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OHMIC-HEATING SOLENOID DESIGN UTILIZING* FORCED-COOLED WINDINGS

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ABSTRACT

This paper discusses the feasibility of using *NbTi* internally cooled cable superconductor (ICCS) in the ohmic-heating central solenoid for the fusion engineering device (FED). The ICCS conductor provides cryostable operation with liberal stability margin. The forced cooled concept has a high winding current density which reduces the size and the cost of the device. The forced-cooled concept requires complex helium manifolding, but a unique approach has been developed to solve the problem. The conductor design, the winding design, and the performance analyses are described. The solenoid is designed to operate at 8-T peak field and provides 60 MAT. The operating current for the solenoid is 21.3 kA, which is 60% of the critical current at 8 T.

INTRODUCTION

The major magnet system components of a tokamak are the toroidal field (TF) system, the poloidal field (PF) system, the associated support structure, and the cryostat. The configuration of TF and PF coils is shown in Fig. 1. The PF system includes the equilibrium field (EF) coils and the ohmic heating (OH) central solenoid. The OH solenoid is located inside the bucking cylinder (not shown) and is sized for 8-T peak field at the winding. Detailed discussion of the FED magnet system can be found elsewhere.[1-2]

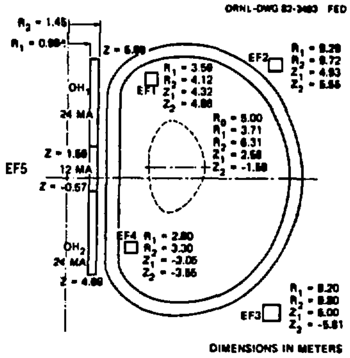

Fig. 1. FED 8-T/10-T magnet system with force-cooled PF coils.

The design of the ohmic heating central solenoid employing forced cooled winding is described. The solenoid is designed to oeprate at 8-T peak field for the fusion engineering device (FED) and provides 60 MAT. The operating current for the solenoid is 21.3 kA, which is 60% of the critical current at 8 T. The solenoid is divided into three modules (OH$_1$, EF$_5$, and OH$_2$) for ease of fabrication and assembly. Each solenoid module is layer wound. The layer winding has the advantage of reducing the number of splices and the helium manifolding as compared to the pancake winding approach. The structural design for the solenoid is described elsewhere.[1-3] All the windings are epoxy impregnated and are capable of operating in the cryostable mode under normal pulsed operation and under plasma disruption.

CONDUCTOR DESIGN DESCRIPTION

The ICCS conductor employed in the solenoid is shown in Fig. 2; relevant parameters are listed in Table 1. The conductor is similar[2] to that proposed for the toroidal field (TF) coils of FED. The conductor is modified to reduce eddy current losses during the pulsed mode. The diameter of the superconducting filaments is reduced and a cupronickel barrier is added between adjacent filaments for reducing

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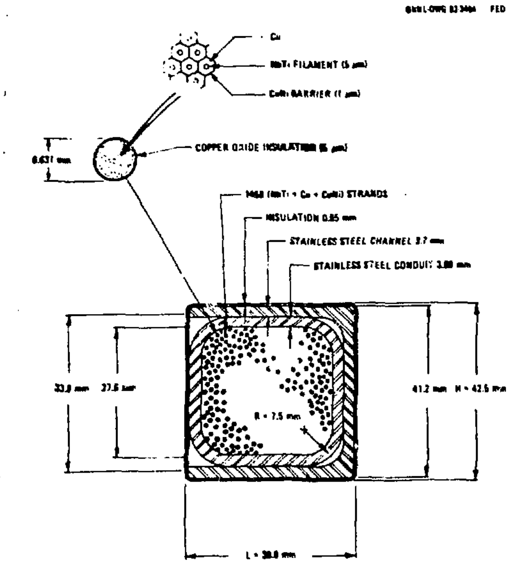

Fig. 2. ICCS conductor dimensions and configuration for the central solenoid.

