Observation of a High-Confinement Regime in a Tokamak Plasma with Ion Cyclotron-Resonance Heating

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The H mode in ion cyclotron-resonance-heated plasmas has been investigated with and without additional neutral-beam injection. Ion cyclotron-resonance heating can cause the transition into a high-confinement regime (H mode) in combination with beam heating. The H mode, however, has also been realized—for the first time—with ion cyclotron-resonance heating alone in the hydrogen minority scheme in deuterium plasma at an absorbed rf power of 1.1 MW.

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Confinement studies on many tokamak plasmas all over the world have revealed an unfavorable phenomenon, called L mode. The good confinement of resistively heated plasmas could not be maintained at high plasma temperatures. With increasing auxiliary heating power, confinement was found to deteriorate severely, obstructing the successful approach of the ignition conditions. Therefore, the discovery of a high-confinement regime, called H mode,[1] which combines the virtues of good global and central confinement even with additional heating was of paramount importance for fusion research.

The characteristic and directly observable signatures of the H mode are a distinct drop of the H_α radiation in the divertor (which is mostly a measure of the reduced power flow across the separatrix into the divertor chamber), a rising electron density (indicating an improved particle confinement), an enhanced plasma energy content (due to the improved energy confinement), a significantly enhanced edge electron temperature, and the existence of an MHD phenomenon, called ELMs (edge localized modes).[2] ELMs are short bursts of energy leaving the plasma, representing short transitions back to degraded confinement accompanied by enhanced power loss.

Since the H mode has been observed so far only in plasmas of divertor tokamaks, heated by neutral-beam injection (NI), it is important to know whether this good-confinement regime is restricted to NI heating alone or whether it is achievable for heating in the ion cyclotron range of frequencies [ion cyclotron-resonance heating (ICRH)], too. Additionally, the realization of the H mode with different auxiliary heating methods will give some insight into the global confinement structure of tokamak plasmas. In particular, ICRH decouples heating and particle refueling, and ICRH changes the ion energy distribution of the plasma differently from NI. Thus, heating by ICRH introduces additional properties extending the range of parameters to study plasma confinement.

Our investigations, where ICRH has been applied alone and together with NI, were based on an H-mode recipe which has been developed during NI experiments.[3] Best conditions have been reported for clean deuterium plasmas ($Z_{\text{eff}} \sim 1-1.5$) in the single-null divertor configuration with the plasma shifted up by about a tenth of the minor radius, corresponding to 2 times the density and temperature falloff lengths of the scrapeoff layer. It was theoretically expected that the ion grad-B-drift direction should have a large impact on the formation of the H mode,[4] which has indeed been observed experimentally.[3] In standard operation conditions the ion grad-B drift is directed upwards in the asymmetric divertor experiment (ASDEX), yielding a much lower power limit for achieving the H mode in the upper single-null configuration [$P_{\text{NI}}(\text{min}) \sim 1.2$ MW at $z = +4$ cm] compared to about 1.8 MW in the double-null topology.

With ICRH the impurity situation[5] is unfavorable for the transition into the H mode. The enhanced ICRH-induced impurity release reduces the energy flux from the center to the plasma periphery because of an increased central iron radiation. Stronger recycling and an enhanced low-Z impurity level may additionally cool the plasma boundary thus hampering the H transition which appears to be strongly linked to high edge-electron temperature.[6] However, the deleterious influence of metal-impurity radiation has been overcome either by increasing the power flow through additional NI heating or by carbonization of the torus walls. In particular, the application of wall carbonization (*in situ* coating of the walls with a carbon layer a few hundred angstroms thick via glow discharge) reduces the central radiation and the iron concentration by almost an order of magnitude, i.e., to a negligible amount with respect to the power balance. Another goal of combining NI and ICRH was to realize the *H* mode with as little NI power as possible, and finally, to achieve it with ICRH alone.

Figure 1(a) displays some typical traces of a discharge where 1.8 MW of launched rf power at $\omega = 2\Omega_{\rm CH}$ ($f = 67$ MHz) was added to an NI power of 2.5 MW. The $\rm H_\alpha$ radiation in the divertor chamber, $\rm H_\alpha$(div), is modulated in a characteristic way: during the *L* phase by the heat pulses due to sawteeth (see also Fig. 2) and during the *H* phase by ELMs. In the case shown in Fig. 1(a) the *H* phase develops only when the ICRH is switched on. Its quality is low as a result of the operation in hydrogen (in hydrogen plasma heating and confinement are reduced with respect to deuterium) and of the high frequency of the ELMs which is found to be typical—as in pure NI-heated plasmas[1]—when the *H* phase is achieved only marginally. Nevertheless, the particle confinement is already improved as indicated by the significant rise of the line-averaged electron density $\bar{n}_e$, which is not observed in ICRH *L*-type discharges.

