AC Loss Analyses of Superconducting Power Transmission Cables Using Narrow BSCCO Tapes

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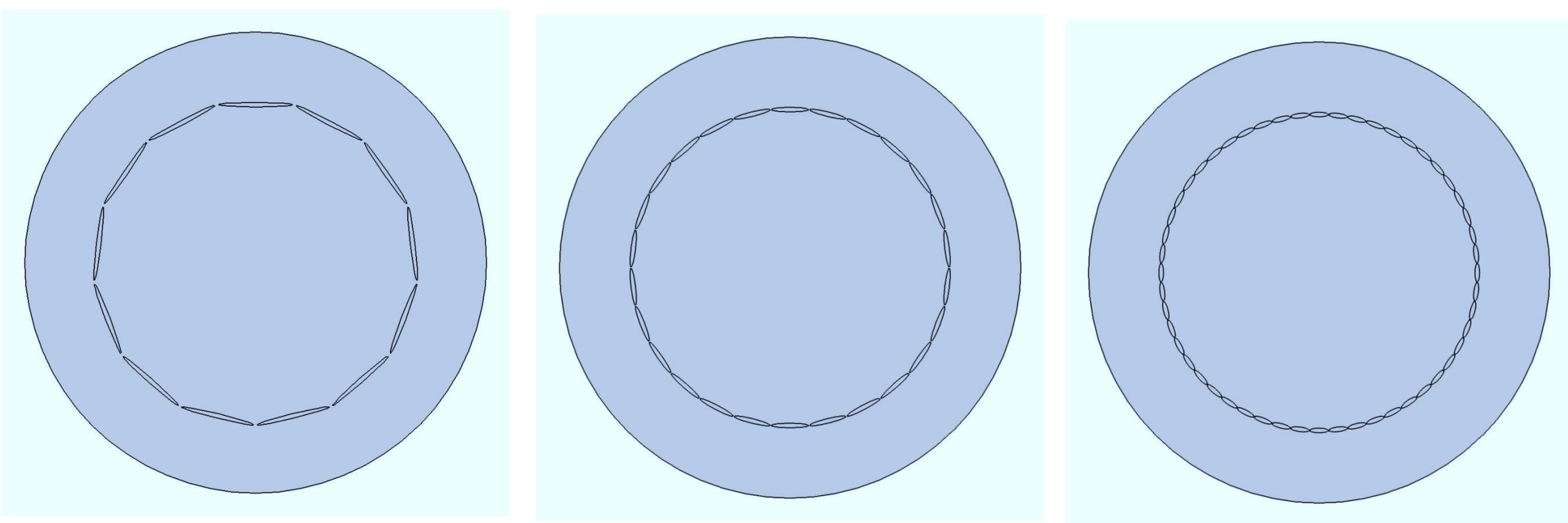
Abstract

Reduction of AC loss in high-T_C superconducting (HTS) power transmission cables is crucial for their practical use. Advanced AC loss analyses of HTS cables, comprised of coated conductors, have reported that the loss is reducible using coated conductors with a narrow width. On the other hand, in a HTS cable comprised of BSCCO tapes, it is unclear whether the AC loss is reduced using the narrow tapes. The authors developed a 2D FEM numerical model to calculate AC loss in HTS cables under the assumption that the cross section of the superconductor in the BSCCO tape can be approximated to an ellipse or a rectangle. Monolayer HTS cables were comprised of 13 tapes with a 4 mm width, 26 tapes with a 2 mm width, and 52 tapes with a 1 mm width. The inner diameters of the cables were identical, and the I_C values of all cables were 2,600 A. Results indicate that AC losses of all cables were almost equal to those theorized by the monoblock model. The loss was found to decrease with a decrease in the tape width at high normalized current values I_t/I_C; however, the reduction effect was small. The dependence of the AC loss on the tape number was also studied for a cable with tape width of 1 mm. The number of tapes decreased from 52 to 48, as the gap between adjacent tapes increased; however, the losses slightly increased because of the decrease in the cable's I_C.

