Development of HTS magnets

K. Hatanaka
hatanaka@rcnp.osaka-u.ac.jp

Research Center for Nuclear Physics
Osaka University

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Outline

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3. Development of HTS magnets
   Scanning magnet
   Dipole magnet
4. Summary
Motivations to develop HTS magnets

- Compact devices
  Beam line, Gantry for particle therapy, Accelerators
- Low power consumption system
- Advantages over LTS system
  No liquid helium is necessary
  Operating temperature is 20K or higher
  Cryogenic components for cooling are simpler
  Cooling power of refrigerators is much larger
  Temperature range for superconductivity is wider
  Possible AC magnets and pulsed magnets
The National Cancer Center (Kashiwa, Chiba)

- Irradiation control room
- C230 Cyclotron
- Gantry
- Fixed port
- Energy defining section
Gantry: Diameter = 13m, Length = 25m, Weight of rotating parts = 570t
Motivations to develop HTS magnets

- Compact devices in Beam line, Gantry for particle therapy, Accelerators
- Low power consuming system
- Advantages over LTS system
  - No liquid helium is necessary
  - Operating temperature is 20K or higher
  - Cryogenic components for cooling are simpler
  - Cooling power of refrigerators is much larger
  - Temperature margin for superconductivity is larger
  - AC magnets and pulsed magnets
Cu-oxide HTS materials

- 1986: discovery of $(\text{La}_{1-x}\text{Ba}_x)\text{CuO}_4$
  J.G. Bednorz and K.A. Müller

- Significant effort went into the development of new and improved conductor materials.
- It became possible to manufacture long HTS wires over km.
  
  1\textsuperscript{st} generation HTS wire $(T_C = 110\text{ K})$
  Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (Bi2223)

  2\textsuperscript{nd} generation HTS wires $(T_C = 95\text{ K})$
  YBa$_2$Cu$_3$O$_7$ (YBCO / Y-123)

- Although many prototype devices using HTS wires have been developed, so far there have been limited applications to accelerators and beam line devices.
First-generation HTS wire

- Wire consists of a flexible composite of filaments in a silver alloy that provides mechanical stability and transient thermal conductivity.
- Wire is in thin tape-form approximately 4mm wide and 0.3mm thick.

Critical current depends on the operating temperature and the strength and direction of magnetic field on the tape surface. It is scaled by $I_c$ at 77K and self-field.
Second-generation HTS wire

- Intermediate layer and superconducting layer are formed on a substrate, and a silver layer is formed to protect the superconducting layer. Copper tape is laminated on the YBCO tape to prevent burnout from over current.
- Tape is 5-10mm wide and the YBCO layer is 0.5-10μm thick.
- Higher performance is expected over the first-generation wire in future.
- They are under development by many industries all over the world.
A scanning magnet

- Scanning magnet consists of two sets of two racetrack coils.
- Each coil is built by stacking three double pancakes.
Structure and Design parameters

- Ic of the HTS wire over the full length was measured at 77K in a 10m pitch and was 125-140A.
- 0.2mm thick layer insulation is put in the middle of each double pancake.
- Double pancake is covered with a 0.5mm thick ground insulation.
- Four 0.9 mm thick brass cooling plates are fixed to a coil with epoxy resin.

<table>
<thead>
<tr>
<th>Coils</th>
<th>Inner size</th>
<th>$B_x$: 150 mm $\times$ 300 mm, $B_y$: 150 mm $\times$ 380 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section</td>
<td>30 mm $\times$ 30 mm</td>
<td></td>
</tr>
<tr>
<td>Separation</td>
<td>70 mm</td>
<td></td>
</tr>
<tr>
<td>Max. field</td>
<td>0.6 T</td>
<td></td>
</tr>
<tr>
<td>Superconductor</td>
<td>Bi-2223/Ag alloy wire</td>
<td></td>
</tr>
<tr>
<td>Total length</td>
<td>$B_x$: 412 m $\times$ 2, $B_y$: 460 m $\times$ 2</td>
<td></td>
</tr>
<tr>
<td>Number of turns</td>
<td>420 $\times$ 2 coils for both $B_x$ and $B_y$</td>
<td></td>
</tr>
<tr>
<td>Winding construction</td>
<td>3 double pancakes/coil</td>
<td></td>
</tr>
<tr>
<td>Inductance of single coil</td>
<td>$B_x$: 75mH, $B_y$: 92 mH</td>
<td></td>
</tr>
<tr>
<td>Critical current at 77 K</td>
<td>40-43 A</td>
<td></td>
</tr>
<tr>
<td>Rated current</td>
<td>200 A</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20 K</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cryostat</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Cooling method</td>
<td>Conduction cooling by two GM refrigerators</td>
<td></td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>Vacuum isolation, 80 K shield, super-insulation</td>
<td></td>
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<tr>
<td>Cooling power of</td>
<td>45 W at 20K, 53 W at 80 K</td>
<td></td>
</tr>
<tr>
<td>the GM refrigerator</td>
<td></td>
<td></td>
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</tbody>
</table>
Measured critical current ($I_c$) of double pancakes and four coils at 77 K

