25th International conference on Magnet Technology(MT25)

MT25

25th International Conference on Magnet Technology

RAI - Amsterdam
August 27 - September 1, 2017

Tue-Af-PI3-03

Development of Superconductors at Furukawa Electric Group

Aug. 29th , 2017

Furukawa Electric Co., Ltd.
Hisaki Sakamoto

Outline

- History of Superconductor Development at Furukawa Electric
- Drivers for Superconductor Development
- Sperconductors at Furukawa Electric Group
  - NbTi Wire and Cable
  - Nb_3Sn Wire and Cable
  - 2G-HTS(REBCO) Tape
- HTS Applications
  - HTS Persistant Current System
  - Superconducting Flywheel Energy Storage System
- Summary

50years of Superconductor Development

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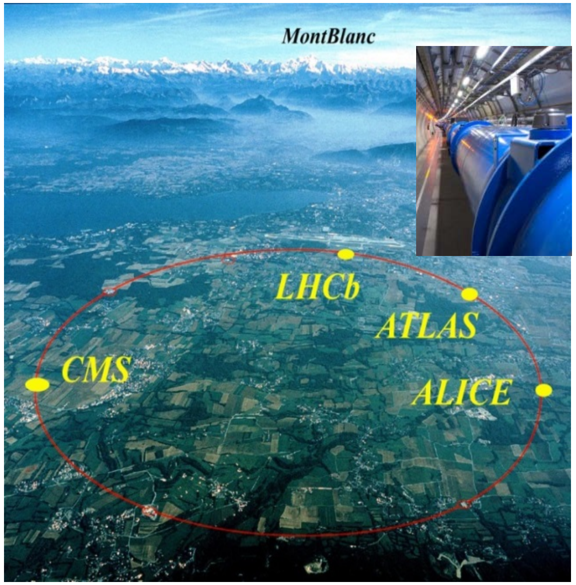
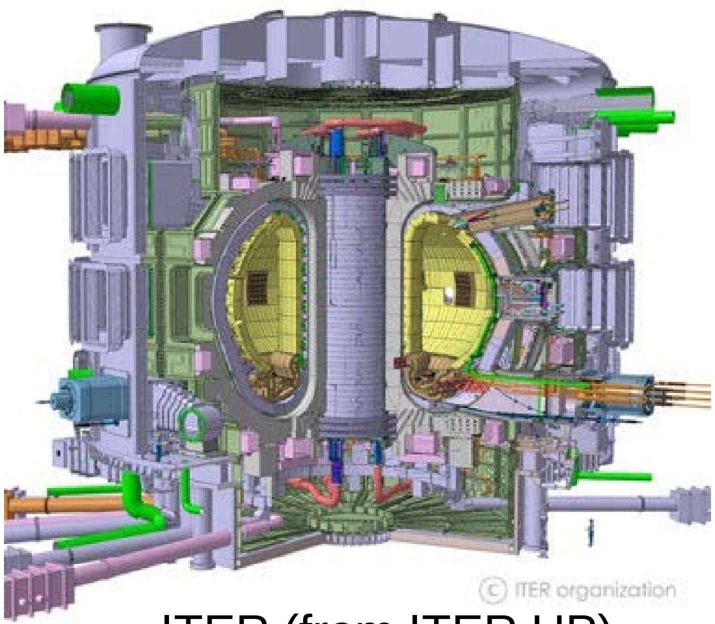
Year	Items
1967	Start development of Superconductor
1968	Start production and distribution of NbTi Superconductor
1970	Start production and distribution of Superconducting Magnet
1972	Development of Bronze-processsed multifilamentaary Nb_3Sn and V_3Ga superconductor
1974-	Participated worldwide projects with superconducting technology Fusion ：LCT, Tore Supra, MFTF-B, ITER Accelalator ：Tevatron, Tristan, Hera, RHIC, SSC, LHC
1983	Superconductor plant（600m^2）
1984	Funded Furukawa Oxford Technology, product and distribute superconducting magnets for MRI
1987	Start development of High-Tc superconductor
1988-	Participated domestic projects with superconducting technology Superconducting Generator, HTS wire, SMES, LHD, Superconducting Ring Cyclotron, J-PARC
1990	New superconductor plant（6,000m^2）
1998	Received order of 100 tons of NbTi rutherford type cable for CERN/LHC
2003	Paid in full of the cable for LHC, received Golden Hadron award.
2008	Received orders of NbTi and Nb_3Sn cables for JT60
2012	SuperPower Inc. joined Furukawa Electric Group
Now	Manufacturing Nb_3Sn Cable for ITER Development of High-Jc type Nb_3Sn wire

Large projects enhanced wire performance, quality and capacity.

- NbTi : SSC, LHC
- Nb_3Sn : ITER, HL-LHC, FCC
- 2G-HTS : ?



LHC (from CERN HP)



ITER (from ITER HP)

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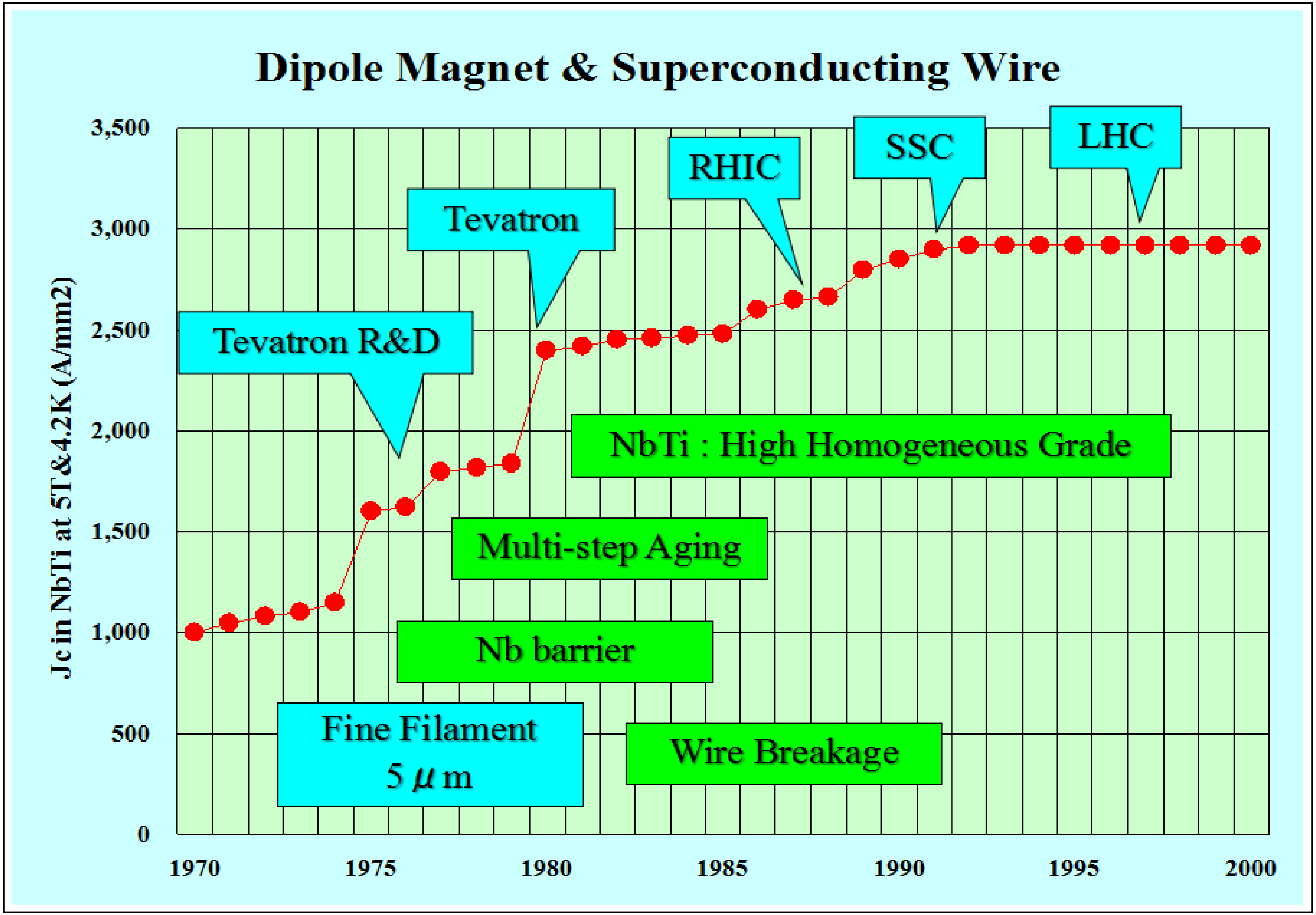
History of NbTi Wire Development



