Intrinsic Rotation in H-mode Pedestal in DIII-D

J.S. deGrassie 1), R.J. Groebner 1), K.H. Burrell 1), and W.M. Solomon 2)

1) General Atomics, PO Box 85608, San Diego, California 92186-5608, USA
2) Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543-0451, USA

e-mail contact of main author: degrassie@fusion.gat.com

Abstract. Intrinsic toroidal rotation in the tokamak exists with no auxiliary momentum input. Possible explanations are given by several theories, both from classical and turbulent considerations. A boundary condition for intrinsic rotation must be known to compute an absolute rotation profile with any theory. In DIII-D H-modes, we measure an intrinsic toroidal velocity in the pedestal that is in the co-I_p direction and is roughly proportional to the local ion temperature, T_i. A simple model of thermal ion orbit loss approximately demonstrates this T_i scaling, and predicts an inverse proportionality to the poloidal magnetic field strength. Experimentally, the T_i scaling of intrinsic velocity is also found inside the pedestal, where thermal ion orbit loss should be negligible. We postulate a momentum pinch in this region to produce this scaling inside the pedestal.

Overview

- Intrinsic toroidal rotation exists without auxiliary momentum input. It is important to understand ITER for stability and confinement issues.
- The boundary condition for intrinsic rotation is needed to obtain an absolute velocity profile from any theory of intrinsic rotation.
- In the pedestal region of DIII-D we find that the intrinsic toroidal velocity is proportional to the ion temperature: $V_\phi \sim T_i$
- This scaling is consistent with a simple model of thermal ion orbit loss from the pedestal region, through the X-point of a diverted discharge.
- The resulting boundary condition has the form of a diamagnetic velocity,

$$V_\phi(\mathrm{ped}) \sim T_i / (B_\theta d)$$

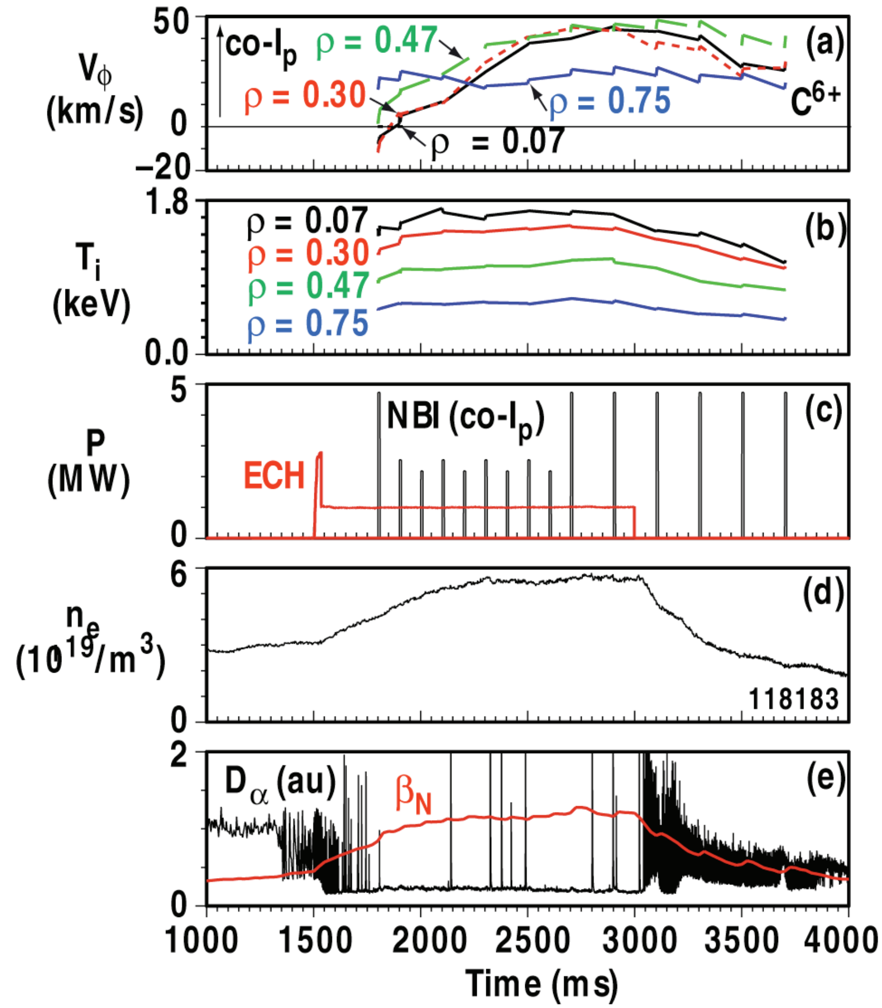
  where d has the units of length.
- Further, $V_\phi \sim T_i$ is found experimentally too far from the LCFS for thermal ion orbit loss to be effective. We postulate that a momentum pinch with $V^{pinch} \sim \partial T_i / \partial r$ could explain this scaling of the boundary condition inward.

Intrinsic rotation is studied in ECH H-modes in DIII-D

Short pulses of NBI, "blips", are used for CER measurements of V_ϕ and T_i.

- **The initial (t=1800ms)intrinsic V_ϕ profile is hollow, co-Ip at larger r, counter near the axis. The co-Ip NBI drives all V_ϕ in this direction. The edge-most channel changes little; it is dominated by intrinsic V_ϕ.**
- **T_i affected relatively little due to NBI; ECH and OH dominate the heating. These are measurements of the minor impurity constituent C^{6+}.**
- **With uni-directed NBI, only the first few msec of the first blip can be used for an intrinsic velocity measurement. Toroidal momentum is well-confined in these ECH H-modes.**
- **ELM-free periods cause a density rise. The added NBI pulses are used to study momentum confinement.**

ρ = minor radius; normalized toroidal flux



Intrinsic toroidal velocity in the pedestal is co-Ip

- V_ϕ is co-Ip (+) throughout the pedestal. The C^{6+} relative density n_{C6+} is measured with CER. The tanh pedestal fit is indicated by the three broken vertical lines: Rsym, Rsym +/- Δ_h, the half-width. The relative C^{6+} pressure profile, p_{C6+} is shown also.

