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Modes of DT and SCD-T Operation In A Compact Ignition Test Reactor

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Abstract

The use of high performance copper magnets makes possible the design of a compact ignition test reactor (CITR) which would have a wide range of operational capability in DT plasmas. Since it may be possible to obtain high values of $n\tau_e$ ($\sim 10^{15}$ cm^{-3} sec), operation in the tritium assisted, semi-catalyzed deuterium (SCD-T) advanced fuel cycle might also be investigated. Modes of DT and SCD-T operation for illustrative CITR parameters are described.

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I. Introduction

The use of high performance copper magnets makes possible the design of a compact ignition test reactor (CITR) which would have a wide range of operational capability. This tokamak device could be used to study both ignited operation and long pulse, $Q > 1$ operation in DT plasmas[1]. The CITR would have considerable physics margin for meeting these goals. With this large margin it may be possible to obtain very large values of $n\tau_e$($\sim 10^{15}$ cm^{-3} sec); hence, operation in the tritium-assisted, semi-catalyzed deuterium (SCD-T) advanced fuel cycle[2] might also be investigated. In this paper we discuss the possible modes of DT and SCD-T operation that might be attainable in a CITR device.

II. Machine Design

The CITR would utilize a toroidal field (TF) magnet of Bitter construction which is inertially cooled with liquid nitrogen. The use of this type of magnet makes possible a compact, high performance reactor design since it does not require neutron shielding and can be operated at high fields, high stress and high current density. Illustrative CITR design parameters have been developed by scaling ZEPHYR ignition test reactor design parameters[3,4] to those of a somewhat larger, more versatile device[1]. An engineering conceptual design has not yet been performed. Table 1 lists major machine parameters for the illustrative CITR design. The stored energy and the stress in the TF magnet are given at values of the maximum magnet field at the plasma axis, B_t. These values will decrease with magnetic field as B_t^2. When the peak magnet temperature is allowed to rise to 350°C during a pulse, about one hour will be required to cool down to -190°C with liquid nitrogen. Shorter cool down times can be obtained for smaller temperature changes.

III. DT Operation

Table 2 shows possible DT modes of operation for the illustrative CITR design. In order to make some projection about the energy confinement time, τ_e, it is assumed that $\tau_e \sim Cna^2$ where n is the plasma density, a is the minor radius and the coefficient C is determined by results from PLT[1]. It is also assumed that $\tau_e << \tau_i$ where τ_i is the ion energy confinement time. A margin of ignition, $MI = \frac{n\tau_e}{(n\tau_e)_{ign}}$, is defined where $(n\tau_e)_{ign}$ is the value of $n\tau_e$ required for ignition. Parabolic temperature and density profiles and $Z_{eff} = 1$ are assumed. The density averaged ion temperature $\langle T_i \rangle_n$ is 10 keV. The CITR would operate with both circular and D shaped plasmas. Average values of toroidal beta, $\langle \beta_t \rangle$, of 0.58 are based upon the assumption of moderately elongated D shaped plasmas.

The burn pulse length, τ_b, given in Table 1 is determined by requiring that the increase in temperature of the inertially cooled magnet be less than 350°C. This temperature rise is mainly determined by resistive heating at low values of MI and by neutron heating at high values of MI. Table 2 shows that by reducing the magnetic field relatively long pulse lengths can be obtained. At B = 3.5 T, corresponding to a MI = 0.2 and a value of thermonuclear $Q = \left(\frac{\text{fusion power}}{\text{heating power}}\right)$ of ~ 1, the burn pulse length is 100 seconds

For MI = 1, the average fusion power density is 5 MW/m^3 and the total fusion power produced is 120 MW.

The primary option for heating the CITR would be ICRH. Approximately 15 MW of ICRH should be sufficient to heat to ignition in ~ 1 second if the energy loss is given by the $\tau_e \sim na^2$ scaling law described earlier and the heating power is centrally deposited. The CITR could be designed to accomodate up to 40 MW of ICRH heating power. Compression boosted start-up with neutral beams could be used as a backup option in the CITR[1,5].

IV. SCD-T Operation

In semi-catalyzed deuterium (SCD) operation the triton produced by the D(D,p)T reaction is assumed to be completely burned up by a DT reaction. The ^3He produced in the equally probable D(D,n) ^3He reaction leaves the plasma before it is burned. In tritium-assisted, semi-catalyzed deterium (SCD-T) operation the triton to deuteron ratio, n_T/n_D, is greater than the equilibrium value in SCD but is considerably less than one. Some amount of tritium must be provided by an external source, such as a tritium breeding blanket. This amount of tritium is determined by the parameters γ_{DT} and γ_{DD}, these parameters represent the ratios of tritons from the external source to DT and DD fusion neutrons generated in the plasma. For illustrative purposes it will be assumed that $\gamma_{DT} = \gamma_{DD} = \gamma$. γ ranges from 1 for DT operation to 0 for SCD operation.

