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Collisionless Drift Waves in the H-mode Edge

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Abstract

Existing theories predict that in ohmic and/or L-mode discharges the drift wave is stable in a sheared slab geometry. But the representative experimental values for the plasma parameters show that due to the very steep density gradient the shear stabilization criteria for collisionless drift waves are not likely to be satisfied at the H-mode edge plasma. Magnetic shear is, therefore, not a candidate to stabilize the slab branch of the drift waves in the H-mode. However, a radially sheared *transverse* (to the equilibrium magnetic field) velocity field is found to play a key role in stability. Velocity profiles corresponding to those observed in a region of a few centimetres inside the separatrix of a H-mode plasma stabilize drift waves. On the other hand, velocity profiles corresponding to the L-mode render drift waves unstable in the experimental range of parameters, even though the magnetic shear continues to play its stabilizing role.

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I. Introduction

It is well established that in a sheared slab geometry with magnetic shear, drift wave eigenmodes are always stable [1,2]. The shear damping of the drift waves is associated with the antiwell potential in which energy convects away from the mode rational surface and eventually gets absorbed by the ion Landau damping far from the rational surface. But even though the sheared-slab stabilisation criteria are well satisfied in ohmic and/or L-mode discharges of tokamaks, the possibility of unstable drift eigenmodes was not ruled out either in the collisionless [3] or the collisional [4] case, for strongly peaked radial density profiles. After the discovery of the H-mode in 1982 [5], present-day tokamaks routinely obtain very steep density gradients (the so-called *transport barrier*) in the edge region of H-mode discharges. So an investigation into whether magnetic shear still is sufficient to stabilize drift waves in the H-mode edge plasma is extremely important. If the answer is negative (we will see that it is indeed the case), an obvious next question is - how to account for the reduced transport in the H-mode edges?

The interest in the possible role of a sheared poloidal flow in suppressing micro-turbulence has recently drawn much attention. This is due to the experimental observations [13, and references therein] that the L-H transition in tokamaks is associated with a clear signature: edge density fluctuations are abruptly suppressed (in approximately 100 micro secs) while the edge poloidal rotation velocity increases. Indeed it has been shown by Shaing and Crume [14] (also see Itoh and Itoh [15]) that a bifurcation in poloidal rotation causes change in the radial electric field. A more negative radial electric field (E_r) or a more positive dE_r/dr then suppresses the turbulent fluctuations and hence could cause the L-H transition. Biglari et al. [16] have shown that the establishment of rotational shear has a quenching influence on the ambient turbulence, although the underlying source of instability remains unidentified.

Instabilities stabilised by *poloidal velocity* shear have recently been discussed. The ion temperature gradient (ITG) mode has been shown to be stabilised by a H-mode type velocity profile [7, 17]. Hassam [18] found that the Rayleigh-Taylor instability of a magnetised plasma is nonlinearly stabilised by the external imposition of transverse velocity shear with a zero second spatial derivative. Also we will see that the magnetic shear stabilization criteria for drift waves are severely restricted in the H-mode edge plasma due to the very steep density gradient. In this situation it is necessary to investigate the effect of a sheared velocity field on drift waves.

In this article we first revisit the magnetic shear stabilization criteria of collisionless drift waves for the steep density gradients as observed in H-mode edges. The shear stabilization criteria are found to be severely restricted in the H-mode edge plasma. We then investigate the effect of a radially sheared transverse equilibrium velocity field on collisionless electron drift waves. The drift wave is found to be linearly stabilised by a velocity profile corresponding to that found in the region a few centimetres inside the separatrix of a H-mode plasma. On the other hand, a velocity profile corresponding to the L-mode is shown to have a destabilizing effect in the experimental range of parameters, even though the magnetic shear continues to play its stabilizing role.

