Electro-mechanical measurements of mechanical lap joint of HTS STARS conductors

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Outline

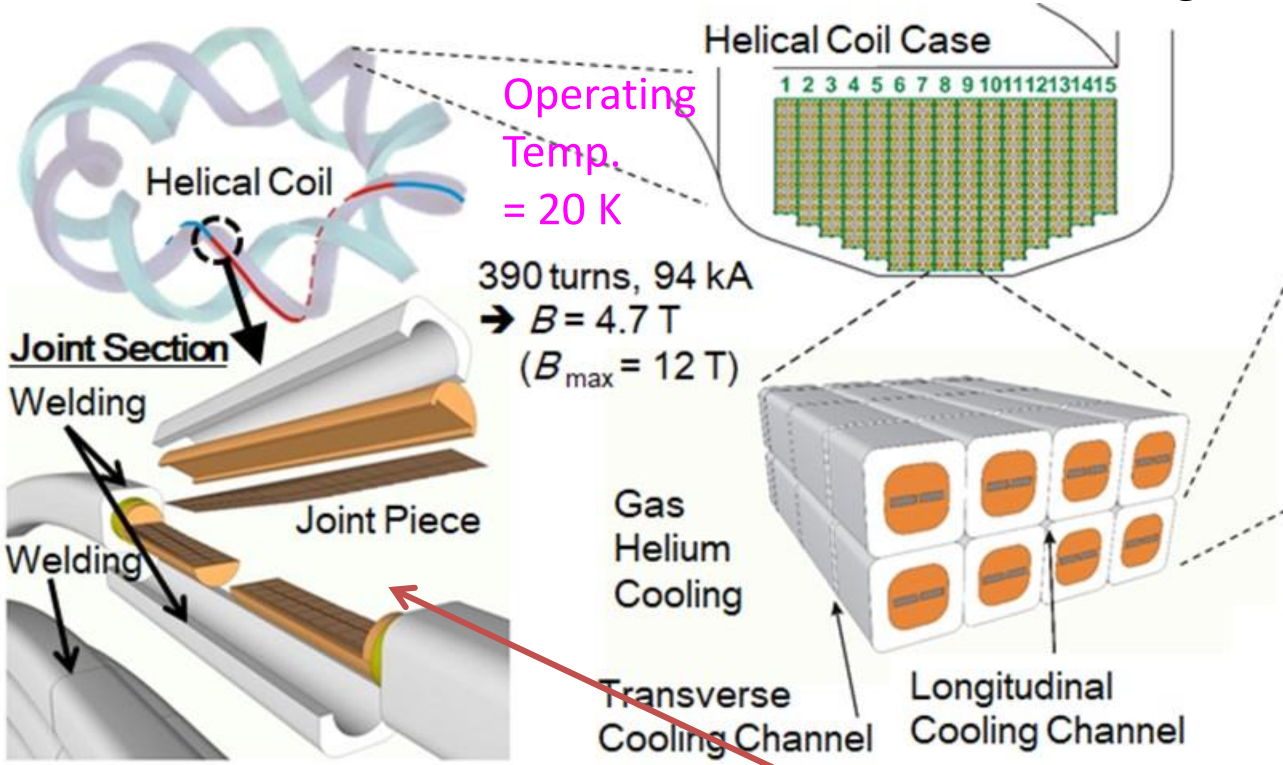
Joint-winding of HTS helical coils is a challenging option for LHD-type helical fusion reactor FFHR-d1. The coil is wound by joining HTS STARS (stacked tapes assembled in rigid structure) conductor segments with mechanical joints.

We plan to do electro-mechanical measurements of mechanical lap joint of middle-scaled HTS STARS conductor (~10 kA) using FBI test facility at KIT. This presentation introduces design, fabrication and pre-measurements of the joint at Tohoku Univ.

Outline of this presentation

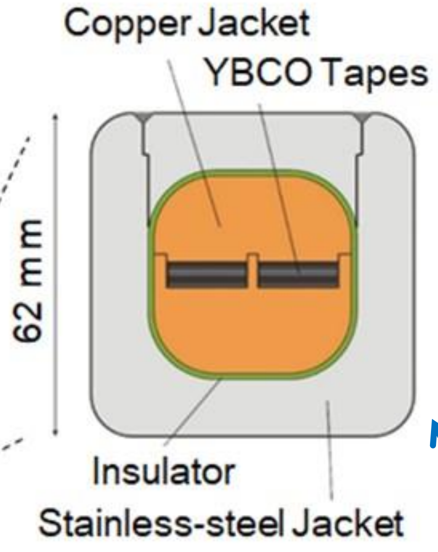
1. Introduction

1-1. Joint-winding of HTS helical coils



Design of a helical coil of FFHR-d1 [1][2]
(Joint-winding [3] as challenging option)

➔ solve technical issue:
difficulty of fabrication of helical coils



HTS Stacked Tapes Assembled in Rigid Structure (STARS) conductors [4]

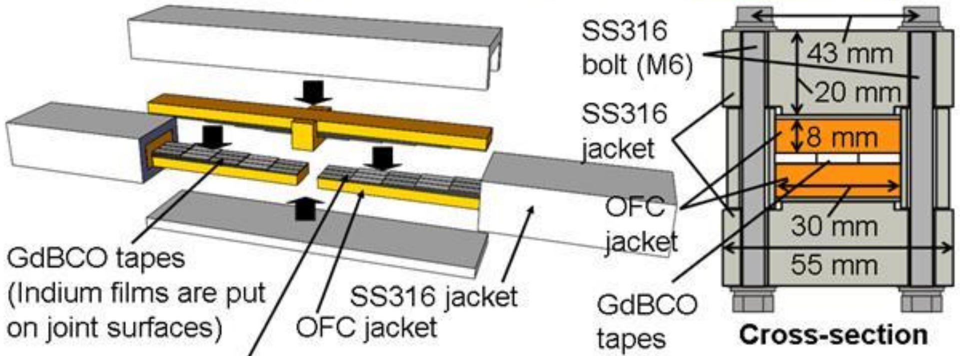
Bridge-type mechanical lap joint [5]

- The joint has a stepwise structure for face-to-face connection of REBCO surfaces
- REBCO tapes are joined by <u>mechanical contact and just pressed together (indium foils are inserted between joint surfaces)</u>.
- Stainless steel jacket is welded to ensure tensile strength.

[1] A. Sagara et al., Fusion Eng. Des., 89, 2014, 2114-.
[2] A. Sagara et al., Nucl. Fusion, 57, 2017, 086046.
[3] N. Yanagi et al., Fusion Sci. Technol., 60, 2011, 648-652.
[4] N. Yanagi, S. Ito et al., Nucl. Fusion, 55, 2014, 053021.
[5] S. Ito et al., Plasma Fusion Res., 9, 2014, 4602305.

