Prospects for the use of HTS in high field magnets for future accelerator facilities

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CERN, Geneva, Switzerland
Outline

- Introduction
- HTS Conductors
  - State of the art development
  - Conductor choices for high fields
  - HTS Cables
- Application to high field magnets
  - HTS Magnet design aspects
  - Coils demonstration
  - Developments for a viable HTS technology
- Conclusions
Introduction

HTS Conductors
- State of the art development
- Conductor choices for high fields
- HTS cables

Application to high field magnets
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Conclusions
Transition temperature of superconductors

- BSCCO 2212
- BSCCO 2223
- REBCO

Transition temperature (K)

Year


Hg, Pb, Nb, Nb₃Sn, Nb₃(AlGe), Nb₃Ge, HgBa₂Ca₂Cu₃Oₓ, HgBa₂Ca₂Cu₃Oₓ at 30GPa, Tl₂Ba₂Ca₂Cu₃O₁₀, (BiPb)₂Sr₂Ca₂Cu₃O₁₀, YBa₂Cu₃O₇₋ₓ, LaBaCuO, MgB₂, Iron-based

Liquid He 4.2K
### Properties of superconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c(0)$ [K]</th>
<th>$B_{c2}(0)$ [T]</th>
<th>$\xi$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Ti</td>
<td>9.5</td>
<td>14.4</td>
<td>$\sim 6$</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.3</td>
<td>28-30</td>
<td>$\sim 4$</td>
</tr>
<tr>
<td>REBCO</td>
<td>93</td>
<td>$&gt; 100$</td>
<td>$\sim 2$</td>
</tr>
<tr>
<td>BSCCO 2212</td>
<td>95</td>
<td>$&gt; 100$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>BSCCO 2223</td>
<td>110</td>
<td>$&gt; 100$</td>
<td>$\sim 1$</td>
</tr>
</tbody>
</table>

$B_{c2}(0)$ = upper critical field at 0 K

$\xi$ = coherence length

$B_{c2}(0) > 100$ T
Properties of HTS superconductors

- $H_{c2}(T)$ much higher than for Nb-Ti and $Nb_3Sn$

- But, thermal fluctuation effects depress the irreversibility field ($B_{irr}$) at which $J_c = 0$ well below $B_{c2}$, except at low $T$
Properties of HTS superconductors

- $H_{c2}(T)$ much higher than for Nb-Ti and Nb$_3$Sn

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High fields $\rightarrow$ Low (liquid helium) temperature
High field for HTS superconductors

**Nb-Ti**

- $\sim 1200 \text{ t in LHC}$
- Up to 10 T

**Nb$_3$Sn**

- RRP 132/169
- PIT 192
- $\sim 25 \text{ t for Hi-Luminosity LHC}$
- $\sim 600 \text{ t for ITER}$
- Up to 15-16 T

**HTS at 4.2 K and for fields above 16 T**
Challenges of HTS superconductors

Copper oxides HTS (cuprates)

- Layered crystal structure
- Orientation of grains needed
- Brittle ceramic materials

→ Long time R&D

Ex. YBa$_2$Cu$_3$O$_7$ (YBCO)
Critical current density

REBCO: $J_c$ higher than any other superconductor

Measurements performed at CERN on commercial materials. The Nb-Ti curve is at 1.9 K. BSCCO 2212 measurements performed at NHMFL.
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Conclusions
**HTS Conductor Choices**

**BSOCCO 2223**
- Multi-filamentary tape
- \( \sim 4.3 \text{ mm} \times 0.23 \text{ mm} \)
- \( \sim 40\% \text{ SC} \)

**REBCO**
- Coated Conductor Tape
- \( \sim 4 \text{ mm} \times 0.16 \text{ mm} \)
- \( \sim 1\% \text{ SC} \)

**BSOCCO 2212**
- Multi-filamentary wire
- \( \Phi = 0.8-1.4 \text{ mm} \)
- \( \sim 30\% \text{ SC} \)

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Sumitomo DI-BSCO tape

SuperPower REBCO tape

OST BSCO 2212 wire
BSCCO 2223 tape

Most mature superconductor

DI-BSCCO 2223 (Sumitomo)

Unit lengths of up to 300-400 m
Production capacity @ Sumitomo = 1000 km/year
Implemented quality control
Ic variation over unit length < 3 %

Good mechanical properties

\(\varepsilon_c = 0.57\ %\)
\(\sigma_c = 430\ MPa\)

\(J_e(77\ K,\ s.f.)\) up 150 A/mm\(^2\)
\(J_e(4.2\ K,\ B_{\perp}=17\ T)\) up to 400 A/mm\(^2\)
REBCO tape

Tapes based on bi-axially textured YBCO film

Highest Jc than any other superconductor

Substrate (Hastelloy C, Stainless steel) thickness ~ 50 μm
Superconductor thickness ~ 1 to 5 μm
Unit lengths of up to 100-200 m
Good mechanical properties
σc > 550 Mpa
It is wound as reacted conductor: Wind and React technology

