JET-P(95)74

Access Conditions for H-modes with Detached Divertor Plasmas

K Borrass[1], R Farengo[2], G Vlases.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA, UK.

[1] Present address: MPIPP, Garching, Germany.

[2] On leave from Comisión Nacional de Energía Atómica, Buenos Aires, Argentina.

Preprint of Papers to be submitted for publication in
Nuclear Fusion

December 1995

This document is intended for publication in the open literature. It is made available on the understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original, without the consent of the Publications Officer, JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK.

Enquiries about Copyright and reproduction should be addressed to the Publications Officer, JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK.

ABSTRACT

Access conditions for H-modes with detached divertor plasmas are derived by considering power threshold, divertor plasma temperature and density limit constraints. It is found that there is a minimum scrape-off layer power and main plasma density for accessing the detached divertor H-mode, and that the required divertor radiated power fraction must increase as the machine size and field increase. The model describes, at least qualitatively, experimental findings on ASDEX-Upgrade, DIII-D, JET, and JT-60.

1. INTRODUCTION

The presently envisaged ITER operating scenario requires H-mode operation compatible with a detached divertor plasma in which a large fraction of the exhaust power is distributed over the divertor sidewalls by radiation from seeded impurities and charge exchange, with the balance radiated as uniformly as possible from the main plasma edge, so that the conducted power to the divertor plates remains below 5 MW/m^2 [1]. This must be accomplished while simultaneously exhausting the He ash effectively and maintaining a low value of Z_{eff} in the core plasma.

This challenge has led to the investigation of detached, highly radiating (seeded) divertor plasmas in all major divertor tokamaks. It has generally been found that the smaller devices, such as ASDEX-Upgrade [2] and DIII-D [3], were able to successfully radiate a significant fraction of the exhaust power, using neon as a seeded impurity, while maintaining H-mode confinement and detachment. It must be noted, however, that in these discharges the H-factor was degraded and the core plasma Z_{eff} became too large. In JET such operation was initially found to be more difficult, although success was achieved subsequently using nitrogen seeding [4]. JT-60 did not find such a regime operating at high toroidal field (3.5-4.0 T) [5] but in a recent study carried out with the same current and B_t reduced to 2 T detached H-mode operation was observed [6]. The question thus arose as to whether the access conditions for what will be called "detached H-mode" might have an adverse size dependence, and what the implications for ITER might be. In this paper we present a simple model for such an access window and discuss the implications for currently operating machines and ITER.

2. CONSTRAINTS WHICH DEFINE THE DETACHED H-MODE ACCESS WINDOW

The first constraint is that the power crossing the separatrix, $P_{SOL} = P_{heat} - P_{rad,bulk}$, must exceed the H-mode power threshold for the L→H transition which we take to be

$$q_\perp = P_{SOL}/S \geq C_T\, nB_t \qquad (1)$$

where $q_\perp$ is the power density crossing the separatrix, S the plasma surface area, n the line averaged main plasma density and B_t the toroidal field. For fixed B_t, Eq. (1) is the straight line through the origin in the n-$q_\perp$ plane shown in Fig. 1. The value of C_T is taken from ASDEX-Upgrade and JET experience and results, C_T=3.03×10^{-16} WmT^{-1} when $q_\perp$ is measured in W/m^2, S in m^2, n in m^{-3} and B_t in T. This is the same value adopted in ITER design studies (when corrected for bulk radiation of 25%). It had been hoped that the window could be made larger by invoking the fact that in studies of non-highly-radiating H-modes the back transition (H→L) occurs at about 60% of the power required for the L→H transition. However, it has been the experience at ASDEX-Upgrade [7] as well as JET that this hysteresis essentially disappears for the highly radiating edge plasma conditions under discussion.

