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Spontaneous Formation of Spherical Tokamak Equilibria under Steady Vertical Magnetic Field on the LATE device

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Abstract

In the LATE (Low Aspect ratio Torus Experiment) device, a fully non-inductive plasma current is generated and an equilibrium with closed magnetic flux surfaces is formed by ECH under a steady external vertical magnetic field. The plasma current increases slowly in the early stage of discharge, and suddenly takes a rapid rise, resulting in the formation of a closed flux surface. The experimental results show that the current in the early stage is driven by the electrostatic field arisen from the charge separation under the external magnetic field. A numerical modeling on the confinement of electrons suggests that confinement asymmetry along the field line exists in the velocity space even under the vacuum field and develops quickly as the self-field from the plasma current increases, which may explain the rapid current rise.

Introduction

Spherical Tokamak (ST) concept is considered to be attractive [1], since it can confine high beta plasmas in a compact shape, suggesting that it might realize economic fusion power plant in the future. Recent studies on ST devices verified the physical advantages of low aspect ratio of STs. However, removal of the ohmic heating (OH) solenoid from the central structure is inevitable to realize economic ST plant. Therefore, non-inductive methods to start up the plasma current without OH solenoid are needed. Electron cyclotron heating and current drive (ECH/ECCD) is an attractive candidate for this purpose, since it can realize breakdown and plasma current generation simultaneously only with simple launchers remote from the plasma.

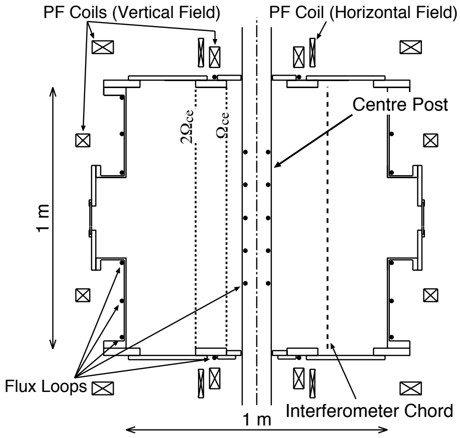

Figure 1: The LATE (Low Aspect ratio Torus Experiment) device.

Main objective of the LATE (Low Aspect ratio Torus Experiment) device (fig. 1) is to demonstrate formation of non-inductive ST plasmas by ECH alone without central solenoid. The vacuum vessel is a stainless steel cylinder with an inner diameter of 1 m and a height of 1 m. The centre post with outer diameter of 11.4 cm encloses 60 turns of toroidal field coils. There are four sets of poloidal field coils: three for external vertical field and one for horizontal field for controlling the vertical position of plasma column. Microwaves (2.45 GHz and/or 5 GHz) are injected for ECH along the mid plane from the weak field side.

Experimental Results

Figures 2 and 3 show a waveform and a time evolution of plasma current profile and poloidal flux distribution of a typical discharge, respectively. The current profile is analyzed by using a model current profile fitted to the observed magnetic flux data. When the 2.45 GHz, 20 kW microwave is injected under a steady vertical magnetic field (shown in fig. 3 - (1)), the pre-filled hydrogen gas pressure decreases quickly, and the plasma current increases slowly (see fig. 2). The current reaches 0.7 kA at $t = 0.412$ s (fig. 2 - (2)), and the current profile has a vertically long profile along the open vertical magnetic field near the second harmonic ECR layer (fig. 3 - (2)). Then the current turns to a rapid increase and the profile expands toward the high field side, with the strong deformation of the flux surface nearby the centre post ($t = 0.4152$ s (3)). By this rapid current rise, I_p reaches 1.8 kA within 2 - 3 ms, then the current profile touches the centre post, and a small closed flux surface is formed in touch with the centre post ($t = 0.4158$ s (4)). After this, the current expands toward the weak field side and are detached from the centre post (5) as I_p increases with growth of the closed flux surface ($t = 0.42$ - 0.60 s). The plasma current rises again at $t = 1.5$ s, and finally reaches 3.3 kA, with the profile spreading to the outer wall ($t = 1.76$ s (6)). The closed flux surface has also grown large.

