# *H* Mode Observed in the JFT-2M Tokamak with Edge Heating by Electron Cyclotron Waves

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(Received 31 March 1989)

The *H* mode is observed by the edge heating of a tokamak plasma solely by electron cyclotron heating with the wave cutoff region in the plasma core. The threshold power for the *H*-mode transition can be as low as 120 kW, which is the lowest threshold power observed in spite of the peripheral power deposition. These experimental results show clearly that the *H* mode can be produced without additional heating of the plasma core, and provide direct confirmation that the *H*-mode mechanism is closely related to an increase in the plasma edge electron temperature.

PACS numbers: 52.55.Fa, 52.25.Sw, 52.70.Gw

Since the discovery of the *H* mode, which has improved particle and energy confinement during the additional heating phase, in the ASDEX tokamak,[1] the physics of the *H* mode has become one of the major subjects in the research of tokamak confinement. The *H* mode has been found in plasma under various additional heating methods, such as neutral-beam-injection heating (NBH) and radio-frequency heating, the frequency of which is in the range of the ion-cyclotron frequency (ICRFH). Recently, the *H* mode was found to occur even by electron-cyclotron heating (ECH) of the plasma edge preheated by NBH in the JFT-2M tokamak,[2,3] and by core ECH in the Doublet III tokamak.[4] Thus the *H* mode is recognized as a general phenomenon which occurs regardless of the additional heating method.

In the previous experiment in the JFT-2M tokamak,[2,3] the ECH power was restricted to 110 kW. This time, the ECH power has been raised to the maximum of 230 kW, and it is found that the *H* mode is produced by edge heating solely by ECH with the wave cutoff region in the plasma core. In the Doublet III tokamak,[4] the experiment was carried out in a plasma density region lower than the density region in the present experiment, and the *H* mode was not found by edge heating.

The JFT-2M tokamak is a noncircular D-shaped tokamak which has plasma major radius of 1.31 m and minor radii of 0.35 m and 0.53 m in its full-size operation. The maximum strength of the toroidal field is 1.5 T.

The frequency of the ECH is 59.8 GHz. The second-harmonic extraordinary mode, the wave electric field of which is perpendicular to the magnetic field, is launched (launched wave is polarized in the circular $TE_{11}$ mode) from the low-field side of the tokamak plasma.[5] The launch angle is 80° (~perpendicular) with respect to the magnetic field vector.

The plasma configuration taken in the experiment is the lower-single-null divertor configuration as shown in Fig. 1.

It is observed that the *H* mode occurs by edge ECH when the second-harmonic electron-cyclotron resonance (ECR) layer is located at 0.85*a*, where *a* denotes the minor radius of the separatrix, as shown in Fig. 2. A clear drop in the intensity of the deuterium Balmer line (denoted by $D_\alpha$) with bursts is observed. The average density increases after the *H*-mode transition, and saturates when bursts appear in the $D_\alpha$ signal. The saturation in density is also typically observed during the *H*-mode bursts when induced by NBH or ICRFH. Though the plasma core region is cut off for the second-harmonic extraordinary mode at frequency 59.8 GHz at the line-average density of $\bar{n}_e = 2.8\times10^{19}$ m$^{-3}$, measured by a far-infrared interferometer (central chord, just before the ECH; the cutoff density is $2.15\times10^{19}$ m$^{-3}$ as shown later), the ECR layer located at 0.85*a* is accessible to the

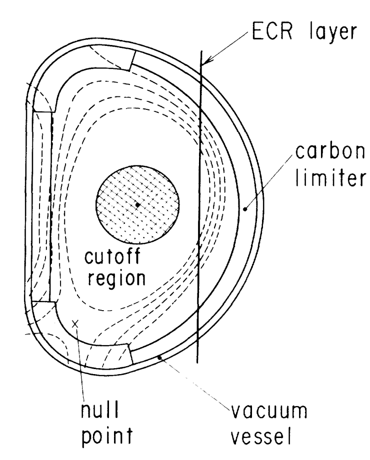


FIG. 1. Position of the second-harmonic ECR layer in the lower-single-null divertor configuration in the JFT-2M tokamak. Null point location is indicated by the cross symbol. $B_{t0}=1.23$ T, $I_p=201$ kA, $r_0/a=0.85$, and $a=0.266$ m. The typical wave cutoff region at $\bar{n}_e=3\times10^{19}$ m$^{-3}$ is illustrated as the hatched region.

