A TOROIDAL FIELD MAGNET SYSTEM FOR NUWMAK+

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ABSTRACT

A conceptual design of a toroidal field coil system is presented for NUWMAK, a compact fusion power reactor. The magnet major radius is 5.13 meters, the minor radius is 3.84 meters and the maximum field in the coil winding is 11.5 Tesla. The magnets are to be cooled with 1.8 K superfluid helium to allow operation at the highest fields present using ductile NbTi instead of brittle Nb_3Sn as the superconductor. Various advantages and disadvantages of this design are compared to those of an optional Nb_3Sn magnet design operating in 4.2 K pool boiling liquid helium. There are only eight superconducting TF coils, allowing excellent access for maintenance, and the resulting field ripple is trimmed with close-in normal metal coils. These trimming coils do not encircle the plasma but are saddle shaped, and so can be changed out without disturbing the plasma chamber or the TF coils.

I. INTRODUCTION

A series of conceptual design studies[1] of tokamak reactors has provided a quantitative understanding of fusion reactor problems. NUWMAK[2] is an optimized reactor based on the knowledge obtained from the previous design studies. It is a compact reactor of high plasma power density (10 MW/m^3), high average neutron wall loading (4 MW/m^2) and high β_T (6%). The plasma requires a magnetic field B_o of 6.05 tesla at a major radius R of 5.13 m, which means a maximum field of 12 tesla at the magnet. Because of the compactness of the reactor, an innovative approach was needed in the magnet design to allow access for maintenance and repair of the system. One of the unique features of NUWMAK is that it has no divertor. Instread, periodic gas puffing is used for impurity control, fueling and ash removal. Therefore, the number of vertical field coils inside the toroidal field (TF) coils can be minimized and the TF coils can be located close to the plasma. Although this reduces the magnet costs, it increases the toroidal field ripple at the plasma edge and hampers accessibility to the system through the spaces between the TF coils. To provide the needed access for maintenance and repair, NUWMAK is designed with only eight large superconducting coils and the increased ripple is corrected with 16 saddle shaped trimming coils located inside the shield as shown in Figure 1.[3] All the ampere turns needed to supply the required flux ($2\pi R_o/B_o/u_o$ = 155 MA turns) are provided by the superconducting coils. The normal copper trimming coils which are located close to the plasma smooth out by adding ampere turns between TF coils and subtracting them in line with the TF coils.

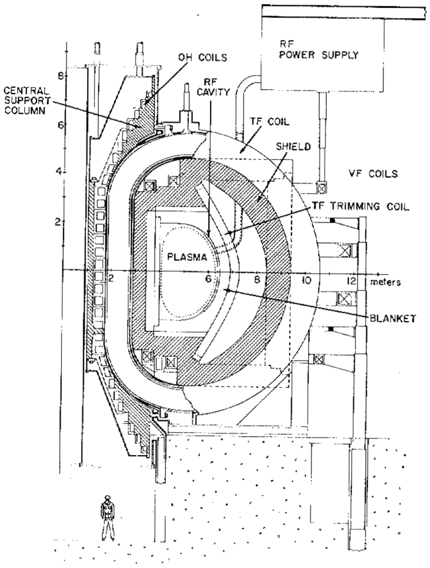

Fig. 1. Cross Section of NUWMAK.

The eight superconducting coils are cryostable and of a constant tension "D" shape. The embedded conductor in a solid "D" shaped structural form is used as in the earlier designs[1] to minimize the material requirements while providing maximum strength and stiffness. The TF coils are supported on the reactor floor permitting the ohmic heating coil system to be removed vertically for servicing without disturbing other elements. An entire module consisting of one TF coil together with a blanket and shield segment can be removed independently.

It appears that there are two technically feasible ways for designing high field (B ~ 12 T) superconductive coils. One is to use NbTi superconductor at reduced temperature (T < 4.2 K) in order to have a reasonably high current density in the superconduct at the required high field. The other is to use Nb_3Sn as the superconducting material at 4.2 K. However, each one of these options has its own advantages and disadvantages and there is no experience in the use of either option for large magnets.

