Generation of Initial Closed Flux Surface by ECH at Conventional Aspect Ratio of $R/a \sim 3$; Experiments on the LATE device and JT-60U Tokamak

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Abstract. Generation of initial closed flux surface by electron cyclotron heating at a conventional aspect ratio of $R/a \sim 3$ has been investigated on LATE and further tested on the JT-60U Tokamak. In both experiments, the plasma current is initiated and increased by ECH under steady external fields composed of a toroidal field and a weak vertical field. In LATE experiments, a movable inboard limiter is used to change the aspect ratio of plasma up to $R/a \sim 3$. The results show that the formation of initial closed flux surface is still possible up to $R/a \sim 3$ while higher decay indices of vertical field are required as the aspect ratio increases. Similar current start-up discharges have been performed on JT-60U and the plasma current is initiated and increased up to 20 kA under the vertical field configuration having a high decay index.

1. Introduction

In Tokamaks, the toroidal plasma current is usually initiated and maintained by induction from a center solenoid (CS). If the CS can be eliminated from the device, the structure of tokamak reactors will be greatly simplified, which enables economical fusion reactor designs [1]. Electron cyclotron heating and current drive (ECH/ECCD) is an attractive candidate for an alternative current startup since the microwave beam can be injected from a simple small launcher remote from the plasma. While an initial closed flux surface was shown to be generated by ECH in a number of low aspect ratio devices including CDX-U, LATE, TST-2, MAST and CPD [2, 3, 4, 5, 6], there was no report at the conventional aspect ratio except for one in DIII-D [2]. In this paper we report experiments and analyses on the LATE device and JT-60U tokamak, showing that the closed flux surface formation by ECH is still possible up to an aspect ratio of $R/a \sim 3$.

In low aspect ratio devices, by injecting an EC power to a steady external magnetic field composed of a toroidal field and a weak vertical field (B_v), a plasma current is observed to be initiated, to increase, and then to jump up rapidly, resulting in the formation of a closed flux surface. This spontaneous formation via the current jump was first found in LATE, and it was shown that there are two stages of the current generation [3]. In the early stage of the discharge, the charge separation caused by the curvature and gradient B drift is shorted by parallel currents along helical magnetic fields and generates a toroidal plasma current [2, 3, 7]. This is the so-called equilibrium current [7] and is proportional to the plasma pressure. When this current reaches a certain level and the field structure is sufficiently deformed due to the self field from the current, another current generation by means of the asymmetric confinement of electrons in the velocity space [3] starts to work and the current jump takes place.

The ratio of the self-poloidal field (B_a) by the equilibrium current to B_v is inversely proportional to the aspect ratio as $B_a/B_v \sim (a/R)p_e/(B_v^2/\mu_0)$, suggesting that the closed flux surface formation becomes difficult with increase of the aspect ratio. In this paper, the spontaneous formation is shown to be still possible up to $R/a \sim 3$ when the decay index of B_v is increased as R_0/a increases.

2. Experimental results and discussion

2.1 Experiments on LATE

LATE is a low aspect ratio device with a cylindrical vacuum vessel with an inner diameter of 1 m and a height of 1 m as shown in Fig. 1. The center post with an outer diameter of 11.4 cm encloses conductors for toroidal field. There is no center solenoid for inductive current drive. To conduct experiments up to a conventional aspect ratio of $R_0/a \simeq 3$, a movable inboard limiter as well as an outboard one (both made of Molybdenum) is installed as shown in Fig. 1 to restrict toroidal plasmas between the limiters. Here, we refer to R_0/a as device aspect ratio, where R_0 is the mean radial location of the two limiters and a is the half of the radial distance between the limiters. Three sets of vertical field coils (Bv-in, Bv-out, and Bv-R in Fig. 1(b)) are used to produce B_v. Two magnetrons at 2.45 GHz with a total injection power of $P_{\rm inj} \leq 40$ kW are used for EC heating. The waves are launched obliquely to the toroidal field via a cylindrical launcher of open waveguide type on the midplane in the form of O-mode (Fig. 1(a)).

