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(Received May 20, 1987)

The additional increases both in the density n and confinement time τ of the beam heated H-mode discharges are observed (nτ value is improved more than 40%) when an electron cyclotron wave (ECW) resonating near the plasma boundary is applied. The ECW is shown to enhance wall fueling, to decrease the minimum heating power for switching the H-mode or to extend the operational regime on n-τ diagram of the H-mode discharges.

Keywords: Wall Fueling, nτ Value, H-mode, Electron Cyclotron Wave, JFT-2M

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* on leave from Mitsubishi Electric Co.

JFT－2Mにおける電子サイクロトロン波による壁からの粒子補給の促進とHモード放電のnτ値の改善

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山本 巧・山内 俊彦

（1987年5月20日受理）

電子サイクロトロン波（ECW）をHモード放電の端プラズマに共鳴させることにより，密度nとエネルギー閉込め時間τを更に上昇することが出来た。(nτ値は40％以上改善された。) ECWは，壁からの粒子補給（Wall Fueling）を促進し，Hモードの誘起に必要な最小加熱パワーを低減する，あるいはHモード放電のn－τダイアグラム上での運転領域を拡大することが示された。

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1. INTRODUCTION

In the recent experiments on an enhanced confinement discharge (H-mode) in JFT-2M tokamak, the wall fueling, plasma fueling by desorbed hydrogen from graphite wall, is shown to play an important role on the improvement of the confinement time.[1,2] This kind of fueling prevents the neutral buildup at plasma periphery and, thus, the plasma edge cooling. In Ref.1, an electron cyclotron wave (ECW) is shown to enhance this wall fueling. The preliminary result of the studies on ECW assisted neutral-beam heated H-mode shows that the ECW extends the operational regime in density-confinement ($n-\tau$) diagram.[1,3,4]

In this report, the ECW resonating near the plasma boundary is used in order to enhance the wall fueling expecting that $n\tau$ value of an H-mode is improved by optimum fueling. The procedures for this enhancement optimization and the results of the application to the H-mode of single-null divertor discharges are presented.

A report on the effects of the location of ECW resonance layer on the H-mode transition phenomena will be appear later.[5]

2. EXPERIMENTAL SETUP

The cross-sectional view of the JFT-2M is shown in Fig.1 with calculated separatrix surface. The plasma minor and major radii, a_p x b_p and R_p, are 35.0 x 42.0 cm and 1.31 m for limiter discharges and 25.2 x 36.7 cm and 1.304 m for divertor discharges. Optimization of the enhancement of hydrogen

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3. ENHANCEMENT OF THE WALL FUELING BY ECW

The hydrogen desorption from the wall due to ECW is significant. Wall fueling efficiency η [defined as the ratio of the increment in density $\Delta \bar{n}_e$ to the increment in the peripheral hydrogen neutral pressure ΔP_{H_2}, measured by a residual gas analyzer (RGA)] due to ECW is about the same as the value due to neutral beam injection ($\eta = 8\mathrm{x}10^{19}$ $\mathrm{cm}^{-3}\mathrm{Torr}^{-1}$).[1]

Such a high efficient value can only be seen when the resonance layer occurs outside the region of the top/bottom ports, which have large port volume, as shown in Figs.2(a) and 2(b). The values of $\Delta \bar{n}_e$ and ΔP_{H_2} are plotted in Fig.2(a) as a function of the location of ECW resonance layer on the midplane R_{res}. This R_{res} is scanned by changing the toroidal magnetic field strength at R = 1.31 m, B_t, ($R_{res} = 1.23B_t$ [m/T]). Figure 2(b) is the replot of the data in Fig.2(a) on $\Delta \bar{n}_e - \Delta P_{H_2}$ plane.

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The neutral gas pressure of hydrogen increases substantially after the onset of ECW while the pressure of gas-puff fueled deuterium remains unchanged. Strong enhancement of the wall fueling is observed when R_{res} is around 1.52 m as shown in Fig.2(a). When R_{res} is located outside the top/bottom port region, $\Delta \bar{n}_e$ increases in proportion to ΔP_{H_2} as shown in Fig.2(b) giving $\eta = 7 \times 10^{19}$ $cm^{-3} Torr^{-1}$. When inside that region, the density increment is small and a density clamp is observed even with comparable gas pressure rise. This is shown in Figs.2(a) and 2(b). Open circles in these figures represent the density increment measured from the clamped level.

