The Tokamak as a Complex Physical System:

Introduction and Focus on L→H Transition

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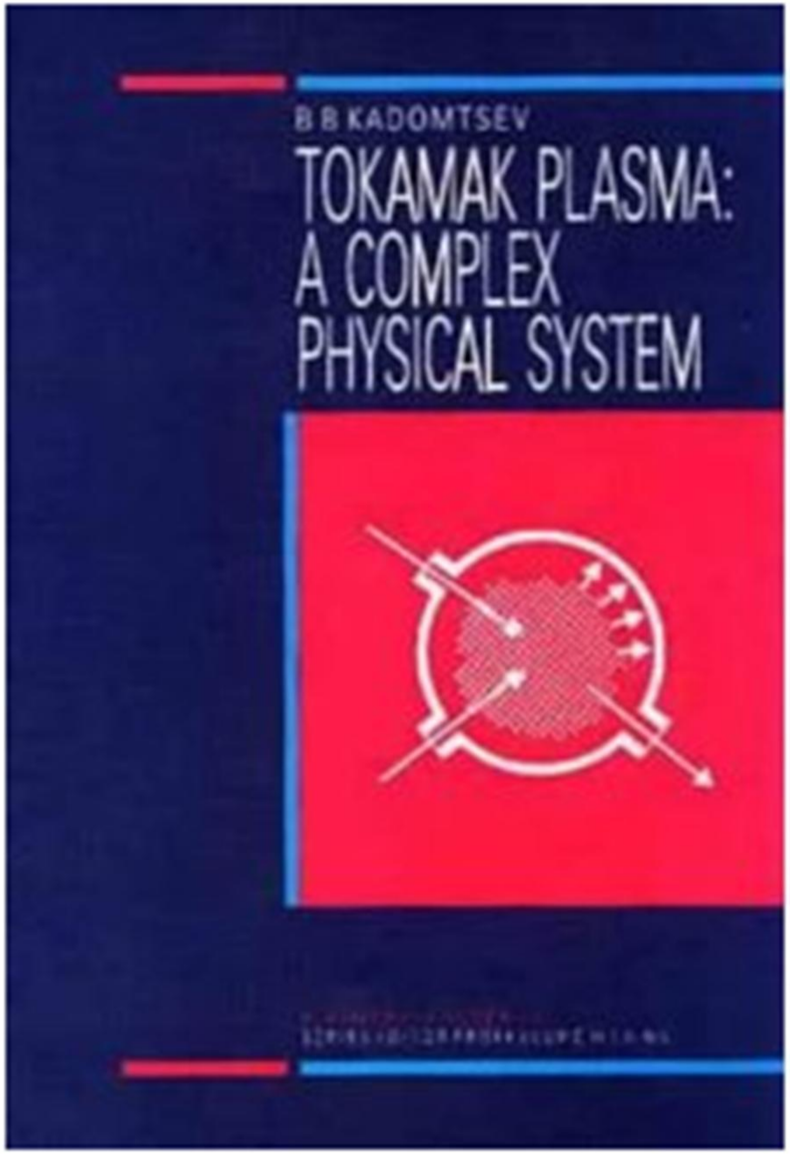
- By request, a 'Colloquium' type talk
- Not an OV of tokamak phenomenology, rather ➔ an introduction focused on *ideas*
- In the spirit of:

  "It is better to *uncover* one thing, than to cover everything equally."

  - Walter Kohn

Credits



B.B. Kadomtsev

Tokamak Plasma:

A Complex Physical System

Metaphor

"The Garden of Earthly Delights" (1503 – 1504)
Hieronymous Bosch
Museo Del Prado, Madrid

Theme

“Tokamak plasma is a complex physical system. Various physical processes exist and interact simultaneously there. That is why the deeper the studies are, the more sophisticated are the discovered phenomena. Here, similar to many paintings by the prominent artist Hieronymous Bosch, there exist many levels of perception and understanding. At a cursory glance at the picture, you promptly grasp its idea. But under a more scrutinized study of its second and third levels, you discover a new horizon of a deeper life, and it turns out that your first impressions become rather shallow.”

- B.B. Kadomtsev

Theme, cont'd

- Thoughts on Perspective
  - complex plasma phenomenology viewed in terms of *states of self-organization* and *bifurcation transitions between them*
  - concepts for description:
    - feedback loops → how do interacting agents regulate one another?
    - structure formation from inverse cascade → how does coherent large scale order emerge from turbulence?
    - pattern selection → which of competing structural states actually emerges?
    - probabilistic formulations → how assess likelihood of states and transition?

Outline

- What is a Tokamak?
- 'Self Organization' ↔ How do profiles form?
  - basic idea, scales
  - a profile as a self-organized criticality (!?)
- Focus: the L→H transition

  ⇒ Layer1: transport bifurcation

  - profiles 'morph'! ➔ the L →H transition
  - some basic results and ideas
  - Intermezzo: flows within flow ➔ zonal modes

  ⇒ Layer2: multi-shear interaction

Outline (cont'd)

⇒ Layer3: The challenge of prediction and control of self-organization process

➔ Focus: L→H transition

- Thresholds and Hysteresis
- Uncovering ELMs
- Controlling ELMs

⇒ Layer4: Now that we have the H-mode, do we really want it?

- Summary

What is a Tokamak?

Magnetic Fusion

What is required for ignition?

- Energy content
- Confinement

- Fuel: D, T
- Amount/density n
- Ignition temperature T
- Energy confinement time τ_E

$$\text{Fusion power} \sim n^2 T^2 (\sim \beta^2 B^4) \geq \text{Loss power} \sim \frac{nT}{\tau_E}$$

$$n \cdot T \cdot \tau_E \geq 3 \times 10^{28}\ \mathrm{m^{-3}Ks}$$

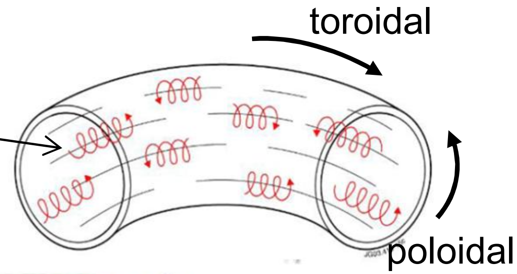
Lawson criterion for D-T fusion

⇒ Good confinement required for ignition!

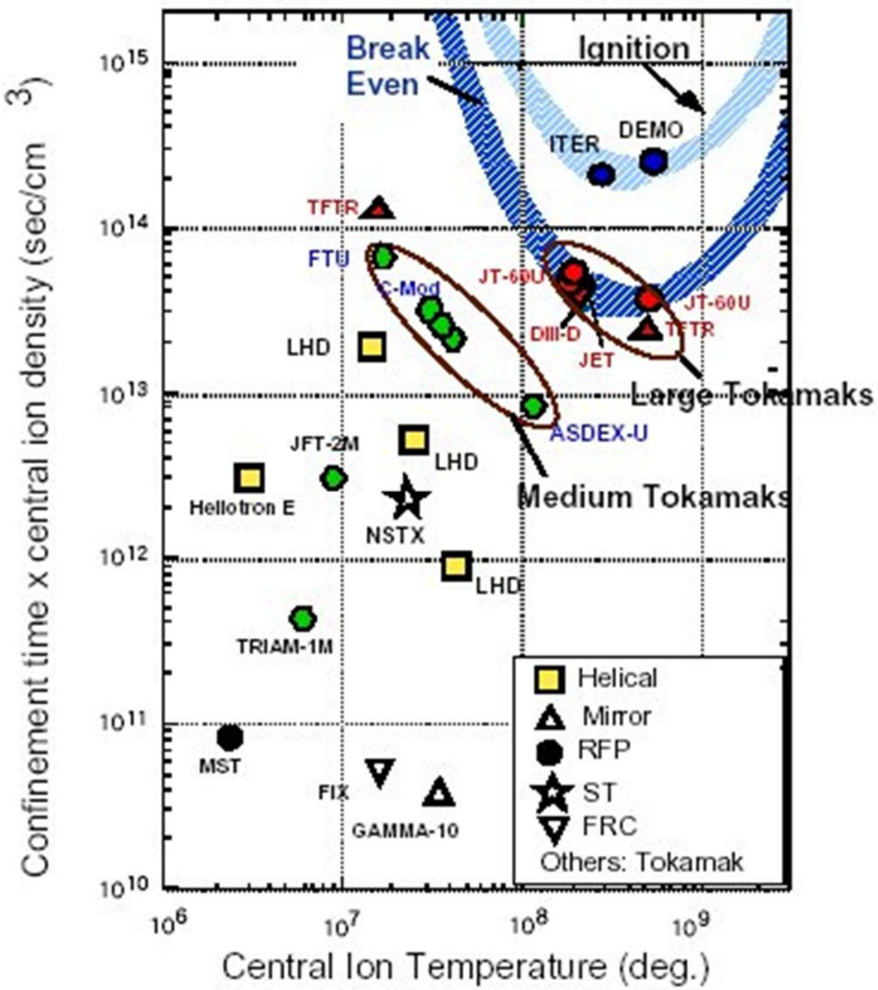
Tokamak: a leading candidate for magnetic fusion

- Magnetic fusion devices
  - ✓ **Tokamak**
  - ✓ Helical device (stellerator)
  - ✓ Spherical tokamak (ST)
  - ✓ Reversed field pinch (RFP)