Figure 2 shows a typical discharge of a closed flux surface formation at a device aspect ratio of $R_0/a \simeq 3$. The inboard limiter surface is located at $R = 23.5$ cm and the outboard one at $R = 47$ cm. Firstly, a steady toroidal field of $B_t = 686$ G and a steady vertical field of $B_v = 13$ G (both at $R = 35$ cm) are applied and hydrogen gas is introduced. After a 2.45 GHz

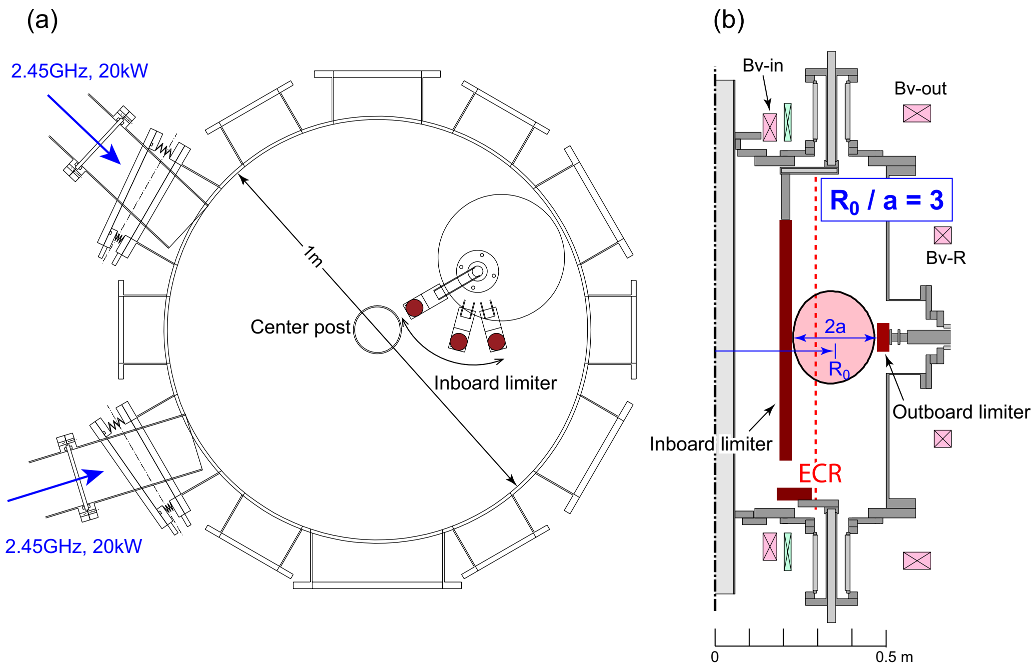

FIG. 1: Experimental setup of LATE. (a): Microwave launchers and an inboard limiter. (b): Limiter locations for $R_0/a \simeq 3$.

