Introduction of Fujikura RE-based High Temperature Superconductor

Superconductor Business Development Division
Fujikura Ltd.

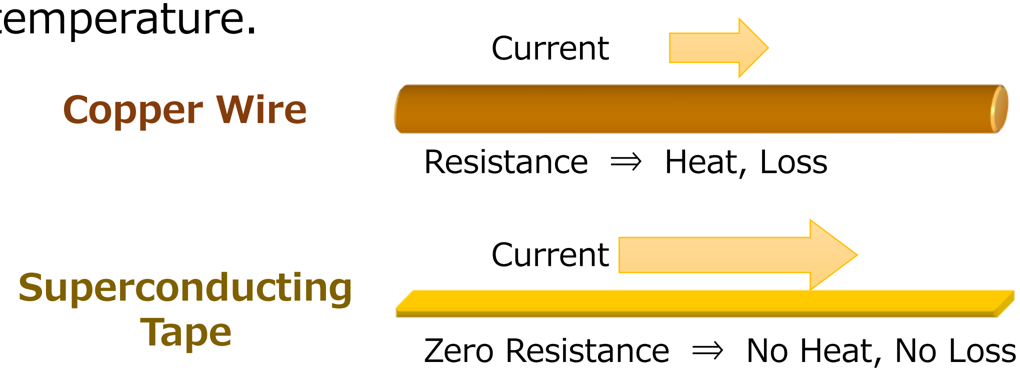
Fujikura

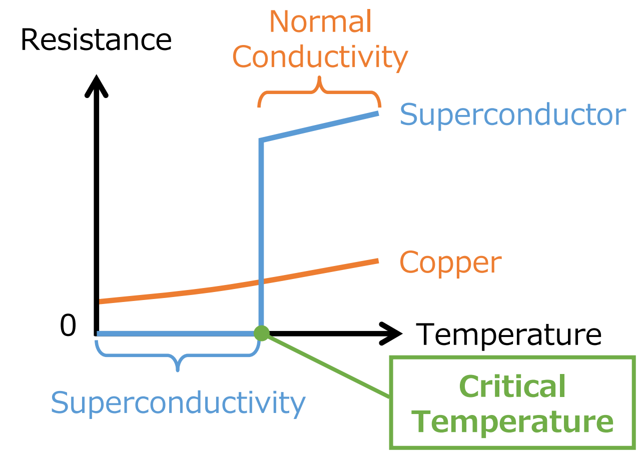
Rev. FEB2024

Characteristics of Superconductivity

■ Superconductivity

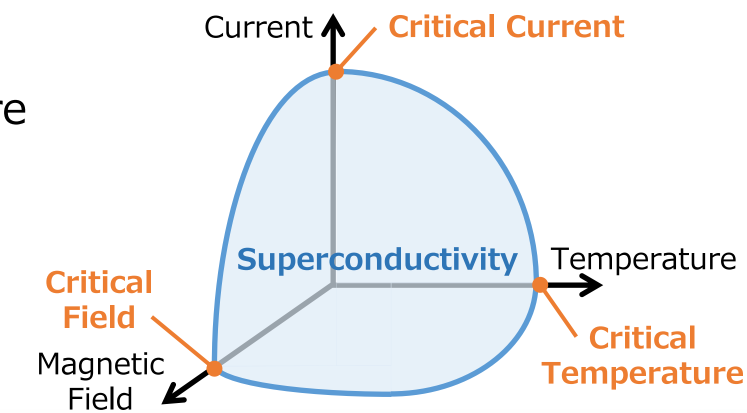
An electrical resistivity becomes exactly zero which occurs in certain materials below a characteristic temperature.



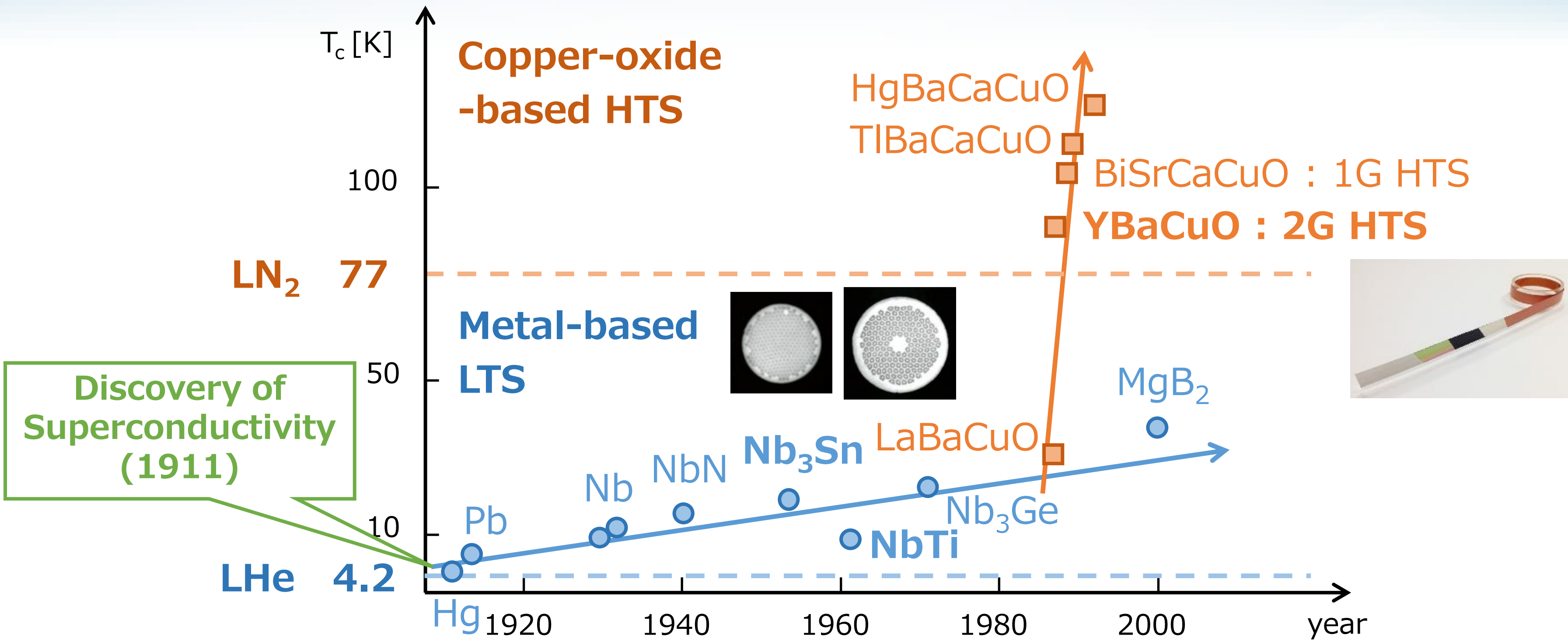


■ Three Critical Points at Superconducting State

- Critical Current --- Maximum current
- Critical Temperature --- Maximum temperature
- Critical Field --- Maximum magnetic field

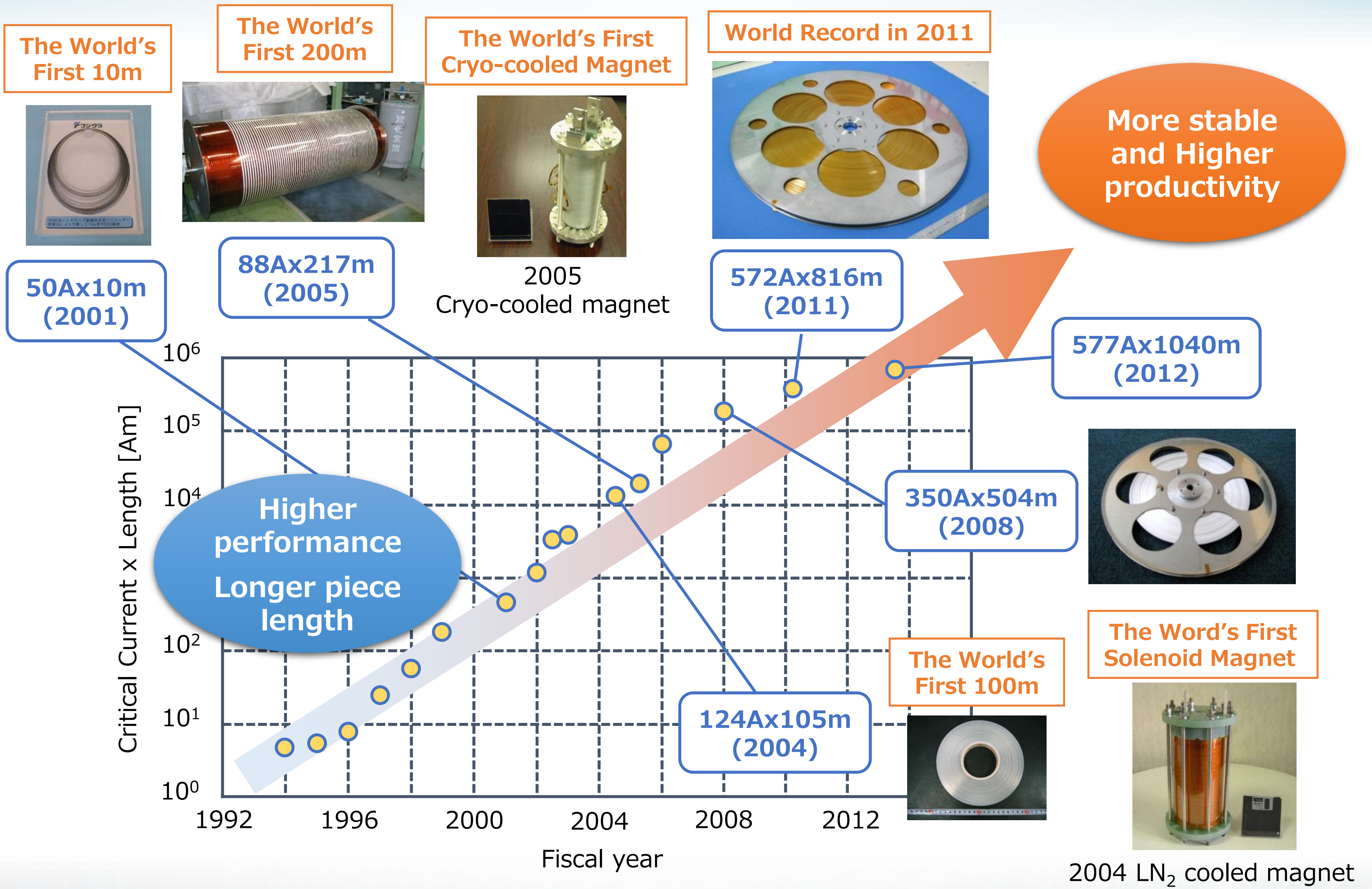


Historical Discovery of Superconductor



Low Temperature Superconductors (Metal-based)	• Cooling below LHe temperature required • Practical use in conventional superconducting applications
High Temperature Superconductors (Copper-Oxide-Based)	• Critical temperature higher than LN_2 temperature • Verification stage for practical use in indutrial applications Bismuth (Bi) : 1st generation (1G) **Yttrium (Y) or Rare-Earth : 2nd generation (2G)**

