Critical Issues in Intrinsic Rotation Bifurcations:

What can we learn from reversals?

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Thought for the Day – from “M.A.S.H.”

- Question:
  - “How did a pervert like this ever get to be an officer in the United States Army?” – Hot Lips
- Answer:
  - “He was drafted” - Chaplain

Outline

- Some important things we “Don’t Understand” about intrinsic rotation and toroidal momentum transport

- Reversals (primarily OH) : a theorist’s perspective

- Routes to an explanation
  - the residual stress : a wave momentum approach
  - reversal mechanisms and their signatures

- OH reversals in a broader context
  - LOC → SOC → IOC/RI
    LOC ↘ pITB
  - Implications for reversals and possible tests

Outline (cont’d)

- Using reversals to probe the boundary

- Conclusions and DISCUSSION

Some Important Issues We Don't Understand

- Reversals
  - OH: TCV, C-Mod
    - appears linked to LOC → SOC cross-over / CTEM-ITG transition
    - exhibits many features of transport bifurcation without enhanced energy confinement
  - RF reversals (and q(r) structure?): C-Mod, DIII-D…
    - LHCD, ECH can reverse core intrinsic rotation
    - q(r), ν_*, mode propagation direction change?
    - relation to OH inversions?

Some Important Issues We Don't Understand (cont'd)

- Effective boundary condition
  - The interplay of turbulence and wave scattering with neoclassical effects and orbit loss in determining the boundary condition for intrinsic rotation → 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

- Saturation of intrinsic rotation
  - turbulence quench
  - EM effects → stress competition

- All meet at topic of reversals

OH Reversals: Overview

- OH Reversals
  - Selected observations, from a theorist's perspective
  - Thanks to John Rice and C-Mod !

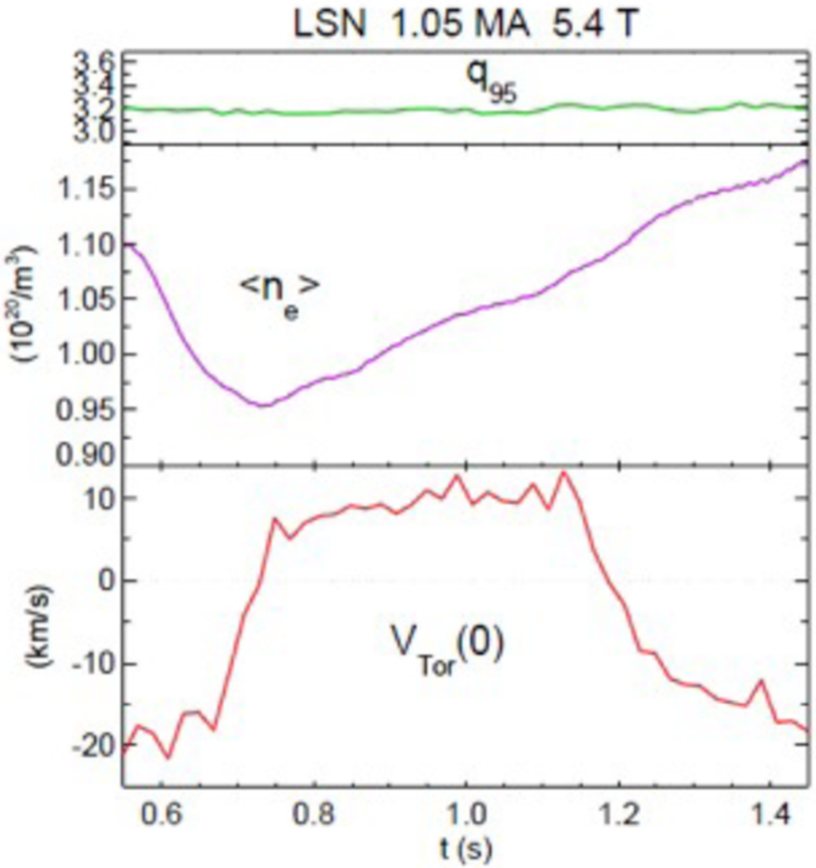


Figure 3: Time histories of q_{95} (top frame), average electron density (middle frame) and central toroidal rotation velocity (bottom frame) for a LSN 1.05 MA 5.4 T discharge with two reversals.

