Intrinsic Rotation and Toroidal Momentum Transport: Status and Prospects (A Largely Theoretical Perspective)

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Thought for the Day:

- "As an economist in good standing, I am quite capable of writing things nobody can read"

  – Paul Krugman

Driver: Milestone for Theory and Computation, F2010

Wet Ware:

- UCSD: P.H. D, G. Dif-Pradalier, C.J. McDevitt, Y. Kosuga, C. Lee
- PPPL: W.X. Wang, T.S.Hahm, S. Ethier
- NYU/CPES: S. Ku, C.S. Chang
- NFRI: J.M. Kwon, S.S. Kim, H. Jhang, S.M. Yi, T. Rhee
- CEA: Y. Sarazin et. al. GYSELA team
- Ecole Polytechnique: O.D. Gurcan

Hard Ware:

- G. Tynan, J. Rice, W. Solomon, K. Ida, M. Yoshida, S. Kaye, M. Xu, Z. Yan

Soft Ware:

- GTS : Wang, PPPL
- XGC1 : Ku, Chang, NYU
- gKPSP : Kwon, NFRI
- TRB : S.S. Kim, NFRI
- GYSELA : Sarazin, CEA

Presentation: J.M. Kwon

Approach: A Critical Appraisal, extended.

- Outline:

I) Some Background

II) What we understand

III) What we think we understand, but would benefit from more work on

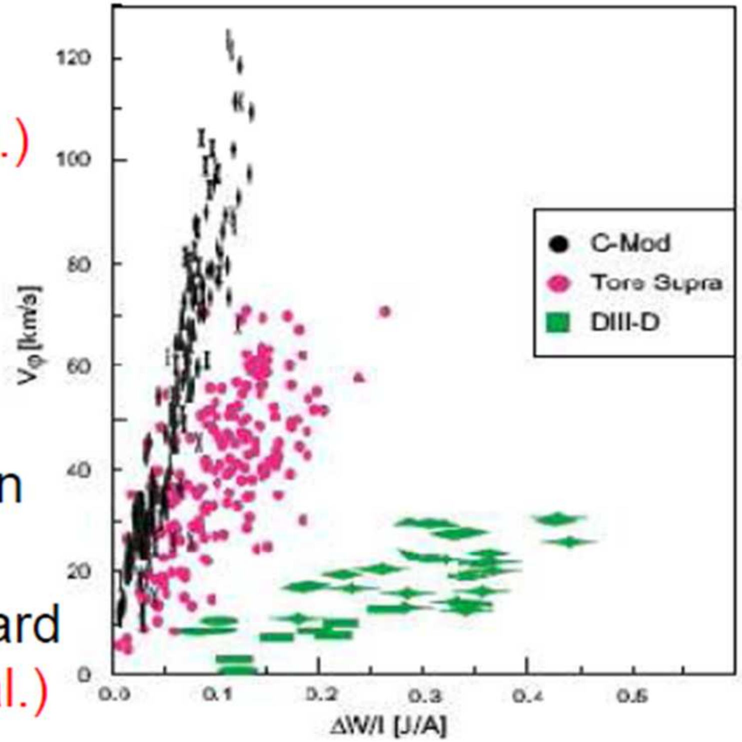
IV) What we don't understand – and should be studying

I) Some Background

i. Summary of Phenomenology

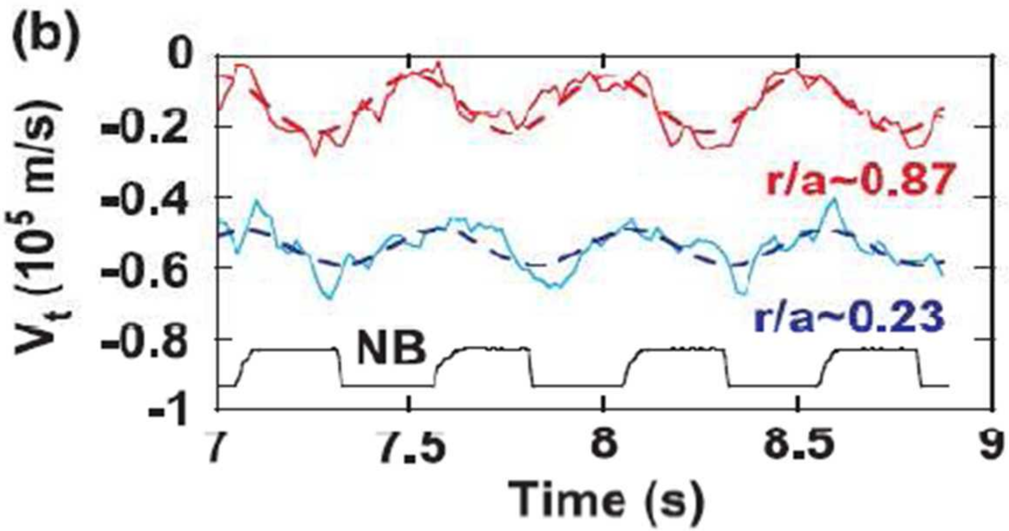
a) Intrinsic Rotation Basics

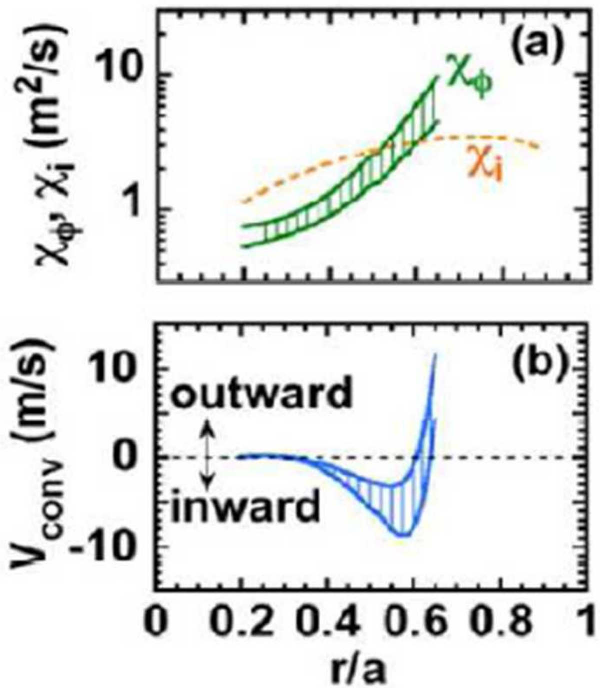
- Intrinsic (spontaneous) toroidal rotation observed in nearly all tokamaks
- H-mode phenomenology demonstrates clear empirical trends, L-mode phenomenology remains murky and complex
- In H-mode:
  - rotation typically co-current
  - $\Delta v_\phi \sim \Delta W / I_p, \; M_A \sim \beta_N$ (Rice et al.)
  - no apparent scalings with $\rho^*, \; \nu^*$
  - offset in torque scan matches intrinsic rotation (Solomon et al.)
- Observations appear consistent with rotation originating at the edge with transition
  - Observed co-current velocity builds inward from periphery (Ince-Cushman,Rice et al.)
  - rotation direction inverts at L→H mode transition



b) Indications of Off-Diagonal Momentum Flux

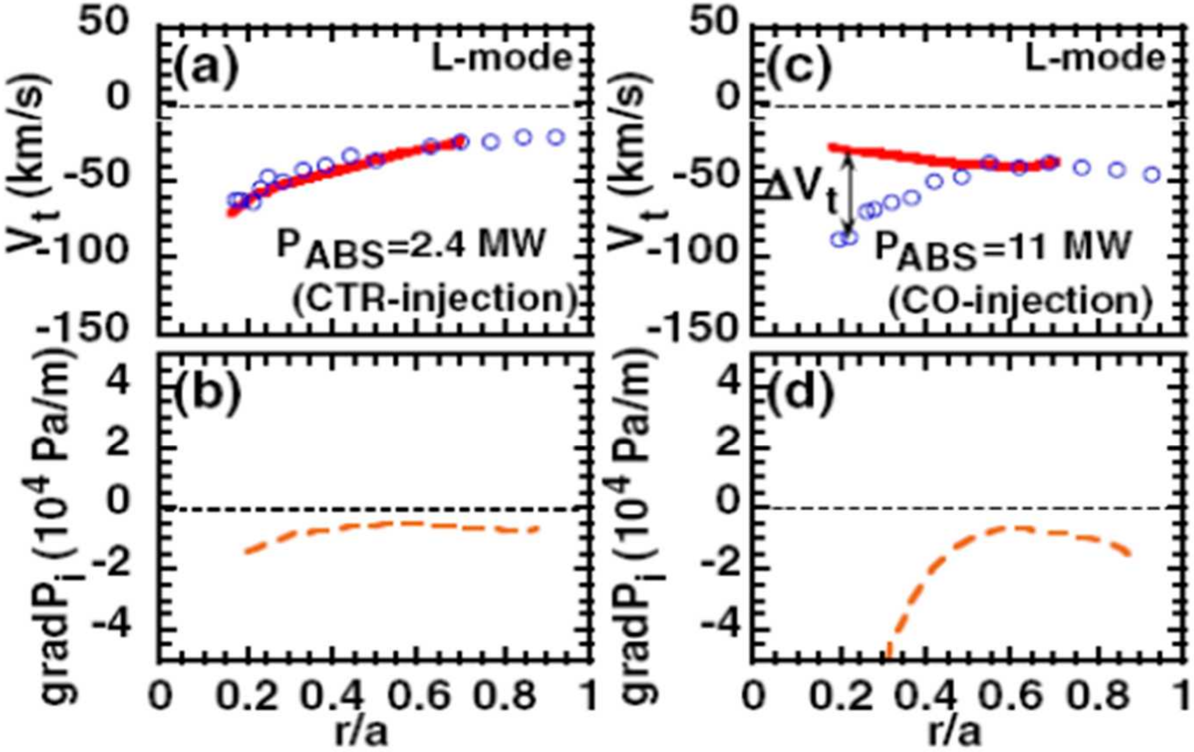
- Historically, $\chi_\phi \sim \chi_i$ (S. Scott et al. `90; Mattor, P.D. `88), yet many deviations from $Pr \sim 1$ observed
- ∇P_i–driven momentum pinch suggested by inductive analysis (Ida et al. 2001)
- Perturbation Experiments From JT-60U (Yoshida et al. 2006)
  - ripple loss + pulsed beams => pulsed torque
  - inward V clearly indicated



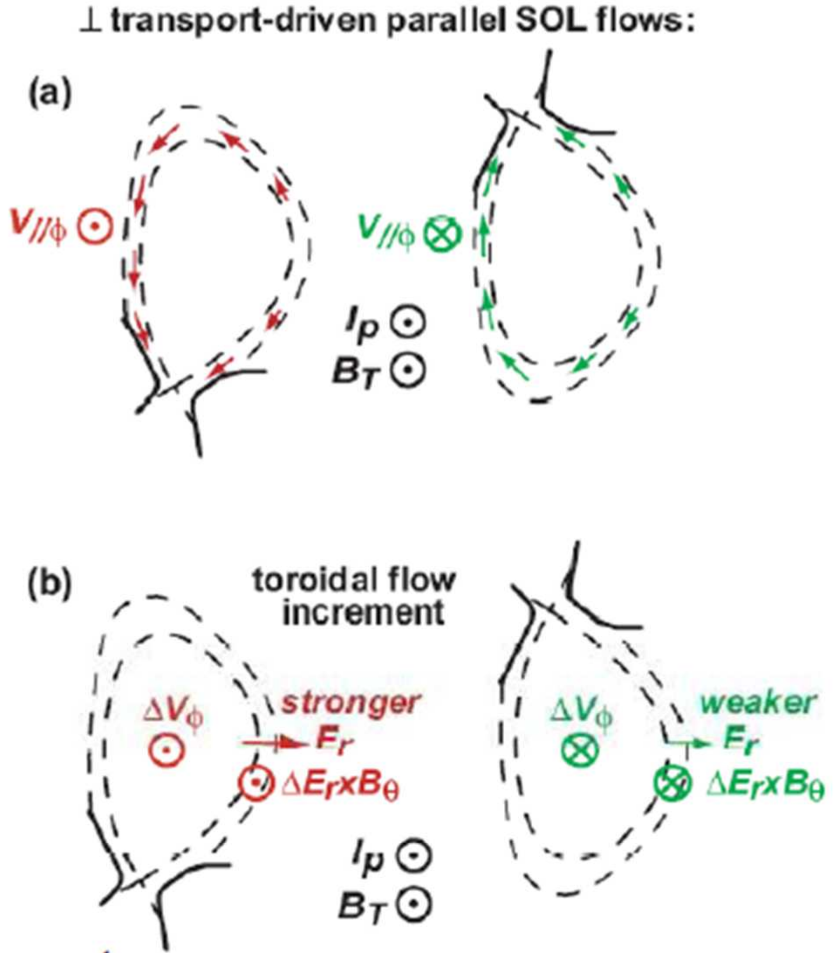


b) Indications of Off-Diagonal Momentum Flux

- $V_{residual} = V_{measured} - V_{perturbation}$ observed in β-scan on JT-60U (Yoshida et al. 2008)
  $V_{residual}$ coincident with region of steep ∇P_i



c) Boundary Condition Effects



- Strong SOL flows observed with
  - "strong ballooning" particle flux↔outboard mid-plane source
  - SOL symmetry breaking (LSN, USN)

- SOL flow correlated with Δv_ϕ increment in L-mode i.e. C-Mod (LaBombard et al. `04)

LSN → $V_{\nabla B}$ toward X-point → Δv_ϕ co

USN → $V_{\nabla B}$ away from X-point → Δv_ϕ counter

But:

- in H-mode, Δv_ϕ is always co

Comparison/Contrast

Stellar Differential Rotation	Tokamak Intrinsic Rotation
Fusion which works $\rightarrow$ heat flux	fusion wanna be: heating (central) $\rightarrow$ heat flux
convection	drift wave turbulence
Rotation, etc... $\boldsymbol{\Omega}$	mean $\mathbf{B}$ structure, radial profile ∇p ...
stellar wind	separatrix and SOL

The Question: Rotation Profile?

Heating $\rightarrow$ flux driven turbulence $\rightarrow \langle \tilde{\mathbf{V}} \tilde{\mathbf{V}} \rangle \rightarrow$ Rotation Profile?

The Theoretical Issue: Mean Field Theory for $\langle \tilde{\mathbf{V}} \tilde{\mathbf{V}} \rangle$

represent $\langle \tilde{\mathbf{V}} \tilde{\mathbf{V}} \rangle \longrightarrow$ transport coeffs + mean quantities

The Difference

Negligible feedback $\longleftrightarrow$ STRONG Flow feedback on turbulence

II) What We Understand

General Structure of Flux

- Toroidal momentum transport is driven by parallel and perpendicular Reynolds stresses, as well as convection
- Both of the above may be decomposed into a turbulent viscous piece, a (toroidal) 'pinch' piece, and a non-diffusive residual stress piece, not proportional to velocity or velocity gradient.

$$\Pi_{r,\phi} = -\chi_\phi \frac{\partial \langle V_\phi \rangle}{\partial r} + V\langle V_\phi \rangle + \boxed{\Pi_{r,\phi}^{resid}}$$ non-diffusive stress

- Easy Part : $\chi_\varphi \sim \chi_i$, with an intrinsic Prandtl number of roughly $0.5 < Pr < 0.7$, depending on deviation from threshold. The detailed physics underpinning of the dependence is the resonant particle velocity.

General Structure of Flux

General Structure of Momentum Flux (cont'd)

$$\Pi_{r,\phi} = -\chi_\phi \frac{\partial v_\phi}{\partial r} + V\langle v_\phi \rangle + \Pi_{r,\phi}^{resid}$$

- χ_ϕ ➠ $\sim \chi_i \rightarrow$ momentum diffusivity
- V ➠ pinch (explicitly toroidal!), $V = V_{TEP} + V_{Thermo}$
- $\Pi_{r,\phi}^{resid}$ ➠ residual stress
  - waves $\begin{cases} \text{momentum transport (non-resonant)} \\ \text{wave-particle momentum exchange (resonant)} \end{cases}$
  - $\partial_r \Pi_{r,\phi}^{resid}$ ➠ local intrinsic torque

Spin-up $\begin{cases} \Pi_{r,\phi}^{resid} \neq 0 \text{ on boundary} \\ V\langle V_\phi \rangle \neq 0 \quad \text{on boundary} \end{cases}$

The Pinch

- The parallel flow pinch V is toroidal in origin, and consists of turbulent equipartition (TEP) and thermoelectric pieces. The thermoelectric pinch is driven by both ∇T_i and ∇n. These tend to oppose one another for a wide range of cases. For the TEP pinch, produced by the compressibility of V_{ExB} in toroidal geometry, $V/X_\varphi \sim O(1/R)$. TEP momentum, particle and heat pinches are closely related.