Historical Development of HTS at Fujikura



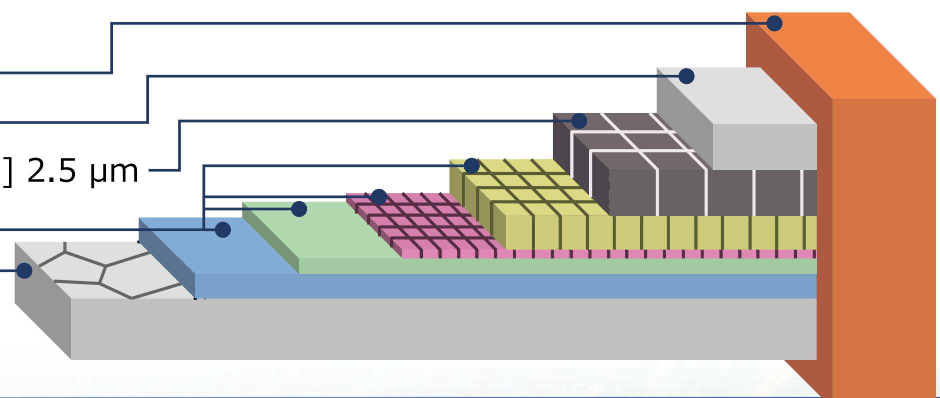
RE-based HTS Tape Products

■ Typical Specifications

Products	Width [mm]	Thickness [mm]	Substrate [μm]	Stabilizer [μm] *5	AP Option	Critical Current [A]	
						77K, S.F.	20K, 5T *4
FYSC-SCH04	4	0.13	75	20	Non-AP *2	≥ 165	368
FYSC-SCH12	12	0.13	75	20	Non-AP *2	≥ 550	1,104
FYSC-S12 *1	12	0.08	75	–	Non-AP *2	≥ 550	–
FESC-SCH02	2	0.11	50	20	AP *3	≥ 30	320
FESC-SCH03	3	0.11	50	20	AP *3	≥ 63	480
FESC-SCH04	4	0.11	50	20	AP *3	≥ 85	640
FESC-SCH04(05)	4	0.07	50	5	AP *3	≥ 85	640
FESC-SCH12	12	0.11	50	20	AP *3	≥ 250	1,920
FESC-S12 *1	12	0.06	50	–	AP *3	≥ 250	–

*1 Non-copper stabilizer specification is available in only 12mm-wide for current lead or low thermal conducting applications.
*2 Non-AP specification is mainly for conductors or other general use at relatively higher temperature.
*3 Artificial pinning specification is mainly for use in magnet applications at low temperature and high magnetic field.
*4 Ic at 20K,5T is a reference value and no guarantee of the actual performance.
*5 If requested, an option customizing copper thickness is also available. (e.g., 5μm, 10μm or 40μm)

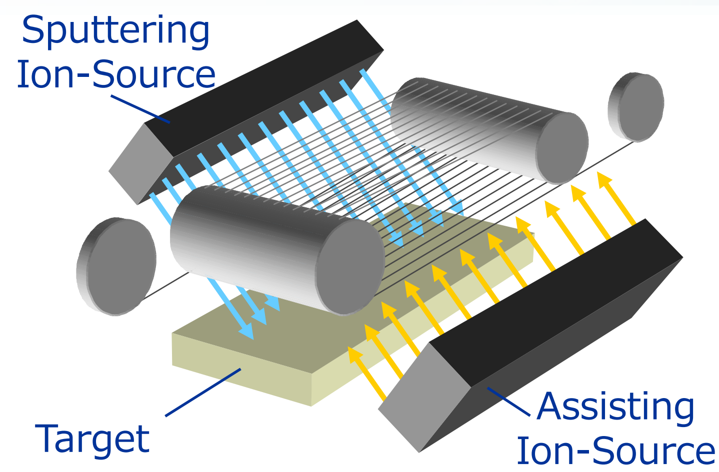
<Schematic of RE-based HTS tape>

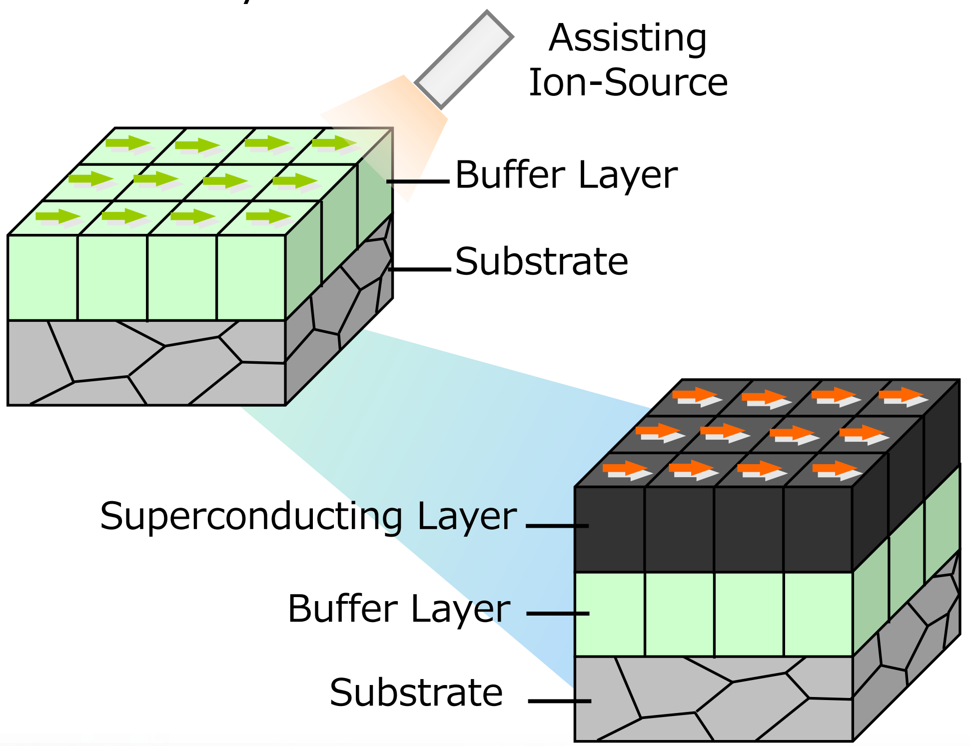


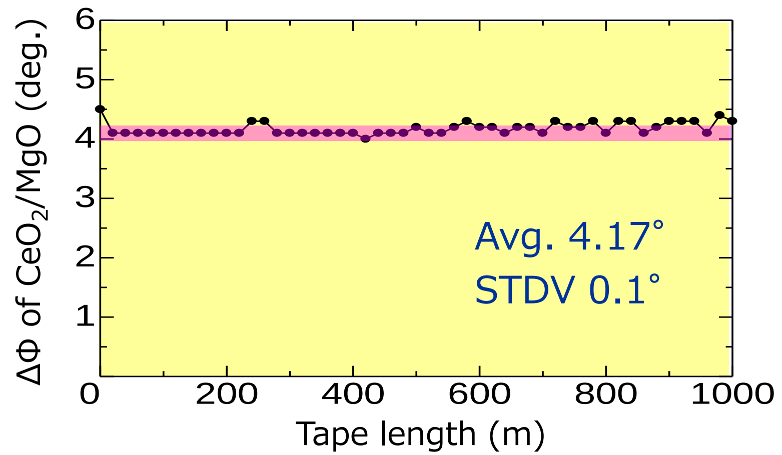
Key Technology for High Ic Performance

■ Ion Beam Assisted Deposition; IBAD

- Fabricating process of buffer layer
- Fujikura original technique (Developed in 1991)
- IBAD enables to fabricate high-textured buffer layer.





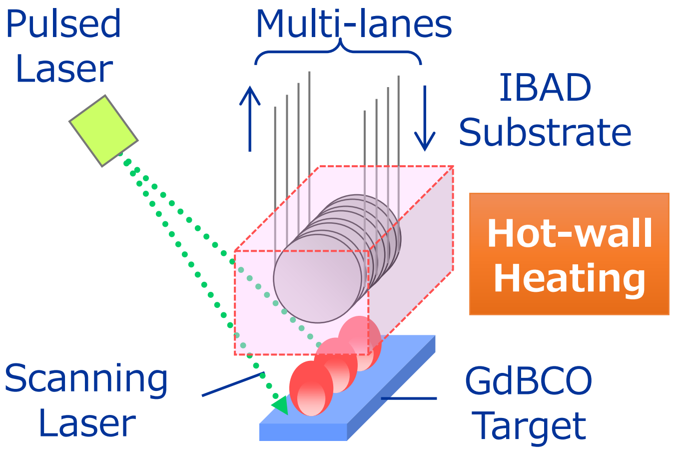


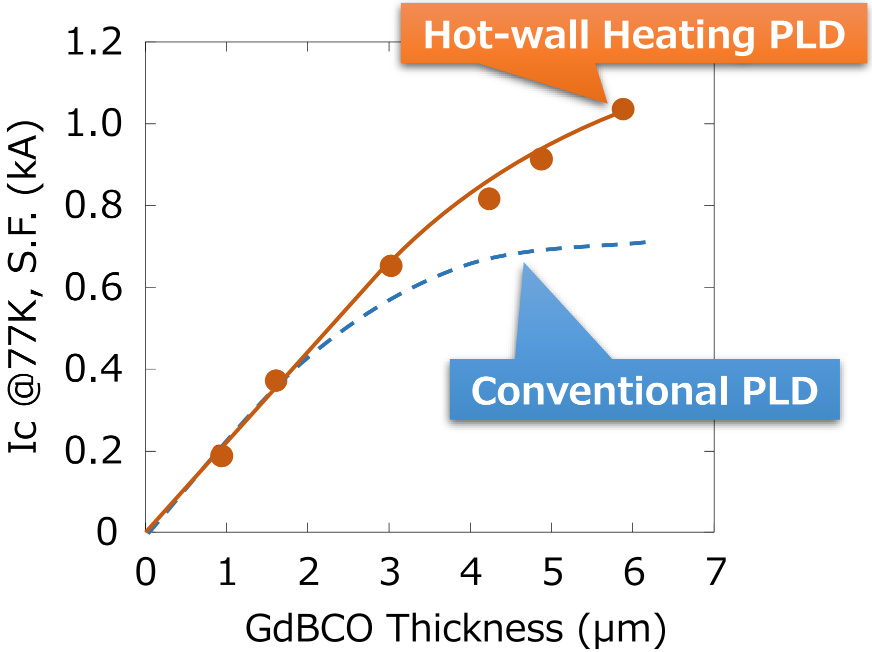
1km-length PLD-CeO_2/IBAD-MgO Substrate

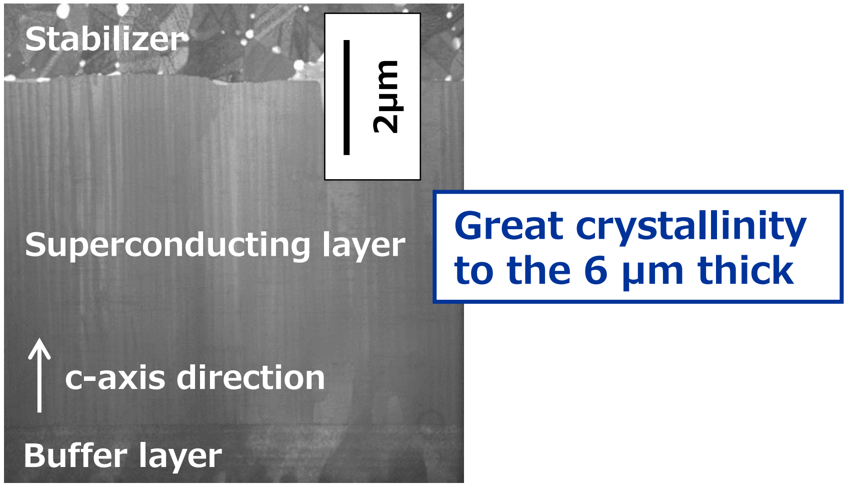
Key Technology for High Ic Performance

■ Pulsed Laser Deposition; PLD

- Fabricating process of superconducting layer
- Hot-wall heating system is Fujikura original.
- Stable temperature during deposition enables higher superconducting performance than conventional type PLD.



