30 T generation using an intra-layer no-insulation (LNI) REBCO coil in a 17 T LTS magnet

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Part of the present work was supported by the JST Mirai-Program Grant Number JPMJMI17A2 and Grant-in-Aid for JSPS Fellows Grant Number 19J11812
1. Background: Towards 1.3 GHz NMR

2. 30 T generation by LTS/Bi-2223/LNI-REBCO coils

3. LNI-REBCO coil quench at 31 T
Our target: Persistent mode 1.3 GHz NMR magnet

Requirements

- **30.5 T** generation by LTS / Bi-2223 / REBCO layer-wound coils.

Primitive designs by Hamada, JASTEC

Previous achievement:
27.6 T generation by LTS / Bi-2223 / REBCO layer-wound coils

Degradation in the middle section of the REBCO coil

Burnout on the REBCO coil

Possible protection method for a REBCO layer-wound coil: “intra-Layer No-Insulation (LNI)” method

- Short field delay
- Self-protection

Homogeneous field decay in the axial direction during quench.

Y Suetomi et al., SuST, 32, 045003 (2019)
Possible protection method for a REBCO layer-wound coil:  
“intra-Layer No-Insulation (LNI)” method

- Short field delay
- Self-protection

The effectiveness of the LNI coil under the following conditions has not been revealed:

- Practical number of layers (~100 layers)
- Under high-fields (>20 T)
Objectives of this work

To demonstrate…

- Generation of >30 T by LTS / Bi-2223 / REBCO layer-wound coils.
- Protection for a REBCO layer-wound coil against a quench under high-fields by an LNI method.
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Configuration of 30 T model test coil

30 T generation test coils

- Nb₃Sn – NbTi (17 T)
- 17.6 mm
- 40.1 mm
- 67.0 mm
- 516.8 mm

LNI-REBCO coil #2

- 710 mm
- Bi-2223 (Insulated)

- 1604 turn
  (~9 turns/layer × 180 layers)
- $\tau$ (4.2 K, S.F.) = 0.21 s
Configuration of 30 T model test coil

30 T model test coil

Parameters

<table>
<thead>
<tr>
<th></th>
<th>REBCO coil</th>
<th>Bi-2223 coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Type</td>
<td>SuperPower Inc. SCS4050</td>
<td>SEI, Ltd. HT-NX</td>
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<tr>
<td>Winding</td>
<td>LNI</td>
<td>Layer-wound</td>
</tr>
<tr>
<td>Inter-layer material</td>
<td>Cu+PET sheet (26 μm)</td>
<td>-</td>
</tr>
<tr>
<td>Impregnation</td>
<td>Paraffin wax</td>
<td>Paraffin wax</td>
</tr>
<tr>
<td>Over-band material / Over-band thickness</td>
<td>Ni-alloy tape / 2.1 mm</td>
<td>Brass round wire / 0.9 mm</td>
</tr>
<tr>
<td>Coil I.D. / O.D. (mm)</td>
<td>17.6 / 66.95</td>
<td>81.1 / 125</td>
</tr>
<tr>
<td>Coil height (mm)</td>
<td>40.1</td>
<td>384</td>
</tr>
<tr>
<td></td>
<td>1604</td>
<td>4640</td>
</tr>
<tr>
<td>Number of turns</td>
<td>(~9 ×180)</td>
<td>(~80×58)</td>
</tr>
<tr>
<td>Number of joints</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Iop (A)</td>
<td>265</td>
<td></td>
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<tr>
<td>Iop / Ic</td>
<td>0.56</td>
<td>0.51</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>9.3</td>
<td>4.0</td>
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<tr>
<td>Self-inductance (mH)</td>
<td>47.7</td>
<td>450</td>
</tr>
</tbody>
</table>

Center magnetic field : 13 T + 17 T = 30 T
Results
30 T generation

July 4, 2019

17.2 T

265 A

241 A

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

✓ 30 T generation
✓ Safely discharged
30 T generation: Coil voltage

Averaged at each current hold.

T = 4.2 K  
$B_{ex} = 17$ T

\[ \text{Voltage at winding} \]

\[ \text{No normal voltage} \]

The junction resistance at the inner electrode slightly increased due to electromagnetic forces.
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31 T generation $\rightarrow$ REBCO coil Quench

1. Quench occurred in the LNI-REBCO coil
2. Power supplies were shut down
3. HTS fields vanished
4. No quench in the LTS coil
5. Diode discharge

Max. BJR : 513 MPa
Max. $\sigma_z$ : 12.9 MPa
**Confirmation of the coil characteristic change**

- **No degradation**

  Degradations due to unbalanced electromagnetic forces as seen in the case of NI DP coils didn’t occur.

- **LNI-REBCO coil was protected from very high-field quench.**

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**Graph:**

- **REBCO coil voltage (µV)**
- **REBCO coil current (A)**
- **Before 31 T quench**
- **After 31 T quench**
- **T = 77 K**
- **Self field**
Short summary

✓31 T was generated by using the LTS / Bi-2223 / REBCO layer-wound coils without any degradation.

(The highest field ever achieved by a LAYER-WOUND superconducting coil)
Behavior of the self-protection
**Initiation of the quench**

![Graph showing the initiation of a quench](image)

- **Charge**
- **Discharge**
- **Voltage increasing**
- **Quench**
The Bi-2223 coil did not quench. During the quench:

- The DC power supply was shut down with 0.2 V of $V_d$.
- The Bi-2223 coil did not quench.
During the quench

- Magnetic fields homogeneously decayed in the axial direction.
- Major benefit of an LNI coil

\[ V_d = 0.2 \text{ V} \]

Supplied current (A)

\[ I_{bi}, I_{re} \]

Time (s)

Calculated from measured \( B_{cen}, I_{bi}, I_{lts} \)

\[ \text{Norm. } B_{up-re}, \text{Norm. } B_{cen-re}, \text{Norm. } B_{low-re} \]
During the quench

\[ I_{re} \]
\[ V_d = 0.2 \text{ V} \]

Differences between \( I_{re} \) and \( B_{cen-re} \)

Current bypass zone ratio
**Assumption**
- Quench was initiated inner layer.
- Current bypassed on layer basis.
- At bypass region, circumferential currents were zero.

**Current bypass zone propagation** started at the same time as the shutting down of supply currents.

Thanks to set $V_d$ to 0.2 V.
Propagation ratio

Supply current (A)

Current bypass zone ratio (null)

0.45 ⇒ 1-54th layer

Full-propagation

Propagating stop

180 layer
Key points

✓ Homogeneously field decay in the axial direction.

✓ Bypass zone propagation started at the same time as the shutting down of supply currents.

✓ Bypass zone propagation stopped at the middle of the winding.

Suppress unbalanced electro magnetic forces during the quench.
Summary
Summary

• 31 T generation by LTS/Bi-2223/REBCO layer-wound coils

• Protection on the LNI-REBCO coil which has practical number of layers against the quench under 31 T

A big step towards a 1.3 GHz NMR magnet.
REBCO coil (30 T magnet)

REBCO coil (27.6 T magnet)

During charging
✓ No degradation
✓ Protected

The LNI method worked.

Why?

During charging
× Premature degradation
Quench
× Burnout