THE NONLINEAR FORCE FROM FLUCTUATIONS AS A SOURCE OF PLASMA ROTATION

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Abstract

The ponderomotive (PM) force due to radiofrequency waves is analyzed as the cause of plasma rotation in toroidal magnetic configurations, considering an arbitrary average force in different situations. A mechanism for rotation with a radial poloidally asymmetric force is described.

1. Introduction

When high-power radiofrequency (RF) waves are injected into a toroidal plasma, or turbulent fluctuations are present, nonlinear forces arrise that influence the plasma dynamics. The force associated with RF waves is the so-called ponderomotive (PM) force, and the one resulting from turbulence is the Reynolds stress. Mathematically, these are the result of time-averaging the momentum balance equation over the fast oscillation time-scale, and in doing so some nonlinear terms remain that keep the effect of the fluctuations. Their nonliearity makes PM forces to be of importance in high amplitude electromagnetic waves, such as those involved in the interaction of high intensity lasers with a plasma. In magnetic confinement, the present requirements for RF heating and current drive in large devices, use an RF power high enough (tens of MW) to make the nonlinear effects important. On the other hand, there is experimental evidence that RF waves, in particular lower-hybrid waves, can influence the dynamics of a toroidal plasma as a whole, by producing bulk rotation [1]. This rotation may well be driven by nonlinear forces by giving momentum to the plasma ions in a preferential direction.

We consider two different mechanisms that have been proposed for the non-resonant drive of poloidal plasma rotation by a PM force: (a) a poloidal drift due to a radial PM force [2], and (b) a direct angular momentum transfer by the angular (toroidal or poloidal) PM force [3]. Although the first mechanism as previously proposed is not operative when viscosity is included, we show here that it becomes important for a poloidally asymmetric radial PM force, which can effectively drive poloidal rotation around a resonant surface, due to the action of either of two dissipative processes: friction with neutral particles; and the resistive action of the poloidal current. This process is most important near the outer regions of the plasma, where it can then give rise to an H-mode, once a sheared poloidal flow is established, which would lead to fluctuations suppression. The advantage of this method of driving rotation is that there is no need for a complicated antena array to launch the wave in the poloidal direction, as with the second mechanism, which is the one being explored by some authors [4]. In this case, the wave can propagate radially and when it is absorbed at the resonant surface the radial PM force is produced. We estimate that the effect is large enough to drive a considerable flow, due to the small extent of the resonant surface.

2. The role of external forces

We start from the fluid equations in toroidal geometry, with inclusion of an external force $\mathbf{F_j}$, that we identify with the PM force. The continuity and momentum balance equations for species j are,

$$\frac{dn}{dt} + n\nabla\cdot\mathbf{v}_j = 0 \tag{1}$$

$$m_j\frac{d}{dt}(n\mathbf{v}_j) = -\nabla p_j - \nabla\cdot\Pi_j + q_j n(\mathbf{E} + \mathbf{v}_j\times\mathbf{B}/c) + \mathbf{R}_j + \mathbf{F}_j, \tag{2}$$

where $d/dt = \partial/\partial t + \mathbf{v}_j\cdot\nabla$, $\mathbf{R_j}$ is the friction force, Π_j is the viscous stress tensor and the other quantities have the usual meaning. Charge neutrality is assumed. The magnetic field is represented by $\mathbf{B} = \nabla\psi\times\nabla\zeta + B_\zeta\mathbf{e}_\zeta$, and $\mathbf{E} = -\nabla\phi$. Following the standard procedure, we consider an ordering in the ratio of the ion gyroradius to the minor radius, and sepparate the lower order as $\mathbf{v}_j = \mathbf{U}_j + \tilde{v}_j$. The lowest order contribution in steady state is the balance between the pressure gradient and the electromagnetic force, assuming the PM force is of lower order (when this is not assumed the radial component of $\mathbf{F_j}$ drives a drift rotation directly). Taking this together with continuity in terms of parallel and perpendicular (to $\mathbf{B}$) velocities: $\nabla\cdot U_{\|j} = -\nabla\cdot U_{\perp j}$, one finds,

$$\mathbf{U}_{\perp j} = \frac{c}{B^2}\mathbf{B}\times\nabla\psi(\phi' + p_i'/nq_j), \quad \mathbf{U}_{\|j} = [\frac{cB_p}{B_\zeta B^2}(\phi' + p_i'/nq_j) + \lambda]\mathbf{B} \tag{3}$$

recalling that ϕ and p are functions of ψ for axisymmetry. Here λ is an undetermined constant that may be obtained going to next order. For the next order equations we take the parallel and poloidal components of the momentum balance, averaged over a flux surface, omitting for the moment the friction, to get,

