HTS Development and Industrialization at SuNAM

Seung Hyun Moon
SuNAM Co., Ltd.

2014. 05. 21.

@ 1st Workshop on Accelerator Magnets in HTS
Contents

Industry of HTS Tapes: performance, length, yield, width. Is it possible to think of round wire? What is now, in 2 years and in 5 years?

- Brief introduction to SuNAM

- SuNAM’s strategy to practical 2G wire (performance, price & availability)
  - Strategy: performance, throughput & yield.
  - RCE-DR: The highest throughput unique SuNAM’s process.

- SuNAM’s now & the future direction
  - Now: product performances & customer oriented R&D results.
Company Overview

SuNAM: Superconductor, Nano & Advanced Materials (서남, 瑞藍)

<table>
<thead>
<tr>
<th>Establishment</th>
<th>2004. 11. 17.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEO</td>
<td>SeungHyun Moon / SoonChul Hwang</td>
</tr>
<tr>
<td>Registered Capital</td>
<td>$3M</td>
</tr>
<tr>
<td>No. of Employees</td>
<td>~ 59 (10 Ph.Ds)</td>
</tr>
<tr>
<td>H.Q.</td>
<td>Gyeonggi-do, Korea</td>
</tr>
<tr>
<td>Current Production Capacity</td>
<td>~ 60 km / month (4 mm/ &gt; 150 A)</td>
</tr>
<tr>
<td>Core Technology</td>
<td>2G HTS manufacturing technology based on RCE-DR process</td>
</tr>
</tbody>
</table>

SuNAM is a technology-intensive venture company established to achieve a noble mission, a commercialization of superconductor and cutting-edge/nano materials.

SuNAM, a specialized green energy material company, pursues the second generation HTS wires and its applications along with associated equipment system under the motto, “Development of highly efficient and environmentally friendly energy-use technology”
SuNAM’s Location

60 km south from Seoul

CCA 2014 in Jeju
Production Facilities

- Site area: 5,500 m²
- Building area: 1,750 m²
- Gross floor area: 3,050 m²
- Class < 10,000 clean room area: 1,000 m²
Critical current; $I_c > 1,000 \text{ A/cm} @77 \text{ K}$, s.f.
(length > 1 km, uniformity > 96%)

In-field performance; $I_c > 1,000 \text{ A/cm} @20 \text{ K}, 10 \text{ T}$

Stacked conductor; $I_c > 1,800 \text{ A/cm} @77 \text{ K}$, s.f.

$I_c$ measurement tech.; 0-10 T, > 1,800 A/cm, 20-77 K

DC reactor demo; 400 mH, 1,500 A

~US$13M; $9M from Gov’t, $4M from SuNAM
(June 2013 ~ May 2017, 4 years)

Sponsored by Ministry of Trade, Industry & Energy (MOTIE),
through Inst. of Energy Tech. Evaluation and Planning (KETEP)
SuNAM’s Strategy to Practical 2G Wire (Performance, Price & Availability)
Motivation

...there is a technology gap from 2G wire to practical applications...

2G Manufacturer

SuNAM, AMSC, Bruker, d-nano, Fujikura, Sumitomo, Superpower, STI, Theva, …

Industry

AMSC, Bruker, GE, Innopower, LS Cable, Nexans, nkt cables, Oswald, Siemens, Sumitomo, Southwire, …

Industry needs

➢ Scalable currents and various geometries
➢ Reproducible quality and quantity within an acceptable time
➢ Mechanical and electrical stability
➢ Low degradation, long lifetime
➢ Reliable and specific electrical insulation
➢ Simple, low ohmic contacts and joints
➢ Low losses
➢ Competitive cost
➢ …

- presented by KIT

...there is a need for ready to use 2G conductor concepts…
How can we realize practical HTS 2G wire? (I)

- Performance: architecture, processes (materials including HTS & packaging)
  - High critical current ($I_c$) & critical current density ($J_c$, $J_e$) at the specific application conditions (temperature ($T$) & B-field ($B$, $q$)).
  - Good mechanical properties ($Y_s$) & low ac loss.
  - Stabilities: mechanical, electrical, low degradation, long life-time in shelf.
  - Ready to use: insulation, joint, ohmic contact, piece length & geometries.

