Parasitic Momentum Flux in the Tokamak Core

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Careful geometric analysis shows that energy transfer from the electrostatic potential to ion parallel flows breaks symmetry in the fully nonlinear toroidal momentum transport equation, causing countercurrent rotation peaking without applied torque.

APS-DPP 2017, Milwaukee
October 24, 2017

Outline

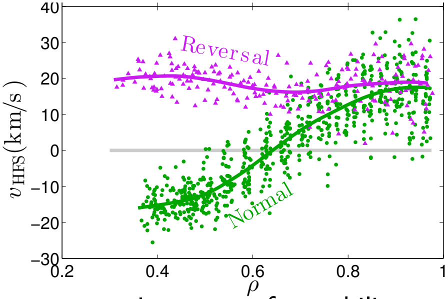
Background

- Experiment:
  - Intrinsic rotation and rotation reversals
- Theory:
  - Intrinsic rotation: Vanishing momentum flux
  - Symmetry and symmetry-breaking mechanisms

Rotation model

- Intuitive cartoon of simple, axisymmetric example
- Model equations and conservation properties
- Symmetry breaking
  - Fluxtube coordinates and v_E^x
  - Free-energy flow in phase space$\Rightarrow$momentum flux

Tokamak plasmas rotate spontaneously without applied torque.



⟸ TCV Ohmic shots
$I_p \approx$155, 195kA,
Stoltzfus-Dueck et al PoP '15

JET ICRH shots ⟹
$I_p \approx$1.5, 2.6MA,
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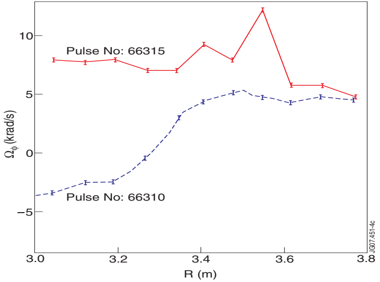

Important for stability against resistive wall modes at low torque (ITER).

Typical intrinsic rotation profiles have three regions:

- Edge: Co-rotating due to ion orbit shifts
- Mid-radius "gradient region": Countercurrent peaking or ∼flat
  - Gradient exhibits sudden 'reversals' at critical parameter values.
- Sawtoothing region inside $q = 1$: Flat or weak cocurrent peaking

In axisymmetric geometry, neoclassical momentum transport is negligible.

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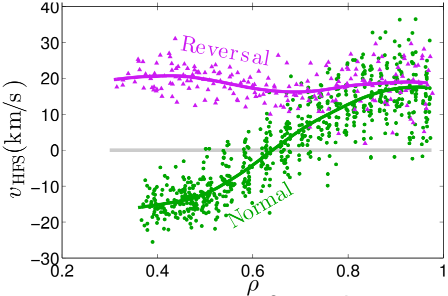

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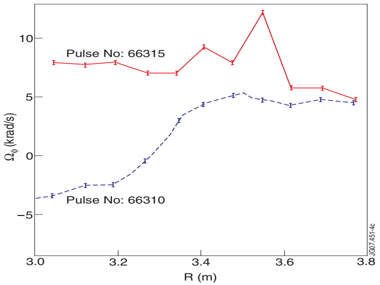

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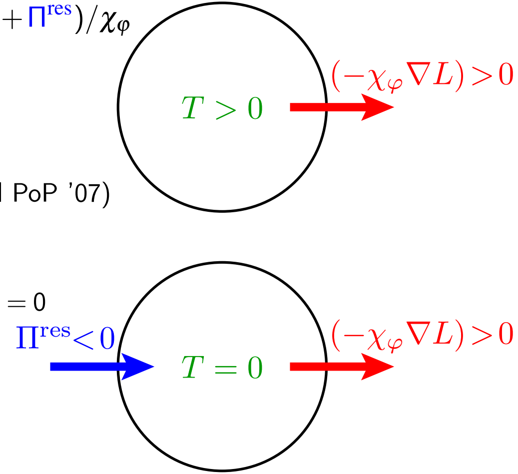
In axisymmetric geometry, neoclassical momentum transport is negligible.

Intrinsic rotation profiles result from vanishing momentum flux.

