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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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PRELIMINARY MAGNET DESIGN FOR A STELLARATOR FUSION REACTOR

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Abstract - Conceptual design of the superconducting magnets for a stellarator fusion power reactor UWTOR-M is presented. The emphasis in the magnet design is toward modularity and maintainability by approximating the continuous helical coil geometry with a number of discrete windings. Magnetic field requirements are reasonable (B_{max} ~ 10 T) allowing for modest extrapolations of present technology. The unique features of the design are: (1) use of NbTiTa with superfluid helium cooling to achieve high current density cryostability; (2) a monolithic conductor, a design made possible by the lack of pulsed magnetic fields; and (3) an innovative construction technique required by the non-axisymmetric geometry of the magnets.

INTRODUCTION

The stellarator system offers a distinct alternative to the main line approaches to magnetic fusion power and has several potentially major advantages. Steady-state magnetic fields simplify superconducting magnet design, remove the need for pulsed superconducting coils and eliminate the need for energy storage to drive the pulsed coils. Plasma confinement during startup is aided by the presence of magnetic surfaces at all times during this phase. Steady-state plasma operation at ignition is possible with the stellarator concept. Such operation would simplify blanket design since there would be no significant fatigue problems. It would simplify the power cycle since no thermal energy storage is required. Impurity control and ash removal are needed for steady-state burn and several options exist to achieve both requirements. The stellarator configuration naturally possesses a magnetic helical divertor. Similar to tokamaks, periodic gas puffing and plasma density and temperature profile control might be able to achieve these ends without divertor operation. Design is simplified in this case and the burn may be steady in a stellarator reactor.

A stellarator can have a plasma aspect ratio of about ten and does not require auxiliary magnets such as ohmic heating, field shaping, and position control coils. This permits access to the device from all sides and facilitates a modular approach to blanket and shield design. Since net current-free stellarators do not exhibit major plasma disruptions, the concern of a major energy dump on the first wall is eliminated.

In the present paper we describe a design for the magnet system of a stellarator fusion reactor, UWTOR-M. As the design is still evolving, the reported parameters may change subject to iterations in the conceptual study. However, the basic features of the magnet system are a set of twisted toroidal field coils which approximate helical windings in a classical stellarator. The magnetic fields are moderate (B_{max} ~ 10 T) and steady-state. Structural support of the magnetic loads is incorporated within the windings and superfluid helium cooling is employed.

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COIL CONFIGURATION

From the reactor point of view, coil modularity is highly desirable if not essential. To achieve this goal, we have adopted a configuration which employs the twisted coil stellarator concept [1], Fig. 1.

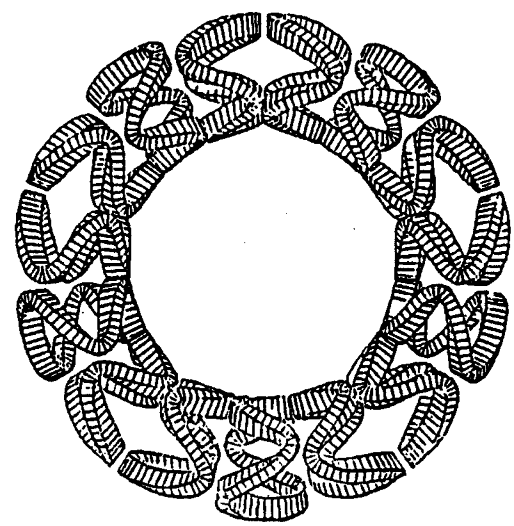


Fig. 1. Modular stellarator coil configuration.

Classical stellarator continuous coils are approximated by a number of discrete coils (in this case 15). We envision this geometry allowing for blanket module servicing by removal of a fraction of the coils thereby facilitating maintenance. The magnet parameters for the present design are given in Table I.

Table I
Magnet Design Parameters for UWTOR-M

Major radius	18.7 m
Minor radius	4.79 m
Total current	39 MA-T
Field on axis	6 T
Peak field	10 T
Energy stored	200 GJ
Overall current density	1250 A/cm^2
Maximum total force	~ 140 MN/m
NET force/coil	425 MN (inward)
Mass of each coil	~ 800 TN

MAGNETIC LOADS

Magnetic forces on these coils have two principal components, the self force on an individual coil and the interactive force between adjacent coils. In the bend regions, where the coils come in close proximity, the mutually attractive forces dominate, while elsewhere the self force determines the loading.

