National Projects on superconducting wires and their applications in Japan

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I. JST(Japan Science and Technology Agency)-MIRAI program
   “Social implementation of super-high field NMRs and DC superconducting cables for railway systems.”

II. JST-ALCA(Advanced Low Carbon Technology Research and Development) program.

III. NEDO(New Energy and Industrial Technology Development Organization) program.
    Promotion of commercialization of high temperature superconductivity (HTS).
JST-MIRAI Program (Nov. 2017~)

By considering social and industrial needs, this program will set technologically challenging goals with clear targets designed to produce beneficial economic and social impacts.

Projects relating to applied superconductivity

Small start Type
1. Superconducting computing for low carbon AI
2. Low-ac-loss and robust high temperature superconductor technology

Large-scale Type
1. Social implementation of super-high field NMRs and DC superconducting cables for railway systems
2. Development of advanced hydrogen liquefaction system by using magnetic refrigeration technology.
## Schedule of the development of super-high field NMR

### 1.3 GHz (30.5 T) NMR

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<tbody>
<tr>
<td><strong>Joint technology (Shimoyama Group)</strong></td>
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- **R&D:**
  1. Persistent-mode HTS inner coil technology
  2. 30 T-class HTS inner coil technology
  3. Operation of a compact 1 GHz-class LTS/HTS NMR (driven-mode)
  4. Conceptual design of a persistent-mode 1.3 GHz NMR magnet

- **1.3 GHz inner coils**
- **1.3 GHz magnet**

**Leader:** H. Maeda, Riken

Presentation AT-1 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.
Development of Persistent-mode HTS inner coil technology

Preliminary magnet design of 1.3GHz NMR

Number of joints

First step towards a persistent mode 1.3 GHz NMR

Partial demonstration

400 MHz (9.39 T) LTS/REBCO NMR

Excitation test of a 30 T model magnet

30 T-magnet (model of the 1.3 GHz NMR magnet)

- REBCO coil (LNI): 9.3 T
- Bi-2223 coil (insulated): 4.0 T
- LTS coil (17 T magnet in NIMS)

July 4, 2019

Magnetic field (T) vs. Time (h)

- 30 T
- 17.2 T
- 265 A
- 241 A

Current (A)

- Max. BJR: 462 MPa
- Max. $\sigma_z$: 10.3 MPa

- 30 T generation without normal voltage on the REBCO coil
- The REBCO coil survived from a 31 T quench.

Y. Suetomi et al, MT26, Fri-Mo-Or27-02, Vancouver, Sep. 22-27, 2019
Development of Superconducting joints

- REBCO
- Bi-2223
- LTS

Number of joints:

- RR joint (16)
- BB joint (60)
- LL joint (~30)
- RL joint (1)
- R(L)B joint (1)
- BL joint (1)
- LL joint (1)

Magnet design:

- 1.3 GHz
- 994 mm
- 1050 mm

Presentation AT-1 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.
Development of REBCO-REBCO joint

Polycrystalline GdBCO was deposited on the GdBCO layer of the joining strap by spin coating.

Decay of persistent current

K. Ohki et al., SUST 30(2017)115017.

Presentation AT-1 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.
Development of BSCCO-BSCCO joint
Superconducting Joints Connecting DI-BSCCO® Tapes
Via Bi-2223 Thick Film Layer

J. Shimoyama et al., Aoyama Gakuin Univ.

Low angle polishing (θ < 0.6°) to expose ~100 filaments is effective for enhance joint I_c.

Termination Joint

Superconducting Joints Connecting DI-BSCCO® Tapes Via Bi2223 Thick Film Layer

**Straight Joint**

\[ \theta \sim 0.5^\circ \]

**Joint Area** \( \sim 100 \text{ mm}^2 \)


**Termination Joint**

\[ \theta \sim 0.4^\circ \]

**Joint Area** \( \sim 70 \text{ mm}^2 \)

**Bi2223 joint**

Heat-treatment: 810°C, \( P_{O_2} = 3 \text{ kPa} \)

**Joint** \( I_c (10^{-9} \text{ W}) \)

\( \sim 100 \text{ A} (77 \text{ K, s.f}) \)

300 A (4.2 K, 1 T)

\( I_c (\text{conductor}) \)

\( \sim 180 \text{A} (77 \text{ K, s.f}) \)

**Hall sensor output (mV)**

\( R (\text{joint}) < 10^{-14} \Omega \)

HT: 810°C, 24 h, \( P_{O_2} = 3 \text{ kPa} \)

\( 4.2 \text{ K, s.f.} \)

\( L \sim 5.6 \mu\text{H}, I \sim 80 \text{ A} \)
JST ALCA Program
(Advanced Low Carbon Technology Research and Development) Programs.
[Five projects are in progress]

- **Development of Low-Cost REBCO Coated Conductors**
  *T. Doi, Kyoto University*

- **System of Superconducting Rotating Machines for Transport Equipment that Supports Low Carbon Society**
  *T. Nakamura, Kyoto University*

