THEVA

THEVA PRO-LINE HTS WIRE

March 2020

General Properties

THEVA Dünnschichttechnik GmbH
Rote-Kreuz-Straße 8 • 85737 Ismaning • Germany • info@theva.com • www.theva.com

THEVA Pro-Line HTS wire – general properties

General remarks on HTS wire technology

High-temperature superconductors (HTS), especially compounds of the family $REBa_2Cu_3O_{7-\delta}$ (REBCO; RE = rare earth element, e.g. Yttrium Y, Dysprosium Dy, or Gadolinium Gd) are powerful for industrial applications. Compared to low-temperature superconductors, cooling with liquid helium is not necessary and very high current densities above 10^{10} A/m² or 10,000 A/mm² can be realised with this material. For technical applications, the following basic properties and remarks are important:

- REBCO is a ceramic compound. To overcome the brittleness of the material, thin films on flexible metallic substrates are used. As the bending strain in a thin film on a thin metal substrate is small, a flexible wire can be realised.

- In superconductors like REBCO irregularities of the crystalline structure in the nanometer range result in a disturbance of the superconductivity.

With increasing grain boundary angle, the disturbance increases leading to a decrease of the maximum possible superconducting current. For high performance, the REBCO has to be similar to a single crystal, i.e. biaxially textured, with only a small spread of the grain orientations. To achieve this texture a buffer layer can be used which is textured by special deposition methods. The REBCO layer is adopting the texture and shows high current density.

- Any superconductor has a certain limit of current that it can carry. If this current is exceeded, a resistance develops which leads to fast heating. This can destroy the thin superconducting layer easily if the current is not switched off fast. In order to achieve a more robust behaviour, an electrical stabilization like an additional copper layer is used typically. The type and thickness of this layer is determined by the specific application requirements. The copper also serves as mechanical and chemical protection.

THEVA Pro-Line wires

The metal substrate for THEVA Pro-Line (TPL) wires is the Nickel alloy NiMo16Cr15W (also known as Hastelloy C-276[1], 2.4819, or N10276). The rolled foil material has excellent mechanical properties which guarantee a high quality HTS wire.

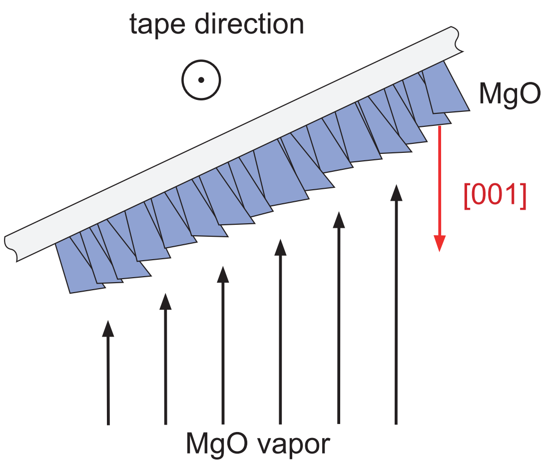

Fig. 1: Sketch of the ISD process.

To achieve the necessary texture a buffer layer of magnesium oxide (MgO) is deposited onto the substrate prior to the $GdBa_2Cu_3O_{7-\delta}$. Texturing of this layer is achieved by THEVA's proprietary inclined substrate deposition (ISD) process[2]. During the deposition of MgO, the substrate is inclined with respect to the source as shown in **Fig. 1** resulting in a MgO layer with a roof tile surface structure and a tilt of the main crystallographic axes (indicated as [001] in **Fig. 1**) as well as a pronounced biaxial texture (**Fig. 2**).

To facilitate epitaxial growth of the superconductor a second thin MgO layer (cap layer) is evaporated onto the ISD layer. The HTS layer is then deposited directly onto this second MgO layer. For Pro-Line wires pure $GdBa_2Cu_3O_{7-\delta}$ is used which has a critical temperature of 92 K. All depositions are performed in vacuum (PVD) using e-beam evaporation.

