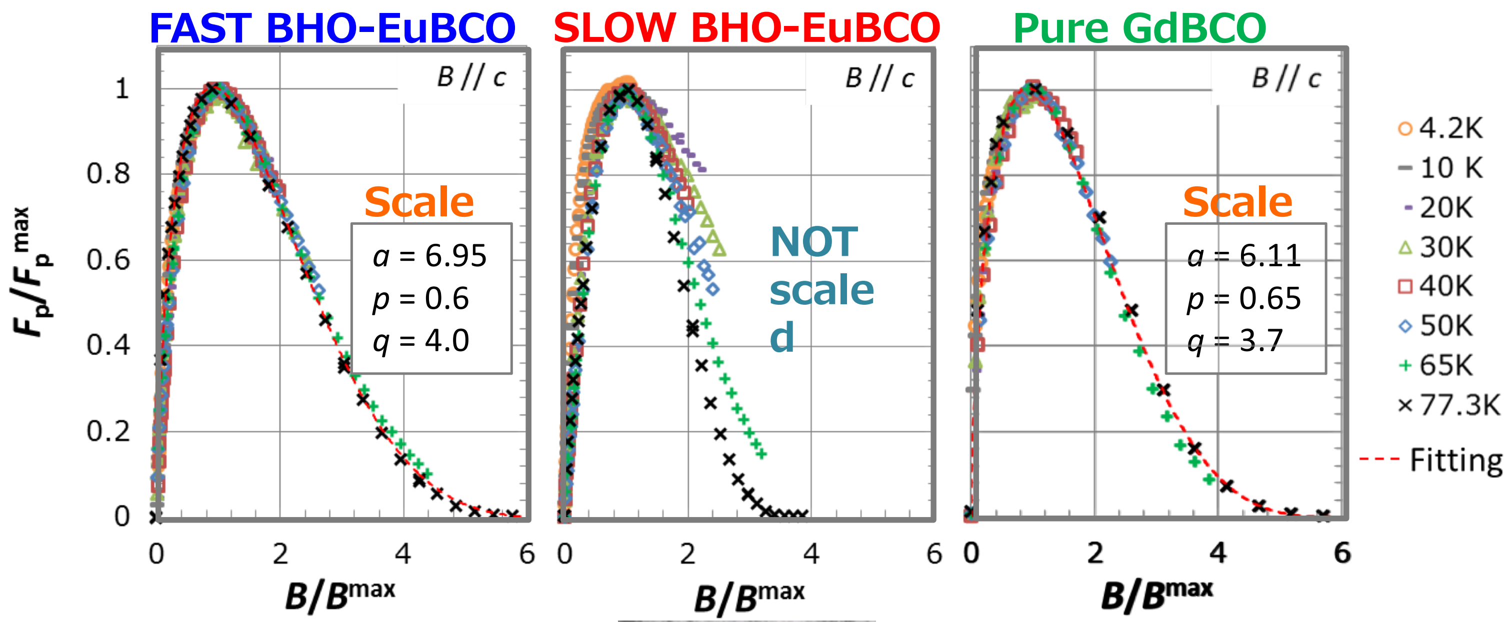
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation 3-MO-PL2 given at EUCAS 2019, 01 - 05 September 2019, Glasgow (UK).

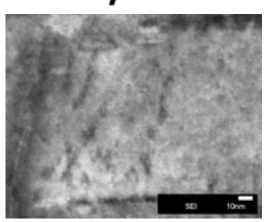
Inclined nanorods

Tsuchiya et al., SuST 30 (2017) 104004

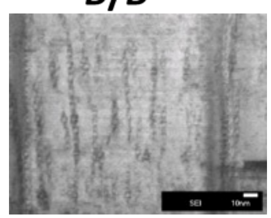


Flux pinning force density, F_p





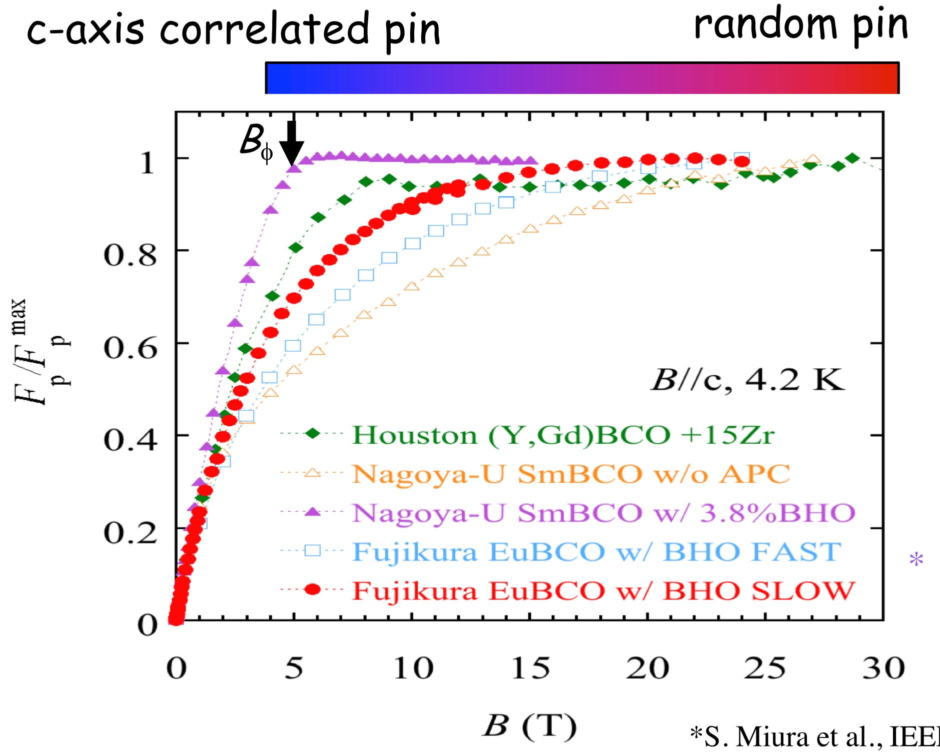
Segmented & randomly oriented nanorods + nanoparticles



Well aligned nanorods

Fujita *et al.*, IEEE TAS, **29** (2019) 8001505.

Comparison of F_p/F_p^{max} curves at 4.2K



*S. Miura et al., IEEE TAS 28 (2018) 8000606.

- ✓ B_{max} becomes higher with stronger random pinning.
- ✓ Fluctuation of growth direction and segmentation of nanorod enhances random pinning behavior.
- ✓ Practical REBCO tapes are in the intermediate state between random and correlated pinning states.

