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Advantages of High Field Tokamaks for Fusion Reactor Development

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Abstract

High field designs could reduce the cost and complexity of tokamak reactors. Moreover, the certainty of achieving required plasma performance could be increased. Strong ohmic heating could eliminate or significantly decrease auxiliary heating power requirements and high values of $n\tau_E$ could be obtained in modest size plasmas. Other potential advantages are reactor operation at modest values of beta; capability of higher power density and wall loading; and possibility of operation with advanced fuel mixtures. Present experimental results and basic scaling relations imply that the parameter B^2a where B is the magnetic and a is the minor radius may be of special importance. A super high field compact ignition experiment with very high values of B^2a (e.g. $B^2a = 150\ T^2m$) has the potential of ohmically heating to ignition. This short pulse device would use inertially cooled copper plate magnets. Compact engineering test reactor and/or experimental hybrid reactor designs would use steady state water cooled copper magnets and provide long pulse operation. Design concepts are also described for demonstration/commercial reactors. These devices could use high field superconducting magnets with 7T - 10T at the plasma axis.

Introduction

Present experimental results and basic scaling relations imply that high field tokamaks could provide a number of advantages for reactor development. These advantages could result in significant improvement in cost and simplicity as well as greater certainty of achieving required plasma performance. Strong ohmic heating could increase certainty of heating to reactor temperatures and eliminate or substantially decrease auxiliary heating power requirements. Moreover, high values of $n\tau_E$ could be obtained in modest size plasmas. Other potential advantages are increased fusion power density and wall loading permitted by limits on plasma density; and DT reactor operation at relatively modest values of beta. The parameter B^2a (where B is the magnetic field and a is the minor radius) may be of special importance. This paper discusses advantages for both test reactors and demonstration/commercial reactors in this context.

Ohmic-Heated Startup

The plasma temperature attainable with ohmic heating can be estimated by the power balance

$$\eta j^2 = \frac{1.5nkT}{\tau_e} + \frac{1.5nkT}{\tau_i} \qquad (1)$$

where T is the plasma temperature, η is the plasma resistivity, j is the current density, τ_e and τ_i are the electron and ion energy confinement times and n is the plasma density. We will assume that the electron and ion temperatures are equal and that $\tau_i >> \tau_e$. The electron energy confinement time is given by the "Neo-Alcator" scaling for ohmically heated plasmas[1]:

$$\tau_e \sim nR^2a \qquad (2)$$

where R is the major radius. Radiation losses will be neglected.

Since

$$\eta \sim T^{-3/2} \tag{3}$$

and

$$j \sim \frac{B}{qR}\,\frac{(1+\kappa^2)}{2\kappa} \tag{4}$$

(where B is the magnetic field, q is the safety factor at the plasma edge, and κ is the elongation in an elliptical plasma), (1), (2), (3) and (4) give the result

$$T \sim \left(\frac{B^2 a}{q^2}\right)^{2/5} \left(\frac{(1+\kappa^2)}{2\kappa}\right)^{4/5} \tag{5}$$

For κ less than about 2, the temperature is not strongly affected by elongation in an elliptical or D shaped plasma.

Operation at sufficiently high values of B^2a and low values of q could provide ohmic heating to a temperature where substantial alpha particle heating would increase the temperature to the fully ignited regime (where alpha particle heating is much greater than ohmic heating)[2]. For $n\tau_E \approx 5 \times 10^{14} cm^{-3}s$ (where τ_E is the total energy confinement time), the required central temperature for substantial alpha particle heating is ~ 4.5 keV.

The Alcator C tokamak provides central temperatures of ≈ 2 keV at relatively high density ($n \approx 3 \times 10^{14} cm^{-3}s$) with B ≈ 10T, $B^2a \approx 15\ T^2m$ and $q \simeq 2.5$. For $B^2a \simeq 150\ T^2m$, $q \simeq 2.5$ and $\kappa \simeq 1.4$, parameters that could be obtained in a compact copper magnet tokamak, scaling relation (5) gives T ~ 5.5 keV. Hence it may be possible to ohmically heat to ignition in such a device.

If pure ohmic heating to ignition cannot be obtained, it may be advantageous to use "ohmic-heating dominated" startup where the auxiliary heating power (rf or neutral beams) is less than the ohmic heating power[3]. This type of startup could provide greater certainty of reaching the desired operating temperature since the "Neo-Alcator" energy confinement scaling law for ohmically heated plasmas may still apply. Moreover, it could result in a substantial reduction in the required auxiliary heating power. With strong ohmic heating, less auxiliary heating power would, of course, be required for a given thermal loss mechanism. In addition, the degradation in energy confinement that could result from substantial auxiliary heating might be avoided.

If the "Neo-Alcator" scaling for the energy confinement time applies, the heating power P (ohmic plus auxiliary) is

$$P \sim \frac{nkTV}{\tau_E} \sim Ta/R \sim T/A \tag{6}$$

where V is the plasma volume. Hence, the heating of large plasmas (plasmas in more advanced test reactors and demonstration/commercial reactors) need not lead to larger power requirements.

