Model for the tokamak H mode

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A model for the appearance and time evolution of the H-mode discharge in a tokamak is proposed. The plasma in the diverter channels and near an X point of the separatrix plays a major role in these processes. Increasing the density of this plasma above a certain critical value can result in a partial stabilization of electrostatic waves at the edge of the plasma column and thus a decrease in the transport coefficients and the onset of the H mode.

The H-mode or H-type discharge in a tokamak was first observed at the ASDEX tokamak in 1982 (Ref. 1) and has since then been studied at many devices. A large body of experimental data has now been acquired, and several hypotheses have been offered regarding the physics of the transition of a discharge to the H mode. In many cases, however, the agreement with experimental data has remained far from complete.[2] In the present letter we propose a model for the appearance and time evolution of the H mode in which a decisive role is played by the plasma in the diverter channels and near an X point of the separatrix (Fig. 1a). If the plasma density in these zones is raised above a certain critical value, there can be a partial stabilization of electrostatic waves at the edge of the plasma column, a decrease in the transport coefficients, and a transition to the H mode.

The average plasma density $\bar{n}_x$ in these zones of the discharge is described approximately by the equation

$$L_{xt}\frac{d\bar{n}_x}{dt} = \frac{F_i}{2\pi R\,\Delta\nu} - \left[\frac{n_t v_t}{4} - \eta\frac{n_t v_t}{4}\left(1-\exp\left(-\frac{n_t\Delta_f}{v_0}\langle\sigma v\rangle_i\right)\right)\right]. \qquad (1)$$

Here L_{xt} is the distance from the X point to the diverter plates; R is the major radius of the tokamak; ν is twice the number of X points of the magnetic configuration; Δ is the poloidal width of the diverter channel (Δ_f is the effective size of the channel in terms of ionization); F_i is the total flux of charged particles out of the bulk plasma; n_t and v_t are the density and velocity of the plasma ions near the plates; v_0 is the velocity of the hydrogen atoms leaving the plates; η is the coefficient for the reflection of ions in the form of atoms (this coefficient is set equal to 1 in the calculations, but it might be either larger or smaller); and $\langle\sigma v\rangle_i$ is the velocity coefficient of the ionization of hydrogen atoms near the plates. The plasma temperature near the plates, $T_t = T_{et} = T_{it}$, is determined by the relation (we are ignoring the radiation from the bulk plasma)[3]

$$\frac{P_h}{2\pi R\nu\Delta} \approx \frac{n_t v_t}{4}\left[(34)T_t + \frac{1+\beta_i}{1-\beta_e}T_t\right] + \eta\frac{n_t v_t}{4}\left(1-\exp\left(-\frac{n_t\Delta_f}{v_0}\langle\sigma v\rangle_i\right)\right)$$

$$\times\,(2T_t + J_i + W_r), \qquad (2)$$

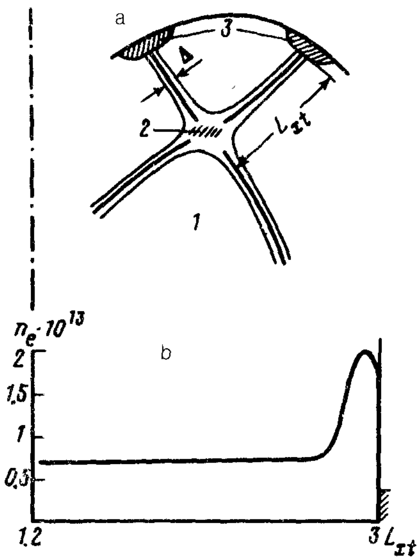

FIG. 1. a: Geometry of the diverter configuration. 1—Bulk plasma; 2—X zone; 3—diverter plates. b: Plasma density distribution along a diverter channel. INTOR, $\bar{n}_e = ?$, $P_n = 80$ MW, $F_i = 5 \times 10^{22}$ ions/s. 1, 2, 3—The same as for part a.

where P_h is the heating power, β_e and β_i are the secondary-electron-emission yields for electrons and ions, J_i is the ionization potential of the hydrogen atom, and W_n is the reduced radiative "cost" of an ionization event.

