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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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D.T. Anderson*, A.W. Bailey, J.D. Callen, J.A. Derr*,
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D.K. Sze, R.C. Sanders, J. Tataronis*, K. Yuan

Fusion Engineering Program
Nuclear Engineering Department
University of Wisconsin
Madison, WI 53706

*Stellarator Torsatron Laboratory
Electrical and Computer Engineering Department
University of Wisconsin
Madison, WI 53706

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Abstract

A preliminary design of a 5500 MW_{th} modular stellarator power reactor, UWTOR-M, is presented.

We briefly describe the parametric considerations which led to the UWTOR-M reference design point. The design has 18 twisted coils utilizing a multipolarity of 3, a major radius of 24 m, a coil radius of 4.77 m and a plasma aspect ratio of 14. An assumed β of 5% was used. This configuration leads to a rotational transform on the edge of 1.125 giving favorable plasma physics conditions. The natural stellarator divertor is used for impurity control in conjunction with innovative high performance divertor targets. A unique blanket design is proposed which minimizes tritium inventory in the reactor. Finally, since maintainability is a prime consideration, we describe a scheme for servicing the first wall/blanket and other reactor components.

1. Introduction

The stellarator is one of the earliest proposed magnetic confinement concepts, having been invented in the early fifties. However, it wasn't until recently that it started to gain recognition in the fusion community. In large measure, this is due to recent encouraging experimental results which show that confinement in a stellarator does not degrade, but in fact improves, when the net plasma current is reduced to a near zero value.(1) These experimental results also verified that above a rotational transform of ~ 0.3, the stellarator does not experience plasma disruption.

In a separate development a breakthrough has taken place in the area of magnets for stellarators. Recent innovations have shown that the continuous helices can be replaced with a set of discrete twisted coils making the system entirely modular.

The encouraging experimental results and the potential for modularity, coupled with the inherent advantages of stellarators, namely steady state magnetic fields, continuous burn cycle, natural divertor and low recirculating power fraction have rekindled interest in the fusion community and given incentive to funding agencies to initiate studies into the technological problems of power reactors based on the stellarator/torsatron concept.

The University of Wisconsin Fusion Engineering Program group in conjunction with the Stellarator/Torsatron Lab has been addressing some of the key technical issues of stellarator/torsatron power reactors. As a result of these deliberations a point reactor design called UWTOR-M, described in this paper, has evolved.

2. Coil Considerations

Three coil systems were considered. They are:

a. Continuous helices
b. Modular torsatron coils
c. Twisted stellarator coils

Since maintainability is an important criterion in the present study, it was decided at the outset that continuous helices would be eliminated from consideration on that basis. We have also considered modular torsatron coils with windbacks.[2] Although these coils certainly offer maintainability, there is still some question about their effectiveness in producing stable flux surfaces.

By the process of elimination we were left with the twisted stellarator coil configuration which we adopted for the present study. These coils have an interesting history. First proposed by workers at the Max Planck Institute of Munich, they became known as Rehker Wobig[3] coils. These coils were wound on a cylinder and were all of identical shape, but simply rotated in pitch to simulate the helical geometry needed. A further improvement consisted of mapping an ultimate stellarator coil system onto the θ-ϕ plane (Fig. 1a) and then representing the resulting triangles by a set of triangular functions of the poloidal angle ϕ, displaced poloidally and toroidally by fixed phase angles. The coil system may then be represented by a corresponding set of Fourier series expansions truncated to a single term resulting in the set shown in Fig. 1b. This improvement, invented at the University of Wisconsin Stellarator/Torsatron Lab. by J. Derr[4], produces flux surfaces which are as good as or better than those produced by helical coils. However, because they are wound on a torus instead of a cylinder, they are not identical. There are, in fact, only two coil geometries (for ℓ=3) needed, as can be seen from Fig. 2, the top view of the coil set adopted for the UWTOR-M point design. There are six field periods, each consisting of three coils. Two of the coils in each field period are identical but are turned around relative to each other. This group of three coils per period will be used in planning the maintainability concept for the reactor which will be described later.

3. Parametric Studies

The reactor design presented here incorporates the "natural" helical divertor of the stellarator configuration as the method of impurity control. This means that the plasma is bounded by the magnetic separatrix, and there is a scrape-off zone between the separatrix and the first wall. This choice imposes a constraint on the reactor design and limits the magnetic volume utilization.

The initial design constraints were coil modularity and a magnetic divertor topology. The chief design goals were a high rotational transform, and an effective magnetic volume utilization within a practical and maintainable coil system. The motivation for the choice of a multipolarity of three was the potential for a high rotational transform and the consequent high shear. For a given number of field periods, there is an optimum coil aspect ratio which maximizes the average separatrix transform. Once the number of field periods and the coil aspect ratio is fixed, then the plasma aspect ratio and the magnetic volume utilization can be obtained, consistent with the thickness allowed for the blanket and shield. A coil system must then be designed subject to the constraints of the divertor topology, the required field on axis, a certain maximum field on the conductor and reasonable force and stress limitations. These parametric considerations led to the selection of the parameters given in Table I.

