THE ROLE OF VELOCITY SHEAR IN THE TEXTOR-94 RADIATIVE IMPROVED MODE

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1. Introduction

In several theoretical and experimental papers the suppression of turbulence and transport by shear in the radial electrical field is discussed. Whereas for the edge transport barrier in the H-mode the poloidal rotation is found to play a dominant role, the shear in toroidal rotation may be the main cause for the improved modes in reversed shear experiments [1,2]. Moreover even in L-modes evidence was found for a dependence of the confinement on the rotation [3].

In TEXTOR-94 an improved mode is found by injecting neon or argon gas to obtain a radiating mantle in a high density discharge, the so-called Radiative Improved RI-mode [4,5]. Empirically it is found that a prerequisite for these RI-mode is the injection of at least 20 % of the input power from the tangential neutral beam. Now the question arises whether velocity shear reduces the transport and forms a transport barrier.

This is investigated using Charge Exchange Recombination Spectroscopy (CXRS) which can provide radial profiles of ion temperature and toroidal rotation. In the next section a brief overview of the RI-mode is given. Then a simple model is discussed which could explain the toroidal rotation profiles in unbalanced injection experiments. RI-mode discharges with balanced injection and hence no or only small rotation velocities are analyzed and discussed.

2. The TEXTOR-94 RI-mode and CXRS diagnostic

The RI-mode in the limiter machine TEXTOR-94 is characterized by the simultaneous occurrence of the following features: i) energy confinement as good as ELM free H-mode in divertor machines, ii) a favorable linear scaling of the energy confinement with density, allowing high density operation around the Greenwald density, iii) up to 90 % of total power can be exhausted by line radiation iv) high β for a circular cross-section machine (β_N around 2) and iv) quasi stationarity, i.e. the RI-mode phase has been demonstrated to last for more than 160 confinement times (limited by machine constraints only).

The CXRS diagnostic has 15 lines of sight, looking tangentially towards a Neutral Beam Injector (H/D beam, $P_{injected} < 1.8$ MW, accelerated voltage < 52 kV). This provides profiles of T_I and V_φ in the region $\rho = r/a = [-0.1, 0.9]$. Time resolution is 40 ms, which is of the same order as the changeover from L-mode to RI-mode, so the transition characteristics cannot be followed by this diagnostic. The CXRS analysis described in this paper is done on the CVI spectrum at 529.0 nm, but data for the NeX line at 524.9 nm was measured as well and gave the same result. A typical example of toroidal rotation profiles in an (unbalanced) L-mode and RI mode are plotted in Fig. 1. Rotation values in excess of 100 km/s are found.

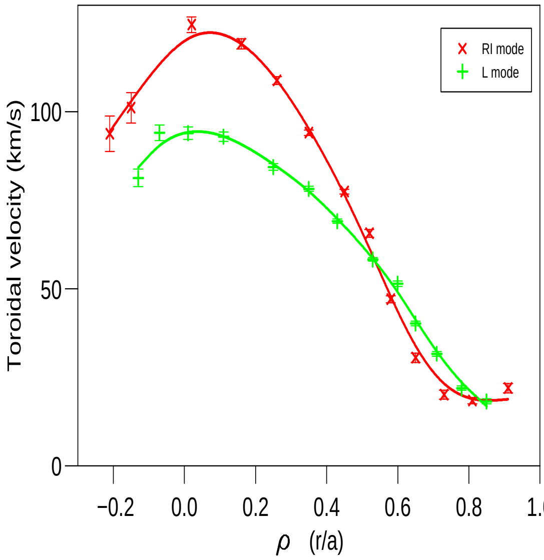

Figure 1: Toroidal rotation velocity profiles as measured by CXRS on the CVI spectrum in an L-mode and RI-mode discharge. For the RI-mode a larger gradient in the region around $\rho = 0.6$ is found.