II. SUPERCONDUCTING COILS

The critical current density of NbTi at B = 11.48 tesla and 4.2 K is too low for practical use in magnets and multifilamentary Nb_3Sn superconductor has only been used in small magnets. However, Nb_3Sn is quite brittle and there are concerns about the use of this material in large magnets, although some reactor design studies have been performed in which this material has been proposed for TF magnets.[4] The use of NbTi at B = 10 tesla in a reduced temperature (T ~ 3 K) has been proposed in order to avoid the use of the brittle Nb_3Sn material.[5] The critical current of NbTi at B = 12 tesla and T ~ 2 K is comparable to the critical current of multifilamentary Nb_3Sn at T = 4.2 K and the same field strength (Figure 2).[6] An extensive study has been performed on the use of 1.8 K superfluid He for large superconductive energy storage magnets[7] and its application to TF magnets has been proposed.[8] The advantage of the 1.8 K subcooled superfluid helium operation are: 1) high critical current density in the ductile NbTi superconductor, 2) large critical heat flux, and 3) excellent heat transfer in He II.

The peak heat flux in He II at 1.9 K and 1.3 atm was found to be Q = 2.3 W/cm^2 in results of experimental work[8] shown in Figure 3. The recovery heat flux is about 1.8 W/cm^2. These values are a significant improvement over those for normal liquid

Manuscript received September 28, 1978.

+This work supported by Department of Energy

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0018-9464/79/0100-0756$00.75 © 1979 IEEE

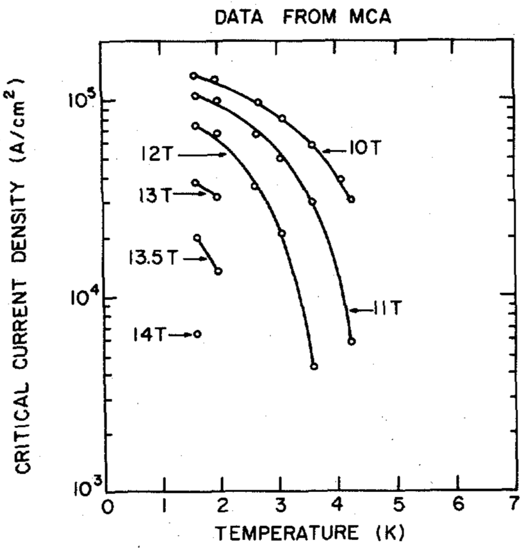

Fig. 2. Temperature Dependence of Critical Current in Nb-46.5% Ti Wire

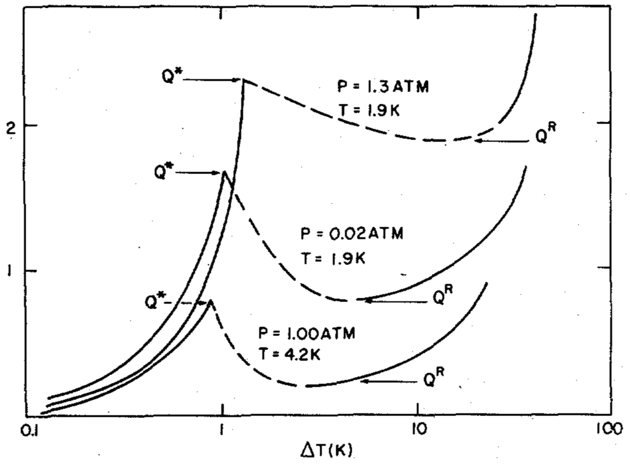

Fig. 3. Critical Heat Flux

helium at 4.2 K and 1 atm. The critical heat flux of superfluid helium at 1.9 K is inferior to He II which has been subcooled in a heat exchanger, moreover, the breakdown voltage v_b of the helium is proportional to $d\rho$ where d is the gap between two electrodes and ρ is the density of helium. It may not be desirable to operate the magnet near the saturated vapor pressure of the helium.

