Improvement of coil performance by optimal use of multifilamentary superconducting tapes

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Abstract. It was theoretically confirmed that improvement of superconducting-coil performance can be obtained by making optimum use of multifilamentary tapes with high aspect-ratio cross-sections. Superconducting tapes, such as NbTi and MgB₂ multifilamentary tapes, are known to have anisotropic electromagnetic properties, i.e., critical current densities and ac losses; under external transverse magnetic fields which are parallel to the tape face, the critical current density is higher than that of the multifilamentary round wire, but the ac loss is lower. For tapes with a high aspect-ratio cross-section, the anisotropic properties are still more remarkable, and therefore it is predicted that such a tape with superior electromagnetic properties will prove valuable as the windings of high performance coils for practical applications. In this paper, some examples of coil arrangements such as single or plural solenoid coil systems are shown in order to highlight the usefulness of this superior tape performance. The effect of the high aspect-ratio of tape cross-section on the electromagnetic coil performance was also discussed, taking the cooling condition of coil windings into account.

1. Introduction

Low temperature superconductors (LTS) such as NbTi and Nb₃Sn have been used in a multifilamentary wire shape for practical applications such as magnetic resonance imaging (MRI) systems, nuclear magnetic resonance (NMR) spectroscopy, accelerators, and the newly developed MgB₂ is also expected to be used in the same shape. Most LTS conductors composed of many strands, i.e., these multifilamentary wires, are formed into a Rutherford cable or a cable-in-conduit (CIC) conductor in order to achieve the high current capacities of the magnet winding used for these applications. None of these conductors can attain both low ac losses and high stability because these two characteristics have been mutually exclusive in almost all superconducting coils.

Recently, a new conduction cooling type of NbTi pulse coil used for the uninterruptible power supply (UPS) superconducting magnetic energy storage (SMES) was successfully developed by Mito and his group [1], [2], to which two authors of this paper belong. They solved the difficult problem of the above-mentioned dilemma by controlling the twist angle of the cylindrical conductor during the winding process; the direction of local magnetic fields at windings was adjusted to the edge-on direction of the NbTi Rutherford cable which was put at the center of the conductor, and as a result the time-varying magnetic field did not produce such high ac losses even in high-stability conductors.

In our previous paper [3], NbTi/Cu multifilamentary tapes with high aspect-ratio cross-sections were fabricated and tested particularly for their anisotropic electromagnetic properties such as critical currents, hysteresis losses, and coupling losses. These tapes are a candidate for use in a main part of NbTi conductors and are proposed as suitable for the winding of conduction cooled NbTi pulse coils.
These newly optimized tapes were obtained by the cold rolling process from multifilamentary wires. Figure 1 shows photographs of the wire and obtained tapes with a tape cross-section aspect-ratio $a_t$ of 7.4. For the edge-on (EO) transverse magnetic field at 4.2 K, some 20% increase in critical current densities at 6 T was observed for the tape, and its hysteresis losses estimated from the observed magnetization were reduced to approximately one-half of those in the wire. In the EO field condition, the observed coupling losses in the tape decreased to some 1/17 times as large as those in the wire. On the other hand, for the flat-on (FO) transverse magnetic field, these properties became worse than those of the wire. These experimental results showed that the NbTi/Cu multifilamentary tape had strong anisotropy of electromagnetic properties such as critical currents, hysteresis losses, and coupling losses.

We also obtained remarkable results on the MgB$_2$ multifilamentary tape with high aspect-ratio cross-sections (partly on the MgB$_2$ monofilament tape) [4]; The experimental results showed that the MgB$_2$ multifilamentary tape had strong anisotropy of electromagnetic properties such as critical currents, hysteresis losses, and coupling losses. Improved performance was also predicted for MgB$_2$ multifilamentary tapes subjected to EO transverse magnetic fields as well as for NbTi multifilamentary tapes.

The purpose of this paper is to clarify theoretically that an improvement of NbTi or MgB$_2$ superconducting-coil performance can be obtained by optimal use of multifilamentary tapes with high aspect-ratio cross-sections, without controlling the twist angle of the cylindrical conductor during the winding process. The coil performance is generally affected by not only electromagnetic properties of coil windings but also by their cooling conditions. In this paper, therefore only two limiting cases for cooling conditions are discussed in order to simplify the subsequent discussions and focus on the relevant criterion. The first is a superior cooling condition (named ‘Cooling condition 1’), where temperature rises can be ignored due to effects such as high thermal diffusivity or a high specific heat of coil structural materials even where high ac losses are induced in windings. The second is the local adiabatic cooling condition (named ‘Cooling condition 2’), where temperature rises at any part of coil windings are determined only by the heat capacity of winding materials because each part is considered thermally insulated from neighboring parts and surroundings. Considering that the real cooling condition exists between these two limiting cases, the knowledge obtained by these two scenarios generates sufficient information for the present purpose.