Furukawa delivers various type of NbTi Superconductors

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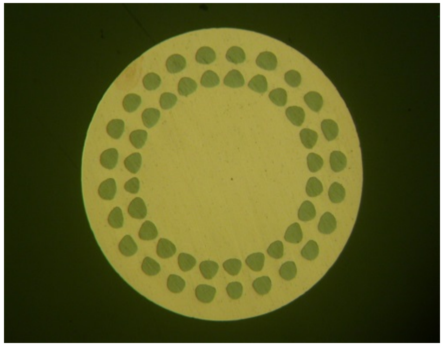
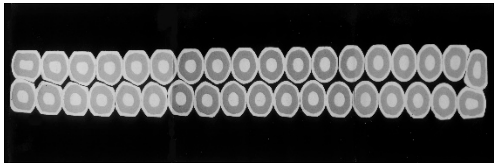
Medical

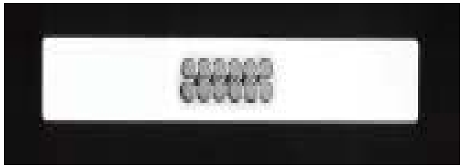


NbTi round wire for MRI

High Energy Physics

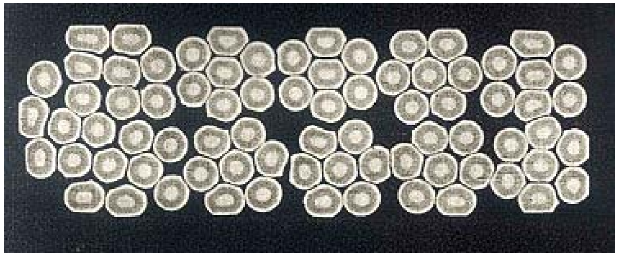


Rutherford type NbTi cable

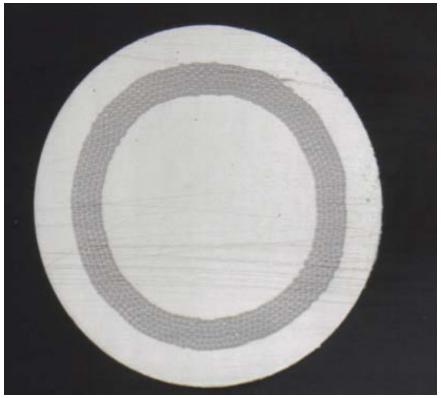


Aluminum stabilized NbTi Cable

Industrial



NbTi Cable for generator



NbTi for Si Single Crystal Pulling Apparatus

NbTi Rutherford Cable for LHC

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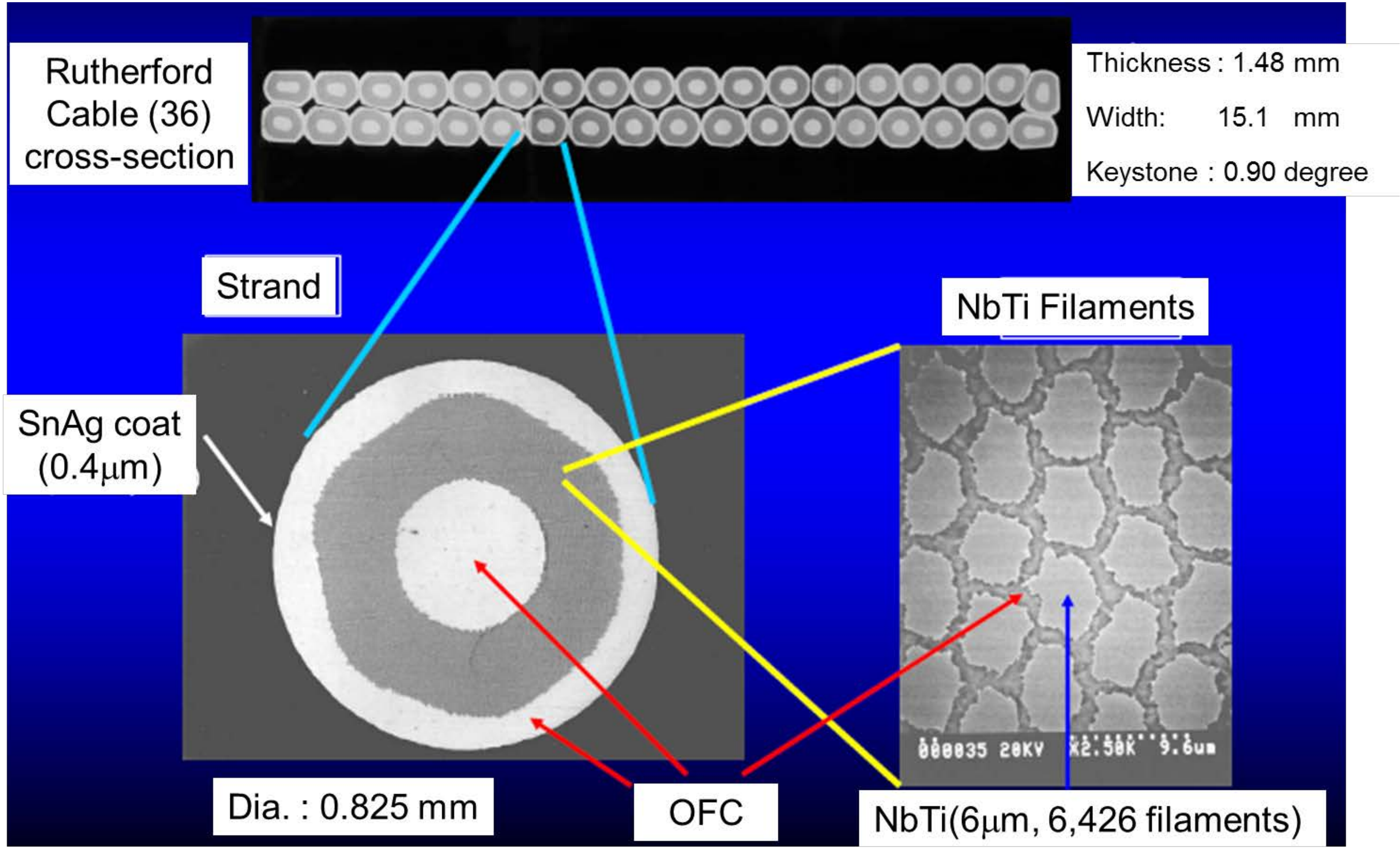

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Development of Nb_3Sn Strand for ITER-CS

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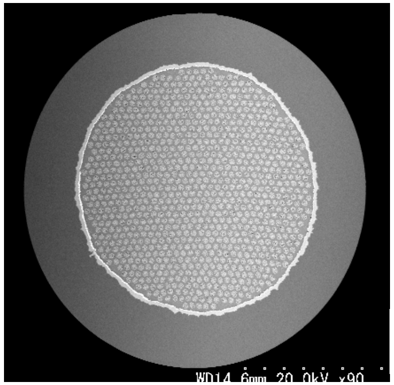
Requirement

Higher Jc with lower Hysteresis Loss

- Non-Cu Jc >1,100A/mm^2@12T,4.2K
- Hysteresis Loss <1,000kJ/m^3 ,±3T,4.2K

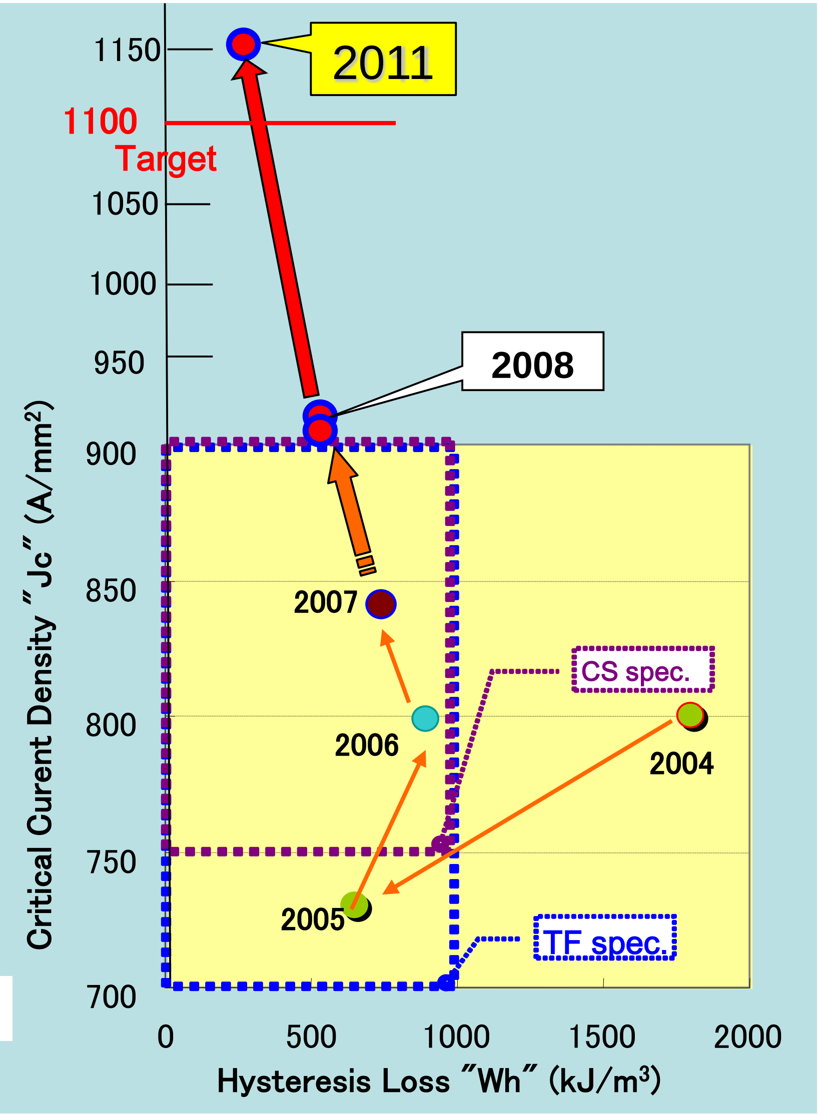
Optimizing design parameter

- ✓ Bronze composition(Sn、Ti content)
- ✓ Bronze / Nb ratio
- ✓ Filament diameter
- ✓ Diffusion barrier material