<table>
<thead>
<tr>
<th>Coil No.</th>
<th>Length (m)</th>
<th>$I_c$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>278</td>
<td>132</td>
<td>56.1</td>
</tr>
<tr>
<td>280</td>
<td>132</td>
<td>57.0</td>
</tr>
<tr>
<td>283</td>
<td>132</td>
<td>61.1</td>
</tr>
<tr>
<td>285</td>
<td>132</td>
<td>58.0</td>
</tr>
<tr>
<td>286</td>
<td>132</td>
<td>62.2</td>
</tr>
<tr>
<td>288</td>
<td>132</td>
<td>57.4</td>
</tr>
<tr>
<td>290</td>
<td>162</td>
<td>60.6</td>
</tr>
<tr>
<td>296</td>
<td>162</td>
<td>58.7</td>
</tr>
<tr>
<td>298</td>
<td>162</td>
<td>59.8</td>
</tr>
<tr>
<td>300</td>
<td>162</td>
<td>60.5</td>
</tr>
<tr>
<td>304</td>
<td>162</td>
<td>61.1</td>
</tr>
<tr>
<td>306</td>
<td>162</td>
<td>59.0</td>
</tr>
<tr>
<td>Bx_1</td>
<td>396</td>
<td>40.8</td>
</tr>
<tr>
<td>Bx_2</td>
<td>396</td>
<td>41.1</td>
</tr>
<tr>
<td>By_1</td>
<td>486</td>
<td>42.7</td>
</tr>
<tr>
<td>By_2</td>
<td>486</td>
<td>42.9</td>
</tr>
</tbody>
</table>

Coil #283

Total tape length 132m
$I_c = 13.2$ mV = 61.1 Amps at 77K
AC losses in superconducting wire

- $Q_H$: hysteretic losses (in the superconductor)

\[
Q_H = \oint P \, dt = -\mu_0 \oint dt \oint \mathbf{M} \, d\mathbf{H} = \oint dt \int_V (\mathbf{i} \cdot \mathbf{E}) \, dV
\]

- $Q_D$: dynamic resistance losses caused by the flux flow

- $Q_C$: coupling losses (between filaments)

- $Q_E$: eddy current losses in the metallic sheath/substrate and supporting structures

- $Q_R$: current sharing in metallic sheath ($I>I_c$)
AC losses per cycle of HTS conductors

- \( Q_H \propto I^{3-4} \)
- \( Q_D \propto I^2 \)
- \( Q_C \propto f \cdot I^2 \)
- \( Q_E \propto f \cdot I^2 \)
- \( Q_R \propto I^2 \)

So far studies have been limited to such simple structures as tapes, cables and simple shape coils both experimentally and theoretically.
AC losses in two Bx coils at 20 K
Comparison with calculations

Data

FEM results at 15 Hz

by Brandt et al.,

Normalized at 50 A

Loss per cycle

Data  $\propto I^{2.4}$

$\propto f \cdot I^2$
Specification of HTS coils for the dipole magnet

Wire: DI-BISCO Type-HT(SS20)
4.6mm × 0.36mm
12.5μm polyimide (Half wrap)

Winding: 600 turns × 2 coils

Inductance: 0.7H

Operating temperature: 20K

Critical current (measured at 77K):
Wire: 160 ~ 178A
Double pancake: 60 ~ 70A
Coil: 47A, 51A

Critical current of wire and the load line of a coil
Specification of the dipole magnet

- Orbit radius: 400 mm
- Deflection angle: 60 deg.
- Pole gap: 30 mm
- Cold pole structure
- Laminated pole and yoke for pulsed operation
Double pancake (DP) was wound applying tensile stress.

Each DP was impregnated with epoxy resin in vacuum.

Three DP and cooling plates are stacked and fixed with epoxy resin in vacuum.

9mm and 4.5mm thick iron plates were put on outside and inside of a coil, respectively.
• Coils are fixed to poles to bear the electromagnetic expansion force of 112,000 N/m.

• Poles are formed by stacking 2.3mm thick carbon steel plates.

• Coils and poles weigh 56 and 90kg, respectively. Total weight of the cold mass is 250kg.
Excitation by DC currents
Excitation by pulsed current (100A/s)
Next generation particle therapy facilities
- Both compact accelerators and compact gantries are indispensable.

Development of HTS magnets at RCNP
- Scanning magnet and a dipole magnet were fabricated.
- Performance tests are ongoing with DC, AC and pulsed currents.
- Presently available HTS wires have relatively large hysteretic losses. Does YBCO show better performance?
- Feasibility study of HTS cyclotrons is continued and conceptual design work has been started.
- UCN polarizer (solenoid) is under construction with HTS wire, which is used for the neutron electric dipole moment (EDM) measurements.
Collaborators


Tohoku U.: Y. Sakemi

Kyushu U.: T. Wakasa

NIRS: K. Noda

KT Science: T. Kawaguchi

Thank you for your attention