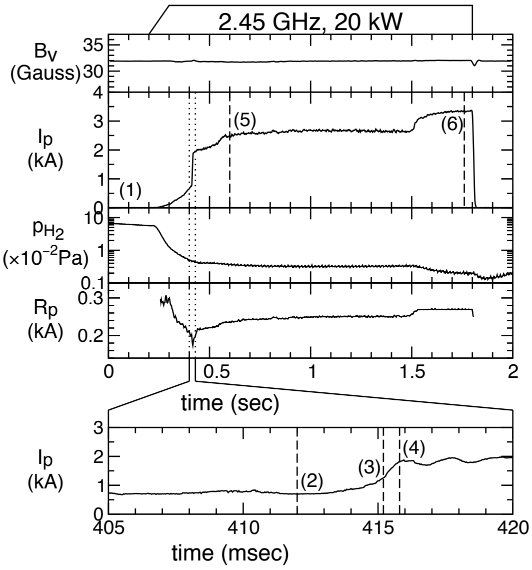

Figure 2: Typical waveform of a discharge.

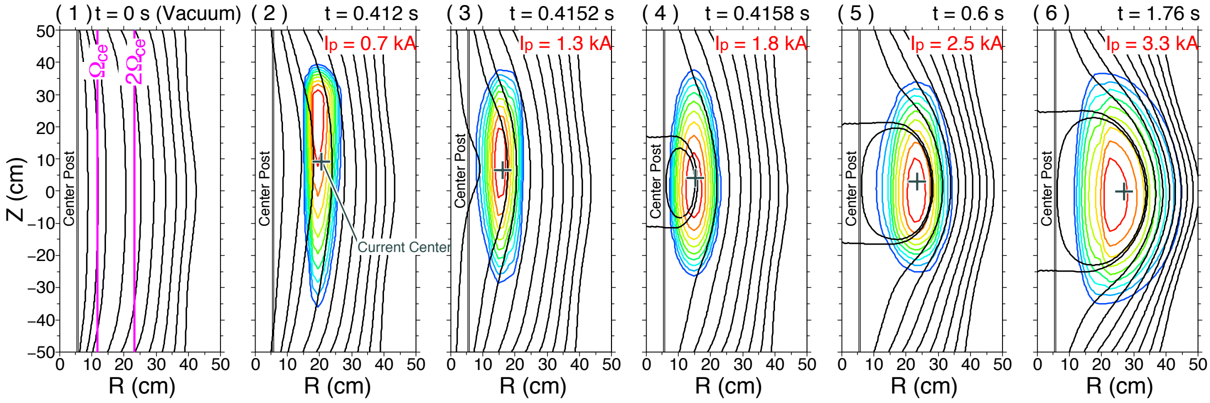

Figure 3: Time evolution of plasma current distribution (color) and poloidal flux (black). The numbers correspond to the time shown in fig. 2.

Initial Plasma Current

It is theoretically predicted that a pressure-driven-current, given by the formula $I_{\mathrm{p}} = 2\langle p\rangle S/RB_{\mathrm{v}}$, is produced to cancel the electrostatic field which arises from the charge separation due to ∇B drift under open vertical magnetic field [2]. Here, $\langle p\rangle$, S and R are the spatially averaged plasma pressure, the plasma cross section and the major radius, respectively. In the experiments conducted under various B_{v} fields at a low microwave power for Langmuir probe measurements, I_{p} at the initial stage of discharges is scaled as $I_{\mathrm{p}} \propto p_{\mathrm{e}}/RB_{\mathrm{v}}$, being consistent with the theory as shown in fig. 4.

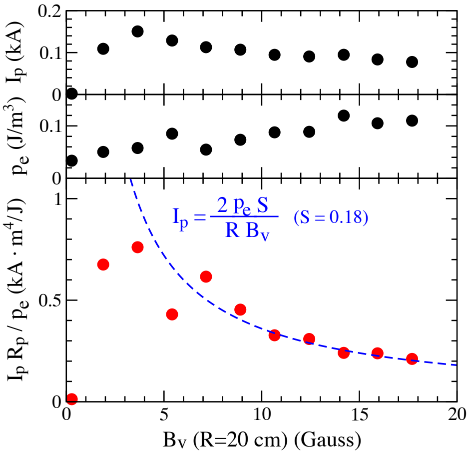

Figure 4: Plasma current just after the breakdown versus the external vertical fields.

Asymmetrical Electron Confinement in Velocity Space

In addition to the pressure-driven-current mechanism under external open fields, there may exist another current generation mechanism that arises from the asymmetric confinement of electrons in velocity space along the field line. The vertical motion of electrons consists of the vertical component of the parallel motion along the field line and the toroidal drift motion. When $B_{\mathrm{v}} \ll B_{\mathrm{t}}$ (B_{t}: toroidal field), the vertical drift velocity (v_{z}) is given by

$$v_{\mathrm{z}} = v_{\parallel}\frac{B_{\mathrm{v}}}{B_{\mathrm{t}}} - \frac{m(v_{\parallel}^2 + v_{\perp}^2/2)}{eRB_{\mathrm{t}}}.$$

When $v_{\mathrm{z}} = 0$, the electron makes a circular orbit along the toroidal field. In the non-relativistic limit, this condition becomes an ellipse in velocity space, given by,

$$(v_{\parallel} - g/2)^2 + v_{\perp}^2/2 = (g/2)^2, \tag{1}$$

where $g = eRB_{\mathrm{v}}/m$. Under the stronger B_{v}, the centre of the ellipse shifts to the higher $v_{\parallel}$, and the axis lengths become longer, and therefore the higher energy electrons are confined.

