AC losses and induced fields in HTS coil wound using two-ply coated conductors

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Abstract. AC losses and screening-current-induced fields (SCFs) in a high temperature superconducting (HTS) inserts for high field magnet are evaluated theoretically. The HTS inserts are composed of stacked pancake coils, which are wound using two-ply conductors, where the superconducting-layer sides of two rare-earth-based coated conductors are attached to each other without electrical insulation. The theoretical formulas of AC loss and SCF in the two-ply conductor are derived for the simultaneous applications of a transport current and an external magnetic field parallel to its broad face. By taking into account the magnetic-field profile in the HTS insert and the magnetic-field dependency of critical current density in the coated conductor, the AC losses and SCFs are estimated using the theoretical formulas for monotonical increase in a central field up to 25.5 T in 60 minutes in combination with low temperature superconducting outsert coils. It is guessed that the AC loss estimated for the HTS insert wound using the two-ply conductor could be cooled by using prepared cryocoolers. The magnitude of SCF in the HTS insert wound using the two-ply conductor becomes smaller than that for the single-tape conductor estimated previously.

1. Introduction
It has been required worldwide that superconducting (SC) magnets generate higher central magnetic fields, especially for nuclear magnetic resonance [1–3] and magnetic field use [4–6]. In particular, the application of a rare-earth-based (RE-based) high temperature superconducting (HTS) coated conductor has been considered as a wire for the magnet because the SC layer is deposited over a high-strength metal substrate and therefore the wire has an excellent mechanical strength necessary to overcome a huge electromagnetic force.

The 25-T-class cryogen-free SC magnets have been developed so far [6]. This magnets are composed of HTS inserts and a set of six low temperature superconducting (LTS) background coils. The HTS inserts have been designed to generate central magnetic fields of 11.5 T. Since the LTS coils themselves have generated a central field of 14.0 T, the total fields had been expected to become 25.5 T theoretically. The HTS and LTS coils are conduction-cooled individually using small-size cryocoolers. Two-stage Gifford-McMahon cryocoolers with a cooling power of 1.5 W at a temperature of 4.2 K have been used for the HTS insert. A ramping time of simultaneous excitations of the HTS and LTS coils up to 25.5 T has been set within 60 minutes. Therefore,
the pre-estimation of AC loss during ramping up or discharging down the cryogen-free magnet is very important to operate them stably.

One of the HTS inserts wound using the RE-based coated conductor have been fabricated and tested [6]. However, this HTS insert during its energization had been burned out just after generation of a local voltage due to a partial damage of winding. In order to solve such a degradation of winding, our group has a plan to develop an HTS insert wound using a new type of bundle conductor composed of two coated conductors. The AC losses in an HTS coil wound using this bundle conductor have not been evaluated as well as screening-current-induced fields (SCFs) at the center of coil up to now.

In this study, the AC losses and SCFs in the HTS inserts for high field magnet during their initial energization are evaluated theoretically. Theoretical expressions of AC loss and SCF in the bundle conductor with a transport current exposed to an external applied magnetic field parallel to its broad face are derived first. In order to validate the obtained theoretical expression of AC loss, a finite element analysis is carried out for stacked bundle conductors, which are modeled as a part of pancake coil for the HTS insert. By using the theoretical expressions in addition to those for a perpendicular applied field, the AC losses and SCFs in the HTS inserts wound using the bundle conductors are estimated as compared with those for a single-tape winding reported previously [7].

2. Theoretical expressions of AC loss and SCF in two-ply conductor

Figure 1(a) shows the schematic illustration of cross-sectional view of a typical RE-based coated conductor [8]. The coated conductor is usually composed of metal substrate, buffer layer, SC layer, silver protecting layer and copper stabilizing layer. The buffer and protecting layers are not considered in this article because they are usually thin. The width and thickness of SC layer is symbolized by $2a$ and $d$, respectively. Figure 1(b) shows the cross-sectional view of two-ply conductor discussed mainly in this article. The SC-layer sides of two coated conductors are attached to each other without electrical insulation to improve thermal stability. The gap between the SC layers is represented as $w$.

