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September 1982

UWFDM-480

9th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, IAEA Mtg., Baltimore, MD, September 1-8, 1982, paper IAEA-CN-41/E-3.

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DOE/ET52048-25
UC-20

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Presented at 9th IAEA International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, MD, 1-8 September 1982.

Progress in Modular Stellarator Fusion Power Reactor Conceptual Designs

Abstract

Recent encouraging experimental results on stellarators/torsatrons/heliotrons (S/T/H) have revived interest in these concepts as possible fusion power reactors. The use of modular coils to generate the stellarator topology has added impetus to this renewed interest. Studies of the modular coil approach to stellarators by UW-Madison and Los Alamos National Laboratory are summarized in this paper.

1. Introduction

The stellarator offers a distinct alternative to the main-line approaches to magnetic fusion by being the only magnetic confinement concept that can maintain an ignited steady-state fusion plasma without external power input. The primary advantages of stellarators are steady state magnetic fields and continuous plasma operation. This removes complications associated with pulsed fields such as pulsed power storage and switching, enormous pulsed loads and fatigue problems on magnet structures, eddy currents in superconductors, thermal fatigue on blanket components and finally, it obviates the need for a thermal flywheel to even out the load on the power cycle. Since plasma heating is only required at startup, there is no recirculating power and because startup is on existing magnetic surfaces, plasma control is vastly simplified. Further, the stellarator has a natural divertor, thus offering a demonstrated impurity control mechanism. Finally, since there is no net current in the plasma there are no identified plasma disruptions.

Experiments with net current free operation which has been achieved with neutral beam injection [1] and with RF heating [2] have shown no MHD activity, no major disruptions, an extremely low level of small-scale turbulence and transport losses which are smaller than in ohmically heated discharges of similar plasma conditions.

The modular coil approach to stellarators is the subject of two ongoing reactor studies, one at the UW-Madison called UWTOR-M and the other at Los Alamos designated MSR. The results and conclusions are summarized in this paper.

2. UWTOR-M Study (University of Wisconsin)

UWTOR-M [3] is a 5200 MWth $\ell=3$ modular stellarator reactor with 18 discrete twisted coils, a major radius of 24 m and a plasma aspect ratio of 14. This magnetic topology leads to a rotational transform of 1.1 on the plasma edge producing high shear, and gives optimism that the assumed β of 6% can be achieved. The natural divertor with externally located divertor targets is used for impurity control. This study, which has primarily emphasized engineering aspects, has concentrated on two areas in its later phase, a credible coil design and overall system integration.

The initial constraints on the study were coil modularity and a magnetic divertor topology. Modularity is deemed essential for a power reactor to be maintainable. A magnetic divertor, if it could be accommodated, would be a definite advantage. Although the assumed 6% β was not quantitatively coupled to any stability/equilibrium model, the design goal was to achieve a high rotational transform with shear, avoid island formation and provide an adequate magnetic volume within a practical coil system.

To this end a one-dimensional tokamak time dependent fluid code "WHIST" [4] was modified to solve particle and energy transport and obtain radial density and temperature profiles. The code allows an externally imposed rotational transform and utilizes stellarator-like transport coefficients. Diffusion was taken as tokamak neoclassical with 1/5 Alcator scaling including helical ripple effects. Ion transport was assumed tokamak neoclassical with helical ripple effects and electron transport, also tokamak neoclassical plus 1/5 Alcator scaling. Bohm diffusion is assumed in the scrape-off layer in all cases. Table I gives the resulting parameters.