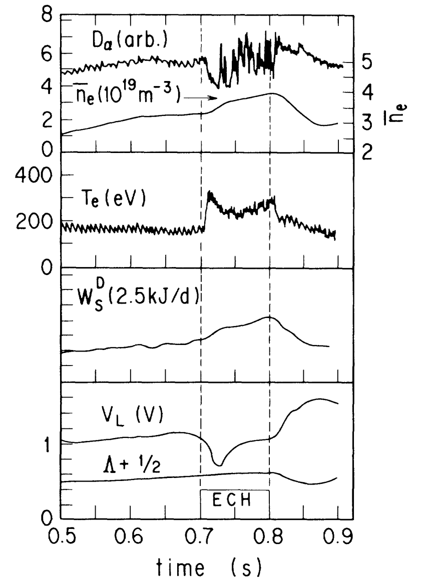


FIG. 2. Time evolutions of the intensity of the deuterium Balmer line $D_\alpha$, edge electron temperature at the radius $0.88a$ measured by ECE $T_e(0.88a)$, stored energy measured by diamagnetism $W_S^D$, loop voltage $V_L$, and Shafranov lambda $\Lambda$. $B_{t0}=1.23$ T, $I_p=201$ kA, and $r_0/a=0.85$.

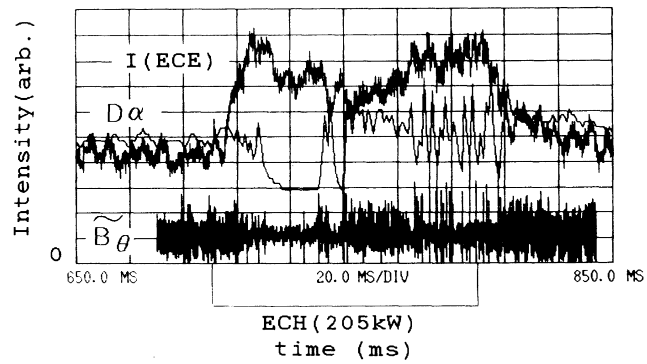


FIG. 3. Time behavior of the magnetic probe signal $\tilde{B}_\theta$ as well as the ECE intensity (86.0 GHz) and $D_\alpha$ intensity. $B_{t0}=1.23$ T; $I_p=200$ kA.

wave. The edge electron temperature at position $0.88a$ [measured by electron-cyclotron emission (ECE) of 86.0 GHz] is relatively high during the *H* mode. The increment of the stored energy measured by diamagnetism is 4.0 kJ, whereas the increment during the *L* mode is 2.6 kJ. It is noted that the increment of the Shafranov lambda ($\Lambda+\frac{1}{2}=\beta_p+\frac{1}{2}l_i-\frac{1}{2}$, where $\beta_p$ and $l_i$ denote the poloidal $\beta$ value and the internal inductance, respectively) is small in spite of the large increase in the stored energy. This indicates a decrease of the internal inductance, and suggests a broadening of the current profile during the *H* mode by edge ECH.

Figure 3 shows a typical magnetic probe signal as well as the ECE intensity (86.0 GHz) and $D_\alpha$ intensity. It is observed that the magnetic fluctuation level in the *H* mode by peripheral ECH decreases to 40%–50% of the fluctuation level during the Ohmic heating.

These experimental results show clearly that the *H* mode can be produced without additional heating of the plasma core, and provide additional direct confirmation that the *H*-mode mechanism is closely related to an increase in the plasma edge electron temperature.

We have already reported[6] that the *H* mode is well characterized by an edge-temperature threshold in JFT-2M. This "threshold temperature" is weakly dependent on density ($\propto \bar{n}_e^{-1/3}$),[7] and is also dependent on plasma current.[8] Furthermore, the edge gradient seems to be a good characteristic of the *H* mode.[8] Therefore, for a fixed configuration with fixed plasma current, the threshold temperature decreases with density, namely, the *H* mode can set in by raising the density while maintaining the same edge temperature.

In this experiment, the peripheral plasma density increases by 16% by edge ECH. On the other hand, combined heating experiment (NBH+ECH)[2,3] showed that the concept of "threshold temperature" applies well. But no decisive role of the density just before the transition was found. Furthermore, we could raise the edge density considerably by ion-Bernstein-wave heating in JFT-2M,[9] but the *H* mode was not produced. In this case, the decrease of the peripheral temperature seems to have overwhelmed the effect of the density increase. Thus edge heating seems to be more important than an increase of the edge density in triggering the *H* mode in our experiment.

