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Suprathermal Electron Effects on ECRH Deposition Profile and Ambipolar Flux in W7-AS

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Abstract

First Monte Carlo simulations in 5D phase space were carried out to study kinetically the ECRH generated suprathermal electrons in W7-AS. The important role of the radial transport of suprathermal electrons in the broadening of the ECRH deposition profile is clarified. The ECRH driven flux is also evaluated and put in relation with the "electron root" feature recently observed in W7-AS. It is found that, at low collisionalities, the ECRH driven flux due to the suprathermal electrons can play a dominant role in the condition of ambipolarity.

Keywords:
suprathermal electrons, ECRH, deposition profile, ambipolar fluxes, stellarator, W7-AS, Monte Carlo

1. Introduction

In stellarators, the particles trapped in a local field ripple tend to drift away from the starting magnetic surface. Therefore, at low collisionalities, ECRH-heated suprathermal electrons can drift radially before being collisionally detrapped and thermalized. The deposition profile of the absorbed ECRH power will generally be broader than the peaked "birth profile" usually predicted by ray-tracing. The existence of a "broad component" in the deposition profile was verified at W7-AS by the analysis of power modulation experiments[1].

Recently, a stronger positive radial electric field, E_r, has been measured in the central plasma region in W7-AS[2,3]. The experimental heat diffusivity becomes much lower than the neoclassical one for $E_r \simeq 0$, leading to highly peaked central electron temperatures (up to 4 keV). The experimental findings strongly suggest a connection between the "electron root" feature and the ECRH driven flux mainly due to the drift motion of ripple-trapped suprathermal electrons.

These facts have put a considerable interest in a quantitative analysis of the ECRH driven transport and its effect on the deposition profile and on the ambipolarity condition. In this paper we study the kinetic effect by suprathermal electrons on ECRH deposition profile and ambipolar flux in W7-AS using a newly developed 5D Monte Carlo simulation code[4,5].

2. Simulation Model

The linearized drift kinetic equation for the deviation of the distribution function from the Maxwellian, $\delta f(x, v_{\parallel}, v_{\perp})$,

$$V(\delta f) = C(\delta f) + S^0_{\mathrm{ql}}, \tag{1}$$

where $V = (v_{\parallel} + v_{\perp}) \cdot \nabla_x + \dot{v} \cdot \nabla_v$, $C(\delta f)$ is the linear

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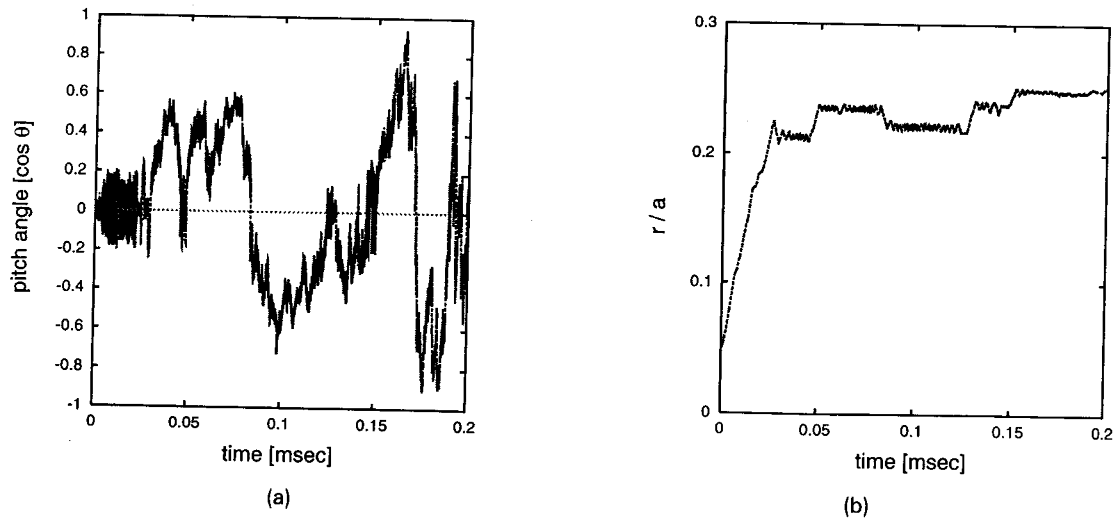

Fig. 1 Time history of the pitch angle and averaged radial position of a test suprathermal electron with a initial energy of 10 keV. The collisional time for this electron is about 0.36 msec. [T_0 = 2 keV, n_0 = 2.0 × 10^{13} cm^{-3}].

