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Experimental studies on toroidal plasma rotation in ASDEX Upgrade

D. Nishijima[1], A. Kallenbach[1], S. Günter[1], M. Kaufmann[1], K. Lackner[1], C.F. Maggi[1], A. Peeters[1], G. Pereverzev[1], B. Zaniol[2] and the ASDEX Upgrade Team[1]

1. Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748, Garching, Germany

2. Consorzio RFX, EURATOM Association - ENEA, Corso Stati Uniti, 4, I-27135, Padova, Italy

1. Introduction

Toroidal plasma rotation is thought to play a crucial role in creating $E \times B$ flow shear, leading to the suppression of turbulent transport, then to an internal transport barrier (ITB) and/or an edge transport barrier (ETB) [1]. This means that momentum transport can affect energy and particle transport and/or be affected by them. In this paper we briefly describe experimental results performed in the ASDEX Upgrade tokamak on toroidal plasma rotation. The toroidal rotation velocity V_ϕ as well as the ion temperature T_i are measured with charge exchange recombination spectroscopy (CXRS) from the C VI 529.05 nm CX line ($n = 8 \rightarrow 7$) [2].

2. Slowing down of toroidal rotation with additional ICRH in NB heated plasmas

Toroidal rotation is usually generated by toroidally oriented neutral beam injection (NBI). In addition, effects of radio frequency (RF) heating may need to be taken into account [3]. Here, discussed is the cause of slowing down of toroidal rotation with additional ICRH in NB heated plasmas. A hydrogen minority in a deuterium plasma is used for ICRH with a central resonance layer, the frequency f_IC = 30 (36.5) MHz for the toroidal magnetic field B_ϕ = 2 (2.5) T. Figure 1 shows radial profiles of V_ϕ in (a) co-current (co-NBI) and (b) counter-current (counter-NBI) rotating plasmas driven by NBI with and without ICRH. It is clear that in both cases V_ϕ decreases with ICRH. As a cause of V_ϕ reduction due to additional ICRH in NB heated plasmas, the following mechanisms can be considered:

- Direct momentum input from ICRF waves with asymmetric antenna spectra [3],
- ICRF-induced toroidal force associated with the radial non-ambipolar transport of resonant particles [4],
- Confinement degradation.

The first mechanism does not apply here because the antenna spectra were symmetric in the shots. According to the second mechanism, the toroidal force generated should be in the counter-current direction, resulting in slowing down of V_ϕ in the co-NBI case and in speeding up in the counter-NBI case. Although this qualitatively agrees with the observation in the co-NBI case (Figure 1 (a)), the V_ϕ reduction in the counter-NBI case (Figure 1 (b)) can not be explained. In JET it has been observed that plasmas heated by ICRF only rotate in the co-current direction [3], which also contradicts the second mechanism. However, mechanisms of driving toroidal rotation in ICRF only heated plasmas are still unclear. The last proposed mechanism is expected to cause V_ϕ reduction regardless of the direction of NBI or the plasma current I_p. Confinement degradation or enhanced transport, caused by a decrease of the $T_\mathrm{i}/T_\mathrm{e}$ ratio, was regarded as a possible mechanism of the V_ϕ reduction due to pure electron heating with ECH and FWEH in DIII-D [5].

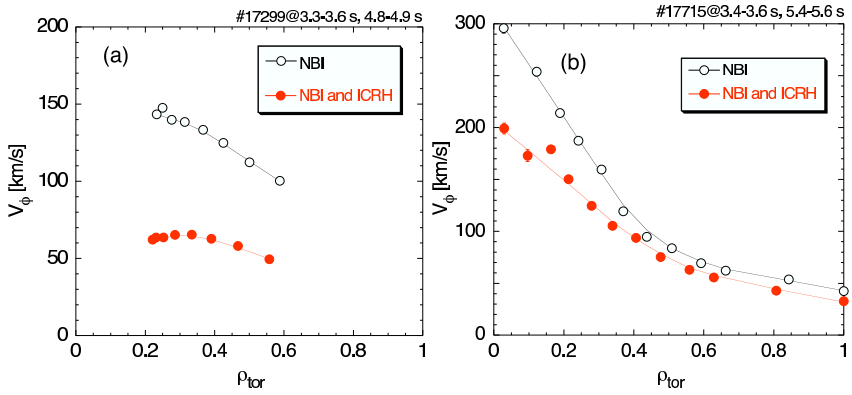

Figure 1: *Radial profiles of V_ϕ in (a) co-current (P_{NB} = 2.5 MW, P_{IC} = 5 MW) and (b) counter-current (P_{NB} = 5 MW, P_{IC} = 1.6 MW) rotating plasmas driven by NBI with and without ICRH.*

