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HIGH-PERFORMANCE TF COIL DESIGN FOR THE TOROIDAL FUSION CORE EXPERIMENT (TFCX)*

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Abstract

The Toroidal Fusion Core Experiment (TFCX) is a proposed concept for an ignited, long-pulse, current-driven tokamak device. TF coil winding cross section in the inboard region is impacted by peak field 10 T, winding current density ~3500 A/cm^2, and peak nuclear heating rates 50 mW/cc. The winding utilizes a Nb_3Sn internally cooled cable superconductor (ICCS), which is a modified version of the conductor used in the Westinghouse LCP coil. These modifications include the increase of void fraction from 32% to 41% of the cable space for withstanding higher nuclear heating rates and a thicker conduit wall to carry larger magnetic loads. The critical current of an Nb_3Sn conductor is strongly dependent on strain in the superconducting strands. The strain in strands is lower when the windings are (a) wound and then reacted (W/R), as compared to (b) reacted and then wound (R/W). The impact of these approaches on winding performance is discussed.

The windings are pancake wound and cooled with supercritical helium. The LHe inlet (~4 K) and outlet (~5.5 K) connections are located on the sides of the TF coils. The conductor design, the winding design, and performance analysis are described.

Introduction

The magnetic system of the TFCX consists of the toroidal field (TF) system, the poloidal field (PF) system, the associated support structure, and the cryostat. The configuration of the TF and PF coils for the high-performance case (50 mW/cc peak nuclear heating in the TF winding at the inboard region — R ~ 2 M) is shown in Fig. 1. There are 16 superconducting TF coils which operate at 10 T, with a winding current density of 3500 A/cm^2. A detailed discussion of the TFCX magnet system can be found elsewhere.[1]

This paper discusses the feasibility of the high-performance TF coil design using an Nb_3Sn ICCS conductor, which is a modified version of the conductor utilized in the Westinghouse Large Coil Program (LCP) coil.[2] The main challenges in the design are the adequate heat removal capability due to large nuclear heat loads (~50 MW/cc in the inboard region) and relatively higher winding current density (~3500 A/cm^2) under these operating conditions. The coils are required to remain superconducting during steady-state, and pulsed operating conditions. The winding has a stability margin of ~420 mJ/cc for safe and reliable operation of these coils. The structural support design for these coils is described elsewhere.[1]

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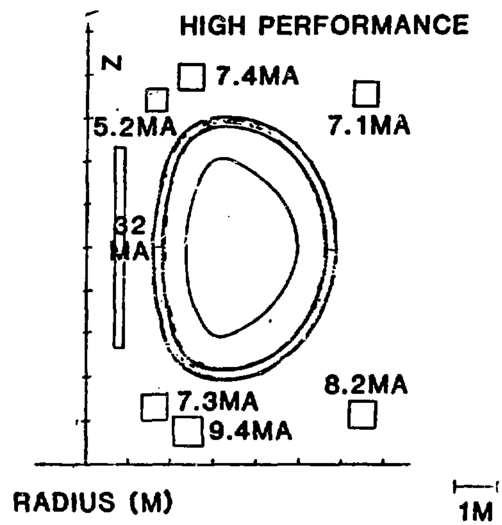

Fig. 1. TFCX poloidal field coil location.

Conductor Design Description

The specified winding current density of 3500 A/cm^2 at 10-T peak field is about 75% higher than achievable current densities in the past studies.[3] This value of specified current density is based on an evaluation of a variety of approaches, including considerations of (1) use of Nb_3Sn ICCS conductors similar to the Westinghouse LCP conductor,[2] (2) epoxy impregnation of the winding which alters the load path and permits elimination of the co-wound structural materials,[3] (3) design to 80% critical current instead of the 67% previously done, (4) winding and then reacting the conductor (W/R) to anneal out winding strains, (5) use of Incoloy instead of JBK-75 stainless steel[2] as the conduit material (Incoloy has cooldown characteristics that closely match that of Nb_3Sn so that the induced cooldown strain is decreased, resulting in a higher operating current), and (6) a larger helium cross-sectional area (41% of the cable space in the conductor instead of 32% as in the Westinghouse LCP conductor,[2] which increases the heat removal capability and reduces the pressure drop for cooling channels. The Nb_3Sn ICCS conductor utilized, with the modifications from the above considerations, is shown in Fig. 2, along with the critical current dependence on magnetic fields with Incoloy and JBK-75 conduits. The advantage of a higher critical current using Incoloy for conduit material is apparent from this figure.

