Superconducting joints between Bi2223/Ag tapes towards persistent current HTS magnets

Yasuaki Takeda[1],
T. Motoki[2], K. Kobayashi[3], A. Uchida[3], H. Kitaguchi[3], S. Nakamura[4], Y. Matsutake[5,7], S. Takahashi[5,7], T. Yagai[5], T. Takao[5], Y. Suetomi[6,7], P. Renzhong[7], Y. Yanagisawa[7], T. Nakashima[8], S. Kobayashi[8], T. Kato[8], and J. Shimoyama[2]

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[5] Sophia Univ. [6] Chiba Univ. [7] RIKEN [8] Sumitomo Electric Industries, Ltd.

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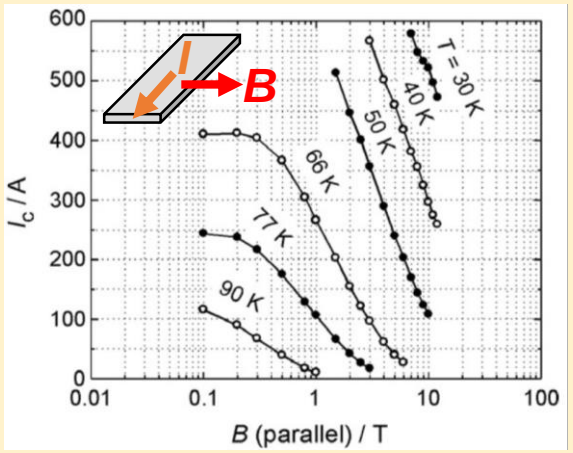
& JSPS KAKENHI Grant Number 19J12011, Japan.

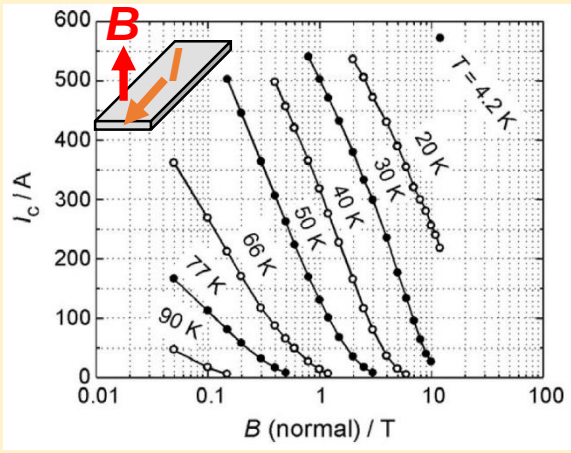
Ag-sheathed multi-filamentary Bi2223 tapes: DI-BSCCO®

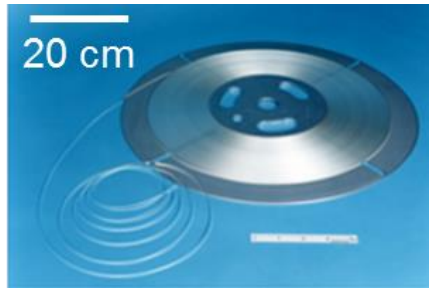
✓ **High I_c**

>200 A
(77 K, ~0 T)

>500 A
(4.2 K, >10 T)



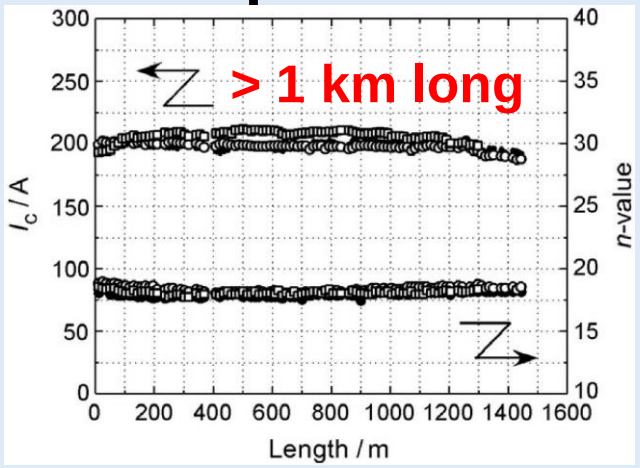




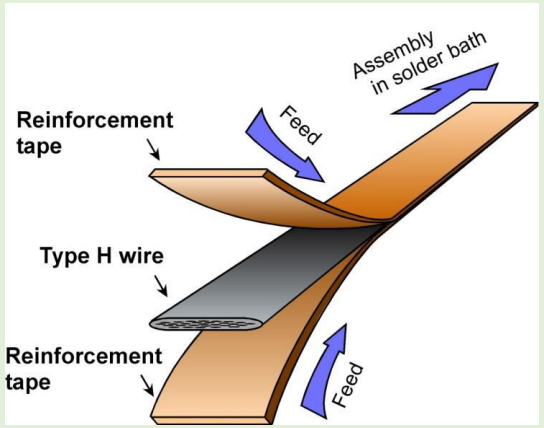
~4 mm^w
× ~0.25 mm^t

121 filaments

✓ **Mass production**



✓ **Reinforcement technique**



Critical tensile stress: >500 MPa

Power Cable

NMR magnet

Superconducting joint methodology between Bi2223 tapes has not been established.

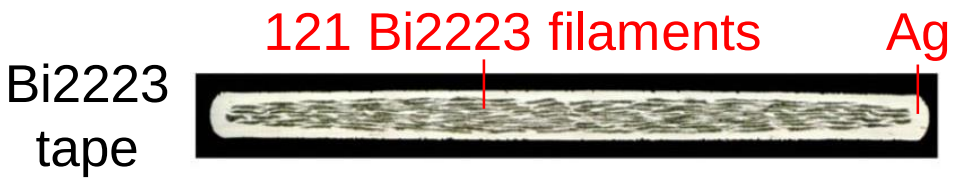
➡ **Indispensable for development of persistent current Bi2223 magnets**

T. Nakashima *et al*., *Cryogenics* (2012). K. Yamazaki *et al*., *IEEE TAS* (2012). T. Nakashima *et al*., *IEEE TAS* (2015). SEI, Ltd. NIMS

Superconducting joints between Bi2223 tapes

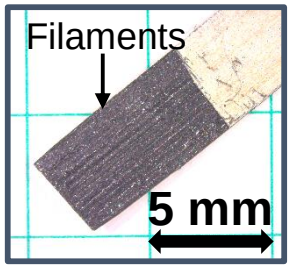
Y. Takeda *et al*., "High I_c superconducting joint between Bi2223 tapes" *Appl. Phys. Express* (2019) 023003.

Step 1: Exposing filaments



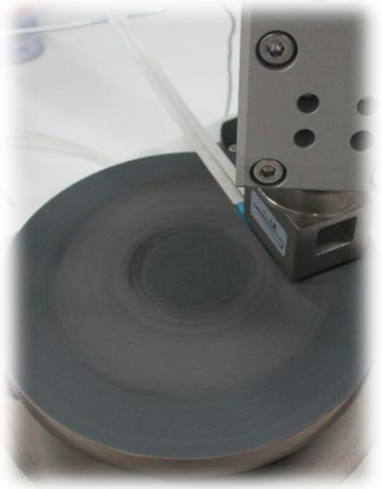
Peeling off Ag sheath

➡ Only ~15 filaments are exposed.



Polishing with a low angle (< 1°)

➡ All filaments are exposed!