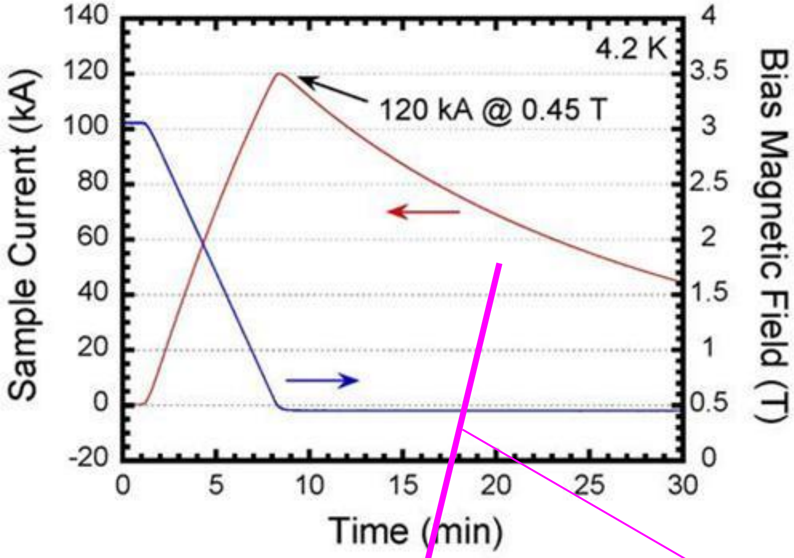
1. Introduction

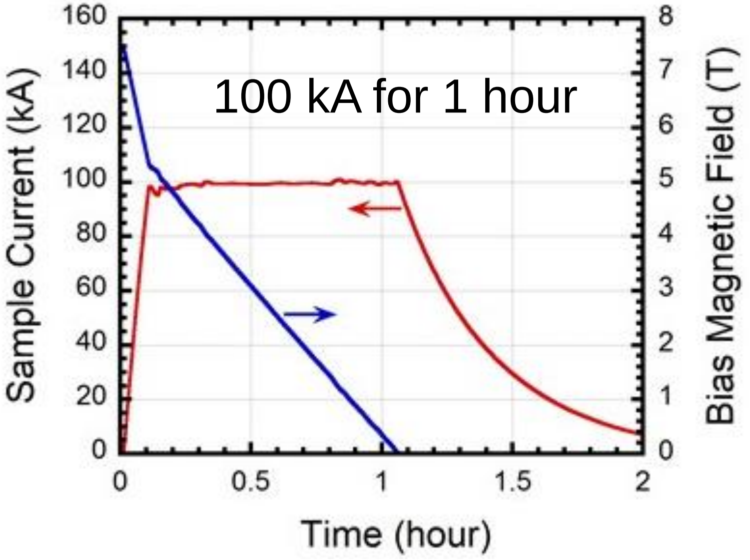
1-2. Test of a prototype STARS conductor joint

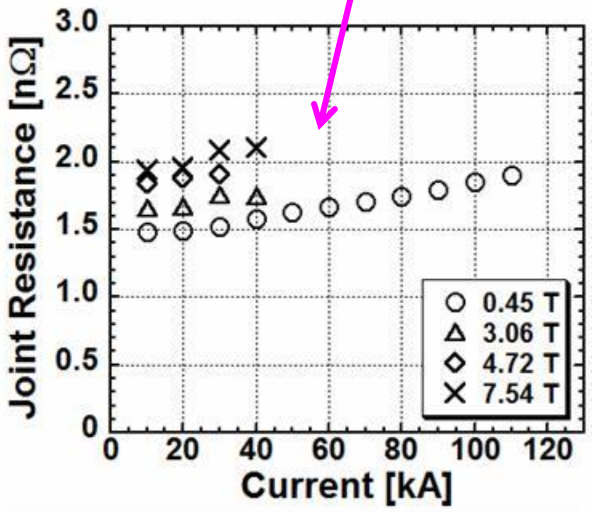


Actual layout is 3-row and 14-layer (42 GdBCO tapes having 10 mm wide)
Length of one joint: 30 mm/1-layer x 14-layer = 420 mm

Prototype STARS conductor joint [4, 5]







Joint resistance is evaluated by decay time constant

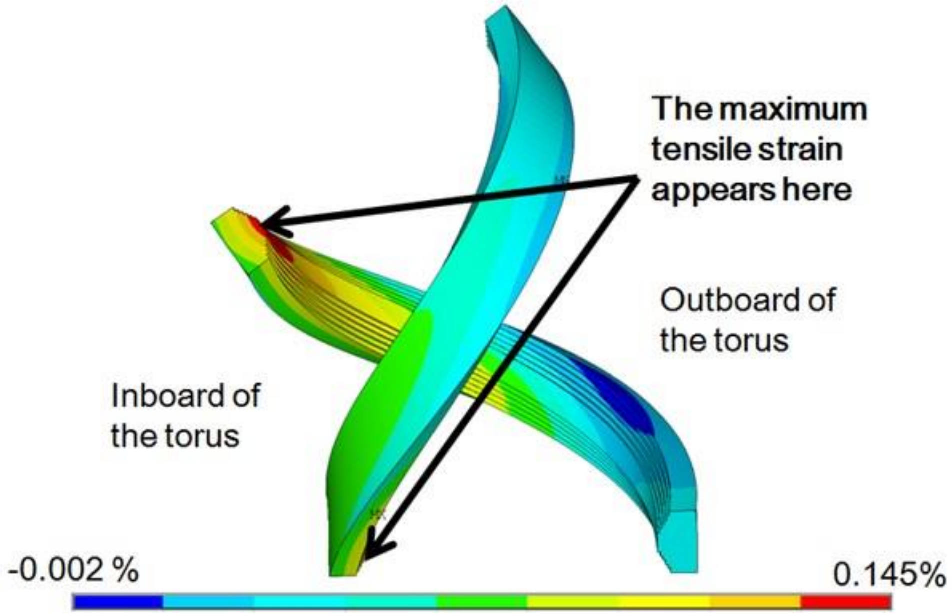
1.8 nΩ at 100 kA → **~10 pΩm^2 (~100 nΩcm^2)**

