Progress in Reducing AC Losses of Bi2223 Tapes with Interfilamentary Resistive Barriers

Ryoji Inada, Yasuhiro Okumura, Akio Oota, Chengshan Li, and Pingxiang Zhang

***Abstract*—This paper presents our recent progress for the development of low-AC loss Bi2223 tapes with interfilamentary oxide barriers. For the compatibility with Bi2223 phase formation during sintering, $SrZrO_3$ was selected as barrier materials. Moreover, small amount of Bi2212 was mixed with $SrZrO_3$ to improve its ductility for cold working. Although some breakages of barrier layers still existed, the effective transverse resistivity was approximately 10 times higher than a tape with pure Ag matrix. By controlling barrier thickness, reducing a tape width below 3 mm and twisting the filaments with its length below 5 mm, coupling frequency f_c attained to 260 Hz in an AC perpendicular transverse field. Critical current densities J_c of our twisted barrier tapes were ranged in 12–15 kA/cm^2 at 77 K and self-field, which was 25–30 % lower than non-twisted one (= 18 kA/cm^2). In our knowledge, this is the first report to achieve both J_c > 12 kA/cm^2 and f_c > 250 Hz simultaneously in a single Bi2223 tapes. Our barrier tapes showed 60-70% lower perpendicular field losses than a conventional 4 mm-width tape with fully coupled filaments at 50 mT and 50 Hz. These results are promising for remarkable improvement in AC performance for Bi2223 tapes in future.**

***Index Terms*—Bi2223 tapes, interfilamentary barriers, AC loss, filament twisting, coupling frequency**

I. Introduction

At present, the Ag-sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi2223) tapes with high critical current density (J_c) of 40-50 kA/cm^2 and long length above 1 km are commercially available [1]. However, their AC losses are still too large for realization of AC power devices such as transformers, motors and cables. The large loss generation in the tape subjected to an AC transverse magnetic field in perpendicular to long axis of the tape is attributed to the electromagnetic coupling between the filaments via the Ag matrix, which has a low electric resistivity (= 0.27×10^{-8} Ωm) at 77 K. Particularly, due to the large aspect ratio of Bi2223 tape, both the hysteresis loss (Q_h) in superconductor and the coupling loss (Q_c) in matrix in a perpendicular transverse field (in perpendicular to both long axis and broader face of the tape) becomes much larger than in a parallel one (in perpendicular to long axis but parallel to broader face of the tape), and the conditions for filament decoupling become more restrictive [2–4]. In order to reduce the filament coupling in an AC perpendicular transverse field, it is necessary – in addition to twisting the filaments with a suitable pitch length – to increase the matrix resistivity by introducing oxide layers among the filaments as resistive barriers [5−11].

Coupling frequency f_c, which is related with coupling time constant τ_c as the expression of $f_c = 1/2\pi\tau_c$, is one of the important parameters to determine the AC operating condition for filament decoupling. To achieve a significant loss reduction by decoupling the filaments, f_c should at least be higher than operating frequency f_{op}. In the previous works for the development of Bi2223 tapes with oxide barriers, f_c under a perpendicular transverse field was increased above 100 Hz by introducing $BaZrO_3$ or $SrZrO_3$ barriers combined with filament twisting [6, 7]. The higher f_c of 400−500 Hz was also achieved in twisted tapes with $SrZrO_3$ with small amount of $SrCO_3$ [8−10] or Bi2212 [11] as interfilamentary barriers. However, J_c of those barrier tapes with f_c > 100 Hz were limited to only 4-6 kA/cm^2 at 77 K and self-field.

The simultaneous achievement of J_c well above 10^4 A/cm^2 and f_c higher than several 100 Hz has crucial importance for widening the applicability of Bi2223 tapes for AC power devices. Generally, thicker barrier is preferable to maintain its continuity and increase matrix resistivity in a fully reacted tape [5]. However, it may cause not only the reduction of the oxygen diffusion paths for Bi2223 filaments but also the serious degradation of flatness for Bi2223 filaments embedded in a matrix due to the degradation for composite workability [11]. They should lead to serious J_c drops as mentioned above. Therefore, precise control in barrier thickness, tape geometries and deforming parameters during twisting and rolling process should be indispensable to obtain both high J_c and f_c.