Superconducting joints between Bi2223 tapes

Y. Takeda *et al*., "High I_c superconducting joint between Bi2223 tapes" *Appl. Phys. Express* (2019) 023003.

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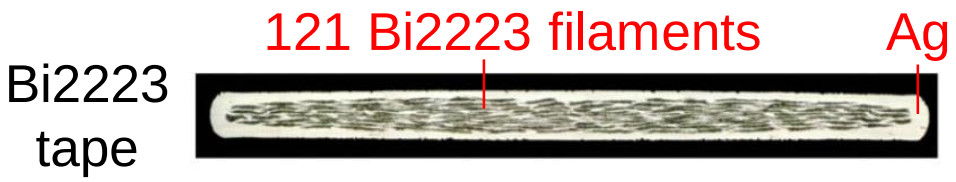

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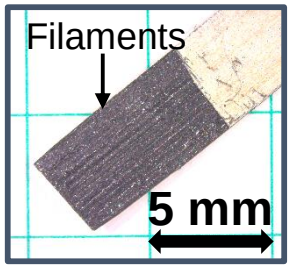

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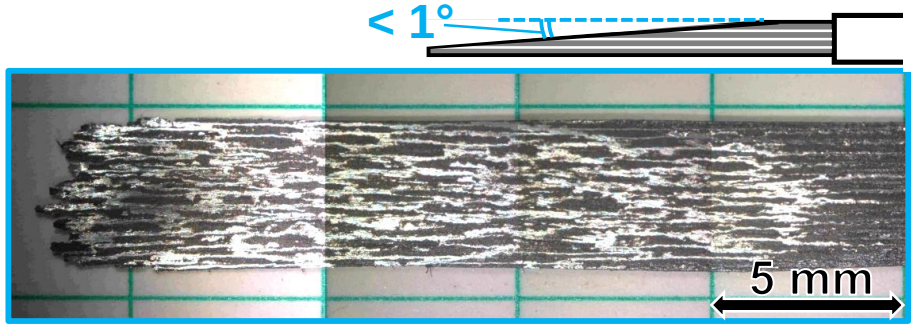
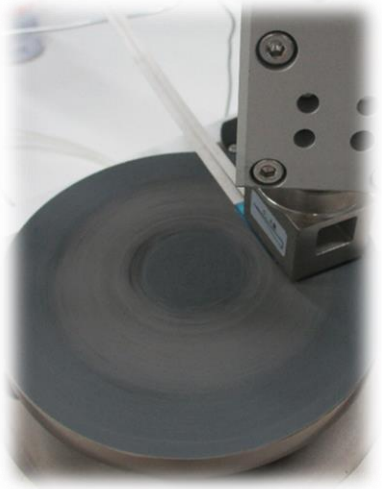
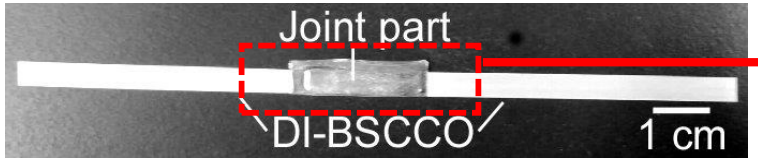
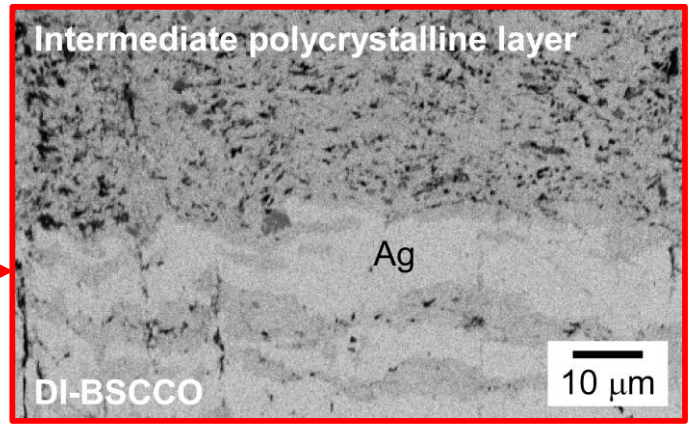




Step 2: Forming joint intermediate layer



Joint intermediate layer



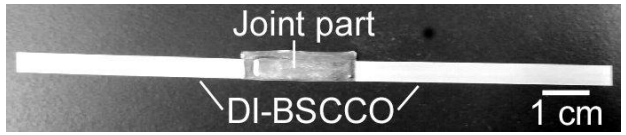
Joint interface

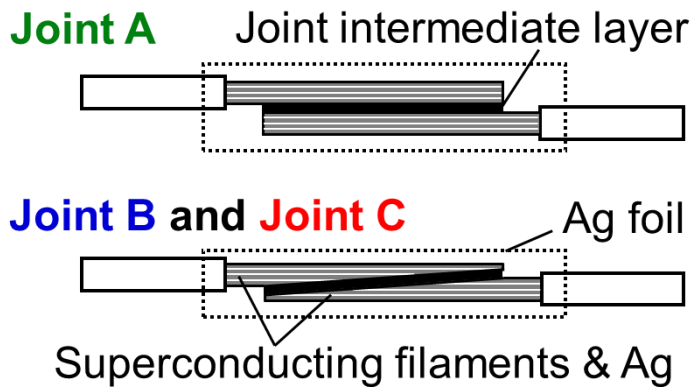
Synthesis of **joint intermediate layer** of Bi2223 polycrystalline thick film

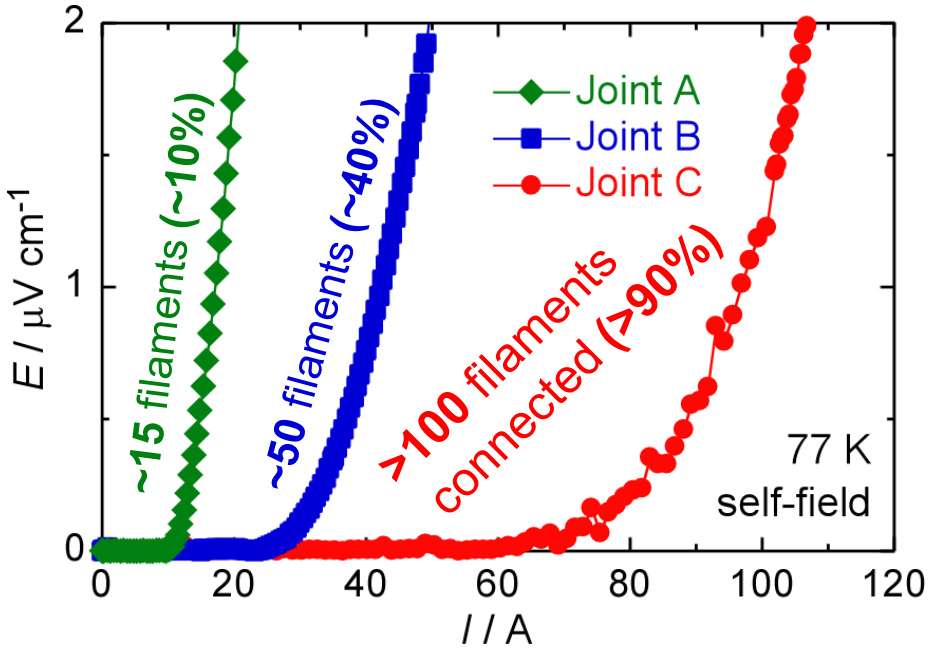
➡ **Superconducting joints are formed!**

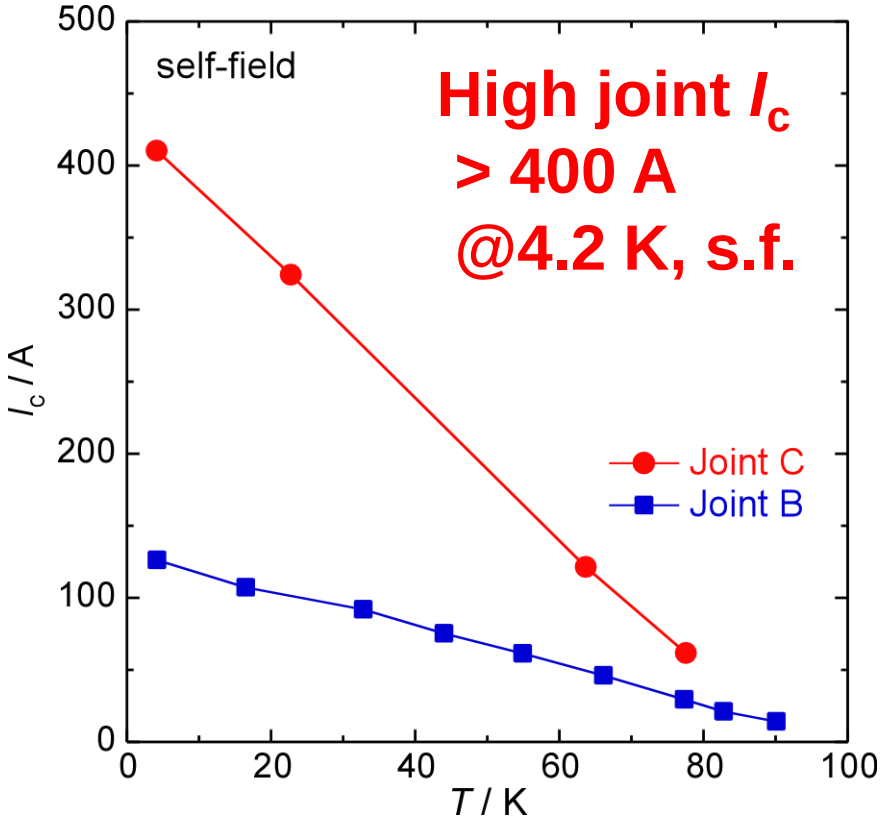
Superconducting joints between Bi2223 tapes

