Development of an Edge Transport Barrier at the H-Mode Transition of ASDEX

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The thermal wave of a minor disruption can initiate the H phase of a neutral-beam–heated divertor tokamak discharge. Its propagation is used to probe the plasma edge conditions at the H transition. The results show the existence of a transport barrier which forms at the plasma edge and impedes the flow of particles and energy across the plasma surface, giving rise to improved confinement properties. Location and extension of the barrier coincide with the edge zone of increased shear specific to the divertor configuration.

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Tokamak experiments generally observe a degradation of the confinement properties with the application of powerful neutral injection heating (L regime). An exception to this is the so-called H-mode discovered on ASDEX[1] in which confinement times comparable to those of Ohmic discharges are recovered. This operational mode was later also observed in other axisymmetric divertor tokamaks.[2–4] As the observed reduction of the energy confinement time τ_E in limiter tokamaks is not simply due to increased impurity radiation, the principal question is what specific feature of the divertor configuration causes the different confinement behavior.

On ASDEX, like PDX, a minimum heating power (1.2 mW) is needed for the H transition to occur.[1,2] At sufficient power, the H regime develops during the heating pulse in a distinct transition out of a phase with L-type behavior. Near marginal conditions, both L and H states can be observed as stationary equilibria under seemingly identical settings of externally controllable parameters. These features are typical for a bifurcated thermal equilibrium.

Identification of the distinguishing feature of divertor tokamaks allowing the H regime and an understanding of the causes for its appearance should be possible from the study of the dynamics of the sudden transition. In this paper we show that the H mode can be initiated by the arrival of an energy pulse of sufficient magnitude in the immediate proximity of the separatrix, and the associated local parameter changes. This has been achieved by monitoring the propagation of a spatially narrow energy pulse across the plasma cross section in an L-type discharge at conditions near marginal for an H transition. Such a situation arises spontaneously after an internal disruption (sawtooth event[5]) when a fraction of the energy stored inside the $q=1$ surface is suddenly released and propagates outwards.[2] For large sawteeth the peak power, associated with it, is sufficient to overcome the power threshold and cause a short transient H phase which, because of the low quasistationary power level, cannot be sustained permanently.

In Fig. 1 the effect of a sawtooth (denoted A) which triggers a short H phase is compared with a subsequent one (denoted B) of smaller amplitude where the plasma stays in the L mode. The injection power is 0.8 MW which is slightly below the power threshold for the H mode. As these two events occur in sequence only 50 ms apart, the dynamics of the H transition becomes evident in a comparison of the parameter changes caused by the two different sawteeth. Figure 1(a) shows the electron temperature variation at four radial positions; Fig. 1(b), the line density; Fig. 1(c), the D_α radiation in the divertor chamber (a signal indicative of the energy flux); and Fig. 1(d), the energetic atom flux ϕ_a backreflected from the neutralizer plate (representative of the particle outflux from the main plasma). Figure 1(e) plots the variation of the soft-x-ray (SX) signals—largely indicative of T_e and n_e—along chords viewing the scrapeoff layer (traces 1 and 2), the separatrix (3), and a region closely inside the separatrix (4) (see Fig. 2 for geometrical reference).