The second condition is that the divertor plasma detaches. A necessary condition for this is that the divertor plasma passes through a state in which its temperature falls to around 5 eV so that ion-neutral interactions become important ("pre-detachment") [8]. While no exact analytic theory for detached divertor plasmas exists, we use the extended two point model of Ref. [9] to relate this pre-detachment divertor temperature to the upstream separatrix density n_s, SOL power and divertor radiated power fraction f_{div}, defined as the fraction of power crossing the separatrix which is radiated in the divertor/SOL. This yields

$$n_s = \frac{C'}{\alpha_B^{5/16}} \frac{q_\perp^{5/8}\; B_t^{5/16}\left(1-f_{div}\right)^{11/16}}{\left(q_\psi R\right)^{1/16}} \cdot \frac{T_D^{11/32}}{\left(\xi+\gamma T_D\right)^{11/16}} \qquad (2)$$

where q_ψ is the safety factor, R the major radius, T_D the divertor temperature, γ the sheath transmission factor, and ξ the deuterium ionisation potential. In this equation it has been assumed that the perpendicular transport is Bohm-like with a multiplying factor of α_B . The temperature dependent expression, $F(T_D) = T_D^{11/32}\ (\xi + \gamma T_D)^{-11/16}$ is quite flat over the range of 2-10 eV so that we can approximate it by its value at 5 eV. Finally, we define f_{prof} as the ratio between n_s and the line averaged main plasma density n, to obtain an expression for the density, n_{det}, at which detachment begins

$$n_{det} = \alpha \frac{q_\perp^{5/8} B_t^{5/16}\left(1-f_{div}\right)^{11/16}}{\left(q_\psi R\right)^{1/16}} \qquad (3)$$

where $\alpha = C'F(5\ \mathrm{eV})/\alpha_B^{5/16}\ f_{prof}$.

In what follows, we will assume that α is discharge independent in the special operating regime under consideration (i.e., for the radiative divertor, near threshold conditions we are discussing). Experimental evidence for this assumption will be discussed in the Appendix. In Fig. 1 n_{det} is plotted versus $q_\perp$ at constant α and otherwise fixed parameters as the curve running from the origin through the point A. In order to have a detached H-mode, it is necessary to operate below the threshold curve ($P_{SOL}>P_{thresh}$) and above the n_{det} curve of Eq. (3).

The high density boundary of the access window will be established by some form of density limit, i.e. a condition of the form $n(q_\perp) \leq n_{dl}(q_\perp)$. The physics governing the density limit has not yet been clarified. There exist for example SOL-based models which exhibit power dependence under certain conditions [9] as well as fully empirical expressions such as that given by Greenwald [10], which is independent of power. In many machines the L-mode density limit shows a behaviour not described by the Greenwald limit and often exceeds it [11- 13]. For the H-mode the database is poor. In H-mode experiments with highly radiating edges reported so far it has not been possible, however, to exceed the Greenwald limit. We thus adopt the expression

$$n_G = C_G\, I / \pi a^2 \quad . \tag{4}$$

where $C_G=10^{14}\,(\mathrm{Am})^{-1}$, as a reference to give an indication of the impact of a density limit in the present context.

In Fig. 1 the density limit is therefore a horizontal line, and the operation window is the shaded area between the intersections of the three curves, namely the points A, B and C. For $q_\perp$ greater than that corresponding to point C, the temperature in the divertor can not be made low enough to reach detachment by raising the upstream density, without exceeding the density limit.

3. REMARKS ON THE WINDOW SIZE

The area defined by the points A, B, and C (window size) as well as the position of the window in the n-$q_\perp$ plane, depend rather sensitively on the parameter f_{div}, the coefficients α and C_T and the field B_t, and less strongly on the machine size. The bulk radiated fraction f_{bulk} also enters through the determination of P_{SOL}.

