Application of RF Power to Plasma Flow Drive in Fusion Confinement

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Abstract—

Wave induced flows can produce radially sheared velocity profiles that can in turn stabilize drift wave turbulence and improve plasma confinement. A second-order kinetic theory is developed in one-dimensional slab geometry to treat radio frequency (RF)-driven plasma flows. The Vlasov equation is solved to second order in the RF electric field. Moments of the second-order distribution function give time-averaged expressions for the heating rate, the wave kinetic flux, and the RF force exerted on the plasma. On the collisional or transport time scale, the RF force in the poloidal direction is balanced by neoclassical viscosity, and the force in the radial direction is balanced direction by ambipolar electric fields. Comparison is made with previous theories which have relied on incompressible fluid approximations. Very substantial differences are seen in situations involving the Ion Bernstein Wave, a compressional wave.

I. Introduction

Use of RF power in fusion devices has progressed from the relatively simple purpose of bulk plasma heating, to driving steady state currents, and now to more sophisticated profile control applications. Recent interest has developed in using power in the ion cyclotron range of frequencies (ICRF) to drive plasma flows, particularly poloidal flows with radial velocity shear. This interest stems from several calculations [1], [2], [3] and some experiments [4], [5], indicating that such sheared velocity can act to stabilize micro-turbulence and thereby improve plasma confinement. Previous calculations have relied on two key assumptions: (1) that the fluctuating velocity field associated with the RF waves is incompressible, and (2) that the RF pressure can be approximated entirely by the Reynolds stress. While these assumptions are valid for fluid turbulence, and may be valid for the low frequency drift wave modes associated with the increased plasma transport, they are questionable for the high frequency RF waves driving the sheared flow. This is particularly true for one of the most promising modes, the ion Bernstein wave (IBW), which is dominantly a compressional electrostatic wave. In this paper we describe the results of a more general theory which eliminates these two assumptions. To accomplish this, it is necessary to develop a kinetic theory in which the perturbed distribution function is expanded to second order in the RF wave fields. A comparison is then made between three levels of approximation: the usual incompressible fluid theory taking the RF pressure as the Reynolds stress alone, the fluid theory including compressibility, and the full kinetic theory including the second-order kinetic pressure tensor.

II. Kinetic Theory of Plasma Flow

Plasma flows can be calculated from the first velocity moment of the kinetic equation, the momentum balance equation,

$$\frac{\partial}{\partial t}(n_s m_s u_s)+\nabla\cdot P_s = n_s q_s(E+u_s\times B)+\langle vC(f_s)\rangle \quad (1)$$

where s labels the particle species, $n_s=\int d^3v f_s$ is the density, $n_s u_s = \int d^3v v f_s$ is the particle flux, $P_s = \int d^3v vv f_s$ is the pressure tensor, and $\langle vC(f_s)\rangle$ is the collisional transfer of momentum due to friction or viscosity. It is convenient to transform to the center of mass frame [$V=\sum_s m_s n_s u_s/\rho_m$, where $\rho_m=\sum_s m_s n_s$ is the total mass density]. In this case, the pressure tensor can be expressed as $P=\rho_m VV+\pi$, where the first term on the right is the Reynolds stress, and $\pi=\sum_s m_s\int d^3v(v-V)(v-V)f_s$ is the thermal pressure in the center of mass system. We now introduce a perturbing RF wave with frequency ω and electric and magnetic fields, $E_1(r,t)$ and $B_1(r,t)\propto\exp[(k\cdot r-\omega t)]$. Equation (1) is expanded in powers of the perturbed RF fields, second-order terms retained, and a time average is taken over the fast RF scale. The tokamak is modeled as a 1-D slab where (x,y,z) refer to radial, poloidal, and toroidal directions, respectively. In true tokamak geometry, we would deal with flux-surface averaged quantities, the collisional term representing flux-surface averaged neoclassical flow damping. For the present slab model, this is just taken to be a drag term $-\mu\rho_m V$, where μ is the neoclassical viscosity[2]. Then in steady state, the poloidal flow velocity is found from the equation