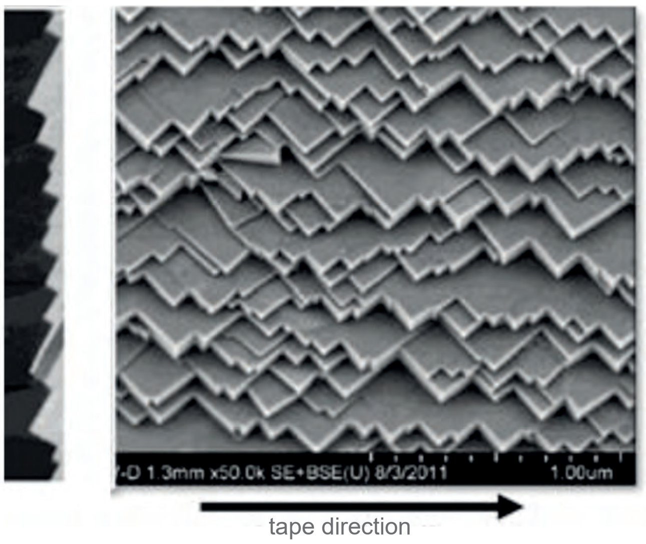

Fig. 2: scanning electron microscope (SEM) cross section image (left) and SEM surface image of the ISD-MgO layer (right) (both at a magnification of 50k).

Due to the epitaxial growth, the orientation of the MgO is adopted by the HTS film including the tilt. Therefore, the c-axis of the HTS film is tilted by approximately 30° with respect to the substrate normal. The tilt is always perpendicular to the tape direction (**see Fig. 2**). As the performance of HTS is related to the crystallographic orientation, the tilt leads to a distinct angular dependence of the magnetic field performance (see below).

[1] Hastelloy C-276 is a trademark of Haynes International
[2] EP0909340, US6265353, US6638598

On top of the HTS layer, a thin silver layer is deposited as electrical contact and chemical protection layer. The final basic layer structure is shown in **Fig. 3**. This type of wire is the **THEVA Pro-Line (TPL) 1000-series**. For example, it can be used directly for fault current limiter applications.

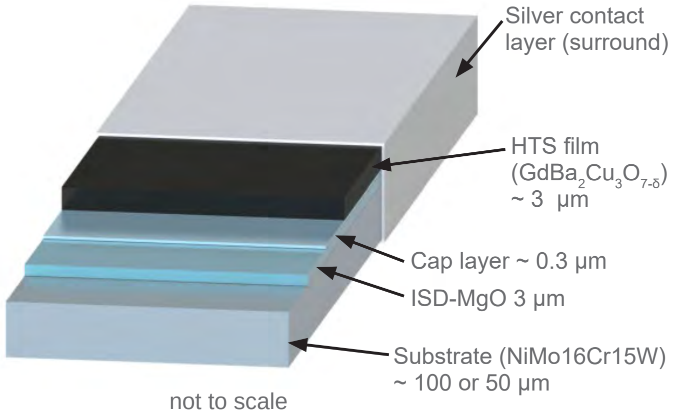

Fig. 3: Architecture of the TPL1000-series. Thicknesses of the layers are typical values only.

For applications that would need better electrical and mechanical stabilization, the TPL2000- and 4000-series are available.

In the case of the **TPL2000-series**, a copper foil, with a thickness of 50 µm or 100 µm, is laminated onto the silver coating on the HTS side (**see Fig. 4**). The thick copper foil ensures a high electrical stability of the wire as well as a robust mechanical protection.

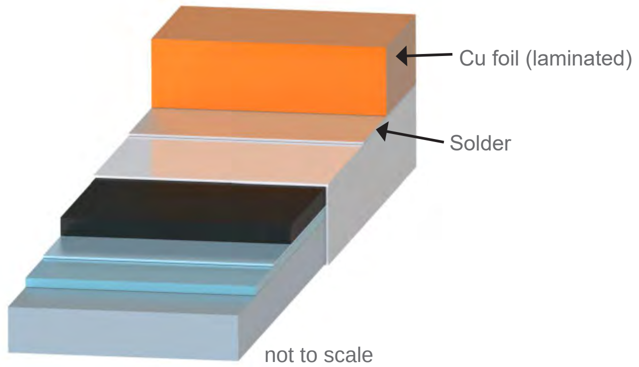

Fig. 4: Architecture of the TPL2000-series

For the **TPL4000-series**, a copper surround layer is deposited around the tape (**see Fig. 5**). Here the thickness of the copper layer is 10 to 20 µm. This type has high engineering current densities useful for e.g. high-performance magnets.