Construction of monolayer HTS cables



(a) 4 mm cable (b) 2 mm cable (c) 1 mm cable

Fig. 1. Schematic diagram of a cross section of the monolayer cable

Table 1. Specifications of monolayer cables

Tape width	4 mm	2 mm	1 mm
Inner diameter	17 mm	17 mm	17 mm
Tape thickness	0.25 mm	0.25 mm	0.25 mm
Tape number	13	26	52
Critical current of tape	200 A	100 A	50 A

The thickness of the tape was fixed at 0.25 mm. The tape width was changed from 1 mm to 4 mm. The critical current I_C values were I_C = 200 A for a 4 mm tape width, I_C = 100 A for a 2 mm tape width, and I_C = 50 A for a 1 mm tape width. The specifications for the monolayer cables are listed in Table 1, and the schematic diagram of the cables is shown in Fig. 1. AC losses of these cables were calculated; the losses were also calculated when the tape number was decreased from 52 to 48 for a 1 mm tape width in order to increase the distance between adjacent tapes.

Calculation of AC losses

The basic equations for the 2D FEM analysis model are described below. The cross section of the tape is along x-y plane, and the current flows in z direction. Ampere's law determines the current density J_z as

$$J_z = \frac{dH_y}{dx} - \frac{dH_x}{dy}. \tag{1}$$

While Faraday's law calculates the electric field $E_z(J_z)$ as

$$\begin{bmatrix} \mu_0 & 0 \\ 0 & \mu_0 \end{bmatrix} \cdot \begin{bmatrix} \frac{dH_x}{dt} \\ \frac{dH_y}{dt} \end{bmatrix} + \nabla \cdot \begin{bmatrix} 0 & E_z(J_z) \\ -E_z(J_z) & 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \tag{2}$$

where $E_z(J_z)$ is the current-dependent electric field. The model calculates this field with the empirical formula

$$E_z(J_z) = E_0 \left(\frac{J_z}{J_C}\right)^{\alpha}, \tag{3}$$

where E_0 and α are constants, $E_0 = 1 \times 10^{-4}$ V/m, and $\alpha = 19$. J_C is the critical current density and $J_C = 2.0 \times 10^8$ A/m^2 for the rectangle superconductor and $J_C = 2.5 \times 10^8$ A/m^2 for the ellipse. The AC loss Q is obtained by

$$Q = f \cdot \int_{\frac{1}{f}} dt \int_S E_z(J_z) \cdot J_z dS, \tag{4}$$

where f is the frequency and f = 50 Hz.

