Bi-2223 Tapes – Specific Performance for Different Applications

T. J. Arndt, A. Aubele, H. Krauth, M. Munz, B. Sailer, and A. Szulczyk

***Abstract*—In the past $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_x$ Ag/Ag-alloy-sheathed High-Temperature Superconductor (HTS) tapes (Bi-2223 tapes) have been proven being suitable for building quite different system components for a variety of applications.**

Nevertheless it revealed that applications like Power Transmission Lines, Transformers, Motors/ Generators, SMES, very high field magnets and MRI put very special requirements on the tapes which differ from application to application.

The most important point is that the tapes will provide cost-efficient performance for the special application. This means that it's not sufficient to analyze the price in $/kAm, but additionally it's necessary to consider e.g., AC-losses, geometry, mechanical strength and insulation properties and how they contribute to cost. We discuss a subset of the different requirements from the view of a tape supplier.

We depict the current status of the tape production (unit lengths > 1000 m, overall current densities ≥ 100 A/mm^2, steep E-I-characteristics (n-value ≥ 30 at standard conditions and even at low temperatures and/ or high magnetic fields), low AC-losses combined with remarkable critical currents of 50 A/mm^2, reliable properties of mechanics and insulation.

***Index Terms*—Bismuth compounds, current density, high-temperature superconductors, losses, superconducting tapes.**

I. Introduction

DURING the last years a lot of prototypes and demonstrators of systems in the field of power engineering have been realized using Bi-2223 tapes [1]–[3]. This demand for Bi-2223 tapes have pushed their performance further ahead.

But nevertheless it revealed that for the different applications the ranking in the importance of special properties may be different.

In the following we define the specific performance for some selected applications. Then the properties and some results are discussed and finally we sum up and give an outlook.

For details regarding the preparation of the tapes refer to [4], [5].

II. Specific Performance

In general the specific performance of the conductors has to be maximized – or in other words: the specific cost has to be minimized. As usually specific cost means $/kAm and we want to consider more properties than current in the following, we will use the "key parameter k" extending the usual specific cost meaning and being defined below.

In a first step we propose the following expressions for k, where c_0, c_1, c_2 are coefficients specific for the application, and $\Gamma_{||}$ and $\Gamma_{\perp}$ represent the AC-loss in parallel (magnetic field is varying parallel to the width of the tape) and in perpendicular (magnetic field is varying parallel to the thickness of the tape) configuration respectively.

- MRI-applications:

$$k = \frac{c_0}{j_e}$$

  A special AC-design of the tape may be required.
- SMES-applications:

$$k = \frac{c_0}{j_e}$$

  Long unit lengths and a special AC-design of the tape may be required.
- Motor/ Generator-applications:

$$k = \frac{c_0}{j_e} + \frac{c_1}{\sigma_c}$$

  An insulation suitable to stand the high forces due to rotation may be required.
- Transformer-applications:

$$k = \frac{c_0}{j_e} + \frac{\Gamma_{||}}{c_1} + \frac{\Gamma_{\perp}}{c_2}$$

  A thin insulation ($< 10\ \mu$m) may be required.
- Power Transmission Line-applications:

$$k = \frac{c_0}{j_e}$$

  The emphasis is on high currents divided by the tape width.

Generally a reduction of the key parameter k can be achieved by increasing the overall critical current density j_e and/ or the production cost.

Furthermore the mechanical properties (stress threshold σ_c for degradation of j_e) should be improved, the AC-loss should be decreased and the critical current I_c should be increased.

But especially when regarding a transformer it becomes evident that the task of minimizing k is a multi-parameter optimization.

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The authors are with the Vacuumschmelze GmbH & Co. KG, 63450 Hanau, Germany (e-mail: Thomas.Joachim.Arndt@vacuumschmelze.com).