Axisymmetric steady state with no torque⇒zero momentum outflux:

$$0 = T = \Pi = -\chi_\varphi \nabla L + v_{\text{pinch}} L + \Pi^{\text{res}} \Longrightarrow \nabla L = (v_{\text{pinch}} L + \Pi^{\text{res}})/\chi_\varphi$$



Toroidal momentum gradient ∇L is set by balancing

- Viscous flux $(-\chi_\varphi \nabla L)$ (saturation) against both
- Momentum pinch $(v_{\text{pinch}} L)$ due to
  - 'Turbulent equipartition' due to ∇B (Hahm et al PoP '07)
  - Coriolis force (Peeters et al PoP '09)
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  - Only explanation for peaked profiles that cross $L = 0$

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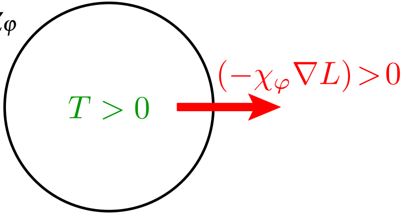

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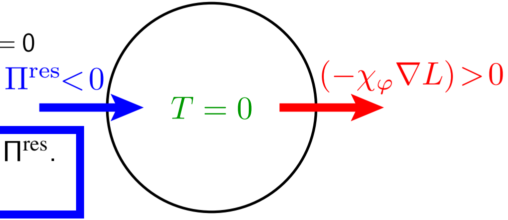

In this talk, I identify and explore one contribution to Π^{res}.
Other contribitions may be as significant or more.

Many mechanisms can drive residual stress, including:

- Background $\boldsymbol{E} \times \boldsymbol{B}$ shear (Dominguez and Staebler Phys. Fluids B '93)
- Up-down asymmetric magnetic geometry (Camenen et al PRL '09)
- Quasilinear: assume phase between $\tilde{v}_r$ and $\tilde{v}_{\|}$ from a linear eigenmode
  - Drift waves (Coppi NF '02)
  - With intensity gradient (Gürcan PoP '10)
- Radially global effects via gyrokinetic simulation
  - GTS: magnetic & $\boldsymbol{E} \times \boldsymbol{B}$ shear, intensity gradients, neoclassical effects (Wang et al PRL '09, '11)
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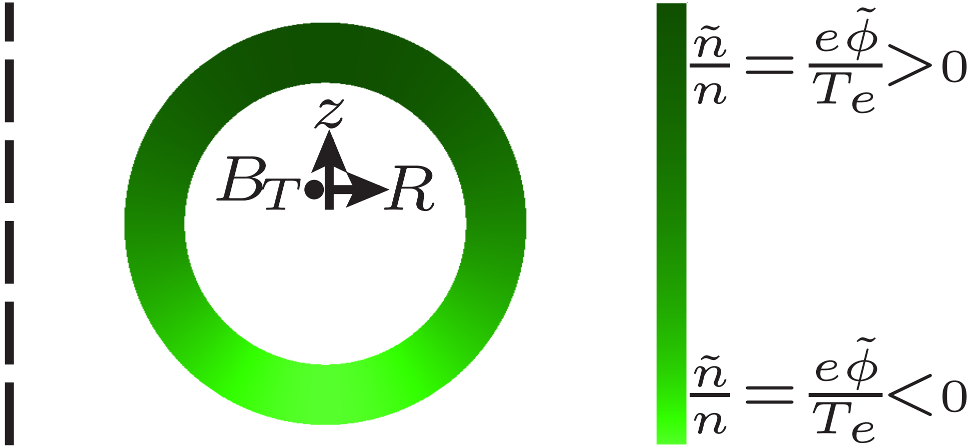
Free-energy flow in phase space + higher-order part of $\boldsymbol{E} \times \boldsymbol{B}$ drift $\Rightarrow$ residual stress

Dual role for slowly varying $\partial_\theta \phi$ causes countercurrent peaking.



Example: axisymmetric, $m = 1$, low-frequency density fluctuations.