Turbulent Equipartition of Magnetically Weighted Quantities

- Turbulence Equipartition Pinch (TEP) of density has been demonstrated via simple model with nonuniform B [Yankov '94, Naulin '98]

$$\partial_t n + \nabla \cdot (n \mathbf{v}_E) = 0 \qquad \nabla \cdot \mathbf{v}_E \neq 0 \qquad (\partial_t + \mathbf{v}_E \cdot \nabla)\left(\frac{n}{B}\right) = 0$$

- Extended to trapped electrons in tokamaks [Isichenko *et al.* '97, Baker-MNR '98]
- Turbulence Mixing ➡ Relaxation towards canonical profiles [Garbet '05]
- Inward Pinch in the observed field *n* as a consequence of a tendency towards homogenization of the locally conserved field *n/B*
- For angular momentum density [Hahm *et al.*, *PoP* 2007]

$$\partial_t \left(n U_\parallel R\right) + \nabla \cdot \left(n U_\parallel R \mathbf{v}_E\right) \approx 0 \qquad \nabla \cdot \mathbf{v}_E \neq 0 \qquad (\partial_t + \mathbf{v}_E \cdot \nabla)\left(\frac{n U_\parallel R}{B^2}\right) \approx 0$$

- Inward Pinch in observed quantity $nU_{||}R$ is a consequence of a tendency towards Homogenization of the locally conserved quantity $nU_{||}R/B^2$

Pinch of momentum from diffusion of magnetically weighted momentum

Homogenization (mixing) of the locally conserved quantity "$nU_{||}R/B^2$" occurs via diffusion of the magnetically weighted angular momentum.

$$\Pi_{MWA} = \langle \delta v_r \, \delta(nU_{||}R/B^2) \rangle = \ldots \text{ quasilinear calc.} = -\chi_{MWA} \, d/dr \, (nU_{||}R/B^2)$$

separating the $d/dr\ (1/B^2)$ drive from the $d/dr\ (nU_{||}R)$ drive, we get

$$= [\, -\chi_{Ang} \, d/dr \, (nU_{||}R) + V_{pinch} \, (nU_{||}R) \,] \, /B^2$$

with $\quad V_{pinch} / \chi_{Ang} = -B^2 \, d/dr \, (1/B^2) \approx -2/R \ !$

Inward Pinch in observed quantity $nU_{||}R$ is a consequence of tendency towards a canonical profile with

$$\nabla \, (nU_{||}R/B^2) \approx 0$$

The Pinch (cont')

More Physics of the Flow Pinch

$V = V_{TEP} + V_{Th}$; TEP pinch: n, V_ϕ

$$(\partial_t + v_E \cdot \nabla)\left(n \frac{v_\parallel}{B^2} R\right) \cong 0$$

$$(\partial_t + v_E \cdot \nabla)\left(\frac{n}{B}\right) \cong 0$$

Thermoelectric pinch mechanisms:

For ITG : $V_{\mathrm{pinch}}/\chi_\phi$	∇n driven	∇T_i driven	∇B driven
Fluid regime in torus	$-1/L_n$ Inward	0	$-4/R$, for $\tau = 1$ Inward
Kinetic regime near marginality in slab	$1/L_n$ Outward	$-\left(\frac{1}{\eta_i^{\mathrm{crit}}} + \Omega^2\right)/L_{Ti}$ Inward	Ignored
Kinetic regime near marginality in torus (This work)	$1/L_n$ Outward	$-\left(\frac{5}{2} - \alpha_c(\omega_k)\right)/L_{Ti}$ Inward	$-\frac{8}{5}\alpha_c(\omega_k)/R$ Inward

$$\Gamma_{L\phi} = -D_T\left[\frac{1}{B^2}\nabla L_\phi - \frac{2}{B^3} L_\phi \nabla B\right]$$

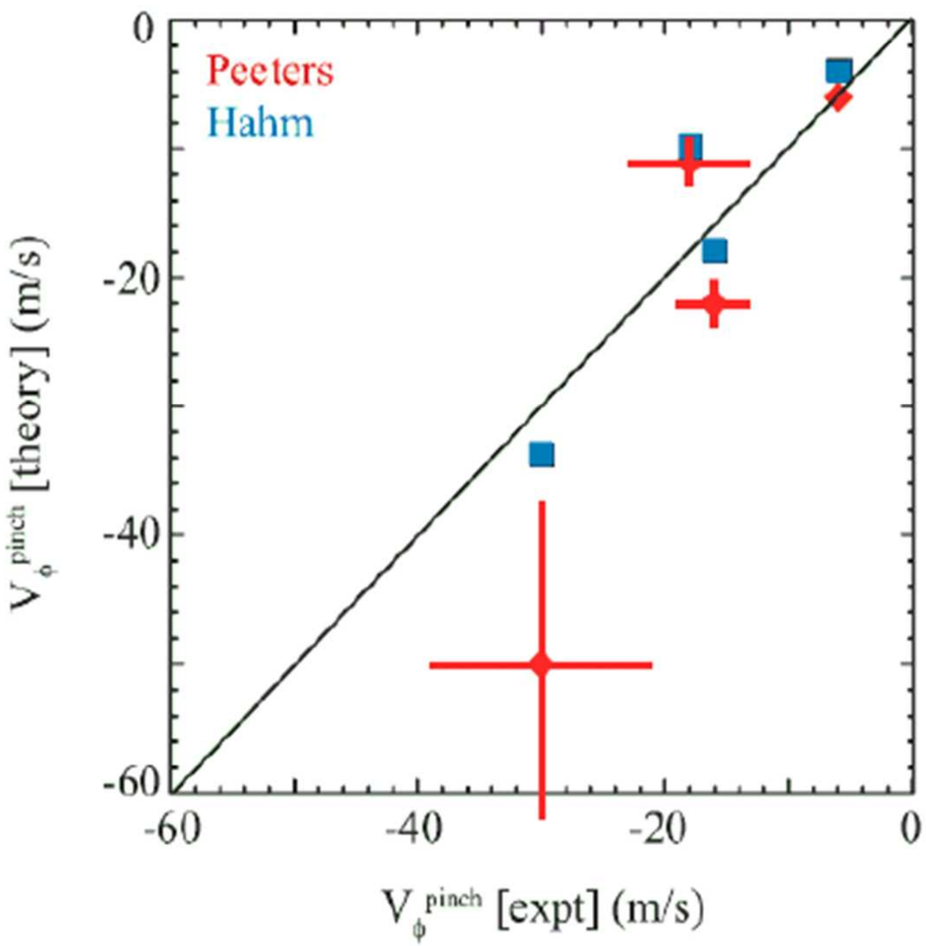
$$\Gamma_n = -D_T\left[\frac{1}{B}\nabla n - \frac{1}{B^2} n \nabla B\right]$$

$$\Gamma_{L\phi} = -D_T \nabla\left(n \frac{v_\parallel}{B^2} R\right) \cong -D_T \nabla\left(\frac{L_\phi}{B^2}\right)$$

$$\Gamma_n = -D_T \nabla\left(\frac{n}{B}\right)$$

➠ TEP pinch is more generic and robust than thermoelectric momentum pinch

Values from theories are in the range of experimental relevance for NSTX



[Solomon *et al.* PRL 101, 065004 '08]

- The two candidates:
  [Hahm *et al.* 2007, Peeters *et al.* 2007]

$$V_{TEP}/\chi_\phi = -3/R$$

$$V_{Coriolis}/\chi_\phi = -4/R - 1/L_n$$

- Perturbative Momentum Studies using Magnetic Braking
  - Pinch at various radii
- Can L_n dependence be discriminated?

Residual Stress: Dynamics and Structure

- The residual stress is driven by ∇T, ∇p, ∇n, and produces a local intrinsic torque by its divergence. Residual stress can spin up the plasma from rest, acting in concert with boundary conditions.

N.B. Boundary conditions are unclear … “No Slip” is intellectual crutch.

Residual Stress

$$\langle \tilde{v}_r \tilde{v}_\phi \rangle = -\chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r} + V \langle v_\phi \rangle + \Pi^{resid}_{r,\phi}$$

Piece of Reynolds Stress without Explicit Dependence on, V_ϕ , $\frac{d}{dr} V_\phi$
(i.e.,∇P, ∇n , etc)

- Beyond Diffusion and Pinch
- particle number conserved → $\Gamma_n = -D \frac{d\langle n \rangle}{dr} + V \langle n \rangle$
  pinch is only “off-diagonal” for particles
- but: wave-particle momentum exchange possible

$$\Pi_{r,\phi} \cong \langle n \rangle \langle \tilde{v}_r \tilde{v}_\phi \rangle + \langle v_\phi \rangle \langle \tilde{v}_r \tilde{n} \rangle$$

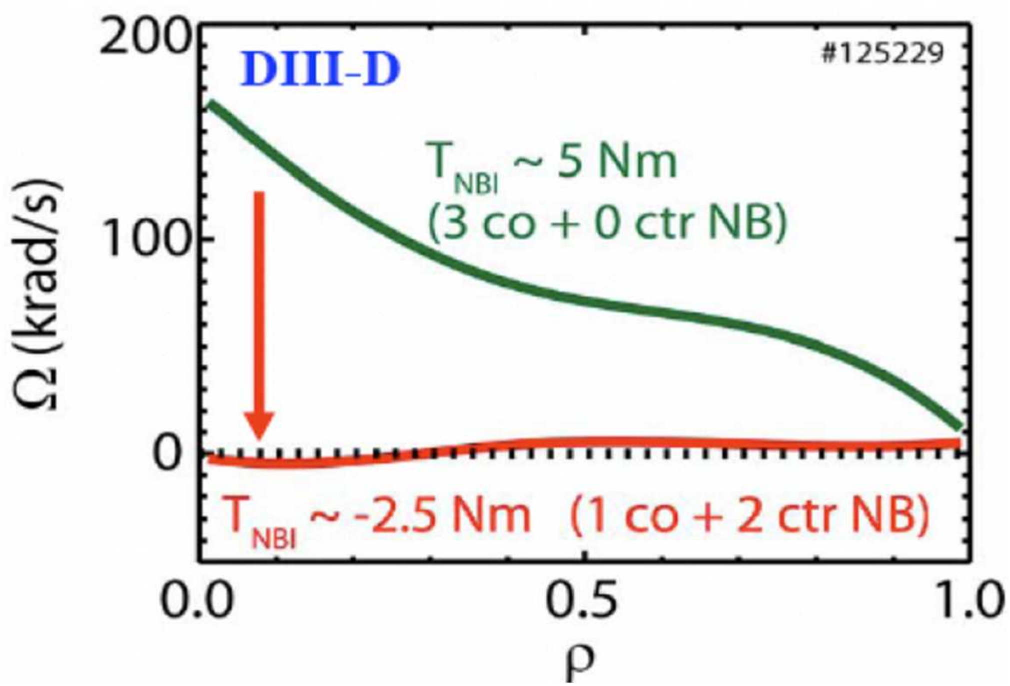
Can accelerate resting plasma: $\partial_t \int_0^a dr \left\langle V_\phi \right\rangle = \partial_t \overline{V_\phi} \approx -\Pi^{resid}_{r,\phi} \Big|_0^a$

$\nabla P_i, \nabla n \rightarrow \quad \Pi^{resid}$

→ residual stress acts with boundary condition to generate intrinsic rotation
[Gurcan, Diamond, Hahm, Singh, PoP 2007]

How ? Broken Symmetry in Turbulence
akin to α-effect in dynamo theory

Evidence for intrinsic torque: Exp



$$\Pi_{r\phi} = \cancelto{0}{-\chi_\phi \frac{\partial u_\phi}{\partial r}} + \cancelto{0}{V u_\phi} + \Pi_{r\phi}^{resid}$$

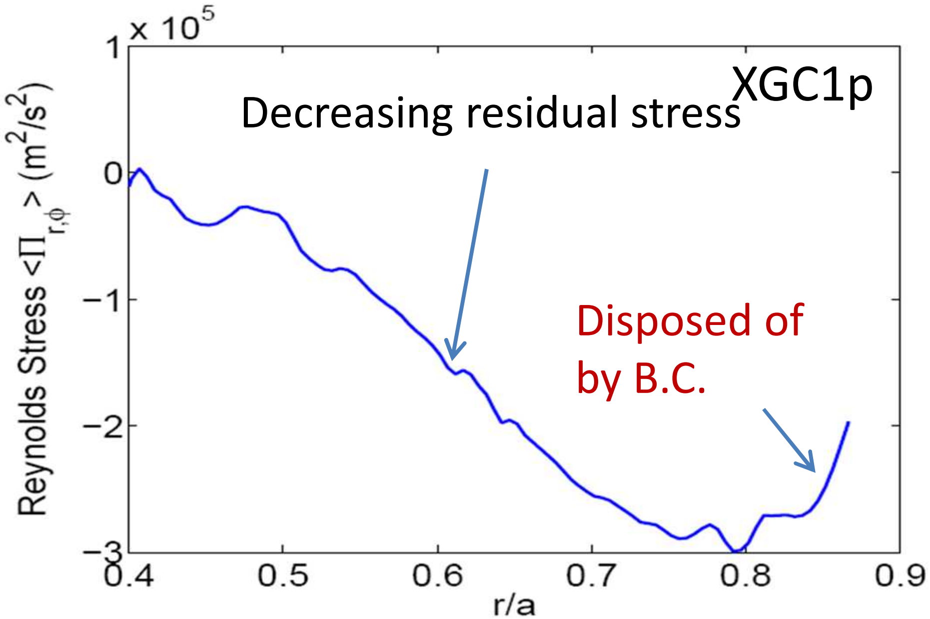
Diffusion Pinch Residual Stress

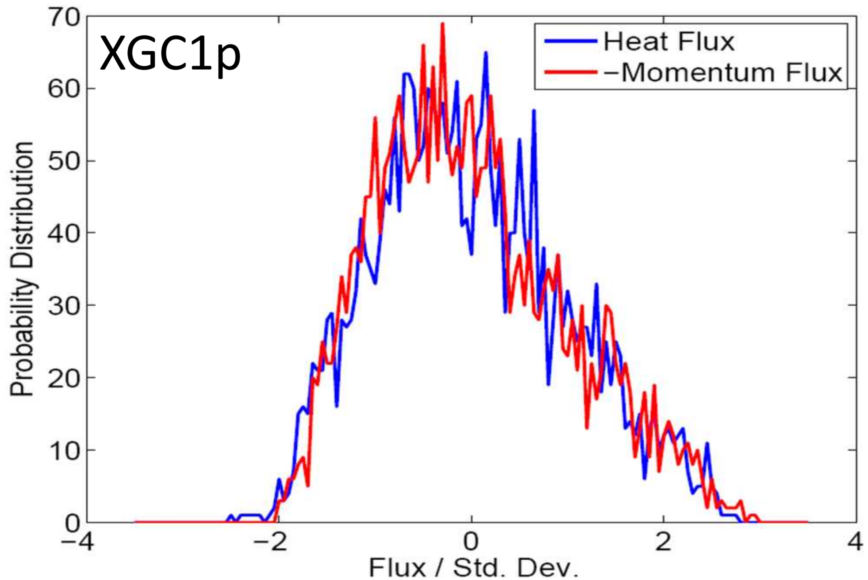
$$0 = -\nabla \cdot \Pi_{r\phi}^{resid} + \tau_{NBI}$$

[Solomon , 2007]

- Intrinsic rotation → Mechanism?
- DIII-D experiments (W. Solomon, A. Garofalo) have demonstrated that a finite external NBI/NRMP torque can null out the intrinsic rotation.
- How reconcile zero rotation with NBI? → need introduce intrinsic torque density ($\tau = -\nabla \cdot \Pi_{r\phi}^{resid}$) (also, [Ida, 2010])

Evidence for intrinsic torque: Simulation





- Residual stress is inward and decreasing towards to edge. (r/a<0.8)

  → Co-current intrinsic torque ($= -\nabla\cdot\Pi$)
- **Counter-current torque r/a>0.8 is disposed of by no-slip B.C.**
- PDF for Heat flux and magnitude of momentum flux are strikingly similar.

  → Outward heat avalanches drive inward momentum avalanches.