Plasmas are confined in closed toroidal magetic fields

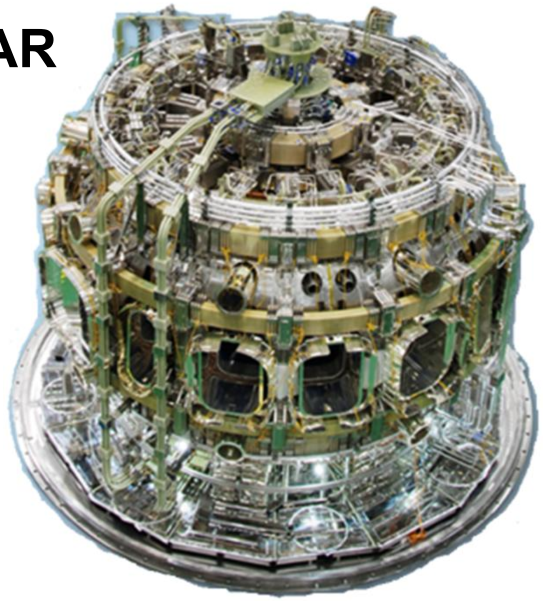


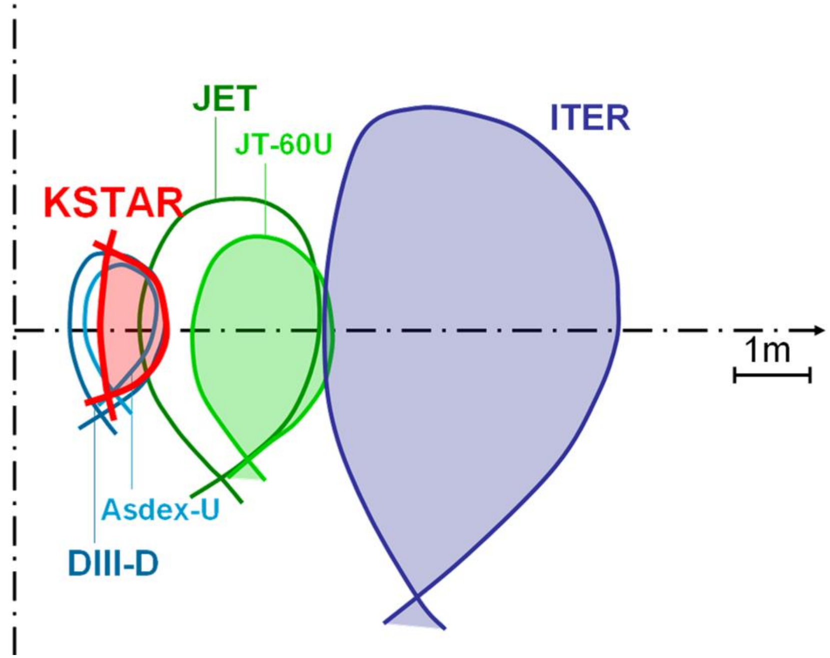
Comparison between magnetic fusion devices



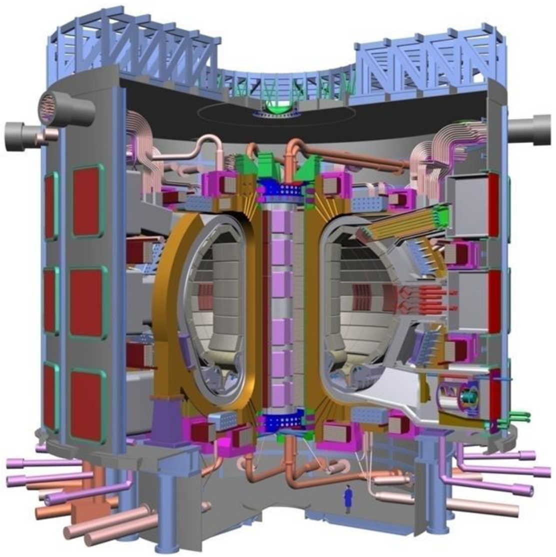
Tokamak: a leading candidate for magnetic fusion

KSTAR





ITER



PARAMETERS	ITER	KSTAR
Major radius	6.2m	1.8m
Minor radius	2.0m	0.5m
Plasma volume	830m^3	17.8m^3
Plasma current	15MA	2.0MA
Toroidal field	5.3T	3.5T
Plasma fuel	H, D-T	H, D-D
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi

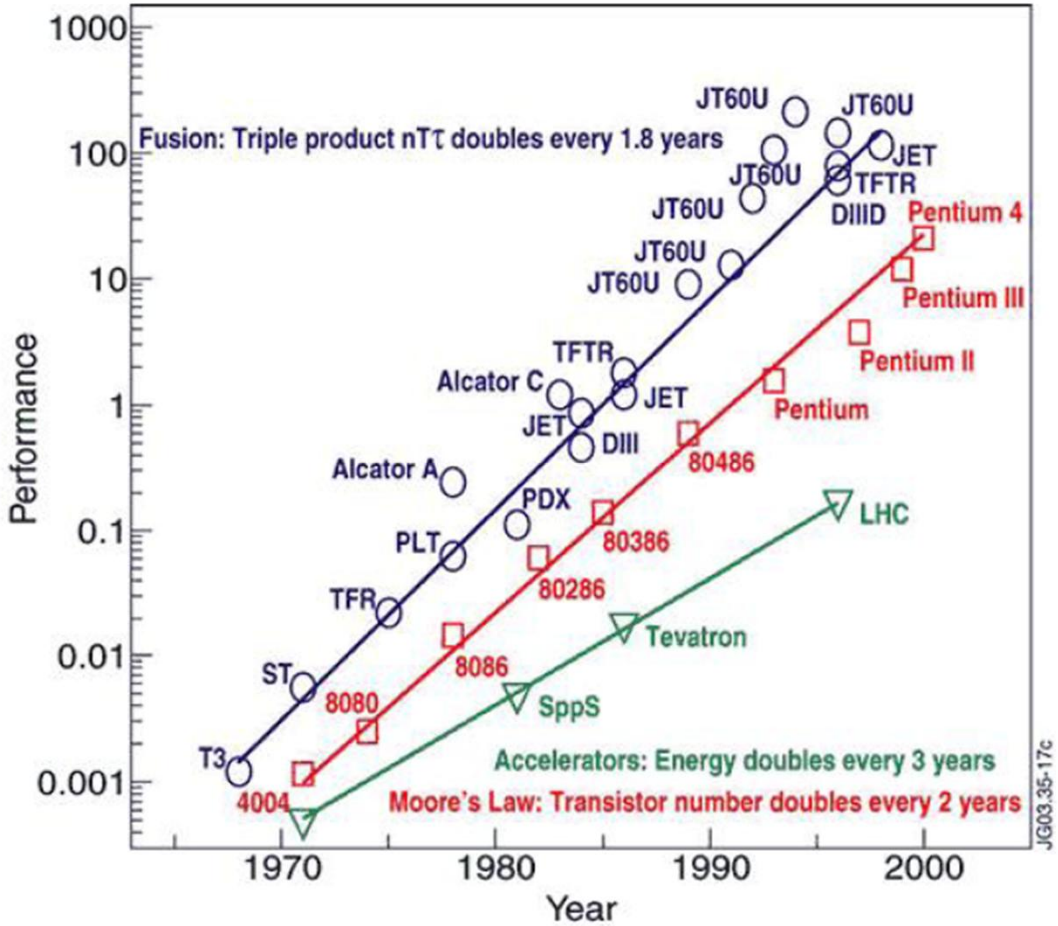
Is Magnetic Fusion a Folly?