Let us discuss the magnetic coupling between the SC layers in the two-ply conductor first. The top view of two-ply conductor is illustrated in figure 1(c), where $l$ is the conductor length. The $x$- and $z$-axes are set perpendicular to the wide surfaces of the two-ply conductor and longitudinal to the conductor, respectively, so that the $y$-axis is normal to them. The metal substrates are not considered in theoretical and numerical analyses carried out in this article under the assumption that they are nonmagnetic and have high electrical resistivity. It is also assumed that all of interlayer contact resistances can be ignored. Although the transport

Figure 1. Schematic illustrations of (a) cross-sectional view of coated conductor, (b) cross-sectional view of two-ply conductor and (c) top view of two-ply conductor.
currents in the SC layers, $I_{t1}$ and $I_{t2}$, are represented in figure 1(c), they will be used in the next paragraph and no transport current is considered here. If an external magnetic field $B_y$ is applied in the $y$-direction, the screening current $I_s$ is induced in the SC layers and crosses the copper stabilizer around both ends of the conductor. The similar situation has already been discussed [9]. If the conductor length is very short, the screening current is small. However, the screening current increases with the conductor length. The conductor length at which the screening current $I_s$ reaches the critical current $I_c (= 2adJ_c)$ of the SC layer defines the critical length $l_c$ given by

$$l_c = 4\sqrt{\frac{d\rho J_c}{2B_y}},$$

where $J_c$ is the critical current density, $\rho$ the resistivity of copper stabilizing layer, and the over dot denotes the time derivative. The Bean model [10], where the critical current density is independent of the local magnetic field, is assumed. For example, the critical length can be estimated as $l_c = 0.21$ m if the typical values of $d = 2.5 \, \mu m$, $\rho = 0.01$ $\mu\Omega$cm, $J_c = 16$ MA/cm$^2$ and $B_y = 25$ T/60 min. are used. Therefore, the full magnetic coupling between the SC layers occurs because the winding length for a practical pancake coil usually becomes the order of hundreds. In the case of the full magnetic coupling, the huge amount of AC loss due to magnetic-flux penetration into the gap between the SC layers might be concerned.

Next, let us consider the current sharing between the SC layers for the application of a total transport current $2I_t$ to the two-ply conductor. In the case of a saturated condition, in which there is no current free region in the SC layers, the following relationships are satisfied,

$$I_{t1} + I_{t2} = 2I_t,$$  \hspace{1cm} (2)
$$I_{t1} + I_s = I_c,$$  \hspace{1cm} (3)
$$I_{t2} + I_s = I_c.$$  \hspace{1cm} (4)

The simultaneous solutions of equations (2)–(4) are given by

$$I_{t1} = I_{t2} = I_t,$$  \hspace{1cm} (5)
$$I_s = I_c - I_t,$$  \hspace{1cm} (6)
so that the net currents flowing in the SC layers, $I_1$ and $I_2$, become

$$I_1 = I_{t1} - I_s = 2I_t - I_c,$$  \hspace{1cm} (7)
$$I_2 = I_{t2} + I_s = I_c.$$  \hspace{1cm} (8)

It is found in equation (5) that the applied transport current $2I_t$ is shared evenly between the SC layers in the two-ply conductor under the saturation condition. The similar even sharing of transport current under a non-saturated condition, in which current free regions exit in the SC layers, is also assumed in this article.

The theoretical expressions of AC loss and magnetic moment in the two-ply conductor with the transport current $2I_t$ in the external magnetic field $B_y$ are derived here. It is assumed that the two-ply conductor can be regarded as an infinite slab with the thickness $w + 2d$, and that the inside profile of magnetic field at a fixed instance in time can be described using the Bean model [10]. Figure 2 shows the field profiles for five different ranges of external fields $B_y$. If the external field $B_y$ and transport current $2I_t$ slightly increase up to $B_y + \dot{B}_y \, dt$ ($\dot{B}_y \geq 0$) and $2(I_t + \dot{I}_t \, dt)$ ($\dot{I}_t \geq 0$), respectively, and also the critical current density $J_c$ slightly decreases down to $J_c + \dot{J}_c \, dt$ ($\dot{J}_c \leq 0$), the theoretical expression of AC loss per unit volume of two SC layers, $P_{\text{bundle}}$, can be obtained as

$$P_{\text{bundle}} = \frac{B_y^2}{\mu_0} (p_1 + p_2 + p_3),$$  \hspace{1cm} (9)
Figure 2. Profiles of magnetic fields inside two-ply conductor with transport current in external field parallel to its broad face for (a) $0 \leq b \leq 2I$, $0 \leq b \leq 2(1-I)$, (b) $2(1-I) < b \leq 2I$, (c) $2I < b \leq 2(1-I)$, (d) $2I < b \leq 2$, $2(1-I) < b \leq 2$ and (e) $b > 2$.