Table 1. Parameters of ICCS conductor for the central solenoid

Operating current at 8 T and 4.5 K	21.3 kA
Conductor current density (including insulation)	12.92 A/mm^2
Critical current at 8 T and 4.5 K	36.0 kA
Limiting current	55.0 kA
Stainless steel area (including insulation)	887 mm^2
Helium area	304 mm^2
NbTi area	59 mm^2
Copper area	264 mm^2
CuNi area	120 mm^2
Strand insulation area	15 mm^2
Total area	1649 mm^2
Copper-to-superconductor ratio	4.5
Void fraction	0.4
CuNi barrier thickness	1 μm
NbTi filament diameter	5.0 μm
Number of filaments per strand	2050
Strand diameter with insulation	0.631 mm
Strand surface insulation thickness	5 μm
Number of strands	1458 × (6 × 3^5)
Filament twist pitch	15 mm
Strand twist pitch	3.9 mm
Overall cross section dimensions including insulation	42.5 mm × 38.8 mm
Thermal capacity ΔH at 8 T, 4.5 K	180 mJ/cm^3
Maximum quench pressure limit	285 atm

the hysteresis and coupling losses, respectively. Individual strands are insulted with a 5-μm thick layer of copper oxide to reduce the eddy current losses. The conductor consists of triplets of NbTi strands loosely packed in a stainless steel conduit similar to that used in the Westinghouse LCP coil.[4]

The conduit thickness (3 mm) is chosen to ensure leak-tight closure welds. The conductor can withstand a maximum quench pressure of 285 atm. A stainless steel C-shaped channel is co-wound with the conductor to provide a direct load path to the coil case for the accumulated magnetic loads in the winding, which would crush the conductor conduit if it were not reinforced. The conductor and C-channel are wrapped with Kapton and fiberglass tape insulation before winding. A similar conductor has been considered for the PF coils of the Japanese *Fusion Engineering Reactor.*[5]

Figure 3 shows the critical current at 4.5 K *as a function of field. The operating* conductor currents for the central solenoid is chosen to provide an adequate stability margin,[6] as discussed in later sections.

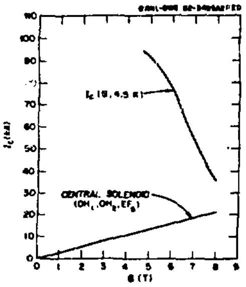

Fig. 3. Critical current I_c vs load line for central solenoid (*OH_1, OH_2, and EF_5*).

SOLENOID DESIGN DESCRIPTION

The major design parameters of the central solenoid (modules OH_1, OH_2, and EF_5) are summarized in Table 2, and the winding cross section is shown in Fig. 4. Each solenoid module is powered with a separate pair of leads. The leads are located in the central bore region. A more detailed design description of the solenoid is given in Reference 7.

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 module are located at the bottom of the winding. The splices (see Fig. 4) are made

Table 2. Design parameters of central solenoid modules OH_1, OH_2, and EF_5

	Forced-cooled design
Geometric	
Winding dimensions	
Inside radius	0.984 m
Outside radius	1.450 m
Height	10.39 m
Electromagnetic	
Maximum field at winding	8.0 T
Ampere-turns	60 MA
Operating current	21.3 kA
Number of turns	2820
Number of layers	12
Winding current density	1292 A/cm^2
Maximum discharge voltage	10.0 kV
Cryogenic	
Helium inlet temperature	4.0 K
Helium outlet temperature	4.5 K
Helium inlet pressure	5.0 atm
Helium outlet pressure	2.0 atm
Total helium mass flow rate	990 g/s
Maximum quench pressure	190 atm
Cooling path length	364 m
Performance	
Maximum rate of change of field	2.7 T/s
Discharge time	6 s
Maximum stored energy	1010 MJ

between the terminations of adjoining layers by bending the conductor out of the plane of the winding. Helium inlet connections are made at the splices, and the metallic tubing from these connections is brought to the manifold located in the central bore region. An insulating tubing (G-10) is employed to electrically isolate the helium port at the conductor splice from the common helium manifold. At the bottom of 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. 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 results in fewer splices and less helium manifolding than required with the pancake winding approach. All windings are impregnated