Because of reduced impurity radiation with hydrogen minority in heating in deuterium plasma [the so-called D(H) scheme], *H*-mode studies have been continued in this scheme. The somewhat lower heating power available in this scenario was compensated by the advantage of basically working in deuterium ($n_{\rm H}/n_e \sim 4\%$). In realizing the goal to achieve the *H* mode with as little NI power as possible, 1.8 MW ICRH and 0.5 MW NI have been combined. The result is given in Fig. 1(b). Although the NI heating power was well below the threshold of 1.2 MW for the *H* mode with beam heating alone, three distinct yet unstable *H* phases developed [indicated by a drop of $\rm H_\alpha$(div) and the simultaneous rise of $\bar{n}_e$]. It is evident that under these conditions the ICRH clearly triggers the *H*-mode formation, which is particularly obvious for the final *H* transition of the discharge occurring about 25 ms after the beams were already switched off (the beam slowing-down time is about 15 ms). The quality of these *H* modes is again low, mainly related to the hydrogen particle injection, which does not allow us to control the minority concentration (here hydrogen) in a proper way.

With D(H) heating, for the first time, the *H* mode has also been achieved reproducibly with ICRH alone at an rf power of $P_{\rm IC} \approx 1.7$ MW launched by two antennas without any NI assistance. An example is shown in Fig. 2. The minority concentration, measured by multichannel hydrogen/deuterium neutral-particle analyzers, has been controlled by a separate hydrogen gas feed to about $n_{\rm H}/n_e \sim (2\text{–}4)\%$. In order to reduce the metal-impurity release, the torus walls were carbonized. In all discharges of this type (Fig. 2) *H* modes have been reached just marginally and developed out of *L* phases with sawteeth. The *H* transitions show all characteristic features like a distinct drop in $\rm H_\alpha$(div), rising $\bar{n}_e$, enhanced plasma energy content W_p, and frequent ELMs. Another important observation is the typical edge-electron-temperature pedestal $T_e(a) \sim 300$ eV,

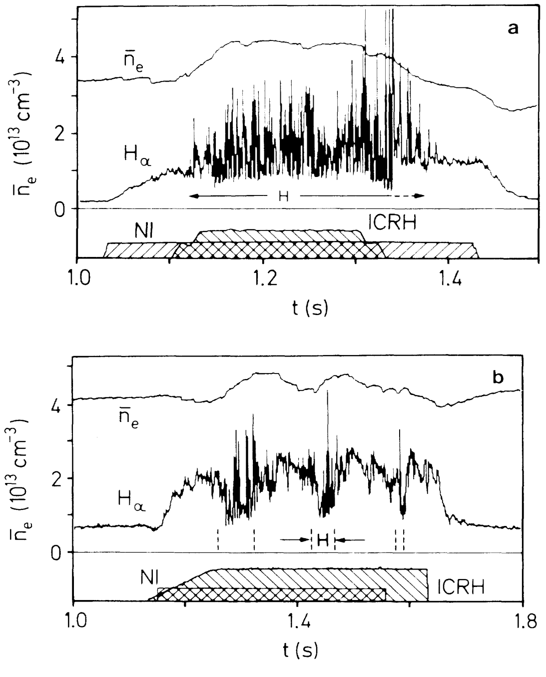

FIG. 1. Line-average density $\bar{n}_e$ and $\rm H_\alpha$ radiation in the divertor chamber of *H*-mode discharges during NI plus ICRH heating. (a) NI ($\rm H^0 \rightarrow D^+$)+ICRH ($2\Omega_{\rm CH}$), $P_{\rm NI} = 2.5$ MW, $P_{\rm IC} = 1.8$ MW (b) NI ($\rm H^0 \rightarrow D^+$)+ICRH [D(H)], $P_{\rm NI} = 0.5$ MW, $P_{\rm IC} = 1.8$ MW.

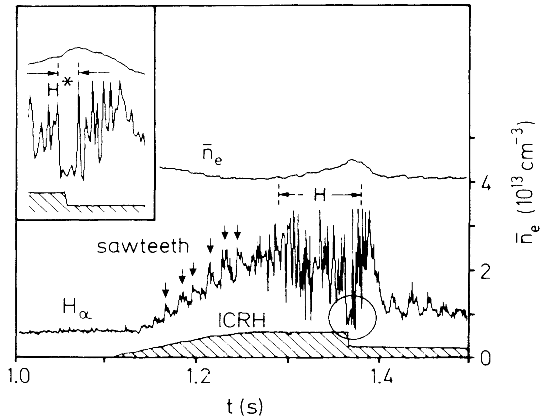

FIG. 2. Pure ICRH [D(H)] heating ($P_{\rm IC} = 1.7$ MW) achieving an *H* phase marginally (the encircled part is enlarged in the inset).

which is illustrated in Fig. 3, in comparison to a profile just prior to the *H* transition. The development is similar to the behavior found with NI heating alone.[2] It has already been pointed out that there is a strong link between the *H* transition and the formation of a rather high electron temperature close to the separatrix leading probably to a thermal (edge transport) barrier.[7]