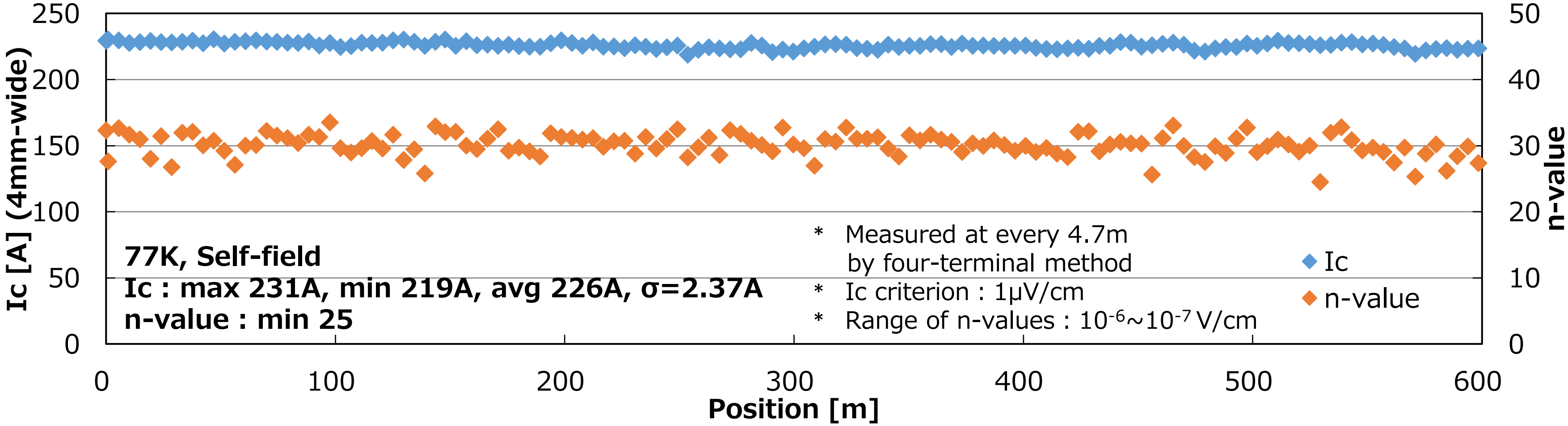




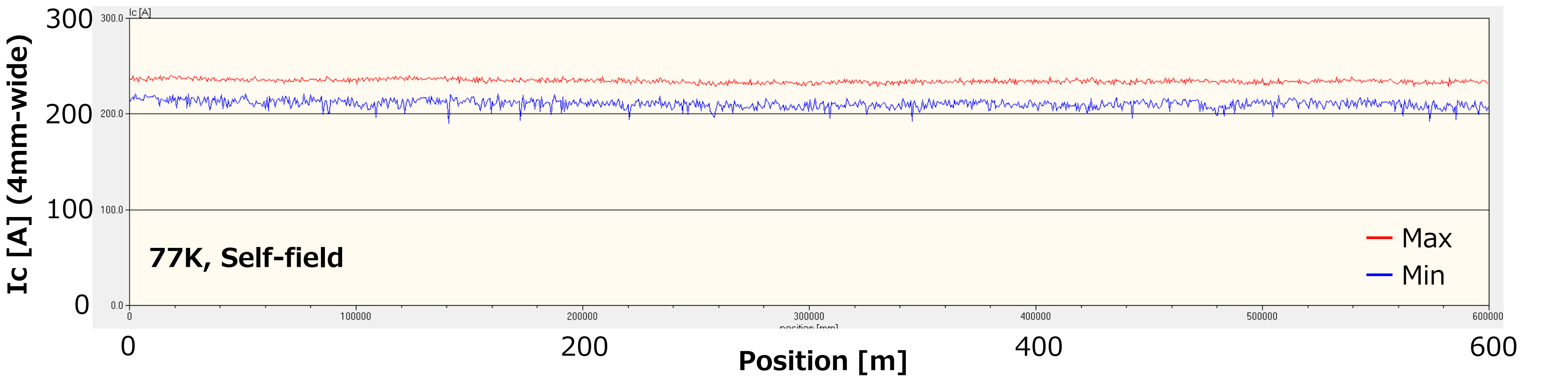
Cross Sectional TEM Image

Ic Uniformity of 4mm-wide - Non AP

■ Current conduction measurement - 4mm-wide without AP (FYSC-SCH04)



■ Magnetic measurement @Tapestar™ - 4mm-wide without AP (FYSC-SCH04)



Ic Uniformity of 12mm-wide - Non AP

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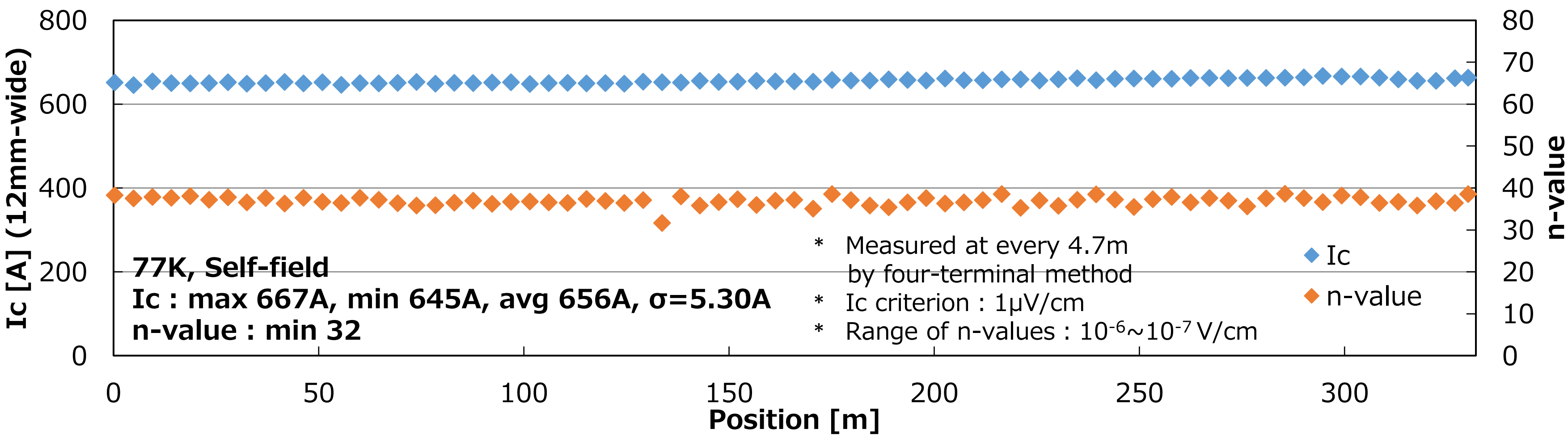
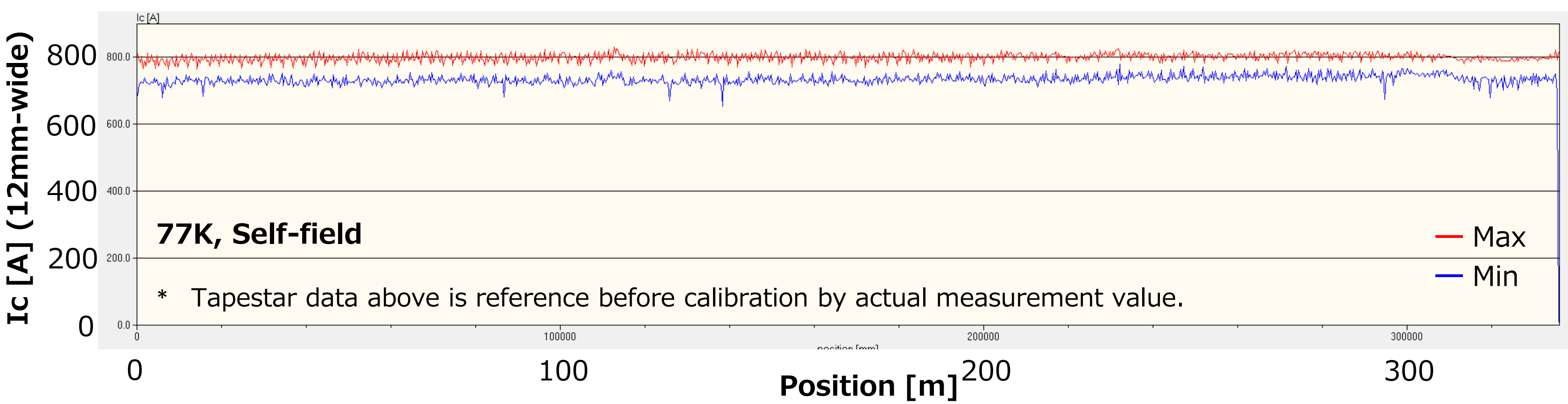
■ Current conduction measurement - 12mm-wide without AP (FYSC-SCH12)



■ Magnetic measurement @Tapestar™ - 12mm-wide without AP (FYSC-SCH12)



