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USE OF HIGH PERFORMANCE RESISTIVE MAGNET TOKAMAKS AS ADVANCED TEST REACTORS AND FISSILE FUEL BREEDERS

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Abstract

Tokamaks with resistive toroidal field magnets operated steady state at relatively high stress and magnetic field levels could provide very high values of $n\tau_e$ and fusion power density. Illustrative machine parameters are given for an advanced test reactor which has these characteristics. This device could provide ignited long pulse DT plasma operation with large physics margins and could produce high wall loadings for possible use as a materials test facility. It could be operated with $Q > 1$ over a wide range of tritium-assisted semi-catalyzed deuterium (SCD-T) fuel mixtures. Somewhat larger high performance resistive magnet tokamaks might be used as fissile fuel production reactors with either SCD-T or DT operation. SCD-T operation could result in high (fissile fuel production rate)/(blanket thermal power) ratios, making possible the support of a large number of fission reactors by a fusion reactor with moderate thermal power production.

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I. INTRODUCTION

High performance tokamaks with resistive toroidal field (TF) magnets operated steady state at relatively high stresses and magnetic field levels can be used as advanced test reactors. Somewhat larger devices could be employed as fissile fuel production reactors. In this paper we discuss general features of these high performance resistive magnet tokamaks and describe illustrative parameters for an advanced test reactor.

Relative to superconducting TF magnets the advantages of high performance resistive TF magnets are:

- Ease of operation at higher magnetic field, making possible much higher plasma performance in terms of fusion power density and the confinement parameter $n\tau_e$. The higher values of fusion power density and $n\tau_e$ can be used to facilitate advanced fuel cycle operation; tritium-assisted, semi-catalyzed deuterium (SCD-T) operation[1] is of particular interest.
- Reduced magnet shielding requirements, allowing for a more compact design.
- Reduced complexity.
- Improved maintainability.

The high performance tokamak reactor design concepts described here represent an extrapolation of the ZEPHYR[2,3] and CITR[4,5] pulsed ignition test reactor design concepts to larger size and steady state, water cooled operation. These concepts also build directly upon the TORFA design, which utilized steady state resistive TF magnets and placed emphasis on relatively near term applications of fusion neutrons,[6] and upon related magnet design studies.[7] Although the size of the plasma in the advanced test reactor concept would be similar to that in TORFA, the magnetic field strength, the fusion power density, and $n\tau_e$ would be much larger. It should be noted that a high performance TF magnet can also be used to increase the fusion power/magnet resistive power loss ratio and to provide a more compact design for constant values of $n\tau_e$ and fusion power density.

II. SCD-T OPERATION

In semi-catalyzed deuterium (SCD) operation, the tritium produced by the D(D,p)T reaction is assumed to be completely burned up by the DT reaction. The He^3 generated in the D(D,n)He^3 reaction, which is equally probable, leaves the plasma before it is burned. In tritium-assisted semi-catalyzed (SCD-T) operation extra tritium is provided by an external source, such as a tritium breeding blanket. The tritium breeding ratio requirement (tritons produced external to the plasma/fusion neutrons) is nonzero but less than one. SCD-T operation provides a range of tradeoffs between plasma performance requirements and tritium breeding requirements.[1] SCD-T operation is useful in fusion reactor operation for a number of reasons:

- Since requirements on neutron economy can be reduced, the number of blanket design options in an electricity producing fusion reactor can be significantly increased. Blankets can be more readily optimized for safety, low activation, low tritium inventory, ease of maintenance and reduced size.

- SCD-T operation can be used to provide makeup tritium for fusion reactors with tritium breeding ratios which are less than one.
- The tritium burn-up fraction is higher than that in DT operation.
- The availability of neutrons for nonelectrical applications, such as fissile fuel breeding and synfuels production, can be significantly increased. This increased availability could result in very high (fissile fuel production rate)/(blanket thermal power) ratios, making possible the support of a large number of fission reactors with a fusion reactor with moderate thermal power production.

III. ILLUSTRATIVE ADVANCED TEST REACTOR PARAMETERS

The goals of an advanced fusion test reactor would include:

- Long pulse, ignited DT operation with large physics margins.
- $Q > 1$ operation over a wide range of SCD-T fuel mixtures.
- Use as a testbed for blankets and possibly as a high fluence materials test facility.