II. Shear Stabilization Revisited

In the early work on collisionless drift waves, Krall and Rosenbluth [6] considered equilibrium variations in the density profile and generated a 1-D radial equation by expanding around the maximum of ω_e^*, where ω_e^* is the diamagnetic drift frequency. They found that unstable exponentially decaying (i.e., non-propagating) radial normal modes can exist only if their shear stabilising criterion $L_s < 8L_n^2/\rho_s$ [henceforth "condition (1)"] is violated. Here, L_s is the magnetic shear scale length, L_n the density scale length and ρ_s the ion Larmor radius. Using realistic experimental values for plasma parameters from DIII-D [7], viz., $L_n \sim 3.5cm$, $\rho_s \sim 1mm$, condition (1) now implies $L_s < 9.8m$ (i.e., $L_s/L_n < 280$), a condition likely to be easily satisfied in all realistic tokamaks. So, for ohmic and/or L-mode discharges, collisionless drift waves are stabilised by magnetic shear. Pearlstein and Berk [8] then introduced outgoing wave boundary conditions into the radial analysis and discovered a new class of propagating normal modes. To obtain a shear stabilisation criterion for universal modes, they estimated the destabilising (radially dependent) effect of resonant electrons by taking its local value at the turning point, $X_T \simeq \rho_s(L_s/L_n)^{1/2}$, and then balancing it with the shear damping term. In the limit of large wavelength their stability criterion is given by $L_s < L_n(m_i/m_e)^{1/3}$ [condition(2)]. Taking m_i/m_e = 1836, and $L_n \sim 3.5cm$ condition (2) implies $L_s < 43cm$, which is much more restrictive than Krall-Rosenbluth criterion. So, accordingly they concluded that large shear does not eliminate unstable normal modes and shear is a relatively ineffective stabilisation mechanisim for the universal mode. However, Ross and Mahajan [1], and Tsang et al. [2], in independent numerical calculations, later found that the universal eigenmodes are stable in a sheared slab geometry if the complete electron response (full Z-function) is retained. While Ross and Mahajan found shear stabilisation for L_n/L_s down to 6×10^{-3} and Tsang et al. down to 10^{-2}, Antonsen [9] in his elegant analytical method proved the absolute stability of the drift wave in sheared slab.

However, most of the earlier works [1,2,9] finding the drift wave stable had treated ω_e^* as a constant. We particularly note that, while Antonsen's method is rather novel, it does not seem to apply when ω_e^* has a parabolic profile. We notice that with a very a sharp gradient in density, as observed in the H-mode edges, assuming ω_e^* *constant* is not a good approximation, particularly when the mode width at half-maximum is $\sim 5\rho_s \sim 5mm \sim L_n$. Neither is it supported by experiments [10]. So the so-called absolute stability obviously does not apply so far as the Krall-Rosenbluth type mode is concerned.

We will show here that for extremely steep density gradients, as observed in the edge regions of H-mode discharges, unstable eigenmodes can again appear. Following DIII-D [11] H-modes (see Fig. 1), we take $L_n \sim 6mm$ for the edge of H-mode plasma and find the shear stabilisation criterion [condition (1)] now requires that $L_s < 28cm$! This extremely high value of shear is generally not observed in present-day tokamaks (Note the drastic change in the shear requirement for a change of L_n from 3.5 cm to $6mm$!). So, contrary to the common perception, collisionless drift waves are not likely to be linearly damped in the H-mode discharges even in a sheared slab configuration.

III. Drift Waves with a Velocity Field

A. The Model

We consider here a plasma of plane slab geometry with an equilibrium density variation and both magnetic and velocity shear and a gradient of velocity shear in x, i.e., $N \equiv N(x)$, $\vec{B}_o\ (x) = \mathrm{B}_o\ (\hat{e}_z + \frac{x}{L_s}\hat{e}_y)$, $\vec{V}_o(x) = V_o(x)\hat{e}_y$. Here, '$L_s$' is the magnetic shear scale length and 'x' is the distance from the mode rational surface defined by $\vec{k}.\vec{B}_o = 0$