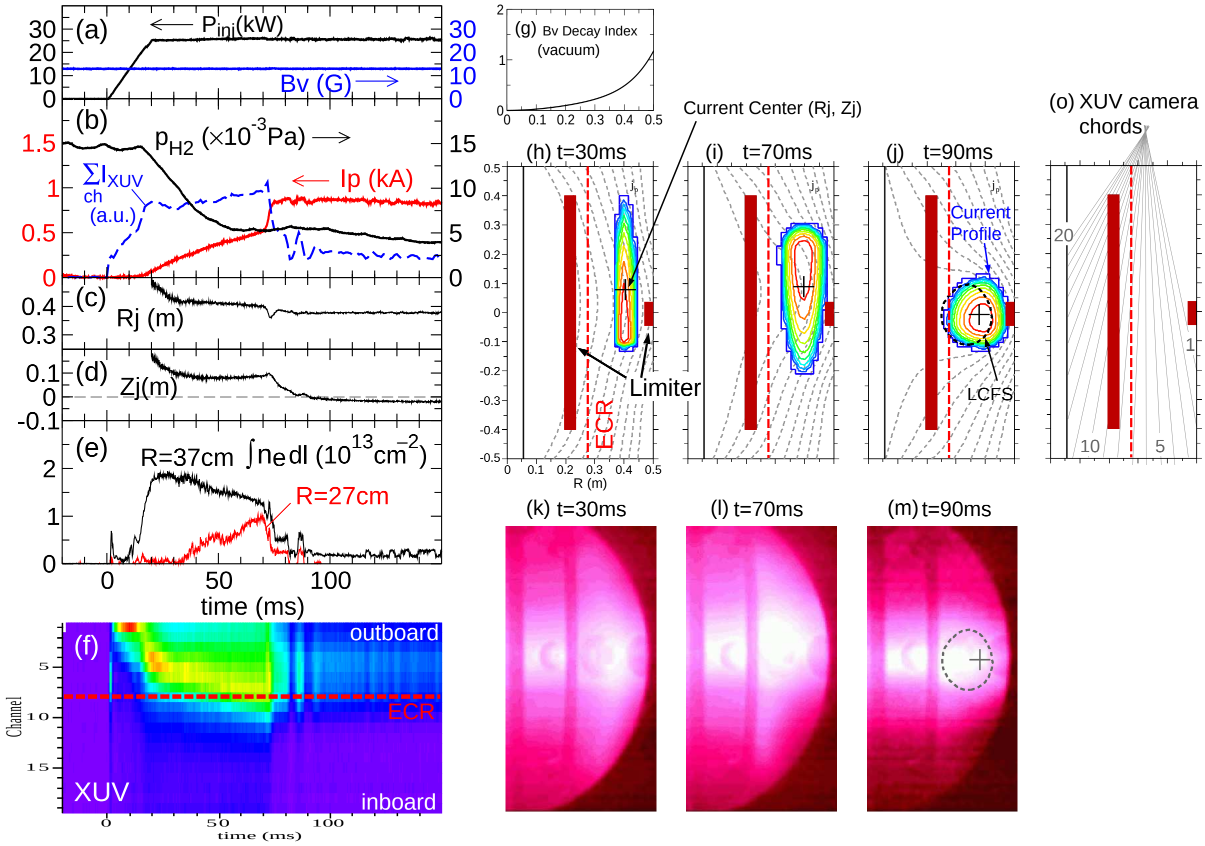

FIG. 2: Formation of closed flux surface at $R_0/a \simeq 3$ on LATE. (a): Injected microwave power and B_v at $R = 35$ cm. (b): Hydrogen pressure and plasma current. Dashed line shows sum intensity of all the XUV chords. (c) and (d): Radial and vertical position of plasma current center, respectively. (e): Line-integrated electron densities along two vertical chords. (f): Time evolution of XUV intensity profile. (g): B_v decay index in vacuum. (h)-(j): Poloidal flux contours and plasma current distributions estimated from the magnetic analysis. (k)-(m): Visible light images of plasma. (o): XUV camera chords.

microwave power of $P_{\text{inj}} \simeq 25$ kW is injected, breakdown takes place immediately along the fundamental EC resonance layer at $R = 27.4$ cm. A plasma current is initiated and increased slowly up to $I_p \simeq 0.5$ kA as the neutral gas pressure decreases (Fig. 2(b)), and then jumps up to $I_p \simeq 0.9$ kA under the steady external field, resulting in formation of the closed flux surfaces (Fig. 2(j) and (m)). The results shows that the spontaneous formation of closed flux surface by ECH is possible at a conventional aspect ratio of $R_0/a \simeq 3$.