A parametric code was used to obtain illustrative parameters based upon an extrapolation of the engineering design of ZEPHYR with Bitter type magnets[3]; an engineering design has not yet been performed. These parameters are also consistent with parameters developed for TORFA devices operated at lower magnetic fields.[6,7] The parameters are given in Table 1. The major radius is 4.1 m and the maximum magnetic field on axis is 6.8 T. The blanket/shield thickness would vary depending upon the mode of operation of the machine. For DT operation the inboard blanket shield thickness would be 55 cm and the outboard maximum blanket/shield thickness would be 85 cm. The blanket/shield would be designed to reduce the integrated neutron fluence on the magnet insulation to 10^{20} nt/cm^2; studies of Bitter type magnet insulation failure indicate that such fluences may be tolerable.[3] For SCD-T operation, the blanket/shield thickness would be reduced to increase the plasma size and $\langle\beta\rangle_t$ (assuming that $\langle\beta\rangle_t \sim$ 1/aspect ratio); the neutron flux, due to a lower fusion power density, would be reduced.

The resistive power, stored energy and stress in the toroidal field magnet vary with B_t (axial toroidal magnetic field) as B_t^2.

The illustrative test reactor parameters are based upon a water cooled, copper-stainless steel magnet design. Reduction in resistive power requirements might be obtained by operation of resistive magnets with helium cooling.[8]

There are three main possibilities for fulfilling maintenance requirements for the Test Reactor:

- The entire magnet could be modularized so that separate modules might be removed.[9,10] The removal of a module would be required for most repairs and maintenance. The estimated time lapse required for removal and installation of a new module is 2-4 weeks, depending on the level of automatization of the process.[10]

- The magnet could be made up of discrete TF coils, assembled from Bitter plates. The TF coils would provide sufficient access between outer legs to remove a module consisting of blanket, shielding and first wall. In order to provide the necessary access, the size of the magnet, the resistive power and the stored energy would increase by ~ 50%, and the stresses in the throat would increase by ~ 30%. The time required for major maintenance of the tokamak may not be reduced from the previous approach.
- The same type of configuration as that described above can be used with the additional characteristics that the coils may be demountable as in TORFA.[6] This approach is attractive in the case that there are internal poloidal field coils or a poloidal divertor. For high performance magnets, however, it is not clear whether access to the blanket, shield and first wall is eased by this approach.

Engineering design efforts will be required to examine the feasibility of these different approaches. Irrespective of the preferred maintenance approach, the resistive TF magnet has advantages over a superconducting magnet in terms of remote maintenance, arising from the absence of cryogenic environment.

The OH transformer would be designed to provide sufficient drive for 200 seconds of operation at maximum field and plasma current.

Pump limiters would be used for impurity control and helium ash removal.

Table II lists possible modes of DT operation. In order to make some projection about the energy confinement time, τ_e, it is assumed that τ_e scales as $\tau_e \simeq Cna^2$ where n is the average plasma density, a is the minor radius, and the proportionality factor C is determined by results from PLT.[4] A margin of ignition, MI, is defined as:

$$MI = (n\tau_e)/(n\tau_e)_{ign}$$

where $(n\tau_e)_{ign}$ is the value of $n\tau_e$ required for ignition. Parabolic density and temperature profiles are assumed. It is assumed that power loss from impurity radiation is negligible.

The average fusion power density P_f, the neutron wall loading P_w, and the total fusion power P_t are proportional to MI. For MI > 1, some additional loss mechanism such as impurities or ripple transport loss must be introduced in order to obtain thermal equilibrium.[11]

It is assumed that the plasma is elongated and that an average value of toroidal beta of 0.064 can be maintained. The density averaged values of the ion and electron temperatures are $\langle T_i \rangle_n = 13$ keV and $\langle T_e \rangle_n = 11$ keV.

A power multiplier Q_m can be defined as:

$$Q_m = P_t/P_m$$

where P_m is the steady state electrical power required for the toroidal field magnet.

For MI = 1.3, a neutron wall loading of 2 MW/m^2 and a value of Q_m of 1.8 can be obtained with a toroidal field magnet power requirement of 260 MW.

Very high neutron wall loadings ($\sim$ 10 MW/m^2) and power production levels can be obtained by operating at 6.5 T, somewhat less than the maximum magnetic field. The use of these high wall loadings could be very useful if the device were operated as a materials test reactor. The design of the vacuum vessel and thermal hydraulics system must be evaluated in order to determine whether such high wall loadings could be tolerated.

The test reactor would be heated with ICRF at the second harmonic of deuterium. Assuming a parabolic power deposition profile, approximately 40 MW would be needed to heat to DT ignition in approximately 3 seconds. It is estimated that the machine could be designed to provide adequate access for up to 120 MW of auxiliary heating power.

Table 3 shows possible modes of SCD-T operation for illustrative machine parameters at maximum magnet field. These modes of operation are based upon the assumptions that the $\tau_e \sim na^2$ scaling holds. Table 3 lists tritium to deuterium ratios in the plasma, N_T/N_D, and the required external tritium production requirements per fusion neutron. The tritium production requirement is determined by the breeding ratios γ_{DT} and γ_{DD}; these parameters represent the ratios of tritons from the external source to DT and DD neutrons produced in the plasma. For illustrative purposes it will be assumed that $\gamma_{DD} = \gamma_{DT} = \gamma$. γ ranges from 0 in SCD operation to one in DT operation.