Sufficiently small from a viewpoint of electric power to run a cryoplant

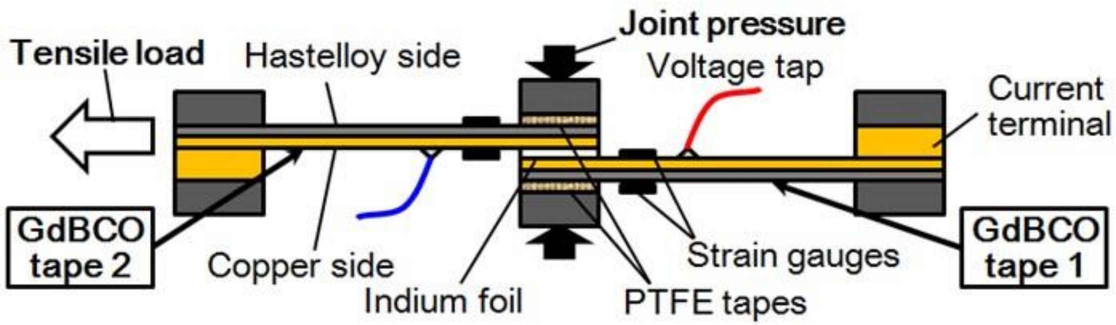
[4] N. Yanagi, S. Ito et al., Nucl. Fusion, 55, 2014, 053021.
[5] S. Ito et al., Plasma Fusion Res., 9, 2014, 4602305.

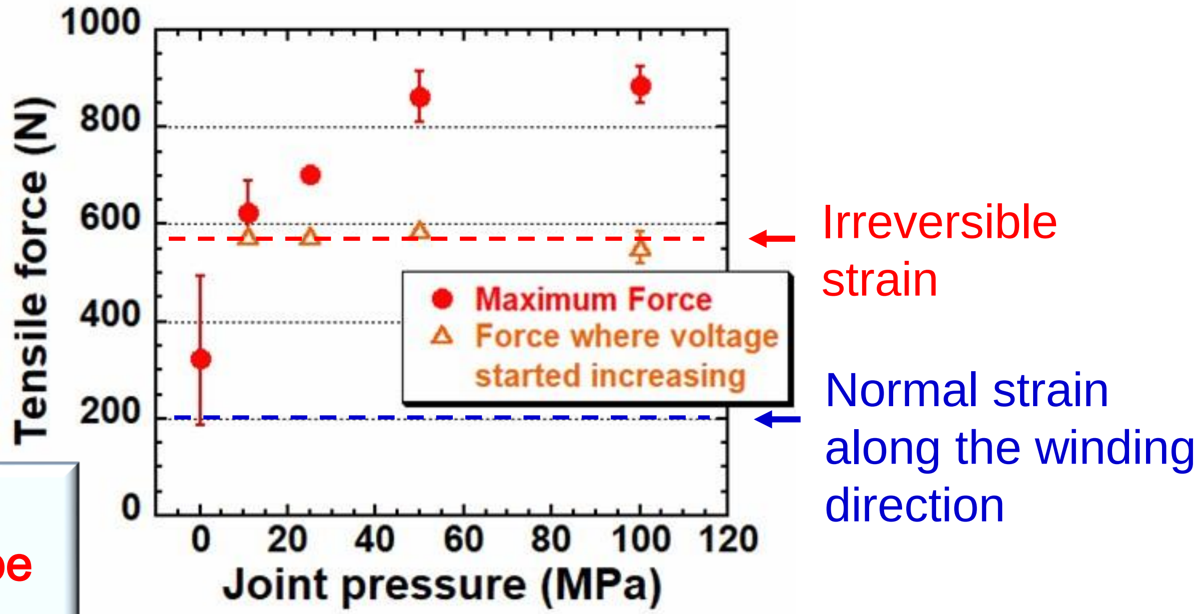
1. Introduction

1-3. Electro-mechanical property of mechanical lap joint of REBCO tapes



Normal strain distribution along the winding direction of the helical coils (Numerical analysis) in FFHR-d1 [6]





Tensile test of mechanical lap joint of REBCO tapes at 77 K [6]

- **Normal strain along the winding direction:**
  - Maximum strain: 0.145% < Irreversible strain of REBCO tape

Irreversible strain { Fujikura's REBCO tape: 0.43%-0.53% [7]
Superpower's REBCO tape: 0.6% [8]

[6] S. Ito et al., IEEE TAS, 25(3) (2015), 4201205.
[7] M. Sugano et. al., Supercond. Sci. Technol. 25(5), 2012, 054014.
[8] H. Song, et. al., IEEE TAS, 23(3) 2013, 4600806.

Strength of joint is sufficiently large
(From a viewpoint of normal strain along the winding direction)

1. Introduction

1-4. Research issue and objective

We successfully achieved…

- 1.8 nΩ (~10 pΩm^2) at 100 kA using prototype STARS conductor joint.
- Sufficient strength at 77 K using mechanical lap joint of REBCO tapes.

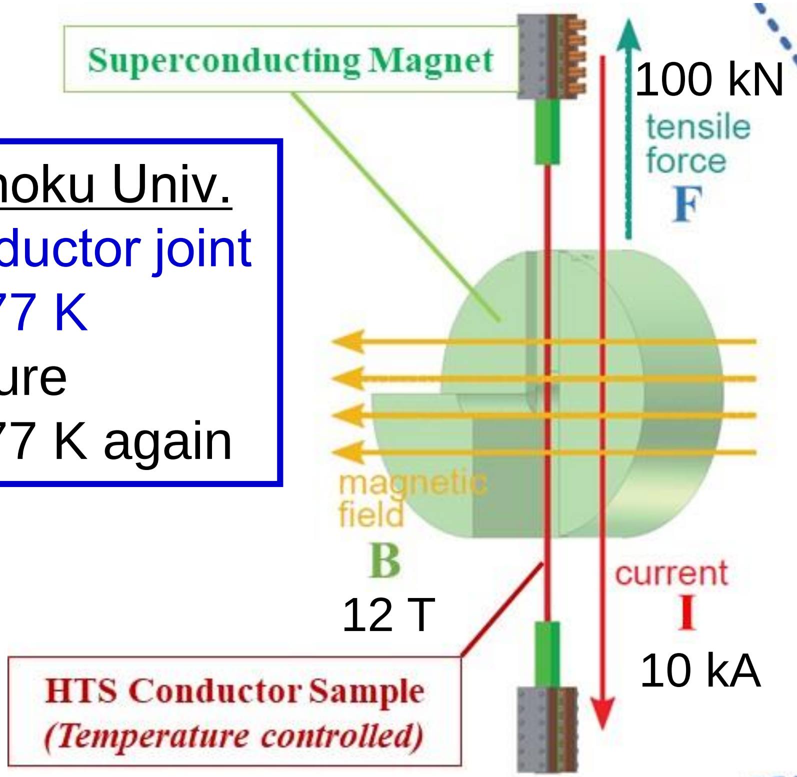
➔ Can we achieve sufficient strength for STARS conductor joint at lower temperature?

