Superconductor Science and Technology

A new finite-element method simulation model for computing AC loss in roll assisted biaxially textured substrate YBCO tapes

Supercond. Sci. Technol. **23** (2010) 025001 (5pp) doi:10.1088/0953-2048/23/2/025001

A new finite-element method simulation model for computing AC loss in roll assisted biaxially textured substrate YBCO tapes

Doan N Nguyen[1], **Stephen P Ashworth**[1], **Jeffrey O Willis**[1], **Frédéric Sirois**[2] and **Francesco Grilli**[3]

[1] Superconductivity Technology Center, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[2] Ecole Polytechnique de Montréal, PO Box 6079 Station Centre-ville, Montréal, QC, H3C 3A7, Canada
[3] Forschungszentrum Karlsruhe GmbH, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany

E-mail: doan@lanl.gov

Received 6 April 2009, in final form 16 October 2009
Published 10 December 2009
Online at stacks.iop.org/SUST/23/025001

Abstract
This paper presents a new finite-element simulation model for computing the electromagnetic properties and AC losses in systems of YBCO (yttrium barium copper oxide) conductors on roll assisted biaxially textured substrates (RABiTS). In this model, the magnetic field dependent permeability and ferromagnetic loss of the substrates in RABiTS YBCO tapes are taken into account. The simulations were employed to simulate the AC loss in stacks of two parallel connected YBCO tapes. The simulation results are compared with the experimental data to check the validity of the simulation model. The result reveals an effective way of significantly reducing AC loss in YBCO tapes by stacking two RABiTS YBCO coated conductors with the appropriate relative tape orientation.

(Some figures in this article are in colour only in the electronic version)

1. Numerical simulation model

Finite-element method (FEM) simulations using the COMSOL Multiphysics® [1] software package have been widely used in recent years for computing the AC losses and electrodynamics in high temperature superconductor (HTS) systems [2–6]. In the 2D simulations, the edge-element model is employed to calculate the magnetic field vector **H** and current density vector **J**, based on the following set of equations:

$$\frac{\partial(\mu_r\mu_0\mathbf{H})}{\partial t} + \rho\nabla\times\mathbf{J} = 0 \qquad (1)$$

$$\mathbf{J} = \nabla\times\mathbf{H} \qquad (2)$$

where μ_0, μ_r and ρ are the vacuum magnetic permeability, relative magnetic permeability and resistivity, respectively. In the case of a superconductor, ρ depends on the current density and can be represented by a nonlinear power-law relation derived from measured current–voltage characteristics:

$$\rho_{sc} = \frac{E_c}{J_c}\left|\frac{J}{J_c}\right|^{n-1}. \qquad (3)$$

The edge-element model has been used extensively and successfully to predict AC loss in superconducting systems with non-ferromagnetic materials, i.e., $\mu_r = 1$, for example, HTS systems of Bi-2223 tapes or YBCO conductors on ion beam assisted deposition (IBAD) template layers on nonmagnetic substrates [2–4]. Moreover, this COMSOL model can also be extended for use with HTS systems with a model magnetic substrate material of constant μ_r [4–6]. However, μ_r of real magnetic substrate materials is usually a function of magnetic field. Therefore, in this paper we propose a modified set of equations implemented in the COMSOL

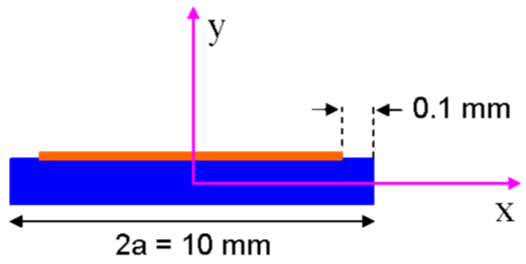

Figure 1. Cross-section of a YBCO tape in an xy coordinate system.