Our new **TPL5000-series** is based on our TPL4000-series. Additionally to the copper stabilization, we apply a thin solder coating as a finish (see **Fig. 6**). This prevents the copper from oxidizing and makes the wire ready-to-use.

Pro-Line HTS wires are available with a width of 12 mm and 4 mm. Information on other deliverable widths as well as different copper or silver thickness is available upon request.

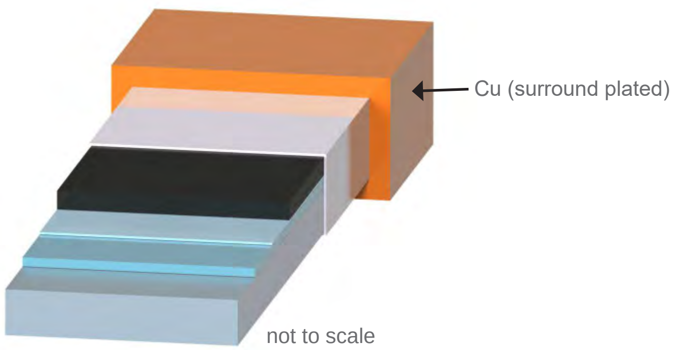

Fig. 5: Architecture of the TPL4000-series

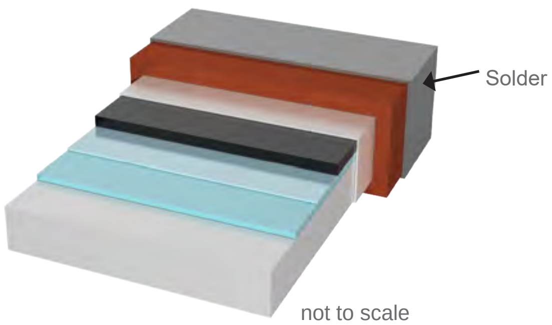

Fig. 6: Architecture of the TPL5000-series

Electrical Properties

In general, the maximum current depends on the temperature, external magnetic field and its angle of impingement. In **Fig. 6** the typical temperature dependence of the I_c-value with no external magnetic field is plotted.

The dependence of I_c on temperature, magnetic field, and its angle relative to the superconducting layer is usually expressed by the so-called lift factor which is the ratio of I_c under this condition (T, B and B-field orientation) and the I_c at 77 K and selffield (s.f.).

If an external magnetic field is applied to the HTS layer, best performance is achieved when the magnetic flux lines are aligned parallel to the REBCO ab-planes due to the so called intrinsic pinning effect. Deviations of the alignment cause a drop of the critical current I_c as shown in the graph of the lift factor as a function of the angle (maximum Lorenz force condition) in **Fig. 7**.

For THEVA Pro-Line wire the peaks are observed at ~120° (or 300°, 0° is defined as B perpendicular to the surface) due to the tilted growth of the superconductor as explained above. This means that B is parallel to the ab-planes of the superconductor (B // ab). The tilt direction of the crystallographic c-axis of THEVA Pro-Line tape is marked on the back side (see below).

