POLOIDAL ROTATION AND RADIAL ELECTRIC FIELDS IN TFTR

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Abstract

New measurements of the impurity ion poloidal rotation profile have been made in the Tokamak Fusion Test Reactor (TFTR), allowing the determination of radial electric field profiles. A bifurcation of the impurity poloidal velocity is observed in reversed shear discharges before the transition to enhanced confinement. Significant differences between measured and neoclassically calculated values of poloidal velocity and radial electric field have been observed. Velocity measurements in a number of confinement regimes (supershot, reversed shear, and L-mode) suggest that the impurity poloidal velocity profile is correlated with the ion temperature profile.

1. INTRODUCTION

Tokamak plasmas with weak or reversed central magnetic shear have demonstrated remarkable improvements in particle, ion thermal, and momentum confinement within a core transport barrier [1,2]. The likely role of $E\times B$ flow shear stabilization of turbulence in the formation of these internal transport barriers has motivated the development of new diagnostic techniques to measure the radial electric field, E_r, in the plasma core [3,4,5]. The importance of E_r shear to the supershot regime in TFTR has recently been shown [6]. E_r can be evaluated using the radial force balance equation, $E_r = \; p/(eZn) + v_\varphi B_\theta - v_\theta B_\varphi$, where p is the ion pressure, e is the electronic charge, Z is the charge number, n is the ion density, v_φ and v_θ are the toroidal and poloidal velocity, B_φ and B_θ are the toroidal and poloidal magnetic fields. The carbon pressure and toroidal velocity have routinely been measured on TFTR using charge exchange recombination spectroscopy. Historically, the carbon poloidal velocity was evaluated using neoclassical predictions to arrive at a neoclassical value for E_r. For the final TFTR run period, a new spectroscopic diagnostic was installed to measure poloidal velocity profiles [7].

2. REVERSED SHEAR DISCHARGES

Deuterium reversed shear (RS) discharges at two toroidal magnetic fields, $B_\varphi = 4.6$ and 3.4 T were studied. The plasma currents were $I_p = 1.6$ and 1.2 MA respectively for the high and low field discharges, resulting in similar edge q values. The plasmas had a major radius of $R_0 = 2.60$ m and a minor radius of $a = 0.95$ m.

2.1 Poloidal rotation precursor to Enhanced Reverse Shear

Similar reverse shear discharges show a clear transport bifurcation after a threshold power is exceeded (Fig. 1a). Measurements of the poloidal velocity of carbon impurity ions showed a bifurcation *before* the time of the transport improvement to enhanced reverse shear (ERS) confinement [8, 9] (Fig 1b). In a narrow radial channel, the ion rotation velocity reversed direction for those discharges which would undergo a transition to enhanced confinement. Other parameters such as carbon v_φ and p showed little or no change at the time of the v_θ excursion. An inversion was used to recover local v_θ values from the chord-integrated measurements[10]. The radial width of the reversal region, although narrower than the separation of sightlines, was estimated to be less than 2 cm. The peak values of v_θ could reach 10^5 m/s, especially in the lower B_φ discharges (Fig. 2a). These measurements are corroborated by measurements from the motional Stark effect (MSE) diagnostic, which measured a transient change in E_r with remarkably similar temporal behavior and spatial extent. Good quantitative agreement was found between the local values calculated with the force balance equation from the E_r spectroscopic data and the transient change in E_r observed using MSE during the excursion[5] (Fig. 2b). The measured $E\times B$ shearing rate, $\omega_{E\times B}$, during the excursion was typically more than an order of magnitude above that required from theory to initiate an ERS transition. However, at least one discharge underwent

