Development of High Stable Magnetic Field HTS Magnet System for MRI

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- MR imaging with HTS 3T mini coil
- Next step NEDO Project: Promoting practical application
- SUMMARY
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Medical MRI Superconducting magnet

Features of MRI

• The **Magnetic Resonance Imaging** does not use X-ray radiation.

• For imaging protons, can vascular imaging without contrast agent, blood flow observation possible
  ⇒ It is very effective for diagnoses such as Brain disease or heart disease

• The state by the hemoglobin concentration imaging in **f- MRI**, it is can be observed a **brain function** in three dimensions

• Due to **high magnetic field** of by superconducting magnet, clear and detailed image is obtained, the capillary and organ condition becomes clear and contribute to early detection

• By **highly uniform magnetic field**, fat separating, soft tissue imaging such as high functionality

Required for MRI

1. High magnetic field, High stable magnetic field, High uniform magnetic field

2. Credibility: non trouble, long-term maintenance

3. **Low Price** → The competition is X-rays CT
Why is a HTS MRI magnet necessary?

- MRI apparatus superconductivity mainstream, and high magnetic field (high resolution) is required. The growth rate of the 3T magnet is higher.
- Features of superconductivity, high magnetic field accrual (>3T), energy saving (R=0).
- In present, a NbTi superconducting magnet need liquid helium for cooling.
- These several years, Supply Crisis and Price Increases of helium, and also Nb material
- High-Temperature Superconductivity: liquid helium less, Nb less and using in high field

Number of MRI Magnets operating in Japan

(Edited from ‘Gekkan Shin-Iryo’ (Monthly New Medicine in Japan))
Development Plan of up to Market

2013 - 2026

- **Test Coil**
  - Mini Coil
  - 3T model coil
  - Imaging at 3T

- **Imaging at 3T**
  - 3T model coil
  - Imaging at 3T

- **3T-1/2size Magnet**
  - Imaging at 3T

- **5T-1/2size Magnet**

- **Imaging at 5T**

- **Imaging whole-body at 3T**

- **Development of a whole-body magnet**

- **Market**
Contents

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➢ MR imaging with HTS 3T mini coil

➢ Next step NEDO Project: Promoting practical application

➢ SUMMARY
We designed it being conscious of a current MRI magnet.
Central field is 2.9T
Uniformity is 1.7ppm/100mmDSV
Stability is less than 1ppm/hr

for Imaging
possibility

Specification of the HTS 3T Model Coil

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>320mm</td>
</tr>
<tr>
<td>Maximum Outer diameter</td>
<td>471mm</td>
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<tr>
<td>Axial length</td>
<td>440mm</td>
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<tr>
<td>Central field</td>
<td>3.0T</td>
</tr>
<tr>
<td>Maximum field</td>
<td>4.5T</td>
</tr>
<tr>
<td>Critical current of wire</td>
<td>351A (20K)/4.1T(36°)</td>
</tr>
<tr>
<td>at field</td>
<td></td>
</tr>
<tr>
<td>Current density of coil</td>
<td>113A/mm²</td>
</tr>
<tr>
<td>Inductance</td>
<td>32H</td>
</tr>
<tr>
<td>REBCO wire Total Length</td>
<td>16km</td>
</tr>
<tr>
<td>Field uniformity on design</td>
<td>1.67ppm/100mmDSV</td>
</tr>
<tr>
<td>Total Weight</td>
<td>180kg</td>
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</table>

1/4 Cross Sectional View of HTS 3T Model Coil
Cooling Characteristics from Room temperature of the HTS 3T Model Coil

- The cooling of the coil was completed. Stable temperature is 7K at one week.
- 3T excitation time is 15 minutes at 0.2A/s. Coil temperature increased about 2K.