$$p_1 = \begin{cases} \frac{b^2}{4} \left( \frac{1}{b} - \frac{bJ}{6} \right), & 0 \leq b \leq 2, \\ \frac{b - 4J}{3}, & b > 2, \end{cases}$$  \tag{10}

$$p_2 = \begin{cases} b \left( I - \frac{b}{4} \right) \hat{b} + \left( \frac{b^2}{2} + 2I^2 \right) \hat{J} - \left( \frac{4I^3}{3} + b^2 I - \frac{b^3}{6} \right) \hat{J}, & 0 \leq b \leq 2I, \\ I \left( ib + 2bi - 2bJ \right), & b > 2I, \end{cases}$$  \tag{11}

$$p_3 = \frac{W}{d} \times \begin{cases} 0, & 0 \leq b \leq 2(1-I), \\ b + 2I - 2J, & b > 2(1-I), \end{cases}$$  \tag{12}

where $B_p$ is the full penetration field given here by $B_p = \mu_0 I_c d / 2$, $b = B_y / B_p$, $I = I_t / I_c$, $\hat{b} = B_y / B_p$ ($\geq 0$), $\hat{I} = I_t / I_c$ ($\geq 0$) and $\hat{J} = J_c / J_c$ ($\leq 0$). The term $p_1$ in equation (10) represents the AC loss in the two-ply conductor without the gap between the SC layers (i.e., $w = 0$) when only the external field $B_y$ is applied, and the terms $p_2$ and $p_3$ in equations (11) and (12) are the
additional losses accompanied by the transport current $2I_t$ and gap $w$, respectively. In the case where only the external field $B_y$ in the parallel direction varies for the unchanging transport current $2I_t$ and critical current density $J_c$, the expressions (9)–(12) are simplified as

$$P_{\text{bundle}} = \frac{B_y^2}{\mu_0} \left( 1 + I^2 + \frac{w}{d} \right) b.$$  \hfill (13)

On the other hand, the corresponding theoretical expression of AC loss for the single tape, $P_{\text{single}}$, is given by [7]

$$P_{\text{single}} = \frac{B_y^2}{2\mu_0} (1 + I^2) b.$$  \hfill (14)

Therefore, the ratio of the losses $P_{\text{bundle}}$ to $P_{\text{single}}$ becomes

$$\frac{P_{\text{bundle}}}{P_{\text{single}}} = 2 \left\{ 1 + \frac{w}{d (1 + I^2)} \right\}. \hfill (15)$$

It is found in equation (15) that the parallel-field loss $P_{\text{bundle}}$ in the two-ply conductor becomes much larger than that for the single tape, $P_{\text{single}}$, if the gap $w$ between the SC layers is much larger than the thickness $d$ of SC layer. The magnetic moment per unit length in the $y$-direction in the two-ply conductor, $m_{\text{bundle}}$, is also expressed from figure 2 by

$$m_{\text{bundle}} = \frac{4adB_y}{\mu_0} (m_1 + m_2 + m_3), \hfill (16)$$

$$m_1 = \begin{cases} b, & 0 \leq b \leq 2, \\ 1 - b^2/4, & b > 2, \end{cases} \hfill (17)$$

$$m_2 = \begin{cases} bI, & 0 \leq b \leq 2I, \\ b^2/4 + I^2, & b > 2I, \end{cases} \hfill (18)$$

$$m_3 = -\frac{w}{d} \times \begin{cases} b/2, & 0 \leq b \leq 2 (1 - I), \\ 1 - I, & b > 2 (1 - I). \end{cases} \hfill (19)$$

The terms $m_1$, $m_2$ and $m_3$ in equations (17)–(19) are related to the contributes from the applied magnetic field $B_y$, transport current $2I_t$ and gap $w$, respectively, as similar to those for the parallel-field loss $P_{\text{bundle}}$ given by equations (10)–(12), respectively.