4. nτ IMPROVEMENT OF DIVERTOR H-MODE BY ECW

Expecting the effect of the enhanced wall fueling on the confinement, the ECW with about 100 kW of the launched power is applied to the H-mode of beam-heated single-null divertor discharges. The R_{res} is located very edge of the main plasma as shown in Fig.2. A ratio of the minor radii of the resonance and divertor separatrix surface is 0.92. The direction of ion grad**B** drift is upwards. Injected beam power into the torus is 450 kW with an accelerating voltage of 32 kV. This power level is sufficiently high to give a clear transition to the H-mode and to maintain the H-mode for a considerable duration.

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The gas-puff valve is closed during the beam heating phase in order to prevent the confinement degradation[1] for relatively low density (< 4×10^{13} cm^{-3}) discharges. Energy confinement time of the H-mode discharges for beam only case is degraded when the strong gas-puff fuel is introduced during the beam heating phase in order to raise $\bar{n}_e$ over 4×10^{13} cm^{-3} [Fig.3(a)]. With the assist of ECW, however, this raised fuel rate during the additional heating phase is allowable. This results in higher attainable density without the degradation in τ_E^* and without an additional increase in radiation loss power P_r in higher density regime as shown in Figs.3(a) and 3(b). The resultant $n\tau$ value is improved over 40%.

In the beam only heating case, P_r increases larger than the value proportional to the density. In the ECW assisted case, P_r does not increase more over the maximum value for the beam only case while the density is higher by 22%.

5. MODIFICATION OF SCRAPE-OFF LAYER PLASMA BY ECW

Divertor scrape-off layer (SOL) plasma plays an important as $\tau_E^* = W/(P_\Omega + P_{NB})$ where W is the stored energy obtained by a poloidal field analysis, P_Ω is the Joule input power and P_{NB} is the beam power deposited into the plasma. The power P_{ECW} is not taking into account since an ECW only heating of plasma edge did not affect the global characteristics of the main plasma in the previous experiment.

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Divertor scrape-off layer (SOL) plasma plays an important role on particle shielding, plasma-surface interactions, heat transportation etc. Because, in SOL, the particle transport parallel to a magnetic field line directed to the divertor plate is dominant. Therefore, the modification of SOL plasma parameters, e.g. temperature, can be a good probe to see the effect of SOL plasma functions.

In this experiment, the SOL plasma is heated by the ECW. The resonance layer is located on outside the separatrix by 2 cm, which is close to the typical radial-characteristic-length of SOL, as shown in Fig.4.

The time evolutions of electron cyclotron emissivity I_{ECE} at R_{res} and the line-integrated electron density $\bar{n}_e l$ of the central chord are compared for the cases with (——) and without (-----) ECW in Fig.4. The operational conditions are the same as the discharges in Fig.3 except B_t and the gas-puff program.

Above change in the operational conditions results in to increase the required power to switch an H-mode and, therefore, to obscure the H-mode transition of beam only heating case as shown in Fig 4. When the ECW is applied, a substantial H-mode is observed which is accompanied by the typical H-mode transition phenomena such as sudden increases in the density and edge temperature (inferred from I_{ECE}: Fig.4) and depression in the recycling light (not shown) as well.

6. DISCUSSION

A clear correlation between the enhanced wall fueling and the location of R_{res} is shown. The desorption of hydrogen due to ECW (inferred by ΔP_{H_2}) is large but the wall fueling efficiency is small and the density rather clamps when R_{res} is located inside the port region. This is presumably due to the expansion effect of the port volume. The wall fueling efficiency in this region increases with R_{res} or B_t as shown in Fig.2. Taking into account that $\Delta \bar{n}_e$ decreases with B_t in the beam heating case,[1] this is presumably due to the increase in the ratio of wall area to the port area by increasing the major radius.