"The Haywain Triptych"
Hieronymous Bosch, Museo Del Prado, Madrid

Advances in Tokamak Performance

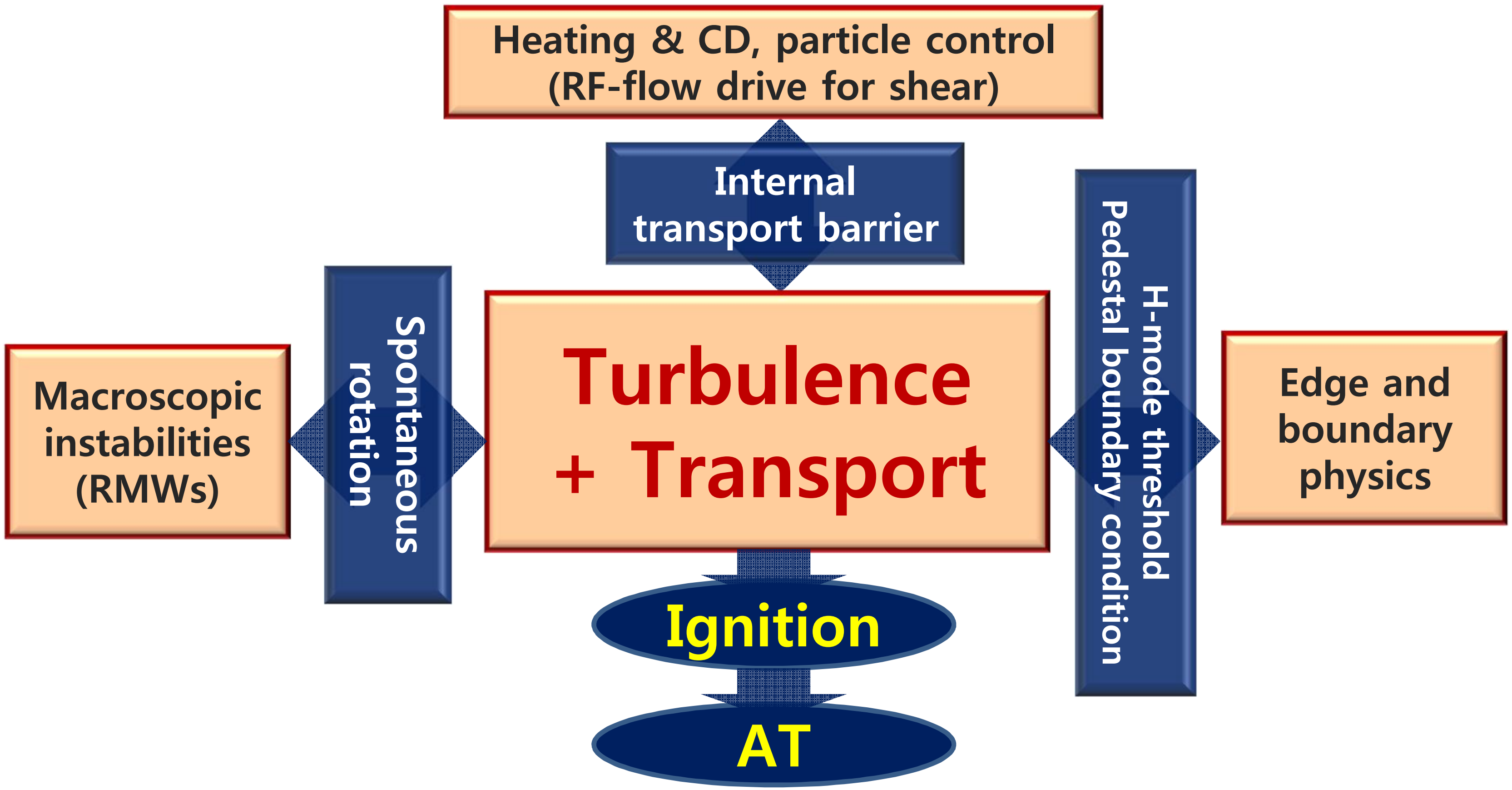
- Progress in tokamak fusion comparable to progress in computing power and particle accelerator energy.

- The next step (ITER) will be operated at high Q (≈ 10).



Major Research Topics in Fusion Science

- Turbulence & transport → Anomalous transport of energy, particle, momentum
- Macroscopic instabilities → Plasma disruption & β limit
- Edge & boundary control → Confinement performance, impurity influx, wall damage
- Heating & CD, Particle control → Steady state operation
- Energetic particles → plasma + alpha particles

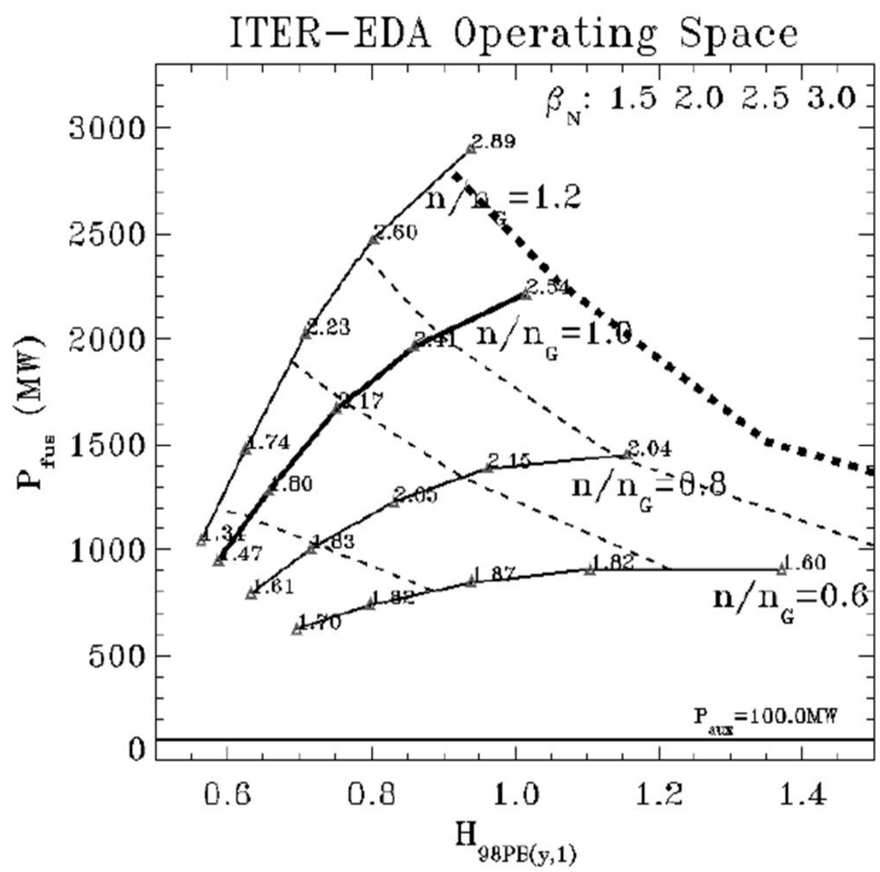


Practical Importance: Ignition and Beyond

- ***Transport determines profiles and thus is critical to ignition!***

- To accurately predict plasma performance
  - Major performance parameters, such as fusion power, depend strongly on transport level   i.e. T, τ_E

- To achieve advanced tokamak plasma through active profile control
  - Control of pressure, current, and rotation profiles consistent with MHD stability
  - Formation and control of transport barriers for high confinement
  - Optimization of profiles for high bootstrap current fraction for steady state



PJ Knight et al., 26th EPS on Conf. on Contr. Fusion and Plasma Physics

Flow Chart

➡ **Self-Organization of Profiles**

Layer 1 : L→H Transition as Transport Bifurcation

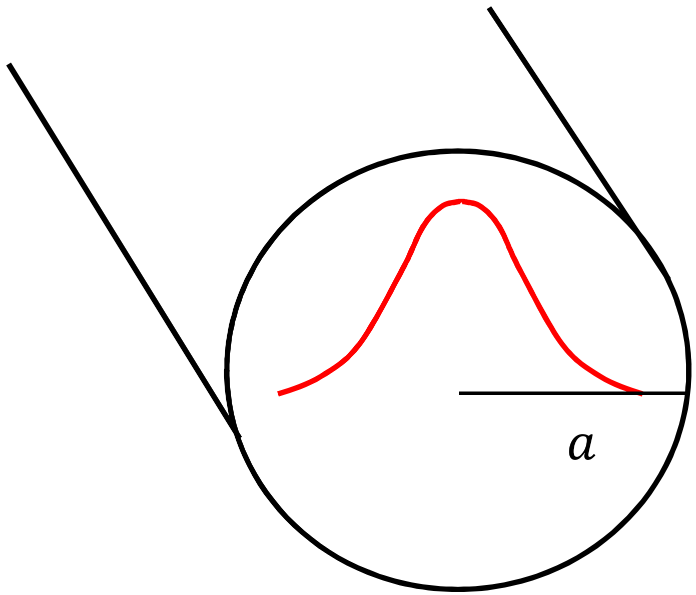
Intermezzo: Zonal Modes

Layer 2 : Multi-shear Interaction

Layer 3 : Challenge of Prediction and Control

Layer 4 : Do we really *want* the H-mode?

Primer on Turbulence in Tokamaks



- $\nabla T, \nabla n$, etc. driver
- Quasi-2D, elongated cells aligned with B_0
- Characteristic scale ~ few ρ_i
- Characteristic velocity $v_d \sim \rho_* c_s$

2 scales:

$\rho \equiv$ gyro-radius

$a \equiv$ cross-section

$\rho_* \equiv \rho / a$ ➔ key ratio

- Transport scaling: $D \sim \rho v_d \sim \rho_* D_B \sim D_{GB}$
- i.e. Bigger is better! ➔ sets profile scale via heat balance
- Reality: $D \sim \rho_*^{\alpha} D_B$, $\alpha < 1$ ➔ why?

- Cells “pinned” by magnetic geometry
- Remarkable similarity

TABLE I. Analogies between the sandpile transport model and a turbulent transport model.