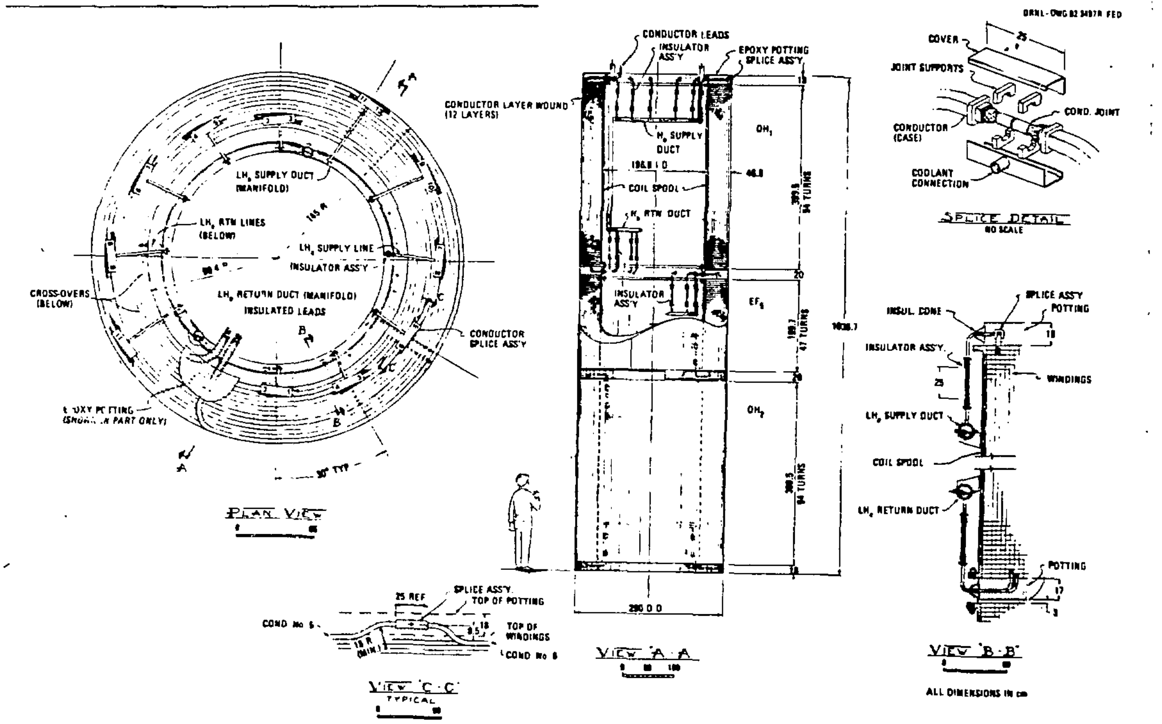

Fig. 4. Central solenoid layout, splices, and manifolding details.

with epoxy and cooled with supercritical helium. The inlet and outlet conditions for the helium (see Table 2) are chosen to provide adequate heat removal capability under normal pulsed operation and plasma disruption.

DESIGN ANALYSIS

AC Losses

The winding ac losses, calculated with the analysis of Ref. 8, are minimized by using insulated strands and by reducing the superconductor filament diameter to 5 μm. Each filament is surrounded by a copper and cupronickel matrix for reducing the coupling losses in the conductor (see Fig. 2). The losses in the windings are listed in Table 3. The hysteresis and coupling losses are major components for the superconducting strands. The major portion of eddy current losses occurs in the stainless steel conduit and the support channel, and they are caused by pulsed field of the solenoid. All the losses occur during the startup period (6 s) and shutdown period (10 s) and are time-averaged over the pulse cycle period of 152 s. The losses must be removed as they occur during the startup and shutdown periods without causing the conductor to lose its cryostability. The conductor losses are removed by flow of supercritical helium through the conductor.