In order to explain quantitatively the V_ϕ reduction due to confinement degradation, a simple analysis is introduced, starting with the global angular momentum conservation equation,

$$\frac{1}{\tau_\phi}\int_{V_{\rm pl}} n_{\rm i} m_{\rm i} V_\phi dV_{\rm pl} = P_{\rm NB}\left(\frac{2m_{\rm b}}{E_{\rm b}}\right)^{1/2}\left(\frac{R_{\rm tan}}{R}\right), \tag{1}$$

where τ_ϕ is the momentum confinement time, $n_{\rm i}$ and $m_{\rm i}$ are the ion density and mass, respectively, $m_{\rm b}$ and $E_{\rm b}$ the mass and energy of the neutral beam species, respectively, and $R_{\rm tan}$ and R the beam tangency and the major radii, respectively, and $V_{\rm pl}$ the plasma volume. Assuming $\tau_\phi \sim \tau_{\rm E}$ (the energy confinement time) [6] with $\tau_{\rm E} \sim I_{\rm p}R^2/\sqrt{P_{\rm tot}}$ [1], a ratio

$$\frac{\int_{V_{\rm pl}} V_\phi({\rm NB+IC})dV_{\rm pl}}{\int_{V_{\rm pl}} V_\phi({\rm NB})dV_{\rm pl}} \sim \frac{n_{\rm eL}(NB)}{n_{\rm eL}(NB+IC)}\sqrt{\frac{P_{\rm NB}}{P_{\rm NB}+P_{\rm IC}}}, \tag{2}$$

is obtained with $P_{\rm NB}$, $P_{\rm IC}$ and $n_{\rm eL}$ being the NB power, ICRH power and line averaged density, respectively. Here, we assume $n_{\rm i} \sim n_{\rm e}$. In figure 2, the relation in equation (2) is plotted with experimental data. It is found that the data appear to obey the relation.

3. Momentum diffusivity χ_ϕ

In various experiments momentum transport has been characterized by the momentum diffusivity χ_ϕ. However, less attention has been given compared to energy and particle transport. In this section we compare χ_ϕ with the ion and electron heat diffusivities $\chi_{\rm i}$, $\chi_{\rm e}$ in H-mode and ITB plasmas heated by NBI only. The experimental χ_ϕ is derived from the momentum balance equation in the toroidal direction with the ASTRA code [7]. In the analysis we neglected the momentum loss due to ion-neutral collisions, which is expected to be small inside separatrix, and the convection. $\chi_{\rm i}$ and $\chi_{\rm e}$ are also obtained using the ASTRA code, where the convective terms are not dealt with. Then, in this study, all the three diffusivities are a so-called total diffusivity.

Figure 3 shows comparisons of χ_ϕ with $\chi_{\rm i}$ and $\chi_{\rm e}$ at $\rho_{\rm tor}$ = 0.35 and 0.75. Relations between the diffusivities at $\rho_{\rm tor}$ = 0.35 and 0.75 can display the typical behavior in the inner ($\rho_{\rm tor} <\sim 0.5$) and outer ($\rho_{\rm tor} >\sim 0.5$) regions, respectively. At $\rho_{\rm tor}$ = 0.35, χ_ϕ is similar to both $\chi_{\rm i}$ and $\chi_{\rm e}$ for all the plasma regimes with exceptions of higher χ_ϕ. χ_ϕ at $\rho_{\rm tor}$ = 0.75 is

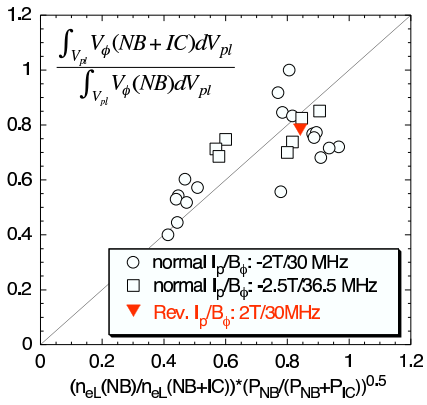

Figure 2: *Reduction of the toroidal rotation velocity due to confinement degradation in both normal I_p/B_ϕ (open symbols) and reversed I_p/B_ϕ (closed triangle) shots. P_{NB} was 2.5 or 5 MW, and P_{IC} ranged from 0.7 to 5.5 MW.*

still comparable to χ_e for standard and improved H-modes, although χ_ϕ becomes higher than χ_e in ITB plasmas. On the other hand, in all plasma regimes, χ_ϕ becomes smaller than χ_i by a factor of about 4 at ρ_{tor} = 0.75. This deviation does not necessarily mean that the ion temperature gradient (ITG) mode is inactive there, in fact the T_i profile is still stiff, but it does contradict theories [8] based on the ITG driven turbulence, which predict $\chi_\phi = \chi_i$. Moreover, it can be recognized that momentum transport is still linked with ion heat transport in the outer region, for instance, from the fact that both χ_ϕ and χ_i have a similar electron density dependence.