Y. Takeda *et al*., "High I_c superconducting joint between Bi2223 tapes" *Appl. Phys. Express* (2019) 023003.







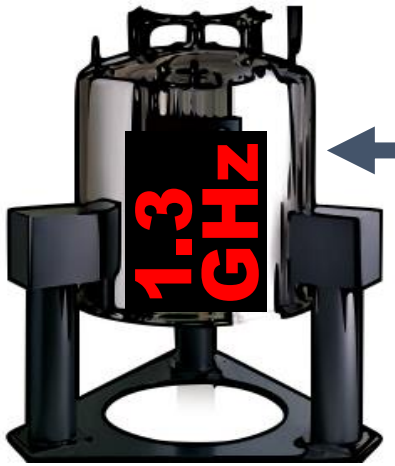


I_c measurement: Four-point-probe transport method
I_c criterion: 10^{-9} Ω resistance generated

High I_c joints between Bi2223 tapes towards persistent current magnets are successfully demonstrated.

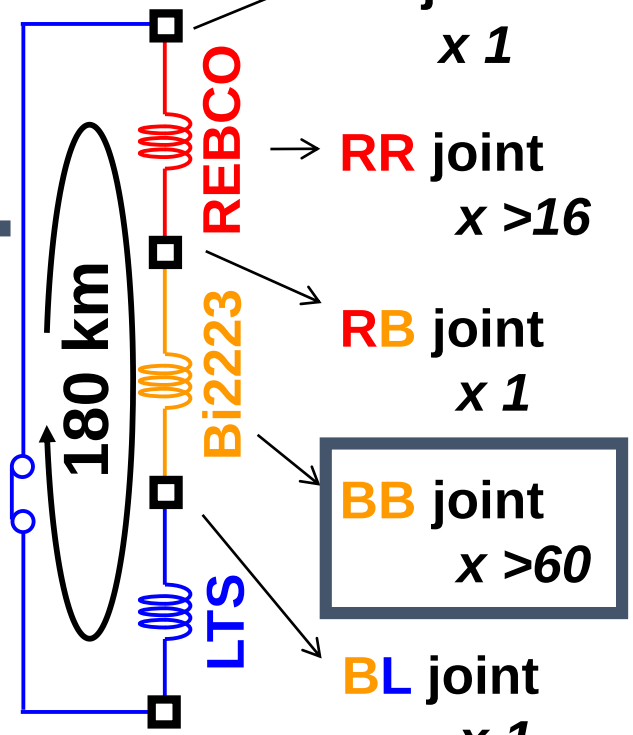
Towards a persistent current mode 30.5 T (1.3 GHz) NMR magnet

Y. Yanagisawa, Mon-Af-Po1.13-01
H. Maeda, *IEEE TAS* 2019.

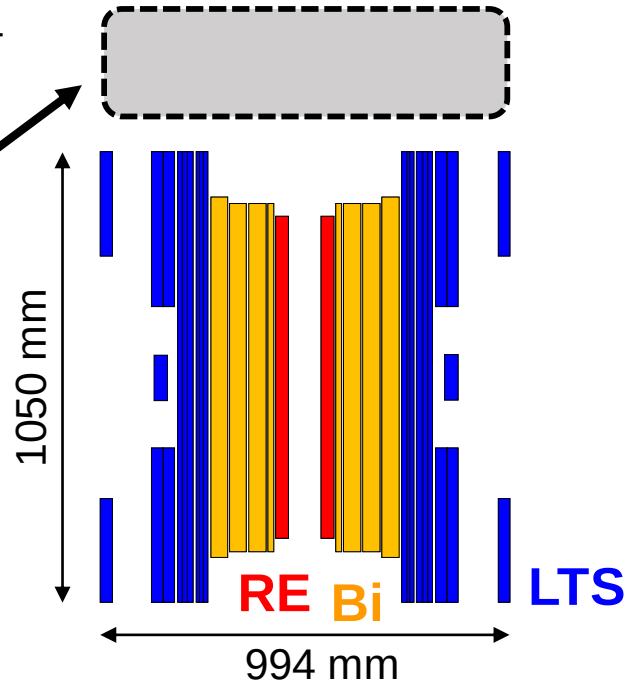


30.5 T = 1.3 GHz

L ~ 1000 H



Magnet design

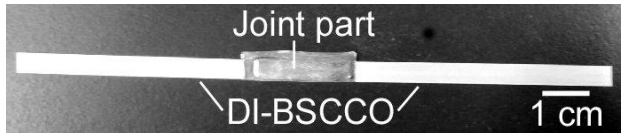


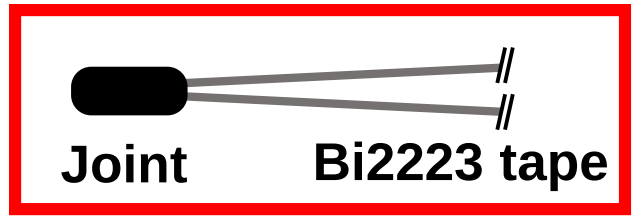
Joints will be arranged **above** the NMR coil.

Requirements

I_c (joint) > 200 A
&
R (joint) < 10^{-12} Ω
(4.2 K, 1 T)

Termination joints are suitable. ✓





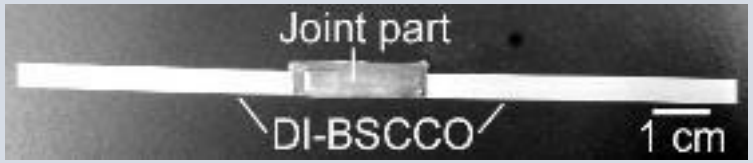
Motivation

Development of superconducting joints between Bi2223 tapes towards persistent current HTS magnets

Strategy

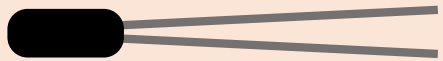
This study

Previous study
(Continuation linear joint)

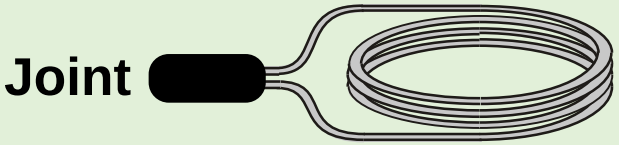


Y. Takeda *et al*., *APEX* (2019).

Joint for magnets
(Termination joint)



Joint of terminal tapes of coil
&
Evaluation of joint resistances



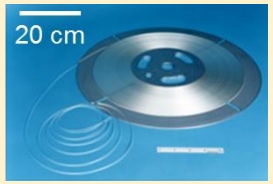
1. Development of termination joints with high I_c properties

2. Evaluation of joint resistances using a joined loop circuit

1. Development of termination joints with high I_c properties

Experimental

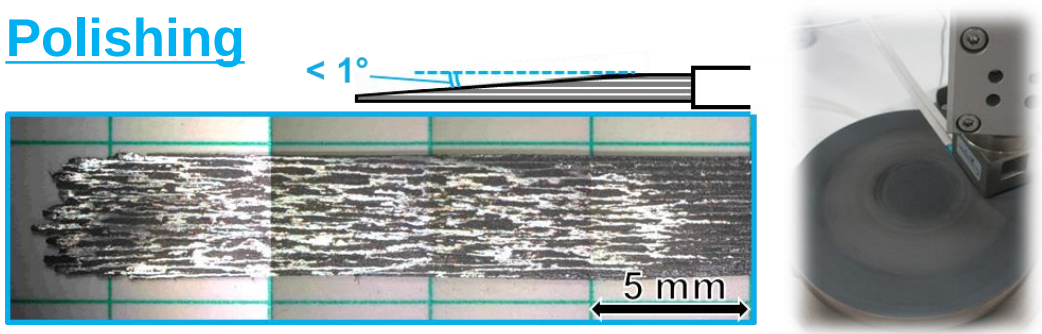
Bi2223 tape
(DI-BSCCO, Type H,
I_c >170 A @77 K, s.f.)



