Development and charging test of a compact 1 GHz (23.5 T)-class NMR magnet with Bi-2223 inner coils

- Charging test to 800 MHz (18.8 T) -

R. Piao\textsuperscript{1}, Y. Yanagisawa\textsuperscript{1}, M. Takahashi\textsuperscript{1}, T. Yamazaki\textsuperscript{1}, H. Maeda\textsuperscript{1,7}, Y. Suetomi\textsuperscript{2}, T. Noguchi\textsuperscript{3}, Y. Miyoshi\textsuperscript{4}, M. Yoshikawa\textsuperscript{4}, K. Saito\textsuperscript{4}, M. Hamada\textsuperscript{4}, S. Matsumoto\textsuperscript{5} and H. Suematsu\textsuperscript{6}

\textsuperscript{1}RIKEN, \textsuperscript{2}Chiba Univ., \textsuperscript{3}IKEGAMI GIZYUTU, \textsuperscript{4}JASTEC, \textsuperscript{5}NIMS, \textsuperscript{6}JEOL RESONANCE, \textsuperscript{7}Japan Science and Technology Agency

This work is supported by the Japan Science and Technology Agency (JST) under the Strategic Promotion of Innovative Research and Development Program and by the JST-Mirai Program Grant Number JPMJMI17A2.
1.02 GHz (24.0 T)


Compact 1 GHz (23.5 T)-class

54 mm RT bore for high-resolution NMR

~17 ton

~1.6 ton


Y. Yanagisawa et al., MT26, Thu-Af-Or23-02, 26 Sep. 2019
Contents

1. Development strategy of >1 GHz NMR magnets

2. Technical features of a compact 1 GHz-class NMR magnet

3. Results of a first charging test to 800 MHz (18.8 T)
Development strategy for >1 GHz NMR magnets (54 mm RT bore)

JST SENTAN
1.02 GHz (24.0 T)

JST S-innovation / Mirai
Compact 1 GHz (23.5 T)-class

JST-Mirai
1.3 GHz (30.5 T) Persistent-mode
(Preliminary designs under optimization)

Model development for a highly HTS-dependent compact NMR magnet

Highly HTS-dependent NMR magnet

The 1st >1 GHz by small $B_0$(HTS)
## A view-point: Which tape is better, REBCO or Bi-2223?

<table>
<thead>
<tr>
<th></th>
<th>REBCO</th>
<th>Bi-2223</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoop stress tolerance for high $J$ operation</td>
<td>Very high (e.g. 469 MPa)</td>
<td>High (e.g. 370 MPa)</td>
</tr>
<tr>
<td>Screening current-induced field</td>
<td>Large (e.g. 1.51 ppm/h*)</td>
<td>Relatively small (e.g. 0.05 ppm/h*)</td>
</tr>
<tr>
<td>Degradation due to electromagnetic force</td>
<td>Frequently (in our experiments)</td>
<td>Rare</td>
</tr>
</tbody>
</table>

*Magnetic field drift rate after 100 h elapsed from the excitation of a 500 MHz LTS/HTS NMR magnet.

---

A view-point: Which tape is better, REBCO or Bi-2223?

- **REBCO**
  - **Hoop stress tolerance for high $J$ operation**: Very high (e.g. 469 MPa)
  - **Screening current-induced field**: Large (e.g. 1.51 ppm/h*)
  - **Degradation due to electromagnetic force**: Frequently (in our experiments)

- **Bi-2223**
  - **Hoop stress tolerance for high $J$ operation**: High (e.g. 370 MPa)
  - **Screening current-induced field**: Relatively small (e.g. 0.05 ppm/h*)
  - **Degradation due to electromagnetic force**: Rare

---

*~1 GHz* Bi-2223 dominant

*~1.3 GHz* Bi-2223 dominant

*~1.5 GHz* REBCO dominant

---

Y. Yanagisawa et al., MT26, Thu-Af-Or23-02, 26 Sep. 2019
Contents

1. Development strategy of >1 GHz NMR magnets

2. Technical features of a compact 1 GHz-class NMR magnet

3. Results of a first charging test to 800 MHz (18.8 T)
## Coil parameters of the compact 1 GHz-class NMR magnet

<table>
<thead>
<tr>
<th></th>
<th>1.02 GHz</th>
<th>Compact 1 GHz-class (at 1.06 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS</td>
<td>Bi-2223 (CA)</td>
<td>Bi-2223 (NX)</td>
</tr>
<tr>
<td>Operation mode</td>
<td>Driven</td>
<td>Driven</td>
</tr>
<tr>
<td>$I_{op}$ (A)</td>
<td>240.5 A</td>
<td>245.5 A</td>
</tr>
</tbody>
</table>