$$-\mu\rho_m V_2 = \left\langle \rho_q^{(1)} E_1 + J_1 \times B_1 \right\rangle_t - \nabla \cdot \left(\rho_m^{(0)} \langle V_1 V_1 \rangle_t \right) - \nabla \cdot \pi_2 + J_2 \times B_0 \,, \quad (2)$$

where subscripts 1,2 refer to order in the perturbed fields, and $\langle \rangle_t$ represents the time average. The first term on the right is the electromagnetic force. In steady state, the radial component of J_2 must vanish by ambipolarity so the poloidal component of the last term of Eq. (2) also vanishes. The simplified models are obtained by assuming incompressible waves, $\nabla \cdot V_1 = 0$, and neglecting the thermal pressure $\nabla \cdot \pi_2 = 0$ in Eq. (2).

To proceed, it is necessary to calculate V_1 which requires the usual first-order perturbed distribution function, f_1, and to calculate π_2, which requires the time-averaged perturbed distribution f_2 evaluated to second order in the RF fields. The second-order, time-averaged Vlasov equation can be written in terms of f_1 as [6]

$$\frac{\partial f_2}{\partial t} + v \cdot \nabla f_2 + \tfrac{q}{m} \left(E_0 + v \times B_0 \right) \cdot \nabla_v f_2 = - \left\langle \tfrac{q}{m} \left(E_1 + v \times B_1 \right) \cdot \nabla_v f_1 \right\rangle \,. \quad (3)$$

A detailed solution of this equation is presented in Ref. [7] with no assumption of smallness of the gyroradius relative to wavelength. The wave electric field itself is obtained from the ORION1D code [8], a full wave solution of Maxwells equations in slab geometry

$$\nabla \times \nabla \times E_1 - \tfrac{\omega^2}{c^2} \left(E_1 + \tfrac{i}{\omega \varepsilon_0} \sum_s J_{1s} \right) = i\omega\mu_0 J_{ext} \,, \quad (4)$$

where the plasma current, J_{1s}, is expanded to third order in gyro-radius, and J_{ext} is the external current due to the antenna. This formulation includes the IBW up to third cyclotron harmonic.

III. Comparison of the models

To make a concrete comparison of the three models considered, we adopt parameters representative of the Alcator C-Mod tokamak: major radius $R_0 = 0.67$ m, minor radius $a = 0.20$ m, magnetic field $B_0 = 4.0$ T on axis. The antenna is located just outside the plasma at $R = 0.88$ m, and is characterized by toroidal wave number $k_z = 10$ m^{-1} and a poloidal wave number $k_y = 0$ (i.e. no net input of poloidal momentum). The plasma profiles are parabolic with central density and temperatures: $n_o = 1.5 \times 10^{20}$, $T_{e0} = 2.5$ keV, and $T_{i0} = 1.5$ keV. Figure 1 shows the poloidal flow velocity for fast waves launched into a ^{3}He plasma with a 10% minority hydrogen (H). The frequency ($f = 50$ MHz) is near the fundamental of the minority H and the power absorbed is 1MW. First, to simplify the comparison, we consider a case in which the parallel wave number is artificially increased ($k_z = 26$ m^{-1}), eliminating the conversion to IBW. Shown are: (a) the incompressible fluid model, (b) the fluid model but including the compressibility of V_1, and (c) the kinetic model with non-zero pressure contribution. The long dashed line shows the contribution from electromagnetic force, the short dashed line is the pressure (Reynolds stress + kinetic) which always tends to cancel with the EM term, and the solid line is the total flow velocity. The effect of compressibility on the fluid model, Fig. 1(b), is to reduce the magnitude of the Reynolds stress, slightly increasing the total flow. Including the kinetic pressure increases the pressure contribution by 20-30%, a relatively modest change, but sufficient to reverse the net flow direction compared to the fluid models. The magnitude of the flow in the three models is similar. A very different picture emerges in situations such that the IBW is important. Figure (2) shows a case of direct IBW launch into deuterium (D) plasma with a 2% minority of ^{3}He. The magnetic field is taken as 3.26 T to put the second harmonic D resonance in front of the antenna. The incompressible model, Fig. (2a), shows a very large, positive flow velocity. Adding compressibility to the fluid model, Fig. (2b), results in a reduction in the peak flow velocity of about a factor of 30. The kinetic model, Fig. (2c), gives a further reduction of about a factor of 100. Thus the peak flow velocity predicted by the kinetic theory is more than three orders of magnitude smaller than that given by the usual incompressible fluid model.

