Recent progress on SuNAM’s coated conductor
development; performance, price & utilizing ways

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SuNAM Co., Ltd.

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Superconductor, Nano & Advanced Materials
SuNAM’s coated conductor; architecture, characteristic.
- Quality control tools for uniformity and yield

Higher Je : Thicker S.C. layer → 1.6 μm, >1,000 A/12 mm.

MCI (Metal Clad Insulation) 2G wire for high field magnet.
- Solution for charging time delay problem in Nl (No-Insulation) coil.

Higher Je : metal substrate removal process.

Summary
SuNAM’s Coated Conductor
High Temperature Superconductivity
Market Readiness Review

Office of Electricity Delivery and Energy Reliability

Investigation of the status of HTS technology, the requirements of key applications and barriers to future success

Peer Review Presentation
July 25, 2006

Wire performance and price requirements vary by application, and will drive the timing of market entry.

<table>
<thead>
<tr>
<th>Application</th>
<th>$J_c (A/cm^2)$</th>
<th>Field (T)</th>
<th>Temp. (K)</th>
<th>$I_c$ (A)</th>
<th>Wire Length (m)*</th>
<th>Strain (%)</th>
<th>Bend Radius (m)</th>
<th>Cost ($/kA-m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Cable (transmission)</td>
<td>$&gt;10^8$</td>
<td>0.15</td>
<td>67-77</td>
<td>200 A, 77 K, sf</td>
<td>$&gt;500$</td>
<td>0.4</td>
<td>2 (cable)</td>
<td>10-50</td>
</tr>
<tr>
<td>Synchronous Condenser</td>
<td>$10^4-10^5$</td>
<td>2-3†</td>
<td>30-77†</td>
<td>100-500†</td>
<td>$&gt;1,000$†</td>
<td>0.2†</td>
<td>0.1†</td>
<td>30-70†</td>
</tr>
<tr>
<td>Fault Current Limiter</td>
<td>$10^5$</td>
<td>0.1-3</td>
<td>70-77</td>
<td>300†</td>
<td>$&gt;1,000$</td>
<td>0.2</td>
<td>0.1</td>
<td>30-70†</td>
</tr>
<tr>
<td>Large Industrial Motor (1,000 hp)</td>
<td>$10^5$</td>
<td>4-5</td>
<td>30-77</td>
<td>100-500</td>
<td>$&gt;1,000$</td>
<td>0.2-0.3</td>
<td>0.1</td>
<td>10-25†</td>
</tr>
<tr>
<td>Utility Generator</td>
<td>$I_c &gt;10^4$</td>
<td>2-3</td>
<td>50-65</td>
<td>125 at $T_{op}$, 3 T</td>
<td>$&gt;1,000$</td>
<td>0.4-0.5</td>
<td>0.1</td>
<td>5-10</td>
</tr>
<tr>
<td>Transformer</td>
<td>$I_c &gt;10^6$</td>
<td>$I_e &gt;12,500$</td>
<td>0.15</td>
<td>70-77</td>
<td>$&gt;100$ at 0.15 T</td>
<td>0.3</td>
<td>0.05</td>
<td>10-25†</td>
</tr>
</tbody>
</table>


*Wire mg, some equipment mg indicate shorter length is adequate for early applications.
† Based on NCI assessment
‡ Cost target for a commercial market to develop. Target cost of wire is likely to be higher today due to rising price of copper.
Once a marginal level of performance is achieved by HTS wire, demonstration devices can be built, but the cost-performance ratio must be reduced for market entry and commercialization.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical current</td>
<td>250 A/cm, 77 K, sf</td>
<td>500 A/cm, 77 K, sf</td>
<td>1000 A/cm, 77 K, sf</td>
</tr>
<tr>
<td></td>
<td>125 A/cm, 65 K, 2 T</td>
<td>250 A/cm, 65 K, 2 T</td>
<td>500 A/cm, 65 K, 2 T</td>
</tr>
<tr>
<td>Cost/Performance Ratio</td>
<td>$400/kA-m, 77 K, sf</td>
<td>$50/kA-m, 77 K, sf</td>
<td>$10/kA-m, 77 K, sf</td>
</tr>
<tr>
<td></td>
<td>$800/kA-m, 65 K, 2 T</td>
<td>$100/kA-m, 65 K, 2 T</td>
<td>$20/kA-m, 65 K, 2 T</td>
</tr>
<tr>
<td>Wire Length</td>
<td>100 m</td>
<td>1000 m</td>
<td>&gt;1000 m</td>
</tr>
<tr>
<td>AC Losses</td>
<td>1 – 2 W/m</td>
<td>0.5 – 1.0 W/m</td>
<td>&lt; 0.50 W/m</td>
</tr>
</tbody>
</table>