4. Transport Modelling

A one-dimensional space-time tokamak transport code (the WHIST[5] code) has been modified to model stellarators. The rotational transform is made an input variable and the toroidal current is set at zero. The flux surfaces are assumed to be circular, although the volume between flux surfaces of the actual stellarator configuration can be made to be an input parameter. The code calculates the time evolution of the density, electron temperature, and ion temperature profiles for a given model of the transport coefficients. The model used here assumes neoclassical ion thermal conductivity, enhanced by the effect of magnetic ripple.[6] The electron thermal diffusivity is taken as 1/5 of the alcator[7] scaling value; this reflects the experimental observation that stellarators do somewhat better than the alcator scaling value. The particle diffusion is taken to be 1/5 the electron thermal diffusivity value and also includes the effect of ripple. The scrape-off layer of the helical divertor is included in the modelling. The transport in the scrape-off layer is assumed to be Bohm diffusion across the field and flow at the ion acoustic speed parallel to the field.

Figure 3 shows the steady state density and temperature profiles for the UWTOR-M design parameters. In this calculation, the volume averaged beta is assumed to be 5% and the magnetic ripple at the edge is 10%. Xenon impurity (.07%) is added to give some power loss by radiation. The plasma is fuelled by pellet injection.[8] The density and electron temperature profiles are fairly normal, but the ion temperature profile is rather flat due to the magnetic ripple near the edge which drastically increases the ion thermal conductivity. Nevertheless, the plasma remains ignited and achieves a fusion power density of ~ 4.8 W/cm^2 at β = 5%.

5. Overall Reactor Description

UWTOR-M has 18 twisted coils as shown in Fig. 2. The major radius is 24.1 m and the coil inner radius is 3.9 m. The magnetic axis is actually shifted slightly inwards to 23.5 m. The coil aspect ratio is 5.05 and the plasma aspect ratio is 14. A distance of 1.7 m was allowed for the blanket and shield and a distance of 3.05 m taken between the edge of the plasma and the center of the coil conductor bundle.

Figure 4a is a cross section of the reactor through the center of a coil showing the triangular shape of the plasma characteristic of a multipolarity of three. Blanket sections are located in the regions between the plasma triangle vertices. Figure 4b is a similar cross section between coils where the divertor action takes place. At these points the plasma actually penetrates the divertor slots where the charged particles are swept out by field lines exiting between coils. Figure 5a shows the toroidal shell at the coil centerline mapped onto one field period. Flux bundle envelopes are shown circumventing the modular coil legs and their signature in the coil centerline plane is shown by the dark outlines.

In the UWTOR-M design, the reactor is contained within an evacuated toroidal tunnel. There are no seals between adjacent blanket modules. The divertor targets are located outside the reaction chamber as can be seen in Fig. 4b. Charged particles striking the divertor targets are neutralized and scatter into zones from which they emerge into the reactor tunnel and are pumped away with pumps located at strategic points within the tunnel. In stellarators, as in tokamaks, the surface heating in the reaction chamber is quite high, necessitating a separately cooled first wall.

The inner wall of the reactor tunnel will be sufficiently reinforced to react the centering forces exerted by the coils. These forces are transferred through fiberglass epoxy struts which penetrate the vacuum dewars of the coils and connect directly to the coil structure.

6. Impurity Control

There are two possible impurity controls that can be used in a stellarator/torsatron reactor, the magnetic divertor and the pumped limiter. The magnetic divertor is ideally suited for the stellarator because it is already there as a natural consequence of the coil configuration. Clearly, divertor targets are needed to recover the energy of the charged particles. The most compelling reason for using the magnetic divertor, in addition to providing a high rotational transform, is that we know it works. The penalty is the smaller magnetic volume utilization resulting from the location of the separatrix.

The pumped limiter, on the other hand, is still an unknown entity. Its major advantage is that it allows more efficient utilization of the magnetic volume. On the other hand, because they have to be located inside the reaction chamber, pumped limiters would be more difficult to service and would be subjected to high heat levels and high sputtering rates, providing a ready source of impurities for the plasma.

The divertor targets proposed for UWTOR-M are quite unique. Each divertor slot will be equipped with a pair of cylinders made of shield material and covered with several centimeters of pyrolytic graphite as shown in Fig. 5b. They will be rotated at a nominal rate of 100 RPM. Charged particles striking the divertor targets are neutralized and scatter into zones from which they emerge into the reactor tunnel and are pumped away. Neutral pressure enhancement(9), similar to that in pumped limiters, can also occur in this design. The peak heating in the center of the flux bundle is spread over a larger area due to the curvature of the cylinders and the energy is radiated away to the cooled surfaces surrounding the cylinders. One main advantage of such divertor targets is that the energy can be recovered at a high temperature, improving the power cycle. The location of the divertor targets on the outside of the torus makes them accessible for servicing without major disassembly of reactor components. Table II summarizes the advantages of the divertor.

7. Blanket Design and Neutronics

The materials chosen for the blanket are $Li_{17}Pb_{83}$ for breeding and HT-9 ferritic steel for structure. To avoid pumping a liquid metal through high magnetic fields and complex geometries, it was decided to immerse cooling tubes in the breeding material and use steam as the cooling medium.