Table I. UWTOR-M Parameters

Major radius (m)	24.1	Avg. elect. density (n/cm^3)	$1.5x10^{14}$
Coil radius (m)	4.8	Avg. elect. temp. (keV)	9.5
Plasma aspect ratio	14	Avg. ion temp. (keV)	9.8
Number of periods	6	Avg. tor. beta (%)	6
Number of coils	18	Xenon concent. (n/cm^3)	$3x10^{10}$
Field on axis (T)	4.5	Part. conf. time (s)	4.0
Max. field (T)	11.7	Ener. conf. time (s)	1.5
Stored energy (GJ)	170	Fract. T_2 burnup (%)	4.4
Neut. wall flux (MW/m^2)	1.8	Edge rot. trans	1.1
Mass utiliz. (tonnes/MWe)	29.4		
Thermal output (MWth)	5160	Edge field ripple (%)	23
Net elect. (MWe)	1700	Plasma volume (m^3)	1650
Direct unit cost ($/kWe)	1419	DT power (MWth)	4300

A top view of UWTOR-M is shown in Fig. 1. Note that there are only two different coil geometries. The most difficult problem in the coil design is the mode of support and force restraint. Any support concept must consider the radial force which produces bending and torsion as well as toroidal and poloidal forces, while preserving modularity. It was determined that the radial force is best reacted by a separate vertical structural ring which surrounds each coil at the midplane as shown in Fig. 1. Toroidal forces are reacted by the coils making contact at the twist extremities and the centering force, by the structural rings bearing against a central column. The stresses are extremely sensitive to how the ring is fixed to its surroundings and the coupling between it and the coil frame. Detailed analysis with a finite element stress code has shown reasonable stresses for central fields of 4.5 - 5 T. Less coil distortion would allow a higher field on axis provided the maximum field does not exceed 12 T.

Although the overall size of a UWTOR-M coil is smaller than a STARFIRE TF coil, it is somewhat heavier (850 vs. 500 tonnes). Construction difficulty would be comparable to Yin Yang coils, which have already been built in moderate size for MFTF-B.

The stellarator flux surface requires twisting in the toroidal direction and so has no planes of symmetry. This tends to make the reaction chamber shape more complicated. There are, however, two mitigating factors in a modular stellarator, namely that twisting occurs in steps rather than continuously, and that the magnetic divertor consists of discrete well focused flux bundles emerging between the bends in the coils. Moreover, the flux bundles are oriented toroidally. The blanket can, therefore, be divided into toroidal segments of constant shape reaction chamber with no twisting within each segment. Instead, each adjacent segment has the reaction chamber rotated to accommodate the helicity of the flux surface. Since UWTOR-M has a multipolarity of three, the plasma shape is triangular and requires three divertor slots in each blanket