0.83 mm in dia.

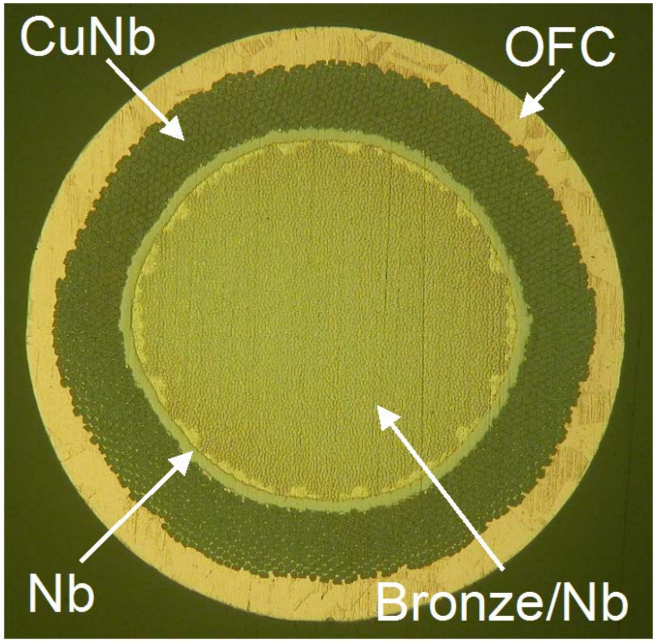
Cross-section of Bronze-processed Nb_3Sn Strand for ITER-CS



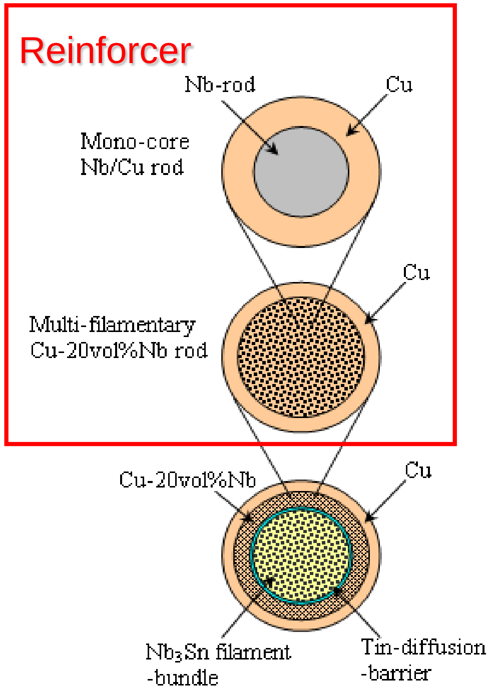
Performance of Nb_3Sn strand

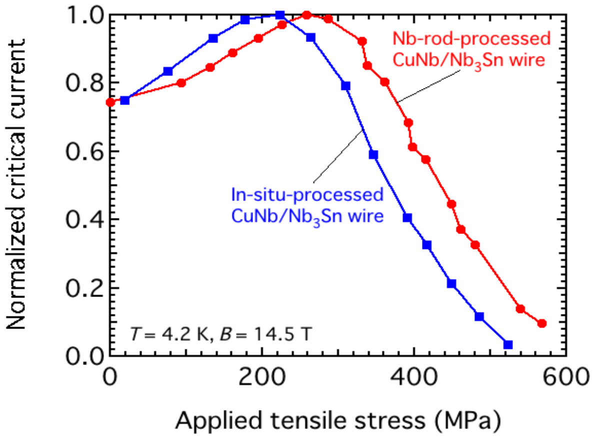
Development of Nb-rod method Cu-Nb reinforced Nb_3Sn wires

Mon-Af-Po1.08-07 Sugimoto *et. al*



Cross-section of prototype strand





The applied tensile stress dependence of Cu-Nb/Nb_3Sn wires

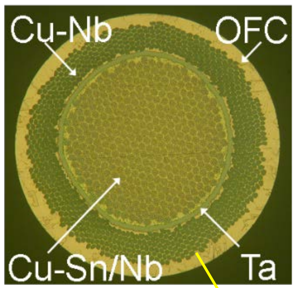
[4] H. Oguro, S, Awaji, K. Watanabe, M. Sugimoto, and H. Tsubouchi, “Mechanical and superconducting properties of Nb_3Sn wires with Nb-rod-processed CuNb reinforcement,” *Supercond. Sci, Technol.*, vol. 26, no.9, p.094002, Sep. 2013.

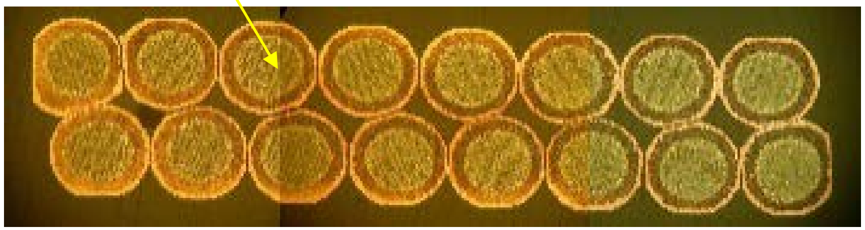
[5] K. Watanabe, S.Awaji, Y. Hou, H. Oguro, T. Kiyoshi, H. Kumakura, S. Hanai, H. Tsubouchi, M. Sugimoto, and I. Inoue, “Upgrade Design to a Cyogen-Free 20-T Superconducting Outsert for a 47-T Hybrid Magnet,” *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, p. 4300304, Jun. 2013.

Advantage of Nb-rod-method Cu-Nb reinforced Nb_3Sn strand

- ✓ Superior mass productivity with Nb-rod-method Cu-Nb
- ✓ Diameter of Nb rod, Spacing, Volume ratio is the Key to control the properties.
- ✓ Higher I_c under the large axial tensile stress
- ✓ High RRR (> 100).

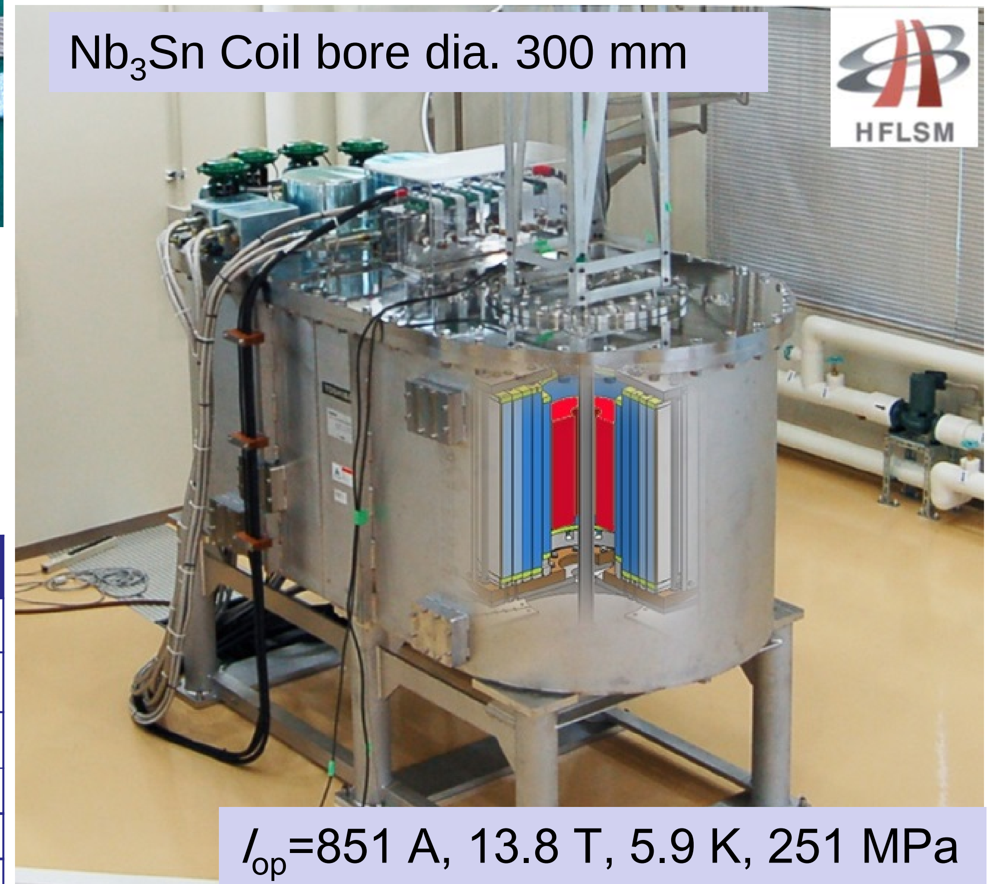
Nb-rod-method Cu-Nb reinforced Nb_3Sn Rutherford cables for React-and-Wind processed wide-bore high magnetic field coils