$Li_{17}Pb_{83}$ is attractive due to its high breeding potential, low lithium activity, low tritium solubility and inertness with respect to water. HT-9 was chosen for its apparent low swelling characteristics. The high tritium particle pressure (10^{-2} torr) resulting from the low solubility combined with the high permeability of HT-9 will allow the diffusion of tritium into the primary steam cycle where it will be immediately oxidized into HTO. The primary steam cycle will exchange heat with a secondary steam cycle which will drive a conventional turbine. Tritium diffusion into the secondary steam cycle will be extremely low due to the oxidized form of the tritium. This is particularly true if stainless steel tubes are used in the steam generator. The tritium concentration in the primary steam cycle will be allowed to reach a level equal to that of deuterium in water. Since the total water inventory in the primary steam cycle is quite small, conventional techniques for recovering deuterium from water can be economically justified for recovering the tritium. A summary of the tritium parameters is given in Table III.

Monte Carlo as well as one dimensional neutronics calculations were performed to determine the overall breeding ratio and the neutron streaming through the divertor slots. For the Monte Carlo calculation 4000 histories were used and the source was modelled as the triangular plasma shown in Fig. 4b. It was discovered that although the divertor slots occupy only 12% of the first wall area, they provide leakage to 26% of all the neutrons, 7.5% of which are primary (14.2 MeV). This necessitated the use of 90% enriched ^{6}Li in order to achieve adequate breeding. The overall breeding ratio is 1.05 and the blanket energy multiplication is 1.08. The neutron wall loading is 1.35 MW/m^2. Although the neutrons streaming through the divertor slots do not breed, a large fraction of their energy is recovered by the divertor targets at a high conversion efficiency.

It can be seen from Fig. 4a that some of the areas in the vicinity of the divertor slots cannot have blankets. These areas will necessarily have heavy shielding with a high fraction of tungsten. In general, we have established that adequate protection can be provided for the coils in UWTOR-M.

8. Magnet Design

The magnet system in UWTOR-M consists of 18 modular steady state coils. There are only two coil geometries as can be seen in Fig. 2. The field on axis is 5.5 T and the maximum field on the conductor is ~ 11 T. As presently envisaged, the coils will have individual dewars and will be cooled with superfluid helium at 1.8 K. The conductor will be a graded NbTiTa/NbTi monolith stabilized with 3/4 hard copper.

The forces on these coils have two principal components, the self force on the individual coils and the interactive force between adjacent coils. In the bend regions where adjacent coils come close together, the mutually attractive forces dominate, while in the straight sections, self forces dominate. There are three forces that act on each coil, a toroidal force, a poloidal force, and a radial force. Figure 6a gives the orientation of these forces on a coil centerline and Fig. 6b shows typical radial and toroidal line forces on a coil. Figures 7a and 7b show the radial, poloidal, toroidal and total line forces as functions of the poloidal angle ϕ. The total force is sinusoidal with a maximum of 180 MN/m occurring at the ends and a minimum of 6 MN/m in the straight sections. Summing the radial forces around the coil produces a net total centering force of about 225 MN/coil. This force will be reacted with struts bearing on the central support column and similar struts will also be provided between coils.

Presently we are in the process of implementing the SAP-4 finite element stress analysis code to complete the coil design, but as yet have no results to report. Such analysis is extremely sensitive to the distribution of structure within the coil bundle and the boundary conditions imposed on the coil nodes and support points. Many iterations will be made before a final design will be adopted.

As in Yin Yang coils a substantial fraction of the structure will be used in the coil case. Besides a heavy outer case, some structure will be used within the conductor bundle to alleviate the pileup of forces from the individual conductors. Thus the coil will be compartmentalized such that the current density in the high field region will be 1650 A/cm^2 while in the rest of the coil it will be 2440 A/cm^2. A monolithic conductor with 3/4 hard copper stabilizer similar to that used in MFTF-B is proposed.

Construction of these coils is similar to Yin Yang with an added degree of difficulty. This is due to the many negative curvature regions in which the conductor cannot be maintained in tension during winding. It should be mentioned that this is only true for coil geometries with multipolarities $\ell \geq 3$. To overcome this difficulty, a special fixture must be provided for restraining the conductor in the negative curvature regions during winding. Alternatively, grooved structure must be provided and the conductor restrained in that way. However, because of the complex coil geometries, this choice is less desirable. Table IV summarizes features of the coil windings and the conductor parameters.

9. Reactor Maintainability

The major aspects of reactor maintainability have to do with maintaining the blanket and the coils. The advent of modular coils have improved immeasurably the prospects for maintaining both systems.

In the UWTOR-M design, the reactor is contained within an evacuated toroidal tunnel. The reactor tunnel is surrounded by a toroidal service hall and is connected to it by doors located behind each of the "figure 8" coils. Each coil period has three coils, one "figure 8" coil and two identical coils on either side of it. Although the coils are identical in construction, they are turned 180° relative to each other.

