ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received - Jan. 20, 1999)

NIFS-582 Feb. 1999

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

Self-Consistent Electric Field Effect on Electron Transport of ECH Plasmas

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Abstract

An algorithm is proposed which treats the ECH generated potential in a self-consistent way, by extending the Monte-Carlo Fokker-Planck method used by Murakami [S. Murakami et al., Proc. 17th IAEA Fusion Energy Conference, Yokohama, 1998 (International Atomic Energy Agency, Vienna, in press), paper CN-69/TH2/1]. The additional physics is expected to influence the transport of both thermal and suprathermal electrons in a helical toroidal system.

keywords; electric field, electron transport, ECH plasma, helical system

1. Introduction

The creation of poloidal electric field by cyclotron waves has been suggested by Hsu *et al.* [1] as an explanation of the modification in transport in electron cyclotron heated (ECH) tokamak plasmas. The tip of the banana orbits of heated trapped particles tend to localize to the resonance surface. Since different trapped particles are heated differently, this results in a poloidally varying pile up or poloidal variation in charge density. Ambipolarity requirement leads to the formation of poloidal electric field. It is conjectured that the resulting $E \times B$ drift can modify particle transport by enhancing the ion vertical drift. The physical picture proposed pertained to a collisionless (banana) regime. In a second paper, Chan and Wong [2] showed that a similar poloidal electric field generation can occur in a collisional plasma through a combination of the localized nature of ECH and the Doppler resonance. This paper used an adjoint method which allows the treatment of the quasilinear operator in more detail, although still in the weak rf limit. The same adjoint method was employed by M. Taguchi [3] to derive a unified treatment for both regimes. All three papers only conjectured the impact on transport, without presenting calculations to substantiate the expectation.

ECH plays an equally important role in non-axisymmetric toroidal systems. ECH was used on W7-AS [4] for confinement studies, where the bootstrap current was canceled by use of

ECH, and ECCD was used to control the shear profile. ECH has been a reliable electron heating method for both W7-AS and CHS [4], and will be used extensively in LHD. In non-axisymmetric devices, the particles trapped in the helical ripples can drift away from the starting magnetic surface resulting in radial transport which dominates over other processes. The contribution of thermal particles to radial transport can be evaluated from neoclassical theory [5]. A radial electric field can be obtained by balancing the neoclassical fluxes. Neoclassical theory alone apparently is not sufficient to explain results of ECH plasmas on W7-AS. In particular, the radial electric field is too small compared with experimental measurements which featured an "electron root" [5]. In a recent study, Murakami *et al.* [6], using a 5-D Monte-Carlo simulation, investigated the contribution of suprathermal electrons to the radial transport during ECH. They found that the ECH induced fast electron radial flux is large and outward which, when balanced with the neoclassical fluxes, should lead to a larger radial electric field. This result is very encouraging and suggests that further refinement may lead to a quantitative predictive theory.

So far, the Monte-Carlo study considered only radial electric field effect. The poloidal and toroidal electric field and the full effect of the electric potential on the trapped particles have been left out. As pointed out in Ref. 3, the magnitude and sign of the electric potential are sensitive functions of ECH. This can have a significant influence on both the thermal and suprathermal transport. In this report, we propose a method to extend the Monte-Carlo approach to account for the 3-D electric potential effect. Following Ref. 6, a weak rf approximation is assumed. This restricts the rf as an energy (and momentum) source to the electrons but does not directly impact their trajectories. To this we add a self-consistent electric potential generated by ECH due to the asymmetric perturbation on the magnetic surface. The radial electric field is still left as a parameter to be determined by balancing the ECH induced flux and neoclassical fluxes. In principle, the self-consistent potential should be included in the evaluation of all three fluxes, *i.e.,* the rf induced flux and both the ion and electron neoclassical fluxes, since it affects both the thermal and suprathermal particles.

In Section 2, the appropriate guiding-center drift equations are set up for non-axisymmetric 3-D systems. Section 3 describes the derivation of the self-consistent electric potential generated by ECH. The summary in Section 4 discusses the implementation of this scheme.

2. Guiding-Center Drift Equations

The derivation of the guiding-center drift equations can be readily found in the literature. However, because the 3-D nature of the electric potential has not been emphasized, the full set of equations appropriate for our purpose is not usually employed. We present the derivation here following the

Hamiltonian approach of White [7] including some details to guide the readers.

