TFCX CURRENT DENSITY AND NUCLEAR HEATING LIMITATIONS
FOR SUPERCONDUCTING TOKAMAKS*

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ABSTRACT

A major goal of the Tokamak Fusion Core Experiment (TFCX) study was to minimize the size of the device and achieve lowest cost. Two key factors influencing the size of the device employing superconducting magnets are toroidal field (TF) winding current density and its nuclear heat load withstand capability. Lower winding current density requires larger radial build of the winding pack. Likewise, lower allowable nuclear heating in the winding requires larger shield thickness between the plasma and coil. To achieve a low-cost device, it is essential to maximize the winding's current density and nuclear heating withstand capability. To meet this objective, the TFCX design specification adopted as goals a nominal winding current density of 3500 A/cm² with 10-T peak field at the winding, peak nuclear heat load limits of 1 mW/cm³ for the nominal design and 50 mW/cm³ for an advanced design. This study developed justification for these current density and nuclear heat load limits.

INTRODUCTION

A value of 3500 A/cm² is about 75% higher than values used in past studies and is based on evaluation of a variety of approaches. The approaches include consideration of (1) use of forced-flow, Nb₃Sn conductors, similar to the Westinghouse Large Coil Program (LCP) conductor; (2) epoxy impregnation of the winding, which alters the load path and permits elimination of the co-wound structural material; (3) designing to 80% of the critical current instead of 67%, as previously done; (4) reacting the conductor after winding to anneal out induced strains; and (5) use of Incoloy instead of JBK-75 as the conduit. Incoloy has cooldown characteristics that closely match that of the Nb₃Sn, so the induced cooldown strain is decreased.

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In the nominal design, the Nb₃Sn conductor employs JBK-75 stainless steel conduit with a thickness of 1.7 mm and a void fraction inside the conduit of 32%. Peak nuclear heat load of 1 mW/cm³ can be removed by forced-flow helium entering at 4.2 K and exiting at 4.5 K. In the advanced design, with peak nuclear heating of 50 mW/cm³, the reasonable winding exit temperature is 5.5 K. To offset the degradation in critical current at the higher temperature, the void fraction is increased to 41% (from 32%) as an Incoloy conduit is used (in place of the JBK-75 conduit). The resulting conductor cross-sectional dimensions change slightly, but the winding current density remains about the same (3500 A/cm²).

This study concludes that the specified TF winding current densities are an aggressive step forward, but are realistically achievable using existing forced-flow, cable-in-conduit conductor or its variations.

During the development of the TFCX superconducting options, there was strong motivation to limit the radial build of the device in the centerpost region, because it is generally agreed that, to a first approximation, the cost of the device varies with the plasma major radius R_0 to a power between 2.5 and 3.0.

Methods for achieving a compact device include designing the TF coils for a high winding current density and a high nuclear heat load, the latter permitting a reduction in the inboard shield thickness. The conductor critical current is enhanced by lowering the operating temperature, whereas increased nuclear heat loads tend to lead to increased conductor temperatures. Consequently, the objectives of high current density and high nuclear heat are mutually conflicting.

The example problems considered in this paper assume use of a Nb₃Sn forced-flow conductor similar in size and void fraction to the Westinghouse LCP conductor. With a single grade of conductor, the TFCX design

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specification¹ winding current density of 3500 A/cm² at 10 T can be met using the present Westinghouse LCP conductor (with JBK-75 conduit), provided the conductor operating temperature is suitably controlled. If the conductor is reacted before winding, the maximum acceptable conductor temperature is 4.5 K. For a TFCX application, this limit can be satisfied with a reasonably straightforward helium manifolding arrangement if the nuclear heat load does not exceed 1 mW/cm³ (nominal design requirement). If the conductor is reacted after winding, a peak conductor operating temperature of 5.5 K is acceptable. At 12 T, the 2300-A/cm² design specification can be met with this conductor only if the conductor is reacted after winding and operated at a temperature of 4.2 K or lower.

If the JBK-75 sheath is replaced by an Incoloy 903 sheath, the cooldown contraction of the conductor composite closely approximates that of Nb₃Sn, so that the degradation of the critical current due to cooldown strain is greatly reduced. The absence of significant cooldown-induced degradation has been demonstrated by the Massachusetts Institute of Technology (MIT). The achievable current density as a function of peak conductor temperature at 10 T and at 12 T is summarized as shown in Fig. 1. It is clear that use of Incoloy in place of JBK-75, or use of the wind-and-react technique, increases the maximum temperature at which the design specification current density can be achieved.