Sample preparation and pre-measurement at Tohoku Univ.

- Design and fabricate a 10 kA class STARS conductor joint
- Measure critical current and joint resistance at 77 K
- Apply a tensile force of 10 kN at room temperature
  Measure critical current and joint resistance at 77 K again

Measurement at KIT

- Critical current and joint resistance at 4.2 K and different fields
- Joint resistance at 4.2 K and 12 T for various sample elongations



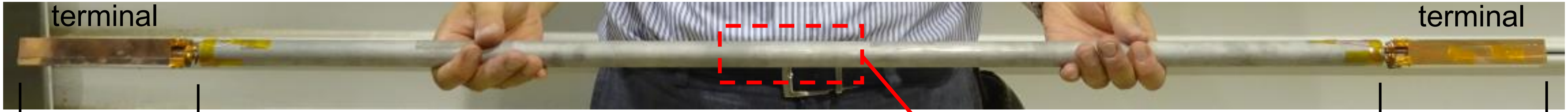
FBI test facility at KIT

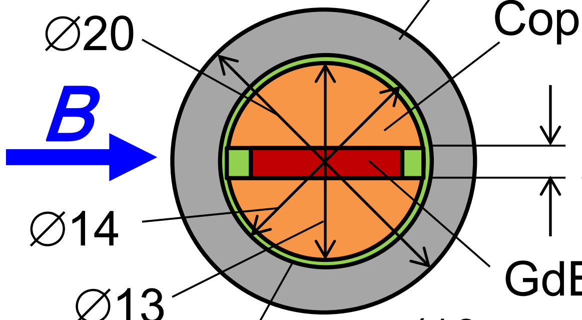
Courtesy of C. Barth, Ph.D. Thesis 2013

(http://digbib.ubka.uni-karlsruhe.de/volltexte/1000035747)

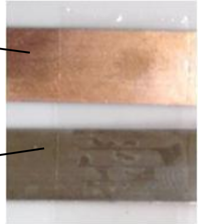
2. Design and method

2-1. Geometry of the sample

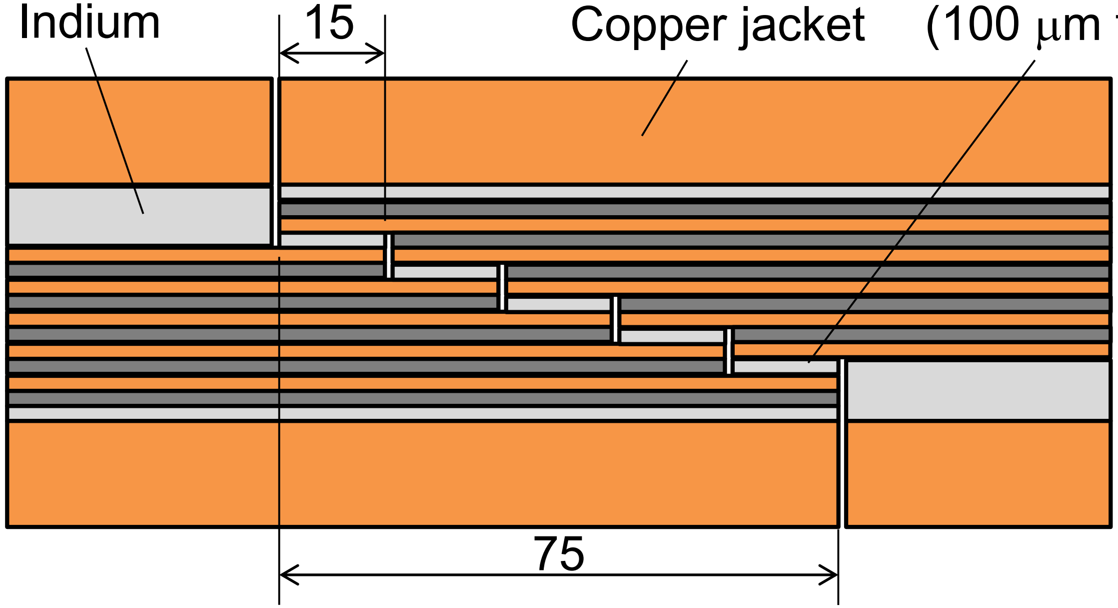




Cross section of the conductor

GdBCO tape (Fujikura, FYSC-SC10)

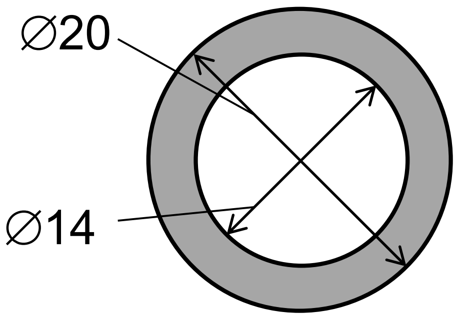


Schematic illustration of the joint section (mechanical lap joints with indium foils inserted between joint surfaces)

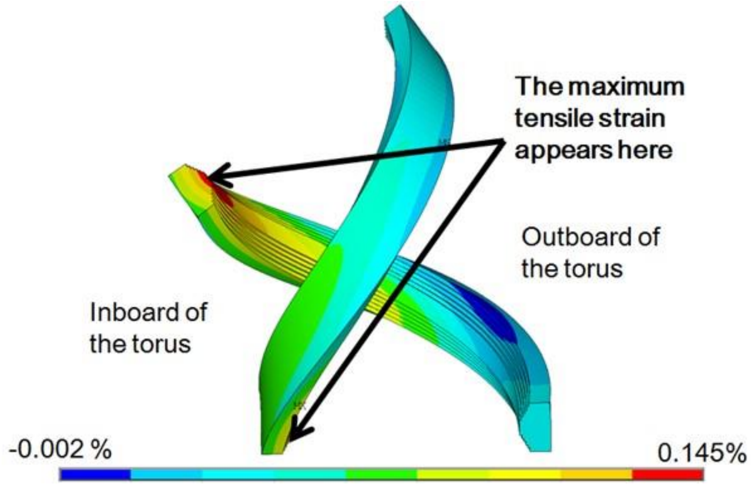
2. Design and method

2-2. Mechanical properties

Applied tensile force
- 10 kN at room temperature (Tohoku Univ.)
- 100 kN at 4.2 K (KIT)



- Rough estimation of strain considering only the stainless steel jacket
- Cross sectional area: 160 mm^2
- Young's modulus: 195 GPa (293 K), 208 GPa (4.2 K)
- Yield stress: 240 MPa (293 K), 550 MPa (4.2 K)