Cross-section of the Rutherford type cable

Item	Parameters
Number of strands	16
Dimensions	$6.45^{+0.015/-0.05}$ mm^{w} x $1.53^{\pm0.05}$ mm^{t}
Cabling pitch/direction	$65^{\pm10}$ mm / Right hand helix
Insulation	E-glass tape
Critical current	>1,900A @4.2K, 12T, 300MPa
RRR	>80

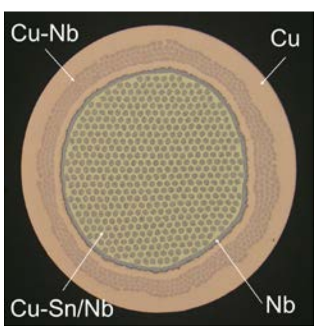


25T cryogen-free superconducting magnet at Tohoku Univ.

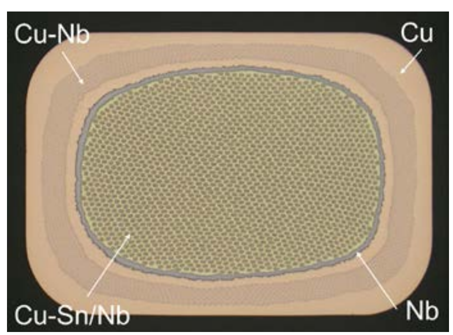
Improvements of Cu-Nb/Nb_3Sn wires for React-and-Wind applications

MAIN PARAMETERS OF CU-NB/NB_3SN WIRES

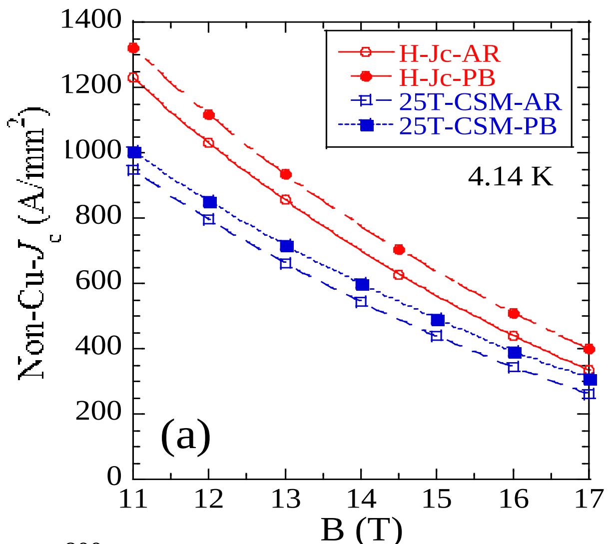
Design	New		Previous
Wire	H-Jc	REC	25-CSM
Dimension (mm)	φ0.80	$1.13^t \times 1.7^w$-0.3^R	φ0.80
Filament dia. (μm)	3.0	3.2	3.3
Twist pitch (mm)	24	50	24
Bronze	Cu-15.7wt%Sn -0.3wt%Ti		Cu-14wt%Sn -0.2wt%Ti
Sn diffusion barrier	Nb		Ta
Cu/Cu-Nb/non-Cu (%)	30 / 20 / 50		20 / 35 / 45
Superconductor	Bronze- processed Nb_3Sn		
Reinforcement	Nb-rod-method Cu-20vol%Nb		

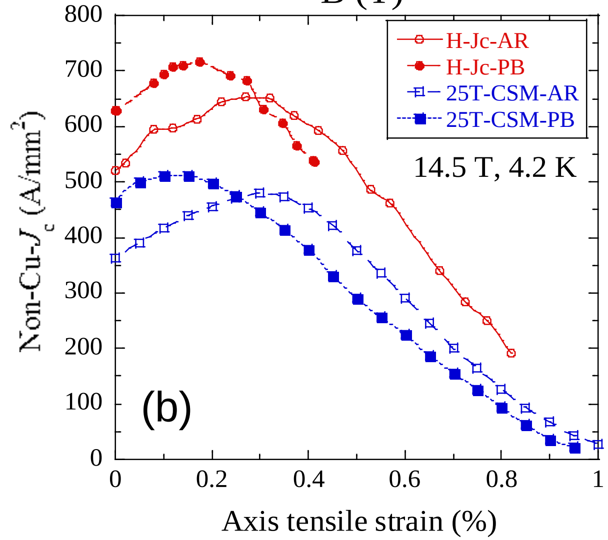


High J_c type round wire



Rectangular type wire





AR: as reacted
PB: pre-bent

Practical performance of Cu-Nb/Nb_3Sn wires for React-and-Wind applications

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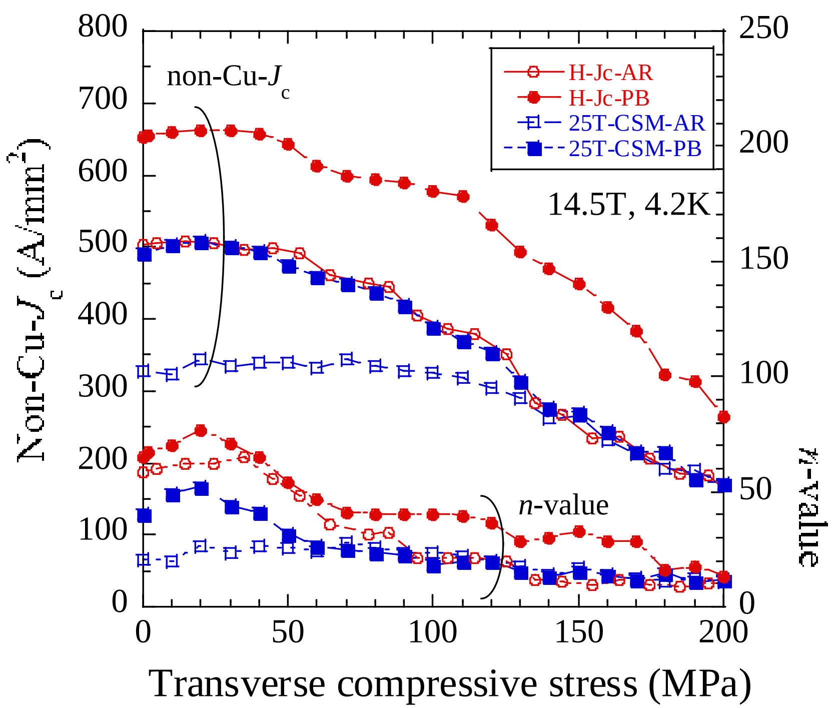
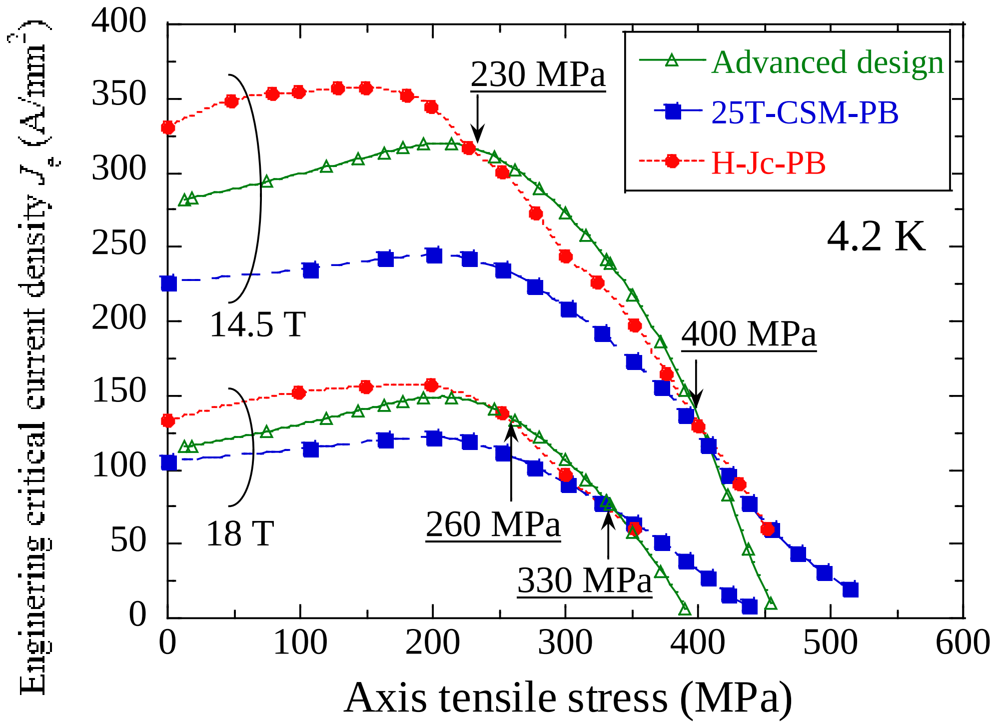