With respect to maximum permissible nuclear heat loads, it is found that for practical helium manifolding arrangements (e.g., winding three-in-hand, a flow path length of four turns is about 72 m), approximately 10 to 12 mW/cm³ may be tolerated purely from a heat-removal standpoint. For more complex manifolding arrangements (e.g., cooling one turn or one-half turn in regions of peak nuclear heat), up to 75 to 100 mW/cm³ become possible. However, these nuclear heat loads entail conductor temperatures up to about 6 K, which degrade the critical current to the point at which the design specification current densities cannot be met. Detailed discussion on this subject is given in Ref. 2.

DISCUSSION

Feasibility of Grading Forced-Flow Windings

If a forced-flow winding is designed to have the same current in all turns, grading requires a transition in conduit cross section when changing from one conductor to another. Joint designs for achieving such cross-section transitions have not yet been developed and demonstrated. While grading is not out of the

Fig. 1. Achievable current density vs peak conductor temperature at 10 and 12 T.

question, it is far from being a state-of-the-art design technique for forced-flow windings. Consequently, the assumption of a graded winding for a near-term device is considered overly optimistic.

Average Winding Current Density vs Conductor Current

This study assumes use of a Nb₃Sn conductor having a void fraction of 32% and a cross-sectional area inside the conduit of 2.93 cm². These are the parameters associated with the Westinghouse LCP conductor (Fig. 2).

Figure 3 shows the average winding current density compared to conductor current for a design developing a peak field of 10 T at a radius of 1.7 m [representative of an early TFCX-S (all-superconducting 1F coil) design]. Figure 4 shows a similar curve for a 12-T peak field at a radius of 2.4 m. In each of these designs, a single grade of conductor is used.

The 10-T examples use a conduit thickness of 2 mm (compared to 1.7 mm in the Westinghouse LCP), whereas the 12-T examples use a jacket thickness of 3 mm and an inside surface bend radius of 6 mm. The conduit wall thickness is

CONDUCTOR DIMENSION OUTSIDE CONDUIT	2.19 cm
CONDUIT THICKNESS	1.70 mm
CROSS-SECTIONAL AREA INSIDE CONDUIT	2.93 cm ²
VOID FRACTION	32%
NUMBER OF STRANDS	1458
STRAND DIAMETER	0.70 mm
HYDRAULIC DIAMETER	0.40 mm

Fig. 2. Westinghouse LCP coil conductor.

Fig. 3. Average current density vs conductor current at 10 T.

determined from the combined stress state due to transverse compressive winding loads and longitudinal dilational tensile loads. A conduit wall thickness is selected to meet established structural design criteria, to withstand realistic quench pressures, and to conform to conduit thickness limitations related to manufacturing considerations.

Fig. 4. Average current density vs conductor current at 12 T.

The selection of the actual conductor operating current depends upon the critical current, which is a function of many variables:

- maximum field;
- residual compressive cooldown strain in the conductor;
- choice of jacket material and heat treatment, both of which affect the residual cooldown strain;
- strain level developed in conductor being bent into the minimum radius of curvature during coil winding, which can be relieved if the conductor is reacted after winding; and
- strain level in conductor resulting from operating loads.

Determination of an appropriate operating current, and the average winding current density resulting from that choice, are discussed next.

Analysis of Critical Current Data

Figure 5, which is reproduced from Ref. 3, shows the critical current of 4.2-K samples of Westinghouse LCP conductor as a function of imposed tensile strain, for field levels of 8, 10, and 12 T. This conductor uses a JBK-75 conduit and is reacted for 30 h at 700°C.

At the 10-T field, the critical current is 24 kA with no imposed tensile strain and reaches 41 kA for an imposed tensile strain of 0.75%. The 0.75% imposed strain is therefore equal and opposite to the residual compressive strain due to cooldown plus winding; MIT has determined that the cooldown portion alone is -0.5%. A compressive strain of 0.75%, therefore, degrades the critical current to 59% of its value in the strain-free state (24 vs 41 kA). This fractional degradation is in reasonably good agreement with Ekin's strain scaling law given in Ref. 4:

Fig. 5. Critical current of the Westinghouse LCP conductor as a function of tensile strain.

$$\frac{I}{I_0} = \sqrt{1 - a|\epsilon|^{1.7}} \left[\frac{1 - \frac{B}{22(1 - a|\epsilon|^{1.7})}}{1 - B/22} \right] \quad (1)$$

where ϵ is the strain, $a = 900$ if $\epsilon < 0$, and $a = 1250$ if $\epsilon > 0$. For $\epsilon = -0.0075$ and $B = 10$ T, Eq. (1) gives $I/I_0 = 0.52$.