- The error bars allow determination of V_θ at only a few locations in these intrinsic conditions. The electron diamagnetic direction is +.
  The T_i gradient is relatively smaller than that of other pedestal kinetic profiles.

- Quantities computed from the data:

$$E_r(\nabla p) \equiv \vec{\nabla} p \bullet \hat{\rho} / neZ$$

$$E_r(total) = E_r(\nabla p) - \vec{V} \times \vec{B} \bullet \hat{\rho}$$

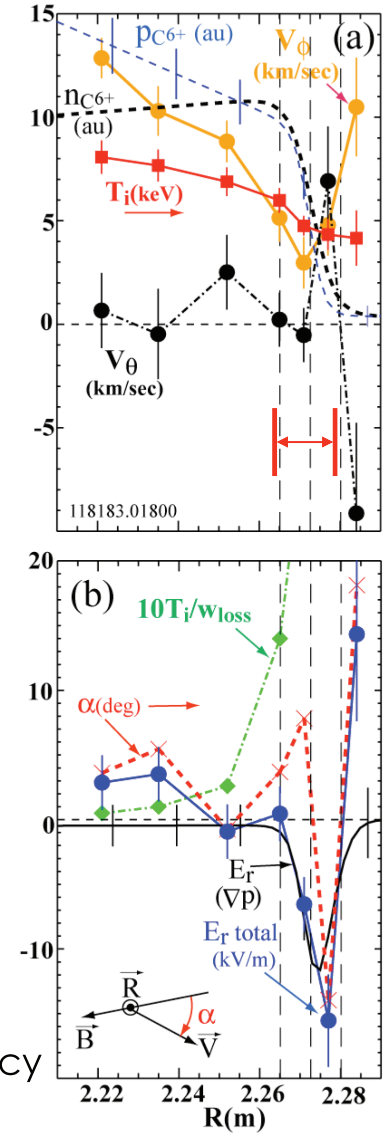
α = angle between V and B

T_i/W_{loss}, where W_{loss} parameterizes thermal ion orbit loss:

$$W_{loss} = (1/2) M (\Delta \omega_\theta)^2$$

Δ = distance to LCFS

ω_θ = "poloidal" gyrofrequency



Data averaged over first msec of first NBI blip.

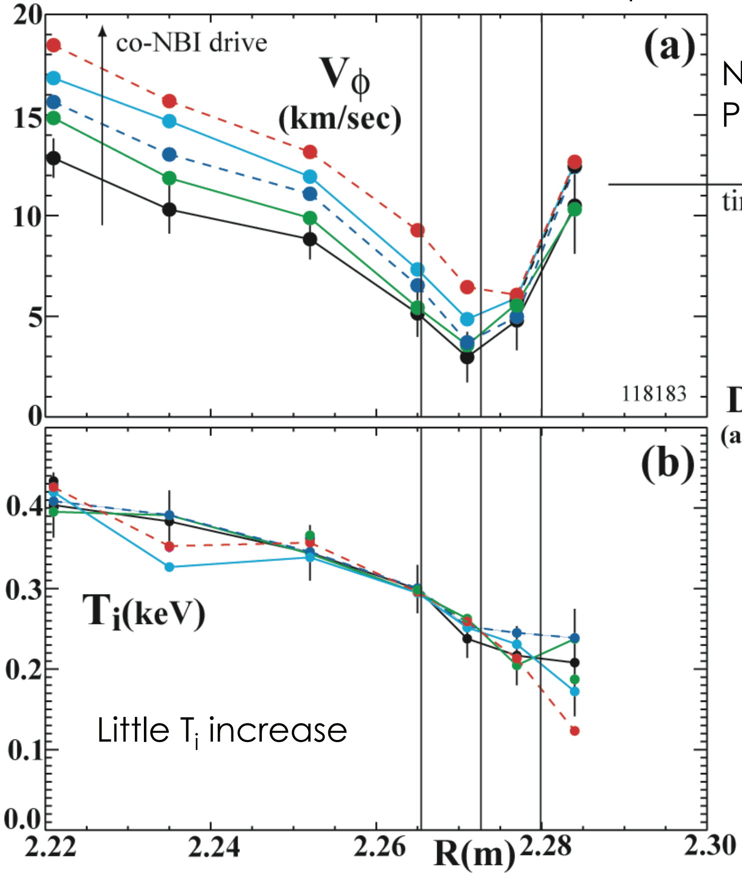
Thermal ion banana width ~ pedestal width

T_i/W_{loss} must be finite for thermal orbit loss.

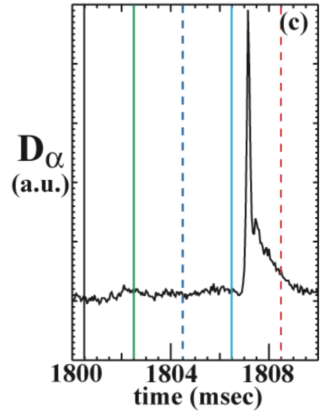
V anti-|| to B at top of ped.