- Yield: Important for availability & cost!!
  - Numbers of process?? $\rightarrow 0.9^5 = 0.59$, $0.9^{10} = 0.35$, $0.95^{10} = 0.60…$
  - Process margin is more important in our experiences.
  - Yield definition?

![Diagram](image.png)
How can we realize practical HTS 2G wire? (II)

- Throughput: Important for availability & cost!!

Throughput is the key

Equipment cost share = capital investment / throughput

Throughput = volume production rate

\[ P = A \times R = L \times W \times R = v \times W \times D \]

Key to lowering cost

Wide web process!!

RCE-DR (melt growth)

- RCE DR: ~ 100 nm/sec or faster (SuNAM)
- PLD, MOCVD ~ 10 nm/sec, MOD ~ 1 nm/sec

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

- **RCE-DR**: Reactive Co-Evaporation by Deposition & Reaction (SuNAM, R2R): Patent pending (PCT)
- 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
SuNAM’s Now
SuNAM’s 2G Wire Architecture – 12 mm width

- Protecting layer (0.6 μm) - DC sputter
- Superconducting layer (1.3 ~ 1.5 μm) - RCE-DR
- Buffer layer ~20 nm - sputter
- Homoeipi-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 or more.

- * Typical $I_c \sim > 700 \text{ A/12 mm at 77 K self-field (} J_c > 4 \text{ MA/cm}^2 \text{)}
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.
Quality Control : RCE Vision 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.
Optimization Properties of GdBSCO CC on STS substrate

Average $I_c = 742 \text{ A/cm}$

$J_c \sim 5.3 \text{ MA/cm}^2$

Thickness: $\sim 1.32 \text{ um}$
RCE-DR Results on Stainless Steel Substrate

\[ \text{COV}_{\text{max-min}} = \frac{|I_{C,\text{max}} - I_{C,\text{min}}|}{\bar{X}} \times 100(\%) \]

\[ \text{COV(coefficient of variation)} = \frac{\sigma}{\bar{X}} \times 100(\%) \]

\[ \sigma : \text{StandardDeviation}, \bar{X} : \text{Mean } I_C \]
Combining Barrier, Seed, IBAD, Buffer Systems in One

We can achieve higher yield > 70 %
RCE-DR Results on Stainless Steel Substrate

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Length (m)</th>
<th>AVG.Ic (A)</th>
<th>1σ(A)</th>
<th>Min.Ic (A)</th>
<th>Max.Ic (A)</th>
<th>COV(%)</th>
<th>Ic x L (Am)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>975</td>
<td>730</td>
<td>30</td>
<td>626</td>
<td>792</td>
<td>5.3</td>
<td>610,350</td>
</tr>
<tr>
<td>10</td>
<td>608</td>
<td>33</td>
<td>522</td>
<td>680</td>
<td></td>
<td></td>
<td>508,625</td>
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</table>

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Length (m)</th>
<th>AVG.Ic (A)</th>
<th>1σ(A)</th>
<th>Min.Ic (A)</th>
<th>Max.Ic (A)</th>
<th>COV(%)</th>
<th>Ic x L (Am)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>980</td>
<td>710</td>
<td>36</td>
<td>571</td>
<td>769</td>
<td>5.1</td>
<td>559,776</td>
</tr>
<tr>
<td>10</td>
<td>592</td>
<td>30</td>
<td>476</td>
<td>633</td>
<td></td>
<td></td>
<td>466,480</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Length (m)</th>
<th>AVG.Ic (A)</th>
<th>1σ(A)</th>
<th>Min.Ic (A)</th>
<th>Max.Ic (A)</th>
<th>COV(%)</th>
<th>Ic x L (Am)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>860</td>
<td>732</td>
<td>18</td>
<td>720</td>
<td>760</td>
<td>2.5</td>
<td>618,770</td>
</tr>
<tr>
<td>10</td>
<td>810</td>
<td>15</td>
<td>600</td>
<td>633</td>
<td></td>
<td></td>
<td>515,642</td>
</tr>
</tbody>
</table>
RCE-DR Results on Stainless Steel Substrate

