Physics 218C

Lecture 6: Confinement Transitions, especially Predator-Prey System and L→H Transition

a.) Predator-Prey ⟺ Drift Wave-Zonal Flow System.

Recall derived the coupled equations for shear flow and turbulence:

WKE for DW Action Density:

$$\frac{\partial \langle N \rangle}{\partial t} - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r} \langle N \rangle = \gamma \langle N \rangle - \frac{\Delta \omega_k}{N_0} \langle N \rangle^2$$

or equivalently, in terms energy,

$$\frac{\partial \langle \varepsilon \rangle}{\partial t} = -\int d^3k \left(\frac{\partial \omega_k}{\partial k_r} \right) \underbrace{D_k}_{O(\langle \tilde{V}^2 \rangle)} \frac{\partial \langle N \rangle}{\partial k_r}$$

$$+ \underbrace{\int d^3k \; \omega \langle C(N) \rangle}_{\gamma \langle \varepsilon \rangle - \frac{1}{\tau_{NL}} \langle \varepsilon \rangle^2} + S.T.$$

and, from Reynolds stress:

$$\partial_t |\phi_q|^2 = \underbrace{\Gamma_q \left[\frac{\partial \langle N \rangle}{\partial k_r} \right] |\phi_q|^2}_{\text{ZF growth}} - \underbrace{\gamma_d |\phi_q|^2}_{\text{ZF drag}}$$

$$\Gamma_q |\phi_q|^2 \simeq + \langle \tilde{V}'^2 \rangle$$

Energy conservation is straight forward!

Show this:

$$\partial_t \left[\int d^3k \, \omega \langle \mathcal{E} \rangle + \sum_q \frac{1}{2} \rho_d |\tilde{V}_q|^2 \right] = 0$$

$+ \gamma, \Delta\omega, \gamma_d$ terms.

akin to energetics in QLT.

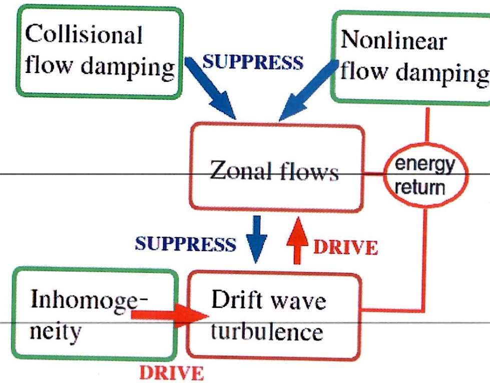
DW $\Leftrightarrow$ "particles"

ZF $\Leftrightarrow$ "waves" / "Fields"

$\Rightarrow$ $\boxed{\text{Coupled system for DW spectrum and ZF spectral Intensity.}}$

Feedback Loops I

- Closing the loop of shearing and Reynolds work



- Spectral 'Predator-Prey' equations

Prey → Drift waves, <*N*>

$$\frac{\partial}{\partial t}\langle N\rangle-\frac{\partial}{\partial k_r}D_k\frac{\partial}{\partial k_r}\langle N\rangle=\gamma_k\langle N\rangle-\frac{\Delta\omega_k}{N_0}\langle N\rangle^2$$

Predator → Zonal flow, $|\phi_q|^2$

$$\frac{\partial}{\partial t}|\phi_q|^2=\Gamma_q\left[\frac{\partial\langle N\rangle}{\partial k_r}\right]|\phi_q|^2-\gamma_d|\phi_q|^2-\gamma_{NL}[|\phi_q|^2]|\phi_q|^2$$

→ Some FAQ's

- What of Geometry ?

What sets $\underline{J}_{pol}$?