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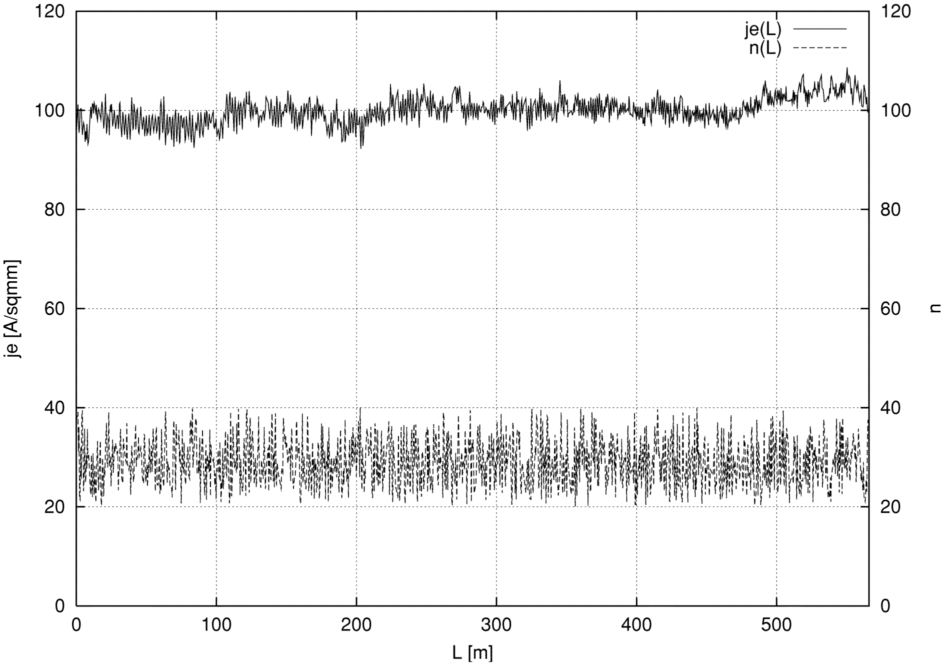

Fig. 1. Overall critical current density j_e and n-value (mean values 100 $\mathrm{A/mm^2}$ and 29 respectively) vs. length L.

III. Discussion of the Parameters Entering the Specific Performance

A. Overall Critical Current Density

The most often requested type of Bi-2223 tape has 121 filaments, a silver matrix, and a outer sheath of Ag-Mg-alloy. This design leads to a critical stress σ_c (degradation of critical current $\geq 5\%$) of 100 MPa and multi-parameter process optimization strongly related to the precursor properties yields an overall critical current density $j_e = 100\ \mathrm{A/mm^2}$ as shown in Fig. 1 on a tape out of standard production and measured in a quasicontinuous way using a four-point method with voltage taps separated by (0.15–1.0)m (here fixed to 0.4 m). The n-values are determined by a linear fit in a double logartithmic plot of electric field vs. current in the range of 0.1 $\mu\mathrm{V/cm}$ to 1 $\mu\mathrm{V/cm}$.

B. AC-Loss

Optimization of the twisting process (twist pitch L_p) itself and its inclusion in the whole preparation process was necessary to reach minimum values of $\Gamma_{||}$ and $\Gamma_\perp$ of $\approx$ 0.25 mW/Am and $\approx$ 8.1 mW/Am (Amplitude 0.1 T, 50 Hz) [6].

As in most applications there are segments of the windings which differ quite a lot in direction and magnitude of magnetic field (e.g., compare the endings of the windings with the center parts), a preparation and analysis of different designs of tapes for AC-applications was motivated and performed. The dependence of $\Gamma_{||}$ on the width b and the thickness d based on the measurements is shown in Fig. 2.

As expected [6] the effect of d on $\Gamma_{||}$ dominates the effect of b. But furthermore from the contour-lines it can be seen that the b, d-window for lowest $\Gamma_{||}$ is quite narrow.

The dependence of $\Gamma_\perp$ on width b and thickness d based on the measurements is shown in Fig. 3.

As expected [6] the effect of b on $\Gamma_\perp$ dominates the effect of d.

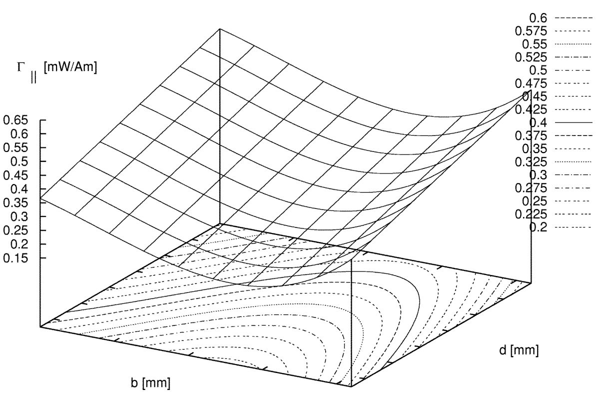

Fig. 2. Dependence of $\Gamma_{||}$ on width b and thickness d of the Bi-2223 tapes ($L_p = 10$ mm).

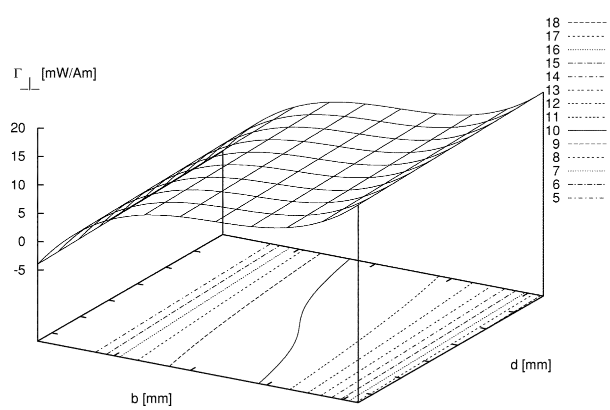

Fig. 3. Dependence of $\Gamma_\perp$ on width b and thickness d of the Bi-2223 tapes ($L_p = 10$ mm).