Ic Uniformity of 4mm-wide - AP

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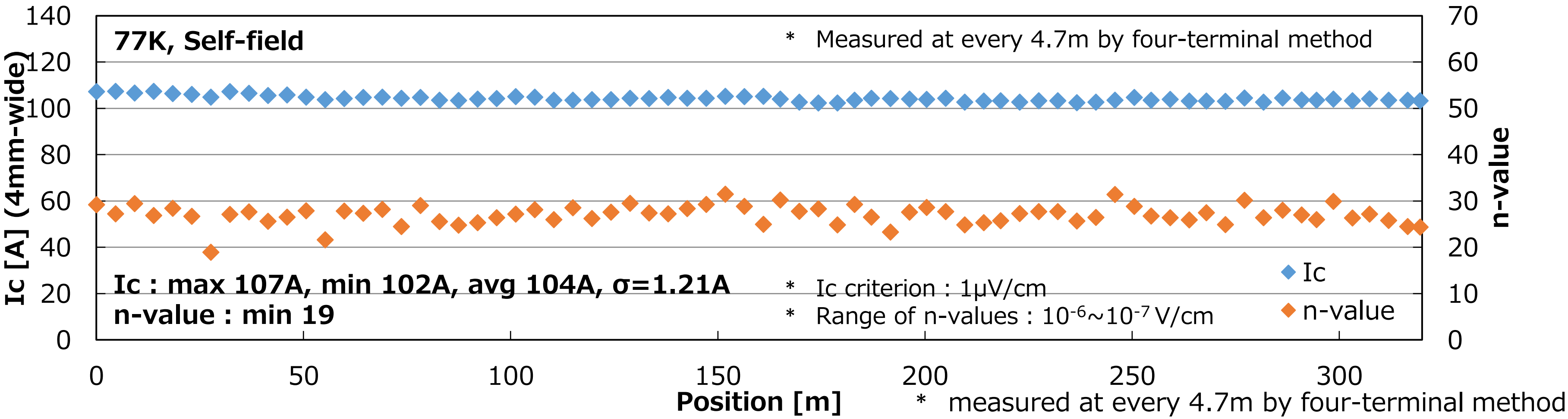
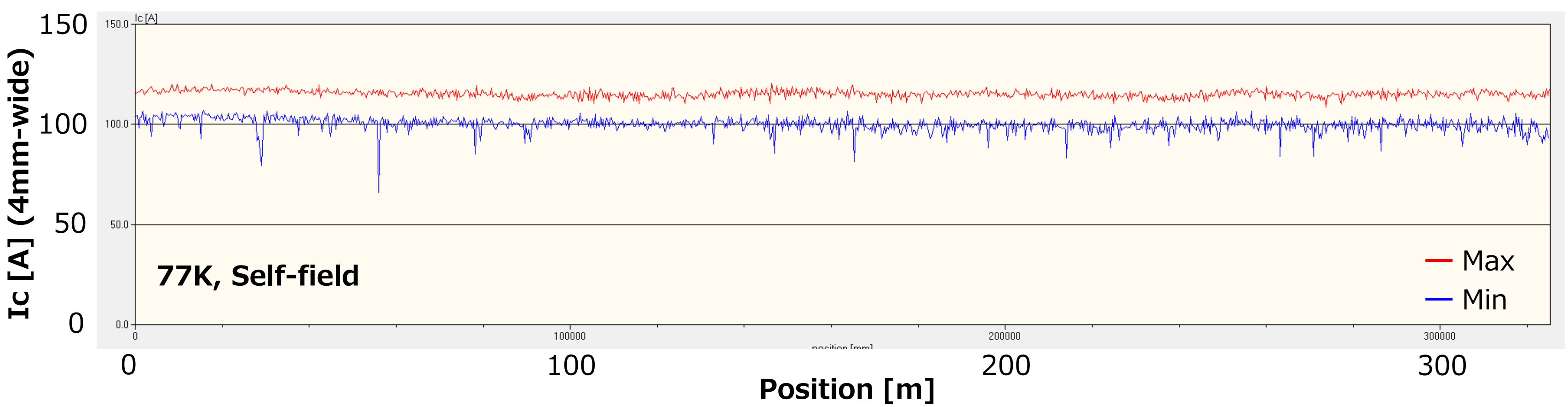
■ Current conduction measurement - 4mm-wide with AP (FESC-SCH04)



* measured at every 4.7m by four-terminal method

■ Magnetic measurement @Tapestar™ - 4mm-wide with AP (FESC-SCH04)



Ic Uniformity of 12mm-wide - AP

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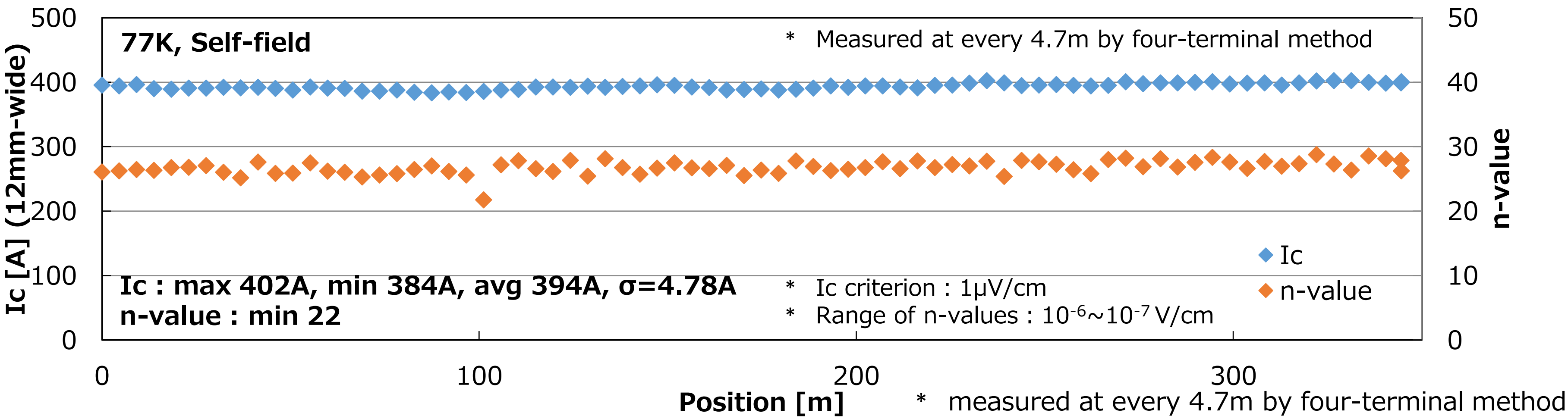
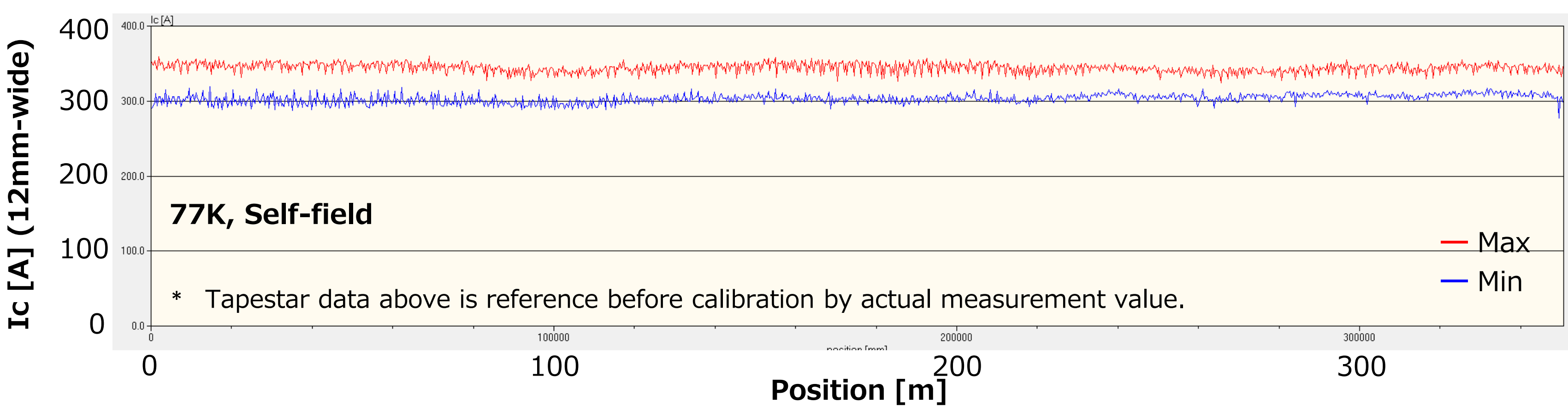
■ Current conduction measurement - 12mm-wide with AP (FESC-SCH12)



■ Magnetic measurement @Tapestar™ - 12mm-wide with AP (FESC-SCH12)

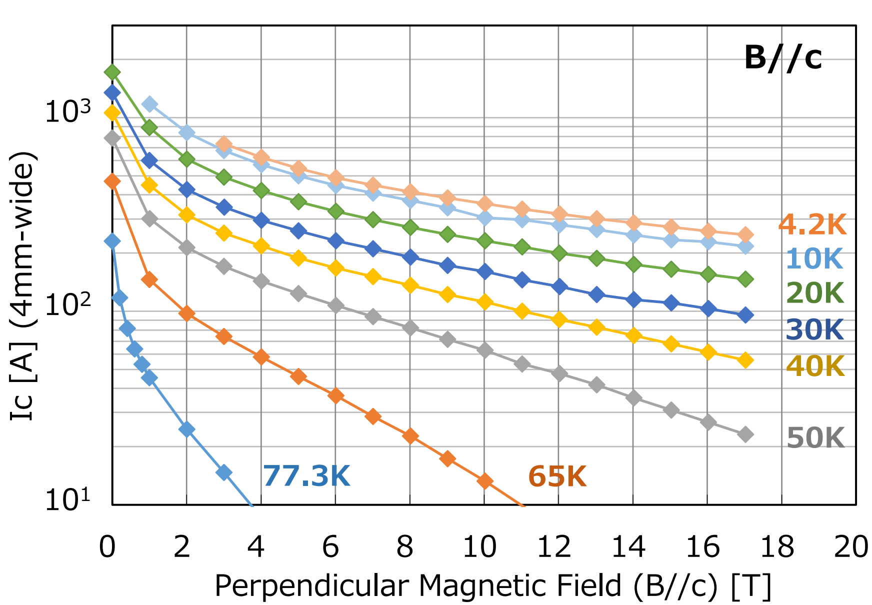


■ **Typical in-field Ic performance without artificial pinning (FYSC) (Reference)**

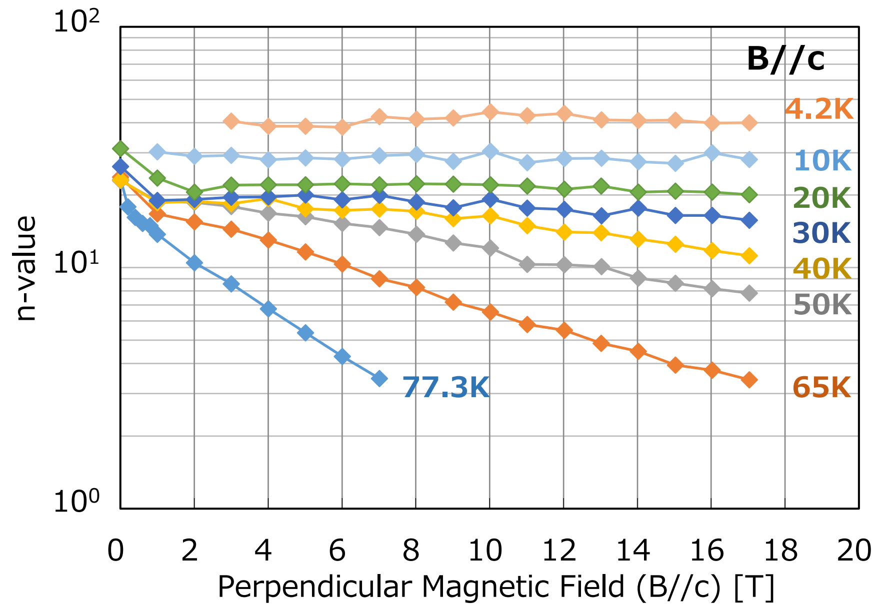
Sample : Ic = 230A at 77K,Self-field (4mm-wide) (Superconducting layer thickness: 1.9μm)

➢ **Perpendicular Magnetic Field (B//c)**

Ic - B - T



n-value - B - T



* This work includes some data measured at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

In-field Ic Performance - Non AP (B//ab)

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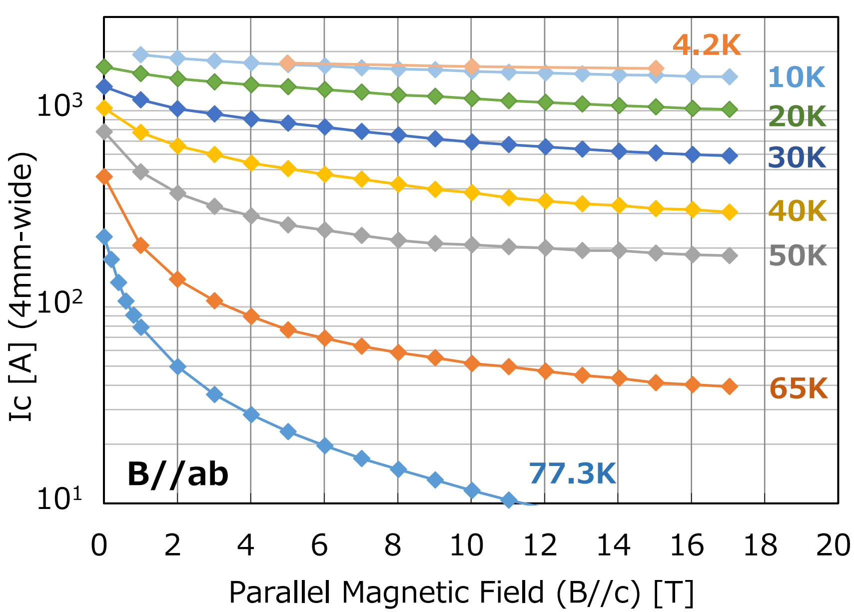
■ Typical in-field Ic performance without artificial pinning (FYSC) (Reference)