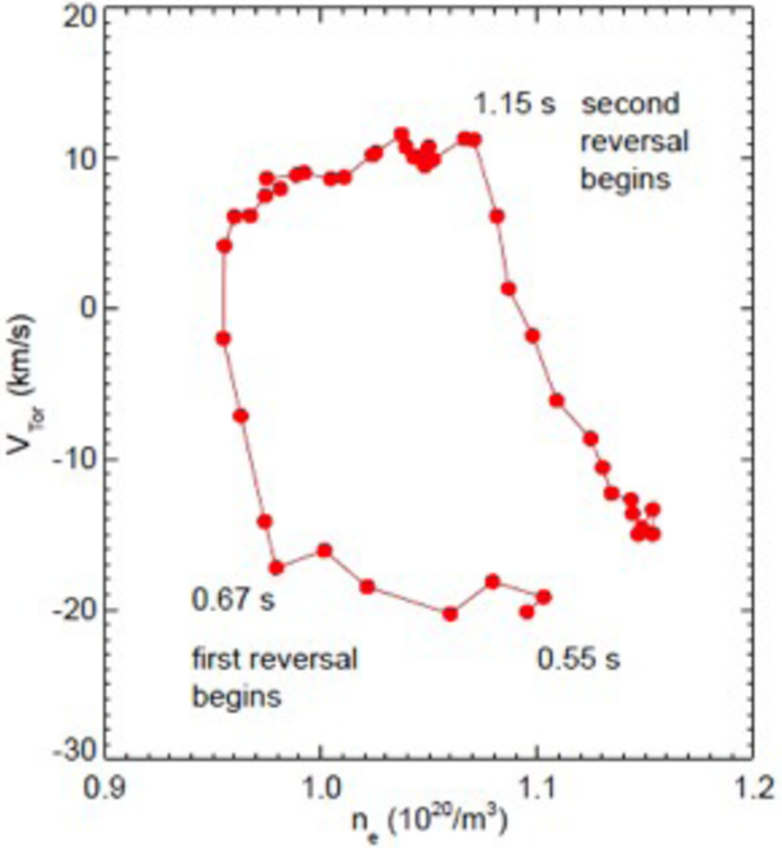
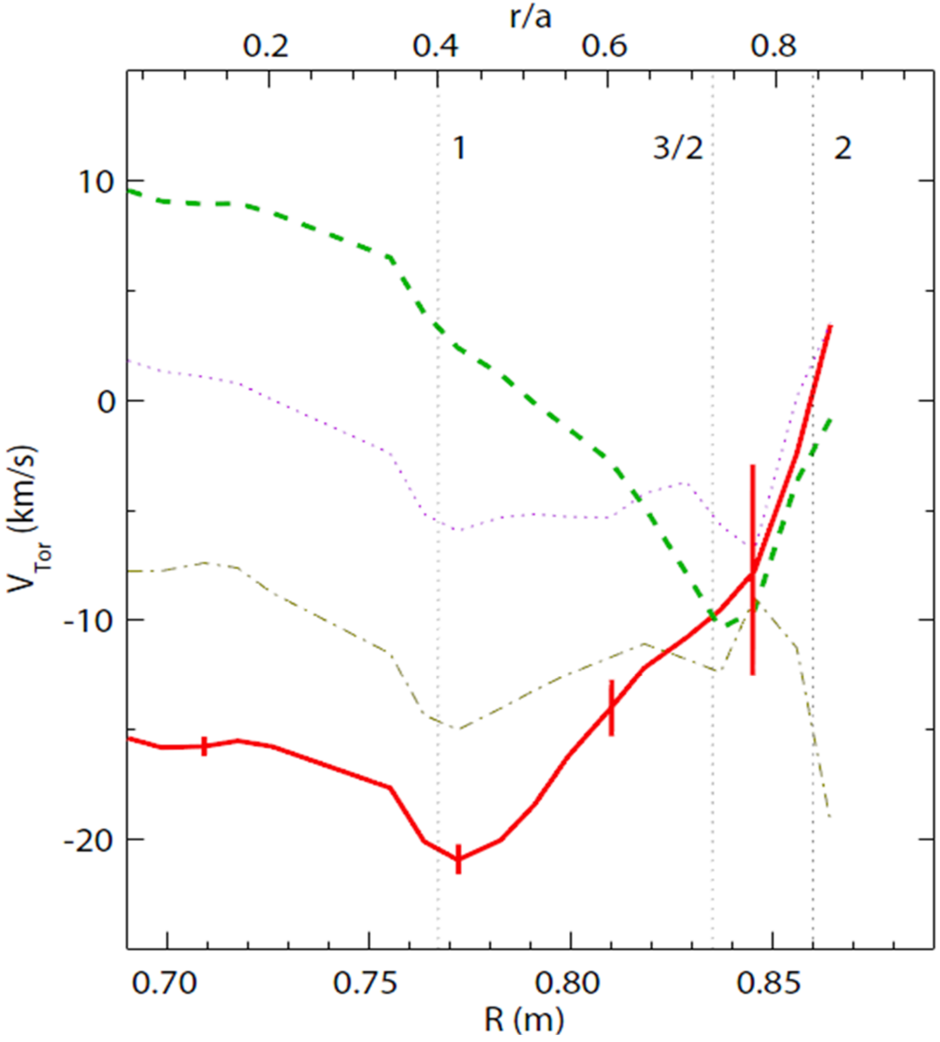


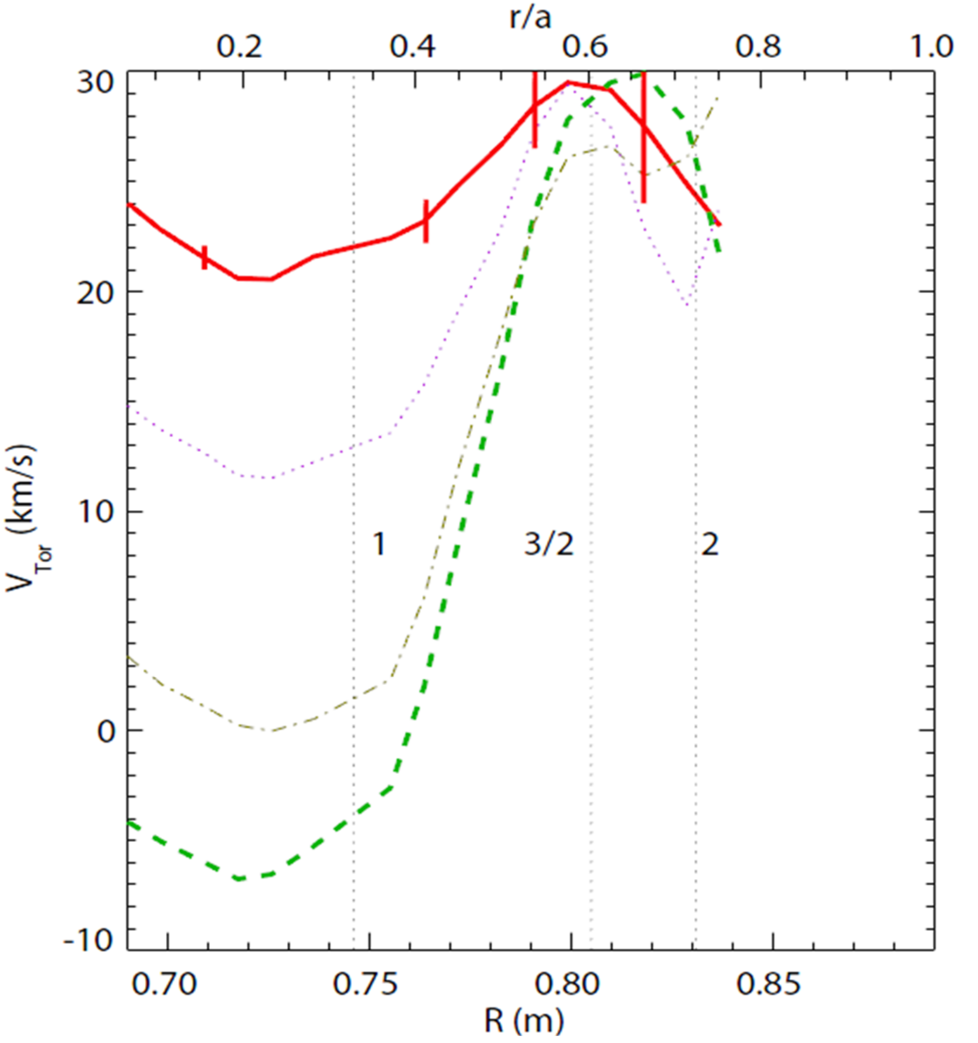
Figure 4: The discharge trajectory in the n_e-V_{Tor} plane for the plasma of Fig.3. Points are separated by 20 ms.

