“Current Status of R&D on REBCO Coated Conductors in Japan”

-for the Aviation of the Future-

Superconductivity Research Laboratory (SRL),
International Superconductivity Technology Center (ISTEC),
Director General, Emeritus

Yuh SHIOHARA

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History of R&D for Coated Conductors in Japan

Discovery of La-Sr-Ca-Cu-O

National Project
Fundamental Materials Science & Engineering
Physics & Chemistry
HTS Mechanism
Search for new HTS
Single X’tal Growth
Bulk HTS Processing
Thin Film Processing

Drs. J.R. Bednorz & K.A. Muller

Prof. Paul Chu

FTSA: Fundamental Technologies for Superconductivity Applications
M-PACC: Materials & Power Applications of Coated Conductors
FT-Coils: Development of Fundamental Technologies for HTS Coils

- Ag/Cu
- (Y or Gd)123
- PLD-CeO₂
- IBAD-GZO/MgO
- Hastelloy C-276

NEDO Project

- 1mx37A (IBAD-PLD)
- 55mx40A (IBAD-PLD)
- 50mx10⁴A/cm² (ISD-PLD)

- 504mx350A (IBAD-PLD)
- 250mx310A (IBAD-MOD)

- 816mx572A (IBAD-PLD)
- 500mx310A (IBAD-MOD)

METI Project

- MRI (3T & 10T)
- Medical Accelerator Gantry

- SMES Transformer
- AC cable
- Refrigerator (Turbo Brayton)

- AC cable
- Transformer
- Refrigerator
- (Turbo Brayton)

- Bulk Flywheel
- Transformer
- Motor
- Refrigerator (Turbo Brayton)

- AC cable
- Transformer
- Refrigerator
- FCL
- Ship Propulsion Motor
- (Turbo Brayton)

- AC cable
- Transformer
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- FCL
- Ship Propulsion Motor
- (Turbo Brayton)

- 55mx40A (IBAD-PLD)
- 50mx10⁴A/cm² (ISD-PLD)
- RABiTS etc.
Commercially Available 2G-Coated Conductors by Fujikura

Current-transport measurements at every 4.7m long

<table>
<thead>
<tr>
<th></th>
<th>Wire A</th>
<th>Wire B</th>
<th>Wire C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Piece length</td>
<td>621 m</td>
<td>700 m</td>
<td>587 m</td>
</tr>
<tr>
<td>2. $I_c$ (max.)**</td>
<td>700 A</td>
<td>590 A</td>
<td>562 A</td>
</tr>
<tr>
<td>3. $I_c$ (min.)**</td>
<td>649 A</td>
<td>555 A</td>
<td>533 A</td>
</tr>
<tr>
<td>4. $I_c$ (avg.)**</td>
<td>677 A</td>
<td>575 A</td>
<td>550 A</td>
</tr>
<tr>
<td>5. Uniformity*</td>
<td>7.5 %</td>
<td>6.1 %</td>
<td>5.2 %</td>
</tr>
</tbody>
</table>

*Uniformity : $(I_c \text{ (max.)} - I_c \text{ (min.)}) / I_c \text{ (avg.)} \times 100$

**$10 \text{ mm-W}$
High Self-Field & In-Field \( I_c \) with High Deposition Rate

(PLD)

*Low Deposition Rate*: \( \sim 10 \mu \text{m/h} \)

*High Deposition Rate*: \( \sim 40 \mu \text{m/h} \)

@77K, 3T

EuBCO with BHO (◇) (low depo. rate)

EuBCO with BHO (●) (high depo. rate)

@77K, s.f.

EuBCO + BHO (◇) (low depo. rate)

EuBCO + BHO (●) (high depo. rate)

\( I_c \) (A/cm-w) vs. Thickness of EuBCO+BHO Layer (\( \mu \text{m} \))

\( I_c \) (A/cm-w) vs. Production rate (m/h)

\( I_c \) min. = 48.7 A/cm-w  
\( I_c \) s.f. = 412 A/cm-w (@77 K)

B//c-axis  
B⊥ tape surface
Extremely High In-Field $I_c$ of 3G - C.C.

PLD

$I_c (A/cm-w) \approx J_e (A/mm^2)$

<table>
<thead>
<tr>
<th>$T$, $B$</th>
<th>EuBCO + BHO</th>
<th>Commercial Based C.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>77K, 3T</td>
<td>141</td>
<td>26</td>
</tr>
<tr>
<td>65K, 3T</td>
<td>616</td>
<td>149</td>
</tr>
<tr>
<td>50K, 3T</td>
<td>1400</td>
<td>395</td>
</tr>
<tr>
<td>50K, 10T</td>
<td>500</td>
<td>124</td>
</tr>
<tr>
<td>30K, 3T</td>
<td>2730</td>
<td>830</td>
</tr>
<tr>
<td>30K, 10T</td>
<td>1180</td>
<td>372</td>
</tr>
<tr>
<td>20K, 10T</td>
<td>1630</td>
<td>516</td>
</tr>
</tbody>
</table>