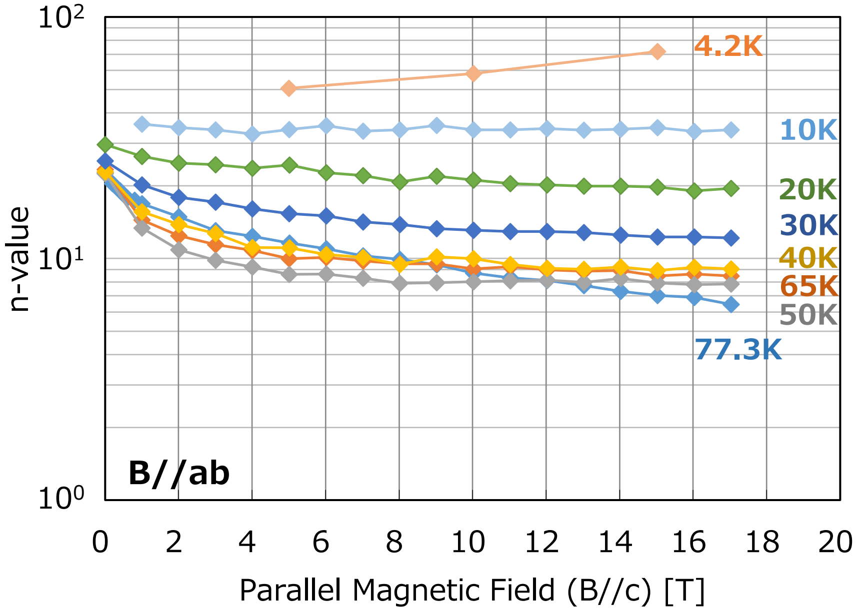
Sample : Ic = 230A at 77K,Self-field (4mm-wide) (Superconducting layer thickness: 1.9μm)

➢ Parallel Magnetic Field (B//ab)

Ic - B - T



n-value - B - T



* This work includes some data measured at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

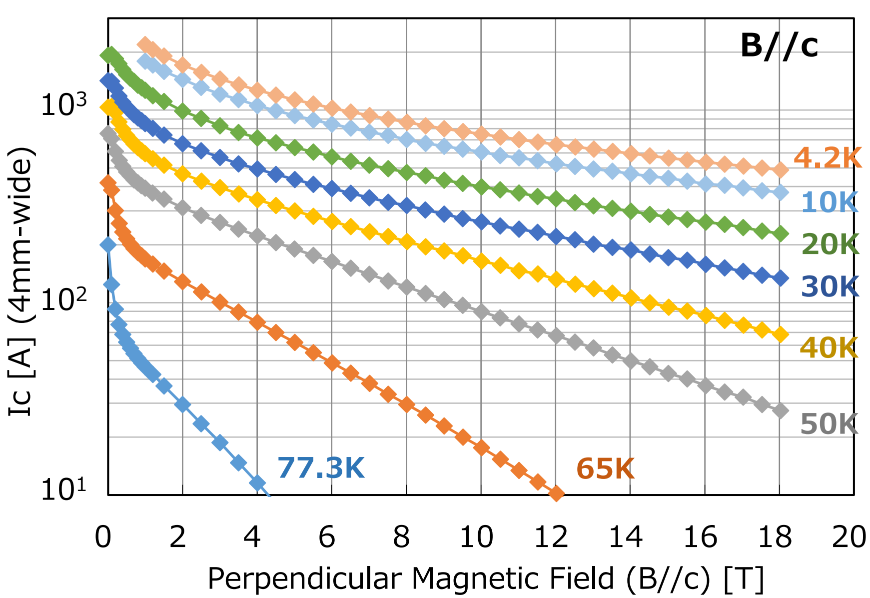
In-field Ic Performance - AP (B//c)

■ **Typical in-field Ic performance with artificial pinning (FESC) (Reference)**

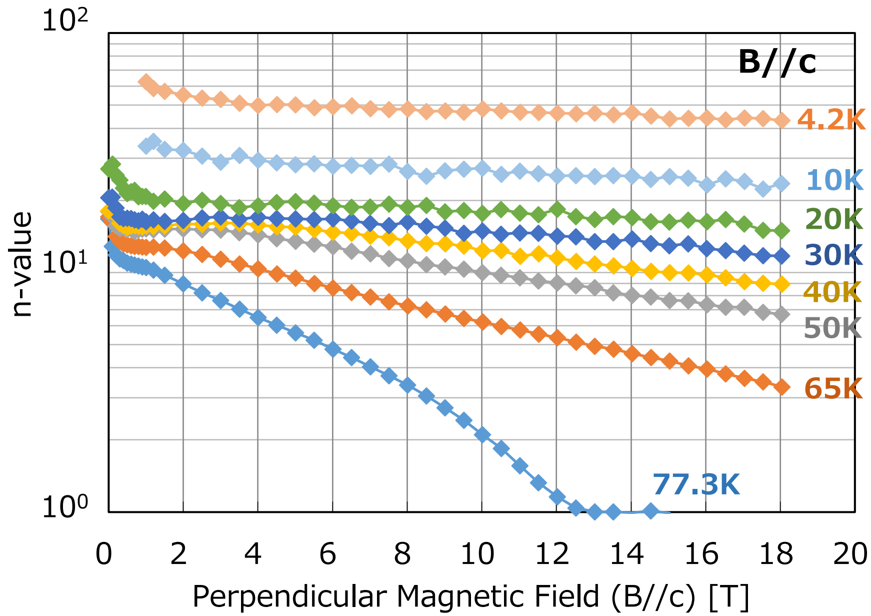
Sample : Ic = 200A at 77K,Self-field (4mm-wide) (Superconducting layer thickness: 2.4μm)

➢ **Perpendicular Magnetic Field (B//c)**

Ic - B - T



n-value - B - T



* This work includes some data measured at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

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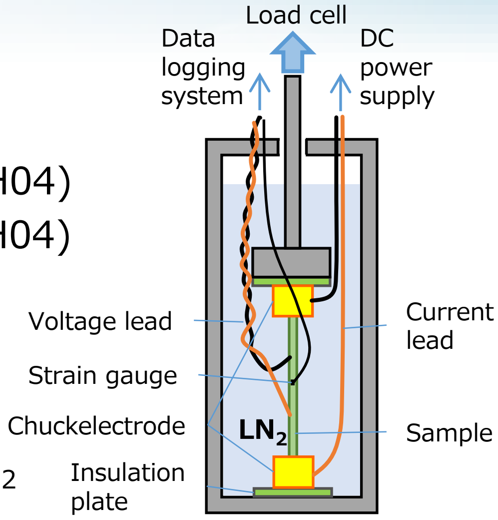
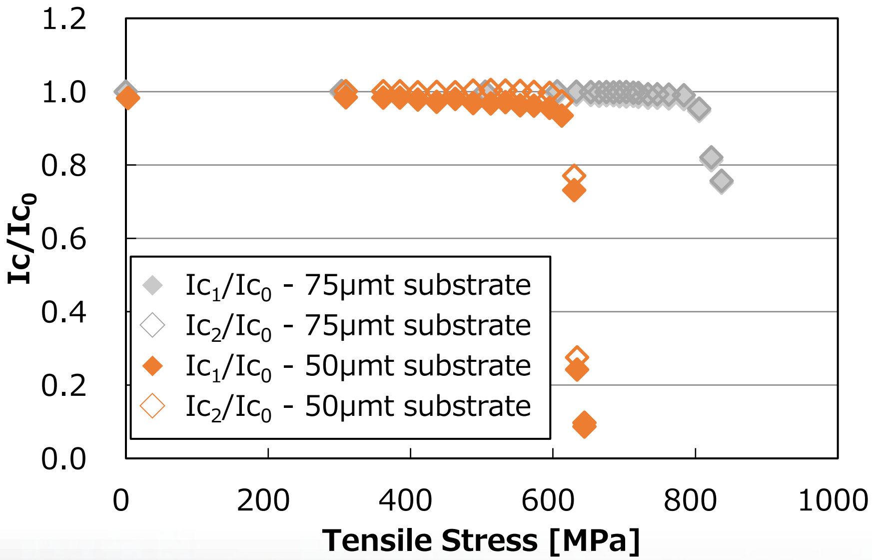
■ Tensile stress evaluation at LN_2 temperature (Reference)

- Sample :
  4mm-wide, 75 µm-thick Hastelloy + 20 µm-thick Cu plating (FYSC-SCH04)
  4mm-wide, 50 µm-thick Hastelloy + 20 µm-thick Cu plating (FESC-SCH04)
- Measurement method :
  1. Ic measurement without load in LN_2 (Ic_0)
  2. Ic measurement with applying tensile strain in LN_2 (Ic_1)
  3. Ic measurement without load (Ic_2) after applying tensile strain in LN_2

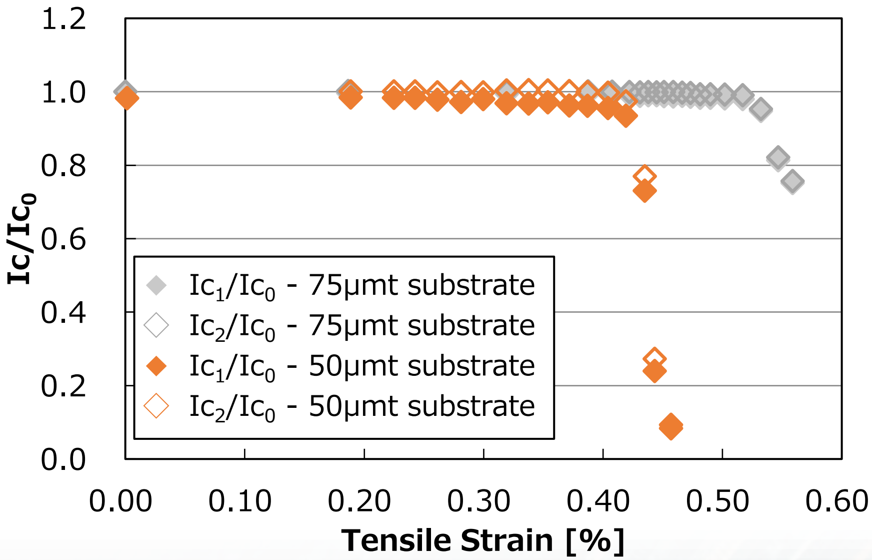


Schematic of tensile test

Ic/Ic_0 versus tensile stress



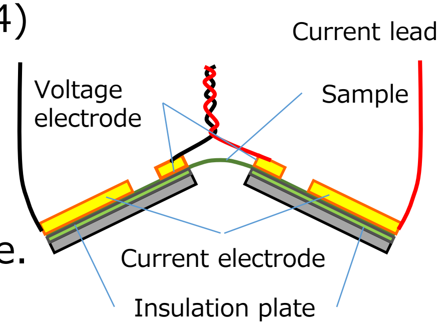
Ic/Ic_0 versus tensile strain



Bending Property

■ Bending property evaluation at LN_2 temperature (Reference)