In this model, we assume fluid ions and model destabilising effects by the so-called "$i\delta$" model [e.g., see ref. 25], where $i\delta$, represents the destabilising effects of the electron Landau resonance and the trapped electrons. For simplicity, we take the ions to be cold and omit the electron temperature gradient. Since the background plasma is inhomogeneous in the x -direction only, perturbations have the form $\phi(\vec{x},t) = \phi(x)\ \exp\ [i(k_y y + k_z z - \omega t)]$. We may then write the linearised equations of continuity and motion for the ions as

$$-i\omega n_i + \nabla_\perp . \left[N(x)\vec{V}_\perp\right] + \nabla . \left[(N+n_i)V_o(x)\hat{e}_y\right] + ik_\parallel N V_\parallel = 0,$$

and,

$$\omega V_\parallel = k_\parallel \left(\frac{e}{m_i}\right)\phi$$

Here, $\nabla_\perp = ik_y\hat{e}_y + \hat{e}_x\frac{d}{dx}$
$\vec{V}_\perp = \vec{V}_E + \vec{V}_p$
$\vec{V}_{E\times B} = -c(\nabla_\perp\phi \times \vec{B}_o)/B_o^2$
$\vec{V}_{ip} = i(c\omega/B_o\omega_{ci})\nabla_\perp\phi$
$k_\parallel = \frac{k_y x}{L_s}$

and n_i, m_i and $V_\parallel$ are respectively the perturbed ion density, the ion mass and the ion parallel fluid velocity. Now using quasineutrality and the usual low frequency assumption we obtain the radial eigenvalue equation

$$\rho_s^2\left(\frac{d^2}{dx^2} - k_y^2\right)\phi - \left\{1 - \frac{\omega_e^*(x) + i\gamma + k_y V_o(x)}{\omega} - \frac{x^2}{x_s^2}\right\}\phi = 0 \qquad (1)$$

where

$$\rho_s^2 = \frac{C_s^2}{\omega_{ci}^2}, \quad C_s^2 = \frac{T_e}{m_i}, \quad \omega_e^*(x) = -k_y\rho_s C_s/L_n(x), \quad \gamma = \omega_e^*\delta$$

$$x_s^2 = \frac{\omega^2}{k_\parallel'^2 C_s^2}, \quad k_\parallel' = \frac{k_y}{L_s}, \quad L_n(x)^{-1} = \mid dlnN(x)/dx \mid$$

In deriving equation (1) we have not taken into account the resultant modification of the ion polarization drift due to the equilibrium velocity. It may be noted that in the leading order perpendicular ion dynamics are due to $\vec{E}\times\vec{B}$ and diamagnetic drifts with polarization drifts occurring only in the next order. Contribution coming from the ion polarization drift is weighted by $k_\perp^2\rho_s^2$ which in our long wavelength approximation is $\ll 1$ and hence is negligible in the leading order.

B. Effects of H-mode Type Velocity Profiles

Following the JFT-2M (Fig. 2) and the DIII-D [13] (see Fig.2 (a) in ref. 13) H-mode profiles for v_θ (poloidal velocity) inside the separatrix, we model the radial profile of our equilibrium velocity for the H-mode as

$$V_o(x) \equiv V_{oo} + \frac{dV_o}{dx}x + \frac{1}{2}\frac{d^2V_o}{dx^2}x^2$$

i.e.,

$$V_o(x) = V_{oo} + \left(\frac{x}{L_{v1}} + \frac{x^2}{L_{v2}^2}\right)V_{oo}, \quad \text{where}$$

$$\frac{dV_o}{dx} = \frac{V_{oo}}{L_{v1}}, \qquad \frac{1}{2}\frac{d^2V_o}{dx^2} = \frac{V_{oo}}{L_{v2}^2}$$

and V_{oo} is a characteristic velocity.

