High field superconducting magnet development with HTS

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• $J_c$ properties of HTSs are enough in high magnetic field beyond 20T.
• High electromechanical properties in REBCO and Bi2223
### Challenges of High field HTS magnets in the world (>20 T)

<table>
<thead>
<tr>
<th>Name</th>
<th>Group</th>
<th>Purpose</th>
<th>B(T) (HTS/LTS)</th>
<th>HTS</th>
<th>J_{con} (A/mm^2)</th>
<th>Max Stress (MPa)</th>
<th>ID (mm)</th>
<th>T_ω (K)</th>
<th>Winding</th>
<th>Impregnation</th>
<th>Status</th>
<th>Year</th>
<th>Insulation</th>
<th>Operation days</th>
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<tbody>
<tr>
<td>32T</td>
<td>IEE/CAS User magnet</td>
<td>32.35 (17.35/15)</td>
<td>RE123</td>
<td>378</td>
<td>610</td>
<td>35</td>
<td>4.2 (LHe)</td>
<td>DP</td>
<td>Wax</td>
<td>NI</td>
<td>2019</td>
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<tr>
<td>32T-SM</td>
<td>NHMFL User magnet</td>
<td>32 (17/15)</td>
<td>RE123</td>
<td>193</td>
<td>378</td>
<td>40</td>
<td>4.2 (LHe)</td>
<td>DP</td>
<td>Dry</td>
<td>Open since 2021</td>
<td>2017 Insulated</td>
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<tr>
<td>1.2GHz-NMR</td>
<td>Bruker NMR</td>
<td>28.2</td>
<td>RE123</td>
<td>118</td>
<td>212</td>
<td>90</td>
<td>4.6</td>
<td>DP</td>
<td>Epoxy/turn separation</td>
<td>2019 Insulated</td>
<td>Persistent, stability &lt;10 ppb, Commercial</td>
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<td>25T-CSM</td>
<td>Tohoku U. User magnet</td>
<td>25.1 (11.1/14)</td>
<td>Bi2223</td>
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<td>323</td>
<td>96</td>
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<td>DP</td>
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<td>DP</td>
<td>Epoxy/turn separation</td>
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<td>Open since 2013</td>
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<td>1020MHz-NMR</td>
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<td>Bi2223</td>
<td>150</td>
<td>194</td>
<td>78</td>
<td>4.2 (LHe)</td>
<td>Layer Wax</td>
<td>Obtained NMR signal, Closed in 2017</td>
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<td>MIRAI</td>
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<td>25T R&amp;D NMR</td>
<td>U. Geneva Demo</td>
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<td>733</td>
<td>139</td>
<td>20</td>
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<td>NOUGAT</td>
<td>LNCOMI/CEA-Saclay</td>
<td>32.5 (14.5/18(RM))</td>
<td>RE123</td>
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<td>716</td>
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<td>32.5T under 18T by resistive magnet</td>
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<td>LBC</td>
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<td>45.5 (14.4/31.1(RM))</td>
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<td>1420</td>
<td>691</td>
<td>14</td>
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<td>SP</td>
<td>Dry</td>
<td>Damaged at 45.5T</td>
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<tr>
<td>28T Demo</td>
<td>RIKEN Demo</td>
<td>27.7 (6.3/4.3/17.1)</td>
<td>RE123/Bi2223</td>
<td>396/238</td>
<td>40</td>
<td>4.2 (LHe)</td>
<td>Layer Wax</td>
<td>Quench and damaged at 27.7T</td>
<td>2016</td>
<td>Insulated</td>
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<td>30.5T</td>
<td>MIT NMR Demo</td>
<td>30.5 (18.8/11.7)</td>
<td>RE123</td>
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<td>91</td>
<td>4.2 (LHe)</td>
<td>NI</td>
<td>Epoxy/turn separation</td>
<td>NI, HTS coils damaged in test</td>
<td>2018</td>
<td>NI</td>
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<td>Tohoku U. User magnet</td>
<td>24 (10/14)</td>
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<td>221</td>
<td>407</td>
<td>104</td>
<td>4-8</td>
<td>SP</td>
<td>Epoxy/turn separation</td>
<td>Quench and damaged at 24T</td>
<td>2015</td>
<td>Insulated</td>
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<td>25T NI</td>
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<td>RE123</td>
<td>404</td>
<td>286</td>
<td>35</td>
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<td>NI-SP</td>
<td>Dry?</td>
<td>NI</td>
<td>2016 NI</td>
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<tr>
<td>25T</td>
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<td>RE123</td>
<td>100-306</td>
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<td>36</td>
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<td>NI-DP</td>
<td>Wax</td>
<td>NI, Quench at 25.7T</td>
<td>2017 NI</td>
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</table>