model to address the presence of real ferromagnetic materials. Given a YBCO tape cross-section in an xy-coordinate system as shown in figure 1, and that $\mu_r = \mu_r(H)$ is a function of the amplitude of the magnetic field, $H = \sqrt{H_x^2 + H_y^2}$, then equation (1) can be rewritten in the 2D model as:

$$\mu_0(\mu_r(H) + H_x^2 f(H))\frac{\partial H_x}{\partial t} + \mu_0 H_x H_y f(H)\frac{\partial H_y}{\partial t} + \rho\frac{\partial J_z}{\partial y} = 0 \qquad (4a)$$

$$\mu_0(\mu_r(H) + H_y^2 f(H))\frac{\partial H_y}{\partial t} + \mu_0 H_x H_y f(H)\frac{\partial H_x}{\partial t} - \rho\frac{\partial J_z}{\partial x} = 0 \qquad (4b)$$

where function $f(H)$ is determined by:

$$f(H) = \frac{1}{H}\frac{d\mu_r(H)}{dH}. \qquad (5)$$

Equation (2) can be rewritten in the 2D model as

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = J_z. \qquad (6)$$

Equations (4)–(6) are the general mathematic formulations for the 2D problem with ferromagnetic substrate materials. These mathematic equations were implemented in the COMSOL Multiphysics software to solve for the magnetic fields and AC loss of RABiTS YBCO tapes with ferromagnetic substrates. The field dependence of the relative magnetic permeability μ_r of the substrate material was determined experimentally and published recently in [7]. These experimental data were fitted by appropriate functions to use in the present simulations. Figure 2 shows the experimental data (squares) and fitting results (solid lines) for the dependence of μ_r on the magnetic field H. The fitting function must be chosen such that it can provide reasonable values of the permeability when the parallel magnetic field goes to zero or infinity. Therefore, the following function was selected:

$$\mu_r(H) = 1 + 30\,600(1 - \exp(-(H/295)^{2.5}))H^{-0.81} + 45\exp(-(H/120)^{2.5}). \qquad (7)$$

With this fitting function, $\mu_r(H)$ tends to 46 when H goes to zero and $\mu_r(H)$ tends to 1 when H goes to infinity. As seen in figure 2, the fit describes the experimental data quite well.

The total AC loss generated in a RABiTS YBCO coated conductor is the sum of the HTS loss Q_{hts} generated in the HTS layer and the ferromagnetic loss Q_{fe} dissipated in the substrate. In the simulations, Q_{hts} is calculated from the current density and electric field distribution over the cross-section of the HTS layer and Q_{fe} is calculated by the magnetic field distribution in the substrate layer. The hysteresis loss in a ferromagnetic material is the area of the B–H loop and is usually a function of the B_m, the maximum magnetic field of that loop. The ferromagnetic loss at each location inside the substrate can therefore be calculated from the maximum value of the induction field B_m at that location during the AC cycle, based on the $Q_{fe}(B_m)$ relation fitted from the experimental data extracted from figure 7 of [7]. The total ferromagnetic loss generated in the substrate is the integral of the loss distribution over substrate cross-section.

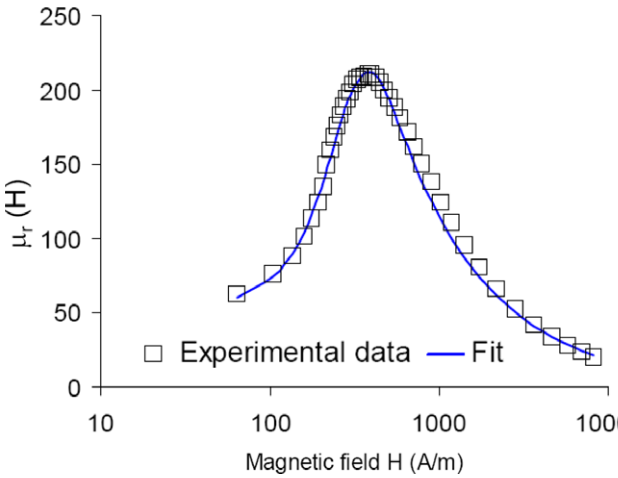

Figure 2. Magnetic permeability of the substrate material as a function of magnetic field. The experimental data are from [7].