In the derivation, covariant representation of **B**,

$$\mathbf{B} = g(\psi_{\mathrm{p}})\nabla\zeta + I(\psi_{\mathrm{p}})\nabla\theta + \delta(\psi_{\mathrm{p}},\theta)\nabla\psi \ ,$$

and contravariant form

$$\mathbf{B} = \nabla\left[\zeta - g(\psi_{\mathrm{p}})\theta\right] \times \nabla\psi_{\mathrm{p}} \ , \qquad (2)$$

are used. The Hamiltonian is the energy

$$H = \frac{1}{2}\rho_{\parallel}^2 B^2 + \mu B + \Phi \ , \qquad (3)$$

where $\rho_{\parallel} = \mathrm{v}_{\parallel} / B$ is the "parallel gyroradius." The canonical variables are P_ζ, P_θ, ζ, θ_{c} with

$$P_\zeta = g\rho_{\parallel} - \psi_{\mathrm{p}} \ ,$$

$$P_\theta = I\rho_{\parallel} + \psi \ ,$$

$$\theta_{\mathrm{c}} = \theta - \frac{\rho_{\parallel}\delta}{q} \ , \qquad (4)$$

and g, I, δ, ψ_{p}, ζ, θ, $q(=d\psi/d\psi_{\mathrm{p}})$, are magnetic coordinate variables. The equations of motions are

$$\frac{\partial\zeta}{\partial t} = \frac{\partial H}{\partial P_\zeta} \ , \qquad \frac{\partial P_\zeta}{\partial t} = -\frac{\partial H}{\partial\zeta} \ ,$$

$$\frac{\partial\theta_{\mathrm{c}}}{\partial t} = \frac{\partial H}{\partial P_\theta} \ , \qquad \frac{\partial P_\theta}{\partial t} = -\frac{\partial H}{\partial\theta_{\mathrm{c}}} \ . \qquad (5)$$

Note that $\mathbf{A} = \psi\nabla\theta - \psi_{\mathrm{p}}\nabla\zeta$, so the canonical momentum as defined in Eq. (4) is $P = p + A$ as in classical electrodynamics.

To expand Eq. (5) in terms of the magnetic coordinate variables, we combine the first two equalities in Eq. (4) to eliminate $\rho_{\parallel}$, and then differentiate with respect to the canonical momenta to obtain

$$\frac{\partial\psi_{\mathrm{p}}}{\partial P_\theta} = \frac{g}{D} \quad \text{and} \quad \frac{\partial\psi_{\mathrm{p}}}{\partial P_\zeta} = -\frac{I}{D} \ , \qquad (6)\,(1)$$

where $D = gq + I + \rho_{\parallel}(gI' - Ig')$, and the prime indicates differentiation with respect to the argument. Differentiating the first two equalities in Eq. (4) in turn by the canonical momenta, and using Eq. (6), we also obtain

$$\frac{\partial\rho_{\parallel}}{\partial P_\theta} = \frac{1-\rho_{\parallel}g'}{D} \quad \text{and} \quad \frac{\partial\rho_{\parallel}}{\partial P_\zeta} = \frac{q+\rho_{\parallel}I'}{D} \ . \qquad (7)$$

Expanding the RHS of Eq. (5) systematically and using Eqs. (6) and (7),

$$\frac{\partial\zeta}{\partial t} = \rho_{\parallel}B^2\frac{1-\rho_{\parallel}I'}{D} - \left(\mu + \rho_{\parallel}^2 B\right)\frac{\partial B}{\partial\psi_{\mathrm{p}}}\frac{I}{D} - \frac{I}{D}e\frac{\partial\Phi}{\partial\psi_{\mathrm{p}}} \ ,$$

$$\frac{\partial\theta_{\mathrm{c}}}{\partial t} = \rho_{\parallel}B^2\frac{1-\rho_{\parallel}g'}{D} - \left(\mu + \rho_{\parallel}^2 B\right)\frac{\partial B}{\partial\psi_{\mathrm{p}}}\frac{g}{D} + \frac{g}{D}e\frac{\partial\Phi}{\partial\psi_{\mathrm{p}}} \ ,$$

$$\frac{\partial P_\zeta}{\partial t} = -\left(\mu + \rho_{\parallel}^2 B\right)\frac{\partial B}{\partial\zeta} - \frac{\partial\Phi}{\partial\zeta} \ ,$$

$$\frac{\partial P_\theta}{\partial t} = -\left(\mu + \rho_{\parallel}^2 B\right)\frac{\partial B}{\partial\theta} - \frac{\partial\Phi}{\partial\theta} \ . \qquad (8)$$

These four equations are complemented by the drift across the flux surface

$$\frac{\partial \psi_p}{\partial t} = -\frac{I}{D}\frac{\partial P_\zeta}{\partial t} + \frac{g}{D}\frac{\partial P_\theta}{\partial t} . \tag{9}$$

and the parallel drift

$$\frac{\partial \rho_{\parallel}}{\partial t} = \left[\frac{(\partial P_\zeta / \partial t) + (\partial \psi_p / \partial t)}{g}\right] - \frac{g'}{g^2}\frac{\partial \psi_p}{\partial t}\left(P_\zeta + \psi_p\right) . \tag{10}$$

In Eq. (8), terms of $O(\delta)$ have been neglected and in Eqs. (9) and (10), terms of $O(\rho_{\parallel})$ have been dropped.