The time evolution of the plasma current profile is estimated from the magnetic analysis using 17 flux loops [8] as shown in Fig 2(h)-(j). The plasma current starts to flow initially on the outboard side apart from the ECR layer (Fig. 2(h)). The profile is broadened and shifts to the inward as the current increases, and extends close to the EC resonance layer just before the current jump (Fig. 2(i)). Along with the evolution of the current profile, the electron density profile is also broadened and shifts from the outboard side to the inboard, as seen in line-integrated densities along two vertical chords by 70 GHz interferometers (Fig. 2(e)), extreme ultra-violet (XUV) emission profile using an AXUV diode camera (Fig. 2(f) and (o)), and visible camera images (Fig. 2(k)-(m)). It can be seen that the peak of XUV profile moves to the inward corresponding to the inward shift of current center as shown in Fig. 2(c) and (f).

In Fig. 2(b), sum intensity of all the XUV chords, $\sum I_{\mathrm{XUV}}$, is plotted. The XUV signal from the present plasma is mostly from the bremsstrahlung emission that is proportional to $n_e^2\sqrt{T_e}$. At the beginning of the discharge, there is almost no I_p whereas $\sum I_{\mathrm{XUV}}$ increases immediately after the microwave injection. In this stage, the plasma pressure mainly contributes to the vertical charge separation current circulating through the vessel by the short-circuit effect [9, 10]. After a while, I_p appears and increases accompanied by increase of $\sum I_{\mathrm{XUV}}$. This current is attributed to the equilibrium current that is proportional to the plasma pressure and is increased mainly with increase of T_e as shown in the previous results [3]. At the current jump phase, $\sum I_{\mathrm{XUV}}$ decreases while I_p rapidly increases. The current generation by the asymmetric confinement starts to work under the magnetic field geometry sufficiently deformed by the self-filed of the current [3], constituting the current jump and resulting in formation of closed flux surfaces. After the closed flux surfaces are formed, the plasma current turn to be maintained by high energy electrons driven by ECCD [3, 11].