Cooperative pinning model
- correlated pinning -

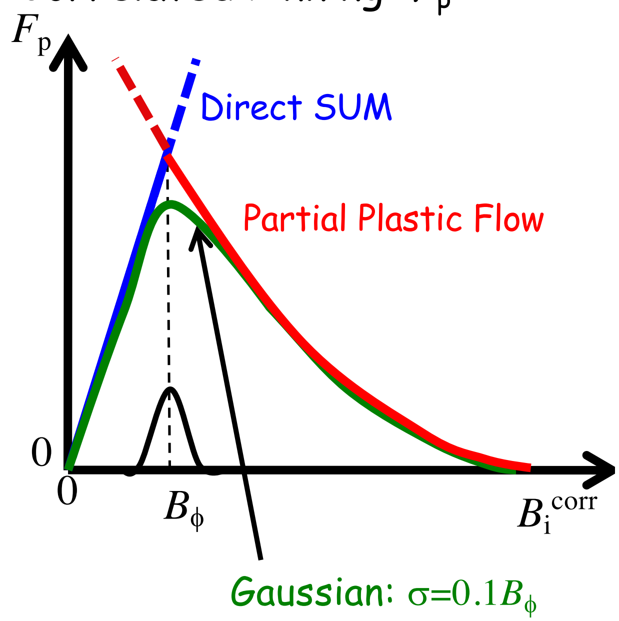
$$F_p = \sqrt{\left(F_p^{rand}\right)^2 + \left(F_p^{corr}\right)^2} \quad : B > B_\phi$$

$$F_p = F_p^{corr} \quad : B < B_\phi$$

F_p^{rand} :Random pinning force density

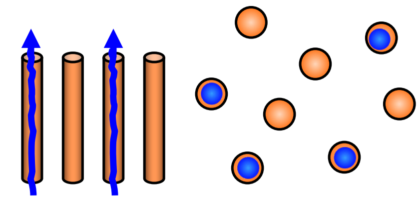
F_p^{corr} :Correlated pinning force density

✓Correlated Pinning: F_p^{corr}



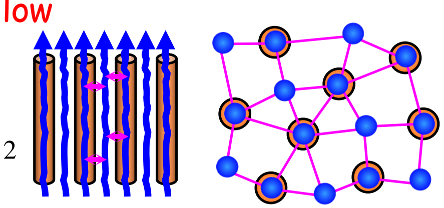
$B < B_\phi$ Direct SUM

$$F_p^{corr} \propto B \Rightarrow \propto B^{1-\alpha}$$



$B > B_\phi$ Partial Plastic Flow

$$F_p^{corr} \propto C_{66} \propto (1 - B/B_i^{corr})^2$$



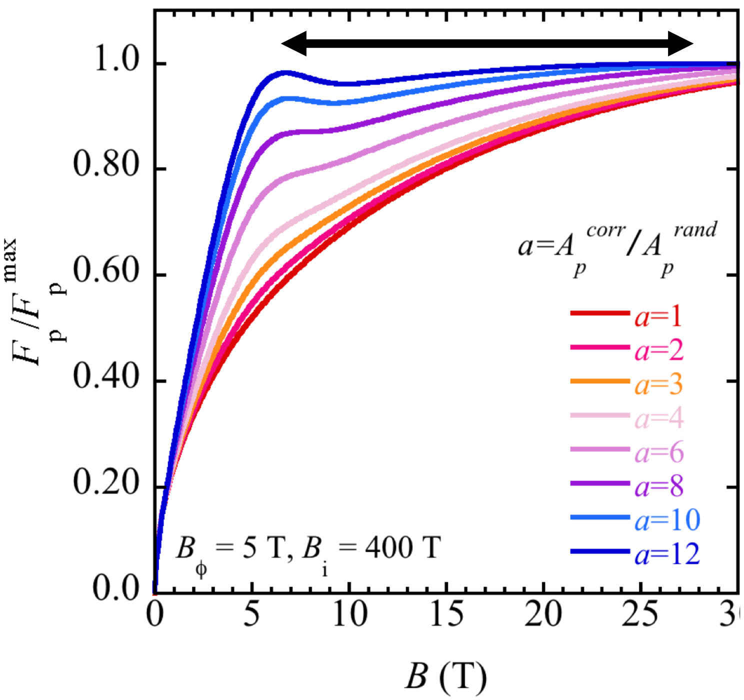
α : magnetic field sensitivity parameter for the nanorod.
($\alpha = 0$ for the ideal c-axis correlated pin)

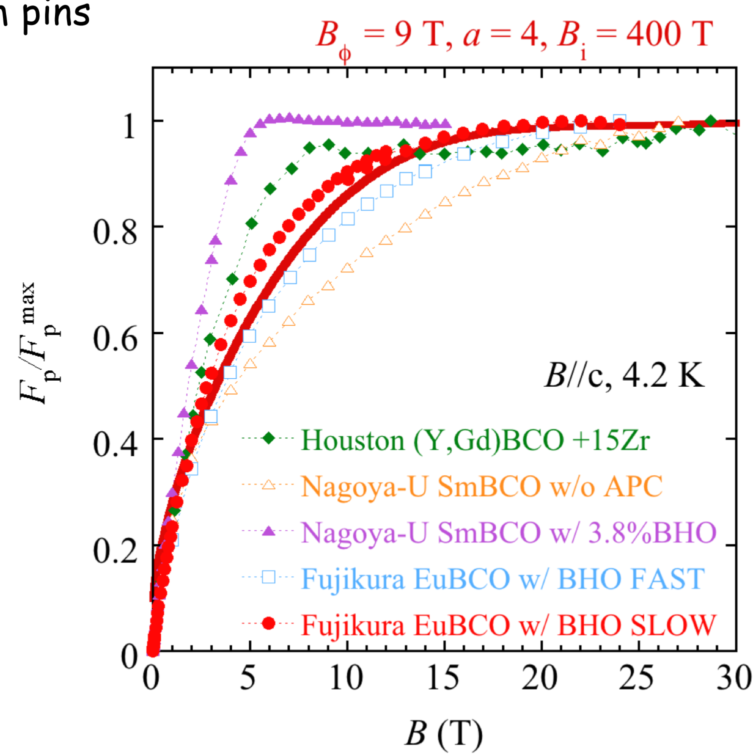
$$F_p^{corr} = \begin{cases} A_{corr} b_{corr}^{1-\alpha} \quad , & b \le b_\phi \\ \dfrac{A_{corr} b_\phi}{\left(1 - b_\phi\right)^2}\left(1 - b_{corr}\right)^2 , & b > b_\phi \end{cases}$$