One sees immediately that, in order to get access to the detached H-mode, the conditions $q_\perp > q_\perp^*$ and $n > n^*$, where $q_\perp^*$ and n^* are defined by point A, have to be fulfilled. From Eqs. (1) and (3) one concludes that

$$n^* = \alpha^{8/3} C_T^{5/3} B_t^{5/2} (1 - f_{div})^{11/16} (q_\psi R)^{-1/6} \tag{5}$$

$$q_\perp^* = C_T\, n^*\, B_t \tag{6}$$

$$P^*_{SOL} \propto B_t^{7/2} (1-f_{div})^{11/16} R^{11/16} q_\psi^{-1/6} \varepsilon , \quad (7)$$

where $\varepsilon = a/R$. For a given B_t, n^* depends primarily on f_{div} and weakly on R, while P^*_{SOL}, the minimum SOL power required, scales the same way with f_{div} but also with $R^{11/6}$.

As a measure of the size of the window we take the ratio n^*/n_G, which must be less than unity for a window to exist. From the above analysis,

$$\frac{n^*}{n_G} \propto B_t^{3/2}(Rq_c)^{5/6}(1-f_{div})^{11/16}, \quad (8)$$

where we have replaced the I_p dependence by a q_c (cylindrical q) dependence. (Throughout the paper we assume that all machines operate at similar q_ψ and hence q_c, because of the similarity of the magnetic configurations). As the machine size and field increase at fixed q_ψ (i.e. JT-60, ITER), the divertor radiated power fraction must be correspondingly increased in order to maintain an access window.

For a given B_t and R, Eq. (8) defines a minimum f_{div}, which we denote $f^\dagger_{div}$, for which the window exists. For this value of f_{div}, $n_G/n^*=1$ and the points A, B, and C coincide. As f_{div} is increased above $f^\dagger_{div}$, point A slides along the threshold curve towards the origin, enlarging the window. This is illustrated for ITER in Fig. 2, from which it is seen that the minimum value of f_{div} at which ITER could operate is about 0.82 for an assumed bulk radiated power fraction of 0.35.

It has been proposed by the ASDEX-Upgrade group that the most desirable ITER scenario is to utilize what they have named the CDH-mode, for which the power crossing the separatrix is reduced to just above the threshold and the balance of the power is then to be exhausted in the divertor [2]. In this way, the Type I ELMs which occur for values of P_{SOL} considerably above threshold, are eliminated and replaced by more benign grassy ELMs. In terms of Fig. 1, this CDH scenario corresponds to operating near the line segment AB. Operationally, the CDH scenario requires rather precise control of both the bulk and divertor radiated power fractions.

4. APPLICATION TO EXISTING TOKAMAKS.

We now apply the considerations of Secs. 2 and 3 to the four operating machines, ASDEX-Upgrade, DIII-D, JET and JT-60. For the sake of illustrating the operating window for the four machines we assume that α is machine independent. In other words, the value of α determined using JET data is used in all cases. All other coefficients are as described earlier.

We also need to know the bulk and divertor radiation fractions f_{bulk} and f_{div} respectively. For ASDEX-Upgrade and JET we use values reported in the literature already cited. For DIII-D and JT-60, these fractions are not known to us, so we have based them on the ASDEX-Upgrade and JET values, in order to be able to make a comparison. The parameters used are summarised in Table I where two values of toroidal field are employed for JT-60.

TABLE I. REFERENCE PARAMETERS [a]

	R	a	s	B_t	I_p	P_{heat}	f_{bulk}	f_{div}
	[m]	[m]		[T]	[MA]	[MW]		
ASDEX-U	1.75	0.5	1.6	2.5	1.0	8.5	0.35	0.6
DIII-D	1.7	0.7	1.7	2.2	1.5	8.5	0.35	0.6
JET	3.0	0.9	1.6	2.4	2.5	15.0	0.35	0.6
JT-60	3.3	0.95	1.3	3.5/2.0	1.2	20.0	0.35	0.6

[a] Here s is the plasma elongation, while all other quantities have been defined in the text. Values quoted are representative of detached H-mode studies and usually differ from the highest values achievable in a particular machine.