Because Q_{fe} increases strongly with increasing B_m at small magnetic field and becomes saturated when B_m is large, we chose the following fitting function for the ferromagnetic loss (in units of J m^{-3}-cycle):

$$Q_{fe}(B_m) = \begin{cases} 4611.4B_m^{1.884}, & B_m \leqslant 0.164 \\ 210(1 - \exp(-(6.5B_m)^4)), & B_m > 0.164. \end{cases} \qquad (8)$$

With this fitting function, $Q_{fe}(B_m)$ saturates at the value of 210 J m^{-3}-cycle when B_m goes to infinity. As seen in figure 3, the fits reproduces the experimental data reported in [7] quite well.

To increase the current carrying capacity and possibly reduce AC loss, YBCO tapes can be fabricated in the form of multilayer structures or simply by stacking two or more YBCO coated conductors. The proposed simulation model was employed to simulate AC loss in a single RABiTS YBCO tape and in stacks of two parallel RABiTS YBCO tapes. The simulation results are compared with experimental data to check the validity of the simulation model. Because of the presence of the ferromagnetic substrate in this conductor, the orientation of the RABiTS conductors in a stack will affect their AC loss properties. This paper will focus on AC loss properties in back-to-back (BTB) and front-to-front (FTF) configurations (figure 4) because the symmetry of the

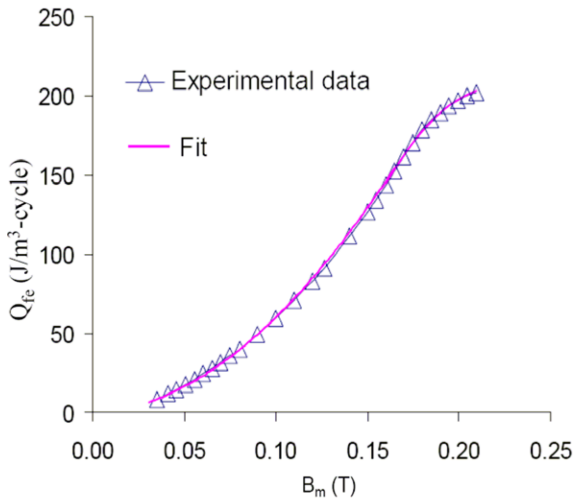

Figure 3. Dependence of Q_{fe} on B_m, the maximum magnetic induction during each AC cycle. The experimental data are from [7].

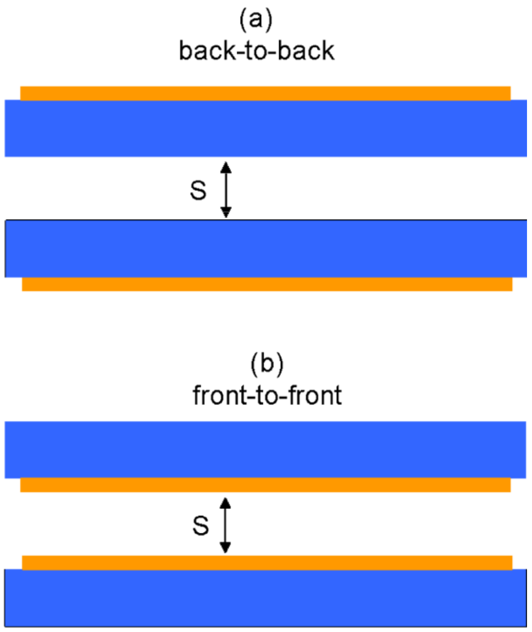

Figure 4. Cross-sections of BTB and FTF configurations for a stack of RABiTS tapes. The HTS layers are orange (thin rectangles) and the ferromagnetic substrates are blue (thicker rectangles).

tapes in each of those stacks provides the simplest and best understanding of the effect of the ferromagnetic substrates on AC loss.

