IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PT-4 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.

Present status of the MIRAI Program; towards a persistent 1.3 GHz NMR and DC feeder cables

H. Maeda[1,2], J. Shimoyama[3], Y. Yanagisawa[2], Y. Ishii[4,2], M. Tomita[5]

[1]Japan Science and Technology Agency; [2]RIKEN; [3]Aoyama Gakuin University; [4]Tokyo Institute of Technology; [5]Railway Technical Research Institute

2020.1.9 (Thursday)
9:20-10:00 PT-4

This work is supported by
JST-MIRAI Program, JPMJMI17A2, Japan

Acknowledgement

We would like to express our gratitude to all the following project members for their dedication and hard work on the project

■ *Superconducting Joints:*

- *Aoyama Gakuin University; J. Shimoyama et al.*
- *NIMS; H. Kitaguchi, Y. Takano, N. Banno, A. Matsumoto, G. Nishijima et al.; Bi-2223/LTS joint, ultra-low resistance joint and NMR magnet*
- *The University of Tokyo; Y. Takeda et al.; Bi-2223/ Bi-2223 joint*
- *Kyushu University; T. Kiss et al.; current path*
- *Kyoto University; T. Doi et al.; REBCO/ REBCO joint*
- *Tohoku University; S. Ito et al.; low resistance joint*
- *Shimane University; S. Funaki et al.; REBCO/REBCO joint*
- *Muroran Institute of Technology; X. Jin et al.; Bi-2223/Bi-2223 joint*
- *Atomic Energy Research Institute; S. Shamoto et al.; solder joint*
- *Japan Fine Ceramics Center; T. Kato et al.; SEM and TEM images*
- *Sumitomo Electric; T. Nagaishi, K. Ohki, T. Yamaguchi et al. ; REBCO/REBCO joint*
- *TEP; K. Naito et al.; low angle polishing*

Acknowledgement

We would like to express our gratitude to all the following project members for their dedication and hard work on the project

■ NMR magnet and NMR spectroscopy:

- RIKEN; Y. Yanagisawa, R. Piao and M. Takahashi et al.; NMR magnet
  T. Yamazaki; NMR spectroscopy
- JASTEC; K. Saito, Y. Miyoshi and M. Hamada et al.; NMR magnet
- Okayama University; H. Ueda et al.; screening current
- Chiba University; Y. Suetomi; protection
- Sophia University; T. Takao, T. Ueno, K. Yamagishi and S. Takahashi, et al.; magnet technology
- Tokyo Institute of Technology; Y. Ishii et al.; NMR spectroscopy
- JEOL RESONANCE; K. Hachitani and H. Suematsu et al.; NMR system

■ Superconducting DC power cable for railway systems:

- Railway Technical Research Institute; M. Tomita et al.; HTS DC feeder cables
- Kyushu Institute of Technology, K. Matsumoto and S. Otabe et al.; soldered joint

Outline

JST MIRAI

1. Overview of the MIRAI Program
2. Present status of the 1.3 GHz NMR development
   - Design of the 1.3 GHz NMR
   - Superconducting joints
   - 400 MHz (9.4 T) LTS/HTS persistent NMR magnet and NMR measurement
   - Issues to be solved for the 1.3 GHz NMR
   - NMR instrumentation and spectroscopy
3. Present status of the intermediate joint between DC feeder cables
4. Summary

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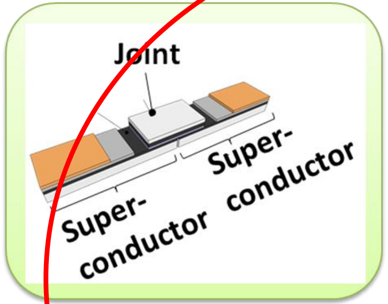
Schematic diagram of the MIRAI Program

Ultra low resistive joints

Superconducting joints



Elongation of the DC superconducting feeder cables for railway systems

Development of joining technology between high temperature superconducting (HTS) conductors

The world's highest field NMR magnet, operated in the persistent current mode

Construction of new technologies, providing a basis for future society

https://www.jst.go.jp/mirai/jp/uploads/saitaku2017/JPMJMI17A2_maeda.pdf

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Development history in Japan

2010- 2015

2006- 2016

1.02 GHz LTS/HTS NMR (24 T)
<u>Driven mode</u>

Medium-field LTS/HTS NMR (500 MHz; 11.75 T)
<u>Driven mode</u>

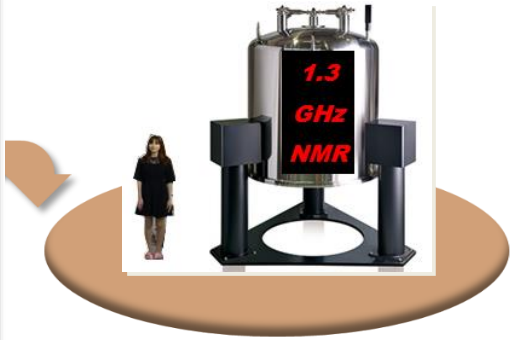
K. Hashi, et al., *JMR*, 256, 30-33 (2015)

Development history in Japan

Target:

- **Development of a world's highest field all-superconducting NMR magnet operated in the persistent mode**

MIRAI Program 2017-2026



1.3 GHz LTS/HTS NMR (30.5 T)
Persistent current mode

https://www.jst.go.jp/mirai/jp/uploads/saitaku2017/JPMJMI17A2_maeda.pdf

K. Hashi, et al., *JMR*, 256, 30-33 (2015)

High impact target of the 1.3 GHz NMR

- **Structures of proteins which link to Alzheimer's disease, Prion disease, Parkinson's disease were determined by solid-state NMR.**

Tokyo Tech

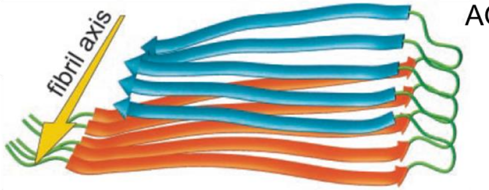
RIKEN

Alzheimer's

Amyloid β

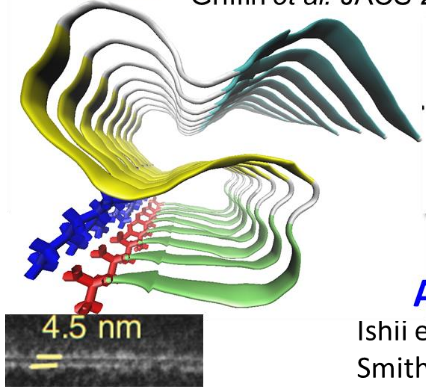
Aβ40

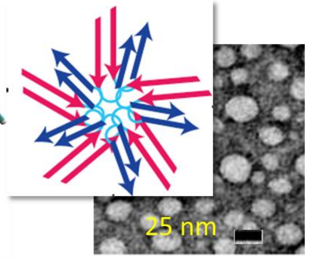
Petkova, Ishii, Tycko *et al.* PNAS 2002
Bertini *et al.* JACS 2011; Reif et al. AGC 2012 etc



Aβ42

Ishii *et al.* NSMB 2015
Griffin *et al.* JACS 2016; Meier et al.

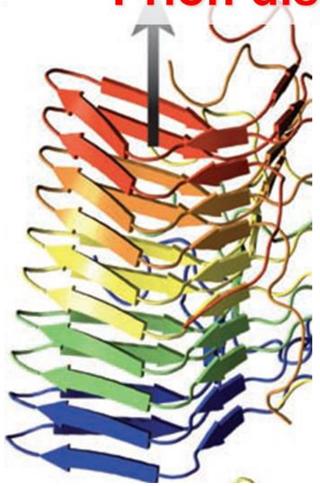




Amyloid Oligomer

Ishii et al. NSMB 2007
Smith et al.