Only first few msec of NBI blip gives unperturbed velocity

Toroidal acceleration at 2 msec steps

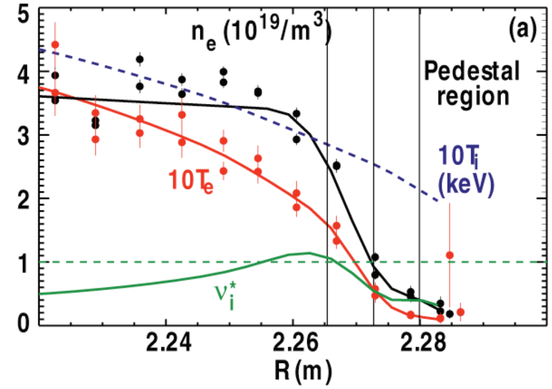


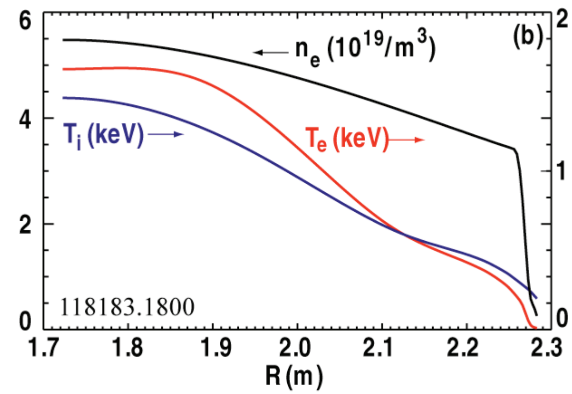
NBI Torque dominated by Prompt $\vec{J}_{fast} \times \vec{B}$ effect



ELM timing during blip

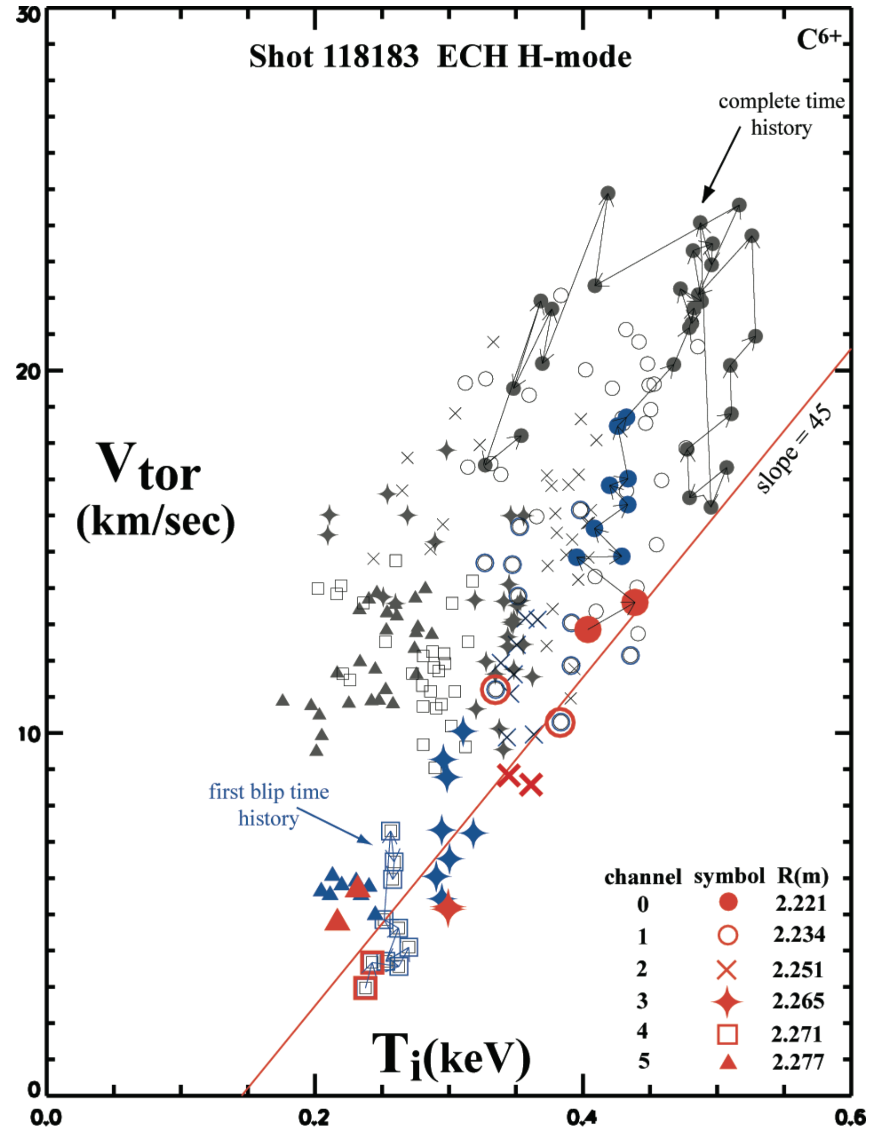
Pedestal region is in the plateau regime (ν^*)





