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Confinement Regimes Transition, Angular Momentum Ejection by Toroidal Edge Modes, and Relation to Current Experiments*

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Introduction

The problem of understanding the transition from the L-confinement regime to the H-regime is connected to that of describing theoretically the characteristics of the spontaneous rotation process, and in particular, the change of rotation direction observed during this transition. Following the line of the "accretion theory" of spontaneous rotation [1], the main body of the plasma column is considered to rotate as a recoil resulting from the ejection of angular momentum from the edge of the plasma column toward the material wall surrounding it. Recent innovative experiments [2,3] measuring the evolution of the radial profile of the toroidal velocity during its rise are consistent with the source of angular momentum being at the edge [3].

The nature of the modes in the edge of the plasma column is considered to change in the transition from the H-confinement regime to the L-regime as in the former case the edge is characterized by a pressure pedestal with a sharp density gradient. At the same time the local temperature is, generally, higher than in the L-regime.

Angular Momentum Ejection Process

Considering all of these factors, in the H-regime the mode that is judged to be prevalent is driven by the combined effects of the plasma pressure gradient and the magnetic field curvature. This mode is of the resistive type [4] and has a phase velocity in the direction of the electron diamagnetic velocity. A ballooning mode with similar characteristics is the collisional trapped electron mode [5]. Clumps of particles are considered to be ejected with a toroidal component of their velocity in the same direction as that of the mode phase velocity [6]. We observe that this mode is the resistive equivalent of the ideal MHD ballooning mode [4,7] that has the same driving factor and gives rise to the so-called ELMs when the local pressure gradient is excessively steep. Considering a simplified confinement geometry in which φ and θ are the toroidal and poloidal angle respectively and r is the minor radial coordinate, a ballooning mode that has a negligible amplitude at $\theta = \pm\pi$ (inner edge) is represented by

$$\hat{n} = \tilde{n}(r,\theta)\exp\left\{-i\omega t + in^0\left[\varphi - q(r)\theta\right]\right\}$$

near a rational surface $r = r_0$ where $q(r_0) = m^0/n^0$, $m^0 \gg 1$, $n^0 \gg 1$, and $\tilde{n}(r,\varphi)$ is a periodic function of θ with its maximum at $\theta = 0$. The particle and angular momentum ejection is driven by the plasma pressure gradient that sustains the mode. In the envisioned process the angular momentum of the mode does not change but the background plasma recoils, acquiring an opposite toroidal velocity to that of the mode.

The dispersion relation for these collisional ballooning modes [6] shows that the mode's phase velocity can be inverted in highly collisional regimes as a result of the effect of finite transverse ion viscosity combined with that of finite resistivity. However, this circumstance that would give a relatively simple explanation of the transition from the H to the L-regime where the inversion of the toroidal rotation is observed, has the drawback that the needed anomaly factor for the transverse viscosity that affects poloidal flows would be quite high.

L-Regime

Consequently we have considered another option, invoking an "impurity-like" mode which is not of the ballooning type and which has a phase velocity in the direction of the ion diamagnetic velocity [8]. We note that a comprehensive set of experiments on the edge fluctuations has been carried out by S. Sharapov on the JET machine [9], showing that the dominant modes have a phase velocity in the ion diamagnetic velocity direction in the L-regime and in the opposite direction in the H-regime. The prevalent "impurity-like" mode relies on the presence of a cold ion population at the edge of the plasma column with a positive gradient $(dn_c/dr > 0)$. This mode has the effect of bringing the cold particles inward and ejecting the particles of the hot population while increasing the toroidal momentum of hot particles and decreasing that of the cold particles. In order to describe the considered process we refer to a plane geometry for simplicity with $\hat{n} = \tilde{n}(x)\exp(-i\omega t + ik_y y + ik_\parallel z)$ representing the density fluctuations and $\mathbf{B} = B(x)\mathbf{e}_z$ the main magnetic field component. The mode is of the "traveling type": it is not ballooning and it has a phase velocity in the range $\mathrm{v}_{th,c}^2 \le (\omega/k)^2 < \mathrm{v}_{th,h}^2 < \mathrm{v}_{th,e}^2$ where the subscripts c and h refer to the cold and hot ion populations. We consider longitudinal wavelengths that are shorter than the collisional mean free path. We also consider frequencies ω that are purely real, as they can be obtained when the growth rate resulting from the mode-particle resonance with the hot ion population is balanced by the damping due to the mode-particle resonance with the cold ion population.