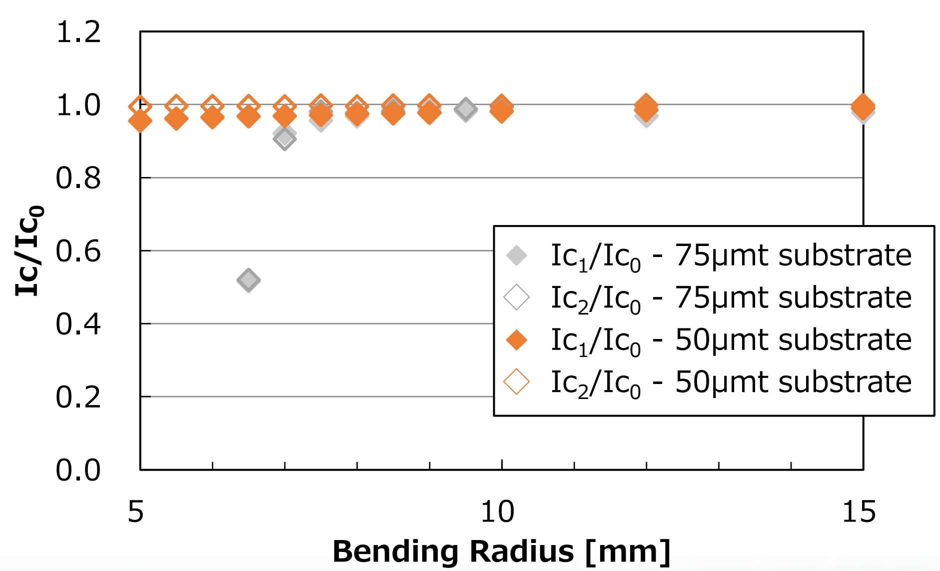
- Sample :
  4mm-wide, 75 µm-thick Hastelloy + 20 µm-thick Cu plating (FYSC-SCH04)
  4mm-wide, 50 µm-thick Hastelloy + 20 µm-thick Cu plating (FESC-SCH04)
- Measurement method ("Goldacker" continuous bending method) :
  1. Ic measurement in straight in LN_2 (Ic_0)
  2. Ic measurement with applying bending strain at LN_2 (Ic_1)
     * Bending direction is tensile direction with superconducting layer outside.
  3. Ic measurement in straight (Ic_2) after applying bending strain in LN_2



Schematic of bending test

Ic/Ic_0 versus bending radius

No Ic degradation for 50µmt substrate observed below the measurement limit bending radius of 5mm



Compressive Stress in Thickness Direction

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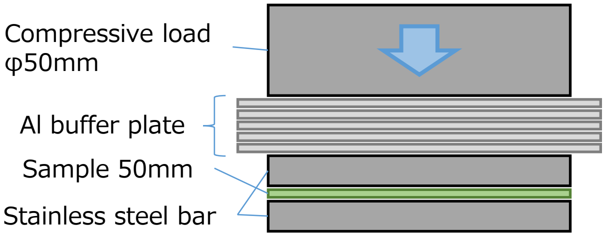
■ Compressive stress evaluation in thickness direction at RT (Reference)

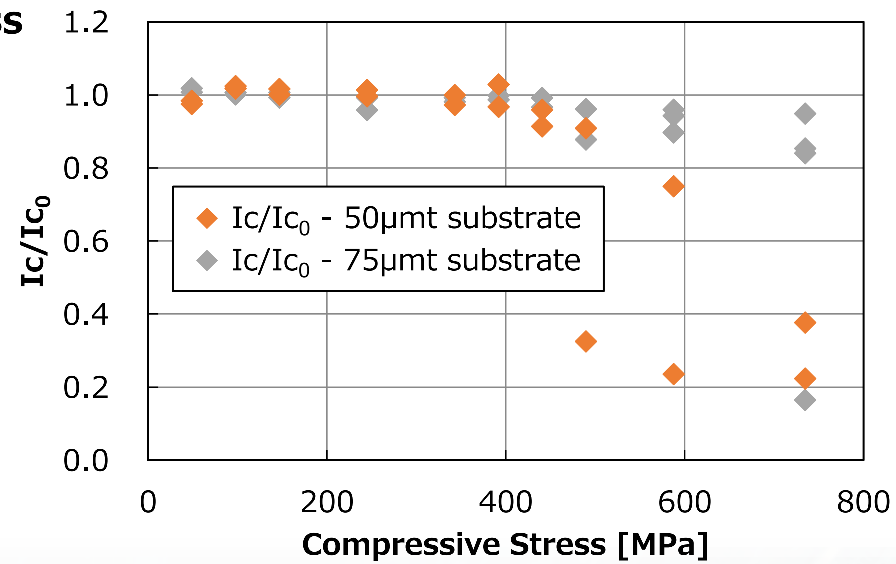
- Sample :
  4mm-wide, 75 μm-thick Hastelloy + 20 μm-thick Cu plating (FYSC-SCH04)
  4mm-wide, 50 μm-thick Hastelloy + 20 μm-thick Cu plating (FESC-SCH04)
- Measurement method :
  1. Ic measurement in LN_2 (Ic_0)
  2. Apply compressive load in thickness direction of the sample at room temperature
  3. Ic measurement in LN_2 (Ic) after removing compressive load



Schematic of compressive test in thickness direction

Ic/Ic_0 versus compressive stress

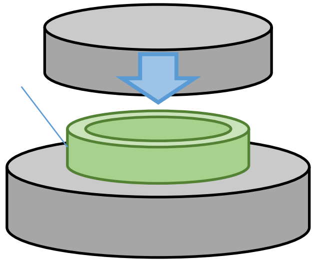
No Ic degradation observed below 400 MPa of compressive stress in thickness direction



Compressive Stress in Width Direction

■ Compressive stress evaluation in width direction at RT (Reference)

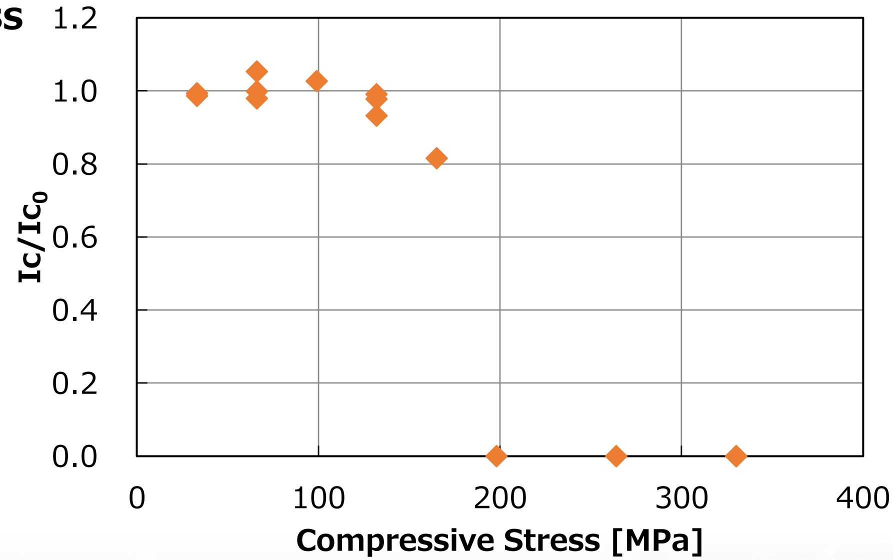
- Sample :
  4mm-wide, 50 μm-thick Hastelloy + 20 μm-thick Cu plating (FESC-SCH04)
- Measurement method :
  1. Ic measurement in LN_2 (Ic_0)
  2. Apply compressive load in width direction of the coiled sample at room temperature
  3. Ic measurement in LN_2 (Ic) after removing compressive load



Schematic of compressive test in width direction

Ic/Ic_0 versus compressive stress

No Ic degradation for 50μmt substrate observed below 100 MPa of compressive stress in width direction



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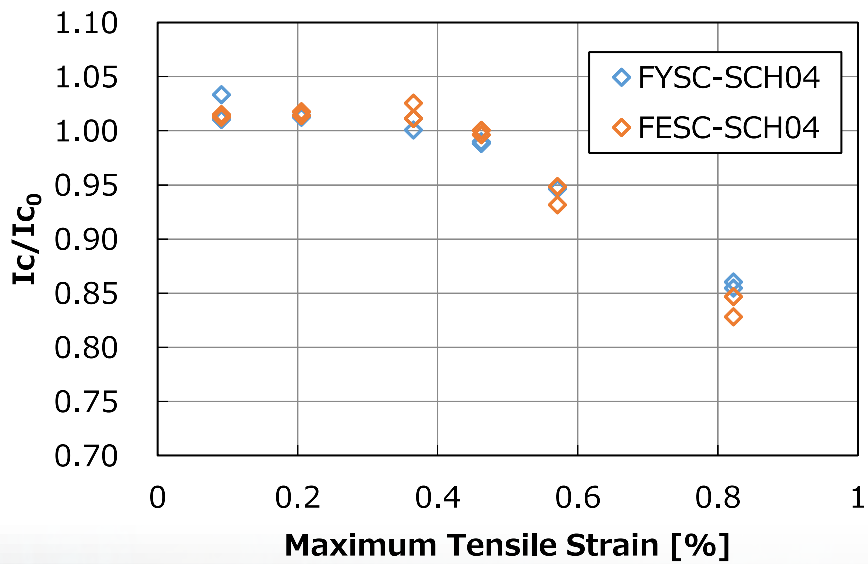
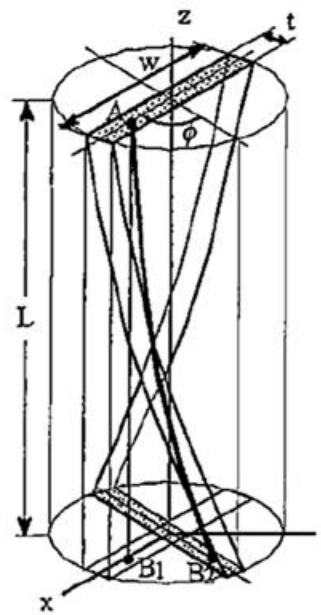
■ Twisting test at room temperature (Reference)

- Sample :
  4mm-wide, 75 μm-thick substrate + 20 μm-thick Cu plating (FYSC-SCH04)
  4mm-wide, 50 μm-thick substrate + 20 μm-thick Cu plating (FESC-SCH04)
- Measurement method :
  1. Ic measurement in straight in LN_2 (Ic_0)
  2. Apply twisting load at one side of the sample at room temperature
     (Twist pitch=240mm, Tension load=2kgf)
  3. Ic measurement in LN_2 (Ic) after removing twisting load

Ic/Ic_0 versus bending radius



$$\varepsilon = \frac{\phi^2}{2L^2}\left(x^2 - \frac{w^2}{12}\right)$$

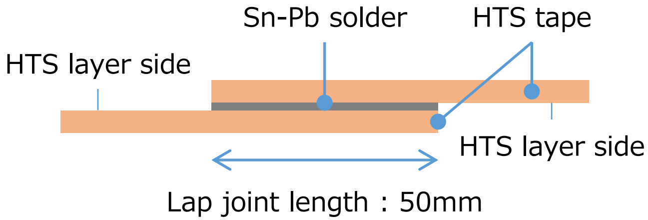


M. Takayasu, et al., AIP Conf Proc 1219, 337 (2010)

Joint Resistivity

■ Solder lap joint resistivity (Reference)