  → Further evidence for non-diffusive, flux – driven nature of momentum flux

Wave Momentum Flux and Residual Stress

- Wave momentum flux from radiation hydrodynamics for short mean free path:

$$\Pi_{r,\|}^{wave} = \int d\mathbf{k}k_{\|}\left\{-\tau_{c,\mathbf{k}}\mathrm{v}_{gr}^{2}\frac{\partial\langle N_{\mathbf{k}}\rangle}{\partial r}+\tau_{c,\mathbf{k}}\mathrm{v}_{gr}k_{\theta}\langle \mathrm{v}_{E}\rangle'\frac{\partial\langle N_{\mathbf{k}}\rangle}{\partial \mathbf{k}_{\mathrm{r}}}\right\}$$

- First term ↔ radiative diffusion of quanta
  - $\frac{\partial}{\partial r}\langle N_k\rangle > 0$, universally increasing
  - inward scattering from edge

- Second term ↔ refraction induced wave quanta population imbalance: important for regimes of strong shear, sharp ∇P relevant to ETB, ITB
  - mode dependence, via v_* sign
  - can flip direction [TCV, C-Mod] in LOC→SOC

Symmetry Breaking

- Growth asymmetry *[Coppi, NF '02]*
  - –Bias in $\gamma(k_{\|})$ from $\langle V_{\|}\rangle'$
  - –unlikely in realistic regime
- Wind-up by shearing packet
  - → akin spiral arm formation: requires $\langle V_E\rangle'$ and magnetic shear
- Refractive Force due to GAMs $\partial k_{\|}/\partial k_r \neq 0$
  - –relevant near edge
  - –polarization effects
  - *[McDevitt et al., PoP '08]*

What we understand (cont')

- Residual parallel stress requires symmetry breaking, so as to convert radial inhomogeneity into parallel spectral asymmetry. Symmetry breaking mechanisms include electric field shear $\langle V_E \rangle'$ and intensity gradient $\partial_r I$ – both of which are self-reinforcing and linked to the driving heat flux – as well as up-down asymmetry of current density. Additional symmetry breaking sets the polarization stress ($\langle k_r k_{||} \rangle \neq 0$) -> essentially a quadrupole spatial moment of the spectrum is required) and the poloidal Reynolds stress, which drives flow through $\langle J_r \rangle B_\theta / c$ (again $\langle V_E \rangle'$ and $\partial_r I$ are critical)

Basic Physics of Symmetry Breaking

- Non-diffusive residual part is crucial
  → Broken symmetry is essential
  (Diamond, et al., NF'09)

$$\Pi_{r\|} = -\chi_\phi \frac{\partial \langle V_\| \rangle}{\partial r} + V_{Pinch} \langle V_\| \rangle + \Pi_{r\|}^{RS}$$

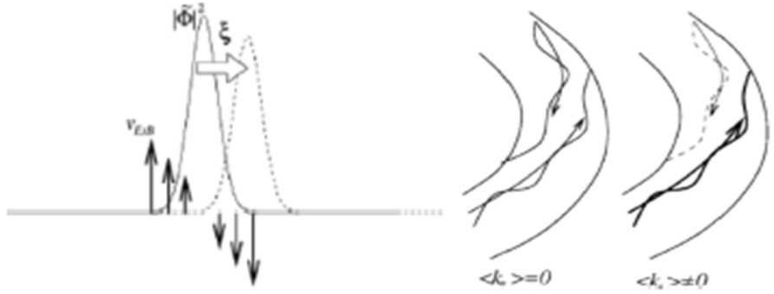
$\chi_\phi \sim \chi_i$ → flow damping

- Symmetry breaking :
  Conversion of radial inhomogeneity to
  → parallel asymmetry
  → rotation generic to confinement

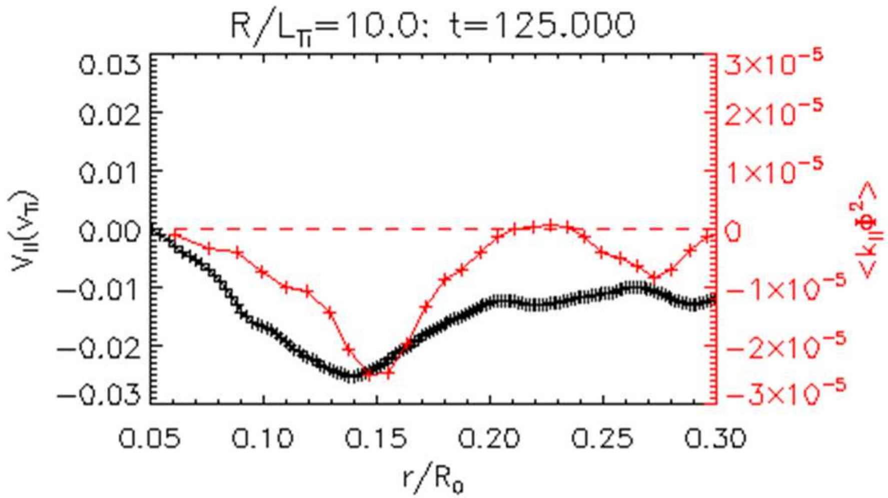
$$\Pi_{r\|}^{RS} \propto v_{th} \chi_\phi / L_{sym}$$

- Well known symmetry breaking by V'_{ExB}
  → Is this universal or fundamental?

$$1/L_{sym} \sim k_\theta \delta_{V'_E} / L_s \ ; \quad \delta V'_E \sim \langle V_E \rangle'$$



Symmetry breaking induced by ExB shear flow (Dominguez, et al., Phys. Fluids B 1993; Gurcan, et al., PoP2007)



Broken symmetry in fluctuating potential for ITG turbulence and Resulting parallel flow

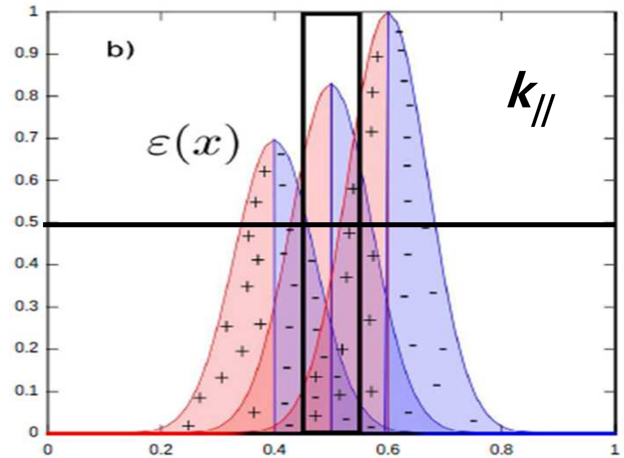
Basic Physics of Symmetry Breaking (cont'd)

- Interesting alternative:
  fluctuation intensity gradient

$$\Pi_{r\parallel}^{RS} = \left\langle k_\theta^2 \frac{\Delta^2}{L_s} \right\rangle \frac{\partial}{\partial r} |\Phi_k|^2$$

- Fluctuation intensity gradient tied to mean profile curvature

$$\frac{1}{I}\frac{\partial I}{\partial r} \sim -\frac{1}{\partial T/\partial r}\frac{\partial^2 T}{\partial r^2} - \frac{1}{\chi_{turb}}\frac{\partial \chi_{neo}}{\partial r},$$



Symmetry breaking induced by radial gradient of turbulence intensity (Gurcan, et al., PoP'10)

- Note V_{ExB} shear is also related to profile curvature

$$\frac{\partial}{\partial r}\langle V_E \rangle = \frac{1}{n|e|}\frac{\partial^2 P_i}{\partial r^2} - \frac{1}{n^2|e|}P_i' n_i' + V_\phi' B_\theta - V_\theta' B_\phi$$

N.B. Profile curvature $\Leftrightarrow$ Π_{resid} link

- Fluctuation intensity gradients ubiquitous to confined plasmas
  - Robust and **Generic** mechanism
  - Closely related to V'_{ExB} → i.e. transport barrier!

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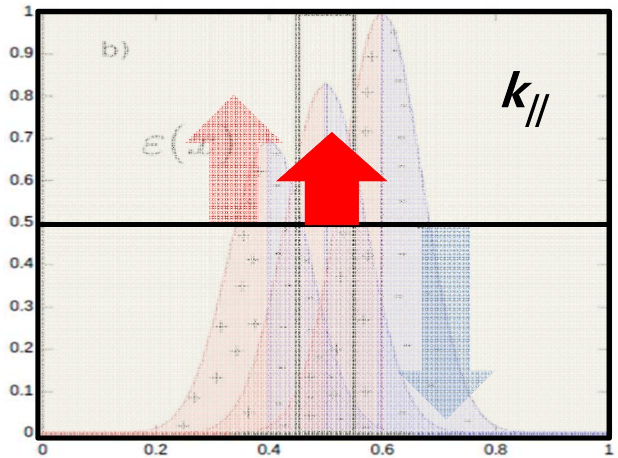

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Testing Symmetry breaking by Intensity Gradient

- Global δf gyrokinetic simulation (**gKPSP**)
  - ITG turbulence with adiabatic electrons
  - $\nabla\Phi=0$ is imposed on boundaries
  - T_i - profile relaxes

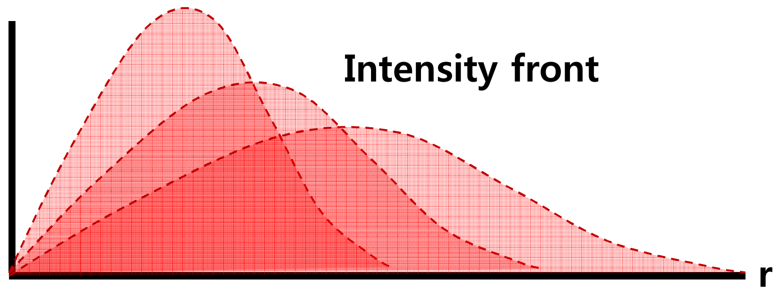
- T_i-profile relaxation

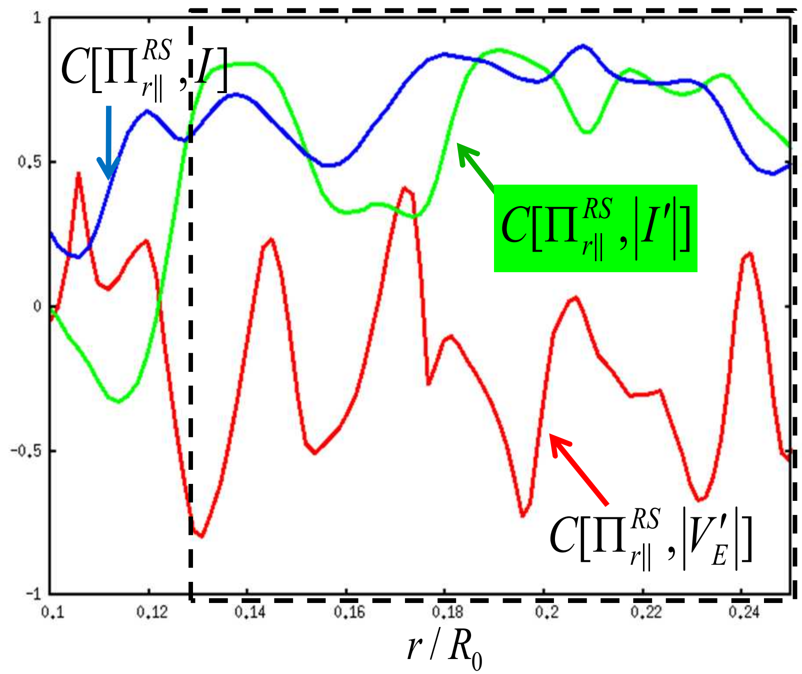
  → Propagating fluctuation intensity front

  (favorable to test the role of intensity gradient)

- Time correlations for $\Pi_{r\|}^{RS}, V'_{ExB}, I'$
  - Strong correlation of $C[\Pi_{r\|}^{RS}, |I'|]$ over most radii
  - Lower zonal flow shearing due collisions

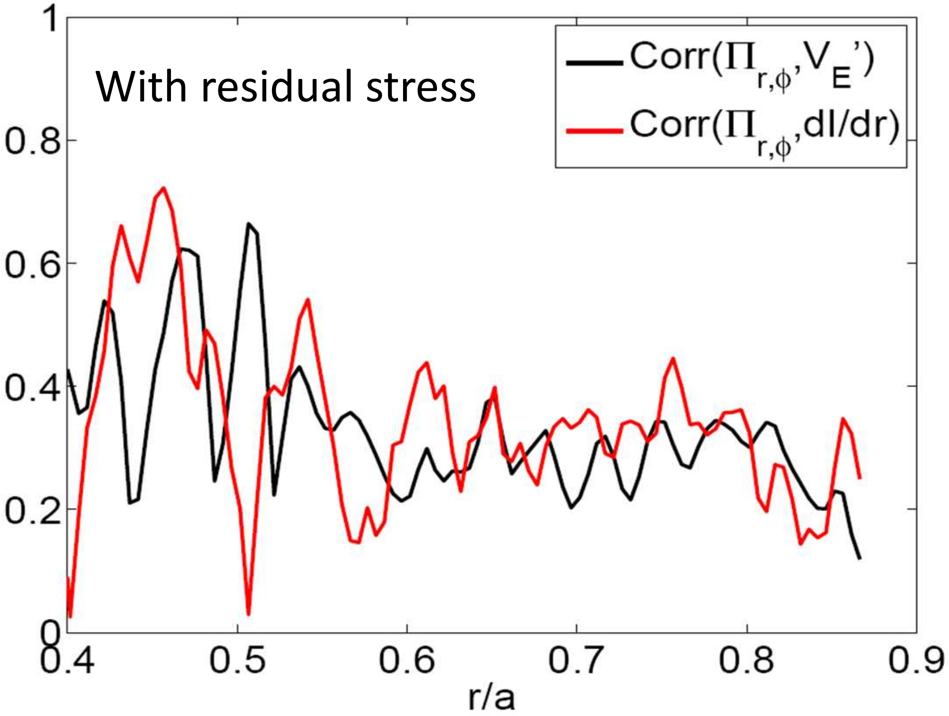
    → Role of intensity gradient more prominent

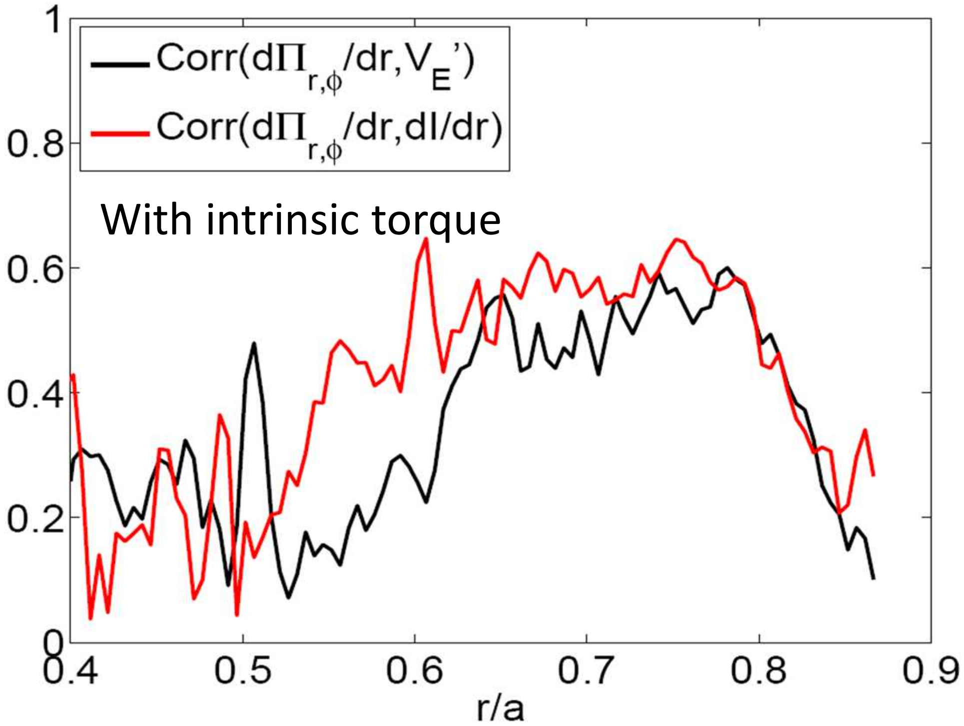




R/L_{Ti} = 10.0, ν* = 0.08

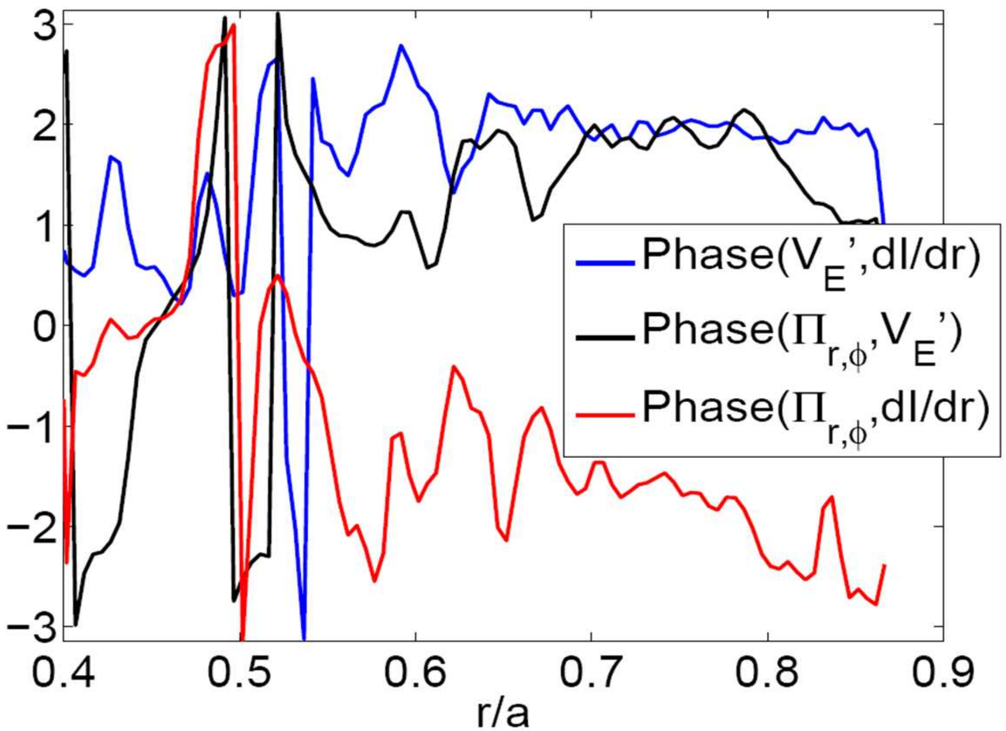
More: Intensity gradient - a major symmetry breaker





