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EXPERIMENTAL SURVEY OF THE L-H TRANSITION CONDITIONS IN THE DIII-D TOKAMAK

by

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Experimental survey of the L-H transition conditions in the DIII-D tokamak

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Abstract. We present the global analysis of a recent survey of the H-mode power threshold in DIII-D using $D^0 \rightarrow D^+$ NBI after boronization of the vacuum vessel. Single parameter scans of B_T , I_p , density, and plasma shape have been carried out on the DIII-D tokamak for neutral beam heated single-null and double-null diverted plasmas. In single-null discharges, the power threshold is found to increase approximately linearly with B_T and n_e but remains independent of I_p . In double-null discharges, the power threshold is found to be approximately independent of both B_T and n_e . Various shape parameters such as plasma-wall gaps had only a weak effect on the power threshold. Imbalancing the double null configuration resulted in a large increase in the threshold power.

1. Introduction

It is important to investigate the scaling of threshold conditions and the operating space of H-mode in order to predict the confinement regime of future devices such as ITER. Measurements of the plasma conditions required to achieve H-mode also provide both inspiration and examination for theoretical models of the transition. Experiments in which one parameter is varied as others are held fixed are especially important in determining the parametric dependence and scaling of the L-H transition. In this paper we present the global analysis of a recent survey of the H-mode power threshold in DIII-D using $D^0 \rightarrow D^+$ NBI after boronization of the vacuum vessel. Detailed analysis of plasma edge conditions leading to a transition will be discussed in future work.

2. Method

The experiments were carried out in a freshly boronized vessel. Following standard operating procedure on DIII-D, helium glow discharge cleaning was used between shots to keep the vessel wall conditioned. A reference discharge was established with parameters set near the midrange of the operating space that can be scanned conveniently in DIII-D. The desired parameter was then scanned on a shot-to-shot basis with a staircase power scan (300 ms/step) on each shot.

In order to lower the step size of neutral beam heating power to below the one source level of 2.4 MW at 75 KV, the beam was modulated at 50 Hz (20 ms period) and the duty cycle adjusted to 25%, 50%, 75%, and 100%. This produced average powers of 0.6, 1.2, 1.8, and 2.4 MW without changing the beam voltage and the corresponding beam deposition profile. Figure 1 shows waveforms of the modulated beam power, the average power, the line density, and the D_α signal from the divertor region during an L to H transition. Since the beam slowing down time is of the order of 20–30 ms, and energy confinement times of 90–120 ms, the plasma was an effective integrator of the power, and no effect of the beam modulation was seen on

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Fig. 1. Time evolution of a discharge showing the modulated NBI power, its average value over 20 ms, and the steady condition of several edge plasma parameters in spite of the modulation. The L-H transition is at 2460 ms. The edge T_e and n_e were measured with a multipulse Thomson scattering system using six lasers with an effective measuring frequency of 120 Hz.

edge of the plasma by sawteeth may account for the lower threshold power. The density scan was severely limited at the low end by locked modes and at the high end by Marfes. Both these phenomena greatly increase the threshold power and those points were omitted from the scaling plot. Unfortunately, this left only a factor of two range in density and few data points. There remains, however, a definite increase in the threshold power with density. Dependence of the threshold power on I_P was weak. The Ohmic power increased from 0.5 MW at 1.0 MA to 1.5 MW at 2.0 MA with a nearly concomitant decrease in the NBI power. The edge safety factor q_{95} changed from 6.2 at 1.0 MA to 3.1 at 2.0 MA. Decreasing the outer gap increased the threshold power weakly. Scans of X-point height, inside gap and a limited scan of the elongation, κ , showed no change in the power threshold over the range examined. The lack of any X-point height dependence is inconsistent with our previous findings (Carlstrom *et al.*, 1989) and is not yet understood. Table 1 summarizes the parameter scans, their range, and the effect of the threshold power.