In considering the problem with a spatial variation of ω_e^*, we treat the simple case in which ω_e^* is peaked at the mode rational surface at x=0 and has a parabolic profile viz: $\omega_e^*(x) \cong \omega_o^*(1 - \frac{x^2}{L_*^2})$, where L_* is the density gradient variation scale length and is typically of the order of L_n. Also it is important to mention here that the poloidal flow is made up of both $\vec{E} \times \vec{B}$ motion ($v_\perp$) and in the next order flow parallel to the magnetic field. The shear in the parallel flow is not included in the investigation and has been reported elsewhere [20]. With this velocity profile, equation (1) becomes

$$\rho_s^2\frac{d^2\phi}{dx^2} + \left[\Lambda - Px^2 + Qx\right]\phi = 0 \qquad (2)$$

where

$$\Lambda = \left(\frac{\omega_o*}{\omega} - k_y^2\rho_s^2 + \frac{V_{oo}k_y}{\omega} + \frac{i\gamma}{\omega} - 1 + \frac{Q^2}{4P}\right),$$

$$P = \left(\frac{1}{L_*^2} - \frac{1}{L_{v2}^2} - \frac{L_n^2}{\rho_s^2L_s^2}\right), \quad Q = \frac{1}{L_{v1}}$$

In deriving equation (2) we have assumed that $\omega \approx k_yV_o \approx \omega_o^* = k_yV_o^*$, where $V_o^* = |\frac{\rho_sC_s}{L_n}|$, which are usually true [e.g., see ref. 23].

Equation (2) is a simple Weber equation. Depending on the sign of 'P' we have two types of solution. If $P > 0$, i.e.,

$$\frac{1}{L_*^2} > \frac{1}{L_{v2}^2} + \frac{L_n^2}{\rho_s^2 L_s^2}, \tag{3}$$

the solution satisfying the physical boundary condition, i.e., $\phi \rightarrow 0$ at $x = \pm\infty$ is given by $\phi(x) = \phi_o \; exp\left[-\frac{\sqrt{|P|}}{2\rho_s}(x - x_o)^2\right]$, where $x_o = \frac{Q}{2|P|}$. So, in this case the mode decays with x, i.e., does not propagate and hence is intrinsically undamped. In the absence of the velocity shear term this condition is likely to be satisfied in the H-mode edge-plasma due to the very steep density gradient. In other words, contrary to the prevailing notion, magnetic shear is not sufficient to stabilise drift-waves in the H-mode edge-plasma, although in ohmic phase and L-mode the magnetic shear continues to play its stabilising role. We have discussed it in detail in the earlier section.

What then stabilises drift waves in a H-mode edge plasma? Introducing the velocity shear term and taking representative values for the plasma parameters for the edge DIII-D plasma [7, 21], $L_* \approx L_n \approx \rho_{i\theta}$ (poloidal ion gyroradius) $\approx 1cm, L_s \approx 67cm, \rho_s \approx 1mm$, we find the inequality (3) is reversed for $L_{v2} \sim L_{v1} \lesssim 1cm$. Currently available experimental data shows that DIII-D [22] finds $L_{v1} \approx \rho_{i\theta} \approx 1cm$, whereas TEXT [23] observes $L_{v1} = 0.5$ to $1cm$. Data from the other tokamaks are not available yet. Both the available sets of data, therefore, indicate that P is likely to become negative when one introduces the velocity contribution. With this reversed inquality, equation (2) has the solution

$$\phi(x) = \phi_o exp\left[-i\frac{\sqrt{|P|}}{2\rho_s}(x + x_o)^2\right].$$

So in this case we have a nonlocalised mode with outgoing energy flux at $x = \pm\infty$. In the absence of any energy source feeding the wave, the perturbation will decay in time due to convective wave energy leakage. The influence of the velocity curvature can then outweigh that of the density gradient and the wave is intrinsically damped. The overall stability of the system is determined by the balance between this intrinsic damping and any destabilising effects modelled by the '$i\delta$' term and is obtained from the dispersion relation

$$\Lambda = \rho_s \sqrt{P}$$

i.e.,

$$\left\{\frac{(\omega_o^* + i\gamma + V_{oo}k_y)}{\omega} - 1 - k_y^2\rho_s^2 - \frac{Q^2}{4P}\right\} = i\rho_s\left(\frac{1}{L_{v2}^2} + \frac{L_n^2}{\rho_s^2 L_s^2} - \frac{1}{L_*^2}\right)^{\frac{1}{2}},$$

which yields the stability criterion,

$$\gamma < \frac{\rho_s\left(\frac{1}{L_{v2}^2} + \frac{L_n^2}{\rho_s^2 L_s^2} - \frac{1}{L_*^2}\right)^{\frac{1}{2}}(\omega_o^* + V_{oo}k_y)}{\left(1 + k_y^2\rho_s^2 + \frac{Q^2}{4P}\right)} \tag{4}$$