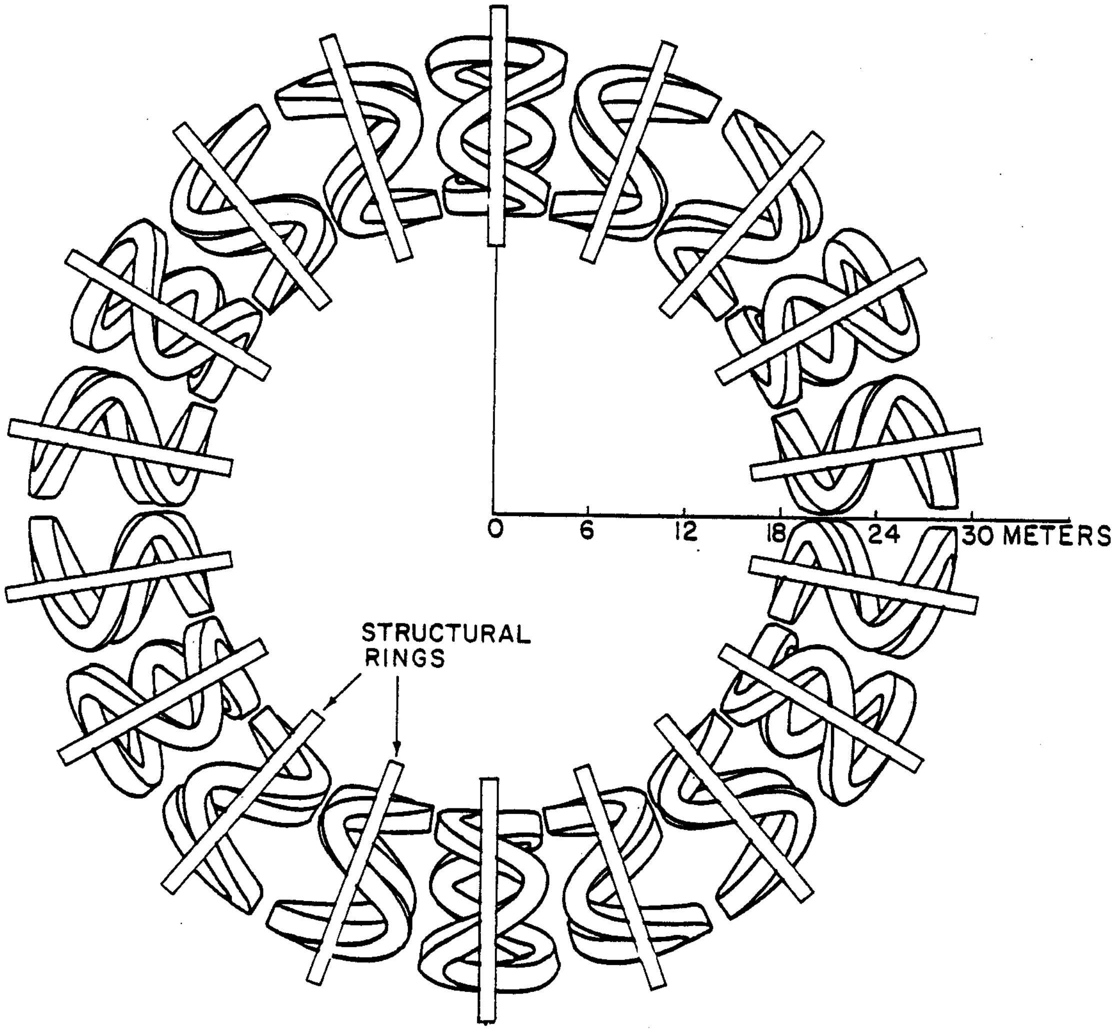

Figure 1 Top View of UWTOR-M
Modular Stellarator Reactor Coil Set

segment. Two segments are needed for each coil.

Divertor targets are located outside the shield and consist of a pair of cylinders for each divertor slot within a cooled housing. The core of the cylinders is a stationary actively cooled shield while the surface, consisting of a graphite covered shell, rotates slowly and radiates energy both to the core and the housing. This high grade energy is converted at a high efficiency in the power cycle. Neutron streaming from the divertor slot is prevented by the core shield.

In the present design the reactor is located within an evacuated toroidal enclosure. Reactor exhaust is vented into the enclosure from the divertor housings and recovered by vacuum pumps. This scheme eliminates seals between adjacent blanket segments, vastly simplifying maintainability. The consequences of a T_2 contaminated reactor enclosure, however, have to be evaluated.

Maintainability is provided by radial extraction of every other coil module, thus providing access to all the blanket segments and the divertor targets. The drained blanket segments are then removed, one from each side of the coil. Although such an operation is by no means easy, it can be accomplished with adequate planning.

Initial cost estimates indicate a direct unit cost of 1419 \$/kWe for UWTOR-M which is fairly competitive with other magnetic confinement fusion reactors.

Conclusions

In conclusion, preliminary indications are that the engineering aspects of modular stellarator reactors are within reasonable extrapolations of present technology. The modular divertor can be used effectively for impurity control. For $\beta > 5\%$, such reactors also appear to be economically competitive with other fusion systems of the 4000 - 5000 MWth range. Although difficult to access economically, advantages such as steady state, non-driven ignited plasma and no disruptions make modular stellarators that much more attractive.

3. Modular Stellarator Reactor Studies (Los Alamos)

Earlier phases of the Los Alamos study of the Modular Stellarator Reactor (MSR) have characterized parametrically the critical relationships between the plasma, first wall/blanket/shield (FW/B/S), coil set, and overall reactor plant performance. The first model led to consideration of interim designs [5,6] with P_{TH} = 4.0-4.8 GWt, N = 24 coils, d/r_c = 0.30-0.41, R_T = 21.35-23.24 m, r_p = 1.94-2.11 m, and $\langle\beta\rangle = 0.04$. Although "self-consistent", this approach used a yet-to-be proven, pessimistic model for stability/equilibrium beta limits based on diffusion-driven plasma currents. A "beta-decoupled" model has been adopted for more recent MSR studies [7] in which beta is treated parametrically in order to better understand the crucial coupling and tradeoffs between the key elements of the design. Potentially attractive design points identified by this parametric survey are being subjected to more detailed engineering analysis and design verification.