Source: NCI Analysis, Southwire, DOE.

The Utility/Energy market may be largest long-term opportunity, but will require HTS sales from other segments to drive improvements in the cost-performance ratio before 2020.
Applications of Superconductivity

- Can carry extremely large current without loss.
- Can generate extremely large magnetic field.
- High energy efficiency with compact volume & mass.

Current carry

HTS 2G Wire

Fusion

Wind Generator

NMR

MRI

Crystal growth

Magnetic separator

Motor

MagLev

Switching

FCL

Transformer

Motor & Generator

Cable

Biz Chance in near(?) future

How can we realize practical HTS 2G wire?

- **Throughput**: growth rate & large deposition area
- **Yield**: process margin & (in-line) Quality Control
- **Robustness**: shelf life, stability (mechanical, thermal cycling, thermal expansion…)
- **Customer friendly**: joints, easy to use…
- **In-line production, automation…**

For reasonable size market creation,
- Target price ($/kA-m): 50, 25, or less?
- Availability: ~ 1,000 km/yr or /month or ??

- **RCE DR**: ~ 100 nm/sec or faster (SuNAM) → The highest throughput process

- **RCE-DR process**: easy to scale-up to wide strip.
Structure

Typical I_c ~ > 700A/12mmW at 77K Self-field (J_c ~ >5 MA/cm²)

- Protecting layer Ag (0.6 μm)
- Superconducting layer (~ 1.3 μm)
- Buffer layer ~20 nm
- Homoepi-MgO layer ~ 20 nm
- IBAD-MgO layer ~ 10 nm
- Seed layer (Y_2O_3) ~ 7 nm
- Diffusion barrier (Al_2O_3) ~ 40 nm
- Hastelloy C276 (Ni-alloy tape) or Stainless Steel-tape ( + Cu electroplating (+ lamination))

* Linear speed of each process : ~ > 120 m/hr (12 mm equivalent)
New Ideas, Directions?
- High rate, large area, high $I_c$ and low cost of materials processes will eventually be required – not immediately but in 10 years.
- High rate may require growth in liquid flux.
SuNAM RCE-DR process

- RCE-DR: Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R)
- High rate co-evaporation at low temperature & pressure to the target thickness (> 1 μm) at once in deposition zone (6 ~ 10nm/s)
- Fast (<< 30 sec.) conversion from amorphous glassy phase to superconducting phase at high temperature and oxygen pressure in reaction zone
- Simple, higher deposition rate & area, low system cost
- Easy to scale up: single path
Growth mechanism of the GdBCO film by RCE-DR

- Very low $PO_2$ zone (~ $10^{-5}$ Torr): **Amorphous Film**
- Lower $PO_2$ zone (~30 mTorr): $Gd_2O_3 + $ Liquid (< 5 sec)
- Higher $PO_2$ zone (~100 mTorr): **GdBCO Film** (< 20 sec)

**GdBCO growth mechanism: a seeded melt-textured growth!!!**
Daily Production 2G wire performances

( ~ 6 hrs deposition time (120 m/hr))
RCE-DR Results on Stainless Steel Substrate

- Min $I_c$ (A/cm-width) x L (m) > 0.6 Million A-m
- Production speed of 120 m/hr (12 mm width)
  (1 km for ~ 8 hrs)
An appropriate feedback algorithm can keep the shape of the RHEED spot in the specific range, while QCM monitoring to adjust the e-gun power.
Feedback route based on RHEED spot analysis

- Because of different evolution of $\Delta \phi$ & $\Delta \omega R$, optimization is very important for high quality 2G wire.
- Intensity & tilt angle of MgO (110) spot is one of the most important parameter.
Quality Control : RCE Vision Inspection System

Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)
RCE Vision System will be introduced for increasing the uniformity of composition in RCE-DR process. The control computer takes (RGB) values in three-dimensional vector space which is transformed from the color of the tape surface.

