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Intrinsic Rotation in H-mode Pedestal in DIII-D EX-C

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The boundary condition for the intrinsic rotation measured in DIII-D H-mode plasmas is consistent with a simple model based on thermal ion orbit loss from the pedestal region. It is now well documented that intrinsic rotation exists in the absence of any auxiliary injected momentum [1,2]. It is likely that the level of such rotation in ITER will strongly influence issues of stability and confinement. Ongoing experiments seek to develop not only an empirical scaling, but also an understanding of intrinsic rotation in order to confidently extrapolate to ITER conditions.

The intrinsic rotation boundary condition is presently an unknown, both experimentally and theoretically. Without the boundary value, no theory will be able to predict an absolute rotation profile for ITER. In DIII-D this H-mode boundary rotation, a few cm inside and at the last closed flux surface (LCFS) is in the direction of the plasma current, co-I_p, and increases with the local ion temperature, T_i.

In Fig. 1, we show the measured boundary region intrinsic toroidal velocity, V_ϕ, related to the rotation, ω_ϕ, by $V_\phi = R\omega_\phi$, where R is the major radius coordinate, just inside from the top of the H-mode pedestal vs T_i, at the same location, $R_L - R \simeq 3$ cm, where RL is the radius of the LCFS. The red symbols are the data points for the intrinsic rotation measurement times, wherein any torque applied by the neutral beam injection (NBI) required for the charge exchange recombination (CER) spectroscopy measurements of V_ϕ and T_i has not accelerated the plasma. We find a linear correlation between V_ϕ and T_i and the line is a simple fit.

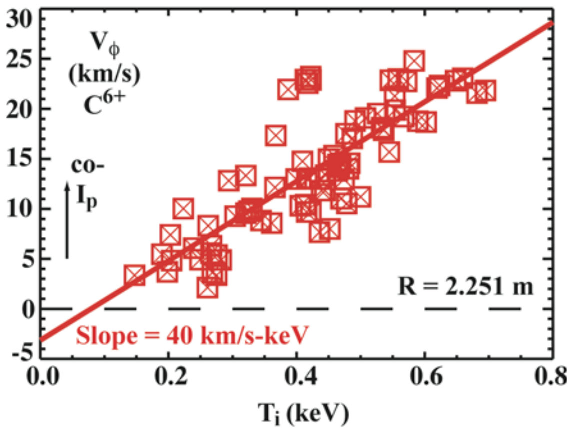

Fig. 1. Intrinsic toroidal velocity ~1 cm inward from the top of the DIII-D pedestal, vs T_i at the same location (red).

These intrinsic rotation data are for V_ϕ measurements of the minor impurity constituent C^{6+} in bulk ion D^+ ECH H-mode, Ohmic H-Mode, and Ohmic pre-H-mode discharges in DIII-D. A far more limited database of ECH H-modes in bulk ion He^{++} discharges in DIII-D shows that the bulk ion velocity at this location is correlated with T_i, as shown in Fig. 2. The slope of the fit line is roughly 1/2 that of the C^{6+} velocity data, although the bulk ion database must be expanded to confirm this comparison.

If NBI torque is added to these intrinsic rotation conditions, the pedestal region velocity is found to increase (co-) or decrease (counter-) depending upon the net direction and details of the NBI torque applied. The boundary velocity is not fixed in these diverted discharges.

The linear correlation of V_ϕ with T_i is consistent with the predictions of a model based upon edge thermal ion orbit loss from the pedestal region. In this model, the counter-I_p velocity ions can be lost, leaving a hole in velocity space and thus a net co-I_p drift for the remaining distribution. This assumes a steady state has been reached, which may happen relatively quickly in the pedestal region, such that there is no net electric current flowing across the LCFS; only the mechanical momentum of the lost ions need be considered.

