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OHMIC HEATING COILS FOR A TOKAMAK

MASTER

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DESIGN AND DEVELOPMENT OF CRYOSTABLE SUPERCONDUCTING OHMIC HEATING COILS FOR A TOKAMAK*

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INTRODUCTION

A conceptual design on the superconducting ohmic heating (OH) coil has been made for the GA/ANL TNS Tokamak Reactor studies. The primary advantage of a superconducting OH coil is the minimization of equipment and operational costs. This is primarily a result of the much reduced power supply and energy storage costs. Three hundred MW peak power and 11 MW rms power would be required to drive a room temperature copper OH coil system, as opposed to 16 MW and 4 MW, respectively, for a superconducting OH coil. Another reason is that, to reduce the overall TNS tokamak cost, the flux core of OH coils should be small. However, a much better utilization of the flux core can be achieved with superconducting OH coils by placing the support cylinder of superconducting toroidal field (TF) coils within the inner diameter of the superconducting OH coils, thus allowing the outer diameter of the OH coils to be in close contact with TF coils. Recent scoping studies indicate that superconducting OH coils will cost only half as much as room temperature copper OH coils (\$15 M versus \$30 M)⁽¹⁾.

The second feature of the superconducting OH coil design is the parallel coil connection. This is very important because it confers several important

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advantages upon the system: (1) in order that the equilibrium field (EF) coils are magnetically decoupled from the OH coil, the OH coil system is required to be connected in parallel with the EF coil and the number of turns of each OH coil and EF coil must be equal. Under these conditions, since each OH coil and EF coil experiences the same flux change, the induced EF coil current is zero in the absence of a plasma current. Consequently, dividing the OH coil into many parallel paths means that the number of turns in each OH coil and EF coil can be greatly reduced. Thus, both the EF coil and OH coil system will require lower voltage and reasonable currents in the coils; (2) superconducting OH coils with multiple parallel-connected paths will inherently adjust their respective currents to minimize the flux leakage within the TF coil envelope. This is because all parallel paths of OH coils see the same volt-seconds (V-s) and therefore must all experience the same interior flux variations.

In the development aspect, the results of basic cable development and tests will be described. The design and construction of a prototype 1.5 MJ cryostable pulsed coil and its nonmetallic cryostat will be presented.

DESIGN DESCRIPTION

Design Requirement and Rationale

The design requirements for the V-s are specified as a result of trade-off studies-for plasma ignition and heating and studies of burn cycle dynamics. The size, stored energy, field levels and dB/dt of the OH coil are directly related to the V-s requirements. The reference design requires a total of

37 V-s in a complete cycle of ignition, heating and burning. The reference design has a mean flux core radius of 0.86 m with a 1.0 m outer radius and a 0.7 m inner radius. A symmetrical bipolar flux change of 37 V-s is achieved with an 8 T central field. The maximum dB/dt is 8 T/s with a 1 s ramp time.

The choice of 8 T for the central field and 8 T/s for the rate of change of flux is based on a study of the rational limits on the central field and the dB/dt ⁽²⁾. It can be seen that, for a given V-s requirement, the smaller the flux core, the higher the central field and the dB/dt would be. On the other hand, higher fields and higher $\dot{B}$ require more superconductor volume, more stabilizer copper volume, more stainless steel for support and larger helium channel volume. Therefore, there exists a minimum of OH coil radius which also minimizes the overall cost of the entire reactor. Although the analyses were based on reasonable size of filaments, twisting pitches and strand diameters in the cable, good engineering intuition is used in selecting these parameters.

Coil Configurations

The coil configurations established for the superconducting OH coil is schematically shown in Figure 1. The coil system consists of a central solenoid, coils 9 through 30, field profile coils, coils 3 through 8, and two trim coils, coils 1 and 2.

The central solenoid contributes essentially the central field. The field profile coils, positioned approximately on the flux line and so spaced that they do not interfere with reactor penetrations, are primarily used to correct the superimposing fields in the TF coil and in the plasma regions. The two trim coils are needed to eliminate the stray fields in the plasma region due to the leakage of flux between the field profile coils and the other stray

fields, either due to misalignments of TF coils or due to the eddy currents of the first wall, etc. Trim coil number 1 is used to primarily correct the axial field component and trim coil number 2, the radial field component.