On the other hand, it might be guessed that the AC loss in the two-ply conductor exposed to an external magnetic field $B_x$ in the $x$-direction is not affected by assembling two coated conductors face-to-face because the screening current is induced independently inside each of SC layer. Since a lot of stacked thin superconductors under consideration can be considered as an infinite slab with the thickness equal to the tape width $2a$ due to the magnetic interaction between the tapes, the AC loss per unit volume of the SC layers, $P_{\text{slab}}$, is expressed as [7]

$$P_{\text{slab}} = \frac{B_x^2}{2\mu_0} (p_e + p_i), \hfill (20)$$

$$p_e = \begin{cases} b^2 \left( b - \frac{2b_j}{3} \right), & 0 \leq b \leq 1, \\ b - \frac{2j}{3}, & b > 1, \end{cases} \hfill (21)$$
\[ p_i = \begin{cases} b(2I-b)\hat{b} + (b^2 + I^2)\hat{I} - 2\left(\frac{I^3}{3} + b^2I - \frac{b^3}{3}\right)\hat{j}, & 0 \leq b \leq I, \\
I\left(\hat{I}\hat{b} + 2b\hat{I} - 2bI\hat{j}\right), & b > I, \end{cases} \tag{22} \]

where \( b = B_x/B_p, \hat{b} = B_x/B_p (\geq 0), B_p = \mu_0\lambda J_0 a \) and \( \lambda = 2d/g \) with the stacking pitch \( g \) of the two-ply conductor. The term \( p_e \) in equation (21) represents the AC loss when only the external field \( B_x \) is applied, and the term \( p_i \) in equation (22) is the additional loss accompanied by the transport current \( 2I_t \). The magnetic moment \( m_{\text{slab}} \) per unit length in the infinite slab is also given by [11]

\[ m_{\text{slab}} = \frac{S_{\text{eff}}B_p}{\mu_0} (m_e + m_i), \tag{23} \]

\[ m_e = \begin{cases} b(2b/2 - 1), & 0 \leq b \leq 1, \\
-1/2, & b > 1, \end{cases} \tag{24} \]

\[ m_i = \begin{cases} b(I - b/2), & 0 \leq b \leq I, \\
I^2/2, & b > I, \end{cases} \tag{25} \]

where \( S_{\text{eff}} \) is the effective cross-sectional area given by \( S_{\text{eff}} = 4ad/\lambda = 2ag \).

The single pancake (SP) coil wound using the two-ply conductor is considered in this article approximately as an assemblage of closed loops corresponding to individual turns. As discussed in section 3, the total AC losses \( Q_{\text{total}} \) in the HTS inserts composed of the SPs are estimated by

\[ Q_{\text{total}} = NC \sum_{j=1}^{C} \left( P_{\text{bundle}}^{(j)} + \frac{P_{\text{slab}}^{(j)}}{\lambda} \right) V^{(j)}, \tag{26} \]

where \( N \) is the number of turns per SP, \( C \) the number of SPs, \( V^{(j)} \) \((= 8\pi a d r^{(j)})\) the volume of SC layers in the \( j \)-the turn and the superscripts \( (j) \) represent the parameters in the \( j \)-the turn. On the other hand, the axial magnetic field \( B_s \) at the origin generated by the magnetic moments per unit length in the \( r \)- and \( z \)-direction, \( m_r \) and \( m_z \), placed at the position \((r, z)\) is given by [11, 12]

\[ B_s = \frac{3\mu_0 r^2 (m_r z - m_z r)}{2 \left(r^2 + z^2\right)^{5/2}}. \tag{27} \]

Therefore, the SCF at the center of HTS insert, which is set at the origin, can be estimated by

\[ B_{\text{SCF}} = \sum_{j=1}^{NC} B_s^{(j)}. \tag{28} \]

If the winding diameter of HTS insert is relatively large, \( m_r = m_{\text{slab}} \) and \( m_z = m_{\text{bundle}} \) could be applied approximately.