- Cutting into small piece (~10 cm)
- Exposing filaments by polishing
- Forming thick film on filaments by dip-coating with slurry
- Preparing joint part by connecting filaments via intermediate layer
- Uniaxial pressing (~200 MPa)
- Heat-treatment (P_{O2} = 3 kPa, 810°C)

Bi2223 joint

Polishing



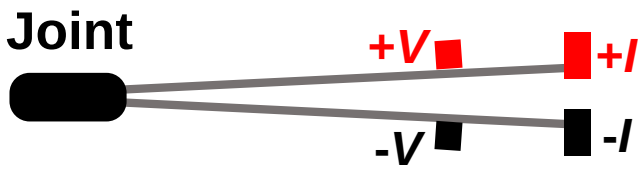
Y. Takeda *et al*., *APEX* (2019).

Slurry
BSCCO powder + EtOH/BuOH
Suitable for synthesis of high J_c Bi2223 polycrystalline thick films

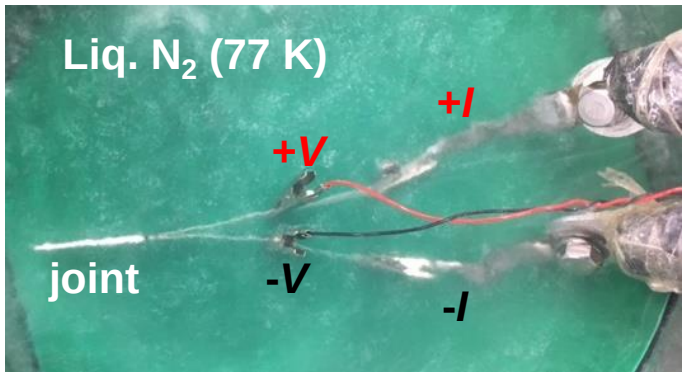
Y. Takeda *et al*., *APEX* (2019).
Y. Takeda *et al*., *SuST* (2018).

Characterization

- Microstructure observation (FE-SEM)
- Transport measurement (Four-point-probe, DC current)



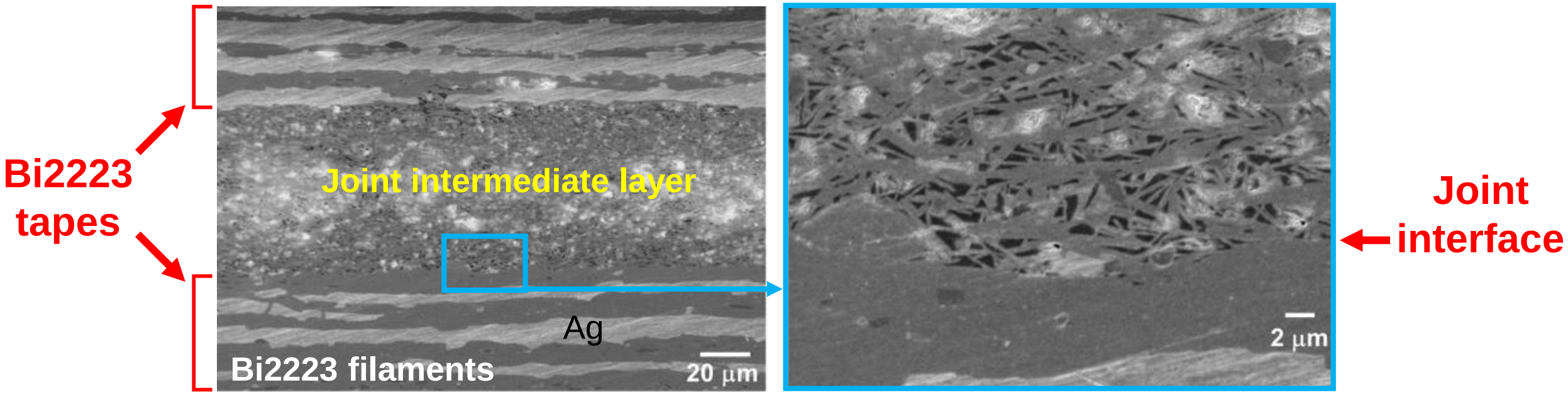
4.2–77 K, 0–2 T,
H // tape surface



Results: Microstructure of joint interface

Sintering condition: 810°C, 24 h, P_{O2} = 3 kPa

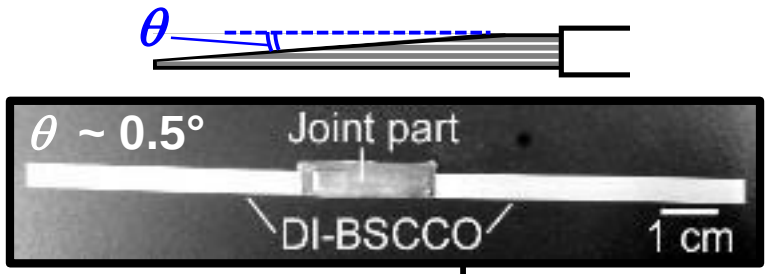
Backscattered electron image for a joint sample



- Joint intermediate layer (~50 μm^t) with thin & small Bi2223 crystals
- Clean joint interface without impurities, cracks nor voids

Microstructure suitable for achieving high joint I_c was formed.

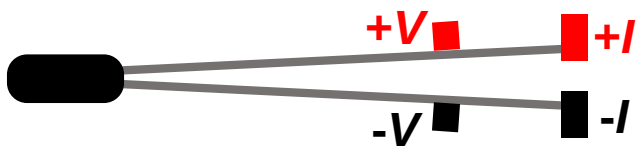
I_c (77 K, s.f.) of termination joint samples



S (joint) ~ 100 mm²

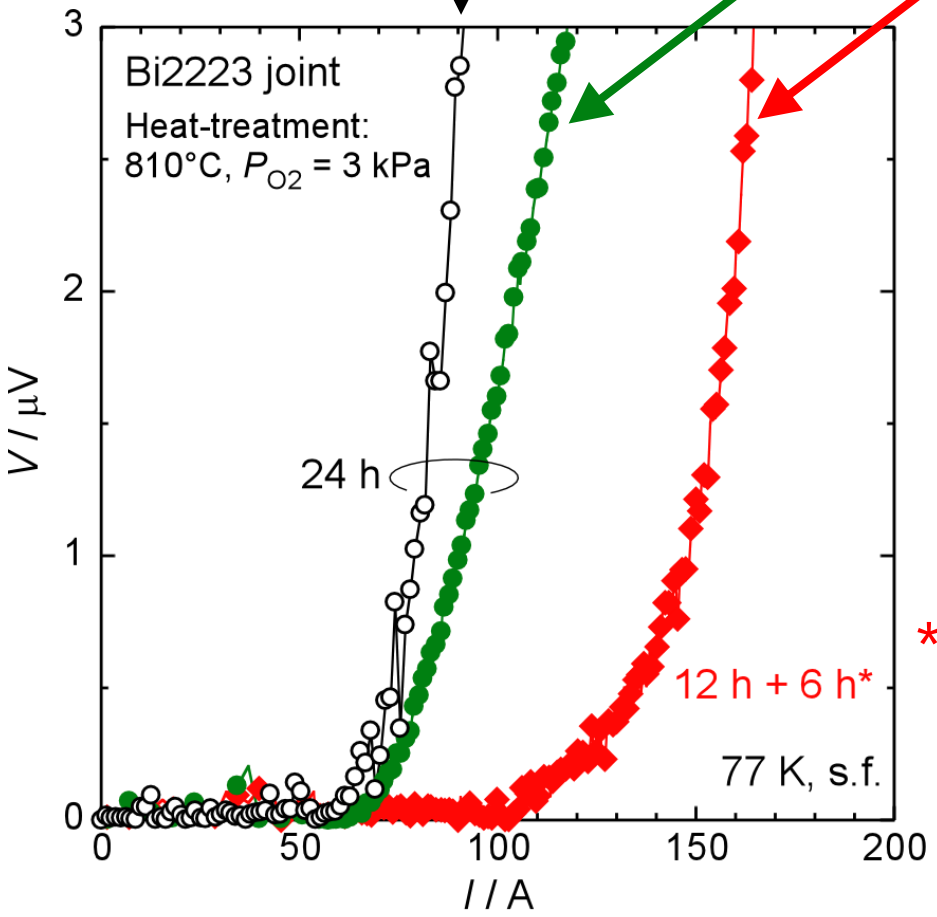
Y. Takeda *et al.*, *APEX* (2019).