Reversal Occurs Inside of q=3/2 Surface, No Change Outside

$q_{95} = 3.23$

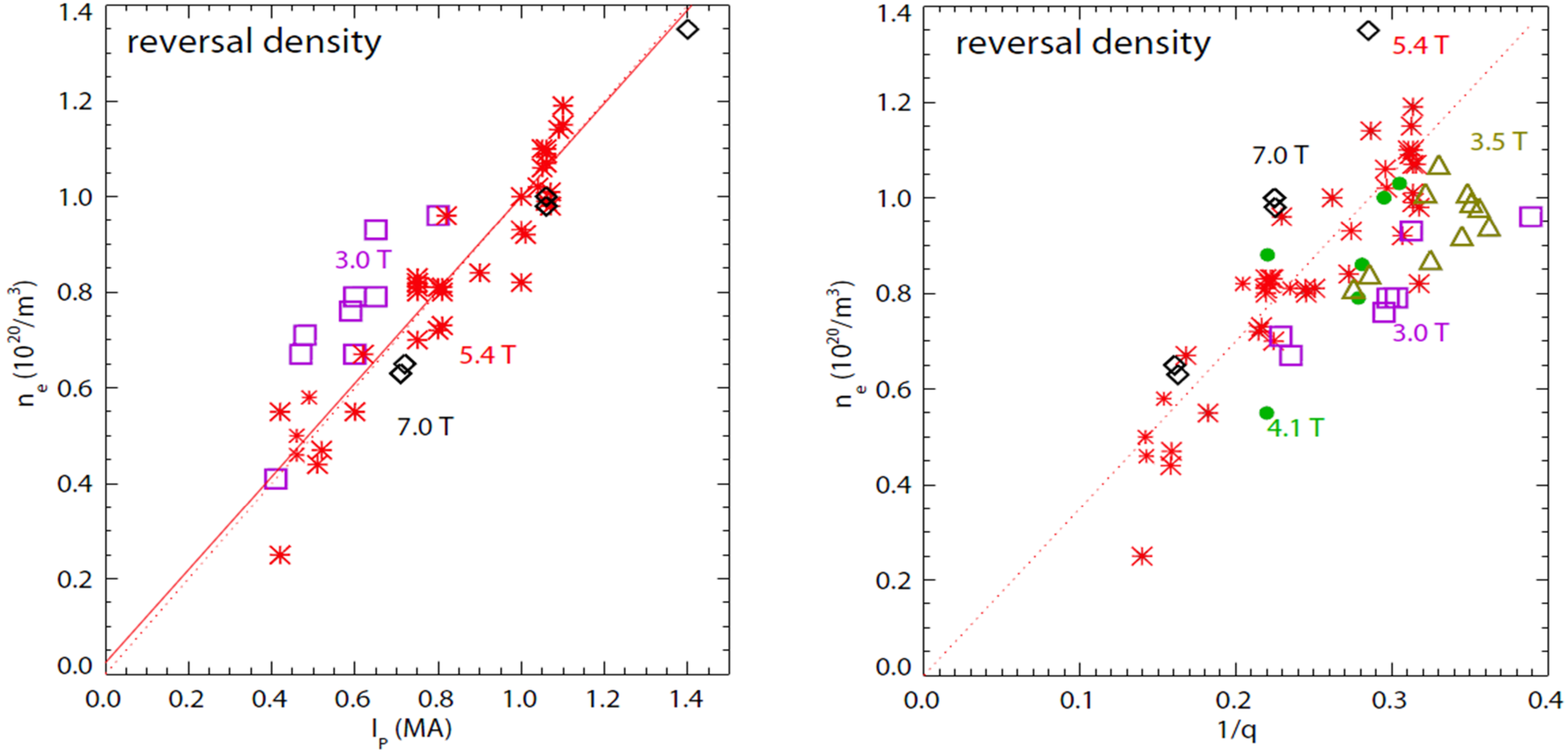


$q_{95} = 4.67$