Prion disease

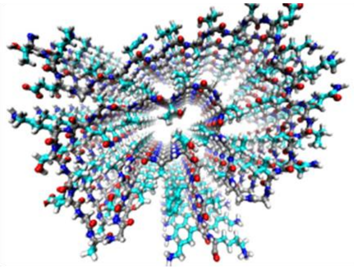


Prion

Meier et al.
Science 2008

Jaroniec et al.
PNAS 2008

Parkinson's



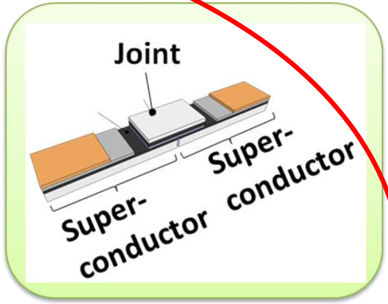
α-Synuclein

Baldus et al. PNAS 2005
Rienstra et al. NSMB 2016

Schematic diagram of the program

Ultra low resistive joints

Superconducting joints



Elongation of the DC superconducting feeder cables for railway systems

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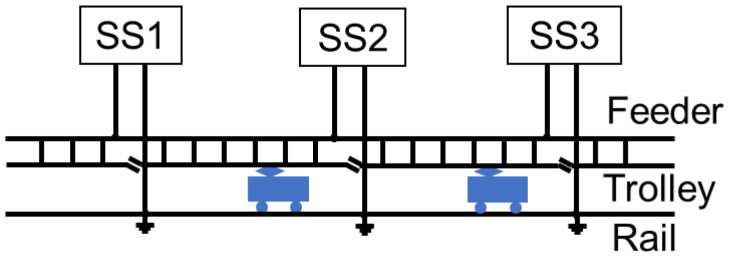
Electrification feeder system for railway systems

DC electrification feeder system for railway systems



Disadvantages:
- **Transmission power loss of the DC feeder cable**
- **Sometimes regenerative braking is canceled(energy consumption)**

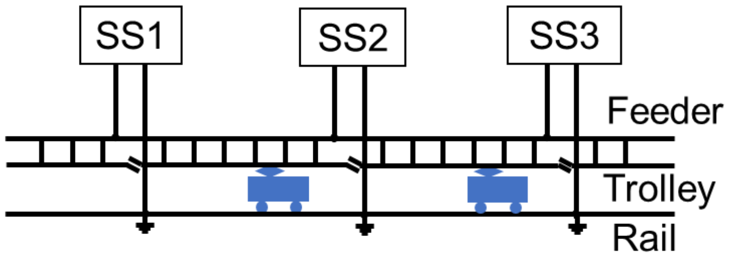
M. Tomita *et al.*, *Energy 122* (2017) 579

Railway Technical Research Institute

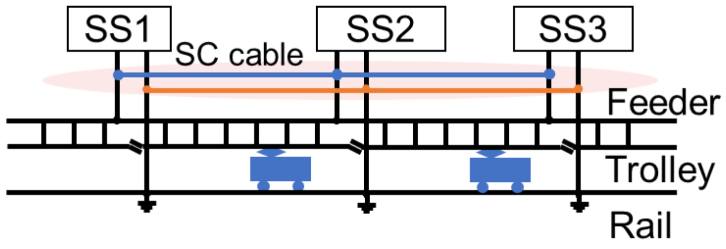
Electrification feeder system for railway systems

JST MIRAI

DC electrification feeder system for railway systems

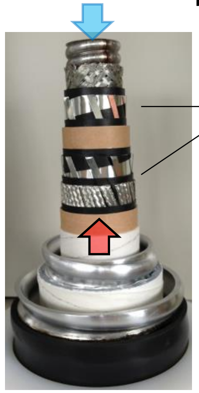


Next generation DC electrification feeder system for railway systems



Advantages:
- **Load leveling between substations**
- **Reduction of transmission loss**
- **Efficient regenerative braking**

Liq. N_2 flow



HTS tapes

HTS DC feeder cable
> 10 cm in OD

M. Tomita *et al.*, *Energy 122* (2017) 579

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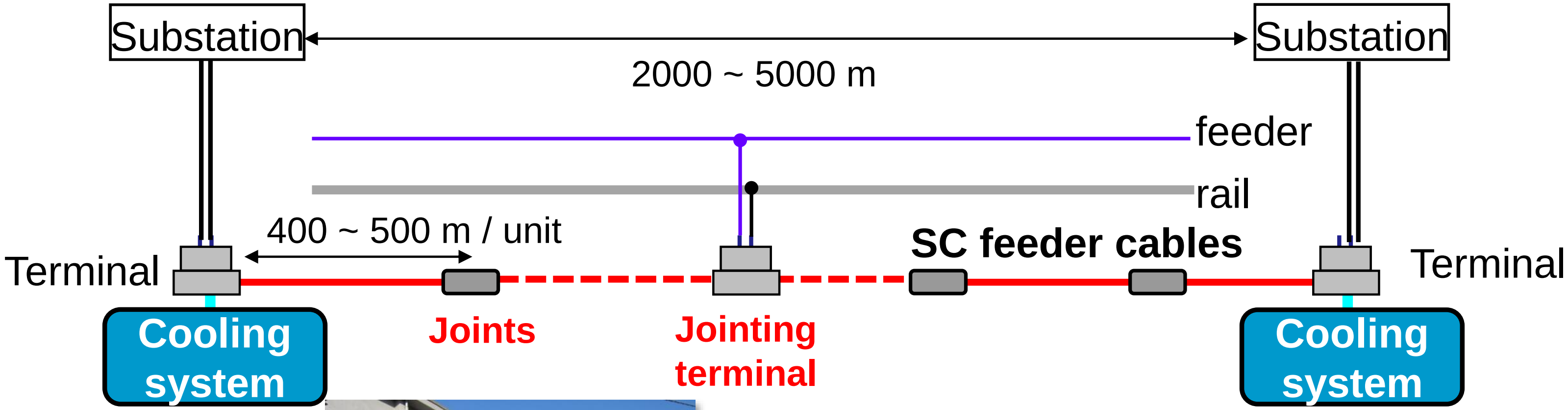
Necessity of the joint



Cable length is < 500m due to truck transportation

Target:

- **Development of ultra-low resistance on-site joints between HTS DC cables**

Railway Technical Research Institute

Organization of the program

Program manager
Hideaki Maeda （PM）

PM Supporting office
PM/RIKEN

Joint technology group
Jun-Ichi Shimoyama （Aoyama Gakuin University）

Aoyama-Gakuin University, NIMS, TEP Ceramics, Sumitomo Electric, Fine Ceramic Center, Kyushu University, Kyoto University, Tohoku University, Muroran Institute of Technology, Shimane University, Japan Atomic Energy Agency

NMR magnet group
Yoshinori Yanagisawa （RIKEN）

RIKEN,JASTEC, OKAYAMA University, NIMS

Proof of social impact of NMR group
Yoshitaka Ishii （Tokyo Institute of Technology/RIKEN）

Tokyo Institute of Technology, RIKEN, JEOL RESONANCE

Superconducting feeder cable for railway systems group
Masaru Tomita (Railway Technical Research Institute）

Railway Technical Research Institute, Kyushu University, Kyushu Institute of Technology

18 universities, research Institutes and companies

Stage timeline of the MIRAI Program

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R&D and conceptual design

- SC joints
- Persistent 400 MHz NMR magnet
- 30 T magnet
- NMR instrumentation
- NMR spectroscopy at ultra-high field

Design and fabrication

- Mass production of the SC joints
- Design and fabrication of the 1.3 GHz NMR
- NMR spectroscopy at ultra-high field

Fabrication and NMR

- Completion and the charge test of the persistent 1.3 GHz NMR
- NMR measurement with the 1.3 GHz NMR

2017 | 2020 | 2023 | 2026

The 1st stage | The 2nd stage | The 3rd stage

R&D and the 1st prototype

- R&D
- The first prototype of the SC cable joint

The 2nd prototype

- The 2nd prototype of the SC cable joint

Test

- The running test of the train with joined SC cables

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3. Present status of the intermediate joint feeder cables
4. Summary

Dr. Y. Yanagisawa
(RIKEN)

Change in preliminary design

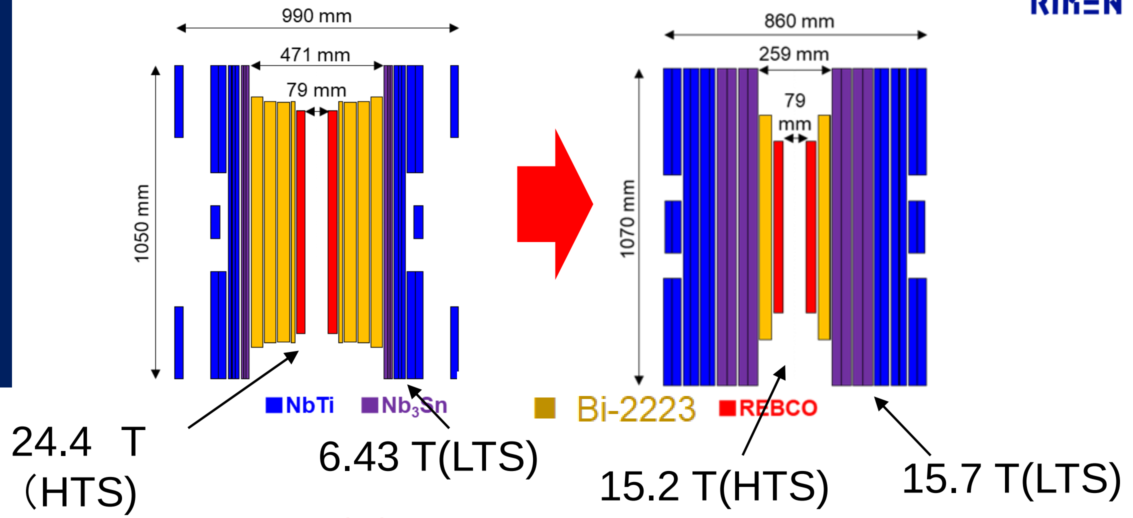
Persistent 1.3 GHz NMR (30.5 T)