The critical heat flux $q = 0.5\ W/cm^2$ is used for the proposed 1.8 K subcooled superfluid helium operation of the NUWMAK TF coil. The stabilizer in the conductor is chosen to be high purity aluminum. The resistivity of the aluminum is taken as 1×10^{-8} ohm cm throughout the entire field range. The strain in the conductor is held below 0.3% because of the indication that the resistance of high purity aluminum increase sharply beyond this strain limit. The 15,000 A conductor, 2.18 cm wide and 1.38 cm thick, is embedded with fiberglass epoxy into the spiral grooves in the 2219 aluminum alloy structural disk as in Figure 4. The epoxy insulation facing the liquid helium is 2 mm thick to prevent dielectric breakdown in the liquid helium at the interface between the structure and conductor. The breakdown voltage in the liquid helium across clean interfaces was reported to be about 20 kV/mm[9] and during the fast discharge period resulting from a fault condition, a considerable voltage can be withstood by the 2 mm gap. The conductor is encapsulated in 1/2 mm of high strength aluminum alloy to prevent plastic flow of the high purity aluminum due to the high magnetic force similar to the conductor designed for the energy storage magnet.[7] Twenty-nine disk pancakes with 23 conductor turns on each side with micarta spacers covering half of the surface are bolted together to form a coil. The coil is a constant tension D shape obtained with the aid of the analytic expression derived by Moses.[10] The TF coil specifications are given in Table 1.

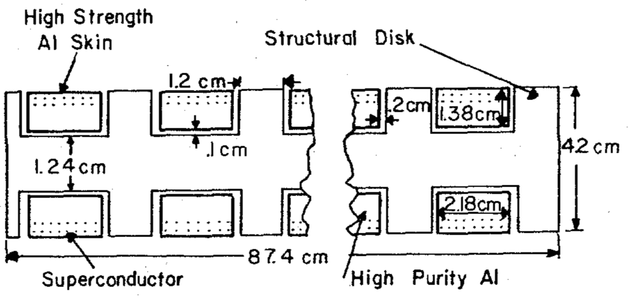

Fig. 4. Cross Section of Magnet

TABLE I
Specification of TF Magnet of NUWMAK

Number of Superconducting TF Magnets	8
Operating Temperature	1.8 K
Number of Trimming Coils	16
Maximum Field at Winding	11.48 Tesla
Total Amp. Turns	155 M Amp. Turns
Current/Turn	15,000 Amp.
Bore: Horizontal	6.8 m
Vertical	9.8 m
Number of Disks/Magnet	29
Number of Turns/Disk	23
Current Density in Stabilizer	6900 A/cm^2
Design Stress in Structure	30,000 psi
Design Strain	0.3%
Inductance of Coil	290 H
Stored Energy	30 GJ

The lateral loads on the magnets due to the pulsed poloidal field coil system as well as the forces occurring because of the failure of one or more TF coils are transmitted to the dewar walls by means of reinforced epoxy struts. Between magnets these forces are reacted with shell structures designed to withstand the large lateral loads without excessive deflection as in the earlier UWMAK studies.[1] In order to minimize the conduction heat load to the 1.8 K helium bath the struts are thermally anchored to the high purity aluminum shield. The shield surrounding the magnet is used to screen the ac component of the pulsed poloidal field in order to stabilize the magnet mechanically and electrically. This scheme has been suggested earlier.[5] The 6 cm thick shield is operated at 4.2 K at the straight leg portion of the TF magnet and 18 K everywhere else.