$$m_j\langle\mathbf{B}\cdot\nabla(n\mathbf{U}_j\mathbf{U}_j)\rangle + \langle\mathbf{B}\cdot\nabla\cdot\Pi_j\rangle = \langle\mathbf{B}\cdot\mathbf{F}_j\rangle \tag{4}$$

$$m_j\langle\mathbf{B}_p\cdot\nabla(n\mathbf{U}_j\mathbf{U}_j)\rangle + \langle\mathbf{B}_p\cdot(\nabla p_j + \nabla\cdot\Pi_j)\rangle = -\langle nq_j\tilde{v}_{jr}B_pB_\zeta/c\rangle + \langle\mathbf{B}_p\cdot\mathbf{F}_j\rangle. \tag{5}$$

Some remarks may be made about these equations. The work of Klima and Petrzilka [3] is equivalent to including only the first and last terms of Eqs.(4-5) (i.e. no viscosity), with the $\tilde{v}_{jr}$ term zero by ambipolarity. So they get U_{pj} and $U_{\zeta j}$ directly in terms of F_{pj} and $F_{\zeta j}$ respectively. In contrast, Tsypin et al. [5] use the equivalent to Eq.(5) without the first (convective) term, together with its toroidal counterpart and ambipolarity. They find U_j since it appears in the stress tensor.

It is possible to find the rotation velocities from Eq.(4) if we write simbolically the viscous stress as $\langle \mathbf{B} \cdot \nabla \cdot \Pi_j \rangle = \mu_p U_p + \mu_\zeta U_\zeta + k$, where the parameters $\vec{\mu} \equiv (\mu_p, \mu_\zeta)$ and k are obtained from the definition of Π_j. For the Braginskii viscosity $k = 0$, but it is non-zero when one uses a Burnett-type viscosity [6] (k is proportional to ∇T), which allows to get a non-zero equilibrium poloidal rotation in an axisymmetric configuration (where $\mu_\zeta = 0$). We use this, with Eq.(3) and the ambipolarity condition ($\Sigma n q_j \tilde{v}_{jr} = 0$), in Eq.(4) neglecting the convective term, and get λ from there. The resulting velocities are,

$$U_\zeta = \frac{B_\zeta}{\vec{\mu} \cdot \mathbf{B}} [\langle F_{j\|} \rangle - \frac{c\mu_p}{B_\zeta} (\phi' + p_j'/nq_j) - k] \tag{6}$$

$$U_p = \frac{B_p}{\vec{\mu} \cdot \mathbf{B}} [\langle F_{j\|} \rangle + \frac{c\mu_\zeta}{B_p} (\phi' + p_j'/nq_j) - k], \tag{7}$$

which depend on the parallel PM force. Notice that in our case $\mu_\zeta = 0$. It is clear that a radial force could not drive rotation. The situation does not change if the neglected convection is included.

There is, however, a possiblity for a radial force that is not poloidally symmetric to give rise to rotation, by a mechanism similar to the Stringer spin-up [7]. In order to have this process it is necessary to have some neutrals friction, so that the radial force produces a steady radial flow. Thus, the mechanism will be most important near the edge region, when the injected waves have their resonant surface there. The same effect may result for a resistive current. We will explain the process in its simplest form starting from Eqs.(1,2), allowing for a radial component of $\mathbf{v}$, and including the friction with neutrals $\mathbf{R}_j = -n\nu_{jN} m_j \mathbf{v}_j$. Continuity gives a field-aligned return flow

$$U_{\|j} = \frac{BqR}{r} \int \frac{1}{B} \frac{\partial}{\partial r} (rU_{rj}) d\theta. \tag{8}$$

The radial velocity is the result of the radial force balanced by friction, so from the radial projection of the momentum balance equation to first order, neglecting viscosity and the pressure gradient, we get

$$U_{rj} = \frac{F_{rj}}{nm_j \nu_{jN}} \tag{9}$$

which can be used in Eq.(8). Since the parallel flow varies with the poloidal angle θ, it drains the plasma flowing radially outwards to keep steady state. But if there is an initial poloidal flow (from a perturbation), the draining region is displaced poloidally, decreasing the density there. The field line curvature tends to rotate the rarefied plasma in the initial direction, thus producing an instability [7].

3. Conclusions

We have made a general analysis of the different ways an external force (in particular, a PM force) may produce plasma rotation. With the standard analysis the force has to have a poloidal or toroidal component to originate rotation. However, a radial force can also give rise to poloidal rotation if it is poloidally asymmetric (as it is usually the case), through a Stringer spin-up mechanism. This may be a simpler way to rotate the plasma with RF power, which could lead in turn to an H mode.

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