- Investigation of correlations between {Residual stress, Intrinsic torque} and symmetry breakers
- Strong correlation(~0.6) with intrinsic torque, smaller correlation(~0.4) with residual stress
- **Intensity gradient shows the same level of correlation as usually invoked ExB shear.**

Stress lags symmetry breakers



$$\langle v_r v_\parallel \rangle$$

$$\updownarrow$$

$$\frac{dv_\parallel}{dt} = -\nabla_\parallel P$$

- **ExB shear** and **intensity gradient** show about π/2 and -π/2 phase lag relative to residual stress.
- Phase between ExB shear and intensity gradient is about π/2.

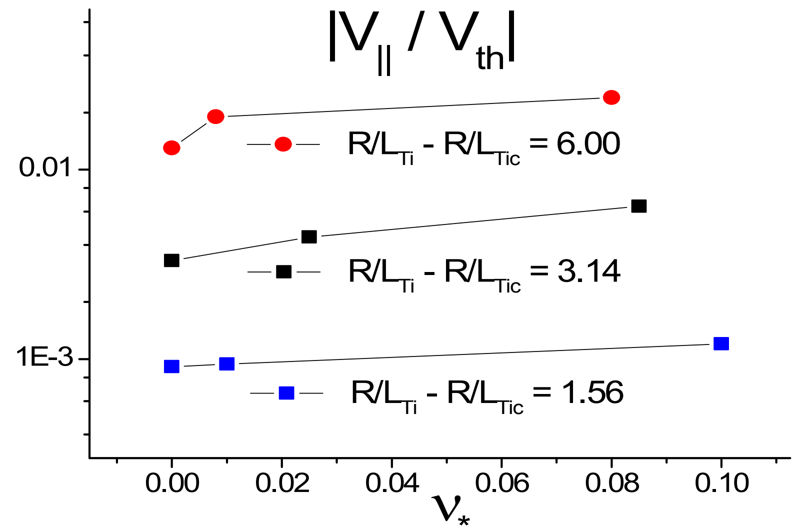
➔ Suggests that drift acoustic response induces phase lag between symmetry breakers and residual stress.

Local Physics of Π^{resid}

- For ITG turbulence, Π^{resid}
  - increases with $R/L_T - R/L_{Tc}$
  - is insensitive to collisional zonal flow damping
  - couples to the zonal flow-turbulence self regulatory predator-prey interaction

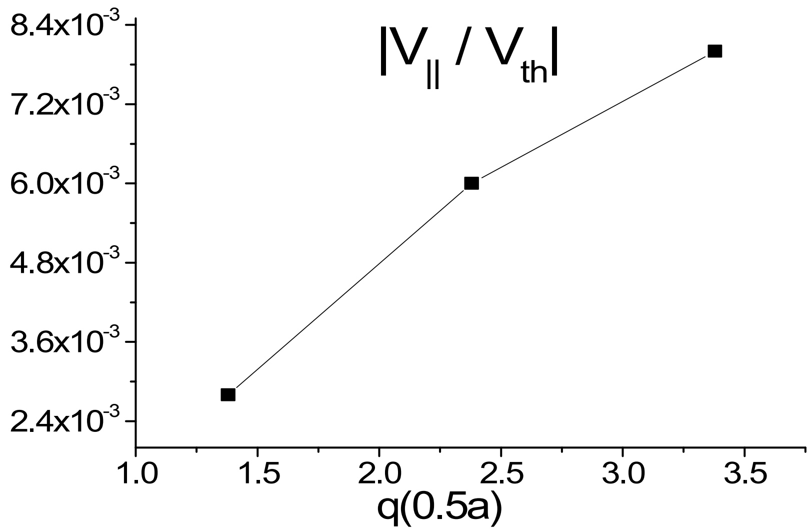
Microscopic Origins of Macro-Scaling?

- Experimentally observed macro scaling
  $\longrightarrow$ Micro Foundations?
  - $\Delta V_\varphi(0) \sim \Delta W/I_p$ for H-mode plasmas (Rice NF'07)
  - $V_\varphi(0) \propto \nabla T_i$ at transport barrier (Rice '10, this conference; Ida NF'10)



- Stronger net rotation as R/L_{Ti} , q-value ↑
  - Increasing R/L_{Ti} : more free energy to drive stronger turbulence
  - Increasing q-value (normal shear)

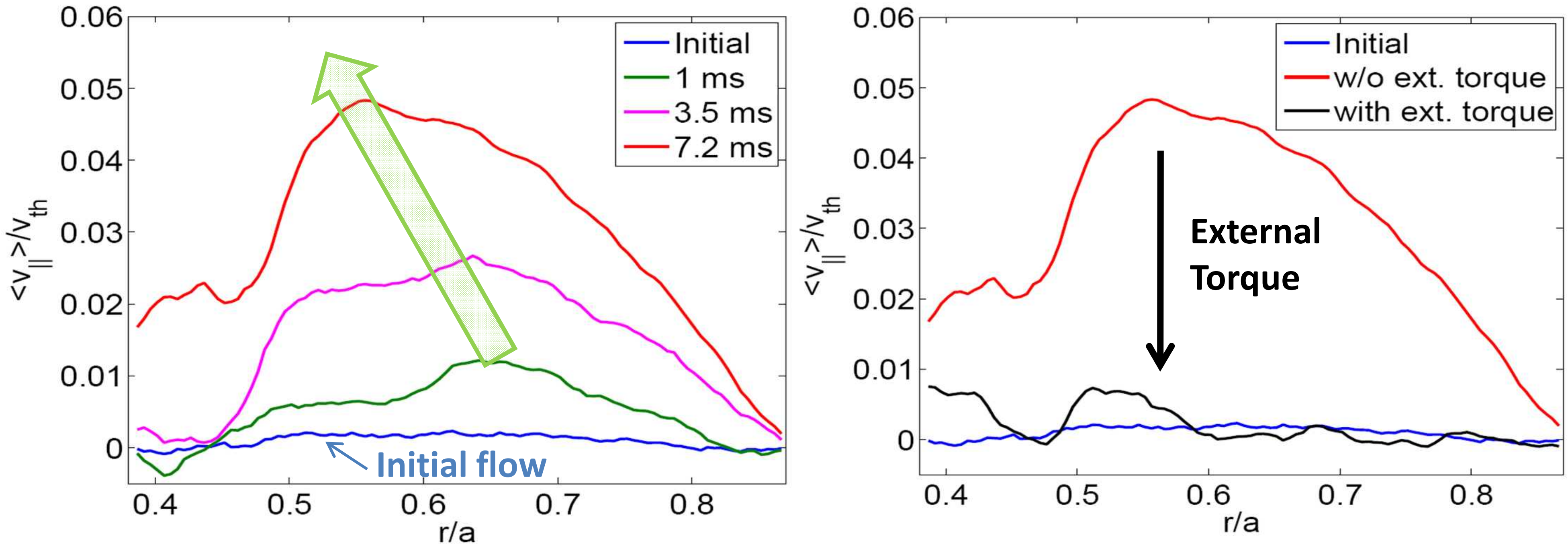
✓ More effective symmetry breaking at higher q-values
✓ Weaker turbulence regulation by ZF for increasing GAM fraction → increase in turbulence and intrinsic flow level



Flux Driven Rotation: $Q_i \Rightarrow V_{intrinsic}$

- Net intrinsic rotation with a peak $\langle V_{\|} \rangle / V_{th}$ = *0.05 ~ 0.15* can be produced in flux driven ITG simulations with no slip boundary conditions

Intrinsic rotation and its cancelation (XGC1p)



- Starting from zero initial flow
  → Net intrinsic rotation at 7 ms: co-current, $M_T \cong 0.05$ (5% of v_{th})
- Peak flow: still increasing & moving from edge to core
- With applied external counter-current torque:
  → Total rotation reduced by more than factor of 5

(Similar result with counter momentum source in GYSELA)

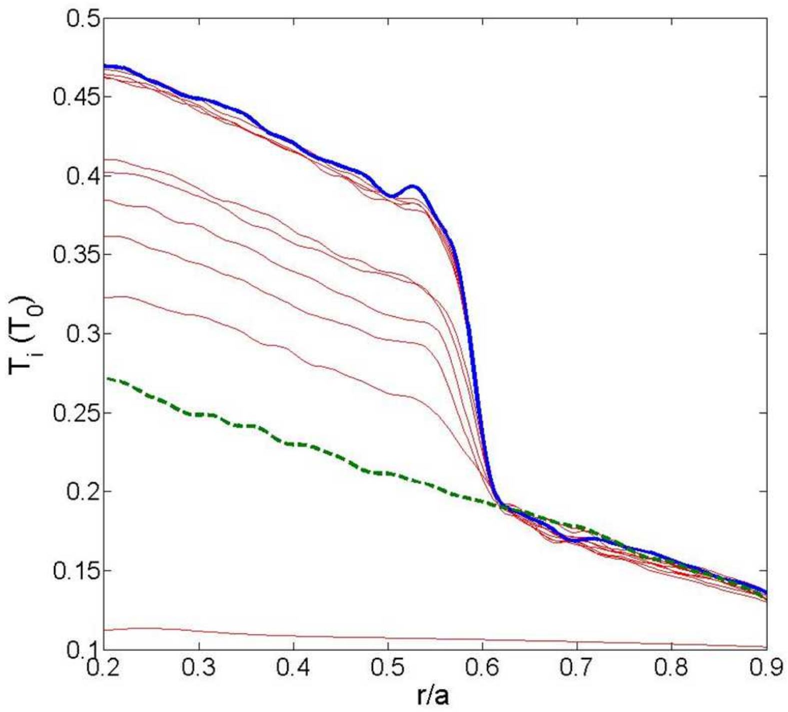
Intrinsic Rotation and ITB's

- Strong intrinsic rotation can be generated by flux driven ITG turbulence in reverse shear ITBs with off-axis minimum $q(r)$, with no slip boundary conditions

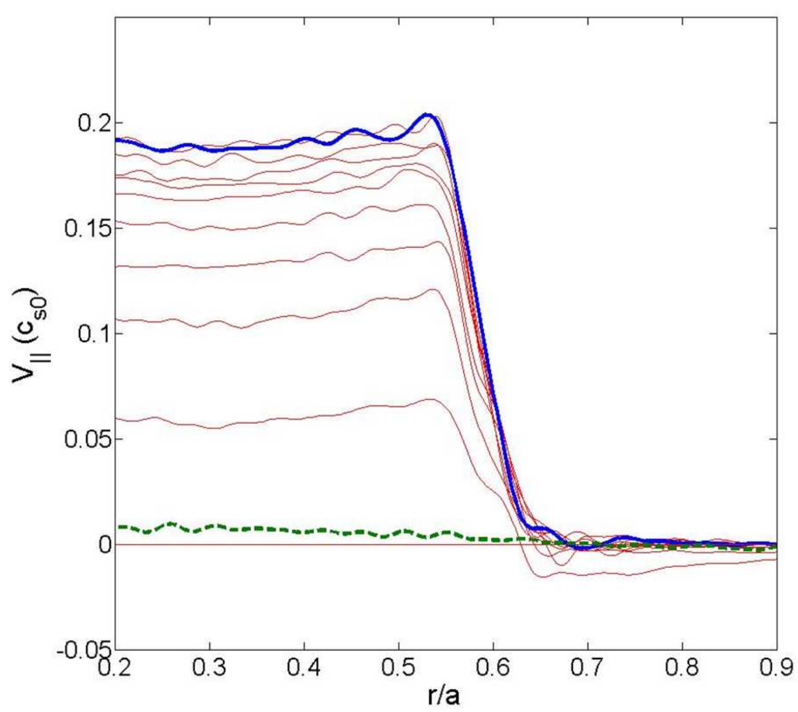
Intrinsic rotation occurs in RS ITB plasmas

- Strong (M_{th} ~ $0.1\text{-}0.25$, $|V_{ITB}| >> |V_L|$) co-current rotation is generated in heat flux driven ITB plasmas with reversed magnetic shear
- The flow is intrinsic rotation generated via the residual stress

Ion temperature vs. r/a



$V_{||}$ vs. r/a



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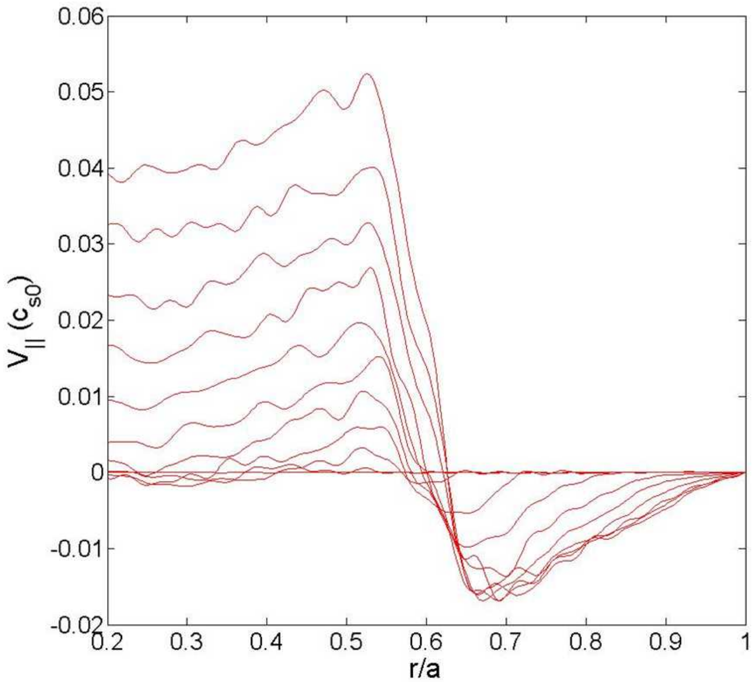
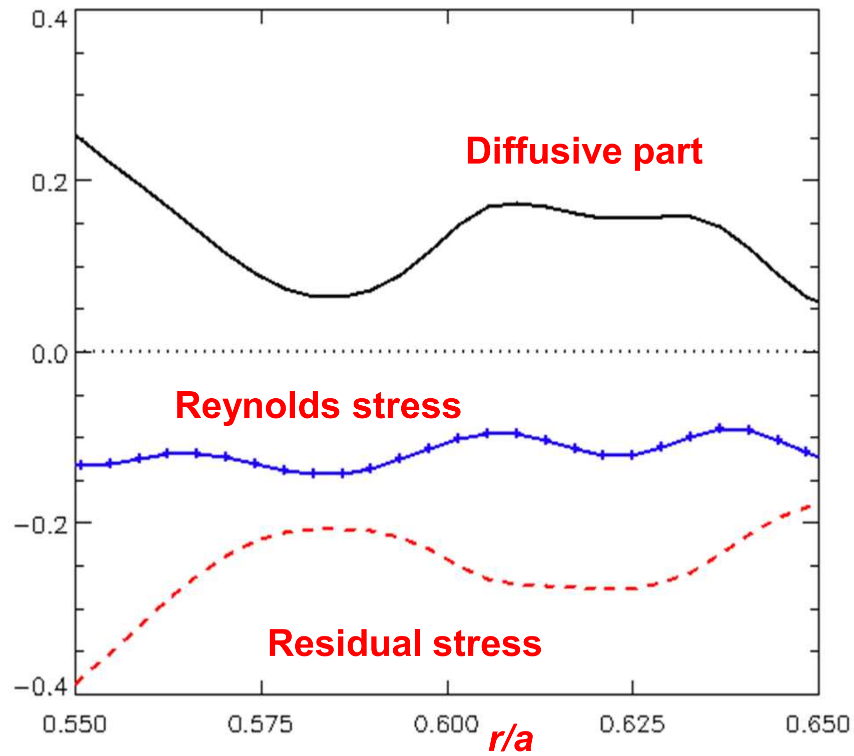
Formation of intrinsic rotation

- Intrinsic rotation is generated near ITB head and, initially, propagates into the core.
- The position of maximum intrinsic rotation coincides with the position of maximal $\left\langle \gamma_{E\times B} |\tilde{\phi}|^2 \right\rangle \rightarrow$ symmetry breaking
- Reynolds stress $\left\langle \tilde{v}_r \tilde{v}_{\|} \right\rangle$ < 0, because of large inward residual stress

$V_{//}$ evolution during initial phase





III) What We Think We Understand but Need More Work On

Alternative Mechanisms

- The mechanism for generation of toroidal rotation by fluctuation driven radial currents – i.e. via the toroidal projection of the perpendicular Reynolds stress.