For the NbTi option the estimated heat load into the 1.8 K helium bath is about 1300 watts and includes conduction losses, nuclear heating, and lead and joint losses. The refrigeration power required to remove this heat is 1.3 MW, which is quite small compared to the 15 MW needed to refrigerate the Al shield, where the bulk of the heating is due to eddy currents. One TF magnet contains about 5000 ℓ of liquid helium and 1.8×10^6 joules are required to raise its temperature from 1.8 K to 2.1 K. It is interesting to point out that the I^2R losses will be about 1.44×10^6 watts in a magnet if the entire conductor goes normal. Assuming that a 4000 watts at 1.8 K refrigerator is provided (which is three times larger than is needed) the capital equipment cost is c_p = \$6,000 $(4,000)^{0.8}$ = \$4.6 x 10^6, which is not excessive. In the following section we will discuss the Nb_3Sn option.

The use of Nb_3Sn superconductor is necessary to obtain a high field at 4.2 K and because it is brittle the strain must be limited. We chose a design strain of 0.1% since the critical current density in the multifilamentary Nb_3Sn wire produced by the bronze process may be sustained even at higher strain levels because of the differential contraction between the Nb_3Sn and the bronze matrix. The critical heat flux is Q = 0.32 W/cm^2 and the conductor size is 5 cm x 1.75 cm in high field regions and is linearly tapered to 2.57 cm x 1.75 cm in the outer low field regions. The disk is 4.4 cm thick and 98.8 cm wide. The maximum stress in the conductor is 8000 N/cm^2, which is below the yield point of copper. The first seven inner turns are made of Nb_3Sn superconductor and the remaining 14 turns are of NbTi since they will be in a lower field zone.

The high purity Al shield surrounding the TF coil will also be used in the 4.2 K operation to provide stability for the magnet. A relatively large pulsed field component ($\Delta B \simeq 1$ tesla) is produced along the TF magnets due to their proximity to the four VF coils and the plasma inside the toroidal enclosure. If the system is designed in such a way that the pulsed field component is parallel to the TF coil,[6] then the 4.2 K operation will be quite a bit more advantageous than the o.8 K option because one may then afford to let the ac losses be dissipated in the conductor.

The use of Nb_3Sn necessitates the use of copper as a stabilizer and steel as the structure. Both of these materials are more expensive than aluminum. The Nb_3Sn superconductor itself costs quite a bit more than the NbTi. On the other hand, a 1.8 K subcooling system is also costly. However, intercepting the various heat losses at higher temperatures makes the system affordable as indicated earlier. The complexity of the system due to the subcooling and the eddy current shield may outweight the advantages of the superb heat transfer characteristics of He II.

III. NORMAL TRIMMING COIL

The normal metal field trimming coils chosen for NUWMAK are saddle shaped. The current runs vertically up one coil leg (shaped to fit along the outside of the blanket) to a cross member on the top of the plasma region, through the cross member in the toroidal direction to the next coil leg, down the leg to a cross member at the bottom of the plasma region, and through this bottom cross member to the starting coil leg. In this way, the currents in the vertical legs of two adjacent trimming coils are going in the same direction, although the currents in the 16 coils are independent of each other. The side view of the coil is shown in Figs. 1 and 5. The normal coils are not located close to and inside of the superconducting coils, as is the case in a usual hybrid magnet system. The functions of the normal and superconducting coils in NUWMAK are quite separate and distinct. The superconducting coils supply the full toroidal field. The normal coils reduce the field in some regions and add to it in others in a symmetrical way that smooths out the field, thus reducing the ripple below the 2% level.

The proximity of the trimming coils to the plasma preclude the possibility os using superconductors, both from radiation damage and heat load considerations. The conductor is water cooled copper operating at 70°C and the structural material is titanium alloy (Ti + 6% Al + 4% V). Because of high radiation levels, conventional insulators of the fiberglass epoxy type cannot be used in the trimming coil. After considering several options, including ceramic insulators, graphite tape has been chosen as the insulator. The specifications of the trimming coils are listed in Table II.