Fusion Power Density and Wall Loading

If the plasma density is constrained by a Murakami limit[4], the allowed density is:

$$n \sim \frac{B\kappa^{1/2}}{qR} \tag{7}$$

A typical value for the central density is

$$n(0) \leq \frac{c_1 B\kappa^{1/2}}{R} 10^{20} \text{ m}^{-3} \tag{8}$$

where B is in Tesla and R is in meters and $q \approx 2.5$. c_1 is a parameter which could be ≈ 1 for ohmically heated plasmas and somewhat higher for auxiliary heated plasmas (and possibly alpha particle heated plasmas).

The fusion power density is

$$P_f = \frac{n^2\overline{\sigma v}E_F}{4} \qquad (9)$$

where $\overline{\sigma v}$ is average of the fusion cross section times the velocity and E_F is the energy produced per fusion reaction (17.6 MeV). Combining (8) and (9)

$$P_f < \frac{c_1{}^2\ B^2\kappa\overline{\sigma v}E_F}{4R^2} \qquad (10)$$

The total wall loading (thermal plus neutron) $P_w \approx P_f a/2$. Hence, according to (10)

$$P_w < \frac{c_1{}^2\ \kappa\overline{\sigma v}E_f(B^2a)}{8R^2} \qquad (11)$$

B^2a again plays an important role.

For an INTOR type device ($B \approx 5T$, $R \approx 5m$, $B^2a \approx 30\ T^2m$, $\kappa = 1.6$) with $c_1 \approx 1$ and $T(0) \approx 30$ keV, the allowed average power density $P_f \approx 2$ MW/m^3 for parabolic temperature and density profiles. The neutron wall loading permitted by (11) is ~ 0.8MW/m^2, lower than that believed necessary for pure fusion commercial reactors. If adverse confinement scaling were to limit reactor operation to lower temperatures, the wall loading could certainly be too low.

On the other hand, for a high field engineering test reactor with $B^2a \sim 60\ T^2m$, $R \sim 3m$ and $\kappa \sim 1.6$, the allowed wall loading would be ~ 4MW/m^2.

If the density is determined by a beta limit

$$n \sim \frac{\beta B^2}{T} \qquad (12)$$

and

$$P_f \sim \frac{\beta^2 B^4 \overline{\sigma v} E_F}{T^2} \qquad (13)$$

Thus the allowed wall loading scales as

$$P_w \sim \frac{\beta^2\ B^4\ \overline{\sigma v}\ E_F a}{T^2} \qquad (14)$$

For $\beta \sim \kappa/A \sim \kappa a/R$

$$P_w \sim \frac{\kappa^2\ \overline{\sigma v}\ E_F\ (B^2 a)^2}{T^2 R\ A} \qquad (15)$$

For both the Murakami and β-limits, the allowed fusion power density and wall loading depend significantly on the parameter $B^2 a$.

$n\tau_E$ Scaling

Next we determine the scaling of $n\tau_E$ as function of $B^2 a$ for several scalings. If the electron energy confinement time is given by "Neo-Alcator" scaling,

$$n\tau_e \sim n^2 R^2 a. \qquad (16)$$

For n constrained by the Murakami limit

$$n\tau_e \sim (B^2 a)\kappa \qquad (17)$$

If n is limited by β, (as in (12)), then

$$n\tau_e \sim \beta^2 B^4 R^2 a/T^2 \qquad (18)$$

For $\beta \sim \kappa a/R$ (18) becomes

$$n\tau_E \sim (B^2 a)^2 \kappa^2 R/AT^2 \qquad (19)$$

For "Kaye-Goldston" scaling[5] that uses data from neutral beam heated tokamaks

$$n\tau_E \sim n^{1.26}\ \kappa^{0.28}\ B^{-0.09}\ I_p^{1.24}\ P^{-0.58}\ a^{-0.49}\ R^{1.65} \qquad (20)$$

where I_p is the plasma current and P is the heating power. For an ignited plasma it may be appropriate to set P equal to the alpha power[6].

Since the alpha power is given by

$$P_{alpha} \sim n^2\overline{\sigma v}a^2R\kappa \sim n^2T^{2.5}a^2R\kappa \tag{21}$$

and

$$I_p \sim \frac{Ba^2}{qR} \quad \frac{(1 + \kappa^2)}{2} \tag{22}$$

(20) becomes

$$n\tau_E \sim \frac{n^{0.1} (B^2a)^{0.6}(1 + \kappa^2)^{1.24}}{A^{0.15}\ T^{1.5}\ \kappa^{0.3}} \tag{23}$$

$n\tau_E$ can be increased by increasing B^2a. However, the dependence of $n\tau_e$ on B^2a is not as strong as it is in the case of "Neo-Alcator" scaling.

Q > 1 Operation at Low Temperatures

If it is not possible to heat to truly ignited operation, it may be useful to operate with $Q \geq 1$ (where Q is the total fusion power divided by the sum of the ohmic and auxiliary heating powers) at relatively low temperature using ohmic heating alone (or perhaps ohmic heating with a small amount of auxiliary heating).