Full minor radial profiles at t = 1800 msec

Intrinsic V_ϕ across the pedestal region is proportional to T_i

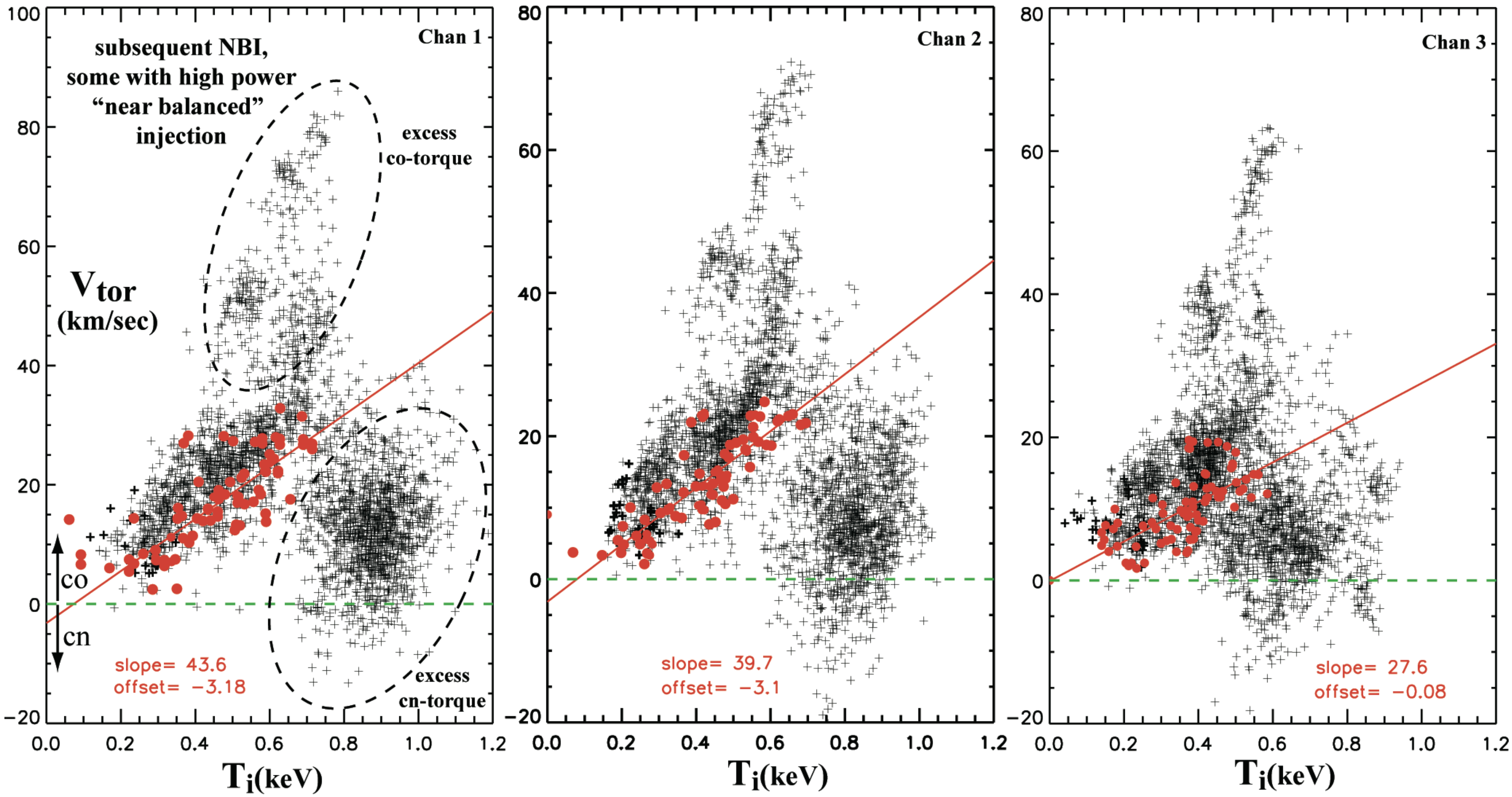


- **First 2 msec** of NBI blip provides the **intrinsic velocity profile**. The T_i variation is due to different T_i at different spatial locations
- **First 10 ms of first NBI blip** - V_{tor} increases in the direction of NBI torque, co-I_p
- Remainder of the shot, as shown in panel 3, with velocity increased more with NBI blips

Database of shots: Intrinsic V_{tor} in the edge region ~ T_i

Now the T_i variation is due to different T_i at a given location in a different shot. 51 shots included.

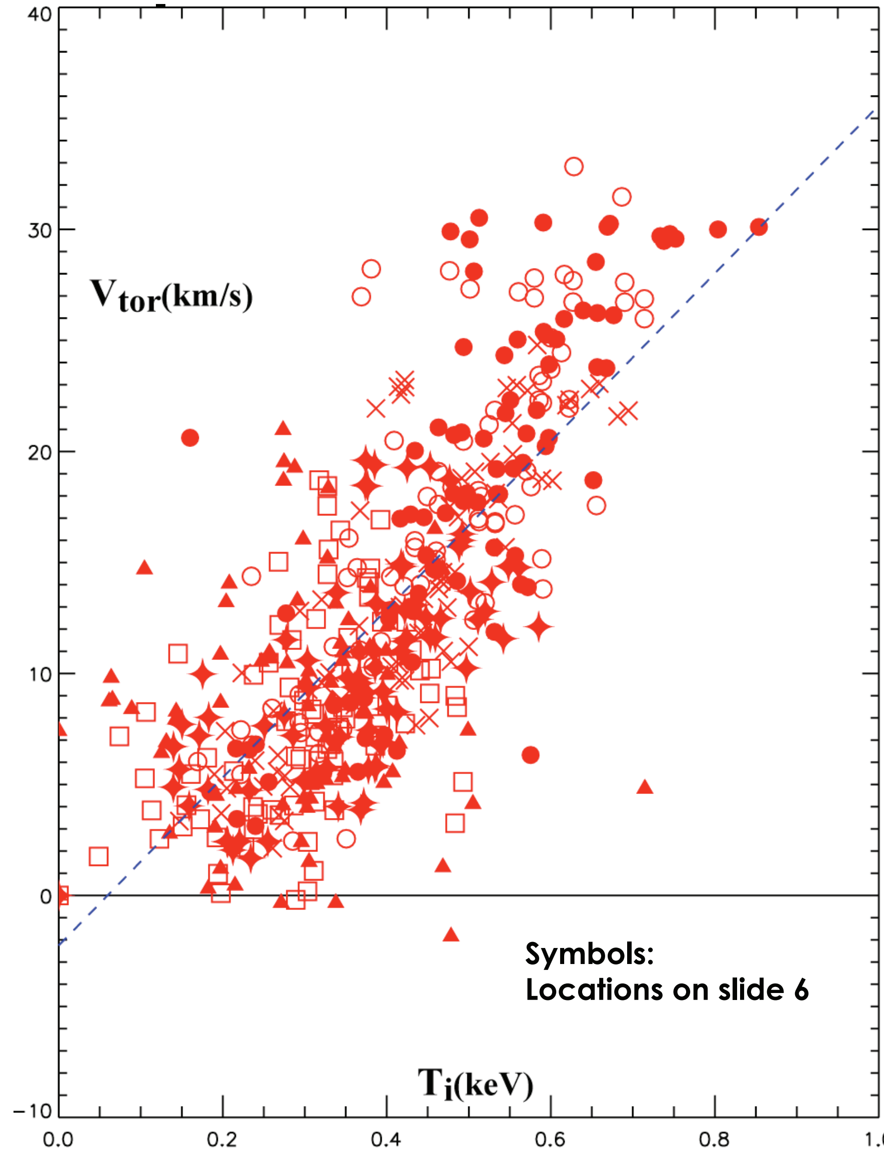
Intrinsic V_{tor}; start of blips. **Subsequent V_{tor}** due to added NBI torque - the boundary value is not fixed.