S. Awaji *et al*., *IEEE TAS* **21** (2012) 3192
S. Awaji *et al*., *JAP* **111** (2012) 013914.

Calculation results

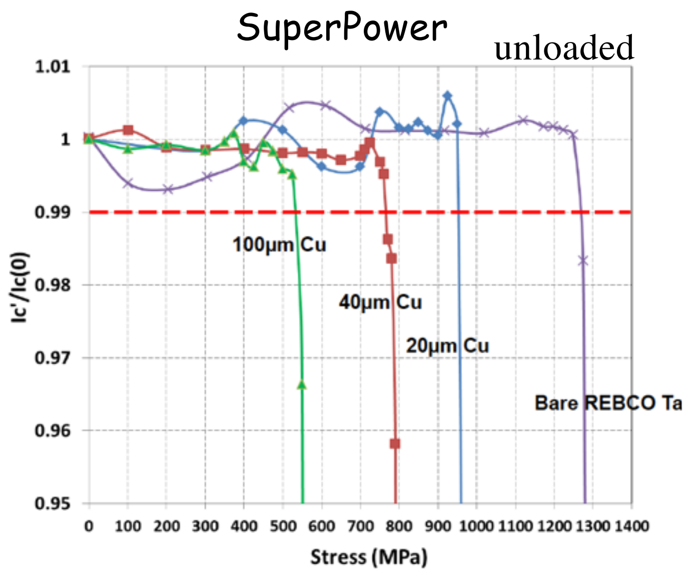
Crossover from correlated to random pins



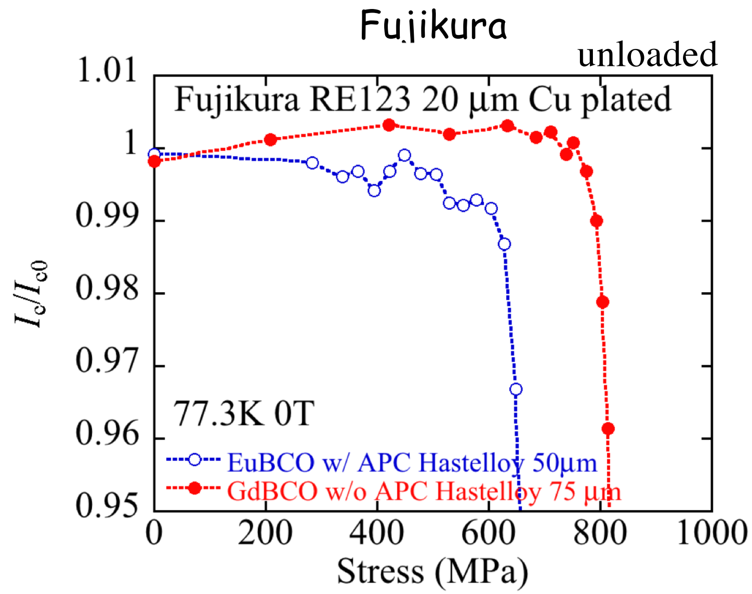


✓ Stronger random pinning contribution shifts F_p peak to higher field.

Electromechanical properties in REBCO



Y. Zhang et al., IEEE TAS 26 (2016)8400406.

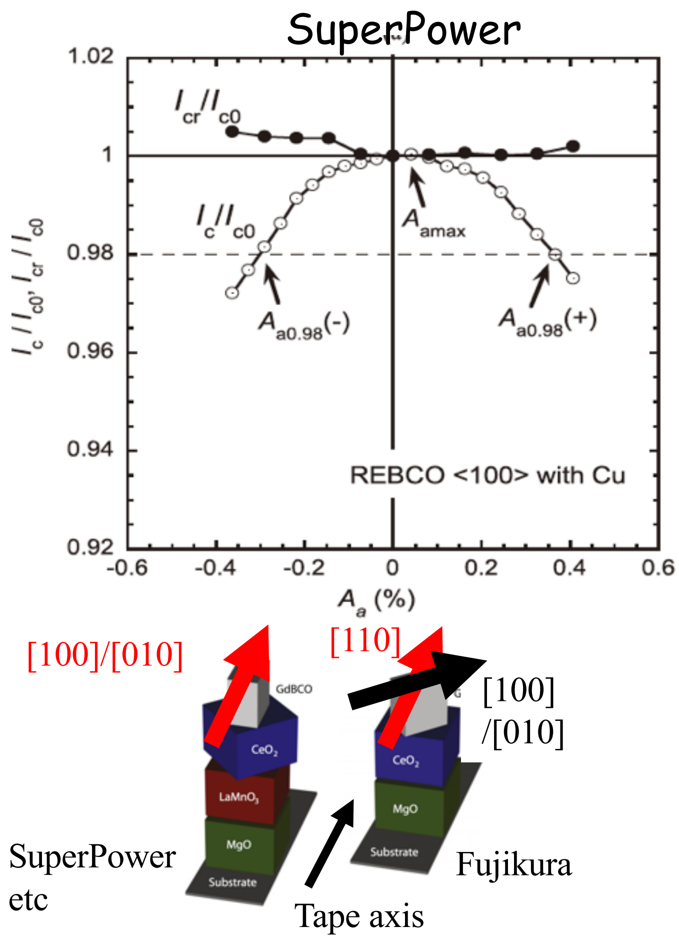


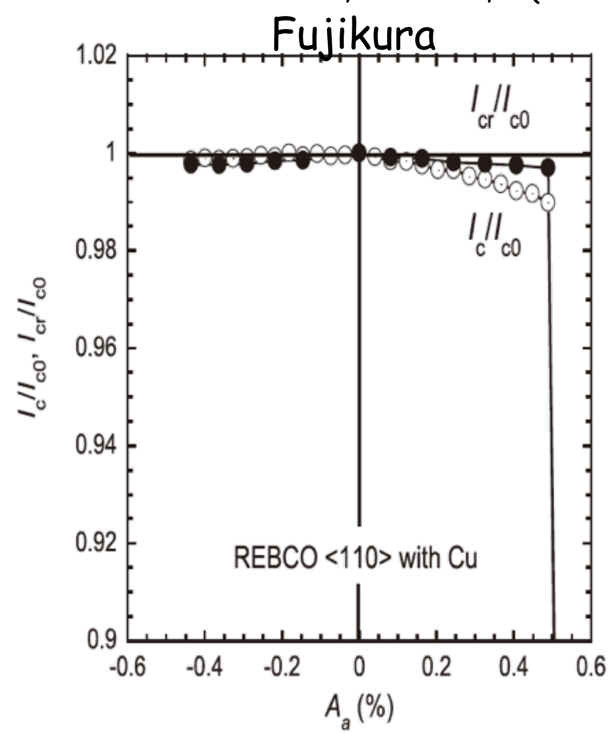
S. Fujita et al., IEEE TAS 24 (2015) 840304.