According to (5) and (16), sufficient temperature (central temperature $\approx$ 4 keV), and $n\tau_E$ for $Q = 1$ operation with no alpha particle or auxiliary heating contribution could be obtained with $B^2a \approx 90\ T^2m$ and $q \approx 2.5$. Another mode of low temperature operation would be to use ohmic heating (perhaps aided by a small amount of auxiliary heating), to reach a temperature where there would be a substantial contribution from alpha particle heating. If a degradation in energy confinement with increasing temperature (due either to increased alpha particle heating or the effect of increased temperature on transport) "clamps" the central temperature at ≈ 9 keV, say, a reactor might still operate at relatively high Q and produce a useful amount of fusion power.

Compact Ignition Experiment With Inertially Cooled Copper Magnets

Tokamaks with copper plate magnets that are inertially cooled and have no special shielding between the plasma and the magnet can provide very compact ignition machine designs[7,8,9,10,11]. Self-supported magnets with strong materials have been used in the "HFITR"[8] and "LITE"[9] ignition experiment design concepts. This arrangement is relatively simple, the loads can be understood in a straight forward way and the general approach has been proven in the Alcator machines. Figure 1 shows a perspective view of a LITE type design. The throat region of the toroidal field would use composite plates of copper that is explosively bonded to Inconel, allowing operation at high stress (~ 560 MPa). If it is not possible to use a copper/inconel composite, a beryllium copper alloy with a lower operating stress (~ 460MPa) could be used with a modest increase in device size and cost.

Illustrative parameters are given in Table 1 for two types of LITE ignition experiment designs. B^2a in the LITE-R4 type device[9] is 50 T^2m. LITE-R4 would utilize a significant amount of RF heating and has the capability for operation with a divertor plasma. A 10 MA current would be possible with limiter operation. The current would be reduced to ~ 9 MA if a divertor plasma were used.

The super high field design in Table 1 has $B^2a = 150$ $T^2{}_m$. For very large values of B^2a the machine size is minimized by use of very high fields. The magnetic field at the plasma axis is 20.7T. For $q = 2.5$ this device could ignite with ohmic heating alone if Neo-Alcator scaling applies and the impurity concentration is low ($Z_{eff} \approx 1$)[12]. The super high field concept differs from the Ignitor[10] through design for substantially higher values of B^2a and B, and a larger major radius. The value of B^2a is more than two times larger than that in Ignitor. (The Ignitor design is optimized on the basis of different physics assumptions.)

Additional ohmic drive in this device could be obtained by operation at a lower value of q. If ignited operation cannot be attained, $Q > 1$ operation with ohmic heating alone could provide a useful fallback.

There is also a concept that utilizes a monolithic or quasi-monolithic magnet in conjunction with high current homopolar power supplies[13]. The monolithic coil approach could provide a stiffer, more robust toroidal field magnet that might be operated at higher fields for given values of major and minor radius.

Compact Long Pulse Ignition Experiment Device With Water Cooled Magnets

Steady state water cooled copper magnets can be used to provide long pulse ignited operation in a relatively compact device. The pulse length is limited by the ohmic drive capability. The device could use magnet plates made out of beryllium copper (as in the LITE-R3 design[14]). Due to substantial resistive power loss in the magnet it may be desirable to reduce the magnetic field after startup. Because long pulse operation is possible, there would be adequate time to ramp the magnetic field up and then down after ignition had been obtained (with either ohmic heating or an ohmic heating dominated startup).

Based on the LITE-R3 design, ($R \simeq 1.75$m) the major radius of a compact copper magnet device with long pulse capability would be around 1.7 - 2.3m. The value of B^2a at burn would be about 60 T^2m.

Figure 2 shows a perspective view of LITE-R3 next to a design concept for a long pulse ignition test experiment device with superconducting magnets[15].

The substantial resistive power requirement of the magnet system (~500 MW for LITE-R-3) need not pose a severe problem due to the low duty factor for the device (<5%). If higher duty factor is desired it would be useful to significantly increase the machine size. The resulting decrease in the magnet current density would decrease the resistive power requirement. The power requirement could also be reduced by the use of copper in the magnet throat instead of a lower conductivity copper alloy.

Engineering Test Reactor or Experiment Hybrid Reactor

An engineering test reactor or experimental hybrid reactor that uses water cooled copper magnets could provide several advantages over a device that uses superconducting magnets:

- A more compact design (less shielding of magnets is required).
- A more reliable magnet (since present technology would be used in this relatively near term device).
- Improved access since the TF magnet could be demountable
- Internal coils for the ohmic heating, poloidal field and divertor magnet systems (facilitated by use of demountable toroidal field coils)

The device would need some shielding between the plasma and the toroidal field coil due to the increased fluence relative to ignition experiment designs. However, if insulation with high radiation resistance could be used, the distance from the plasma to the magnet on the inboard side might be kept at ~ 25cm. The magnet would use copper rather than a copper alloy in order to minimize the resistive power requirement.