This study



θ ~ 0.4°, S (joint) ~ 70 mm²

~80 filaments connected **(~70%)**

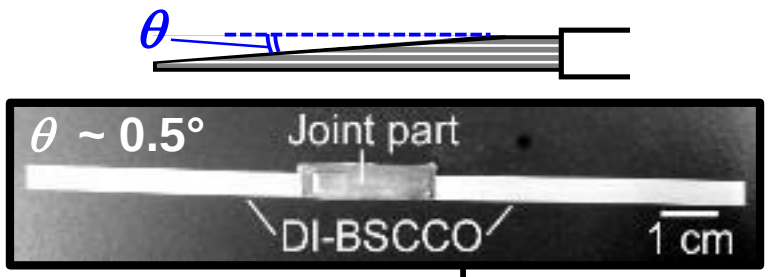


I_c (77 K, s.f.) / A
- ~62
- ~67
- ~108

(10^{-9} Ω criterion)

*Intermediate pressing (~200 MPa) before 2nd sintering

I_c (77 K, s.f.) of termination joint samples



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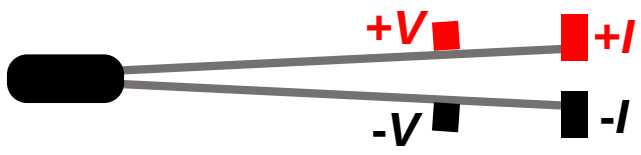

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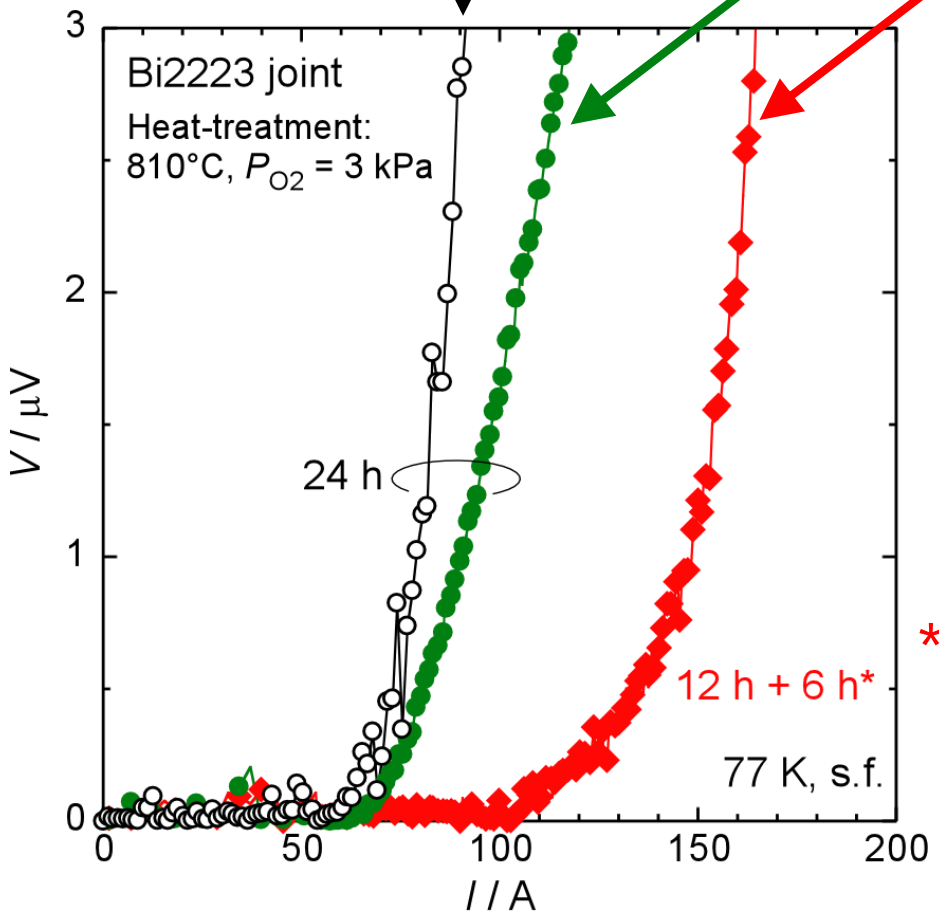


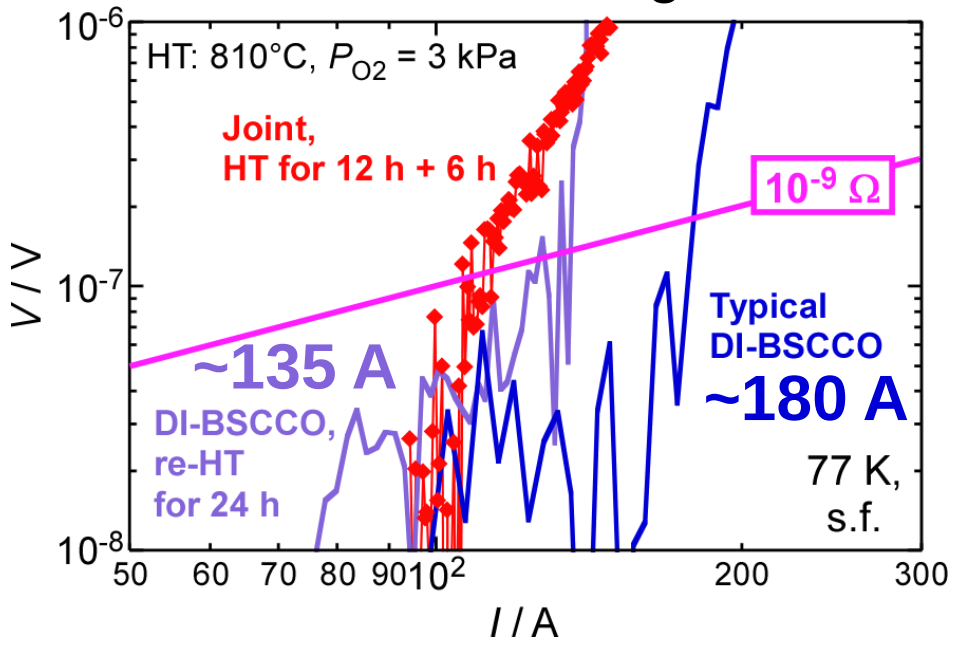
I_c (77 K, s.f.) / A
- ~62
- ~67
- ~108

(10^{-9} Ω criterion)

*Intermediate pressing (~200 MPa) before 2nd sintering

I_c criterion of V = 1 μV is not suitable for evaluation of joint I_c towards persistent current mode.

