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# Start-up and Formation of Spherical Torus Plasma by Electron Cyclotron Heating and Current Drive

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In order to realize low-cost, economical Spherical Torus (ST) reactors, eliminating the central Ohmic solenoid from the center of the device is considered to be necessary [1]. It is then strongly desired to develop a non-solenoidal start-up scenario to initiate and ramp-up the plasma current. For this purpose, start-up and formation of ST by electron cyclotron heating and current drive (ECH/ECCD) have been studied in the Low Aspect ration Torus Experiment (LATE) device. ECH/ECCD method is attractive for reactors since the microwave power can be injected from a simple small launcher remote from the plasma. In this paper, we report a successful start-up discharge by a microwave power alone, where a plasma current is initiated and ramped-up to $I_{\rm p} \simeq 20$ kA, resulting in the formation of a ST.

The experiment was carried out in the LATE device [2] as shown Fig 1. The vacuum chamber is a cylinder with a height of 1 m and a diameter of 1 m, containing a slim center post with a diameter of 11.4 cm. The center post encloses 60 conductors to produce a toroidal field. Four sets of poloidal field coils produce an external vertical field for the equilibrium of the plasma loop and a horizontal field for the feedback control of the plasma vertical position. There is no central solenoid for the inductive current drive. A microwave power at 5 GHz up to 200 kW is injected from a radial port on the mid-plane as shown in Fig 1(b). The power is launched with a cylindrical launcher at an oblique angle to the toroidal field in the left-hand circular polarized mode to have a good mode-conversion efficiency to the electron Bernstein (EB) waves.

Figure 2 shows a typical start-up discharge. A steady toroidal field of $B_{\rm T} = 960$ G and a steady vertical field of $B_{\rm v} = 70$ G (both at $R = 25$ cm) are applied and the hydrogen gas is filled before the microwave injection. The microwave pulse is then injected, a breakdown takes place immediately along a field line around the second harmonic resonance layer at $R = 27$ cm as shown in Fig. 2(b) and a plasma current is initiated. After a while, an initial closed surface is produced (Fig. 2(c)) via a spontaneous current jump [3], in which the plasma current is increased to 7 kA in several ms under the steady vertical field. Subsequently, the plasma current is further ramped up with the increase of the vertical field for the equilibrium at the higher $I_{\rm p}$ and reaches up to $I_{\rm p} = 20$ kA at $B_{\rm v} = 190$ G at the end of microwave pulse of 70 ms, where an ST plasma having an aspect ratio of $R/a = 20$ cm$/14$ cm$= 1.4$ and an elongation of $b/a = 1.8$ is formed (Fig. 2(d)). The current ramp-up rate reaches as fast as $\sim 260$ kA/s, for the first time,

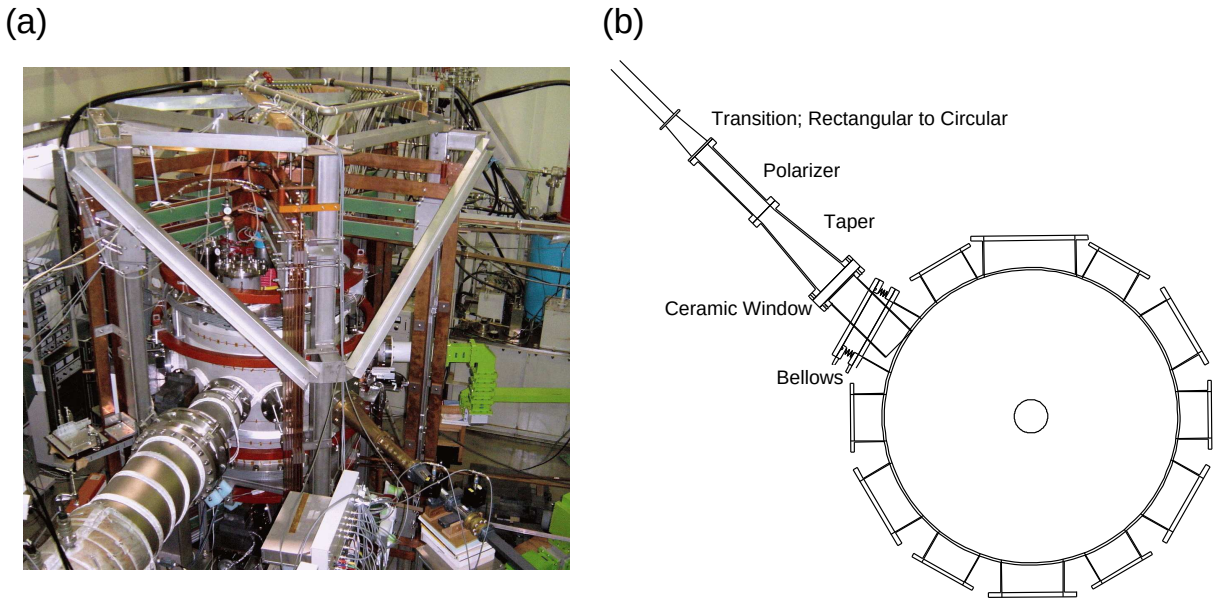


Figure 1: (a) Photograph of LATE device, (b) 5 GHz ECH Launcher

comparable to the lower hybrid ramp-up rate.