Several manufacturers (Europe, USA, Korea, Japan, Russia)
Ic anisotropy

Ic(B,T,θ)
REBCO tape

Potentials for \textit{Je enhancement} by reduction of thickness of substrate and increase the thickness of superconducting layer (texture vs thickness)

Addition of nanoscale defects (nanoparticles and nanorods) with strong pinning properties for \textit{enhancement} of in-field \textit{Jc} - BaZrO3 (BZO) nano-columns
REBCO tape

\[ J_e(4.2 \text{ K, } B_{\perp} = 20 \text{ T}) \sim 1000 \text{ A/mm}^2 \]
Pinning force in REBCO

\[ F_p(Nb-Ti) \sim 17 \text{ MN/m}^3 \ (4.2 \text{ K and } 5 \text{ T}) \]

Xu et al., APL Materials, 2009
BSCCO 2212 round wire

It requires Wind & React technology

D. Larbalestier et al, Nature Materials, NMAT 3887

Isotropic material
MgB$_2$ tape and wire

- Potentially large $H_{c2}$
- Excellent chemical and mechanical compatibility with high-strength alloys (steels)
- Weak-link free grain coupling

Lack of natural defects may be the responsible for fast decrease of $J_c$ in increasing fields

$H_{c2}$ of optimally dirty MgB$_2$ exceeds those of NbTi and Nb$_3$Sn

- Round wire
- Well-known PIT technology
- Low raw material cost
- Moderate anisotropy

Needed enhancement of $H_{c2}$ and $H_{irr}$ in wires
**MgB$_2$ wire**

**Industrial Wire**

Superconducting Links for Hi-Luminosity LHC

Reached @ CERN

20 kA @ 24 K

2×20 m long MgB$_2$ cables

First demonstration of high-current capability in MgB$_2$ cables

Low-field application for electrical transfer lines

Φ = 0.85 mm

Round MgB$_2$

Columbus wire

CERN-Columbus development

L = 20 m
Iron-based superconductors

Tc up to 56 K

High Bc2 – Bc2(0) up to 100-200 T

$\xi \sim 1$-3 nm

Low electromagnetic anisotropy

Wire

Tape

Coated conductor

H. Kumakura, NIMS

A. Ballarino
Iron-based superconductors

Upper Critical field $B_{c2}(T)$

C. Tarantini et al., ASC Center
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Conclusions
Engineering critical current density

Graphic courtesy of P. Lee, ASC Center at NHMFL
## Summary of conductor characteristics

<table>
<thead>
<tr>
<th></th>
<th>BSCCO 2223</th>
<th>REBCO</th>
<th>BSCCO 2212</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tape</strong></td>
<td>Tape</td>
<td>Tape</td>
<td>Wire</td>
</tr>
<tr>
<td><strong>Multi-filamentary</strong></td>
<td>Thin-film</td>
<td>Multi-filamentary</td>
<td></td>
</tr>
<tr>
<td><strong>Single-layer</strong></td>
<td>Twisted-filaments</td>
<td>Twisted-filaments</td>
<td></td>
</tr>
<tr>
<td><strong>Anisotropic</strong></td>
<td>Anisotropic</td>
<td></td>
<td>Isotropic</td>
</tr>
<tr>
<td>$I(B,T,\vartheta)$</td>
<td>$I(B,T,\vartheta)$</td>
<td>$I(B,T)$</td>
<td></td>
</tr>
<tr>
<td><strong>New cables</strong></td>
<td>Reacted conductor</td>
<td></td>
<td>High pressure HT</td>
</tr>
<tr>
<td><strong>Lower Je</strong></td>
<td>High Je</td>
<td></td>
<td>High Je</td>
</tr>
<tr>
<td><strong>L~300 m</strong></td>
<td>L=100-200 m</td>
<td></td>
<td>Not an issue</td>
</tr>
</tbody>
</table>
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Superconducting cables

Superconducting cables for accelerator technology:

- High current
- High compactness $\rightarrow$ High Je
- Full transposition
- Dimensional accuracy
- Controlled inter-strand resistance
- Good mechanical properties
- Windability

Rutherford cables made from Nb-Ti and Nb$_3$Sn round wires

Large Hadron Collider: 7600 km (1200 tons)

Nb-Ti Rutherford cables
Superconducting cables

Nb$_3$Sn Hi-Luminosity LHC Rutherford cables

Rutherford cables from BSSCO 2212 round wires

REBCO and BSCCO 2223: the tape geometry requires new cable concepts

D. Dietderich et al., LBNL
REBCO Roebel Cables

Meander-tape cut from a 12 mm wide REBCO tape

Patent (1912) of Ludwig Roebel (BBC) Low-loss Cu cables for power generators

Cables produced by KIT and General Cable Superconductors from commercial REBCO tape
REBCO Roebel cables

Measurements performed at CERN show current capability

- \( I_c (B_\perp=9.6 \, \text{T}, \, 4.2 \, \text{K}) = 3.4 \, \text{kA} \)
- \( J_e (B_\perp=9.6 \, \text{T}, \, 4.2 \, \text{K}) = 400 \, \text{A/mm}^2 \)