I. $E_\| v_\| = -b_p v_\| (\partial_\theta \phi)/r$ transfers energy to ion parallel flows.

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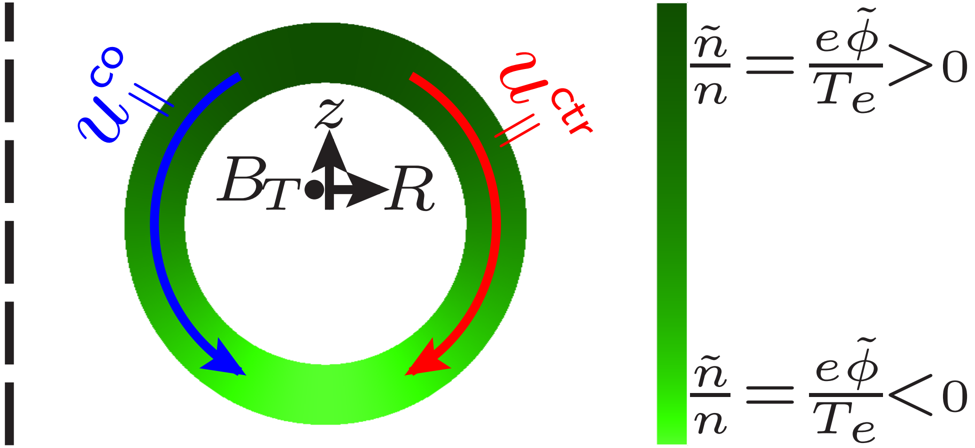

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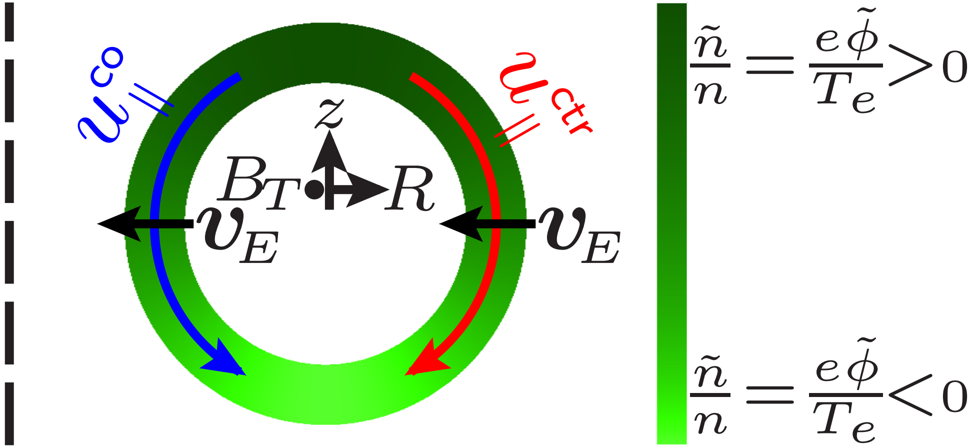

II. Weak radial $\boldsymbol{E} \times \boldsymbol{B}$ drift $v_E^x \sim -(cb_T/Br)\partial_\theta \phi$ advects ions, transporting momentum. Momentum flux∝energy transfer because $E_\parallel / b_p = -\partial_\theta \phi = E_\perp / b_T$.

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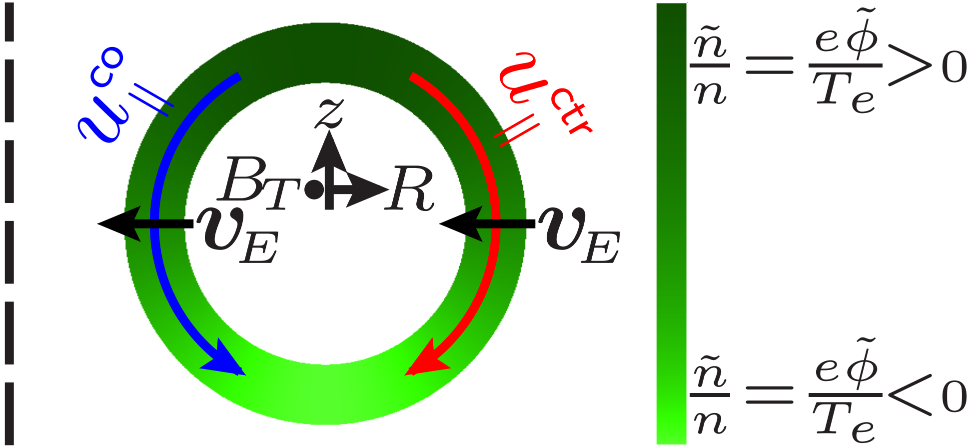

Slow poloidal potential variation in $\partial_\theta \phi \sim k_\parallel \phi / b_p$ neglected by fluxtube orderings, but breaks symmetry because $\hat{b}$ neither parallel nor perp to $\hat{\varphi}$.