The value $n\tau$ is improved over 40% by the assist of ECW with a total additional power of 550 kW. If this amount of the power is delivered by beam only, the estimated improvement is about 10% because the additional density increase is about 10% and the confinement time is about the same estimated by using our previous scaling.[1]

The degraded confinement time of the H-mode is recovered by an assist of ECW even if the resonance occurs very edge of the confined plasma. From the viewpoint of fueling, following explanation may be possible to explain this recovery. The confinement time at higher density is supposed to be recovered by the improvements of fueling efficiency due to the enhancement of wall fueling[1] and/or due to the edge heating by ECW. Because the expansion of dominant cooling region into the core plasma degrades the confinement. This improvement in the fueling efficiency can also results in higher attainable density as is seen in this experiment. These speculations are, however, not confirmed experimentally so far.

The heating of SOL plasma may be compensated by increased impurity influx and/or can enhance the radiation loss power, if the edge cooling by impurity radiation is dominant in JFT-2M. In the SOL heating experiment, however, the electron temperature at SOL increases substantially (Fig.4) and the radiation loss power is depressed (not shown) when ECW is applied.

On the other hand, it is well known that an impurity influx is suppressed by introducing strong gas-puff by an edge cooling. The difference in radiation enhancement of with and without ECW case shown in Fig.3(b) opposes to this. The radiation enhancement is larger without ECW in which the edge temperature is supposed to be low due to strong gas-puffing in the highest density regime.

Therefore this enhancement is presumed to be caused by deuterium radiation. It appears that, in JFT-2M, the edge cooling by gas-puff fueled neutrals is the dominant cause of preventing the H-mode development and of degrading the confinement as well.

Higher electron temperature at the scrape-off layer as well as the edge region of confined plasma can increase ionization cross-section which results in higher fueling efficiency and can prevent further edge cooling. This is the case with the ECW.

Increase of the temperatures at the edge and SOL and a clear correlation between this increase and ECW are well confirmed by a follow-up experiment performed recently.[5]

The experiment on the SOL heating shows that it is not necessary to deposit the power into the confined region to assist switching an H-mode. It is speculated that the ECW acts as a function of preventing edge cooling by cold fuel gas as well as an edge heating. This saves the ionization loss power in the confined region.

If above speculation is true, this technique is useful to improve fueling efficiency of a local cold gas-puffing for not only the H-mode realization but also confinement improvement. This is especially effective in a high density operation where the edge neutral gas strongly builds up. This is supported by the fact presented here that the higher gas-puff rate during the additional heating phase is allowable with edge heating by ECW. We call this technique "pre-heated fueling" by ECW.

7. CONCLUSION

In conclusion, results obtained by applying an electron cyclotron wave to the wall fueling and H-mode discharges are summarized as follows.

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(3)Electron heating at the divertor scrape-off layer by ECW assists a transition to the H-mode or saves the heating power to switch an H-mode.

Above results show that the ECW extends the operational regime of a divertor H-mode discharge. An optimization of the fueling could be one of the key issues for the confinement improvement.

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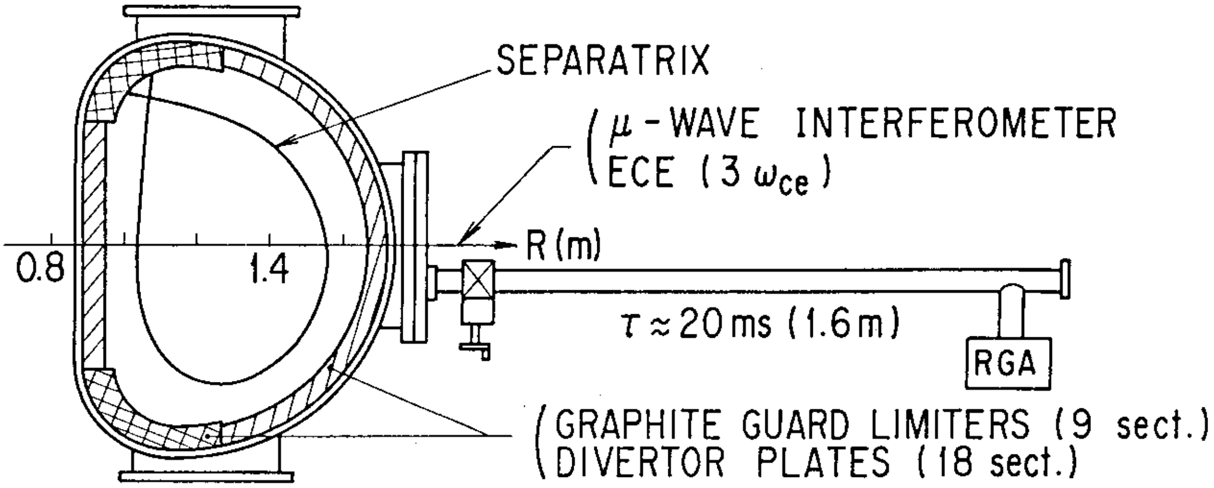