$\Rightarrow$ Is the emphasis on $k_{||}$ symmetry breaking warranted?!

Alternative Mechanisms

- One more... $\langle J_r \rangle$ from Wave Propagation

$$\langle J_r \rangle \frac{B_\theta}{c} = \frac{B_\theta}{B_0} \frac{\partial}{\partial r} \Pi_{r,\perp}^{wave}$$

$$\frac{B_\theta}{B_T} \frac{\partial}{\partial r} \Pi_{r,\perp}^{wave} = \frac{B_\theta}{B_0} \frac{\partial}{\partial r} \sum_{\mathrm{k}} v_{gr} k_\theta N_{\mathrm{k}}$$

$$\Pi_{r,\perp}^{wave} = -D_w \frac{\partial \langle P_\theta \rangle}{\partial r} + \alpha \langle v_E \rangle'$$

$$D_w = \sum_{\mathrm{k}} v_{gr,\mathrm{k}}^2 \tau_{c,\mathrm{k}}$$

$$\alpha = -\sum_{\mathrm{k}} \frac{2 k_\theta^2 \rho_s^2 \tau_{c,\mathrm{k}}}{\left(1 + k_\perp^2 \rho^2\right)^2} k_r \frac{\partial}{\partial k_r} \langle \Omega \rangle$$

$\Rightarrow$ equivalent to toroidal projection $\langle \tilde{v}_r \tilde{v}_\perp \rangle$

$\Rightarrow$ most conveniently formulated in terms of wave population

Note:- Almost always $(B_\theta / B_T) \langle \tilde{v}_r \tilde{v}_\perp \rangle > \langle \tilde{v}_r \tilde{v}_\parallel \rangle_{resid}$, apparently

Are we focusing on strongest mechanism?

- $\langle V_E \rangle'$ and intensity gradient still critical

Scalings

- The basic structure of the Rice scaling ($\Delta v_T \sim \Delta W_p/I_p$) originates from:
  - strong localized temperature gradients, as in the pedestal and ITBs (i.e. the local origin of ΔW_p)
  - q(r) scaling
    - the origin of I_p dependence
    - sensitivity to q(r) structure

Simple Illustrative Model – Reduced Model

Conservation Laws:

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_n) = S_n$$

$$\frac{\partial P}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rQ) = H$$

$$\frac{\partial L_\phi}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Pi_\phi) = \tau_\phi$$

Angular Momentum

Fluxes:

$$\Gamma_n = -D_0\frac{\partial n}{\partial r} - D_1\varepsilon\left(\frac{\partial n}{\partial r} + V_r n\right)$$

$$\Pi_\phi = -\nu_0\frac{\partial L_\phi}{\partial r} - \nu_1\varepsilon\left[\frac{\partial L_\phi}{\partial r} + V_r L_\phi\right] + S$$

TEP Pinch for Momentum and Density

where $S = -\varepsilon\alpha(r)\left(1 - \frac{\sigma}{P_0}\frac{\partial P}{\partial r}\right)\frac{\partial v_{Ey}}{\partial r}$

$$Q = -\chi_0\frac{\partial P}{\partial r} - \chi_1\varepsilon\frac{\partial P}{\partial r}$$

Residual Stress due to ExB Shear

Radial Force Balance:

$$E_r \cong \frac{1}{ne}\frac{\partial P}{\partial r} - u_{\theta,Neo}B_\phi + u_\phi B_\theta$$

$$\varepsilon = \frac{\varepsilon_0}{1 + \beta\left(\frac{\partial u_{Ey}}{\partial r}\right)^2}$$

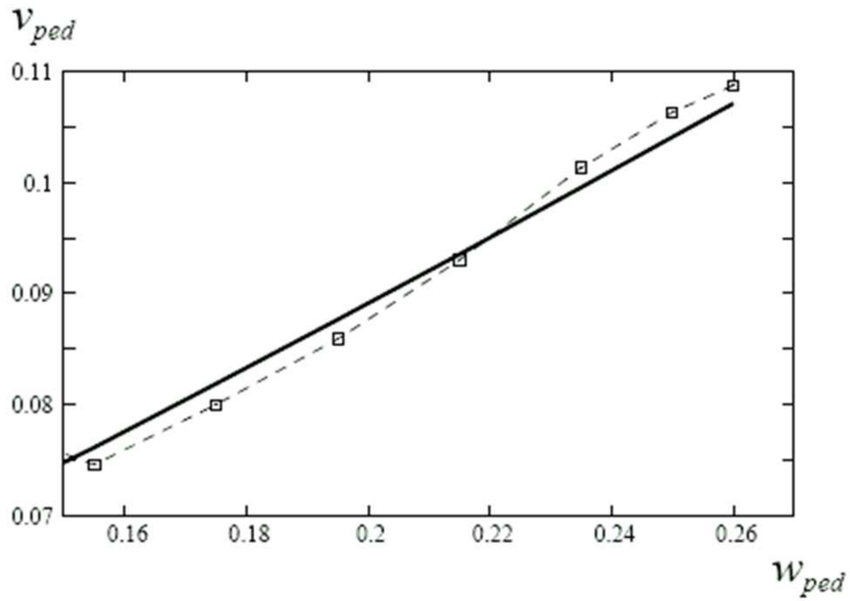
ExB Shear Reduction
[Hinton, PF-B '91]

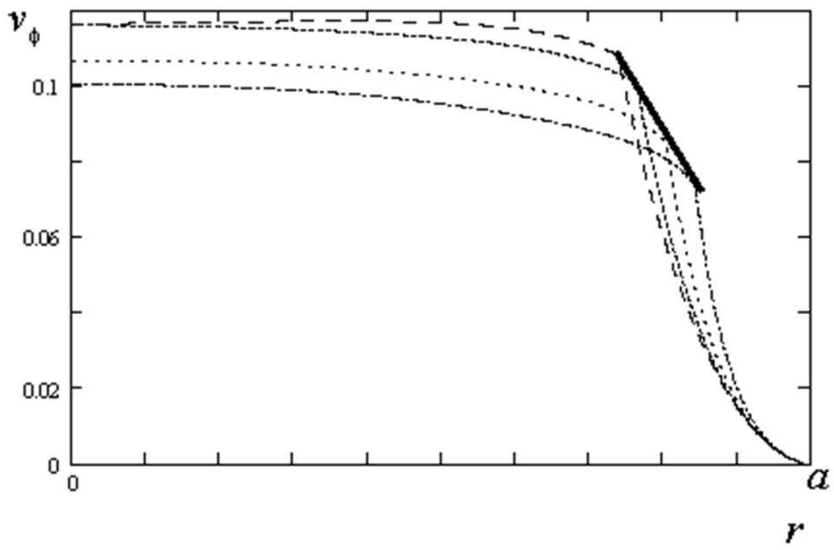
L-mode Turbulence Intensity only adjustable parameter ε_0

B.C.'s: $L_\phi(a), V_\phi(a), n(a)$: given

Boundary conditions critical!

Scaling Trends manifested by Model





- Dimensional analysis for pedestal flow velocity suggests scaling with width:

Scaling with ρ from turbulence characteristics

$$\mathrm{v}_\phi / \mathrm{v}_{Ti} \propto (\Delta r_{Turb} / a)(\Delta_{ped} / a) \propto (\rho^*)^\alpha (\Delta_{ped} / a)$$

- With the simple model linking width to height,

$$\Delta_{ped} \propto P_{ped} \longrightarrow \Delta \mathrm{v}_\phi / \mathrm{v}_{Ti} \propto (\rho^*)^\alpha \Delta W_p$$

where ΔW_p : Incremental Stored Energy

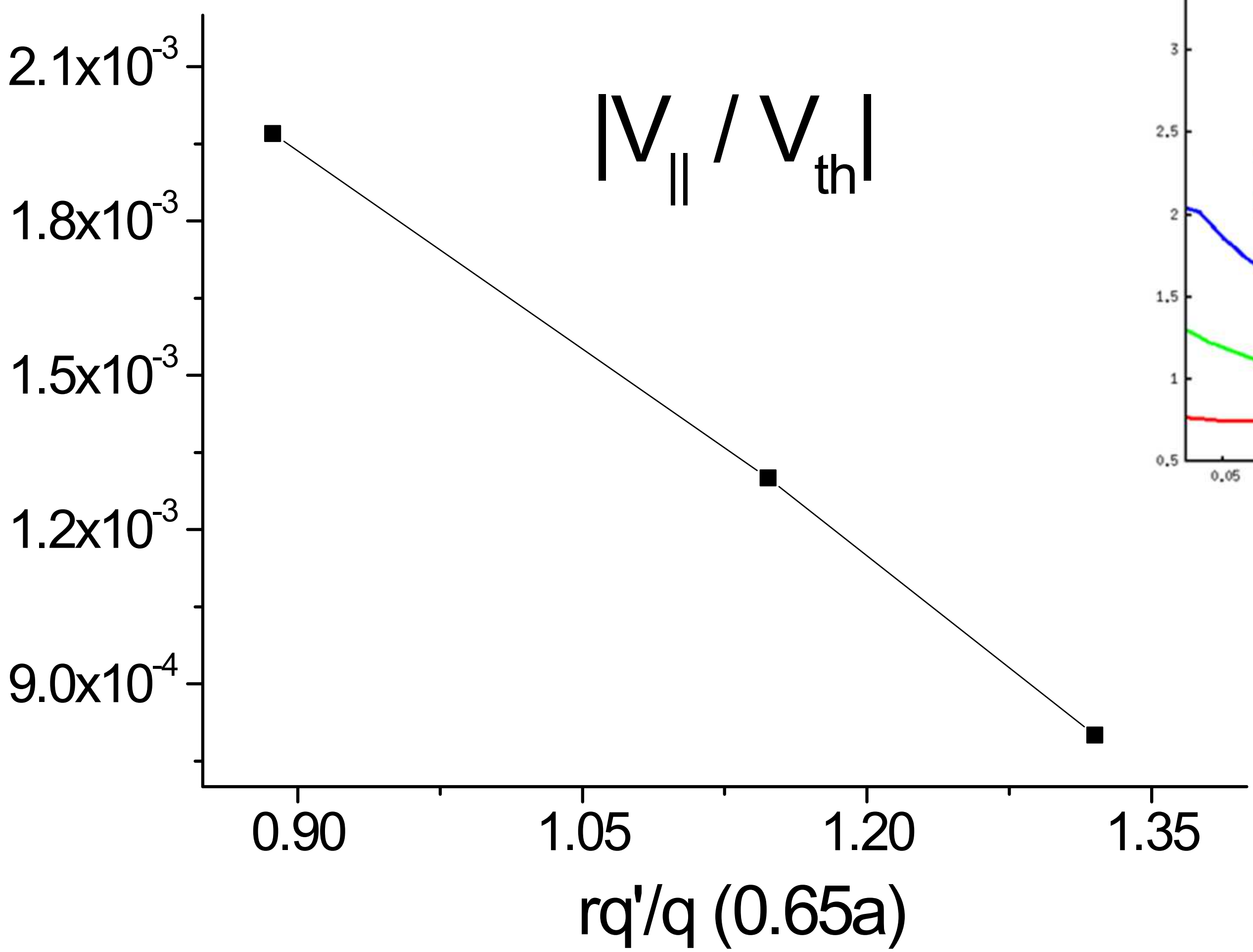
- I_p scaling not recovered for GB model→ pedestal/edge turbulence issues?

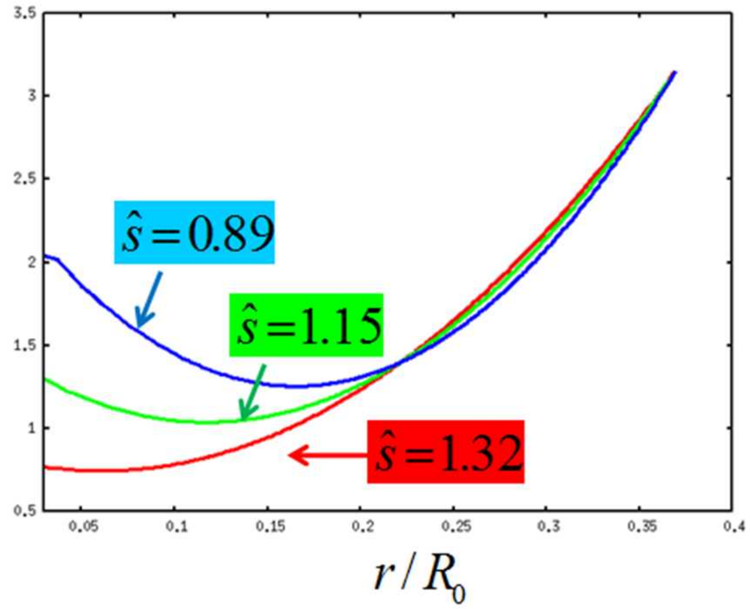
- Model is not quantitatively accurate,
  - predicts a scaling of the pedestal toroidal velocity with the pedestal width.

$$V_{\phi,ped} \sim \Delta_{ped} \sim P_{ped}$$

but recovers qualitative behavior

q(r) Shape Can Enhance Intrinsic Flow





⇒ Weak but positive shear is favored

Observation re: q(r) structure

- Key correlator for residual stress:

$$\Pi_{r,\phi}^{resid} \sim \left\langle \widetilde{V}_r \nabla_{\|} \widetilde{\phi} \right\rangle \sim \left\langle k_\theta k_{\|} |\widetilde{\phi}|^2 \right\rangle$$

$$k_{\|} = \underbrace{nq'x}_{\text{shear}} + \underbrace{nq''x^2/2}_{\text{curvature – flat q(r)}} + \ldots$$

$$\Pi_{r,\phi}^{resid} \sim n^2 q' \left\langle x |\widetilde{\phi}|^2 \right\rangle + n^2 q'' \left\langle x^2 |\widetilde{\phi}|^2 / 2 \right\rangle + \ldots$$

spectral centroid ~ $\langle V_E \rangle'$ etc $\Rightarrow$ sensitive   spectral variance $\Rightarrow$ robust – set by spectral width

- Expect strong Π^{resid} in flat-q regimes (i.e. q'=0, q''≠0) ⇒ Intrinsic rotation in ITB's, low torque "de-stiffened" regimes ?!

Aside: Why Care?