We note that the variations of B and Φ in all three dimensions in physics space are accounted for in Eq. (8). In Murakami *et al.* [6] only the radial electric field, $-\partial\Phi/\partial\psi_p$ is self-consistently determined by balancing the fluxes using ambipolarity. We propose here a way to determine $-\partial\Phi/\partial\zeta$, $-\partial\Phi/\partial\theta$ as an ECH effect. The inclusion of these two terms changes $\partial P_\zeta / \partial t$ and $\partial P_\theta / \partial t$ which in turn changes $\partial \psi_p / \partial t$ through Eq. (9). Radial transport occurs when the rates of change of the canonical momenta are irreversibly changed by Coulomb collisions, boundary conditions, and wave-particle resonance. Reference 6 treated the first two mechanisms but not the third. The same assumption will be used in the proposed extension. Examination of the last two equations in Eq. (8) also shows that when $e\Phi / T \cong L_\Phi / L_B$, where L_Φ is the local gradient of the potential and L_B is that for the helical ripple, the electric potential can begin to significantly influence transport of the thermal particles. This is especially important for quasi-helical and quasi-axisymmetric systems where thermal particle neoclassical transport due to helical ripples is being minimized. Even larger potential will also influence the suprathermal particles. Another effect Φ has is on the turning point of the trapped particles given by Eq. (3). Depending on the variation and sign, it can shift the banana orbits away from its original position in a favorable or unfavorable way. This effect on the trapping boundary is expected to impact both thermal and suprathermal particles.

3. ECH Produced Electric Potential

In the derivation of the self-consistent electric potential, we use the following argument to simplify the starting equation. Because of the nature of electron cyclotron resonance, particles with energy close to the thermal energy are resonantly heated by the waves in the quasilinear approximation. According to the physical picture in Refs. 1–3, these particles are responsible for creating the density and temperature perturbation on a flux surface which leads to the formation of an electric potential to satisfy ambipolarity. Unlike very energetic particles, the drift velocity across flux surface for these particles is small compared with the velocity along the magnetic field. We can thus linearize the drift-kinetic equation for electron accordingly,

$$\begin{aligned} & \mathrm{v}_{\|}\mathbf{b}\cdot\nabla f_{\mathrm{e}1} - C(f_{\mathrm{e}1}) \\ & \quad = -q_{\mathrm{e}}\,\mathrm{v}_{\|}\mathbf{E}\cdot\mathbf{b}\,\frac{\partial f_{e0}}{\partial w} + Q_{\mathrm{rf}}(f_{\mathrm{e}0}) \\ & \qquad - \mathbf{v}_{\mathrm{De}}\cdot\nabla f_{\mathrm{e}0} - \frac{\partial f_{e0}}{\partial t}\ , \end{aligned} \tag{11}$$

with $w = m_{\mathrm{e}}\mathrm{v}^2/2$, μ and $\sigma = |\mathrm{v}_{\|}|/\mathrm{v}_{\|}$ as independent variables in velocity space, $\mathbf{b} = \mathbf{B}/|B|$, $\mathrm{v}_{\|} = \mathbf{b}\cdot\mathbf{v}$, $\mathrm{v}_{\perp} = (\mathrm{v}^2 - \mathrm{v}_{\|}^2)^{1/2}$, C is the Coulomb operator, Q_{rf} is the quasilinear rf operator, $\mathbf{E} = -\nabla\Phi$, and $\mathbf{v}_{\mathbf{De}} = (\mathrm{v}_{\|}^2 + \mathrm{v}_{\perp}^2/2)/\Omega_{\mathrm{ce}}\mathbf{B}\times\nabla B/B^2$. We note that Ω_{ce} carries the sign of charge and

$$\mathbf{E}\cdot\mathbf{b} = -\mathbf{b}\cdot\nabla\Phi = -\frac{B^\theta}{B}\left(\frac{\partial\Phi}{\partial\theta} + q\frac{\partial\Phi}{\partial\zeta}\right).$$