Turbulent transport in toroidal plasmas	Sandpile model
Localized fluctuation (eddy)	Grid site (cell)
Local turbulence mechanism:	*Automata rules*:
Critical gradient for local instability	Critical sandpile slope (Z_{crit})
Local eddy-induced transport	Number of grains moved if unstable (N_f)
Total energy/particle content	Total number of grains (total mass)
Heating noise/background fluctuations	Random rain of grains
Energy/particle flux	Sand flux
Mean temperature/density profiles	Average slope of sandpile
Transport event	Avalanche
Sheared electric field	Sheared flow (sheared wind)

Automaton toppling
↔ Cell/eddy overturning

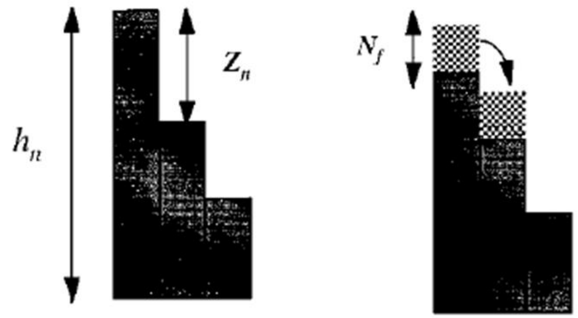
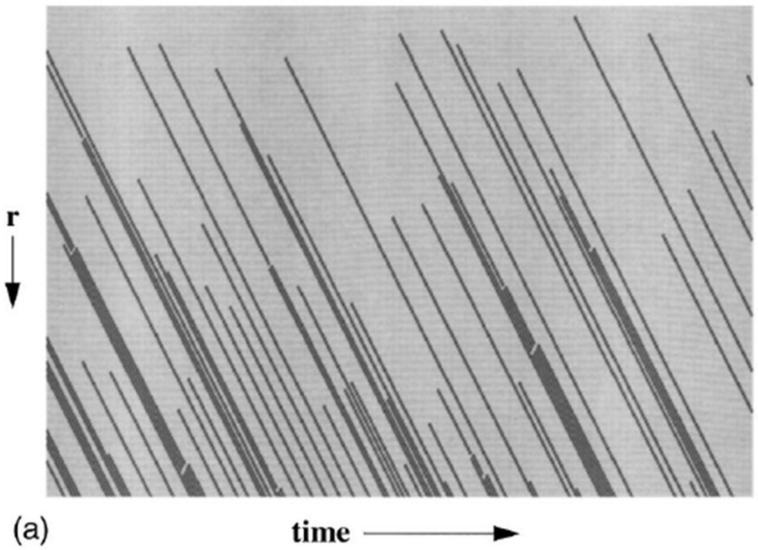
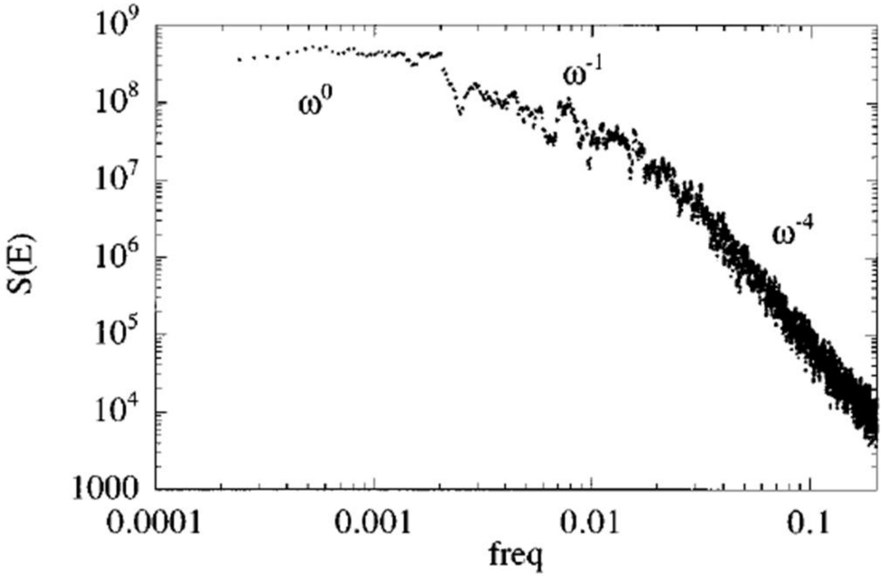


FIG. 1. A cartoon representation of the simple cellular automata rules used to model the sandpile.

- ‘Avalanches’ form!



Extended avalanches form



Low frequency ‘transport events’ produce 1/f spectrum

- Avalanching is a likely cause of ‘gyro-Bohm breaking’

➔ localized cells self-organize to form transient, extended transport events

- Akin domino toppling:

- Self-Organized Profiles can be non-trivial

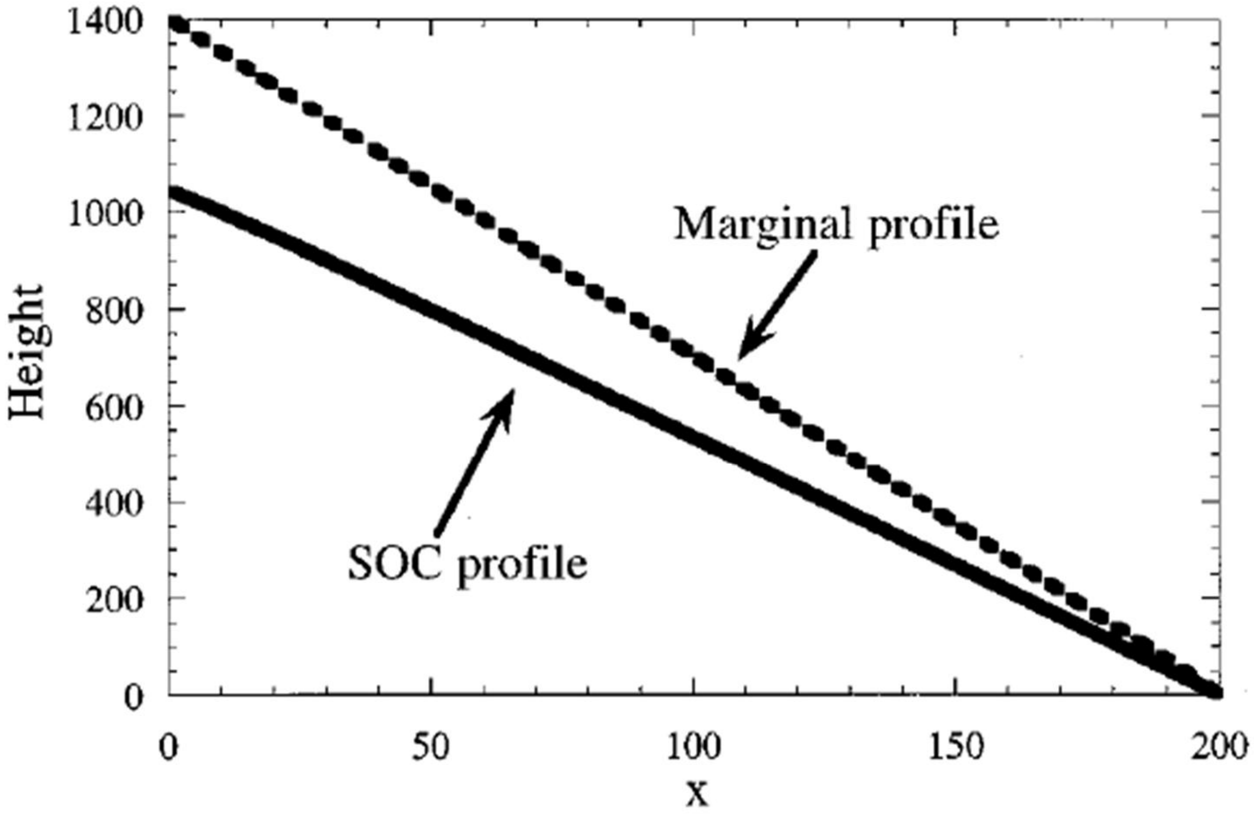


FIG. 3. The average sandpile profiles for a marginal case and a SOC case.

Note: SOC profile ≠ (linearly) marginal profile

Flow Chart

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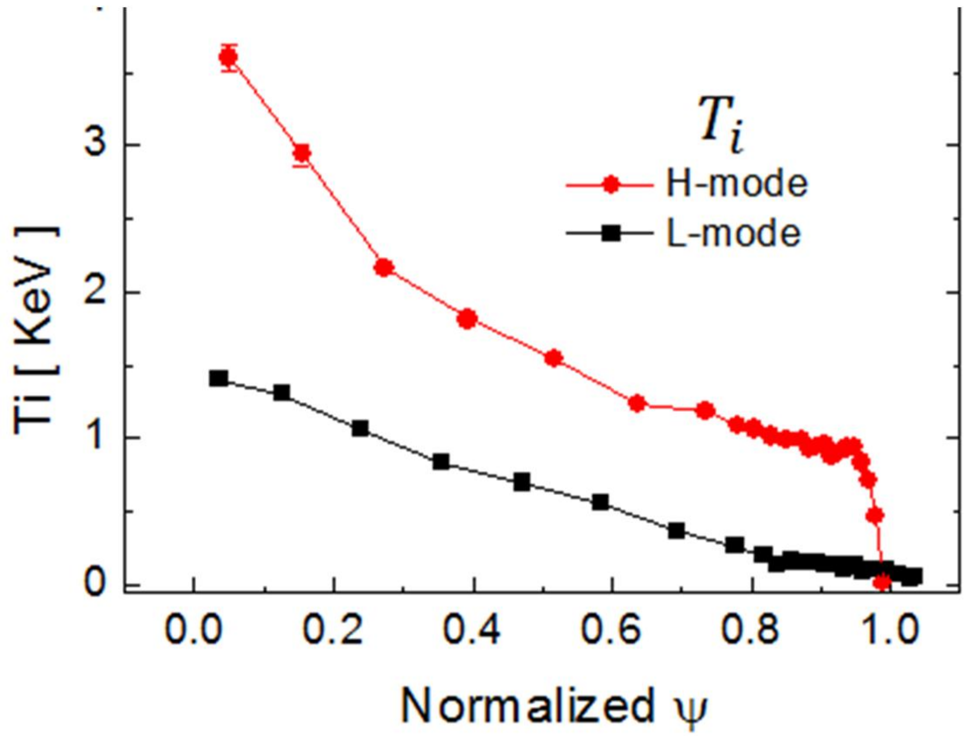
What is L→H Transition