3. Finite element analysis of AC losses in stacked two-ply conductors

In order to evaluate the influence of the radial component of an applied magnetic field on the magnetization in a pancake coil, the electromagnetic-field distribution in a bunch of stacked two-ply conductors is numerically calculated by means of a finite element method (FEM) [13, 14]. Figure 3 shows the schematic illustration of two-dimensional numerical analysis model for the FEM, where a part of single pancake coil with 219 turns is modelled. Since the thickness corresponding to eleven two-ply conductors under consideration is much smaller than the radius
of winding, it is assumed that the conductors in the analysis model are infinitely long in the z-direction. Eleven two-ply conductors with the width of \(2a = 5\) mm are arranged in parallel with the stacking pitch of \(g = 420\) \(\mu\)m. A copper layer with the thickness of \(w = 50\) \(\mu\)m is located between the SC layers in every two-ply conductor. The x- and y-axes are parallel to the stacking direction and the broad face of the conductor, respectively. The external magnetic field with the x- and y-components, \(B_x\) and \(B_y\), is applied to the bunch of stacked conductors. The transport current is not taken into account here because the contribution of the transport current to the AC loss is slight due to a small load factor as discussed later. The numbering for individual two-ply conductors in the stacked bunch is carried out in series from the left (#1) to the right (#11). The thicknesses of the SC layers used for the numerical analysis are virtually enlarged up to \(kd\) that is \(k\) \((\gg 1)\) times as large as the actual thickness of the SC layer, \(d = 2.5\) \(\mu\)m, because the CPU (central processing unit) time consumed for calculation can be suppressed by reducing the total number of discretized elements. In order to keep the influence of such a treatment on obtained numerical results as few as possible, the critical current density for the numerical analysis is decreased down to \(J_c/k\) that is \(1/k\) times as small as the actual one \(J_c\). As a result, the full penetration field \(B_p = \mu_0 J_c d/2\) in the SC layer exposed to an external magnetic field parallel to its broad face is unchangeable. The fixed parameter of \(k = 20\) is used in this study.

The numerical calculation conditions are listed in table 1. Three representative positions inside the HTS insert composed of 68 SP coils with 219 turns are extracted. The actual helical windings in the pancake coils are regarded as assemblages of closed loops of individual turns in this article. The numbering for the SPs in the HTS insert is carried out in series from the top (#1) to the bottom (#68). On the other hand, the numbering for the closed loops in the SP is from the innermost (#1) to the outermost (#219). Both the LTS coils and the HTS insert are simultaneously and monotonically energized up to the central field of 25.5 T in 60 minutes. Condition 1 corresponds to a position at the center of two-ply conductor (pancake #1 and turn #145) exposed to the largest radial component of maximum magnetic field (4.75 T). Conditions 2 and 3 are positions at the centers of #6-turn two-ply conductors (pancakes #1 and #9) exposed to the maximum radial fields of about 3 and 1.5 T, respectively, placed close to the innermost turns. The field dependence of the critical current density is taken into account [15]. The resistivity \(\rho\) of copper is assumed to be 0.01 \(\mu\)\Omegacm.

In order to confirm the effect of increasing thickness of the SC layer on the calculated result in
Table 1. Numerical calculation conditions.

| Parameter                                      | Condition 1 | Condition 2 | Condition 3 |
|------------------------------------------------|-------------|-------------|-------------|
| Ordinal number of target pancake               | #1          | #1          | #9          |
| Ordinal number of target turn                  | #145        | #6          | #6          |
| Parallel component of maximum applied field     | 14.38 T     | 18.33 T     | 22.30 T     |
| Perpendicular component of maximum applied field| 4.75 T      | 3.01 T      | 1.48 T      |

Figure 4. Theoretical curves of AC loss components for condition 1 in two-ply conductors with superconductor thicknesses of (a) $d = 2.5 \mu m$ and (b) $kd = 50 \mu m$. The transport currents are also monotonically increased up to its maximum of 270 A. The symbols in (b) represent the numerical results of AC losses in the stacked two-ply conductors obtained from the finite element method without the transport current exposed to the parallel magnetic field.

advance, the AC losses are estimated by using the theoretical expressions, equations (9)–(12) and (20)–(22), described in section 2. The calculated results of loss components for the condition 1 are drawn using various lines in figure 4, where the transport currents are also monotonically increased up to its maximum of 270 A. The thicknesses of SC layers are set as $d = 2.5 \mu m$ and $kd = 50 \mu m$ in figures 4(a) and (b), respectively. By comparing both the results, every loss component, $p_3$, $p_e$ or $p_i$, is equal to each other, and therefore is not affected by the increase in the thickness of SC layer. On the other hand, the loss component, $p_1$ or $p_2$, varies with depending on the thickness and simply becomes $k$ times larger than that for the thickness $d$. These changes of loss properties should be taken into account carefully when the actual AC losses in the two-ply conductor with the thickness $d$ of SC layer are considered on the basis of the numerical results for the thickness $kd$ carried out in the forthcoming paragraphs of this section.