2. Single solenoid coils wound with either NbTi multifilamentary wires or tapes
For the sake of performance comparison between various coils, we shall first consider the reference coil wound with NbTi multifilamentary wires (named ‘RC-NT’), which is a single solenoid coil with the special size ratios among the inner diameter, the outer diameter and the coil length, i.e., 3:5:4; In such a special size ratio coil, the maximum magnetic field obtained at the winding near the coil bore has the smallest value under the condition in which the total winding length is fixed [1].

In order to show examples of coil performance improvement, a small size coil as shown in figure 2 (a), i.e., the inner diameter, the outer diameter and the coil length were 120mm, 200mm and 160mm, respectively, was adopted; these absolute values of coil sizes do not affect experimental conclusions as long as the special size ratios are kept. The main reason for selecting the relatively small size of coil is...
to facilitate subsequent experiments to confirm the theoretical result obtained in this paper. (Experimental results will shortly be submitted elsewhere.).

In this section, performance of single solenoid coils wound with NbTi multifilamentary tapes with high aspect-ratio cross-sections is discussed, comparing the performance of RC-NT, where all coils have the same size as that of RC-NT. Flat-wise winding is adopted for all coils wound with tapes. As is shown later, we shall introduce the imaginary coil (named ‘IC-NT’) which is wound with NbTi multifilamentary tapes by controlling the twist angle around the longitudinal tape axis; as the result the direction of local magnetic fields at windings was adjusted to the EO direction of the tape. In IC-NT, we ignore spaces in coil winding cross-section needed for controlling the twist angle, and therefore we cannot realize the coil. When we have to distinguish between IC-NT and the conventional flat-wise wound coil in figures, we denote the latter coil as ‘FC-NT.’

2.1. Specifications of NbTi multifilamentary wires and tapes

As windings of the single solenoid coil shown in figure 1, we selected the parameters of both NbTi multifilamentary wires and tapes based on the data obtained for the electromagnetic properties of the wire and the tape deformed from the wire [3]. Table 1 shows main specifications of the original multifilamentary wire.

In figure 3, characteristic curves of critical currents vs. cross-section aspect-ratios of tapes are shown for cases of both EO and FO transverse magnetic fields, where these curves have the closest fit

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**Figure 2.** Dimensions of model coils introduced to discuss improvement of coil performance by optimizing use of multifilamentary tapes; (a) single solenoid coils, and (b) plural solenoid coils composed of a main-coil placed at the centre and two sub-coils placed on both sides.

| Table 1. Specifications of NbTi multifilamentary wires |
|---------------------------------------------|
| Wire diameter | 1.24 mm |
| Filament diameter | 16 μm |
| Number of filaments | 1767 |
| Copper/NbTi ratio | 2.4 |
| Twist pitch | 27 mm |
| Critical current at 6 T, 4.2 K | 861 A |
to the observed data in [3] and the suffixes ‘t’ and ‘w’ represent properties for tapes and wires, respectively. In order to estimate the temperature and the magnetic field dependences of the critical current of wires and tapes, we shall use the following relations:

\[
I_c = J_{cf} S_f = \alpha(T) B^{\gamma-1} \left[ 1 - \frac{B}{B_{c2}(T)} \right]^\delta S_f;
\]

\[
\alpha(T) = \alpha(T_0) \frac{T_c - T}{T_c - T_0}, \quad B_{c2}(T) = B_{c2}(0) \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right],
\]

where \(J_{cf}\) and \(S_f\) are critical current densities and total cross sections of filaments, respectively; \(T\) is the temperature, \(T_0 (=4.2 \text{ K})\) is the temperature under normal coil operations. \(B_{c2} (=13.5 \text{ T})\) is the upper critical magnetic field and \(\mu_0\) is vacuum permeability. In equation (1), \(\alpha, \gamma (=0.5)\) and \(\delta (=1)\) are pinning parameters of the critical state model defined for type II superconductors; the dependence of \(\alpha\) (4.2 K) on the filament cross-section aspect-ratio \(a_f\) is shown in figure 4, where empirical relations of cross-section aspect-ratios between tapes and filaments, i.e., \(a_t=6a_f-5\), were adopted for the present estimation.