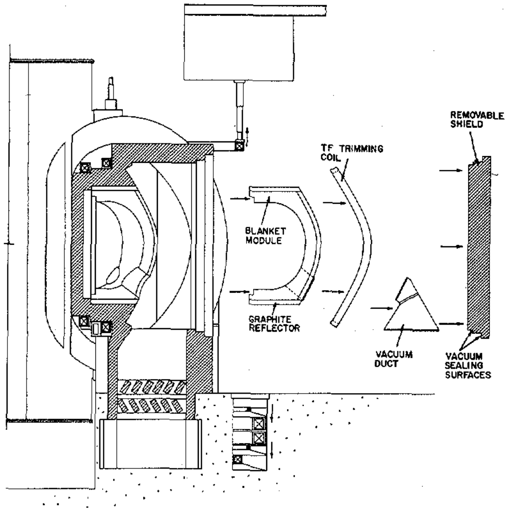

Fig. 5. Cross Section of NUWMAK (showing internal component removal scheme)

TABLE II
Trimming Coil Specifications

Number	16
Conductor Material	OFHC Copper
Cooling Medium	Water at 200 Liters/Second
Max. Operating Temperature	70 C
Current in Each Coil	0.4 MA
Current Density in Copper	800 a/cm^2
Insulation Material	Graphite Tape
Mass of Copper	144 Tonnes
Structural Material	Titanium Alloy (Ti+6%Al+4%V)
Mass of Structural Can	16 Tonnes
Nuclear Heating	15 MW
I^2R Heating	20 MW
Bending Restraint	External Removable Structure

The major force acting on the trimming coils is due to the interaction between the toroidal field and the trimming coil current. Even though the force is substantial, it appears manageable if one approaches the problem with the thought of making the coils constant tension (or compression, depending on the direction of the force). The trimming coil shape in NUWMAK deviates slightly from a constant tension shape. Additional external structure will be provided to resist the bending moments at the points where the coil deviates from the constant tension shape. In order for the coils to carry their own force (tension or compression), mechanical restraint must be provided at the top and bottom of the vertical legs of the coils which transfers the tensile (compressive) forces to a structural ring running circumferentially around the reactor. The net force on this structural ring will be zero, although there will be substantial bending moments in it from the alternatively applied tensile and compressive force transmitted by the vertical legs.

IV. ACCESSIBILITY AND MAINTENANCE

The accessibility to the blanket and the inner components of tokamak reactors is largely determined by the magnet system. Even though some accessibility can be provided by placing the return leg of the TF coils far back from the plasma, the resulting large TF coils are expensive and difficult to service. In NUWMAK the TF magnets are located relatively close to the plasma and the number of the vertical field coils inside and outside of the TF coils is minimized by taking advantage of gas puffing for the fueling and impurity control rather than using a divertor. The high degree of accessibility provided by the small number of superconducting coils augmented by the removable trimming coils makes it possible to remove blanket and shield segments without disturbing the TF coils as shown in Fig. 5.

Provision has also been made to maintain the TF coils in NUWMAK by making them removable. Each of the four cryogenic VF coils inside the torus has a demountable section. The coils are rotated to line up the demountable sections with the TF coil which needs maintenance, and the TF coil along with a blanket and shield segment is then removed from the reactor on a carriage which is a permanent part of the TF coil installation.

V. SUMMARY

A toroidal field magnet system is presented for NUWMAK, a high beta, high wall loading compact tokamak fusion reactor conceptual design. Two schemes have been proposed, one using NbTi subcooled to 1.8 K and another using Nb_3Sn at 4.2 K. A high degree of accessibility for maintenance has been provided by reducing the number of TF coils and correcting the resulting field ripple with removable normal copper saddle shaped trimming coils closely coupled to the plasma. Provisions have been made for maintaining all the components of the magnetic system, with special emphasis on accessibility and removability.

ACKNOWLEDGMENTS

The authors would like to thank Dr. S.W. Van Sciver for the valuable discussion and Dr. H.R. Segal for the available data on the NbTi.

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