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INTERNALLY COOLED CABLE SUPERCONDUCTOR (ICCS) FOR TF AND PF COILS OF FED*

Vishnu C. Srivastava
Fusion Engineering Design Center/General Electric Company
and
J. Winston Lue, Martin S. Lubell
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

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Abstract

Internally Cooled Cable Superconductor (ICCS) concepts developed for TF and PF coils of FED are described. These concepts represent one of the options for FED, and other conductor concepts are still being explored, i.e., no decision has been made for the conductor concepts to be utilized for FED. The TF coil conductor design is based on an ICCS successfuly used in a small test magnet at ORNL. The conductor consists of triplets of NbTi strands loosely packed in a stainless steel conduit similar to the Westinghouse LCP coil. The operating current for the conductor is 25.5 kA at 10T and 3.1 K. The conductor is co-wound with a stainless steel C-shaped channel to provide a direct load path to the coil case for the accumulated magnetic loads in the winding. The strand diameter in the conductor is optimized to reduce the eddy current losses. The nuclear heating in the winding is the most dominant heat load. In order to remove these heat loads due to nuclear heating and ac losses in the winding, it is necessary to lower the inlet temperature of helium to 2.2 K. The conductor has a thermal capacity of ∿200 mJ/cc, which provides a comfortable stability margin under the operating conditions.

The PF conductor is similar to the TF conductor, but it is modified to meet the requirements of the PF coils. For this conductor, the superconducting filament diameter has been reduced and cupro-nickel barrier is provided between adjacent filaments for reducing the hyteresis and coupling ac losses under relatively higher pulsed fields. The conductor is designed to carry 21.3 kA at 8T and 4.5 K.

Introduction

The magnetic system for FED consists of the toroidal field (TF) system, the poloidal field system (PF), the associated support structure, and the cryostat. The configuration of the TF coils and PF coils is shown in Fig. 1. The PF system includes the equilibrium field (EF) coils and the ohmic heating (OH) solenoid. There are ten superconducting TF coils which are capable of operating at fields up to 10T. The OH solenoid is located inside the bucking cylinder (not shown) and designed for 8-T peak field at the winding. Detailed discussion of the FED magnet system can be found elsewhere.[1-3]

This paper discusses the feasibility of using NbTi internally cooled cable superconductor (ICCS) for TF coils and PF coils. The ICCS conductor provides cryostable operation with a liberal stability margin. The forced cooled concept offers the higher operating winding current density which has a direct impact on the size and the cost of the device. The forced cooled TF and PF conductors and winding designs are described in the following section. The structural support design for these coils is described elsewhere.[1-3]

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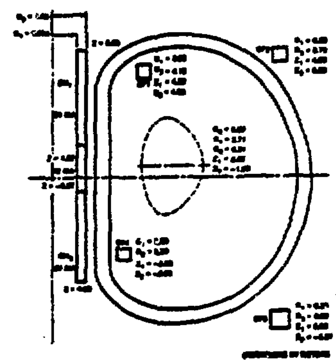

Fig. 1. FED 8-T/10-T magnetic system with forced cooled TF and PF coils.

Toroidal Field Coil System

Conductor Design

The TF coil conductor design is based on an ICCS successfully tested in a small test magnet[4,5] at ORNL. The overall conductor dimensions are shown in Fig. 2 and its relevant parameters are given in Table 1. The conductor is similar to the Westinghouse LCP, and it consists of triplets of NbTi strands loosely packed in a stainless steel conduit. The conductor operating current is 25.5 kA at 10T and 3.1 K. The number of strands, diameter of the insulated strands and filaments in the conductor are chosen to minimize the ac losses in the winding.

The conduit thickness (2.8 mm) was chosen to ensure leak tight closure welds from the manufacturing considerations. The conductor can withstand a maximum quench pressure of 218 atmospheres. The conductor is co-wound with a stainless steel C-shaped channel to provide a direct load path to the coil case for the accumulated magnetic loads in the winding that would otherwise crush the conductor conduit. The conductor-in-channel is wrapped with Kapton and fiberglass tape insulation before winding. The conductor is cooled by forced flow supercritical helium with an outlet temperature of 4.5 K and 3.1 K for 8-T and 10-T operation, respectively. The conductor has a thermal capacity[1] of ∿200 mJ/cc, both at 8-T and 10-T operation, which provides a comfortable stability margin under the operating conditions.

Table 1. TF conductor characteristics

Operating current (10.2 T, 3.1 K)	25.5 kA
Critical current	48.3 kA
Limiting current	61.4 kA
Helium area	215 mm^2
Strand area	323 mm^2
NbTi 59	
Copper 264	
Number of strands	1458 (6×3^5)
Strand twist pitch	3.9 mm
Heat absorption capacity at 10 T and 3.1 K	200 mJ/cc

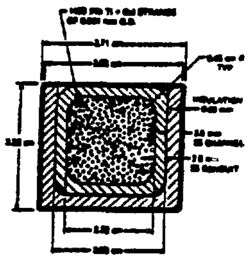

Fig. 2. TF coil ICCS conductor dimensions and configuration.