2. Sample and measurement set-up

The sample used in this study is a RABiTS tape provided by American Superconductor Corporation [8]. It is 10 mm wide with a self-field critical current of 330 A at 75 K. The sample substrate is a Ni–W layer with 75 μm thickness. In the simulations, the width of the HTS layer was assumed to be 9.8, 0.2 mm less than the entire width of the tape as seen in figure 1. This assumption is to account for the fact that some HTS material near the edges of the tape was damaged or peeled off during the manufacturing process. Figure 5 is an illustration of the experimental set-up. Two identical YBCO tapes, the top and the bottom, are place parallel with the separation distance s = 0.8 mm. In a real device, such as a coil, these two tapes are energized in parallel to that the currents flowing in the tapes should be identical in both amplitude and direction. To achieve that condition in the test set-up, a return loop to connect the end of the top tape to the beginning of the bottom tape (figure 5) is used. The AC losses in those tapes was measured by an electric method using voltage loops soldered to the tapes. More details about the electrical AC loss measurement for a stack of superconducting tapes has been published previously [6]. All the AC loss measurements were performed at 75 K.

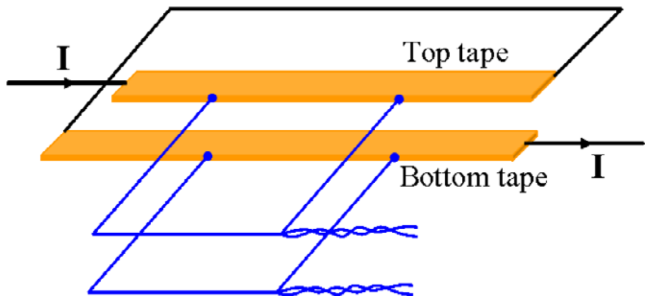

Figure 5. Illustration of the sample arrangement and electrical connections in the AC loss measurement of a parallel stack.

Because of the symmetry of the BTB and FTF configurations, the AC loss in the top and bottom tapes of each stack should be equal. This expectation, in fact, was confirmed in our experimental data.

3. Results and discussion

All the measurements and simulations were performed at a frequency of 50 Hz. The values of the transport current referred to should be understood as the peak values, I_p. For the simulation, the ferromagnetic loss generated in the substrate and the superconducting loss generated in the HTS layer (HTS loss) were calculated separately. Figure 6 plots the simulation results for these loss components as functions of I_p. As seen in the figure, the ferromagnetic loss in the substrate is the dominant component in the low current region ($I_p/I_c < 0.5$), and this loss saturates quickly when the current is higher than 90 A ($\approx 0.3 I_c$). In the high current region, the HTS loss component plays the more important role. Similar observations for the behavior of ferromagnetic and HTS losses have been discussed elsewhere [9–12]. The sum of the modeled HTS loss and ferromagnetic loss provides the calculated results for the total self-field loss in this sample. In general, the modeled total self-field loss agrees well with that obtained from the measurement: the solid line for the simulation results lies on the top of the open squares representing the experimental data in figure 6. The good agreement between simulation and experiment for transport loss suggests that the substrate material measured in reference [7] has quite similar magnetic properties as the substrate of our RABiTS sample. This result encourages us to do further comparisons between the simulation and experiment for AC loss in BTB and FTF stacks.

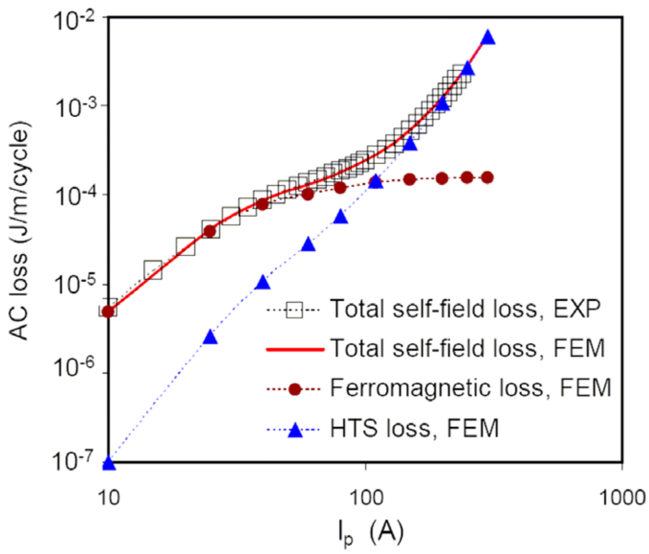

Figure 6. FEM and experimental results for the AC loss components in the RABiTS YBCO sample ($I_c = 330$ A).