The symbols in figure 4(b) represent the numerical results of AC losses in the stacked two-ply conductors obtained from the FEM without the transport current exposed to only the parallel magnetic field $B_y$. Only the numerical results for the conductors #1 and #6 are plotted because the parallel-field losses in all the conductors almost agree with one another. The losses in the copper parts are in the order of $10^{-10}$ times as compared with those for the SC layers, so that
they are negligible. It is found that the numerical results can be reproduced well with the theoretical expressions (9)–(12) derived in this article. This means that the expressions (9)–(12) are very useful to estimate the parallel-field loss in the two-ply conductor.

The numerical results for the bunch of stacked two-ply conductors exposed simultaneously to both the parallel and perpendicular magnetic fields, $B_y$ and $B_x$, are shown in figure 5. Only the AC losses in the individual two-ply conductors from #1 to #6 are plotted for the sake of symmetry. In the case of the condition 1 shown in figure 5(a), the AC losses increase monotonically in the beginning of the excitation, and then starts to decrease after becoming local maxima around 5 minutes. After that, the AC losses rebound and become maxima around 30 minutes, and turn to decrease again. The first and second peaks of AC losses mean that the parallel and perpendicular applied fields reach average full penetration fields, respectively, and the AC losses after the peaks decrease with the critical current density. In the case of the condition 2 shown in figure 5(b), the perpendicular field reaches the average full penetration field around just ending of the excitation. On the other hand, only the parallel applied field reaches the average full penetration field in the case of the condition 3 as shown in figure 5(c).

The comparison among the AC losses in the individual conductors in figure 5 indicates that the losses in the conductor #1 are the largest especially after the first peak due to the edge effect.

![Figure 5](image)

**Figure 5.** Comparison among numerical and theoretical results of AC losses for individual two-ply conductors in stacked bunch without transport current exposed to external magnetic fields of (a) condition 1, (b) condition 2 and (c) condition 3. The symbols represent the numerical results of AC losses calculated using the FEM, whereas the curves are the AC losses obtained from the theoretical expressions.
effect. The influence of the edge effect in the conductors #5 and #6 is negligible because their AC losses have a good agreement with each other.

The dotted lines in figure 5 represent the parallel-field losses in the two-ply conductor estimated from the derived theoretical expressions (9)–(12), which matches the numerical results in the beginning of the excitation well, so that the parallel-field losses are dominant at first. After that, the perpendicular-field losses become dominant. If the simple sums of the parallel- and perpendicular-field losses estimated using equations (9)–(12) and (20)–(22), respectively, are compared with the numerical results, the loss properties qualitatively agree with each other. The reason why the quantitative deviations between them occur is that it is easy for the perpendicular applied fields to penetrate into the superconductors due to the demagnetizing effect because the total thickness of stacked bunch in the $x$-direction used for the numerical analysis is 4.35 mm, which is comparable to the tape width $2a = 5$ mm. Therefore, the total AC loss in the HTS insert wound using the two-ply conductor is evaluated in section 4 from the simple sum of the parallel- and perpendicular-field losses as similar to that for the single-tape conductor [7].

4. Evaluation of AC losses and SCFs in HTS inserts

The specifications of HTS inserts to evaluate the AC losses and SCFs are listed in table 2. The HTS inserts wound using the two-ply conductors are an almost same size as that for the single-tape conductor [7]. However, the number $N$ of turns per SP and the operating current of HTS insert are changed into half and double, respectively. The eddy current losses in the copper are not taken into account here because they are negligible as described in section 3. Figure 6 shows the time evolution of only the parallel-field losses in the HTS inserts wound using the two-ply conductors estimated from equations (9)–(12) and the first term on the right-hand side of equation (26) as compared with that for the single-tape conductor [7]. The gap between the SC layers in the two-ply conductor, $w$, is set as 0, 25 or 50 $\mu$m. The parallel-field losses in the HTS inserts wound using the two-ply conductors become maximum at about 10 minutes, when the external fields reach average full penetration fields in the two-ply conductors. After that, the losses monotonically decrease with the critical current density. The increasing rates of the parallel-field losses in the HTS inserts wound using the two-ply conductors exposed to relatively high applied fields on the basis of that for the single-tape conductor can be explained