The maintenance scheme proposed for this reactor involves the capability of radial extraction of a "figure 8" coil module, consisting of coil, blanket and shield through the door into the service hall as shown in Fig. 8. The module is removed to a location where segments of the blanket within it are removed and replaced. At the same time, a specially equipped carriage reenters the reactor tunnel into the place vacated by the extracted module. This carriage can work on blankets on either side, thus reaching the remaining blanket segments within that period. By only moving one-third of the coils in the reactor, accessibility has been provided for the whole reactor blanket. It must be noted that the neutral beams are not disturbed in this process.

Coils that are adjacent to the "figure 8" coil can also fail and will require servicing. In that event, the failed coil will have to be moved circumferentially first and then radially. Although this operation is by no means simple, provided with guided rails and appropriate stops, it can be performed using present day technology.

10. Conclusions

- Preliminary indications are that the engineering issues of modular stellarator reactors, although far from being easy, are technically feasible with modest extrapolations of present day technology.

- A low plasma aspect ratio and high rotational transform with reasonable plasma volume and adequate space for blanket/shield are difficult to achieve.

- In spite of rather conservative physics assumptions, the stellarator still appears to be competitive with other magnetic fusion concepts.

- The stellarator natural divertor, although complicating the mechanical design, can be exploited for higher rotational transform and consequent prospect for better MHD equilibrium and stability.

- Blanket maintainability can be provided by radial extraction of 1/3 of the coil set.

- Modular coils and recent encouraging plasma physics results, coupled with the original advantages, have made the stellarator/torsatron concept into an attractive magnetic confinement fusion reactor.

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Table I Preliminary Parameter List (UWTOR-M)

Major radius (m)	24.1
Coil centerline radius (m)	4.77
Magnetic axis (m)	23.5
Coil aspect ratio	5.05
Plasma aspect ratio	14
Plasma minor radius (m)	1.72
Average β (assumed) (%)	5
Rotational transform at edge	1.12
Multipolarity	3
No. of field periods	6
Average neutron wall loading (MW/m^2)	1.36
Coils/period	3
Total no. of coils	18
Coil current (MA)	37
Field on axis (T)	5.5
Max. field on conductor (T)	11.0
Stored energy in coils (GJ)	190
Plasma volume (m^3)	1500
Thermal power output (MWth)	5500

Table II Advantages of the UWTOR-M Divertor

No additional coils required
Compatible with blanket/shield
Modular, localized collection regions
Effective for trapped particles
Well defined scrape-off zone
Low stray fields
Compatible with desired large rotational transform
Compatible with practical coil system

Table III Tritium Summary

Tritium partial pressure in $Li_{17}Pb_{83}$	10^{-2} torr
Tritium inventory in $Li_{17}Pb_{83}$	60 g
Water inventory in primary steam cycle	$2x10^3$ kg
Tritium inventory in primary steam cycle	100 g
Tritium dissolved in blanket structure	4 g
Total blanket system tritium inventory	164 g

Table IV Coil and Conductor Parameters

Number of coils	18
Multipolarity	3
Overall current density (A/cm^2)	1265
Field on axis (tesla)	5.5
Max. field on conductor (tesla)	11.0
Conductor current (kA)	10
Number of turns	3700
Conductor current density - high field (A/cm^2)	2000
Conductor current density - elsewhere (A/cm^2)	3000
Superconductor current density (A/mm^2)	1500
Structural material	304 LN SS
Superconductor(10,11)	NbTiTa/NbTi
Stabilizer	3/4 hard Cu
Coolant	He II at 1.8 K

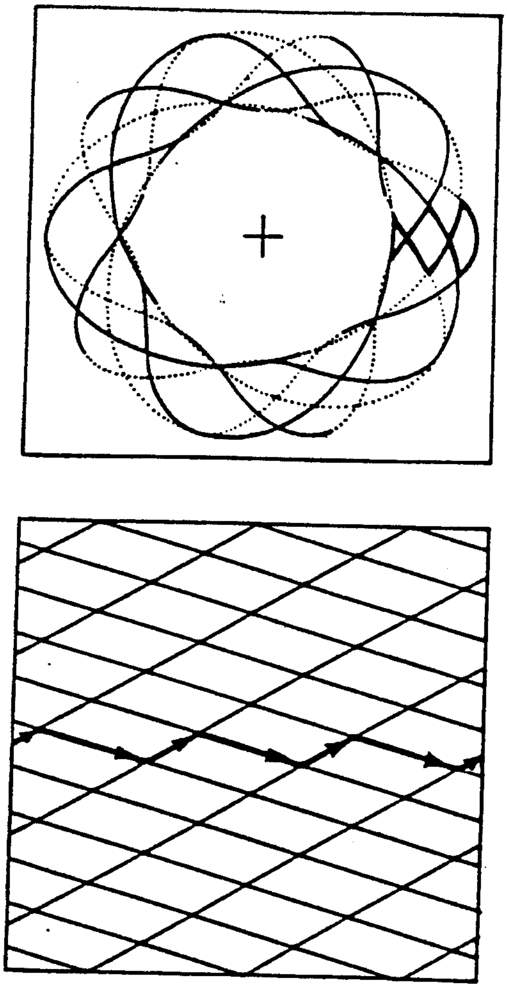

Fig. 1a Helical coil system for $\ell=3$, 5 period ultimate stellarator (top) and corresponding mapping in the $\theta - \phi$ plane (bottom)

