Strong High-Temperature Superconductor
Trapped Field Magnets

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OUT LINE

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  *(importance & improvement of large grain LRE-123)*
- Recent results on critical current density \( (J_c) \)
  *(around liquid nitrogen temperature)*
- Summary of Trapped Field Magnets
  *(MMPSC process)*
- Improved Mechanical Performance and its importance for the Industrial Applications
- Concluding summery
Melt-processed high $T_c$ bulk superconductor

(Large magnetic field ($B_T$) can be trapped)

Permanent magnets: $B_r \approx 1.5$ T under the best condition

Superconducting magnets
- $B_{tr} \approx 17$ T at about 29 K (Y-123), RTRI
- $B_{tr} \approx 2.6$ T at 77 K (Gd-123), SRL
- $B_{tr} \approx 1.5$ T at 90 K (NEG-123), SRL

$B_T \propto J_c r$
Trapped magnetic field is proportional to $J_c$ and size of the bulk

Development of melt-processed high $T_c$ bulk superconductor

NEG-123 (33 mm) (SRL-ISTEC)
Sm-123 (60 mm) (Nagoya University)
Gd-123 (140 mm) (SRL-ISTEC)
**Human Levitation Disk**

**HTS**: melt processed YBaCuO
**Cooling**: LN₂
**Processing**: in air
**Size**: 80% - 40 mm (> 200 pucks)
**Performance**: > 0.5 T at 77 K
**Seeding method**: cold seeding

melt processed GdBaCuO
LN₂
in air
80% - 25 mm (~ 45 pucks)
~ 1 T at 77 K
cold seeding (batch process)
Develop ternary NEG-123 type materials and process to improve the flux pinning capability at 77K.

(Nd, Eu, Gd)-Ba-Cu-O

Neodymium, europium, gadolinium mixing ratio (1:1:1)

\[ H_{irr} = 7 \text{T (at 77K, } H \parallel c\text{-axis)} \]

(SRL-ISTEC)

Patent 1998

United States Patent, Patent Number 6 063 753

Develop ternary NEG-123 type materials and process to improve the flux pinning capability at 77K.

(Nd, Eu, Gd)-Ba-Cu-O

Neodymium, europium, gadolinium mixing ratio (1 : 1.25 : 0.85)

$H_{\text{irr}} \approx 15 \, \text{T} \text{ (at 77K, } H \parallel c\text{-axis)}$

(SRL-ISTEC)

Submitted the patent 2002
(Nd,Eu,Gd)-Ba-Cu-O

neodymium, europium, gadolinium
with new class of Zr rich nano pinning media

Levitation at 90.2 K

(SRL-ISTEC)

Submitted the patent 2003
and
Submitted the patent 2004

Press Release : June 27th, 2003
Develop the critical current density \( (J_c) \) around 77.3 K

At 65 K tremendous super-currents were achieved, reaching more than 920 kA/cm\(^2\) at 0 and 4.5 T. All the \( J_c \) values presented here are the highest reported so for bulk RE-123 material at the respective temperatures.

Experiments at liquid oxygen temperature

Liquid oxygen is attracted to the magnet due to its paramagnetism

Suspension of NEG123 superconductor at 90.2 K

• The same levitation with large Fe-Nd-B ring magnet
Develop the critical current density ($J_c$) at 77.3 K and higher magnetic field

![Graph showing $J_c$ vs. $\mu_0 H_a$]  

$T = 77 \text{ K}$  
$H // c-axis$

Note the nano-lamellar structure formation with the average spacing around 3 to 4 nm, close to the coherence length (in YBCO $\xi$ (77 K) $\approx$ 4.5 nm)

Nanotechnology / Nanopinning can dramatically improve the melt processed LRE-123 material properties at higher magnetic field
High $J_c$ at low/intermediate fields due to secondary phase nanoparticles

- **Graph**: Shows $J_c$ vs. $H_a$ for NEG-123 with 30 mol% Gd-211 (100 nm).
- **Note**: T = 77 K, H//c-axis, Ar~1% O$_2$.

**Images**:
- DFM and HAADF Detector images indicating secondary phase nanoparticles.
- Note the clouds of < 10 nm sized particles in the NEG-123 matrix.
- Elemental ratio analysis showing < 10 nm sized particles.