A regular sawtooth (B in Fig. 1) gives rise to a

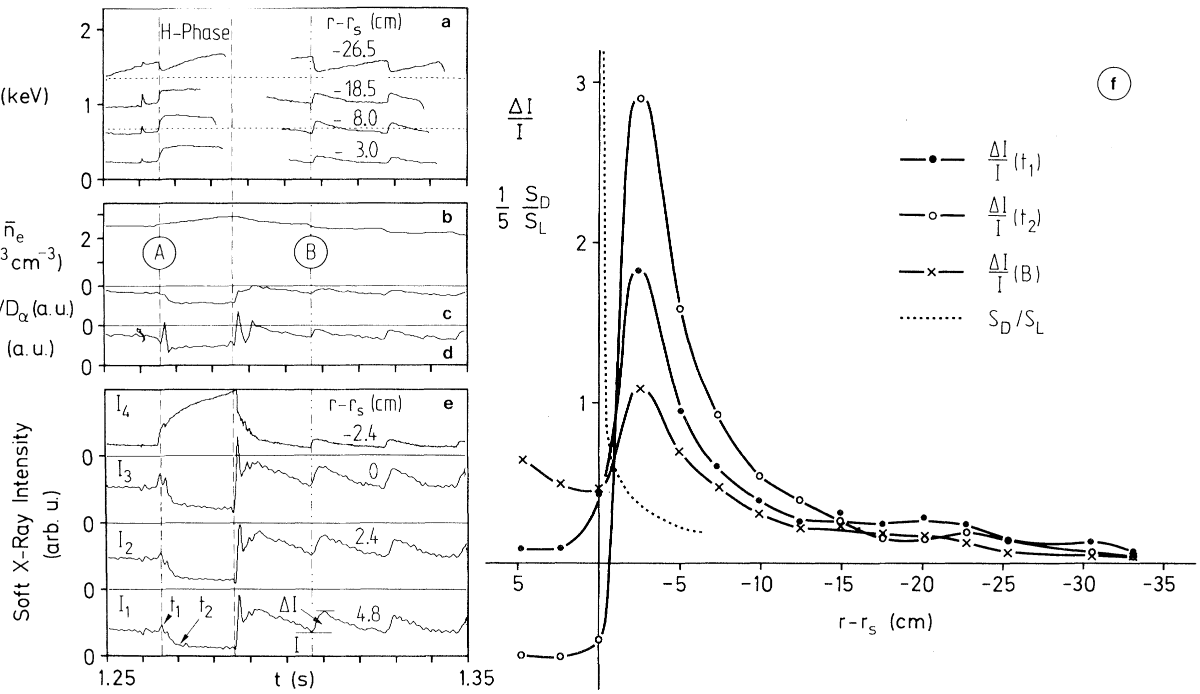

FIG. 1. Time evolution of (a) ECE electron temperature T_e (measured by electron cyclotron emission), (b) line-averaged density $\bar{n}_e$, (c) D_α radiation in the divertor, (d) backreflected flux ϕ_a from the neutralizer plate, and (e) four SX traces from the plasma edge. (f) Radial dependence of the normalized SX signals $\Delta I/I$ for three cases: a normal sawtooth (B), the sawtooth which triggers the H phase at t_1, and the one 3.5 ms later in the H phase at t_2. The dashed curve is the ratio of shear of the divertor to limiter configuration. (The ECE traces are interrupted by a chopper.)

rapid T_e reduction within the $q=1$ surface and a thermal wave propagating to the plasma edge, into the scrapeoff layer, and finally into the divertor chamber. On its way, the thermal wave causes T_e to increase first in the main plasma [as shown by Fig. 1(a) and by trace 4 of Fig. 1(e)], subsequently in the scrapeoff layer where the T_e variations modulate the SX signals [see Fig. 1(e), traces 1 and 2], and finally inside the divertor chamber, where it temporarily increases the D_α radiation [see Fig. 1(c)].

The large sawtooth (A), which triggers an H-phase transition, gives rise to a totally different behavior: The edge electron temperature does not show the transient variations caused by a passing thermal wave. The transition occurs amid the sawtooth rise which is initially still resolvable at the separatrix ($r-r_s=0$). At the instant of transition, the SX signals, viewing the boundary layer and the nominal separatrix location, *decrease* sharply. Within the separatrix, the sawtooth, triggering the H phase, causes a continuously rising signal.

Comparison of the different parameter variations during the two subsequent sawtooth events clearly demonstrates that the arrival of a thermal wave of sufficient intensity in the edge region causes there a reduction of the anomalous transport coefficients and provides an effective barrier for both energy and particle fluxes. The reduction causes the decrease in SX signals from the scrapeoff layer and of the energy (D_α) and particle flux (ϕ_a) signals within the divertor. The reduction of T_e and n_e in the scrapeoff layer after the H transition can also be inferred from laser scattering and Langmuir probe measurements; similarly T_e and n_e in the divertor chamber (measured by the same techniques) are reduced. Inside the separatrix, energy and particle flow stagnate, causing good confinement and a continuous rise of the SX signal [see trace 4 in Fig. 1(e)] and the total energy content.