- FLR → $\rho_s^2 \nabla_\perp^2 \phi^2$

or ↓ ↓ torus

- Drifts + Particle Trapping

Length scale:

$$\delta r \sim V_D \tau_b$$

V_D → drift velocity

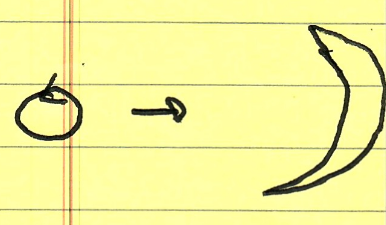
τ_b → bounce time

$$\sim \frac{\rho_i v_{Ti}}{R} \frac{Rq}{v_{Ti}\sqrt{\epsilon}}$$

$$\sim \sqrt{\epsilon}\, \rho_{\theta i}$$

$\rho_{\theta i}$ → poloidal gyro-radius

i.e. $\rho_{\theta i}$ sets polarization screening length



$\rho_{\theta i} \gg \rho_i$

→ enhanced screening length and inertia

For full analysis, see Rosenbluth and Hinton, 98.

→ What seeds / triggers Z.F. ?

Answer: Nonlinear noise!

i.e. Can write:

$$\frac{\partial}{\partial t}(\nabla_\perp^2\phi)_q \sim -(\tilde{V}\cdot\nabla\,\nabla^2\tilde{\phi})_q$$

beats of DW at $\underline{k}$

$\tilde{V}_{\underline{k}}\cdot\nabla(\nabla^2\phi)_{\underline{q}-\underline{k}}$ etc.

then treat as Langevin equation, with τ_{c_q} set by coherence time of stochastically driven ZF field.

then

$$\frac{\partial}{\partial t}\langle(\nabla^2\tilde{\phi})^2\rangle \sim \sum_{\underline{k}}(\underline{\tilde{V}}\cdot\nabla\,\nabla^2\tilde{\phi})_{\underline{q}}\,\tau_{c_q}\,(\tilde{V}\cdot\nabla\,\nabla^2\tilde{\phi})_{\underline{q}}$$

So

$$\langle (\nabla^2 \phi)^2 \rangle \sim D\,t$$ → grow linearly in time!

and can add noise term to zonal mode growth

→ can drive flow, absent modulational instability

→ also seeds zonal density

→ see R. Singh, P.D. PPCF '21 for a complete analysis.

Zonal noise is the answer to the question of "What triggers the trigger?".

→ What limits ZF? / Zonal Mode?

– Tertiary instability

i.e. DW $\rightarrow$ Zonal $\xrightarrow{\text{instability}}$ Tertiary

Coupling Modes

primary – secondary – Tertiary

i.e. $\downarrow\uparrow \rightarrow \nabla V_{ZF} \rightarrow$ KH type

or

$\left.\begin{array}{l}\nabla n_Z \\ \nabla T_Z\end{array}\right\}$ Drift wave.

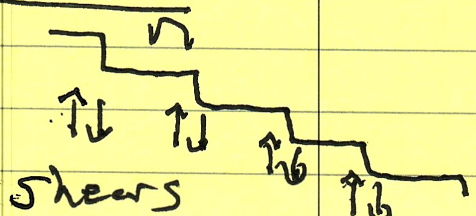
Tertiary controversial, especially in magnetically sheared systems.

Other? → turbulent viscosity (Li, PD)

Key Question: How translate into effective NL ZF damping for coupled spectra – Flow system?

→ ongoing

→ Staircase – 1D spatial pattern.



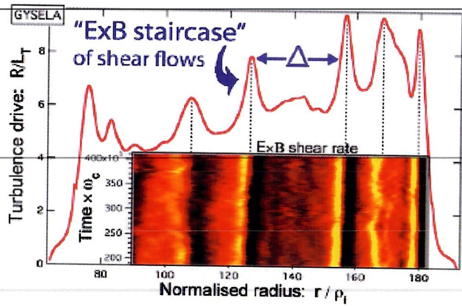
steps + shear layer pattern.

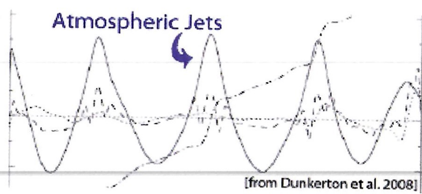
→ Bistable mixing.

Provocation: Staircase and Nonlocality (with G. Dif-Pradalier, et. al.)