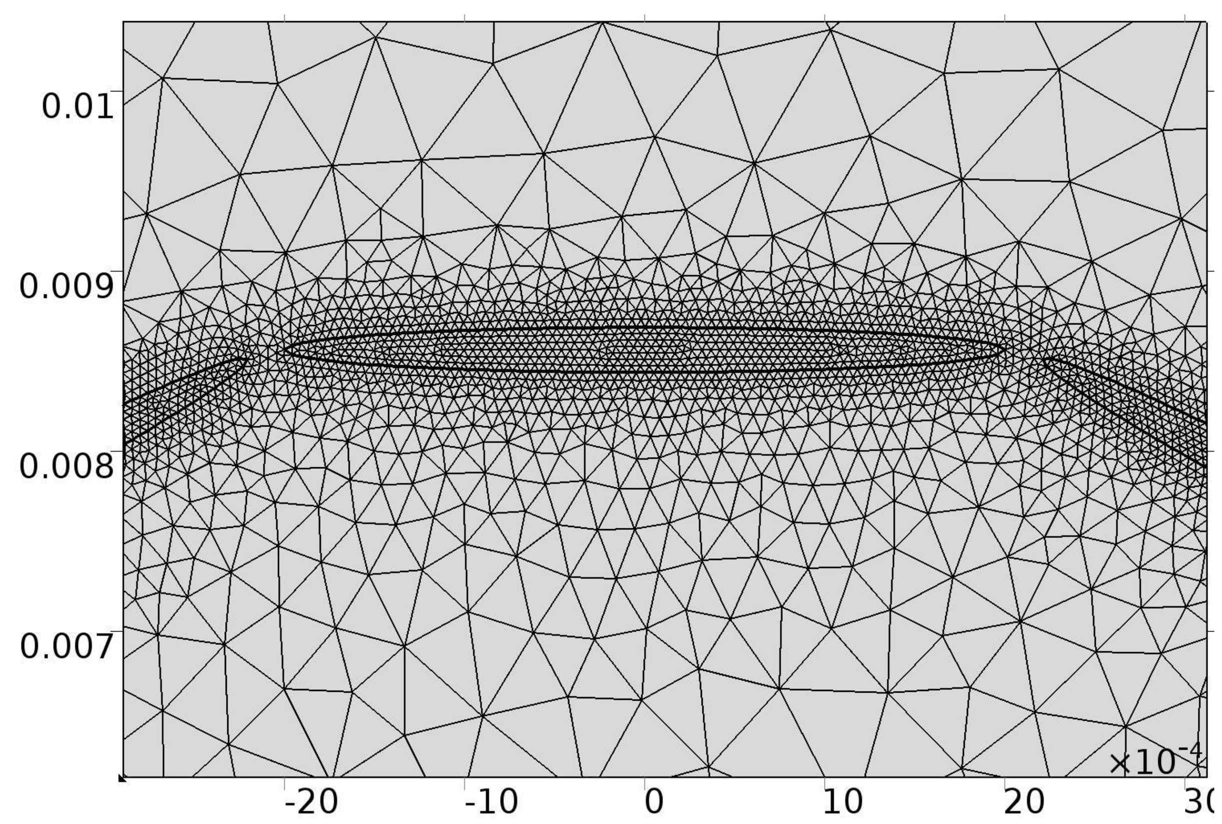
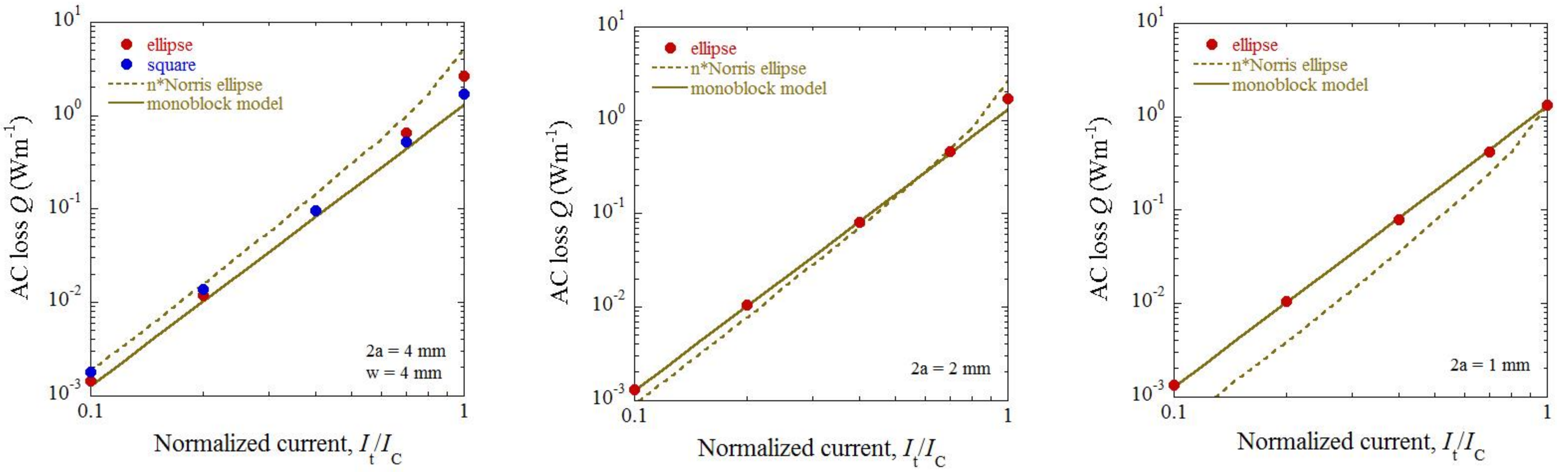


