OPERATING POINT SELECTION AND BURN STABILITY CONTROL FOR THE INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR

S.W. Haney and L.J. Perkins
Lawrence Livermore National Laboratory
P.O. Box 808, L-644
Livermore, California 94550

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Abstract

The selection and burn stability control of near-ignited operating points for the International Thermonuclear Experimental Reactor (ITER) are considered. It is suggested that high density ($\langle n_e \rangle \sim 1-2 \times 10^{20} \text{ m}^{-3}$), low temperature ($\langle T_e \rangle_n \sim 6-10 \text{ KeV}$) operating points are preferred from considerations of proximity to magnetohydrodynamic (MHD) stability limits, divertor operation, and fueling even though those points are intrinsically thermally unstable. Results from simple 0-D transport simulations suggest that these operating points can be effectively stabilized at $Q > 50$ if neutral beam feedback based on total neutron flux measurements is employed.

Introduction

One of the missions of ITER is the demonstration of the capability for long pulse, ignited (or high- Q) operation at fusion power levels sufficient to ensure that the heating power required is insignificant compared with the alpha particle power produced [1]. The success of this mission depends (1) on the ability to obtain plasma conditions yielding power and particle balance equilibria consistent with constraints imposed by MHD stability, divertor operation, and fueling and (2) on the ability to devise control strategies for maintaining the plasma conditions for the desired pulse length.

In this paper, we will address the questions of operating point selection and control for the ITER physics phase machine which is characterized by major radius $R_0 = 6 \text{ m}$, minor radius $a = 2.15 \text{ m}$, elongation $\kappa_5 = 2.22$ (at the separatrix), elongation $\kappa = 1.96$ (at the 95% flux surface), triangularity $\delta = 0.6$ (at the separatrix), plasma current $I_p = 22 \text{ MA}$, and vacuum toroidal field $B_0 = 4.85 \text{ T}$.

Model

Our analysis consists of simulations of the time-dependent, 0-D transport equations for fuel ions, thermalized alpha particles, and electron/ion energy density in the presence of fueling and a time-varying neutral beam heating input. These equations are derived by averaging the two-fluid transport equations over the plasma volume (assumed to be elliptical) under the assumption that the density and temperature profiles are of the form

$$n, T = n_0, T_0 \left(1 - \frac{(R - R_0)^2}{a^2} - \frac{Z^2}{\kappa^2 a^2} \right)^{\alpha_n, \alpha_T} \quad (1)$$

where $\alpha_n = 0.5$ and $\alpha_T = 1.0$ for all time. The $\alpha_{n,T}$ choices reflect the belief that central fueling might not be

achievable in ITER [2]. The 0-D approach was chosen over more accurate and elaborate methods such as 1.5-D transport to allow consideration of a relatively wide range of plasma conditions and control strategies.

We model L-mode energy confinement using the new ITER offset-linear scaling developed by Yushmanov, *et al* [3]

$$\tau_E (\text{L-mode}) = 0.64 M^{0.2} I_p^{0.8} R_0^{1.6} a^{0.6} \kappa_5^{0.2} \bar{n}_e^{0.6} B_0^{0.35} / P + 0.04 M^{0.5} I_p^{0.5} R_0^{0.3} a^{0.8} \kappa_5^{0.6} \quad (2)$$

where M is the average isotopic mass, $\bar{n}_e$ is the line-averaged electron density, and P is the net plasma heating power (alpha power + neutral beam power + ohmic power - radiation power). We further assume that H-mode operation will be possible so $\tau_E = H \tau_E (\text{L-mode})$ where H is the L-mode enhancement factor. Fuel ion particle confinement times are taken to have the scaling $\tau_p = 3 \tau_E$ while the net thermal alpha particle confinement time (which actually depends sensitively on edge effects such as recycling and pumping) is simply chosen to yield a specific equilibrium concentration of thermal alpha particles c_α .

Operating Point Selection

We address ITER operating point selection using a convenient graphical representation for reactor performance developed by Houlberg, *et al* [4]. This method consists of plotting contours of the neutral beam power required for power balance equilibrium $P_{NB,E,q}$ as a function of the density-weighted volume-averaged electron temperature $\langle T_e \rangle_n$ and the volume-averaged electron density $\langle n_e \rangle$. Each point in these plots corresponding to a non-negative value of $P_{NB,E,q}$ represents a physical solution to the steady state 0-D transport equations and, hence, is a potential operating point.

A set of these contours (constructed assuming $c_\alpha = 5\%$ and $H = 2.3$) for the ITER physics phase machine is shown in Fig. 1. Also shown are contours describing those $\langle n_e \rangle - \langle T_e \rangle_n$ combinations yielding an average neutron wall loading $P_w = 1 \text{ MW/m}^2$ (corresponding to a fusion power $P_f = 1082 \text{ MW}$) and those $\langle n_e \rangle - \langle T_e \rangle_n$ combinations characterized by beta values at the MHD stability limit (assumed to be represented by $\beta(\%) < 2.5 I_p / a B_0$ [2]). We select the ITER operating point from this 1 MW/m^2 contour because parametric studies [5] have shown that $P_w = 1 \text{ MW/m}^2$ and $H = 2.3$ are necessary to ensure high- Q .