Reasons for the change of the magnet design:

- **Design A needs a piece of HTS conductor with a length of >1km , which is unlikely at present**
- **High cost of the magnet**

Design A — LTS/Bi-2223/REBCO

Design A2 — LTS/Bi-2223/REBCO



REBCO
Bi-2223 NX
LTS

Field contribution of the HTS coils is reduced

Designed by Dr. Hamada, JASTEC

H. Maeda et al., *IEEE Trans. Appl. Supercond.* **29** (2019) 4602409.

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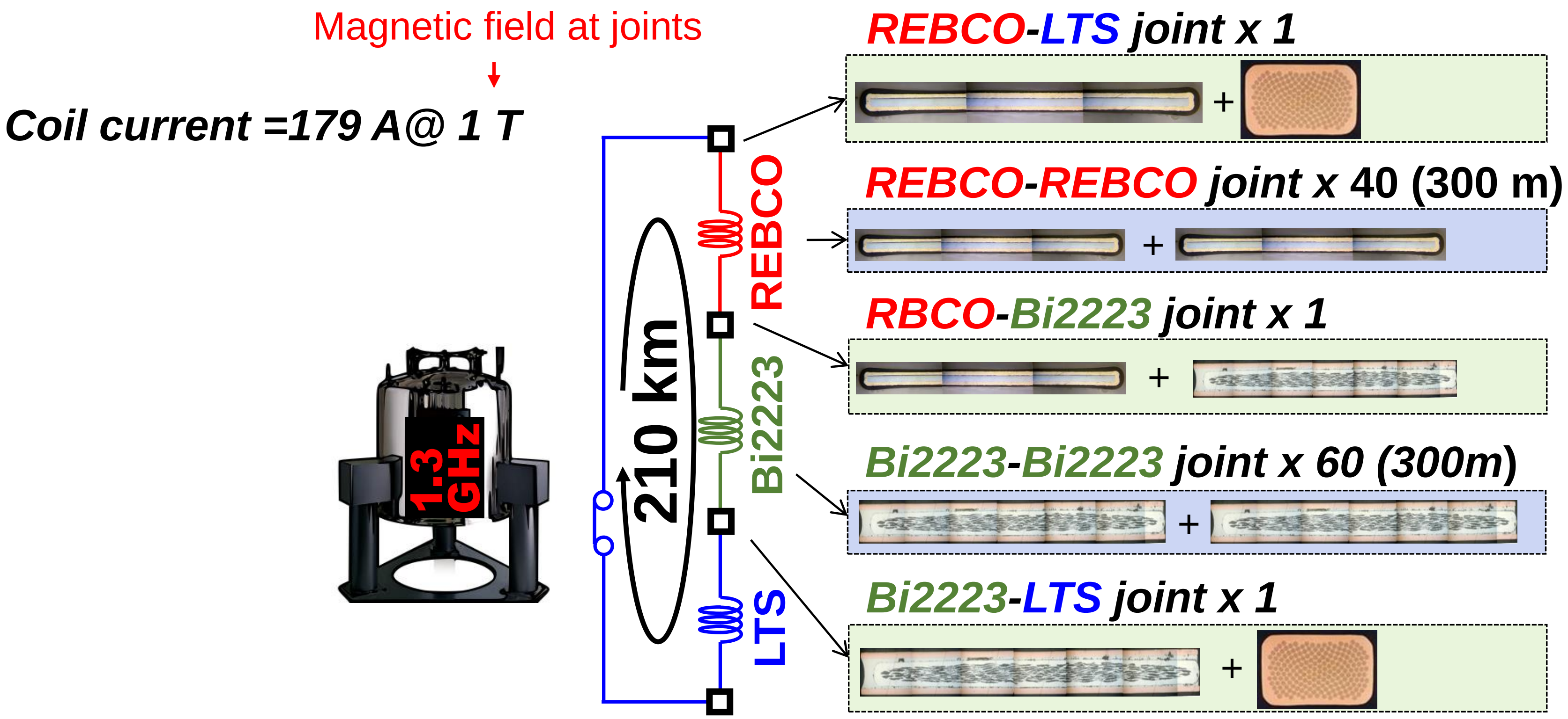
Prof. J. Shimoyama
(Aoyama Gakuin University)

Superconducting joints necessary for the 1.3 GHz NMR magnet

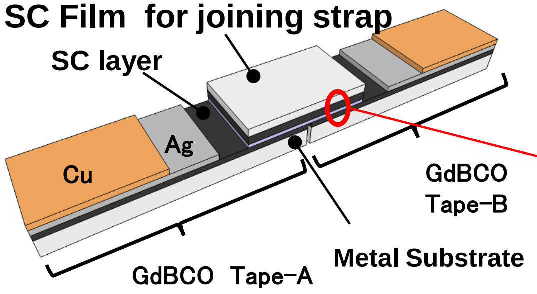


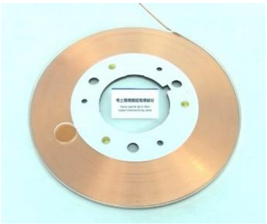
Permissible total resistance necessary for the field decay rate of 10^{-8}/h is 10^{-9} Ω , corresponding to a joint resistance of 10^{-12}~10^{-11} Ω/ joint

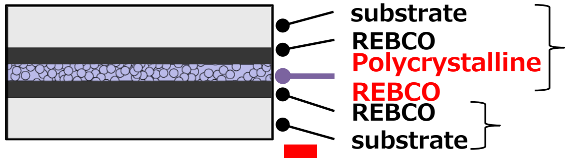
Superconducting joint REBCO/ REBCO (RR)

Manufacturing process of an indirect type of RR joint

SUMITOMO ELECTRIC





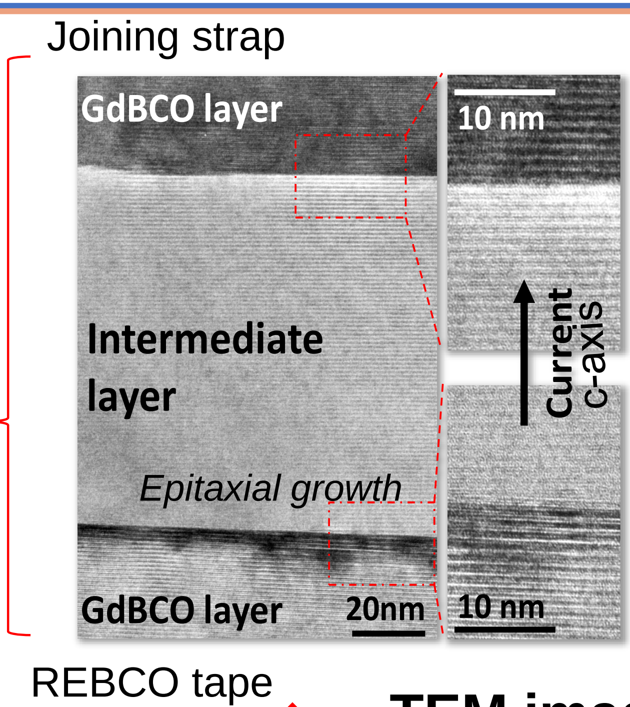


Joining strap

REBCO Tape

Crystal growth
800℃, 20 min, 40 MPa

Oxygen annealing
500-200℃, 6 h



TEM images

Japan Fine Ceramics Center

Intermediate Grown Superconducting Joint (iGS Joint)