Model: energy- and momentum-conserving gyrokinetics

Full-F gyrokinetic equation conserves energy and toroidal angular momentum.
After exact cancellations, toroidal angular momentum evolves as

$$\partial_t \underbrace{\left\langle F_s m_s v_\parallel b_\varphi \right\rangle}_{\parallel \text{ tor mom}} - \partial_t \underbrace{\left\langle \boldsymbol{P} \cdot \nabla A_\varphi \right\rangle / c}_{\boldsymbol{E}\times\boldsymbol{B} \text{ tor mom}} = -\partial_V \underbrace{\left\langle F_s m_s v_\parallel b_\varphi \dot{\boldsymbol{R}} \cdot \nabla V \right\rangle}_{\text{flux of } \parallel \text{ tor mom and} \ldots} - \underbrace{\left\langle F_s \partial_\varphi H \right\rangle}_{\text{of } \boldsymbol{E}\times\boldsymbol{B} \text{ tor mom}} \quad .$$

To evaluate fluxes, simplify to delta-f system using small-amplitude and fluxtube approximations:

$$\partial_t f_s + \frac{c}{B_0}\{J_0\phi, h_s\} + v_\parallel \nabla_\parallel h_s - \frac{\mu \nabla_\parallel B}{m_s} \partial_{v_\parallel} h_s - \frac{m_s v_\parallel^2 + \mu B}{2Ze} \mathscr{K}(h_s) = F'_{sM} \frac{c}{B_0} \partial_y J_0 \phi,$$

$$h_s \doteq f_s + (F_{sM}/T_{s0}) Ze J_0 \phi, \qquad \sum_s \int \mathrm{d}W\, Ze J_0 f_s = \sum_s n_{s0} Z^2 e^2 \frac{1-\Gamma_{0s}}{T_{s0}} \phi,$$

- Conserves a free energy, essential for momentum result.
- In fluxtube limit, satisfies symmetry $(x, y, s, v_\parallel, \mu) \to (-x, y, -s, -v_\parallel, \mu)$.

Symmetry restricts contributions to residual stress.

In the simplest radially local fluxtube limit with

- up-down symmetric magnetic geometry,
- no background rotation or rotation shear, and
- no background $\boldsymbol{E} \times \boldsymbol{B}$ shear,

the delta-f gyrokinetic equations satisfy a symmetry $[y \propto (\zeta - q\theta), s \propto \theta]$:

If $f(x, y, s, v_\parallel, \mu, t),\ \phi(x, y, s, t)$ is a solution
so is $-f(-x, y, -s, -v_\parallel, \mu, t),\ -\phi(-x, y, -s, t)$

with opposite sign of the dominant toroidal momentum flux.
(Peeters and Angioni PoP '05, Parra et al PoP '11)

This implies: toroidal momentum flux should vanish for terms that flip sign, but does *not* imply that invariant terms *must* drive momentum flux.

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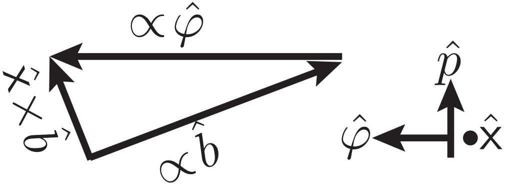
What drives symmetry-breaking momentum flux, in the absence of rotation and rotation shear?

The radial $\boldsymbol{E} \times \boldsymbol{B}$ drift with true $\nabla_\perp \phi$ breaks the symmetry.