- Spontaneous transition from low to high confinement in region of edge layer

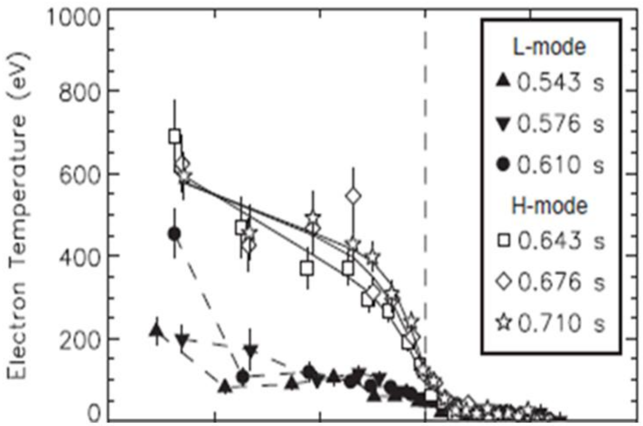


- Edge transport barrier forms: $\Delta T \sim 1keV$ in 1~2cm
- Turbulence and transport suppressed in edge transport barrier region

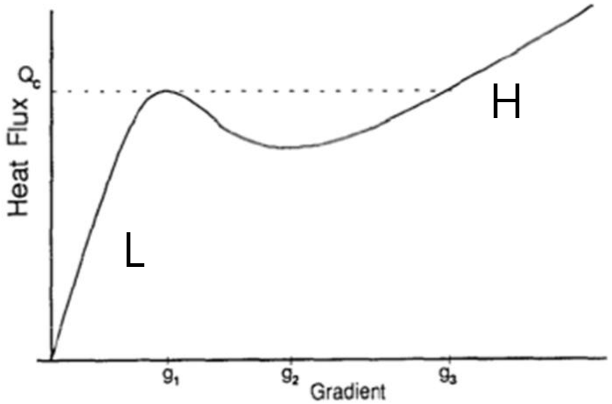
L→H Transition

- Key Application: Triggering the L →H Transition
  - L→H Transition

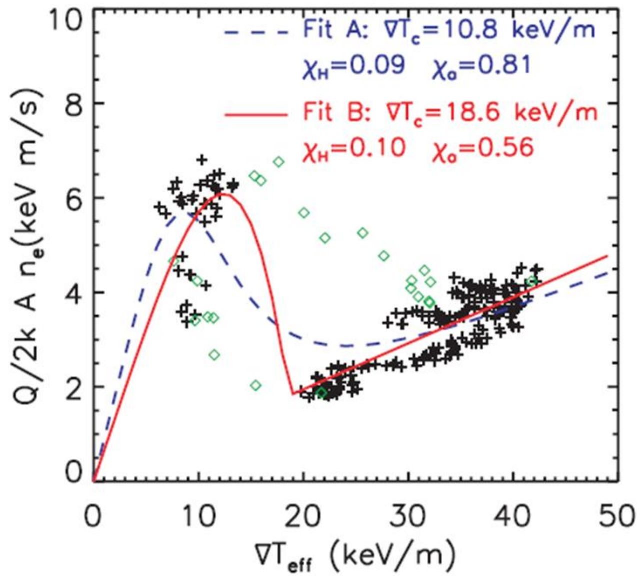
A. Hubbard et. al. 2002



J.W. Huges et al., PSFC/JA-05-35



-∇T



  - Transport bifurcation, 'phase transition' ⇒ P_{thresh}, hysteresis, etc.
  - Characterized by reduction of transport, turbulence in localized edge layer
  - Likely related to V_{ExB} shear suppression of turbulent transport in edge layer

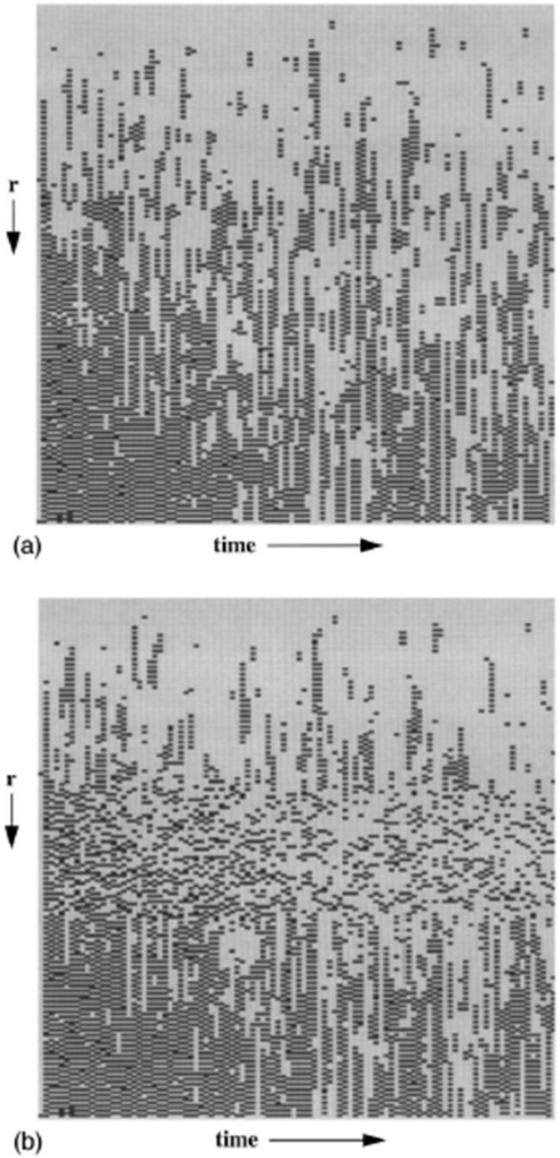


FIG. 11. Time evolution of the overturning sites (like Fig. 4). The avalanches do not appear continous in time because only every 50th time step is shown. (a) The shear-free case shows avalanches of all lengths over the entire radius. (b) The case with sheared flow shows the coherent avalanches being decorrelated in the shear zone in the middle of the pile.

How is transport suppressed?

➔ shear decorrelation!

Back to sandpile model:

2D pile +

sheared flow of

grains

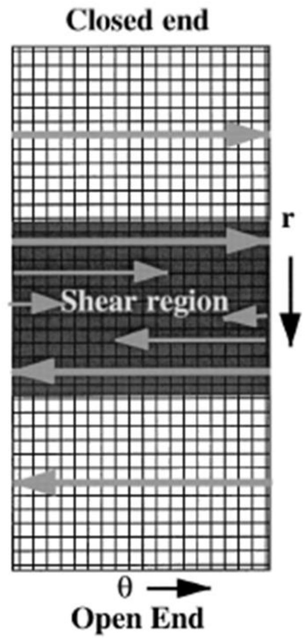


FIG. 10. A cartoon of the sandpile with a shear flow zone. The whole pile is flowing to the right at the top and to the left at the bottom connected by a variable sized region of sheared flow.

Avalanche coherence destroyed by shear flow

- Implications

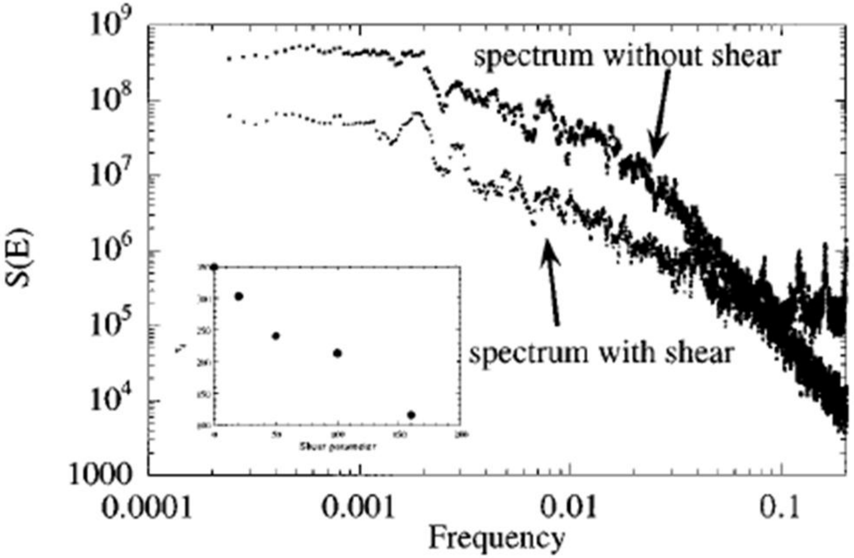


FIG. 12. (a) Frequency spectra with and without a shear flow region. This shows a marked decrease in the low-frequency power (with shear) and a commensurate increase in high-frequency power. (b) The insert shows the decorrelation time ($\tau_d = 1/\varpi$) as a function of the shear parameter (the product of the shearing rate and the size of the shear zone).