- ✓ Stress tolerances decreases with increasing Cu and decereasing Hastelloy.
- ✓ Hastelloy thickness tends to decrease for increase Je recently.

Strain dependence of J_c in REBCO tapes

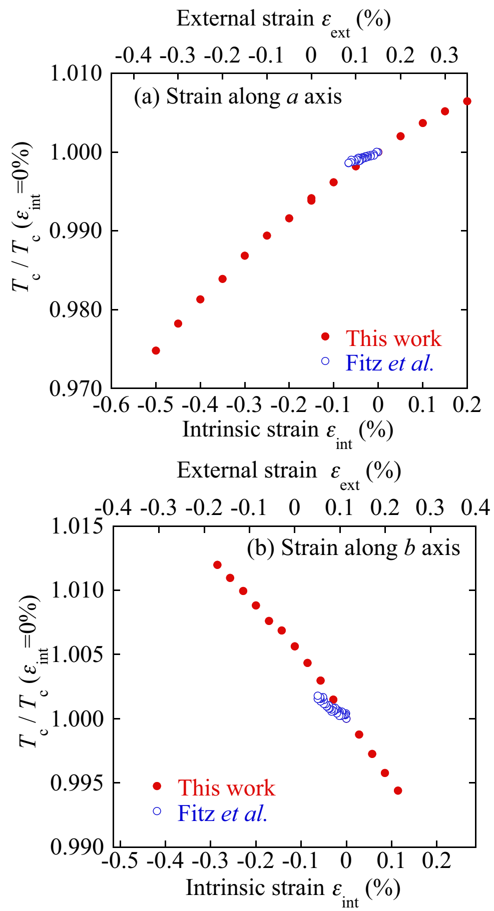
Osamura et al., AIP Adv., 9 (2019) 075216.





Strain dependence is more sensitive along [100]/[010] than along [110].

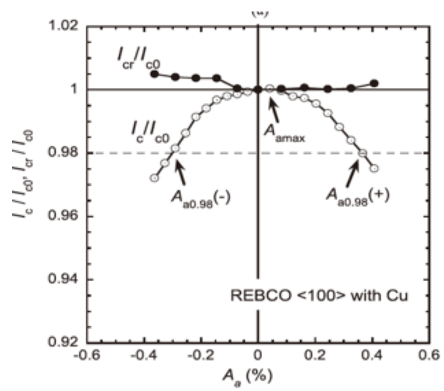
Strain dependence of T_c along *a*- and *b*- axes

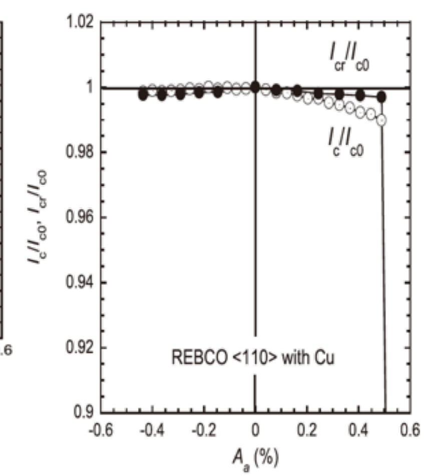


S. Awaji et al., Sci. Rep. 5 (2015) 11156.

- Strain dependence along *a*- axis is opposite to that along *b*-axis.

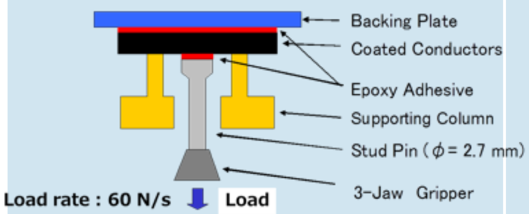
- Strain along [110] cancels the strain dependences along [100] and [010] which are opposite each other.