The snake-like contour line for 10 mW/Am, the slight d-effect on $\Gamma_{||}$ and the s-shaped b-effect are related to the hidden dependence of critical current I_c on b and d respectively (hidden in this cutting plane representation of Fig. 3).

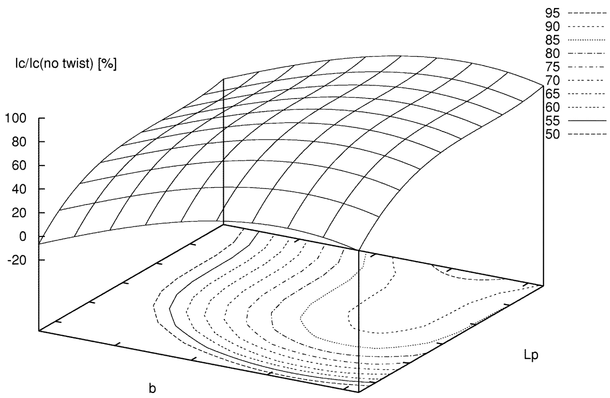

Fig. 4. Percentage of maximum I_c depending on width b and twistpitch L_p.

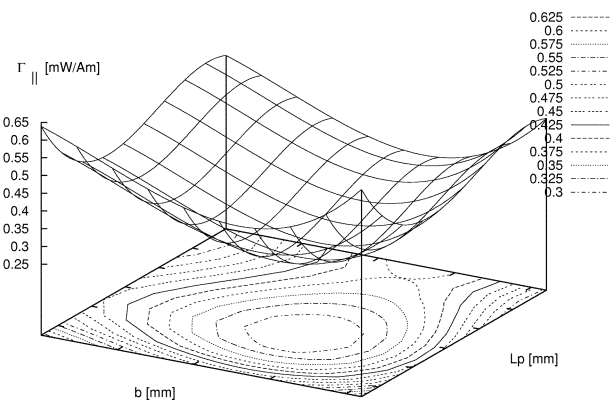

Fig. 5. Dependence of $\Gamma_{||}$ on width b and twistpitch L_p of the Bi-2223 tapes.

This hidden dependence is also present when considering the dependence of $\Gamma_{||}$ and $\Gamma_{\perp}$ on L_p.

Fig. 4 shows which percentage of maximum I_c is achievable for a combination of width b and twistpitch L_p.

Especially for large widths there is a strong dependence of critical current on L_p which results from the larger enlongation of the noncenter filaments within the tape during the twisting process. In this region increasing L_p may decrease $\Gamma_{\perp}$ via the $I_c(L_p)$-dependence.

Considering the cutting plane spanned by width b and twistpitch L_p in this multi-dimensional space it reveals that the window for preparing low loss AC-tapes is very narrow as is shown in Fig. 5 for $\Gamma_{||}$.

For $\Gamma_{\perp}$ the window for lowest losses in the b-L_p-plane changes its form from the lense-shaped in Fig. 4 to a more complicated shape.

C. Insulation

The insulation is not entering the specific perfomance as a continuous parameter (except when decreasing the current density in the winding due to the width of the insulation) but has to fit the boundary conditions of the application. Together with our partners we succeded to prepare insulated Bi-2223 tapes of more than 1000 m, a width $b = 4.095$ mm (standard deviation $< 0.6\%$), $d = 0.267$ mm (standard deviation $< 1.2\%$), a DC breakdown voltage > 4 kV and suitable for all operating temperatures for HTS.

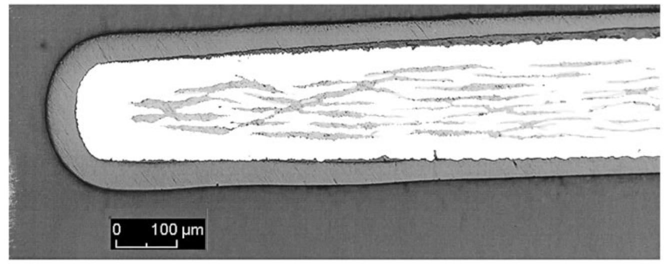

Fig. 6. Cross sectional view of an insulated Bi-2223 tape (only partly displayed to show the coverage on the edge).

