HTS Coated Conductors: Up-Scaling to Long Length, Properties, Applications and Expectations

Alexander Usoskin
Agenda

Part I: HTS wires
A. European High Temperature Superconductors (EHTS, Bruker)
B. 1G and 2G HTS tapes
C. From single crystalline substrates to metallic foils
D. HTS deposition: Short history and actual state of art
E. Economical aspects

Part II: EHTS Coated Conductors
F. CC architecture and technological steps
G. Critical current
H. Mechanical performance
I. Production costs: outlook
J. Applications
K. Status worldwide
Part I: HTS wires
Bruker worldwide

more than 3600 employees
The Product Lines of the Bruker Group

NMR Spectrometer

MALDI-TOF Mass spectrometer

x-ray Diffractometer

FT-IR Spectrometer
Bruker’s major worldwide sites

- Billerica, MA, USA
- Freemont, CA, USA
- Madison, WI, USA
- Rheinstetten, Germany
- Fällanden, Switzerland
- Wissembourg, France
- Tsukuba, Japan

- R&D
- Manufacturing
- Service
- Sales
Analytical Instrumentation
Over 3600 Bruker Employees Worldwide
Offices in over 20 Countries

BRUKER BIOSCIENCES

Over 3600 Bruker Employees Worldwide
Offices in over 20 Countries

BRUKER BIOSPIN

VAC VACUUMSCHMELZE

Superconductors

EAS

EHTS
Production of metallic superconductors at EAS (Hanau, Germany)
European High Temperature Superconductors

- EHTS facility in Alzenau, Germany
- High Temperature Superconductors:
  - 1st generation - Bi-conductors, 200km/year
  - 2nd generation - YBCO coated conductors
The companies *EAS* and *EHTS*

*EAS* and *EHTS* are members of Bruker BioSpin-Group.

The focus of *EAS* are metallic superconductors while *EHTS* is focused on ceramic high temperature superconductors.
The product range of EAS and EHTS

 NbTi

 NbSn

 Bi-2223

 Y-123
BiSCCO & YBCO CC wire designs

**HTS: Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{y}$**

Polycrystalline material with uniaxial texture by thermo-mechanical treatment

Textured Bi-2223-Filaments in Silveralloy matrix

Typical dimensions:
4 mm x 0.22 mm

**HTS: Y$_1$Ba$_2$Cu$_3$O$_{7-\delta}$**

Bi-axially oriented oxide-buffer-layer grown on polycrystalline stainless steel tape

Typical cross-section:
4 mm x 0.1 mm
B2. 1G and 2G HTS tapes

Bi-2223 tapes
Production of 2500 m long length

- world record!
- longest length in one piece
Irreversibility field

$H^*$: relevant field for applications

**Bi:**
- $T < 30-35$ K

**Y:**
- $T < 60-70$ K

P. Tixador, Grenoble INP/Institut Néel-G2Elab
Irreversibility field in EHTS tapes measured at TU Vienna (H. Weber & Co., Sept 2007)

The irreversibility temperature decreases, to 69.5 K at 15 T for the field parallel to the c-axis. The irreversibility field was found to be 7.7 T at 77 K. The decrease of the irreversibility temperature is much smaller for fields perpendicular to the c-axis, \( T_{irr} \) is 81.5 K at 15 T.

Irreversibility line for the two main field orientations.
C1. towards metallic substrates

Coated Conductors: two different routes

Forced Texturing
ABAD, IBAD, ISD

Thermo-mechanical Texturing of Substrates (TMT), RABiTS
YBCO CC key: hyper texturation

Rolling Assisted Biaxially Textured Substrates

Substrate:
- Rolling
- Annealing
- Electropolishing

IBAD or ABAD

Text. sub

Text. YSZ

Untext. sub

C2. towards metallic substrates
### Comparison of metallic substrates

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Axial Stress</th>
<th>Ferromagn.</th>
<th>Production Costs, a.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RABiTS tape</td>
<td>130 MPa</td>
<td>yes</td>
<td>highest</td>
</tr>
<tr>
<td>Hastelloy</td>
<td>&gt;700 MPa</td>
<td>no</td>
<td>&gt;20 Euro/kAm</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>650-700 MPa</td>
<td>no</td>
<td>~0.5 Euro/kAm</td>
</tr>
</tbody>
</table>
D1. HTS deposition

Why HTS deposition is not easy?

Example of $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ film:

1. tendency to decomposition

2. high temperature is needed to get the right structure

3. oxygen loading
MOD route

MOD/AmSC:

MOD uses a trifluoroacetate (TFA)-based precursor.

- The organic components are decomposed in a humid, oxygen atmosphere up to a temperature of 400 °C, to form a BaF2-based precursor film with stoichiometric Cu and Y oxides for YBCO.

