Start-Up of Spherical Torus by ECH without Central Solenoid in the LATE Device

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Spherical torus plasma is started-up by electron cyclotron heating alone without Ohmic heating in the LATE (Low Aspect ratio Torus Experiment) device. By injecting a 2.45 GHz microwave pulse up to 10 kW for 4 seconds, a plasma current is initiated and ramped up to $I_p \simeq 4$ kA by adjusting the external vertical field for the equilibrium of the plasma loop. Magnetic measurements show that the last closed flux surface has an aspect ratio of $A \sim 1.4$ and an elongation of $\kappa \sim 1.3$. The line-averaged electron density is 1.3×10^{11} cm^{-3} which is almost twice the plasma cutoff density, suggesting that electron cyclotron heating by mode-converted electron Bernstein waves may take place.

Keywords:

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

The spherical torus (ST) concept was proposed to be attractive [1] since it allows high beta plasmas to be realized in a compact shape and at a low aspect ratio. Recent experiments on START [2], MAST [3], and NSTX [4] have verified these advantages. For future ST fusion plants, however, removing the central solenoid is considered to be a crucial step [5], since STs have only a limited space at the center column of the devices to ensure the virtue of a low aspect ratio. It is therefore necessary to develop a non-inductive start-up scenario to initiate and ramp-up the plasma current to a level sufficient for the second heating and current drive by NBI to reach ignition. Electron cyclotron heating and current drive (ECH/ECCD) is potentially an attractive candidate for this purpose, since plasma initiation, and current start-up and ramp-up might be realized simultaneously by injecting microwave power from a launcher remote from the plasma. Here, we report a recent experimental result on the start-up of a spherical torus by ECH in a small LATE (Low Aspect ratio Torus Experiment) device.

The main objective of LATE is to demonstrate the above ECH/ECCD scenario and to study its basic mechanism. The vacuum chamber is a stainless steel cylinder with an inner diameter of 100 cm and a height of 100 cm. The center stack is a stainless steel cylinder with an outer diameter of 11.4 cm, enclosing 60 turns of toroidal field coil. There is no central solenoid for OH.

Figure 1 shows a typical discharge. First, a steady external vertical field ($B_v \simeq 12$ G at R = 20 cm) is applied and hydrogen gas is introduced by gas puffing. It is noted that the B_v decay index in the present experiment is set to be very low ($n(R$ = 20 cm$)$=0.02) and the vertical field line is almost straight along the vertical direction as shown in Fig. 2(a), in contrast to the high value case of CDX-U [6].

Second, microwaves at 2.45 GHz generated by two magnetrons are injected from the outboard side through two radial ports at the midplane at oblique angles. The injected waves are linearly polarized with the electric field parallel to the equatorial plane. Then, an initial plasma is produced instantly at the fundamental EC resonance (Ω_{ce}) layer at R = 13.7 cm. The plasma quickly expands to the low field side and an initial plasma current is generated. The plasma current rapidly increases up to $\simeq$ 1.2 kA (t = 0.6 s), and an initial closed magnetic flux surface is produced as shown in Fig. 2(b). This is similar to the previous experiment in CDX-U, but in the present case the outermost flux surface is significantly elongated vertically due to the low decay index in contrast to the CDX-U case.

Third, the plasma current slowly ramps-up by increasing the B_v field gradually in order to keep the higher plasma current in equilibrium as well as increasing the 2nd magnetron power. The magnetic flux through the center stack at the midplane (Φ_{C0}) increases gradually in accordance with the increase of the plasma current during the ramp, indicating that an extremely weak voltage ($\sim 5\mu$V) in the reverse direction to the plasma current is applied on the plasma surface. The current reaches $I_p \simeq 4$ kA at B_v = 45 G.

Finally, the plasma current is kept constant with the steady B_v field of B_v = 45 G for 0.5 second until the micro-

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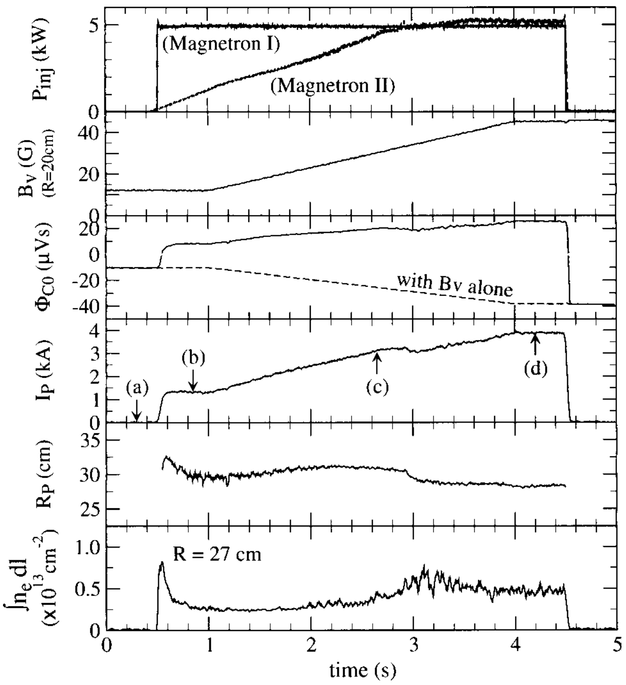