Irreversible strain of Fujikura's REBCO tape: 0.43%-0.53%

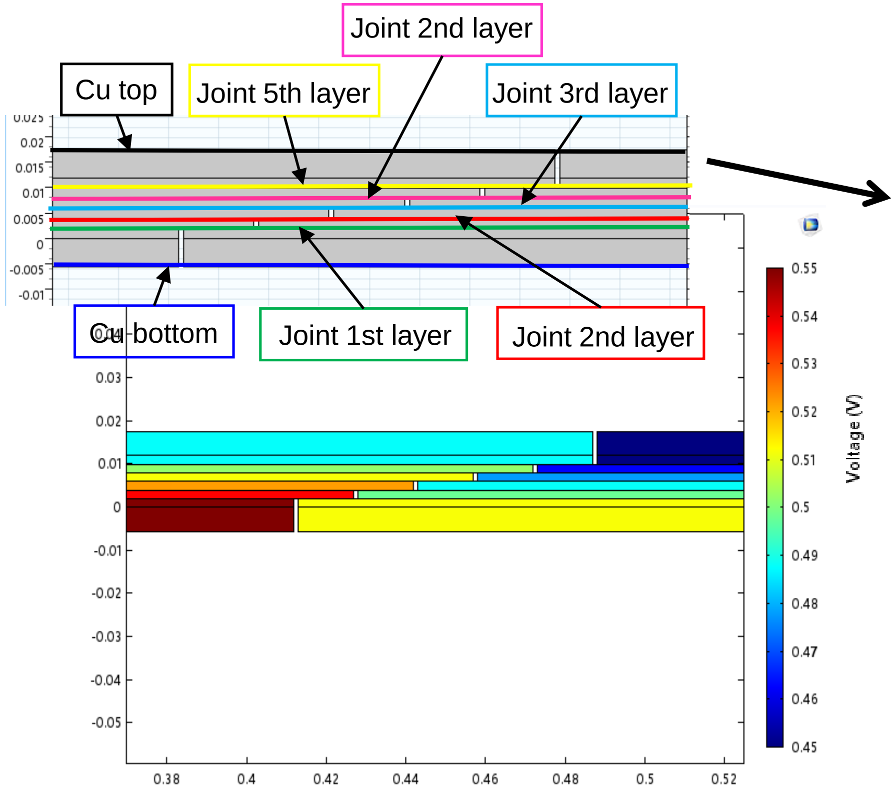
10 kN at room temp. (Tohoku Univ.)
- Tensile stress = $(10\times10^3)/(160\times10^{-6}) = 6.24\times10^7$ = 62.4 MPa
- Tensile strain = $(6.24\times10^7)/(195\times10^9) = 3.20\times10^{-4}$ = 0.032%
  < Normal strain along the winding direction
  < Irreversible strain of REBCO tape

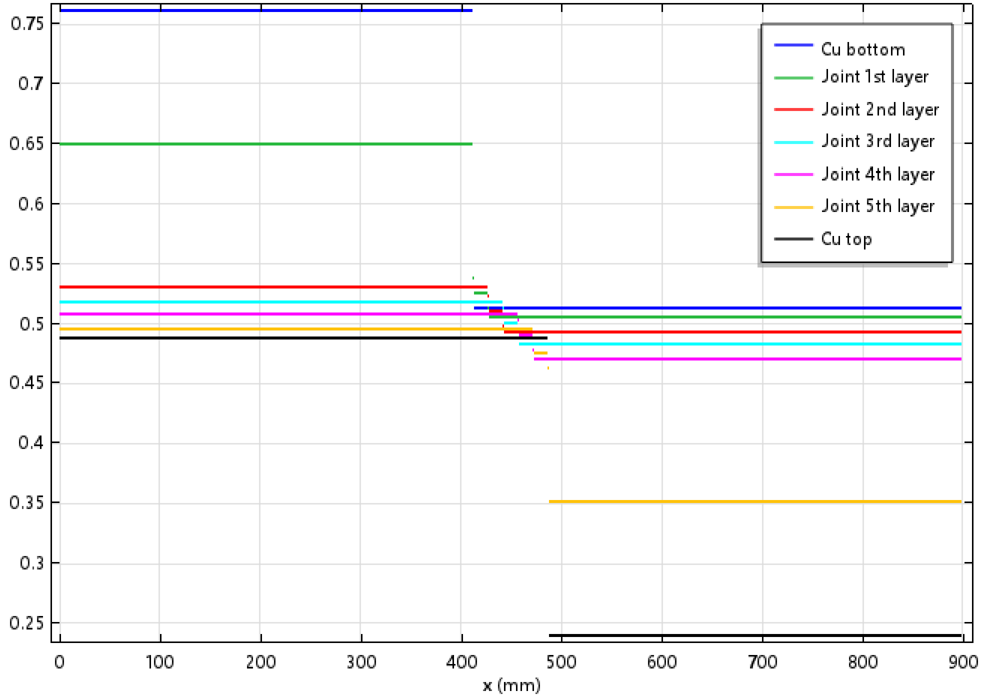
100 kN at 4.2 K (KIT)
- Tensile stress = $(100\times10^3)/(160\times10^{-6}) = 6.24\times10^8$ = 624 MPa
- Tensile strain = $(6.24\times10^7)/(208\times10^9) = 3.00\times10^{-3}$ = 0.3%
  > Normal strain along the winding direction
  < Irreversible strain of REBCO tape

2. Design and method

2-3. Problem of voltage measurement

- If there is no interface resistance, potential distribution of every GdBCO tape layers and copper jackets are the same, but with interface resistance, they are different.
- Voltage drop of each joint section (each layer) can not be evaluated by taps attached on copper jacket according to numerical analysis taking inter-layer resistance.





Potential distribution in the joint section

Joint resistivity for mechanical lap joint with indium: 10 pΩm^2 for every layers

Interface resistivity between GdBCO layers: 1 $\mu\Omega$m^2 for every layers

2. Design and method

2-4. Experimental procedure

1) Joint resistance and I_C measurements for each GdBCO tape.