- This precursor is continuously converted to the epitaxial super-conducting phase in a tube furnace in a humid, low oxygen partial pressure environment.
D4. HTS deposition

**Progress on HTS Materials – 2G Wire Architecture**

- RABiTs™/ MOD low cost approach
- Fully continuous process (Reel-to-Reel)
- Lamination of copper stabilizer gives:
  - Enhanced electrical stability
  - Superior mechanical properties
  - Easy electrical joints and terminations

**Second generation wire goal:** Form-Fit-Function replacement at 2-5X lower cost

AmSC latest known status
D5. HTS deposition

Slitting of wide strip into multiple 2G wires

AmSC latest known status

4-cm technology in CY2005…

…migrating to 10-cm technology

One manufacturing pass through yields 8 to 23 wires – not just one
How nanodots increase current in 2G HTS wire

Cross section of 344 superconductors: a 2G HTS wire with a substrate, thin buffer/HTS/Ag layers and two copper laminates (AmSC)
MOCVD (e.g. SuperPower)

Phosphine (PH₃) molecules react on surface, leaving phosphorus to react with TMIn subspecies, forming InP and CH₄

Trimethylindium (TMIn) molecules react on surface, depositing TMIn subspecies

Incorporation is at lattice step edge

Reaction By-Products (CH₄) Leave Reactor

D7. HTS deposition
MOCVD
(SuperPower, ...)

D8. HTS deposition
## Physical Vapor Deposition (PVD)

<table>
<thead>
<tr>
<th>Method</th>
<th>Short Tapes</th>
<th>Long Tapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash evaporation</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Thermal coevaporation (Theva)</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Pulsed laser deposition (PLD)</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Nobody mentions this, but precursors’ costs by PVD about 5-10 times less!
Part II: EHTS Coated Conductors
EHTS Coated Conductors

EHTS processing route

- Deep polishing
- US cleaning
- ABAD YSZ buffer
- HR-PLD CeO2
- HR-PLD YBCO
- PVD Ag or Au
- Annealing
- Cu plating

150µm

Vacuum, mbar

- 10^{-5}
- 10^{-1}
- 10^{-1}
- 10^{-5}
EHTS Coated Conductors

YBCO coated conductors: production route

Cu plating

Cu Shunt layer (~20 μm)

Au Protective/stabilizing layer (~0.2 μm)

YBCO (~1 μm)

CeO₂ Buffer (~0.05 μm)

YSZ Buffer (~1.5 μm)

SS-Substrate

Currents: up to 400 A/mm²

ABAD set-up

HR-PLD

Au/Ag deposition

2nd-polishing step
EHTS Coated Conductors

EHTS: alternating beam assisted deposition (ABAD)

Benefits:

a) by 1-1.5° better texture (as a result of reduction of deposition temperature)

b) Homogeneity of the in-plane texture: ΔFWHM=0.2 deg. over 45m length

c) Processing yield of 90% was achieved in 2007

106m long tape with YSZ buffer:

Up-scaling to production speed of 35 m/hour is already in progress
EHTS Coated Conductors

EHTS ABAD

- Target
- Substrate tape
- Ion source for target sputtering
- Assisted ion source

Space for transport systems

Substrate holder

Source 1

Source 2

YSZ target

55°
EHTS Coated Conductors

**EHTS: IBAD/ABAD**

**SS/IBAD-YSZ**

**TEM cross-sectional view of IBAD-YSZ**

**Improvement of the out-of-plane-texture**

![Graph showing improvement of out-of-plane texture.](image)

**Selected area diffraction**

![Selected area diffraction image.](image)
**Fig. PD1:** Conversions of the surface relief of a cobalt target after 500 simulated ablation pulses with different energy densities. Curve 0 corresponds to the initial surface wave. Curves 1-4 correspond to the number of thresholds $D = 1.1, 1.7, 2.2$ and 5.5, respectively. $K = 2 \times 10^3 \text{ cm}^{-1}$.

**Fig. PD2:** Change of the surface relief after a series of ablation pulses performed with a tilted incoming beam. Simulated ablation with tilting angle of $22.5^\circ$; curve 0 corresponds to the initial surface wave; curves 1-3 correspond to the number of pulses of 250, 500, and 1000; $D = 2.2$; $K = 2 \times 10^3 \text{ cm}^{-1}$.
EHTS Coated Conductors

YBCO-Coated Conductors Manufactured by High-Rate Pulsed Laser Deposition
Fig. PD5: Dependences of film deposition speed $V$ on number of ablation pulses $N_a$ for conventional PLD (1), VAA with spiral scan (2), and VAA with meander scan (3). Energy density of the laser beam on the target is 2.5 J/cm$^2$. 