Figure 1: Contours of equilibrium neutral beam power $P_{NB,Eq}$ as a function of density $\langle n_e \rangle$ and temperature $\langle T_e \rangle_n$ with alpha particle fraction $c_\alpha = 5\%$ and L-mode enhancement $H = 2.3$. Also shown are contours yielding a wall loading $P_w = 1 \text{ MW/m}^2$ and a $\beta (\%) = 2.5 I_p / aB_0$. A potential ITER operating point is labeled with a *.

operation of the ITER physics phase machine at end of burn conditions (where c_α may approach 10%). We assume that both P_w and H remain fixed for the entire burn.

Notice from Fig. 1 that there are two ignited equilibrium points (i.e., places where the $P_w = 1 \text{ MW/m}^2$ contour intersects the $P_{NB,Eq} = 0$ contour): one characterized by high density, low temperature and another characterized by low density, high temperature. There are also two regions of sub-ignited ($P_{NB,Eq} > 0$) operation. From the point of view of power/particle balance, all of these equilibrium points are equally acceptable. However, it can be argued that the high density, low temperature equilibrium points might be the most desirable for ITER high- Q operation. In particular, the low density equilibrium points are typically characterized by beta values close to the MHD stability limit and, in fact, for the conditions in Fig. 1, we see that the low density points actually exceed the beta limit (and, hence, are not acceptable). Additionally, higher densities tend to reduce the energies of particles impacting on the divertor plates (thus reducing sputtering) and lower temperatures tend to reduce the effect of fuel pellet ablation (thus allowing better pellet penetration).

Although favored from MHD stability, divertor, and fueling considerations, the high density equilibrium points suffer from a potentially serious drawback: they are susceptible to thermal instabilities (i.e., uncontrolled increases or decreases in temperature). To see this, consider the point labeled with a * in Fig. 1. If the temperature increases from its equilibrium value, perhaps due to a random fluctuation, the plasma enters a region in

$\langle n_e \rangle < \langle T_e \rangle_n$ space where the neutral beam power required to maintain equilibrium is less than at the original operating point. This means that power sources exceed losses and the temperature must continue to increase even more. A similar argument can be made regarding a decrease in the temperature. On the basis of this discussion, one can reason that an operating point is unstable to temperature perturbations if [6]

$$\frac{\partial P_{NB,Eq}}{\partial \langle T_e \rangle_n} < 0 \quad (3)$$

Applying Eq. (3) to the contours in Fig. 1 confirms that the high density, low temperature points represent thermally unstable equilibria. If ITER is to operate at these points, methods for controlling the thermal instabilities must be demonstrated. This is the topic of the next section.

Operating Point Control

Figure 2 shows a simulation of a typical ITER thermal instability. In this case, the electron and ion temperatures associated with the equilibrium point labeled with the * in Fig. 1 (where $P_{NB,Eq} = 25 \text{ MW}$) are instantaneously increased by an amount $\Delta T_{e,i} = +0.36 \text{ KeV}$ (which yields a fractional change in the neutron flux ϕ_N of $\Delta \phi_N / \phi_N = +15\%$). Then, the plasma is allowed to evolve freely (with H and $P_{NB,Eq}$ held fixed). We see from Fig. 2a (dashed curve) that the fusion power rapidly increases past 1500 MW over a 2 sec period. Subsequently, the MHD beta limit is exceeded, presumably resulting in a hard disruption at a high fusion power level.

Negative excursions must also be considered. As Fig. 3a shows (dashed curve), assuming $\Delta T_{e,i} = -0.38 \text{ KeV}$ (which yields $\Delta \phi_N / \phi_N = -15\%$) leads to a rapid decrease in the fusion power level. It is likely that this instability will also result in a disruption due to exceeding a density limit which, for ITER, currently takes the form [2]

$$P_{rad} \text{ (within the } q = 2 \text{ surface)} < 0.7 P \quad (4)$$

where P_{rad} is the total radiation power, q is the MHD safety factor, and P is the total plasma heating power. In the simulation shown in Fig. 3, Eq. (4) is violated within 4 sec at the point when the fusion power drops to approximately 720 MW.

Since the time required for the thermal instability to cause either beta or density limit disruptions is short compared to the expected ITER burn length (~200 sec), it is necessary to consider methods for actively controlling the instability. One of the more credible methods is control by modulated auxiliary heating [7]. In this scheme, the plasma is operated slightly sub-ignited, but at high Q . Then, in response to an increase in the plasma temperature or fusion power, some or all of the heating power is temporarily removed, hopefully returning the plasma to equilibrium conditions. Similarly, when the temperature or fusion power decreases, additional power is applied. Modulated auxiliary heating has been chosen as the baseline control method for the proposed Compact

Ignition Tokamak (CIT) [8]. Other approaches to ITER burn control are analyzed by Mandrekas and Stacey [9].

