Spontaneous Formation of Low-Aspect-Ratio Torus Equilibria by ECH under Steady Vertical Field

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Spontaneous current jump resulting in the formation of closed magnetic flux surfaces was observed in electron-cyclotron-heated toroidal plasmas under a steady vertical magnetic field in the LATE device. This bridges the gap between the open field equilibrium maintained by a pressure-driven current in the external vertical field and the closed field equilibrium at a larger plasma current.

Keywords:

spherical tokamak, electron cyclotron heating, non-inductive current start-up

Because of limited central space in spherical tokamak (ST) devices, it is highly desirable to remove the central solenoid (CS) from future ST reactors [1]. Thus, other methods than induction from CS are needed to start up ST. Electron Cyclotron Heating and Current Drive (ECH/ECCD) is an attractive candidate since plasma initiation and current start-up might be realized simultaneously.

In small scale experiments some plasma currents were observed in ECH plasmas under an external steady vertical field B_v [2,3]. In these experiments the generated plasma current I_p changed with B_v. It attained a maximal value at a weak level of B_v, after which it decreased inversely proportional to B_v consistent with the formula,

$$I_p = 2 \langle p \rangle S / RB_v, \quad (1)$$

which was given for the regime of open field configurations where the self poloidal field was small compared with B_v [4]. Here $\langle p \rangle$ is spatially averaged plasma pressure, S the plasma cross section and R the major radius, respectively. Meanwhile, B_v necessary to maintain the plasma loop in equilibrium is given by $B_v = (\mu_0 I_p / 4\pi R) \{\ln(8R/a) + l_i/2 - 3/2 + \beta_p\}$, where $\beta_p = 8\pi^2 a^2 \langle p \rangle / \mu_0 I_p^2$. Although formula (1) matches B_v in the range of small I_p (pressure-ballooning-force dominant regime), it does not for the regime of closed field configurations with larger I_p (current-hoop-force dominant regime). Here we report experimental results showing that a spontaneous current jump bridges the open field equilibrium and the closed field one at larger plasma currents.

The experiment was performed in the LATE device. The vacuum vessel is a stainless cylinder (diameter = height = 1 m) with a center post (diameter = 11.4 cm) enclosing 60 turns of conductors for the toroidal field (Fig. 1).

Figure 2 shows a typical discharge. The discharge initiates near the EC resonance layer at R = 13.6 cm by injecting a microwave power (2.45 GHz, 5 kW) under a

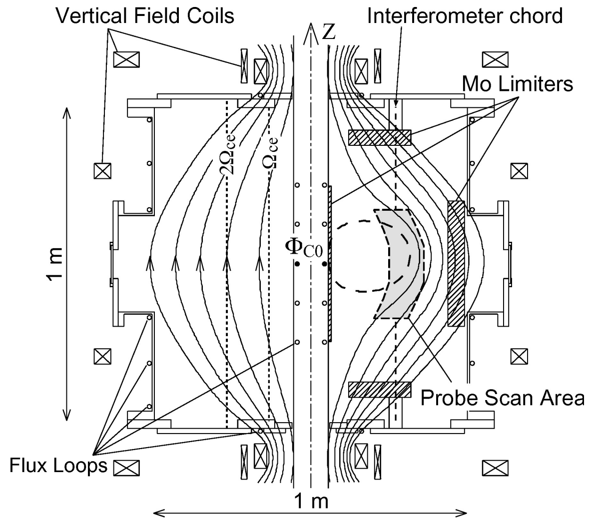

Fig. 1 The LATE device. The external poloidal field in vacuum and poloidal flux surfaces just after the current jump in Fig. 2 are also plotted in the left and right sides, respectively.

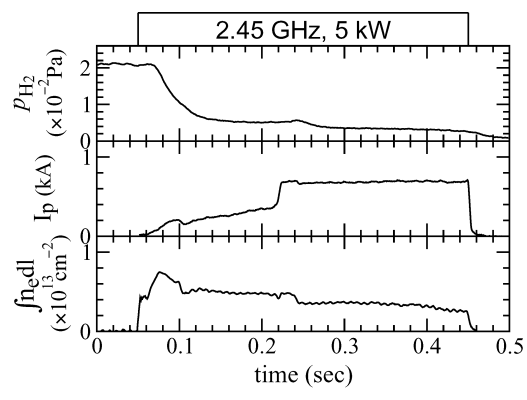

Fig. 2 Typical discharge waveform.