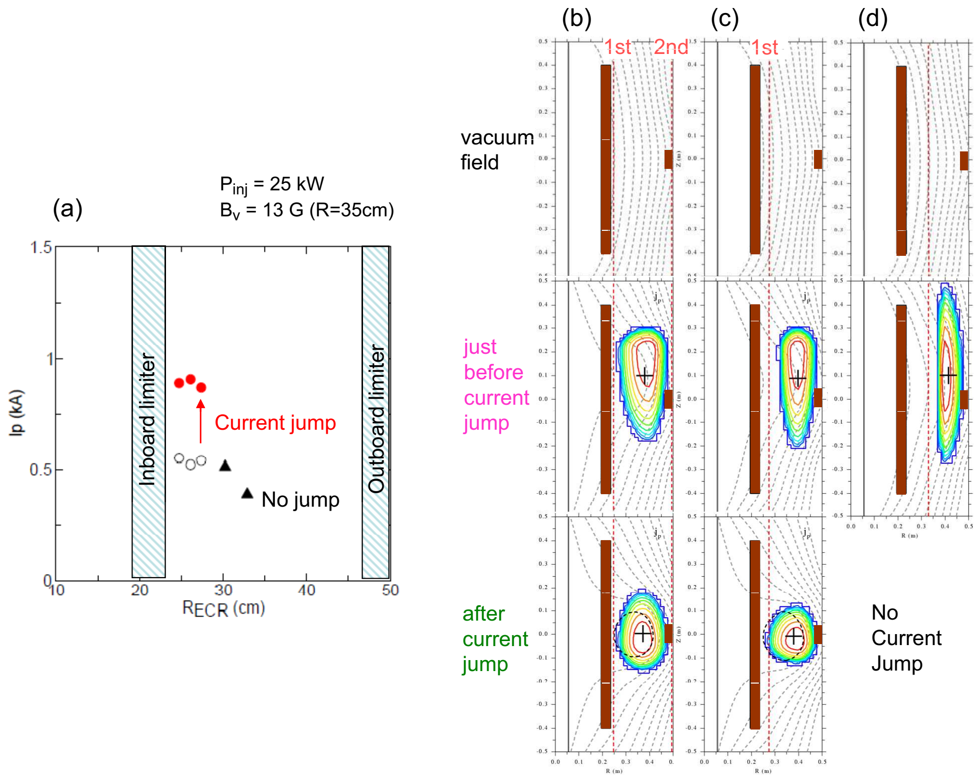

FIG. 3: Dependence on EC resonance location at $R_0/a \simeq 3$. (a): Plasma current before (open circles) and after (filled circles) the current jump. as a function of EC resonance position. Triangles show the maximum current in the discharge with no current jump. (b)-(d): Poloidal flux contours and current profiles for the discharges with (b):R_{ECR} =24.7 cm, (c):27.4 cm, and (d):32.9 cm.

Figure 3(a) shows obtained plasma currents as a function of the EC resonance position. The plasma current is observed to increase as the EC resonance layer gets closer to the inboard limiter. The spontaneous formation of the closed flux surface is observed when the

EC resonance layer is located sufficiently close to the inboard limiter. Current profiles from the magnetic analysis for Discharges with various EC resonance positions are shown in Fig. 3(b)-(d). In all the cases, time evolutions of the current profile are quite similar and the profile just before the current jump is broadened and extended close to the EC resonance layer. It is also noted that there is no current inside the EC resonance layer in open geometry (before the current jump) since there is no direct heating mechanism inside the resonance. As the EC resonance location is set outer, the current channel becomes narrow and the total current becomes low, resulting in no current jump (Fig. 3(d)).

The spontaneous formation depends significantly on the B_v decay index n. Figure 4 shows the obtained plasma current I_p as a function of n at various values of the device aspect ratio, including $R_0/a \simeq 1.3$, 2.0 and 3.0. In the experiments at a device aspect ratio of $R_0/a \simeq 1.3$, the inboard limiter is removed from the device. For the discharge with the current jump, the value just before the current jump is also plotted. It is shown that as the aspect ratio increases higher decay indices are required for the current jump. This suggests that mirror confinement of the EC heated electrons is essential for the current jump.

In the case of higher aspect ratio, higher decay index is needed to keep a sufficient mirror ratio along the open field lines. For the geometry shown in Fig. 5, the mirror ratio between $Z = a$ and $Z = 0$ along the field line passing through R_0 on the midplane can be approximately written,

$$\frac{B(z=a)}{B(z=0)} \approx \exp\left(\frac{n(R=R_0)}{2}\frac{1}{R_0^2/a^2}\right). \quad (1)$$