Photographic View of Test Setup for HTS 3T Model Magnet
(At the Time of Generating Central Magnetic Field of 3T)

High temperature superconducting 3T model magnet with NMR probe installed

NMR frequency reading (127.8 MHz)

NMR magnetic field measuring equipment (3.0T)
TOKYO, May 24, 2016 – Mitsubishi Electric Corporation (TOKYO: 6503), Kyoto University and Tohoku University announced today the world's first successful 3 tesla Magnetic Resonance Imaging (MRI) using a small model MRI with high-temperature superconducting coils that do not require cooling with increasingly scarce liquid helium. Mitsubishi Electric expects that the high-quality images made possible at this magnetic field strength will contribute to earlier detection of illnesses.
The Project promoting practical application is commissioned by the New Energy and Industrial Technology Development Organization (NEDO:FY2016-FY2020).

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Image of Human-Left-Hand in the 150mm area by wide bore system
Half size HTS magnet for MRI

Fundamental Commercialization Promote Technological Development

Development of a high temperature superconducting magnet system having high stable magnetic field

Main Objective

- Test producing 3T and 5T half size HTS coils for MRI
- Measurement of field uniformity and stability
- High current density coil (>200A/mm² at 7T)
- Design of 3T whole body MRI magnet by HTS
  → Compact and lightweight than the current magnet

Image to demonstrate high stable magnetic field and high homogeneous magnetic field

With a active shield coil

1st: FY2016~2018  2nd: FY2018~2020
R & D items and collaborators

1. Development of practical technology for HTS coil
   1) **Coil Production Technology** : Mitsubishi Electric Corp.
   2) Magnetic field disturbance measures by magnetization : Kyoto univ. and Tohoku univ.

2. Development of system optimization technology for HTS magnets
   1) **High magnetic field and high current density coil design technology** : Mitsubishi Electric Crop.
   2) Development of energy-saving and low-cost system : Kyoto univ.
   3) Economic efficiency study : Kyoto univ.

3. Development of superconducting joint technology for HTS wire : National Institute of Advanced Industrial Science and Technology (AIST), others

4. Development of the coil protection and burnout measures approach
   1) Development of the coil protection for persistent mode : AIST, others
   2) Development of burnout measures approach : Mitsubishi and Tohoku univ.
## Development schedule

<table>
<thead>
<tr>
<th>R &amp; D items</th>
<th>1(^{st}) year (2016)</th>
<th>2(^{nd}) year (2017)</th>
<th>3(^{rd}) year (2018)</th>
<th>4(^{th}) year (2019)</th>
<th>5(^{th}) year (2020)</th>
<th>development results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Development of practical technology for HTS coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Demonstration of outer diameter m class coil</td>
</tr>
<tr>
<td>① Coil Production Technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Imaging with 3T-1/2 size magnets</td>
</tr>
<tr>
<td>② Magnetic field disturbance measures by magnetization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>→ Demonstration of a AS coil</td>
</tr>
<tr>
<td>③ Study on coil protection method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Imaging with 5T-1/2 size magnets</td>
</tr>
<tr>
<td>(2) Development of system optimization technology for HTS magnets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>→ Miniaturization verification</td>
</tr>
<tr>
<td>① High magnetic field and high current density coil design technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>→ High magnetic field verification</td>
</tr>
<tr>
<td>② Development of energy-saving and low-cost system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Optimization of cooling structure and excitation system</td>
</tr>
<tr>
<td>③ Economic efficiency study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Cooling temperature and current optimization, energy saving effect verification</td>
</tr>
<tr>
<td><strong>Development items</strong></td>
<td><strong>Product of a half size 3T HTS coil</strong></td>
<td><strong>Magnet completed</strong></td>
<td><strong>Product of a half size 5T HTS coil</strong></td>
<td><strong>Magnet completed</strong></td>
<td><strong>Imaging at 5T</strong></td>
<td>• Economically of market input</td>
</tr>
<tr>
<td><strong>Basic study of the coil protection scheme</strong></td>
<td><strong>Measurement of long-term change of magnetic field by the HTS model coil</strong></td>
<td></td>
<td><strong>Practical study of the coil protection scheme</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Design of a half size 3T coil</strong></td>
<td><strong>Design of a half size 5T coil</strong></td>
<td></td>
<td><strong>Design of a full size 3T HTS coil</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Development of energy-saving and low-cost system</strong></td>
<td><strong>Study of the magnet market research and economy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>AS: Active Shield</strong></td>
</tr>
</tbody>
</table>