Table 3. Summary of ac losses in the central solenoid (OH_1, EF_5, and OH_2)

Loss Component	Conductor (kJ)	Conduit and channel (kJ)	Splices (kJ)	Total (kJ)
B_Z losses	35.0			35
B_R losses	14.4			14.4
Resistive losses			4.6	4.6
Eddy current losses		69.9		69.9
Total	49.4	69.9	4.6	123.9
Time averaged over the cycle period of 152 s (W)				
Total	325	460	30	815

Cooling Requirements

The coil windings are cooled by the flow of supercritical helium (T_{in} = 4.0 K, P_{in} = 5 atm, T_{out} = 4.5 K, P_{out} = 2 atm). The winding is divided into sections so that the pressure drop in each cooling path is limited to ∿3 atm. The mass flow rate of helium, the pressure drop, and the cooling path length for the central solenoid are given in Table 2. The pressure drop ΔP along the channel length L is calculated[9] from

$$\Delta P = \frac{\dot{m}^2 P_{cool} L f}{2\rho A_{He}^3} , \qquad (1)$$

where $\dot{m}$ is the mass flow rate of the helium, P_{cool} is the cooled perimeter of the conductor, ρ is the density of helium, A_{He} is the flow cross-sectional area for helium, and f is the friction factor, evaluated from the Reynold's number,

$$Re = \frac{4\dot{m}}{\eta P_{cool}} , \qquad (2)$$

where η is the viscosity of helium (a function of both temperature and pressure). The friction factor f has been measured as a function of the Reynold's number for conductor[9] with superconducting strands. The friction factor for the conductor is calculated from these experimental measurements[9] for turbulent helium flow.

Once the pressure drop is established at a reasonable level (∿3.0 atm), the coolant mass flow rate $\dot{m}$ is calculated from the enthalpy change $\Delta h = h_{out} - h_{in}$, and the steady-state time-averaged heat load q for the inlet and outlet conditions of the helium flow is given by

$$q = \dot{m}\Delta h . \qquad (3)$$

The heat transfer coefficient[10] from the conductor strands to the helium fluid was calculated from

$$h = \frac{Nu K P_{cool}}{4A_{He}} , \qquad (4)$$

$$Nu = 0.023(Re)^{0.85} Pr^{0.4} , \qquad (5)$$

and

$$Pr = \frac{\eta C_p}{K} , \qquad (6)$$

where Nu is the Nusselt number, Pr is the Prandtl number, and K and C_p are the thermal conductivity and specific heat, respectively, for the bulk coolant conditions in the conductor. The value of h obtained using these equations is roughly 0.07 $W/cm^2 \cdot K$, which provides a sufficient heat transfer capability even for a temperature difference ΔT of 0.1 K between the strands and the bulk helium. Because the peak heat flux at the conductor strands is only 0.05 mW/cm^2, the heat removal capacity per unit area is much higher than the heat generation rate. As a result, the temperature of the coil winding stays at ∿4.5 K and, therefore, the winding operates in a cryostable mode.

Stability Considerations

The central solenoid is designed to operate in a cryostable mode during normal pulse operation and following a plasma disruption. The helium flow in the windings is maintained sufficiently to remove steady-state heat loads and to ensure recovery to the cryostable mode from localized normal zones (due to strand or conductor movements, localized ac losses, etc.).

The winding stability analysis for the central solenoid is performed, and a summary of peak heat loads is given in Table 4. The ac losses in the winding are calculated[8] using the peak pulsed poloidal field components during the startup period and during a plasma disruption. The instantaneous peak heat loads (W/M of the conductor) are integrated over the startup period (6 s) to give the maximum heat load per unit length of the conductor. This integrated heat load is divided by the volume of the superconducting strands in unit length of the conductor to estimate the maximum heat load density. The maximum integrated heat load density in the conductor is 54 mJ/cm^3, which is less than the thermal capacity (∿180 mJ/cm^3) available in the helium within the winding. Thus, the winding is expected to remain cryostable during normal pulsed operation and following a plasma disruption.