Figure 1(f) compares the variation of the relative SX amplitude $\Delta I/I$ [as defined in Fig. 1(e)] of the normal sawtooth B (crosses) with the one of sawtooth A at two moments [as indicated by arrows in Fig. 1(e)]. $\Delta I/I$ of the regular sawtooth increases towards the plasma edge because the stationary radiation decreases sharply towards the boundary. On open field lines, beyond the separatrix, $\Delta I/I$ de-

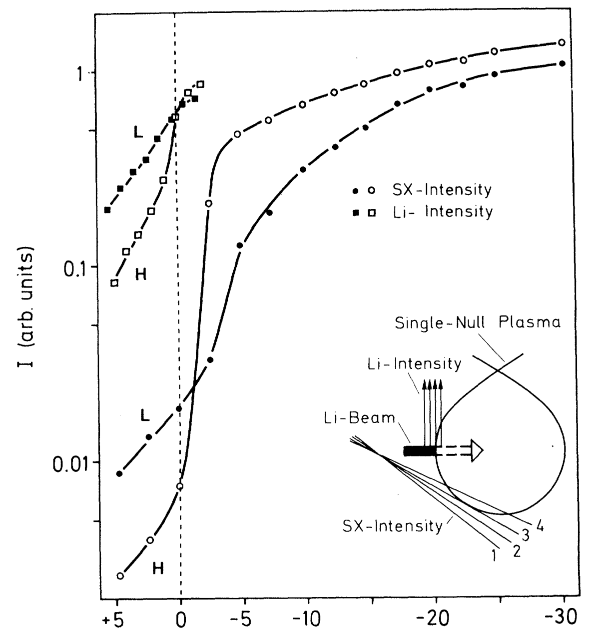

FIG. 2. Radial profiles of the SX (2-μm Be filter) and Li-beam intensities in the L phase prior to the H transition and shortly afterwards (SX, $\Delta t = 20$ ms; Li, $\Delta t = 55$ ms). $I_p = 375$ kA, $B_T = 2.2$ T, $\bar{n}_e = 3.3 \times 10^{13}$ cm^{-3}, $P_{\rm NI} = 0.8$ MW. The inset depicts the observation geometry.

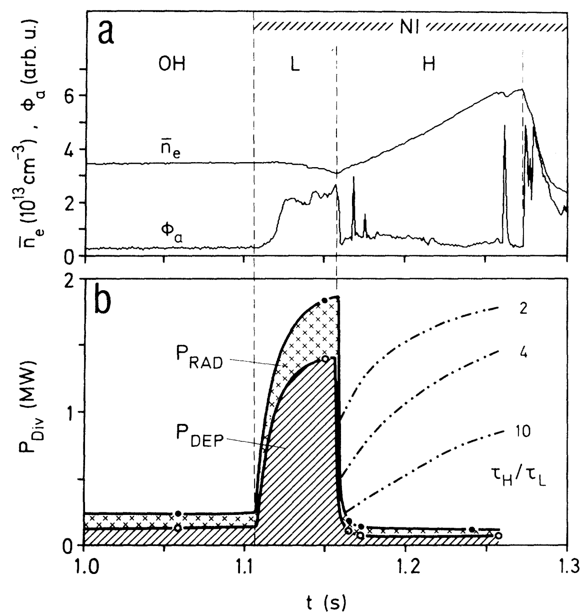

FIG. 3. (a) $\bar{n}_e$ and ϕ_a and (b) the total power flow $P_{\rm DIV}$ into the divertor chambers. The dashed-dotted curves show the variation of the normalized transport losses for energy confinement time changes at the H transition ($I_p = 315$ kA, $P_{\rm NI} = 3.5$ MW).

creases because of the parallel losses into the divertor chamber. The sawtooth which triggers the H phase shows a somewhat higher amplitude inside the separatrix but only an evanescent rise within the scrapeoff layer as a result of the development of the barrier. In the range of about 10 cm inside the separatrix, the signal continues to rise on account of the improved confinement due to the edge barrier. The plasma core still remains unaffected, indicating that the transition into the H phase originates from the plasma edge.

The consequence of a boundary barrier with low transport coefficients is the developement of steep gradients at the plasma edge.[6] Figure 2 plots the intensity profiles of SX radiation and of light emitted along a lithium beam (Li) probing the plasma edge (proportional to density). Profiles at the end of the L phase prior to the H transition are compared with those in the H phase 20 msec after the transition. Both quantities document the development of steep gradients at the separatrix location and a reduction in signal beyond the separatrix. (The location of the separatrix with respect to the diagnostic geometry is obtained from magnetic signals. The accuracy is about 1 cm.)