It can be seen from expressions (1) and (2) that the increase in the heat and particle fluxes from the diverter plasma at the transition from ohmic to auxiliary heating results primarily from an increase in the density n_t, since a doubling (for example) of F_i due to T_t should increase the energy flux by a factor of eight, but this is not what is seen experimentally. We also see that the total number of particles lost from the plasma in a diverter channel (at a given T_t) goes through a maximum at $n_t^0 = v_0/\Delta_f \langle \sigma v \rangle_i$. If F_i is greater than this limiting flux, the average density $\bar{n}_x$ will increase until a new equilibrium is reached, at which the number of particles lost is comparable to F_i. This evolution can be seen clearly in Fig. 2, where the density which is the "optimum" density in terms of the loss, n_t^0, and the "maximum flux density of lost particles," $f_l = n_t^0 v_t/4$, are plotted against T_t for hydrogen and deuterium. Experimentally, it is simpler to measure the energy fluxes out of the plasma, since they are simply equal to the heating power. Accordingly, Fig. 2 also shows the calculated energy fluxes out of the diverter channel for the conditions under which the loss of particles is at a maximum. These calculations are simply illustrative, although they are quite successful in describing the "energy thresholds" for neutral-injection regimes (2–2.4 MW for DIIID and ASDEX; 5 MW for JET). For the effect of interest here, the governing factors are the fluxes of particles, not the fluxes of energy, which play only a secondary role. We recall that the transition to the H mode was observed in DIIID during the injection of neutrals at a power of 2.4 MW, during electron-cyclotron-resonance heating at a power of only 0.75 MW, and even in the ohmic-heating regime with a low value of q, under the influence of sawtooth oscillations.[5]

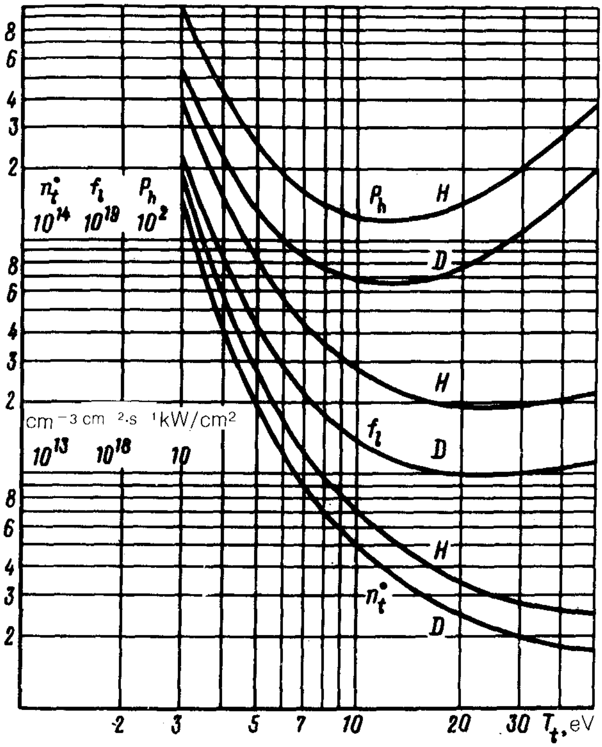

FIG. 2. The plasma density which is the "optimum" density in terms of the loss n_t^0; the "maximum flux density of lost particles," $f_e = n_t^0 v_t/4$; and the specific power loss $p_h = P_h/2\pi R v\Delta$ corresponding to these conditions.

The distribution of the plasma density along the diverter channel is also extremely important for the mechanism which we are discussing here. One such distribution, found by numerical calculations based on hydrodynamics, is shown in Fig. 1b (Ref. 4). At densities which are not very high ($\sim 10^{13}$ cm^{-3}), however, the hydrodynamic approximation is hardly adequate, and the density distribution in the diverter channel should gradually flatten out. The time required for this flattening to occur can be estimated from $L_{xt}^2 B_t^2 / B_\theta^2 D_\|$ or L_{xt}^2/D_B; it turns out to be on the order of some tens of milliseconds, in good agreement with experiment.[5] (Here B_t and B_θ are the toroidal and poloidal magnetic fields in the diverter zone, and $D_\|$ and D_B are the longitudinal and Bohm diffusion coefficients.)