A schematic representation of the magnetic loading of one coil is shown in Fig. 2. Two components are indicated, radial and toroidal, both having magnitudes in excess of 100 MN/m. Specific force components in the radial, poloidal and toroidal directions as well as force magnitude are shown in Fig. 3. All components are given on a per unit length of coil basis as a function of poloidal angle. Summing the forces gives a net centering force of about 425 MN per coil. This force must be reacted against a central column similar to those proposed for tokamak designs.

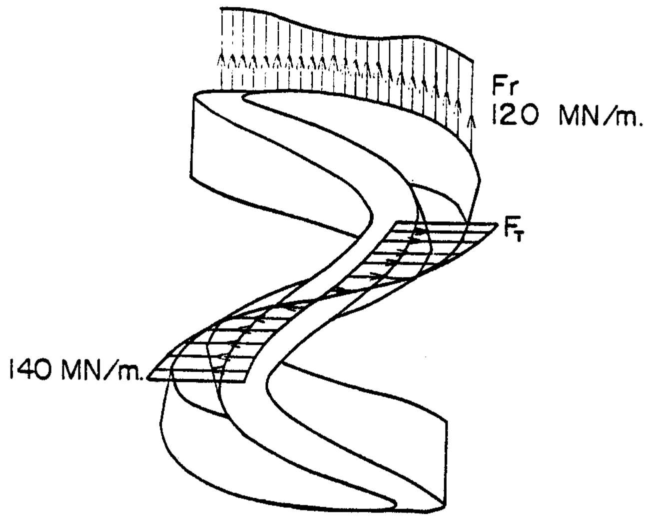


Fig. 2. Schematic representation of magnetic loads on one coil assembly.

At present we are considering structural containment of the magnetic loads by combining the load bearing structure within the winding cross section. This approach has several advantages. Since magnetic loads are high (~ 200 MN/m), the overall current density must be limited to about 1250 A/cm^2, which has the advantage of limiting the peak fields at the conductor. Additionally, it is necessary to position divertors in the gaps between coils thereby negating the use of this space for structural purposes. One difficulty with this approach is that the coils become more massive.

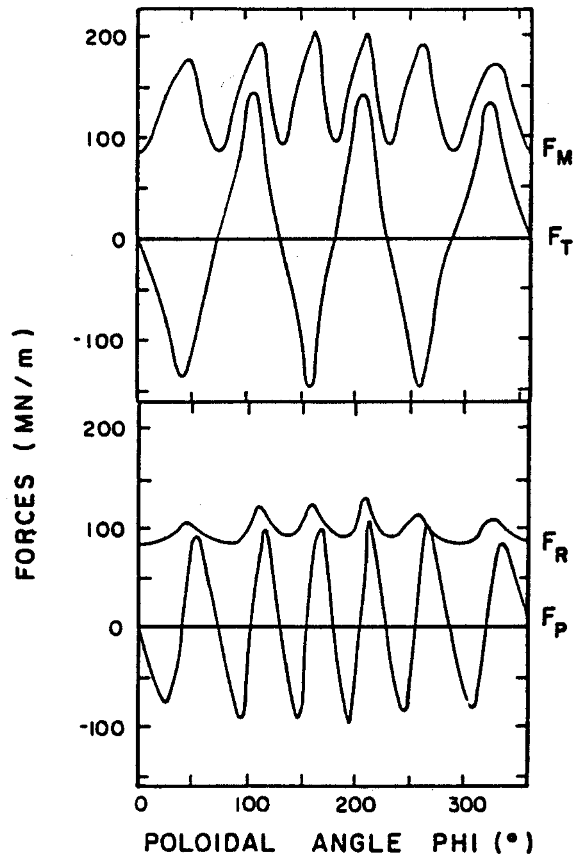
COIL DESIGN

The major driver for the coil design as presently considered is the structural requirement. At an overall current density of 1250 A/cm^2, minimum structural requirements [2] demand that the winding consist of 55% stainless steel stressed to 80 ksi. The problem of how to distribute the structural material requires careful consideration. The compressive loads in the conductor can exceed the yield strength of the OFHC copper unless measures are taken to prevent accumulated loads. We prefer to incorporate a large fraction of the structural stainless steel along with the conductor. This approach has the added advantage of distributing the current density across the winding window, thereby reducing the peak field.