Figure 4 shows the density region where the *H*-mode transition occurs when the ECR layer is located at $0.85a$. It shows a power threshold of 120 kW for the *H*-mode transition as well as the existence of a low-density limit at $\bar{n}_e=2.2\times10^{19}$ m$^{-3}$ with the maximum ECH power of 230 kW now available. The broken line shows the threshold power for the *H* transition solely by NBH which was taken at the same experimental conditions. Comparison of the data points with the broken line shows little reduction of the threshold power for ECH, but we note that the threshold power for the edge ECH is smaller than the threshold power of NBH (core heating) at a density around $\bar{n}_e=3.0\times10^{19}$ m$^{-3}$, in spite of the edge power deposition of ECH. Even at an ECH power of 112 kW ($\bar{n}_e=3.0\times10^{19}$ m$^{-3}$), a reduction in $D_\alpha$ intensity of 30% is observed during the last 20 ms of the ECH pulse. It appears to be important to raise the average plasma density to $(2.5\text{–}4.0)\times10^{19}$ m$^{-3}$ to obtain the *H* mode solely by ECH edge heating. At these densities, the plasma core is cut off for the wave.

We note that the threshold ECH power increases by lowering the density. Therefore, it seems important to increase the power absorption at the peripheral ECR layer by raising the density in order to obtain the *H* mode by edge ECH.

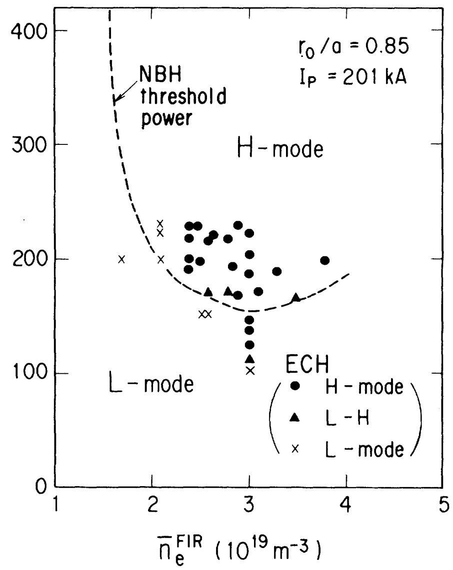


FIG. 4. Density and ECH power plot which shows the parameter region in which the $H$ mode was obtained. Triangles show the boundary between $H$ mode and $L$ mode in the parameter space. Broken line shows the threshold power for the $H$-mode transition by NBH.

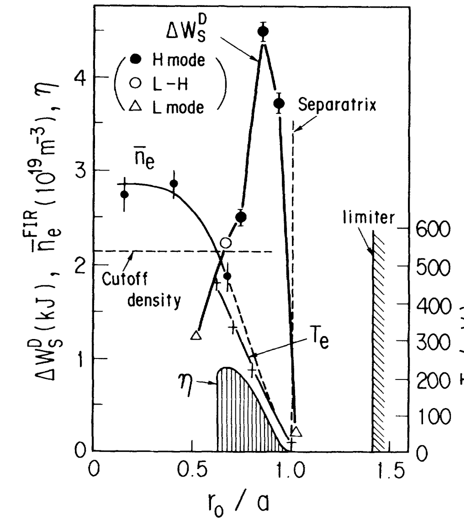


FIG. 5. Increment of the plasma stored energy when the position of the ECR layer is varied. $I_p = 201$ kA, $\bar{n}_e = 2.9 \times 10^{19}$ m$^{-3}$, $P_{EC} = 210$–$230$ kW, $B_{t0} = 1.6$–$1.27$ T. $\eta$ denotes the calculated single-path absorption rate obtained by using the measured $T_e$ profile and $\bar{n}_e$ at different chords of the target plasma.

