Observation of toroidal and vertical currents in EC heated plasmas under vertical field in the LATE device

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Non-inductive current drive and formation of a closed flux surface by EC-heating have been studied in the low aspect ratio torus experiment (LATE) device [1-4], which are important for stable start-up and reducing the size of the reactor [5,6]. A model for the non-inductive formation of a closed flux surface in EC-heated toroidal plasmas has been proposed [7]. In a toroidal ECR plasma a vertical charge separation current is generated by the vertical drifts of ions and electrons due to the toroidal field gradient and curvature. Hereafter the vertical drift is referred to as vacuum toroidal field (VTF) drift. The current density is written in terms of local electron and ion pressure p_e and p_i as

$$j_{VTF} = \frac{2(p_e + p_i)}{RB_{\varphi}},$$

where B_φ is the toroidal field at the radial coordinate R in the cylindrical coordinate (R, φ, Z). Here we consider the case of B_φ>0. Since p_e is much higher than p_i in the main part of ECR plasmas, the current density is almost proportional to p_e. When no vertical field is superposed, the vertical charge separation current flows from the bottom to the top and circulates through the vacuum vessel. When a vertical field is superposed, an internal another return path along helical field lines is provided in addition to the external path through the vessel. The vertical component of the internal return current along helical field lines is cancelled and the toroidal component becomes a toroidal current. As the toroidal current increases and its self field is developed, the cross field passing (CFP) orbit electrons which are EC-heated and asymmetrically confined tail electrons increase. These electrons provide an additional toroidal current and a closed flux surface is formed eventually.

We have observed the equilibrium characteristics that maintain discharges in the various toroidal ECR plasmas superposed a steady vertical field in the range of Bv=0G to 10.5G at which a closed flux surface forms. The vacuum vessel of the LATE device is a cylinder with an inner size of R=5.8~50cm and Z=-50~50cm. The top and bottom panels which almost cover the ceiling and the flooring of the vacuum vessel are installed at Z=30cm and Z=-30cm, respectively. A radial array of small electrodes is embedded on the each panel and an ion energy analyzer is attached behind the top panel. Plasmas are generated between the panels using 2.45GHz microwave pulse of 2s. The toroidal field is B_φ=480G at R=25cm in all discharges.

Figure 1 shows plasma images captured by a CCD camera, plasma profiles measured by Langmuir probes, the toroidal current profiles obtained by signals of thirteen flux loops surrounding the vessel (refer to P5 149 in this conference [8]) and radial profiles of the vertical circulation current flowing to the top and bottom panels measured by the radial arrays and ion current flowing to the top panel measured by the ion analyzer in the discharges with Pinj=1.5kW and Bv=0G, 2.7G, 6.8G and with Pinj=2.0kW and Bv=10.5G, respectively. Here Bv denotes the Z-component of external field at R=22cm. The toridal current flowing in the negative φ direction and vertical circulation current through the external path are generated. A closed flux surface is observed in the discharge with Pinj=2.0kW and Bv=10.5G.

In the case of Bv=0G, a vertically uniform electron pressure ridge drives a vertically uniform current by the electron VTF drift and a space potential hill which crosses the field and shifts upward regulates the drift flows of electrons and ions without accumulating charges. [9]