Coulomb collision operator and $S^0_{\rm ql}$ is the quasi-linear diffusion term describing ECRH (assumed to be a given function and evaluated by ray-tracing), is solved based on a technique similar to the adjoint equation for dynamic linearized problems. The deviation δf is evaluated as,

$$\delta f(x, v) = \int_0^\infty {\rm d}t \int {\rm d}x' \int {\rm d}v' \; S^0_{\rm ql}(x', v') g(x, v, t|x', v'), \quad (2)$$

where The time dependent Green function $g(x, v, t|x', v')$ is the solution of the drift kinetic equation, $\frac{\partial g}{\partial t} + V(g) = C(g)$, with initial condition $g(x, v, t = 0|x', v') = \delta(x - x')\delta(v - v')$. The function g is obtained using the Monte Carlo simulation in which the complex magnetic field configuration and the radial electric field can be included.

3. Effect on ECRH Deposition Profile

First we analyze the (collisional) orbit of a test suprathermal electron in W7-AS (standard magnetic field configuration). Figure 1 shows the time history of the pitch angle and averaged radial position of a typical suprathermal electron born in the ECRH launching plane with an initial energy of 10 keV. As time passes, the electron energy was slowed down and the pitch angle scattered by Coulomb collisions. The fast oscillations of the pitch angle across the zero line indicate that the test electron has become trapped. One can see that when trapped the test electron tends to drift radially. This confirms the fact that trapped orbits play the main role in the radial transport of suprathermal electrons.

We can also see this fact by looking at the distribution function δf (the deviation from the Maxwellian). Figure 2 shows the isosurface plots of (magnetic surface averaged) δf in the dimensional space (r, $v_\perp$, $v_\parallel$). The lower (upper) surfaces show the negative (positive) regions of δf, respectively. ECRH tends to push resonant electrons towards higher perpendicular energies, consequently a depletion (with respect to the Maxwellian) tends to appear at lower energies and a tail at higher energies. Interestingly, we can see a "nose-like structure" at the upper surface. This is related to the radial

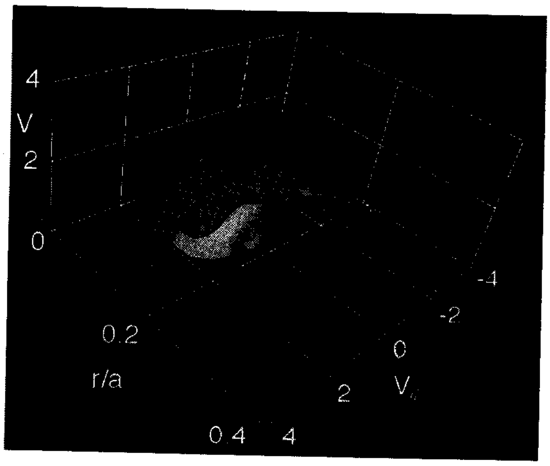

Fig. 2 Isosurface plots of the distribution δf (the deviation from the Maxwellian driven by ECRH).

(convective) transport of the trapped energetic particles. This confirms that trapped suprathermal electrons are mainly responsible for radial transport.