In this paper, we report simultaneous achievement of J_c > 12 kA/cm^2 in self-field and f_c > 250 Hz in perpendicular field at 77 K for a Bi2223 tape, by controlling coating thickness of barriers before stacking and geometrical parameters such as tape widths and twist pitch lengths. Comparing the data for tapes with fully coupled filaments, loss reduction at power-grid frequency in a perpendicular transverse field was investigated at 77 K.

II. Experimental

Bi2223 tapes with oxide barriers among the twisted filaments were prepared by a conventional powder-in-tube (PIT) method. $SrZrO_3$ with a mean grain size below 1 μm was used as barrier materials for its compatibility with Bi2223

Manuscript received 3 August 2010. This work was supported in part by Grant-in-Aids for Scientific Research from MEXT (No.20686020) and JSPS (No.22560270) of Japan. It was also supported in part from TEPCO Research Foundation, Research Foundation for the Electrotechnology of Chubu (No.R-20302) and DAIKO Foundation.

R. Inada, Y. Okumura, and A. Oota are with Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 4418580 Japan (e-mail: inada@ee.tut.ac.jp).

C.S. Li and P.X. Zhang are with Northwest Institute for Nonferrous Metal Research, P.O. Box 51, Xi'an Shaanxi 710016 P.R. China.

superconductor. Moreover, an additional Bi2212 powder corresponding to 20wt% was mixed with $SrZrO_3$ to improve its ductility for cold working [11]. The precursor powders with a composition of $Bi_{1.76}Pb_{0.34}Sr_{1.93}Ca_{2.02}Cu_{3.1}O_x$ were packed into a pure Ag tube with an outer diameter of 9.6 mm and a wall thickness of 0.8 mm. Then, the composite was deformed into a hexagonal cross-sectional shape by drawing, with its diagonal length of 1.8 mm. The outside surface of the monocore wire was coated by $SrZrO_3$ + Bi2212 pastes. To obtain the sufficient workability of the composite, coating thickness of the pastes was reduced to 50–60 μm, which is approximately one half the value in our previous work [11]. After a heat treatment at 550°C in air to eliminate the organic binder in the pastes, 19-pieces of coated monocore wire were stacked and packed into an Ag-Mg alloy tube with an outer diameter of 15.6 mm and wall thickness of 0.8 mm. The composites were drawn to the diameter of 1.33 mm and then twisted very carefully with intermediate heat treatments at 400°C in vacuum. Finally, the twisted round wires were formed into tape shapes by flat rolling, and sintered at 830–840°C with an intermediate rolling. In fully reacted tapes, cross sectional sizes are 2.7 mm × 0.23 mm and volume fractions of filaments are 23%, respectively. Twist pitch lengths L_t were measured after removing the sheath parts from final tapes by etching and ranged from 4 to 7 mm. For comparison, non-twisted tape without barriers was also fabricated by the same fabrication process.

The critical current I_c was measured in all tapes with DC four-probe method at 77 K in a self-field, with an electric field criterion of 1 μV/cm. The critical current density J_c was determined from I_c and transverse cross-sectional area of the filaments. The AC losses Q_m at 77 K in a perpendicular transverse field were measured by a saddle shaped pick-up coil and a conventional lock-in technique [12]. For the loss measurements, the lengths of tapes were fixed to 80 mm.

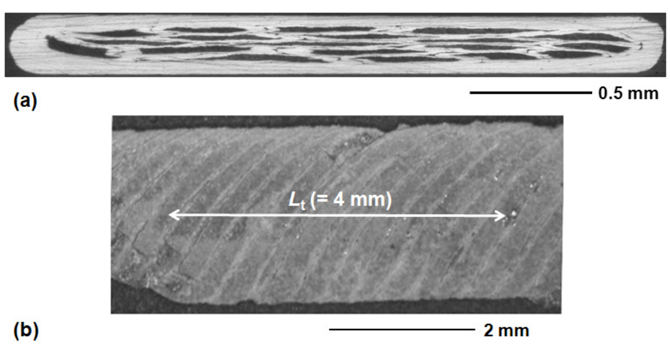

Fig. 1. (a) Transverse cross section and (b) plan view (after removing sheath part by etching) for twisted barrier tape. The size of tape section and twist pitch length are 2.7 mm × 0.24 mm and 4 mm, respectively.