Introducing an adjoint equation[2]

$$\begin{aligned} & \mathrm{v}_{\|}\mathbf{b}\cdot\nabla g^e_{mn} + C\left(g^e_{mn}\right) \\ & \quad = -\nu_{\mathrm{ee}} f_{\mathrm{e}0} B^\theta e^{-i(m\theta - n\zeta)} \oint \frac{d\theta d\zeta}{B^\theta}\ , \end{aligned} \tag{12}$$

with $B^\theta = \mathbf{B}\cdot\theta$, we can multiply Eq. (12) by $f_{\mathrm{e}1}/f_{\mathrm{e}0}$ and average over a flux surface, with flux surface averaging defined by

$$\langle A\rangle = \oint d\theta d\zeta \frac{A}{B^\theta} \Big/ \oint \frac{d\theta d\zeta}{B^\theta}\ .$$

Upon integrating by parts and making use of the adjoint property of the Coulomb collision operator and Eq. (11) the left-hand side of Eq. (12) becomes

$$\begin{aligned} \mathrm{LHS} = & -\Bigg\langle \int d^3\mathrm{v} \\ & \times\left(Q_{\mathrm{rf}} - \mathbf{v}_{\mathrm{De}}\cdot\nabla f_{\mathrm{e}0} - \frac{\partial f_{e0}}{\partial t}\right)\frac{g^e_{mn}}{f_{\mathrm{e}0}}\Bigg\rangle \\ & + \nu_{\mathrm{ee}} n_{\mathrm{e}0}\oint d\theta d\zeta\, e^{-i(m\theta - n\zeta)}\Phi\ , \end{aligned} \tag{13a}$$

and the right-hand side is

$$\mathrm{RHS} = -\nu_{\mathrm{ee}}\frac{\oint d\theta d\zeta\, e^{-i(m\theta - n\zeta)} n_{\mathrm{e}1}}{\oint d\theta d\zeta / B^\theta}\ . \tag{13b}$$

where $n_{\mathrm{e}1} = \int d^3\mathrm{v}\, f_{\mathrm{e}1}$.

A similar procedure can be applied to the ions without the quasilinear rf operator, which only operates on the electrons, to yield

$$\begin{aligned} & \left\langle \int d^3v \left(\mathbf{v}_{\mathrm{Di}}\cdot\nabla f_{\mathrm{i}0} + \frac{\partial f_{i0}}{\partial t}\right)\frac{g^i_{mn}}{f_{\mathrm{i}0}}\right\rangle \\ & \quad + \nu_{\mathrm{ei}} n_{\mathrm{i}0}\frac{q_{\mathrm{i}}}{T_{\mathrm{i}}}\oint d\theta d\zeta\, e^{-i(m\theta - n\zeta)}\Phi \\ & \qquad = -\nu_{\mathrm{ei}}\frac{\oint d\theta d\zeta\, e^{-i(m\theta - n\zeta)} n_{\mathrm{i}1}}{\oint (d\theta d\zeta / B^\theta)} \end{aligned} \tag{14}$$

Combining Eqs. (13) and (14) with charge neutrality satisfied order by order, *i.e.*,

$$-n_{\mathrm{e}0} + Z_{\mathrm{i}} n_{\mathrm{i}0} = 0\ ,$$

$$-n_{\mathrm{e}1} + Z_{\mathrm{i}} n_{\mathrm{i}1} = 0\ ,$$

we obtain

$$\frac{e}{T_e}\left[1+\frac{Z_i T_e}{T_i}\right]\oint d\theta d\zeta\ e^{-i(m\theta-n\zeta)}\Phi$$
$$=-\left[\frac{\nu_{rf}}{\nu_{ee}}\left\langle\int d^3\mathrm{v}\right.\right.$$
$$\left.\times\left(Q_{rf}-\mathbf{v}_{De}\cdot\nabla f_{e0}-\frac{\partial f_{e0}}{\partial t}\right)\frac{g^e_{mn}}{f_{e0}}\right\rangle$$
$$\left.+\frac{\nu_{rf}}{\nu_{ei}}\left\langle\int d^3\mathrm{v}\left(\mathbf{v}_{De}\cdot\nabla f_{i0}-\frac{\partial f_{i0}}{\partial t}\right)\frac{g^i_{mn}}{f_{i0}}\right\rangle\right]$$
$$\div\left\langle\int d^3\mathrm{v}\ \frac{w}{T_e}Q_{rf}\right\rangle, \qquad (15)$$

with $\nu_{rf}\equiv\langle\int d^3\mathrm{v}(w/T_e)Q_{rf}\rangle$ introduced to bring the equation into dimensionally correct form. Defining a double Fourier series by

$$h(r,\theta,\zeta)=\Sigma_{m.n}H_{mn}(r)\,e^{-i(m\theta-n\zeta)}\ ,$$

and

$$H_{mn}(r)=(2\pi)^{-2}\oint d\theta d\zeta\ h(r,\theta,\zeta)e^{-i(m\theta-n\zeta)}\ .$$