Two representative MSR design points (Table II), respectively emphasizing traditional performance (MSR-IIA, $\langle\beta\rangle = 0.04$) and optimistic performance (MSR-IIB, $\langle\beta\rangle = 0.08$) have been identified by means of the more recent parametric approach. Both commercial electric plants are assumed to operate as ignited, steady-state DT systems with 8% recirculating power (coolant pumps and cryogenic refrigeration) and 35% thermal conversion efficiency. These design points are being used to answer quantitatively two fundamental questions: 1) What is the influence of key physics parameters and assumptions (e.g., magnetics, $\langle\beta\rangle$, and transport) on reactor size performance, and cost and 2) What are the comparative advantages and disadvantages of torsatron and modular-coil configurations?

Three-dimensional magnetics computations are performed using the TORSIDO magnetics code developed for this study. Both MSR coil configurations consist of N = 36 Rehker-Wobig modular coils with modest lateral deformation, d/r_c = 0.23-0.28 in order to reduce individual coil mass, the ratio of peak coil field and on-axis field, the toroidal-field ripple, and lateral

Table II. Modular Stellarator Reactor Design Points(a)

Parameter	MSR-IIA (m=16)(b)	MSR-IIB (m=20)(b)
Average beta, $\langle\beta\rangle$	0.4	0.08
Average density, $\langle n\rangle$ (10^{20} m^{-3})	1.38	3.64
Lateral coil distortion, d/r_c	0.235	0.28
Rotational transform, $\iota(0)/\iota(r_p)$	0.48/0.43 (0.74/2.0)	0.69/0.92 (1.03/1.7)
Major radius, R_T(m)	27.9	23.0
Average plasma radius, r_p (m)	2.25	0.81
Conductor minor radius, r_c(m)	5.0	3.31
Outer coil radius, r_o(m)	6.165	4.465
Plasma volume, V_p(m^3)	2788.	298.
Coil surface area coverage(c)	~ 0.35	~ 0.42
Mass utilization, M/P_{TH} (tonne/MWt)(d)	8.4	6.1
Module mass (tonne)(d)	1280.	680.
Plasma power density, P_{TH}/V_p (MWt/m^3)	1.83	14.81
System power density, P_{TH}/V_c (MWt/m^3)	0.27	0.53
Total thermal power, P_{TH}(GWt)	5.1	4.0
Net electric power, P_E(GWe)	1.64	1.29
First-wall neutron loading, I_w(MW/m^2)	1.0	1.9
On-axis field, B_o(T)	5.72	6.56
Peak field at coil, B_{CM}(T)	10.9(11.2)	~ 12(10.9)
Total coil current, T(MAT/coil)	22.3(50.0)	21.0(37.9)
Stored magnetic energy, E_M(GJ)	230.(607.)	109.(290.)
Unit direct cost ($/kWe)	1737.	1331.
Cost of electricity (mills/kWeh)	106.	81.

(a) $\ell=2$, m=4, N=36, $\langle T\rangle=8$ keV, j_{cond} = 19 MA/m^2

(b) Numbers in parentheses are torsatron systems with same B_o and size

(c) Fraction of outer shield surface area covered by magnet casing

(d) M is mass of coil, blanket and shield coil force components. Torsatron coils have lower peak lateral forces than the MSR cases (i.e., 9-12 MN/m versus 27-33 MN/m) and hence require less structural support between coils, but the fabrication and maintenance questions are more severe, unless life-of-plant coils can be postulated. Relatively few MSR toroidal-field periods (m=4) allow radial rotational transform profiles, $\iota(r)$, in the ranges 0.5-0.4 (MSR-IIA) and 0.7-0.9 (MSR-IIB), providing significant non-zero transform on-axis, avoiding rational surfaces within the plasma, and, with the addition of appropriate higher-harmonics into the coil winding law [8], providing significant positive shear at the plasma edge (MSR=IIB). Except for the out-of-plane winding, the internal coil technology is comparable to other recent superconducting fusion reactor system designs.

