Core Toroidal Rotation Changes Observed with ECRH Power in NBI Heated H-modes on ADSEX Upgrade

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The realization of the connections between rotation and plasma stability and confinement has made the predictive capability and active control of the rotation profile a critical area of tokamak research. The rotation profile on most contemporary tokamak experiments is dominated by externally applied torque from neutral beam injection (NBI). The torque from NBI is quite well understood. However, the momentum transport controlling the final rotation profile is not. In addition, there are intrinsic torques, which must also be understood for a complete picture of tokamak rotation. This is especially important for extrapolations to next generation devices in which the effectiveness of NBI will be diminished. These devices will depend more heavily on alternate heating schemes such as ion and electron cyclotron resonance heating (ICRH, ECRH), both of which have been observed experimentally to impact the plasma rotation [1,2,3,4]. This paper reports on core toroidal rotation changes observed in NBI heated H-mode plasmas in the ASDEX Upgrade tokamak with the application of ECRH power.

All of the results presented in this work were obtained in near identical plasma discharges. The plasma current was 600kA, the magnetic field was between 2.4 and 2.6T, and the magnetic topology was lower single null with moderate elongation (χ=1.65) and low average triangularity (δ_l=0.44 and δ_u=0.04). The plasmas all had a line averaged core density in the non-ECRH phases of 4.7-5x10^{19}m^{-3} (density peaking was observed in the ECRH phases) and were all in a standard ELMy H-mode regime with a confinement scaling, H98, of order 0.8. A combination of NBI and ECRH heating was used for all of the experiments. Each discharge was heated continuously with either 2.5 or 5MW of NBI power. The ECRH system was configured for X-mode second harmonic heating at 140GHz [5]. The deposition location was set using steerable mirrors and in all cases the ECRH gyrotrons were balanced such that the amount of current driven was negligible. The impurity ion (B^{5+}) toroidal rotation, temperature, and density were determined by means of charge exchange recombination spectroscopy (CXRS) and the electron temperature and density profiles were taken from the electron cyclotron emission (ECE) and integrated data analysis (IDA) diagnostics, respectively [6, 7].

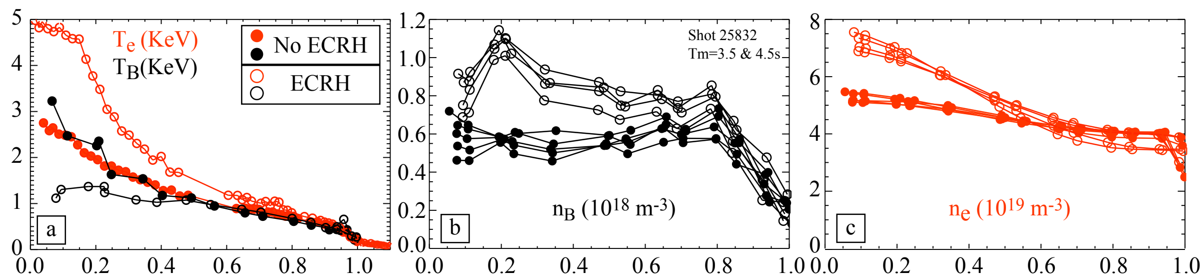

Figure 1: Core impurity ion (black) and electron (red) temperature (a) and density (b,c) profiles during ECRH (open symbols, 4.5s) and non-ECRH (closed symbols, 3.5s) phases of AUG discharge 25832.

In purely NBI heated discharges the core ion and electron temperatures tend to be quite similar. When ECRH is added to these discharges the core electron temperature and temperature gradient increase significantly concomitant with a drastic decrease or flattening of the ion temperature profile (Fig. 1a). The electron and impurity ion density profiles also react to the addition of the ECRH. The electron density profile (Fig. 1c), initially quite flat, is observed to peak with the largest change in the density gradient around mid radius (ρ_{pol} =0.4-0.5). This peaking is consistent with theory based on the framework of ion temperature gradient (ITG) and trapped electron mode (TEM) instabilities, which predicts an increase in electron density peaking with decreasing collisionality [8]. The impurity ion density profiles, shown in Fig. 1b, are initially slightly hollow and also peak when ECRH is applied to the plasma. The hollow profiles during the pure NBI phase are inconsistent with neoclassical transport alone, which would predict significantly more peaked profiles than what is measured. The peaking of the boron density in conjunction with the electron density during the ECRH phases might be due to a combination of inward neoclassical convection and a turbulent transport contribution. However, accurate comparisons between theory and measurement require dedicated calculations, which are presently ongoing.