The central solenoid is broken into 22 parallel electrical paths of 20 turns each. The field profile coils of 20 turns each, are connected in parallel with the central solenoid coils. The two trim coils, however, are excited independently by a small power supply. Adjustments of both coils will permit minimization of the chamber field prior to plasma startup. The magnet characteristics of the superconducting OH coil are listed in Table I.

Coil Structure, Cryostat and Current Leads

The proposed TF coil support cylinder is a fiberglass reinforced plastic such as G-10 or G-11. The cylinder is positioned inside the OH coil with axial support rings transmitting the load between the support cylinder and the TF coil. The plastic rings of 5 cm thickness are axially compressed to 30 kpsi. These rings could be solid or hollow discs depending upon the outcome of cost and stress analyses. For a 6000 psi centering pressure from the TF coils (at 10 T), the axial thickness for each of the coils in the central solenoid is 20 cm. It is proposed that liquid helium be penetrated to the bottom of coils and the gas be vented at the top. It is tentatively decided that two concentric arrays of holes of about 3 cm diameter each, will be made in each of the supporting plastic rings as illustrated in Figure 1. The separation of the liquid supply from the gas venting is important to assure the success of a fast pulsed OH coil in a pool boiling system.

The current leads with a total of about 60 pairs are arranged in concentric circles at the top. This arrangement will minimize the stray fields due to the leads. The arrangements will also simplify the support of current leads because a clamping ring inserted between the leads will neutralize the external forces. The refrigeration requirements for the 60 pairs of 80 kA leads could be significantly reduced if the leads were designed for the rms current of about 25 kA instead of 80 kA because the on cycle is 30 s in a total cycle time of about 300 s. Nb_3Sn stabilized with sufficient copper will also reduce the refrigeration cost of leads because the refrigerated cold gas could be introduced at about 15 K rather than 4.2 K.

The helium vessels will be plastic G-10. The outer wall will be about 5 cm thick. This is sufficient for a 500 volt coil voltage. The inner wall will be thick enough to prevent buckling. The cryostats for the remaining bundle coils will have circular cross-sections, and will be supported by the reactor structure.

80 kA Cable Design and ac Losses

The 80 kA cable design, as illustrated in Figure 2, was based on the results of an on-going Argonne National Laboratory pulsed-coil program as described in the following sections. The requirements of low loss and cryostability are conflicting requirements. A compromise between the two must be made when selecting a cable design. The basic principle chosen is to achieve cryostability within basic cables. The final cable may consist of many basic cables stranded with full transposition. To limit eddy current loss, only limited current sharing among basic cables is allowed. These principles are incorporated in the 80 kA

cable design. The ac losses are the filament loss, the eddy current loss within the cryostable basic cable, and the eddy current loss in the structural member of the cable. These losses are listed in Table I.

Parallel Operations and Stability

Considerable effort has been spent in developing codes to determine the currents for multiple parallel paths. The codes consist of the computations of self and mutual inductance of all parallel paths and computations of currents in each parallel path by solving a set of simultaneous equations for the parallel-connected loop currents. The coil currents in the parallel-connected coils are tabulated in Table I. These currents give a minimum stray field in the plasma and the TF coil regions as shown in Figure 1.

The effects due to change in coil locations have been calculated. The effects of some coils going normal were also investigated. These effects will be reported elsewhere⁽³⁾.

DEVELOPMENT OF CRYOSTABLE PULSED COILS

Basic Cable Studies

Figure 3 illustrates three basic cables chosen. As stated previously, the basic principle chosen is to achieve cryostability within the basic cables. It was originally hoped that mechanical contact through stranding processes may provide enough electrical contact for current sharing while simultaneously fulfilling the requirement of low ac loss. To provide a cushion-like contact, each strand, superconducting composite or pure OFHC wire is tinned with staybrite.