- Sample :
  4mm-wide, 50 µm-thick substrate + 20 µm-thick Cu plating (FESC-SCH04)
  Joint sample with lap joint length of 50mm using Sn-Pb solder, with both superconducting layer sides facing
- Measurement method :
  1. Measure joint resistance in LN_2 (at 77K) with DC of 100A
  2. Calculate a solder lap joint resistivity



Schematic of sample

Example measurement results of FESC-SCH04

Sample (n=6)	Joint resistance at 77K (50mm) [nΩ]	Joint resistivity at 77K [nΩcm^2]
Avg	27.3	54.5
Max	33.6	67.2
Min	21.4	42.8

AC Loss (Reference)

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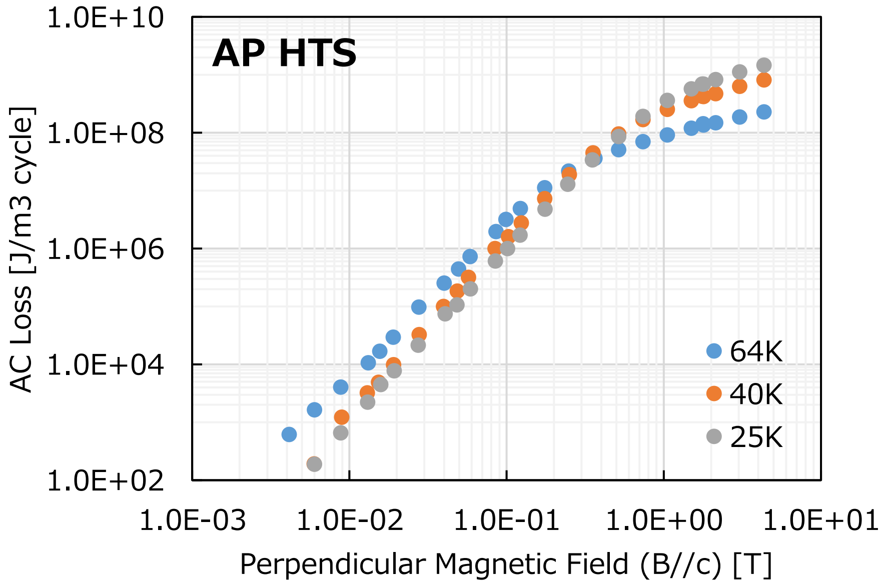
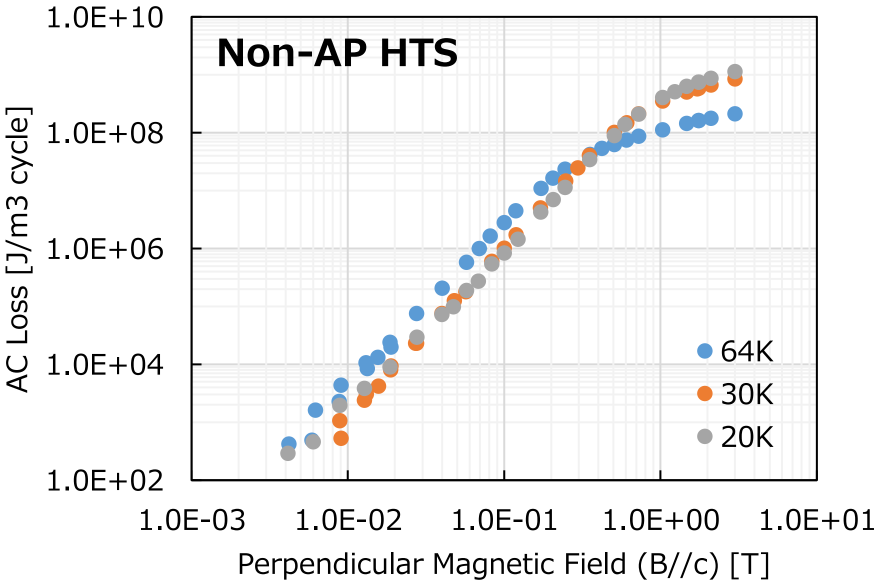
■ Measurement Condition

Sample	• Artificial pinning (AP; FESC) type, 4mm wide, 50um thick substrate + 20um thick copper plating • Non-artificial pinning (Non-AP; FYSC) type , 4mm wide, 75um thick substrate + 20um thick copper laminate (Old specification)
Temperature	20 - 64 K
Magnetic field (B//c)	0.04 - 4.3 T
Magnetic field frequency	0.01 - 0.2 Hz

■ Measurement Results

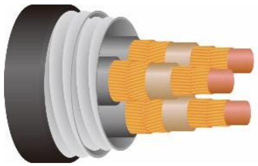


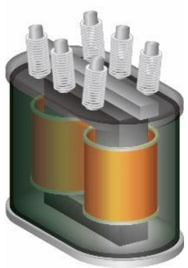


This work includes the data measured at Kyushu University, Japan.

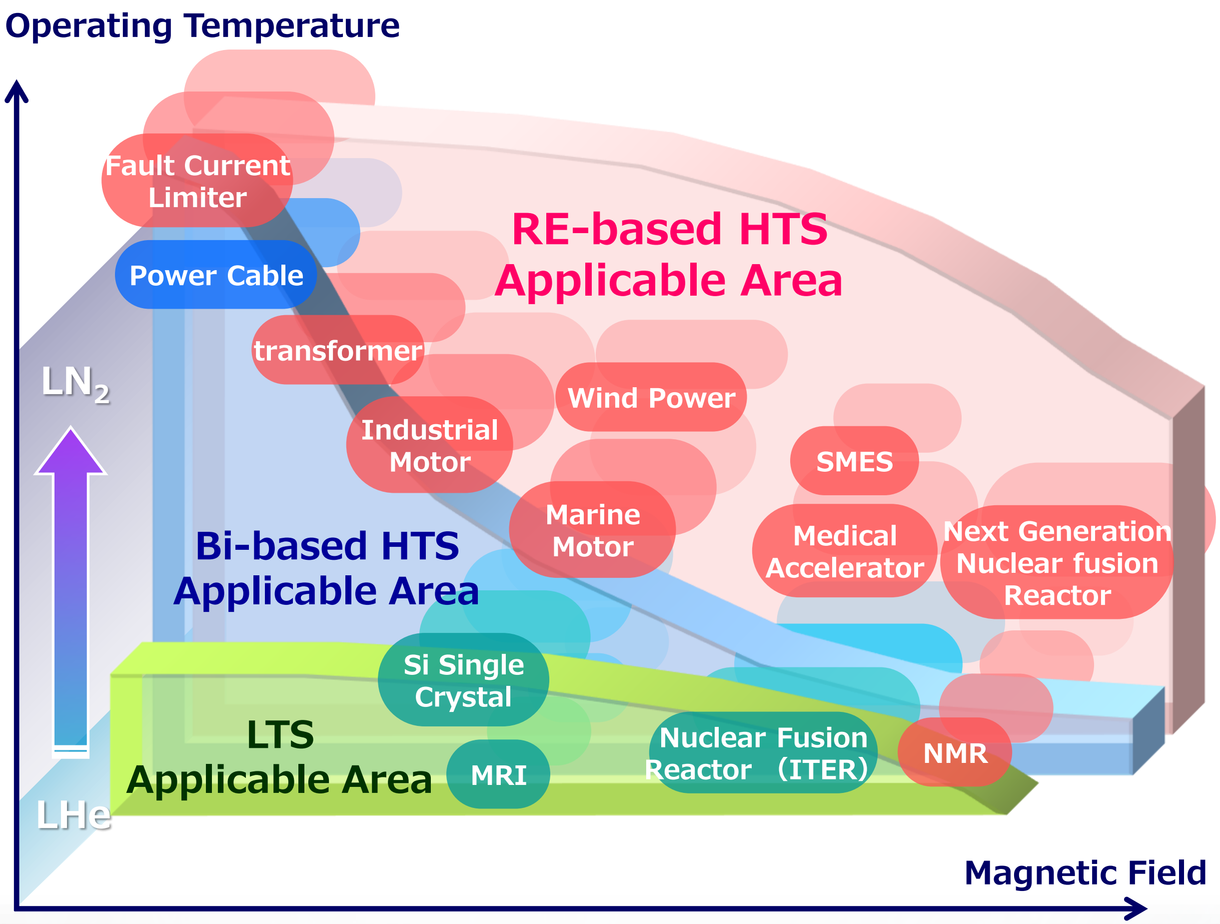
Applications of Superconductor

Advantages of Rare-Earth-based HTS	• Higher operating temperature (no use of liquid helium) • Higher critical current at higher magnetic field • Smaller size and lighter weight