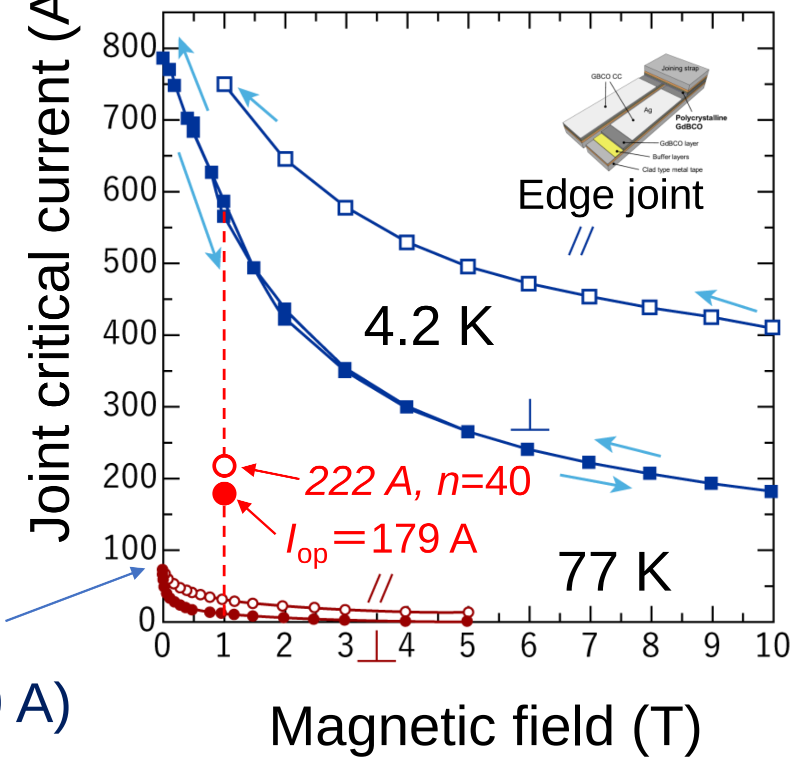
K. Ohki et al., *SuST* 30 (2017) 115017.
K. Ohki et al., *ASC-2018*, 1LOr1C-03.

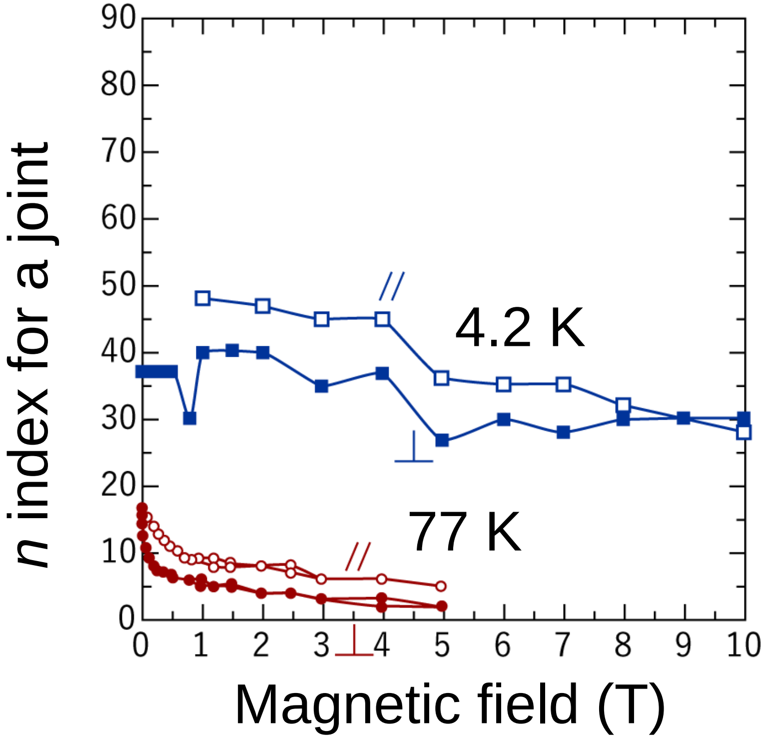
Joint critical current vs. *magnetic field*

Lift factor =11

70 A
(70- 100 A)

Conductor I_c = 160 A at 77 K





<u>The indirect RR joint is sufficient for the 1.3 GHz NMR</u>

K. Yamagishi et al., *ASC2018*, 4LPo1G-05.

Superconducting joint
Bi-2223/ Bi-2223 (BB)

Manufacturing process of an indirect-type of BB joint

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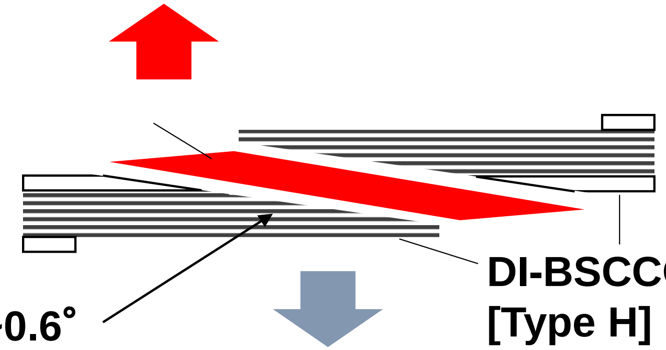
TEP CERAMICS K.K.

DI-BSCCO [Type H]

■ **Bi-2223 precursor was coated**

Lap joint



~0.6°

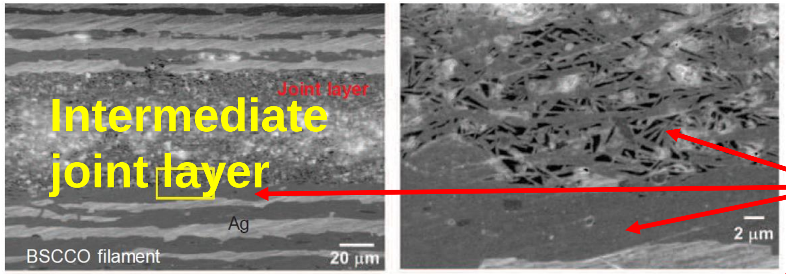
DI-BSCCO [Type H]

810℃x ~20h

■ **Low angle polishing (~0.6°) was applied, which increased a number of exposed filaments**

length

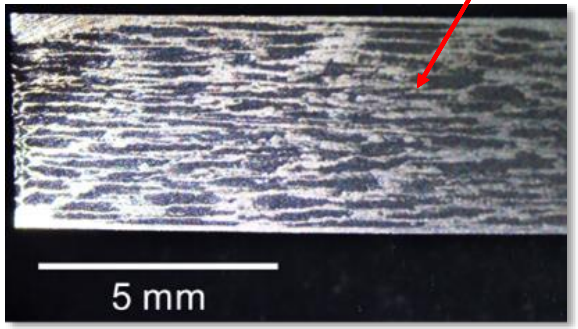
Backscattered electron image for a joint sample



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

Filaments

Cross sectional view of the joint



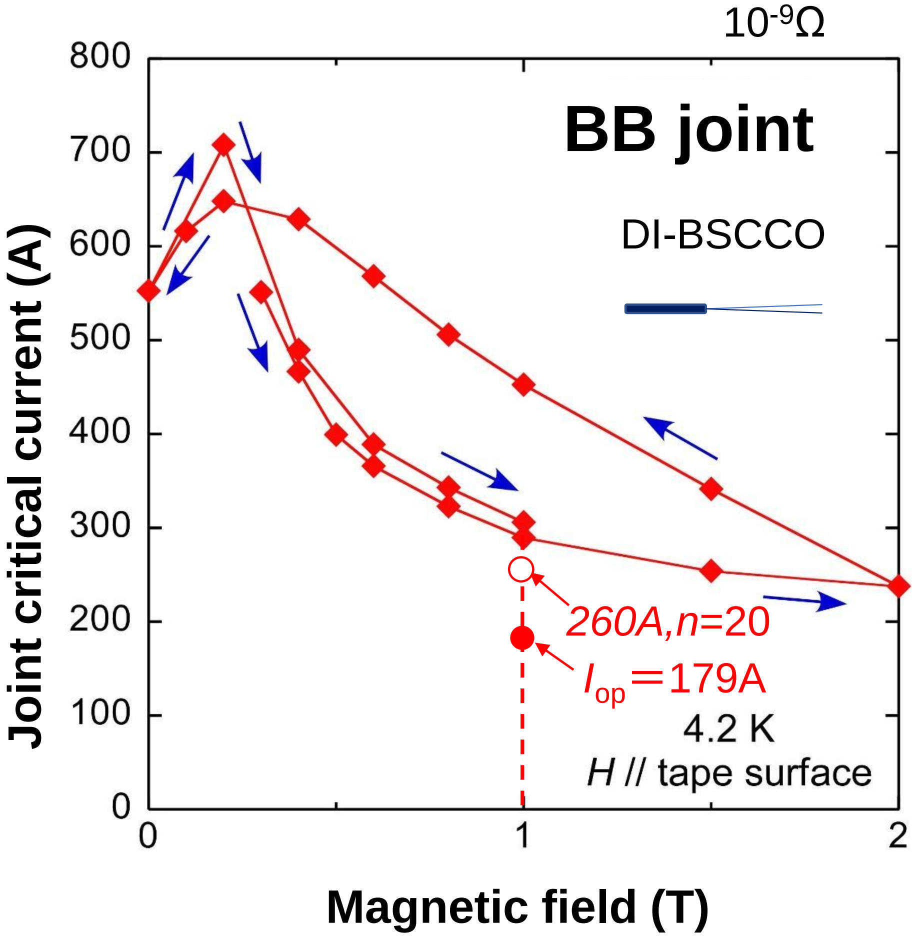
Polished surface

The University of Tokyo

Aoyama-Gakuin

Y. Takeda et al., *SuST* **31** (2018) 074002
Y. Takeda et al., *ASC2018*, 3MPo2D-08, **Y. Takeda** at al., *Appl. Phys. Express*, **12** (2019) 023003.