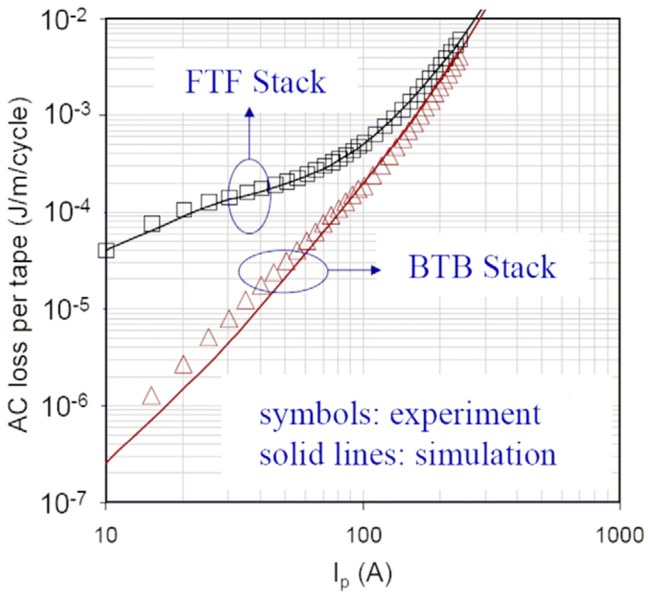

Figure 7. FEM simulation and experimental results for the AC loss per tape as a function of peak current for BTB and FTF stacks.

The comparison between experimental and simulation results for AC losses in the BTB and FTF stacks is presented in figure 7. In that figure, the AC loss per YBCO tape is plotted as a function of I_p. Again, very good agreement between simulation and experiment is observed. In the low current region where the ferromagnetic loss dominates, the loss in the BTB stack is significantly smaller than that in the FTF counterpart. This implies that the ferromagnetic loss is reduced significantly in the BTB configuration. In the high current region where the superconducting loss is the dominant component, the loss in the BTB configuration is still the lower. For example, at 240 A (or $0.7I_c$), the loss in the BTB stack is about 70% of that in the FTF configuration. Thus, the presence of the ferromagnetic substrate in the BTB configuration also helps to reduce the hysteresis loss in the YBCO layers.

The above features can be seen perhaps more clearly in figure 8, which depicts the simulation results for ferromagnetic loss and superconducting loss components for both BTB and FTF stacks. As seen in the figure, the FTF stack has a higher superconducting loss than does the BTB stack for the entire range of transport current. Compared with the BTB stack, the ferromagnetic loss in the FTF configuration is also higher and saturates more quickly at quite a small current, $I_p \sim 70$ A. This can be explained quantitatively based on the different parallel magnetic fields present at the ferromagnetic substrate in the two configurations. This difference is caused by the different physical location of the substrates in these two structures as seen in figure 4. For a parallel stack (i.e., a stack of two parallel connected YBCO tapes), the self-magnetic-fields generated by the two tapes in the stack have opposite directions in the space between the tapes (or the inside space) and have the same direction for the outside spaces as seen in figure 9. Consequently, for a parallel stack with separation s small enough, the parallel magnetic field is enhanced in the outside space and weakened in the inside space. In the FTF stack, the substrates are located in the outside space, where they are subjected to an enhanced parallel magnetic field. Therefore, a much higher ferromagnetic loss is expected in this case. On the contrary, the substrates in the BTB configuration are located in the inside space where the parallel magnetic field is nearly canceled. As a result, there is a much lower ferromagnetic loss for this configuration.