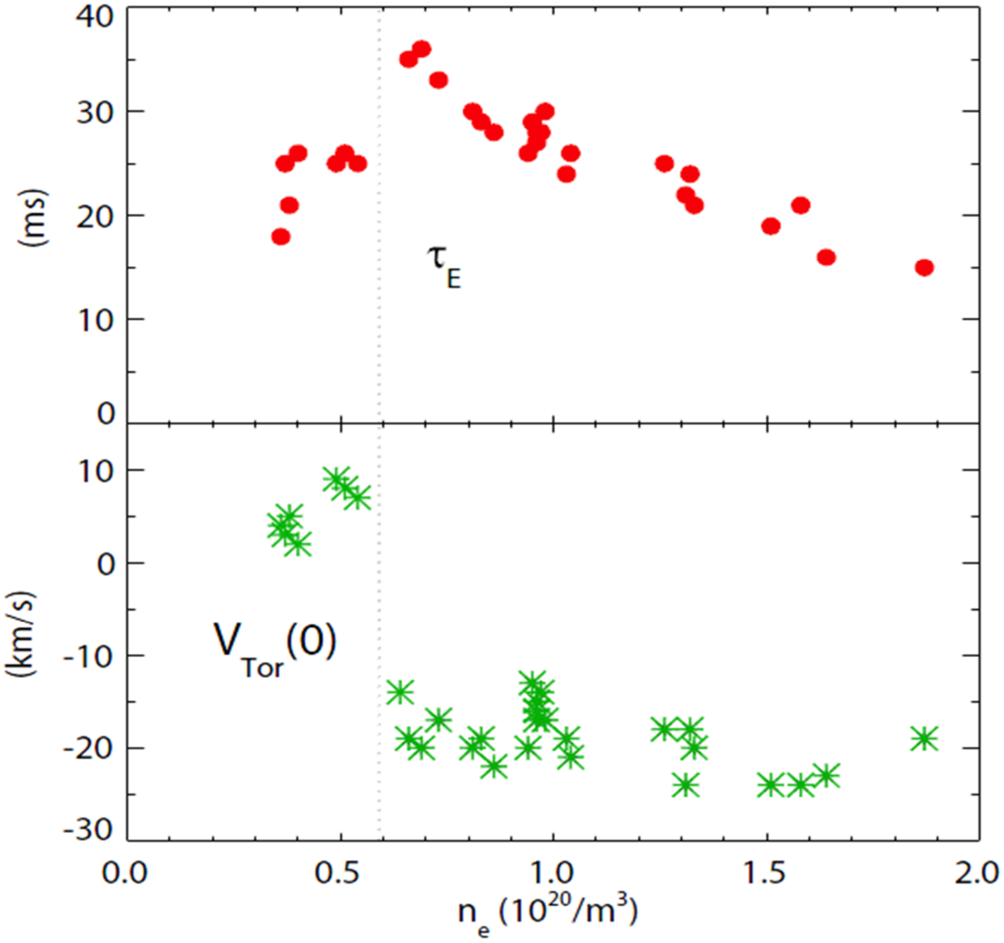


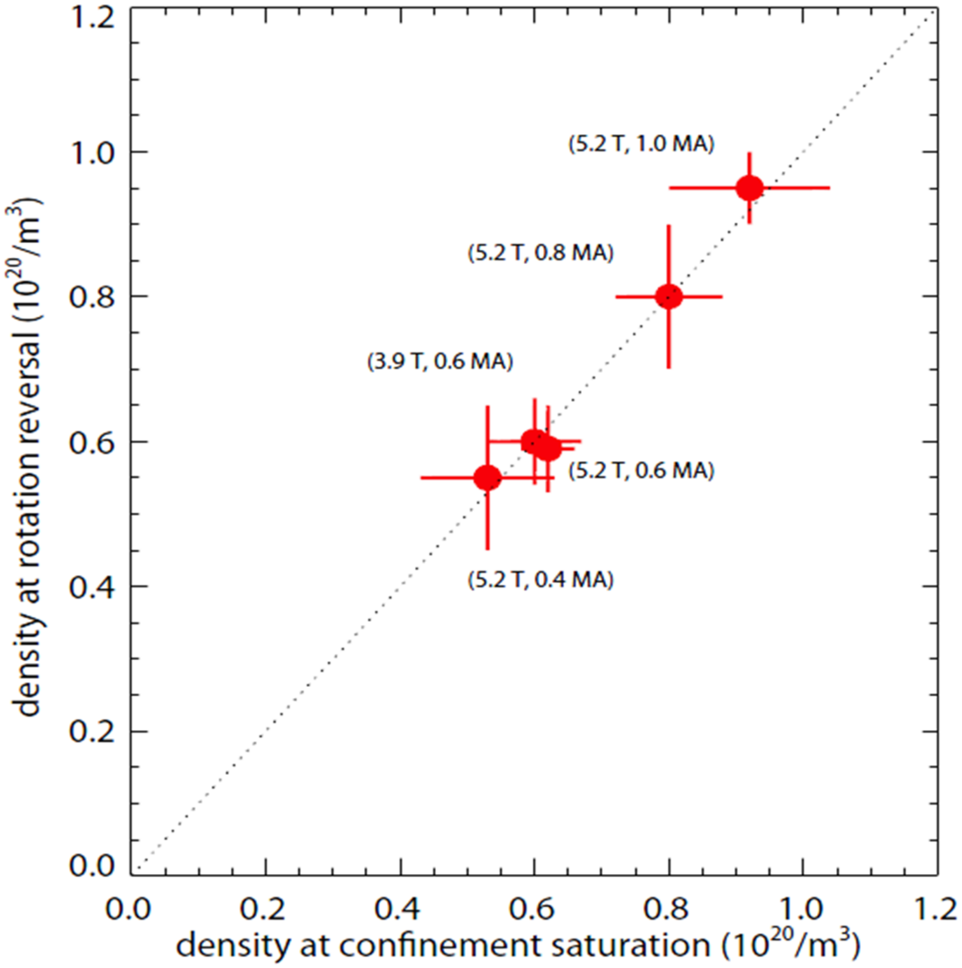
Scaling of Reversal Density with Plasma Current and Magnetic Field