UCSD cea

Analogy with geophysics: the '$\mathbf{E} \times \mathbf{B}$ *staircase*'





$$Q = -n\chi(r)\nabla T \Rightarrow \boxed{Q = -\int \kappa(r, r')\nabla T(r')\,dr'}$$

- '$\mathbf{E} \times \mathbf{B}$ staircase' width $\equiv$ kernel width Δ
- coherent, persistent, jet-like pattern
  $\Rightarrow$ the '$\mathbf{E} \times \mathbf{B}$ staircase'
- staircase NOT related to low order rationals!

Dif-Pradalier, Phys Rev E. 2010
and many follow-ons.

Guilhem Dif-Pradalier APS–DPP meeting, Atlanta, Nov. 2009

Provocation, cont'd

- The point:
  - fit: $Q = -\int dr'\kappa(r,r')\nabla T(r')$ $\quad \kappa(r,r') \sim \dfrac{S^2}{(r-r')^2 + \Delta^2}$ $\rightarrow$ some range in exponent
  - $\Delta >> \Delta_c$ i.e. $\Delta \sim$ Avalanche scale >> $\Delta_c \sim$ correlation scale
  - Staircase 'steps' separated by Δ ! $\rightarrow$ stochastic avalanches produce quasi-regular flow pattern!?

    N.B.

    - The notion of a staircase is not new – especially in systems with natural periodicity (i.e. NL wave breaking…)
    - What IS new is the connection to stochastic avalanches, independent of geometry
  - What is process of self-organization linking avalanche scale to zonal pattern step?

    i.e. How extend predator-prey feedback model to encompass both avalanche

    and zonal flow staircase? Self-consistency is crucial!

Feedback Loops II

- Recovering the 'dual cascade':
  - Prey → <N> ~ <Ω> ⇒ induced diffusion to high k_r { ⇒ Analogous → forward potential enstrophy cascade; PV transport
  - Predator → $|\phi_q|^2 \sim \langle V_{E,\theta}^2 \rangle$ { ⇒ growth of *n=0, m=0* Z.F. by turbulent Reynolds work; ⇒ Analogous → inverse energy cascade

- Mean Field Predator-Prey Model

  (P.D. et. al. '94, DI²H '05)

$$\begin{cases} \frac{\partial}{\partial t} N = \gamma N - \alpha V^2 N - \Delta\omega N^2 \\ \frac{\partial}{\partial t} V^2 = \alpha N V^2 - \gamma_d V^2 - \cancel{\gamma_{NL}(V^2)V^2} \end{cases}$$

Reduced Model (0D)

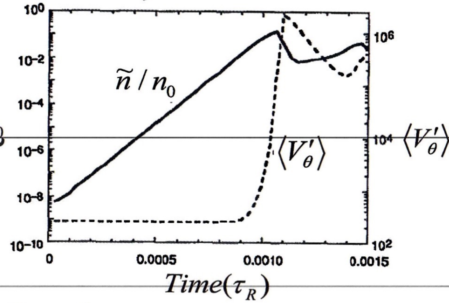
System Status

State	No flow	Flow ($\alpha_2 = 0$)	Flow ($\alpha_2 \neq 0$)
N (drift wave turbulence level)	$\frac{\gamma}{\Delta\omega}$ usual	$\frac{\gamma_d}{\alpha}$	$\frac{\gamma_d + \alpha_2\gamma\alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
V^2 (mean square flow)	0	$\underbrace{\frac{\gamma}{\alpha} - \frac{\Delta\omega\gamma_d}{\alpha^2}}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
Drive/excitation mechanism	Linear growth	Linear growth	Linear growth
Regulation/inhibition mechanism	Self-interaction of turbulence	Random shearing, self-interaction	Nonlinear damping of flow Random shearing, self-interaction
Branching ratio $\frac{V^2}{N}$	0	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\gamma_d}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\gamma_d + \alpha_2\gamma\alpha^{-1}}$
Threshold (without noise)	$\gamma > 0$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$

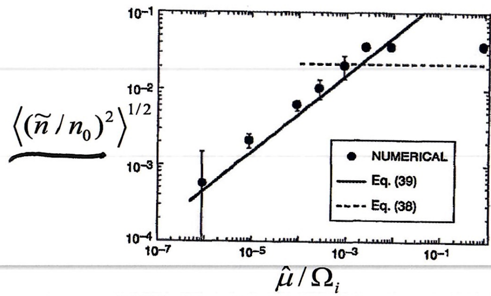
Feedback Loops II

- Early simple simulations confirmed several aspects of modulational predator-prey dynamics