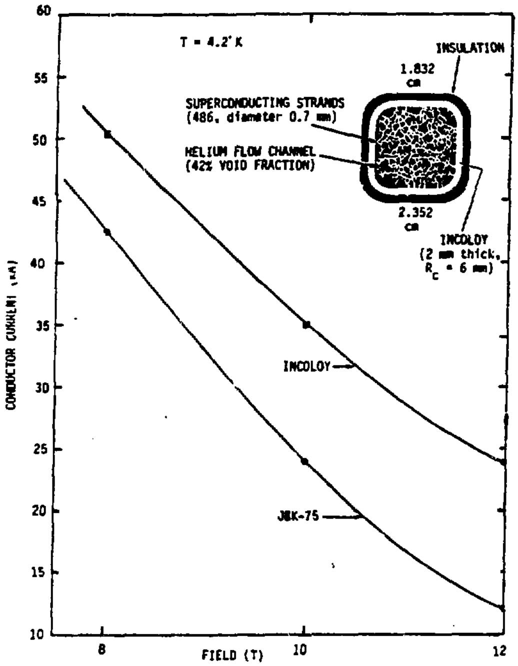

Fig. 2. Nb_3Sn ICCS conductor critical current as a function of field with JBK-75 stainless steel and Incoloy conduits.

The relevant parameters of the conductor are given in Table 1. The conductor consists of triplets of 486 Nb_3Sn strands loosely packed (41% void fraction) in an Incoloy conduit. The operating current is 20.3 kA, which is 80% of the critical current at 10 T and 5.5 K, corresponding to the operating conditions for the winding. The conduit thickness and the corner outer radii of 2 and 6 mm, respectively, were chosen to insure leaktight closure welds fabrication. The conductor can withstand a maximum quench pressure of 309 atm. The conductor is wrapped with a suitable insulating material (needs to be identified and developed) capable of withstanding a reaction temperature of ~750°C for several hours before winding. The conductor is cooled by forced-flow, supercritical helium with an outlet temperature of 5.5 K and has a thermal capacity of ~420 mJ/cc, which provides a comfortable stability margin under the operating conditions.

Table 1. Nb_3Sn ICCS conductor characteristics

Operating current (10 T, 5.5 K)	20.3 kA
Critical current (10 T, 5.5 K)	25.4 kA
Outside dimensions with insulation	2.35 cm x 2.35 cm
Conduit material	Incoloy
Conduit thickness	2 mm
Outside corner radii	6 mm
Strand diameter	0.7 mm
Helium area (41% of cable space)	1.34 cm^2
Strand area (copper 1.22 + non-copper 0.68)	1.90 cm^2
Number of strands	486 (6×3^4)
Heat absorption capacity at 10 T and 5.5 K	420 mJ/cc
Quench pressure limit	309 atm.

Winding Design Description

The cross section of the TF coil in the inboard region is shown in Fig.3, and the main design parameters are summarized in Table 2. The coils are pancake wound and consist of 14 full pancakes of 15 turns plus four partial pancakes, for a total of 234 turns. Each pancake is wound with a single conductor with enough space between the turns to bring out LHe inlet and outlet connections to the sides (see Figs. 4 and 5). Electrical connections (current leads and splices) are located in the top region of the coil. The helium exit temperature is limited to 5.5 K [below the current sharing temperature, T_{cs}, (10 T) ~6.2 K]. The coolant path length is limited to one turn in the first third of the winding, two turns in the next third, and five turns in the remainder of the winding. Manifolding (LHe inlet and outlet) connections are brought from various points within the winding, through the case sidewall to a common manifold. The assembled winding is reacted to form the Nb_3Sn. The current density goal (3500 A/cm^2) could not be achieved if the conductor is reacted before winding (R/W), due to degradation of critical current arising from induced winding strain (achievable current density for the R/W approach is ~2800 A/cm^2). The reacted winding is vacuum impregnated with an epoxy potting compound which reinforces the electrical insulation, eliminates the need for co-wound structure reinforcement on the conductor and minimizes the possibility of interturn conductor slippage. These proposed concepts for reacting and then winding (R/W) and manifolding discussed above are feasible but require development.