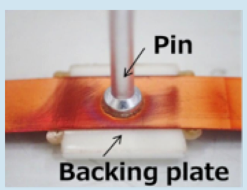




Delamination in REBCO tapes

Stud-pull

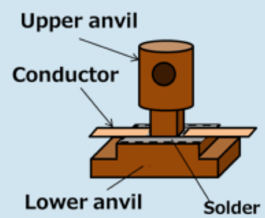


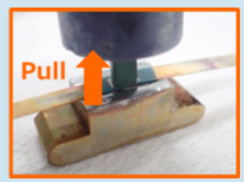


Test area : 5.7 mm^2
(φ2.7 mm pin)
Strength : ~ 40 MPa

T. Oyama, *et al.*, Journal of The Surface Finishing Society of Japan, **58** (2007) P. 292

Anvil

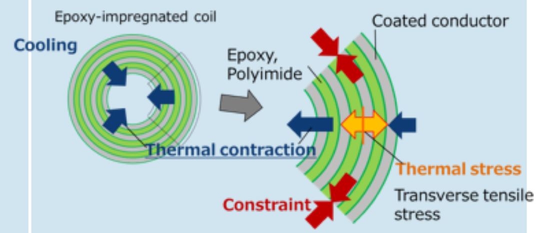


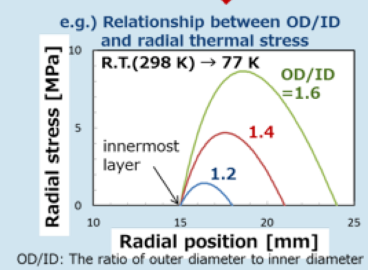


Test area : 32 mm^2
(4×8 mm anvil)
Strength : ~ 10MPa

H. Shin, *et.al.*, SuST, **27** (2014) 025001

Impregnated coil





Test area : 16000 mm^2
(4 mm^w×4 m coil)
Strength : ~ 5 MPa

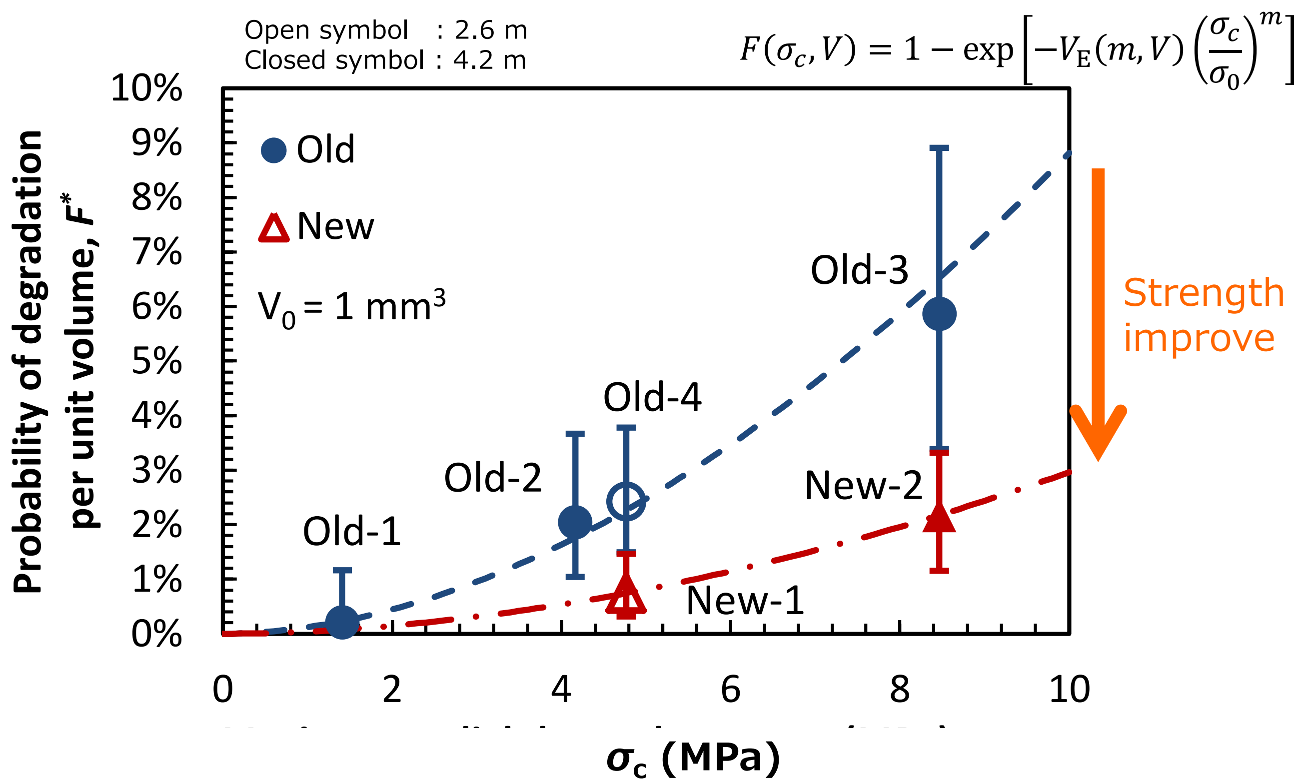
H. Miyazaki *et al.*, IEEE TAS, **25** (2015) 6602305

Delamination strength depends on the methods

Fujikura

Courtesy of S. Muto (Fujikura)

Weibull analysis considering size effect



- Delamination strength as a function of volume-> depending on thickness
- Is Local degradation unavoidable?

  -> Need strategy for the local degradation in REBCO magnet.