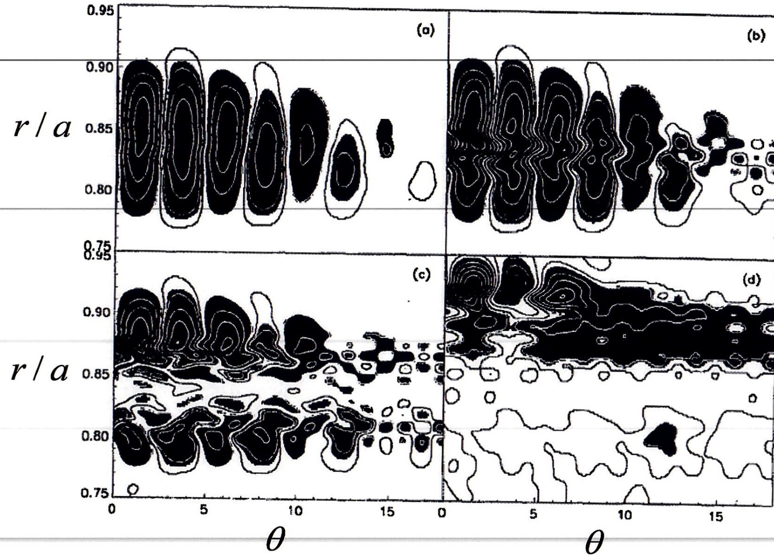
(L. Charlton et. al.'94)



Shear flow grows above critical point



'With Flow' and 'No Flow'.
Scalings of $\langle (\tilde{n}/n_0)^2 \rangle$ appear. Role of damping evident



Generic picture of fluctuation scale reduction with flow shear

$\mu \to 0 \Rightarrow$ Dimits Shift

What of Electromagnetics? — Neglected in this course.... 13

Progress II : β-plane MHD (with S.M. Tobias, D.W. Hughes)

Model

- Thin layer of shallow magneto fluid, i.e. solar tachocline
- β-plane MHD ~ 2D MHD + β-offset i.e. solar tachocline

$$\partial_t \nabla^2 \phi + \nabla \phi \times \hat{z} \cdot \nabla \nabla^2 \phi - \nu \nabla^2 \nabla^2 \phi = \beta \partial_x \phi + \underbrace{B_0 \partial_x \nabla^2 A + \nabla A \times \hat{z} \cdot \nabla \nabla^2 A}_{} + \tilde{f}$$

$$\partial_t A + \nabla \phi \times \hat{z} \cdot \nabla A = B_0 \partial_x \phi + \eta \nabla^2 A \qquad \vec{B}_0 = B_0 \hat{x}$$

- Linear waves: Rossby – Alfven $\omega^2 + \omega \beta \frac{k_x}{k^2} - k_x^2 V_A^2 = 0$ (R. Hide)
- cf P.D., et al; Tachocline volume, CUP (2007)

  S. Tobias, et al: ApJ (2007)

Progress II, cont'd

Observation re: What happens?

- Turbulence $\rightarrow$ stretch field $\rightarrow$ $\langle \tilde{B}^2 \rangle >> B_0^2$ i.e. $\langle \tilde{B}^2 \rangle / B_0^2 \sim R_m$ (ala Zeldovich)

- Cascades : - forward or inverse?
  - MHD or Rossby dynamics dominant !?

- PV transport: $\frac{dQ}{dt} = -\int dA \langle \tilde{v}\tilde{q} \rangle$ $\longrightarrow$ net change in charge content due PV/polarization charge flux

Now $\frac{dQ}{dt} = -\int dA \left[\langle \tilde{v}\tilde{q} \rangle - \langle \tilde{B}_r \tilde{J}_\parallel \rangle \right] = -\int dA \partial_x \left\{ \langle \tilde{v}_x \tilde{v}_y \rangle - \langle \tilde{B}_x \tilde{B}_y \rangle \right\} \longrightarrow$ Reynolds mis-match

PV flux — current along tilted lines — New player $\longrightarrow$ vanishes for Alfvenized state