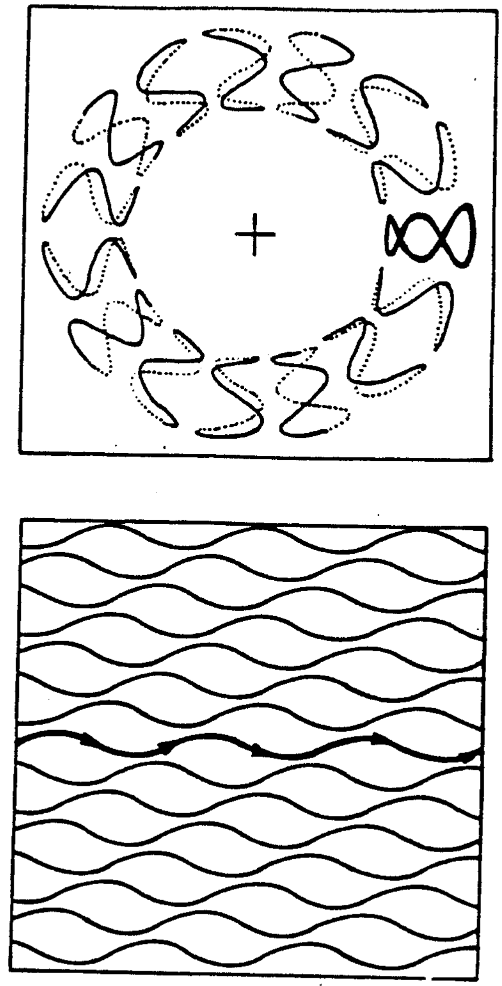

Fig. 1b Modular coil system from the one term Fourier series expansion to the ultimate stellarator (top) and corresponding mapping in the θ-ϕ plane