Equation (15) becomes, after setting $\partial/\partial t=0$ at steady-state

$$\frac{e\Phi_{mn}}{T_e}=-\left(1+\frac{Z_i T_e}{T_i}\right)^{-1}(2\pi)^{-2}$$
$$\times\left\{\frac{1}{\nu_{ee}}\left\langle\int d^3\mathrm{v}\,Q_{rf}(f_{e0})\frac{g^e_{mn}}{f_{e0}}\right\rangle\right.$$
$$+\frac{1}{\nu_{ei}}\left\langle\int d^3\mathrm{v}\ \mathbf{v}_{Di}\cdot\nabla f_{i0}\,\frac{g^i_{mn}}{f_{i0}}\right\rangle$$
$$\left.-\frac{1}{\nu_{ee}}\left\langle\int d^3\mathrm{v}\ \mathbf{v}_{De}\cdot\nabla f_{e0}\,\frac{g^e_{mn}}{f_{e0}}\right\rangle\right\}\ . \qquad (16)$$

Equation (16) is the main result of this formulation. It provides a self-consistent 3-D electrostatic potential generated by ECH and radial transport under the assumption of quasilinear rf and parallel drift much larger than radial drift. The first term in { } on the RHS gives the contribution from ECH and the second and third term are the transport contribution. We note that the adjoint equations are linear, hence the solutions are linearly proportional to the collision frequencies. Φ_{mn} is thus explicitly independent of the choice of ν_{ee} and ν_{ei}, and we may set both of them equal to unity in the adjoint equations and Eq. (16). Because of the nature of ECH, Eq. (16) should provide a reasonable estimate of the ECH created potential. The potential due to radial transport in a helical system may be better estimated using more elaborate transport codes.

4. Discussion

An iterative way to implement the self-consistent electric potential for transport studies is to extend the Monte-Carlo approach used in Ref. 6. In this approach, a Green's function G defined by

$$\frac{\partial G}{\partial t}+\left(\mathbf{v}_D+\mathbf{v}_{\parallel}\right)$$
$$\cdot\frac{\partial G}{\partial \mathbf{x}}+\dot{\mathbf{v}}\cdot\frac{\partial G}{\partial \mathbf{v}}-C(G)=0\ , \qquad (17)$$

is solved by Monte-Carlo technique with the initial condition $G(x,v,t=0,x',v')=\delta(x-x')\delta(v-v')$. Any response function of the inhomogeneous Fokker-Planck equation can be obtained by the convolution of the forcing function with G. For stationary state, the convolution is performed in the limit $t\to\infty$.

Comparing Eq. (17) with the adjoint equation, Eq. (12), we note that in the limit $\Phi \to 0$, the definition of energy is the same. Since only static magnetic field is considered, $\dot{v} = 0$. In the limit of small radial drift, $\mathbf{v}_\mathrm{D}$ can be set to zero. Finally, by changing the sign in front of $v_{\parallel}$, the solution of Eq. (17) provides the Green's function for the adjoint equation, and g^e_{mn} can be obtained by the convolution of G with the RHS of Eq. (12). Equation (16) can then be applied to evaluate Φ_{mn}. By repeating this for all (m,n), the total potential $\Phi(r,\theta,\zeta)$ can be reconstructed.

In Ref. 6, the ECH driven transport flux was computed as a function of the radial electric field $E_\mathrm{r}(=-\partial\Phi/\partial\psi_\mathrm{p})$ with $\partial\Phi/\partial\zeta = \partial\Phi/\partial\theta = 0$. The proposed extension will remove this restriction, in the second iteration when Eq. (17) is solved with the more exact guiding-center drifts given by Eqs. (8)–(10).

In conclusion, an algorithm is proposed which treats the ECH generated potential in a self-consistent way, by extending the method used in Ref. 6. The additional physics is expected to influence the transport of both thermal and suprathermal electrons in a helical toroidal system. Implementation of the new algoithm to the Monte-Carlo Fokker-Planck code is underway.

Acknowledgment

The work of Vincent Chan was supported by U.S. Department of Energy Grant No. DE-FG03-95ER54309, and performed when he was a JIFT Visiting Professor at NIFS. He gratefully acknowledges the hospitality of NIFS during his visit.

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