- Core stiffness, no man's land place SEVERE demands on ITER pedestal

- Need reconsider either:
  - ITB
  - de-stiffened, hybrid mode approach

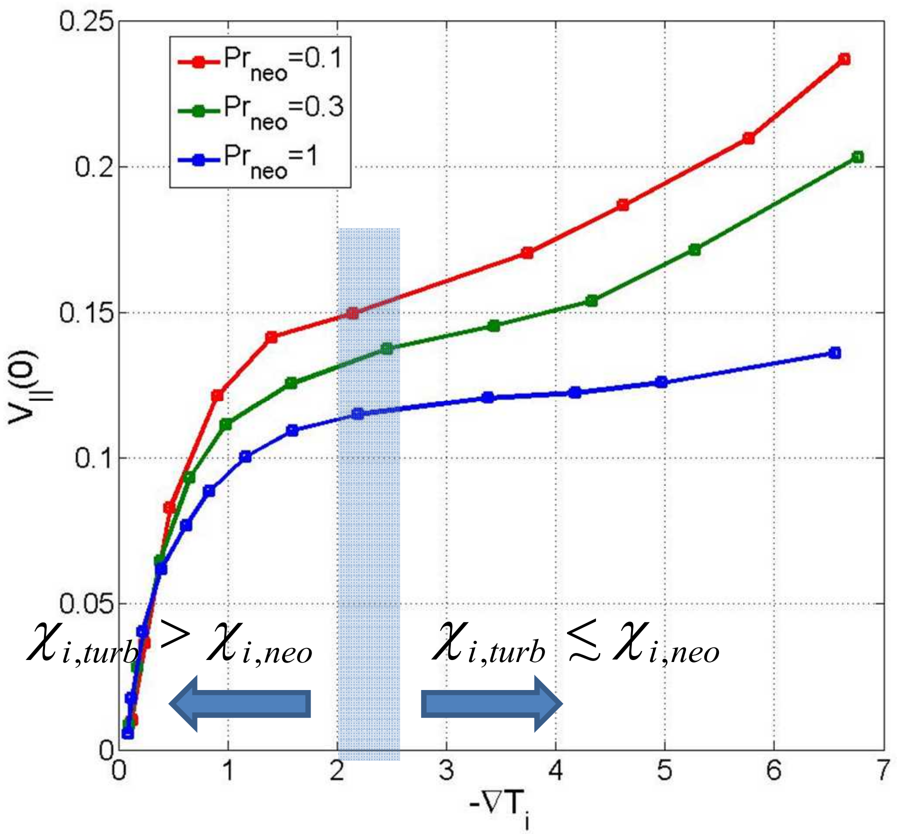
- Current understanding suggests:
  - intrinsic flow shear will dominate ITB $\langle V_E \rangle'$, absent external torque
  - intrinsic rotation very sensitive to q(r) profile structure

Saturation of Intrinsic Rotation – Especially ITB

- Saturation of Rice scaling in high power ITBs and the ultimate limit on intrinsic rotation. Of particular note here is dependence on collisional Prandtl number or its equivalent.

New regime of $V_{||}(0)$ vs ∇T_i scaling found

- ~ Linear $V_{||}(0)$ vs. $-\nabla T_i$ enters roll-over for $\chi_{i,turb} \lesssim \chi_{i,neo}$ (strong turbulence suppression in ITB) → Ultimate limitation on intrinsic rotation?



- Why? There are intermediate states between "active" and "fully suppressed" turbulent states → determined by residual heat and momentum transport in barrier

$Pr_{neo} = \chi_{\phi,neo} / \chi_{i,neo}$

$$\frac{\nabla V_\phi}{\nabla T_i} \sim \frac{I\gamma_E^\alpha}{Q_i}\left(\frac{Q_i}{\chi_{i,t}}\frac{1}{1+\hat{\chi}_i}\right)^\beta \frac{\chi_{i,t}}{\chi_{\phi,t}}\frac{1+\hat{\chi}_i}{1+\hat{\chi}_\phi},$$

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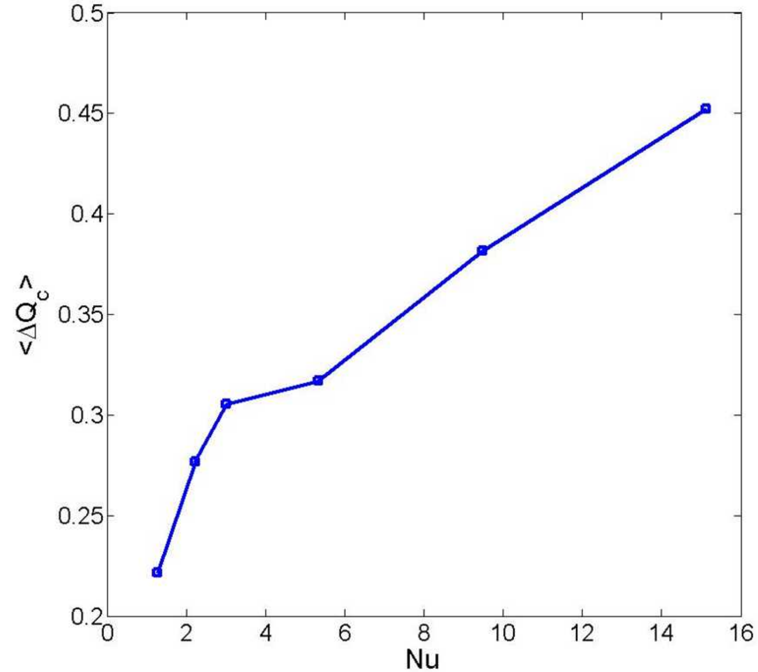
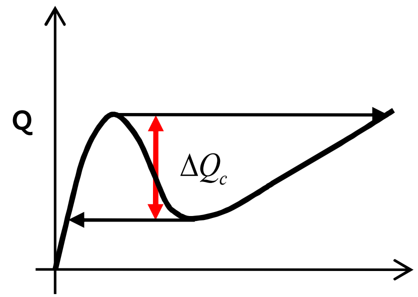
ITB – Relative Hysteresis

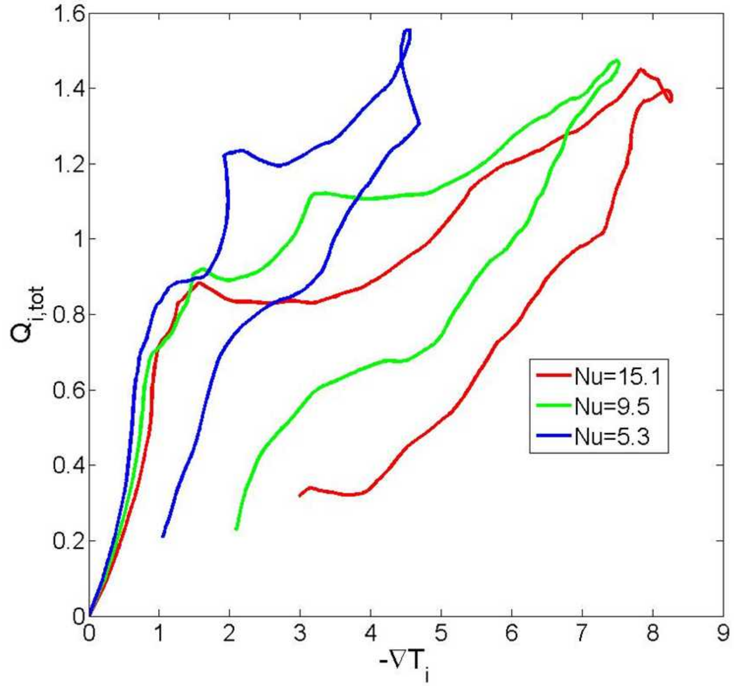
- Relative hysteresis of ∇V_φ and ∇T in ITG intrinsic rotation (K. Ida 2010)

Hysteresis happens!





$\langle \Delta Q_c \rangle = A / \Delta(\nabla T_i)$,
where A is area spanned
by hysteresis curve



- Strength of hysteresis increases with Nusselt number (*Nu*= $\chi_{i,turb} / \chi_{i,neo}$) increases → agrees with prediction based on bifurcation theory

- Open loop hysteresis is seen in $Q_{i,tot}$ *vs.* $-\nabla T_i$ plot
→ Contrast to closed loop S-curve model

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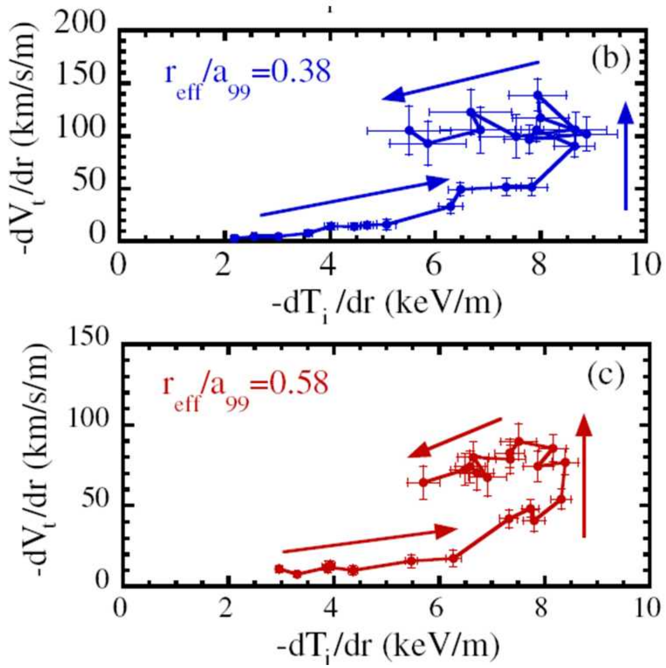
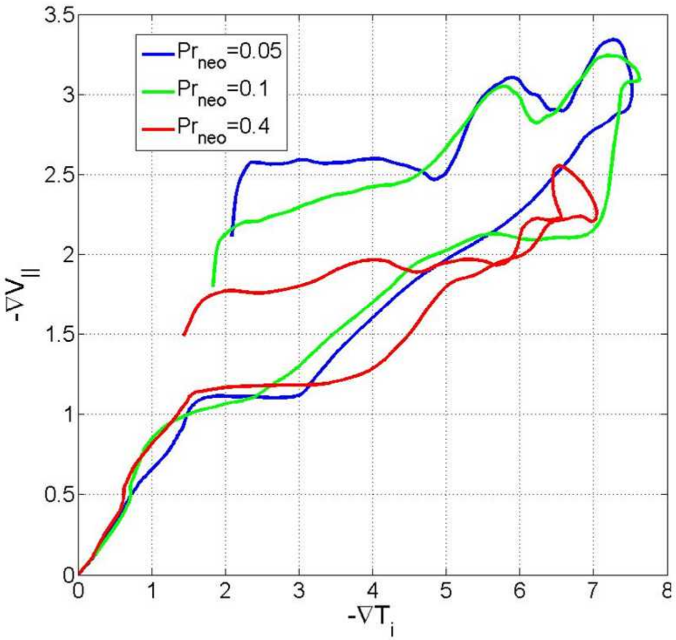
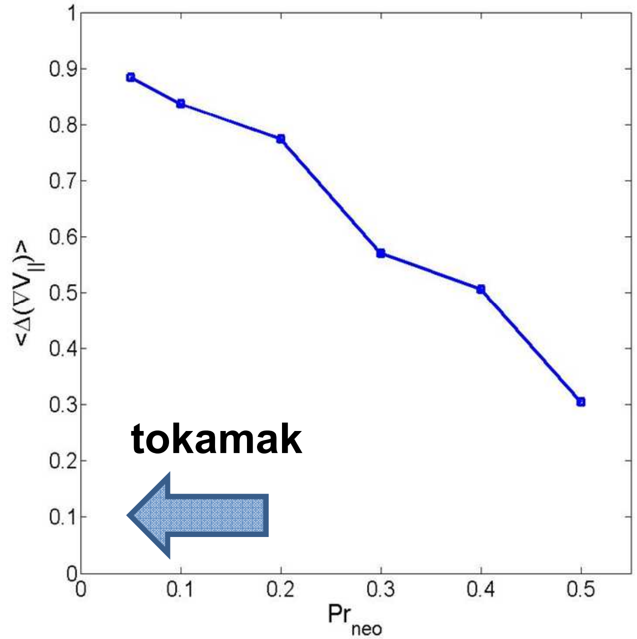
Relative hysteresis between ∇T_i & $\nabla V_{||}$ observed and explained





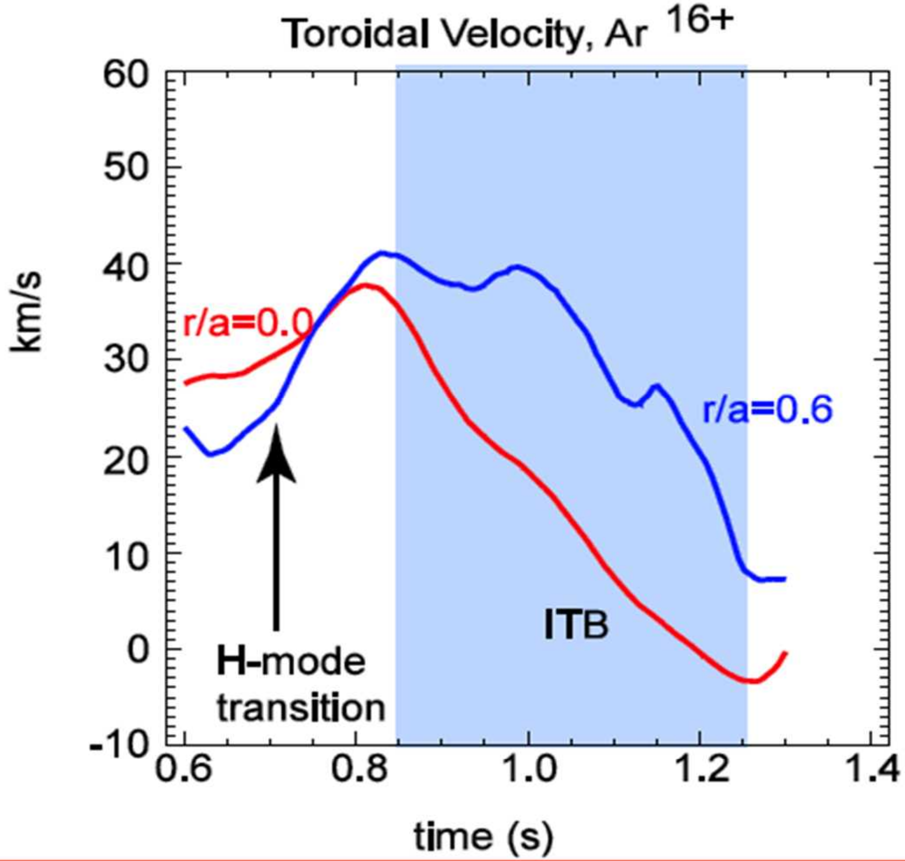


- Relatively stronger hysteresis of intrinsic rotation over temperature gradient is observed → Recovers features of recent experimental observation in LHD [K. Ida et. al., NF 50 (2010) 064007]
- Residual transport (Pr_{neo}) governs strength of relative hysteresis → $\Delta(\nabla V_{||})$ decreases as Pr_{neo} increases.

- C-Mod: ITBs in $q' > 0$ plasmas (C. Fiore, et. al.)
  - ITB develops in H-mode with H-mode pedestal-generated intrinsic rotation
  - Intrinsic V_ϕ' is largest contributor to $\langle V_E \rangle'$
  - Core rotation can reverse in ITB

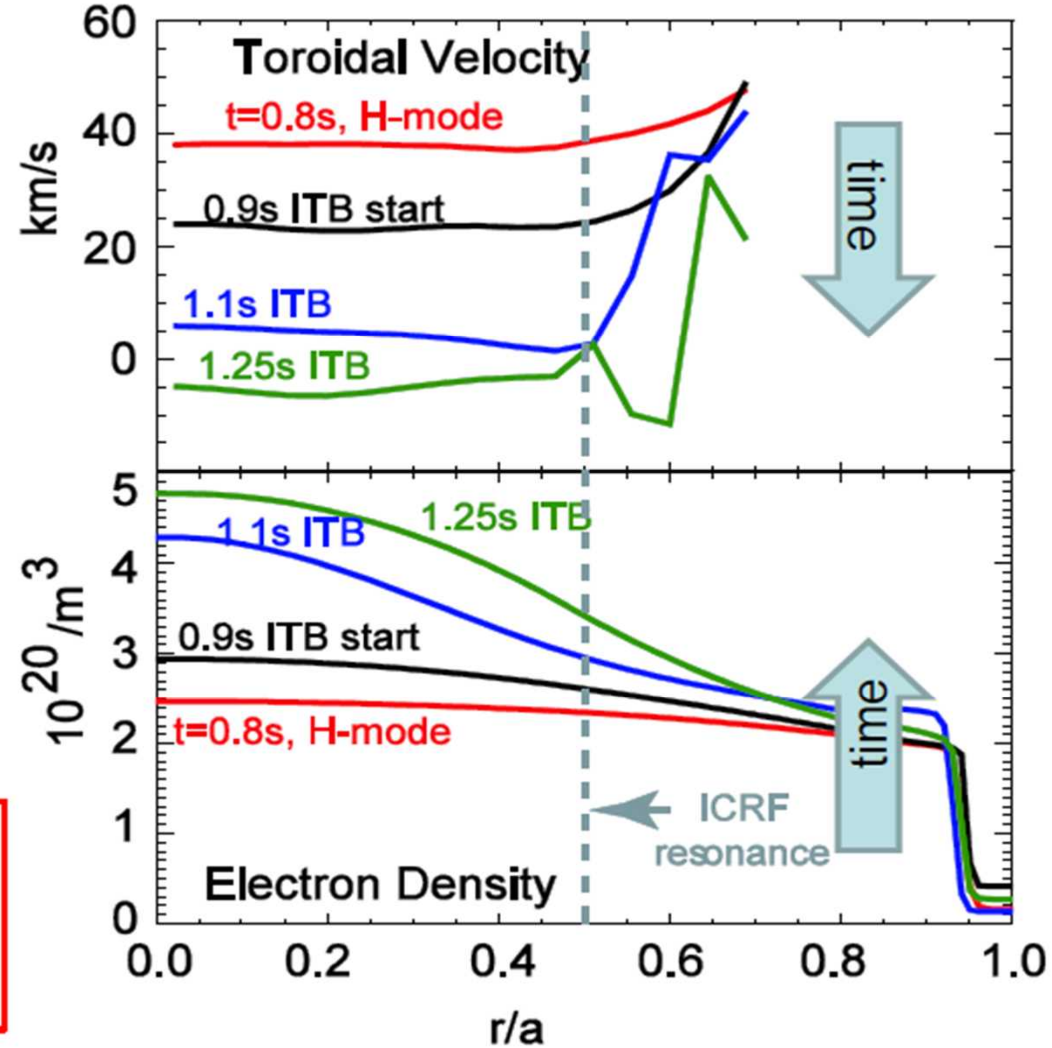
With off-axis ICRF heating, the central toroidal rotation decreases, often reverses direction; an ITB usually develops

Off-axis ICRF:



Rotation increases in co-current direction at the H-mode transition. As the ITB develops, core rotation decreases, moves in counter current direction.