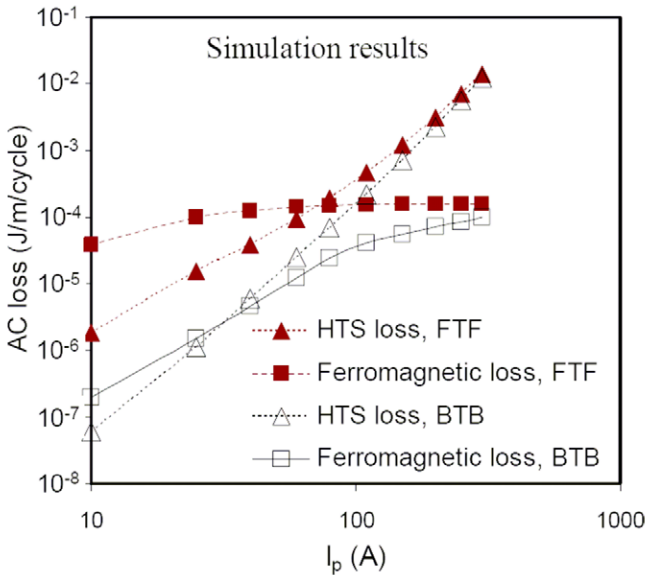

Figure 8. FEM simulation results for the ferromagnetic and HTS losses per YBCO tape for BTB and FTF stacks as a function of peak current.

Finally, to compare the AC loss behavior of the stacks and of a single tape, we consider the stack as a single superconducting tape (FTF tape or BTB tape) with critical current $I_{c,\mathrm{stack}} = 2I_{c,\mathrm{single}}$, where $I_{c,\mathrm{single}}$ is the critical current of a single tape. We then plot in figure 10 the dependence of the normalized AC loss, $q = \mu_0 Q/I_c^2$ (where Q is the transport loss and I_c is the critical current of a single tape) as a function of normalized current $i = I_p/I_c$. The analytical

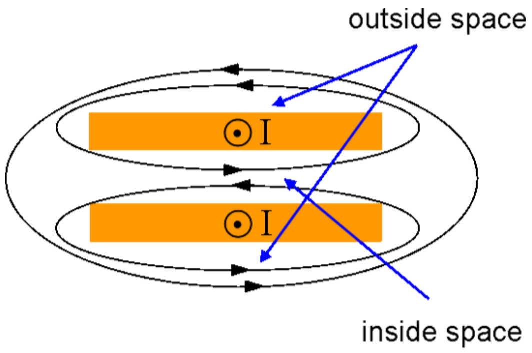

Figure 9. Sketch of the magnetic field distribution near a parallel stack of two HTS tapes.

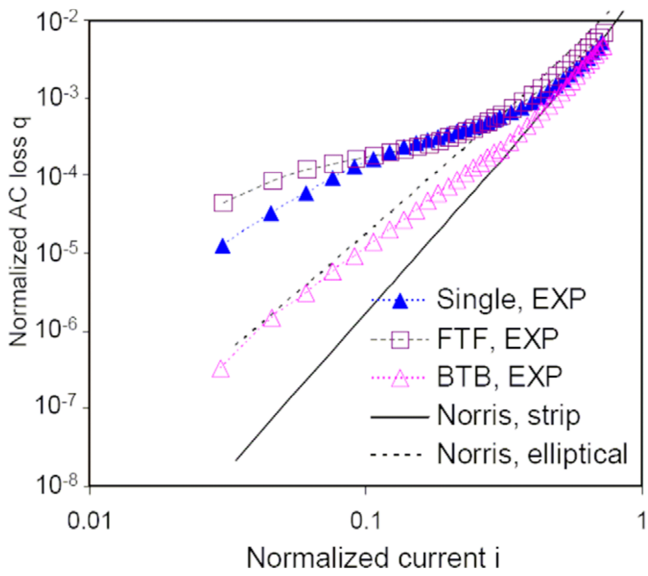

Figure 10. Experimental results for the normalized AC losses of single, BTB and FTF tapes. In this case, BTB and FTF stacks are treated as single superconducting tapes.