4. Double-null results

In double-null discharges, the power threshold is found to be approximately independent of both B_T and n_e . (The dependence on I_P was not measured.) However, the threshold power is very sensitive to the balance between the two X-points, measured by the parameter Dr_{SEP} , which is the distance between the separatrix surfaces associated with the two X-points, measured at the midplane. Figure 2(b) shows the flux surfaces for a balanced double-null, ($Dr_{SEP}=0.0$), and

edge SXR, the D_α measurements, or the edge T_e and n_e measured by multipulse Thomson scattering.

Because threshold powers were often comparable to the Ohmic heating power, the power threshold includes both the Ohmic and absorbed neutral beam powers, Total Input Power = $P_{nbi} + P_{ohmic}$. P_{ohmic} is calculated from smoothed $V_{loop} * I_P$. During the L phase, V_{loop} is reasonably steady and comparisons between $V_{loop} * I_P$ and Ohmic power calculated from Z_{eff} measurements and time dependent analysis of magnetics using EFIT and TAUFIT codes agree to an accuracy of ± 0.2 MW.

3. Single-null results

In single-null discharges, the power threshold is found to increase approximately linearly with B_T and n_e but varies only weakly with I_P . Figure 2(a) shows the equilibrium poloidal flux surfaces and various shape parameters for a lower single-null discharge. The ∇B drift direction is toward the X-point. Figure 3 shows the individual scans of B_T , n_e , I_P , and outer gap. At the lowest toroidal field, Ohmic H-mode was observed, and these data leverage the power threshold to vary approximately linearly with B_T . At 1.35 MA, Ohmic H-modes were observed for $B_T \leq 1.6$ T and input powers of approximately 1 MW. This point falls below the L-mode points shown in Fig. 3(a). Since Ohmic H-modes in DIII-D are always triggered by a sawtooth crash, the modulation of power flow to the

Fig. 2. Poloidal flux contours obtained from an equilibrium reconstruction code based on magnetic measurement are shown for four cases: (a) single-null discharge with X-point in direction of ∇B drift, (b) balanced double-null discharge ($Dr_{SEP} = 0.0$ cm), (c) imbalanced double-null discharge with lower X-point dominant ($Dr_{SEP} = -0.6$ cm), and (d) imbalanced double-null discharge with upper X-point dominant ($Dr_{SEP} = 0.6$ cm).

for single-null discharges is consistent with the results from other devices (Ryter *et al.*, 1993).

A comparison of the total radiated power in single-null discharges showed almost no change from our previous survey. Because of the low power thresholds in the current survey, the fraction of total radiated power has actually increased.

The threshold power scales with B_T in the single-null configuration but is only weakly dependent on B_T in the double null configuration. This suggests that the power threshold is probably not due to an intrinsic plasma parameter within the separatrix that may depend on the toroidal field such as the gyro radius, but rather that phenomena at the plasma edge or in the SOL plasma that depends on the field line geometry may be responsible. The lack of B_T

the midplane. Figure 2(b) shows the flux surfaces for a balanced double-null, ($Dr_{SEP}=0.0$), and the imbalanced double-nulls are shown in Figs. 2(c) and (d). Figure 4 shows the double-null parameter scans of B_T , n_e , Dr_{SEP} and inside gap. The threshold power does not change as the plasma is imbalanced toward the X-point in the ∇B drift direction. However, the power threshold increases from 4 MW to over 14 MW when the plasma is imbalanced toward the X-point away from the ∇B drift direction. This scan showed the most dramatic effect on the power threshold in our survey. Table 2 summarizes the double-null parameter scans, their range, and the effect of the threshold power.

5. Discussion and conclusions

The use of deuterium beams and advances in wall conditioning techniques such as boronization and helium glow discharge cleaning before each plasma discharge has resulted in 40%–60% lower power thresholds than previously reported using hydrogen beams (Carlstrom *et al.*, 1989). The threshold power in double-null discharges scales differently than single null discharges. The lowest power thresholds were found in single-null discharges at low field where the Ohmic heating power was sufficient to obtain H-mode. Ohmic H-modes have not been observed in the double-null configuration. Figure 5 shows the threshold power normalized to the plasma surface area $\{S = 4\pi^2 a R [(1 + \kappa^2)/2]^{1/2}\}$ plotted against nB for single and double-null discharges. This scaling relation and the proportionality constant

Fig. 3. Single-null threshold power scans of (a) B_T , (b) $\bar{n}_e$, (c) I_p , and (d) the outer gap.