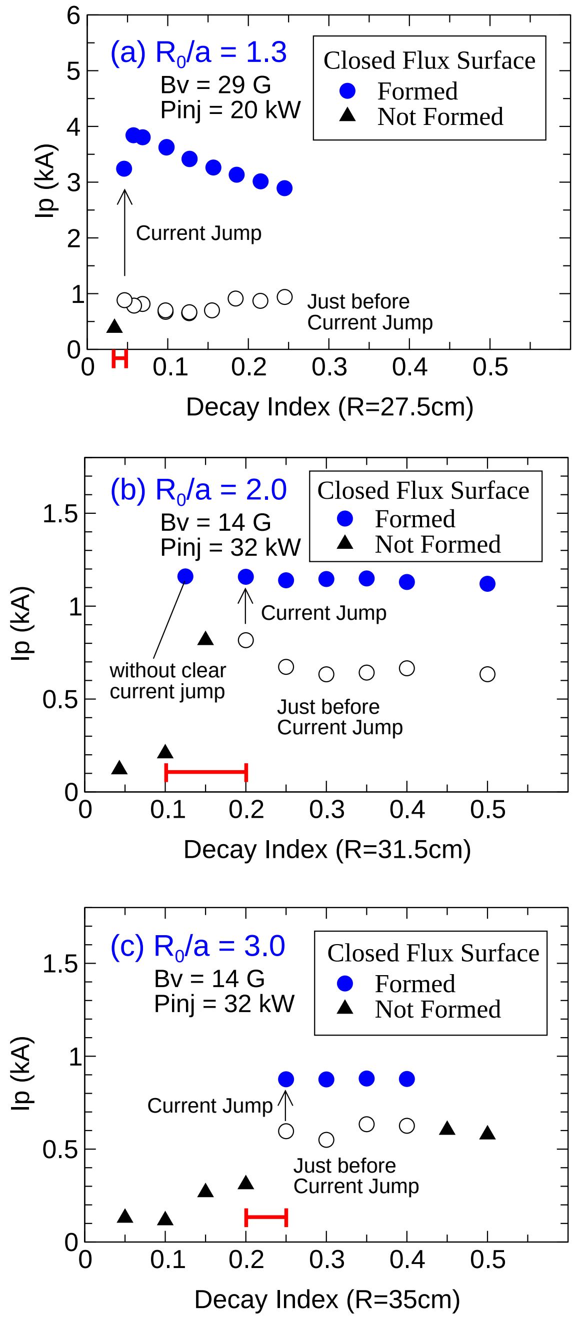

FIG. 4: Obtained plasma current as a function of decay index at $R = R_0$. (a): $R_0/a \simeq 1.3$ (no inboard limiter). (b): $R_0/a \simeq 2$. (c): $R_0/a \simeq 3$. For the discharges with the current jump, the value just before the current jump is also plotted.

This indicates that the decay index should be increased as $n \propto R_0^2/a^2$ to keep the mirror ratio at the same value. It is shown in Fig. 6 that the minimum decay index required for the closed flux formation in Fig. 4 is roughly consistent with the scale as $n \propto R_0^2/a^2$. In this figure, the error bars correspond to the red bars in Fig. 4 and filled circles indicate the minimum decay index where a clear current jump is observed.

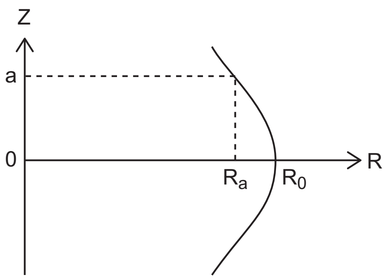

FIG. 5: Geometry for equation (1)

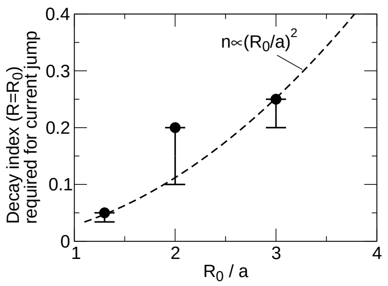

FIG. 6: Decay index required for the current jump as a function of aspect ratio

In the early stage of the discharge, where the plasma current is nearly proportional to the pressure, the mirror confinement is expected to be important to increase the electron temperature and density, thereby increasing the current in open field geometry. It can be seen that obtained currents for the no current jump discharge in Fig.4(b) and (c) are increased with increase of the decay index. If the current reaches a level enough for the current jump under a sufficient mirror ratio the current jump takes place.

Figure 7 shows plasma currents at the steady stage after the current jump as a function of B_v at $R = R_0$ at various aspect ratios under an injected microwave power of $P_{\rm inj} = 30$ kW. It is noted that the formation of initial closed flux surface is possible in a wide range of the B_v strength. In all the cases, obtained plasma currents are nearly proportional to B_v. On the other hand, the maximum B_v in which the spontaneous formation is possible decreases with increase of the aspect ratio. This may be due to the limitation in the present experiment using the limiters where a plasma cross section (i.e. minor radius a) is decreased with increase of the aspect ratio. In spite of the limitation, it is shown that the formation of closed flux surface is still possible up to $R_0/a \simeq 3$ when the B_v decay index is increased as R_0/a increases.