- The appropriate pre-bending treatment enable the Cu-Nb/Nb_3Sn wires to enhance not only superconductive performance at cryogenic temperature, but also mechanical performance for R&W process at room temperature.
- The Cu-Nb/Nb_3Sn wires are able to be designed to optimize superconducting properties according to the target application.

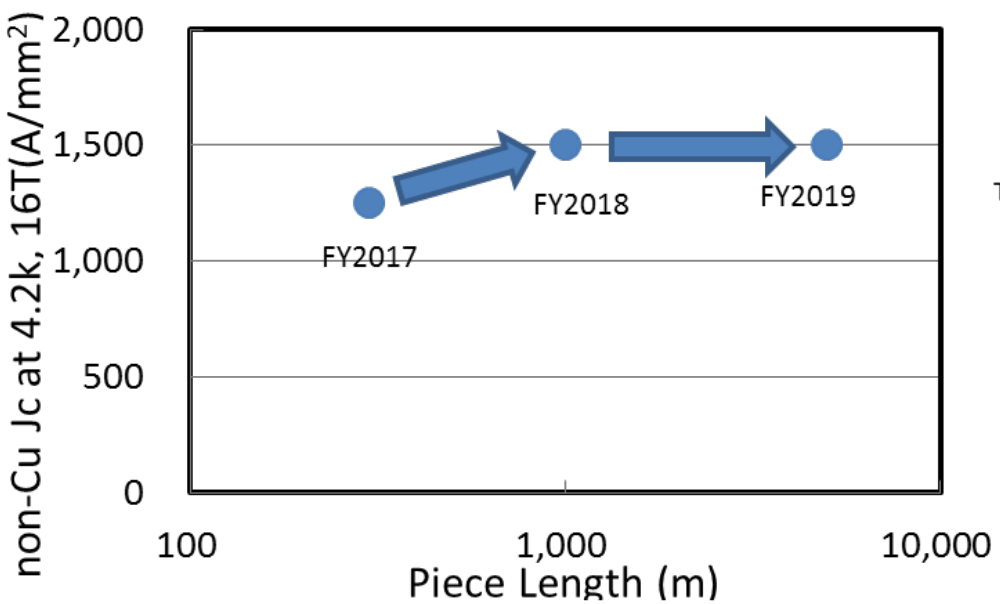
Motivation

- Jc of Bronze processed wire is limited by Sn content in bronze matrix.
- High Jc type wire is needed to respond future demand such as FCC.

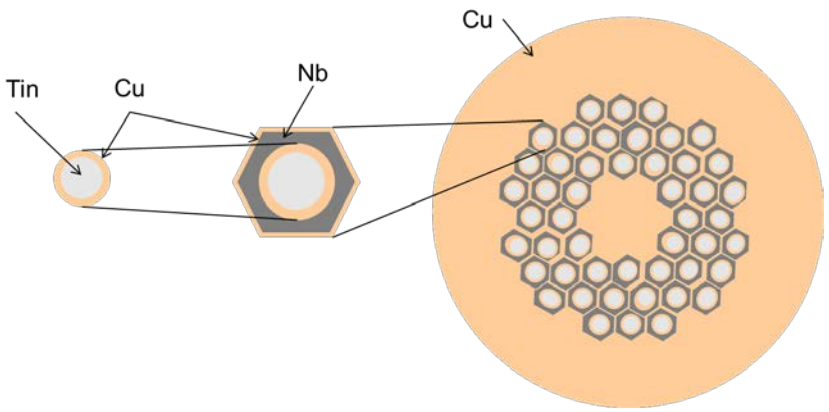
Process	Bronze	Internal Tin / Nb Tube
Sn source	△	◎
Non-Cu Jc	○	◎
Hys. Loss	◎	△
Uniformity	◎	○
Piece Length	◎	○

Milestone at the end of FY2019

- Non-Cu Jc at 4.2K, 16T: 1,500 A/mm^2
- Piece length : 5,000 m



Milestones for the Development



Schematic View of Wire (Nb tube)

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2G-HTS(REBCO) wire

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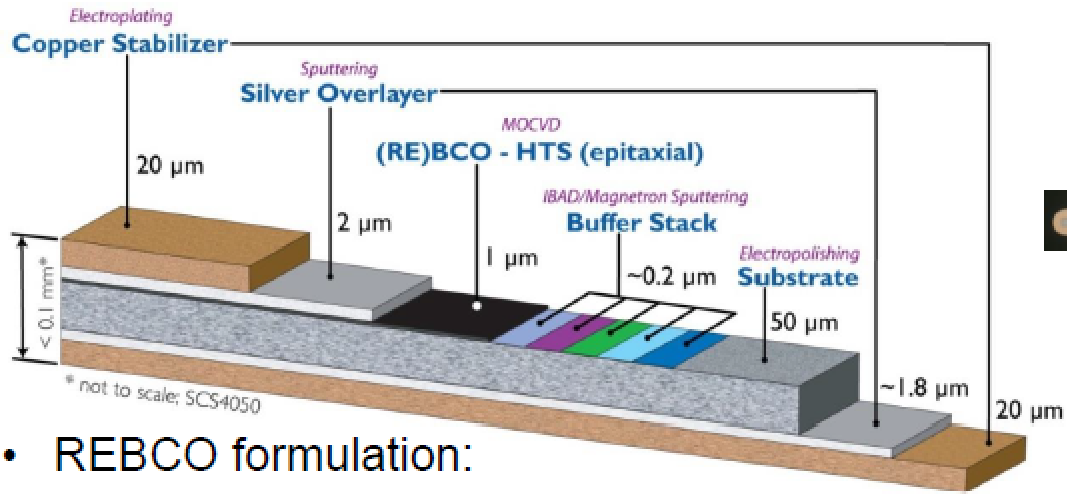
IBAD-MOCVD based REBCO wire on Hastelloy® substrate with artificial pinning



Schenectady, NY USA

Cross-sectional image of a Cu-plated wire

- REBCO formulation:
  - **AP** (Advanced Pinning) – with enhanced in-field performance for B//c, targeting at coil applications such as high-field magnets, SMES, motors/generators
  - **CF** (Cable Formulation) – for cables, transformers, FCL
- I_c(77K, s.f.)/12mm = 400-600A, piece length = up to 500m.
- Variations in width (2-12mm), substrate thickness (30, 50 or 100μm)
  Ag thickness (1-5μm), Cu thickness (10-115μm), and insulation
- Bonding conductors : 2x2mm, 2x4mm, 2x12mm (face to face / back to back)

Thinner substrate (30μmt)

