PLASMA ENGINEERING CONSIDERATIONS FOR AN IGNITION TEST REACTOR: THE NEXT STEP (TNS) BEYOND TFTR*

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The purpose of the plasma engineering studies has been to establish credible ranges of physics parameters which are being integrated into the TNS study program.[1] The TNS program aims to achieve overall credibility in physics and technology and to assure minimum cost in the reactor design.

HIGH β EQUILIBRIUM

Neutral beams with power roughly 10 to 20 times the ohmic heating power will be used to achieve plasma temperatures in the 2-5 keV range in ISX-B, PLT, ORMAK-Upgrade, and TFTR. With such high heating power and plasma temperature, the plasma is expected to heat up in a time scale much shorter than the plasma skin time. This has led to the concept of the Flux Conserving Tokamak (FCT)[2] and resulted in calculations[3] of D-shaped MHD equilibria of high volume averaged $\bar{\beta}$ (up to 20%) and high safety factor q_a (up to 5). Although MHD instability may limit $\bar{\beta}$ to less than 20%, increasing $\bar{\beta}$ values substantially beyond a few percent is expected to increase the D-T fusion power density, and hence permit the use of medium toroidal field strengths ($B_T \simeq$ 4-7T) and a substantial reduction in the reactor size.

HIGH DENSITY

High fusion power density requires plasma densities above $10^{14} cm^{-3}$. A recent study by Murakami et al.[4] shows that the maximum densities for various ohmically heated tokamaks scale linearly with B_T/R_o, which for constant q_a is in turn proportional to the ohmic heating power density. When the heating power is augmented by neutral injection (in ORMAK and ATC), higher maximum densities are obtained with gas puffing; a reduction of impurities (in Alcator and Pulsator) can increase the density further. While future experiments with large injection power and controlled impurity level will shed more light on this scaling law, high plasma densities now appear to be achievable in relatively pure plasmas ($Z_{eff} \lesssim 2$) with sufficiently large power densities in a medium field tokamak.

BASIC ASSUMPTIONS

The assumptions of $\overline{\beta}$ values substantially above a few percent, plasma densities above $10^{14}cm^{-3}$, and medium B_T values then form the basis of the plasma engineering studies for a medium-field ignition test reactor as a TNS tokamak beyond TFTR. The following presents recent results of the plasma engineering studies in areas of particle and energy transport, MHD equilibria, and instability.

ZERO-DIMENSIONAL SCALING

Based on empirical scaling,[5] a 0-D study[6] chooses a reference reactor with B_T = 4.3 T, n = 2.2 x $10^{14}cm^{-3}$, R_o = 5 m, a = 1.25 m, σ = b/a = 1.6 and D-shaped plasma (see Table 1). The plasma ignites at $\overline{\beta}$ = 11% using 75 MW injection power and burns at $\overline{\beta}$ = 15% producing 1500 MW fusion power. Since $\overline{T}$ = 11 keV at ignition, the plasma collisionality $C(=\nu_{ie}A/\omega_{be}^{T})$ is roughly 0.02 and the trapped ion loss rate (D_{TIM})[7] should be considered. It is found that the plasma $n\tau$ depends sensitively on the values used for D_{TIM}.[6] A value of $(D_{TIM}/10)$ is found to correspond to the empirical scaling.

ONE-DIMENSIONAL EFFECTS

Since the plasma collisionality is a sensitive function of the plasma minor radius r (through its dependence on the density gradient $\partial n/\partial r$), D_{TNS} is also expected to be dependent on r. The density profile effect on the effective global D_{TNS} is studied with a 1-D multifluid transport code incorporating particle and energy balance equations.[8] With edge fueling, it is found that $D_{TNS} \lesssim (D_{TIM}/10)$ is satisfied for reasonable density profiles, supporting the use of $(D_{TIM}/10)$ in the 0-D scaling calculations. The 1-D profiles permit steady state burns over a wide range of density and fusion power levers. This is in contrast with a single burning "point" in the 0-D plasma model.