Fig. 2. Example of a mesh for 4 mm cable

Dependence of AC losses on tape width



(a) 4 mm cable (b) 2 mm cable (c) 1 mm cable

Fig. 3. AC losses of the monolayer cable with different tape width

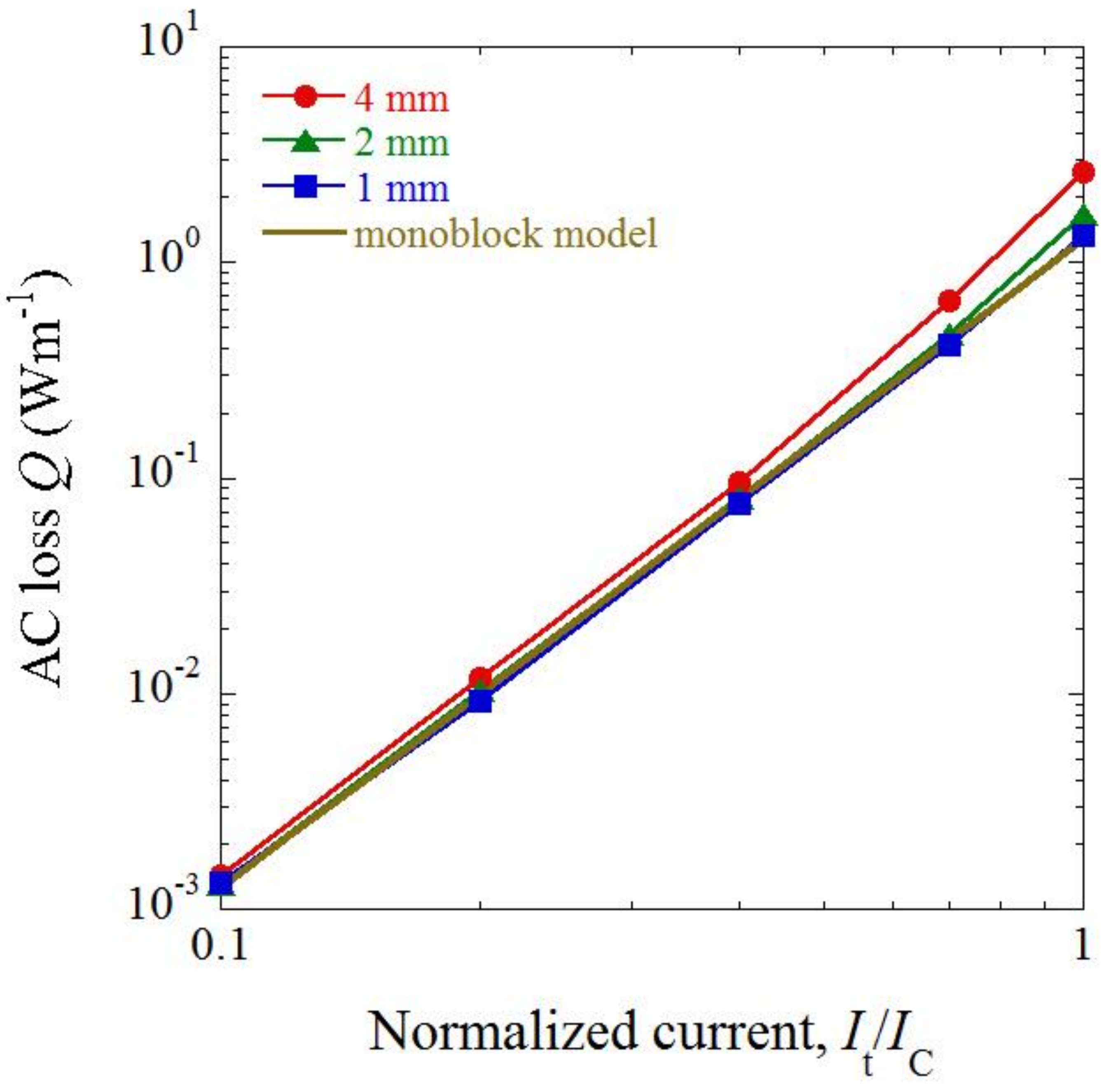
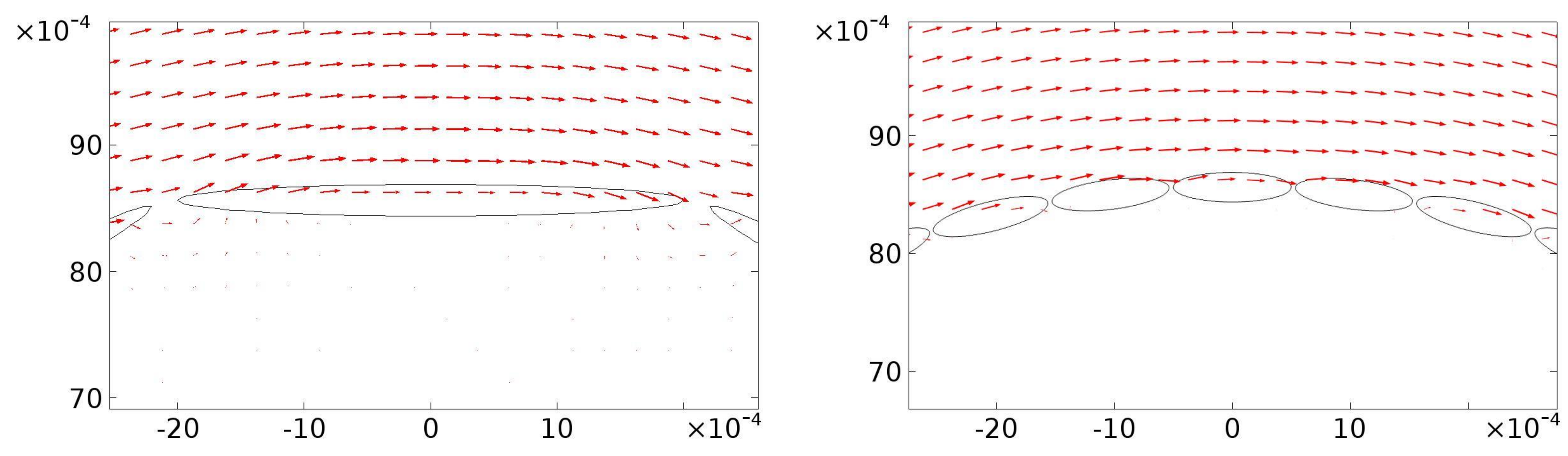
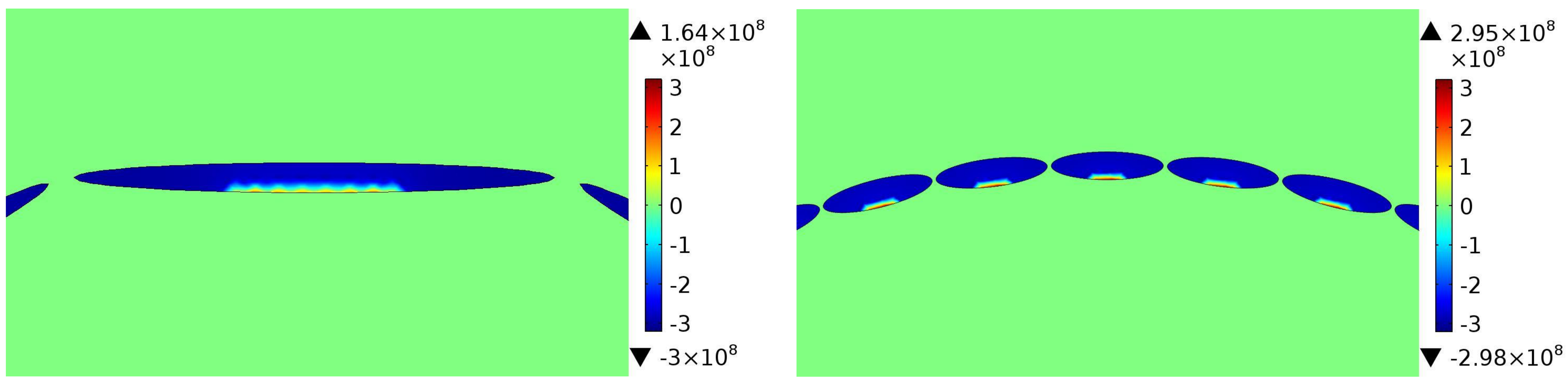


