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The Influence of Angular Momentum on Energy Confinement on the TEXTOR-94 Tokamak

H.L.M. Widdershoven[1,2] and R. Jaspers[1]

Partners in the Trilateral Euregio Cluster
[1]*FOM instituut voor Plasmafysica Rijnhuizen, Association EURATOM-FOM, P.O.Box 1207, 3430 BE Nieuwegein, The Netherlands*
[2]*Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM association, D-52425 Jülich, Germany*

Recently, experimental data became available indicating a strong relation between rotation and confinement. For example, in TFTR L-mode plasmas increased confinement was observed for both strong co- and strong counter rotation [1]. Also, velocity shear in general is believed to play an important role in improved confinement regimes [2][3].

The mechanism behind the influence of rotation, and more importantly it's shear, on transport is not clear. The energy confinement scaling laws used to predict the performance of new fusion machines do not account for the effect of rotation. In the experiment reported in the present paper the influence of v_ϕ on energy transport. This is done by controlling v_ϕ using the angular momentum input $\dot{L}_\phi$ from neutral beams.

After having established a relation between the central toroidal rotation $v_\phi(0)$ and $\dot{L}_\phi$, the influence of $\dot{L}_\phi$ on the energy confinement time τ_E is investigated.

Not only the effect of rotation on transport is unclear. There is also no comprehensive theory predicting the rotation profile $v_\phi(r)$. Therefore we have measured the rotation profile in two distinct confinement regimes, and compared them to predictions of the revisited neoclassical theory (RNT) [4] [5].

Experimental Set-up

In TEXTOR-94 (major radius R_0 = 1.75 m, minor radius a = 0.46 m) two NB injectors (NBIs) are available. One injects in the co direction (with respect to the plasma current), the other in the counter direction. Both NBIs have a nominal power of 1.5 MW at an accelerator voltage V_{ac} of 50 kV. The beams can be operated with hydrogen, deuterium or helium gas. The experiments described in this paper all use H injection into a D plasma.

The NB power input can be adjusted in two ways. Firstly, V_{ac} can be changed from 0 to 60 kV. Since ionisation and charge exchange cross sections are strongly energy dependent, this has a severe impact on the power deposition profile. Secondly, both beams have a so-called V-target. This consists of two cooled plates in front of the neutralizer of which the mutual distance can be varied, controlling the amount of injected beam particles. This only has a small impact on the power deposition profile, and is therefore the method we have used.

The $\dot{L}_\phi$ scan has been performed in L mode discharges, at two densities and two toroidal magnetic fields. During this scan, the input power was kept constant, whereas the ratio co to counter power was varied. $\dot{L}_\phi$ ranged from -0.9 Nm to 1.2 Nm, resulting in $v_\phi(0)$ to range from approx. -150 km/s to +200 km/s, respectively.