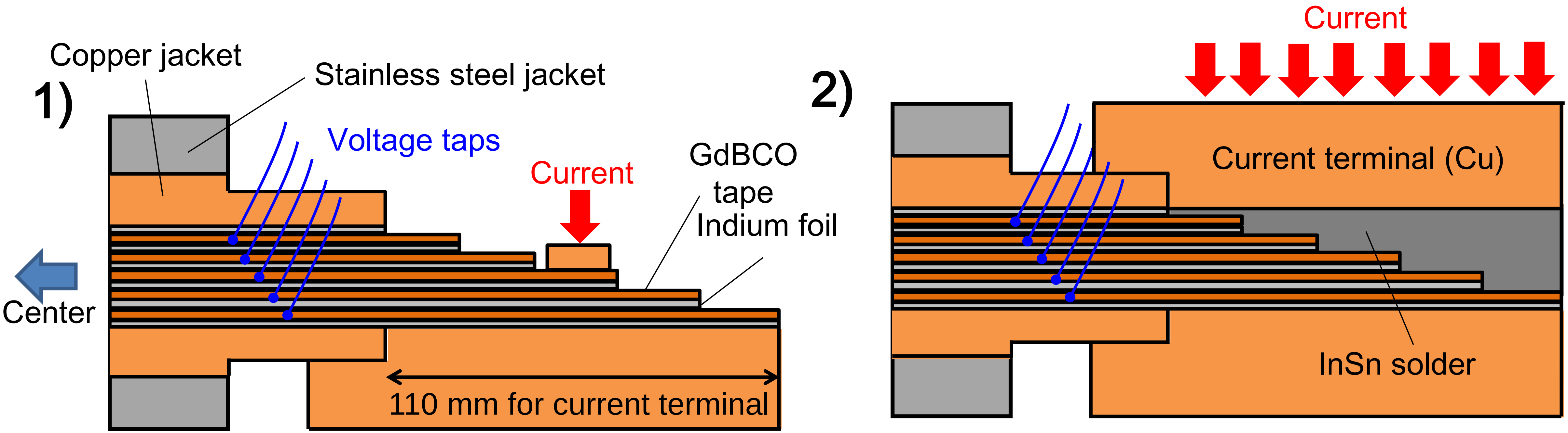
Current is applied to each GdBCO tape one by one before fixing current terminal (copper block).
The data is used as joint resistance and I_C at 77 K, self field.

2) Evaluation of current distribution

After fixing the current terminal, current is applied from the current terminal. We've already known each joint resistance by 1), so we can evaluate current flowing each GdBCO tape by voltage measurement.

3) Pre-tensile test at room temp.

Applying tensile force upto 10 kN at room temp. Then repeat 2).



3. Fabrication and measurement

3-1. Preparation of mechanical lap joint of each layer

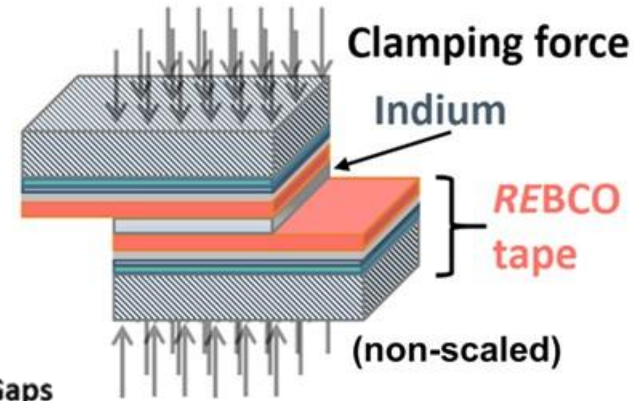
- **REBCO tape**

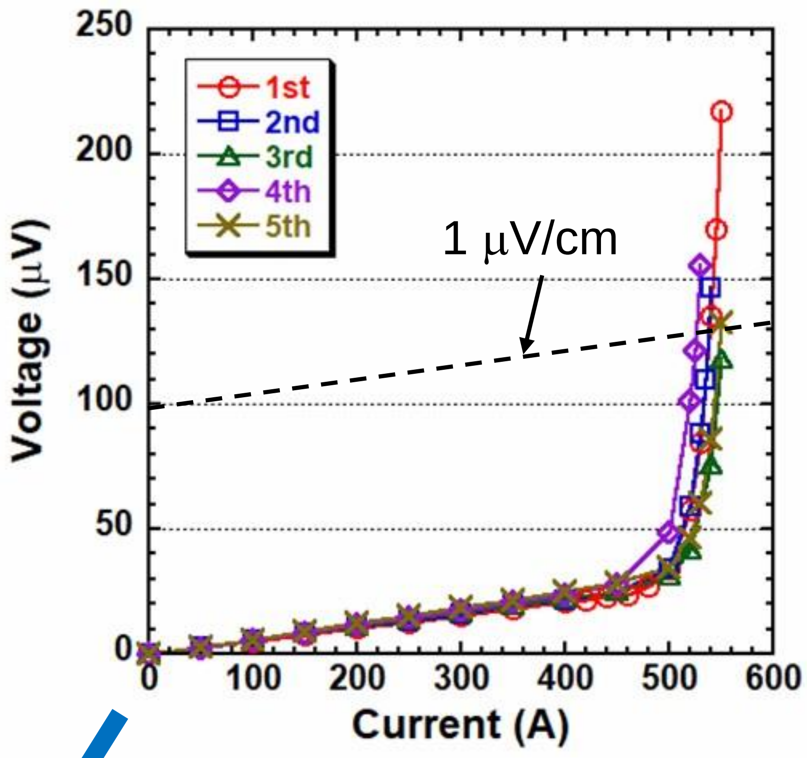
  Copper stabilized GdBCO tape (Fujikura, FYSC-SC10)

  - Thickness: ~190 μm
    Cu (100 μm) / Sn (2-4 μm) / Ag (8.2 μm) / GdBCO (1.8 μm) / Buffer (~0.5 μm) / Hastelloy (75 μm)
  - Width: 10 mm

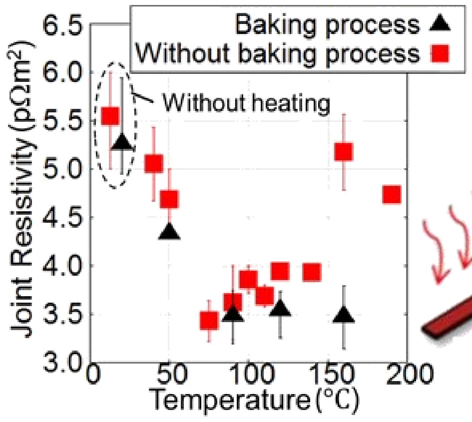
- **Mechanical lap joint with low-temperature heat treatment [1]**

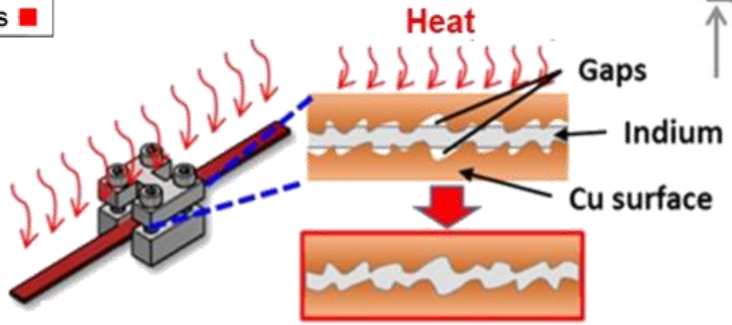
  - Joint area: 10 mm (width) × 15 mm (length)
  - Inserted indium foil: 100 μm thick
  - Joint pressure: 100 MPa
  - Heating treatment: 90 °C for 30 min