The line averaged electron density is estimated from interferometers along two chords to be $n_e \sim 4 \times 10^{11}$ cm$^{-3}$ in the last 10 ms, which is higher than the plasma cutoff density, suggesting that the EB waves mode-converted from the incident electromagnetic waves support the plasma and drive the current.

The plasma current distribution is estimated from a magnetic measurement with seventeen flux loops using a current distribution model having eight fitting parameters,including the position of the profile center $(R_0, Z_0)$, radius $(a)$, ellipticity $(\kappa)$, triangularity $(\delta)$, peak current density $(j_0)$, radial shift of the peak $(\rho)$, and broadness $(\nu)$. The fitted results at $I_p = 20$ kA (at the end of the microwave pulse) is shown in Fig. 3(a).

The poloidal beta, $\beta_p$, is estimated from the values of $\beta_p + l_i/2$ obtained by the magnetic analysis[4] and the internal inductance, $l_i$, calculated from the estimated current distribution, to be in the range of $\beta_p = 1.5 - 2.0$. The contribution of the thermal electrons to $\beta_p$ is estimated to be $\beta_p \leq 0.05$, indicating the presence of energetic electrons. The existence of the energetic electrons are also found in the time evolution of hard X-ray spectra, in which the energy range expands with $I_p$ and is developed up to 200 keV at $I_p = 15$ kA. These suggest that the current is curried mainly by energetic electrons.

The estimated current distribution shows the current outside the last closed flux surface (LCFS) is significant (Fig 3(a)), suggesting that the equilibrium equation for isotropic pressure is not appropriate. We use an equation for anisotropic pressure, $\mathbf{j} \times \mathbf{B} = \nabla \cdot \mathsf{P}$, to study