**Critical Current, $I_c$ ($A/cm-w$)**

- @77K, 3T EuBCO+BHO: 141A/cm-w
- @77K, 3T GdBCO+BHO: 85A/cm-w

**Thickness of SC Layer ($\mu$m)**

- Commercially available

**Materials**

- Ag/Cu
- (Y or Gd)123
- PLD-CeO$_2$
- IBAD-MgO
- Hastelloy C-276

**Other Key Points**

- Extremely High In-Field $I_c$ of 3G-C.C.
- IBAD-MgO, PLD-CeO$_2$, (Y or Gd)123, Hastelloy C-276.
Dependence of HTS Layer Thickness on Critical Currents of CCs Fabricated by TFA-MOD Process

Critical Current, $I_c$ (A/cm²)

Thickness (μm)

@77 K, Self-Field

Y-TFA, Gd-TFA, Ba-TFA, Cu-Oct + Zr-Oct
(0.77 : 0.23 : 1.6 : 3.0 : 0.1)

500m Batch type Furnace for 123 phase Crystallization

TFA-MOD

Multi-Turn

MO Solution

RTR Coating & Calcination
Improvement of In-Field Critical Currents of CCs Fabricated by Low Cost TFA-MOD Process in Comparison with PLD Process

Critical Current Density, $J_c$ (MA/cm$^2$) vs. Angle of Applied Magnetic Field, $\theta$ (°)

- **MOD (New)**: $0.56 \mu m^t$
  - $J_c$(min.) = 1.63 MA/cm$^2$
- **PLD**: $3.6 \mu m^t$
  - $J_c$(min.) = 1.14 MA/cm$^2$
- **MOD (conventional)**: $2.6 \mu m^t$
  - $J_c$(min.) = 0.82 MA/cm$^2$

@65 K, 3 T
Comparison of Performance of C.C. in the World

Long Length CCs ($I_c \times L$)
- Fujikura 603 kAm
- SuNAM 566 kAm
- SuperPower 300 kAm

in-Field $I_c$ and Length (Vapor Phase Deposition) ($I_c \times L$)

Long C.C.
- ISTEC
  - 200m x 54A @77K,3T
  - 94m x 108A @77K,3T
- SuperPower
  - 50m x 14A @77K,3T
  - 43A (Commercial) @77K,3T

Short C.C.
- ISTEC
  - 141A @77K,3T
  - 2730A @50K,3T
- SuperPower
  - 86A @77K,3T B\//c
  - 2742A @50K,3T B\//c
- SuNAM 30A @77K,3T

in-Field $I_c$ and Length (Liquid Solution Process) ($I_c \times L$)

Long C.C.
- ISTEC, SWCC
  - 124mx 50A @77K,3T
Short C.C.
- ISTEC
  - 55A @77K,3T
- amsc
  - 10A @77K,1T
“Development of HTS Coiling Technology”

Realization of He-less Medical Magnets

1. HTS Coils for 3T & 10T MRI
   - 10ppm in 40cmφ with 1 ppm/h @ 3, 10T

2. HTS Coils for Medical Accelerator & Gantry
   - 100ppm Deviation of B in 10cmφ under Pattern Excitation to 3T

3. Common Core Technologies for HTS Coils
   “Coil operated with He-free” and “Low Loss Coil”
   “Long CC with High $I_c(B)$” and “Ultra-low Loss CC”

Current National Project (METI) in JAPAN
<table>
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<tr>
<th><strong>Coated Conductors</strong></th>
<th><strong>Theme of R&amp;D</strong></th>
<th><strong>Expected Goals</strong></th>
</tr>
</thead>
</table>
|                       | ➢ Long Coated Conductor (CC) with High in-field $I_c$ | ➢ 200m long C.C. with $I_c$: 600A/cm-w@65K,3T  
 $I_c$:1000A/cm-w@35K,10T |
|                       | ➢ Reduction of Heat Generation for Long CC  
(Uniform $I_c$, Filamentation, Joints with low resistivity) | ➢ Filament width $\leq 500\mu$m  
$\Delta I_c/I_c$ (ave) $\leq 0.05$ |
|                       | ➢ Joint Resistance $\leq 3\Omega$ | ➢ New Evaluation Technique |
|                       | ➢ 200m long C.C. with $I_c$: 600A/cm-w@65K,3T  
$I_c$:1000A/cm-w@35K,10T | ➢ Fundamental data-base of Characteristics of CCs & Coils |
|                       | ➢ Filament width $\leq 500\mu$m  
$\Delta I_c/I_c$ (ave) $\leq 0.05$ | ➢ Evaluation of 500 m CC Coil in Liquid $N_2$ |
|                       | ➢ Joint Resistance $\leq 3\Omega$ | ➢ Evaluation of 500 m CC Coil with Conduction Cooling |
|                       | ➢ Fundamental Evaluation of CCs & Coils  
(Flux Creep, AC loss etc.) | ➢ Fundamental data-base of Characteristics of CCs & Coils |
|                       | ➢ Coiling Technology  
Coils by 300 & 500m CCs | ➢ Evaluation of 500 m CC Coil in Liquid $N_2$ |
|                       | ➢ Fundamental data-base of Characteristics of CCs & Coils | ➢ Evaluation of 500 m CC Coil with Conduction Cooling |