2.2. Operating conditions of the coil

As an operating condition of the coil used for theoretical analyses, we selected an energy dump process with a linear sweep from a level of energy stored in coils to just half that level during a decay time of 1 sec. Transport current flowing in the coil winding linearly decays from 90 amps to 63.6 amps during the 1 sec period, and at that time the maximum magnetic field changes from 2.28 T to 1.61 T. For Cooling condition 1, the temperature of coil windings is kept to be the liquid helium temperature, i.e., 4.2 K, during the energy dump. On the other hand, for Cooling condition 2, the temperature changes from 4.2 K to higher temperatures. This is determined by the heat generation due to the coupling losses induced in the windings because the hysteresis loss can be neglected in pulse coil operations with a decay time of 1 sec.
2.3. Critical currents of NbTi coils and coupling losses induced in coil windings
Fundamental to calculating critical currents of NbTi coils, the profile of local magnetic fields at all positions of winding needs to be well-known. By using this profile for Cooling condition 1, the critical current of coils can easily be obtained from the magnetic field dependence of critical current densities of wires or tapes as shown in figure 3. Because of the existence of the anisotropic critical current density, the smaller value of critical current densities of the two different directions of transverse magnetic fields, EO or FO, decides the coil critical current.

In contrast, for Cooling condition 2, additional information on both the heat generation and the heat capacity of the coil winding are needed for the estimation of the temperature rise of coil windings. The residual procedure to estimate coil critical currents is the same as that for the case of Cooling condition 1.

In cases when external transverse magnetic-fields are decreasing with a linear sweep rate of \(dH_e/dt\), coupling loss power induced in the multifilamentary tape with rectangular cross-sections, \(P_{cr}\), is given by

\[
P_{cr} = \frac{1}{480} \frac{(7a_i^2 + 20a_i + 35)a_i^2}{(a_i + 1)^2} L_s \sigma_i \mu_0^2 \left(\frac{dH_e}{dt}\right)^2,
\]

where \(L_s\) is the twist pitch, \(\sigma_i\) is the transverse conductivity. The heat generation estimated from the amount of coupling losses produced during the 1 sec period increases the winding temperatures for adiabatic cooling conditions, where hysteresis losses can be neglected for pulse coils as shown in [2]. The dependence of coupling losses on the cross-section aspect-ratio \(a_i\) is shown in figure 5, where the vertical axis is normalized by the value for the reference coil wound with NbTi multifilamentary wires; RC-NT. Figure 5 represents that the coupling loss shows a big increase with an increase in \(a_i\).

Calculation of the temperature rise to estimate coil critical currents for Cooling condition 2, needs not only the dependence of coupling losses on the cross-section aspect-ratio \(a_i\) shown in figure 5 but also the absolute value of the loss. If we adopt the parameter of wires and tapes such as \(L_s\) and \(\sigma_i\) just as those of trial samples fabricated in [3], i.e., \(L_s=27\) mm and \(\sigma_i=2.2\times10^9\) S/m (this value corresponds to the conductivity of half-hard copper with RRR=45 at 2.2 T), the obtained result on coil critical currents becomes trivial from the point of view of the present purpose as shown in figures A1 and A2 in the Appendix. Therefore, as an example we shall assume that the value of \(L_s^2 \sigma_i\), which determines the absolute value of coupling losses, is 1/8 times as large as that given by using the upper value.

(Hereafter, we use the 1/8 time value of \(L_s^2 \sigma_i\) except in the Appendix.) As a result, the dependence of coil critical currents on the cross-section aspect-ratio \(a_i\) of NbTi multifilamentary tapes became significant as shown in figure 6, where the coil critical current is normalized by the value for RC-NT, the solid line and the dotted line represent the result for the flat-wise wound coil; FC-NT and the imaginary coil; IC-NT, respectively. As shown in figure 6, FC-NT has considerable difference between the two cooling conditions. For Cooling condition 2, the normalized critical current of coils is larger than 1.0 only for small \(a_i\). The normalized critical current of coils increases along that of IC-NT for a smaller value of \(a_i\) than \(a_i=3\) which gives its peak. On the other hand, for the Cooling condition 1, the critical current of coils is monotonically increasing with \(a_i\), however its value is 1.03 at most for \(a_i=7\). We can reasonably say that extremely small losses for the imaginary coil; IC-NT are the main origin of large values of normalized critical current of coils for larger values of \(a_i\) as shown in figure 6.