best fit relation: $nB^{0.6}/I_p = 2.8$

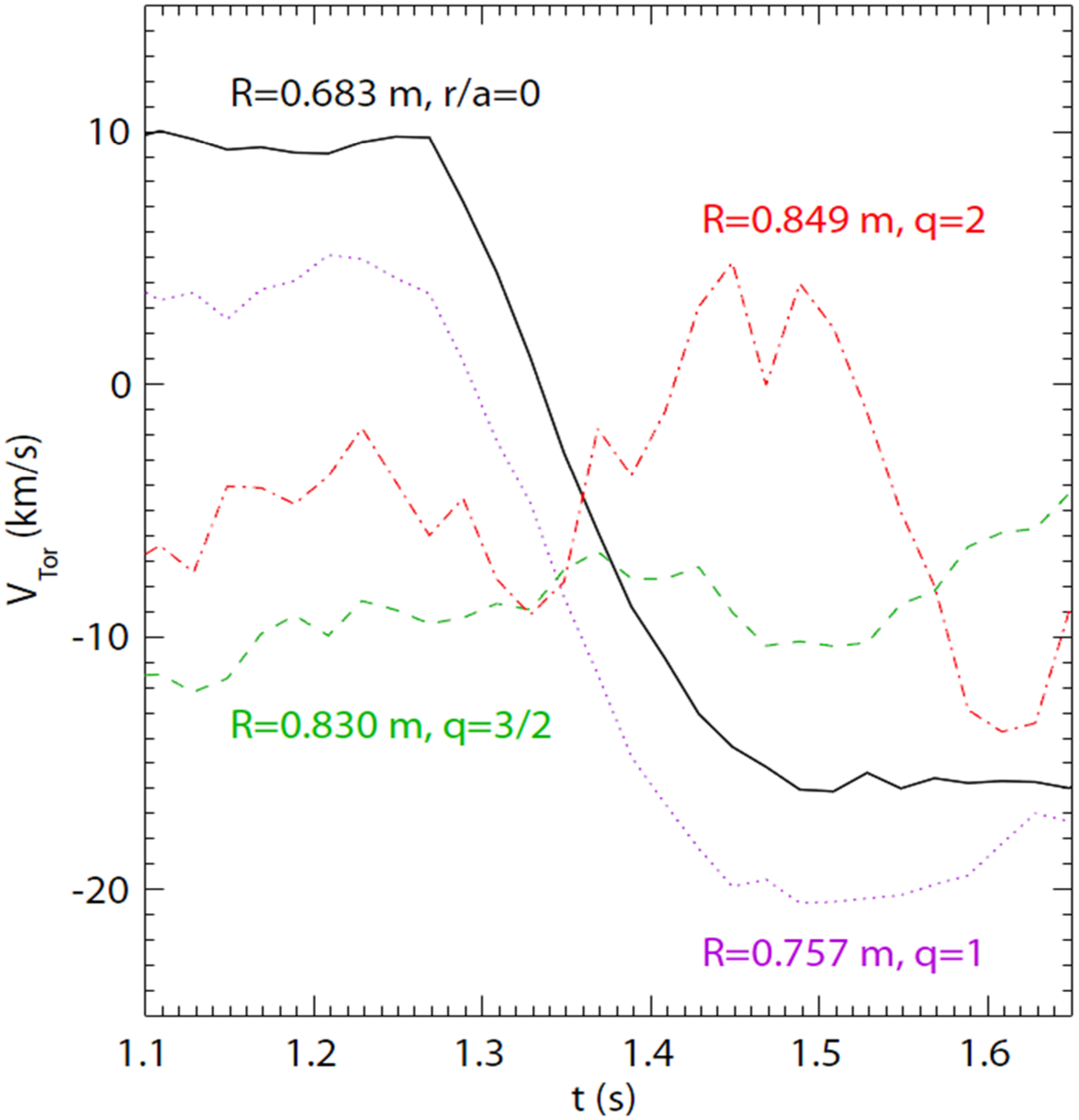


Rotation Reversal and Change from LOC to SOC Correlated





Transient ‘Spike’ in Edge Rotation in Direction Opposite Original Rotation



Does this play a role in momentum conservation?

Some Comments

- Reversal is novel type of momentum transport bifurcation
- Note clear indication of:
  - threshold } classic 'symptoms'
  - hysteresis }
  - but no confinement enhancement, as in L→H (!?)
- Suggestion of
  - close relation of reversal and OH "regime change"
    i.e. LOC → SOC
  - L_n^{-1} clamps at reversal

  → change in turbulence?, place in bigger picture (IOC?)
- Edge plays a role
  - transient spike observed
  - TCV: some differences between limited, diverted

III. Addressing the Phenomenology

i. Focus: Off-Diagonal Momentum Flux in Electrostatic Drift Wave Turbulence - Non-Diffusive stress

ii. Beyond "Diffusion and Convection"

- 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!

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

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

Π^{resid} is critical !

→ residual stress/flux possible and distinct from pinch

→ residual stress acts with boundary condition to generate intrinsic rotation

→ need either $\Pi^{resid}\big|_{bndry} \neq 0$ or $V\langle v_\phi\rangle\big|_{bndry} \neq 0$

iii. Key Theoretical Issues – Π^{resid}

- flux of wave momentum?
- origins of symmetry breaking?
- boundary conditions?

a) Wave Momentum (P.D. et al. 2008)

→ Momentum Budget: $\begin{cases} \text{Resonant + Non-Resonant} \\ \text{Particles + Fields} \end{cases}$

"Non-Resonant" = "Waves"

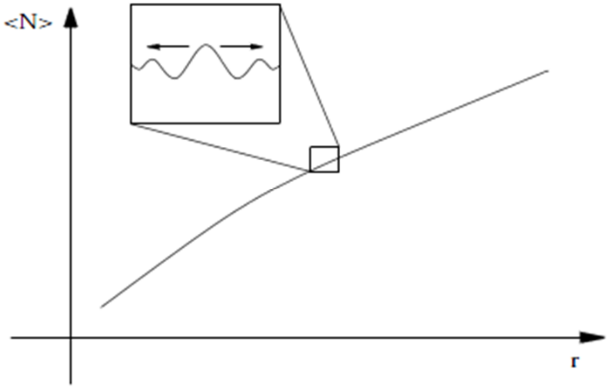
→ Wave momentum flux crucial for fluid-like DWT

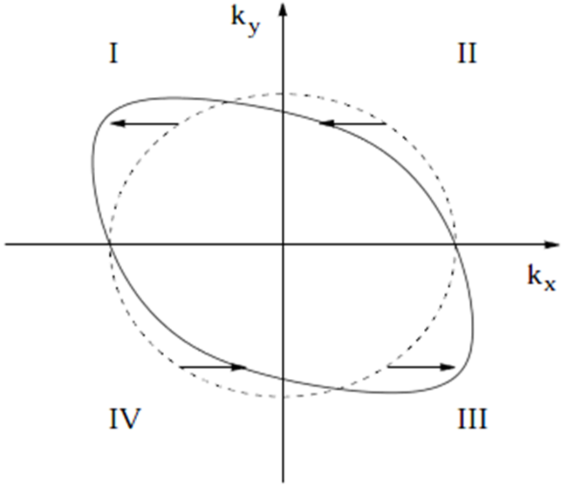
a) Calculating $\Pi_{r,\|}^{wave}$

- Necessary to compute radial flux of parallel mom. ↔ $\mathbf{\Pi}_{\|}^{W} \equiv \sum_k v_{grx} k_{\|} N_k$
- In simplest scenario, finite momentum flux requires:
  - radial wave flux ↔ $\langle v_{grx} \rangle \neq 0$
  - symmetry breaking ↔ $\langle k_{\|} \rangle \neq 0$