Joint *critical current vs. magnetic field*



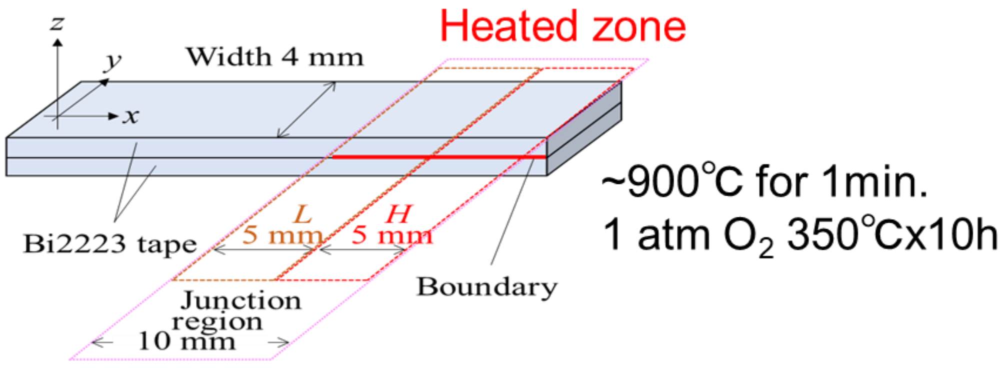
The University of Tokyo
Aoyama-Gakuin

The indirect BB joint satisfies the requirement for the 1.3 GHz(30.5T) NMR; however, the joint critical current must be further increased

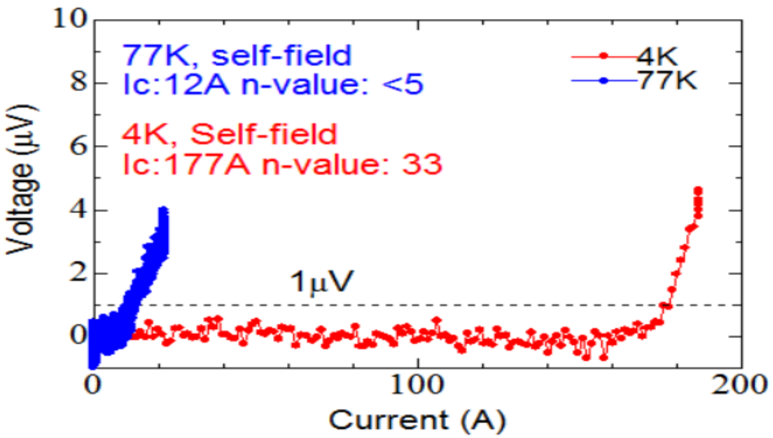
Y. Takeda et al., this conference, 9P-15.

Other topics

Direct type BB-joint



Partial melting and solidification



Based on SEM images, it is demonstrated that Bi2212 connects Bi-2223 filaments

The joint I_c is dominated by Bi-2212

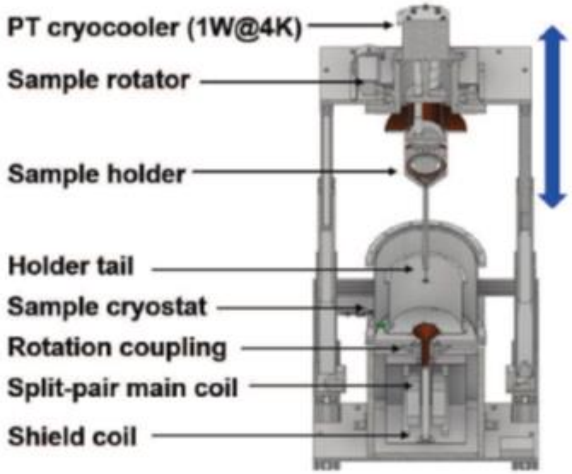
Insufficient for the 1.3 GHz NMR at present

Bi2212 bridges Bi-2223 filaments

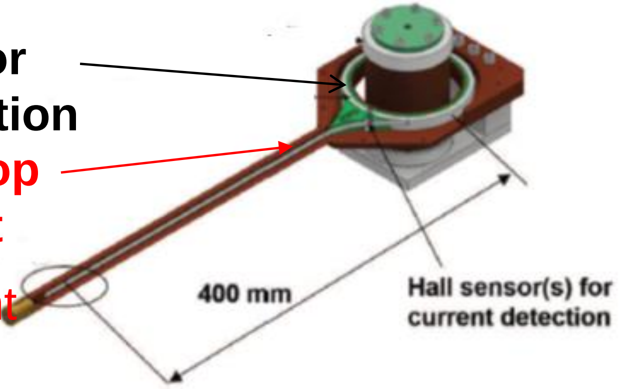
X. Kanazawa et al., *SuST* **32**(2019) 035011.

Development of a joint resistance evaluation system

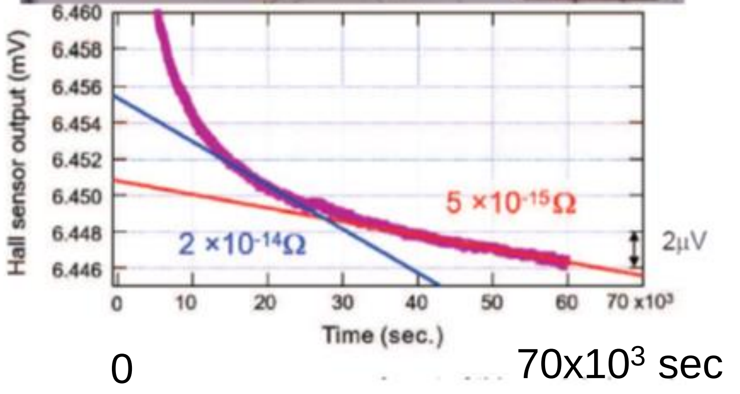
- The persistent current is induced in the loop by discharging a copper coil
- Temporal field decay provides joint resistance in a short time



Specification
- R-range: $10^{-8} \sim 10^{-15}\ \Omega$
- Temperature: 3 ~120 K
- External field: 0 ~ 3 T (rotatable)
- Current injection: 0 ~ >400 A



Commissioning: 1 turn Nb-Ti wire, solder joint @4.2K

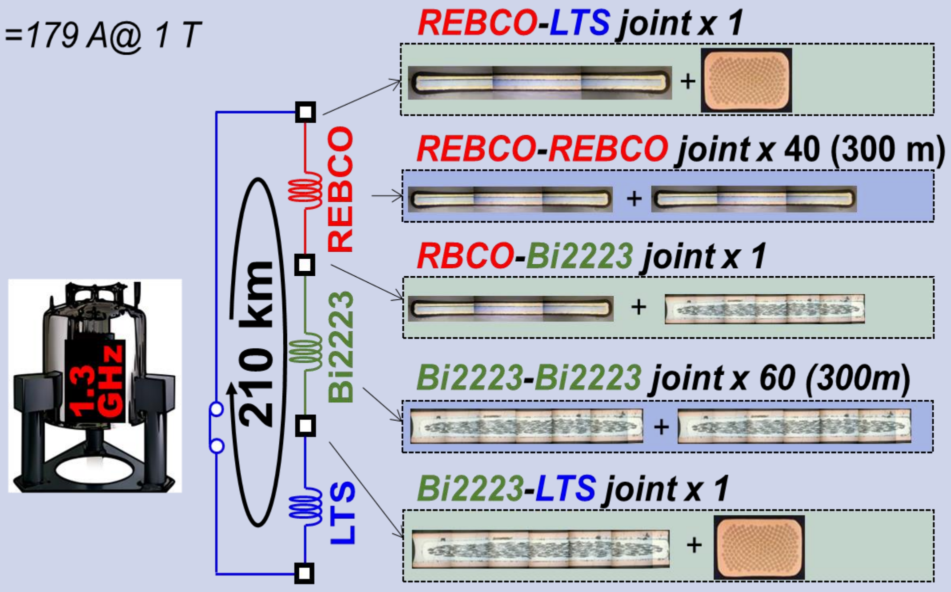


A part of this work is based on results obtained from a project commissioned by NEDO[No. 16100555-0]

K. Kobayashi et al., *IEEE Trans. Appl. Supercond.*, accepted for publication (2020), DOI: 10.1109/TASC.2020.2967680.
H. Kitaguchi et al., this conference, 9A4-1 (2020).