Taylor: $\langle \tilde{B}_x \tilde{J}_\parallel \rangle = -\partial_x \langle \tilde{B}_x \tilde{B}_y \rangle$

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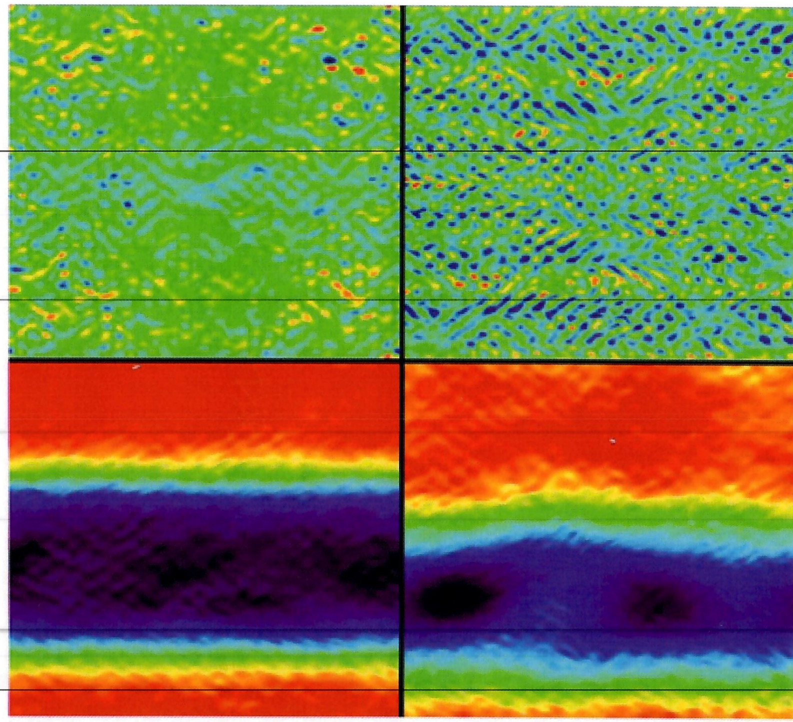
Progress II, cont'd

- **With Field**

$B_0 = 10^{-1}$

$B_0 = 10^{-2}$



$B_0 = 0$

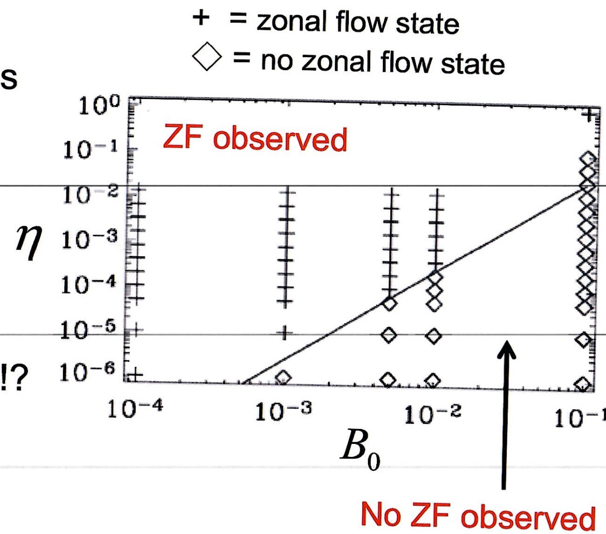
$B_0 = 10^{-3}$

Progress II, cont'd

- Control Parameters for $\vec{\tilde{B}}$ enter Z.F. dynamics

  ~~Like RMHD~~ Ohm's law regulates Z.F.

- Recall
  - $\langle \tilde{v}^2 \rangle$ vs $\langle \tilde{B}^2 \rangle$
  - $\langle \tilde{B}^2 \rangle \sim B_0^2 R_m$ $\longrightarrow$ origin of B_0^2 / η scaling !?