![Graph showing RCE-DR results on stainless steel substrate with dimensions and data points.](image)

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Length (m)</th>
<th>Avg. Ic (A)</th>
<th>1s (A)</th>
<th>Min. Ic (A)</th>
<th>Max. Ic (A)</th>
<th>COV(%)</th>
<th>Ic x L (Am)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>978</td>
<td>770</td>
<td>19</td>
<td>695</td>
<td>797</td>
<td>2.5</td>
<td>679,456</td>
</tr>
<tr>
<td>10</td>
<td>642</td>
<td>579</td>
<td>664</td>
<td></td>
<td></td>
<td></td>
<td>566,214</td>
</tr>
</tbody>
</table>
Development of HTS 2G Wire

(by Dr. Izumi, ISTEC, Japan & EUCAS2013)
Development of HTS 2G Wire

Ic (A/cm-w) @ 77 K

Length (m)

Ic x L :
700kAm
600kAm
500kAm
400kAm
300kAm
200kAm
100kAm
10kAm

(2009.8) 1065mx282A
(2010.10) 540mx466A
(2011.2) 816mx572A
(2013.12) 860mx600A
(2014.03) 978mx579A

(2006.7) 100mx253A
(2008.10) 500mx300A
(2010.10) 500mx400A
(2014.02) 270mx370A

(2012.02) 500mx400A
(2016 Target)

2017 Goal
$I_C/4\text{mm}$ and Joint Resistance for Brass Laminated CC

Joint overlap length: typically 100~150 mm
Coil winding service up to 1.4 m diameter is available now

- No-insulation, polyimide(tape & solution) insulations
- Various kinds of epoxy, paraffin molding(or wet winding)
### Superconducting magnet parameter

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Width; Thickness [mm]</th>
<th>4.1(12.1); 0.21(0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic @ 20 K, B⊥=1.5 T [A]</td>
<td>&gt; 180A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coil</th>
<th># of DP coils, (4mmW; 12mmW) [28; 2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>turn per pancake</td>
<td>133</td>
</tr>
<tr>
<td>Winding i.d.; o.d.; [mm] 245(274); 300.9</td>
<td></td>
</tr>
<tr>
<td>Overall height [mm]</td>
<td>452</td>
</tr>
</tbody>
</table>

| Conductor per DP (4mmW; 12mmW) [m] | 232; 255 |

| Total Conductor (4mmW; 12mW) [m] | 6,496; 510 |

<table>
<thead>
<tr>
<th>Operation</th>
<th>Bc [T]</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iop [A]</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Top [K]</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cryostat</th>
<th>Clear bore [mm]</th>
<th>203</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold bore [mm]</td>
<td>245</td>
<td></td>
</tr>
</tbody>
</table>

#### Cryostat:
- Clear bore: 203 mm
- Cold bore: 245 mm

### Operation:
- Bc: 4.0 T
- Iop: 205 A
- Top: 8 K

### Cryogen:
- 72 hr to 8K

---

**Image:**
- Diagram showing temperature over time with marked 72 hr to 8K transition.
# Development of $I_c (B, T, \Theta)$ Measurement System

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum current</td>
<td>1000A</td>
</tr>
<tr>
<td>Temperature</td>
<td>12K ~ 70K</td>
</tr>
<tr>
<td>Angle</td>
<td>0~135°</td>
</tr>
<tr>
<td>Sample length, width</td>
<td>30 ~ 90mm, &lt;15mm</td>
</tr>
</tbody>
</table>
RCE-DR: in B-field Properties

(measured by ENEA, 2013)
In-field Performance

Measured at LNCMI (by Miyoshi)
Increase the pinning by composition control

Compositions studied here give a more Cu rich liquid which influences growth dynamics and pinning.

