LATEST DEVELOPMENTS IN COATED CONDUCTORS WILL REVOLUTIONIZE MAGNET TECHNOLOGY

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THEVA AT A GLANCE

Company: THEVA GmbH, HQ in Ismaning, Germany, established 1996
Team: 50 FTE (mainly R&D engineers and production team)

Product portfolio

- HTS wire
  THEVA Pro-Line
- HTS coils
- Inspection tools
  Tapestar™

Value proposition
- Robust, high performance products
- Reliable wire supply
- Expertise and engineering support

Main applications
- HTS cables and bus bars for high current
- Current leads (with low heat input)
- Magnets: high field, fusion, industry

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HTS Wire: Production & Properties
THEVA Pro-Line HTS Wire and Latest Improvements

Basic wire architecture

- Silver contact layer (surround) ~ 1.5 µm
- HTS layer (GdBa$_2$Cu$_3$O$_{7-y}$) 3 – 4.5 µm
- MgO cap layer 0.4 µm
- ISD-MgO ~ 3 µm
- Substrate (Hastelloy C276)

Not to scale

Low heat conductivity for current leads (1.5 mW/100A)

Performance improvements

- **High performance (HP) wire**
  - Increased HTS thickness
  - $I_C$ (77K, sf) 700 A → 900+ A

- **Artificial pinning (AP) formula**
  - BaHfO$_3$ nano-particles
  - Randomly dispersed – no columns
  - $I_C$ (20K, 20T) > 500 A/cm

- **Reduced substrate thickness**
  - 50 µm → 40 µm
  - Higher engineering current density
  - AP-wire: $j_e$ (20K, 20T) > 800 A/mm$^2$

Invited presentation HF-8 was given at the virtual CCA 2021, October 11-15, 2021.

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**HIGH - PERFORMANCE HTS WIRE**

**Regular production wire**

Width: 12 mm

3, 4, 6 mm available by Laser slitting

$I_{C,min}$ (77 K, s.f.) = 500 A – 700 A

Piece length: 100 m – 200 m

**High performance wire**

Enhanced HTS thickness (4.5 μm)

$I_{C,min}$ (77 K, s.f.) = 750 A – 1000 A

Piece length: 50 m – 200 m

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MAGNETIC FIELD PERFORMANCE OF AP-REBCO WIRE

Field dependence of ReBCO-wire (+ BaHfO$_3$)

THEVA Pro-Line AP wire performance

Current density for B $\parallel$ c of total 60 µm thick tape (40 µm substrate and 5 µm surround Cu coating)

- 10 T: 3000 A/mm$^2$
- 20 T: 2000 A/mm$^2$
- 30 T: 1550 A/mm$^2$

@ 20 K, 20 T: 800 - 900 A/mm$^2$

Reduced anisotropy
- AP randomly dispersed
- no columnar growth

Below 50 K: I$_c$(B) improvement by factor 2.5
LASER-SLITTING

Cost aspect: slitting can destroy substantial value
Edge defects are critical for high field applications

Technical characteristics
- High speed 1000 m/h (for 100 µm HC276)
- High accuracy, narrow tolerances
- No waste material
- No $I_C$ – reduction ($I_{C-12mm} = 4 \times I_{C-3mm}$)
- No cracks or defects induced
- Clean, straight edge – no burr

High yield Laser tape slitting

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Quality Control: TAPESTAR™ - Enhanced Functionality

Enhanced operating range

In-field measurement
HTS field coil up to 1 Tesla in LN

Low temperature option
Subcooling LN down to 68 K

Yield forecast for (Laser) slitting

Algorithm using full 2D Tapestar data of wide tape
analyzing existing defects and predicting slitting yield

- black: $I_C$-simulation for 3 mm slitting
- green: measured $I_C$ after 3 mm slitting
High Field Magnet Applications
SUPERCONDUCTING WIRE MATERIALS – A COMPARISON

How does ReBCO compare to classical superconductor wire?

➢ LTS, MgB$_2$ or BSCCO produced by classical, metallurgical PIT – route
  ▪ Round, filamentary wire, easy twisting and flexible handling and packaging
  ▪ Some materials (Nb$_3$Sn, BSCCO 2212) require “wind and react” processing

➢ ReBCO “wires” are coated tapes (coated conductors)
  ▪ Additive fabrication: coatings are applied layer by layer by PVD
  ▪ Growth can be controlled and manipulated (e.g. adding artificial pinning)
  ▪ 12 mm production width – Laser-slit to custom-width (3 – 12 mm)
  ▪ Customized electrical stabilization applied afterwards
  ▪ Tape geometry, no filaments, only stacking possible
  ▪ Mechanical strength determined by substrate choice (mostly HC276)