**Flowchart:**
- **Start color**
- **Color detection**
- **Is the (RGB) vector in the range?**
  - Yes
  - **End color** (79,166,189)
  - No
  - **Control the power**

**Diagrams:**
- Start color
- End color

**Text:**
- Quality Control: RCE Vision Inspection System

**Notes:**
- Presentation IO-16 given at CCA 2016; Aspen, Colorado, USA, September 11 – 14, 2016.
Higher Je : Thicker S.C. layer
Normal RCE-DR process : before optimization

Thickness dependence of Ic and surface color for GdBCO

<table>
<thead>
<tr>
<th>Thickness</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>1.3μm</td>
<td>1.6μm</td>
<td>1.8μm</td>
<td>2.0μm</td>
<td>2.2μm</td>
</tr>
<tr>
<td>Surface color for GdBCO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ic</td>
<td>750A/12mm</td>
<td>600A/12mm</td>
<td>300A/12mm</td>
<td>100A/12mm</td>
<td>0A/12mm</td>
</tr>
</tbody>
</table>

As increasing the thickness, Jc and Ic are decreased.
All the samples were prepared by same process speed.
Optimization of deposition region for making thick GdBCO films

For uniformity,
1. Decrease deposition region from 55 cm to 45 cm.
2. Increase distance between source and substrate.
3. Increasing turns of deposition region (14 turns → 19 turns)

As increasing the thickness, $J_c$ is decreased

<table>
<thead>
<tr>
<th>Normal</th>
<th>Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>As increasing the thickness, $J_c$ is decreased</td>
<td>As increasing the thickness, $J_c$ is not decreased</td>
</tr>
<tr>
<td>Same total thickness</td>
<td></td>
</tr>
<tr>
<td>Layer thickness is different</td>
<td></td>
</tr>
</tbody>
</table>

All the samples were prepared by same process speed.

Cross section of amorphous GdBCO
1.6 μm-thick
Optimization of Deposition region

Distance between source and substrate: ~

Distance between source and substrate: ~
Optimization of RCE-DR process for thick superconducting layer

(77 K, s.f.)

Criteria = \( \mu \text{V/cm} \)

\( I_C = 905 \text{ A / 12 mm} \)

N-value = 44.2
RCE-DR results (with optimization deposition region)

@ 77 K, self-field

1,050A/12mm-w
(→ 875A/cm-w)
1.6 μm-thick
5.5 MA/cm²

2016 Plan for making 400 A / 4 mm CC

<table>
<thead>
<tr>
<th>Speed (m/min)</th>
<th>Turns</th>
<th>Thickness (μm)</th>
<th>I_c (A/cm)</th>
<th>J_c (MA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>14</td>
<td>1</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>1.3</td>
<td>600</td>
<td>4.6</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>1.9</td>
<td>400</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>1.6</td>
<td>800</td>
<td>5</td>
</tr>
</tbody>
</table>

The same process speed(120 m/hr).
MCI (Metal Clad Insulation) 2G wire for high field magnet
26.4 T all 2G wire one-body (non-nested) magnet

No-insulation, multi-width, and compact!