Figure 5 shows the increment of the stored energy measured by diamagnetism against the normalized position of the ECR layer for plasma at $\bar{n}_e = 2.9 \times 10^{19}$ m$^{-3}$. The deposition radius, $r_0$, is normalized to the minor radius of the separatrix $a$. The $H$ mode is produced by ECH of power 220 kW when the ECR layer is located in the region of $0.7 < r_0/a < 1.0$. The discharge remains in the $L$ mode at $r_0/a = 0.5$ and at $r_0/a = 1.02$ (ECR layer is located in the scrape-off layer). The chord-average density and electron temperature profile just before the ECH pulse are also shown in the figure. The cutoff density of the second-harmonic wave which has frequency $f = 59.8$ GHz and parallel refractive index $n_\parallel = 0.17$ is obtained to be $2.15 \times 10^{19}$ m$^{-3}$ from the relation[6] $\omega_{pe}^2/\omega^2 = (1 - n_\parallel^2)/2$. Therefore the ECR layer located at $r_0/a = 0.52$ is in the cutoff region for the wave. But it seems that at $r_0/a > 0.6$–$0.7$, the accessibility of the wave to the ECR layer is good. The calculated power absorption rate at the ECR layer in a single path[5] using the measured $T_e$ profile and $\bar{n}_e$ is also shown in the figure. The calculated absorption rate $\eta$ at $r_0/a < 0.7$ is larger than 90% in the absence of the cutoff. But $\eta$ decreases as the position of the ECR layer approaches the separatrix. Inclusion of the effect of multiple reflection between the chamber wall and cutoff layer enhances the power deposition at the ECR layer. We can expect that the wave traverses the ECR layer at least twice. But as there is a large pumping duct adjacent to the horn antenna, the multiple-reflection effect is not considered to be large in the JFT-2M tokamak. The deposition power estimated from the time derivative of the stored energy when the ECR layer is located at the plasma core $r_0/a < 1/2$ (at the peripheral region, we could not obtain an accurate $dW_S^D/dt$ because it is small in the $L$ mode) is always smaller than the calculated single-path absorption rate. The experimental result in Fig. 5 shows that the increment in the stored energy is the largest when the ECR layer is located at $0.85a$, where the deposition power is supposed to be small. Therefore peripheral heating seems to be more efficient for the production of the $H$ mode than its appearance suggests. In our combined heating (NBH+ECH) experiment[2,3] in the lower-density region ($\bar{n}_e = 2.2 \times 10^{19}$ m$^{-3}$), edge heating was more efficient than core heating for the production of the $H$ mode.

In the case of Fig. 5, the stored energy in the Ohmic heating phase is $9.5 \pm 1.0$ kJ, yielding an energy confinement time of $41 \pm 5$ ms. If we assume 50% power deposition (twice as large as the single-path absorption rate) at the ECR layer, we observe no degradation in the energy confinement time during the $H$ mode induced by edge ECH at $0.85a$ compared to the energy confinement time during the Ohmic heating. If we assume 100% power deposition by the multiple wall reflection of the wave, the energy confinement time is calculated to be 31 ms during the $H$ mode. The incremental confinement time ($= \Delta W_S^D/\Delta P$) is 24 ms, which shows an improvement of 60% over the $L$-mode value of 15 ms.

Further, we found that a short ECH pulse of pulse length of 20 ms can induce the $H$ transition, as shown in Fig. 6. A marked feature is that a burst-free $H$ mode lasts as long as 50 ms after the ECH pulse is switched

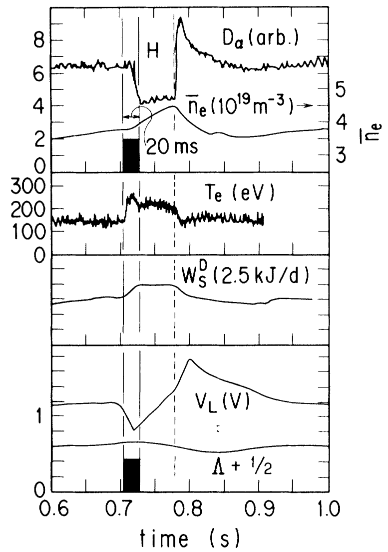


FIG. 6. Time evolution of the $H$ mode shot by a short (20 ms) ECH pulse. $H$ mode lasts for 50 ms after the switchoff of the ECH pulse. $B_{t0}=1.23$ T; $I_p=201$ kA.

off. The density increases continuously after the ECH is off, and the high edge temperature is maintained throughout the $H$ mode. The time scale of the duration of the $H$ mode seems to be related to the decay speed of the edge electron temperature as we observed in Refs. 3, 6, and 7.

In conclusion, the $H$ mode is shown to be closely related to the increase in the electron temperature of the plasma periphery by peripheral electron heating solely by electron cyclotron waves.

We would like to thank the operation group of the JFT-2M tokamak for their excellent cooperation and Dr. S. Shimamoto, Dr. M. Tanaka, and Dr. M. Yoshikawa for their continuous encouragement.

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