**Practical use** | **Demonstration** | **Damaged**

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 March 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

May have left out. Apologize if so.
Practical high field superconducting magnets

25.1 T (Bi2223)  
Cryogen-free

28.19 T (REBCO)  
LHe, Persistent

32 T (REBCO)  
LHe

25.1 T - 52 mm RT (HFLSM)  
LTS: 300 mm -14 T  
HTS: 96 mm-11.1 T  
(Bi2223)  
S. Awaji SuST, 30 (2017)  
065001  
K. Takahashi et al, under review

1.2 GHz-NMR Comercial  
(Bruker)  
28.19 T - 54 mm RT  
https://www.bruker.com/

32T-32mm LT (NHMFL)  
LTS: 250 mm -15 T  
HTS: 32 mm-17 T  
(REBCO)  
H. Weijer, IEEE TAS. 24 (2014)  
4301805
Steady High Magnetic Field Facilities in the world

HFML (Nimegen)
- 21MW-45T-HM (Under construction)
- 20MW-37.5T(WM)
- 24MW-43T-HM (Under construction)
- 24MW-36T-WM
- 40T-SM (R&D)

CHMFL-CAS (Hefei)
- 20MW-45T-HM
- 46T-SM

NHMFL (Tallahassee)
- 32MW-45T-HM
- 32T-SM
- 40T-SM (design phase)

LNCMI (Grenoble)
- 8MW-30T-HM
- 25T-CSM
- 33T-CSM (under construction)

HFLSM-IMR (Sendai)
- 21MW-45T-HM (Under construction)
- 20MW-37.5T(WM)
- 40T-SM (R&D)

HM: Hybrid magnet
WM: Water-cooled resistive magnet
SM: Superconducting magnet
CSM: Cryogen-free superconducting magnet

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 March 2024.
Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China
Cryogen-free magnet developments at HFLSM, Sendai, Japan

We have many failures of REBCO coils behind these successes.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 March 2024.

Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China
Cryogen-free magnet developments at HFLSM, Sendai, Japan

28T-CHM (ϕ32RT)
- ϕ360-9T-CSM
  - CuNbTi/Nb₃Sn strand
- ϕ32-19T-WM (8MW)
  - Double Bitter

20T-CSM(ϕ52RT)
- ϕ196-15.57T-LTS
  - CuNbTi/Nb₃Sn, NbTi: 234 MPa
- ϕ90-4.45T-HTS
  - Cu-alloy/Ag/Bi2223 (SEI HT-CA): 212 MPa

25T-CSM(ϕ52RT)
- ϕ300-14T-LTS
  - CuNb/Nb₃Sn Rutherford, NbTi: 251 MPa
- ϕ96-11T-HTS
  - Ni-alloy/Ag/Bi2223 (SEI HT-Nx): 323 MPa

33T-CSM(ϕ32RT)
- ϕ320-14T-LTS
  - CuNb/Nb₃Sn Rutherford, NbTi: 267 MPa
- ϕ96-11T-HTS
  - REBCO (Robust coil concept)

Failures

- 50 REBCO Pancakes for upgrading to 22 T (Insulation & Impregnation)
  - ϕ96mm x ϕ177mm, J = 217 A/mm², σ = 297 MPa
  - Degradation in the outer windings after cooling down due to axial thermal shrink in large-scale coil.

- 56 REBCO Pancakes (Insulation & Impregnation)
  - ϕ104mm x ϕ262mm, J = 130 A/mm², σ = 407 MPa
  - Quenched at 24 T due to a local degradation and damaged.
25T Cryogen-free Superconducting Magnet (25T-CSM)

**Cooling system**
Conduction cooling using He circulation
- Shield: 2 x 1 stg GM cryocooler
- HTS: 2 x 4K-GM cryocooler (3W@4.2K, 10W@8K)
- LTS: 2 x GM/JT cryocooler (8.6W@4.3K)

**Magnets (HTS-Bi2223):** 10.6T@188A
- 38 Ni-alloy/Bi2223 double pancakes
  - φ96mm x φ280 mm x h390 mm
  - Max. hoop stress 323 MPa

**Magnets (HTS-RE123):** 10.5T@131A
- 56 GdBCO single pancakes
  - φ104mm x φ263 mm x h336 mm
  - Max. hoop stress 366 MPa