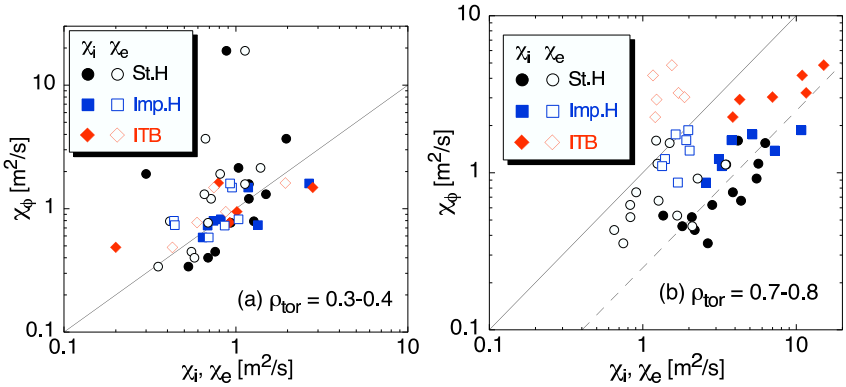

Figure 3: *Comparison of χ_ϕ with χ_i (closed symbols) and χ_e (open symbols) at (a) ρ_{tor} = 0.3-0.4 and (b) 0.7-0.8 in standard H-mode (circles), improved H-mode (squares) and ITB plasmas (diamonds), heated by NBI only. The values are averaged over the region. Solid and dashed lines show χ_ϕ = χ_i, χ_e and χ_ϕ = 0.25 χ_i, χ_e, respectively.*

4. Normalized gradient length R/L

Normalized gradient analysis offers advantages compared to deducing diffusivities, since the deposition profiles of heat, momentum and particles from NBI, ICRF etc, do not need to be calculated [1]. Although the normalized gradient length of T_i, R/L_{T_i}, has been intensively investigated, there is little knowledge about the normalized gradient length of V_ϕ, R/L_{V_ϕ}.

Plotted in figure 4 is the relation between $R/L_{\mathrm{T_i}}$ and R/L_{V_ϕ} for standard H-mode, improved H-mode and ITB plasmas heated by NBI only. In all these plasma regimes, R/L_{V_ϕ} tends to become smaller than $R/L_{\mathrm{T_i}}$. In standard H-mode plasmas, R/L_{V_ϕ} varies from 0 to 7, indicating that the V_ϕ profile is not stiff. On the other hand, the T_i profile is stiff ($R/L_{\mathrm{T_i}} \sim 5$). In ITB plasmas both $R/L_{\mathrm{T_i}}$ and R/L_{V_ϕ} exceed the values observed in H-modes, meaning that both profiles are not stiff any longer and the ITG mode is thought to be suppressed. The difference between $R/L_{\mathrm{T_i}}$ and R/L_{V_ϕ} in standard H-modes results from the different behavior with respect to the line averaged density n_{eL}. At high density of $n_{\mathrm{eL}} > 8 \times 10^{19}$ m^{-3}, R/L_{V_ϕ} becomes small ($<\sim 2$) in the case of two on-axis beams, while $R/L_{\mathrm{T_i}}$ with two on-axis beams is still around 4-6. With the combination of on- and off-axis beams, R/L_{V_ϕ} stays around 3-5 even in the high density region, which is similar to $R/L_{\mathrm{T_i}}$. In line with the low R/L_{V_ϕ} at high density with on-axis beams only, χ_ϕ tends to become higher than χ_i and χ_e. The exceptions with higher χ_ϕ in the inner region, shown in figure 3 (a), are connected to this flattening of the V_ϕ profile.

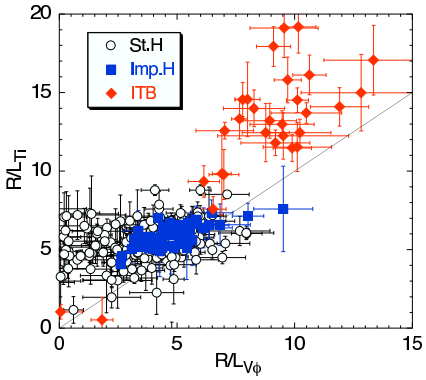

Figure 4: *Comparison of $R/L_{\mathrm{T_i}}$ and R/L_{V_ϕ} at ρ_{tor} = 0.3, ..., 0.7 in standard H-mode, improved H-mode and ITB shots. A solid line shows $R/L_{\mathrm{T_i}} = R/L_{\mathrm{V}_\phi}$.*

5. Conclusions

Reduction of V_ϕ in NB heated plasmas with additional ICRH is found to be mainly due to confinement degradation from a simple analysis based on global confinement. χ_ϕ is similar to χ_i and χ_e in the inner half of plasmas, although in the outer region χ_ϕ becomes smaller than χ_i in H-modes and ITB plasmas. In ion-ITB regions the V_ϕ profiles are steeper compared to H-mode profiles, as observed for the T_i profile. R/L_{V_ϕ} is smaller than $R/L_{\mathrm{T_i}}$ in H-modes and ITB plasmas. In the core region of H-modes, where the T_i profile is stiff ($R/L_{\mathrm{T_i}} \sim 5$), the V_ϕ profile is not stiff ($0 < R/L_{\mathrm{V}_\phi} < 7$). The V_ϕ profile tends to become flat at high densities with on-axis NBI only. This flattening of the V_ϕ profile is caused by χ_ϕ higher than χ_i and χ_e.

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