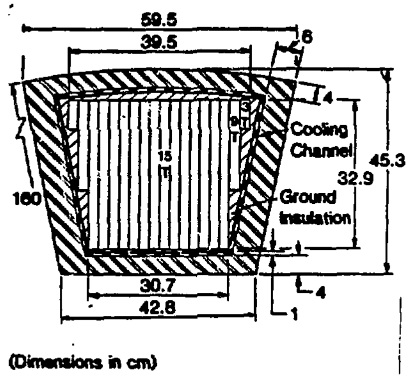

Fig. 3. TFCX-S winding configuration.

Table 2. Summary of major design and performance parameters.

Parameter	Value
Peak field at winding (T)	10
Coil bore size (M)	4.08 x 6.03
No. of coils	16
Ampere-turns/coil (MAT)	4.75
Winding current density (A/cm^2)	3500
Overall current density (A/cm^2)	1800
Operating current (kA)	20.3
No. of turns per coil	234
Mean coil perimeter (M)	19.2
Stored energy per coil (MJ)	440
Winding heat load (kW)	15
Case heat load (kW)	34
Helium inlet temperature (K)	4.0
Helium outlet temperature (K)	5.5
Helium inlet pressure (Atm)	5.0
Helium outlet pressure (Atm)	2.5
Maximum quench pressure (Atm)	132
Maximum discharge voltage (kV)	3.0

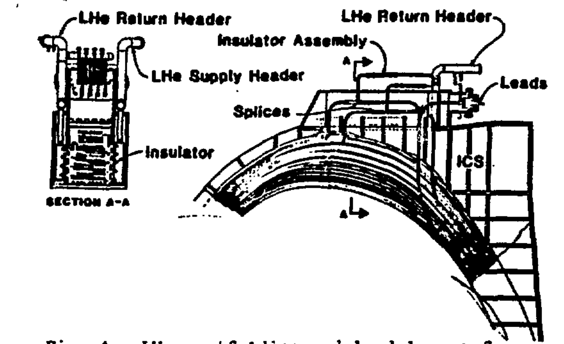

Fig. 4. LHe manifolding and lead layout for high performance.

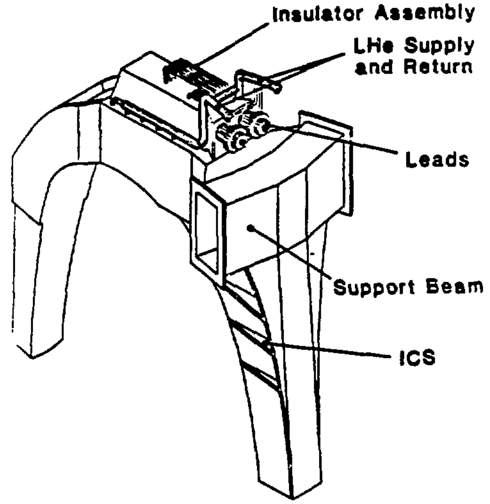

Fig. 5. TFCX-S TF coil concept (high performance).

During normal pulsed operation, major heat loads are nuclear heating in the winding and coil case, and eddy current heating in the coil case and the intercoil support structure (ICS, see Fig. 5). The case and support structure heat loads are too high to be removed by the helium flowing in the conductor. To isolate the winding from this heat load, LHe coolant channels (inlet temperature 5.5 K) are incorporated between the windings and the inside surface of the coil case (see Fig. 3).[4] The LHe returning from the winding is utilized in these cooling channels before it is returned to the main refrigerator. With this cooling scheme, the heat leak from the case to the winding is negligible compared to the total heat load for the winding. The nuclear heating in the winding is the dominant heat load. The temperature and pressure conditions given in Table 2 for inlet and outlet LHe are based on an estimate of the heat load occurring in the hottest channel comprising a single turn at the inner surface of the coil. The winding is capable of withstanding all credible heat loads arising during normal pulsed operation and during plasma disruption, without quenching, as discussed in the following section.

Performance Analysis

Cooling requirements. The TF coils are required to remain in operation without quenching during normal pulsed operation and plasma disruption. For this purpose, it is necessary to adequately remove all the heat loads and limit the temperature of the winding below the current sharing temperature, T_{cs}, (~6.2 K) of Nb_3Sn at 10-T. The cooling calculations were made with the code developed for forced-flow TF coil design with nuclear heating as the dominant component of the heat load by P. Materna.[5] It is required to cool every turn in the first third of the winding facing the plasma by a flow of supercritical helium (T_{in} = 4.0 K, P_{in} = 5 atm, T_{out} = 5.5 K, P_{out} = 2.5 atm). As discussed previously, the winding is divided into sections, with manifolding provided to satisfy this requirement.