A simplified analytic model for the phase space thermal ion loss cone [3] is used to compute the average co-I_p parallel velocity, $\langle V_{||}\rangle$, of the bulk ions with the loss cone empty. The result is shown in Fig. 3, where we plot $\langle V_{||}\rangle/\sqrt{W_{loss}/M}$ vs T_i/W_{loss}, where W_{loss} is an energy that parameterizes the edge ion loss, and M the ion mass. A roughly linear relation between $\langle V_{||}\rangle$ and T_i is found. The empty loss cone approximation probably sets an upper bound to $\langle V_{||}\rangle$. What is required is a computation of the steady-state bulk ion distribution function including collisions, most likely using the large edge simulation codes which have been developed [4].

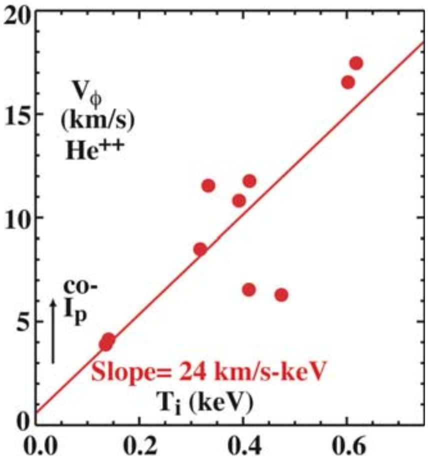

Fig. 2. Same plot as Fig. 1 but for bulk ion intrinsic velocity in He^{++} H-mode discharges.

The energy loss parameter is defined to be $W_{loss} = M(\Delta r\omega_\theta)^2/2$, Δr is the distance on the midplane between the ion starting radius, R_s, R_L, and ω_θ is the ion gyrofrequency in the poloidal magnetic field at R_s. A calculation of the absolute value of $V_\phi \simeq \langle V_{||}\rangle$ is reasonable when compared with the measurement. However, the accuracy is limited by the determination of R_L with the EFIT equilibrium computation, taken to be typically ±5 mm [5], roughly a factor of only 2 below Δr where significant orbit loss sets in.

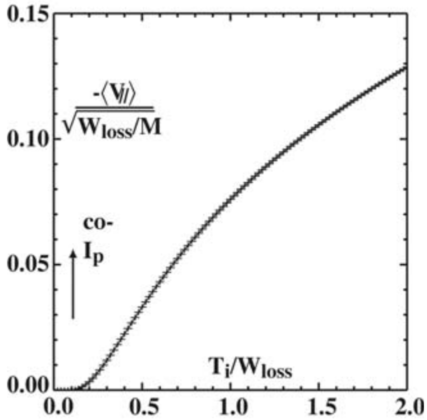

Fig. 3. Estimate of intrinsic toroidal velocity due to thermal ion orbit loss from the pedestal region. The computation assumes an empty loss cone in velocity space $W_{loss} = M(\Delta r\omega_\theta)^2/2$.

The perpendicular projection of the drift orbit, of a lost ion for example, is invariant if the ion energy is scaled by Z^2/M, where Z is the ion charge number. This effectively shuts off the pedestal region ion loss mechanism for C^{6+} at the temperatures shown in Fig. 1. The computation in Fig. 3 is done for D^+ ions. To apply this model to these data we must assume that the bulk D^+ ions are lost, generating $\langle V_{||}\rangle$ for the bulk constituent and then frictionally dragging along the minority C^{6+} ions, whose velocity is measured. The scaling inherent in Fig. 3 indicates that $\langle V_{||}\rangle/T_i$ for bulk He^{++} ions will be 1/2 that for bulk D^+ ions, which is consistent with the data in Figs 1 and 2.

We have not included the effect of the edge electric field well, E, in the H-mode pedestal region upon the loss mechanism. However, previous numerical orbit studies including the E effect [6] indicate that it can be neglected to first order for the pedestal T_i and E values in this DIII-D intrinsic rotation database. This may not be the case in H-modes driven by strong NBI.

Orbit loss is only an edge effect. Some other mechanism such as a momentum pinch due to turbulence or a higher order neoclassical effect is required to establish a rising momentum profile going inward from the pedestal.

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