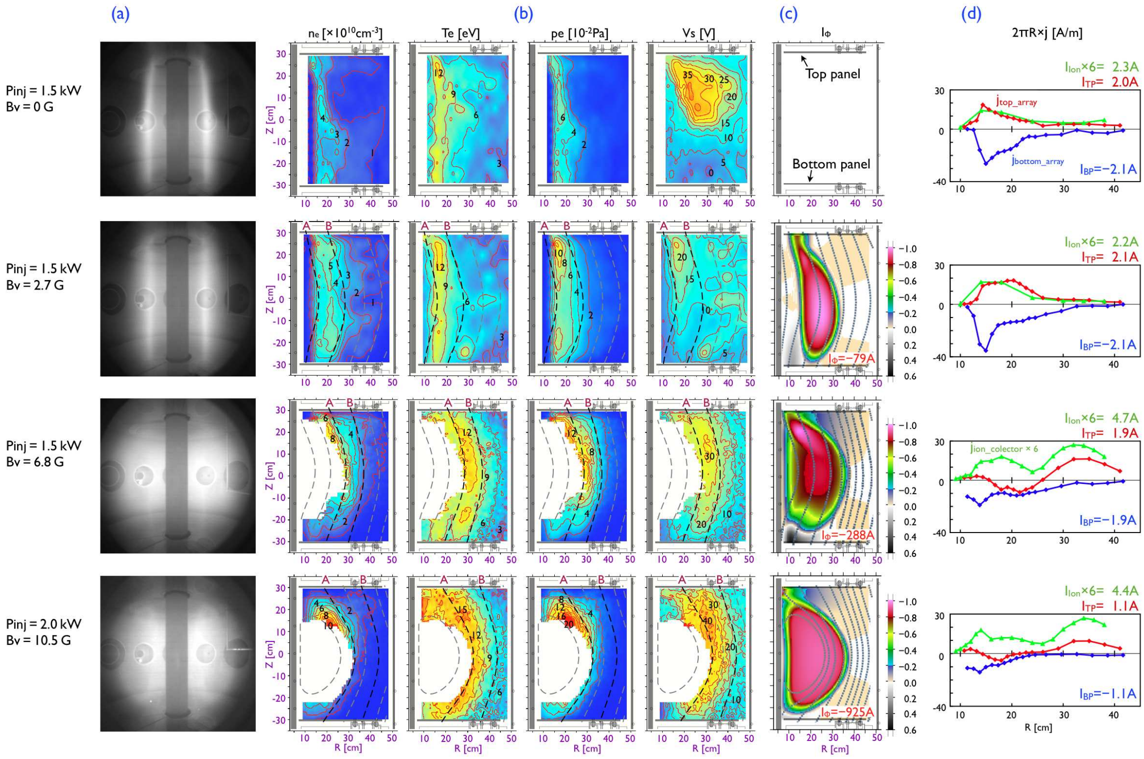

Figure 1 (a) CCD plasma images. (b) Plasma profiles of electron density (ne), temperature (Te) and pressure (pe) and space potential (Vs). The data are not shown when the disturbance of a interferometer line density of the chord Rt=12cm becomes more than 10% by probe insertion. (c) Toroidal current profiles. (d) Radial profiles of vertical circulation current densities on the top and bottom, $j_{top\ array}$ and $j_{bottom\ array}$, and ion current density on the top, $j_{ion\ collector}$. The radial profiles are weighted by 2πR. I_{TP} and I_{BP} are total amounts of current on the top and bottom. I_{ion} is a estimated total amount of ion current on the top.

In the case of Bv=6.8G and 10.5G, as shown in Fig. 1(d), the negative current flowing at R~18cm on the top panel shows there are more electrons flowing along field lines to the panel than the ions flowing by the drifts. The ion's flow by the drift increase at R~32cm on the top panel, where a steep potential slope forms, and I_{TP} and I_{BP} are balanced. The electron density decreases near the bottom panel and the electron VTF drift current is low relative to the current flowing to the panel. The result shows the electron's flow along field lines to the bottom panel decreases the electron density near the panel and the flow contributes to the toroidal current which is opposite direction of the toroidal current in the main part.

The main electron's flow changes from the flow by the drifts across the field to the flow along helical field lines by superposing a week vertical field and the plasma profiles change drastically. The space potential hill across field at Bv=0G is relaxed significantly at Bv=2.7G as shown in Fig. 1(d). Along helical field lines, the electron temperature becomes uniform and the density obeys the Bolzman's law "$n_e \propto \exp\{V_S/T_e\}$" at Bv=6.8G and 10.5G as shown in Fig. 2 . On the other hand ion's flow along helical field lines is much slower than the flow by E×B drift, which is simulated by ion particle orbits (refer to P5 149 in this conference [8]).