- Further study $\rightarrow$ differentiate between :
  - cross phase in $\langle \tilde{v}_r \tilde{q} \rangle$ and O.R. vs J.C.M
  - orientation : $\vec{B} \parallel \vec{V}$ vs $\vec{B} \perp \vec{V}$
  - spectral evolution

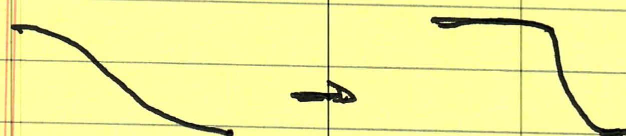
b.) L→H Transition

{ Converging from Wagner '82, but not yet fully converged

Phenomenology:

⇒ LH characterized by:

→ edge gradient steepening



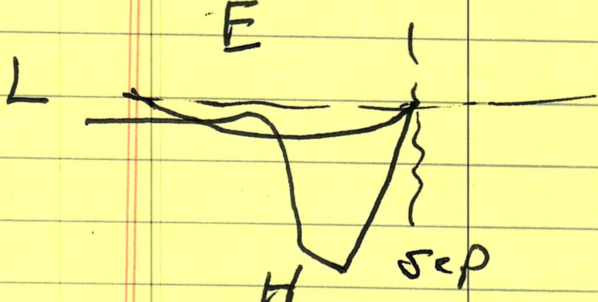
→ pedestal formation

→ confinement improvement

→ fluctuation (low k) drop ↓

High k's persist in pedestal.

→ Increase in E×B shear, formation of Er well



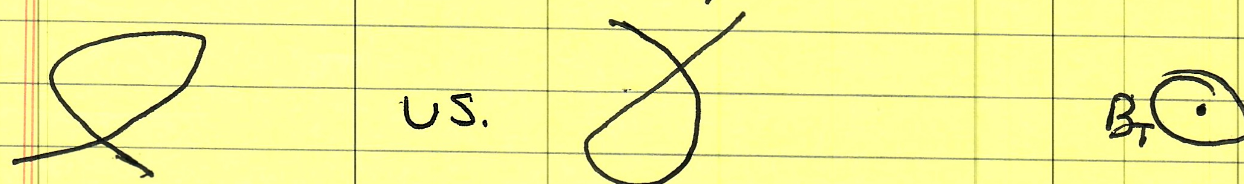
barrier can develop from inner, outer layer. (Schmitz 2021)

⇒ Power threshold (P_{crit})

– critical to ITER

⇒ recall P_{crit} – ∈ ⊕ Sawtooth
HPP

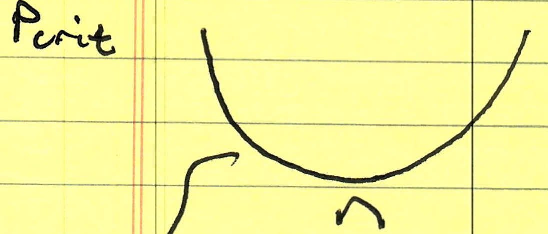
⇒ ∇B drift asymmetry



Lower P_{crit} Higher P_{crit}

(unclear) cf. Fedorczak et. al. 2012

→ P_{Thresh} – major concern ITER



related LOC–SOC

why? ⇒ coupling to ions

i.e. $\nabla P_i \sim E_r$

increased n assures stronger electron–ion coupling $\sim nT\nu_\epsilon (T_e - T_i)$

Some evidence $P_{Th} \sim n B_T$

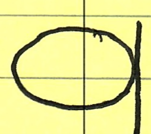
Current ??

→ isotope $\downarrow$ — lower in D than H, etc.

<u>Relation</u> to <u>microphysics</u> <u>unclear</u>.

→ Other points:

- universal to all heating method
- limiter and diverted plasmas, but:
  - → <u>never</u> in outside limiter



  - → P_{Th} higher for limiter plasma.

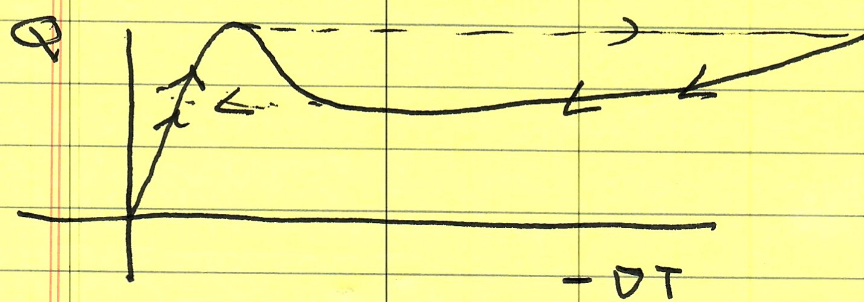
→ observed in stellarators

W7AS, TJ II, LHD

→ RFP ? → QSH ?!