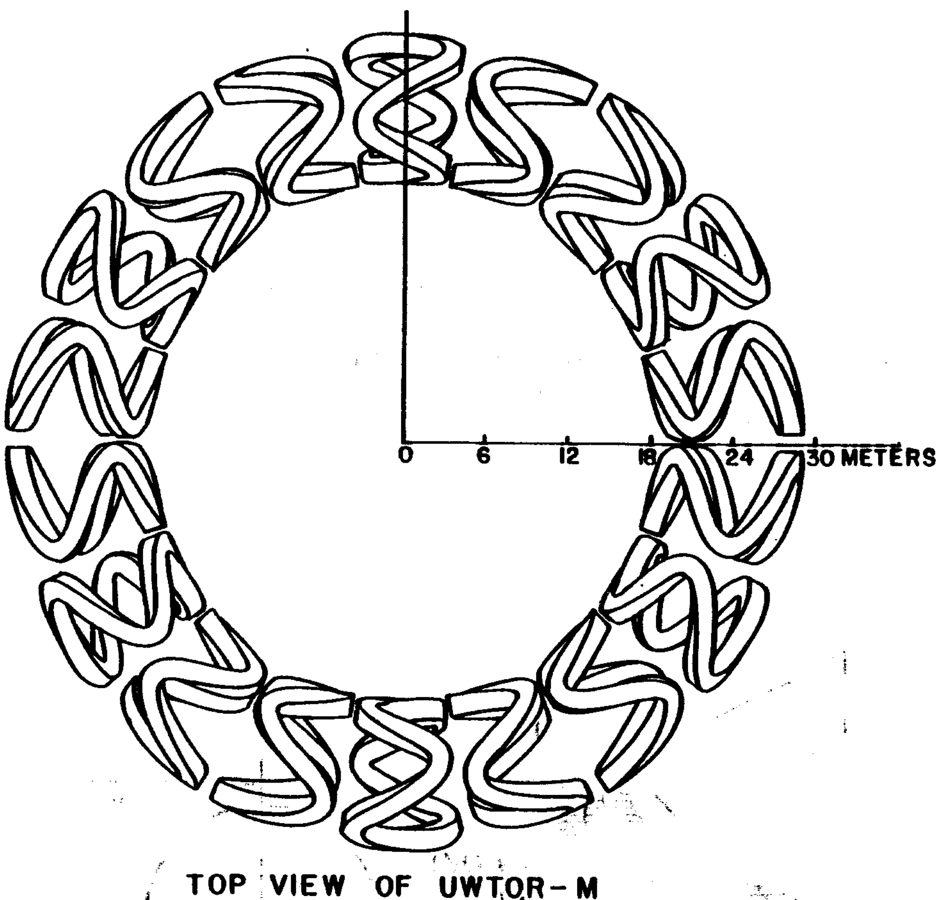

Fig. 2 Top view of UWTOR-M coil set

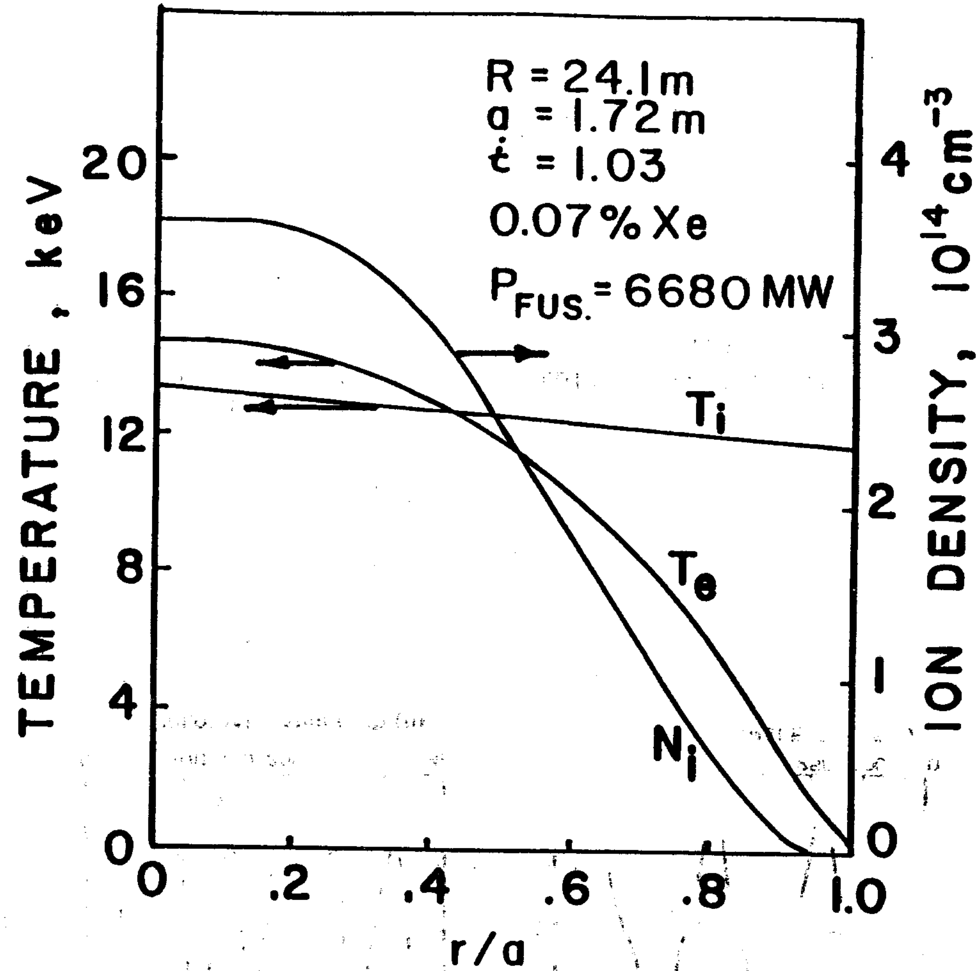

Fig. 3 Electron and ion temperature and ion density as functions of plasma radius