- **Removing Iron Oxide Particles from Boiler Feed-Water of Thermal Power Plants**
  *S. Nishijima, Fukui University of Technology*

- **Development of REBCO Fully Superconducting Rotary Machines**
  *M. Iwakuma, Kyushu University*

- **Development of High Performance MgB$_2$ Long Conductors**
  *H. Kumakura, National Inst. Material Science*
**Development of low-cost YBa$_2$Cu$_3$O$_7$ tape conductors**

T. Doi et al., Kyoto Univ.

**Conventional coated conductor**
Template is insulative → Stabilizing Ag and Cu layer is required on REBCO.

**Concept**
By using \{100\}<001> textured pure Cu tape as the template of in-plane aligned REBCO and using conductive Ni and Nb-doped SrTiO$_3$ as a buffer layers, the textured Cu tape can also work as a stabilizer layer.

The new structure does not require the expensive Ag.

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**Conventional coated conductor (IBAD)**

- Hastelloy
- Epi-MgO
- IBAD-MgO
- $\text{Y}_2\text{O}_3$
- $\text{Al}_2\text{O}_3$

**Stabilizing Layer**

- CeO$_2$, etc
- $\text{REBa}_2\text{Cu}_3\text{O}_7$

**Insulative Layer**

- Ag
- Cu

**Template Layer**

- No expensive Ag layer!
**Fabrication method of new type coated conductor**

<table>
<thead>
<tr>
<th>Component</th>
<th>Ni</th>
<th>Nb-doped SrTiO₃</th>
<th>YBa₂Cu₃O₇</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>{100}&lt;001&gt; textured pure Cu / SS316 lamination tape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposition Method</td>
<td>electroplating</td>
<td>PLD (Pulse Laser Deposition)</td>
<td></td>
</tr>
</tbody>
</table>

{001}<100> textured Cu layer can be obtained by cold rolling and heat treatment (recrystallization).

(110)_{Nb-STO} pole figure

(102)_{YBCO} pole figure

SEM micrograph of the YBCO surface of the sample
The measured voltages of the sample were lower than those of the calculated values by \( n \)-value model in normal state region (\( I > I_c \)).

Some current flew into the Cu tape through the conductive Nb-STO and Ni buffer layers.

\( J_c = 2.5 \text{ MA/cm}^2 \) at 77 K, in self field.

Nb-STO/Ni and YBCO/Nb-STO interfaces are clean and sharp over a wide area.
Development of high performance MgB$_2$ wires

Fabrication of MgB$_2$ wires by the Internal Mg diffusion(IMD) method

B powder
Mg rod
Fe tube
drawing
Mono-filamentary wire
Heat treatment

$J_c = 1.06 \times 10^5$ A/cm$^2$ 4.2 K

$J_e = 1.28 \times 10^4$ A/cm$^2$ 4.2 K

$C_{24}H_{12}$ was added as carbon source.

Density: ~50%

Density: ~80%

$J_c$ vs $B$ for IMD wires, $\phi = 0.6$ mm

$J_e$ vs $B$ for IMD wires, $\phi = 0.6$ mm

Presentation AT-1 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.
100m-class mono- and 7-filamentary IMD MgB$_2$ wires

Critical current $I_c$ (A)

Critical current density $J_e$ (A/cm$^2$)

Magnetic field $B$ (T)

Scattering of $I_c$ is mostly due to the scattering of MgB$_2$ cross sectional area.
Development of high density PIT MgB$_2$ wires

**Conventional**
- In situ
- Cold working
- Heat treatment
- Metallic sheath
- Conventional
- Packing factor $\sim 0.6$
- 50 $\mu$m
- 2 $\mu$m

**Hitachi method**
- Mechanical milling (MM)
- Cold working
- Heat treatment
- High density MgB$_2$ core
- Packing factor $\sim 0.82$
- 50 $\mu$m
- 2 $\mu$m
Fabrication and evaluation of 100m-1km class MgB$_2$ wire

$I_c$ distribution of 100m long MM processed MgB$_2$ wire

Sampling position (m)

<table>
<thead>
<tr>
<th>Normalized $I_c$ (4.2K, 7.5T)</th>
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<tbody>
<tr>
<td>0%</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

$4.2K$, $7.5T$

1.2km long MgB$_2$ wire

$I_c$(uniformity)

$= (I_{c,ave} - I_{c,min})/I_{c,ave}$

$= 11.5% < \text{target}(15%)$

$= (I_{c,min} = I_{c,ave} - 3\sigma)$

$\sigma$: standard deviation

Evaluation of $I_c$ distribution from the short samples

MM processed MgB$_2$ wire(φ0.77mm)

[C$_{24}$H$_{12}$ was added as carbon source]

$4.2K$, $7.5T$

$I_{c,ave} = 3.9A$

$88.5%$ of ave.