III. Results and Discussion

Fig. 1 shows the transverse cross sectional view and the plan view (after removing sheath part) of twisted barrier tape with L_t = 4 mm. In our previous study [11], it was confirmed that in barrier tapes with L_t < 10 mm, the filaments positioned at an inner part of a tape section were distorted irregularly and physically connected each other through the broken parts of barrier layers. On the other hand, the filament shape in newly prepared barrier tape with tightly twisted filaments (L_t = 4 mm) seems to be flat. Each filament was partitioned by barrier layers and interfilamentary connections were not observed. Such fine structure would be attributed to improvements for workability of a composite by reducing coating thickness of barrier oxide and applying careful twisting. Transport critical current density J_c at 77 K and self-field for twisted tape with $SrZrO_3$ + Bi2212 barrier are shown in Fig. 2, as a function of inverse of twist pitch lengths L_t. For comparison, our previous data for barrier tapes are also plotted [11]. As can be seen, J_c of both non-twisted and twisted barrier tapes with different L_t were improved remarkably compared with previous data. For twisted barrier tapes with L_t < 7 mm, their J_c values were ranged in 12–15 kA/cm^2 at 77 K and self-field, which was 25–30% lower than non-twisted one (= 18 kA/cm^2). We consider that avoidance of irregularly distorted filaments strongly contributes to J_c improvement in twisted barrier tapes.

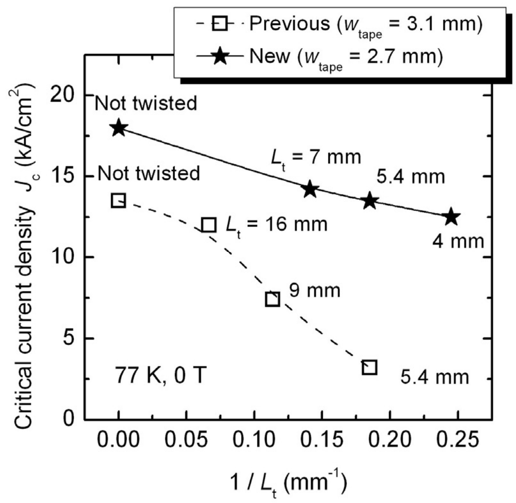

Fig. 2. Critical current densities J_c at 77 K and self-field for barrier tapes plotted against the inverse of twist pitch lengths L_t. Our previous data for barrier tapes are also shown for comparison [11].

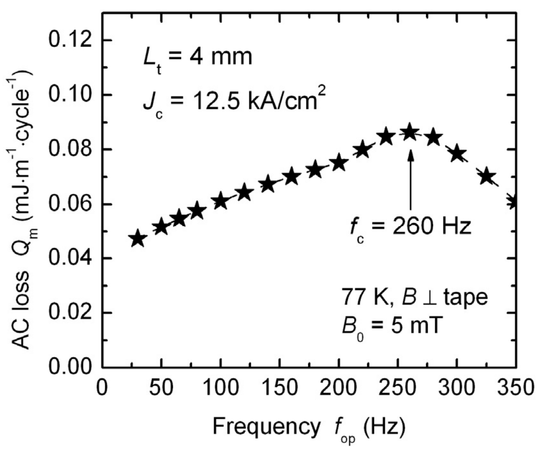

Fig. 3. Frequency dependence of AC losses Q_m per-cycle at 77 K and B_0 = 5 mT for twisted barrier tape with L_t = 4 mm under an AC perpendicular field.