Fig. 1 The cross-section of JFT-2M tokamak. Calculated divertor separatrix surface and the location of residual gas analyzer (RGA) are shown. The chords of 2 mm μ-wave interferometer and electron cyclotron emission (ECE) measurement are on the midplane.

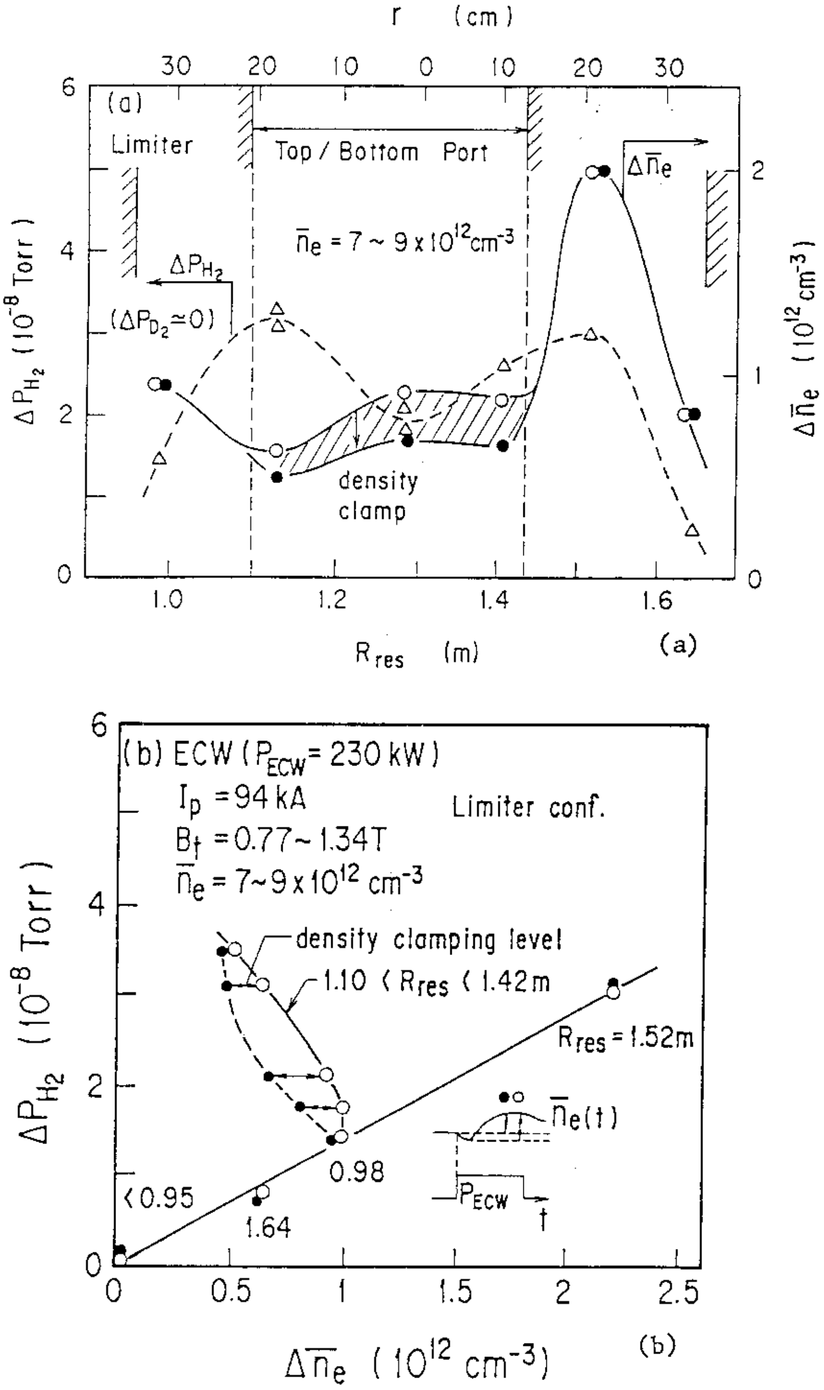

Fig.2 (a)The increments of line-averaged electron density $\Delta \bar{n}_e$ and hydrogen neutral pressure ΔP_{H_2} due to electron cyclotron wave (ECW), launched power of 230 kW, plotted against the major radius of the ECW .resonance R_{res} for full-sized limiter discharges. The locations of the guard limiter, minor radius r = 35 cm, and the top and bottom ports are shown. Dip in the density (clamp) just after the onset of ECW is seen only when R_{res} is inside the top/bottom port region. (b)Replot of the data in (a) on the $\Delta \bar{n}_e$ - ΔP_{H_2} plane.