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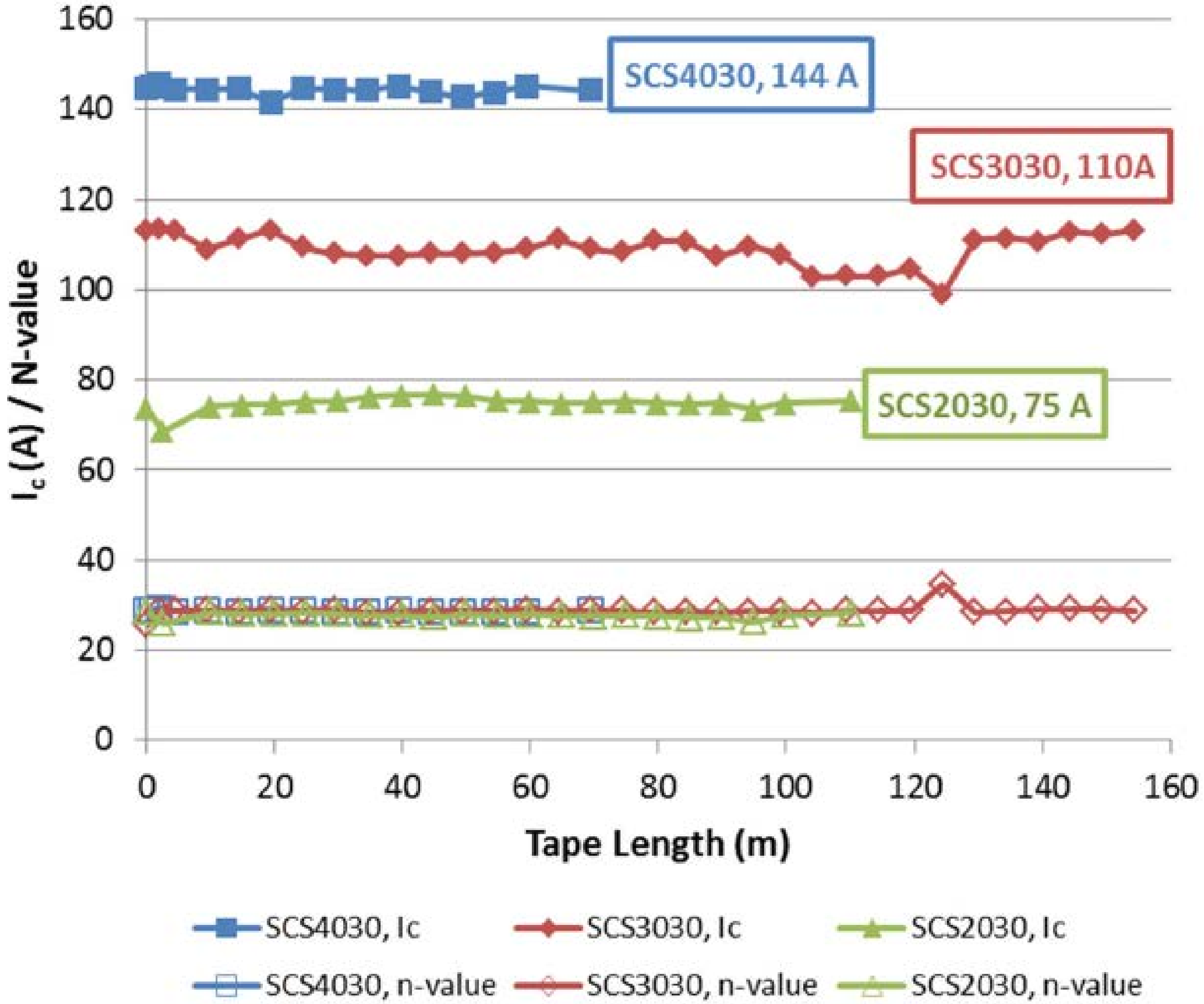

Improved Je demonstrated with 30μm tapes

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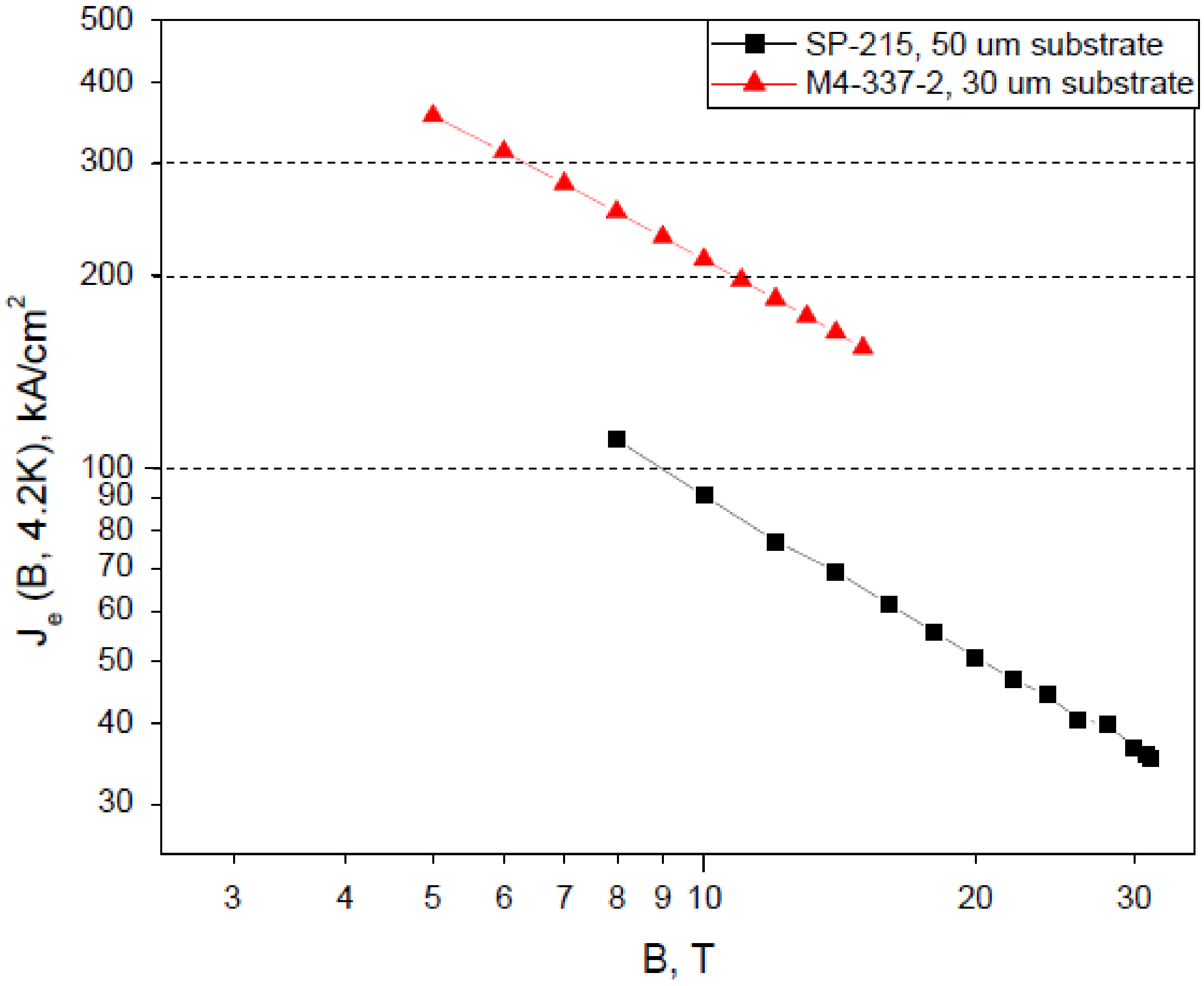
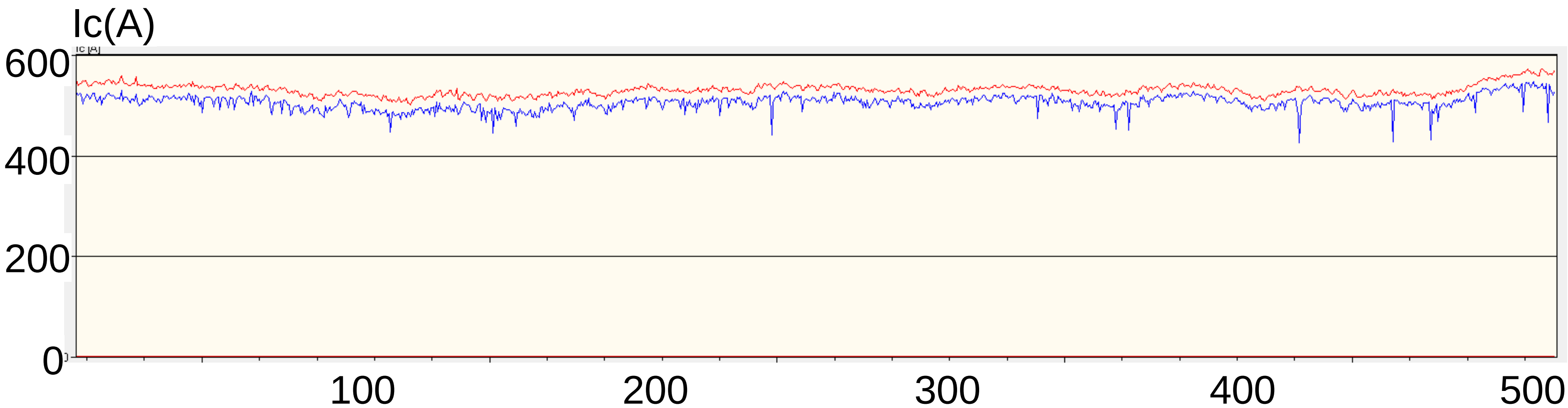
Engineering current density at 4.2 K vs. applied field for 30 um and 50 um ReBCO tapes with 7.5% Zr