There will be excess Gd$_2$O$_3$ in all the samples but the specific composition, pO2, T is key to performance. It is clear what is best place to get very fine nanoparticles. Particles in C could be made smaller.
In-field Performance (77 K)

Only with composition control in RCE-DR process, we can achieve strong pinnings without APCs.

SuNAM’s present: 1.4 um
SuNAM’s future direction for magnet: ~ 3 um

(By Dr. Izumi, ISS2012(Japan))
Tensile stress

- 5% reduction of $I_c$ @ 581 MPa
- Reversible strain limit: 812 MPa
- Reversible strain limit:
  - ~0.73% for GdBCO/SUS
- Mechanical Properties of CC on SUS good enough
$I_c(e,B)$ Characteristics in Various 2G Wires – Strains

(a) Cu-stabilized CC

(b) Brass-laminated CC

B//C

Hastelloy

STS
### Bending Characteristics

**Sample length subjected to bending:** 18.5 mm

**Voltage tap separation:** 10 mm

#### Graphs:

1. **Normalized critical current, $I_c/I_{c0}$ vs. Bending strain (at GdBCO film), %**

   - **RCE-DR-Hastelloy-GdBCO**
   - **RCE-DR-STS-GdBCO**

2. **$I_c/I_{cmax} = 1 - 0.177|\varepsilon_b - \varepsilon_{@Icpeak}|^2$**

3. **$I_c/I_{cmax} = 1 - 0.25|\varepsilon_b - \varepsilon_{@Icpeak}|^2$**

#### Equations:

- $I_{cpeak}$ (0.2%)

#### Graph Details:

- **GdBCO CC tapes**
  - Bending deformation
  - RCE-DR-Hastelloy
  - RCE-DR-STS-GdBCO
  - Uniaxial tension
    - RCE-DR-Hastelloy
    - RCE-DR-Stainless steel
De-lamination Strength Test Results

Mechanical delamination strength, MPa

Superconducting side
Substrate side
(Side)

Copper Stabilized
Brass laminated

Superconductor side
center
side
Substrate side
center

12 mm_RCE-DR_STS substrate_RIST
Stacking Wire

- CC tape width: 2 ~ 4 mm
- Cu buffer layer width: 10 mm
- Stacking method: soldering

**I_c** for stacking wire

![Graph showing I_c vs Current][1]

- **I_c**: 343 A/4mm-w.
- 857 A/cm-w.
- @ 77 K, sf

Cross section of 5-ply stacking wire

- Stacking wire made of 2G HTS CC

[1]: https://via.placeholder.com/150
Stacking Wire

The diagram shows the current (I) versus current (A) for different tapes labeled as Tape 28, Tape 27, Tape 26, Tape 25, Tape 24, and pristine tape. The graph indicates that the critical current density, $I_c$, is 173 A. The data is represented with different colors for each tape, and the current is measured in mA. The figure also notes that the values of n range from 30 to 35.
SuNAM’s Future Direction
### Direction of Technology Development in the Future

**Price Reduction**

<table>
<thead>
<tr>
<th>Width</th>
<th>Capacity</th>
<th>Max Revenue</th>
<th>CAPEX*</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm</td>
<td>1,000 km/y</td>
<td>$ 20 Mil.</td>
<td>$ 7 Mil.</td>
</tr>
<tr>
<td>120 mm</td>
<td>15,000 km/y</td>
<td>$ 75 Mil.</td>
<td>$ 20 Mil.</td>
</tr>
<tr>
<td>360 mm</td>
<td>75,000 km/y</td>
<td>$ 150 Mil.</td>
<td>$ 30 Mil.</td>
</tr>
</tbody>
</table>