For the tape with the shortest L_t = 4 mm, AC loss properties at 77 K in a perpendicular transverse field were examined. Fig. 3 shows the frequency dependence of losses Q_m per-cycle at 77 K and fixed field amplitude B_0 = 5 mT. As can be seen, Q_m data show the maximum around operating frequency f_{op} = 260 Hz. This specific frequency corresponds to coupling frequency f_c at which coupling loss Q_c per-cycle included in total Q_m show the maximum. Although the achievement for higher f_c of 400–500 Hz in barrier tapes was already reported [8–11], transport J_c of these barrier tapes with such high f_c were limited to several kA/cm^2. It should be noted that this is the first achievement for both J_c > 12 kA/cm^2 and f_c > 250 Hz simultaneously in a single Bi2223 tape. To estimate the effective transverse resistivity $\rho_{t\perp}$ of our barrier tape, we also measured f_c for twisted tape with resistive Ag-8%Au alloy matrix and the same geometrical parameters as the barrier tape. It was found that Ag-8%Au sheath with resistivity 7–8 times higher than pure Ag at 77 K give f_c = 160 Hz. From the extrapolation using the relation of $f_c \propto \rho_{t\perp}/L_t^2$, $\rho_{t\perp}$ of our barrier tape is suggested to be 10–12 times higher than a pure Ag-sheathed tape without barriers.

Perpendicular field amplitude dependence of losses at 77 K and 45 Hz are shown in Fig. 4. The data for non-twisted tapes with their tape widths (w_{tape}) of 4 mm and 2.7 mm are also plotted as the references. These two reference tapes have no barrier layers and all filaments are electromagnetically coupled among them and behave as a single superconductor under a perpendicular field at 45 Hz. In addition, the loss values for each tape are normalized by its critical current I_c at 77 K and self-field for direct comparison among the tapes. As can be seen, the losses for twisted barrier tapes with L_t = 4 mm are reduced by 45–60%, compared with the reference tape with w_{tape} = 2.7 mm at B_0 from 10 to 50 mT. Such remarkable loss reduction around power-grid frequency is attributed to achievement for both f_c > 250 Hz and $J_c > 10^4$ A/cm^2. In addition, the losses for the twisted barrier tapes are 60–70% lower than those for the reference tape with wider w_{tape} = 4 mm.

To examine the loss generation mechanism of our barrier tape, Fig. 5 shows normalized loss factors $\Gamma = \mu_0 Q_m / 2B_0^2 S_{tape}$ (S_{tape}: cross sectional area of the tape) for the barrier tape with L_t = 4 mm at different fixed frequencies f_{op} from 30 to 105 Hz, as a function of applied field amplitude B_0. For comparison, the Γ curve derived from the analytical prediction of hysteresis loss Q_h for fully coupled filaments using an elliptical model approximation is also plotted [13]. Here, B_0 at which Γ shows a maximum is defined as a parameter B_{max}. B_{max} nearly corresponds to the full penetration field B_p for the tape and changes depending on the conditions for filament coupling under AC fields. As can be seen, B_{max} for our barrier tape at different f_{op} are nearly the constant (~ 1.5 mT) and lower than the calculation assuming the filaments are coupled (~ 7 mT). This indicates that all filaments in the tape are decoupled and hysteresis loss component Q_h is reduced by the level for decoupled filaments below 105 Hz. At B_0 > 1.5 mT, there are greater losses for the higher f_{op} while calculated Γ for coupled filaments is higher than measured ones at different f_{op}. We preliminarily confirmed that eddy current losses Q_e for a pure Ag tape with the same size as our barrier tape are much smaller than Q_m for our barrier tape at f_{op} < 100 Hz. Therefore, it is considered that the contribution of Q_e in sheath of barrier tape is negligible and the increase of Γ with frequency in Fig. 5 is mainly caused by the contribution of coupling loss Q_c.

