Boundary Intrinsic Velocity in DIII-D H-modes

by
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Overview — Focus Upon the Pedestal Region

- Intrinsic toroidal rotation exists without auxiliary torque input (NBI)
- Important to understand for issues related to stability and confinement
- Intrinsic conditions - ECH, OH H-modes, and OH conditions; NBI blips
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Local picture is a poor representation of the complicated pedestal region.

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Inside the pedestal we also measure co-Ip $V_\phi \sim T_i$. We postulate a pinch, $V^p$, with $V^p/\chi_\phi \sim \nabla T_i/T_i$

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Pedestal Intrinsic Velocity is co-Ip

First msec of NBI blip in ECH H-mode

$V_{\phi}(\text{km/sec})$

$P_C(\text{au})$

$C^6^+$

$T_i(\text{keV})$

$R_{L0} = R(\text{LCFS})_{\text{EFIT}}$

$R_{L0}$

$\beta_N = 0.85$

$q_{95} = 4.25$

$n_e = 4.0 \times 10^{19}$

$P_{\text{OH}} = 0.4 \text{ MW}$

$P_{\text{ECH}} = 1.0 \text{ MW}$

$B_T = 1.79 \text{ T}$

$I_p = 1.1 \text{ MA}$

$L_S N$

$\hat{\phi}, \hat{I_p}$

$V_{\phi} \approx -V_{\parallel}$

$R_{\text{L0}} = R(\text{LCFS})_{\text{EFIT}}$
$V_\phi \sim T_i$ Across Database at Fixed Location
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Many data points with added NBI after the intrinsic phase of a shot

- Excess co-NBI torque
- Excess counter-NBI torque

The boundary condition is not fixed. The velocity responds to external torque.

The $V_\phi \sim T_i$ scaling does not persist.
$V_\phi \sim T_i$ Across Database at Fixed Location

Bulk ion, He$^{++}$, also shows this correlation - limited database

$V_\phi$ (km/sec)

$T_i$ (keV)

Near Top of Pedestal
Pedestal Thermal Ion Orbit Loss Weighted to Counter-$I_p V_{||}$ loss
Pedestal Thermal Ion Orbit Loss Weighted to Counter-\( I_p \) \( V_{\parallel} \) loss

Dominant region pedestal orbit loss tends to leave a counter-\( I_p \) hole in velocity space.

\[ V = \sqrt{\frac{T_i}{M}} \]
Pedestal Thermal Ion Orbit Loss Weighted to Counter-$I_p V_{\parallel}$ loss

Loss boundaries from constants of the motion: midplane start

- $G.C.\ orbits D^+$
- Outboard, counter $V_{\parallel}$ can be lost, co $V_{\parallel}$ confined.
- Inboard, co $V_{\parallel}$ can be lost, counter $V_{\parallel}$ confined.

- $\vec{B} \times \nabla B$
- $p = \text{pitch angle}$
- $p_t = \text{trap/pass boundary}$
- $p_x = \text{X-point turn}$
- $R_L = R_{LCFS}$
- $\alpha_E = \text{energy parameter} \sim \left( \rho_\theta / \Delta \right)^2$
- $\Delta^2 = (R_L - R_1)^2$

“1” are initial values

A.V. Chankin & G.M. McCracken, NF 10, 1459 (1993).
Loss Model Predicts a “Diamagnetic-Like” Boundary Value, $V_\phi \sim T_i/B_\theta$

G.C. loss region defined by:

\[
\frac{1}{\sqrt{\alpha_E}} \leq -\sigma_\phi \cos(p_1) \pm \sigma_\phi \left( \frac{R_x}{R_i} \right) \sqrt{1 - \left( \frac{R_i}{R_x} \right) \sin^2(p_1)}
\]

\[\sigma_\phi \equiv \text{sign}(B_T)\]

- Assume this loss cone is empty. No collision limit
- Consider only dominant counter-$l_p$ finger region
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- Compute $\langle V_\parallel \rangle$ for remaining distribution $(D^+)$:

$$\langle V_\parallel \rangle \sim -\left( \frac{2}{\pi} \right)^{1/2} V(b + 1) e^{-b}(x - r_1) / 2D(b,x,r_1)$$

$$b = \alpha_E^{av} W_{loss} / T_i$$

$$\overline{V} = \sqrt{T_i / M}$$

$$x = R_x / R_1$$

$$r_1 = R_{lin} / R_1$$

$$D \approx 1$$

$$W_{loss} = M \Delta^2 \omega_\theta^2 / 2$$

$$V_\phi(\text{ped}) \sim \delta_p T_i / \Delta B_\theta$$
Absolute Comparison Limited by Uncertainty in EFIT Determination of $R_{L0}$ the Midplane LCFS Location

$\delta R_{L0} = +/- 5 \text{ mm}^*$

* Porter et al, Phys Plasmas 1998
\( \delta R_{L0} = +/\text{-} 5 \text{ mm}^* \)

**Caveat**

- Orbit escape \( W_{\text{loss}} \sim Z^2/M \), thus \( C^{6+} \) is negligible compared with \( D^+ \), at the same \( T_i \).

- To provide the measured boundary condition we must assume that \( D^+ \) sets the velocity and \( C^{6+} \) is dragged along in the pedestal region.

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* Porter et al, Phys Plasmas 1998
Summary

• In the H-mode pedestal, we find $V_\phi$ is co-$I_p$ and correlated with the local $T$

• We observe this correlation for the carbon impurity, and for the bulk ion in helium ECH H-mode discharges

• This scaling is consistent with a simple approximate model of thermal ion orbit loss from the pedestal region, which gives $V_\phi \sim T_i/B_\theta$, co-$I_p$ directed

• Our approximation is for an empty loss cone; collisionless. The recent simulation of Chang and Ku including collisions finds that thermal orbit loss produces a co-$I_p$ velocity in the pedestal region. In DIII-D intrinsic H-mode conditions, at the pedestal top $v_i^* \sim 1$

• This classical effect may provide a robust minimum pedestal velocity in intrinsic conditions, and act as the boundary condition
Phenomenological Model to Carry \( V_\phi \sim T_i \) Inside of the Pedestal Boundary Region

- Local momentum flux: 
  \[-\chi_\phi \left( \frac{\partial \ell}{\partial r} \right) + V^p \ell = H(r)\]
  
  0 internal source

\( \ell = M n_i \langle R^2 \rangle \omega_\phi \) momentum density

\( \chi_\phi \) = momentum diffusivity

\( V^p \) = momentum pinch velocity

- for \( \frac{n'}{n} \ll \frac{V_\phi'}{V_\phi} \sim \frac{T_i'}{T_i} \) weak density gradient inside pedestal, and
  \[ \left| \frac{R_0 V_\phi'}{V_\phi} \right| >> 1 \]

- the local momentum equation becomes
  \[-\chi_\phi \left( \frac{\partial V_\phi}{\partial r} \right) + V^p V_\phi = 0\]

- If we use
  \[ \frac{V^p}{\chi_\phi} = k \frac{\partial T_i}{\partial r} \]
  turbulence

\[ \left\{ \begin{array}{l}
  \text{Coppi, NF 42, 1 (2002) qualitatively} \\
  \text{Shaing, Phys. Plasmas 8, 193 (2001).} \\
\end{array} \right. \]

- Then
  \[ V_\phi = V_\phi(a) \left[ \frac{T_i}{T_i(a)} \right]^k \]