It is worth noting that the quantity $q_\perp^{5/8}(1 - f_{div})^{11/16}$ is relatively insensitive to the split between bulk radiation and divertor/SOL radiation for a given total radiative fraction f_{tot}, since we can write

$$q_\perp^{5/8}(1-f_{div})^{11/16} = (P_{heat} / S)^{5/8}(1-f_{tot})^{5/8}(1-f_{div})^{1/16}, \quad (9)$$

where $f_{tot} = P_{rad,total} / P_{heat}$. Thus, the curve labelled n_{det} in Fig. 1 depends mainly on f_{tot}. (We note, however, that the determination of C_T in Eq. 1 depends directly on f_{bulk}, to the extent that the assumption that the threshold depends on power crossing the separatrix is correct and thus may be revised as the H-mode threshold database improves).

The resulting windows are shown in Fig. 3. The vertical dashed lines on these figures represent typical powers at which the machines run detached divertor H modes. In the JT-60 plot the dotted lines correspond to the case with 2 T while the 2 vertical dashed lines indicate the range of values used for $q_\perp$.

From Fig. 3 several conclusions can be drawn. First, each of the devices has an operating window for the conditions of Table I because $n_G > n^*$. In addition, they have operated at high enough power ($q_{\perp,max} > q_\perp^*$) to access the detached H-mode. ASDEX-Upgrade has a slightly larger operating space for the parameters of Table I than does JET, primarily due to a higher Greenwald density limit. The windows for JET and DIII-D are predicted to be very similar. Finally, we note that, in agreement with the results reported in

Refs. [5] and [6], JT-60 does not have a window for B_t=3.5 T but does have a small one operating at 2 T.

5. SUMMARY AND CONCLUSIONS

An operating window has been derived for an H-mode with a detached divertor plasma using power threshold, density limit and divertor temperature constraints. A number of assumptions had to be made, which were based on experimental data wherever possible.

The inclusion of the requirement of low divertor temperature, necessary to achieve detachment, considerably reduces the operation window in comparison to that derived by considering only the H mode threshold and density limit. The analysis shows the existence of a minimum SOL power and main plasma density below which the detached H-mode cannot be accessed. The required power scales as $B_t^{7/2}\ R^{11/16}(1 - f_{div})^{11/16}$. If the ASDEX-Upgrade CDH-mode is adopted, the window is smaller than if operation well above threshold is allowed.

The simple analytical relations derived provide some general guidelines. Low toroidal field eases access to the detached divertor H mode, as does high f_{div}. As machine size and toroidal field increase, the minimum radiative fraction that provides a window, must increase.

The model used here appears to be in qualitative agreement with experimental results from the four divertor tokamaks we have discussed. The model is too simple, of course, to deal with subtle effects brought about, for instance, by variations in divertor geometry. It is possible that for the highly closed divertors soon to be tested in various devices, the degradation in H-mode confinement currently reported by JET and ASDEX-Upgrade when operating near threshold conditions may be reduced, and some of the threshold hysteresis may reappear. These effects would clearly be beneficial.

ACKNOWLEDGEMENT

The authors wish to thank R. Monk for his assistance in evaluating the JET data. One of the authors gratefully acknowledges the observation by R. Goldston that the operating window appears to depend on machine size.

APPENDIX

In this appendix we present experimental data that supports the assumption that α is constant and has the same value in detached L and H-mode discharges in JET. A similar analysis should be performed in other machines to test whether α is also device independent.

Using Eq. (3) we can write α as:

$$\alpha = n\left\{\frac{q_{\perp}^{5/8}B_t^{5/16}\left(1-f_{div}\right)^{11/16}}{\left(q_{\psi}R\right)^{1/16}}\right\}^{-1} \quad \text{(A.1)}$$

Most of the quantities needed to calculate α in Eq. (A.1), namely n, P_{heat}, S, R, B_t and q_{ψ}, can be determined easily and reliably. The determination of $q_{\perp}$ and f_{div} are imprecise but, as shown above, they can be replaced by the better measured quantities P_{heat}/S and f_{tot}.