Define convenient directions

$$\hat{x} \doteq \frac{\nabla x}{|\nabla x|}, \quad \hat{p} \doteq \hat{\varphi} \times \hat{x}$$



and decompose $\hat{b} = b_T \hat{\varphi} + b_p \hat{p}$.
Use $\hat{x} \times \hat{b} = (\hat{\varphi} - b_T \hat{b})/b_p$ to evaluate

$$\boldsymbol{v}_E \cdot \hat{x} = \frac{c}{B} \hat{b} \times \nabla (J_0 \phi) \cdot \hat{x} = \frac{c}{B} \hat{x} \times \hat{b} \cdot \nabla (J_0 \phi) = \frac{c}{b_p B} (\hat{\varphi} - b_T \hat{b}) \cdot \nabla (J_0 \phi),$$

Symmetry prevents first term $\propto \hat{\varphi} \cdot \nabla J_0 \phi \propto \partial_y J_0 \phi$ from driving residual stress.
Second term cancels the parallel gradient included in $\hat{\varphi} \cdot \nabla J_0 \phi \neq \hat{x} \times \hat{b} \cdot \nabla J_0 \phi$:

- Nominally smaller than the first term, by $k_\parallel / k_\perp b_p$, but
- Contributes a symmetry-breaking term to momentum flux $[f_s m_s v_\parallel b_\varphi v_E^x]$:*

$$\Pi^{(2)}_{\varphi i} = \frac{1}{V_{\mathrm{pl}}} \frac{-2\pi c}{B^\theta V'} \int \mathrm{d}\Lambda \, f_i m_i v_\parallel b_\varphi^2 \nabla_\parallel J_0 \phi$$

*T. Sung et al, Phys. Plasmas **20**, 042506 (2013).

Free-energy balance causes $\partial_\theta \phi$ to break symmetry.

Turbulent Free-energy Balance:

- Heat flux drives pressure fluctuations
- Conservative transfer to ***E*** and parallel flows
- Viscous and resistive damping of parallel flow

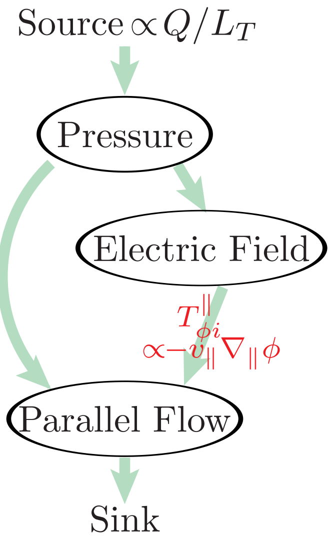
> Energy flows from source to sink
> $\Rightarrow T^{\parallel}_{\phi i} > 0 \Rightarrow$ Co-current outflux

Estimate of rotation gradient:

$$a\partial_r v_\varphi \sim 5 \frac{f_L}{\mathrm{Pr}} \frac{a^3}{L_{Ti}^2 r} \frac{T_{i0}(\mathrm{keV})}{Z I_p(\mathrm{MA})} \left[\sum_s \frac{Q_s/L_{Ts}}{Q_i/L_{Ti}} \right] \mathrm{km/s},$$

roughly agrees with experimental observations.

Only acts when $\omega \lesssim k_\parallel v_{ti}$, otherwise ion inertia blocks parallel acceleration.



Summary

A geometrically higher-order portion of the $\boldsymbol{E} \times \boldsymbol{B}$ drift causes a nondiffusive momentum flux:

- results from symmetry-breaking by excitation of ion parallel flows,
  - does not require $\langle v_\varphi \rangle$ or $\nabla \langle v_\varphi \rangle \Rightarrow$residual stress
  - a fully nonlinear mechanism, not quasilinear
- causes counter-current rotation peaking in the core,
- may drive experimentally relevant rotation gradient around

$$a\partial_r v_\varphi \sim 5 \frac{f_L}{\mathrm{Pr}} \frac{a^3}{L_{Ti}^2 r} \frac{T_{i0}(\mathrm{keV})}{Z I_p(\mathrm{MA})} \left[\sum_s \frac{Q_s / L_{Ts}}{Q_i / L_{Ti}} \right] \mathrm{km/s},$$

- acts only when turbulence is at low enough frequencies to excite ion parallel flows, allowing both hollow and flat rotation profiles

Ongoing: Will Hornsby is investigating numerically with the GKW code.
I am interested in further experimental and numerical comparisons.

Gyrokinetic: Stoltzfus-Dueck and Scott, NF **57**, 086036 (2017).
Gyrofluid: Stoltzfus-Dueck, PoP **24**, 030702 (2017).