For a TFCX-size coil, the minimum radius of curvature imposed on the conductor during coil winding is about 1.5 m, corresponding to a bending strain in the conduit wall of about 0.7%. According to Ref. 3 (Vol. VI, Part 1, pp. 7-55), the strands experience about one-third the bending strain developed in the conduit, or about 0.23%. Furthermore, when the coil is energized, a dilational tensile strain of about 0.1% is developed. Thus, the net strain, including cooldown strain, is $-0.50 - 0.23 + 0.10 = -0.63\%$. Ekin's formula, with $\epsilon = -0.0063$ and $B = 10$ T, gives $I/I_0 = 0.64$. Under TFCX conditions, the critical current at 10 T becomes $0.64 \times 41 = 26.3$ kA at 4.2 K.

The maximum conductor temperature depends upon the amount of nuclear heat that the coil must withstand. A separate analysis has shown that for 1 MW/cm^3 (the nominal design value per Ref. 2), a temperature rise of about 0.5 K occurs. Reference 5 predicts that the critical current at temperature T degrades from its 4.2-K value by the fraction

$$\frac{I_c(B, T)}{I_c(B, 4.2)} = 1 - \frac{T - 4.2}{10.7 - 0.61B} \quad (2)$$

If helium enters at 4.0 K and exits at 4.5 K, then for $B = 10$ T, Eq. (2) gives a fractional degradation of 0.935, so that the critical current at 4.5 K is 24.6 kA. If the conductor current is set at 80% of the critical current, it follows that the Westinghouse LCP conductor, without modification, would operate in a TFCX application at 19.7 kA at 10 T. This corresponds to an average current density (with a single grade) of 3500 A/cm^2 , which meets the design specification.

One way to increase the critical current of the Westinghouse LCP conductor (with the present JBK-75 sheath material) is to react the conductor after winding. This process anneals out the strain introduced during winding, although cooldown compressive strain and tensile strain due to dilation remain during coil operation.

The critical current for wound-and-reacted, JBK-75-wrapped Westinghouse LCP conductor at 4.2 K is estimated by scaling down the peak critical current of 41 kA (with zero strain) by the degradation per Eq. (1) for $B = 10$ T and $\epsilon = -0.0050$ (cooldown) + 0.001 (dilation) = -0.0040 ; the result is $I_c = 34.2$ kA. Since an operating current of 19.7 kA is needed to achieve 3500 A/cm^2 , the critical current must not go below 24.6 kA. Therefore, a temperature degradation of $24.6/34.2 = 0.72$ is acceptable when the conductor is reacted after winding; this corresponds to a peak conductor temperature of 5.5 K.

References 6 through 9 describe recent work performed at MIT dealing with the effect on critical current of using different heat treatments and/or substituting Incoloy 903 for JBK-75 as the conduit material. Figure 6 summarizes critical current data gathered from these references. All the data shown in Fig. 6 are for 4.2-K operation, and therefore include the effects of cooldown strain.

There is a dramatic difference between the short-sample (10 cm) and the long-sample (375 cm) MIT data for JBK-75, although the long-sample results are not significantly different from the Westinghouse data. It would therefore appear that the MIT dual heat treatment in itself has a relatively minor impact on critical current and that the difference between short- and long-sample results for JBK-75 is due to effects related to specimen length.

The short-sample curves in Fig. 5 show that use of Incoloy 903 in place of JBK-75 offers a modest increase in critical current at fields of 10 T and higher. More importantly, however, the cooldown contraction of the Incoloy-wrapped conductor closely matches the cooldown contraction of Nb_3Sn , so that the

Fig. 6. Cable-in-conduit (32% void) conductor current vs field.

degradation due to cooldown contraction is small.³ The short-sample Incoloy 903 curve in Fig. 6 was used for the calculations. Degradation in the critical current is small for long samples.

At 10 T, the critical current of an Incoloy 903-wrapped conductor (at 4.2 K with cooldown strain only) is 37.5 kA. In the absence of a significant cooldown strain, the degradation of critical current may be estimated using Eq. (1) with $\epsilon = 0.0023$ (bending) + 0.0010 (dilation) = $+0.0033$; the result is $I/I_0 = 0.855$. If, as before, an operating current of 19.7 kA is needed to achieve 3500 A/cm², the required critical current of 24.6 kA can be attained under these conditions with a temperature-degradation factor as low as 0.78, corresponding to a peak conductor temperature of 5.2 K when the conductor is reacted before winding. In like manner, if the conductor is reacted after winding, the winding strain disappears and the maximum conductor temperature can be as high as 5.7 K.