$V$ [nm/pulse] vs. $N_a$ [pulses]
PLD: Variable Azimuth Ablation (VAA)
High Rate Pulsed Laser Deposition (HRPLD)

Up-scaling: 8m/hour => 80m/hour
100m => 2000m

Status:
- New Laser for multi-zone deposition installed and operating
- Remaining HRPLD equipment is ordered
- Testing and installation early 2008

Means for increasing the production speed:

a) efficient ablation kept at low pulse energy (~100 mJ)

b) formation of “focused” laser plumes

c) “wide-window” concept of quasi-equilibrium heater (QEH).

d) multi-zone deposition: utilizing of the whole energy of the laser

> 85% efficiency of material transfer:

EHTS Coated Conductors
Over 100m long Y123 coated tape with over 200A

This system can produce the SC tape with uniform Ic distribution.

- $I_c \approx 250\,\text{A} (77\,\text{K0T}) \times 2.0\,\mu\text{m}$
- Throughput: 7m/h $\rightarrow$ 20m/h
- Material yield: 20% $\rightarrow$ 50%
- Laser power: 150W $\rightarrow$ 180W

Ave. $I_c$

variation within plus or minus 3% for the average $I_c$ value

one point defect of the substrate
EHTS Coated Conductors

6B-HRPLD: New laser at tests with old beam delivery system

Preparation of system for tests is completed on June 15, 2007
EHTS Coated Conductors

100m tape coated with YBCO
Efficient optics for homogenizing and delivery of laser beam (308nm, 300Hz)

- Efficient optics in beam delivery system allowed to use 40\% lower energy of the laser beam; this provides the same deposition speed in high-rate pulsed laser deposition (HR-PLD) used in YBCO film deposition previously.
- Low optical losses (of 5\% in total) allow to save beam energy in order to use it in further deposition channels.
Up-scaling goals

- New 6-zones HRPLD machine
  Processing speed: 70-75 m/h
  Unit length of CC: 2 300 m
  Status: developed, installation in progress

- New ABAD machine
  Processing speed: 35 m/h
  Unit length of CC: >2 000 m
  Status: development to be finished in 2009
EHTS Coated Conductors

Cu Plating at EHTS

- Cu plated CC: new degree of quality?
  - Mechanical performance
  - Currents
  - AC losses

![Cu plating](image)

![Graph showing Ic vs Length](graph)

1S
2SA
2SQS

Length, m

0 10m 20m

-20m -10m 0 10m 20m

Ic, A

40 80

0
CC tapes: bending tests

Critical current, A

1 / R, 1/mm

reversibility range

EHTS Coated Conductors
4mm wide CC, Cu plated; $I_c$(strain) dependence exhibited a maximum at tensile strain of 0.4 %.

Critical current is about 240 A/cm-w in this maximum. This effect is caused by a pre-stress determined by a substrate form during film deposition.
CC axial stress

$I_c$ variation by axial mechanical stress

Degradation of critical Current $I_c/I_{c0}$

Axial Stress [MPa]

Tape NSS 158, $I_c = 103$ A

measurements at Siemens: B. Utz, W. Schilling
EHTS Coated Conductors

CC tape: high edge bending tests at NIST

Rcr = 0.5m !!

(NIST, Aug 2007)

Axial stress: 650-700 MPa
EHTS Coated Conductors

**Mechanical tests: Tape torsion under axial stress**

- **Critical current [A]**
- **Tape torsion [deg/m]**

<table>
<thead>
<tr>
<th>Tape Torsion [deg/m]</th>
<th>Critical Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>75</td>
</tr>
<tr>
<td>5.6</td>
<td>75</td>
</tr>
<tr>
<td>8.3</td>
<td>75</td>
</tr>
<tr>
<td>11.1</td>
<td>75</td>
</tr>
<tr>
<td>13.9</td>
<td></td>
</tr>
</tbody>
</table>

**YBCO coated tape, stainless steel substrate 4 mm wide, 40 N axial force, 77K, self field**

- **Reversibility**
- **Irreversibility**
- **Threshold of Ic-irreversibility**
- **Threshold of tape instability**
Currents
Critical currents: field and temperature dependences
EHTS CC tapes measured at TU Vienna, H. Weber and EHTS

Figure 48: Critical currents for the two main field orientation and under 45°.
Critical currents: field and temperature dependences

(EHTS CC tapes measured at TU Vienna, H. Weber)
EHTS Coated Conductors

Critical current densities: field and temperature dependences
EHTS CC tapes measured at TU Vienna, H. Weber

Figure 54: Critical current densities from 85 K to 4.2 K.
Angular dependence of Ic:
EHTS tapes measured at TU Vienna (H. Weber, 2007)

Figure 18: Critical currents as function of the angle between the field and the a/b-plan.
A maximum n-value of 44 is found at low fields and 40 K.