Recently the accuracy of probe based temperature measurements under detached or pre-detached divertor conditions has become a matter of concern. On the other hand experimental evidence clearly indicates that the onset of detachment is associated with a rollover of J_{sat} as the main plasma density is increased, and we have used this as an indicator for the achievement of a pre-detached state and evaluated the quantities on the right hand side of Eq. (A.1) at this time.

One of the methods employed at JET to induce detachment is to increase the density at fixed input power. In L-mode discharges detached plasmas can be obtained with deuterium alone, but in H-mode an additional impurity (usually nitrogen) is needed. In some cases the density is increased fairly rapidly and the rollover of J_{sat} occurs when the bulk density profile is still hollow. In these cases the data required to determine α is taken as soon after the rollover as the density profiles become flat.

In Figs. 4 and 5 α is shown versus line-averaged density and heating power, respectively, for a number of L-mode (circles) and H-mode (triangles) discharges in JET, determined as described. Within the experimental errors, the assumption of constant α is well justified over a wide range of parameters for divertor plasmas on the verge of detachment. Most surprisingly there is no difference between L and H-mode discharges confirming the previously mentioned observations that macroscopic parameters of L and H-mode discharges show virtually no difference in the regime under consideration.

REFERENCES

[1] ITER-JCT and Home Teams (presented by G Janeschitz), Plasma Phys. and Controlled Fusion **37 Suppl 11 A**, A19 (1995). (Proc. 22nd EPS Conf. on Controlled Fusion and Plasma Physics, Bournemouth, 1995).

[2] J.O. Gruber et al. Phys. Rev. Letter **74** 4217 (1995).

[3] S.L. Allen et al., Journal of Nuclear Materials **196-198** 804 (1992).

[4] JET Team (presented by G. Matthews), Plasma Phys. and Controlled Fusion **37 Suppl 11 A**, A227 (1995). (Proc. 22nd EPS Conf. on Controlled Fusion and Plasma Physics, Bournemouth, 1995).

[5] N. Hosogane, ITER Divertor Experts Group Meeting, Garching, January 1995 (unpublished).

[6] N. Hosogane, ITER Divertor Experts Group Meeting, Naka, October 1995 (unpublished).

[7] A. Kallenbach et al., Proc. 22nd EPS Conf. on Controlled Fusion and Plasma Physics, **19c II** pag. 005, 1995.

[8] P.C. Strangeby, Nuclear Fusion **33** 1695 (1993).

[9] K. Borrass, Nuclear Fusion **31** 1035 (1991).

[10] M. Greenwald et al., Nuclear Fusion **28** 2199 (1988).

[11] H. Neidermayer et al., Controlled Fusion and Plasma Physics **9F**, Part 1, 159 (1985).

[12] H. Niedermayer et al., Plasma Physics and Controlled Fusion **30** 1443 (1988).

[13] K. Borrass et al. Nuclear Fusion **33** 63 (1993).