Wave Momentum Flux

- Proceed via Chapman-Enskog expansion (radiation hydrodynamics in large optical depth limit) in Wave Kinetics
  - in short mean free path limit, expansion parameter given by: $\tau_{c,\mathbf{k}}\left(v_{gr}/L_I\right), \tau_{c,\mathbf{k}}\left\langle v_E\right\rangle' \sim \varepsilon$
- Lowest order: $C_w(N_k)=0$ => saturated spectrum due to wave interactions
- Next order, yields: $\delta N_{\mathbf{k}} = -\tau_{c,\mathbf{k}} v_{gr}\frac{\partial\langle N_{\mathbf{k}}\rangle}{\partial r} + \tau_{c,\mathbf{k}} k_\theta \langle v_E\rangle' \frac{\partial\langle N_{\mathbf{k}}\rangle}{\partial k_r}$
- 1st term ~ $\tau_{c,\mathbf{k}}/\tau_{\ln N}$
- 2nd term ~ $\tau_{c,\mathbf{k}}\left\langle v_E\right\rangle'$





Wave Momentum Flux (cont'd)

- Wave momentum flux:

$$\Pi^{w}_{r,\|} = \int d\mathbf{k}\, k_{\|} \left\{ \langle v_{0r} \rangle \langle N_{\mathbf{k}} \rangle - \tau_{c,\mathbf{k}} v_{gr}^{2} \frac{\partial \langle N_{\mathbf{k}} \rangle}{\partial r} + \tau_{c,\mathbf{k}} v_{gr} k_{\theta} \langle v_E \rangle' \frac{\partial \langle N_{\mathbf{k}} \rangle}{\partial k_r} \right\}$$

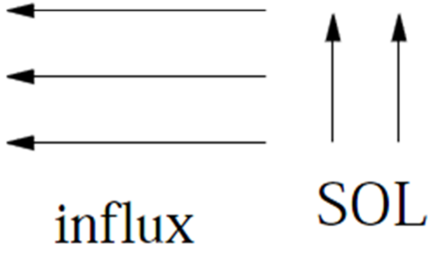
- Second term ↔ radiative diffusion of quanta
  - requires gradient in turbulence intensity profile (universally increasing)
  - related to momentum flux from edge?

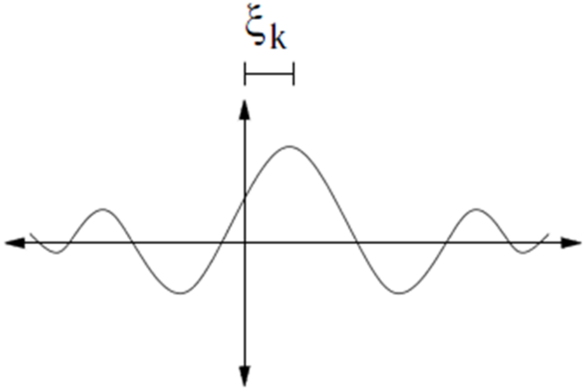
- Third term ↔ refraction induced wave population imbalance
  - crucial for regimes of strong shear flow
    →most active near edge, or ITB
    →sensitive to L→H mode transition, local steepening in ∇P
  - mode dependence, via v^* dependence v_{gr}

Wave Momentum Flux (cont’d)

- Mechanisms of symmetry breaking: → Moments of W.K.E.

1. Influx: radial inflow of wave momentum
   - potentially critical in edge region
   - captures possible influx of momentum from SOL
2. Wind-up: mode sheared by poloidal velocity → ala’ spiral arm
   - requires magnetic shear, i.e. $\partial k_{\|} / \partial k_r \neq 0$
   - critical in barrier regions, either pedestal or ITB, but not limited to these
3. Growth asymmetry
   - enters due to parallel velocity shear - unlikely
4. Refraction due to GAMs → refractive force
   - largely unexplored
   - likely to be most important near edge





- Reversals and drift wave turbulence
  - intrinsic torque $\tau_{\text{intr}} = -\partial_r \Pi^{resid}$
  - reversal $\leftrightarrow$ τ_{intr} sign flip !
  - how flip τ_{intr}? $\rightarrow$ flip sign V_{gr} !

    i.e. $V_{\text{gr}} \sim V_*$ so natural to expect τ_{intr} flips when V_* direction flips ! (P.D. 2008)

- Natural hypothesis that reversals occur when turbulence evolves from CTEM to ITG (TCV suggested reversal coincides with linear stability change)

- Change in sign $\langle k_{||} \rangle$ is another possibility

- Further
  - need τ_{intr} to flip in sufficiently broad region → extent of ITG excitation highly relevant → n_{crit} ?!
  - origin of hysteresis:
    - co-existence of and competition between ITG and CTEM!
    - turbulence spreading (?!)

      i.e. penetration of ITG → CTEM ≠ CTEM → ITG
    - obvious parallel with L → H and H → L

      i.e. penetration of H into L ≠ penetration of L into H

      (L-mode transport) (H-mode/neo transport)
    - interesting simulation study (somebody, please …!)

a) Electromagnetics and Saturation

- Resonant component of turbulent momentum flux is proportional to $\left|\delta E_{||}\right|^2$
    - inclusion of inductive component allows for reduction/enhancement of $\delta E_{||}$
- For large aspect ratio, a quasilinear calculation yields resonant component (McDevitt, P.D., PoP2009)