It is interesting to note that the sign of the first derivative of the velocity field has no effect on the stability criterion (as it occurs through the 'Q^2' term in (4)) - a result which was also found in the nonlinear calculation of Biglari et al. [16] and in a recent study of ITG modes [7]. The same conclusion can be reached by observing the invariance of the differential equation (2) under the combined operation of reflection $x \rightarrow -x$ and change in sign of $Q \rightarrow -Q$. The linear term shifts the potential, but does not alter the quadratic structure. It also shifts the centre of the mode away from the x=0 rational surface. The main stabilising effect comes from the quadratic term which forms an additional *antiwell* which pushes the wave function away from x=0, thus increasing the shear stabilising effect and weakening the driving term simultaneously.

C. Effects of L-mode Type Velocity Profiles

Next, to show the destabilising action of velocity fields in the L-mode we choose a velocity profile following the JFT-2M [19, 24] (also see the DIII-D result [13]) ohmic phase and L-mode profile for v_θ inside the separatrix -

$$V_o(x) \equiv V_{oo} - \frac{dV_o}{dx}x - \frac{1}{2}\frac{d^2V_o}{dx^2}x^2$$

$$\equiv V_{oo} - \left(\frac{x}{L_{v1}} + \frac{x^2}{L_{v2}^2}\right)V_{oo}$$

With the same assumptions and normalizations as before, the eigenvalue equation (1) then reduces to

$$\rho_s^2 \frac{d^2\phi}{dx^2} + \left[\Lambda - Rx^2 - Qx\right]\phi = 0$$

where

$$\Lambda = \left(\frac{\omega_o^*}{\omega} - k_y^2\rho_s^2 + \frac{V_{oo}k_y}{\omega} + \frac{i\gamma}{\omega} - 1 + \frac{Q^2}{4R}\right)$$

$$R = \left(\frac{1}{L_*^2} + \frac{1}{L_{v2}^2} - \frac{L_n^2}{\rho_s^2 L_s^2}\right), \quad Q = \frac{1}{L_{v1}}$$

So now the velocity curvature deepens the potential well and if

$$\frac{1}{L_*^2} + \frac{1}{L_{v2}^2} > \frac{L_n^2}{\rho_s^2 L_s^2} \tag{5}$$

is satisified, the velocity curvature can nullify the stabilising action of the magnetic shear and render drift waves unstable, as in this case we have a decaying mode solution. Taking representative values for the plasma parameters for the DIII-D L-mode [7, 22] $L_* \approx L_n = 3.4cm, L_s \approx 67cm, \rho_s \approx 1mm$ and $L_{v2} \sim L_{v1} \approx 1cm$, we find that the inequality (5) is usually satisfied. The exact growth rate is given by the dispersion relation

$$\omega = \frac{(\omega_o^* + i\gamma + V_{oo}k_y)}{\left(1 + k_y^2\rho_s^2 - \frac{Q^2}{4R}\right) + \rho_s\left(\frac{1}{L_*^2} + \frac{1}{L_{v2}^2} - \frac{L_n^2}{\rho_s^2 L_s^2}\right)^{\frac{1}{2}}}$$

Thus there is no shear stabilization.