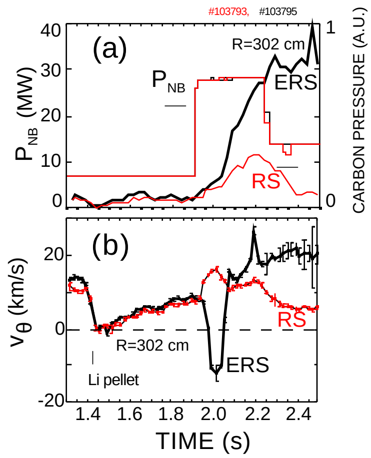

Fig. 1 (a) The bifurcation in local carbon pressure indicates start of ERS transition. (b) A bifurcation in the carbon v_θ *precedes ERS.*

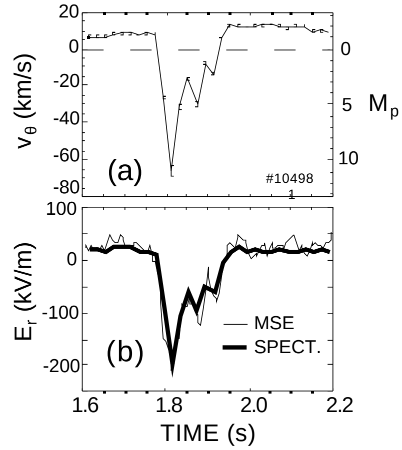

Fig. 2 (a) A large excursion in the carbon v_θ *is seen in a low* B_T *discharge with the approximate poloidal Mach number. (b)* E_r *determined spectroscopically and from MSE show good agreement.*

a transition to ERS without a precursor, indicating the precursor was not necessary for the transition. All discharges with a precursor, did transit into ERS.

2.1 Super poloidal sonic flow

The factor $U_{pm} = M_p - p/(e\,Z\,n\,v_{th}\,B_\theta)$, the effective poloidal Mach number, has been proposed as a critical parameter in the L-H transition[11], where $M_p = v_\theta\,B/(v_{th}\,B_\theta)$ is the poloidal Mach number and $v_{th} = (2T_i\,/\,m_i)^{1/2}$ is the ion thermal velocity. For $U_{pm} > 1$ the number of trapped ions decreases exponentially and therefore the poloidal viscosity decreases, even with $M_p < 1$. A shock develops when M_p is near 1, if the ion diamagnetic flow is small compared to the poloidal velocity [12, 13]. If this occurs, the pressure on a flux surface is no longer constant.

During the large v_θ / E_r excursion in RS plasmas, $M_p > 10$ for carbon ions (Fig. 2a). Though the main ion flow was not measured, its poloidal velocity can be related to the measured carbon v_θ through the radial force balance equation. With little change in the plasma pressure during the excursion, the *change* in the $E{\times}B$ flow of deuterium is approximately equal to the *change* in carbon v_θ during the excursion. Assuming that deuterium is subsonic before the excursion and its toroidal flow is relatively unchanged during the excursion, as is the case with carbon, then $M_p > 4$ for deuterium ions during the excursion. Within the narrow shear layer, which is on the order of the banana width, trapped ions should be depleted which also should result in a reduction in heat transport [14, 15]. However, after the excursion when v_θ relaxes, the observed suppression of the transport must be due to other mechanisms. Since the diamagnetic flow is comparatively small, a shock would be expected as the poloidal flow neared $M_p = 1$. However, there were no measurements which might have confirmed the presence of a shock, such as measuring a density variation on a flux surface.

3. COMPARISON OF MEASUREMENTS WITH NEOCLASSICAL PREDICTIONS

Aside from the large excursion velocities in the precursor, there were clear differences between the local core measurements of v_θ for reversed shear plasmas and the values predicted by neoclassical theory [9]. This difference leads to a more positive measured value of E_r than previously inferred using neoclassical predictions for v_θ. The resulting differences in E_r' would suggest that shearing rate, $\omega_{E\times B}$, was previously underestimated before the transition and overestimated after the transition, when neoclassical predictions were used. Measurements of carbon v_θ in supershot plasmas also show clear differences from neoclassical predictions, with the measured values more positive than the neoclassical values (see Fig. 3). Like the RS discharges, the carbon v_θ was generally in the ion diamagnetic drift direction with either co- or counter-neutral-beam injection.