The development of a perpendicular transport barrier at least transiently also affects the energy losses out of the main plasma. The power which is transported into the divertor chamber (predominantly by parallel electron heat conduction) shows a sharp reduction at the H transition.[7] Figure 3(b) plots the variation of the power deposited onto the neutralizer plates $P_{\rm DEP}$ (measured by infrared thermography), and the power radiated within the divertor chambers $P_{\rm RAD}$ (from a bolometer). In this case a power of 3 MW is injected giving rise to a fully developed H phase. The transport losses across the separatrix $P_{\rm DIV} = P_{\rm DEP} + P_{\rm RAD}$ which amount to more than 70% of the power input during the Ohmic and L phases drop to 8% after the H transition. Despite the high power input, the accounted transport losses of the plasma are comparable to those during the Ohmic phase!

The transient reduction of transport losses into the divertor chamber is the consequence of the sudden improvement in τ_E. Figure 3(b) illustrates the expected variation of the divertor losses (normalized to the peak value prior to the H transition) for a sudden τ_E increase from its value during the L phase (20 msec) by a factor of 2, 4, or 10. The comparison with the measured losses indicates τ_E values clearly above 100 ms.

Figure 3(a) shows the nearly linear rise of the bulk plasma density after the H transition. The plasma particle content increases at a rate of 2×10^{21} s^{-1} and is mostly fueled from the divertor chambers (the external gas flux is zero). The beam contributes typically 5×10^{20} s^{-1}. From the particle balance or the linearity of the density rise over 100 ms, a particle confinement time τ_p also above 100 ms must be inferred.

The exclusive observation of the H mode in divertor discharges, the narrow extent of the transport barrier of a few centimeters, and its proximity to the separatrix suggest it to be linked to the specific field topology in this region. Approaching the separatrix, both safety factor q and shear $S=(r/q)dq/dr$ increase towards infinity. In Fig. 1(f), the ratio of S_D of the actual divertor configuration to S_L of the limiter case is plotted. The location of the transport barrier, as deduced from the SX signals, coincides with the zone of increasing shear. Thus, as a tentative conclusion, the transport barrier of the H phase is caused by shear stabilization of otherwise transport-enhancing instabilities at the plasma edge.

The power threshold for the H regime and the correlation of the formation of the transport barrier with the arrival of a heat pulse suggests that a high edge temperature is necessary for the shear stabilization to become effective. This is in line with the expected effect of resistivity changes on ballooning or interchange modes, but could also be associated with variations in collisionality (ν_{*e}, 2 cm inside the separatrix, drops from slightly above 1 in the L phase to about 0.4 in the H phase). At a beam power above the power threshold, T_e at the plasma edge increases so rapidly that shear stabilization and the H transition can occur without assistance by a sawtooth. The role of the edge temperature was also pointed out by a sequence of experiments, in which a limiter was moved to the separatrix.[6] Thereby the edge T_e is reduced and at a separatrix-limiter distance of 2.5 cm the H mode disappears though the shear condition is unchanged.

The similarity in confinement scaling of L and H discharges, both deviating from the Ohmic scaling,[7] may indeed support the assumption that the H mode differs from the L mode only by the development of the edge barrier by otherwise enhanced transport coefficients governing the plasma interior. On the other hand, transport analysis indicates a reduction in electron heat conductivity across the whole plasma cross section.[2] We conclude that the development of an edge barrier initiates the H transition. The new conditions at the edge additionally affect the transport characteristics of the main plasma in a favorable way. Whether this is due to the development of broad pressure and current density profiles[7] or the highly electrical conductive plasma periphery is still an open question.

[1]F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).

[2]S. M. Kaye, *et al.*, in Proceedings of the Eleventh European Conference on Controlled Fusion and Plasma Physics, Aachen, Germany 1983, edited by A. Gibson (Pergamon, New York, 1983), Vol. I, p. 19.

[3]M. Nagami *et al.*, Nucl. Fusion **24**, 183 (1984).

[4]K. H. Burrell *et al.*, Ref. 2, p. 11.

[5]G. L. Jahns *et al.*, Nucl. Fusion **18**, 609 (1978).

[6]F. Wagner *et al.*, J. Nucl. Mater. **121**, 103 (1983).

[7]M. Keilhacker *et al.*, Comments Plasma Phys. Controlled Fusion **26**, 49 (1984).