Short ELM-free phases (H^*), as they suddenly occur (see insert of Fig. 2), change the boundary-layer properties in a fashion which is well known from our NI investigations: The scrape-off layer shrinks fast and strongly. The sudden variation of the plasma parameters in front of the antennas modified the antenna coupling to such an extent that always one of the generators terminated operation by voltage breakdown in one of the vacuum transmission lines about 10 ms after the H^* transition, when the system was operating at the rf power and line-voltage limit. This has also been observed when we combined ICRH and NI at high power where long ELM-free phases (up to 50 ms duration) have been achieved. The ICRH-triggered H^* phases, accompanied by a strong increase of electron density and plasma energy, continued to exist although the termination of one generator shortly after the H^* transition reduced the ICRH power to half the initial value. The duration of these H^* phases has been found to be mainly limited by the continuously increasing central radiation due to a strong high-*Z* impurity accumulation which is directly related to the good particle confinement. Unfortunately, the technical constraint described above could not be avoided so far. In order to overcome it a higher ICRH power and voltage standoff capability is required which will be provided to the ASDEX ICRH system in near future.

If we compare the minimum power to be absorbed by the plasma for achieving the *H* mode in NI-heated discharges, $P_{\text{abs}}(\text{NI}) \geqq 1$ MW, with that for ICRH, a good coincidence is found: $P_{\text{abs}}(\text{ICRH}) \geqq 1.1$ MW, where an ICRH power absorption coefficient, $a = P_{\text{abs}}/P_{\text{IC}} = 0.6$ as determined experimentally, has been taken. Therefore, it is not surprising to get the *H* mode at that ICRH power level just marginally. Another analogy to the NI *H*-mode behavior is the influence of a vertical displacement of the plasma[3]: At equal initial plasma parameters the *H* mode with ICRH alone forms only in case of upper single-null conditions ($z = +4$ cm). Downward shifts clearly prevent the *H* transition.

Figure 4 compares H_α(div), $\bar{n}_e$, and W_p of typical *L*- and *H*-type discharges of about equal rf power in the minority scheme under single-null conditions. An H_2-gas puff yielding $n_H/n_e \sim 9\%$ kept the plasma in the *L* mode, while without additional hydrogen puffing ($n_H/n_e \sim 4\%$) the *H* transition occurred. Because of the shortness of the *H* phases, the confinement properties could not be assessed, but, as indicated by the W_p trace in Fig. 4, they appear to be already better than those of the *L* mode, particularly, if the time derivative of the plasma energy, dW_p/dt, is taken into account when one calculates the global energy confinement time by $\tau_E^* = W_p/(P'_{\text{OH}} + aP_{\text{IC}} - dW_p/dt)$, where P'_{OH} is the Ohmic power during additional heating. However, the quality of the *H*-mode phases with ICRH was still poor perhaps because of the low available power. The issue of improved confinement in ICRH-driven *H* modes remains to be investigated thoroughly.

In summary it appears that NI and ICRH give rise to similar confinement structures, either *L* or *H* mode. The dominant confinement regimes of auxiliary heated plasmas are found to be independent on the heating method. Additional aspects of NI, like particle and momentum transfer, seem to be of minor importance. The partly strong distortion of the energy distribution function with ICRH yielding ion tails perpendicular to the toroidal field has also shown no negative influence on global confinement which was also observed on PDX where the *H* mode was found with perpendicular beam injection[8] (note that the ASDEX NI system injects tangentially to B_0, thus distorting the ion energy distribution essentially in the parallel direction). In particular, it has been

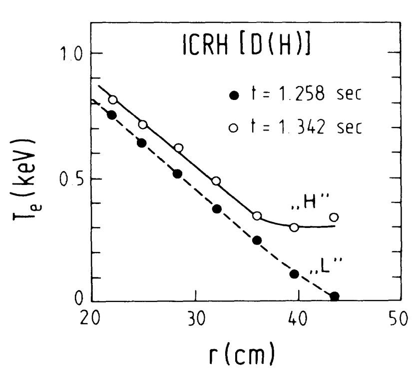

FIG. 3. Edge-electron–temperature profiles during *L* and *H* phases of purely ICRH-heated plasmas (see Fig. 2).

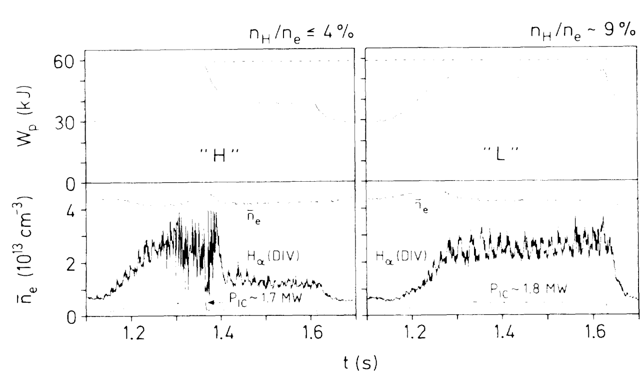

FIG. 4. Comparison of line-averaged electron density, plasma energy content W_p, and H_α radiation in the divertor of ICRH-heated *L*- and *H*-type discharges.

demonstrated that the H mode is accessible with ICRH alone, which is of significant importance both for the understanding of confinement physics and for the choice of this rf heating scenario in future fusion experiments.

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