Measured at NHMFL

Recent progress of SCS12030 AP wire

- Piece length : 515m
- Transport Ic(ave)=525A, Ic(min)=515A

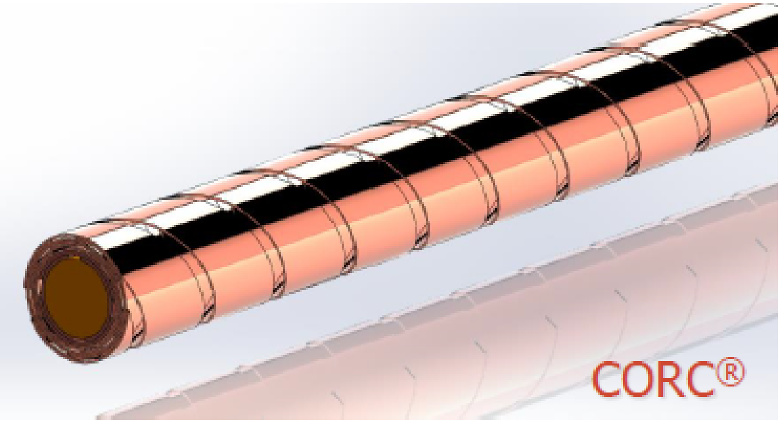


Ic of SCS12030-AP, 77K, self-field

CORC® wires using SuperPower tapes

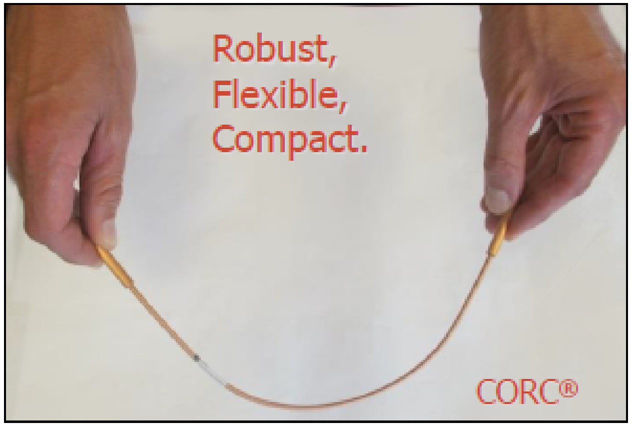
16 superpower tapes wound helically

- Copper core: 2.2 mm diameter
- 2 mm wide tapes with 30 μm substrate
- 6 mm twist pitch with partially transposed tapes for low AC loss
- Wire outer diameter: 3 mm
- Terminal diameter: 6.35 mm
- Nominal wire I_c: > 1,000 A (77 K)

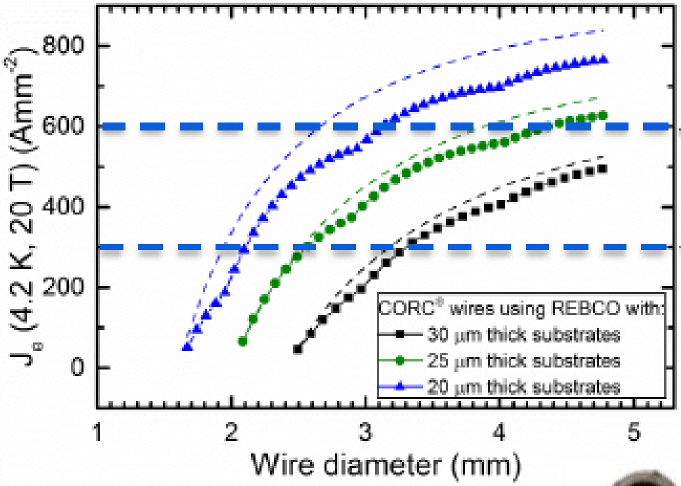


Applications

- High field magnets
- Accelerator magnets
- Fusion magnets
- High power density transmission



High magnetic field critical current density obtainable by increasing wire diameter and decreasing substrate thickness



Value desired for accelerator magnets such as CCT dipoles

Value desired for high-field research magnets

Advanced Conductor Technologies LLC
www.advancedconductor.com

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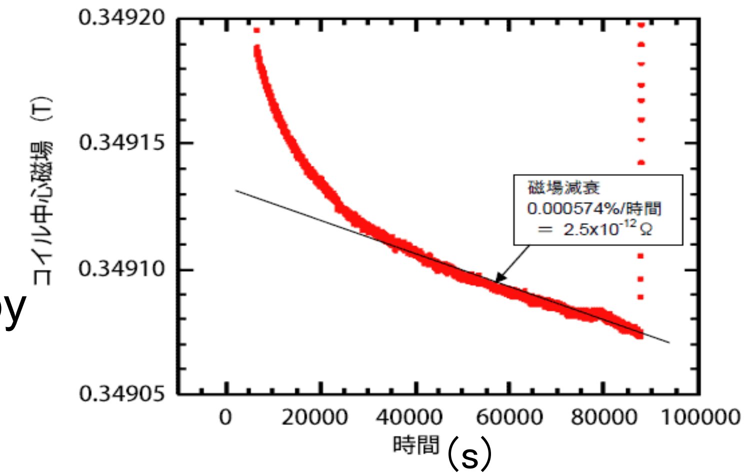
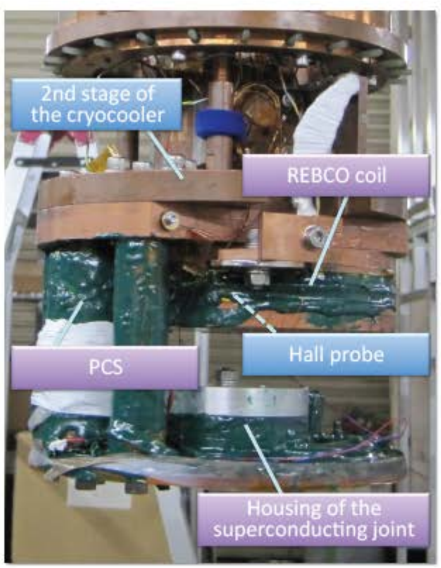
HTS Persistent Current System

- FEC has successfully developed the joint technology with a resistance of around $10^{-12}\Omega$ and PCS using REBCO tape.
- Performance of the System has investigated by Tohoku Univ.

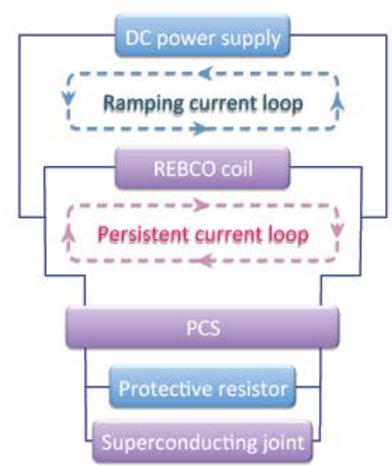
Mon-Af-Po1.09-13 Takahashi *et. al*



Magnetic field decay behavior of a REBCO coil in a persistent current operation[1]



REBCO tape	
Type	SuperPower® 2G-HTS SF6100-AP
Tape width / thickness (mm)	6 / 0.1
Substrate thickness (μm)	100
Superconductor thickness (μm)	1
Silver overlayer thickness (μm)	2
REBCO coil	
Coil type	Double pancake
Number of turns	80 × 2
Tape length (m)	14 × 2
Inner / outer diameter (mm)	44 / 68
Inductance (mH)	1.54
Reinforcement	SUS316 tape (50 μm)
REBCO PCS	
Tape length (cm)	50
Off resistance (mΩ)	> 50
Heater	Manganin wire (3 m)
REBCO superconducting jyoint	
→ EUCAS 2017 (A. Nakai, *et al.*, 4LP4-4)	



Schematic circuit diagram.

AMED
This work is supported by AMED

[1] News release of Furukawa Electric Co., Ltd., http://www.furukawa.co.jp/en/release/2016/kenkai_160427.html

Performance of a HTS Persistent Current System for REBCO Pancake Coil

HFLSM

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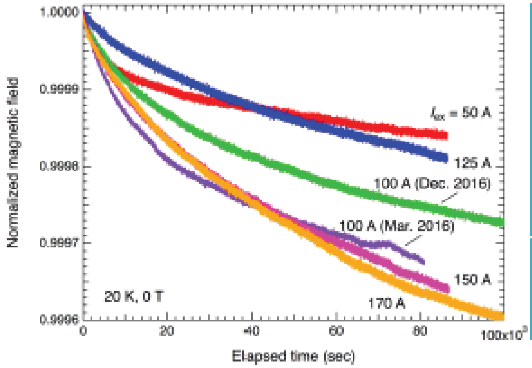
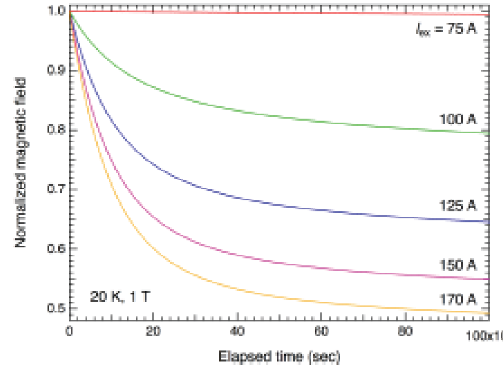


0 T	B_0 (T) @t = 0	Decay rate after 1 day (ppm/h)
50 A	0.175	1.9
100 A	0.348	3.1
125 A	0.434	4.8
150 A	0.521	8.1
170 A	0.590	6.0
		Decay rate after 5 days (ppm/h)
100 A		1.0
170 A		1.7

Magnetic field decay behavior of the REBCO coil in the persistent current operation at 20 K in the self field.