results obtained from the Norris model for the transport AC loss of elliptical and thin strip conductors are also plotted for comparison. As seen in the figure, the very significant contribution of the ferromagnetic loss of a single tape and of the FTF tape in the low current region makes the transport loss in those tapes much higher than that predicted by the Norris model. For the BTB tape, there may still be some contribution of the ferromagnetic loss in the low current region as the transport loss in that tape is higher than the loss predicted by the Norris model for a strip. For the high current (and the actual device application) region, i.e., for $i = 0.6$, the measured loss in a single tape is nearly coincident with the analytical results obtained from the Norris strip model. At that current, the loss in a single tape is about 30% lower than that in the FTF structured tape but still 20% higher than the loss in the BTB counterpart. These observations suggests that a multilayer structured RABiTS tape that has a single ferromagnetic substrate and two YBCO layers deposited on both sides of the substrate will be very effective not only in increasing the current carrying capacity, but also in reducing the AC loss.

4. Conclusion

In this paper, we proposed a new FEM model implemented using the COMSOL Multiphysics® software package to simulate the electrodynamics and AC loss in systems of YBCO RABiTS superconducting tapes. The model is capable of taking the magnetic field dependent permeability and ferromagnetic loss of the RABiTS into account. The simulation model was then employed to study the AC loss in single YBCO RABiTS tapes and in BTB and FTF parallel stacks of two tapes. Good agreement between the simulation and experimental results for all the cases studied confirmed the validity of the simulation model.

The BTB configuration helps to reduce the loss significantly for the entire range of transport currents. This configuration not only eliminates most of the ferromagnetic loss in the substrates but also reduces the HTS loss generated in the superconducting layers. This finding confirms suggestion proposed in [13] that a multilayer structure YBCO RABiTS tape with a single ferromagnetic substrate and two YBCO layers deposited on both sides of the substrate will be very effective not only in increasing the current carrying capacity, but also in reducing AC loss.

Acknowledgments

We would like to thank Dr O Tsukamoto (Department of Electrical Engineering, Yokohama National University, Japan) and Dr D Miyagi (Department of Electrical and Electronic Engineering, Okayama University, Japan) for providing the experimental data of $Q_{\mathrm{fe}}(B_{\mathrm{m}})$ and $\mu_{\mathrm{r}}(H)$ which have been reported in [7]. American Superconductor Corporation is acknowledged for providing the high performance YBCO samples.

References

[1] COMSOL, Inc. http://www.comsol.com
[2] Hong Z, Campbell A M and Coombs T A 2006 *Supercond. Sci. Technol.* **19** 1246–52
[3] Nguyen D N, Ashworth S P and Willis J O 2009 *J. Appl. Phys.* **105** 063917
[4] Brambilla1 R, Grilli F and Martini L 2007 *Supercond. Sci. Technol.* **20** 16
[5] Grilli F, Ashworth S P and Civale L 2007 *J. Appl. Phys.* **102** 073909
[6] Nguyen D N, Grilli F, Ashworth S P and Willis J O 2009 *Supercond. Sci. Technol.* **22** 055014
[7] Miyagi D, Yunoki Y, Umabuchi M, Takahashi N and Tsukamoto O 2008 *Physica* C **468** 1743
[8] American Superconductor Corp 64 Jackson Road, Devens, MA 01430 USA, Tel +1 978.842.3000 http://www.amsc.com
[9] Duckworth R C, Gouge M J, Lue J W, Thieme C and Verebelyi D T 2005 *IEEE Trans. Appl. Supercond.* **15** 1583
[10] Nguyen D N, Sastry P, Knoll D C and Schwartz J 2006 *Supercond. Sci. Technol.* **19** 1010
[11] Ijaduola O, Thompson J R, Goyal A, Thieme C and Marken K 2004 *Physica* C **403** 1
[12] Tsukamoto O, Nakayama H, Odaka S, Ciszek M, Hahakura S, Ueyama M, Ohmatsu K and Miyagi D 2005 *Physica* C **426–431** 1290
[13] Tsukamoto O, Alamgir A K M, Liu M, Miyagi D and Ohmatsu K 2007 *IEEE Trans. Appl. Supercond.* **17** 3195