Winding Design

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 28 pancakes of 15 turns plus four pancakes of six turns for a total of 444 turns. Each pancake is wound with three conductors in parallel, so that a full coolant channel consists of five complete turns. Electrical connections (current leads and splices) are located in the top region of the coil. Liquid helium enters the coils through headers located inside the coil bore and exists through headers located outside the coils. The length of each cooling path is about 173 m; this path length results[1] in a pressure drop of about one atmosphere during 10-T operation. The assembled winding is vacuum impregnated with an epoxy potting compound which reinforces the electrical insulation, eliminates the possibility of interturn conductor slippage, and slippage of the conductor within the channel.

During normal pulsed operation, major heat loads are nuclear heating and eddy current heating in the winding, the coil case and the intercoil support structure (ISS). The case and the support structure heat loads are too high (see Table 2) to be removed by the helium flowing in the conductor. To isolate the winding from this heat load, liquid helium coolant channels (~4 K) are incorporated between the winding and the inside surface of the coil case (see Fig. 3). The heat load from the intercoil support structure is removed by incorporating[6] gaseous helium channels (~20 K) between intercoil support structure and coil case. With this cooling scheme, the heat leak[6] from the case to the winding is about 20 W, which is a small fraction of the total heat load for the winding. The nuclear heating in the winding is the dominant heat load. In order to remove these heat loads due to nuclear[1] heating (280 W) and ac losses[1] in the winding (45 W) for 10-T operation, it is necessary to lower the inlet temperature of helium to 2.2 K; just barely above the λ-point temperature. The temperature and pressure conditions given in Table 2 for the inlet and outlet helium are based on an estimate of the heat load occurring in the hottest channel.

Table 2. TF coil data for 8-T and 10-T operation of FED

Parameter	Unit	8-T Operation	10-T Operation
Field on plasma axis	T	3.6	4.6
Peak field at the winding	T	8.0	10.2
Ampere-turns/coil	MAT	9	11.5
Operating current	kA	20	25.5
Winding current density	A/cm^2	1720	2200
Number of turns		444	444
Number of full pancakes		28	28
Number of partial pancakes		4	4
Ratio operating/critical current	A/cm^2	0.555	0.521
Helium inlet temperature	K	4	2.2
Helium outlet temperature	K	4.5	3.1
Helium inlet pressure	Atm	5	5
Helium outlet pressure	Atm	4.3	4
Helium flow rate per coil	g/s	250	400
Maximum quench pressure	Atm	135	216
Maximum temperature rise during quench	K	200	200
Maximum discharge voltage	kV	5	6
Stored energy/coil	GJ	1.5	2.4
Coil case time averaged (152 s) eddy current losses	W	—	3175
ISS time averaged eddy current losses	W	—	4625
Total time averaged (152 s) heat load for each coil	W	6035	9125

Stability Considerations

TF coils are required to remain operating in cryostable mode for the normal pulse operation and following plasma disruption. To meet this requirement, adequate helium flow must be maintained in the windings to effectively remove steady-state heat loads and to ensure recovery to the cryostable mode from localized heat inputs (due to strand or conductor movements; localized ac losses, etc.)

The winding stability is evaluated for the 10-T operation. A summary of peak heat loads is given in Table 3. The peak ac losses occur in the vicinity of the EF_3 ring coil. The ac losses are calculated[7] using the peak pulsed poloidal field components during the start up period. The peak nuclear heating occurs in the inboard region during the burn phase. The maximum integrated heat load density during burn phase in the conductor is ~69 mJ/cc (due to nuclear heating), which is less than the thermal capacity (~200 mJ/cc) available[1] in the winding. The basis and detailed calculations for the thermal capacity of ~200 mJ/cc is described elsewhere.[1] Thus the winding is expected to remain cryostable during normal pulse operation and under plasma disruption.

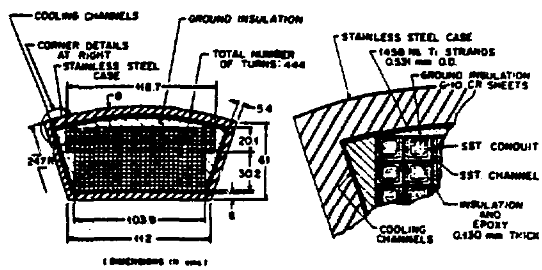

Fig. 3. Winding pack configuration for TF coils (inboard region).