IV. Conclusion

In summary, we have found that although the shear stabilisation criteria for collisionless ("universal") drift waves are well satisfied in ohmic and/or L-mode shots of tokamaks; they are not likely to be satisfied in the edge regions of H-mode discharges. This is due to the extremely steep density gradients observed in the H-mode edges. So, magnetic shear, contrary to the common belief, is not a candidate to stabilise drift waves in the H-mode edge plasma. We have found that the velocity profile curvature $V_o(x)''$ rather than the magnetic shear may be the key element in stabilizing collisionless drift waves in the H-mode edge plasma. We have endeavoured to focus on the representative values for the plasma parameters at the edge. Our full analytic stability analysis, including both first and second derivatives for the velocity field, quite unambiguously shows that stabilization is mainly due to the enhancement of the antiwell in the potential structure. Another important part of our result is that we have shown that L-mode type velocity profiles have a destabilizing action on drift waves. Using realistic L-mode plasma parameters it has been shown that, contrary to the common belief that the influence of magnetic shear is considerably more significant than $V_o(x)''$ [18], the curvature of velocity can outweigh magnetic shear-stabilization and render drift waves unstable in the L-mode. For simplicity, we have not kept the full Z-function in the electron dynamics. Notwithstanding the simplicity of the model, however, the basic stabilizing and destabilizing role of the velocity curvature in the H- and L-mode respectively is, however, quite unambiguously shown by our simple model and is not expected to be seriously modified.