Proportionality of Vtor to T_i is similar spatially

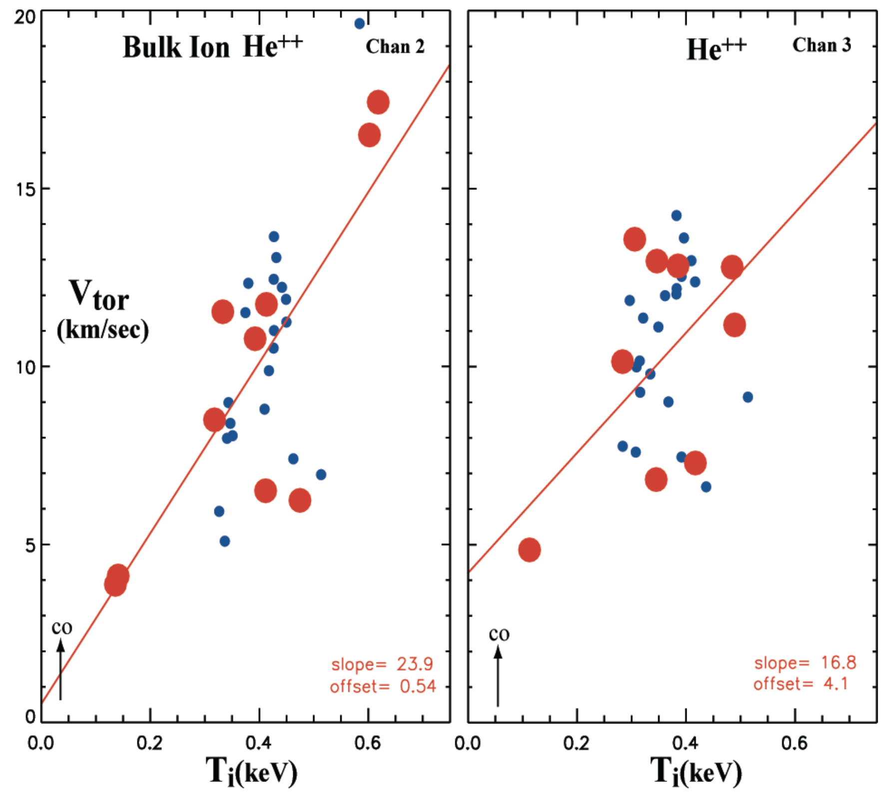
Plotting the intrinsic Vtor vs T_i for the inner 6 channel location indicated in slide 4, for the entire dataset. The proportionality constant is similar across spatial locations.

A power a bit higher than 1 may be indicated here for Vtor ~ T_i^k, that is, k > 1.



Measurements in the edge region for BULK ION He^{++} also indicate $V_{tor} \sim T_i$ scaling.

The dataset for ECH H-modes in bulk ion helium is limited. These data may indicate that the slope of Vtor vs Ti is roughly 1/2 that of D^+ discharges, which would fit with the thermal ion orbit loss mechanism.

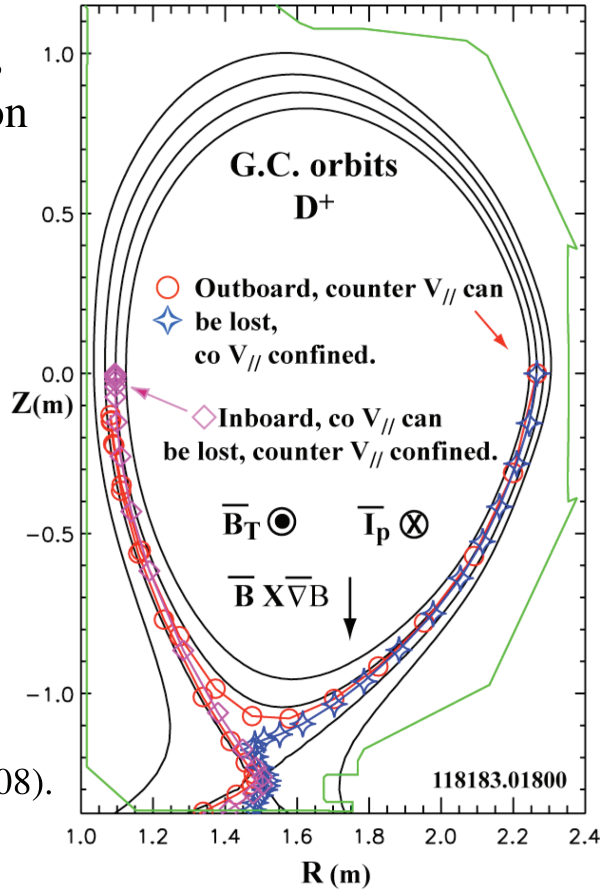


Thermal Ion Orbit Loss from the pedestal region leaves a hole in velocity space, with net co-Ip $V_{||}$ remaining.