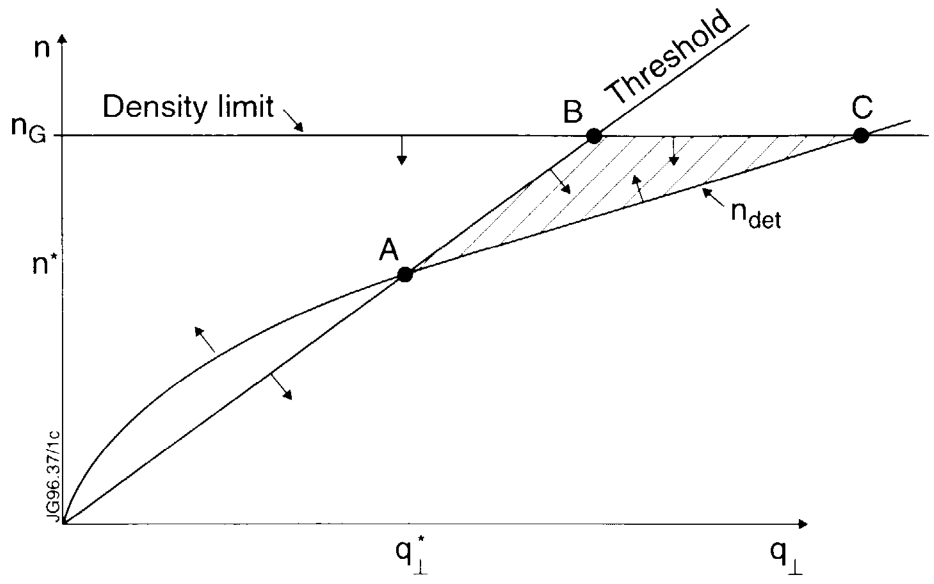

Fig. 1: Schematic diagram of the detached divertor H-mode access window. The constraint curves are drawn for fixed B_t and f_{div}. The full access window is shaded.

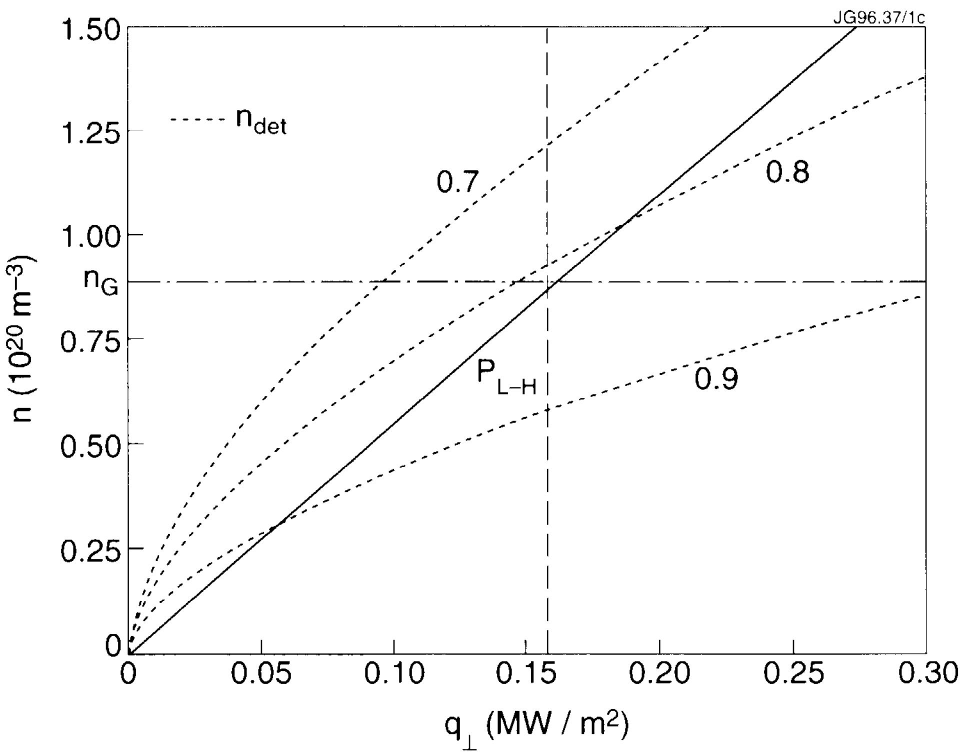

Fig. 2: The access window for ITER for three values of f_{div}, assuming B_t = 6T, f_{bulk} = .35, and I_p = 25MA.