- Required management of stress and of stress distribution

J. Fleiter, PhD thesis
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Field of $\text{Nb}_3\text{Sn}$ dipole magnets

Plot courtesy of A. Godeke, LBNL
High-field magnets

Graded-block design

Standard $\cos \theta$ dipole coil

Low field

L. Rossi and E. Todesco
20 T for 100 TeV in 80 km

Cosine theta type magnet, **Nb-Ti** and **Nb$_3$Sn** and **HTS** insert. Bore $\Phi = 40$ mm

<table>
<thead>
<tr>
<th>20 T magnet in 80 km tunnel</th>
<th>Width (mm)</th>
<th>Average radius (mm)</th>
<th>Overall Jc (A/mm$^2$)</th>
<th>Strand Jc (eng) (A/mm$^2$)</th>
<th>Conductor mass (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS layer</td>
<td>25</td>
<td>32.5</td>
<td>231</td>
<td>600</td>
<td>1409</td>
</tr>
<tr>
<td>10 mm collar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb$_3$Sn layer 1</td>
<td>20</td>
<td>65</td>
<td>193</td>
<td>386</td>
<td>2930</td>
</tr>
<tr>
<td>Nb$_3$Sn layer 2</td>
<td>20</td>
<td>85</td>
<td>385</td>
<td>770</td>
<td>3685</td>
</tr>
<tr>
<td>20 mm collar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb-Ti layer 1</td>
<td>15</td>
<td>122.5</td>
<td>337</td>
<td>523</td>
<td>5275</td>
</tr>
<tr>
<td>Nb-Ti layer 2</td>
<td>15</td>
<td>137.5</td>
<td>433</td>
<td>672</td>
<td>5925</td>
</tr>
</tbody>
</table>

1400 tons of HTS + 6600 tons Nb$_3$Sn + 11300 tons of Nb-Ti

$\sim$13 times Nb$_3$Sn for ITER  $\sim$10 times Nb-Ti for LHC
HTS High-field magnets

HTS Solenoids to provide focusing

- Very high fields (> 30 T, hybrid, LHe operation)
- Next generation of high resolution NMR
- REBCO tape well-suited. It is wound in pancakes with stainless steel for both insulation control of the large hoop (and radial) stresses

Conductor considerations:
(+ ) Field parallel to the tape plane
(+ ) Mechanical reinforcement to mitigate radial forces
HTS High-field magnets

32 T User magnet at NHMFL

- Total field: 32 T
- Field inner YBCO coils: 17 T
- Field outer LTS coils: 15 T
- Cold inner bore: 32 mm
- Current: 186 A
- Inductance: 436 H
- Stored Energy: 7.54 MJ
HTS High-field magnets

Cos$\theta$ - LHC Dipole

Block design

Common-coil design (R. Gupta, BNL)

Field direction $\rightarrow$
Isotropic conductor

Field direction $\rightarrow$
REBCO tape
Stress easier to manage

Field direction $\rightarrow$
Isotropic conductor
HTS High-field magnets

Cos$\theta$ - LHC Dipole

Block design

Common-coil design

Canted Cos$\theta$ Dipole

Stress interception and management, S. Caspi et al., LBNL
HTS Aligned coil block design

Aperture = 40 mm

5 T in a background field of 15 T

J. Van Nugteren and G. Kirby, CERN, Eucard 2
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### HTS Coils Demonstrators

#### 33.8 T, REBCO, NHMFL

- **REBCO coil**
  - 2.8 T in background field of 31 T

- **REBCO and BSCCO 2223 coils**
  - R. Gupta et al., BNL

#### 33.8 T, BSCCO 2212, NHMFL

- **BSCCO 2212 coil**, heat treatment at 10 bar
  - 2.6 T in background field of 31.2 T
  - D. Larbalestier et al, NMAT 3887

- **BSCCO 2212 coil from Rutherford cable**
  - A. Godeke et al, 2010
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Quench protection

Low quench propagation

- **Quench detection**
  Sensitive systems to detect in the 10-20 mV range

- **Quench protection**
  Fast propagation of resistive zone
Technologies to be developed

Need for mastering technologies for coil fabrication with HTS materials:

- Electrical insulation techniques
- Electrical joints techniques
- Winding techniques
- For BSCCO 2212: high pressure on coils during high temperature heat treatment - Wind & React technology
Conclusions (1/3)

- **HTS** Conductors are available today with characteristics that make them suitable for use in high field magnets.

- Demonstration coils show capability. There is a clear route to boosting solenoids to > 30 T, and work is on going to find a route to use in dipole magnets.
Conclusions (2/3)

- Differences with classical LTS conductors are such that the use of HTS materials in high field magnets requires a major rethink of existing technology and mode of operation.

- Prototype coils shall be made in order to learn about HTS performance in magnets.

- HTS conductors are presently expensive. A large application (like MRI for Nb-Ti) would be required to justify boosting production to a level that would enable significant cost reduction.
Conclusions (3/3)

- More recent conductors are potentially more affordable than those presently available, but a determined R&D effort is needed to boost the performance to a level that would be useful for improving the field in a high field magnet.

A magnet can never perform better than the conductor it is made of.
Thanks for your attention