Table I. Magnet Characteristics of TNS Superconducting Ohmic Heating Coil

Central Field (T)	8
Maximum dB/dt (T/s)	8
Total Ampere-Turns (A-T)	82×10^6
Total Ampere-Meters (A-M)	490×10^6
Source current (A)	4.1×10^6
Source voltage (V)	360
Total Inductance (μ H)	85.1
Stored Energy	715 MJ
AC Losses per Cycle (estimations)	694.241 J
Filament Loss (J)	120,000
Conductor Eddy Current Loss (J)	574,241

Central Solenoid (coils 9 through 30)

I.D.	1.4 m
O.D.	2.0 m
Height	11.0 m
Current	$(81 \pm 7.6) \text{ kA}$ 18.2

Field Profile Coils

<u>Coil No.</u>	<u>R (m)</u>	<u>Z (m)</u>	<u>I (kA)</u>
3	9.12	6.12	3.96
4	7.12	7.12	6.54
5	3.62	7.12	19.76
6	1.47	6.55	80.12
7	1.31	6.14	53.85
8	1.07	5.72	88.12

Trim Coils

1	10.00	2.05	87.00
2	5.11	6.10	225.00

The basic cables have a short sample current of 405 A at 5 T and a ratio of Cu/NbTi of 15:1. The cryostability test was made using a 4-foot long sample, noninductively wound. The current sharing characteristics of all three cables indicate that the minimum propagating current, I_{mp} , is slightly greater than the critical current, I_c , but the recovery current, I_r , is less than I_c . There is little difference in the current sharing characteristics among the three basic cables. Therefore, the stranding contacts apparently did not provide a sufficient margin for current sharing.

About 300 m lengths were fabricated of each of three cables. These cables were wound into three test coils with a axial winding length of 14 cm, the coil i.d. is 3.2 cm and the coil o.d. is 22.2 cm. The inductance is 25.7 mH and the stored energy is 3000 J. These coils were cycled many times between 0 A and 580 A (critical current at 3.3 T) with a ramping rate of as much as 3.3 T/s without going normal. However, if the coils are charged beyond 600 A, sections of conductor in the coils go normal and they recover completely at a current lower than the critical current.

The ac losses of these coils were measured by a gas boil-off calorimeter. A heater was attached at the top of the coil for losses calibration. The ac losses for coils using cable (b) and (c) in Figure 3 are nearly identical and are about 2 W for a $\dot{B}$ of 1.65 T/s and a central field of 3.3 T. The losses are 4 W for a dB/dt of 3.3 T/s and a central field of 3.3 T. The ac losses for coil using cable (a) was found to have a surprisingly high ac loss of 8 W at a $\dot{B}$ of 1.65 T/s with a central field of 3.3 T.

Current sharing characteristics of cable (b) under various conditions are illustrated in Figure 4. Since stranding contact does not provide enough of a

margin for current sharing (curve a), the current sharing terminal characteristics for the case where the entire cable is soldered together were investigated. The results indicated that both I_r and I_{mp} are much greater than I_c as shown in curve b, Figure 4. However, it is quite obvious that the ac losses of the soldered cable is rather large.

The cable configuration giving the best compromise between stability and ac losses is shown in Figure 5a. The six pure copper wires are soldered to the superconducting composite forming an essential current sharing subgroup. A thin coating of glyptal varnish is brushed on the surface of each of the three subgroups in the basic cable. The high dielectric strength coating serves to reduce the eddy current losses among the subgroups. The coating is thin enough (~ 0.0125 mm), however, so that limited current sharing among subgroups will be allowed. Also, the heat transfer of the boiling helium will not be affected because the coating is thin. In fact, the minimum film boiling heat transfer rate will be enhanced as a result of the thin coating. The current sharing of the cable was tested and shown in curve c, Figure 4.

Frictional heating of the basic cable was also studied. This and other results will be reported elsewhere^(4,5).

12 kA Cable Development and Parallel Coil Operation

Figure 5b illustrates the 12 kA cable design for a 1.5 MJ pulsed coil. To form the 12 kA cable, twenty-four basic cables are twisted around a stainless steel strip about 0.8 mm thick by 28.5 mm wide at a twisting pitch of about 114 mm. The stainless steel strips, which are well insulated from the basic cables, will serve as the backbone in the cabling process and as the structural member

to support loop stress of the 1.5 MJ coil. Supercon, Inc., is commissioned to produce a 600 m long cable by August, 1977. The first 69 m will be fabricated first as a dry run cable. The cable conductor will be wound into two 20-turn pancake coils for parallel operation tests. Each pancake coil shall have 20 turns with a pancake o.d. of 61 cm and an i.d. of about 36 cm. Feasibility and stability of parallel operations over a wide range of $\dot{B}$ will be fully investigated.