By using an effective medium approximations for the composite [14], frequency dependence of Q_c per-cycle at fixed B_0 are approximately described as

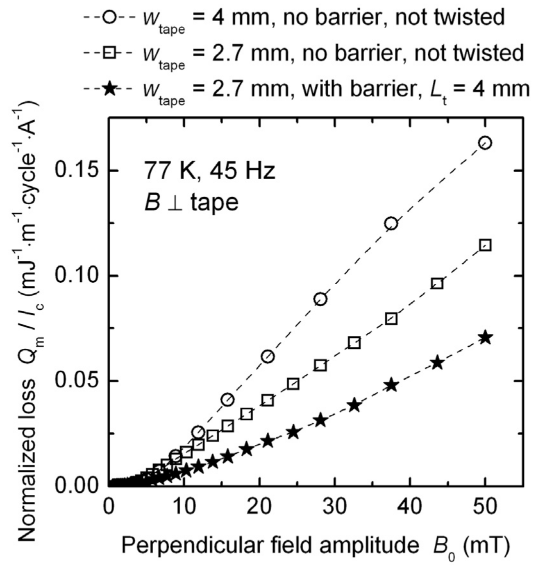

Fig. 4. Perpendicular field amplitude dependence of normalized AC losses Q_m/I_c at 77 K and 45 Hz for twisted barrier tape with L_t = 4 mm. The data for non-twisted tapes with tape width of 4 mm and 2.7 mm are also plotted as the references. These two reference tapes don't have barrier layers and the filaments in them are fully coupled at 45 Hz.

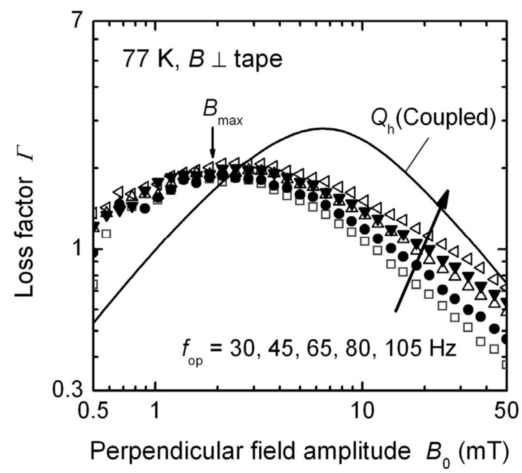

Fig. 5. Loss factor $\Gamma = \mu_0 Q_m / 2B_0^2 S_{tape}$ for twisted barrier tape with L_t = 4 mm at 77 K and various fixed frequency f_{op}, plotted against perpendicular field amplitude B_0. The analytical prediction of Γ for hysteresis loss Q_h for fully coupled filaments is also shown.

$$Q_c \propto \frac{\omega\tau_c}{1+(\omega\tau_c)^2} \tag{1}$$

Here, ω is equal to $2\pi f_{op}$ and $\tau_c = 1/2\pi f_c$ is the coupling time constant. For more precise evaluation, one should expect a skin-effect type behavior at higher frequencies, i.e., Q_c per cycle is inversely proportional to the square root of the frequency $f_{op} > f_c$, which is expressed as follows [15, 16]:

$$Q_c \propto \frac{1}{\pi\sqrt{\omega\tau_c/2}} \frac{\sinh\left(\pi\sqrt{\omega\tau_c/2}\right)-\sin\left(\pi\sqrt{\omega\tau_c/2}\right)}{\cosh\left(\pi\sqrt{\omega\tau_c/2}\right)+\cos\left(\pi\sqrt{\omega\tau_c/2}\right)} \tag{2}$$

Here, we used the latter expression to describe the frequency dependence of Q_c for our barrier tape. On the other hand, as mentioned above, Q_h for our barrier tape at fixed B_0 is nearly independent of f_{op} < 110 Hz. Therefore, total loss Q_m for our barrier tape is expressed as the sum of Q_h and Q_c:

$$Q_m = Q_h + \frac{q_c}{\pi\sqrt{f_{op}/2f_c}} \frac{\sinh\left(\pi\sqrt{f_{op}/2f_c}\right)-\sin\left(\pi\sqrt{f_{op}/2f_c}\right)}{\cosh\left(\pi\sqrt{f_{op}/2f_c}\right)+\cos\left(\pi\sqrt{f_{op}/2f_c}\right)} \tag{3}$$