P_{OH} big! → Boundary

→ Hysteresis happens



$P_{LH} > P_{HL}$.

Poorly understood → very important.

→ P_{LH} ↑ in RMP plasmas

important for ELM mitigation.

How ?   Trigger + ∇P Feedback

Energy to Shear Flow (ZF)

$\downarrow$

∇P steepen

$\downarrow$

Turbulence collapses

Implications for transition thresh, if any ?

→ Multi-step

⇒ Many examples. DIII-D, EAST, TJ-II, AUG, HL-2A, Textor, ...

⇒ A few dissenters ..... not many
JFT-2M, AUG, HL-2A

→ ? Orbit loss ?

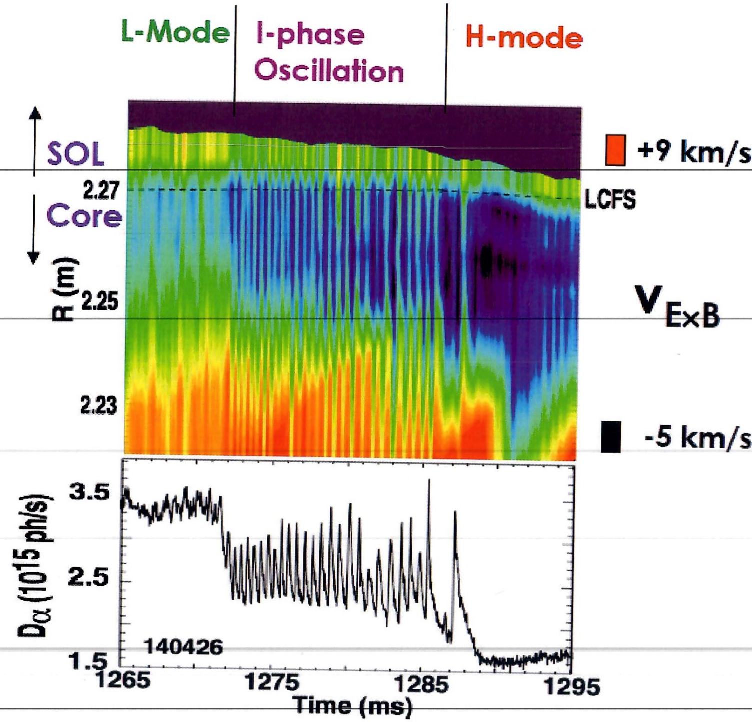
→ Is there a unique route to transition ?

The Oscillating Flow Layer Widens Radially (Frequency Decreases) - Steady Flow after Final H-Mode Transition

A weak ExB flow layer exists in L-mode (L-mode shear layer)

At the I-phase transition, the ExB flow becomes more negative first near the separatrix, flow layer then propagates inward

The flow becomes steady at the final H-mode transition (after one final transient)



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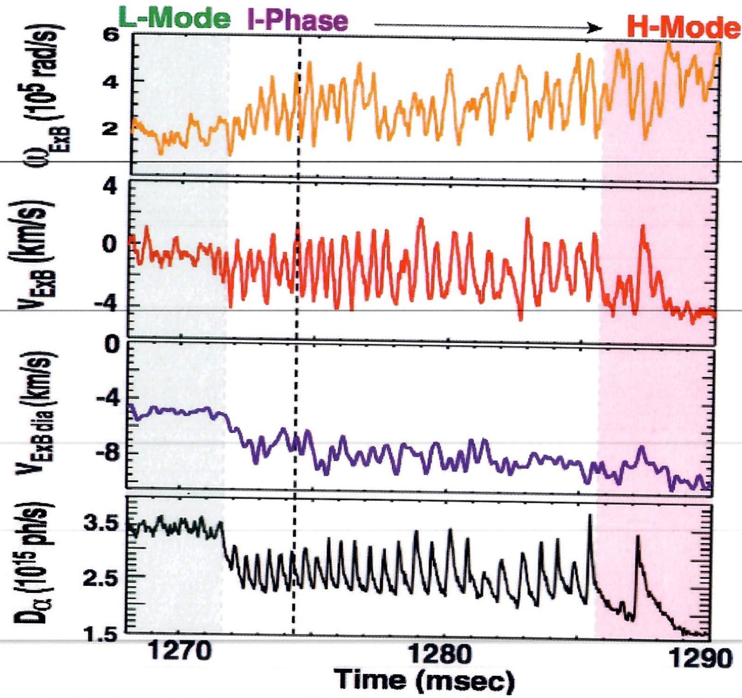
During the I-phase, the Mean Shear $\langle\omega_{ExB}\rangle$ Increases with Time and Eventually Dominates