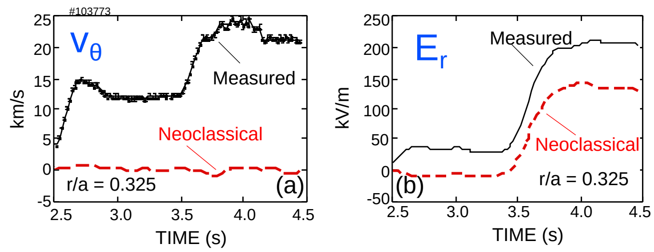

Fig. 3 Measurements of (a) carbon v_θ and (b) resulting E_r differ from neoclassical predictions .

4. POLOIDAL ROTATION IN SUPERSHOT AND L-MODE PLASMAS

Dynamic changes in the v_θ have been seen in discharges modified with a puff of helium [10]. The poloidal velocity was seen to fall as the He puff spoiled the good supershot confinement. A deuterium supershot plasma, which displays large changes in v_θ without large changes in energy confinement, is examined here with I_p = 1.6 MA, R_0 = 2.52 m and a_0 = 0.97 m with a neutral beam (NB) injected power of 14 MW. (See Fig. 4). The initial direction of injection of the neutral beams was balanced and was shifted to all co-injected beams at 3.5 s. This caused dramatic changes in the rotational flow of the plasma. Shown in Fig. 4a and 4b are the carbon poloidal and toroidal rotation at two radii corresponding to roughly r/a = 0.25 and 0.5. The toroidal rotation was near zero during balanced NB injection and increased as the momentum input was changed. The poloidal rotation rose markedly as the balanced NB injection began. It increased again after the all co-injection started. The measured carbon v_θ shows a remarkably similar temporal behavior to the carbon ion temperature (T_i). Not only was the initial rise after the NB direction change captured, but when a sudden reduction in confinement occurs near 4.0 s, there was a corresponding drop in the measured v_θ reflecting the change in T_i and v_φ near the plasma center. The profiles for v_θ, T_i, and E_r are shown in Fig. 5 for times of balanced and co-directed injection. Fig. 5a and 5b show the components of the force balance equation used to determine E_r . During co-injection, the toroidal component was large and broad yielding a positive E_r. During balanced injection, the toroidal component was small and only the v_θ term was important in determining E_r , which remained positive in the core. The profile of v_θ was similar to that of T_i (although at the axis it must go to zero from symmetry), and broader than would be expected if it were proportional to T_i. The profile data shown in Fig. 5c and 5d are plotted in Fig. 6a and show that the measured carbon v_θ was proportional to the measured T_i across the profile. The constant of proportionality is in the range 1-1.5 (m/s)/eV. In Fig. 6b are chord-averaged v_θ measurements plotted against T_i, at about the half radius for a number of L-mode plasmas with a range of applied NB torques with I_p = 1 and 2 MA, showing a similar linear relationship. Note that the range of poloidal velocities for these L-mode discharges is quite small, varying less than 1 km/s. Reversed shear discharges also show similar trends when comparing time histories and profile shapes of v_θ and T_i, except for the RS precursor described above. Though