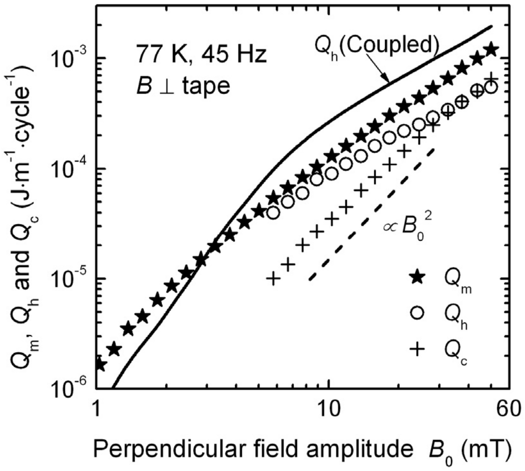

Fig. 6. Comparison of hysteresis loss Q_h, coupling loss Q_c and total loss Q_m at 77 K and 45 Hz for twisted barrier tape with L_t = 4 mm, as a function of perpendicular field amplitude B_0. An analytical prediction of Q_h of an elliptical model for fully coupled filaments is also shown.

where q_c is the constant related to the magnitude of Q_c at fixed B_0. From the data shown in Fig. 3, f_c of our barrier tape was confirmed to be 260 Hz, so that τ_c of the tape was estimated to be 0.6 ms. By fitting Eq. (3) into measured frequency dependence of total Q_m below 110 Hz, both Q_h and q_c in barrier tape can be roughly estimated. Using q_c obtained from fitting and f_{op}, Q_c per-cycle is calculated by the second term in Eq. (3).

Fig. 6 shows the comparison of Q_h and Q_c at 45 Hz for twisted barrier tape, obtained by fitting by Eq. (3) into measurement. For comparison, total Q_m measured at 45 Hz and analytical Q_h curve for fully coupled filaments are shown [13]. As can be seen, Q_h shows linear dependence on B_0 and approximately 70–80% lower than fully coupled level at B_0 > 10 mT. On the other hand, Q_c is nearly proportionate to B_0^2, which is expected from analytical prediction [14–16]. At B_0 > 30 mT, it is evident that the magnitude of Q_c at 45 Hz is nearly the same as Q_h. Consequently, total Q_m at B_0 > 30 mT are two times higher than Q_h for decoupled filaments. This suggests that around power-grid frequency, the loss reduction of our twisted barrier tape is still limited by significant Q_c contribution. To achieve more remarkable loss reduction and also to maintain the effect in higher B_0 range (~0.1 T), both increasing coupling frequency f_c to reduce the absolute Q_c values and improving J_c to reduce the fraction of Q_c in total Q_m should be necessary. The optimization of fabrication process and tape structure (tape width, barrier thickness and twist pitch length) is currently being studied, to improve the electromagnetic performance (both f_c and J_c) for twisted barrier tapes.

IV. Conclusion

Our recent activities for the development of low-AC loss Bi2223 tapes with interfilamentary $SrZrO_3$ + Bi2212 as resistive barriers were presented. By controlling coating thickness of barriers before stacking, reducing a tape width (< 3 mm) and careful filament twisting, distorted filaments and their physical connections were greatly reduced in fully reacted barrier tapes with tightly twisted filaments. For the tape with twist pitch length L_t = 4 mm, coupling frequency f_c exceeded 250 Hz in an AC perpendicular field. Critical current densities J_c of tightly twisted barrier tapes with twist pitches L_t = 4–7 mm were ranged in 12–15 kA/cm^2 at 77 K and self-field. In our knowledge, this is the first achievement for both J_c > 12 kA/cm^2 and f_c > 250 Hz simultaneously in a single Bi2223 tape. The barrier tape with L_t = 4 mm also showed 60–70% lower perpendicular field losses than a conventional 4 mm-width tape with fully coupled filaments at 10–50 mT and 50 Hz. These achievements are promising for remarkable improvement for AC performance of Bi2223 tapes in near future.

References

[1] N. Ayai, S. Kobayashi, M. Kikuchi, T. Ishida, J. Fujikami, K. Yamazaki, S. Yamade, K. Tatamidani, K. Hayashi, K. Sato, H. Kitaguchi, H. Kumakura, K. Osamura, J. Shimoyama, H. Kamijyo, and Y. Fukumoto, "Progress in performance of DI-BSCCO family," *Physica C* 468, pp. 1747-1752, 2008.