1.5 MJ Coil Design and Fabrications

The design of the 1.5 MJ prototype cryostable pulsed coils is completed. Fabrication of a G-10 coil form has started. Coil winding is planned for the end of August, 1977. The magnet characteristics are tabulated in Table II. The magnet and its plastic dewar are shown in Figure 6. The 1.5 MJ coil will be cryostable. The ac losses will be large but tolerable. The large eddy current losses were derived from the fact that the twisting pitch of the superconducting composite is too long for fast pulsed application. These composites are available at ANL and the level of funding did not permit purchase of more suitable superconducting composites. Another important goal of building the 1.5 MJ coil is to energize and deenergize the magnet over a wide range of dB/dt (from 2 T/s up to 14 T/s). The power supply for the 1.5 MJ coil is a 7 MW power supply with 700 V peak voltage and 11 kA peak current. AC loss measurement by an electrical method is also planned. For this purpose construction of a linear mutual inductor, cooled in liquid nitrogen, is underway.

Development of a Large Plastic Dewar

The 1.5 MJ pulsed coil requires rapid charging and discharging; consequently, it is necessary to use nonconducting dewars to minimize eddy current losses.

Table II. ANL 1.5 MJ Pulsed Superconducting Coils

Central Field	4 T
Peak Field	4.3 T
$I_{\max}$	12 kA
L	20 mH
E	1.5 MJ
Coil I.D	40.6 cm
Coil O.D.	86.4 cm
Axial Length	61 cm
Cable Length	531 m
No. of Layers	15
No. of Turns/Layer	16
Layer-to-Layer Spacing	6.35 mm
Cryostable Recovery Heat Flux	0.5 W/cm ²
Conductor Current Density	6446 A/cm ²
Average Current Density	2600 A/cm ²
Exposed Surface	Approx. 50%
<u>AC Losses ($\dot{B} = 2$ T/s)</u>	
Instantaneous Matrix Eddy Current Loss	50 W
Instantaneous Hysteresis Loss	17.2 W
Instantaneous Eddy Current Loss in S.S. Strip	10 W

The plastic cryostat, as shown in Figure 6, will consist of two tanks with 100 layers of superinsulation between. The inner tank will have an i.d. of 91.4 cm and a depth of 152.4 cm with internal pressure rating of 30 psig. The wall thickness is 0.95 cm. The outer tank has an i.d. of 107 cm, a depth of 156.5 cm and a wall thickness of 1.27 cm. Two rings are provided to reinforce the tank against buckling. Both tanks are made of fiberglass reinforced Hietron 31 polyester with 35% glass components. Hasbrouck Plastics, Inc., New York is commissioned to fabricate both tanks in July, 1977. The superinsulation is slit at two places to reduce the eddy current heating. The heat leak of the plastic tank is estimated at 5 W.

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FIGURE CAPTIONS

- Figure 1 Schematics of TNS superconducting ohmic heating system.
- Figure 2 80 kA cable design.
- Figure 3 Three cryostatic stable basic cables superconducting wire (SC):
40 mils dia., 2041 filaments, filament diameter 5μ , cu/sc = 1.8
and twisting pitch 1.27 cm (= 2 TPI). (a) three sc wires are
twisted at 4 TPI and six cu wires are twisted around the sc at
1.5 TPI, (b) and (c): six cu wires and one sc wire are twisted
at 2 TPI and those three subgroups are twisted at 1.5 TPI.
- Figure 4 Current sharing characteristics of cable (b) of Figure 3. (a)
bare wires and stranding contact, (b) completely soldered and (c)
subgroups are soldered and insulated.
- Figure 5 (a) selected basic cable, (b) 12 kA cryostable cable.
- Figure 6 Fiberglass reinforced plastic dewar and 1.5 MJ coil.

1000A BASIC CABLE

(a)

(b)

(c)

(a)

(b)