Stability considerations. The TF winding is designed to operate without quenching during normal pulsed operation and during plasma disruption. The LHe flow in the winding is maintained sufficiently to remove all the credible heat loads and to ensure recovery from localized normal zones due to strand or conductor movement, localized nuclear heating, and ac losses.

The operating current was determined by taking into consideration the strain level[2] on the Nb_3Sn strands, peak temperature[6] (5.5 K), and peak fields[6] (10 T) in the winding. The critical current[2,6] (35 kA at 4.2 K and 10 T) was successively degraded to arrive at an operating current providing sufficient stability margins.

The thermal capacity ΔH of helium between the operating temperature T_B and current sharing temperature, T_{cs}, is given by

$$\Delta H \geq A_{He}/A_{cond} \int_{T_B}^{T_{cs}} \rho \, C_p \, d\,T \qquad (1)$$

where A_{He} and A_{cond} are the areas of helium an etal cross-section in the conductor and $\rho\,C_p$ is the product of helium density and the specific heat. ΔH for the proposed conductor under the operating conditions is ~420 mJ/cc. The instantaneous peak heat load density is ~82 mJ/cc due to nuclear heating ac losses and joule heating in the normal zone for the normal pulsed operations; whereas, during a plasma disruption with a decay time constant of 0.1 s at the TF coils, the peak heat load density is 54 mJ/cc. Thus, the winding will remain in operation without quenching during normal pulse operation and under plasma disruption.

Quench analysis and protection. The TF coil protection scheme is based on controlled dissipation of the stored energy through an external dump resistor. All the 16-TF coils are connected in a series and are charged by a single power supply. The current in the entire system is reduced to zero level in the event of a quench detected in any of the coils. Each coil is provided with its own dump resistor, R_D. The discharge voltage and the hot spot temperature in the winding are limited to 3000 V and 200 K, respectively.

The quench pressure, P_{max}, is 132 atm, which is less than half of the 309 atm, the maximum pressure which the conductor can withstand safely. Thus, the winding would safely withstand the quench pressure if it is quenched during an abnormal condition.

Conclusions

The proposed design concept for the high-performance, superconducting TF coils is considered technically feasible. The specified current density of 3500 A/cm^2 at 10 T can be achieved, and nuclear heat loads (50 mW/cc) can be adequately removed while providing reliable operation of the coils. The proposed concepts for reacting and winding (R/W) and manifolding are feasible, but some development work is necessary. Operating experience with the Westinghouse LCP coil should confirm the adequacy of the conductor design.

References

[1] C. A. Flanagan, et al., "Superconducting Toroidal Field Coil Options for the Tokamak Fusion Core Experiment (TFCX)," Proc. of the 13th Symp. of Fusion Tech., Varese, Italy, September 24-28, 1984.

[2] M. O. Hoenig, M. M. Steeves, and C. J. Cydes, "Niobium-3-Tin Internally Cooled, Cabled Superconductor (ICCS) Technology," presented at the 8th Internat. Magnet Tech. Conf., Proc. to be published in Annals of Physics, 1983.

[3] V. C. Srivastava, J. W. Lue, and M. S. Lubell, "Internally Cooled Cable Superconductor (ICCS) for TF and PF Coils of FED," IEEE Trans. Magnetics MAG-19,398, 1983.

[4] V. C. Srivastava, "Enhanced Cooling with Helium Channels in the TF Coil Casing for FED," Proc. of 9th Symp. Eng. Prob. Fus. Res., p. 352, 1982.

[5] P. Materna, "Design Considerations for Forced-Flow Superconductors in Tokamak Toroidal Field Coils," Proc. of 10th Symp. on Fusion Engineering, p. 1741, 1983.

[6] P. A. Hudson, F. C. Yin, H. Jones, "The Critical Current Density of Filamentary Nb_3Sn as a Function of Temperature and Magnetic Field," IEEE Trans. MAG, MAG-19, p. 903, 1983.

[7] C. A. Flanagan, D. Steiner, and G. E. Smith, eds., "Fusion Engineering Device Design Description", ORNL/TM-7948, p. 4-82, Oak Ridge, TN, 1981.