[2] H.G. Knoopers, J.J. Rabbers, B. ten Haken, and H.H.J. ten Kate, "Magnetization loss in twisted multifilament Bi-2223 tape conductors," *Physica C* 372-376, pp. 1784-1787, 2002.

[3] K. Funaki, Y. Sasashige, H. Yanagida, S. Yamasaki, M. Iwakuma, N. Ayai, T. Ishida, Y. Fukumoto, and Y. Kamijo, "Development of low-AC-loss Bi-2223 superconducting multifilamentary wire," *IEEE Trans. Appl. Supercond.* 19, pp. 3053-3056, 2009.

[4] E. Martínez、Y. Yang, C. Beduz, and Y.B. Huang, "Experimental study of loss mechanisms of AgAu/PbBi-2223 tapes with twisted filaments under perpendicular AC magnetic fields at power frequencies," *Physica C* 331, pp. 216-226, 2000.

[5] K. Kwasnitza, St. Clerk, R. Flükiger, and Y.B. Huang, "Alternating magnetic field losses in high-T_c superconducting multifilament tapes with a mixed matrix of Ag and $BaZrO_3$," *Physica C* 299, pp. 113-124, 1998.

[6] M. Dhallé, A. Polcari, F. Marti, G. Witz, Y. B. Huang, R. Flükiger, St. Clerc, and K. Kwasnitza, "Reduced filament coupling in Bi(2223)/$BaZrO_3$/Ag composite tapes," *Physica C* 310, pp. 127-131, 1998.

[7] K. Kwasnitza, S. Clerk, R. Flükiger, and Y. Huang, "Reduction of alternating magnetic field losses in high-Tc multifilament Bi(2223)/Ag tapes by high resistive barriers," *Cryogenics* 39, pp. 829-841, 1999.

[8] H. Eckelmann, J. Krelaus, R. Nast, and W. Goldacker, "AC losses in perpendicular external magnetic fields in ring bundle barrier multifilamentary BSCCO(2223) tapes with a central resistive barrier," *Physica C* 355, pp. 278-292, 2001.

[9] H. Eckelmann, R. Nast, C. Schmidt, and W. Goldacker, "Coupling current losses and time constants in multifilamentary BSCCO(2223) tapes with resistive barriers in external magnetic fields," IEEE Trans. Appl. Supercond. 11, pp. 2955-2958, 2001

[10] R. Nast, H. Eckelmann, O. Zabara, S.I. Schlachter, and W. Goldacker, "Reduction of coupling current losses by internal resistive barrier structures in multifilamentary Bi(2223) tapes in external magnetic fields," *Physica C* 372-376, pp. 1777-1780, 2002.

[11] R. Inada, Y. Nakamura, A. Oota, C.S. Li, and P.X. Zhang, "Fabrication and characterization of Bi2223 tapes with interfilamentary $SrZrO_3$ + Bi2212 barriers for AC loss reduction," *Supercond. Sci. Technol.* 20, 085014, 2009.

[12] R. Inada, K. Tateyama, Y. Nakamura, A. Oota, C.S. Li, and P.X. Zhang, "Total AC loss of Ag-sheathed Bi2223 tapes with various filament arrangements carrying AC transport current in AC parallel transverse magnetic field," *Supercond. Sci. Technol.* 20, pp. 138-146, 2007.

[13] B. ten Haken, J.J. Rabbers, and H.H.J. ten Kate, "Magnetization and AC loss in a superconductor with an elliptical cross section and arbitrary aspect ratio," *Physica C* 377, pp. 156-164, 2002.

[14] A.M. Campbell, "A general treatment of losses in multifilamentary superconductor," *Cryogenics* 22, pp. 3-16, 1982.

[15] S. Takács, H. Kaneko, and J. Yamamoto, "Time constants of normal metals and superconductors at different ramp rates during a cycle," *Cryogenics* 34, pp. 679-684, 1994.

[16] K. Kwasnitza and St. Clerk, "AC losses of superconducting high-T_c multifilament Bi-2223/Ag sheathd tapes in perpendicular magnetic fields," *Physica C* 233, pp. 423-435, 1994.