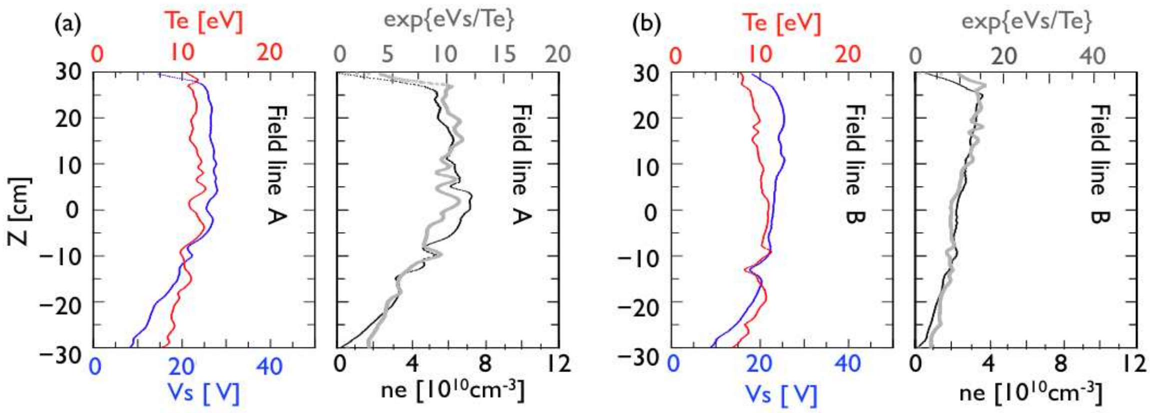

Figure 2 Profiles of electron density and temperature, space potential and the value of Boltzmann's law "exp{eVs/Te}" along field lines (a) A and (b) B in Fig 1(b) in the discharge with Pinj=1.5W and Bv=6.8G.

Figure 3(a) shows that the toroidal current increases linearly with Bv up to Bv=6.8G and increases furthermore at Bv=10.5G where a closed flux surface is formed, while the vertical circulation current is almost constant at about 2A at Bv=0~6.8G and decreases to about 1A after formation of a closed flux surface. The ballooning force of plasma pressure is balanced with the counter forces by the interaction of the toroidal current and the vertical circulation current with the field. Figure 3(b) shows the counter forces roughly estimated as follows (for detailed analyses, refer to P5 149 in this conference [8]).

$$F_{CF}[I_\varphi \times B_Z] = I_\varphi \times B_V \times 2\pi \times 0.25m$$

$$F_{CF}[I_Z \times B_\varphi] = I_{BP} \times 0.048T \times 0.6m$$

The former force due to the toroidal current is estimated using the current of I_φ, the field strength of Bv and the current path length of $2\pi \times 0.25m$ and the later force due to the vertical circulation current is estimated using the current of I_{BP}, the field strength of 480G that is B_φ at R=25cm and the current path length of 60cm that is the plasma height. While the ballooning force of plasma pressure is balanced by only F_{CF} [$I_Z \times B_\varphi$] due to the vertical current at Bv=0G, F_{CF} [$I_\varphi \times B_Z$] increases much larger than F_{CF} [$I_Z \times B_\varphi$] at Bv>5G. The plasma becomes mainly maintained by the toroidal current and the pressure profile should change depending on the toroidal current. Figure 1 shows that as Bv is increased, the electron pressure and the plasma image change from cylindrical profiles to spherical profiles and spread outward in corresponding to the increasing toroidal current and the spreading area of the current profile. The line integrated density along the chord of Rt=12cm increases as shown in Fig. 3(a) and the peaks of electron density, temperature and pressure also rise with increasing the toroidal current as shown in Fig. 1.

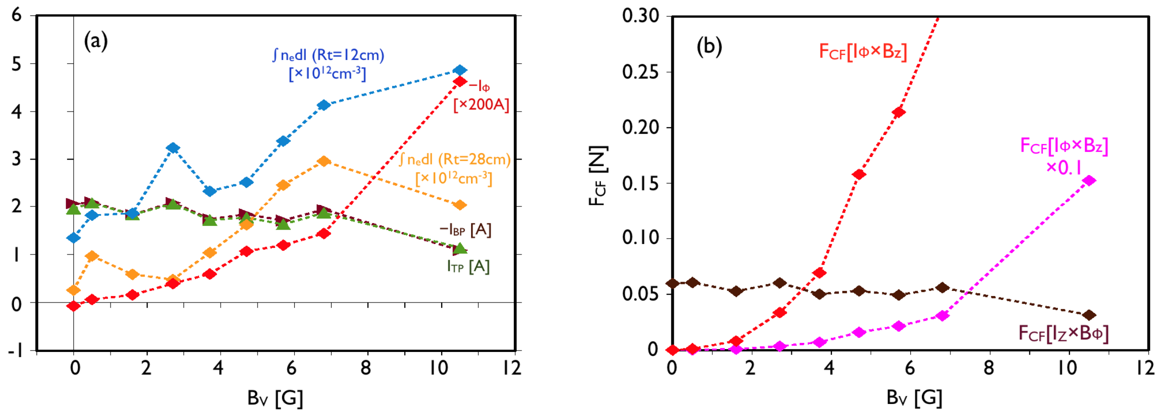

Figure 3 Changes with Bv of (a) the line integrated densities along the mid-plannes chord of Rt=12cm and Rt=28cm, toroidal current, I_φ and vertical circulation current on the top and bottom panels, I_{TP} and I_{BP}, and (b) roughly estimated counter forces by "$I_\varphi \times B_Z$" and "$I_Z \times B_\varphi$".

Acknowledgements

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