- Multi-width Double Pancake Coils
- Stacked Double Pancake Coils
- Fully assembled

Immersed in liquid Helium

(Designed by S. Hahn (MIT→NHMFL/FSU)
NI-MW winding technic – No insulation

- **Pros:**
  - Compactness: without thick stabilizer
  - Strong mechanical strength: without soft insulation material
  - Self protection: automatic bypass
  - Rapid quench propagation

- **Cons:**
  - Charging time delay.
    (excess heat generation/Impractically slow for charging)

Quench current: "Automatic bypass" of the exceeding current and better protection to quench

\[
Q_{RC} [W] = I_R^2 \cdot R_C
\]

where, 
\[
I_R = I_{PS} - I_\theta = I_{PS} - \frac{B_0}{k_0}
\]

(by S. Hahn)
Metal Clad HTS 2G wire & coil

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>58 mm</td>
</tr>
<tr>
<td>outer diameter</td>
<td>115 mm</td>
</tr>
<tr>
<td>Turns</td>
<td>275</td>
</tr>
<tr>
<td>Inductance</td>
<td>7.8 mH</td>
</tr>
</tbody>
</table>

Burn out test @ 77 K (SPC with Copper stabilizer vs. MCI)
Magnet Operation Results

- Time constant, $\tau$, is calculated to 11 seconds.
- Contact resistance between turns, $R_{S,STS} = 165 [\mu\Omega\cdot\text{cm}^2]$
Reduction of Charging Delay

If magnet was wound with copper plated tape,

STS cladded tape  Charging time is 41 times shorter
Higher Je: metal substrate removal process
Combining Barrier, Seed, IBAD, Buffer Systems in One

For standard process,
Stainless steel ~ 100 μm thick
Hastelloy ~ 60 μm thick
Stress limits for HTS tapes under various loading conditions

**REBCO conductor**

- Axial tensile stress: Copper $\rightarrow$ REBCO $\rightarrow$ Hastelloy $\rightarrow$ >700MPa
- Transverse tensile stress: $\rightarrow$ 10-100MPa
- Transverse compressive stress: $\rightarrow$ >100MPa
- Shear stress: $\rightarrow$ >19MPa
- Cleavage stress: $\rightarrow$ <1MPa
- Peel stress: $\rightarrow$

**Bi2223 conductor**

- In-plane characteristics of REBCO CC tapes were significantly improved:
  - higher strength substrate materials
  - addition of Cu stabilizer and brass laminate
- Safe due to enough margin in In-plane loading
  - Not to worry?
- Significantly weaker in out-of-plane loading conditions
  - major concern especially in superconducting coils and magnet application designs

**Utilize these properties!!**

High Je wire by removal of thick metal substrate

For Je, substrate thickness must be thin

For thin substrate, easy to damage during the reel to reel process

Improvement of Je

Soldering thin substrate

Remove bottom substrate

Intentionally making a weak interface by some treatment
Demonstration of High Je wire by removal of thick metal substrate

- Easily reduce the thickness ~ < 20 μm
- Choice of any materials (SUS, Copper…)

May possible…

Easily reduce the thickness ~ < 20 μm
Choice of any materials (SUS, Copper…)

Presentation IO-16 given at CCA 2016; Aspen, Colorado, USA, September 11 – 14, 2016.
Summary

- SuNAM has been producing high $I_C$ coated conductors consistently.


- With thicker (1.3 $\mu$m $\rightarrow$ 1.6 $\mu$m) S.C. layer, we achieved $>1,000$ A/12 mm in production.

- We demonstrated 3 T magnet using MCI coated conductor.

- Initial test of substrate removal & suggesting a new way of high Je wire structure.
“Increasing Demand for HTS 2G wire has surpassed the supply”

“For market entrance $ 50 / kAm is the threshold ”

“Price Reduction will ignite an exponential growth of demand for HTS 2G wire”

“High throughput, low material cost, High yield is 3 Critical Success Factor”

Price Reduction in RCE DR process

(Unit: USD / kAm)

<table>
<thead>
<tr>
<th>Width</th>
<th>Capacity</th>
<th>Achievable with Existing Line of SuNAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm</td>
<td>1,000 km/y</td>
<td>SuNAM</td>
</tr>
<tr>
<td>120 mm</td>
<td>15,000 km/y</td>
<td>SuNAM</td>
</tr>
<tr>
<td>360 mm</td>
<td>75,000 km/y</td>
<td>SuNAM</td>
</tr>
</tbody>
</table>
Thanks for Attention!

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Thanks for Attention!