**Magnets (LTS):** 14T@854A
- 3 CuNb/Nb3Sn Rutherford solenoids
  - φ300 mm x φ539 mm x h628 mm
  - Max. hoop stress 251 MPa

- 3 NbTi Rutherford solenoids
  - φ545 mm x φ712 mm x h628 mm
  - Max. hoop stress 138 MPa

**Insulated mono-tape winding**

**Fujikura Ltd.**

Awaji et al., SuST. 30 (2017) 065001
Performance of 25 T-CSM

Bi2223 insert

Quench at $B_{\text{cal}} = 24.01 \text{ T (124.6A)}$

RE123 insert

Quench at $B_{\text{cal}} = 25.1 \text{ T was achieved!}$
REBCO insert achieved 10 T with 125 A in the stand-alone test but deteriorated from an initial state in the background field of 14 T.

Broad IV properties (small $n$-value) was observed under 14 T.
Degradation Gd123 insert of 25T-CSM after quench

- Quench was initiated from the pancakes #3-5 by the observations of damage.
- Many pancakes were deteriorated seriously because of arc discharge.

-> The risk of local degradation should be taken into account in design at the moment.
Quench behavior of 25T-CSM with REBCO

The quench protection looks well at least for 6 s after the quench?
Simulation results of the quench

Single 2 cm defect at 18.8 % of Ic

Detection less than 20 mV would have enable magnet protection

the maximum temperature with 20 mV detection

A. Badel et al, IEEE TAS

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56 March 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China
Lessens learned from failures of REBCO high field coils (insulated and impregnated coils)

✓ A risk of local degradation should be taken into account in design at the moment.
  ➔ Two tape co-winding for current shearing in order to mitigate and reduce hotspot temperature

✓ Broad IV property in case of a local degradation and not too short time to burn-out after thermal runaway
  ➔ Protection is possible if we set adequate threshold in balance voltage.

✓ Protection for the hot-spot related to local degradation and inhomogeneity is crucial.
  ➔ Early detection of thermal runaway is one of solution
## Concept of Robust REBCO coil

### Two tape bundle winding with a face-to-back configuration
- Current share at local damaged area.
- Reduce amount of insulation (Increase $J_{\text{space}}$).

### Edge impregnation
- Thin FRP plate glued on coil & Impregnation
  - (Improve coil stiffness)

### All turn separation with F-coated polyimide
- (Reduce delamination force on REBCO tape)

### 40 µm Cu stabilizer
- (Reduce hot-spot temp.)

**S. Awaji IEEE TAS 31 (2021) 4300105**
Robust against local degradation:
Two bundle insulated double pancake coil with a damaged area

**EuBCO tape with BHO**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Width</td>
<td>4 mm</td>
</tr>
<tr>
<td>full thickness</td>
<td>0.11 mm</td>
</tr>
<tr>
<td>REBCO thickness</td>
<td>2.5 µm</td>
</tr>
<tr>
<td>Hastelloy® thickness</td>
<td>50 µm</td>
</tr>
<tr>
<td>Cu thickness</td>
<td>20 µm</td>
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<tr>
<td>$I_c$ (4mm, 77 K, s.f.)</td>
<td>213.5 A</td>
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</table>

**Double pancake coil**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>tape</td>
<td>EuBCO+BHO</td>
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<tr>
<td>Turn number</td>
<td>101 turn × 2 layer</td>
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<tr>
<td>Inner diameter</td>
<td>40.0 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>94.0 mm</td>
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<tr>
<td>Position of damage*</td>
<td>55 turn of bottom coil, outer tape</td>
</tr>
<tr>
<td>Coil constant</td>
<td>$3.87 \times 10^{-3}$ T/A</td>
</tr>
</tbody>
</table>

*Damage was introduced by double bending with $\phi 12$ mm bending dia.*

**$I$-$V$ property of damaged EuBCO**

* $T = 77$ K (LN2)
  $I_c \approx 2$ A, $n \approx 2.8$

* $T = 4.2$ K (LHe)
  $I_c = 28$ A, $n \approx 6$

Abe *et al.*, IEEE TAS, 32 (2022) 4603306
Robust against local degradation:
Two bundle insulated double pancake coil with a damaged area

- Monotape coil with a damage shows low performance.
- Bundle tape coil with damage shows similar performance to that without a damage at 77K and slightly lower with decreasing temperature.
- $I_c$ difference may be related to $I_c$ distribution in the coil.
  ⇒ Bundle winding is effective!