Within this context, there can be two substantially different conductor designs. The first is referred to as the internally cooled cable conductor (ICCS) which is being employed in several magnets presently under design and construction [3,4]. This design calls for hollow stainless steel structure with standard composite conductors inside. An alternative is a helium bath cooled arrangement incorporating the structure and conductor into one integral unit. At present we prefer the latter concept because we believe bath cooling provides better heat transfer and conductor stability.

An additional complication results from the lack of axial symmetry axis in these magnets. Unlike most magnet concepts, these coils have regions where the winding procedure demands that the conductor be pushed into place rather than simply wound in tension. This is a construction problem which has been addressed when considering possible structure and conductor design concepts.

Two methods are under consideration for combining the structure with the conductor into one contiguous unit. The first employs the imbedded conductor concept introduced in the previous UWMAK designs [5]. Shown in Fig. 4 is a schematic cross section



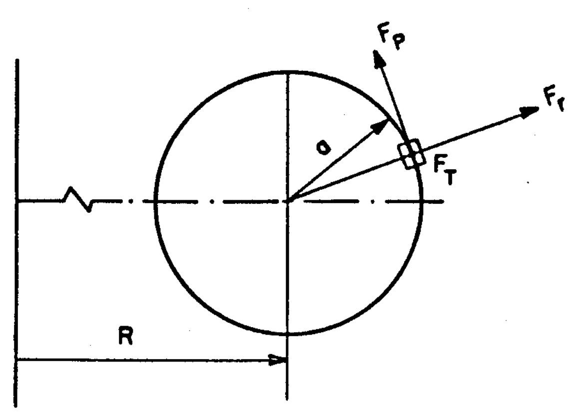


Fig. 3. Magnetic forces per unit length of coil.

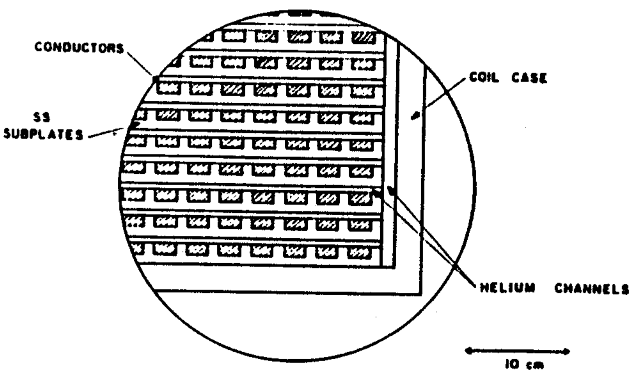


Fig. 4. Schematic of coil winding cross section.

of a portion of a winding designed in this fashion. Stainless steel subplates are assembled within the winding cross section. Once a complete layer of subplates is installed and welded, an insulated monolythic conductor is embedded into the grooved assembly. On completion of a layer another subplate assembly would be installed. Between layers G-10 CR spacers provide layer-to-layer insulation and insure adequate cooling channels. Insulating spacers covering 1/3 of the surface area should be sufficient to carry magnetic loads and provide a 0.5 cm wide cooling channel. Alternatively, since the conductors are insulated from the base plates, it may be possible to use stainless steel spacers covering a smaller fraction of the surface. It would then be possible to weld the entire structure on assembly. Table II lists the principal design features of the magnet windings. An admitted difficulty with this approach is that subplates are not interchangeable. However, it provides adequate load transfer from conductor to structure and entails straightforward construction.

The second method of construction incorporates the structure as part of the conductor. In this design, the winding machine rotates the coil from about a central axis with the conductor fed in at one location while a specially designed set of hydraulic rams continuously conform to the coil contour and hold the conductor into the regions of negative curvature. Mechanical fingers hold the conductor in place while the ram retracts to allow subsequent turns to be added. This scheme provides a simplified conductor but requires a somewhat more complex winding machine.