Table 2(a) gives parameters for an engineering test reactor. $B^2a = 60\ T^2m$ during burn. It could be increased to 90 T^2m during startup.

Table 2(b) shows characteristics of an experimental hybrid reactor that has the same basic parameters as the engineering test reactor. This reactor would use a fissioning blanket with an effective energy multiplication factor of 5. If ignited operation at $T(0) = 20$ keV could be achieved, the total thermal power would be 1600MW. The gross electric power would be ~530MW if an electricity producing blanket were used. The net electric power would be ≈ 150MW. Unlike the very compact Riggatron reactor concepts [16], the blankets in the copper magnet reactor designs described in this paper are inside the toroidal field magnet.

Demonstration/Commercial Reactors with Superconducting magnets

Operation at high values of B^2a is possible in Demonstration/ Commercial reactors with superconducting magnets. The HFCTR (High Field Compact Tokamak Reactor) commercial reactor design developed by an MIT-PPPL-Westinghouse team used a Nb_3Sn magnet and had a major radius of 6m, a magnetic field of 7.4T and a minor radius of 1.2m[17]. B^2a was 66 T^2m. Parameters for the HFCTR are given in Table 3. The mass utilization (net electric power/fusion core weight) is almost twice that of the STARFIRE design[18]. Figure 3 shows a perspective view of HFCTR.

Higher values of B^2a should be possible without a substantial increase in size. As an example, consider a reactor with a toroidal field magnet that provides 14T at the coil. Assume that the major radius is 7m, the minor radius is 1.75m and the distance between the plasma and the TF coil on the inboard side is 1.3 m. Hence the field at the plasma axis is 7.8T and B^2a ~105 T^2m. This value of B^2a might be sufficient to eliminate or substantially reduce the auxiliary heating power requirement (possibly with low q operation or a specially shaped plasma).

If inductive current drive is used, very long pulse operation (>3 hrs) should be attainable with a high performance ohmic heating transformer[19].

A high field demonstration/commercial reactor might use a moderately elongated plasma ($\kappa \leq 1.6$). Sufficient wall loading might well be attained with $\beta < 4\%$. The use of a modest elongation reduces the equilibrium field design requirements.

The demonstration/commercial reactor might be constructed in a modular form. Each module would consist of two toroidal field coils, blanket/shield and vacuum vessel[17,19]. Since the auxiliary heating power requirement is small (or perhaps eliminated) and major maintenance operations would be performed mainly by removal of the magnet-blanket/shield-vacuum vessel module, the port size could be quite small. The small port size could facilitate a much closer fitting magnet than that used in other commercial reactor designs. This arrangement could ease requirements on external equilibrium field coils and reduce the overall fusion core size.

The elimination of the auxiliary heating power requirement and the use of a closer fitting magnet could substantially reduce the cost of the fusion core. Moreover, the overall fusion core cost may not be strongly increased by the use of high field magnet[17]. Hence, a high field tokamak commercial reactor could have a significantly lower cost than other approaches. It could also be simpler and have better prospects for meeting availability goals.

An additional benefit from high field operation is that there could be significantly better prospects for current drive with lower hybrid waves. High efficiency is facilitated by high field, low beta operation due to higher allowed wave velocity resulting from increased accessibility[20].

Demonstration/Commercial Reactors with Copper Magnets

Tokamaks with copper magnets that are designed to reduce power consumption might also be used for demonstration/commercial reactors[21], particularly fusion-fission systems. The resistive power requirements are substantial at moderate values of beta but need not be prohibitive. These power requirements can, of course, be reduced by use of high beta operation and lower magnetic fields. However, some of the benefit of operation with high B^2a might then be lost.

Copper magnet reactors could provide the advantages of a more robust magnet, reduced shielding requirements, and the possibility of increasing the toroidal field during startup. It also should be possible to use demountable toroidal field coils to facilitate maintenance and permit the use of a single vacuum vessel as well as equilibrium field and divertor coils that are internal to the toroidal field magnet. Figure 4 shows a perspective view of a design concept for a copper magnet reactor with demountable coils[22,23].

Illustrative parameters for a pure fusion copper magnet reactor with copper magnets are given in Table 4. The mass utilization factor is 70 kWe/tonne. Lower recirculating power and/or better mass utilization could be obtained by use of a fissioning blanket. The lower fusion power requirements, due to the blanket power multiplication, could result in a lower magnetic field requirement during burn.

Advanced Fuels

High field reactors might ultimately provide the capability to operate with advanced fuels (DD, DD-DT where the tritium breeding ratio is greater than zero but less than one; or D-He^3 where the He^3 is produced in a DD reactor). Relatively high beta ($\beta > 0.1$) would be needed in conjunction with high fields. Moreover, the operating density would have to be considerably greater than that which is allowed by the Murakami limit. Heating to ignition in an advanced fuel mixture could proceed by ohmic-heating dominated startup to alpha driven thermal runaway in a DT fuel mixture. The thermal runaway would then be used to reach the temperature needed for ignited advanced fuel operation. With appropriate burn control the fuel could then be changed to the desired mixture. Copper magnet toroidal field coils would very likely consume too much power for advanced fuel applications and the use of superconducting magnets would thus be a necessity.