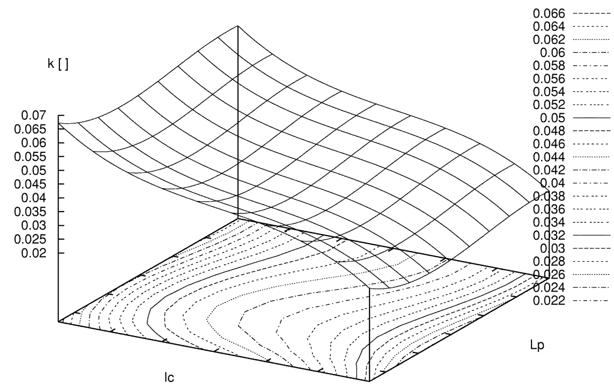

Fig. 7. Dependence of key parameter k on critical current I_c and twistpitch L_p.

Fig. 6 shows the homogenous coverage of the tape around the circumference even at the edges.

IV. Discussion of the Specific Performance/ The Key Parameter

A. Specific Performance/ Key Parameter

For this section we have chosen the functional form of the key parameter k as already shown for the transformer. Of course this is only *one* example and the coefficients and parameters can be adjusted to represent different applications.

Fig. 7 shows that -for the given functional form of k and fixed $d = 0.2$ mm, $b = 3.0$ mm which might be chosen according to Fig. 2 to get quite low losses in $\Gamma_{||} - I_c$ strongly effects k, but that L_p still determines the absolute minimas for all I_c -values.

This analysis has to be performed for each segment in the application (e.g., transformer) and gives the possibility to get out maximum performance for the specific application at minimum cost.

B. Recipe to Design the Applications Best Choice Type of Tape

Following the example of the functional form of k as proposed for a transformer, first one has to select a $\Gamma_{||}(b, d)$-combination out of Fig. 2, as $\Gamma_{||}$ can be controlled quite nicely. Then—using Fig. 4–this combination has to be fitted with a value of L_p. Afterwards Fig. 5 will give the available I_c-percentage. This process has to be repeated with slightly modified parameters and finally Fig. 7 can be used for the fine-tuning.

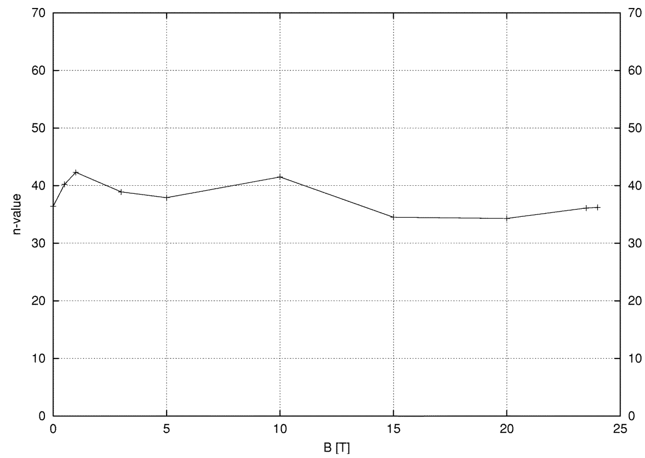

Fig. 8. Dependence of n-value on magnetic field at a temperature of 4 K.

V. PROPERTIES AT LOW TEMPERATURES AND HIGH MAGNETIC FIELDS

A. Tape Properties

Bi-2223 tapes have outstanding properties at low temperatures and high magnetic fields. We performed some measurements of the electric field vs. current characteristic of Bi-2223 tapes of a separation of the voltage taps > 1 m and being prepared in a helical form on a mandrel of Ø30 mm and the Lorentz-force directed outwards.

Fig. 8 shows the results concerning the dependence of the n-value at a temperature of 4 K (determined in the electric field regime (10^{-7}–10^{-6}) μV/cm. Such high values may open the way to persistent-mode applications at temperatures of 4 K.

The corresponding critical current density in a magnetic field of 23.5 T is more than 200 $\mathrm{A/mm^2}$.

VI. SUMMARY

We have proposed a concept of a specific performance/ key-parameter special to the different applications for HTS tapes.

We used this concept to analyze the results of a series of experiments concerning the AC-properties of Bi-2223 tapes of different designs (e.g., width b, thickness d, twistpitch L_p). The experimental results with respect to the geometry-effect on losses are in agreement with theoretical predictions [6]. The analysis allows to tailor Bi-2223 tapes for the needs of special applications and may consider cost, too.

We presented latest results on properties of Bi-2223 tapes out of the production line and showed a reliability insulation for the whole temperature regime of HTS-application.

The actual unit lengths of more than 1000 m and their properties (n-values) open the possibility to develop magnets for persistent mode operation.

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