3. Bifurcation Mechanism for Rotation Profile

As shown in Fig. 1 the profile of toroidal rotation has an enlarged gradient around ρ=0.6 in the RI-mode as compared to the L-mode case. In [6] a model was proposed which could account for the formation of a transport barrier in the RI-mode induced by the peaking of the density profile (as a results of the edge cooling by the line radiation) and the shear in the rotation. Starting point of this model is the toroidal momentum balance for the ions:

$$\rho\frac{\partial V_\varphi}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(-r\eta_\perp\frac{\partial V_\varphi}{\partial r}\right)=\frac{2Q_b}{V_b} \tag{1}$$

where r is the minor radius of the flux surfaces, $\rho = nm_I$ the mass density and $\eta_\perp$ is the perpendicular viscosity of the plasma. The right hand side gives the momentum input from the neutral beam where V_b is the beam velocity and Q_b is the power density of the beam. The viscosity $\eta_\perp = \eta_0 + \eta_1$ is divided into two parts corresponding to a weak transport inside the barrier and a strong anomalous momentum transfer outside. The latter is assumed to be due to toroidal ITG modes [7] and taken to be proportional to the instability linear growth rate:

$$\gamma = 0.5\frac{V_{th}}{R}\sqrt{\frac{R}{L_T}-\beta\frac{R}{L_n}}-\left|\Omega_{E\times B}\right| \quad \text{where} \quad \Omega_{E\times B}=c\frac{B_\theta}{B_\varphi}\frac{\partial}{\partial r}\left(\frac{E_r}{B_\theta}\right)\approx\frac{B_\theta}{B_\varphi}\frac{\partial V_\varphi}{\partial r} \tag{2}$$

In this last equality contributions from poloidal rotation and pressure gradients have been neglected since they are almost an order of magnitude lower than the V_ϕ term in the case of unbalanced injection where V_ϕ can exceed 100 km/s. V_{th} is the thermal velocity, $L_{T,n} = |\partial r/\partial T_{I},n|$ the e-folding lengths of the ion temperature and density and β a numerical factor taken to be 1 here. From Eq. 2 it can be seen that the plasma viscosity is a decreasing function of velocity shear.

If Eq. 1 is integrated for the stationary phase over r the left hand side depends on $|dV_\phi/dr|$, whereas the right hand side is a constant as a function of $|dV_\phi/dr|$. In [6] it was shown that in L-mode discharges there is only one solution for $|dV_\phi/dr|$ possible for which the equality holds, $|dV_\phi/dr|$=3.9 km/s/cm close to the experimental value of 3.7 km/s. In the RI-mode the density profile peaks as a results of the neon seeding, giving rise to a smaller value of L_n. Because of this change in γ there now exists two solutions for $|dV_\phi/dr|$ and a bifurcation into a state with a higher $|dV_\phi/dr|$ can occur. According to the model this transition should occur around $\rho=r/a\approx0.6$ and an increase of $|dV_\phi/dr|$ by a factor of 3 for the discharge analyzed here is predicted. Experimentally, indeed a larger gradient in the rotation profile is observed at $\rho\approx0.6$, where $|dV_\phi/dr|$ increases from 3.7 km/s/cm to 6.9 km/s/cm. Although this increase is less than predicted one should note that the radial resolution of the rotation is limited by the beam-width and the measured gradient is a lower limit.

Summarizing, we have found that in unbalanced RI-mode discharges an enhanced gradient in the toroidal rotation profile is found in the region as predicted by the model. A shear of this rotational motion can lead to a suppression of the turbulence and the anomalous transport might be reduced further and a transport barrier can develop. However, in the next section it is shown that this transport barrier is not a prerequisite to reach the RI-mode. Nevertheless, this mechanism may give rise to an additional channel for reduced transport, which is investigated in the next section.

4. RI-mode with Balanced Neutral Beam Injection

The effect of the rotation on the confinement in the RI-mode was studied in discharges with co and counter injection. The co-injection power was kept fixed at approximately 1.0 MW (D-beam at 22.5 keV/amu), and the counter injection power was varied from 0 to 1.0 MW, thereby replacing part of the ICRH power, to keep the total input power constant at 3.6 MW. In all discharges neon was injected to reach the RI-mode and kept constant at a radiated power fraction of about 80%.

The dependence of the central toroidal rotation on the ratio between co- an counter-injection is shown in Fig. 2. An almost linear dependence is found. This shows that it is also possible to reach the RI-mode with nearly balanced injection, so the shear in the toroidal velocity is not the main reason to reduce the transport. Furthermore, this plot does not show an improved momentum confinement at higher toroidal velocities.