Table 3. TF coil winding stability data

Normal pulse — 6 s start up period and 50 s burn period at 10 tesla

Parameter	Instantaneous Heat Load (W/m length of conductor)	Load Density (J/m length of conductor)
o Peak ac loss during 6 s start up	0.2	0.62 mJ/cc
o Nuclear heating during the burn phase (50 s)	22.1	68.4 mJ/cc
o Joule heating in a normal zone	1	31 mJ/cc

Abrupt plasma disruption — 0.1 s decay time constant at TF coils

Parameter	Integrated Heat Load (J/m length of conductor)	Load Density (J/m length of conductor)
o Peak ac loss	4.5	14
o Joule heating in a normal zone	0.1	0.3

Poloidal Field Coil System

Conductor Design

The ICCS conductor used for PF coils is shown in Fig. 4 and its relevant parameters are listed in Table 4. It is similar to the conductor used for the TF coils, but it is modified to meet the requirements of the PF coils. The superconducting filaments diameter has been reduced, and cupro nickel barrier is provided between adjacent filaments for reducing the hysteresis and coupling losses. Individual strands are insulated with a (5-μm thick) layer of copper oxide (similar strand insulation has been used for Westinghouse LCP conductors) for reducing the eddy current losses. The conduit thickness (3 mm) was chosen to assure leak-free closure welds from manufacturing consideration. The conductor can withstand a maximum quench pressure of 285 atmospheres. The stainless steel U-shaped channel is co-wound with the conductor to provide a direct load path to the coil case. The conductors for the ring coils (EF_2 and EF_3) have the same configuration (conduit and cable space) as for the central solenoid, except the U-channel thickness, which is higher for these coils. The conductor and channel are prewrapped with Kapton and fiberglass tape insulation before winding. A similar ICCS[8] has been proposed for the PF coils of the Japanese Fusion Engineering Reactor (FER).

Table 4. PF conductor characteristics

Operating current		21.3 kA
Critical current		36.0 kA
Limiting current		55.0 kA
Helium area		304 mm^2
Strand area		458 mm^2
NbTi	59	
Copper	264	
CuNi	120	
Insulation	15	
Number of strands		1458 (6×3^5)
Strand twist pitch		3.9 mm
Heat absorption capability at 8T, 4.5 K		180 mJ/cm^3

The conductor is designed to carry 21,300 amperes at 8.0 T and is cooled by supercritical helium at 4.5 K. The operating conductor currents for the central solenoid and coils EF_2 and EF_3 are chosen to provide adequate stability margin.[9]

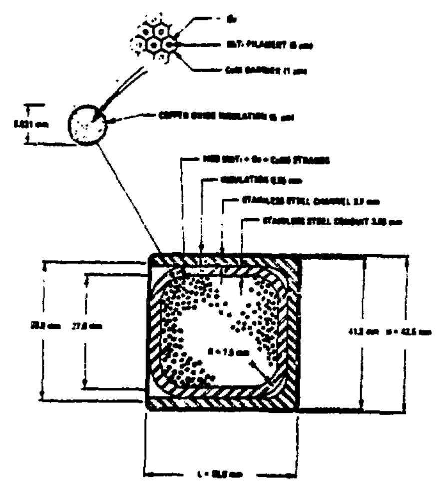

Fig. 4. PF conductor configuration.

Central Solenoid Design

The major design parameter[9] of the central solenoid (modules OH_1, OH_2, and EF_5) are summarized in Table 5 and the winding cross section is shown in Fig. 5. The operating current for the solenoid is 21,300 A, which is 60% of the critical current at 8 T. Each solenoid module is powered with a separate pair of leads. The leads are located in the central bore region.

The OH_1 and EF_5 modules are layer wound with transition joints (splices) made at the top of the winding. The splices for the layer wound OH_2 are located at the bottom of the winding. The splices are made between the terminations from adjoining layers by bending the conductor out of the plane of the winding. Helium inlet connections are made at the splice, and the metallic tubing from this connection is brought to the manifold located in the central bore region. An insulating tubing (G10) is employed for electrically isolating the helium port at the conductor splice from the common helium manifold. At the bottom of the modules OH_1 and EF_5, the helium outlet connections are made by attaching metallic tubing to the conductor conduit. No conductor-to-conductor splice is made on this end. The helium manifolds and splices can be accommodated within a 20-cm axial gap between adjacent modules. The solenoidal modules OH_1 and OH_2 are layer wound with two conductors in hand in order to limit the helium pressure drop to less than 3 atm in the cooling path length of roughly 360 m. The EF_5 coil is wound with a single conductor in hand. The layer winding approach for these coils has the advantage of reducing the number of splices and the helium manifolding as compared to the pancake winding approach. All windings are epoxy impregnated. These windings are cooled with supercritical helium (T_{inlet} = 4.0 K, P_{inlet} = 5 atm, T_{out} = 4.5 K, P_{out} = 2.0 atm). These inlet and outlet conditions for the helium are chosen to provide adequate heat removal capability under normal pulsed operation and plasma disruption.