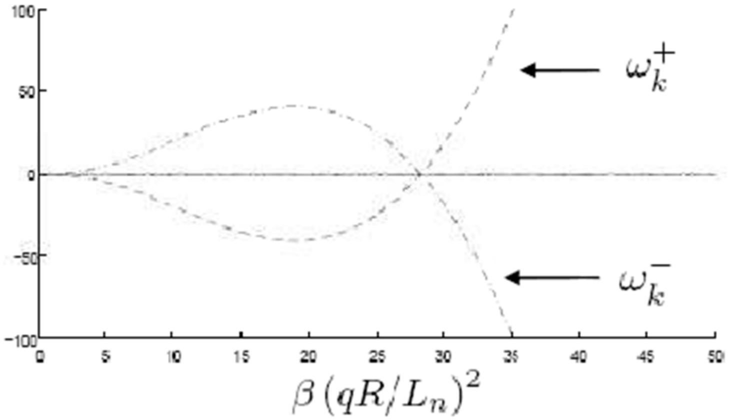
$$\Pi_{|}^{\mathrm{tot}} = \sum_k \frac{\Pi_{||k}^{ES}}{\left(1+\mathrm{Re}\chi_k^{AA}\right)^2}$$

$\mathrm{Re}\chi_k^{AA} \sim \beta\left(qR/L_n\right)^2 \rightarrow$ either high β or steep density gradients lead to significant EM impact

- For drift waves: $\mathrm{Re}\chi_k^{AA} > 0$
    - novel means of quenching $\Pi_{||}^{ES}$ for high β or steep density grad.
    - model asymmetry!
- For ITG: $\mathrm{Re}\chi_k^{AA} < 0$
    - slight enhancement of $\Pi_{||}^{ES}$ above level predicted by ES prediction
- Non-resonant component qualitatively similar, with important exception that only off-diagonal terms are modified to lowest order

a) Electromagnetics (cont'd)

- Alfven waves provide alternate channel for momentum transport aside from well studied limit of ES microturbulence – B.P. relevant
- Off-diagonal component of momentum flux requires finite $\delta E_\parallel$
- KSAWs provide natural candidate for transport of parallel momentum
  - dispersive corrections introduce a radial group velocity/finite $\delta E_\parallel$
  - mode conversion of TAEs at resonant surfaces provide robust generation mechanism



- Residual stress for each branch computed via a quasilinear calculation
  - imbalance in Elsasser populations required for finite levels of off-diagonal transport
  - symmetry breaking likely induced by asymmetry in energetic particle drive

iv) OH Reversals in a Broader Context…

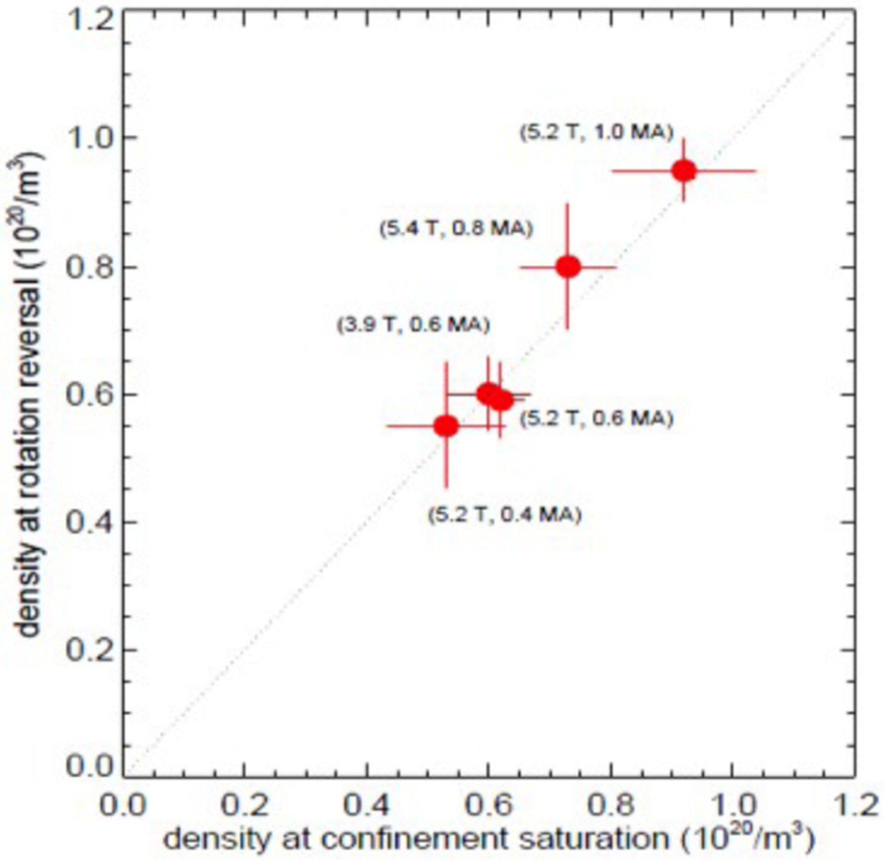
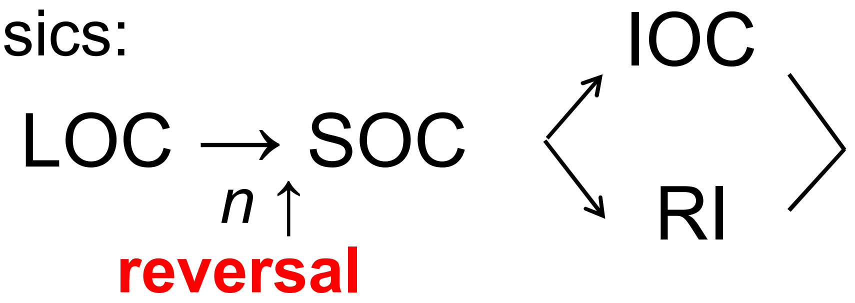


Figure 6: The rotation reversal density as a function of the transition density between linear and saturated energy confinement. Magnetic fields and plasma currents for each point are listed. The dotted line has a slope of unity.

- Data suggests excellent correlation between reversal and LOC → SOC
- Recall trends:

Classics:



LOC → SOC ↗ IOC ↘ RI

n ↑

reversal

Global, peaked n states with ~ LOC confinement

New: (W. Xiao, et al, 2010)

LOC → p-ITB → Locally, steepened n state with enhanced particle (and energy?) confinement

n ↑

(threshold)

- Key Q and A:

Q: Why does n(r) peak ?