Current status of the joint development

Coil current =179 A@ 1 T



Current status

Ultra-low resistance normal conducting joint or superconducting joint

Completion of the development

Ultra-low resistance normal conducting joint or superconducting joint

Nearly completion of the development

By using the solder dip method, ultra-low resistance joint（$10^{-10}\Omega$）or superconducting joint (<20A) was achieved

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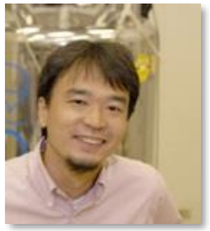
Dr. Y. Yanagisawa (RIKEN)



Prof. Y. Ishii (Tokyo Institute of Technology/ RIKEN)

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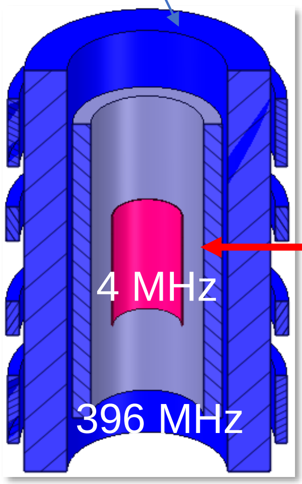
The medium-field persistent NMR magnet with superconducting joints

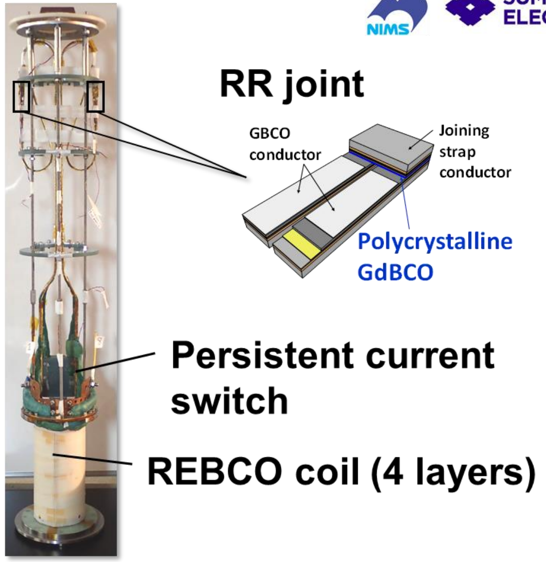
400 MHz (9.4 T)
LTS/ REBCO NMR

Persistent REBCO inner coil

Persistent
LTS outer coils

JNM-ECZ series NMR spectrometer
Installed in RIKEN





It is proved that high resolution NMR spectra are achievable by the use of persistent LTS/HTS NMR magnet with superconductinng joints

K. Ohki et al. *SuST* **30** (2017) 115017.
Y. Yanagisawa et al., *ASC2018*, 4LPo1E-05.

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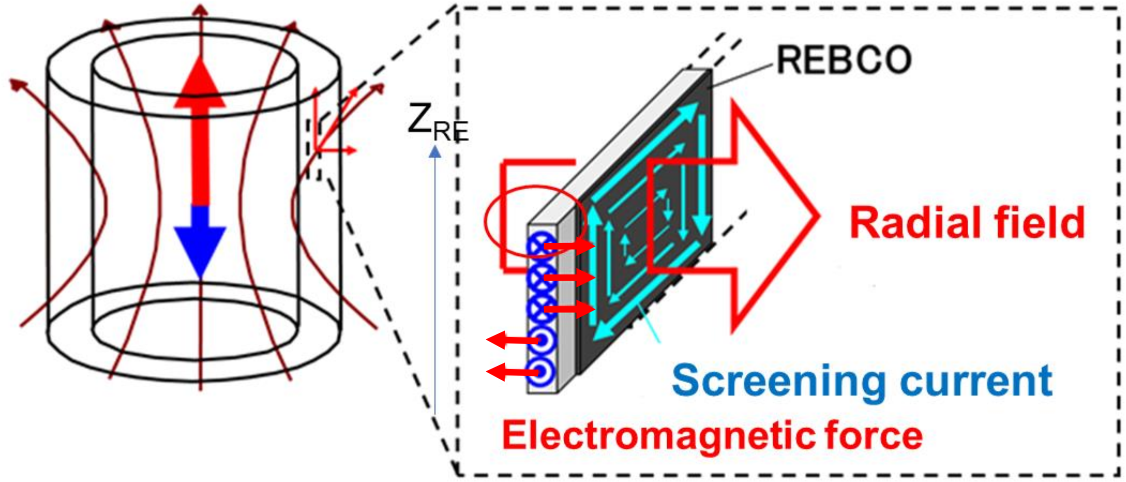
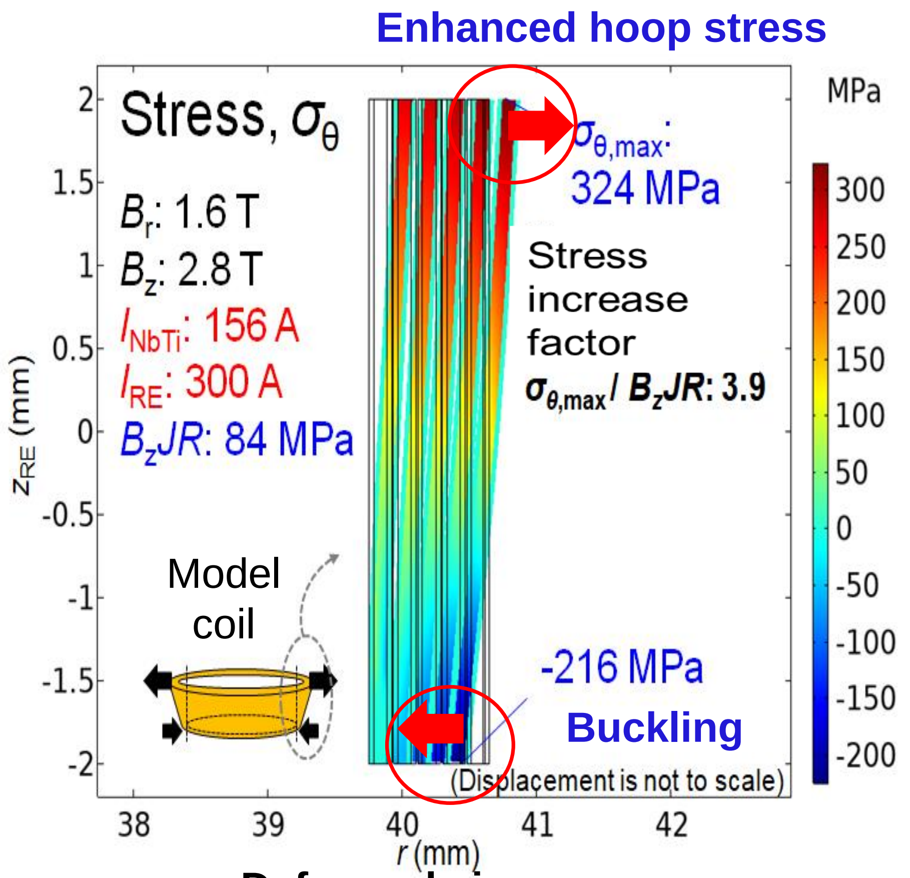
4. Summary

a . Degradation of the REBCO inner coil due to the screening current





Deformed view

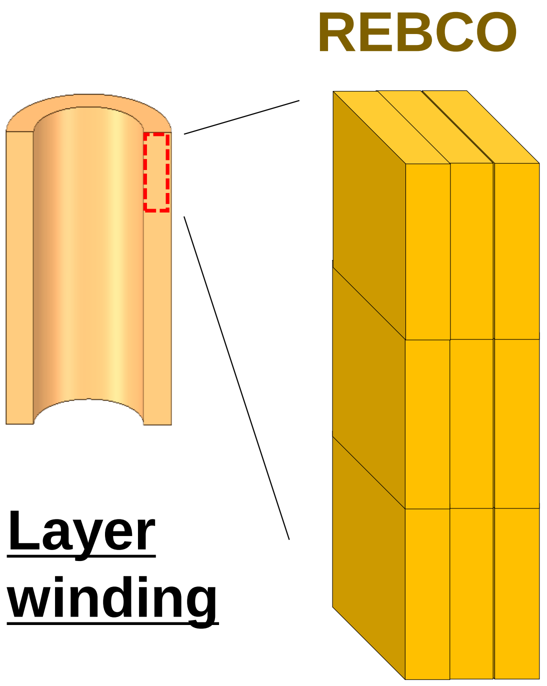
The interaction between B_z and the screening current results in hoop stress modification

The excessive hoop stress or buckling at a conductor edge damages the REBCO coil. More investigations are necessary.