Conclusions

The use of high magnetic fields could provide significant advantages for tokamak reactor development. It may be possible to develop compact ignition experiment devices and engineering test reactors that have little or no auxiliary heating requirements. Demonstration/commercial reactors could also benefit from substantial reduction or possible elimination of auxiliary heating power requirements, as well as high values of $n\tau_E$. In addition they could have the advantages of reduced beta requirements and higher allowed values of fusion power density and neutron wall loading. Significant improvements in the cost and complexity of tokamak reactors may thus be attainable through the use of high magnetic fields.

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Table 1

Illustrative Parameters for Compact Ignition Experiments

	LITE-R4	Super High Field LITE Device
$B^2a(T^2m)$	50	150
κ	1.8	1.4
Major Radius(M)	1.33	1.64
Aspect Ratio	2.8	4.7
Minor Radius(M)	0.47	0.35
Magnetic Field(T)	10.2	20.7
Plasma-magnet GAP(M) (on inboard side)	0.045	0.045
Plasma Current(MA)	10	5.2
Beta Limit (%)	6.3	3
Maximum fusion power at beta limit(MW)	340	1200†
Maximum neutron wall loading at beta limit (MW/M^2)	8	35†
Fusion power level at standard operation (MW)	240	240
Neutron wall loading at standard operation (MW/M^2))	5.9	7
TF magnet power(MW) (AT 80 K)	65	190
TF magnet stored energy(GJ)	0.9	3.1
TF magnet flat top(S)	5	6
TF magnet stress(MPa)	560	560
Auxiliary Heating Power (MW)	20	0

† Ignited operation should be attainable well below the beta limit. The machine could operate in a regime where the fusion power and neutron wall loading are substantially lower.

Table 2

(a) Illustrative Parameters for an Engineering Test Reactor with Copper Magnets

$B^2a(T^2m)$	60*
Major radius(m)	3.0
Minor radius(m)	0.7
Plasma-magnet distance(m) (on inboard side)	0.25
Elongation	1.3
Toroidal field*(T)	9.26
Toroidal field magnet power(MW)	290
Total electrical power requirement (magnets, pumps)	390
β (%)	1.7 - 2.8
Central temperature(keV)	20
Fusion power(MW)	110 - 320
Neutron wall loading(MW/M^2)	1 - 2.8
Burn pulse length(s)	200

(b) Operation as Experimental Hybrid Reactor

β (%)	2.8
Blanket energy multiplication	5
Blanket thermal power(MW)	1600
Gross electric power(MW)	530
Net electric power(MW)	140
Burn pulse length(s)	200

*A higher value of magnetic field might be used during startup.

Table 3

Parameters for HFCTR Commercial Reactor with Nb_3Sn Superconducting Magnet

$B^2a(T^2m)$	66
Major radius(m)	6.0
Minor radius(m)	1.2
Plasma-magnet distance(m) (on inboard side)	1.3
Elongation	1.5
Magnetic field on axis (T)	7.4
Magnetic field at coil (T)	13.1
Beta (%)	4
Central Temperature (keV)	12.4
Fusion power (MW)	2440
Neutron wall loading(MW/M^2)	3.4
Net Electric Power (MW_e)	775
Weight of Fusion core (tonnes)	9000
Mass utilization (kW_e/tonne) (net power/fusion core weight)	85