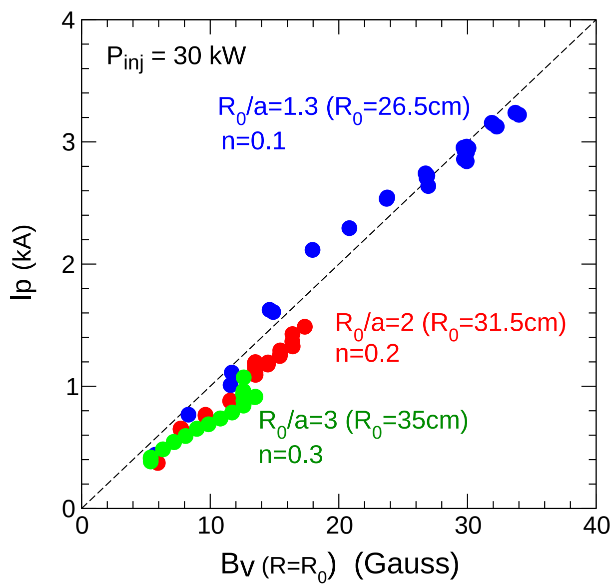

FIG. 7: Obtained plasma current after the current jump versus B_v at various aspect ratios on LATE.

2.2 Experiments on JT-60U

Similar current startup discharges have been performed on JT-60U ($R/a \sim 3$). ECH power up to 4 MW at 110 GHz is used for the experiments. The waves are launched in O-mode from the upper outside. Figure 8 shows a typical discharge where a plasma current is initiated and increased to $I_p \simeq 20$ kA. Here, we set the B_v decay index to be $n \simeq 0.4$ at $R = 3.4$ m keeping the current jump condition in Fig. 4(c) as well as the vertical and horizontal stability condition of $0 < n < 1.5$ in the central region of the vacuum chamber since its spatial variation is quite large in the JT-60U case as seen in Fig. 8(h). Magnetic analysis shows that the current is initiated on the outboard side as shown in Fig. 8(i) and shifts to the inward, and finally the current profile extends close to the EC resonance layer at $t = 1.1$ s as shown in Fig. 8(j), which is quite similar to the profile just before the current jump in LATE (Fig. 2(i)). The H_α emission profile is also broadened at t 1 s corresponding to the broadening of the current profile (Fig. 8(g) and (j)). In