➡ I_c criterion: 10^{-9} Ω resistance generated



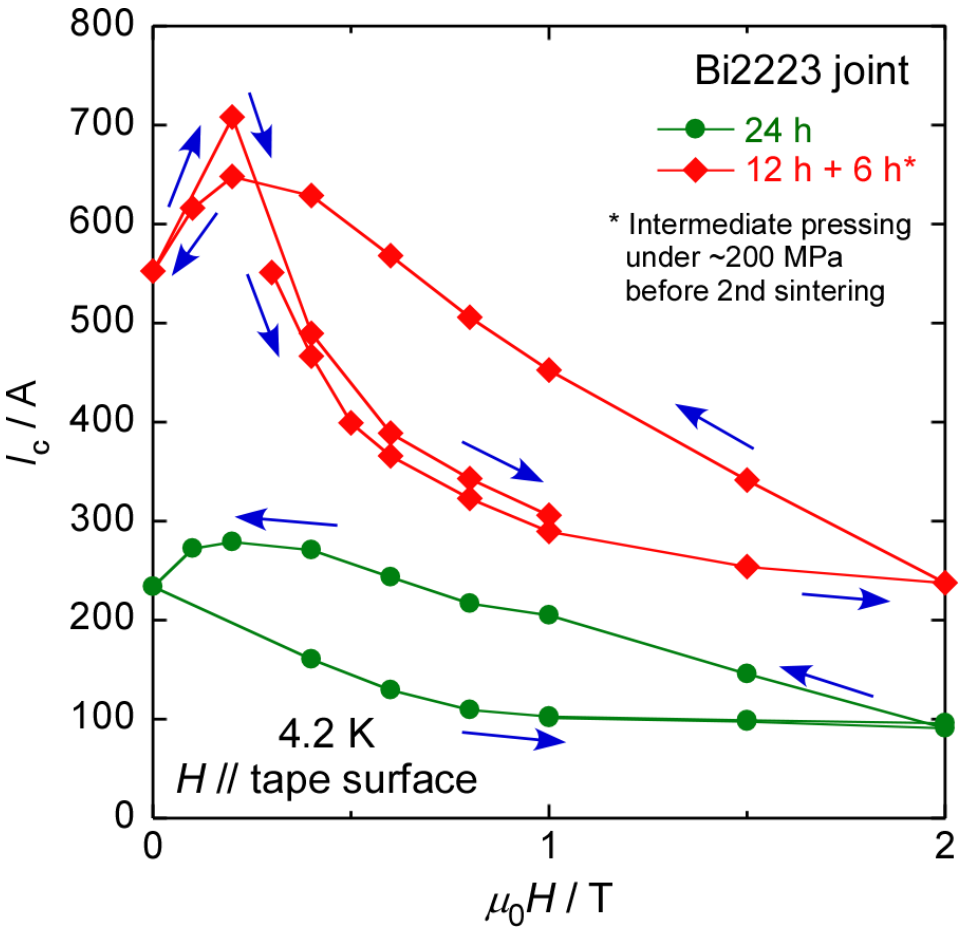
- I_c of Bi2223 tape (DI-BSCCO) decreased by HT for joining.
- Filaments were well connected!

Transport joint I_c characteristics at 4.2 K under fields

I_c measurement: Four-point-probe transport method, I_c criterion: 10^{-9} Ω resistance generated

High joint I_c > 300 A @4.2 K, 1 T

Satisfying requirements for our 30.5 T NMR magnet (> 200 A @4.2 K, 1 T)



High joint I_c was demonstrated towards persistent current magnets.

Transport joint I_c characteristics at 4.2 K under fields

I_c measurement: Four-point-probe transport method, I_c criterion: 10^{-9} Ω resistance generated

High joint I_c > 300 A @4.2 K, 1 T

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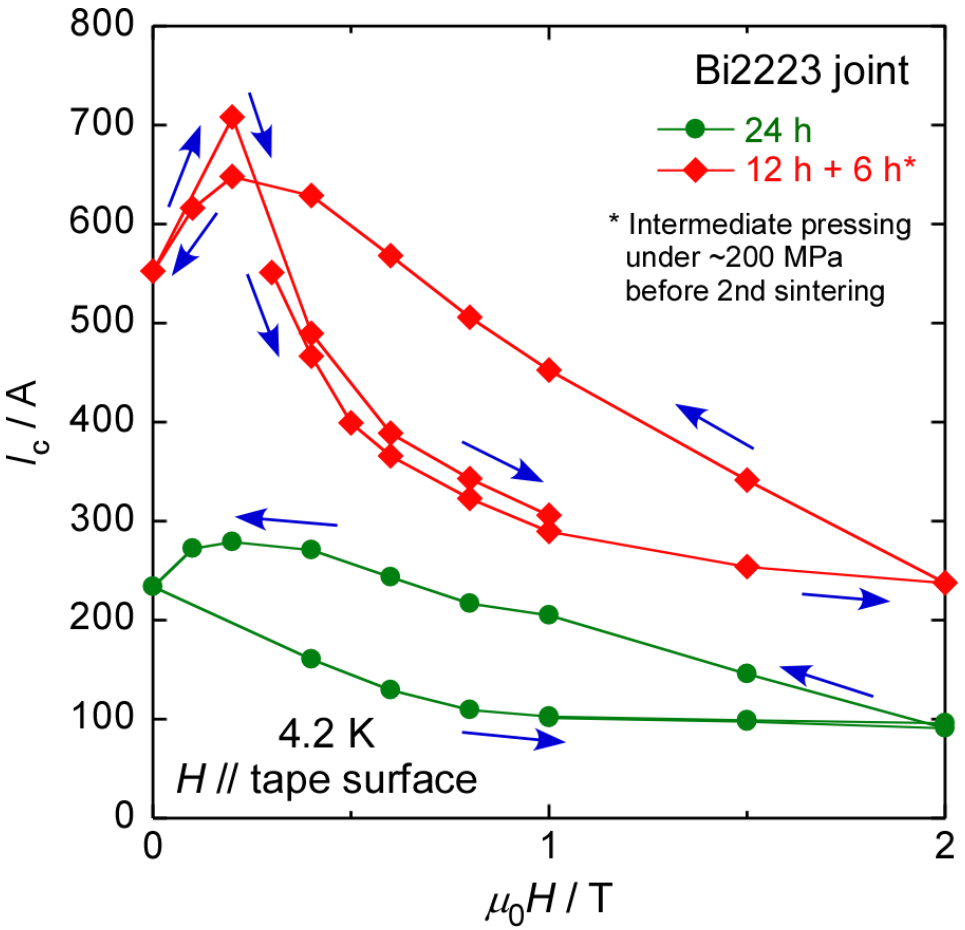
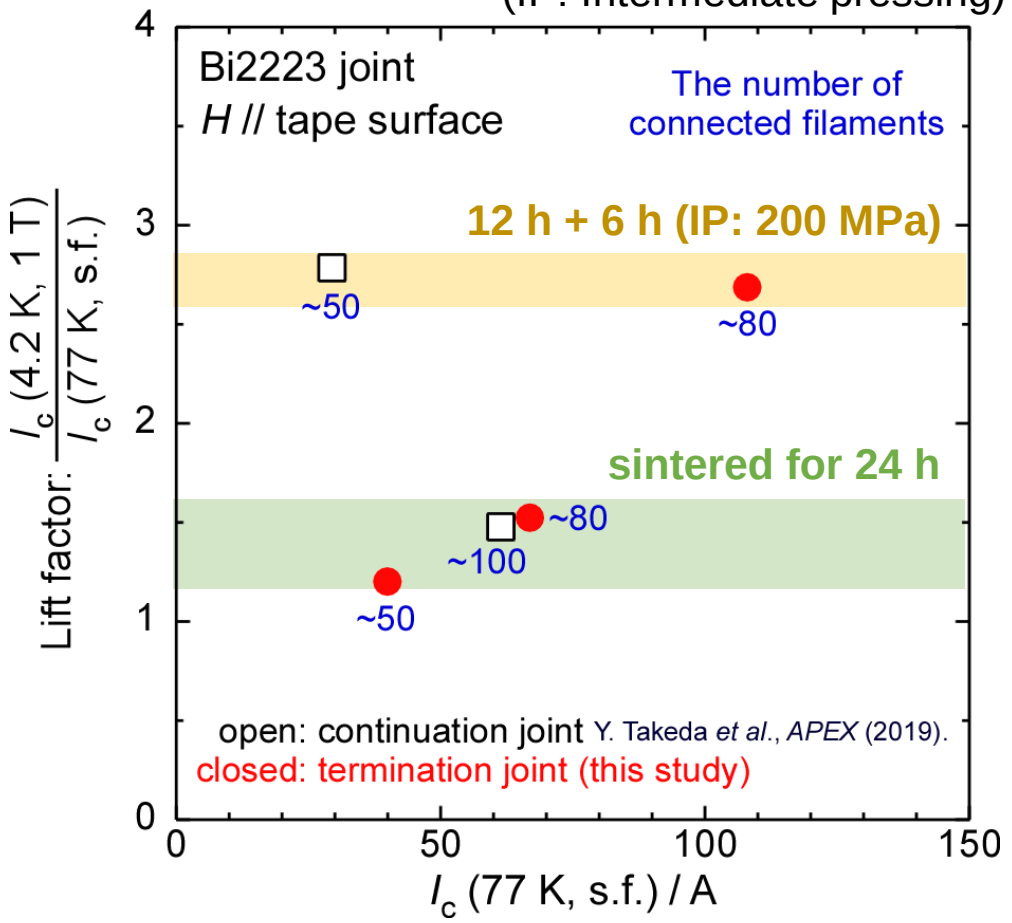