Fujikura

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

TOHOKU UNIVERSITY

Fe-based Superconductor
(Ba, K)Fe_2As_2

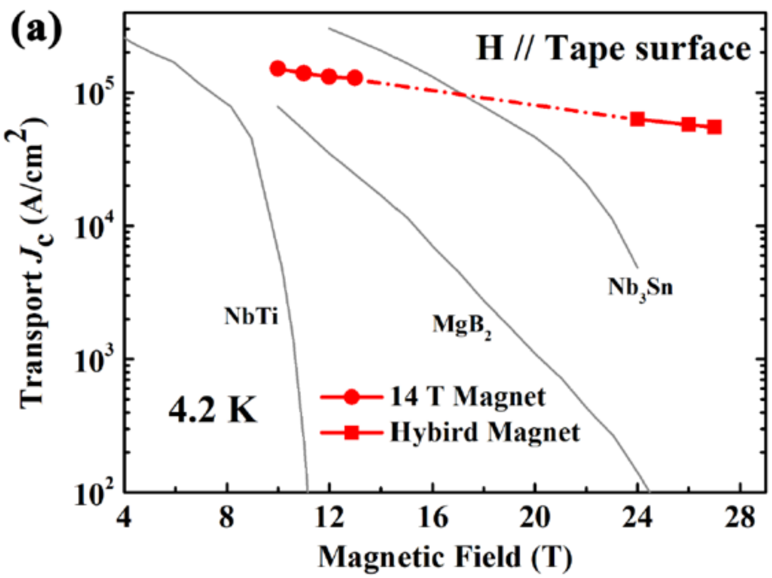
HFLSM Sendai

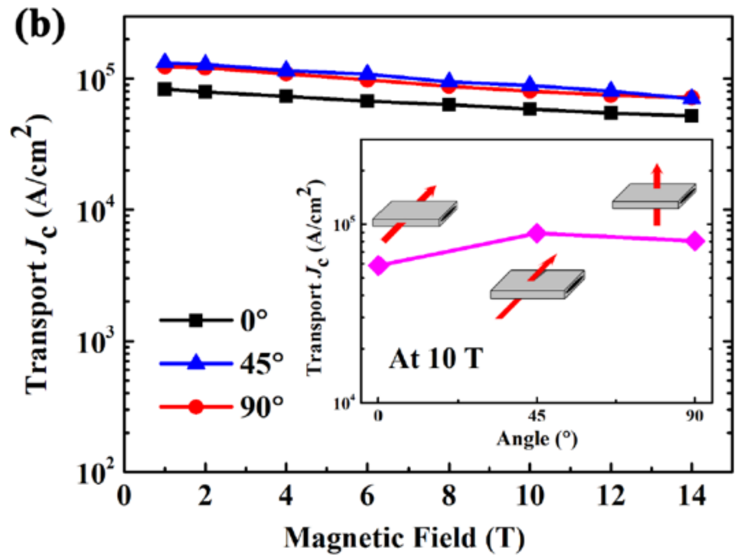
Research

Courtesy of Prof. Ma

High transport Jc values were achieved in Ba122/Ag tapes

At 4.2K, 10 T, I_c=437 A, J_c~150000 A/cm^2





At 4.2K, 14 T, J_c~140000 A/cm^2

At 4.2K, 27 T, J_c~55000 A/cm^2

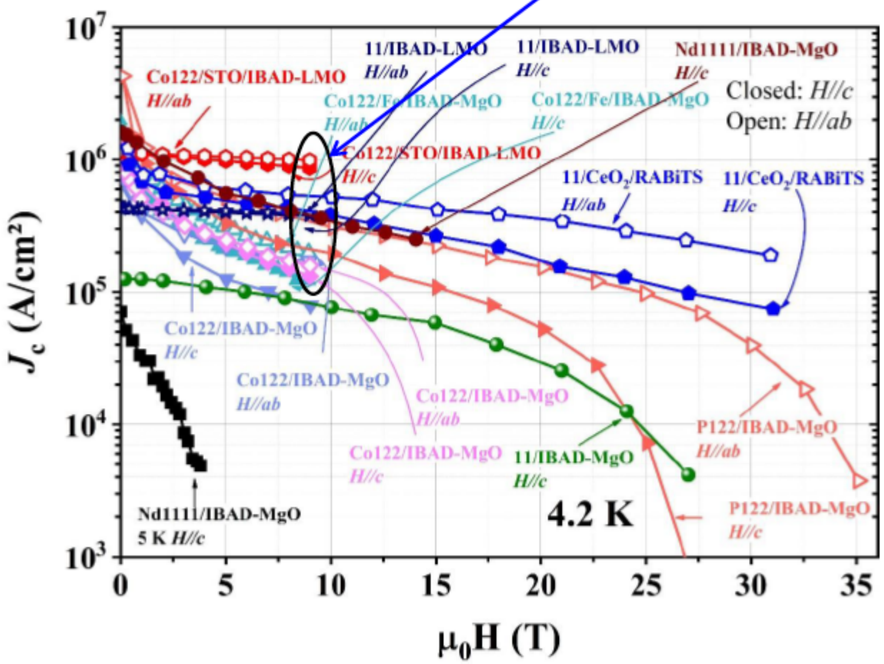
The anisotropy of J_c at 10T is 1.37

H. Huang, et al., ***SuST*** 31 (2018) 015017

Y. Ma Plenary talk at EUCAS 2019

Sumary: J_c of different IBS coated conductors

- From the point of view of possible applications, many groups tried film deposition on technical substrates.
- Three main systems (11, 122, and 1111) with superior J_c have already been realized on technical substrates, e.g., **most of J_c at ~10T are > 10^5 A/cm², from 10^5 to 10^6 A/cm²**.



The J_c anisotropy of 11 and 122 was quite small

To further improve J_c, the introduction of APC is necessary.

K. Iida *et al*. APL 105, 172602 (2014)
Courtesy of K. Iida
S. Trommler *et al*. *SuST* 25, 084019(2012)
T. Katase *et al*. *APL* 98, 242510 (2011)
H. Hiramatsu *et al*. *SuST* 30, 044003(2017)
K. Iida *et al*. *Sci. Rep*. 7, 3995 (2017)
Z. T. Xu *et al*. *SuST* 31, 055001 (2018)
Z. T. Xu *et al*. *SuST* 30, 035003 (2017)
W. Si *et al*. *Nat. Commun*. 4, 1347 (2017)
W. Si *et al*. *APL* 98, 262509 (2011)

Task: to develop simpler and scalable techniques for making long coated conductors

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation 3-MO-PL2 given at EUCAS 2019, 01 - 05 September 2019, Glasgow (UK).

TOHOKU
UNIVERSITY

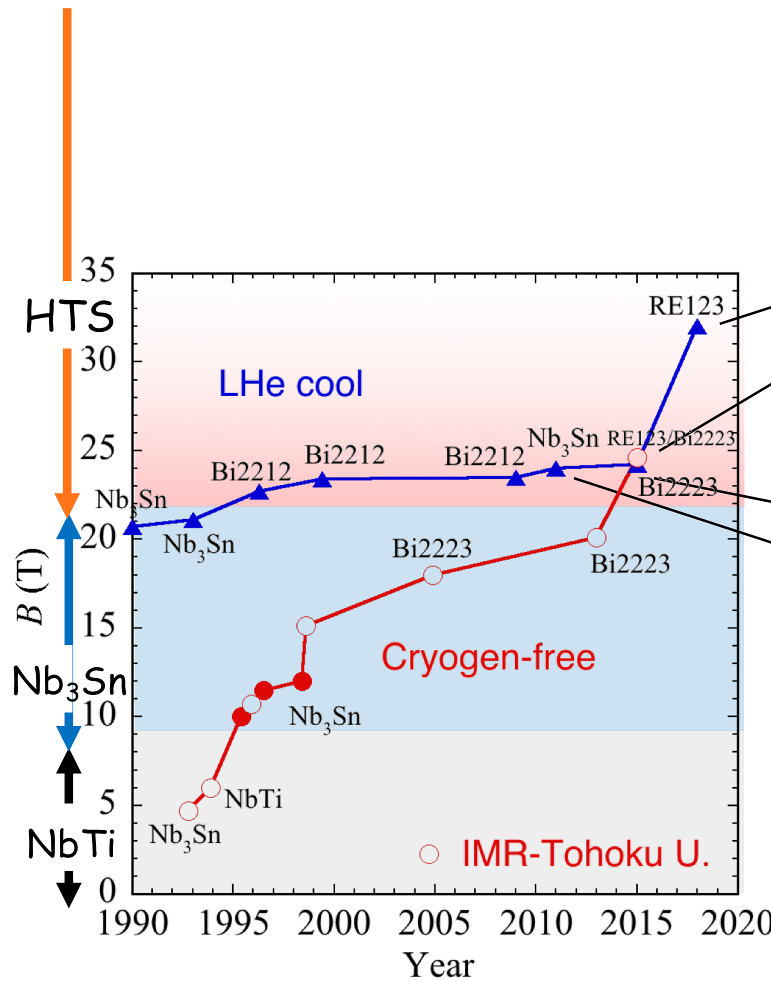
To develop
high field superconducting magnet