Lost guiding center orbits, from numerical calculation with actual EFIT equilibrium.

Outboard; counter-Ip $V_{//}$ lost.

Inboard; co-Ip $V_{//}$ lost.



Recent simulation finds co-Ip edge parallel velocity due to thermal ion orbit loss: Chang & Ku, PoP **15**, 062510(2008).

Some past thermal orbit loss treatments:
Chankin & McCracken, NF **10**, 1459 (1993).
Miyamoto, NF **36**, 927 (1996).

Loss boundaries from our analytic approximation. Actual computed orbit values from left shown here.

$\vec{V}_1$ = starting V

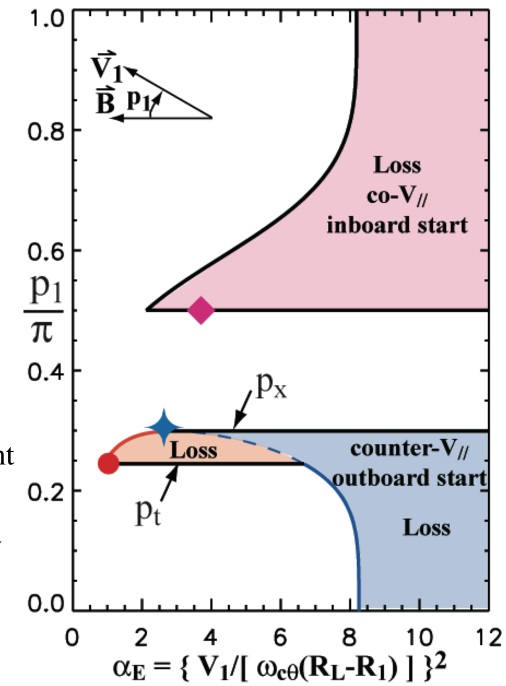
p_1 = starting pitch

co-I_p $\pi/2 < p_1 < \pi$

counter-I_p $0 < p_1 < \pi/2$

p_x = trap-turn at X-point

p_t = trap/pass boundary

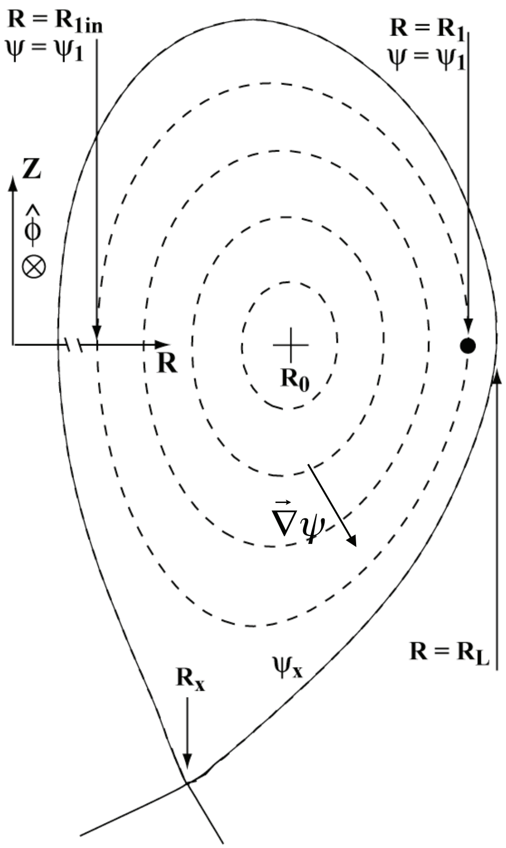


R_1= midplane starting R

R_L= midplane R of LCFS

$\omega_\theta = Z_i e B_{\theta 1} / M$

Approximate model for orbit loss boundary matches numerical g.c. computations



Use constants of motion:

$$\mu = MV_\perp^2/2B$$
$$W = M(V_{//}^2 + V_\perp^2)/2 + Ze\Phi$$
$$P_\phi = IV_{//}/\omega_c - \psi$$
$$\omega_c = Z_i eB/M$$

Field definition:

$$\vec{B} = [I(\psi)\hat{\phi} + \hat{\phi} \times \vec{\nabla}\psi]/R = \vec{B}_\phi + \vec{B}_\theta$$

$I(\psi) < 0$ DIII-D here

Define midplane distance: $\Delta = R_L - R_1$ In terms of ψ: $\delta\psi = \psi_{Rx} - \psi_1 \geq \psi_x - \psi_1 \approx R_1 B_{\theta 1}\Delta$

Loss criterion: $\psi > \psi_x$ $R = R_x$ Guiding Center outside LCFS at R_x cylindrical surface

Neglect δΦ: $E_\rho \rho_\theta << T_i$

Loss boundary: $$\frac{I_{Rx}\cos(p_{Rx})\sin^2(p_1)}{I_1 \sin^2(p_{Rx})} \geq \cos(p_1) + \frac{\omega_{c1} R_1 B_{\theta 1}\Delta}{I_1 V_1}$$