(IP: Intermediate pressing)



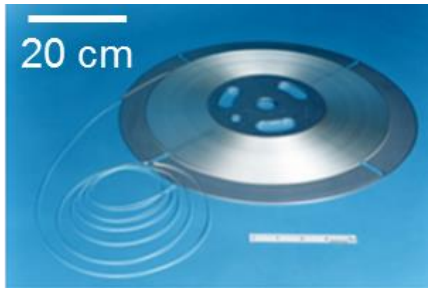
High joint I_c was demonstrated towards persistent current magnets.

I_c (4.2 K, ~1 T) can be estimated by I_c (77 K) & fabrication condition.

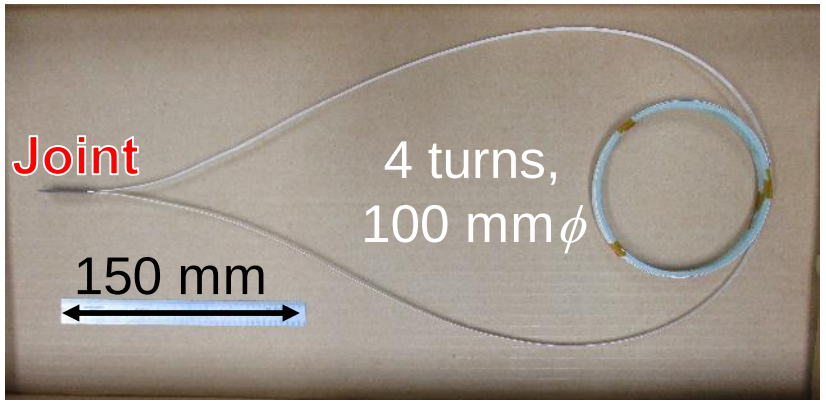
2. Evaluation of joint resistances using a terminal joined loop circuit

Bi2223 tape

DI-BSCCO (Type H)

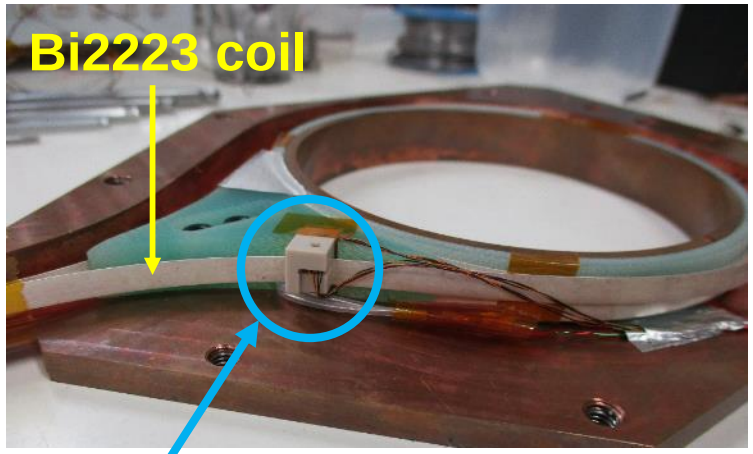


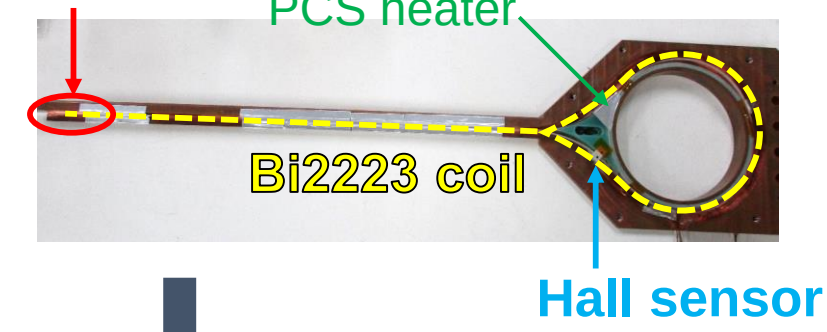
Preparing a small Bi2223 coil



Self-inductance, L ~ 5.6 μH

Sample setting





Joint resistance evaluation system

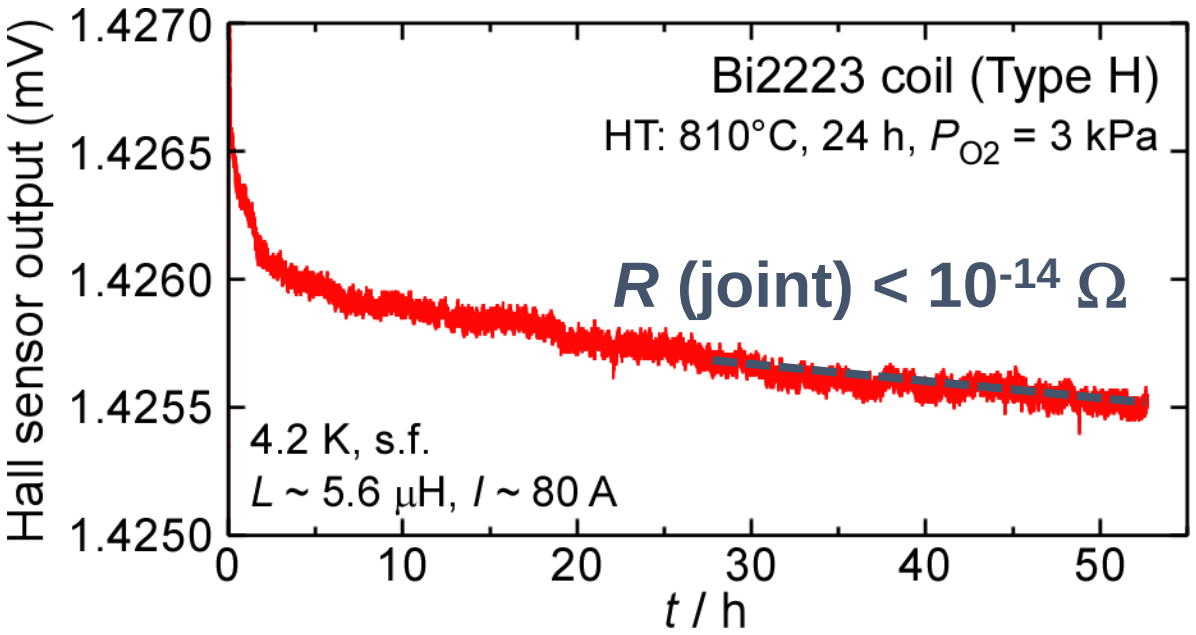
K. Kobayashi, Thu-Mo-Po4.09-02 [64]

Measuring current decay behavior

➡ **Joint resistance: *R* (joint)**

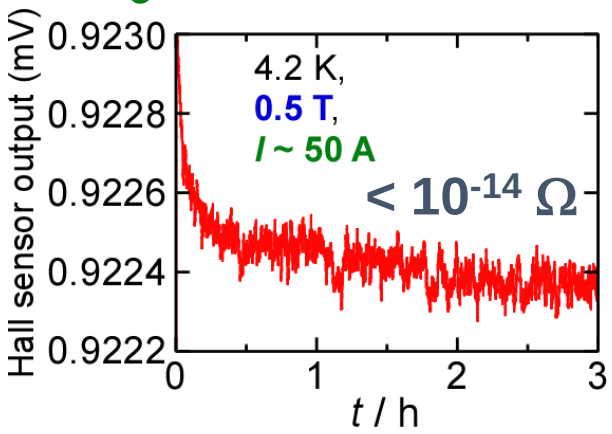
Demonstration of low R (joint) < 10^{-14} Ω even under fields

t = 0: Bi2223 coil current was induced.