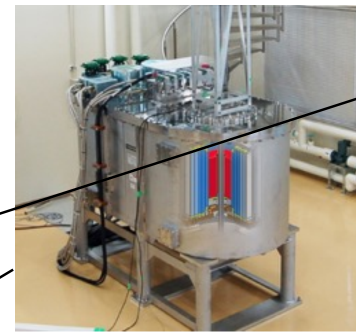
HFLSM
Sendai

Research

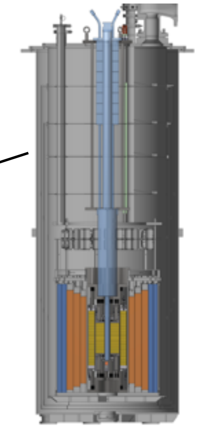
HFLSM Sendai

High Field SC Magnet Developments - Practical Magnets -





24.6T- 52mm (HFLSM)



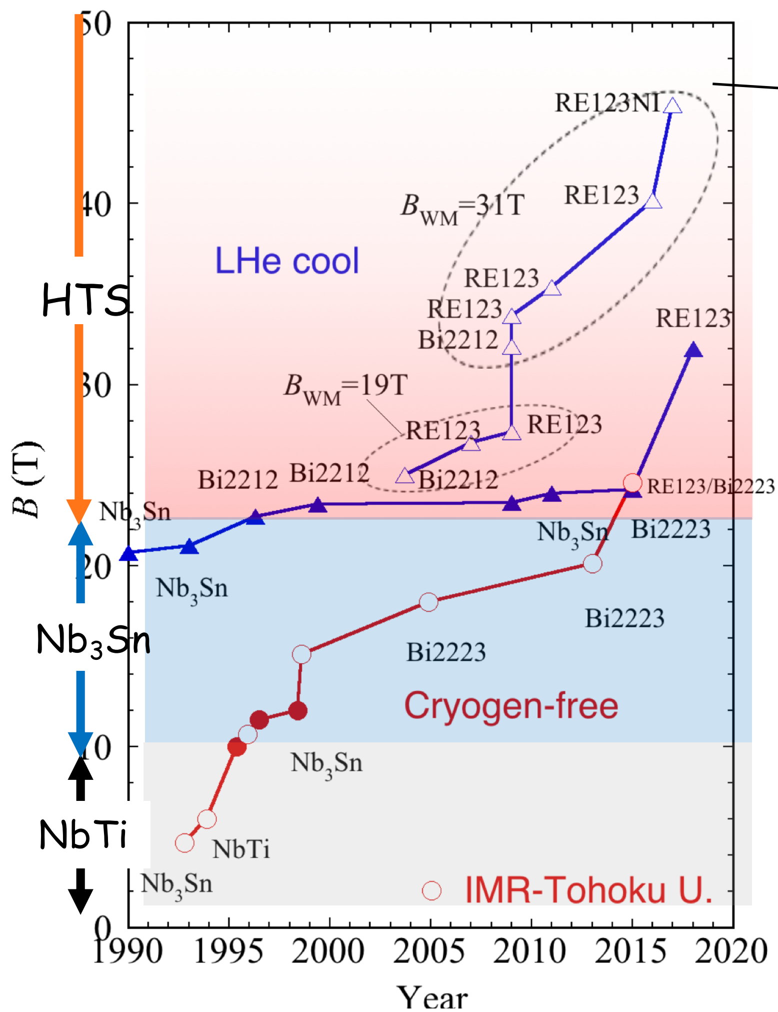
32T-36mm (NHMFL)

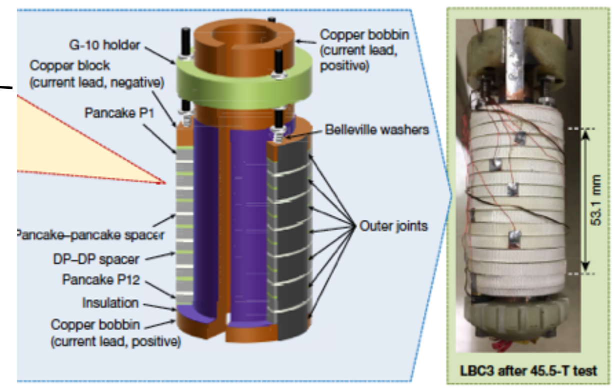
1GHz-NMR (Bruker)

1.02GHz-NMR (NIMS)

HFLSM Sendai

High Field SC Magnet Developments - Practical Magnets +Demonstrations -





45.46T- 14mm(NHMFL)

S. Hahn et al., Nature 570 (2019) 497.

Superconducting magnet beyond 40T can be targeted.

On going projects

- 40T-SM project (NHMFL)
- 1.3GHz (30.5T)NMR project (RIKEN)
- 30T-CSM (upgrade of 25T-CSM) (Tohoku U.)

etc

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation 3-MO-PL2 given at EUCAS 2019, 01 - 05 September 2019, Glasgow (UK).

HFLSM Sendai

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
27T	IEE/CAS	Demo	27.2	RE123	389		36	4.2 (LHe)	NI-DP	Wax	NI	2019	[17]	NI
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
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

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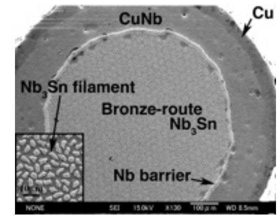
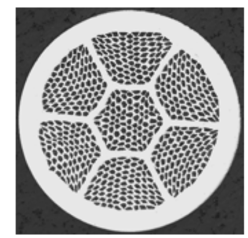
From a viewpoint of magnet application 1

- Nb_3Sn
  - Non-Cu J_c is improving with the improvement of phase formation and an introduction of additional pinning centers
  - A mechanical strength is still improving.



- Bi2212
  - Unique round wire.
  - High in-field J_c due to the in-plane alignment.
  - Improvement of mechanical properties is expected.



- Fe-based Superconductor
  - Low cost and small anisotropy
  - Good in-field J_c in high filed
  - Performance is improving.

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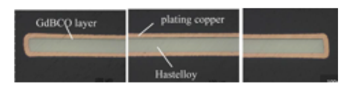
From a viewpoint of magnet application 2

- Bi2223
  - The mechanical strength is improving with the reinforcement and pre-compression. It is still improving.
  - Good homogeneity



- REBCO
  - High performance of in-field Jc and mechanical properties.
  - Jc increases with an introduction of APC.
  - A thickness of Hastelloy is decreasing in order to increase non-Cu Jc.
  - Local degradation due to the complex stress should be overcome.