The most dramatic profile changes are seen in the impurity ion toroidal rotation. In purely NBI heated discharges the plasma spins up in the direction of the beams (co-current in standard configuration) and forms peaked rotation profiles. When ECRH power is added to these discharges the rotation decreases significantly leading to flat and occasionally even slightly hollow profiles. An example of this is shown in Fig. 2. The change in the core rotation can be as large as 100km/s and the effect extends typically over more than half of the plasma radius ($0<\rho_{pol}<0.6$). In the highest ECRH power cases (P_{ECRH} ~2MW) the change in rotation is observed to extend all the way to the top of the pedestal (cf. Fig. 2). However, for P_{ECRH} < 1.2MW the edge profiles are entirely unaffected. Hence, the observed profile changes appear to be entirely a core effect. With the available temporal resolution no propagation from or toward the plasma edge is observed. The large change in the core plasma rotation has also been corroborated by a similar change observed in core mode frequencies. The main ion toroidal rotation profiles were calculated with the neoclassical code NCLASS [9] and show nearly identical behavior to the impurity rotation. This is particularly true for the high power ECRH cases, in which the gradient of the ion temperature profile is small. In these discharges, the gradients of the main and impurity ion rotation profiles were identical within the error bars of the measurement.

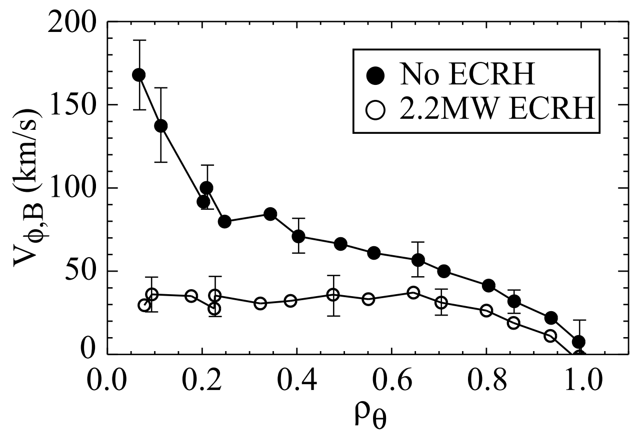

Figure 2: Change in impurity ion toroidal rotation with application of ECRH in discharge 25832 (3.5 and 4.5s).

The change in toroidal rotation is sensitive to both the amount of ECRH power deposited as well as to the deposition location. The latter was tested using a series of three identical discharges in which the ECRH deposition location, ρ_{ECRH}, was scanned shot-to-shot from ρ_{pol}=0.5 to ρ_{pol}=0. The level of power (1.1MW) was kept constant for all three discharges. The results from this experiment can be seen in Fig. 3. The rotation profiles before the application of the ECRH (Fig. 3a) overlay very well indicating that the initial conditions for all three discharges were indeed very similar. The final rotation profiles after the application of the ECRH are shown in Fig. 3b. With off-axis deposition (ρ_{ECRH}=0.25 and ρ_{ECRH}=0.5) nearly no change (<10km/s) was observed. However, when the ECRH power was placed on axis, the rotation profile collapsed by roughly 80km/s in the core forming a hollow profile. It seems likely that the change in rotation is linked to the changes in the ion and electron temperature profiles, which were the greatest with on-axis ECRH deposition. If this is the case then higher levels of off-axis ECRH power should be able to alter the gradients sufficiently to induce a change in toroidal rotation.

The sensitivity of the rotation change to the level of ECRH power was also examined. The rotation profiles from plasmas with identical parameters and beam configurations, but varying levels of centrally applied ECRH power, were compared. The flattest and in some cases most hollow rotation profiles were obtained for the highest levels of ECRH power. This can be seen in Fig. 4, which shows the normalized gradient of the main ion and impurity ion rotation profiles at r/a=0.3 versus the level of ECRH power. The correlation is more pronounced for the main ions than for the impurities due to the corresponding changes in the T_i profile, which contributes to the main ion rotation calculation. Note that here the main ion rotation was calculated by a simplified neoclassical code based on reference [10] not by NCLASS. However, the results from the two codes were found to be in reasonable agreement. The flatness of the T_i profile as well as the level of peaking in the T_e, n_e and n_B profiles also trend with the level of ECRH power.

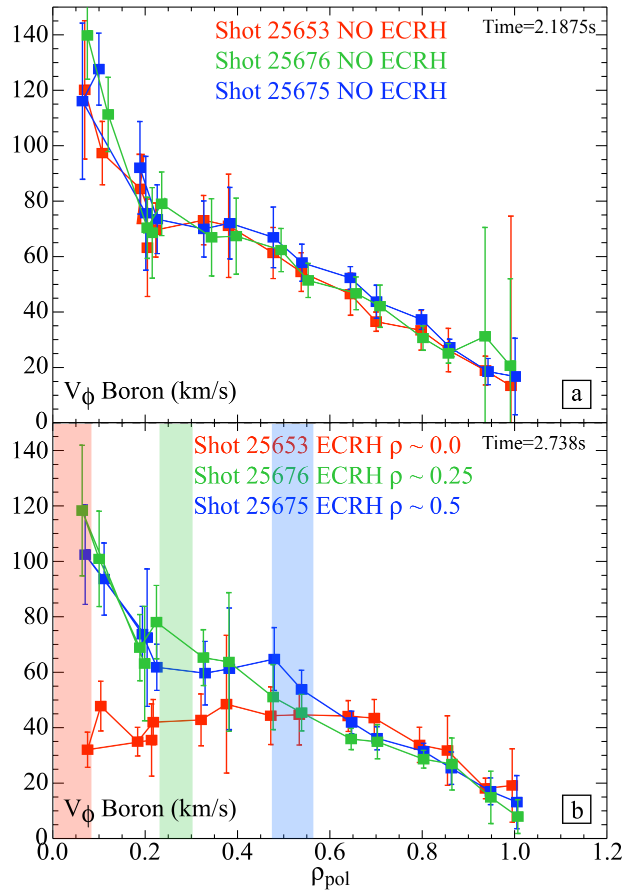

Figure 3: Initial (a: no ECRH) and final (b: with ECRH) rotation profiles from three discharges, in which the ECRH power deposition location was scanned from mid radius (blue), to ρ_p=0.25 (green) to on-axis (red).