In the presence of the self-field from the plasma current, the field is deformed and the confinement of electrons may be changed. In order to investigate the electron confinement with the self-field, the orbits of electrons, which start with various velocities and pitch angles at the vessel centre ($R = 25$ cm, $z = 0$ cm), are numerically calculated. The following conditions are assumed in the calculation. (1): The external B_{v} field is mirror shaped with the decay index of $n = -d(\ln B_{\mathrm{v}})/d(\ln R) = 0.1$. The strengths of B_{v} and B_{t} are 30 and 500 Gauss at $R = 25$ cm, respectively. (2): The plasma has the circular cross section with the centre position at $R = 25$ cm and the minor radius of $a = 10$ cm. (3): The plasma current profile is parabolic, and its field on the boundary is $B_{\mathrm{a}} = \mu_0 I_{\mathrm{p}}/2\pi a$.

Figure 5 (a) shows the case with no plasma current ($B_{\mathrm{a}}/B_{\mathrm{v}} = 0$). Because of the mirror shaped external B_{v} field, some electrons are mirror confined in the vacuum vessel. These electrons are distributed around the $v_z = 0$ ellipse and are asymmetric in the parallel direction in the velocity space.

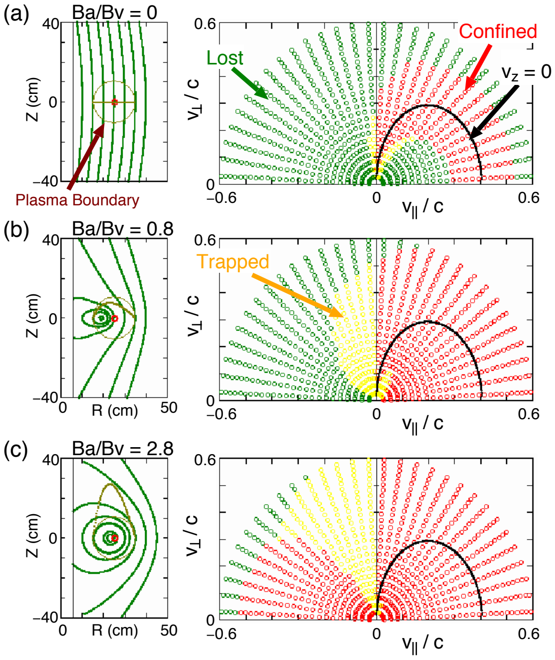

Figure 5: Development of electron confinement area in the velocity space with the self-field from the plasma current.

When the self-field increases to $B_a/B_v = 0.8$, the confinement asymmetry in the velocity space is enhanced under the deformed field with a higher mirror ratio and a small closed flux surface in the high field side (fig. 5 (b)). Especially the low-energy electrons in the positive $v_{||}$ direction becomes all confined and the trapped electron region appears in the negative direction. Since there are many electrons in the low-energy region, the asymmetrical growth of the confinement area in this region may increase the plasma current effectively. This may cause the rapid current rise.

When the self-field increases further ($B_a/B_v = 2.8$), most of electrons in the velocity space are confined or trapped under the large closed flux configuration, as shown in fig. 5 (c). Since the electrons in the negative direction are confined, no more plasma current is generated due to asymmetry in this configuration, and another current-drive mechanism, such as ECCD, is needed.

The mechanism of the electron confinement asymmetry in the velocity space cannot work in collisional plasmas, since the electrons must stay in a closed orbits long enough without change of velocity due to collisions. This mechanism cannot generate plasma current at the initial collisional stage of discharges with high neutral gas pressure, although there exists the asymmetrical confinement area in the velocity space. Therefore, the currents in the initial stages of discharge are generated by the pressure-driven-current, as the Langmuir probe experiments confirmed. When the neutral gas pressure decreases, the asymmetric-electron-confinement mechanism may take place, and the increase of I_p is accelerated with the growth of the self-field in the rapid current rise phase. In the experiments, hard X-ray emission is observed. Especially the energy range just before the rapid current rise where the dominant field is the external one, is increased with B_v in consistent with eq. (1).

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