Fig. 1 Time traces of discharge

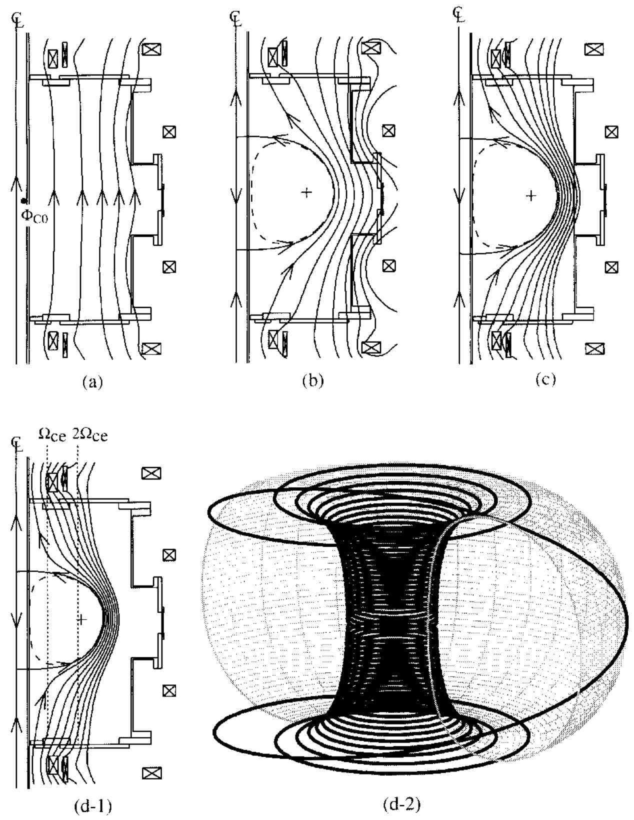

Fig. 2 Evolution of poloidal flux contours. (a)-(d-1): Poloidal flux contours for the times indicated in Fig. 1. Plus symbol denotes the center of plasma current. (d-2): 3-D view of the last closed flux surface and the line of magnetic force.

wave power is turned off. At this final stage, the last closed flux surface has an aspect ratio of A ~ 1.4 and an elongation of κ ~ 1.3, as shown in Fig. 2(d-1). Figure 2(d-2) shows the line of magnetic force on the last closed flux surface with the edge safety factor of $q_{\mathrm{edge}} \simeq 50$, where the characteristic of ST plasma is seen by the present current of $I_{\mathrm{p}} \simeq 4$ kA which has already reached ~ 7% of the toroidal coil current of I_{T} = 59.4 kAT.

The line-averaged electron density along the vertical chord (R = 27 cm) near the current center gradually increases as the plasma current increases and finally reaches $\overline{n_{\mathrm{e}}} \simeq 1.3 \times 10^{11}$ cm^{-3}, as shown in Figure 1, which is almost twice the plasma cutoff density for a 2.45 GHz microwave. The current center (R_{p}) is maintained near the second-harmonic EC resonance layer ($R_{2\Omega_{\mathrm{ce}}}$ = 27.4 cm). In addition to these experimental results, the electron Bernstein waves have very short wave lengths ($k_{\perp}\rho_{\mathrm{e}}$ ~ 1, where $k_{\perp}$ is the perpendicular wave number and ρ_{e} electron Larmor radius) and, therefore, are supposed to be effective for the second-harmonic heating even in low temperature plasmas. These observations suggest that the second-harmonic ECH by the mode-converted electron Bernstein waves could be responsible for heating and current drive in the present plasma. This is in contrast to the previous experiments in WT-3 [7] where plasma current was started-up by the second-harmonic X-mode ECH in an extremely underdense plasma and, therefore, no mode conversion could take place.

Finally, we estimate the current driven by ECCD. The central electron temperature is roughly estimated as $T_{\mathrm{e}} \leq 50$ eV since the O v line emission appears in the final discharge stage. For T_{e} = 50 eV, the driven current is estimated to be I_{CD} ~ 20 kA. This might suggest that the driven current is attributed to the current drive by electron Bernstein waves. On the other hand, the bootstrap current is estimated to be negligible since β_{p} ~ 0.05 for the present plasma of low temperature and low density.

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