***I-V* curve for each layer**





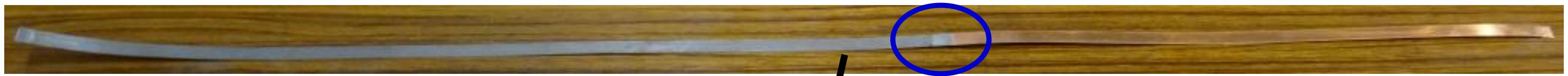
1st layer: I_C = 540 A, R = 52 nΩ, RS = 7.8 pΩm^2 (78 nΩcm^2)
2nd layer: I_C = 535 A, R = 54 nΩ, RS = 8.1 pΩm^2 (81 nΩcm^2)
3rd layer: I_C = 550 A, R = 56 nΩ, RS = 8.4 pΩm^2 (84 nΩcm^2)
4th layer: I_C = 525 A, R = 58 nΩ, RS = 8.7 pΩm^2 (87 nΩcm^2)
5th layer: I_C = 550 A, R = 62 nΩ, RS = 9.3 pΩm^2 (93 nΩcm^2)

[1] T. Nishio et al., IEEE TAS, 26(4), 2016, 4800505.

3. Fabrication and measurement

3-2. Assembling the joint sample

Joint



Voltage taps

Putting GdBCO tapes jointed by mechanical lap joint with indium foils on the copper jacket.
100-μm-thick Indium foils are inserted between GdBCO tapes.
Voltage taps made of 50-μm-thick copper foil are set between GdBCO tapes.

Fixing the GdBCO tapes, the indium foils and the copper jacket by pressing them.

➔ Failed: Difficult to press them accurately…
The sample was rotated and can not be fixed by the pressing…

Terminal copper block was not soldered at this time
(Boundary region between the jacket and the terminal connected by bolts to protect GdBCO tapes for the current terminal)

3. Fabrication and measurement

3-2. Assembling the joint sample

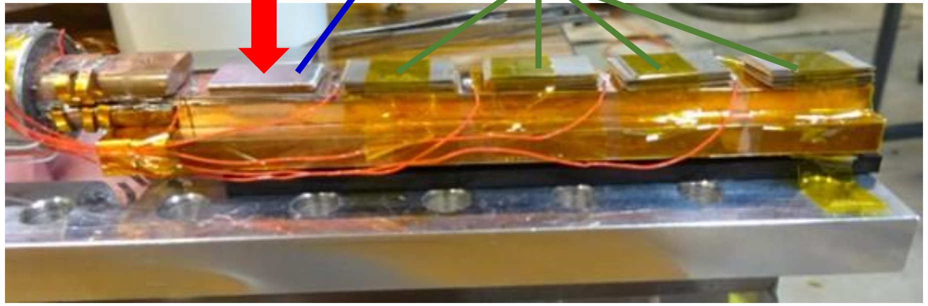
Wrapping the copper jacket with prepreg sheets of GFRP.
Inserting the sample into the stainless steel jacket.

Curing GFRP at 100 °C for 5 hours

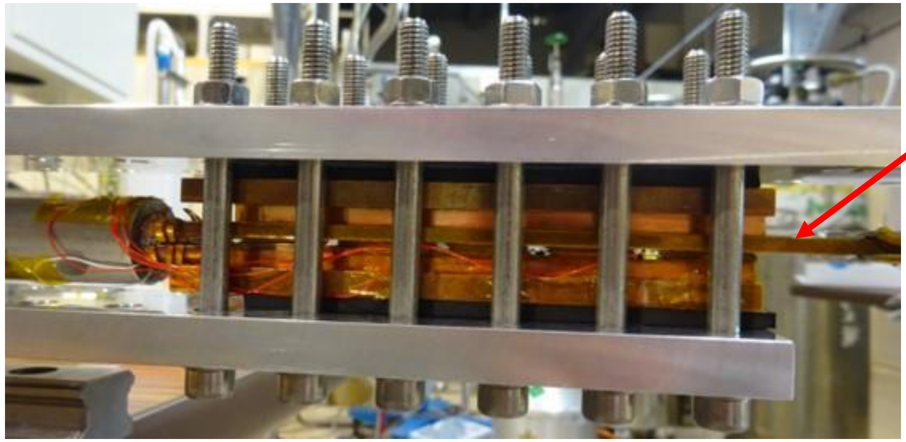
Applying current only to this layer

Copper plate

Spacers (insulated)



Setting the terminal to apply current to only one layer



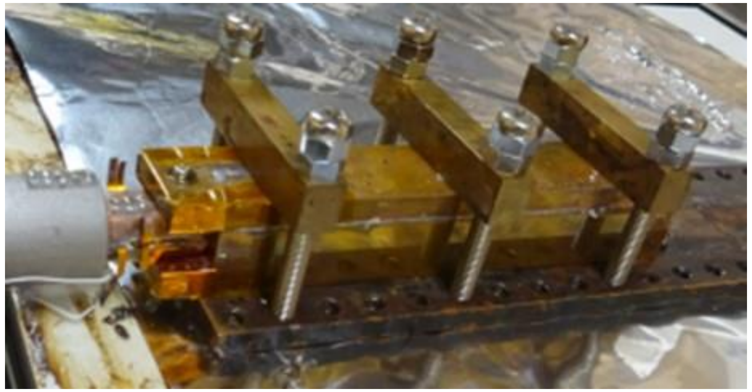
Connector to DC current supply

Measuring the voltage signals in liquid nitrogen.