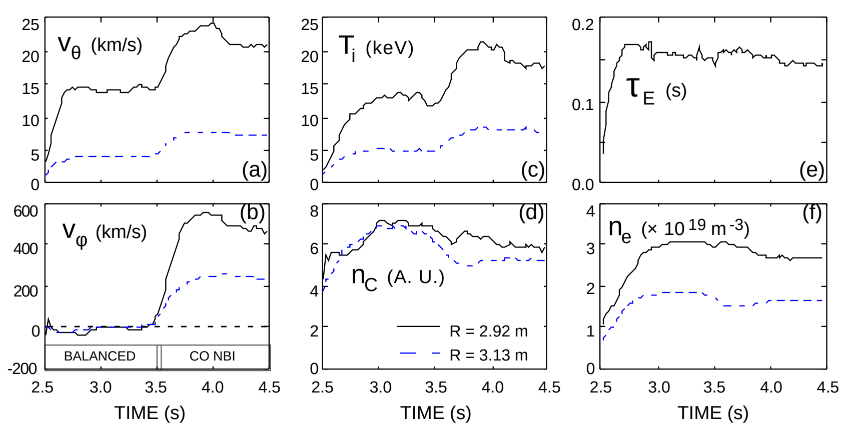

Fig. 4 Changes in v_θ are observed as NBI is shifted from balanced to co-injection. Correlation of v_θ with T_i is observed.

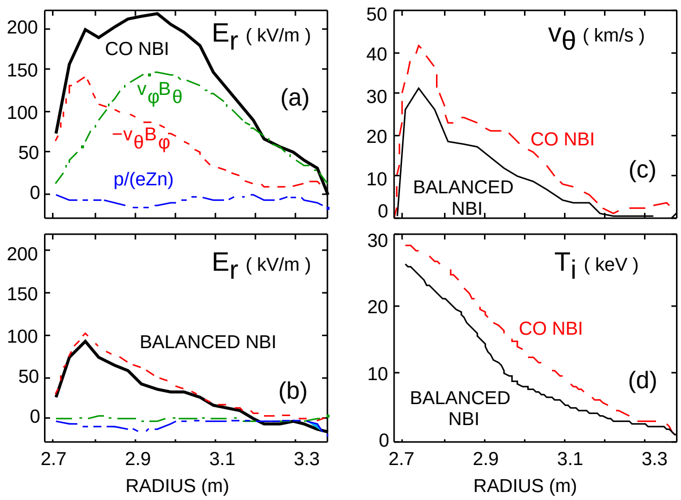

Fig. 5 Profiles of measured radial electric field and components during a supershot with (a) co-inected neutral beams and (b) balanced beams. (c) poloidal velocity profiles show similar profile shape as (d) ion temperature profiles.

there are other influences on the impurity poloidal rotation, the correlation of v_θ and T_i seems to capture much of the behavior of the measured poloidal rotation over a number of plasma regimes in TFTR.

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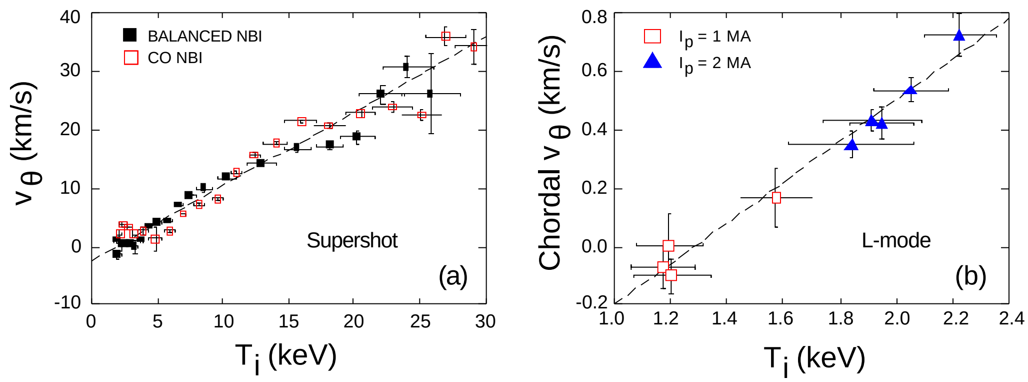

Fig. 6. (a) Carbon v_θ proportional to T_i across supershot profile. (b) Chord-averaged v_θ proportional to T_i for L-mode discharges with varied neutral beam direction.

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