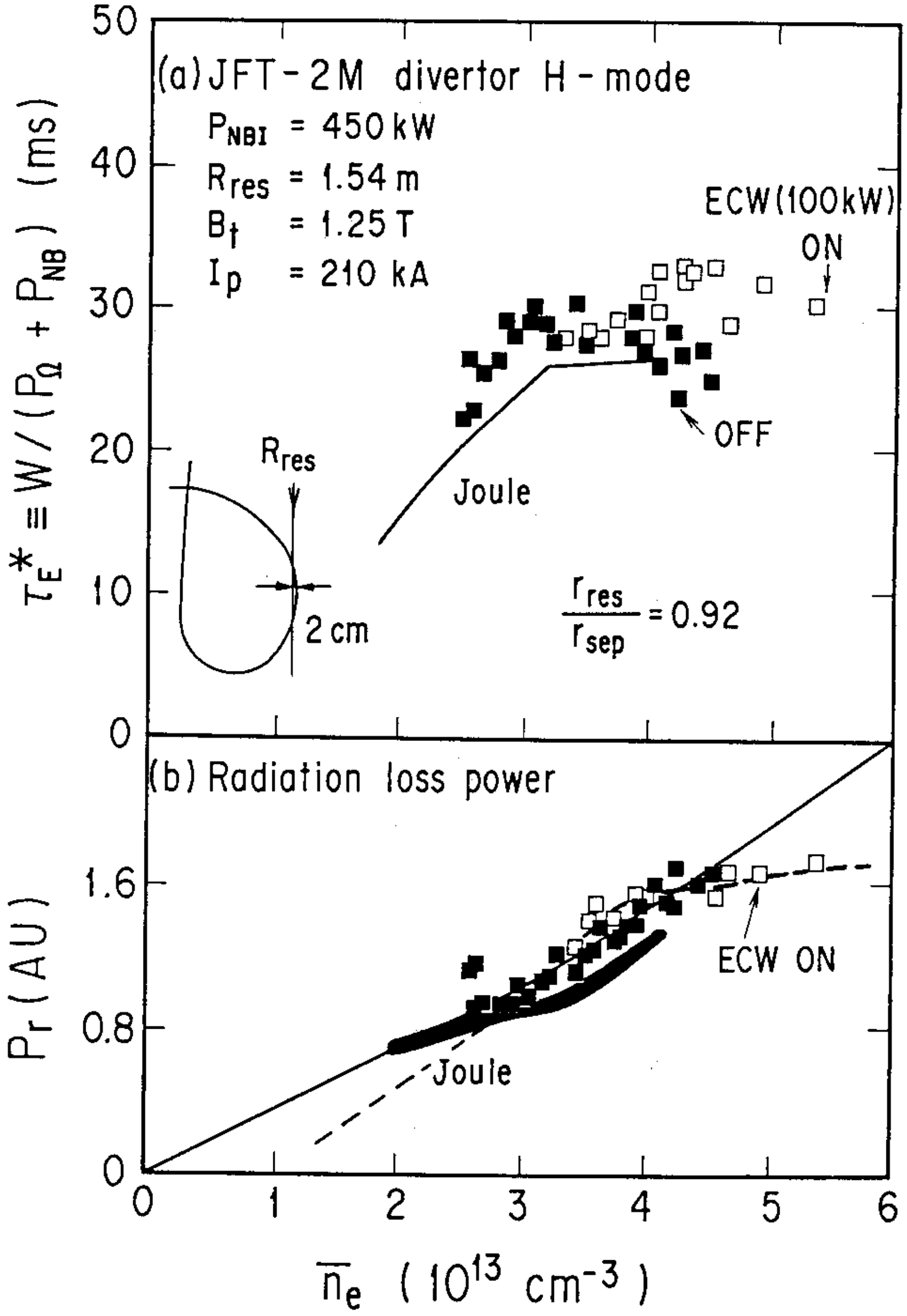

Fig.3 The density dependences of (a)energy confinement time and (b)radiation loss power for Joule heating phase and H-mode phase with and without ECW. The ratio of minor radii of the ECW resonance r_{res} and the separatrix surface r_{sep} is 0.92.