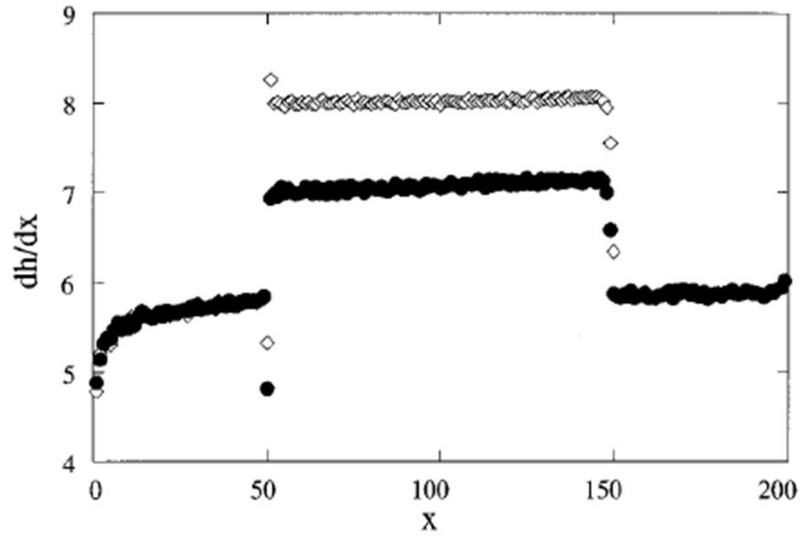
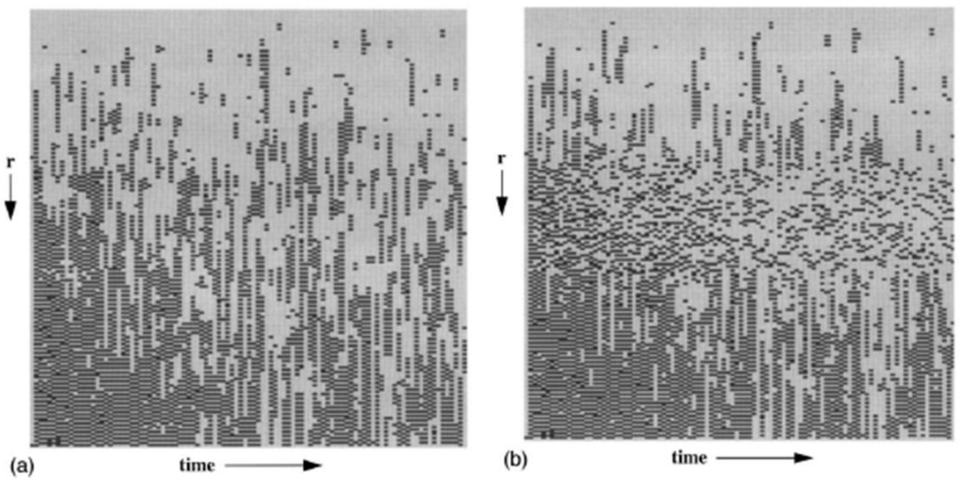


FIG. 14. The slopes of a sandpile with a shear region in the middle, including all the shear effects (diamonds) and just the transport decorrelation and the linear effect (circles).



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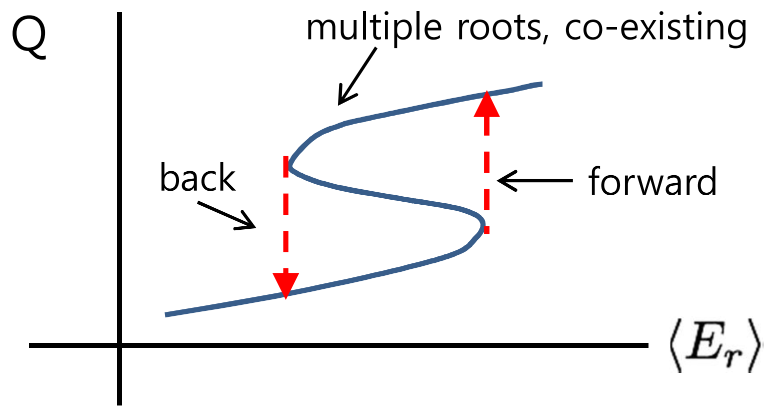
Layer I : Concept of a Transport Bifurcation (1988-1998)
i.e. how generate the sheared flow?

→ First Theoretical Formulation of L→H Transition as an

- Transport Bifurcation
- $\langle E_r \rangle$ Bifurcation



➔ First Appearance of S-curve in a Physical Model of L→H Transition

➔ First Formulation of Criticality Condition (Threshold) for Transport Bifurcation

→ First Theoretical Ideas on Hysteresis, ELMs, Pedestal Width, ...

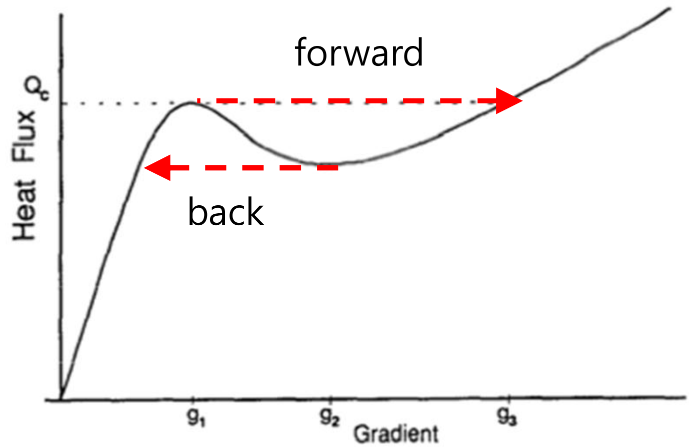
→ Coupling of Transport Bifurcation to turbulence, $\langle v_E \rangle'$ suppression

→ Hinton '91, et. seq. (some extension to 1D)

$$Q = -\frac{\chi_T}{1+\alpha {v'_E}^2}\nabla T - \chi_{neo}\nabla T$$

Shearing feedback

$$v'_E = -\frac{\partial}{\partial r}\left(\frac{c}{eB}\frac{\nabla p}{n_0}\right) \quad p = n_0 T$$



Heat flux S-curve induced by profile-dependent shearing feedback

Profile Bifurcation

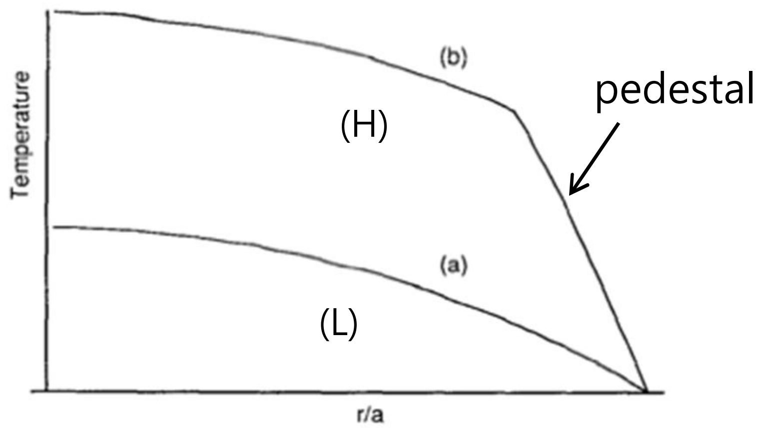


FIG. 2. Temperature profiles near the power threshold (arbitrary units): (a) $Q(a) = 0.99Q_c$; (b) $Q(a) = 1.01Q_c$.