Fig. 4. Dependence of AC losses on tape width



(a) 4 mm cable (b) 1 mm cable

Fig. 5. Direction of magnetic flux density ($I_t/I_C = 1$, $\omega t = 3\pi/2$)



(a) 4 mm cable (b) 1 mm cable

Fig. 6. Distribution of current density($I_t/I_C = 1$, $\omega t = 3\pi/2$)

Dependence of AC losses on tape number

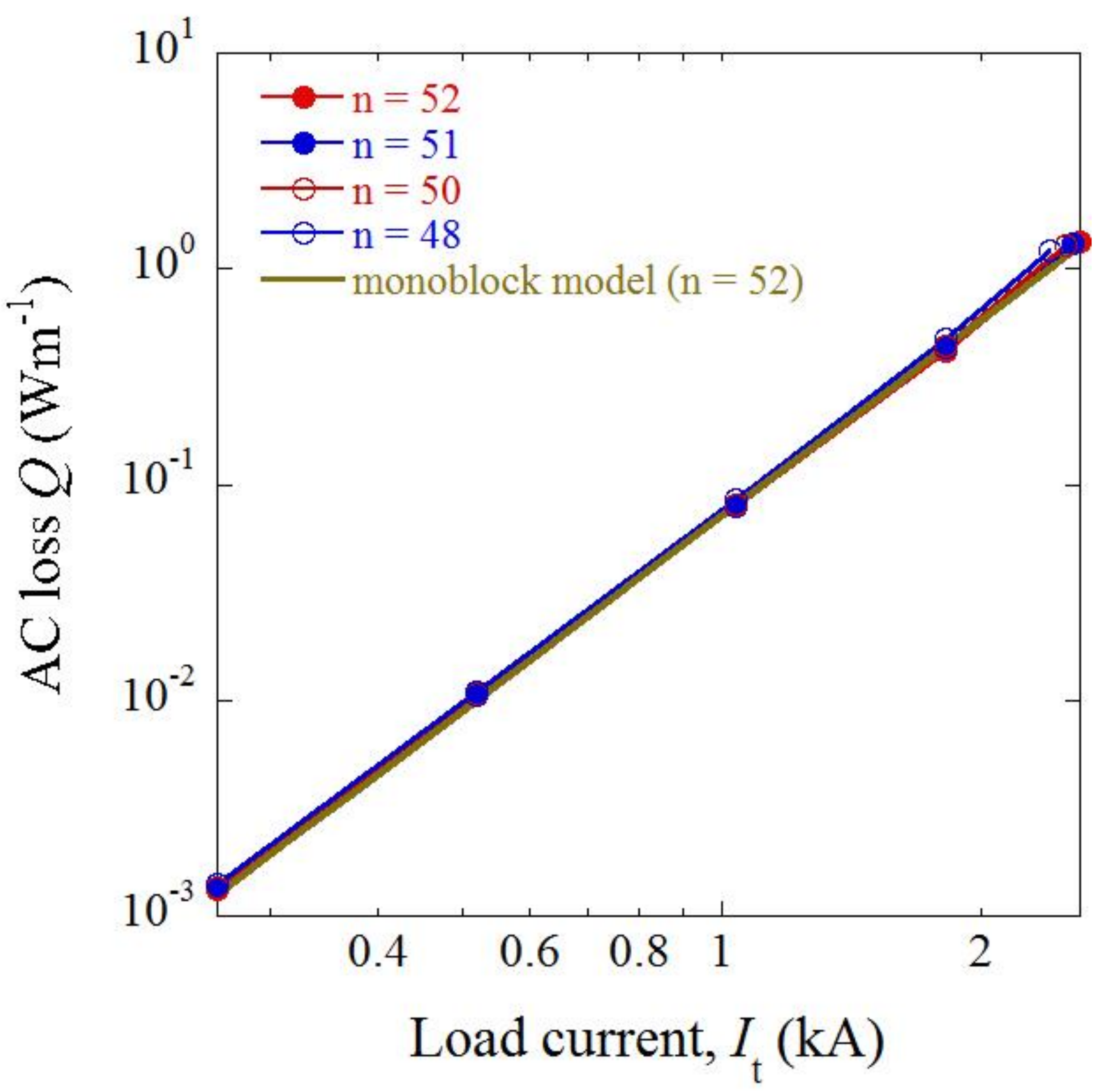
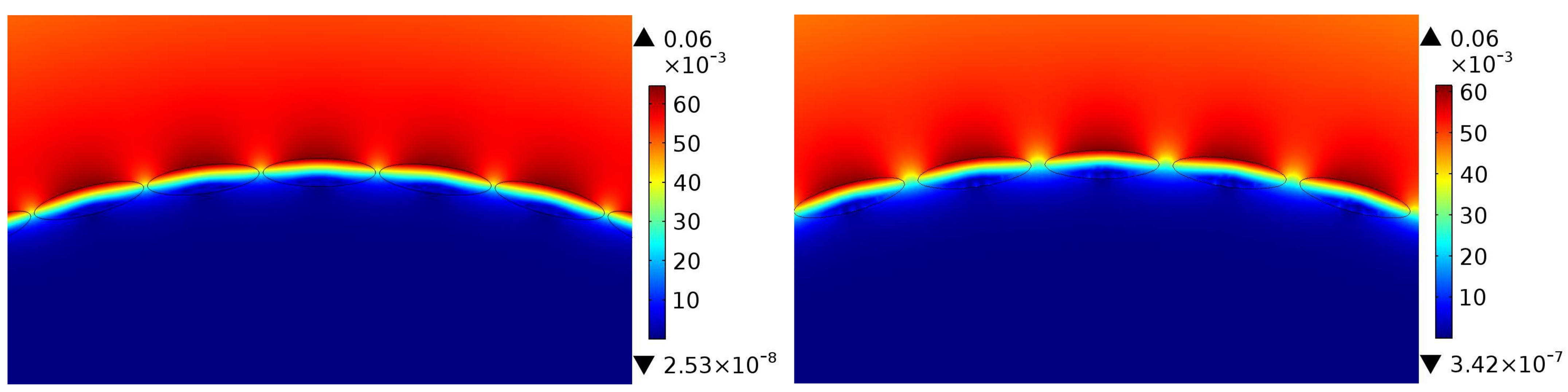