Simplifyng approximations, faithfully matches numerical orbit calculations.

neglect $(B_\theta/B_\phi)^2$ I = constant $\sigma_\phi \equiv$ sign of B_ϕ

So, trapped orbit turns at: $R_{turn} \approx R_1 \sin^2(p_1)$

Trap/pass boundary: $p_1 > p_t = \sin^{-1}\left(\sqrt{R_{1in}/R_1}\right)$

Turn outside R_x: $p > p_x = \sin^{-1}(\sqrt{R_x/R_1})$

Orbit Loss: $$\frac{1}{\sqrt{\alpha_E}} \leq -\sigma_\phi \cos(p_1) \pm \sigma_\phi (R_x/R_1)\sqrt{1 - (R_1/R_x)\sin^2(p_1)}$$

where $\alpha_E \equiv \frac{MV^2}{2} / W_{loss}$ $W_{loss} \equiv M(\Delta\omega_\theta)^2/2$

Empty loss cone calculation shows approximate scaling $\langle V_{||} \rangle \sim T_i$

distribution $f = f_M(1-g)$

$$f_M = \frac{n}{\left(2\pi\bar{V}^2\right)^{3/2}} e^{-V^2/2\bar{V}^2}$$

$$g = 1 \quad \left[\begin{array}{l} p_t \le p \le p_x \\ \alpha_E \ge \alpha_E(\bar{p}) \\ \bar{p} = (p_t + p_x)/2 \end{array}\right]$$

"finger region" of loss cone dominates

Result $$\langle V_{//} \rangle = -\sqrt{\frac{2}{\pi}}\bar{V}\frac{(b+1)e^{-b}(x-r_1)/2}{1-\left(\frac{1-\mathrm{Erf}\left(\sqrt{b}\right)}{2}+\sqrt{\frac{b}{\pi}}e^{-b}\right)\left(\sqrt{1-r_1}-\sqrt{1-x}\right)}$$