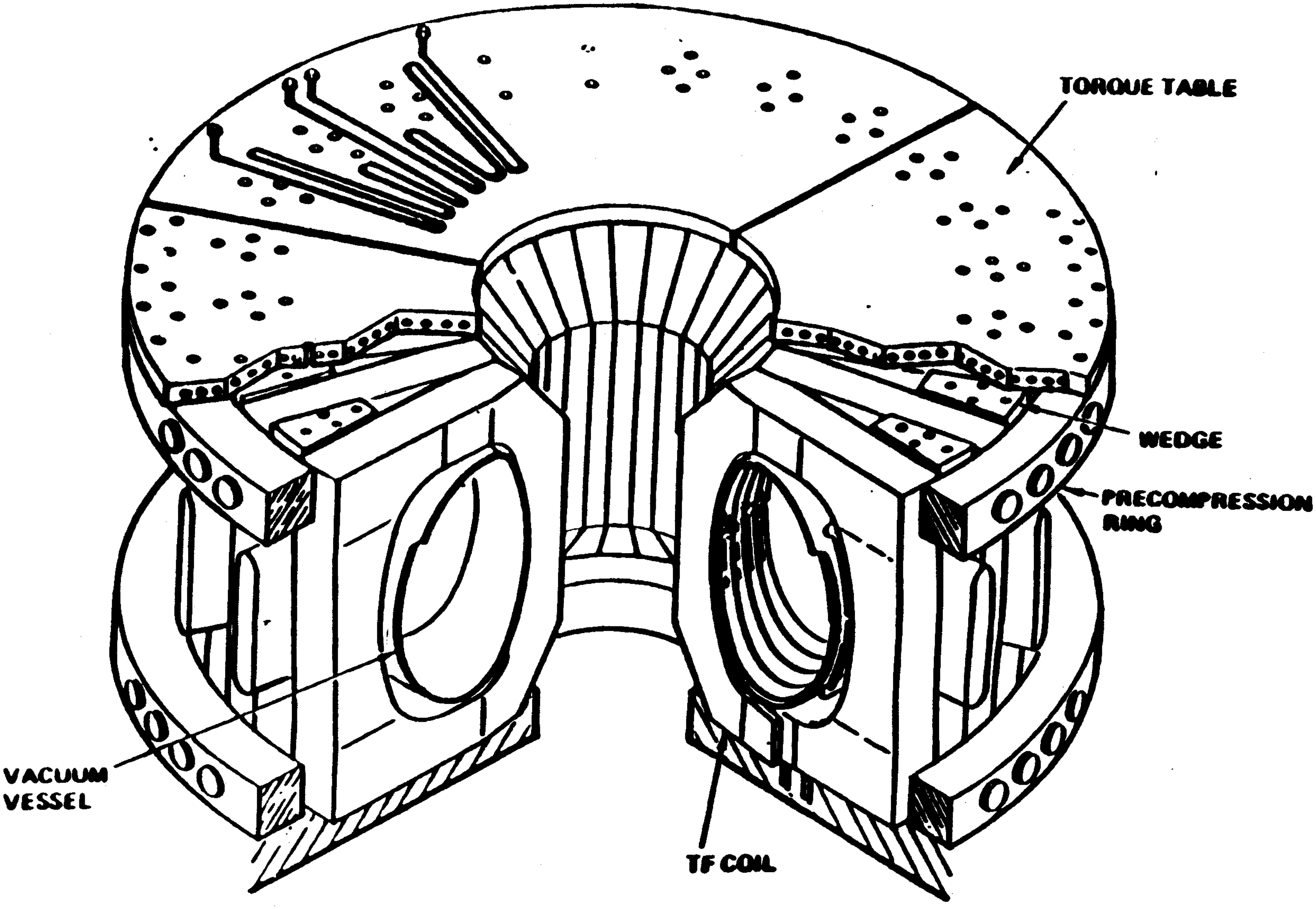
Table 4

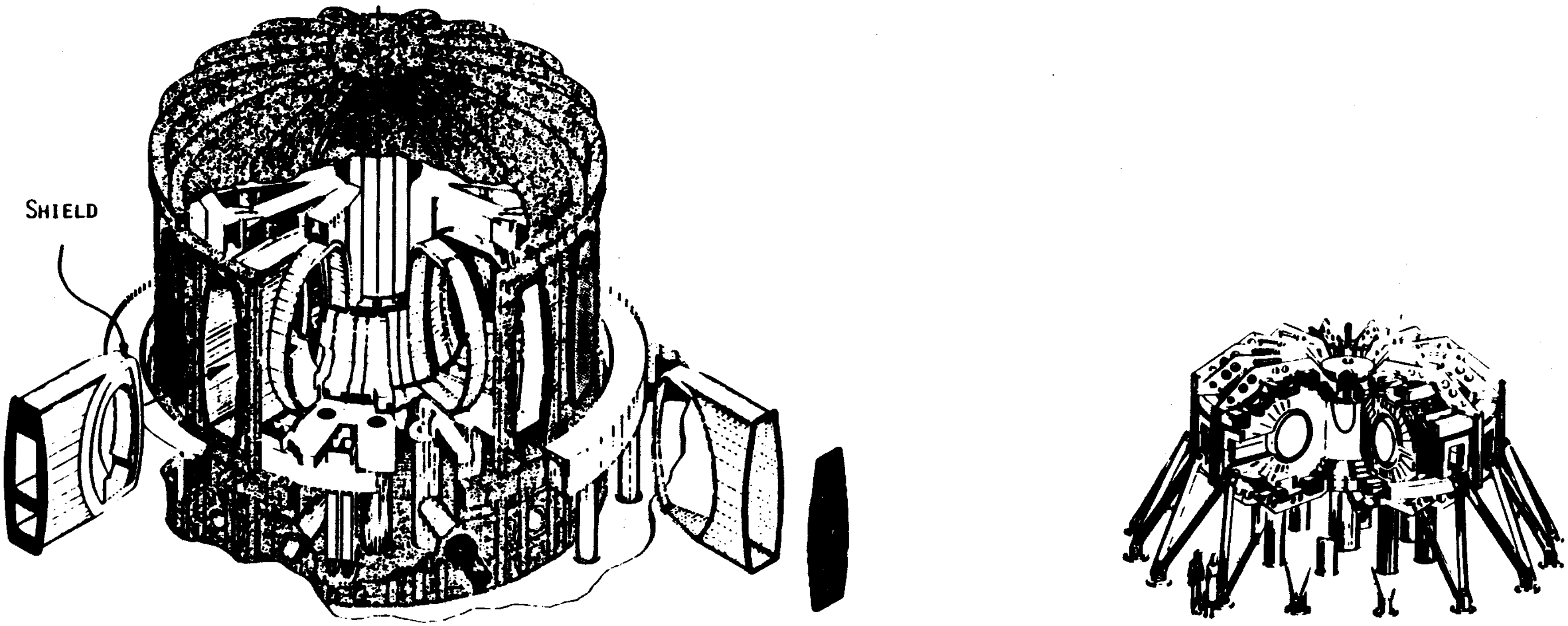
Illustrative Parameters for Moderate Beta Commercial Reactors with Copper Magnets