Fig. 7. Dependence of AC losses on tape number



(a) n =52 (b) n =48

Fig. 8. Distribution of magnetic flux density ($I_t/I_C = 1$, $\omega t = 3\pi/2$)

The losses when the tape number was decreased from 52 to 48 in a 1 mm tape width were calculated. These results are shown in Fig. 7. Results of FEM analysis indicated that the losses were almost equal to those obtained by the monoblock model and appeared to be independent of the tape number. However, a more thorough observation of the results found that the losses increased slightly with a decrease in the tape number. This means that the increase phenomenon of the loss is dominant over the decrease in cable's I_C.

Conclusion

To calculate the AC loss of a BSCCO monolayer cable, a 2D FEM analysis model was developed. As the tape width decreased from 4 mm to 1 mm, tape width was found to impact the cable loss. The results of the FEM analysis indicated that the losses were almost equal to those of the monoblock model and were independent of the tape width at a low current. However, the losses decreased with a decrease in the tape width at a high current. For a 1 mm tape width, the loss agreed with the value calculated by the monoblock model for all currents. Moreover, an influence of tape number on cable loss was studied in which to the gap between tapes was increased by decreasing the tape number. As the tape number decreased from 52 to 48, FEM analysis showed that the losses increased slightly with a decrease in the tape number. This was thought to be caused by the decrease in cable's I_C due to the decrease in the tape number.