**Magnet and Superconductor**
- Liquid oxygen environment.
Development of MgB$_2$ Superconducting Magnet

**MgB$_2$ fabrication**

- Mg + 2B powder
- Pressing to disk shape (10, 20, 30 mmΦ, 5, 10 mm$^t$)
- Heating (in Ar)
- MgB$_2$ bulk magnet

**Superconducting performance**

- Graph showing superconducting performance

Railway Technical Research Institute
Fabrication of larger MgB$_2$ bulks

- 20 mm\(\phi\) (~4 g)
- 60 mm\(\phi\) (~36 g)
- 100 mm\(\phi\) (~100 g)
Ideal circle-shape, uniform field distribution with circularity >99%!
- suggesting uniform current flow on the whole bulk
Weak-link-free uniform current in polycrystal and uniformly distributed natural, nanoscale pinning by GBs.
Batch Process: As-Grown Bulk Samples
Morphology, and Orientation

- the four-fold growth facet lines clearly visible on the top surface of all pellets. Which indicate that the crystal growth was perfectly controlled in all positions in the furnace.
Development of the Train Modal using Bulk LRE-123
Development of Permanent Magnet System based on Single Grain Gd-123

Test Result:

Magnetized using the Gd-123 annular superconducting PM

Magnetized using the 10T superconducting PM

Note that both results are almost the same and found that Gd-123 based PM system works very well
Development of Permanent Magnet System based on Single Grain Gd-123

Summary for the magnetic field strength at center as a function of rings

<table>
<thead>
<tr>
<th></th>
<th>Magnetic Field [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single bulk</td>
<td>0.75 T</td>
</tr>
<tr>
<td>Two bulks</td>
<td>1.32 T</td>
</tr>
<tr>
<td>Three bulks</td>
<td>1.62 T</td>
</tr>
<tr>
<td>Four bulks</td>
<td>2.02 T</td>
</tr>
</tbody>
</table>

- Note that one can make desired permanent magnet system adjusting the ring magnets.

Railway Technical Research Institute
Development of Permanent Magnet System based on Single Grain Gd-123

Compact, lightweight, movable PM system Based on Gd-123 material

Importance of new process and formation of plate like crystals

2 REBa$_2$Cu$_3$O$_y$ $\rightleftharpoons$ RE$_2$BaO$_4$+3BaCu$_2$O$_2$

Normal process

New process

Er-123 on MgO substrates
Scoring Criterion and $I_c$ development

Performance – High $I_c$

1. orientation
2. density & quality control
3. grain size & grain coupling
4. reduction of liquid phases at grain boundary

Progress in $I_c$

Critical Current $I_c$ (A)

T=77.3 K
self field

Jan-06 May-06 Oct-06 Mar-07 Aug-07 Jan-08

0 20 40 60 80 100 120 140 160
SRL developed pre-annealing, second rolling and two step heating process for high performance tapes. PASRTSH process is used due to its effectiveness in improving grain coupling and in increasing the film homogeneity in order to obtain good quality long superconducting tapes.
Development of Prototype 2 meters long Bi-2223 DC Superconducting Cable for Railway System

Schematic cross section of the HTS cable structure

- Former (Cu): Φ 16mm
- Electric Insulation (2mm): Φ 22mm (PPLP)
- HTS Conductor: Φ 17mm
- HTS Shield Layer: Φ 23mm
- Protection (1mm): Φ 25mm

Specifications of the 2 meter long prototype DC HTS cable

<table>
<thead>
<tr>
<th>Part</th>
<th>Size</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Former</td>
<td>Φ16 mm</td>
<td>Filled-core fine-stranded copper</td>
</tr>
<tr>
<td>HTS tape</td>
<td>0.35mm (t) / 4.5mm (w)</td>
<td>Bi-2223, $I_c = 160$ A at 77.3 K</td>
</tr>
<tr>
<td>HTS conductor</td>
<td>Φ17 mm</td>
<td>$I_c = 1720$ A at 77.3 K, 1 layer with 10 tapes</td>
</tr>
<tr>
<td>Electrical insulation</td>
<td>Φ22 mm</td>
<td>Polypropylene Laminated Paper “PPLP”</td>
</tr>
<tr>
<td>HTS shield</td>
<td>Φ23 mm</td>
<td>$I_c = 2430$ A at 77.3 K, 1 layer with 14 tapes</td>
</tr>
</tbody>
</table>

HTS DC cable system works around 77.3 K
Note that the tests were performed in pool boiling nitrogen at 77 K. Inset shows the photograph of a 5 m-long cable.
DC voltage-current curves for 5 m-long cable at 77 K
300 m-long Bi-2223 HTS DC cable at RTRI