A: ITG drives inward $V_{conv} = V_{TEP} + V_{thermo}$

⬇ “self-healing” feedback

Q: origin of confinement improvement?

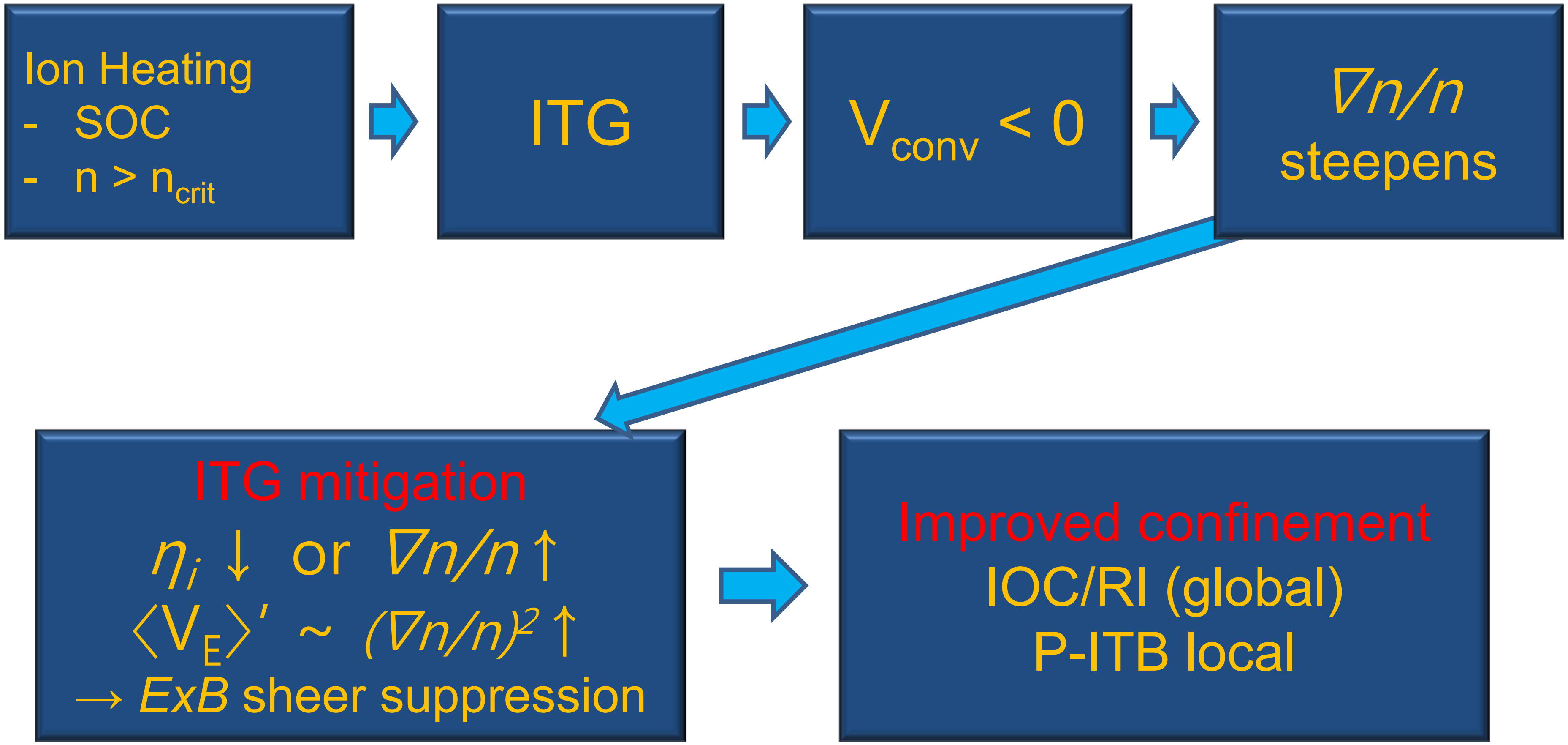
A: ITG quenched (B.C., M.N.R.- in B.C. epoch)

Q: What of p-ITB?

A: $n > n_{crit} \rightarrow$ ITG $\rightarrow V<0 \rightarrow \nabla n/n$ steepens

$\rightarrow \langle V_E \rangle' \rightarrow$ turbulence reduced

Unified Mechanism and Feedback Loop



Ion Heating
- SOC
- $n > n_{crit}$

ITG

$V_{conv} < 0$

$\nabla n/n$ steepens

ITG mitigation

$\eta_i \downarrow$ or $\nabla n/n \uparrow$

$\langle V_E \rangle' \sim (\nabla n/n)^2 \uparrow$

→ *ExB* sheer suppression

Improved confinement

IOC/RI (global)

P-ITB local

- Implication for reversals
  - is there a reversal in p-ITB ? (HL-2A)
  - if : LOC → SOC → IOC; (C-Mod?)
    (TEM → ITG → TEM)
    - 2 reversals ?
    - net hysteresis ?
    - back-reversal threshold ?
  - if : LOC → p-ITB → IOC; (HL-2A)
    - 2 reversals ?
    - back-reversal triggered by Z-injection
  - many interesting studies suggested…

Transient Spike – Probe of Edge B.C.

- True edge B.C. poorly understood

  “no slip” is intellectual crutch
- Spike
  - reflects how boundary disposes of excess momentum due reversal
  - possible probe of boundary dynamics
- So Study Spikes !
  - vary deviation from reversal criticality → scan rate, size, etc of reversal?
  - propagation to boundary, lifetime and dissipation of spike?
  - response of edge fluxes?
  - what knobs control spikes? (n_n, limiters vs divertors, …)

Questions for Discussion

- What common features do OH and RF-induced reversals exhibit? (spikes? hysteresis?)

- Might R.F.I.R. be related to:
  - mode population change?
  - q(r) structure change?

- Theoretical picture of co-existing, competing ITG and CTEM?

- Other means to flip τ_{intr}?