§5. Study on Electron Bernstein Wave Heating and Current Drive in High Density Plasmas

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Electron Bernstein (EB) wave is attractive for electron heating and current drive (ECH/ECCD) in a over-dense plasma because conventionally-used electromagnetic waves can not propagate into the over-dense plasma. EB wave is mode-converted from electromagnetic waves at the upper hybrid resonance layer and can propagate without density limit. It can be absorbed by electron cyclotron (EC) damping even in a low temperature plasma. The purpose of this study is to establish the physical basis of mode-conversion, ECH/ECCD by EB wave in torus plasmas through experiments in the LATE device, and to research application to the LHD plasma.

As shown in Figure 1(a), when a microwave pulse (5 GHz, 180 kW, 65 ms) is injected through a circular waveguide-type antenna obliquely to the toroidal magnetic field of Bt = 960 G, toroidal plasma current Ip starts up and ramps up to 20 kA as Bv is increased from 70 G to 185 G, resulting in formation of a spherical tokamak equilibrium without ohmic heating. The electron density exceeds the plasma cutoff density and current distribution encompasses multi-EC resonance layer, which suggest ECH/ECCD by EB

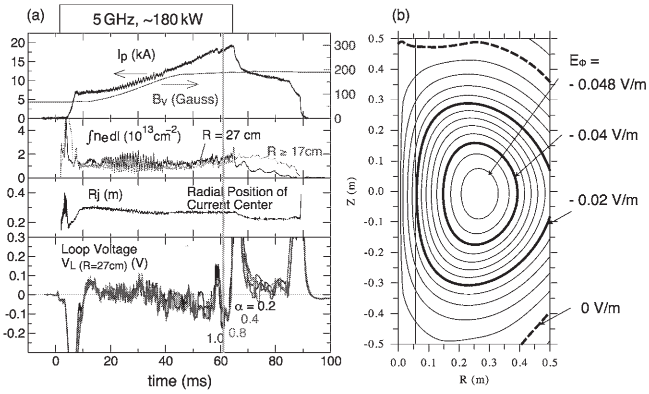

Fig.1 (a) Time evolution of plasma current, density, radial position of current center and loop voltage at the plasma core. (b) Contour plot of toroidal electric field at t = 61 ms calculated from magnetic flux measurement.

wave. Ramp-up rate of Ip is ~300 kA/s, which is comparable to that by lower hybrid current drive. Loop voltage in the plasma core calculated from magnetic flux measurement becomes negative during t = 40 ~ 65 ms. Such negative voltage is induced by the self-induction during the current rise. The inverse electric field at the plasma center is about -0.05V/m at t = 61 ms (Fig. 1(b)). From hard X-ray pulse height analysis, a high energy electron tail is produced with energy range of 100 ~ 200 keV far beyond the runaway critical energy (~ 4 keV). Plasma current is carried by the high energy electron tail. Such high energy tail may be created by EB wave with high refractive index along the magnetic field N// which can push electrons not only perpendicular to the magnetic field but also along the magnetic field against the reverse electric field induced by self-induction.

Poloidal beta βp and energy range factor Cf of the tail electrons are estimated from the magnetic flux measurement. When Ip < 15 kA, Cf increases with Ip. But when Ip > 15 kA, Cf becomes constant. Calculations of single high energy electron orbit without collision show that the maximum energy of electrons going round the torus increases with Ip and exceeds 1 MeV when Ip > 15 kA. These facts imply that the velocity distribution is determined by the confinement property of single particle orbit when Ip < 15 kA, but by the wave N// spectra when Ip > 15 kA.

From the magnetic flux measurement, 1/4 ~ 1/3 of Ip flows in the open field area. In order to satisfy the toroidal equilibrium, the plasma pressure must be anisotropic between the perpendicular and the parallel direction to the magnetic field. A simple model calculation of equilibrium shows that the peak area of parallel pressure p// is near the current center while the peak area of perpendicular pressure p⊥ is nearly outside the last closed flux surface (LCFS) at the low field side on the midplane. This means that the current in the LCFS is carried mainly by passing electrons, but the current outside the LCFS is driven by the toroidal precession of trapped electrons.

Effect of the position of EC resonance layer on the formation of initial closed flux surface by current jump is studied by injecting 2.45 GHz microwave pulses and changing

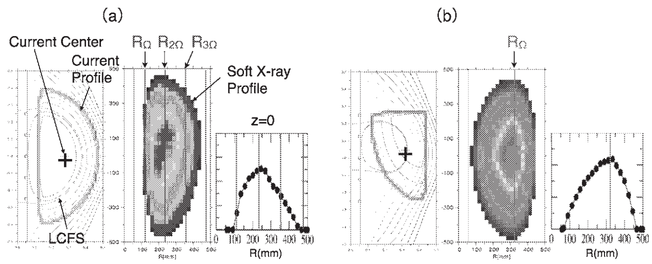

Fig.2 Plasma current, poloidal flux and soft X-ray distribution when the fundamental EC resonance layer is at (a) R = 12.1 cm and (b) R = 32.9 cm.

Bt. When Bt is weak and multi-EC resonance layers up to 3rd harmonics are in the vacuum vessel, the peak area of soft X-ray emission is near the 2nd EC resonance layer (Fig. 2(a)). When Bt is strong and only the fundamental EC resonance is in the vacuum vessel, the peak area moves to the fundamental EC resonance area (Fig. 2(b)). These variation should be caused by the Doppler shifted EC absorption of EB waves.