Abe et al., IEEE TAS, 32 (2022) 4603306

$V$ defined by $V = 0.1 \text{ mV}$
### 20-stacked Coil

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<td>Tape stacking configuration</td>
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<td>Inter bundle insulation</td>
<td>fluorine-coated polyimide tape</td>
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<td>Inner diameter (mm)</td>
<td>68</td>
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<tr>
<td>Outer diameter (mm)</td>
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<td>No. of turns / PCs</td>
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<td>$I_c$ of pancake</td>
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<td>$n$-value of pancake</td>
<td>22-27</td>
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<tr>
<td>No. of pancakes</td>
<td>20</td>
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Robust coil structure reduces the maximum stress and optimizes its distribution in coil.

Overview of 33T-CSM

LTS insert
- 14 T-ϕ320 mm layer wound impregnated coil with Rutherford Cables

HTS insert
- 19 T- ϕ68 mm (ϕ32mm RT bore)
- Impregnated two REBCO tape co-wound insulation coil

Cooling system
- Conduction cooling with He circulation
- 4 x 4K-GM cryocooler for HTS coils (4 x 1.5W@4.2K)
- 1 x GM/JT cryocooler for LTS coils (8W@4.2K)
- Thermally separated LTS and HTS coils

Protection
- Passible protection with a dump resistor

Others
- < 90min ramping
- Magnetic field monitor
Concept of Robust REBCO coil

Two tape bundle winding with a face-to-back configuration
- Current share at local damaged area.
- Reduce amount of insulation (Increase $J_{\text{space}}$).

Edge impregnation
- Thin FRP plate glued on coil & Impregnation
  (Improve coil stiffness)

40 $\mu$m Cu stabilizer
- (Reduce hot-spot temp.)

Reinforcement with Hastelloy co-winding

All turn separation with F-coated polyimide
- (Reduce delamination force on REBCO tape)

S. Awaji IEEE TAS 31 (2021) 4300105
## Primitive design of 33T-CSM

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<tr>
<th>Strand</th>
<th>HTS</th>
<th>NS1</th>
<th>NS2</th>
<th>NS3</th>
<th>NT1</th>
<th>NT2</th>
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<td>210.2</td>
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<tr>
<td>No of PCs</td>
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<td>24</td>
<td>26</td>
<td>28</td>
<td>20</td>
<td>22</td>
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<tr>
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<td>T</td>
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<td>3.22</td>
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<tr>
<td>No of strands</td>
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<td>16</td>
<td>18</td>
<td>16</td>
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<td>&gt; 20641</td>
<td>&gt; 23221</td>
<td>&gt; 63002</td>
<td>&gt; 85502</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>2 x 0.1 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation thick</td>
<td>mm</td>
<td>0.06</td>
<td>0.075</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jcon</td>
<td>A/mm²</td>
<td>220.1</td>
<td>107.8</td>
<td>107.8</td>
<td>95.8</td>
<td>90.8</td>
</tr>
<tr>
<td>Jcoils</td>
<td>A/mm²</td>
<td>154.8</td>
<td>70.1</td>
<td>70.1</td>
<td>62.6</td>
<td>61.5</td>
</tr>
<tr>
<td>Tcs</td>
<td>K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial stress</td>
<td>MPa</td>
<td>-51</td>
<td>-50</td>
<td>-50</td>
<td>-49</td>
<td>-43</td>
</tr>
<tr>
<td>Hoop stress</td>
<td>MPa</td>
<td>271</td>
<td>269</td>
<td>247</td>
<td>164</td>
<td>83</td>
</tr>
</tbody>
</table>

*1 12 T, *2 5 T

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Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China
\( I_c \) under mechanical stresses

**Axial tensile stress**

- \( \sigma_{\text{hoop}} \max = 270 \, \text{MPa} \)
- 14.5 T, 4.2 K
- 1 \( \mu \text{V/cm} \)

**Transverse compressive stress**

- \( \sigma_{\text{ax}} \max = 50 \, \text{MPa} \)

- HT-B
- HT-A
- Success of the improvement for 33T-CSM

- Improvement of elctoromechanical and \( I_c \) properties with "pre-bending".
- Strands with HT-A has higher \( I_c \) than with HT-B.

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High Field Magnet Development at HFLSM
- Road map -

2015

25 T cryogen-free Superconducting Magnet (25T-CSM)

- 25.1 T in a 52 mm RT bore with 1 hour ramping
- Advanced high strength Nb$_3$Sn technologies and high strength Bi2223 (Type HT-Nx (SEI))
- World highest field in CSM
- Open for users since 2016 (250 days operation in 2018)
- Long time, high precision experiments.