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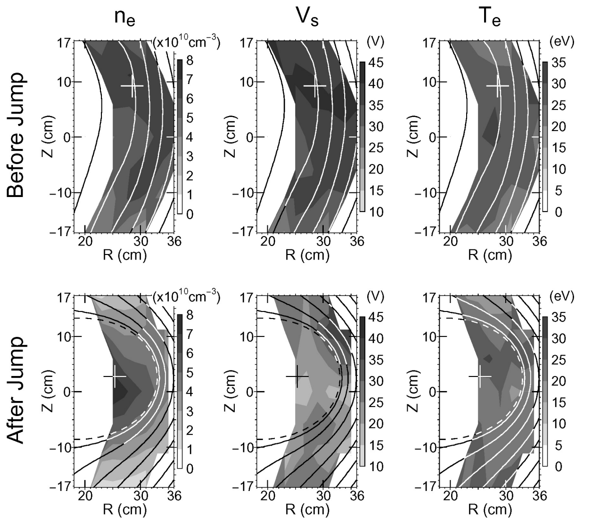

Fig. 3 n_e, V_s and T_e profile just before and after the current jump at $t = 0.22$ s in Fig. 2.

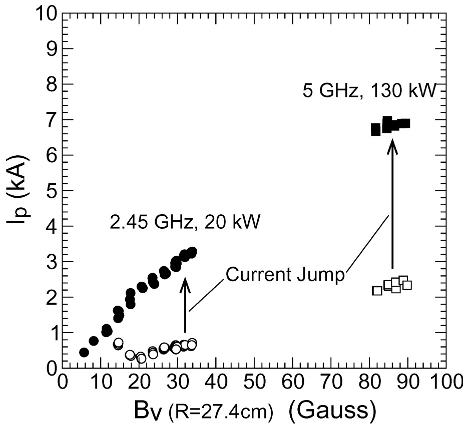

Fig. 4 Plasma current versus external vertical field strength.

steady vertical field (B_v = 11 Gauss with a decay index of n = 0.25 at R = 20 cm). Pre-filled hydrogen gas pressure decreases quickly and then keeps a low value of 5×10^{-3} Pa. In accordance with the decrease of H_2 pressure the plasma current I_p is generated and increases gradually. When I_p approaches 0.4 kA, I_p jumps up to 0.7 kA within 3 msec. The magnetic flux through the center post on the mid plane (Φ_{C0} in Fig. 1) changes its sign at this moment, indicating that the direction of the poloidal magnetic field along the the center post is reversed and a closed magnetic flux surface is formed as shown in Fig 1. After the current jump, I_p remains constant to the end of the microwave pulse.

Profiles of the electron density n_e, temperature T_e and space potential V_s just before and after the current jump are measured by a movable Langmuir probe and plotted in Fig. 3 with contour plots of poloidal flux surfaces. Before the current jump, the n_e profile is broad, while it has a hill near the current center (denoted by a cross) coincident with the closed flux surface after the jump. Before the jump the V_s profile is also broad with a weak charge separation due to ∇B drift in the open field configuration. After the jump the charge separation dissappears and V_s has a hole near the current center. The T_e value, however, maintains its broad profile and remains globally at 20–30 eV, with no apparent structures. An estimation of I_p from formula (1) using the above profiles for n_e and T_e gives $I_p \sim 0.2$ kA, roughly consistent with the pressure-driven current in the open field configuration before the current jump.

After removing all the obstacles including the Langmuir probe and limiters from the vacuum vessel, larger current jumps have been successful under stronger vertical fields by injecting higher microwave powers as shown in Fig. 4. In this study, a closed field equilibrium with the plasma current of $I_p \simeq 7$ kA was obtained by a jump from an open field equilibrium with $I_p \simeq 2.5$ kA under $B_v \simeq 85$ Gauss. Thus, the current jump bridged the gap between the open field equilibrium maintained by pressure-driven current in the external vertical field and the closed field equilibrium at a larger plasma current. Furthermore it has been shown that once the closed flux surface is formed, I_p can be further increased by ECCD by subsequent ramps of B_v and microwave power [5,6].

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