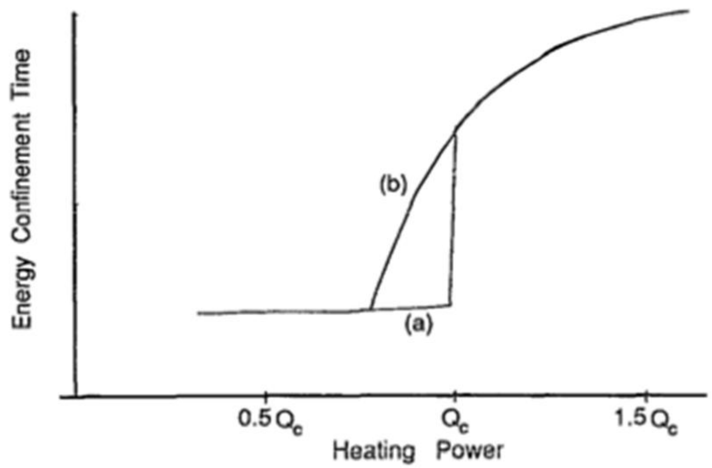
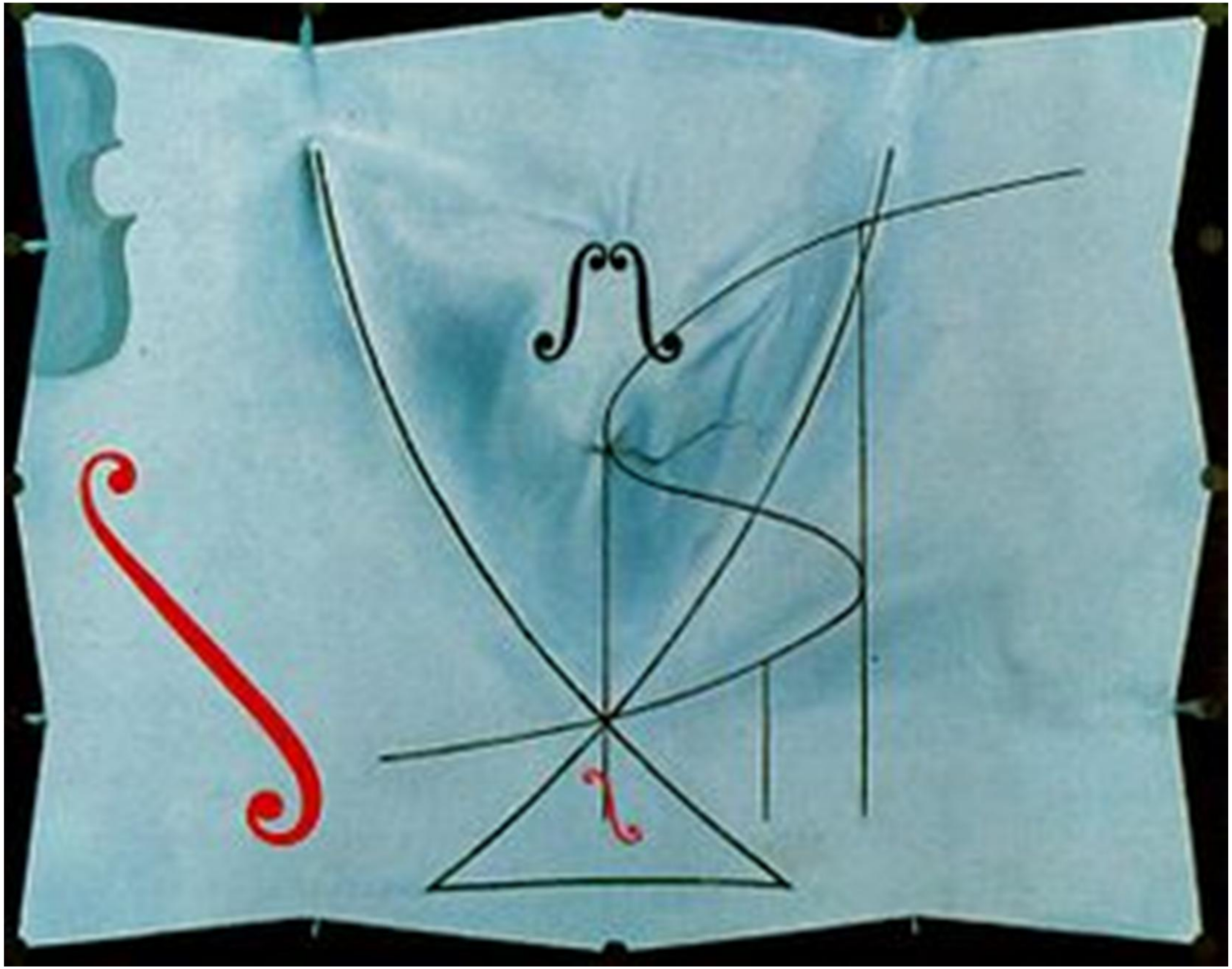


FIG. 4. Power hysteresis in the energy confinement time (arbitrary units): (a) increasing power; (b) decreasing power.

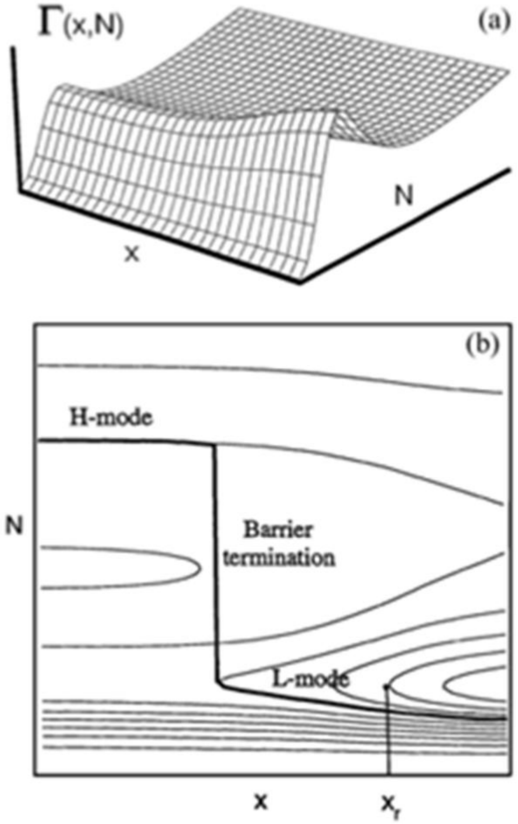


→ Swallow’s Tail - Series on Catastrophes by Salvador Dali

→ Flux Landscape and Speed scaling for 1st order transition (P.D. et al, '97, Lebedev, P.D., '97)

→ motivated by ERS/NCS experiments

Flux Landscape in radius, gradient space



Constant flux and barrier transition layer

Cross-cuts of landscape at different positions

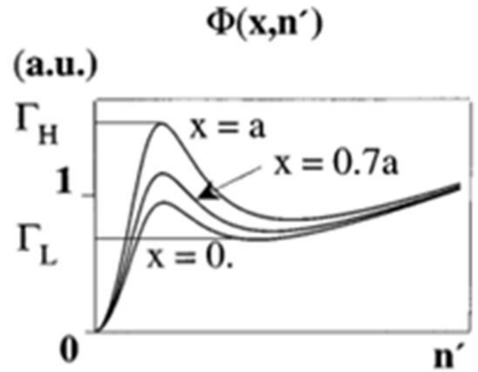


FIG. 2. Dependence of the flux function Φ on the value of density gradient in different radial locations.

→ Transition Front Location

$$X_F \sim (D_{neo}t)^{1/2} \left(\frac{\Gamma - \Gamma_{crit}}{\Gamma_{crit}} \right)^{1/2}$$

→ Generalized Maxwell Criterion to problem with radial structure

Layer I, cont'd

→ mechanism for confinement improvement and turbulence suppression:

→ Shear enhanced decorrelation: BDT '90, Hahm-Burrell '94

→ nonlinear simulations, analysis (90's) → support trend especially for stress driven flows

→ First vs. Second order Transition (still ongoing)

→ Reynolds stress driven flow shear — P.D. and Kim, '90

→ Predator - Reynolds stress driven shear
Prey - Turbulence intensity — P.D., et.al., '94

→ Combined 0D Predator-Prey with transport bifurcation — Carreras, et. al., '95

Flow Chart

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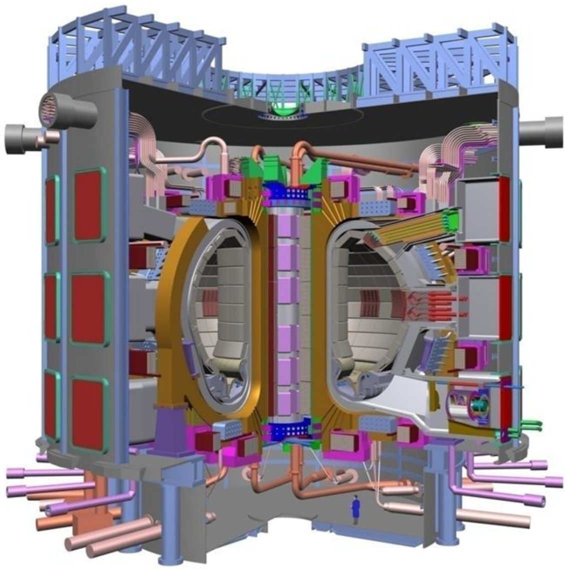
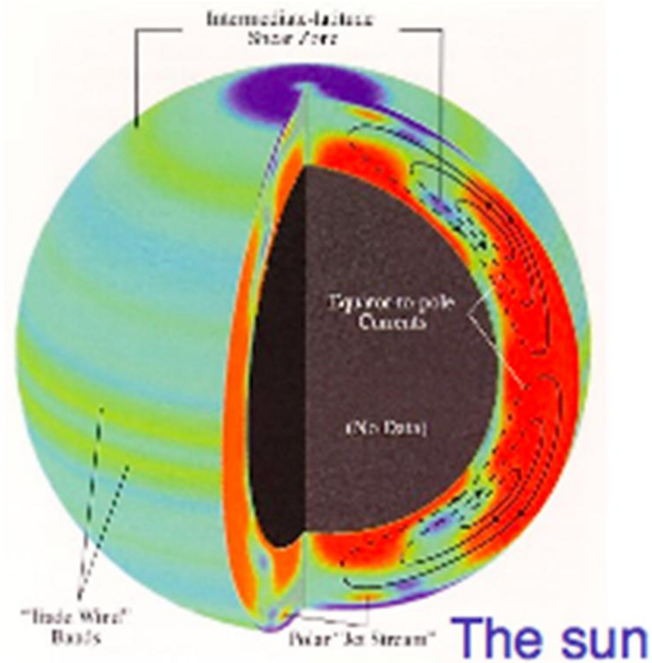
Preamble I

