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

H. Maeda¹,², J. Shimoyama³, Y. Yanagisawa², Y. Ishii⁴,², M. Tomita⁵

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

Plenary presentation PT-4 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.
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. Otake et al.; soldered joint
Outline

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
Outline

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
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

Development history in Japan

2006-2016

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

2010-2015

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

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


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.

- Amyloid β
  - Alzheimer's
    - 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
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

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
Electrification feeder system for railway systems

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

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

Plenary presentation PT-4 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.
Necessity of the joint

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

Cable length is < 500m due to truck transportation
Organization of the program

- Program manager
  Hideaki Maeda (PM)

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

- NMR magnet group
  Yoshinori Yanagisawa (RIKEN)

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

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

- PM Supporting office
  PM/RIKEN

18 universities, research Institutes and companies

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

RIKEN, JASTEC, OKAYAMA University, NIMS

Tokyo Institute of Technology, RIKEN, JEOL RESONANCE

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

Plenary presentation PT-4 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.
Stage timeline of the MIRAI Program

**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

---

**The 1st stage**
- R&D and the 1st prototype
  - R&D
  - The first prototype of the SC cable joint

**The 2nd stage**
- The 2nd prototype
  - The 2nd prototype of the SC cable joint

**The 3rd stage**
- Test
  - The running test of the train with joined SC cables

Railway Technical Research Institute
Outline

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
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

Field contribution of the HTS coils is reduced


Designed by Dr. Hamada, JASTEC
Outline

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 persist 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
Superconducting joints necessary for the 1.3 GHz NMR magnet

Magnetic field at joints

Coil current = 179 A @ 1 T

Permissible total resistance necessary for the field decay rate of $10^{-8}$/h is $10^{-9} \, \Omega$, corresponding to a joint resistance of $10^{-12} \sim 10^{-11} \, \Omega/\text{joint}$
Superconducting joint
REBCO/ REBCO (RR)
Manufacturing process of an indirect type of RR joint

Crystal growth 800°C, 20 min, 40 MPa

Oxygen annealing 500-200°C, 6 h

Joining strap

SC Film for joining strap

SC layer

Cu

Ag

GdBCO Tape-A

GdBCO Tape-B

Metal Substrate

REBCO substrate

REBCO Poly crystalline

REBCO Tape

REBCO Tape

Intermediate layer

Epitaxial growth

GdBCO layer

GdBCO layer

10 nm

10 nm

Current C-axis

Intermediate Grown Superconducting Joint (iGS Joint)

TEM images

K. Ohki et al., ASC-2018, 1LOr1C-03.

K. Ohki et al., ASC-2018, 1LOr1C-03.
Joint critical current vs. magnetic field

The indirect RR joint is sufficient for the 1.3 GHz NMR

Conductor $I_c = 160$ A at 77 K

Lift factor $= 11$

Magnetic field (T) 4.2 K

Joint critical current (A)

70 A (70 - 100 A)

77 K

Edge joint

$n$ index for a joint

4.2 K

$n=40$

$I_{op} = 179$ A

K. Yamagishi et al., ASC2018, 4LPo1G-05.
Superconducting joint
Bi-2223/ Bi-2223 (BB)
Manufacturing process of an indirect-type of BB joint

- Bi-2223 precursor was coated
- Low angle polishing (~0.6°) was applied, which increased a number of exposed filaments

810°Cx ~20h

Y. Takeda et al., *SuST 31* (2018) 074002
Joint critical current vs. magnetic field

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

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**

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

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

H. Kitaguchi et al., this conference, 9A4-1 (2020).
Current status of the joint development

<table>
<thead>
<tr>
<th>Current status</th>
<th>Joint Development Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultra-low resistance normal conducting joint or superconducting joint</strong></td>
<td>By using the solder dip method, ultra-low resistance joint ($10^{-10}\Omega$) or superconducting joint (&lt;20A) was achieved</td>
</tr>
<tr>
<td><strong>Completion of the development</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Nearly completion of the development</strong></td>
<td></td>
</tr>
</tbody>
</table>

Coil current = 179 A at 1 T

**REBCO-LTS** joint x 1

**REBCO-REBCO** joint x 40 (300 m)

**BCO-Bi2223** joint x 1

**Bi2223-Bi2223** joint x 60 (300 m)

**Bi2223-LTS** joint x 1

Outline

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 NMR instrumentation and spectroscopy
3. Present status of the intermediate joint between DC feeder cables
4. Summary
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

Y. Yanagisawa et al., ASC2018, 4LPo1E-05.

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

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 magnet
   • NMR instrumentation and spectroscopy
3. Present status of the intermediate joint between DC feeder cables
4. Summary
Degradation of the REBCO inner coil due to the screening current

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

Conventional NI method

REBCO

Layer winding

Disadvantage:
Long time delay of the magnetic field

New NI method (LNI)

REBCO

Polyimide sheet

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
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 development
   • Design of the 1.3 GHz NMR
   • Superconducting joints
   • 400 MHz (9.4 T) LTS/HTS persistent NMR 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

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

NMR console and solid-state NMR probes

Outline

1. Overview of the MIRAI Program
2. Present status of the 1.3 GHz NMR
   • 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 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
Requirement of the intermediate joint

Easily fabricated ultra-low resistance joint of HTS tapes
Joint with indium foil inserted between joint surface

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

Ultrasonic welding (UW)
Joining time ~0.1 sec

Easily fabricated ultra-low resistance joint of HTS tapes
Joint with indium foil inserted between joint surface

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

REBCO joint: 25–35 nΩcm² (MJ)
30–40 nΩcm² (UW)

BSCCO joint: 11–25 nΩcm² (MJ)
14–40 nΩcm² (UW)

Ref: Sn63Pb37 joint (77 K)[7–9]

REBCO joint: 20–60 nΩcm²
BSCCO joint: 30–50 nΩcm²

MJ: Mechanical joint
UW: Ultrasonic welding

No need Oxygen annealing process

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

Outline

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 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
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!