For fixed values of $n\tau_e$, $\langle T_i \rangle_n$, $\langle \beta_t \rangle$, and B_t, there is a continuum of tradeoffs between γ, Q_p (fusion power/heating power), and P_f. The auxiliary heating power requirements, P_{aux}, represents the minimum startup power.

Improvement in SCD-T performance can, of course, be obtained by increasing the test reactor size. Increased performance may also be realized by refinements in the magnet design.

IV. FISSILE FUEL PRODUCTION REACTORS

The use of high performance resistive magnet tokamaks as practical fissile fuel production reactors would generally require machine parameters which would be somewhat larger than the illustrative test reactor parameters. More space would be allocated for blankets and shielding.

Operation of these tokamak devices with the SCD-T fuel cycle could lead to very high (fissile fuel production rate)/(blanket thermal power) ratios. At these very high ratios a very large number of fission reactors might be supported by a fusion reactor with moderate thermal power production. The overall system cost (fission reactors plus the fusion reactor which supports them) might then be quite insensitive to the capital cost of the fusion reactor. In addition, the net electrical power of the overall system (electrical power produced by the fission reactors minus the electrical power required by fusion reactor) might be relatively insensitive to the electrical requirements of fusion reactor; the fusion breeder could be run in a mode where it did not produce any of the electricity required for its operation. The use of tokamak reactors with SCD-T operation for fissile fuel production is relatively sensitive to the values of $\langle \beta_t \rangle$ that can be achieved.

The use of DT operation for fissile fuel breeding reduces fusion breeder electrical requirements, decreases the sensitivity to $\langle \beta_t \rangle$ and could lead to smaller machine designs. However, the attainment of moderately high (fissile fuel production rate)/(blanket thermal power production) ratios becomes very sensitive to blanket design.

V. CONCLUSIONS

A high performance resistive magnet tokamak could be used as a test reactor which would provide a wide range of physics and technology data needed for fusion reactor development. Somewhat larger devices could be used as fissile fuel production reactors with either DT or SCD-T operation. SCD-T operation could facilitate the attainment of high (fissile fuel production rate)/(blanket thermal power) ratios. High performance resistive magnet tokamaks might also be employed for other nonelectrical fusion applications, such as synfuel production.

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TABLE 1

ILLUSTRATIVE TEST REACTOR PARAMETERS

	DT	SCD-T
Plasma major radius:	4.1 m	4.1 m
Plasma minor radius:	1.25 m	1.45 m
Plasma elongation:	1.5	1.5
Inboard blanket/shield thickness:	0.55 m	0.35 m
Outboard blanket/shield thickness:	0.80	0.60
TF magnet plate dimensions:	6 m x 7.7 m	6 m x 7.7 m
Maximum magnetic field on plasma axis:	6.8 T	6.8 T
Maximum magnetic field at TF magnet:	13.6 T	13.6 T
TF magnet current density at max field:	2 kA/cm^2	2 kA/cm^2
Electrical power dissipation in magnet at max field (copper/stainless steel ratio = 2:1)	650 MW	650 MW
TF magnet stored energy at max field:	12 GJ	12 GJ
Max TF magnet stress at max mag field (in copper plates):	140 MPA	140 MPA

TABLE 2

DT MODES OF OPERATION FOR ILLUSTRATIVE TEST REACTOR PARAMETERS

$\langle\beta\rangle = 0.064$ | $\langle T_i\rangle_n = 13$ keV | $a = 1.25$ m

	MI = 6.5	MI = 1.3
B_t	6.5 T	4.2 T
P_t	2300 MW	460 MW
P_w	10 MW/m^2	2 MW/m^2
P_m	600 MW	260 MW
Q_m	3.8	1.8

TABLE 3

SCD-T MODES OF OPERATION FOR ILLUSTRATIVE TEST REACTOR PARAMETERS

$\langle\beta_t\rangle = 0.074$ $\langle T_i\rangle_n = 17$ keV $a = 1.45$ m

$B_t = 6.8$ T $n\tau_e = 5.1 \times 10^{20} m^{-3}$ $P_m = 650$ MW

n_T/n_D	γ	P_{aux} (MW)	Ω_p	P_f (MW/m^3)	P_w (MW/m^2)	P_t (MW)	Ω_m
0.03	0.83	50	∞	3.2	2.4	830	1.3
0.011	0.64	75	5.	1.5	1.1	390	0.60
0.007	0.53	90	3.	1.1	0.8	290	0.45
0.0006	0.09	120	1.	0.5	0.4	130	0.20