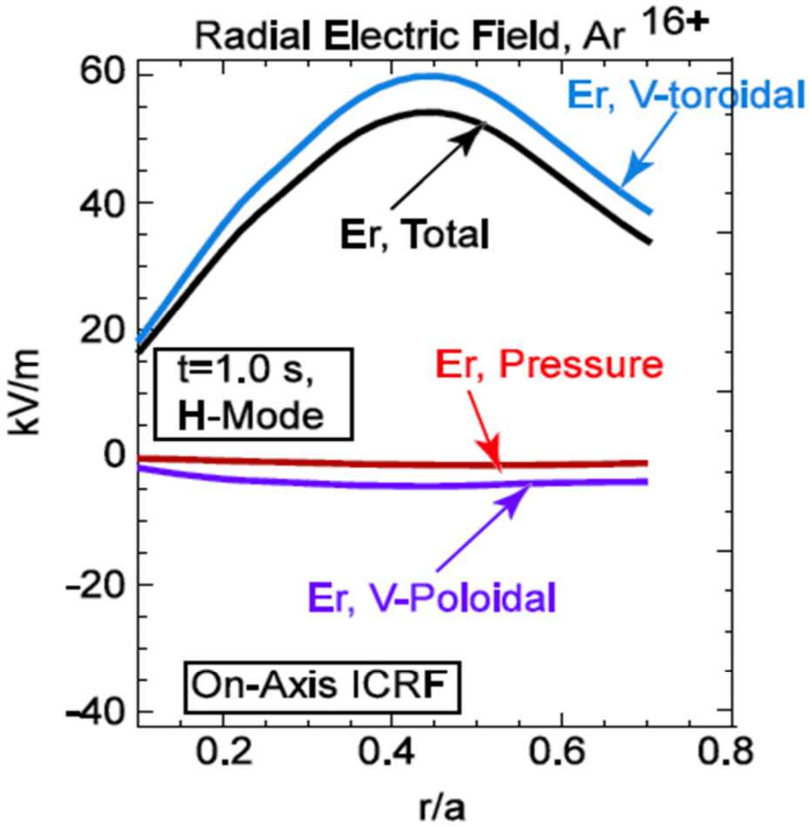
As density peaks, a well in the toroidal rotation develops inside of the ITB foot region.

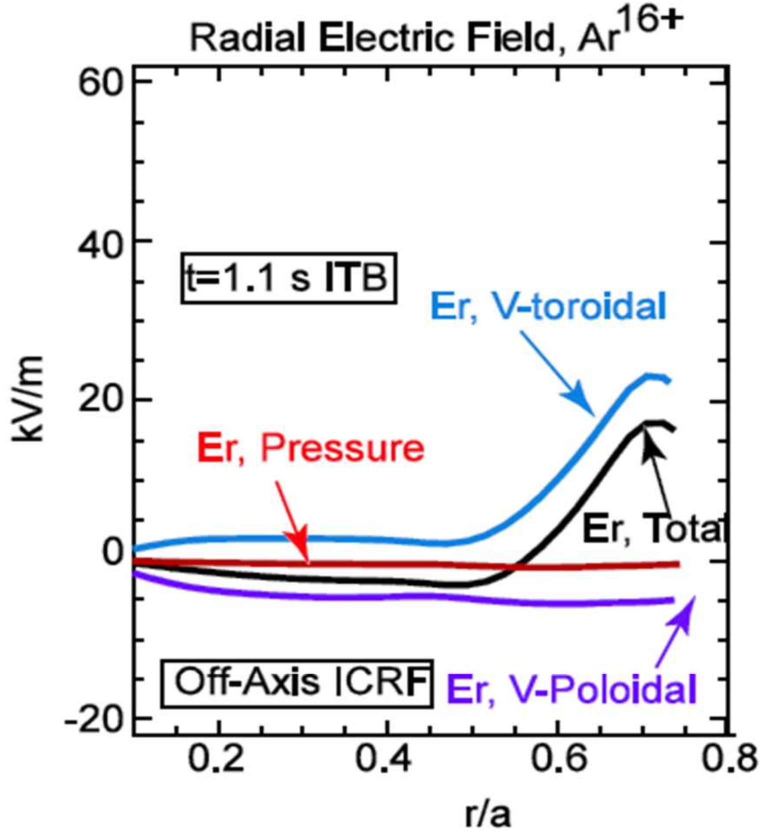


The radial electric field profiles are different for on-axis, off-axis ICRF heated discharges

With on-axis ICRF E_r profile is broad with peak of 55 kV/m at r/a=0.45

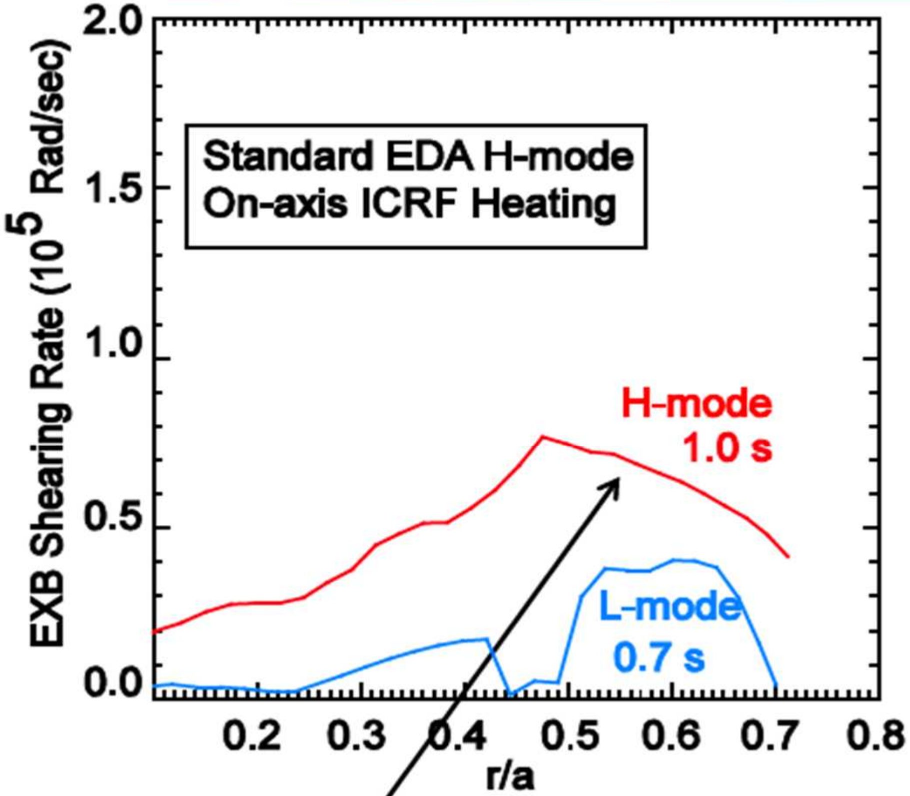
Off axis ICRF heating leads to an E_r profile that is flat in the core, then rises beyond r/a=0.5. An ITB forms in this plasma

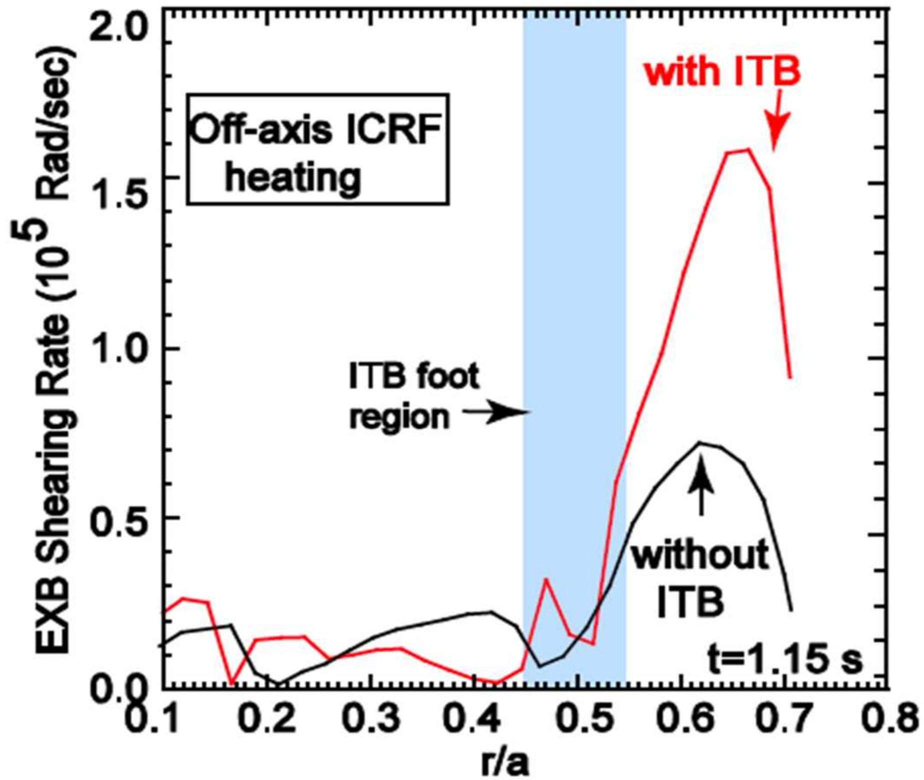




Toroidal rotation data are used in TRANSP to determine the radial electric field; Contributions from toroidal rotation, poloidal rotation, and pressure profile are shown. Toroidal rotation is the largest contribution to the radial electric field.

EXB shearing rate is 2-3 times higher in ITB foot region in plasmas where ITB develops





On axis ICRF heated H-mode has shearing rate peaked off-axis; the magnitude is lower than in the off axis heating with ITB

In off-axis ICRF heated H-mode the shearing rate is peaked to the outside, r/a>0.6.

If the shearing rate is not high enough, no ITB forms.

What we think we understand but would benefit from more work on (cont')

- The theory of poloidal momentum transport by turbulence

  ⇒ See C. McDevitt, et. al. PoP 2010 for discussion

Reversals – A New Type of Transport Bifurcation

- The precise relation between turbulence propagation direction (i.e. v_{*e} vs. v_{*i}) and toroidal rotation direction

  $\Rightarrow$ Reversals?

  - Observed in TCV, C-Mod
  - Appears linked to CTEM-ITG, LOC $\Rightarrow$ SOC cross over
  - Exhibits many features of transport bifurcation without enhanced energy confinement
  - Likely relation to p-ITB of W.W. Xiao et al

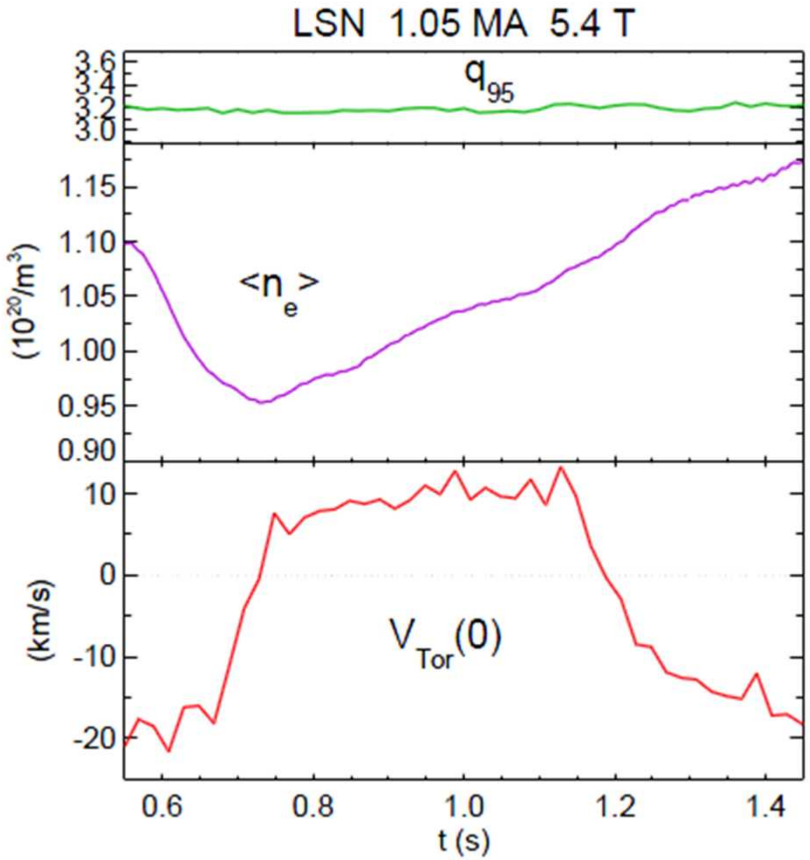


Figure 3: Time histories of q_{95} (top frame), average electron density (middle frame) and central toroidal rotation velocity (bottom frame) for a LSN 1.05 MA 5.4 T discharge with two reversals.

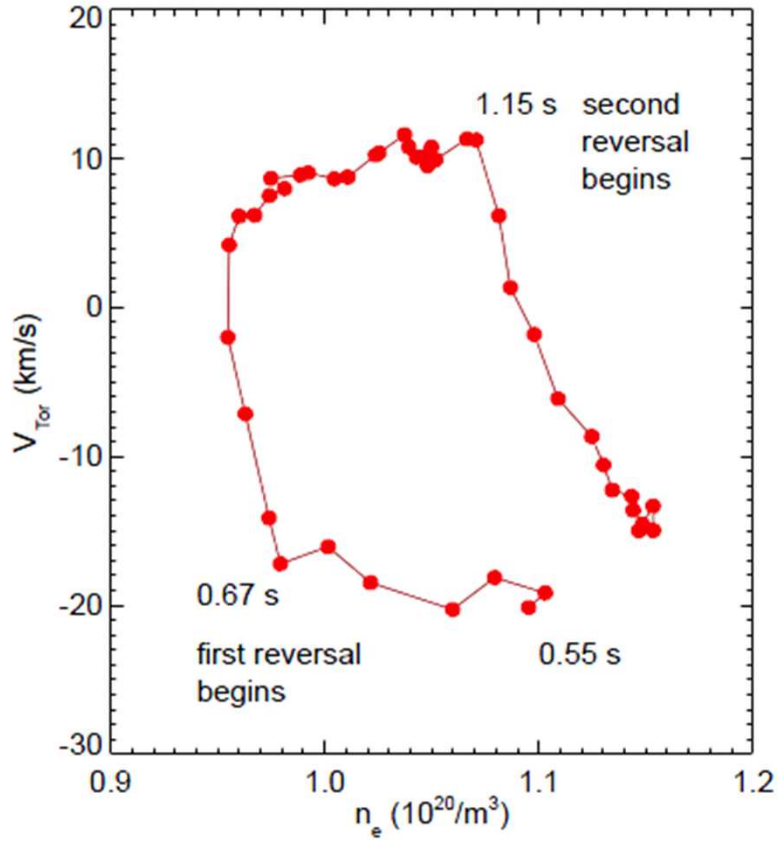


Figure 4: The discharge trajectory in the n_e-V_{Tor} plane for the plasma of Fig.3. Points are separated by 20 ms.