IV. Discussion

The kinetic model tends to predict smaller values of driven poloidal flow than does the incompressible fluid model; in some cases substantially smaller values. However, we find that in many cases the velocity shear driven by achievable power levels is sufficient to impact turbulence. For stabilization of turbulent modes, the important issue is the magnitude of the radial shear in the $E \times B$ velocity, $\omega_{E\times B}$

$$\omega_{E\times B} = \frac{(RB_P)^2}{B} \frac{\partial}{\partial \psi} \left(\frac{E_\psi}{RB_P} \right) \,. \quad (5)$$

Using the theory of Biglari, Diamond, and Terry for shear stabilization of drift wave turbulence, [9] we find, for example, that typical edge conditions in Alcator C-mod requires shearing rates $\omega_{E\times B} \geq \omega_e^* \approx 2 \times 10^5 s^{-1}$. This is obtained with power at the one-megawatt level for the case shown in Fig. (2).

In addition to the RF driven poloidal flow, the kinetic model predicts a steady flow driven in the x (or radial) direction. For practical parameters such as we have been considering, we find $V_{x2} \sim 1$ m/sec, which is comparable to the radial diffusion velocity in tokamaks. Thus, to maintain ambipolarity, an additional radial electric field must appear and radial transport must be modified. This effect may also have a significant effect on plasma confinement.

A further benefit of the present theory is that expressions are obtained for the local power deposition and the wave kinetic flux which are valid to all orders in $k_\perp \rho$. In fact, this calculation is the first to obtain the local heating and kinetic flux directly from the dis-