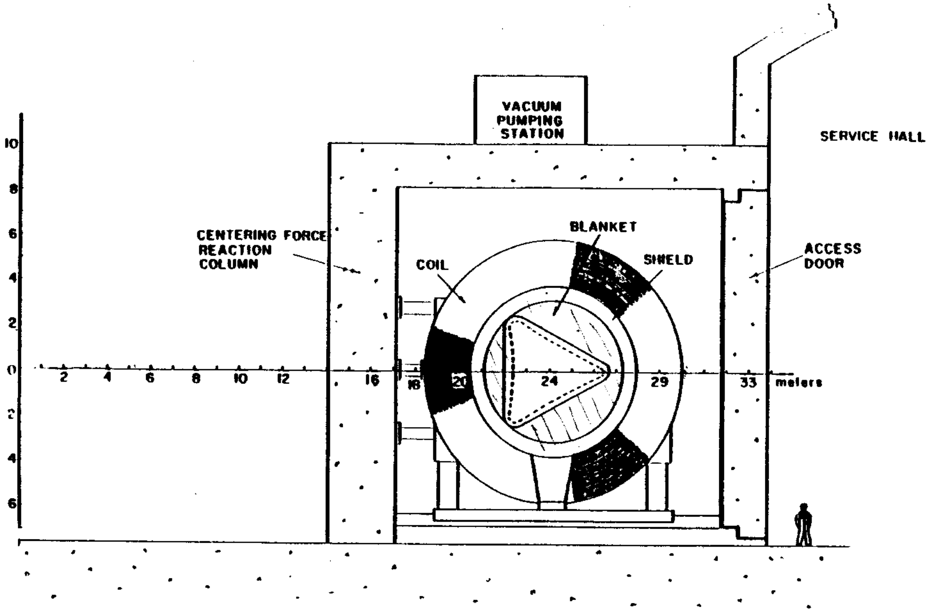

Fig. 4a SIDE VIEW OF UWTOR-M

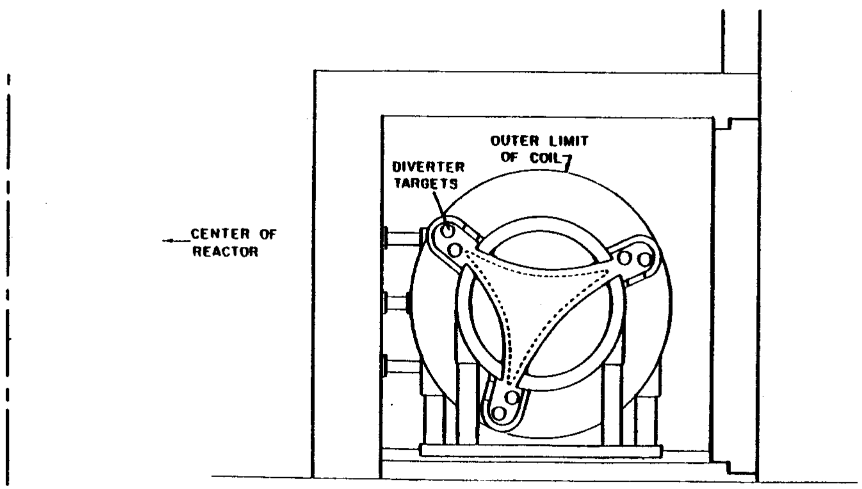

Fig. 4b SIDE VIEW SECTION BETWEEN COILS SHOWING DIVERTER TARGETS

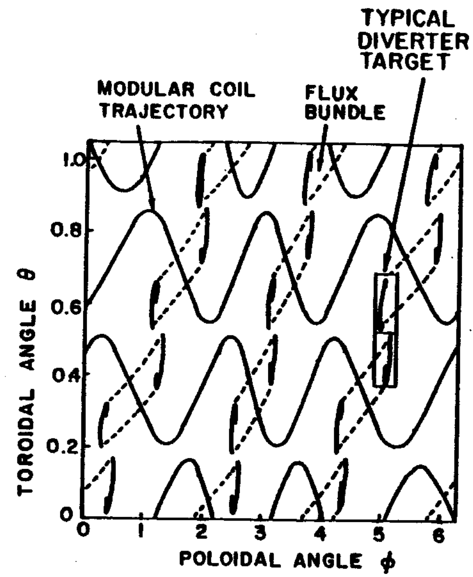

Fig. 5a One period in the coils centerline mapped onto the θ-ϕ plane showing location of the divertor flux bundles

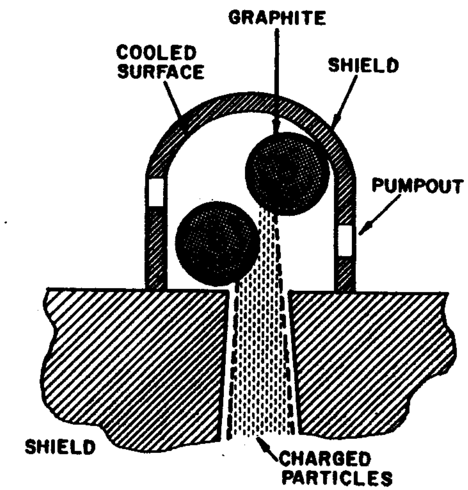

Fig. 5b Proposed rotating cylindrical divertor targets

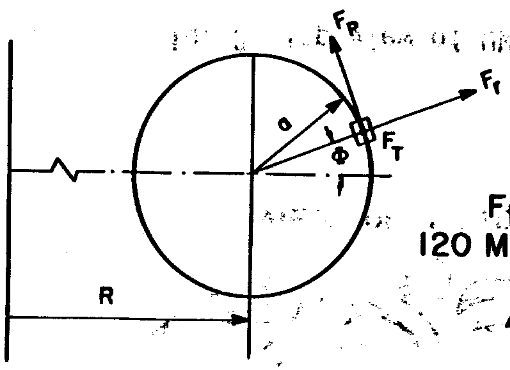

Fig. 6a Schematic of coil force orientation

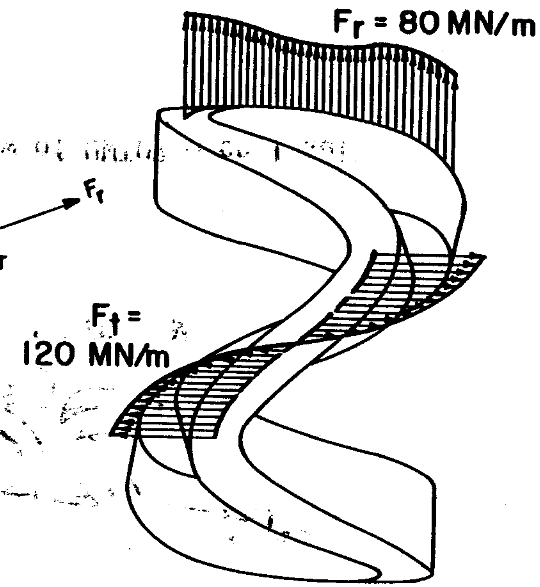

Fig. 6b Typical radial and and toroidal forces on a modular coil

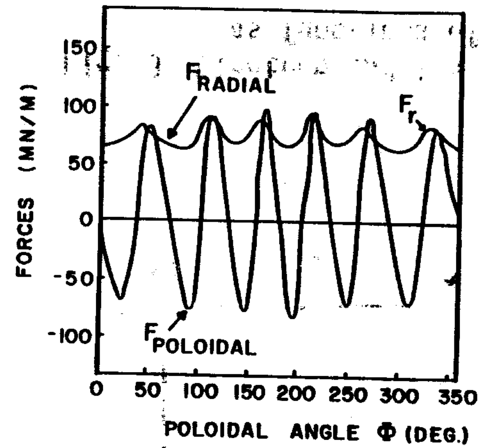

Fig. 7a Poloidal and radial forces as functions of the poloidal angle ϕ.