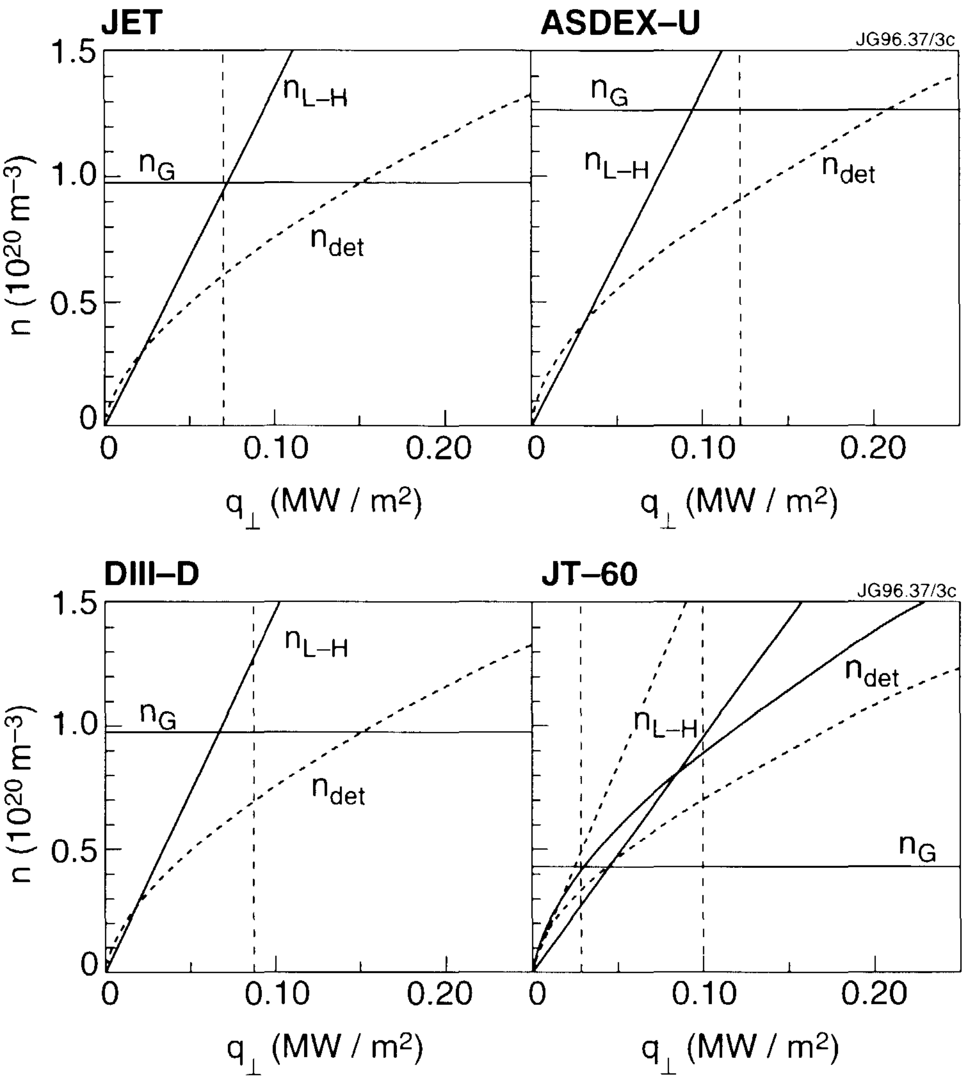

Fig. 3: Access window for four operating tokamaks.