Analysing the obtained results in this subsection, it seems difficult to enable a clear performance improvement of single solenoid coils wound with NbTi multifilamentary tapes with high aspect-ratio cross-sections although we adopted the 1/8 time value of \(L_s^2 \sigma_i\).
3. Plural solenoid coils wound with both NbTi multifilamentary wires and tapes

In order to produce a more considerable improvement of coil performance, we shall consider the plural solenoid coil as shown in figure 2 (b), which is composed of a solenoid main-coil with both the special size ratio and relatively small sizes compared with RC-NT and two additional solenoid sub-coils required to reduce transverse magnetic fields applied in the face-on (FO) direction to the tape of the main-coil wound flat-wise, without controlling the twist angle of the tape such as IC-NT. Three coils are connected in series and, therefore, are energized by the same transport current. The size of each coil was selected under the condition that the whole stored energy of these plural solenoid coils is almost equal to that of the single solenoid coil discussed in the previous section. The inductances of the two model coils are some 1.45 H. Their outer size is also the same; however the height of the plural solenoid coils is about twice that of the single solenoid coil. It must be noted that the volume of superconducting materials of this plural solenoid coil is 1.27 times as much as that of the single solenoid coil, which will be discussed in subsection 3.2 in detail.

In this section, specification of NbTi multifilamentary wires and tapes used as the coil winding and transport current conditions of theoretical analyses are the same as those defined in the previous section.

3.1. Critical currents of NbTi coils and coupling losses induced in the coil

The dependence of coupling losses on the tape cross-section aspect-ratio \( a_t \) is shown in figure 7, where the vertical axis is normalized by the value for RC-NT. From this result, the obtained dependence of coil critical currents on the cross-section aspect-ratio of NbTi multifilamentary tapes used for the main-coil is shown in figure 8, where the coil critical current is normalized by the value for RC-NT. As shown in figure 8, similar differences between the two cooling conditions is also seen similarly to that shown in figure 6. For Cooling condition 2, the normalized critical current of coils is larger than cooling condition 1 over wide ranges of \( a_t \); the normalized critical current of coils has a peak around \( a_t =3 \). This corresponds to a dip of coupling losses shown in figure 7. On the other hand, for Cooling condition 1, the critical current of coils steadily increases from 1.06 for \( a_t =1 \) with an increase in \( a_t \), and its value becomes 1.09 for \( a_t =7 \).
3.2. Volume reduction of NbTi materials used as coil windings

As noted at the beginning of section 3, the demerit of a 27% increase in superconducting volume outweighs the gains achieved in both the coil critical current and the coupling loss. Therefore, in this subsection, we look for a more optimum design, and try to reduce the amount of superconducting material in the sub-coils. The focus is on the fact that critical currents in the sub-coil have a large margin when the main-coil reaches the critical current.

The coil critical current was estimated by using the load line drawn on the graph of currents vs. magnetic fields as shown in figure 9. Figure 9 shows an example of the procedure to determine the coil critical current by drawing graphs, where 4.2 K is the temperature of all coils before pulse operations, and 5.3 K and 4.6 K are the maximum temperature of the main-coil and the sub-coil due to the coupling losses induced by the pulse operations. In figure 9, the solid line represents the critical current of NbTi multifilamentary tapes with $a_t = 5$ or the load line for the main-coil. The broken line represents the critical current of NbTi multifilamentary wires or the load line for the sub-coil. The open circle represents the critical current of the main-coil, and the closed circle represents that of the sub-coil, from which we can find that the main-coil critical current dominates the critical current of the plural solenoid coil system as long as all coils are connected in series. In case where the sub-coil has enough current margin, we can reduce the superconductor volume used for the sub-coil. The dotted line shows the critical current of the reduced sub-coil with a 50% reduction of the amount of wires. The reduction corresponds to the reduction of wire cross-sections, and results in a 50% increase in space in the winding regions. By combining the reduced sub-coil with the main-coil, the critical current of both coils becomes equal as shown by the open circle and the open square, which results in the effective use of the current margin of the sub-coil to reduce the amount of superconducting materials.