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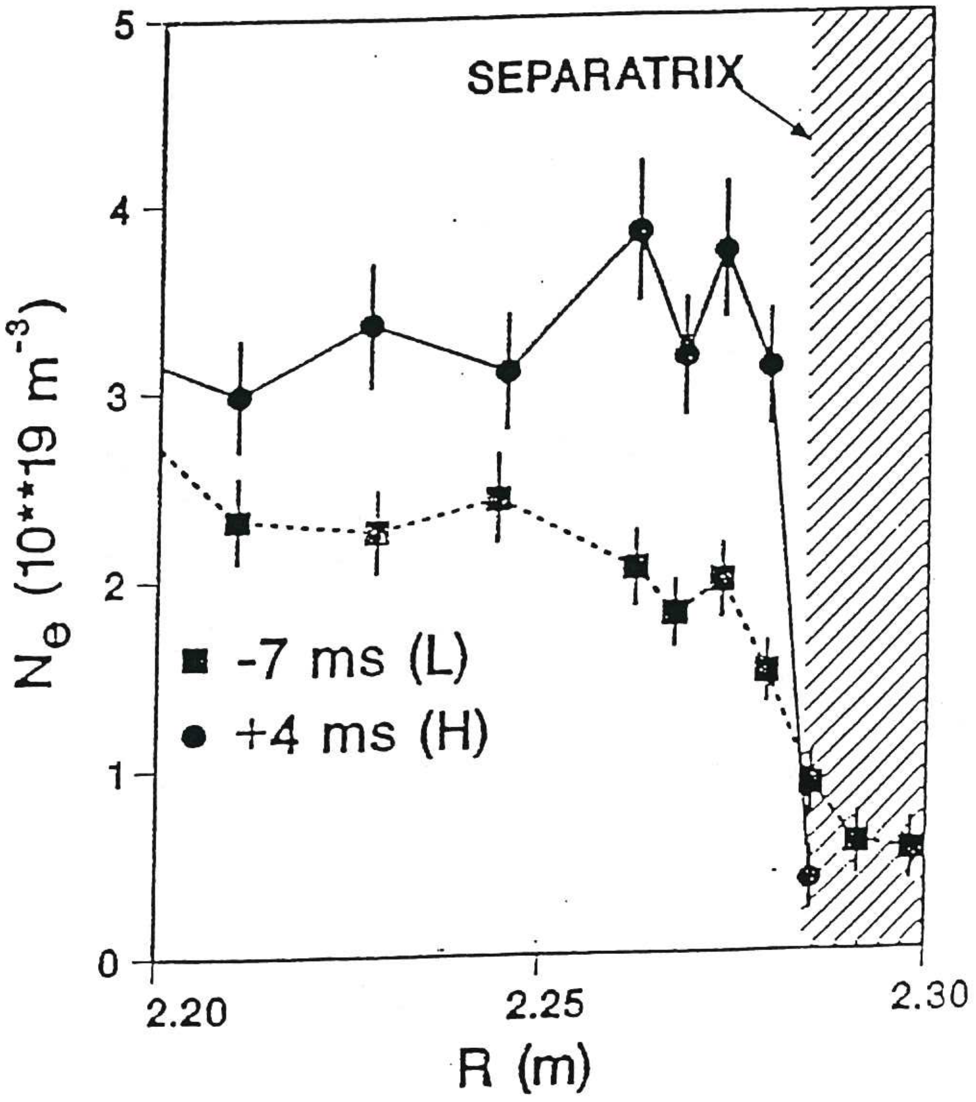
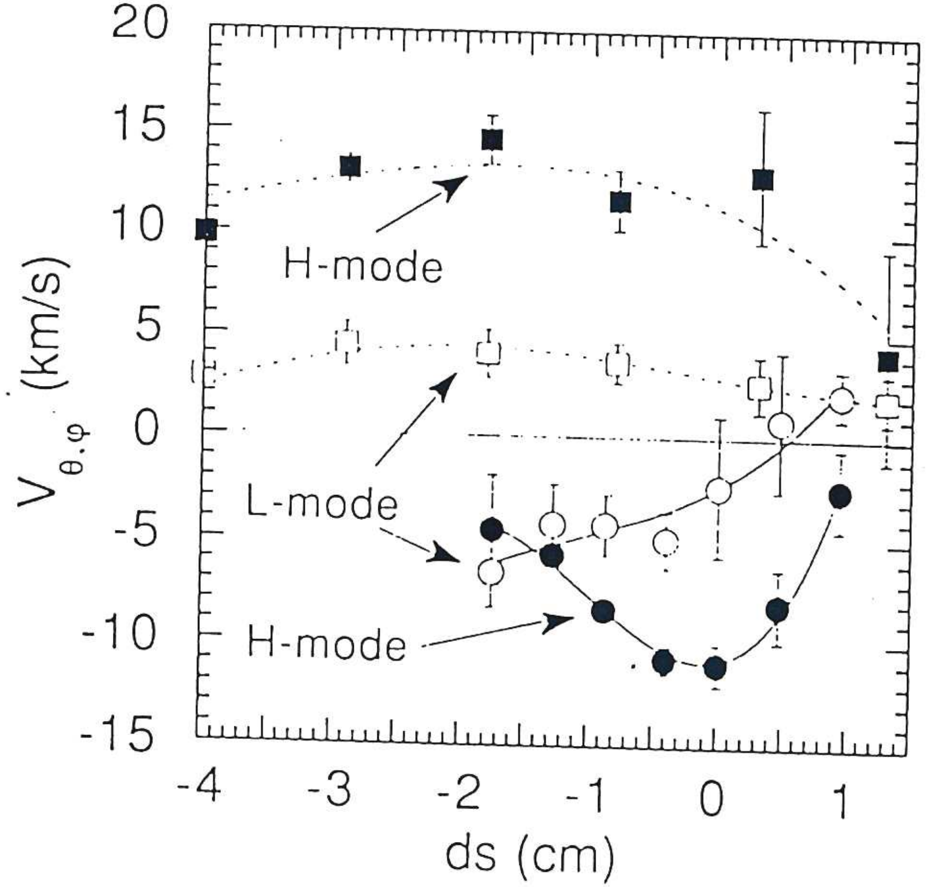
Figure Captions

Fig. 1. Profile of electron density, 7ms before and 4ms after, the L-H transition from the Thomson scattering system [11].

Fig. 2. Radial profiles of poloidal (circles) and toroidal (squares) rotation velocities as a function of the distance from the separatrix, for L-mode (t = 710 ms, open symbols) and H-mode (t = 740 ms, closed symbols) plasmas. d_s is negative inside and positive outside of the separatrix [19].



SEPARATRIX
5
4
3
2
1
0
N_e ($10^{**}19$ m^{-3})
-7 ms (L)
+4 ms (H)
2.20
2.25
2.30
R (m)



H-mode
L-mode
H-mode
$V_{\theta,\varphi}$ (km/s)
ds (cm)