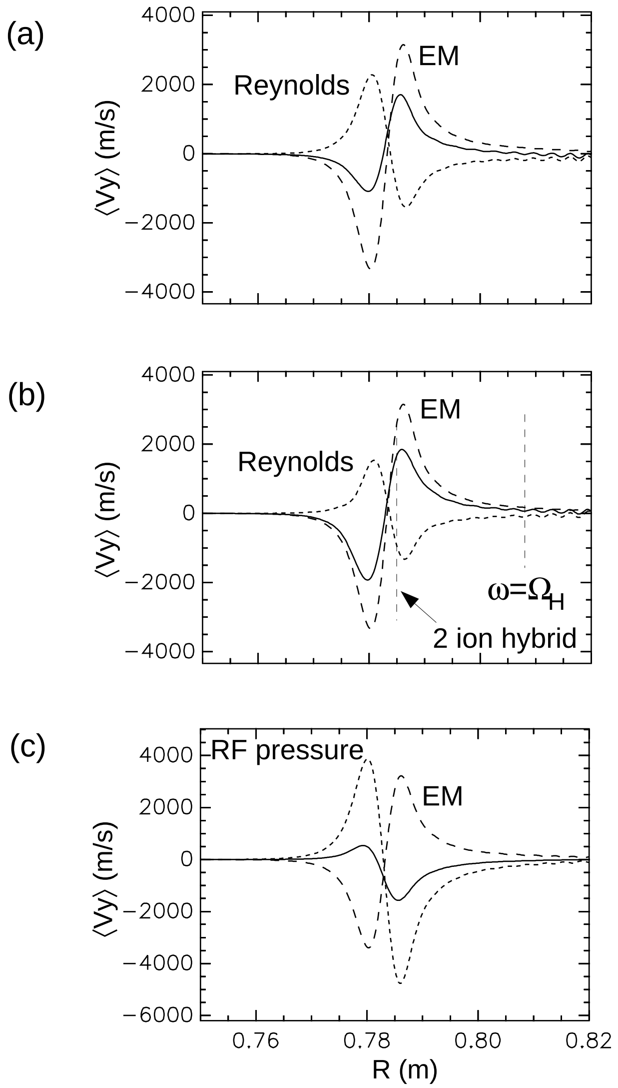

Fig. 1. Poloidal flow velocity for fast waves absorbed near the two ion hybrid resonance with 10% H in He^3, $f = 50$ MHz, $B(0) = 4.0$ T, and $k_z = 26\mathrm{m}^{-1}$: (a) incompressible fluid, (b) compressible fluid, and (c) kinetic model.

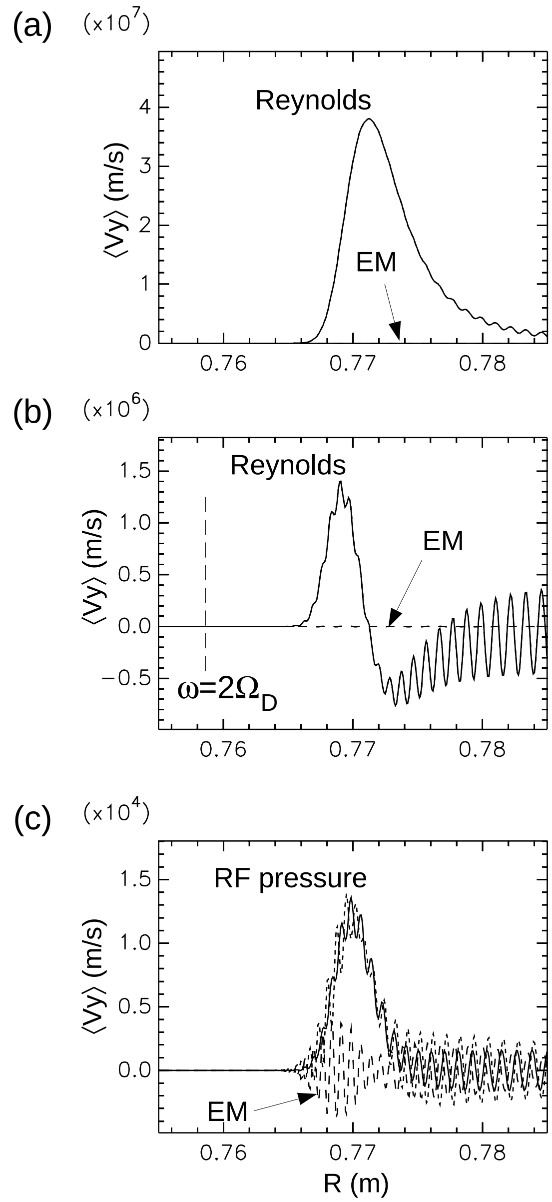

Fig. 2. Poloidal flow velocity for directly launched IBW absorbed by electron LD and TTMP with 2% He in D, $f = 44$ MHz, $B(0) = 3.26$ T, and $k_z = 10\mathrm{m}^{-1}$: (a) incompressible fluid, (b) compressible fluid, and (c) kinetic model.

tribution function, f_2. In this way, purely local Joule heating and wave energy flux are explicitly calculated and are distinguished from energy transport due to net particle transport. Previous theories required a specific definition of local heating, then a grouping of terms in terms in the expression for $J \cdot E$ into power deposition versus kinetic flux, a process subject to some ambiguity.

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