Figure 10 shows the volume reduction ratio of superconducting wires for the reduced sub-coil. Figure 11 shows the total volume of the superconducting materials for the plural solenoid coil system with the reduced sub-coil, where the volume is normalized by that for RC-NT. Some 15% decrease in superconductor volumes were obtained for plural solenoid coils composed of both a main-coil wound with NbTi multifilamentary tapes of $a_t = 4$ or 5, and two reduced sub-coils wound with NbTi multifilamentary wires under various cooling conditions. As a result, coupling losses in the plural...
solenoid coil system with the reduced sub-coil become considerably smaller (figure 12) compared with the losses in the plural solenoid coil system with the normal sub-coil which was first introduced.

4. Single solenoid coils wound with either MgB$_2$ multifilamentary wires or tapes

In this section, we discuss performance of single solenoid coils wound with either MgB$_2$ multifilamentary wires or tapes. Specifications of MgB$_2$ multifilamentary wires and tapes are shown in the following subsection. The cooling condition is restricted to one limiting case (Cooling condition 1), because considerable, clear improvement of coil performance would appear in even the most

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**Figure 9.** Magnetic field dependences of critical currents of main-coils, sub-coils and reduced sub-coils, and their load lines for NbTi plural solenoid coils, where main coils are wound with wires and both sub-coils and reduced sub-coils are wound with tapes with $a_t = 5$.

**Figure 10.** Tape cross-section aspect-ratio dependences of NbTi wire reduction ratios in reduced sub-coils.

**Figure 11.** Tape cross-section aspect-ratio dependences of tape volumes of all NbTi plural solenoid coils, where their values are normalized by those of RC-NT.

**Figure 12.** Tape cross-section aspect-ratio dependences of coupling losses in all NbTi plural solenoid coils, where their values are normalized by those of RC-NT.
ineffective case (see subsection 4.2). The various conditions other than cooling conditions are the same as those define in section 2.

For the sake of performance comparison with various coils, we shall also define a reference coil wound with MgB$_2$ multifilamentary wires (named ‘RC-MB’). This is a single solenoid coil the same size as that of the reference coil wound with NbTi multifilamentary wires (RC-NT). The size of the single solenoid coils wound with MgB$_2$ multifilamentary tapes is also the same.

4.1. Specification of MgB$_2$ multifilamentary wires and tapes
In order to estimate performance of MgB$_2$ coils wound with multifilamentary wires and tapes, we shall consider the critical current property of the wire and the tape as shown in figure 13. The data used for figure 13 are not practically obtained but are deduced by using our recent experimental data on the MgB$_2$ multifilamentary wires and tapes [4] including MgB$_2$ monofilamentary wires and tapes [5]. Table 2 shows the specification of MgB$_2$ multifilamentary wires used for the calculation. From the characteristic curve of critical currents $I_c$ shown in figure 13, the characteristic curve of $a_t$(4.2 K) vs. $a_f$ can be estimated as shown in figure 14 by using empirical relations between $a_t$ and $a_f$, i.e., $a_t$=$0.5a_f+0.5$.

4.2. Expected improvement of coupling losses and critical currents of MgB$_2$ coils
The tape cross-section aspect-ratio $a_t$ dependence of coupling losses induced in the single solenoid coils wound with MgB$_2$ multifilamentary tapes for pulse operation can be deduced by the solid line shown in figure 5. In order to get absolute values of these losses, we have to substitute the loss value

| Wire diameter | 1.24 mm |
| Filament diameter | 130 μm |
| Number of filaments | 6 |
| Normal metal/ MgB$_2$ ratio | 12 |
| Critical current at 6 T, 4.2 K | 6.4 A |

**Figure 13.** Tape cross-section aspect-ratio dependences of critical currents of MgB$_2$ multifilamentary tapes normalized by those of wires, where ‘EO’ and ‘FO’ mean the edge-on and the flat-on directions of transverse magnetic fields, respectively.

**Figure 14.** Filament cross-section aspect-ratio dependences of a pinning parameter of MgB$_2$ multifilamentary tapes normalized by that of wires.
of RC-MB for the loss value of RC-NT. As already mentioned in subsection 2.3, the coupling loss shows a big raise with increase in $a_t$, therefore, considerable improvement of coil critical currents is required in order to get some benefit from making optimal use of MgB$_2$ multifilamentary tapes with high aspect-ratio cross-sections.