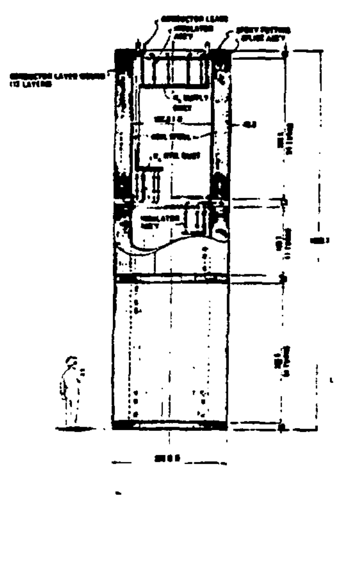

Fig. 5. Central solenoid schematic cross section.

Table 5. Design parameters of the ICCS central solenoid OH1-OH2-EF5

Geometric		
Winding dimensions	(m)	
Inside radius		0.984
Outside radius		1.450
Height		10.39
Electromagnetic		
Maximum field at winding	(T)	8.0
Ampere turns	(MA)	60
Operating current	(kA)	21.3
Number of turns		2820
Number of layers		12
Winding current density	(A/cm^2)	1290
Maximum discharge voltage	(kV)	10.0
Cryogenic		
Helium inlet temperature	(K)	4.0
Helium outlet temperature	(K)	4.5
Helium inlet pressure	(atm)	5.0
Helium outlet pressure	(atm)	2.0
Total helium mass flow rate	(g/s)	990
Maximum quench pressure	(atm)	190
Cooling path length	(m)	364
Total time averaged heat load (152 s)	(W)	815
Performance		
Maximum rate of change of field	(T/s)	2.7
Discharge time	(s)	6
Maximum stored energy	(MJ)	1010

Ring coil design

The schematic cross section of the EF_3 winding with ICCS conductor is shown in Fig. 6. The U-channel thickness for EF_2 and EF_3 conductors are 8.2 mm and 7.6 mm, respectively. The operating current for EF_2 and EF_3 coils is 50,830 A and 41,300 A, respectively. These operating currents are 60% of the critical current of the conductor

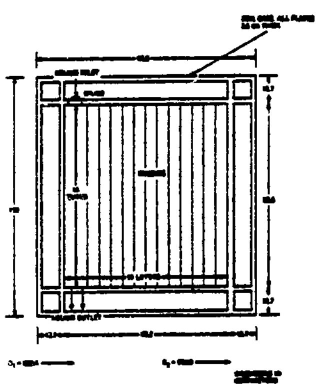

Fig. 6. Schematic cross section of EF_3 Coil.

The coils (EF_2 and EF_3) are layer wound with splices and helium inlet manifolding located on the top of the winding. The helium outlet manifolding is located at the bottom of the winding. Both EF_2 and EF_3 coils are layer wound with four conductors in hand for limiting the cooling path lengths to roughly 240 meters and 180 meters for coils EF_3 and EF_2, respectively. The coil case, shown schematically in Fig. 6, is based on the structural analysis described elsewhere.[2]

Cooling requirements and stability considerations

The PF coils are also required to remain in the cryostable mode during normal pulsed operation and plasma disruption. The winding ac losses[9] for the central solenoid and ring coils were calculated.[7] All the losses occur during the start up period (6 s) and shut down period (10 s). These losses must be removed as they occur during start up and shut down periods without causing the conductor to lose its cryostability. The temperature and pressure conditions given in Table 5 for the inlet and outlet helium have been estimated to satisfy[9] this cryostability condition. The stability of the winding was evaluated[9] using the approach used for the TF coils. The maximum integrated[9] heat load density for 0.1 s (under plasma disruption) in the conductor is 54 mJ/cc, which is less than the thermal capacity (~180 mJ/cc) of the helium within the winding. Thus these windings will remain cryostable during normal pulse operation and under plasma disruption.

Conclusion

The design of the TF and PF coils using an ICCS appear feasible.[1,9] The forced cooled winding has the advantage of reduced ac losses, a better cryostability margin, higher current density, higher operating fields, a monolithic integral winding, and higher charge/discharge voltages. The main drawbacks of the forced cooled concept are the extensive manifolding requirement and a concern for heat removal following a thermal quench. The TF coils are capable of operating up to 10-T peak field and the central solenoid is designed to operate at 8 T.

Poloidal field coil designs employing a forced cooled conductor appear attractive because they are compact and a need for a nonmetallic helium vessel is eliminated. However, additional analysis is needed for demonstrating that the forced cooled windings provide adequate performance during normal pulsed operation and during and following a fault.

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