$3.8\%$ of ave.
New evaluation technique of MgB$_2$ wires

Hybrid method of visualization of 3-dimentional microstructure and $I_c$ distribution [with X-ray micro CT and scanning Hall probe microscope] (T. Kiss et al, Kyusyu Univ.)

Wire fabrication process

Improvement of microstructure and $I_c$

X-ray micro CT ⇒ local distribution of microstructure

Scanning Hall probe microscopy ⇒ local $I_c$ distribution
Analyses of 10-filamentary PIT MgB$_2$ wire (Hitachi Ltd.)

Non destructive visualization of 3-dimentional structure of MgB$_2$ wire

- Good correlation between $I_c$ and $S$.
- $I_c$ scattering is mostly comes from the scattering of cross sectional area.

$I_c = 7.85 \times 10^3 \times S$
$y = 2$ to $9 \text{ mm}$
NEDO Identified Four Areas for Technology Development to Promote Commercialization of High-Temperature Superconductivity

—Promotion of Commercialization through Comprehensive Implementation of Fundamental and Demonstration Technology Development—
(Fiscal year:2016~2020)

1. R&D for the practical use of superconductivity cable systems (In the field of electric power)

2. Demonstrations of superconductivity DC power transmission system (In the field of transportation)

3. The application of HTS to magnetic resonance imaging (MRI) (In the field of industrial technology)

4. The technology development of HTS wire to improve the magnetic field characteristics and to reduce the cost with the aim of promoting rapid commercialization.
The application of HTS to MRI

1/3 scale 3T REBCO He-free MRI (2016)

Conductors: REBCO IBAD C.C. (Fujikura)

High resolution Imaging of mouse baby
Length: ~25mm

Pancake coil

Brain
Tongue
Spinal cord
Lunge
Heart
Digestive tract
Development of half size He-free 3T HTS (REBCO) MRI

They fabricated 272 pancake coils and used 220 of them for the construction.

**Specification of the half size 3T HTS Coil**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Inner diameter</td>
<td>580mm</td>
</tr>
<tr>
<td>Maximum outer diameter</td>
<td>1200mm</td>
</tr>
<tr>
<td>Axial length</td>
<td>980mm</td>
</tr>
<tr>
<td>Operating central field</td>
<td>2.9T</td>
</tr>
<tr>
<td>Maximum field</td>
<td>Bzmax=4.2T, Brmax=2.9T</td>
</tr>
<tr>
<td>Current density of coil</td>
<td>121A/mm²</td>
</tr>
<tr>
<td>Inductance</td>
<td>145H</td>
</tr>
<tr>
<td>Stored energy at operation</td>
<td>1.6MJ</td>
</tr>
<tr>
<td>REBCO wire Total Length</td>
<td>70km</td>
</tr>
<tr>
<td>Field uniformity on design</td>
<td>1.7 ppm/250mm DSV</td>
</tr>
<tr>
<td>Leak magnetic field area</td>
<td>2.5m x 3.4m (0.5mT)</td>
</tr>
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</table>

Photograph of the half-size active shield-type 3T coil
Initial cooling properties of half-size 3T magnet

Excitation test of the coil

- Temperature <6K
- Voltage of 25mV was generated at the joints due to the shear stress.
- They will change the joint structure and carry out an excitation test again.
Program to promote rapid commercialization of HTS
- Development of long length Eu-123 coated conductors having artificial pinning centers -

Eu-123 layer was deposited with PLD method.

Hot wall heating is applied to obtain stable temperature during PLD.

IBAD substrate tape

Artificial pinning centers: BaHfO₃
(Target material: EuBa₂Cu₃O₇-δ+BaHfO₃)

http://www.fujikura.co.jp/products/newbusiness/superconductors/01/superconductor.pdf
Microstructure and $I_c$ of Eu-123 coated conductors with artificial pinning centers

Two types of PLD deposition

Table 1. Specifications of the samples used for evaluation of the in-field characteristics.

<table>
<thead>
<tr>
<th>Sample Index</th>
<th>REBCO layer</th>
<th>Deposition rate [nm/sec]</th>
<th>REBCO thickness [µm]</th>
<th>$I_c$ (77.3 K, s.</th>
<th>$T_c$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAST</td>
<td>EuBCO-BHO</td>
<td>20-30</td>
<td>2.2</td>
<td>387</td>
<td>91.2</td>
</tr>
<tr>
<td>SLOW</td>
<td>EuBCO-BHO</td>
<td>5-15</td>
<td>1.1</td>
<td>250</td>
<td>91.8</td>
</tr>
<tr>
<td>Pure</td>
<td>GdBCO</td>
<td>10-20</td>
<td>1.9</td>
<td>575</td>
<td>93.1</td>
</tr>
</tbody>
</table>

BHO nano rods $\parallel$ c-axis

BHO short nano rods

Magnetic field orientation
$I_c$ homogeneity of Eu-123 coated conductor with artificial pinning centers

$I_c$ tolerance to bending strain

Scattering of $I_c$ in the 5 tapes