Figure 15 shows the expected improvement of critical currents of MgB$_2$ coils wound with tapes with various cross-section aspect-ratios $a_t$. The vertical axis is normalized by the critical current of RC-MB ($a_t = 1$). The obtained result shows that some 80% increases in coil critical currents can be expected for the extremely high cross-section aspect-ratio of $a_t = 5$.

5. Discussion

The results obtained in sections 2 and 3 on the improvement of coil performance by use of NbTi multifilamentary tapes with high aspect-ratio cross-sections are as follows:

(1) It is difficult to get clear performance improvement of single solenoid coils wound with the NbTi multifilamentary tape.

(2) A clear performance improvement can be expected for plural solenoid coils composed of both a main-coil wound with NbTi multifilamentary tapes and two sub-coils wound with NbTi multifilamentary wires. However, superconductor volumes are increased by some 30% in order to get significant benefit with regard to coil critical current and coupling loss.

(3) Superconductor volumes of the above plural solenoid coil can be inversely decreased by some 15% by introducing a reduced sub-coil with about half the current density of the normal sub-coil with the same current density as that of the main-coil.

These results were obtained for an example case in which transport currents flowing in all coil windings were changed from 90 amps to 63.6 amps during the 1 sec period, where maximum magnetic fields changed from 2.28 T to 1.61 T for single solenoid coils, and from 2.12 T to 1.50 T for plural solenoid coils. In order to see the effect of transport currents on these results, estimations of coil performance for cases of higher transport currents than the above are required. Figures 16-20 are the calculated results for transport currents changing from 150 amps to 106 amps during the 1 sec period, where figures 16-20 correspond to figures 6, 8, 10, 11 and 12, respectively. The figures obtained for the high transport current case show a similar tendency to those for the low transport current case.
6. Conclusion

In this paper, we estimated theoretically the improvement of coil performance by use of NbTi and MgB₂ multifilamentary tapes with high aspect-ratio cross-sections for single and plural solenoid coil system under two limiting cases of cooling conditions. The following remarkable results were obtained:

except for the remarkable point where optimum values of the tape cross-section aspect-ratio shift to the slightly lower side.
From 30% to 8% increase in coil critical currents, some 55% decrease in coupling losses and some 15% decrease in superconductor volumes were obtained for plural solenoid coils composed of both a main-coil wound with NbTi multifilamentary tapes of $a_t = 4$ or 5 and two reduced sub-coils wound with NbTi multifilamentary wires under various cooling conditions.

From 47% to 80% increase in coil critical currents was obtained even for single solenoid coils wound with MgB$_2$ multifilamentary tapes of $a_t = 3$ to 5 under the best cooling condition. In addition, the induced coupling loss increased by from 15% to 40%. A more remarkable result would be expected under worse cooling conditions or for a plural solenoid coil system.

From these theoretical results, we conclude that a large improvement of superconducting-coil performance such as critical currents and coupling losses can be obtained by making better use of the NbTi and MgB$_2$ multifilamentary tape with high aspect-ratio cross-sections.

Experimental confirmation of the present theoretical result is necessary. In addition, similar research for YBCO and BISCCO tapes to those for the NbTi and MgB$_2$ multifilamentary tapes shown in this paper should be followed up by considering both the differences of cross-sectional structure due to fabrication and the resultant characteristics of electromagnetic properties. The obtained results will be submitted elsewhere, along with experimental confirmation.

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Appendix

We show the preliminary results where the absolute values of coupling losses are obtained from equation (2) by using $L_s=27$ mm and $\sigma_i=2.2\times10^9$ S/m. Figure A1 and A2 correspond to figures 6 and 8. As seen in these figures, the coil performance improvement appears at smaller cross-section aspect-ratios of NbTi multifilamentary tapes than those shown in figures 6 and 8.

**Figure A1.** Tape cross-section aspect-ratio dependences of coil critical currents of single solenoid coils wound with NbTi multifilamentary tapes where $L_s=27$ mm and $\sigma_i=2.2\times10^9$ S/m. The vertical axis is normalized by those of RC-NT.

**Figure A2.** Tape cross-section aspect-ratio dependences of coil critical currents of plural solenoid coils wound with NbTi multifilamentary wires and tapes where $L_s=27$ mm and $\sigma_i=2.2\times10^9$ S/m. The vertical axis is normalized by those of RC-NT.