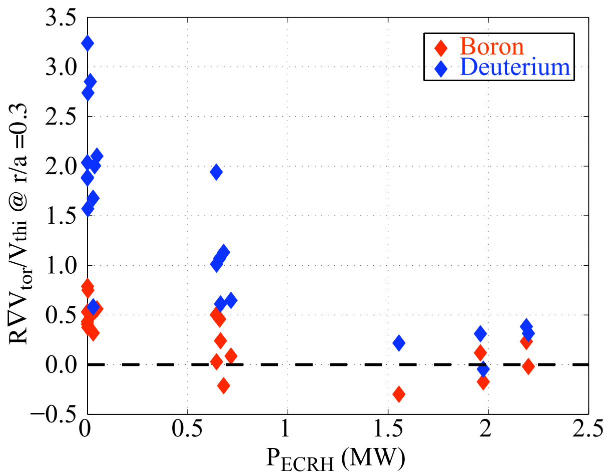

Figure 4: Normalized gradient of the main and impurity ion rotation at r/a=0.3 versus the applied level of ECRH power.

Several different possibilities to explain the observed rotation behavior have been considered. First, the flattened ion temperature and rotation profiles can be explained in part by a simple, albeit large, increase in the ion thermal and momentum diffusivities, χ_i and χ_ϕ. This explanation is obviously insufficient to explain hollow rotation profiles, however, many of the rotation profiles were merely flat, not hollow. If the transport is assumed to be purely diffusive then the requisite diffusivities can be calculated. It should be noted that in many cases the uncertainties in the gradient of the rotation profile are very large and the derived momentum diffusivities had to be considered with care. Despite this difficulty, it was determined that some of the data sets can be explained fully by reasonable increases in diffusivity with

Prandl numbers ($P = \chi_\phi/\chi_i$) of order 1-2, while others require Prandl numbers of order 10 or greater (χ_ϕ>100m^2/s). The hollow rotation profiles of course result in non-physical, negative diffusivities. Therefore, although an increase in the momentum diffusivity certainly plays a significant role in determining the final rotation profile in these discharges, it is unlikely to be the only mechanism at work.

Second, as a partial explanation it was suggested that the changes in the core temperature and density profiles could change the beam torque deposition profile in the ECRH phases, leading to altered rotation profiles. This possibility was refuted through comparison of the TRANSP calculated deposition profiles from ECRH and non-ECRH phases of several discharges. In all cases the deposition profiles were almost identical. Third, the Coriolis momentum pinch [11] in ECRH and non-ECRH phases was calculated by means of the GS2 code [12, 13]. However, the inward directed Coriolis pinch increases with density peaking. Therefore, it was higher during the ECRH phases leading, theoretically, to more peaked rotation profiles rather than less. Lastly, it is possible that a change in the beam delivered fast ion distribution could help to account for the observations. If the fast ions were transported out of the core by MHD activity before they could impart their energy and momentum then this could help to explain both the lower ion temperature and rotation profiles. However, almost no mode activity was observed during the ECRH phases of the discharge and there is no evidence for a change in the fast ion distribution with ECRH power. A comparison of the measured and TRANSP calculated neutron rates shows remarkably good agreement. Hence, the changes in plasma rotation cannot be explained by enhanced fast ion transport.

In summary, dramatic decreases in the core toroidal rotation profile were observed when ECRH power was applied to these NBI heated H-mode discharges in the ASDEX Upgrade tokamak. In the pure NBI phases the plasma spins up and forms peaked rotation profiles. However, when ECRH power is added the rotation decreases significantly leading to flat and occasionally slightly hollow profiles. The change in the core toroidal rotation is sensitive to both the amount of ECRH power deposited as well as to the deposition location most likely through the corresponding changes in the temperature profiles. The measured rotation changes cannot be explained by a simple increase in momentum diffusivity, a modification to the NBI torque deposition profile, or a preferential loss of fast ions from the plasma core. Additionally, the inward directed Coriolis momentum pinch is predicted to increase, not decrease, during the ECRH phases. Altogether, the data suggests the presence of either an outward momentum pinch or an intrinsic, counter-current directed torque. The data from other devices [1, 3] make the latter more likely. Although the physics behind this phenomenon remains unclear, it is presumably related to a residual stress drive mechanism, which responds to the ECRH-induced changes in the plasma kinetic profiles.

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