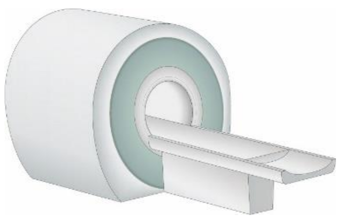

Power Cable


Transformer


FCL



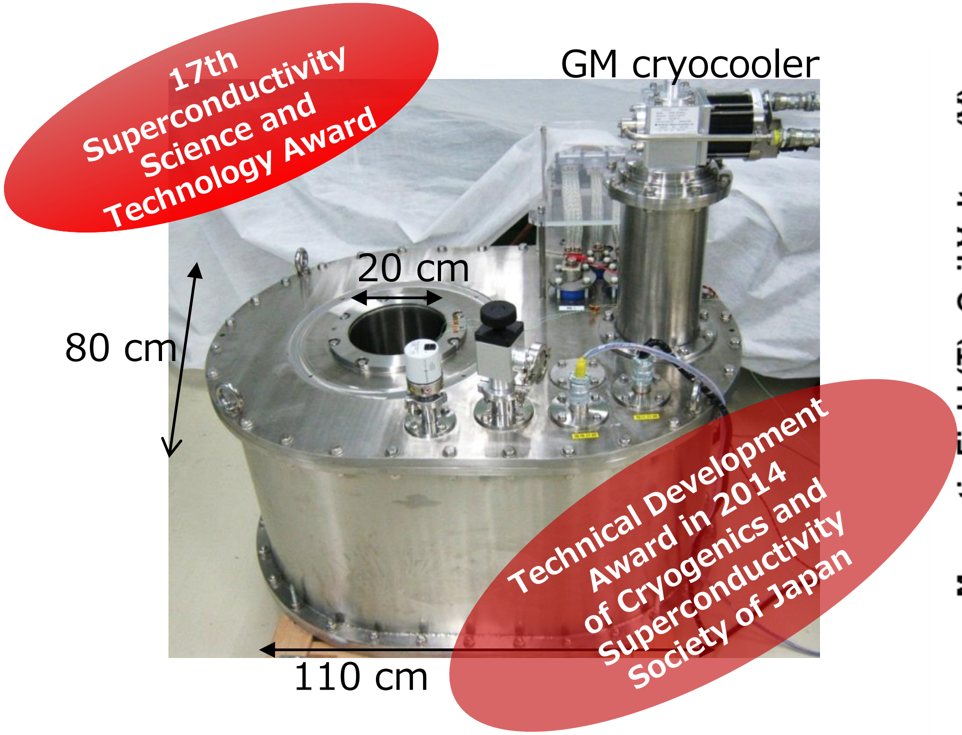

Marine Motor

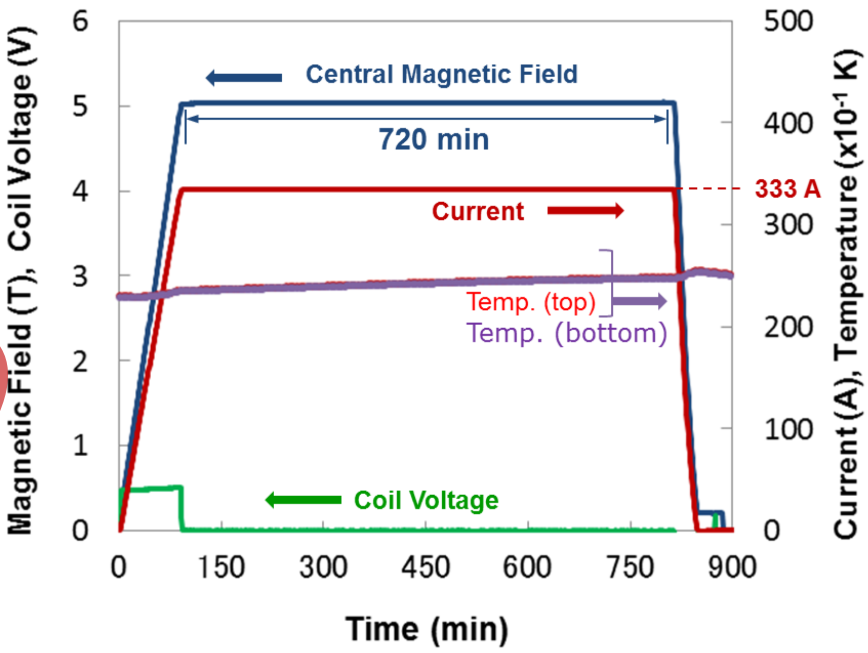

MRI


NMR

Development of 5 T 2G HTS Magnet

- Fujikura's 10 mmw Y-based HTS wire
- Total tape length : 7.2 km (300 m x 24)
- Stored energy : 426 kJ
- Composed of 24 pancake coils
- Total number of turns : 5775
- Operating temperature : 25 K





5 T 2G HTS cryocooled magnet developed successfully in 2012

The magnet excitation performance up to 5 T retained so far after the fabrication

M. Daibo, et al.,IEEE Trans. Appl. Supercond. 23-3 (2013) 4602004

66kV/5kA Class Power Cable (NEDO)

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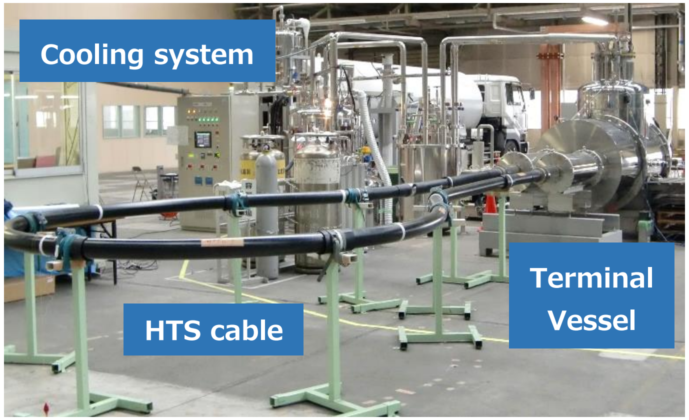
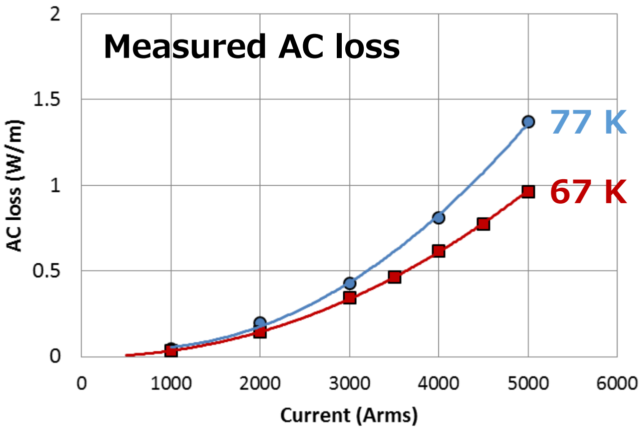
■ Development of HTS power cable with 500A class HTS tape

- Verification of AC Loss reduction with higher Ic HTS
- Single-core in one pipe cable system /66kV-5kA /10m long
- Long term current loading test : 20 cycles
  (1 cycle : 8h ON / 16h OFF)
- Target AC loss : < 2 W/m @5kA
  Measured AC loss : 1.4W/m@77K, 1.0W/m@67K



< Design and Fabrication >

Items	Specifications
Former	Stranded copper wires (140 mm^2), 20 mmφ
HTS conductor (Ic=14 kA)	4mm-wide wires, 4 layers Ic = 240 A/4 mm-w
Electric insulation	Craft papers (6mm-thick)
HTS shield (Ic=12.7 kA)	All 4mm-w tapes, 2 layers Ic = 240 A/4mm-w
Copper shield	Copper tapes (100mm^2), 44mm
Core protection	non-woven fabric, 45mmφ
Cryostat / Outer sheath	Stainless steel double corrugated pipes with PE jacket, 114mmφ



This work includes results supported by NEDO

Fujikura has succeeded in developing RE-based HTS power cable with 5 kA and extremely low AC loss 1.4 W/m in 2013.

http://www.nedo.go.jp/news/press/AA5_100196.html

Basic Instruction of Soldering

■ Recommendable solders

- It shall be generally recommendable to use solders with low melting point and to heat below 200 degrees C within few minutes. In case it would be difficult to melt solder, heating over 200 deg C could be also acceptable with full attentions.
- Pb-free solder could be available with full attention to heating condition. Other solders could be also available depending on application designs or environmental regulation.
- Sn-Bi based or more preferably Sn-Bi-Ag based solder would be recommendable for HTS tapes with silver protection layer such as FYSC-S or FESC-S series. Especially solder including Ag is relatively easy to solder silver protection layer.

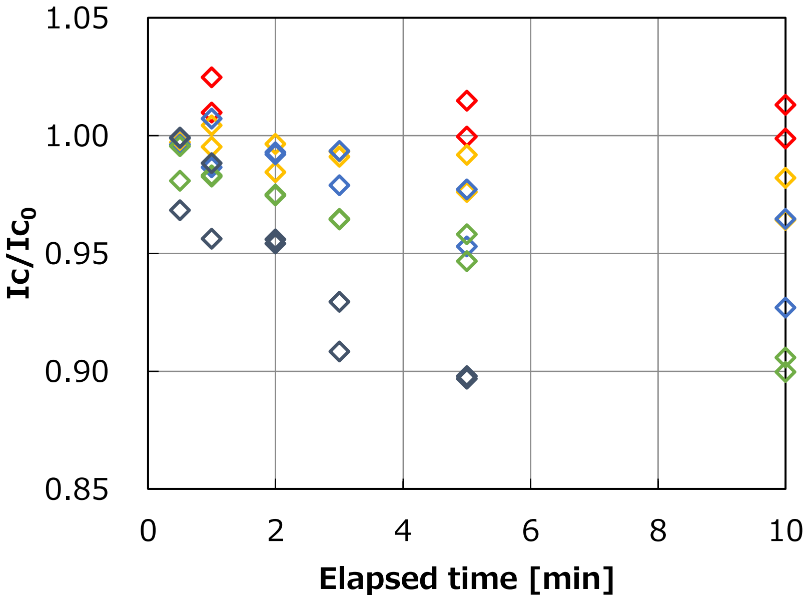
■ Physical properties (Reference)

Solder		Sn-Pb	Sn-Bi	Sn-Ag-Cu	Sn-In	Sn	In
Composition [wt%]		Sn63-Pb37	Sn42-Bi58	Sn96.5-Ag3 -Cu0.5	Sn48-In52	Sn (4N)	In (4N)
Melting point [deg C]		183.0	138	217	118	231.9	156.6
Resistivity [nΩm]	297K	167.3	510.6	154.0	168.1	123.1	90.3
	77K	34.6	178.8	19.4	90.3	23.0	17.5

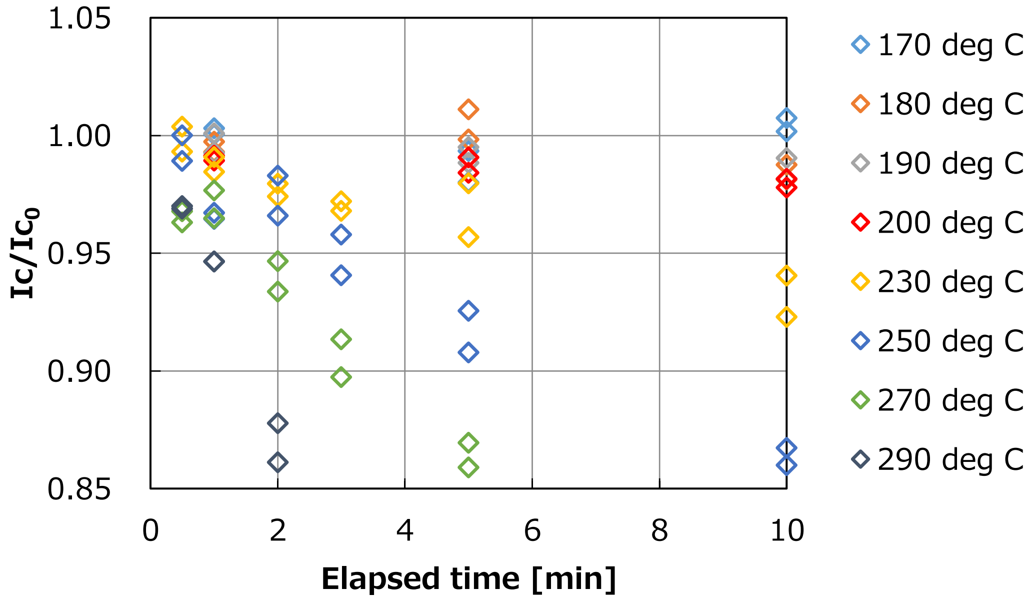
* Resistivity is measured value at Fujikura.

■ Ic degradation during heating

Non artificial pinning (FYSC series)



Artificial pinning type (FESC series)



* It shall be generally recommendable to heat below 200 degrees C within few minutes. Heating over 200 degrees C could be also acceptable with full attentions to heating condition.

* These conditions shall not be necessarily applicable to HTS tapes with silver protection layer due to soldering erosion of silver layer.

Notes

■ Handling

- Do not exceed the minimum bending radius. The tape will be permanently damaged.
- Do not exceed the maximum tensile stress. The tape will be permanently damaged.
- Do not expose the tapes to moisture.
- Avoid twisting the tapes during spooling.
- The insulating tape may loosen when cut. To avoid this clamp both sides while cutting.
- Do not touch the tapes directly with bare hands. This will cause oxidation and discoloration.
- Do not apply excessive pressure.

■ Storage

- Electroplated copper is susceptible to Oxidation. The storage in sealed conditions are recommendable.
- Store at room temperature, away from heat and moisture.
- Avoid condensation or exposure to corrosive substances.
- Do not place heavy objects on superconducting tapes and reels.

■ Environmental regulation

- All the HTS tapes and packing materials are compliant to RoHS.

■ Export control

- The export of the HTS tapes are controlled under Foreign Exchange and Foreign Trade Law of Japan.

Contact Information

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