Using obtained distribution δf, we can evaluate the ECRH deposition profile. Figure 3 shows the comparison of the experimental and numerical results for X-mode 2nd-harmonic ECRH in the standard configuration. In Fig. 3(a) the dashed and solid lines refer to the experimental results n_0=1.0 and 2.0 × 10^{13} cm^{-3}, respectively[1]. Fig. 3(b) shows the prediction of ray-tracing and Monte-Carlo, for the same plasma parameters. We can see a relatively good agreement between the experimental and numerical results. This confirms the importance of radial convection of suprathermal electrons in the ECRH deposition profile broadening.

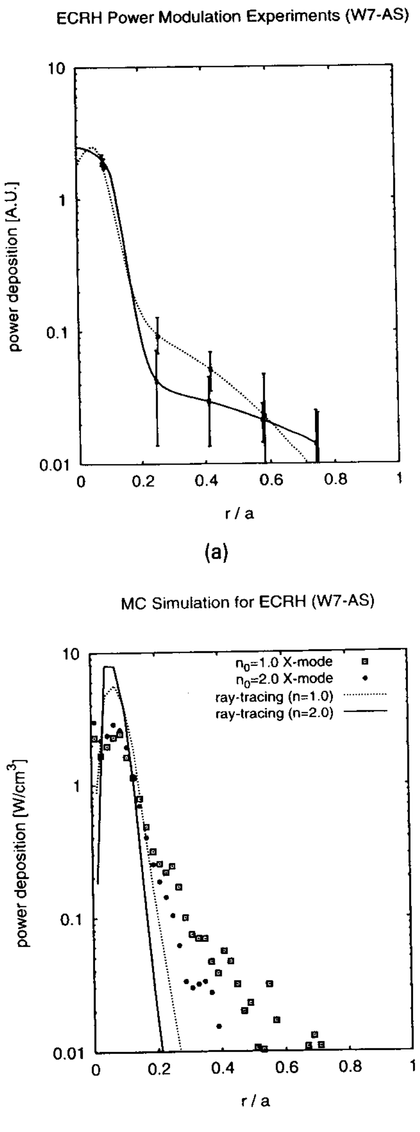

Fig. 3 ECRH deposition profile. (a) experimental (b) predicted: ray-tracing (lines) and Monte Carlo (symbols). The dotted lines and the open squares refer to n_0 = 1.0 × 10^{13} cm^{-3}, while the full line and the closed circles to n_0 = 2.0 × 10^{13} cm^{-3}, respectively.

4. Effect on Ambipolarity Condition

Next we consider the effect on the ambipolar fluxes in relation with the "electron root" experiments at W7-AS. The "electron root" feature was only observed in low density discharges with high power ($\geq$400 kW) X-mode 2nd-harmonic ECRH and, up to now, could not be driven by O-mode 1st-harmonic. Figure 4(a) shows the simulations of the radial profile

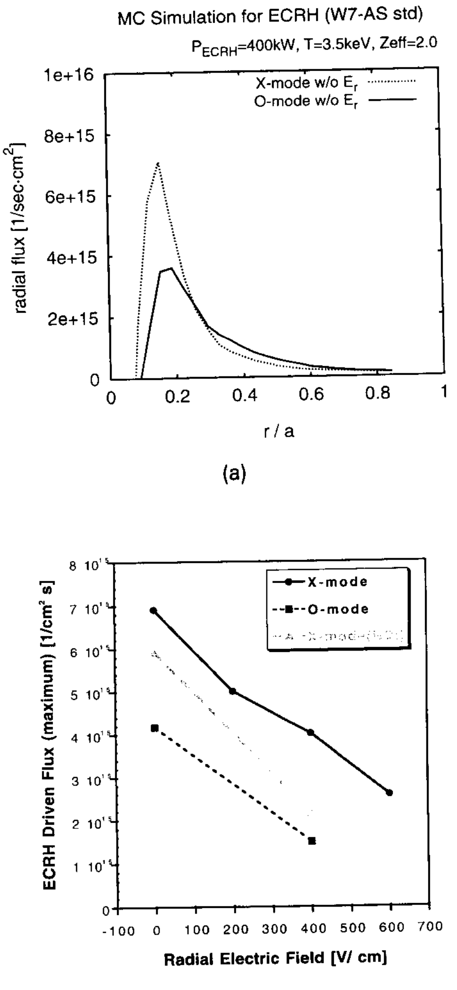

Fig. 4 ECRH driven electron flux. (a) comparison of the radial profile for X- and O-mode cases, and (b) E_r dependencies of the maximum value of the driven flux.