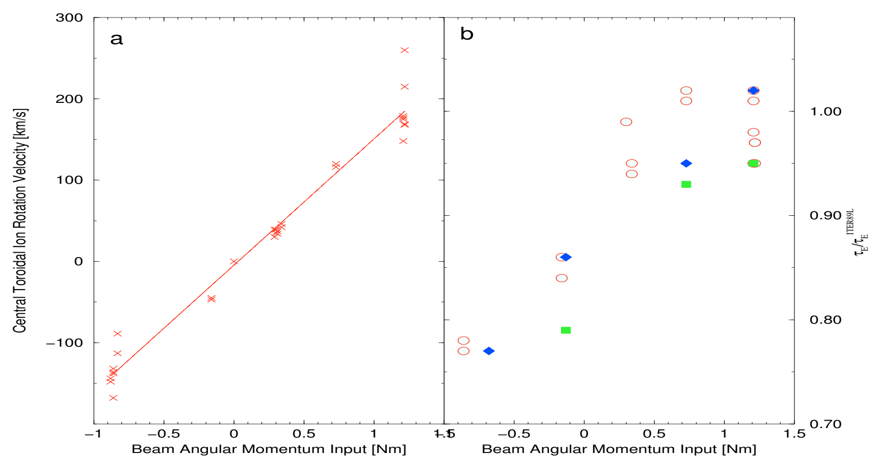

Figure 1: *Angular Momentum Scan. a) The central toroidal rotation velocity of* C^{6+} *is shown versus the angular momentum input by means of Neutral Beams. The line is to guide the eye. b) shows the energy confinement time, normalized to the ITER89L scaling law, versus the angular momentum input. The red circles feature a density* $n_e = 2 \cdot 10^{19}\ m^{-3}$ *and a field* $B_\phi = 2.25$ *T, the blue diamonds have* $n_e = 2 \cdot 10^{19}\ m^{-3}$ *and* $B_\phi = 2.5$ *T, and the green rectangles have* $n_e = 3 \cdot 10^{19}\ m^{-3}$ *and* $B_\phi = 2.5$ *T.*

The toroidal velocity is measured using the Charge eXchange Recombination Spectroscopy (CXRS) diagnostic. This diagnostic measures the spectral lines emitted by a plasma ion species (a C^{VI} line was used here). The width of the measured spectral line gives the ion temperature. The Doppler shift is proportional to the plasma rotation. For the tangential CXRS geometry this is v_ϕ.

The CX radiation is emitted only in the region determined by the intersection of the NBI and the line of sight. By choosing the line of sight to be tangential to the magnetic surface in this region, a radial resolution of 3-10 cm is obtained, although the beamwidth has a FWHM of 25 cm. Presently, 15 lines of sight are available, covering the region $R = [170, 217]$ cm.

Energy confinement and angular momentum input

The results of a momentum scan (at a plasma current of 350 kA) are shown in figure 1.

In figure 1a, $v_\phi(0)$ is plotted versus $\dot{L}_\phi$. As expected, there is a clear dependence between angular momentum input and the velocity. The data available strongly suggest a linear dependence, as represented by the line. This suggests that the momentum confinement time τ_ϕ does not vary significantly within the investigated $\dot{L}_\phi$ range. Figure 1b shows the influence of $\dot{L}_\phi$ on τ_E, where τ_E is normalized to the ITER89L mode scaling law. Three observations can be made in this graph. Firstly, counter injection degrades the confinement. Secondly, even in the best case (full co beam) τ_E does not increase beyond the predicted confinement time. Thirdly, the direction of the rotation is important. The energy confinement time at $v_\phi = 100$ km/s is better than at $v_\phi = -100$ km/s. Similar experiments were done on TFTR [1], reporting a decrease in τ_E with decreasing momentum input. However, on TFTR an *increasing* τ_E at very high counter beam input was also reported, as well as normalized τ_E values above one at strong beam power. This has not been observed on TEXTOR-94.

In figure 2, a discharge with dominating counter and only co injection are compared.

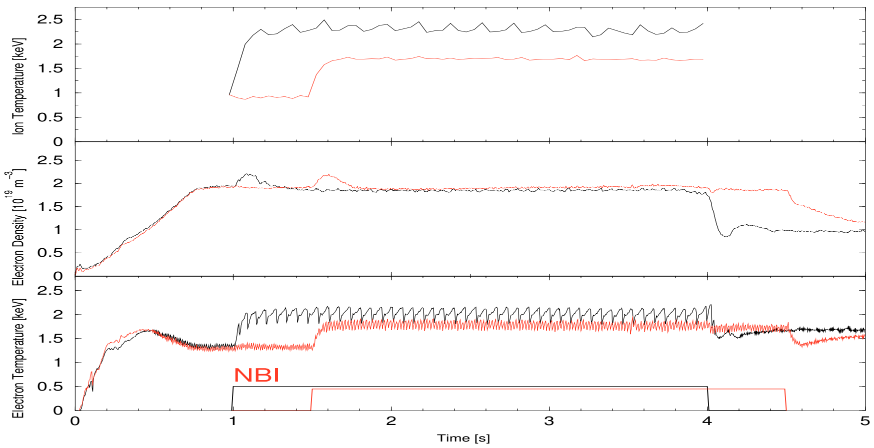

Figure 2: *Timetraces of two discharges with opposite beam input. Black represents the full power co-beam discharge, red the almost full power counter beam discharge. The neutral beam timing is indicated by the rectangles.*