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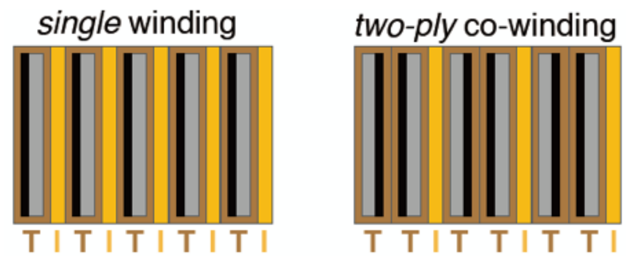
-View point of REBCO coil-

1. Bundles
   - ✓ Current share at the local degradation
   - ✓ Reduce fraction of insulation



2. Improve the stiffness of pancake coil

3. Protection from thermal runaway
   - ✓ Dumping without thermal runaway (Passive protection).
   - ✓ Dumping as fast as possible with normal states (Active protection using Q-heater)
   - ✓ Non-insulation technique (Self protection)

As conclusion

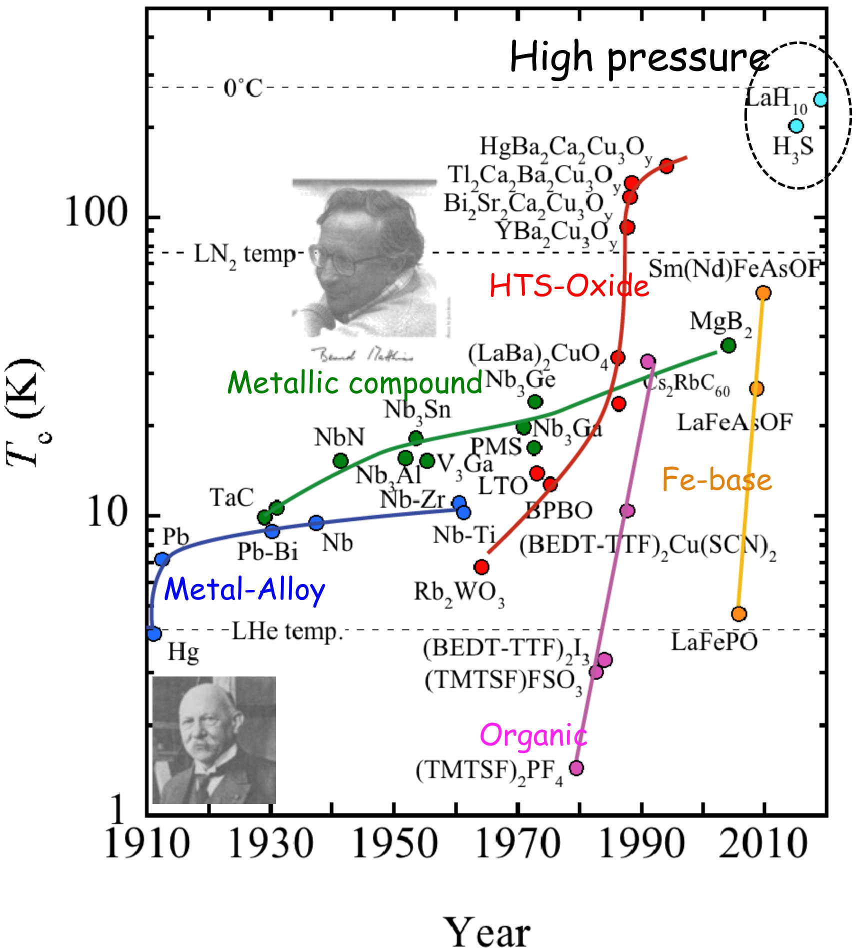
- ✓ HTS wires have the ability to develop high field superconducting magnets beyond 20T.
- ✓ Key properties of high field superconductors are … in-field J_c and electromechanical properties.

Generate a high magnetic field with toughness.

Develop 50T superconducting magnet!

Thank you for your kind attention!

Superconducting materials - Critical temperature T_c -



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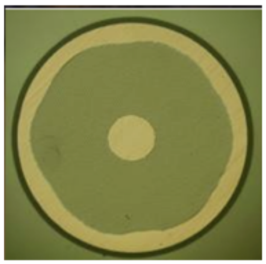
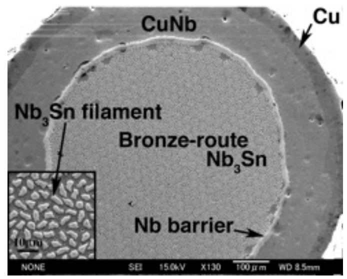
Practical Superconducting Wires

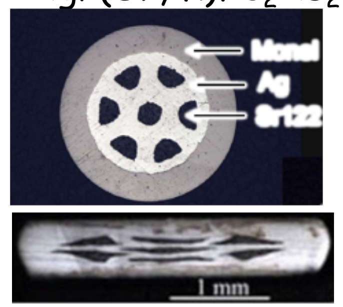
Cu/NbTi



Bz-CuNb/$(Nb,Ti)_3Sn$



Ag/(Sr, K)Fe_2As_2

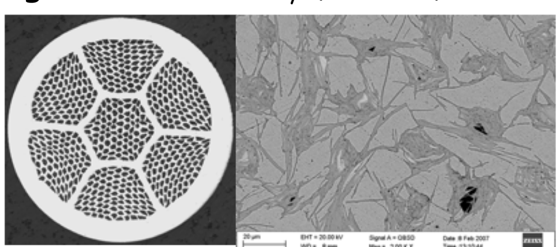


Ag/MgB_2

Brass/Ag/$Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223)

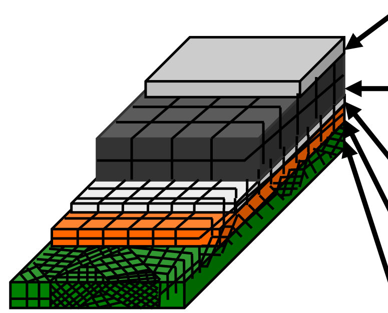
4mm x 0.2-0.3mm

Ag/$Bi_2Sr_2Ca_1Cu_2O_y$ (Bi2212)

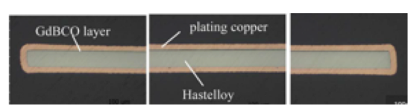


ϕ0.8mm

Ag/$REBa_2Cu_3O_y$/Hastelloy (RE123, RE:rare earth)



Stabilization layer	Ag	5-50 μm
Superconducting layer	REBCO	1-2 μm
Buffer layer	PLD-CeO_2	0.4 μm
Buffer layer	IBAD-MgO /$Gd_2Zr_2O_7$	0.7 μm
Substrate	Hastelloy C276	25-100 μm



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