Table 1
Single-null threshold power survey

Parameter	Range	Effect on Power Threshold
1. B_T	1.0 to 2.1 (Telsa)	Increases roughly linearly
2. $\bar{n}_e$	2.0 to 5.0 (10^{19} m^{-3})	Increases
3. I_p	1.0 to 2.0 (MA)	Increases weakly
4. X-point height	0.0 to 25 (cm)	No dependence
5. κ	1.78 to 2.04	No dependence
6. Inside Gap	0.3 to 4.5 (cm)	No dependence
7. Outside Gap	0.0 to 10 (cm)	Weakly decreases

Fig. 4. Double-null threshold power scans of (a) B_T , (b) $\bar{n}_e$, (c) Dr_{SEP} , and (d) the inner gap.

Table 2
Double-null threshold power survey

Parameter	Range	Effect on Power Threshold
1. B_T	1.3 to 2.1 (Telsa)	Weakly increases
2. n_e	2.0 to 5.0 ($10^{19}m^{-3}$)	Weakly increases
3. Dr_{SEP}	-0.8 to +0.8 (cm)	Strong dependence for $Dr_{SEP} > 0$
4. Inside Gap	1.0 to 8.0 (cm)	Weakly decrease

dependence in the double-null case may be consistent with earlier ASDEX results which did not see a B_T dependence either (Wagner *et al.*, 1989). ASDEX was a circular machine that may have always acted like a double-null (see Dr_{SEP} scan). Although the effect of the relationship

Fig. 5. Total input power normalized to the plasma surface area showing the nB scaling for single-null discharges and the lack of nB scaling for double-null discharges. Open points remained L-mode, filled points obtained H-mode.

single null. This suggests that the nB scaling of P_{th} for single null may saturate at higher nB values. The ITER value for nB is about 5 times the highest DIII-D value and S is about 13 times greater. Accordingly, accurate size scaling of P_{th} as well as plasma parameter scaling is important for predicting P_{th} for ITER.

Although there is some consistency in single-null discharges for the threshold power to scale with nB , more work remains to be done before an understanding of the conditions leading to an L-H transition is achieved.

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References

- Carlstrom T N *et al.* 1989 *Controlled Fusion and Plasma Physics* Vol. 13B, p. 241.
- ITER Tokamak Device 1991 ITER Documentation Series, No. 25 (IAEA, Vienna)
- Ryter F *et al.* 1993 *20th European Conf. on Controlled Fusion and Plasma Physics*; Hutchinson I *et al.* 1993 *35th Annual Meeting of the Division of Plasma Physics*.
- Wagner F 1989 Proceedings of 1989 IAEA Technical Committee Meeting on H-mode Physics, *Plasma Phys. and Contr. Fusion*.

between the ∇B drift direction and the X-point location has been observed in many devices, the effect in this survey was very pronounced. For double-null discharges, the ∇B drifts and their relationship to the X-point have a dominant role in determining the threshold power. The lack of dependence on the X-point height in single-null is inconsistent with our previous results and operating experience. Boronization may have changed effects of radiation in the divertor which in turn, changed the X-point dependence.

It is interesting to use the present scalings to estimate the power thresholds for ITER. For single null, P_{th_SN} (MW) $\sim 0.04 n(10^{20} \text{ m}^{-3}) B(T) S(\text{m}^2)$. Using values from the ITER CDA (ITER, 1991) of $n = 1$, $B = 4.85$, $a = 2.15$, $R = 6$, and $\kappa = 2$, we obtain P_{th_SN} (ITER) ~ 156 (MW). For double null, P_{th_DN} (MW) $\sim 0.06 S(\text{m}^2)$ and P_{th_DN} (ITER) ~ 48 (MW). Having a single null threshold higher than a double null is inconsistent with the results from many machines which find the lowest thresholds for

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