§15. Physical Mechanism of Self-organization of Novel Density Distribution in a Pure Electron Plasma Driven by Rotating Wave Field

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Observations have been accumulated that demonstrate substantial contribution of azimuthally-rotating radio-frequency (RF) electric fields to the reduction of radial particle losses and sometimes to the compression of the radial distribution of non-neutral plasmas. Physical mechanism of this "rotating-wall technique" [1] has not been well clarified in spite of its implications in fundamental plasma physics as well as in understanding processes involved in improved confinement in fusion-oriented plasmas.

The purpose of this collaboration program is to precisely examine details involved in the RF-driven transport phenomena toward the integration of the whole processes into a unified model. The experimental advantage of high controllability, high confinement properties and high resolution diagnostics inherent to pure electron plasmas has led us to the construction of a clear model as proposed in this report.

Technical achievements in FY2004 are,

(1) Improvement of mode-selectivity of rotating electric field and widening of the ramp-up width of the RF frequency from 0.1 -2MHz to the new range of 0.1-40MHz.

(2) Extension of the magnetic field strength from B< 0.05T to B<2.2T.

(3) Improvement in the capability of correlation analyses of experimental data.

Relevant observations include the following,[2]

(1) It is found that, as the frequency of the rotating electric field is ramped-up linearly in time, the on-axis density increases in such a way that the wave frequency normalized by the on-axis plasma frequency goes down to eventually be locked at a small number that corresponds to an eigen frequency of Trivelpiece-Gould mode that has a global radial structure satisfying the boundary condition.

(2) The wave signals in the downstream are heavily attenuated while the on-axis density goes up. This observation suggests that the radial transport process includes Landau-damping, resonant interaction parallel to the magnetic field.

(3) The electric field rotating in the direction of the equilibrium $E \times B$ drift drives inward flux. The direction of the radial flux is reversed when the sign of the azimuthal mode number changes. The outward flux forms a flattened density distribution that drops abruptly to zero at the expanding boundary.

A theoretical model [3] is constructed on the basis of the experimental studies. The key points are summarized as follows:

(1) The essential features are described by the drift-kinetic equation that include resonant wave-particle interactions in the axial direction (i.e. Landau-damping on warm plasma), equilibrium azimuthal rotation $\omega_r(r)$ with radial shear associated with observed density profile, and guiding-center drifts of the particles in the transverse plane.

(2) The RF voltages applied to the azimuthally-segmented wall generate a Trivelpiece-Gould mode wave that satisfies the wave equation constructed on the basis of the drift-kinetic equation and the Poisson equation under the condition of the observed density profile that is surrounded by the conducting wall. The wave function as a solution has a unique spatial structure that maintains its global shape under the axial dissipation due to Landau damping.

(3) Particles axially running resonantly with the wave suffer resonant $E \times B$ drift in the radial direction due to the azimuthal wave field. The average of the microscopic drift leads to the expression of radial flux.

$$\Gamma = \frac{\pi e n_0 \ell |\phi|^2}{2mBr} \left\{ \frac{\partial \hat{f}_0}{\partial v} - \frac{\ell}{kr\omega_c} \frac{1}{n_0} \frac{\partial n_0}{\partial r} \hat{f}_0 \right\}_{v=(\omega-\ell\omega_r)/k}$$

where ℓ is the azimuthal mode number.

(4) The increment of the potential energy dU due to the radial flux is found to be equal to the work exerted by the torque of the azimuthal electric field to the macroscopic body of the plasma.

(5) Within a radial shell between r and $r+dr$ the wave energy dW is converted to the axial kinetic energy dK and to the potential energy dU at the ratio of $dK/dU = (\omega - \ell\omega_r)/\ell\omega_r$. We also obtain a relation $d(K+U+W)/dt = 0$, indicating that the damped energy of the wave is totally converted to the axial heating of the particles an to the radial compression that leads to the increase in the potential energy.

The theoretical model successfully provides a closed scenario of the wave-driven compression process.

References

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2) Soga, Y., et al. Contributed paper in *12th International Congress on Plasma Physics*, Nice 2004/10/25-29.
3) Kiwamoto, Y., Soga, Y. and Aoki, J., submitted for publication in Phys. Plasmas (May, 2005).