- **Long wires with high in-field performance**
  - As high in-field performance as short samples
  - Evaluation technology for in-field characteristics

- **Long wires with low heat generation (AC losses & Joule Losses)**
  - Uniform $I_c$ distribution (for reduction of AC losses)
  - Small damage due to scribing processing (for reduction of AC losses)
  - Small joint resistance
What Can We Expect by High $I_c(B)$ C.C.?

Reference
“Design by Kyoto Univ.”

Specifications of **HTS MRI**

- 3 T @ Bore Center
- BSCCO-2223
- Conduction Cooling (20 K in design)
- Power Supply Drive
  (#Persistent current Mode)

$I_{op} = 185\, A @ 3.6\, T$  
Load Factor = 0.77  
$S = 4.5 \times 0.3\, mm^2$

$$\Rightarrow I_c = \frac{185}{0.77 \times (10/4.5)} = 534\, A/cm-w$$

Can we expect the above performance in Liq. $N_2$?
Possibility of Operation in Liq. $N_2$ for 3T-MRI

MRI in Liq. $N_2 \rightarrow$ Feasible!

@77K, 3T

\[ 141 \text{ A/cm-w@77K,3T} \Rightarrow 527 \text{ A/cm-w@65K,3.6T} \]

≈ 534 A

(Design by Kyoto Univ.)
Multi-filamentary coated conductors are effective and promising for reduction of AC losses in a coil form!
Reduction of AC Loss by filamentation (relative factor: vs without scribing)

**Filamentation & Low AC Loss (Vapor Phase Deposition)**

- **Long C.C.**
  - ISTEC: 5mm-w, 10 Filaments, 100m AC Loss: 1/10
  - SuperPower: No Report

- **Short C.C.**
  - ISTEC: 10mm-W, 20 Filaments, AC Loss: 1/20
  - SuperPower: 12mm-w, 15 Filaments, AC Loss: 1/15

**Filamentation & Low AC Loss (Liquid Solution Process)**

- **Long C.C.**
  - ISTEC: 5mm-w, 10 Filaments, 100m AC Loss: 1/10

- **Short C.C.**
  - ISTEC: 5mm-w, 10 Filaments, AC Loss: 1/10

- **ams: No Report**

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Comparison of Filamentation Performance of C.C. in the World
Currently Commercially Available Refrigerators 2 years ago

Turbo Brayton refrigerator was successfully developed in the M-PACC Project.
- 2 kW @ 65 K, COP ≥ 0.06 @ 80 K
- ~6 ton/2kW ⇒ 3 kg/W (Lighter weight could be possible)
Purpose
Research and development of fully REBCO superconducting rotating machines

Brief Summary
Applying our original technologies, we will first develop superconducting armature windings with low ac loss characteristics and a large current capacity. Combination with rotating REBCO superconducting field windings makes it possible to install the both windings into the same casing resulting in reduction of the gap distance and constitute it as a compact superconducting synchronous rotating machine of high output power density and the high efficiency. This rotating machine will bring us the realization of the “low-carbon society” through effective energy savings.
Proposed R&D for Coated Conductors

Development of REBCO Coated Conductors (3G-CC)

- **High Critical current**: $I_c (J_e)$
  - e.g. 2,000A/cm-w, e.g. 2μm in thickness
    - $J_c > 10 \text{ MA/cm}^2$
- **High In-Field Critical Current**: $I_{c, \text{min}} - B$
  - e.g. $I_c: > 600 \text{A/cm-w@65K,3T}$  $I_c: > 1000 \text{A/cm-w@35K,10T}$
- **Low AC (hysteresis) Loss**
  - Uniformity of $I_c$ & $J_c$ in width and length directions of CC
  - Multi Filamentation (Laser Scribing) ≤ 500μm
- **Low Resistance Joint** (incl. persistent joint)
- **High Mechanical Strength**
  - Delamination, Tensile, Bending
- **Low Cost Process**
  - High Production Rate, High $I_c$, High Production Yields

**Development of Coiling (Winding) Technology**

- Pancake (Race-track), Solenoid, Uniform & High Magnetic Field Generation

**Development of Cryo-cooling Technology**

- Compact, Light weight, Efficient (high COP) Refrigerator, He-free

**Demonstration of Feasibility of HTS Power Devices**

- Electric Power Devices (incl. Magnets),
- Rotating Machines (Motor, Generator (incl. Wind Power))
Beginning of HTS Application to Aeronautics

END

Thank you for your attention