Table 4. Peak heat loads and winding stability data for the central solenoid

Normal operation			
	Instantaneous heat load (W/m of conductor)	Integrated heat load (6 s) (J/M of conductor)	Load density (mJ/cc)
Central solenoid	1.1	6.6	15

Plasma disruption - 0.10 s decay time constant at the solenoid		
	Integrated heat load (0.10 s) (J/m of conductor)	Load density (mJ/cc)
Central solenoid	24	54

The thermal capacity of ∿180 mJ/cm^3 is established as follows. The thermal capacity[6] of helium between the bath temperature T_B and the conductor current-sharing temperature T_{cs} is given by

$$\Delta H_u \geqslant \frac{A_{He}}{A_{cond}} \int_{T_B}^{T_{cs}} \rho C_p \, dT \ , \tag{7}$$

where A_{He} and A_{cond} are the areas of helium and conductor, respectively, and ρC_p is the product of the helium density and the specific heat. The thermal capacity of helium between temperatures T_{cs} and T_B is shown in Fig. 5 The current-sharing temperature T_{cs} for the peak field of 8 T is calculated from the relationships[6]

$$T_{cs} - T_B = (T_c - T_B) \left[1 - \frac{I_{op}}{I_c(4.5\ \mathrm{K},\ 8\ \mathrm{T})} \right] \tag{8}$$

and

$$T_c(B) = 9.09 - 0.439B \ , \tag{9}$$

where T_c is the critical temperature at field B (in tesla). The critical current I_c, as a function of field at 4.5 K, is shown in Fig. 2 and has been scaled[6] by

$$I_c(T_B,B) \propto (0.55 - 0.026B)(T_c - T_B) \ . \tag{10}$$

With these relationships, T_{cs} is calculated to be 4.93 K.

For an 8-T maximum field at the central solenoid with $T_B = 4.5$ K, $(T_{cs} - T_B)$ for the conductor is 0.43 K. The helium thermal capacity of ∿260 mJ/cm^3 is obtained from Fig. 5 for this condition. The area ratio A_{He}/A_{cond} is 0.70, and, therefore, the effective thermal capacity is ∿180 mJ/cm^3.

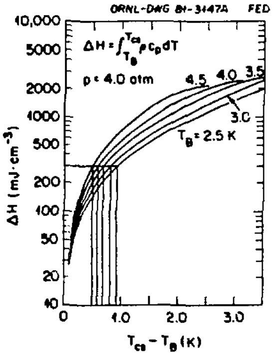

Fig. 5. Available stability margin in the ICCS conductor (referenced to the helium fraction) when operated below the region of multiple stability.

The operating current density must be kept well below the limiting current density in order to avoid the region of multiple stability.[11] The limiting current density J_{limit}, below which stability is single valued and has only the *upper value, scales according to the following* relationship:

$$J_{\mathrm{Limit}} \propto [f_{\mathrm{Cu}}(1 - f_{\mathrm{cond}})f_{\mathrm{cond}}]^{1/2}$$

$$\times [(T_c - T_B)^{1/2}\rho_{\mathrm{Cu}}^{-1/2}\tau_H^{-1/15}\ell_H^{2/15}D_c^{-1/2}D_f^{-1/2}] \qquad (11)$$

where

f_{cond} = the volume fraction of metal in the cable space,

f_{Cu} = the volume fraction of copper in the metal,

ρ_{Cu} = the resistivity of copper under the operating conditions, including magnetoresistance and nuclear radiation

τ_H = the duration of the heat pulse being stabilized against,

ℓ_H = the heated length of the conductor,

D_c = the hydraulic diameter of the flow path for cooling,

D_f = the hydraulic diameter of the flow path for helium flow.

Experimental results[11] from a test coil recently built and operated at the Oak Ridge National Laboratory (ORNL) indicate that the scaling holds as well in a real coil as it does in the small-scale conductor tests. The limiting current density J_{limit} at a peak field of 8 T has been calculated to be 1.2×10^8 A/m^2, which is considerably higher than the operating current density of 4.8×10^7 A/m^2. Thus, the windings will operate with an upper stability margin of roughly ~180 mJ/cm^3 for the normal pulse operation as well as under plasma disruption.

CONCLUSIONS

The design of the central solenoid using an ICCS conductor appears feasible. The force-cooled winding has low ac losses, a good cryostability margin, high current density, high operating fields, and a monolithic integral winding. Simple analysis indicates that the winding provides an adequate safety margin during the normal pulsed operation and following an abrupt plasma disruption. However, this needs to be confirmed by a detailed dynamic stability analysis later.

It is quite likely that the operating field at the solenoid could be increased to 10 T if the winding temperature is reduced[12] to 3 K. The feasibility of this option will be studied in the future.

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