Radial energy transport in both MSR systems is assumed conservatively to scale as $\tau_E = 3.0(10)^{-21} \langle n \rangle r_p^2$ [i.e., 40% reduced Alcator scaling]. This results in similar confinement to that of UWTOR-M. Use of the Alcator scaling relation allows convenient minimization of the $\langle \beta \rangle B_o^2 r_p$ ignition parameter, which is 2.94 T^2 m and 2.79 T^2 m at $\langle T \rangle$ = 8 keV for the respective design points, reflecting a higher trapping of fusion-product alpha-particle energy in the higher-aspect-ratio MSR-IIB case [9]. The higher beta of the MSR-IIB case is reflected directly in a lower plasma radius, r_p, for a $\langle \beta \rangle B_o^2 r_p$ value fixed by ignition and nr_p^2 scaling.

The lower plasma radius for MSR-IIB allows the concentric annuli of blanket/shield/coil to be reduced in minor radius, giving higher system power density, P_{TH}/V_C and lower mass M. Impurity control is assumed to be provided by a pumped limiter, although divertors are also compatible with the design. Routine maintenance and replacement of limiter/first-wall/blanket components would be accomplished without moving modular coils in order to promote high plant availability. The coils in the MSR-IIA and MSR-IIB configurations cover 35% and 41%, respectively, of the outer B/S surface area, compared to 34% and 41% for torsatron systems designed to similar constraints (i.e., same P_{TH}, R_T, B_0). In the worst case the MSR unit module (i.e., single coil and underlying FW/B/S components) could be decoupled from the support structure and translated radially outward without lifting, as is postulated for UWTOR-M.

A comparison of MSR costs given in Table II with other fusion systems is given elsewhere [10]. These costs are based on a conservative ten-year construction period, 10%/y interest and 5%/y escalation, 15%/y capital return, 2%/y operating costs, and 76%/y plant availability. The reactor equipment represents 53% and 40% of the direct costs for the systems. In both respective cases, the dominant cost item within the reactor equipment category is the coil set, representing 36% and 53%, respectively.

The following conclusions have emerged to date from the MSR study.

- Modular-coil configurations sacrifice magnetics performance relative to continuous-coil configurations [rotational transform (~ 2% less), shear (comparable at high transform), volume utilization (~ 2% less), peak coil field (~ 10% higher for same B_0), $B_{CM}/B_0 \sim 10\%$ (less), etc.] in return for fabrication advantages and lower stored energy.
- Radial forces are larger for the torsatron, while lateral forces are smaller when compared to modular coils. Access is diminished primarily in proportion to the lateral forces; the modular-coil approach is adversely affected most by the lost access as B is increased, but has the option to be moved as part of the routine maintenance scheme.
- Access to first-wall/blanket components for fixed modular or torsatron systems is comparable, suggesting a similar maintenance scheme that does not require coil movement.
- Modular-coil and torsatron configurations with similar plasma performance (size, field, beta, etc.) are comparable in terms of access and cost. Modular coils are preferable if life-of-plant (LOP) coils cannot be assumed. Availability of LOP coils and desire to maximize plasma performance (beta) would favor torsatron coils. Availability of

breakable joints without LOP coils favors torsatron coils.

- Marginally competitive MSR designs are available for $\langle\beta\rangle$ as low as 0.04 at $\gtrsim$ 25% higher power. Truly competitive (i.e., STARFIRE-like) designs at lower power output would require $\langle\beta\rangle$ of at least 0.08. The magnetics performance of simple, modular coils raises questions about obtaining the latter, based on current understanding of stability/equilibrium beta limits.
- Beta remains the major issue for S/T/Hs.
  - If high transform and shear are required, torsatron or advanced modular configurations (e.g., M&S or Heliac) are preferable.
  - Reactor performance is critically coupled to the magnetics performance of the coil set.

Acknowledgement

Support for these studies has come from the U.S. Department of Energy.

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