| Parameter                          | Single-tape conductor | Two-ply conductor |
|-----------------------------------|-----------------------|-------------------|
| Width of SC layer, $2a$           | 5 mm                  | 5 mm              |
| Thickness of SC layer, $d$        | 2.5 $\mu$m            | 2.5 $\mu$m        |
| Gap between SC layers, $w$        | —                     | 0, 25, 50 $\mu$m  |
| Number of SPs, $C$                | 68                    | 68                |
| Number of turns per SP, $N$       | 438                   | 219               |
| Winding pitch of turns in SP, $g$ | 0.21 mm               | 0.42 mm           |
| Inner radius of HTS insert        | 48 mm                 | 48 mm             |
| Outer radius of HTS insert        | 140 mm                | 140 mm            |
| Height of HTS insert              | 393.6 mm              | 393.6 mm          |
| Operating current of HTS insert   | 135 A                 | 270 A             |
| Excitations of LTS coils & HTS insert | Simultaneous         | Simultaneous     |
| Excitation time up to 25.5 T      | 60 min.               | 60 min.           |
Figure 6. Time evolution of parallel-field losses in HTS inserts wound using two-ply conductors as compared with that for single-tape conductor.

Figure 7. Time evolution of total AC losses in HTS inserts wound using two-ply conductors as compared with that for single-tape conductor.

Figure 8. Time evolution of screening-current-induced fields in HTS inserts wound using two-ply conductors as compared with that for single-tape conductor.

Theoretically from equation (15).

Figure 7 shows the time evolution of total AC losses in the HTS inserts wound using the two-ply conductors estimated from equations (9)–(12), (20)–(22) and (26) as compared with that for the single-tape conductor [7]. It can be seen in the cases of the HTS inserts wound using the two-ply conductors that the parallel-field losses are dominant in the beginning of excitation. After that, the perpendicular-field losses, which are almost identical to that for the single-tape conductor because they are not affected by assembling two coated conductors face-to-face, become dominant after about 30 minutes, so that the total AC losses increase gradually. In the case where the gap between the SC layers, \( w \), is 50 \( \mu \text{m} \), the maximum of the total AC loss is estimated as about 20 W, which is about three times as large as that for the single-tape conductor. If the temperature rise due to the estimated total AC loss is permissible, the HTS insert could be cooled continuously by using prepared cryocoolers.
Figure 8 shows the time evolution of SCFs in the HTS inserts wound using the two-ply conductors estimated from equations (16)–(19), (23)–(25), (27) and (28) as compared with that for the single-tape conductor. In the cases of the two-ply conductors, it is found as similar to the total AC losses shown in figure 7 that the contribution from the parallel components of magnetic moments is dominant in the beginning of excitation, and that the SCFs become positive. After that, the contribution from the perpendicular components of magnetic moments becomes dominant, so that the SCFs become negative.

5. Conclusion
The AC losses and SCFs in the HTS inserts for high field magnet composed of the stacked pancake coils wound using the two-ply conductors were estimated numerically. The sharing of the applied transport current between two SC layers in the two-ply conductor exposed to the changing external applied magnetic field was considered. The theoretical expressions of AC loss and SCF were derived from the profiles of magnetic fields inside the two-ply conductor. In order to evaluate the influence of the radial component of applied magnetic field on the magnetization in the pancake coil, the electromagnetic-field distribution of stacked two-ply conductors exposed to only the external field was calculated by means of the two-dimensional finite element analysis. The total AC losses in the two-ply conductors located inside the bunch of stacked conductors a little far from its flat edges could be estimated roughly by the simple sum of the parallel- and perpendicular-field losses due to the magnetic interaction between the conductors. In the case where the gap between the SC layers was 50 μm, the maximum of the total AC loss was estimated as about 20 W, which was about three times as large as that for the single-tape conductor. The SCF at the center of the HTS inserts wound using the two-ply conductors became negative just after the end of excitation mainly due to the radial components of magnetic moments.

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