*Demonstration of outer diameter m class coil

- **Imaging with 3T-1/2 size magnets**
  - **Demonstration of a AS coil**
    - **Imaging with 5T-1/2 size magnets**
      - **Miniaturization verification**
      - **High magnetic field verification**

- **Optimization of cooling structure and excitation system**
- **Cooling temperature and current optimization, energy saving effect verification**
- **Economically of market input**
A design of a half size HTS 3T-coil

- Maximum axial stress is **30 MPa** near the center part of the main coil
- Maximum hoop stress is **55 MPa** around one quarter of the main coil

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<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 Bzmax=4.2T,Brmax=2.9T</td>
<td></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>1.7ppm/250mmDSV</td>
</tr>
<tr>
<td>Leak magnetic field area</td>
<td>2.5mX3.4m (0.5mT)</td>
</tr>
</tbody>
</table>

Room bore is 480mm Dia. Imaging is a region of 150 mm or more
Magnetic field uniformity of the coil

1. Magnetic Field Distribution is **1.7 ppm/φ250 mmDSV** on designed
2. Leakage Magnetic Field regions are 1.6mx1.2m at 100gauss and **3.2mx2.5m at 5gauss**. Ref.: 3T model coil’s region is 3.8mx4.8m at 5gauss
### REBCO Coil Production Technology

#### Specifications of the REBCO superconducting conductor

<table>
<thead>
<tr>
<th>Conductor Dimensions</th>
<th>Width</th>
<th>4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.17 mm with Insulator</td>
<td></td>
</tr>
</tbody>
</table>

**Structure**

<table>
<thead>
<tr>
<th>Insulation (Double insulated Tapes)</th>
<th>Inner: Polyimide Tape with fluorine coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilizer</td>
<td>Copper plating (0.02mm thickness)</td>
</tr>
<tr>
<td>Metal Substrate</td>
<td>Ni-based Alloy (Hastelloy equivalent)</td>
</tr>
</tbody>
</table>

**Superconducting Characteristic**

| Critical Current | 160 A or higher at 77K, self-field |

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**Cross-section Image of REBCO Superconductive Wire Material** (Courtesy of Fujikura)

**Prevention of degradation by peeling**

**Rigidification of impregnated coil**

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**Photograph of a pancake coil with inner diameter of 560 mm for main coil. Vacuum impregnated with epoxy.**

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**Producing high precision coils**

**Winding error <0.1mm**

**measuring the positions by Laser**

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#### Conductor Position

- Polymer film
- HTS conductor
- each conductors
- Winding

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High stability excitation system

Using a highly stable excitation power supply, it was possible to generate a magnetic field of 1 ppm or less for a long time by over-shoot method and feedback control.

Highly stable magnetic field generation by overshoot method and magnetic field holding power supply and control. Measured by REBCO 3T model coil.
As a next-generation MRI, we started the research and development of high stable magnetic field coil system fundamental technology using the REBCO superconducting coil.

We promote the development aimed at imaging verification magnetic field of 3 T of stability less than 1 ppm/hr and uniformity of 10 ppm / 20 mm DSV. We successfully MRI Images of Mouse fetus using a HTS 3T Test Magnet at 2.9T were obtained.

Advance research and development to solve problems related to the manufacture of large-diameter magnets and obtain highly stable magnetic fields as NEDO project for practical application of the high temperature superconducting coils.

Next year, we will complete half size active shield type 3T REBCO magnet and plan to carry out imaging of hands and feet.
Thank you for your attention

ありがとうございました。

Acknowledgements)
Part of this study is commissioned and supported by the Ministry of Economy, Trade and Industry (METI) and Japan Agency for Medical Research and Development (AMED). The Project promoting practical application is commissioned by the New Energy and Industrial Technology Development Organization (NEDO).