A similar analysis of the critical current data has been made for each of the combinations of possible conditions:

- JBK-75 or Incoloy jacket (affects cooldown strain),
- React-and-wind or wind-and-react (affects winding strain), and
- 10- or 12-T peak field.

Figure 1 summarizes the attainable current density as a function of peak conductor temperature for each combination of peak field, jacket material and manufacturing sequence. The design specification current densities are shown for comparison. The curves afford a convenient method of comparing the current densities that result from each possible combination.

Permissible Nuclear Heat vs Cooling System Parameters

As the nuclear heat load rises, more and more helium must be circulated. Not only does this increasing mass flow increase pressure drops, but also the associated frictional heating increases the heat load further. In conventional piping system designs, these frictional heat terms are negligible, but in cryogenic systems, they are of the same order of magnitude as the imposed heat load. These heat loads limit the length of the coolant path and therefore affect the required number of coolant lines.

Permissible nuclear heat loads were determined some time ago, using a representative TF coil design that differs somewhat from the cases discussed in the previous section. The TF coil design studied here develops a peak field of 10 T using a single grade of conductor and operates at a winding current density of about 2850 A/cm². The conductor is a forced-flow design with 32% void fraction and a cross-sectional area inside the conduit of 5.2 cm² (vs 2.93 cm² in the Westinghouse LCP). The conduit thickness is 3 mm, and the inside corner bend radius is 6 mm. The radial build of the TF winding is 12 turns.

Several coolant-path lengths, corresponding to different manifolding arrangements, were considered. For each selected path length, the assumed nuclear heat load was gradually increased until it became impossible to select inlet helium conditions that would result in acceptable pressure drops and helium exit temperatures of 6 K or lower.

Helium outlet conditions were calculated using a computer program that accounts for spatial variation of the nuclear heat load around the perimeter of the TF coil and also accounts for attenuation of the nuclear heat load turn-to-turn. Pressure drops and frictional heat are calculated using the friction factor correlation in Ref 3. The program contains thermodynamic properties of helium as defined in Ref. 10.

A mean TF coil perimeter of 18 m was assumed, and coolant path lengths of one-half, one, and four turns were considered. The TF coil configuration has a radial build of 12 turns, and if it is assumed that the coil is

wound three-in-hand, a path length of four turns is considered about as simple a manifolding scheme as is reasonably achievable. The shorter path lengths represent more complex manifolding but offer the potential for higher incident nuclear heat.

Table 1 summarizes the maximum nuclear heat capability for three cooling system configurations (denoted A, B and C) that differ in flow path length and in helium inlet and outlet conditions. A nuclear heat level of 10 to 12 mW/cm³ appears feasible from a heat-removal standpoint for a practical manifolding arrangement, whereas up to about 100 mW/cm³ can be accommodated with many short helium flow paths. The nuclear heat load may be limited to lower values, however, to avoid unacceptable degradation of the critical current.

Table 1. Nuclear heat capability for several cooling system configurations

	Configuration		
	A	B	C
Number of turns in coolant path	4	1	1/2
Coolant path length, m	72	18	9
Helium inlet temp., K	4.2	4.2	4.2
Helium outlet temp., K	5.8	6.0	5.9
Helium inlet pressure, atm	9.0	8.0	10.0
Helium outlet pressure, atm	2.7	2.3	2.6
Helium flow rate per channel, g/s	15	30	50
Maximum nuclear heat, mW/cm ³	12	75	100

CONCLUSIONS

Maximum achievable current densities have been developed using a Nb₃Sn cable-in-conduit type of conductor. The recommended current densities were established by including effects of peak conductor temperature, cooling path length, conductor strain, conduit load-carrying capability, and peak nuclear heating. With a single grade of conductor, the TFCX design specification winding current density of 3500 A/cm² at 10 T can be met using the Westinghouse LCP conductor with JBK-75 conduit, provided that conductor temperature is maintained below 4.5 K.

With respect to maximum permissible nuclear heat loads, it is found that for practical helium manifolding arrangements (e.g., winding three-in-hand, a flow path length of four turns is about 72 m), approximately 10 to 12 mW/cm³

may be tolerated purely from a heat-removal standpoint. For more complex manifolding arrangements (e.g., cooling one turn or one-half turn in regions of peak nuclear heat), up to about 100 mW/cm³ become possible. However, these nuclear heat loads require conductor temperatures up to about 6 K, which would degrade the critical current to the point at which the design specification current densities could not be met.

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