(Unit: USD / kAm)

- **Achievable with Existing Line of SuNAM**

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“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”

* Capital Expense : Required Investment in Production Line
# SuNAM’s 2G HTS Wire

## [Specification Table]

<table>
<thead>
<tr>
<th>Model</th>
<th>AN</th>
<th>CN</th>
<th>LB/LS</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Silver(+Cu…) Dry coating</td>
<td>Copper Wet Coating</td>
<td>Brass/ Stainless steel Lamination</td>
<td>Polyimide tape(+) Insulation</td>
</tr>
<tr>
<td>Substrate</td>
<td>Hastelloy or Non-magnetic Stainless Steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width [ mm ]</td>
<td>Commercial: 4 mm, 12 mm. Special Order: 2 ~ 10 mm multi width is available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness [ mm ]</td>
<td>HAS: 0.06<del>0.07, SS*: 0.11</del>0.12</td>
<td>HAS: 0.09<del>0.11, SS*: 0.14</del>0.16</td>
<td>HAS: 0.18<del>0.22, SS*: 0.23</del>0.27</td>
<td>+ 0.1</td>
</tr>
<tr>
<td>Final Process</td>
<td>Silver Sputter</td>
<td>Copper Plating</td>
<td>Brass or SS* Lamination</td>
<td>Wrapping</td>
</tr>
<tr>
<td>Piece Length</td>
<td>Above 100 m, 200 m, 300 m + without Splice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Ic @ 77 k S.F.</td>
<td>(100) / 150 / 200 A + @ 4 mm</td>
<td>(300 / 400) / 500 / 600 / 700 A + @ 12 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Stabilizer** [Ag/Cu/Brass/STS]
- **Superconducting layer** [GdBCO]
- **Buffer layer** [Al₂O₃/Y₂O₃/MgO/LMO]
- **Substrate** [HAS/STS]
- **Stabilizer** [Ag/Cu/Brass/STS]
SuNAM’s Future

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ic(77K, 0T) (A/cm-w)</td>
<td>&gt; 700</td>
</tr>
<tr>
<td>ic(20K, 10T) (A/cm-w)</td>
<td>&gt; 600</td>
</tr>
<tr>
<td>Uniformity (1σ, %)</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Stacked wire ic (A/cm-w)</td>
<td>&gt; 1,200</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>= &lt; 12</td>
</tr>
<tr>
<td>Max. piece length (m)</td>
<td>~ 1.2</td>
</tr>
<tr>
<td>Price ($/kA-m)</td>
<td>~ 100</td>
</tr>
</tbody>
</table>

Present, 2014

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>ic(77K, 0T) (A/cm-w)</td>
<td>&gt; 1,000</td>
</tr>
<tr>
<td>ic(20K, 10T) (A/cm-w)</td>
<td>&gt; 1,000</td>
</tr>
<tr>
<td>Uniformity (1σ, %)</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>Stacked wire ic (A/cm-w)</td>
<td>&gt; 1,800</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>= &lt; 120</td>
</tr>
<tr>
<td>Max. piece length (km)</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Price ($/kA-m)</td>
<td>&lt; 50</td>
</tr>
</tbody>
</table>

5 years later

2 years later
Acknowledgement

- KERI : H. S. Ha, S. S. Oh.
- Andong Nat’l Univ. : H. S. Shin.
- RIST : J. S. Lim

- Stanford Univ. : R. H. Hammond.
- iBeam Materials : V. Matias
- Univ. of Cambridge : J. M. Driscoll
- MIT : S.Y. Hahn, Y. Iwasa
Thanks for Attention!

See you at

CCA 2014

(Nov. 30 ~ Dec. 3)