It is assumed that

\[ U = \text{const} \times I^n \]
Applications:

CC based devices
• Circuit ac current in 1kVA FCL demonstrator at higher overloads

• Short recovery time of 0.5 ms is achievable in CC based fault current limiters!!
• Circuit ac current in 1kVA FCL demonstrator

• FCL voltage in expanded scale
EHTS (ZFW) FCL: resistive design
Originally developed FCL-modules based on CC tapes (2002)

SUPERPOLI FCL-5.5-50 module based on YBCO-coated stainless steel tubes and Au shunt layer.

Nominal (non-limited) current: 2 500 A (ampl.)
Nominal power losses: ~ 0.1 W
Fault current, max.: 50 000 A (ampl.)
Peak power at fault current: 150 000 W
FCL tests at Alstom

SUPERCONDUCTING POWER LINK

- 1 GVA-class
- 100 to 200 meter long
- 3-phased
- phase current of $28 \text{kA}_{\text{rms}}$
- phase-to-phase voltage of $20 \text{kV}_{\text{rms}}$
- fault currents of (50...100) $\text{kA}_{\text{rms}}$.

EXPECTED PERFORMANCE: EHTS YBCO COATED SUPERCONDUCTOR

![Graph showing expected performance of EHTS YBCO coated superconductor](image)
CC based transformer: EC Project READY

2 CC-tapes
8m x 4 mm

P. Tixador
Grenoble 2003
Project “READY”
CC Resonance Coil, designed and manufactured at EHTS (Forschungszentrum Jülich, Project, 2007)

High-temperature superconducting quantum interference device with cooled LC resonant circuit for measuring alternating magnetic fields with improved signal-to-noise ratio, Rev. Sci. Instrum. 78, 054701 (2007); DOI:10.1063/1.2735561

Biomagnetic Liver Susceptometer

Measurement of Liver Iron Stores by Magnetic Biopsy
Flux Transformer / Sensor: Cleveland / Tristan (2005-2007)

Production Costs
Outlook: HR-PLD - production cost limit

Costs without target: 3,12 €/kAm
Total: 3,71 €/kAm

40% less!!

Costs without target: 1,92 €/kAm
Total: 2,42 €/kAm

+ cost effective Substrate!
Cost evaluation for IBAD/PLD process

- Initial installation and maintenance cost

Throughput (m/h)

1.2 yen/Am ~ 10 dollars/kAm

Throughput of over 20m/h is needed.
EHTS status
Förderung und Stand der Technik

jährliche staatliche Förderungen in M$ für HTSL-Leiter im Zeitraum ca. 2004-2007
(THEVA Applied Superconductivity Conference 2006, Seattle)

Rekordwerte für Coated Conductors bezüglich Längen und kritischen Ströme

USA
Asien
Europa

SP
7 cm
721A/cm

SP
595 m
173 A

Technische Universität Braunschweig
Institut für Oberflächentechnik
Status of Long Coated Conductors

JAPAN: Fujikura - Chubu - Sumitomo - Showa - SRL-Tokyo - SRL-Nagoya

USA - Super Power - AMSC

EU - EHTS (Germany)

KOREA - KEPRI

Goal for Current Project (2008.3)

Ic (A)@77K, self-field

Length (m)

790m 190A

(2007.10)
# Goals for National Project of C.C. in Japan (2003-2007)

<table>
<thead>
<tr>
<th>Name</th>
<th>High Performance Type</th>
<th>Low Cost Type</th>
<th>Extremely Low Cost Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>YBCO(PLD)/GZO(IBAD)</td>
<td>YBCO(MOD)/GZO(IBAD)</td>
<td></td>
</tr>
<tr>
<td>Length (m)</td>
<td>≥500m</td>
<td>≥50m</td>
<td></td>
</tr>
<tr>
<td>( I_c )</td>
<td>( I_c \geq 300\text{A/cm-w (}@77\text{K,0T))</td>
<td>( I_c = 200\text{A (}@77\text{K,0T))</td>
<td>( \text{---------})</td>
</tr>
<tr>
<td>Production Rate</td>
<td>≥5m/h</td>
<td>( \text{---------})</td>
<td>( \text{---------})</td>
</tr>
<tr>
<td>Cost</td>
<td>( \leq 12\text{Yen/Am (}@77\text{K,0T))</td>
<td>( \leq 8\text{Yen/Am (}@77\text{K,0T))</td>
<td>( \text{Confirmation of Reliability for (}@77\text{K,0T)) ≤ 3\text{Yen/Am})</td>
</tr>
</tbody>
</table>