S. Takahashi et al. MT26(2019),Tue-Mo-Or8-04.
S. Takahashi et al., IEEE Trans. Appl. Supercond., to be published (2020).

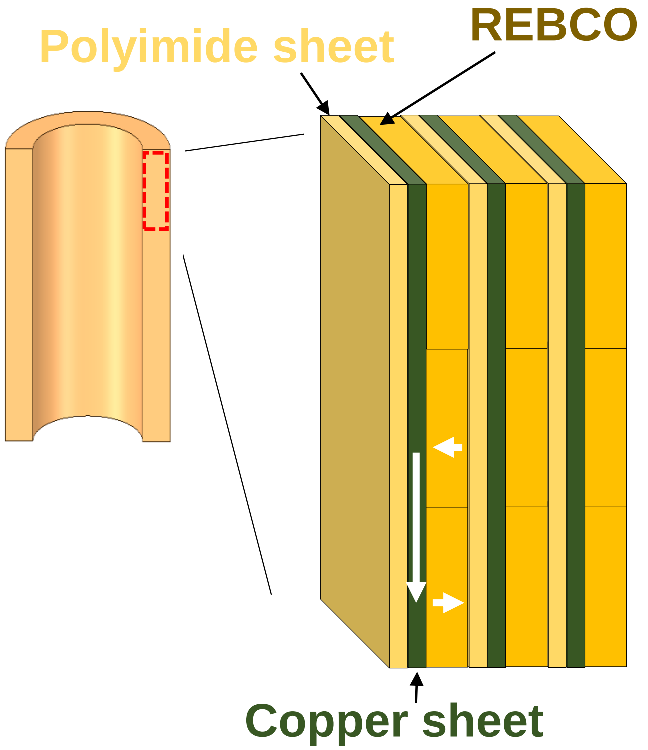
b. Protection of the REBCO inner coil against thermal runaway (quench)

Conventional NI method



Disadvantage:
Long time delay of the magnetic field

New NI method (LNI)



Advantage:
Time delay is short

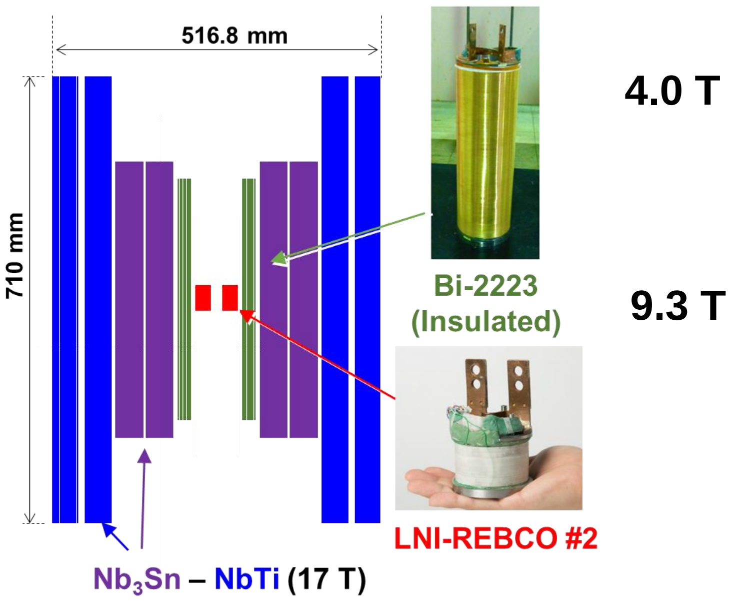
It was proved in our laboratory that the REBCO coil is protected safely against quench by the use of the LNI method

The LNI method will be used in the 1.3 GHz NMR magnet

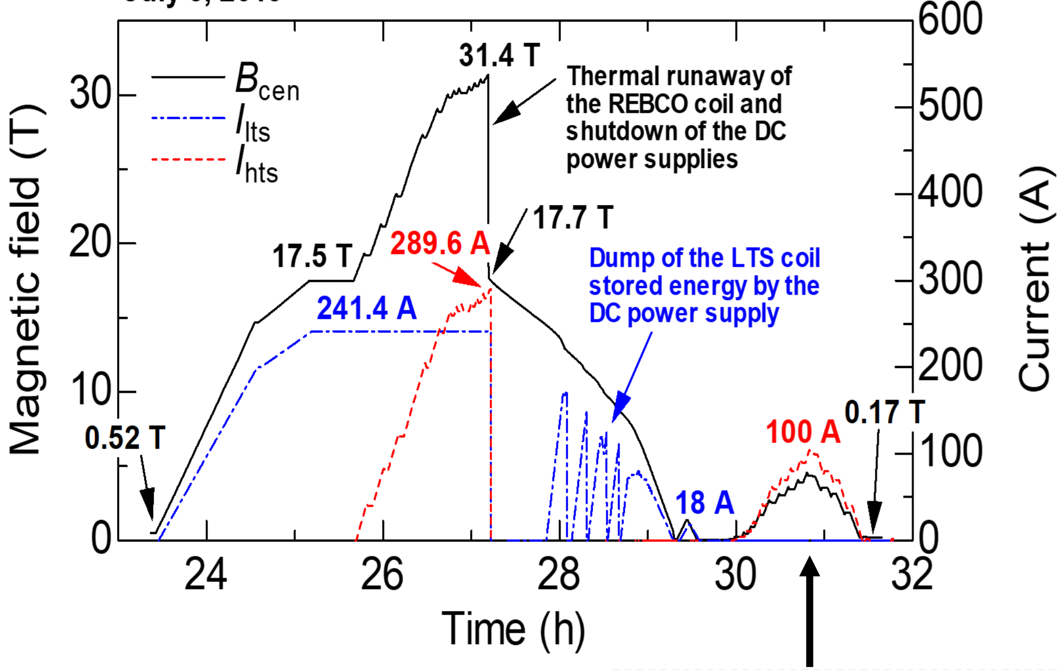
Y. Suetomi et al., *SuST* **32** (2019) 045003

c. 30 T-class LTS/Bi-2223/REBCO magnet

30 T test coil



July 5, 2019



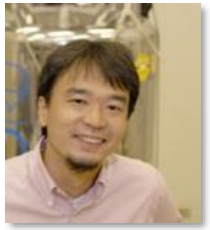
No degradation after thermal runaway

The LTS/Bi-2223/REBCO magnet operated at > 30.5 T is demonstrated

Y. Suetomi, G. Nishijima, H. Kitaguchi, Y. Yanagisawa et al., *MT26* (2019,Vancouver), Fri-Mo-Or27-02

Outline

1. Overview of the MIRAI Program
2. Present status of the 1.3 GHz NMR deve
   - Design of the 1.3 GHz NMR
   - Superconducting joints
   - 400 MHz (9.4 T) LTS/HTS persistent N and NMR measurement
   - Issues to be addressed for the 1.3 GHz NMR magnet
   - **NMR instrumentation and spectroscopy**
3. Present status of the intermediate joint between DC feeder cables
4. Summary



Prof. Y. Ishii (Tokyo Institute of Technology/ RIKEN)

NMR instrumentation development for the 1.3 GHz LTS/ HTS NMR magnet

JST MIRAI

Another 1 GHz-class (23.5 T) LTS/HTS NMR magnet is being developed, granted by the S-Innovation program, JST

→ The magnet achieved 800 MHz(18.8 T), which will be used for the development of NMR instrumentation