We propose using modulation of the neutral beam power based on measurements of total neutron flux as the primary control method for ITER. In particular, we employ the simple proportional feedback law

$$P_{NB} = P_{NB,Eq} - G_{\phi} \left(\frac{\phi_N}{\phi_{N,Eq}} - 1 \right) \quad (5)$$

where G_{ϕ} is the feedback gain (taken to be 1000 MW for this study, indicating essentially instantaneous power response) and $\phi_{N,Eq}$ is the equilibrium neutron flux. The applied neutral beam power P_{NB} is further constrained by

the inequality $0 \leq P_{NB} \leq P_{NB,max}$ where $P_{NB,max} \sim 75$ MW is the expected maximum neutral beam power capacity for ITER.

The choice of total neutron flux as the control signal is motivated by the observation that small changes in temperature lead to larger, and easier to measure, changes in neutron flux. For instance, measuring the $\Delta T_e = +0.36$ KeV perturbation from the simulation in Fig. 2 might be difficult using current temperature diagnostic techniques such as electron cyclotron emission. However, the resulting 15% fractional change in ϕ_N is thought to be within the measurement capabilities of current neutron diagnostics [10].

Figure 2: Simulations of an ITER thermal instability due to $\Delta T_{e,i} = +0.36$ KeV (or $\Delta\phi_N/\phi_N = +15\%$) perturbation of the equilibrium point labeled with a $\bullet$ in Fig. 1. Shown are plots of (a) fusion power P_f and (b) neutral beam power P_{NB} as function of time for cases with (solid line) and without (dashed line) feedback.

Figure 3: Simulations of an ITER thermal instability due to $\Delta T_{e,i} = -0.38$ KeV (or $\Delta\phi_N/\phi_N = -15\%$) perturbation of the equilibrium point labeled with a $\bullet$ in Fig. 1. Shown are plots of (a) fusion power P_f and (b) neutral beam power P_{NB} as function of time for cases with (solid line) and without (dashed line) feedback.

Figure 4: Plots of critical positive and negative initial perturbations $\Delta\phi_N/\phi_N$ as a function of $P_{NB,Eq}$. Shown are curves for $c_\alpha = 1, 5$, and 10% .

We see from Figs. 2 and 3 (solid lines) that applying neutral beam feedback as described by Eq. (5) readily stabilizes perturbations that resulted in disruptions (see dashed lines) without the feedback. In the case of both positive and negative excursions, equilibrium conditions are largely restored within 10 sec.

The equilibrium neutral beam power $P_{NB,Eq}$ is a critical parameter in our control scheme and must be chosen with some care. Ideally, one would like to choose the smallest $P_{NB,Eq}$ possible since that maximizes the nominal Q value for the reactor. On the other hand, decreasing $P_{NB,Eq}$ reduces the magnitudes of the initial positive perturbations that can be stabilized. This trade-off is illustrated in Fig. 4 which describes simulations for a number of equilibrium points characterized by different $P_{NB,Eq}$ and c_α . At each point, the ion and electron temperature were instantaneously perturbed by an amount sufficient to produce a given $\Delta\phi_N/\phi_N$ and the plasma was allowed to evolve in the presence of feedback described by Eq. (5). The initial perturbation was varied to yield the critical positive and negative $\Delta\phi_N/\phi_N$ values that could barely be stabilized. The curves in Fig. 4 are these critical perturbations.

We notice from Fig. 4 that increasing $P_{NB,Eq}$ increases the magnitude of the stabilizable positive perturbations but decreases the magnitude of the stabilizable negative perturbations. This occurs because of the limit on $P_{NB,max}$. Furthermore, we see that the minimum allowable choice for $P_{NB,Eq}$ is primarily limited (for a particular c_α) by the minimum positive $\Delta\phi_N/\phi_N$ value to be stabilized. This, in turn, is set by neutron diagnostic capabilities which we assume are no better than $\Delta\phi_N/\phi_N = \pm 15\%$ [10]. The minimum $P_{NB,Eq}$ is also seen to decrease as c_α increases. However, recognizing that stability must be ensured both at the start of burn (when

$c_\alpha = 1\%$) and at the end of burn (when $c_\alpha = 10\%$), we choose $P_{NB,Eq}$ based on the $c_\alpha = 1\%$ curve. This gives $P_{NB,Eq} = 21$ MW corresponding to $Q \approx 54$.

Based upon this analysis, we conclude that high- Q ITER operation consistent with MHD stability, divertor, and fueling requirements might be possible at high density, low temperature equilibrium points if a neutral beam feedback system based on neutron flux measurements is employed to control thermal instabilities. Calculations with more complete plasma models will be undertaken to confirm this.

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