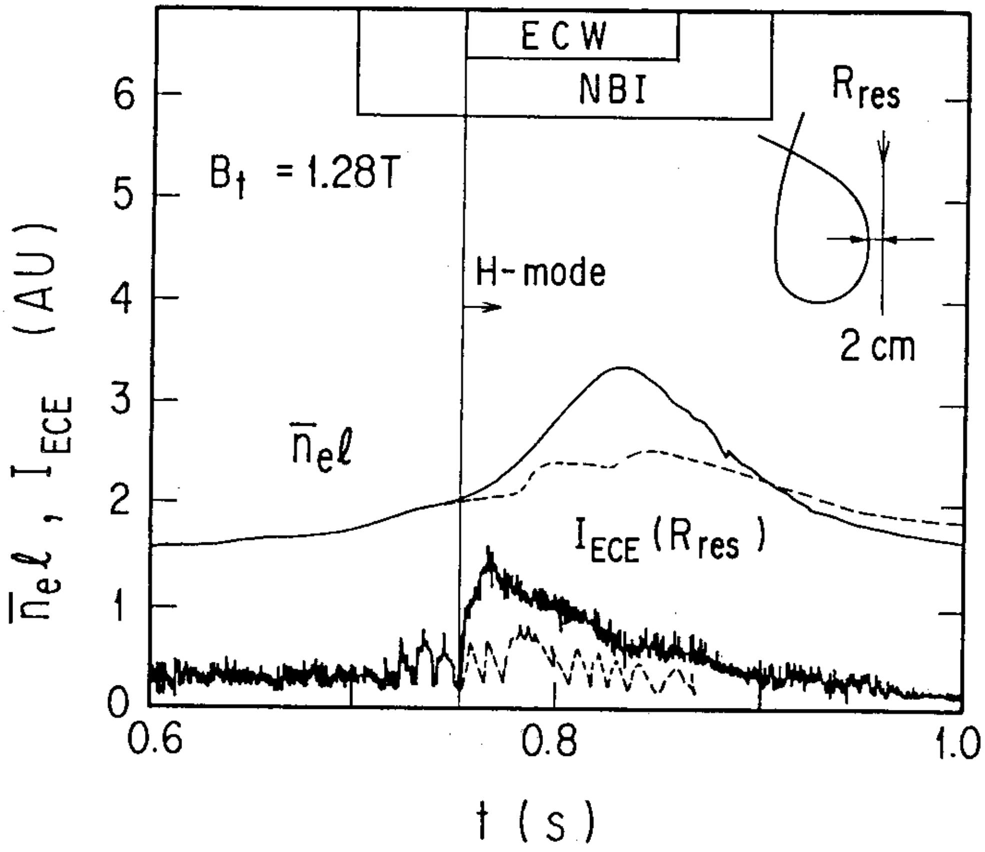

Fig.4 The temporal evolutions of the central line-integrated density $\bar{n}_e l$ and electron cyclotron emissivity I_{ECE} at R_{res} for the cases with (——) and without (-----) ECW. The resonance of the ECW is occur at the divertor scrape-off layer, 2 cm outside of the separatrix surface.