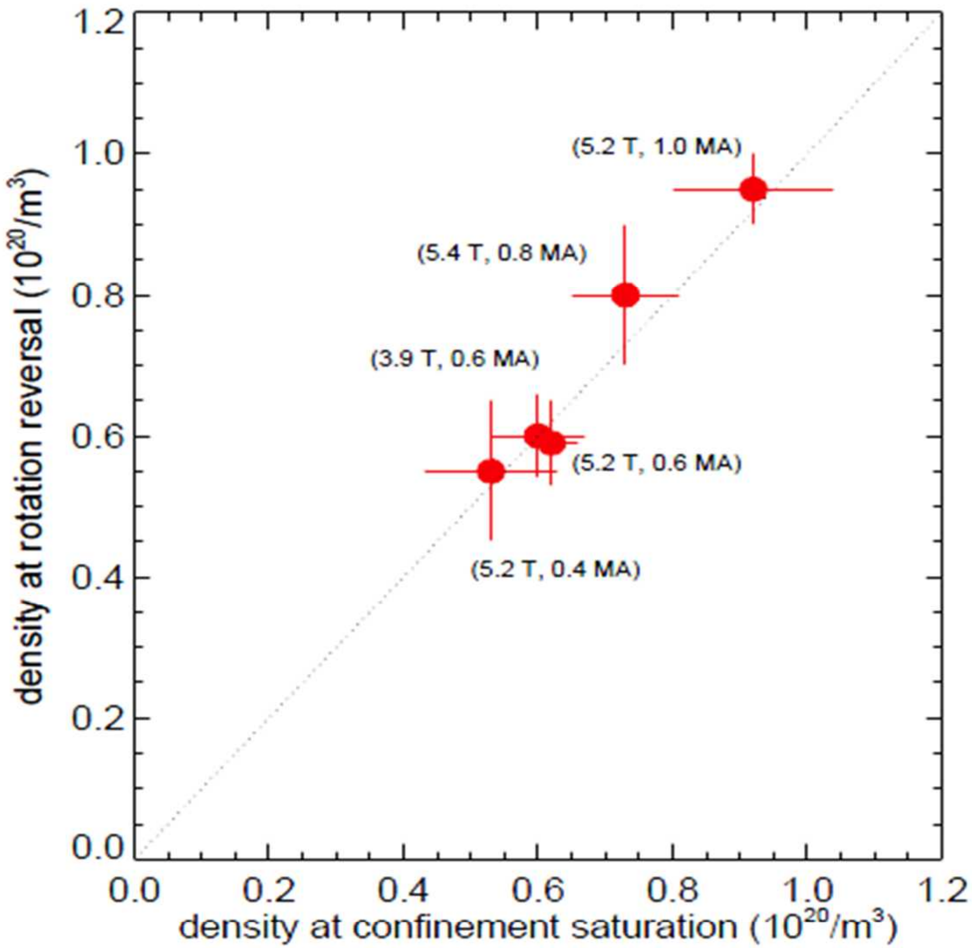


Figure 6: The rotation reversal density as a function of the transition density between linear and saturated energy confinement. Magnetic fields and plasma currents for each point are listed. The dotted line has a slope of unity.

Residual ⇔ Mode Propagation

Residual Stress –General Structure

$v_{gr} \sim v_*$

- wave: $\Pi_{r,\parallel}^{wave} = \int d\mathrm{k}\, k_\parallel \left\{ -\tau_{c,\mathrm{k}} v_{gr}^2 \frac{\partial \langle N_\mathrm{k} \rangle}{\partial \mathrm{r}} + \tau_{c,\mathrm{k}} v_{gr} k_\theta \langle V_E \rangle' \frac{\partial \langle N_\mathrm{k} \rangle}{\partial \mathrm{k}_r} \right\}$

Key parameter : $v_{gr} \langle V_E \rangle'$

See P.D. et al PoP 2008

intensity gradient
→ diffusive

'wind-up'
δN responds to shear
akin Z.F. generation

- broken symmetry: $\frac{\partial}{\partial t}\langle k_\parallel \rangle = -\frac{1}{r}\frac{\partial}{\partial r}\left[r\Pi_{r,\parallel}^{wave} \right] - \int d\mathrm{k}\, \frac{\partial k_\parallel}{\partial k_r} k_\theta \langle v_E \rangle' \langle N \rangle - \int \mathrm{kb} \cdot \ddot{\mathrm{D}}_\mathrm{k} \cdot \nabla_\mathrm{k} \langle N \rangle + 2\int d\mathrm{k}\, k_\parallel \gamma_k \langle N \rangle - \gamma_{NL} \langle k_\parallel \rangle$

$\sim \int dk \, \frac{\partial k_\parallel}{\partial k_r} k_\theta \langle v_E \rangle' \langle N \rangle$ ➠ shearing

$\sim$ also $\begin{cases} \text{wave flux} \\ \text{random refraction (GAM)} \\ \text{growth asymmetry (C. Lee)} \end{cases}$

Intrinsic Rotation as Heat Engine

- The theory of fluctuation entropy balance and how it relates to the notion of intrinsic rotation as the output of a plasma heat engine

  ⇒ See: Y. Kosuga, et. al. PoP 2010

  J. Rice, et. al. PRL 2011

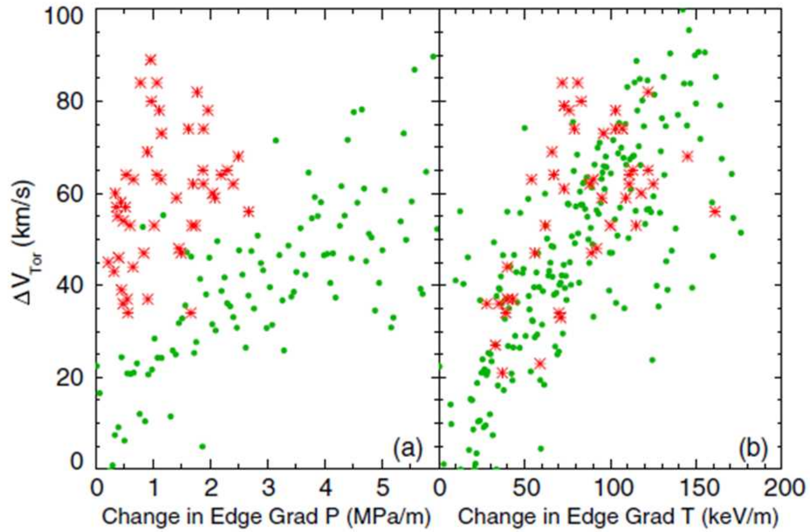


FIG. 5 (color online). The change in the core rotation velocity as a function of the change in the pedestal ∇P (a) and pedestal ∇T (b) for *H*-mode (green dots) and *I*-mode (red asterisks) plasmas.

- Punchlines:
  - ∇T_i correlates well with $V_T(0)$ in C-Mod H-mode, I-mode

    ∇P fails for I-mode
  - Theory based on heat engine (low efficiency!) picture calculated C-Mod $V_T(0)$ to good accuracy

IV) What We Do Not Understand – and should be studying

Boundary Condition

VERY IMPORTANT

- The interplay of turbulence and wave scattering with neoclassical effects and orbit loss in determining the boundary condition for intrinsic rotation $\Rightarrow$ need quantify the amount of 'slip'.

- The detailed interplay between core intrinsic torque and the edge boundary condition, and its role in determining net rotation direction. The connection between SOL flows and core rotation.

- The impact of filaments and ELMs on intrinsic rotation

Physics of Boundary Condition Effects

- SOL Flows: *[LaBombard et al., NF `04]*

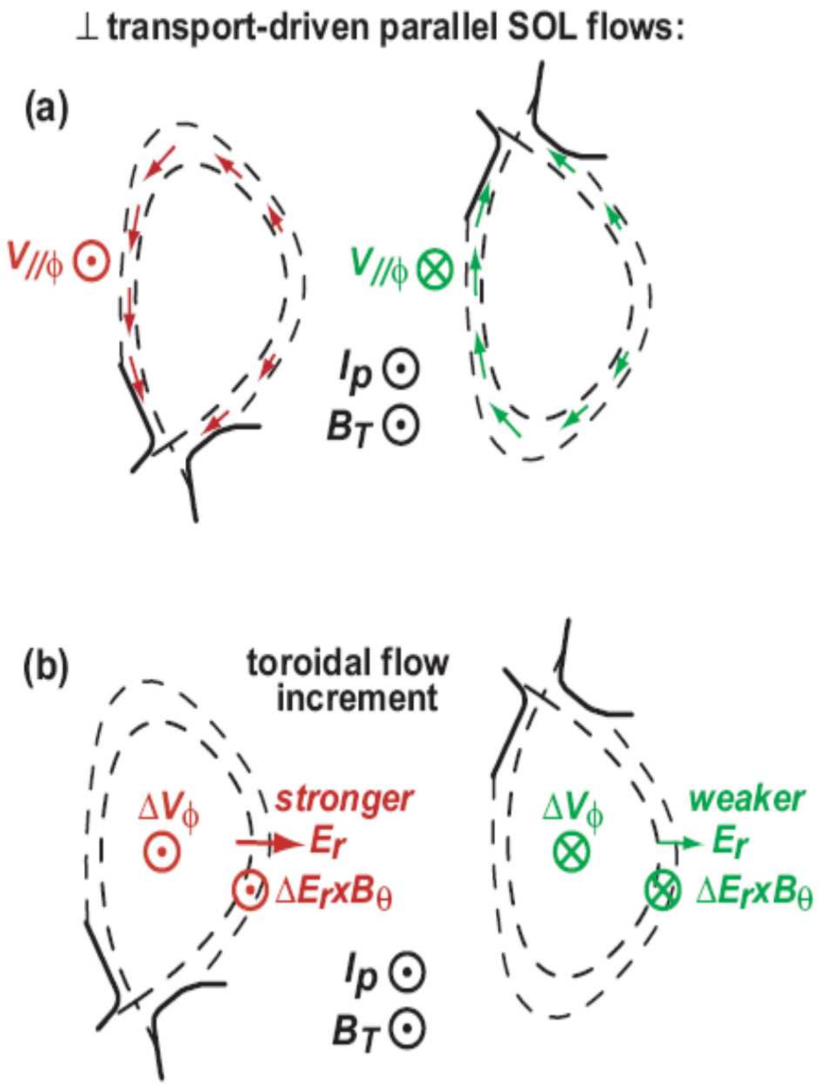
  "ballooning" particle flux produced by outboard source and SOL symmetry breaking (LSN vs USN)

  Influence core Δv_ϕ in L-mode

  LSN → $V_{\nabla B}$ toward X-point → Δv_ϕ co

  USN → $V_{\nabla B}$ from X-point → Δv_ϕ counter

But, in H-mode, Δv_ϕ is always CO



- Key question: How can SOL flow influence core plasma ?
- For $S_{||}(r)$ = speed profile of SOL flow

$\frac{dS_{||}(r)}{dr}$ > 0 in SOL ---> Inward viscous stress of SOL flow on core

Key: SOL symmetry breaking sets Δv_ϕ direction

Strong for parallel shear flow instability for $\nabla V_{||}$ > ∇n

Alternative: Recoil from Blob Ejection (Myra)

ρ_* Scaling

- The apparent absence of ρ_* scaling of intrinsic rotation

  ~ is this real?

- More generally, the obvious problem of:
  - the general, qualitative success of drift wave theories of momentum transport, which universally ρ_* predict dependence
  - the apparent absence of ρ_* dependence in intrinsic rotation scalings

- Isotope dependence

What we do not understand

- The effect of energetic particles on rotation

  At least two Issues:

  - E.P. momentum scattering – i.e. deposition
  - Momentum transport by A.E.'s etc.

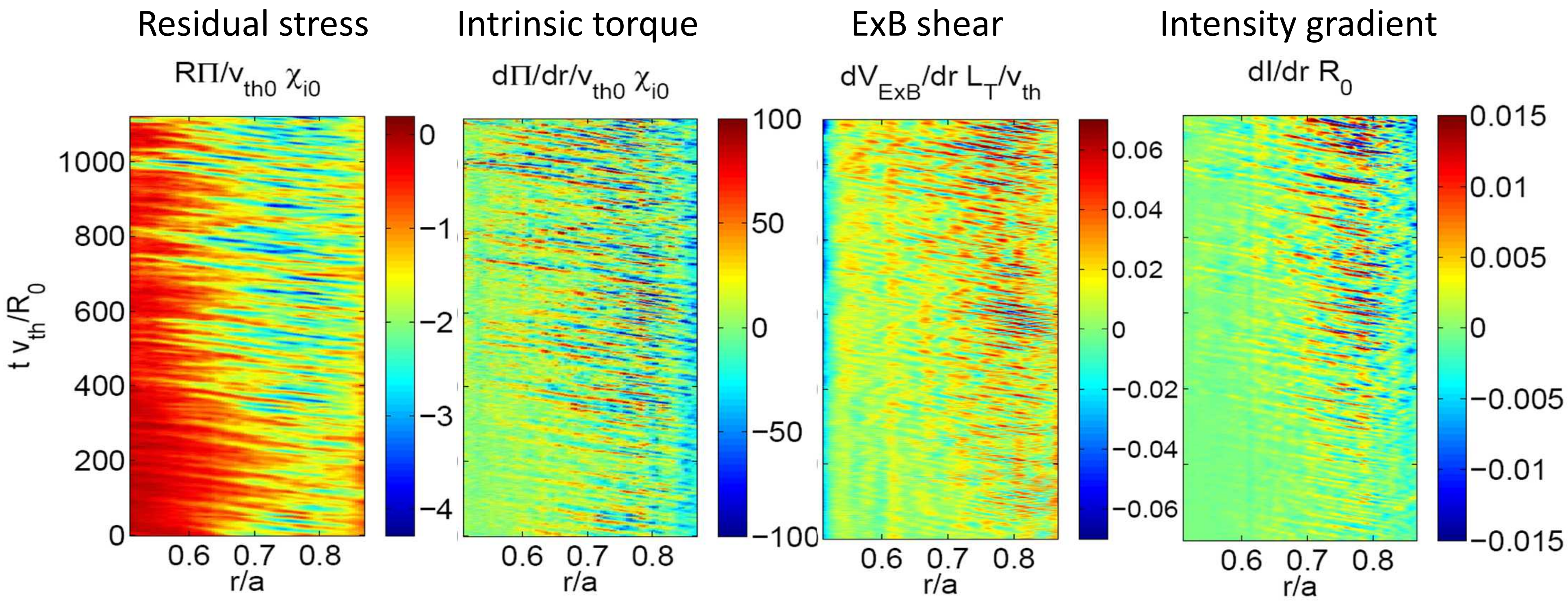
RF and q(r) Structure

- The effect of q-profile structure on intrinsic rotation
- The detailed dynamics of how RF and current drive (i.e. LHCD, ECH) affect intrinsic rotation. Is this via q(r)? Is it ν_* change?
- Recent EAST results (Shih, et.al.; PRL 2011) are an interesting challenge
- Relation to inversion phenomena

Dynamical Evolution

- The detailed spatio-temporal dynamics of intrinsic rotation profile build-up

Space-time evolution of intrinsic torque



- The turbulence arises near the outside boundary and propagates inward. [Ku, 2009]
- ExB shear and intensity gradient show the same inward propagation pattern.
- Residual stress and intrinsic torque evolution history correlated with that of intensity gradient.

Low Torque vs No Torque

- The critical torque-to-power ratio that likely delimits pinch vs. residual stress dominated momentum transport regimes

$\Rightarrow$ How Low is “Low” ?

Some Long Term Issues

- $\langle \tilde{v}_r \tilde{v}_\perp \rangle \Leftrightarrow$ intrinsic rotation connection
- EM fluctuation, $\langle \tilde{B}_r \tilde{B}_\theta \rangle$ role in rotation saturation – unexplored!
- Elucidate 'Boundary Condition' Issue: Degree of 'slippage'
  - SOL flows (USN vs LSN)
  - RMP
  - n_n deposition – SMBI

Insightful experiments are badly needed!

- Study intrinsic rotation in flat q discharges
- Elucidate physics of residual stress, pinch in electron channel dominated discharges
- Explore the poloidal ⇔ toroidal rotation synergy, especially in ITB