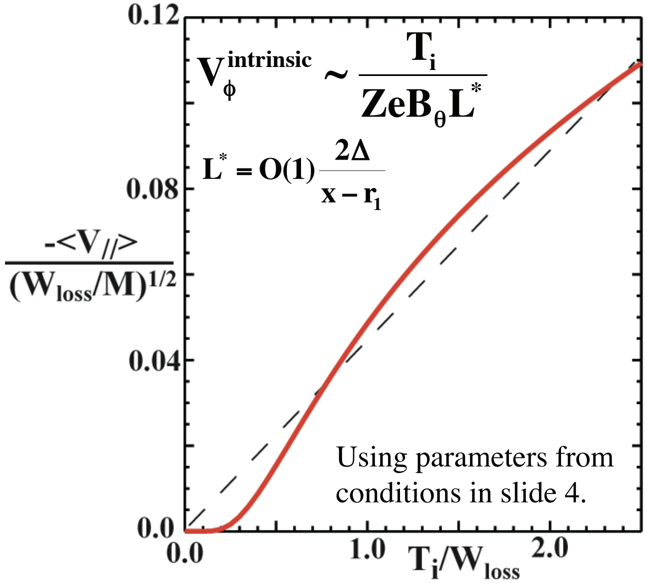
Co-I_P direction

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

$$\alpha_E^{av} = 1\Big/\left[\sqrt{1-(x+r_1)/2}+x\sqrt{(1-r_1/x)/2}\right]^2$$

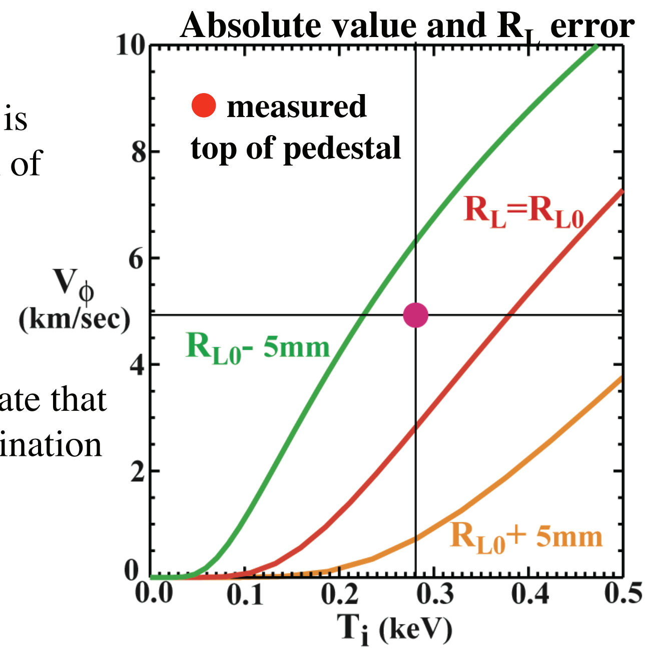
$$x = R_x/R_1 \quad r_1 = R_{1in}/R_1$$

Normalized plot shows T_i scaling

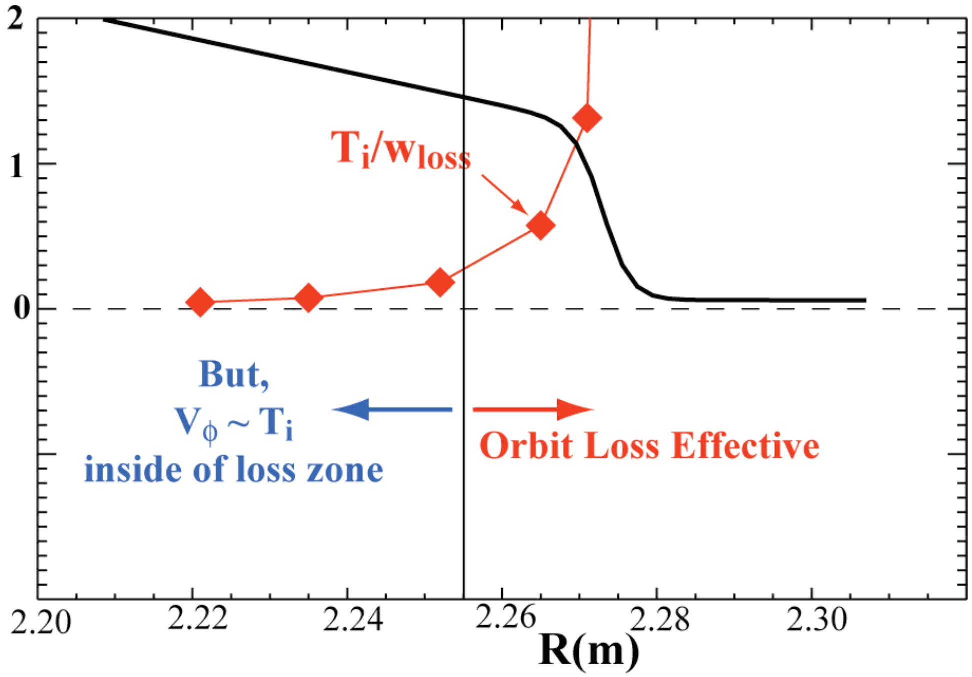


Quantitatively, the value is sensitive to determination of the LCFS location, R_L

DIII-D experiments indicate that the error in EFIT-determination of R_L is +/- 5mm



Thermal ion orbit loss can not explain T_i scaling inside of the pedestal region



Another mechanism is required to produce the scaling $V_\phi \sim T_i$ in this region.

In the absence of any interior turbulent momentum source, we postulate a momentum pinch, with $V_{pinch} \equiv V^p \sim \nabla T_i$

There are existing theories that predict this form for V^p in relevant limits.

An additional caveat with the thermal orbit loss model is that the model predicts a lower $|\langle V_{\parallel} \rangle|$ with greater distance from the LCFS. However the measurements show a rising co-Ip velocity going into the plasma. The large orbit width compared with the pedestal width shows our local calculation picture to be only an approximation. The whole pedestal region should be considered together, coupled by collisions. We are encouraged that the model may have relevance because of the recent simulation of Chang and Ku, that includes collisions. Orbit loss may be the mechanism behind the diamagnetic-like toroidal velocity scaling observed experimentally.

A phenomenological model for V^p produces the T_i scaling

In absence of interior sources $\Gamma_\phi = -\chi_\phi \, \partial \ell / \partial r + V^p \ell = 0$ **(1)**

Γ_ϕ = Radial flux of toroidal momentum

r = a generic radial coordinate

$\ell = M n_i \langle R^2 \rangle \omega_\phi$ Surfaced-averaged momentum density

χ_ϕ = momentum diffusivity

Locally $L_\ell^{-1} \equiv -(\partial \ell / \partial r) / \ell = -V^p / \chi_\phi$

Inside the pedestal, the density gradient is small $L_n^{-1} << L_{V_\phi}^{-1} \sim L_{T_i}^{-1}$ For the discharge in slide 4, $L_n^{-1} / L_{T_i}^{-1} \approx 1.5/13$

(With similar definitions for the three L_x^{-1})

Using also $R_0 L_{V_\phi}^{-1} >> 1$ We can approximate $L_\ell^{-1} \approx L_{V_\phi}^{-1}$ i.e., we can drop dn/dr and dR/dr from the momentum flux equation (1) in this spatial region.

So $\dfrac{\partial V_\phi / \partial r}{V_\phi} = \dfrac{V^p}{\chi_\phi}$ T_i scaling results with $\dfrac{V^p}{\chi_\phi} = k \dfrac{\partial T_i / \partial r}{T_i}$ **(2)**, With constant k sol'n $V_\phi = V_\phi(a)\left[T_i / T_i(a)\right]^k$

The boundary scaling is carried inward.
From the data in slide 8, we need
k ~ 1, but not exactly.

There are current turbulence theories that obtain a result like eqn (2) in the limit of a weak density gradient, for example:

K.C. Shaing, Phys. Plasmas **8**, 193 (2001).

P.H. Diamond, C.J. McDevitt, O.D. Gurcan, T.S. Hahm, and V. Naulin, Phys. Plasmas, **15**, 012303 (2008))

Summary

- In the pedestal region we measure that the intrinsic toroidal velocity is proportional to the ion temperature: $V_\phi \sim T_i$
- This scaling is consistent with a simple model of thermal ion orbit loss from the top of the pedestal, through the X-point of a diverted discharge.
- The resulting boundary condition has the form of a diamagnetic velocity,
  $$V_\phi(\text{ped}) \sim T_i/(B_\theta d)$$
  where d has the units of length.
- $\rho_\theta/\Delta_{\text{ped}} \sim 1$ means that understanding the velocity profile in the pedestal, and any density dependence, requires including collisions.
- High-Z, C^{6+}, loss is negligible compared with the bulk ion (V~1/Z). We must further assume that the bulk ion pedestal $V\phi$ drags the impurity along.
- And, $V_\phi \sim T_i$ is found experimentally too far from the LCFS for thermal ion orbit loss to be effective. We postulate that a momentum pinch with $V^{pinch} \sim \partial T_i / \partial r$ could explain this scaling of the boundary condition inward.