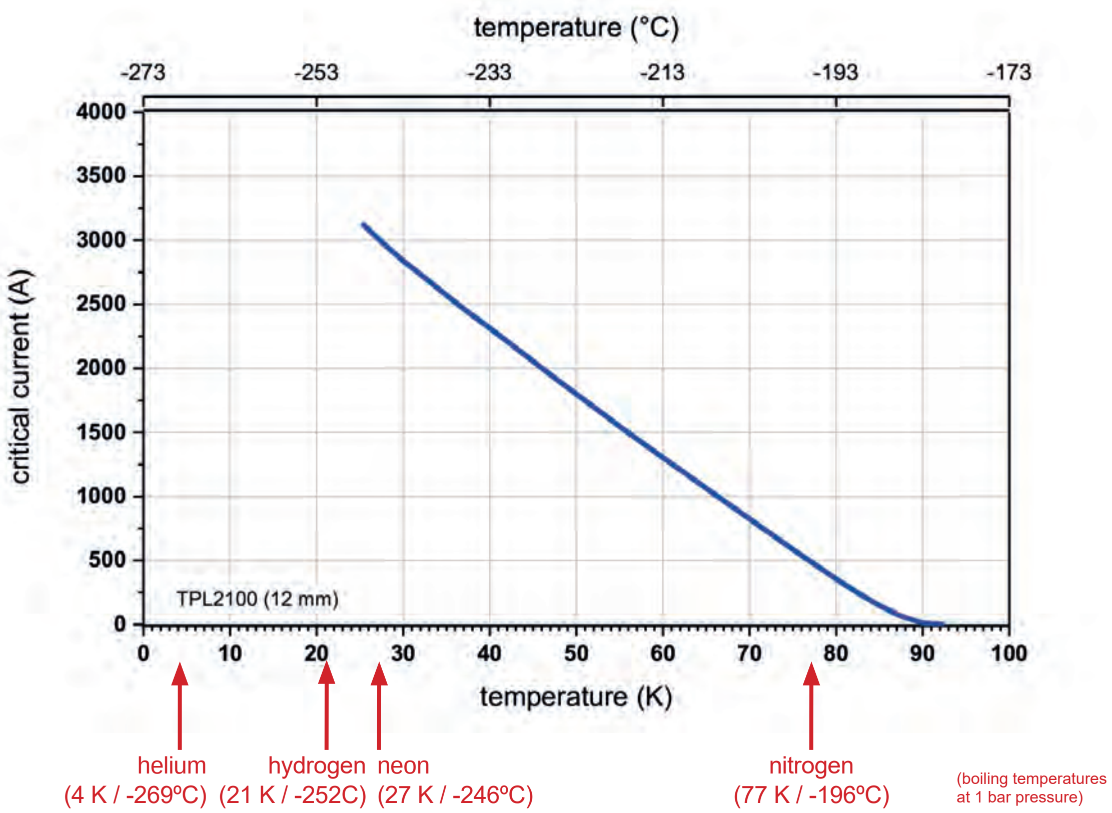

Fig. 6: Typical critical current I_c of a TPL2100 wire as a function of the temperature T. Boiling temperatures at 1 bar of various cooling agents are also marked.

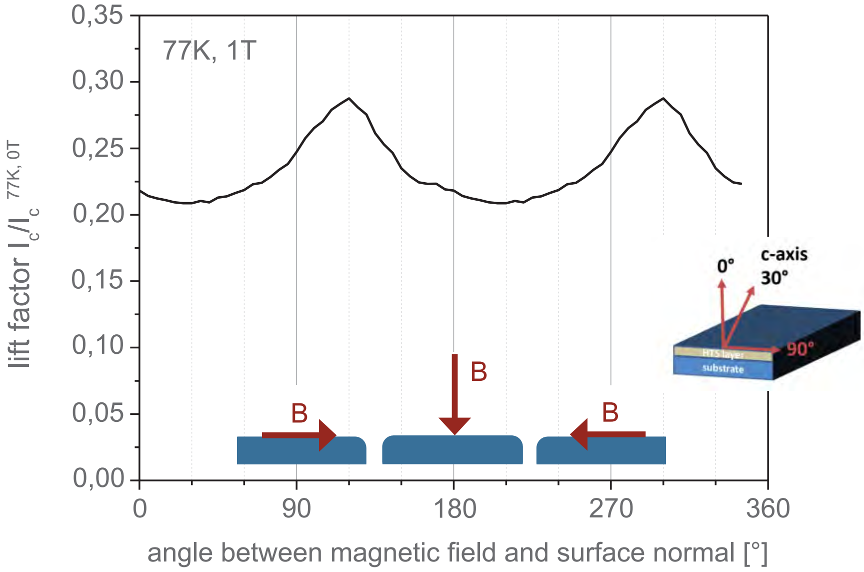

Fig. 7: Lift factor as a function of the direction of the magnetic field (77 K, 1 T)

A similar angular dependence is found at all temperatures and fields but the shape varies depending on the specific conditions as can be seen in **Fig. 8** for intermediate temperatures and 3 T.

For many applications the direction of the magnetic field is not constant. Therefore, it is useful to know the lift factor under worst case conditions, i.e. at the angle where the I_c is minimal.

This is the case at about 30° where the magnetic field is parallel to the c-axis of the superconductor. The lift factor under this condition is shown in **Fig. 9**.

Detailed data of the lift factor for THEVA Pro-Line wire for temperatures ranging from 77 K down to 4.2 K and for magnetic fields up to 8 T is available upon request.