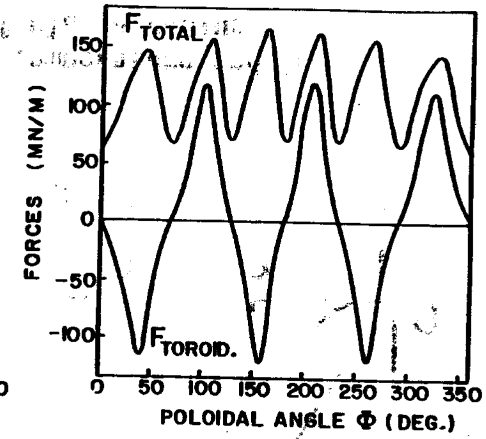

Fig. 7b Toroidal and total forces as functions of the poloidal angle ϕ

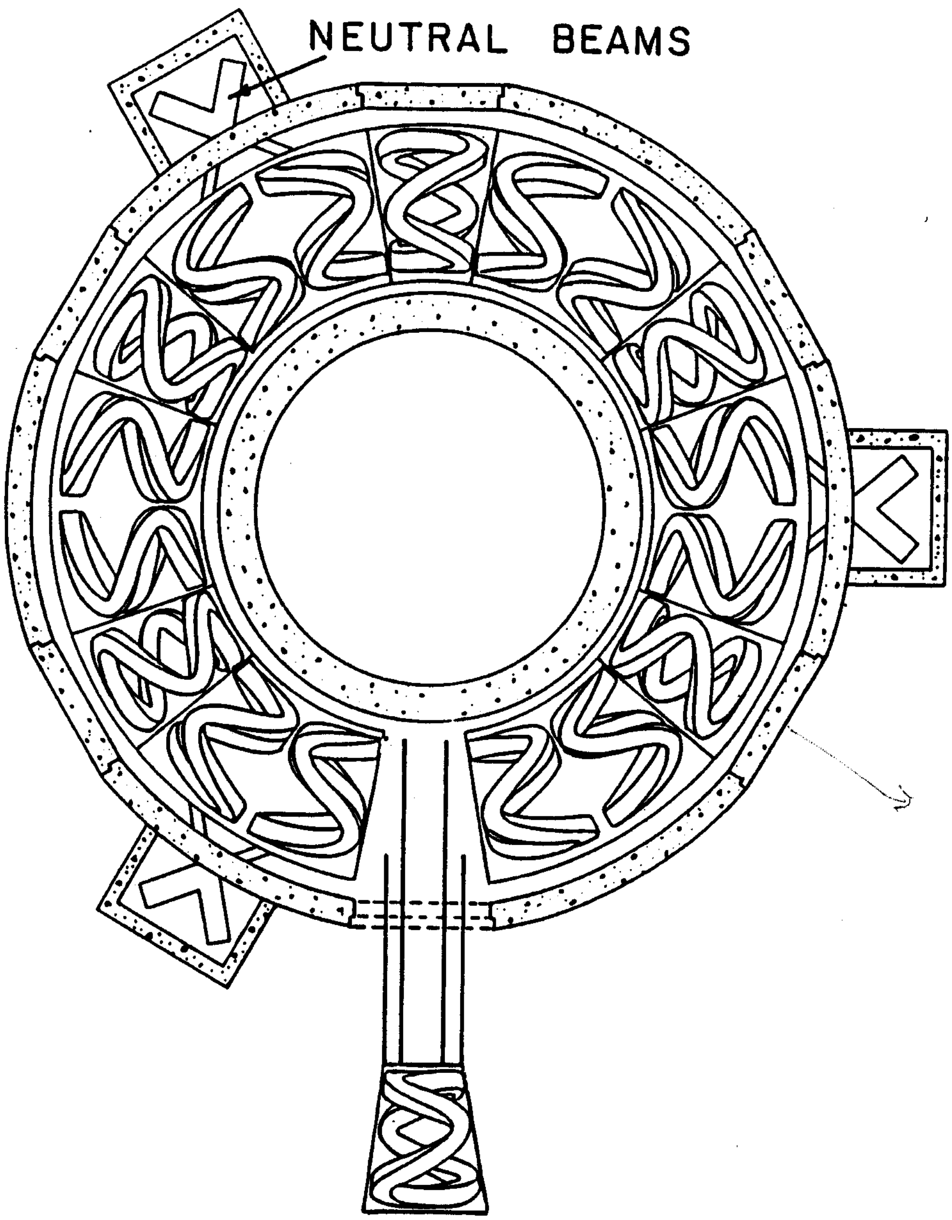

Fig. 8 Radial extraction of a coil/blanket/shield module for maintainance