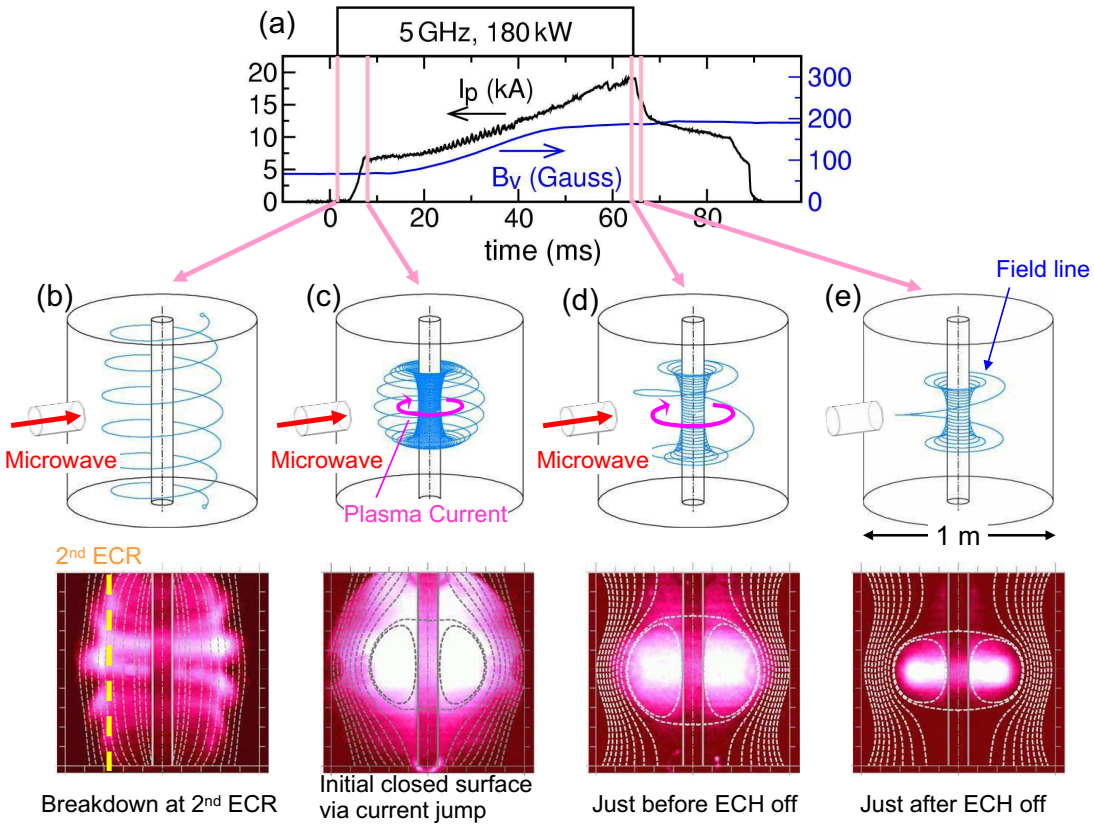


Figure 2: (a) Time evolution of a 20 kA current start-up discharge. (b-d) Field lines and plasma images at (b) just after the microwave injection, (c) initial closed field formation, (d) before ECH pulse off and (e) after ECH pulse off.

details of the equilibrium. where $\mathsf{P} = p_\perp \mathsf{I} + (p_\parallel - p_\perp)\mathbf{bb}$ and $\mathbf{b}$ is the unit vector along a filed line, $p_\parallel \equiv n_e m\langle \gamma v_\parallel v_\parallel \rangle$, $p_\perp \equiv n_e m\langle \gamma v_\perp v_\perp \rangle$, $\parallel$ and $\perp$ denotes the parallel and perpendicular components to the magnetic field respectively, and $\langle\ \rangle$ the average over the velocity space. In a cylindrical coordinate system $(R, \phi, Z)$ with $Z$-axis being the axisymmetric axis of the torus, the $R$ and $Z$ components of the equation together with the constraints $\nabla \cdot \mathbf{j} = 0$ give the 'sum' pressure as shown in Fig. 3(b). Furthermore, the 'sum' pressure is resolved into the parallel and perpendicular pressure profiles by using the $\phi$ component of the equilibrium equation. The radial profiles of pressures on the mid-plane are plotted in Fig. 3(d). The parallel pressure ($p_\parallel$) is much smaller than the perpendicular pressure ($p_\perp$) outside the LCFS, while it becomes comparable at the inside. These suggest that the inside current is mainly carried by passing electrons, while the outside current is carried mainly by trapped electrons as a result of their toroidal precession.

In the final stage of the discharge as shown in Fig 2, the increase of the vertical field turns to be gentle while the plasma current continues to ramp up, the loop voltage at the plasma

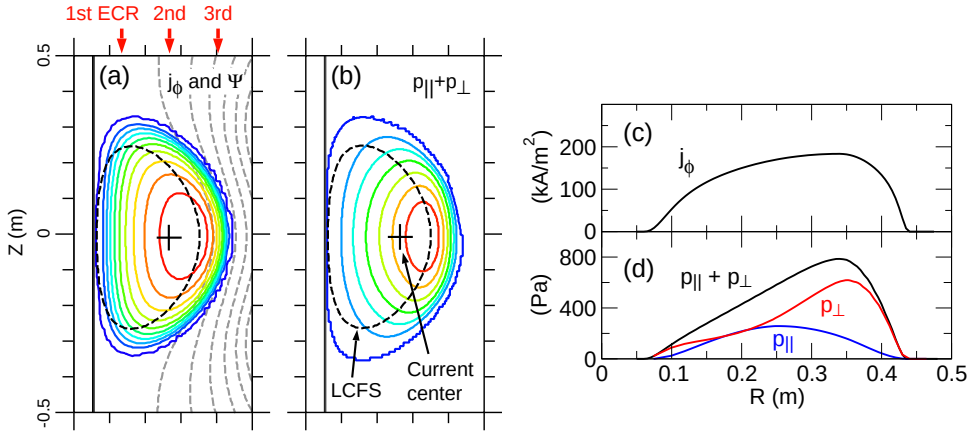


Figure 3: (a) and (b) contours of plasma current density and poloidal flux and 'sum' pressure. (c) and (d) Radial profiles of plasma current density and pressures on the mid-plane.

core becomes significantly negative due to the self induction of the plasma. Thus, the current carrying passing electrons are developed against this large reverse voltage. This suggests the presence of a large forward force via electron cyclotron absorption of high $N_{||}$ EB waves. In the electron cyclotron resonance absorption of waves, the resonance electron gains a parallel momentum and an energy at the ratio $\delta p_{||}/\delta E = N_{||}/c$. Hence, power deposition of high $N_{||}$ waves pushes the resonance electrons forwardly against the reverse electric field.

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