2018-2022

Upgrade to 30T-CSM (JSPS project)

- Replace from Bi2223 insert to REBCO one.
- 25 T under $B_{BG} = 14$ T with “Robust REBCO coil”
  S. Awaji IEEE TAS 31 (2021) 4300105

2022-

NEW 33T-CSM

- High strength Nb$_3$Sn Rutherford Cable
- Robust REBCO coil technol.

Under construction!

Upgrade to 40 T

50T Superconducting magnet

Under “High Magnetic Field Collaboratory Japan” project
Many high field superconducting magnet developments with HTS are on-going in the world.

We have serious issues for REBCO especially complicated mechanical stress/strain.

Local degradation due to mechanical stress looks unavoidable for high field superconducting magnet.

Multi-tapes such as co-winding, cables are necessary at the moment.

From R&D studies for REBCO tapes, we reached the “robust REBCO coil concept” consisting of two tape co-winding and edge impregnation.

- Two tape co-winding can reduce the risk of hot-spot due to the local degradation.
- Edge impregnation can reduce the maximum hoop stress by the optimization of stress distribution, and screening current induced stress.

Thank you!
Field monitor for 25T-CSM

Cu coil for field monitor

Field monitor with a magnetoresistance of Cu works very well!
Weibull analysis on delamination strength

D. Hazelton. WAMHTS-4, 2017

Muto et al., IEEE TAS 28 (2018) 6601004

$F(\sigma_c, V) = 1 - \exp\left[-V_E(m, V)\left(\frac{\sigma_c}{\sigma_0}\right)^m\right]$  

\[ \text{Coil 77K} \]

Delamination strength as a function of volume $\rightarrow$ depending on thickness

The local degradation is unavoidable.

$\rightarrow$ Need strategy for the local degradation in REBCO magnet.

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Although large hysteresis appears, the magnetic field can be monitored all the time.
Magnetic field stability of the 25T-CSM (Bi2223)

In case of REBCO with higher $J_c$, better field stability is expected.

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Screening current induced stress
- effect of impregnation -

REBCO insert for 32T-SM
($B_{LTS}=15T$, $B_{HTS}=10.7T)$

Max hoop stress (MPa)

Pancake number

(a) Dry wound coil

H. Maeda, ASC2020 Wk2LOR2A-2, Ueda et al, to be published.

Impregnation – $\Rightarrow$ reduce the screening current induced stress.

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FEM modelling of 20 pancake coil under 14 T

Modelling assumption: Homogenous J
turn to turn separation as soft elastic interface
Elastic regime: Young modulus 130 GPa (for tape), 30 GPa (for flanges)

Under 300 A
(limit of power supply)

Estimated hoop stress up to 346 MPa

Estimated radial stress up to 100 MPa in flanges

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20 stacked REBCO pancake coil

24.9 T
14 T + 10.9 T @ 298 A

$T = 4.2\ K, B_{BG} = 14\ T$

25T was achieved combined with $B_{BG}=14\ T$

Although screening current is dominant on field error, relaxation of coupling current appears first.
Local degradation (maybe due to a local unexpected stress) should be considered.

- All turns separation to make a delamination stress minimum
- Mitigate a possibility of local degradations as small as possible. (stiffness of pancakes)
- More than two tape bundle conductor (two tape co-wind) in order to mitigate a hotspot.

Screening current induced magnetic field
- Magnetic field monitor works well if its hysteresis is accepted

Screening current induced stress
- High stiffness of coil can reduce it (edge impregnation)
- Reduce a volume of polyimide in coils may be more effective (hopefully replace to ceramic insulation)

Inhomogeneity and different grade in critical currents
- Quality analysis by performances of pancakes

Large stress operation
- Optimization of stress distribution and reinforcement (edge impregnation)

Protection for the hot-spot related to local degradation and inhomogeneity is crucial.

- Dump resistor (Passive protection) -> need detection and quick dump before burn-out
- No-insulation (self-protection) -> delay of magnetic field and heating are issues.
- Quench heater (Active protection) -> need huge power in quench heater with short time.
Electromechanical properties
- effect of Cu stabilizer -

Stress tolerance of REBCO decreases with decreasing a volume fraction of Hastelloy.

Effect of stabilizer thickness ratio on critical stress under uniaxial tension

S. Fujita et al., Presented at MT26, Tue-Mo-Po2.09-02
Y. Zhang et al., IEEE TAS 26 (2016)8400406.

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