EQUILIBRIUM EVOLUTION

The evolution of equilibria during injection heating to ignition and burn is studied with a model based on the flux-surface average of the one-fluid empirical energy balance equation together with the axisymmetric FCT equilibria. It is found that for the parameters in Table 1, the cnetrally localized α-particle heating density exceeds the injection heating density at relatively low values of $\overline{\beta}$ ($\gtrsim$ 2.5%). Depending on the density, the centrally ignited plasma at $\overline{\beta} \gtrsim 3.5\%$ can bring about burning equilibria with $4\% \lesssim \overline{\beta} \lesssim 15\%$, $200\ \text{MW} \lesssim P_{D-T} \lesssim 3000\ \text{MW}$ and $0.75 \times 10^{14}\text{cm}^{-3} \lesssim \overline{n} \lesssim 3 \times 10^{14}\text{cm}^{-3}$.

INJECTION SCENARIO

Because of the centralized α-particle heating, the need for full neutral penetration beyond $\overline{\beta} \simeq 2.5\%$ is avoided. This leads naturally to a heating procedure which begins with low density and β at injection turn-on to facilitate penetration. Density is increased simultaneously to reduce penetration only to the degree that the α heating more than replaces the reduction of the injection heating at the center.[9] With this, it is found that beam energy E_b between 150 keV to 200 keV should be sufficient for perpendicular injection at $Z_{eff} \lesssim 1.5$.

MHD STABILITY LIMITS

MHD ballooning modes are expected to place severe limits on the $\overline{\beta}$ values. Recent calculations have shown a stable $\overline{\beta}$ of nearly 5% for a not-yet optimized D-shaped FCT equilibrium in TNS, while for a circular plasma it is shown to be around 1.5%.[10] Imporvements beyond these preliminary values are expected with optimization. Current estimates are that stable $\overline{\beta}$ values between 5% to 10% could be obtained with shaping and profile modifications. This $\overline{\beta}$ range overlaps that calculated for D-T steady state burns.

EQUILIBRIUM FIELDS

Free-boundary FCT equilibria contained by currents in bundled coils displaced from the plasma edge are examined to ensure plasma shaping over large changes in β and determine the required poloidal field coils and currents.[11] It is found that for TNS, coils more than 3 m away from the plasma edge can be properly located to produce D-shape equilibria. However, the power supply required by these coils is 20-30 times that required by coils 0.6 m away.

FLEXIBILITY

Based on these considerations, a refined set of reactor parameters can be obtained and is given in Table 1. It is seen that the 1-D profile effects tend to substantially lower the ignition and burn requirements from those based on the 0-D model. The stability requirements for the ballooning mode can also be satisfied now. A range of plasma parameters is available for reactor operation. Upcoming tokamak experiments will further refine stability limits in $\overline{\beta}$ and plasma confinement scaling laws. Since B_T = 4.3 T is near the lower end of the medium field strength, a large margin of flexibility can be built in by using B_T = 6-7 T. These field strengths are nearly within present-day coil technologies.

Table 1

Typical parameters for a D-shaped TNS

	Unit	Parameters based on the O-D model	Parameters refined with 1-D transport, MHD equilibrium, and stability
R_o	m	5	5
a	m	1.25	1.25
A		4	4
σ elongation		1.6	1.6
B_T on axis	T	4.3	4.3
B_T at coil	T	8.0	8.0
I_p low β	MA	4.0	4.0
I_p burn	MA	6.0	4.5-5.5
q_a		4	4
$\bar{n}$ low β	cm^{-3}	0.5×10^{14}	$0.3\text{-}0.5 \times 10^{14}$
$\bar{n}$ ignition and burn	cm^{-3}	2.2×10^{14}	$0.8\text{-}2.5 \times 10^{14}$
$\bar{T}$ low β	keV	2	1.0-2.0
$\bar{T}$ ignition	keV	11	4.0-7.0
$\bar{T}$ burn	keV	13	5.0-10
$\bar{\beta}$ ignition	%	11	3.0-5.0
$\bar{\beta}$ burn	%	15	3.5-10
C collisionality, low		0.5	0.14-0.96
C collisionality, burn		0.02	0.02-0.15
$\overline{n\tau}$ burn	$cm^{-3}.S$	3×10^{14}	$1\text{-}3 \times 10^{14}$
Average fusion power density	MW/m^3	6	0.8-8.0
Plasma volume	m^3	247	247
Average neutron wall loading	MW/m^2	3.7	0.5-5.0
Total fusion power	MW	1500	200-2000

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