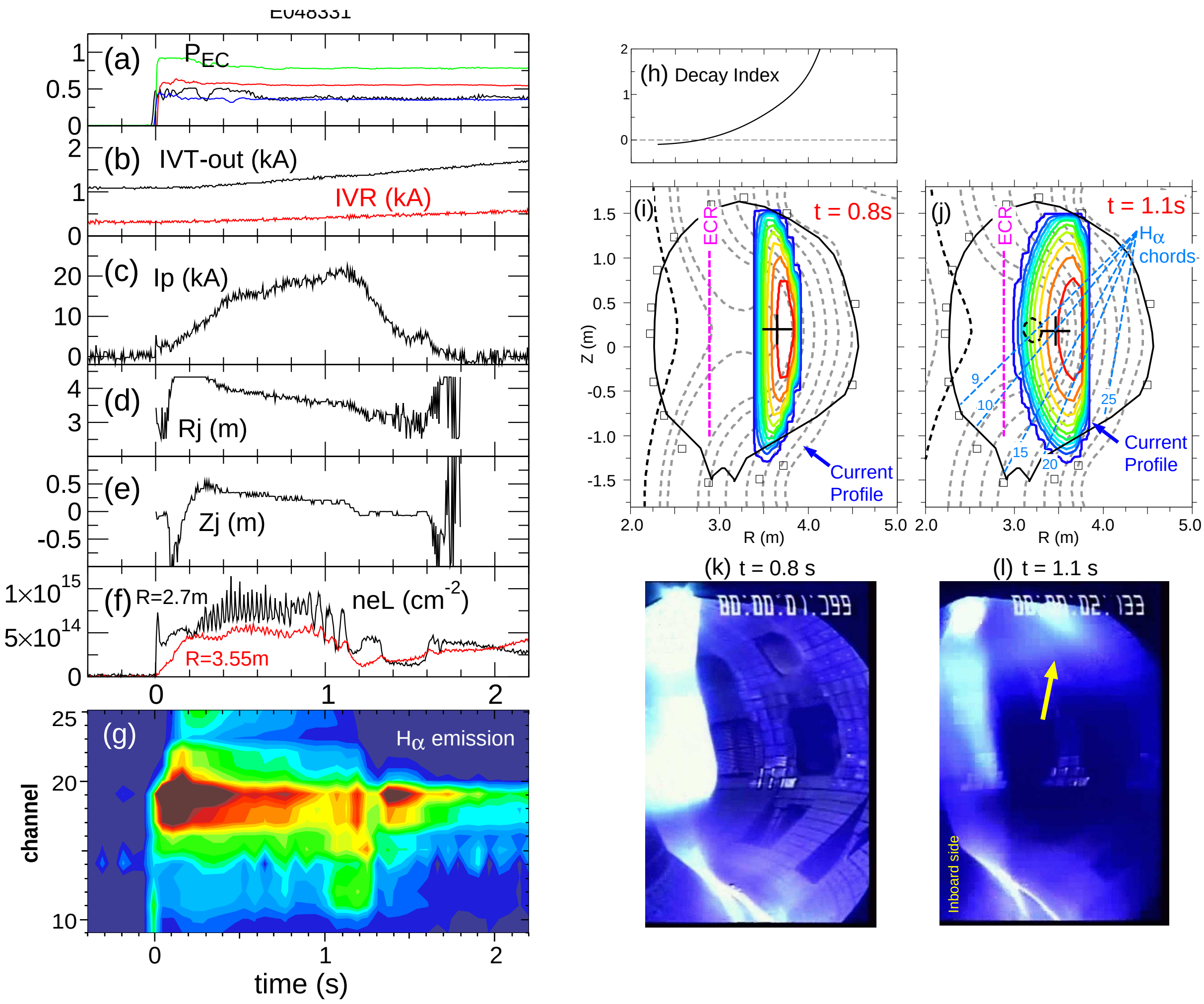

FIG. 8: Typical discharge on JT-60U. (a): ECH power. (b): Poloidal field coil currents. (c): Plasma current. (d): Radial position of the current center. (e): Vertical position of the current center. (f): Line-integrated electron density along vertical chords. (g): H_α emission profile. (h): B_v decay index in vacuum. (i) and (j): Poloidal flux contours and plasma current profiles. (k) and (l): Visible images.

this shot, however, the plasma current decreases after $t = 1.1$ s at which an intensive spot on the upper vacuum vessel abruptly appears on the visible camera image as seen in Fig. 8(l) (yellow arrow), suggesting an impurity contamination due to interactions of the plasma and the vacuum vessel.

Although the device scale is quite different from LATE, quite similar current profile evolutions are observed. These results suggest the underlying physics is common and emphasize that the formation of initial closed flux surfaces by ECH is possible at a conventional aspect ratio of $R/a \sim 3$.

3. Summary

Generation of initial closed flux surface by electron cyclotron heating at conventional aspect ratio of $R/a \sim 3$ has been investigated on LATE and further tested on JT-60U Tokamak. In LATE experiments, a movable inboard limiter is used to change the aspect ratio and the spontaneous formation at a conventional aspect ratio up to $R/a \simeq 3$ is investigated. The results show that the formation of initial closed flux surface is still possible up to $R/a \sim 3$ and higher decay indices of vertical field are required as the aspect ratio increases. Similar current start-up discharges have been performed on JT-60U and the plasma current is initiated and increased up to $20\,\mathrm{kA}$ under the bv configuration having a high decay index. Although the device scales are quite different, similar current profile evolutions are observed in the two devices. These results suggest that the underlying physics is common and emphasize that the formation of initial closed flux surfaces by ECH is possible at a conventional aspect ratio of $R/a \sim 3$ with a high decay index B_v configuration, which may encourage to apply this technique to startup in ITER.

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