The mechanism outlined above for the increase in the plasma density in the X zone obviously correlates with such experimental facts concerning the onset of the H mode as the dependence of the "threshold power" R_h on the ion species ($v_0 \sim m_i^{-1/2}$), on the number of X points of the magnetic configuration, on the direction of the toroidal drift of ions (F_i is higher in one direction than in the opposite direction), and on the effect of an external limiter (as it is brought up to the separatrix, F_i decreases because of a partial trapping of flux). At a small value of L_{xt} ($< \Delta_f$) only a small fraction of the atoms reflected from the plates is trapped in the channel, and the plasma buildup decreases.

As we have already mentioned, an increase in the plasma density in an X zone can stabilize electrostatic waves by virtue of the electron neutralization currents in the X zone and the diverter channels. A similar effect was observed experimentally by Babykin *et al.*,[6] who also estimated the wave stabilization conditions, but for a mirror configuration, in which the potentials of the waves are neutralized by electron currents which flow to the end walls of the chamber. For a tokamak it is sufficient to consider the currents which flow along the X zone, i.e., nearly along the magnetic field, but to also take account of the effects of Coulomb collisions and waves (through the introduction of ν^*). The imaginary part of the current density j_x, in which we are interested, then becomes

$$j_x = \frac{e^2 n_x E_{\parallel}}{i\omega m (1 + (\nu^*/\omega)^2)}, \tag{3}$$

where $E_{\parallel}$ and n_x are the longitudinal field of the waves and the electron density in an X zone, and ω is the frequency of the waves under consideration. The stabilization condition is

$$\frac{n_x}{n_b} \gtrsim \frac{1}{n_b} \frac{dn_b}{dr} (2\pi q)^2 \frac{2\rho_e^2 R}{S_x (m + nq)} (1 + (\nu^*/\omega)^2). \tag{4}$$

Here ρ_e is the electron Larmor radius, m and n are the wave numbers of the waves, S_x is the poloidal cross section of the X conduction zone, and n_b is the plasma density at the edge of the column. Under the conditions in Ref. 6, even an extremely low density of a cold, collisionless plasma ($n_x/n_b \sim 10^{-3}$) turned out to be sufficient to suppress the waves. For a tokamak we have $n_x/n_b \approx 1$; i.e., the quantity $(\nu^*/\omega)^2$ is on the order of 10^2 before the transition to the H mode and about 10 after the transition. In the H mode, F_i decreases substantially, and n_x begins to fall off. However, the value of $(\nu^*/\omega)^2$ is small in the H mode, and condition (4) continues to hold, until n_x falls below stabilization boundary (4). The course of events after the establishment of the H mode thus depends on the relation between the rate of increase of the plasma pressure gradient at the plasma edge and the rate of decrease of n_x. If the density of the X plasma decreases most rapidly, the stabilization condition will be violated explosively (because of an increase in ν^*) at some instant, and a burst of the *EL* mode will occur. Some of the plasma from the main column is scattered into the diverter channel at this time; the plasma density in the channel (and also that in an X zone) increases, and—if condition (4) holds again—the H mode will reappear. If F_i is slightly greater than F_{icr} [the minimum flux when (4) holds], and if L_{xt} is small, such bursts will occur frequently and with a small amplitude (an additional gas puffing into the diverter should help stabilize it in this regime). As the difference $F_i - F_{icr}$ and L_{xt} increase, a new feature may arise: A plasma with a stability-limit value of dp/dr will form in a broad zone near the stabilized layer. A disruption of the stability at any point in the zone propagates over the entire zone in a manner reminiscent of a shock wave, and it causes a "giant" burst of the *EL* mode. As in the first version, however, the increase in n_x will result in the reoccurrence of the L–H transition. In the third case, which is observed only if there are impurities, the plasma energy does not increase, because of the radiative loss, even if the density is increased. Accordingly, the value of dp/dr at the edge remains below the critical value. If the density n_x also varies slightly (due to $\eta > 1$, for example), this version usually terminates in a thermal collapse and a transition to the L mode.

It can be seen from this discussion that the saddle point of the separatrix is important only for the formation of a zone of sufficient conductivity. Such a zone, however, like a marfe, can also form near an internal limiter. If such a zone has a sufficiently large value of the parameter $n_x/[1+(\nu^*/\omega)^2]$, a neutralization of the perturbation potentials may occur through it. In such a case, the H mode may set in even without a separatrix.[7]

It follows from the model proposed here for the H mode that in order to control the characteristics of the H mode, it is necessary to achieve an extremely fine regulation of the plasma density in an X zone and in the diverter channels.

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