The longitudinal momentum exchange due to the resonance with the hot ions is represented by

$$m_i\, n_h^{res}\left(\Delta \mathrm{v}_z\right)_h + k_z\left(\Delta N_k\right)_h = 0 \tag{1}$$

and the momentum exchange due to the resonance with the cold ions is

$$m_i\, n_c^{res}\left(\Delta \mathrm{v}_z\right)_c + k_z\left(\Delta N_k\right)_c = 0 \tag{2}$$

where $\left(\Delta N_k\right)_h = -\left(\Delta N_k\right)_c$ is the variation of wave occupation number [9] for the relevant interaction and n_h^{res} and n_c^{res} indicate the density of the resonating hot and cold ions respectively. The energy conservation equation for the hot ions is $\omega\left(\Delta N_k\right)_h = m_i\, n_h^{res} \mathrm{v}_z^{res}\left(\Delta \mathrm{v}_z\right)_h$ where $\omega\left(\Delta N_k\right)_h > 0$ implies $\left(\Delta \mathrm{v}_z\right)_h \mathrm{v}_z^{res} > 0$, corresponding to an increase of the hot ion velocity in the direction of the mode phase velocity as $\mathrm{v}_z^{res} = \omega / k_z$. It follows that

$$n_c^{res}\left(\Delta \mathrm{v}_z\right)_c = -n_h^{res}\left(\Delta \mathrm{v}_z\right)_h \tag{3}$$

implying that the cold ions recoil under the effects of the considered mode. We note that the simplest form of the dispersion relation, when the contribution of mode-particle resonances are neglected, is

$$\omega \approx -\frac{k_y c}{eB}\overline{\left(\frac{T}{n}\right)}\frac{dn_c}{dx} \qquad \text{where} \qquad \overline{\left(\frac{T}{n}\right)} = \frac{1}{n_c / T_c + n_h / T_h}. \tag{4}$$

Comments on Inward Angular Momentum Transport

With the source of (recoil) angular momentum at the edge, another kind of process is needed to transport angular momentum toward the magnetic axis. Traveling modes of the VTG (velocity and temperature gradient driven) type [6] have been shown to be capable of providing the inflow that is present in the global angular momentum transport equation

$$\Gamma_J = -nD_J\left[\frac{\partial}{\partial r}\left(\Omega R^2\right) + \alpha_J\,\frac{r}{a^2}\left(\Omega R^2\right)\right]. \tag{5}$$

This equation has been used to reproduce the velocity profiles $\mathrm{v}_\varphi = \Omega(r)R$ observed in a variety of experiments. In particular, one of the main conclusions of the recently published Ref. [10] is that the experiments reported on the spontaneous rotation phenomenon in toroidal plasmas are well interpreted by Eq. (5). This equation was first adopted to reproduce the spontaneous toroidal velocity profiles in a paper presented at the 1998 I.A.E.A. Conference [11]. Previously the same equation had been introduced [12] in 1994 on the basis of theoretical considerations and independently in Ref. [13] in connection with a classic set of experiments on induced rotation by neutral bean injection in toroidal plasmas. In both these papers it was pointed out that the relevant transport equation, used also in Ref. [1], was inspired by that introduced earlier to describe transport of particles in well confined plasmas [14]. In fact, the particle transport equation included both a diffusion and inflow term to account for the observed density profiles [14]. No mention of these facts is made in Ref. [10]. The observation included in the relevant abstract [10] that “intrinsic rotation is locally determined by the local pressure gradient and increases with increasing pressure gradient” is consistent with the results of previous papers such as Ref. [1] and Ref. [6] that considered the ion pressure gradient as responsible for the angular momentum inflow from the edge of the plasma column towards its center. In fact, experiments preceding those reported in Ref. [10] are consistent with this theoretical conclusion.

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