JEOL, Tokyo Tech, RIKEN, JASTEC SUPERCONDUCTOR

NMR console and solid-state NMR probes

JEOL

JNM-ECZ series NMR spectrometer

JEOL

NMR MAS probe

K. Sato, ASC2018, 2LOr2A-01.
R. Piao et al., *IEEE Trans. Appl. Supercond.* *29* (2019) 4300407.

Outline

JST MIRAI

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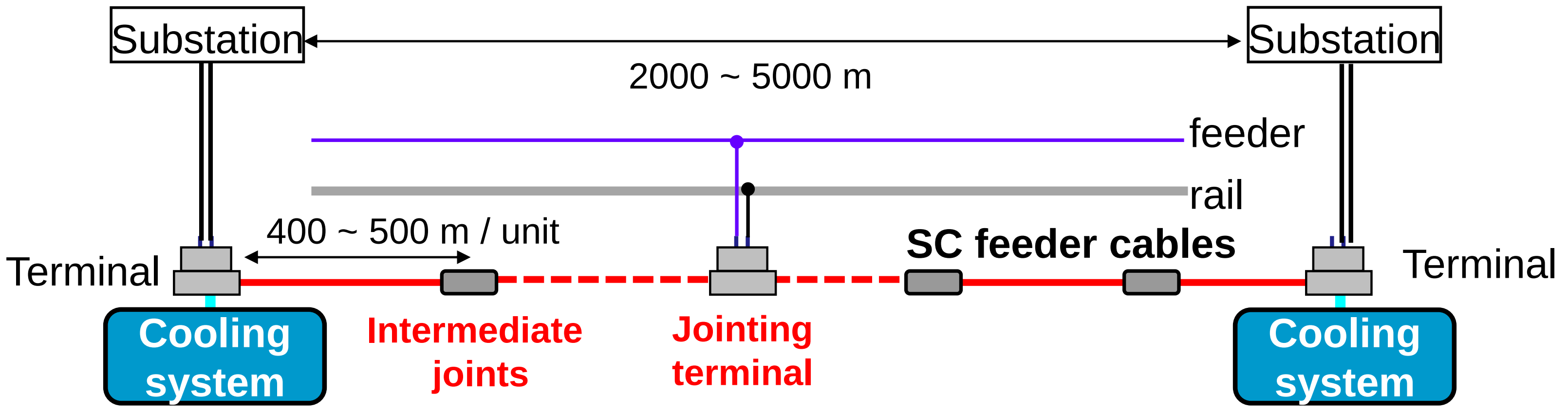
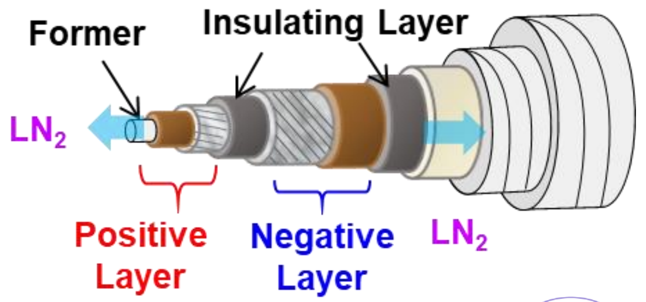
4. Summary

Dr. M. Tomita
(Railway Technical Research Institute)

Requirement of the intermediate joint





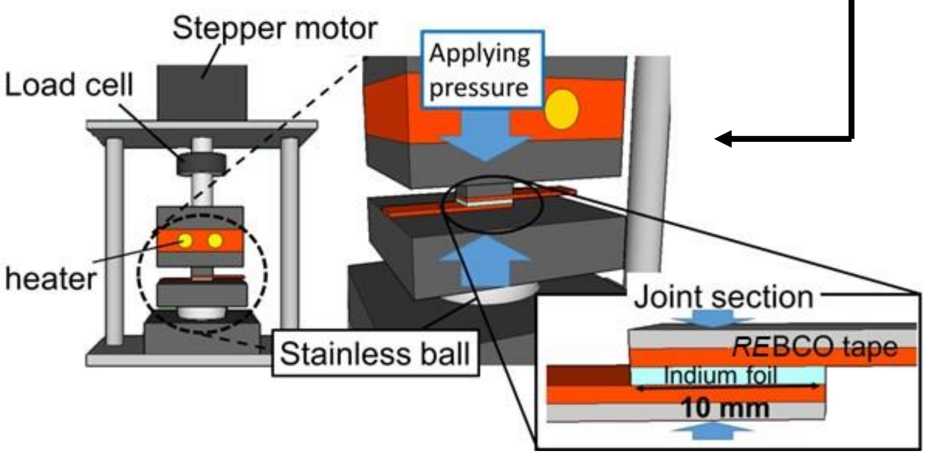
Railway Technical Research Institute

M. Tomita *et al.*, *Energy* (2017) 122.

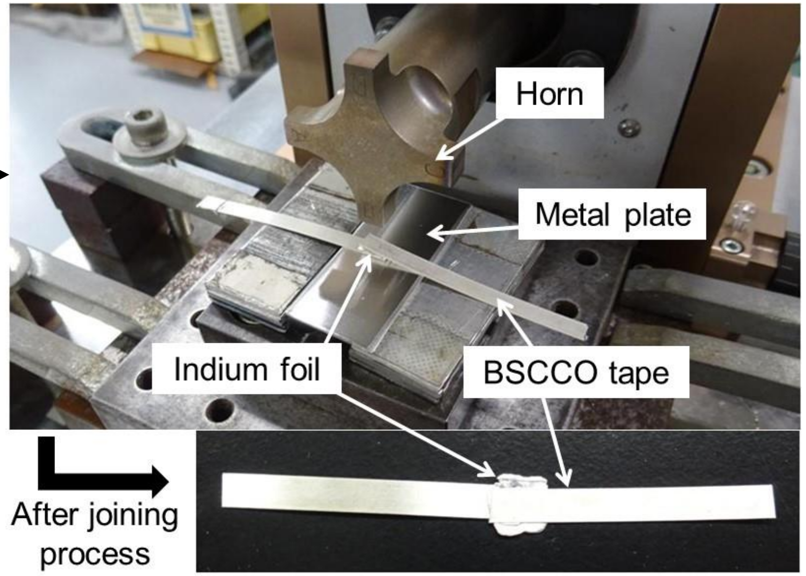
Easily fabricated ultra-low resistance joint of HTS tapes

Joint with indium foil inserted between joint surface

Soldered joint



Mechanical joint (MJ) with low-temperature heat treatment (100–120 °C for 1–15 min)



Ultrasonic welding (UW)

Joining time ~0.1 sec

[1] R. Hayasaka et al., *EUCAS 2019*, 2-MP-CC2-S04.
[2] T. Nishio et al., *IEEE TAS*, **26** (2016) 4800505.
[3] T. Nishio et al., *IEEE TAS*, **27** (2017) 4603305. .
[4] S. Ito et al., *IEEE TAS*, 29 (2019) 6600405.
[5] S. Ito et al., *EUCAS 2019*, 1-MP-SPR-I08.
[6] S. Ito et al., *10th ACASC/2nd Asian ICMC/CSSJ Joint Conf.*, 9P-21.
[7] C. A. Baldan et al., *IEEE TAS*, **19** (2009) 2831.
[8] J. Lu et al., *IEEE TAS*, **21** (2011) 3009.
[9] G. Osabe et al., *Physica C*, **470** (2010) 1365.

Easily fabricated ultra-low resistance joint of HTS tapes

Joint with indium foil inserted between joint surface

JST MIRAI

MJ: Mechanical joint
UW: Ultrasonic welding

TOHOKU UNIVERSITY

Achieved joint resistivity (77 K)[1–6]

REBCO joint : 25–35 nΩcm^2 (MJ)
30–40 nΩcm^2 (UW)

BSCCO joint : 11–25 nΩcm^2 (MJ)
14–40 nΩcm^2 (UW)

No need Oxygen annealing process

Ref: Sn63Pb37 joint (77 K)[7–9]

REBCO joint : 20–60 nΩcm^2

BSCCO joint : 30–50 nΩcm^2

The joint resistivity is comparable or less than that of well-fabricated soldered joints.
(w/o I_c degradation)

[1] **R. Hayasaka** et al., EUCAS 2019, 2-MP-CC2-S04.
[2] **T. Nishio** et al., IEEE TAS, 26 (2016) 4800505.
[3] **T. Nishio** et al., IEEE TAS, 27 (2017) 4603305. .
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[6] **S. Ito** et al., 10th ACASC/2nd Asian ICMC/CSSJ Joint Conf., 9P-21.
[7] **C. A. Baldan** et al., IEEE TAS, 19 (2009) 2831.
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Summary

1. We commenced a MIRAI Project, developing joint technologies between HTS conductors at first, which will be applied to high-field persistent NMR, and HTS feeder-cable joints for railway systems.
2. Practical superconducting RR joints and BB joints have been successfully developed, whereas others are still under development.
3. The excellent NMR spectra were achieved with the world's first persistent current 400 MHz LTS/HTS NMR magnet with SC joints.
4. The first prototype of the intermediate joint between HTS feeder cables has been demonstrated.

Thank you very much for your kind attention !