Table II
Design Features of Torsatron/Stellarator Magnet Windings

Overall current density	1250 A/cm^2
Structure	304 LN-SS
Max. stress	533 MPA (80 KSI)
Conductor current density	4000 A/cm^2
Current	10 KA
Inductance/coil	30 H
Number of turns	3500
Insulation	G10-CR
Volume cross section:	
Stainless steel	56%
Copper	23%
Superconductor	1%
Helium	10%
Insulation	7%

CONDUCTOR DESIGN

Stellarator reactors require DC magnetic fields with $B_{max} \sim 10$ T. The absence of time varying fields allows consideration of monolithic conductors, which may otherwise have prohibitive AC losses. Schematic representation of the current carrying elements is shown in Fig 4. The present design is for a monolithic composite of NbTiTa in OFHC copper. One surface is exposed to a 0.5 cm wide channel containing superfluid helium while the remaining three surfaces are insulated and bonded to the stainless steel base plate. Any instability and induced heat generation must be transmitted through the helium channel to the bath on the sides of the winding. The specific parameters of the conductor design are listed in Table III.

Table III
Conductor Design Parameters

Conductor current density	4000 A/cm^2
Stabilizer	OFHC copper
Superconductor	NbTi Ta
Superconductor current density [6,7]	1500 A/mm^2
Coolant	He II - 1.8 K, 1 atm
Heat generation (Q/ℓ)	2.8 W/cm
Surface heat flux (q)	1.25 W/cm^2
Max. energy flux (Ec)	1 J/cm^3 of conductor

The relatively high conductor current density necessitates an innovative approach to conductor stability. We are considering the use of a maximum energy deposition criterion based on the enthalpy of the superfluid helium in the region of the normal zone [8]. The approach assumes a steady-state normal zone and defines a length of time which the conductor can remain stable before film boiling initiates. Although somewhat less conservative than the fully steady-state stability criterion, this approach provides a method of achieving higher conductor current density in large magnet systems. The results of this calculation are listed in Table III.

CONCLUSIONS

Several approaches for the construction of modular stellarator magnets for a power reactor have been investigated. Preliminary indications are that ~ 55% of the winding area will be occupied by stainless steel. The absence of axial symmetry in the coils complicates the placement of structure and the winding procedure. Additional work is needed to determine the most beneficial distribution of structure and the method for reacting the large centering force on each coil.

REFERENCES

[1] "Modular Torus With Twisted Toroidal Field Coils", Princeton University, Plasma Physics Laboratory, Princeton, New Jersey, September 1979.

[2] Y.M. Eyssa and R.W. Boom, "Considerations of a Large Force Balanced Magnetic Energy Storage System", IEEE Trans. on Magnetics, Mag. 17, pp. 460-463, January 1981.

[3] P.N. Haubenreich, J.N. Luton, P.B. Thompson and D.S. Beard, "Progress on Large Superconducting Toroidal Field Coils", in Proceedings 8th Symposium on Engineering Problems of Fusion

Research, IEEE Pub. No. 79CH1441-5NPS, pp. 1140-1142, 1979.

[4] M.O. Hoenig, M.M. Steeves, A.G. Montgomery, and M.M. Olmstead, "Progress in the ICCS-HFTF 12 Tesla Coil Program", IEEE Trans. on Magnetics, Mag. 17, pp. 638-641, January 1981.

[5] B. Badger, et al., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design", UWFDM-68, Nuclear Engineering Department, University of Wisconsin, Madison, WI, March 1974.

[6] H.R. Segal, T.A. de Winter, Z.J.J. Stekly and K. Hemachalam, "The Use of NbTi Ta as a High Field Superconducting Alloy", IEEE Trans. on Magnetics, Mag. 17, pp. 53-56, 1981.

[7] D.C. Larbalestier, "Niobium Titanium Superconducting Materials", to appear in Superconducting Materials", ed. S. Foner and B.B. Schwartz, Plenum Press (1981).

[8] S.W. Van Sciver, "Enthalpy Stability Criterion for Magnets Cooled With Superfluid Helium II", IEEE Trans. on Magnetics, Mag 17, pp. 747-750, 1981.