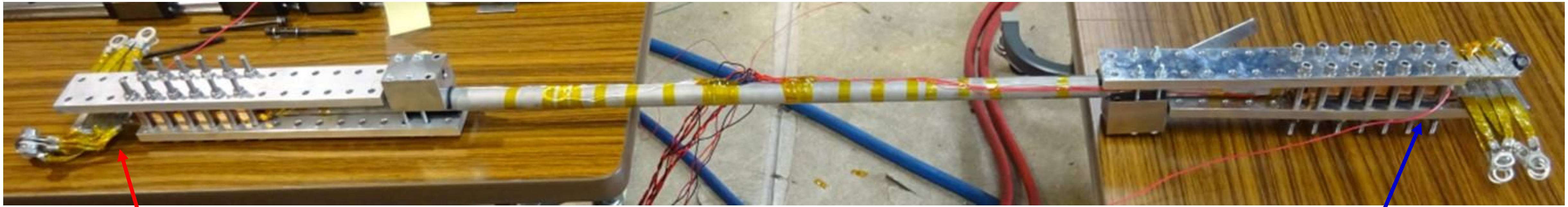
Repeat the measurement changing layers where current is applied.
(5th → 4th → 3rd → 2nd → 1st layers)

3. Fabrication and measurement

3-2. Assembling the joint sample


Soldering (InSn solder) the GdBCO tapes with the copper block at the terminal



Connector to DC current supply

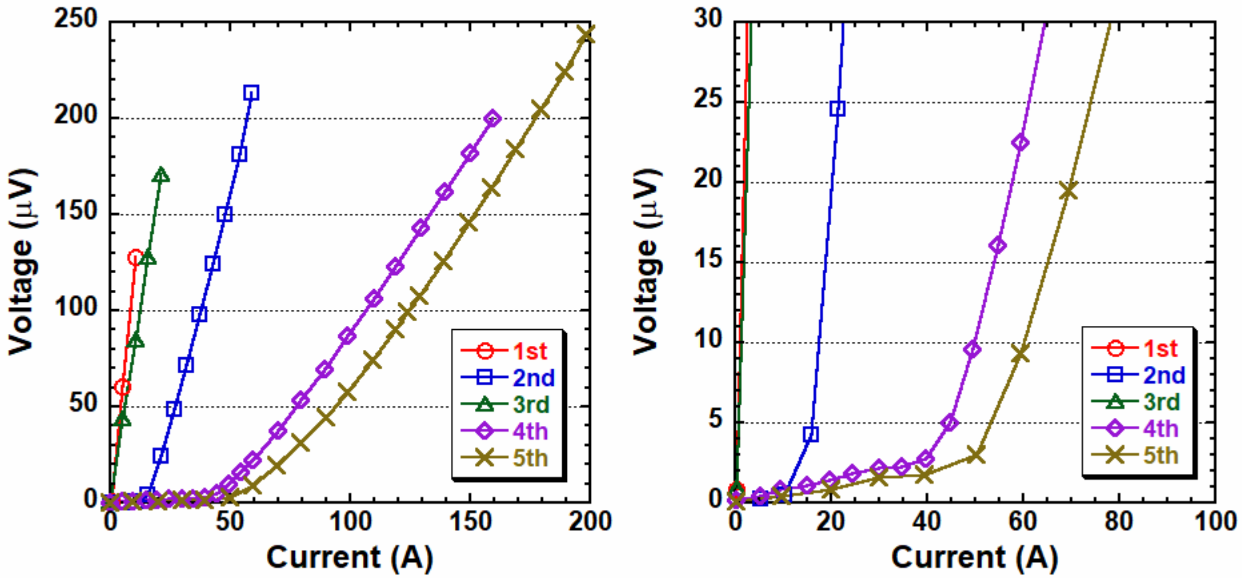
Fixing the connectors to DC current supply to the current terminal.

Measuring the voltage signals in liquid nitrogen.

Voltage tap to measure voltage whole region of the sample including terminal resistance

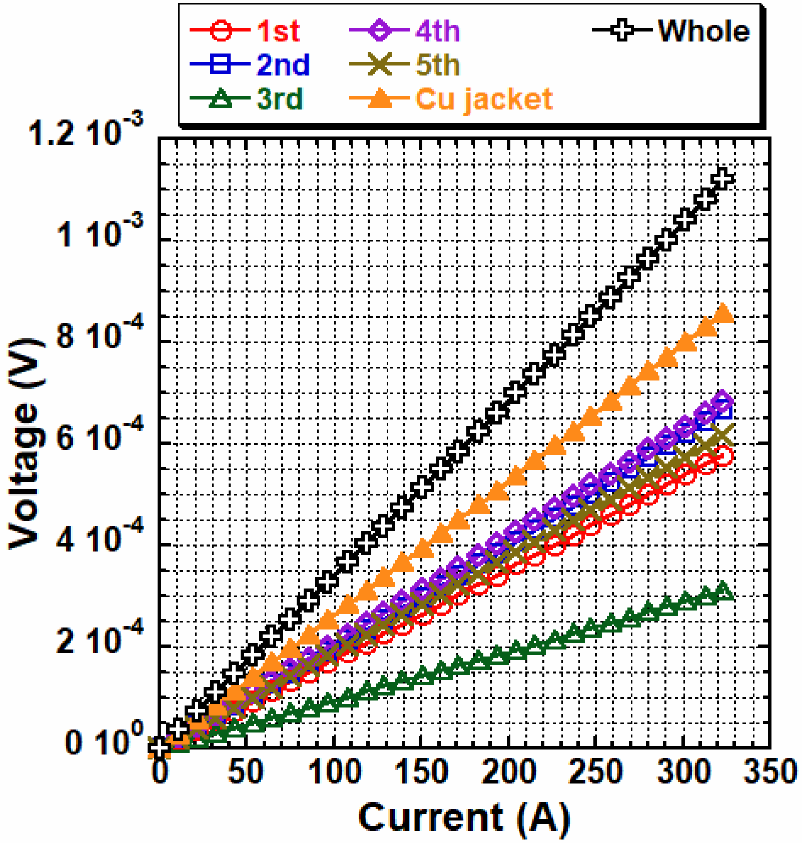
3. Fabrication and measurement

3-3. Voltage measurement



***I-V* curve for each layer before fixing the current terminal**

Critical current for every layers were degraded.
Joint resistance was kept to be its original value for 2nd, 4th and 5th layers.



***I-V* curve after fixing the current terminal**

Voltage drop measured by taps attached on the copper jacket showed meaningless data
I-V curve shows further degradation of critical current (= 0 A for all layers)

The GdBCO tapes were not fixed to the copper jacket. Pressing process was failed.
➔ The GdBCO tapes could be bent locally during both the pressing process and the setting for measurement.

4. Summary

Background of this study

- Joint-winding of HTS coils is the challenging option for design of FFHR-d1.
- Prototype STARS Conductor joint achieved 120 kA and 1.8 nΩ at 4.2 K
- The joint of REBCO tapes had sufficient strength at 77 K.

Objective of this study

- To show sufficient strength for STARS conductor joint at lower temperature, we plan to do electro-mechanical measurement of 10-kA-class STARS conductor joint at FBI test facility.
- For the measurement, the joint sample was tried to be prepared at Tohoku Univ.

Present situation

- A method to measure voltage of the joint sample was proposed.
- The joint sample was fabricated and tested at 77 K, but failed at fabrication process.

➔ Try to fix problems of the fabrication process and continue to advance the project.