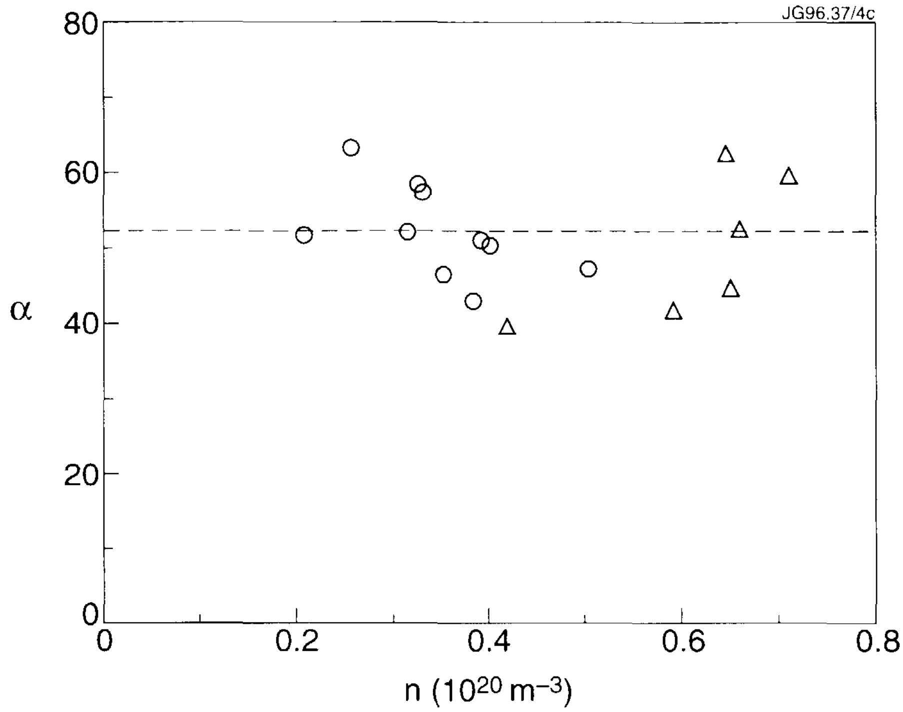

Fig. 4: α as a function of line averaged density for L-mode (circles) and H-mode (triangles) discharges in JET.

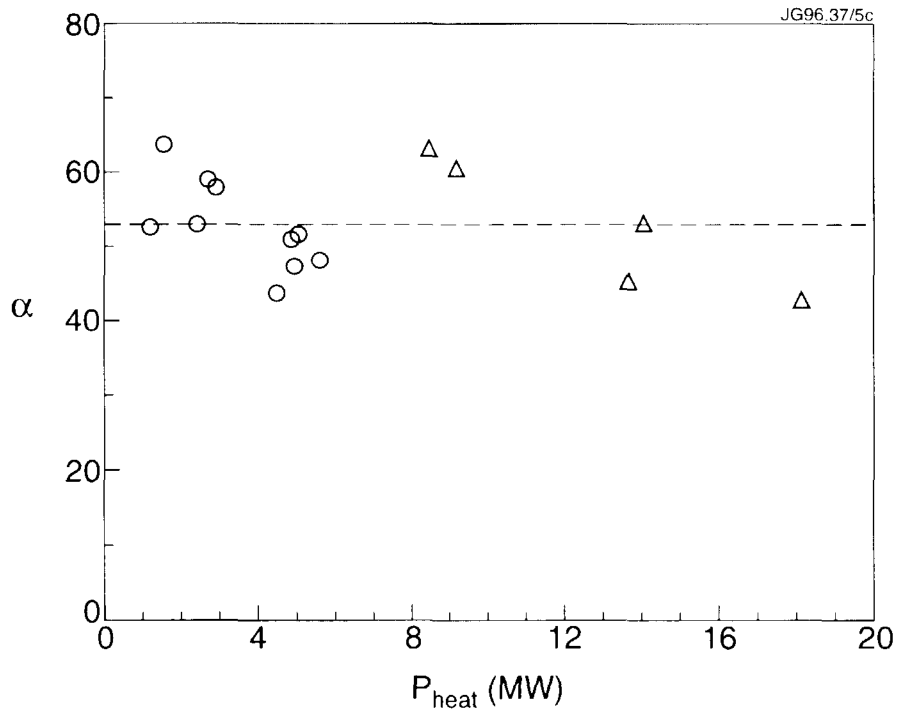

Fig. 5: α as a function of input power for L-mode (circles) and H-mode (triangles) discharges in JET.