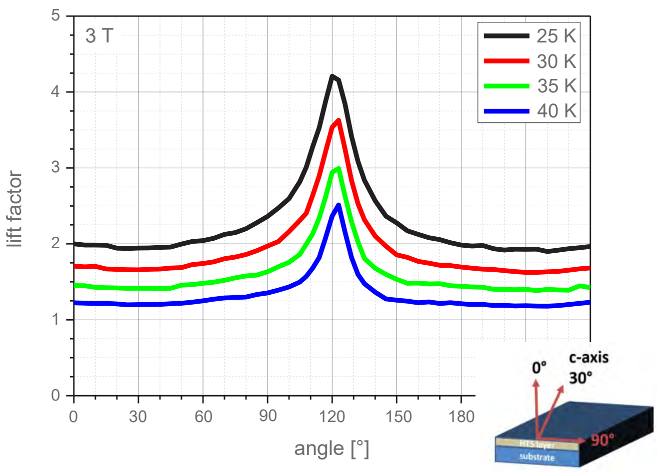

Fig. 8: Lift factor as a function of the direction of the magnetic field (25 – 40 K, 3 T)

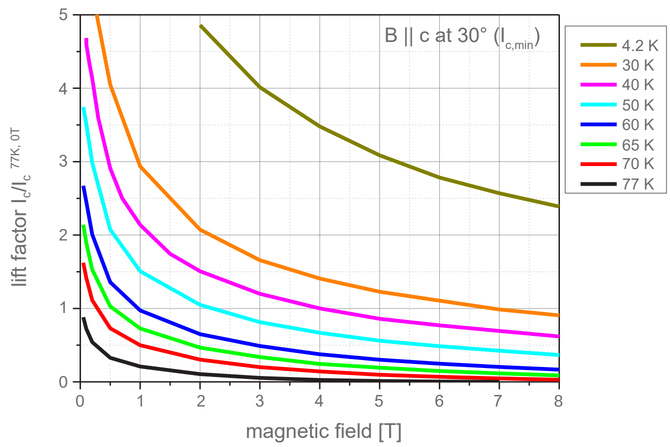

Fig. 9: Lift factor for B // c at various temperatures

Marking

All THEVA Pro-Line wires are marked on the substrate side (back side) as shown in **Fig. 10**. The marking consists of a symbol and a number. The number indicates the position in m which correlates directly and precisely to the available I_c measurement data whereas the symbol indicates the c-axis orientation.

As shown in **Fig. 11**, the triangle has to be taken as a projection to the HTS side (front side) of the tape. The tip (first tip) of the leg perpendicular to tape direction indicates the c-axis orientation of the HTS layer whereas the tip of the other leg (second tip) is pointing into the direction of the tape's end (increasing meter values printed on the tape's back side).

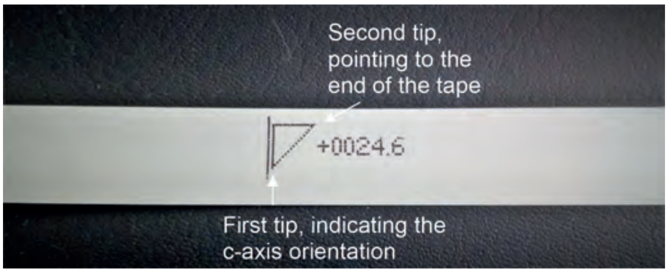

Fig. 10: Photograph of the substrate side (back side) of a TPL1100 tape. The length position (24.6 m) and the triangle (marking for the c-axis orientation) are visible.

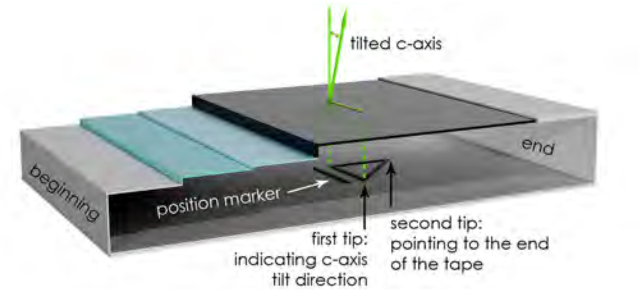

Fig. 11: Sketch of the triangle printed to the back side of a TPL tape and the corresponding c-axis tilt direction.

THEVA

THEVA Dünnschichttechnik GmbH
Rote-Kreuz-Straße 8 • 85737 Ismaning • Germany • info@theva.com • www.theva.com