$B^2a(T^2m)$	60*
Major radius(m)	6.6
Minor radius(m)	2.1
Magnetic field(T)	5.3
Plasma-magnet distance(m) (on inboard side)	0.60
Elongation	1.3
Beta (%)	4.7
Thermal Power(MW)	4100
Neutron wall loading(MW/M^2)	4
Toroidal field magnet power(MW)	390
Total recirculating power(MW)	550
Net electric power(MW)	1200
Burn pulse length(s)	20,000
Weight of fusion core (tonnes)	16,700
Mass utilization (kW_e/tonne)	70

*A higher value of magnetic field might be used during startup.

LITE Vacuum Vessel/TF Magnet Assembly





SUPERCONDUCTING EXPERIMENT

LITE
(LONG PULSE IGNITION TEST EXPERIMENT)

FIGURE 2: A COMPARISON OF LITE-R3 (LONG PULSE IGNITED TEST EXPERIMENT DEVICE WITH STEADY STATE WATER COOLED COPPER MAGNETS) AND A LONG PULSE IGNITION TEST EXPERIMENT DEVICE WITH SUPERCONDUCTING MAGNETS

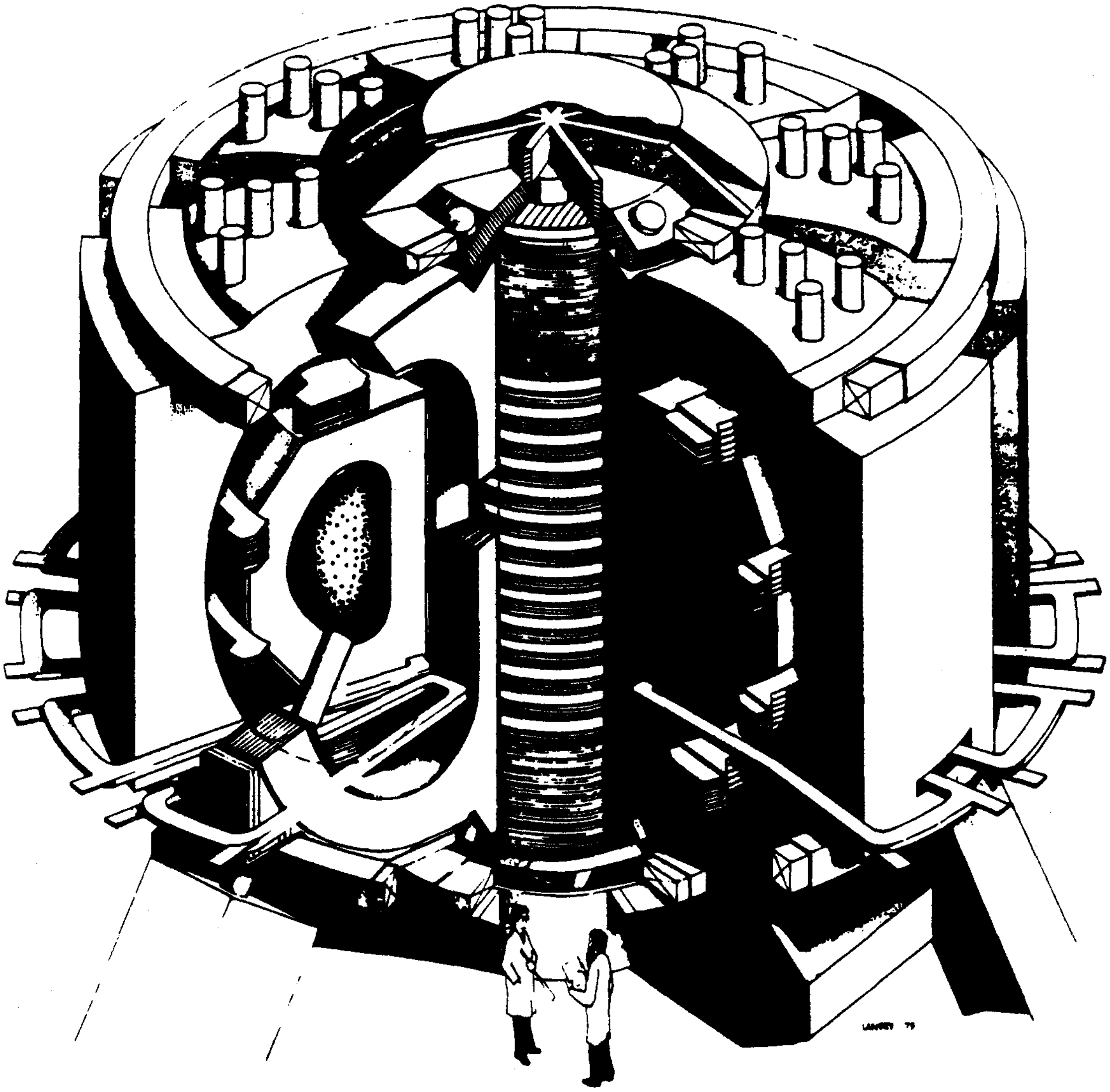


FIGURE 3: PERSPECTIVE VIEW OF HFCTR DEMONSTRATION REACTOR WITH Nb_3Sn SUPERCONDUCTING MAGNETS

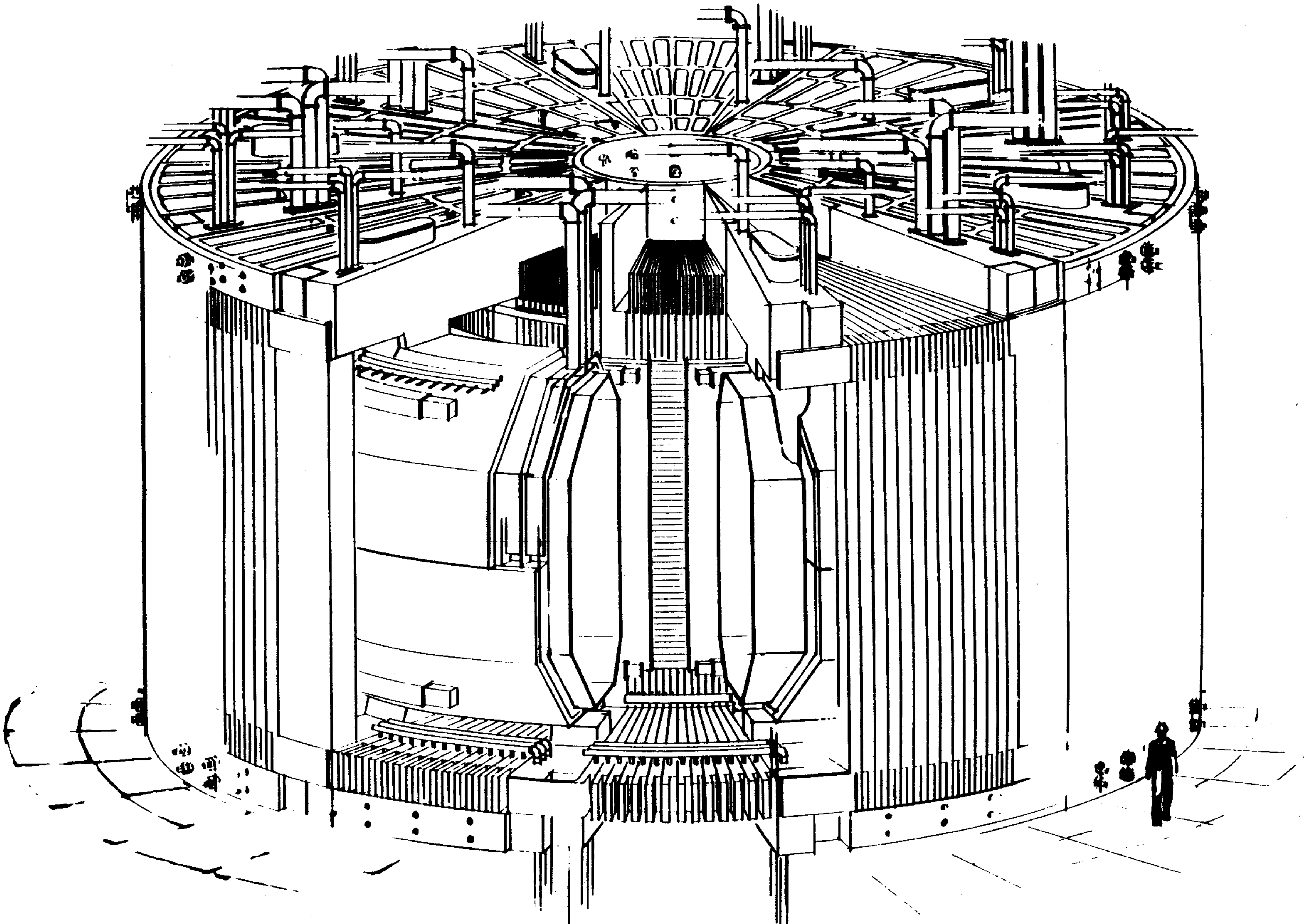


Figure 4: Perspective View of Design Concept for a
Copper Magnet Reactor with Demountable Toroidal