The only difference between the discharges was $\dot{L}_\phi$. The density (fig. 2b) is in both cases equally low and the ions and electrons are only weakly coupled. It can be seen that the electron temperature differs approx. 10%, whereas the ion temperature differs 25%, the higher temperatures in the co injection case. This indicates that the major additional loss channel in the case of counter injection is via the ions. This has also been indicated by the experiments on TFTR[1]. It should be noted that the co and counter injection cases show different sawteeth. Therefore it can not be concluded whether the confinement changes are related to a change in v_ϕ or to the current profile.

Rotation profiles

The rotation profiles of two distinct confinement regimes have been measured and compared to theory. Measurements were done in L mode and in an enhanced confinement regime, the Radiative Improved (RI) mode[6]. RI mode is obtained in high density, additionally heated discharges with impurity seeding, resulting in a radiating mantle.

For comparison between RI mode and L mode two typical discharges were taken. The discharges were, apart from the Neon puff in the RI mode case, identical. Their velocity profiles are shown in figure 3, together with the profiles predicted by the RNT.

In this figure, a clear difference in gradient between the L-mode and RI mode v_ϕ profile can be observed. Compared to the RNT, the gradient as well as the size of v_ϕ agree better with the RI mode data than the L mode data for the region outside the $q = 1$ surface. The RNT is expected not to apply to the central sawtoothing region of the plasma. The fact that predictions and RI mode measurements agree so well implies that anomalous transport is strongly suppressed in RI mode.

A satisfactory modeling of $v_\phi(r)$ for both cases is given in [7], where it was found that the L mode profile was determined mainly by the anomalous viscosity, but that in the RI mode RNT effects become more important since the anomalous viscosity decreases and the gradients increase.

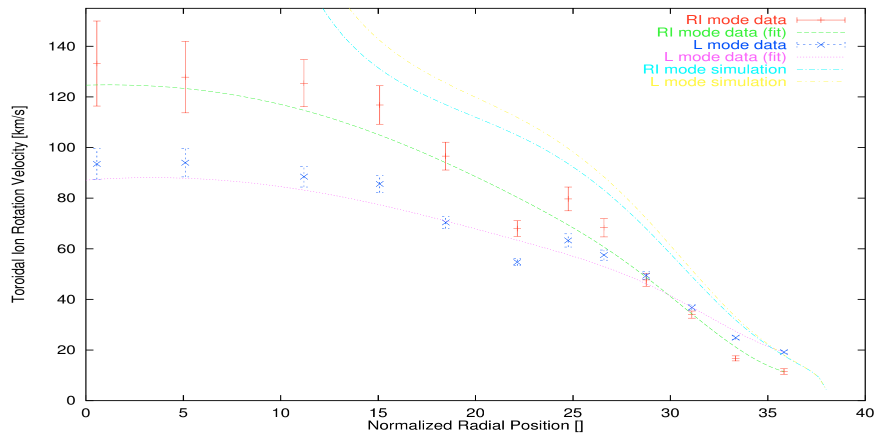

Figure 3: *A L-mode and RI mode toroidal velocity profile compared with the Revisited Neoclassical Theory[4]. The curves are to guide the eye. Note the large difference in velocity gradient between the L and RI mode discharge.*

Discussion

A $\dot{L}_\phi$ scan at TEXTOR-94 did not show an improved confinement but instead a deterioration for the case of counter injection. These results are partly conflicting with results found elsewhere [1], where at high rotation speeds (both co and counter) increased confinement was found. A reason for this might be that the achieved rotation speeds are insufficient to reach these conditions. This is due to the available beam power. In the near future, a dynamic ergodic divertor (DED)[8] will be installed at TEXTOR-94. The DED will be able to exert a torque on the plasma and increase rotation.

Comparison of RNT predictions with L and RI mode measurements showed a better agreement with the latter case. Taking anomalous viscosity in account a better correspondence is obtained in both cases.[7].

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