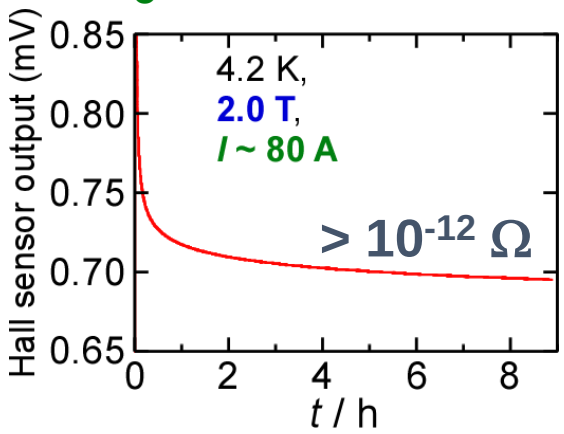


Results under fields

$I < I_c$



$I \sim I_c$



- **Very Low R (joint) of < 10^{-14} Ω** was observed.
  Satisfying requirements for our 30.5 T NMR magnet (< 10^{-12} Ω)
- Joint resistances were low **even under fields** ($I < I_c$).

Persistent current Bi2223 magnets with superconducting joints are expected!

Summary

Motivation: Development of superconducting joints between Bi2223/Ag tapes towards persistent current HTS magnets

1. Development of termination joints with high I_c properties

A termination joint sample exhibited

high joint I_c > 300 A (4.2 K, 1 T, 10^{-9} Ω criterion).

2. Evaluation of joint resistances using a joined loop circuit

Low joint resistances (< 10^{-14} Ω)

were observed even under fields ($I < I_c$).

Requirements towards a 30.5 T (1.3 GHz) NMR magnet were almost satisfied in termination joints in this study.

Persistent current Bi2223 magnets with superconducting joints are expected!

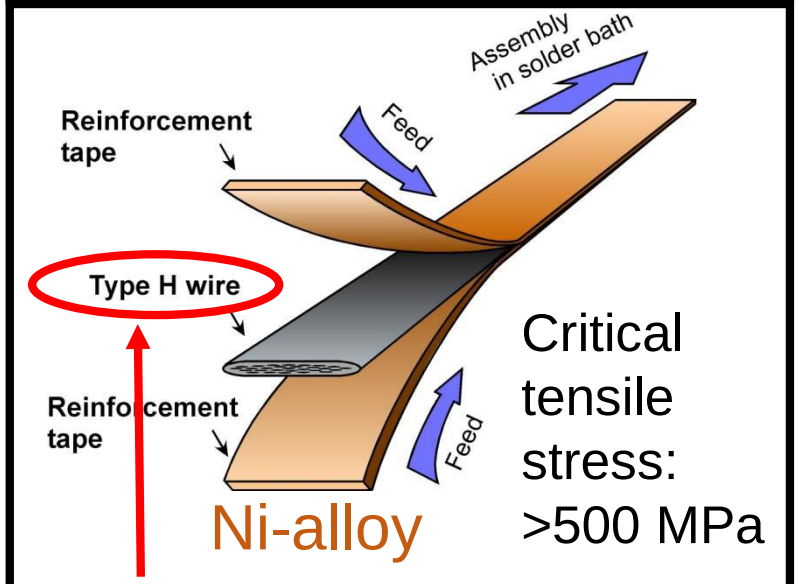
Future plan

1. Further improvement in joint I_c

- Optimizing joint processes & joint configuration
- Controlling microstructure & chemical compositions of joint intermediate layer, etc.

2. Joints for “tough” Bi2223 tapes (Type HT-NX) & installation in NMR

DI-BSCCO Type HT-NX



- Bi2223 tapes for high field magnet applications
- Reinforcement materials **must be removed** for joining.

  ➡ Optimizing the preprocessing steps

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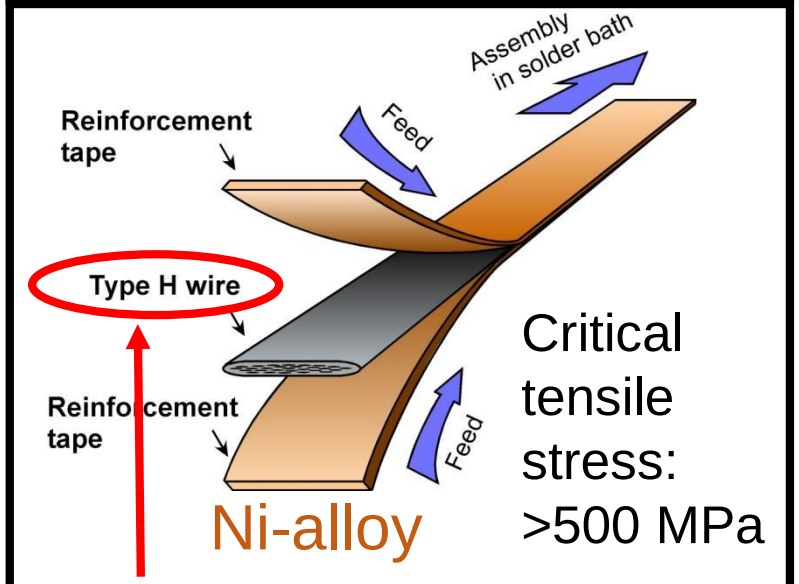


Critical tensile stress: >500 MPa

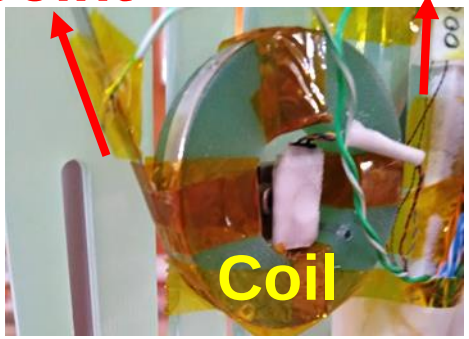
Joined in this study

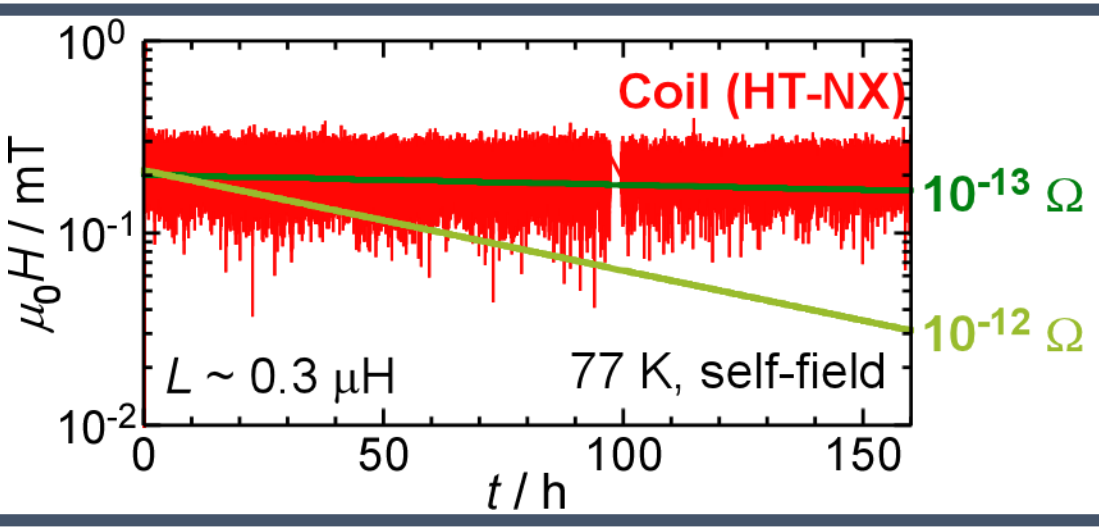
- Bi2223 tapes for high field magnet applications
- Reinforcement materials **must be removed** for joining.

➡ Optimizing the preprocessing steps

Latest news!

Joint





We will challenge persistent current experiment in NMR system this winter!