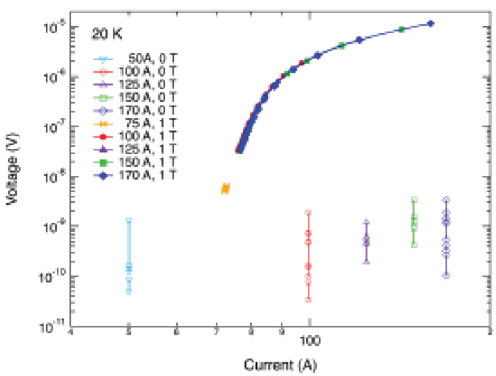


1 T	B_0 (T) @t = 0	Decay rate after 1 day (ppm/h)
75 A	0.254	1.6 x 10^2
100 A	0.339	1.1 x 10^3
125 A	0.420	1.2 x 10^3
150 A	0.497	1.3 x 10^3
170 A	0.556	1.3 x 10^3

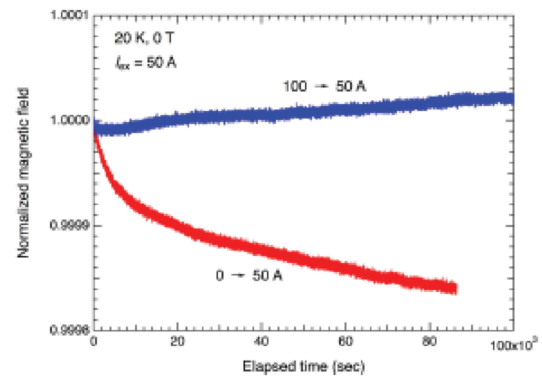
Magnetic field decay behavior of the REBCO coil in the persistent current operation at 20 K in 1 T.

- **No degradation was observed in 9 months.**
- **The decay rate of 170 A after 5 days was evaluated to be 1.7 ppm/h.**

- **Magnetic fields decay rapidly compared to ones in 0 T.**
- **The decay rate of 170 A after 1.5 days was evaluated to be 1.3 x 10^3 ppm/h.**



V–I characteristics obtained from the field decay curves.



Excitation process dependence of the magnetic field decay behavior.

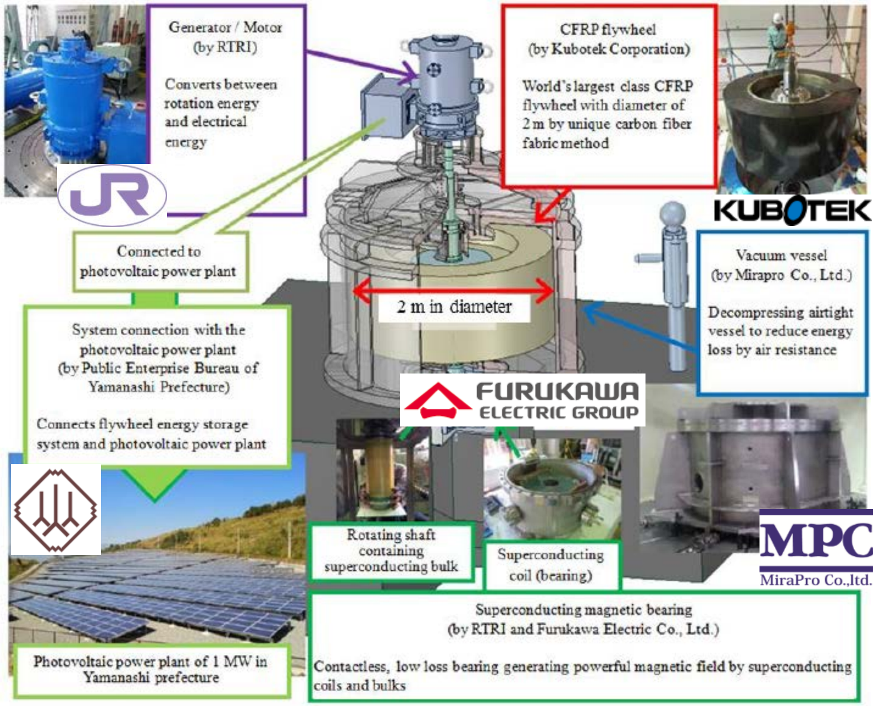
- **Curve for 1 T shows a typical behavior around the I_c.**

  I_c ≈ 90 A (1 μV criterion)
- **Voltages in 0 T show no systematic current dependence.**

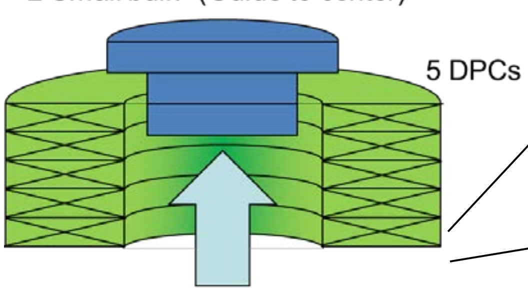
- **Decay behavior is changed by the excitation process.**

  Control of the shielding current is more important for improvements for the magnetic field stability.

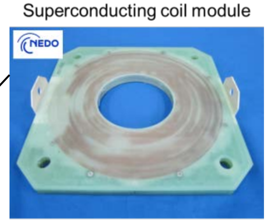
Superconducting Flywheel Energy Storage System(FESS)



1 Large bulk (Levitation force)
2 Small bulk (Guide to center)



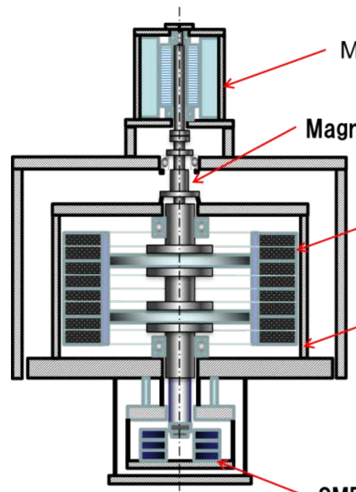
Superconducting coil module

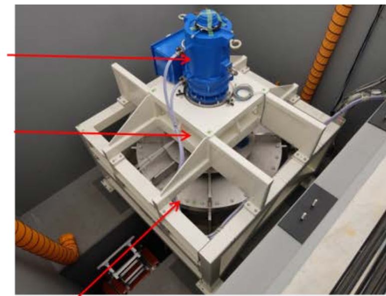


YOROI coil structure

Superconducting Magnetic Bearing(SMB)

KUBOTEK

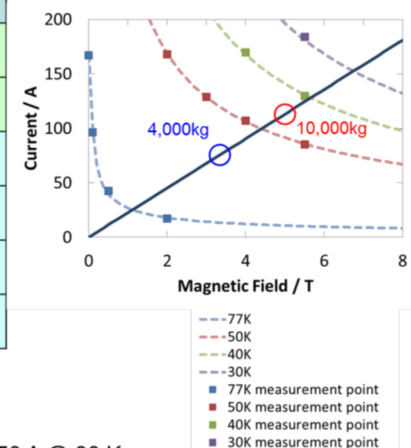




	Specification
Input / Output	300kW
Storage Energy	100 kWh at 6000 rpm
CFRP rotor	2 m diameter
	4000kg

	300kW model	1MW model
Rotor weight	4,000 kg	10,000kg
Rotor speed	6000 min^{-1}	6000 min^{-1}
Levitation height	20 mm	20 mm
Number of coils	5 Coils	5 or 7 Coils
Operation current	74 A	117A @ 5 coils 101A @ 7 coils
Maximum Field	3.4T	5.2T @ 5 coils 5.7T @ 7 coils

Load Line at 5 coils



Use 5 coil modules for 10,000kg load test
(Design was 7 coils)

Coils have enough Ic at 30K → Coil I_c = 150 A @ 30 K

NEDO This work is supported by NEDO

Summary

Furukawa Electric Group

- Has 50 years of Experience on Superconductor development.

- Distributes of Wide Range of Superconductors, such as NbTi, Nb_3Sn and 2G-HTS.

- Will contribute the progress of superconducting applications.

Thank you for your attentions !!

Bound to Innovate