### B$_0$ (T)

<table>
<thead>
<tr>
<th></th>
<th>HTS</th>
<th>LTS</th>
<th>HTS</th>
<th>LTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>156 MHz / 864 MHz</td>
<td></td>
<td>559 MHz / 501 MHz</td>
<td></td>
</tr>
</tbody>
</table>

### E (MJ)

|                      | 33        | 4.54      |

### $J_{\text{cond}}$ of HTS (A/mm$^2$)

|                      | 148       | 236       | High      |

### $BJR_{\text{max}}$ in HTS coils (MPa)

|                      | 189       | 320.5     |

### $\sigma_{z,\text{max}}$ in HTS coils (MPa)

|                      | -13       | -60.9     |

### Total weight of the superconductors (ton)

|                      | 4.7       | 0.6       |

---

Y. Yanagisawa et al., MT26, Thu-Af-Or23-02, 26 Sep. 2019
Technical features and issues of the magnet

- **LTS-HTS series connected coil circuit** operated in the power supply-driven mode

- **LHe (4.2 K) cooling** with two pulse-tube cryocoolers for zero boiloff of LHe

- **Thick Bi-2223 inner coils** (182 layers)
  - High $BJR$ (320 MPa) and $\sigma_z$ (-61 MPa) at 1.06 GHz
  - 24 splice joints inside the winding under 11-16 T and hoop stress of 150-245 MPa

- **Stability and homogeneity of the magnetic field** under screening currents
Manufacturing of the Bi-2223 inner coils

The most challenging issue: splice joint for the Ni-alloy reinforced Bi-2223 conductor

24 splice joints inside the winding made of 10 km conductor in total

Combination of small joint resistance and high strength
- Several tens of nΩ at 4.2 K in 16 T
- 99% $I_c$ recovery stress >300 MPa at $D = 120$ mm
Test procedure

Basic evaluation on the magnet, shimming and NMR measurements

NMR measurement for proteins

$B_0$ present work

800 MHz (18.8 T)

~1 GHz (~23.5 T)
Contents

1. Development strategy of >1 GHz NMR magnets

2. Technical features of a compact 1 GHz-class NMR magnet

3. Results of a first charging test to 800 MHz (18.8 T)
Overview of the charging test to 800 MHz (18.8 T)

- Step by step charge to 800 MHz (18.8 T) for ~1 month
- No LHe level reduction in the charging process (zero boiloff)
V-I characteristics of the Bi-2223 inner coils

800 MHz
BJR: 183 MPa
$\sigma_z$: -35 MPa

1.06 GHz
BJR: 323 MPa
$\sigma_z$: -61 MPa

- Splice joints work well.
- Joule heating from the joints is sufficiently small under the cooling margin.
- 1 GHz-class operation seems feasible.
Magnetic field inhomogeneity due to screening currents

- Z2 harmonic caused by the screening currents saturates at -44 kHz/cm², which can be compensated with ferro. shim.
- Z2 is proportional to the number of layers of the Bi-2223 inner coil(s).
- The saturation behavior is advantageous compared to an REBCO inner coil.

Y. Yanagisawa et al., MT26, Thu-Af-Or23-02, 26 Sep. 2019
Magnetic field instability due to screening currents

- Amplitudes of the magnetic field drifts are almost constant regardless of $B_0$. => The drift rate reduced with $B_0$.
- Overshooting (current sweep reversal) suppresses the drifts.
Summary

• A compact 1 GHz (23.5 T)-class NMR magnet (highly HTS-dependent NMR magnet)

• Successful charge to 800 MHz (18.8 T)
  - Good V-I performance with 24 joints
  - No LHe level reduction
  - The effect of screening currents was moderate and manageable.

• We will continue the magnet test and make NMR evaluation.