of the ECRH driven electron flux for the two polarizations. It is found that, in the central plasma region, the ECRH driven flux for the X-mode case is about 2 times higher than that for O-mode. This is related to the different absorption mechanism for the two polarizations. The X-mode is mainly absorbed by deeply trapped particles (maximum of absorption by resonant electrons with $v_{\parallel} \simeq 0$), while the absorption for perpendicularly injected O-mode, requiring finite values of $v_{\parallel}$, is shifted towards the passing particle region[1]. In the O-mode case, no "nose-like structure" (as that in Fig. 2) appears in δf. The X-mode polarized waves, injected perpendicularly from low-field-side, are strongly absorbed close to the resonance. O-mode waves, due to the lower absorption, can propagate further and deposit part of their power to electrons of higher energies. This is responsible for the fact that the O-mode driven flux in Fig. 4(a) is broader than the X-mode case.

The ECRH driven flux depends on the radial electric field itself. To study this dependence we introduced an E_r profile similar to the one observed in the "electron root" experiments. The dependence of the maximum value of the ECRH driven flux on E_r is shown in Fig. 4(b) for the standard configuration (two polarizations) and for a "neoclassically improved configuration" without trapped electrons in the ECRH launching plane (X-mode). The largest electron flux is found in the case of X-mode for the standard configuration. Interestingly, the E_r dependency seems to be weaker than that of the neoclassical flux which is proportional to $E_r^{-3/2}$.

Figure 5 shows the comparison of the ECRH driven flux and the ambipolar neoclassical fluxes obtained by the DKES code. The full and dashed lines show the X-mode ECRH driven flux for the case without and with a strong positive E_r, respectively. The circles refers to the DKES results. We can see that the ECRH driven flux is comparable to the ambipolar neoclassical thermal one with the ion root and dominates at higher E_r. The validity of standard neoclassical theory in case of strong E_r is analyzed in Ref. [3].

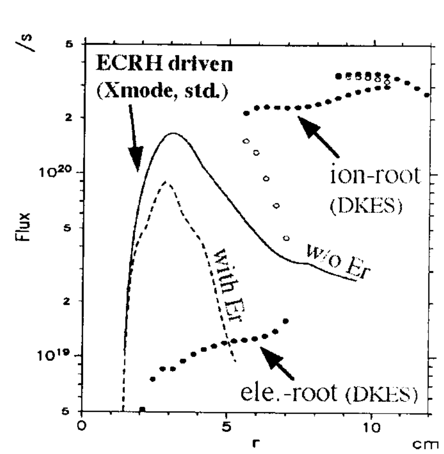

Fig. 5 Comparisons of the simulation results of the ECRH driven fluxes with DKES results (standard neoclassical theory).

5. Conclusion

The kinetic effects of ECRH generated suprathermal electrons have been studied in W7-AS using a 5D Monte Carlo code. The orbit analysis and the distribution δf clearly show the important role of the radial (convective) transport of trapped suprathermal electrons driven by the ECRH. The simulated broadening of the ECRH deposition profile is found to be in relatively good agreement with the experimentally inferred one.

The code was also applied to evaluate the ECRH driven flux in the "electron root" experiments at W7-AS. Simulation results show that in the central plasma region X-mode 2nd-harmonic ECRH is more "efficient" than O-mode 1st-harmonic in driving radial electron fluxes. This could explain why the "electron root" (and the related improvement of confinement) was experimentally found only for X-mode. Comparisons with neoclassical predictions (DKES code) have shown the dominant role played by the ECRH driven flux in the ambipolarity condition for the central region where the strongly positive E_r is experimentally observed.

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