Outer layer Shearing Rate (Mean flow+ ZF)

ExB Flow from DBS (includes ZF)

Diamagnetic component of ExB flow (from ion pressure Profile)

R~2.265m



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Feedback Loops III

- ∇P coupling
  - γ_L drive
  - $\langle V_E \rangle'$

i.e.
$\gamma = \gamma(\nabla P)$

$$\partial_t \varepsilon = \varepsilon N - a_1 \varepsilon^2 - a_2 V^2 \varepsilon - a_3 V_{ZF}^2 \varepsilon$$

$$\partial_t V_{ZF} = b_1 \frac{\varepsilon V_{ZF}}{1 + b_2 V^2} - b_3 V_{ZF}$$

$$\partial_t N = -c_1 \varepsilon N - c_2 N + Q$$

transport

source, flux

$\varepsilon \equiv$ *DW energy*

$V_{ZF} \equiv$ *ZF shear*

$N \equiv \nabla \langle P \rangle \equiv$ *pressure gradient*

$V = dN^2$ *(radial force balance)*

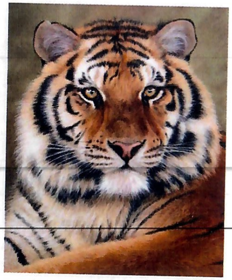
- Simplest example of 2 predator + 1 prey problem (E. Kim, P.D., 2003)

i.e. prey sustains predators
predators limit prey
} usual feedback

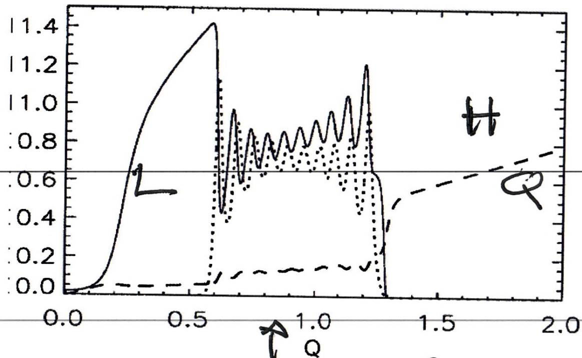
now:
- 2 predators (ZF, $\nabla \langle P \rangle$) compete
- $\nabla \langle P \rangle$ as both drive and predator

- Relevance: LH transition, ITB
  - Builds on insights from Itoh's, Hinton
  - ZF $\Rightarrow$ triggers
  - $\nabla \langle P \rangle \Rightarrow$ 'locking in'

Multiple predators are possible



Feedback Loops III, cont'd

- 

I-phase (LCO)

Solid - $\mathcal{E}$

Dotted - V_{ZF}

Dashed - $\nabla\langle P\rangle$

— simple, useful model of L-H transition,

— turbulence extinguished on H.

- Observations:
  - ZF's trigger transition, $\nabla\langle P\rangle$ and $\langle V\rangle$ lock it in
  - Period of dithering, pulsations .... during ZF, $\nabla\langle P\rangle$ oscillation as Q $\uparrow$
  - Phase between $\mathcal{E}$, V_{ZF}, $\nabla\langle P\rangle$ varies as Q increases
  - $\nabla\langle P\rangle \Leftrightarrow$ ZF interaction $\Rightarrow$ effect on wave form

extended.