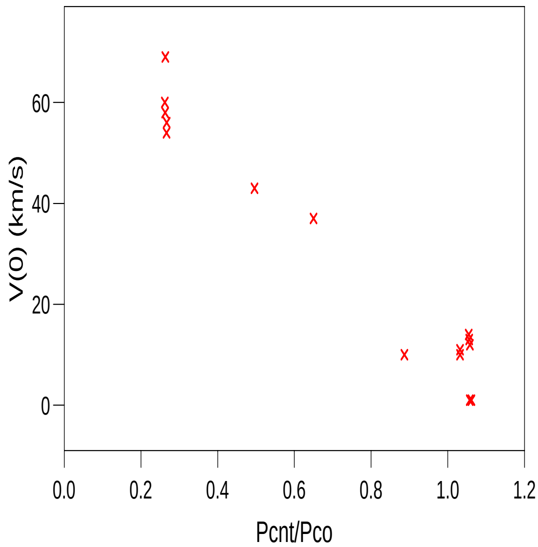

Figure 2: Central toroidal rotation as a function of the ration between co and counter injected power. An almost linear relation shows that no (large) improvement of momentum with increasing rotation is found.

To account for slight changing plasma conditions these rotation data are also plotted against the confinement factor F93H (which is the factor with respect to the ELM-free H mode scaling law ITER93H) in Fig. 3. A rather large scatter of the data is observed, although one might see a slight trend of higher rotations having higher confinement times. Nevertheless it is clear that this is not a dominant feature. The same is observed if the gradient in the rotation around $\rho=0.6$ is plotted.

5. Discussion

It was shown that the toroidal rotation does not play a decisive role to reach the RI-mode. However, in some strongly rotating RI-mode discharges, with $V_\varphi(0)>120$ km/s$\approx0.45\ c_s$ (ion sound velocity) indications for increased shear in the rotation are found. The position and the value of this is close to estimates from a model based on the dependence of the anomalous plasma viscosity on the velocity gradient.

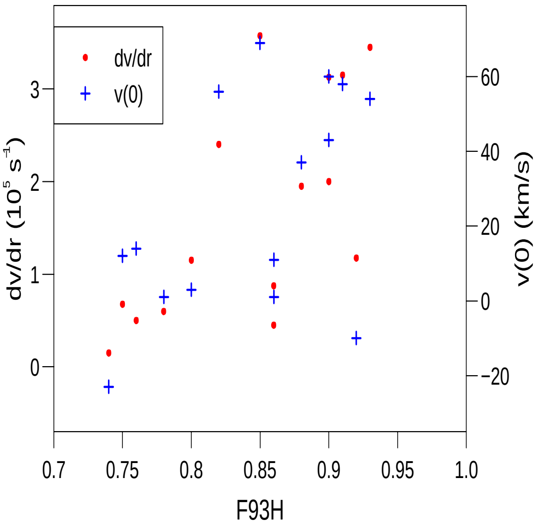

Figure 3: Dependence of central rotation and gradient in the rotation at $\rho = 0.6$ on the improvement enhancement factor F93H. No clear relation is observed.

Nevertheless it should be remarked that the experimental CXRS–data have to be treated with some caution: 1) Due to the rather large beam-width (FWHM≈20-25cm), only a limited spatial resolution is reached in the region of interest (Δr≈5-8 cm) , 2) To calculate from the measured Doppler shift the toroidal rotation a correction should be made as a consequence of the energy dependence of the CX-cross-section. This can be done analytically [8] if the reaction is from beam neutrals in ground state. However, for the TEXTOR D-beam (E_{beam} <26 keV/amu) a large fraction of the emission (up to a factor 2-5!) comes from excited beam particles [9] and the velocity correction is unknown (and not taken into account here), 3) In the case of neon injection the carbon spectrum is disturbed by three spectral lines originating from lower ionization stages of neon, complicating the spectrum fitting procedure. 4) The RI-mode discharges are performed at high densities, resulting in a strong beam attenuation and thus to a low CX-signal.

Not solved in these investigations is the question why empirically it is found that at least 20% NBI co-injection power is necessary. Moreover in other investigations [5] it was found that recycling properties of neutrals where a dominant factor for achieving the RI-mode. For instance the plasma position with respect to the ALT-II limiter plays a crucial role [10]. This position is different for balanced than for unbalanced neutral beam injection. For the scan described here this is only partly compensated and it therefore could obscure the results.

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