SCD-T operation facilitates a continuum of possibilities for reduction in reactor blanket tritium breeding requirements by improvement in plasma physics performance[2]. The reduction in breeding requirements can significantly increase the range of blanket design options relative to DT operation. In addition the availability of fusion neutrons for nonelectrical applications can be considerably increased. If the ^3He

produced in the D(D,n) ^{3}He reaction could be reinjected into the plasma performance could be further improved. Another possible use of ^{3}He might be as fuel for reactor operation on the D(^{3}He,p)^{4}He cycle.

Table 3 shows an example of possible modes of SCD-T operation which might be obtained for the illustrative CITR design. These modes of operation are based upon the assumptions that the $\tau_e \sim na^2$ scaling holds, that $<\beta_t> \approx .06$ can be obtained and that impurity radiation loss is negligible. For fixed values of $n\tau_e$, $<T_i>_n$ and $<\beta_t>$ there is a continum of tradeoffs between n_T/n_D, Q and average fusion power denstiy, P_f. The auxiliary heating power requirements, P_{aux}, represent the minimum start-up power requirement for ignited ($Q = \infty$) operation and the steady state heating requirement for driven operation.

V. Conclusions

A compact tokamak device using high field, high performance copper magnets can be designed to provide considerable margin to achieve ignited operation and long pulse, Q > 1, pulse operation in DT plasmas. If confinement physics and MHD stability limits are favorable, this large margin can be utilized to investigate various modes of SCD-T operation.

References

1. Bromberg, L., Cohn, D.R., Williams, J.E.C. and Becker, H., "Compact Ignition Test Reactor (CITR)," Plasma Fusion Center Report PFC/RR-80-23, (December 1980)(to be published in the Journal of Fusion Energy).

2. Greenspan, E., Blue, T. and Miley, G.H., Proc. of ANS Topical Meeting on Tech of Controlled Fusion, King of Prussia, PA, October 1980.

3. ZEPHYR Experiment Internal Status Report, prepared by Max Plank Institut fur Plasmaphysik, Garching, FRG (1980).

4. Bromberg, L., Cohn, D.R. and Williams, J.E.C., MIT Plasma Fusion Center Report PFC/RR-80-12 (March 1979).

5. Cohn, D.R., Jassby, D.L., Kreischer, K., Nucl. Fusion 18 (1978), 1255.

Table 1

Illustrative CITR Parameters

Plasma Major Radius:	2 m
Plasma Minor Radius:	0.85 m
Possible Plasma elongation: (D shape plasma)	1.4
Weight of Toroidal Field Magnet:	800 tonnes
TF Magnet Plate Dimensions:	3.0 m × 3.7 m
Maximum Magnetic Field at Plasma:	8.8 T
TF Magnet Stored Energy at Max. Magnetic Field:	2.6 GJ
Max TF Magnet Stress at Max. Magnetic Field: (in copper plates)	40 kpsi

Table 2

DT Operation

$\langle T_i \rangle_n$ = 10 keV, $\langle T_e \rangle_n$ = 8 keV

B_t(T)	$\langle\beta_t\rangle$ (%)	$\bar{n}$ ($10^{14}cm^{-3}$)	$\bar{n}\tau_e$ ($10^{14}cm^{-3}sec$)	MI	τ_b(sec)
8.8	5.8	5.6	9	9	3
8.8	4.5	4.2	5	5	5
7.6	2.6	1.8	1	1	17
5.1	5.8	1.8	1	1	30
4.0	4.5	0.8	0.2	0.2 (Q = 1)	75
3.5	5.8	0.8	0.2	0.2 (Q = 1)	100

Table 3

SCD-T Operation

B_t = 8.8 T $\langle\beta_t\rangle$ = .058 $\tau_b \simeq$ 14 sec

$\bar{n}\tau_e \simeq 9.5 \times 10^{14}$ cm^{-3} $\langle T_i\rangle_n$ = 14 keV

n_T/n_D	Υ	P_{aux}(MW)	Q	P_f(MW/m^3)
.04	.88	13	∞ (ignited)	7.2
.02	0.75	25	5	3.6
.01	0.65	30	3	2.8
.003	0.35	40	1	1.3