Pros & Cons

- Modifications tricky
- Design freedom
- Adversity, risk
- Easy modification
- Flexible adaptation
- Flexible adaptation
- Limited freedom
- Strength adjustable
Material Choice for High Field Magnets (HFM)

For HFM the choice has considerably increased

- Classical, well-established Nb$_3$Sn (OST/BEST), W&R
- BSCCO 2212 – experimental material, high pressure processing, W&R, single source, cost ?
- ReBCO (2G HTS)
  - Extremely wide operation range (B & T)
  - High pinning forces & $H_{irr}$
  - Sprouting industrial (volume) production
    Perspective: commodity product, cost decline
  - RE/NM-content negligible – not a cost factor

W&R = wind & react material
RE = rare earth, NM = noble metal

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Superconductors for Extremely High Field Magnets

Artificial pinning (AP) ReBCO wire

- Giant progress made in ReBCO wire recently
- All suppliers offer special AP-material
- Extremely high pinning forces
  1.2 TN/m³ @ 4 K, 18 T *
- Broad HF operating range (up to 20 K)
- Quench – resilient

Beyond 18 T the future belongs to ReBCO wire

MgB₂: M. Tomsic, Hypertech 2015
BSCCO: Z. Melhem, OST @ ASC 2020
Nb₃Sn: Supercon 2020

* T. Yoshida et al., Fujikura Technical Review 2017

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**QUENCH BEHAVIOR OF HTS MAGNETS**

Comparing LTS (4K) to HTS (20K) operation

- **Trigger event**
  - Flux jumps $F_L > F_P$

- **Pinning forces (GN/m$^3$)**
  - $F_P(HTS) >> F_P(LTS)$
  - $F_P(HTS) = 1200$, $F_P(LTS) = 3 - 20$

- **Shunt**
  - $\alpha \cdot \rho_C \cdot \Delta I$

- **Dissipation**
  - $Q_{in}$

- **Reservoir**
  - $c_p(T) \cdot \Delta T$
  - $c_p(20K) \approx 20 \cdot c_p(4K)$

- **Heat sink**
  - $Q_{out} \propto \lambda(T) \cdot \Delta T$
  - $\lambda(20K) \approx 2-3 \cdot \lambda(4K)$

- **Qout < Qin**
  - **Quench**

- **Sensitivity**
  - $\frac{\partial I_C}{\partial T} \propto \frac{1}{T_C}$
  - $T_C(HTS) \approx 5 - 10 \cdot T_C(LTS)$

- **Stable operation**
  - $I = I_{C,min} + \Delta I > I_{C,min}$
  - $I < I_{C,min}$

- **HTS material:** quench – resilient, lots of safety margin
- **Benign behavior (phys. properties) at higher temperature**
- **No LHe inventory – no He gas burst**

**HTS magnets are much more stable to operate**

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b) S. Russenschuck, 2011; https://doi.org/10.1002/9783527635467.app1
**Comparison 1G vs. 2G - Wire in Moderate Field Applications**

Comparison of commercial 1G and 2G wires

**Standard ProLine ReBCO without AP**

- @ 2 T, same temperature 2G performs 3× better
- Up to 3 T 2G-wire @ 45K better than 1G @ 20K
- For moderate field applications 1-5 T
  - standard 2G-wire outperforms 1G by factor of 3
- THEVA’s 2G-AP wire even 6-8 times superior
- 2G-wire has a clear cost advantage
  - in motor- and MRI applications

1G DI-BSCCO 2223 data from SEI datasheet SCT02-2020-041

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**RoWaMag: HTS Magnet System for Aluminum Billet Heater**

FEM design and manufacturing of HTS magnet system

**Robust coils for industrial applications**

Coil design and manufacturing technology

- Square-shaped, 1×1 m² double pancake coils
- Resin potted
- Smooth surfaces for dry cooling

**Status**

- All coils successfully tested in LN
- Magnet system assembled
- Induction heater assembly ahead

**Partners**

- Cryogenic system
- OEM induction heater

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SUMMARY

ReBCO – wire is …

➢ a novel product that differs in many ways from classical superconductors
➢ offering new perspectives for robust magnets even at extremely high fields
  ▪ extremely high pinning forces
  ▪ large operation window
  ▪ quench-resilient
➢ Ready to use material (no W&R) with high resolution inspection data available
➢ Attractive cost perspective
  ▪ Raw material < 20% of product cost
  ▪ HTS content of wire < 5%
  ▪ Production cost scale with volume: 10× production volume ⇒ ½× cost

2G HTS wire will revolutionize high field magnet design
Thank you!

... and the THEVA - team

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