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

Seung Hyun Moon, Jae-Hoon Lee & Hunju Lee
SuNAM Co., Ltd.

2016. 09. 13.

CCA 2016, Aspen, Colorado, US.
Contents

- SuNAM’s coated conductor; architecture, characteristic.
  - Quality control tools for uniformity and yield

- Higher Je : Thicker S.C. layer $\rightarrow 1.6 \, \mu m, >1,000 \, A/12 \, mm$.

- MCI (Metal Clad Insulation) 2G wire for high field magnet.
  - Solution for charging time delay problem in NI (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**

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### HTS Technology Platforms » Wire Requirements

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/cm²)</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;10^5$</td>
<td>0.15</td>
<td>67-77</td>
<td>200 A, 77 K, sf</td>
<td>$&gt;500$</td>
<td>0.4</td>
<td>2 (cable)</td>
<td>10-50</td>
</tr>
<tr>
<td>Synchronous Condenser</td>
<td>$10^5$‡</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>$10^4-10^5$</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>$I_e &gt; 10^4$</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>0.15</td>
<td>70-77</td>
<td>$&gt;100$ @ 0.15 T</td>
<td>$&gt;1,000$</td>
<td>0.3</td>
<td>0.05</td>
<td>10-25‡</td>
</tr>
<tr>
<td></td>
<td>$I_c &gt; 12,500$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Original Data: R. Blaughter, etc., Updated by Gouge, Ashworth – January, 2006.*

*Wire mig, some equipment mig 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.

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*HTS Peer Presentation Document – July 25, 2006*
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>
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</tr>
</thead>
<tbody>
<tr>
<td>Critical current</td>
<td>250 A/cm, 77 K, sf 125 A/cm, 65 K, 2 T</td>
<td>500 A/cm, 77 K, sf 250 A/cm, 65 K, 2 T</td>
<td>1000 A/cm, 77 K, sf 500 A/cm, 65 K, 2 T</td>
</tr>
<tr>
<td>Cost/Performance Ratio</td>
<td>$400/kA-m, 77 K, sf $800/kA-m, 65 K, 2 T</td>
<td>$50/kA-m, 77 K, sf $100/kA-m, 65 K, 2 T</td>
<td>$10/kA-m, 77 K, sf $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 generated extremely large magnetic field.
- High energy efficiency with compact volume & mass.

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 ($J_c > 5 \text{ MA/cm}^2$)
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.

Cost Example

\[
C/P \Rightarrow \$ \text{ per year}/R(L \times W)J_c
\]

Study ISS '95:
\[
\begin{align*}
R &= 100 \text{ Å/sec} \\
L &= 30 \text{ cm} \\
W &= 1 \text{ meter} \\
J_c &= 10^6 \text{ A/cm}^2
\end{align*}
\]

\[
C/P = \$10 / \text{kA-m} @ 6000 \text{ km/year}
\]
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 a morphous 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

![SuNAM RCE-DR diagram](image)
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$_2$O$_3$ + 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 $I_c (A/cm-width) \times L (m) > 0.6 \text{ Million A-m}$
- Production speed of 120 m/hr (12 mm width) (1 km for ~ 8 hrs)

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Length (m)</th>
<th>AVG $I_c$ (A)</th>
<th>1σ(A)</th>
<th>Min.$I_c$ (A)</th>
<th>Max.$I_c$ (A)</th>
<th>COV(%)</th>
<th>$I_c \times L$ (Am)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>480</td>
<td>799</td>
<td>23</td>
<td>684</td>
<td>938</td>
<td>2.8</td>
<td>318,765</td>
</tr>
<tr>
<td>10</td>
<td>480</td>
<td>666</td>
<td>19</td>
<td>553</td>
<td>699</td>
<td></td>
<td>265,638</td>
</tr>
<tr>
<td>12</td>
<td>534</td>
<td>768</td>
<td>110</td>
<td>8</td>
<td>838</td>
<td>14.3</td>
<td>4,474</td>
</tr>
<tr>
<td>10</td>
<td>534</td>
<td>640</td>
<td>91</td>
<td>7</td>
<td>899</td>
<td></td>
<td>3,728</td>
</tr>
</tbody>
</table>
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.
Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)
Quality Control: RCE Vision Inspection System

- 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.

[Start] [End]

Start color

Color detection

Is the (RGB) vector in the range?

Yes

No

Control the power

(Composition DB)

End color

(79,166,189)
Higher $J_e$ : 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.

- TEM analysis
  → 1.3 μm-thickness:
    Gd₂O₃ are randomly distributed
  → 1.9 μm-thickness:
    Gd₂O₃ are distributed the boundary of the layers
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

As increasing the thickness, $J_c$ is not decreased

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: ~

7th turn

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

Criteria = $\mu$V/cm
$\text{IC} = 905\, \text{A} / 12\, \text{mm}$
N-value = 44.2

(77 K, s.f.)
RCE-DR results (with optimization deposition region)

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>
<tr>
<td>2</td>
<td>&gt; 20</td>
<td>2 ~ 2.5</td>
<td>&gt; 1,000</td>
<td>&gt; 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)
No-insulation 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)

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

Power supply current

30 A operating at 77 K

95% target field

3.1 seconds

45.3 seconds

15 times shorter !!!

Parameters

| Inner diameter | 58 mm |
| outer diameter | 115 mm |
| Turns          | 275   |
| Inductance     | 7.8 mH |
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

System for $\text{Al}_2\text{O}_3$ barrier & $\text{Y}_2\text{O}_3$ seed

System for IBAD, homo-epi & buffer

For standard process,
Stainless steel ~ 100 $\mu$m thick
Hastelloy ~ 60 $\mu$m thick

Cutting side

Before combining

After combining

After bending
Stress limits for HTS tapes under various loading conditions

**REBCO conductor**

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

**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

**Utilize this properties!!**

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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.

Superconductor layer
Substrate
Stabilizer

Improvement of Je

Soldering thin substrate on top of CC

Remove bottom substrate

Intentionally making a weak interface by some treatment

Ag
ReBCO
LaMnO$_3$
Epi-MgO
IBAD-MgO
Y$_2$O$_3$
Al$_2$O$_3$
Hastelloy or SUS
Demonstration of High Je wire by removal of thick metal substrate

Laminated CC

Removing Bottom Substrate

Substrate Removed CC

May possible...

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

- 45 µm-thick (brass)
- 100 µm-thick

<table>
<thead>
<tr>
<th>Laminated Substrate</th>
<th>Stabilizer</th>
<th>Superconductor layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 µm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Substrate remove machine
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.
Direction of Technology Development in the Future

“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”

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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>75,000 km/y</td>
</tr>
<tr>
<td>120 mm</td>
<td>15,000 km/y</td>
<td></td>
</tr>
<tr>
<td>360 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Thanks for Attention!

www.i-sunam.com
Acknowledgement

- KERI : H. S. Ha, S. S. Oh.
- Andong Nat’l Univ. : H. S. Shin.
- Stanford Univ. : R. H. Hammond.
- iBeam Materials : V. Matias
- Univ. of Cambridge : J. M. Driscoll
- FSU/NHMFL : S.Y. Han, D. Labalastier
- MIT : Y. Iwasa

Thanks for Attention!