- Zonal Flows Ubiquitous for:
  - ~ 2D fluids / plasmas with Ro < 1

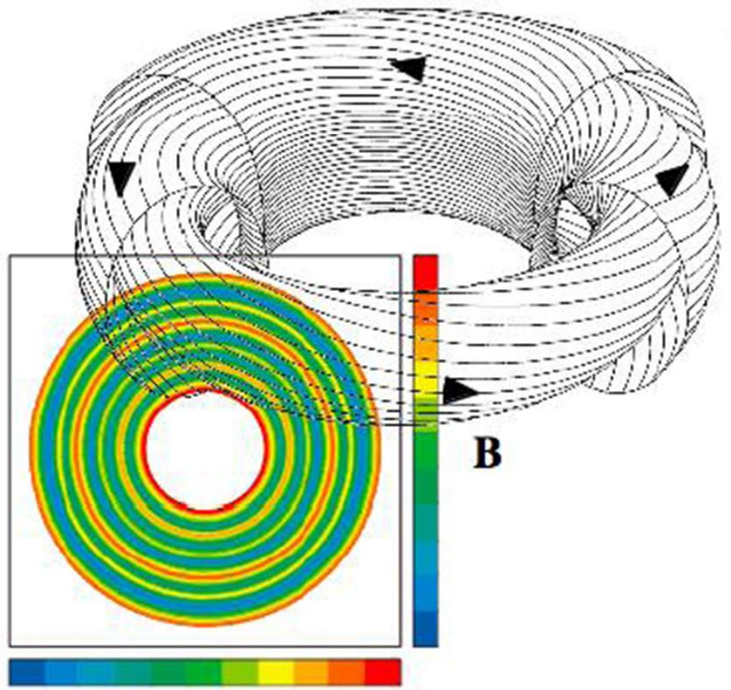
    Ro < 1 $\leftrightarrow$ Rotation $\vec{\Omega}$, Magnetization $\vec{B}_0$, Stratification

  Ex: MFE devices, giant planets, stars…

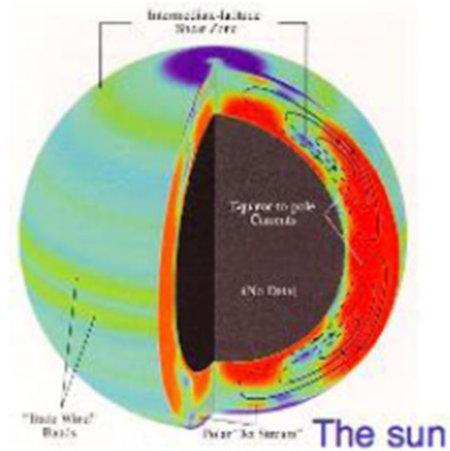




Zonal Flows



Tokamaks

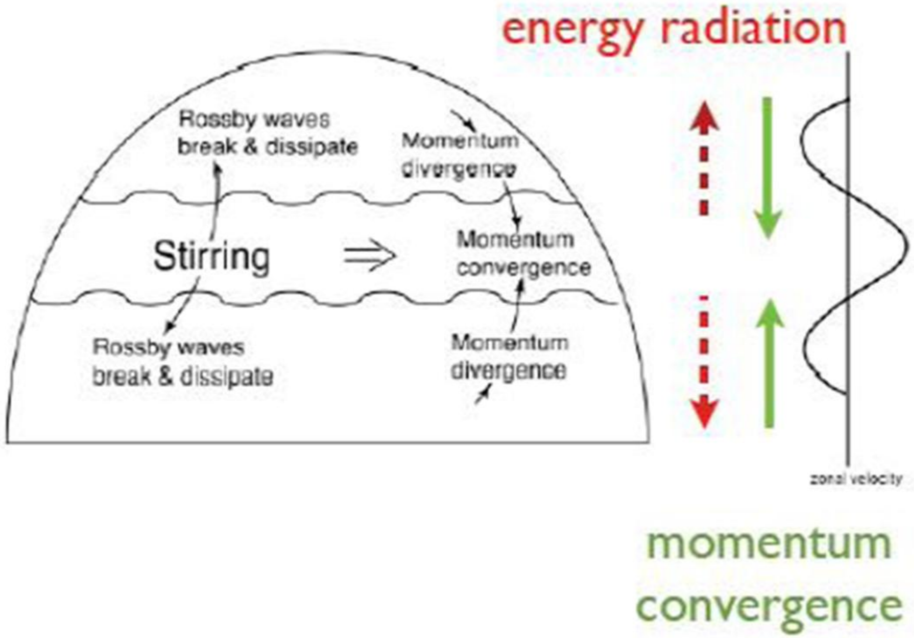


planets

Heuristics of Zonal Flows a):

Simplest Possible Example: Zonally Averaged Mid-Latitude Circulation

- classic GFD example: Rossby waves + Zonal flow (c.f. Vallis '07, Held '01)
- Key Physics:



Rossby Wave:

$$\omega_k = -\frac{\beta k_x}{k_\perp^2}$$

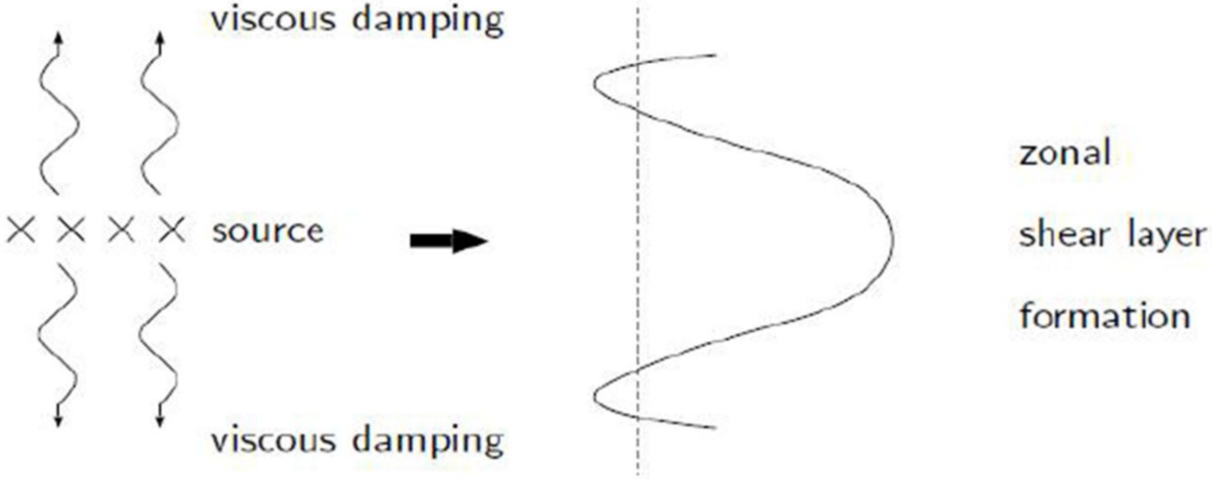
$$v_{gy} = 2\beta \frac{k_x k_y}{k_\perp^2} \quad \langle \tilde{v}_y \tilde{v}_x \rangle = \sum_{\vec{k}} -k_x k_y \left| \hat{\phi}_{\vec{k}} \right|^2$$

$\therefore \; v_{gy} v_{phy} < 0$

$\rightarrow$ Backward wave!

$\Rightarrow$ Momentum convergence at stirring location

- ..."the central result that a rapidly rotating flow, when stirred in a localized region, will converge angular momentum into this region." (I. Held, '01)
- Outgoing waves $\Rightarrow$ incoming wave momentum flux



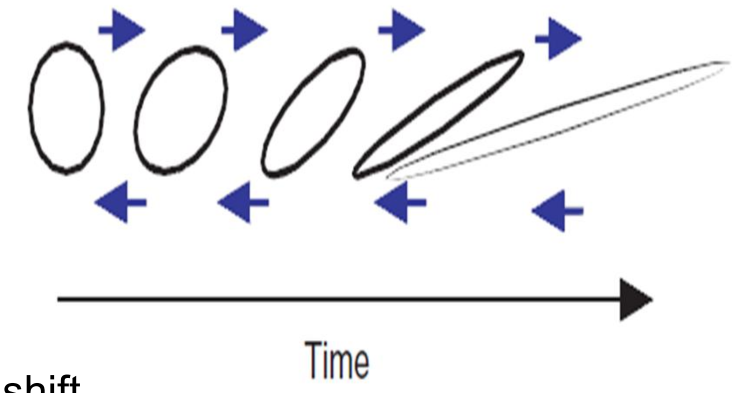
- Local Flow Direction (northern hemisphere):
  - eastward in source region
  - westward in sink region
  - set by $\beta > 0$
  - Some similarity to spinodal decomposition phenomena...

Preamble II

- What is a Zonal Flow?
  - *n = 0* potential mode; *m = 0* (ZFZF), with possible sideband (GAM)
  - toroidally, poloidally symmetric *ExB* shear flow
- Why are Z.F.'s important?
  - Zonal flows are secondary (nonlinearly driven):
    - modes of minimal inertia (Hasegawa et. al.; Sagdeev, et. al. '78)
    - modes of minimal damping (Rosenbluth, Hinton '98)
    - drive zero transport (*n = 0*)
  - natural predators to feed off and retain energy released by gradient-driven microturbulence

Shearing I

- Coherent shearing: (Kelvin, G.I. Taylor, Dupree'66, BDT'90)
  - radial scattering + $\langle V_E \rangle' \rightarrow$ hybrid decorrelation
  - $k_r^2 D_\perp \rightarrow (k_\theta^2 \langle V_E \rangle'^2 D_\perp / 3)^{1/3} = 1/\tau_c$
  - shaping, flux compression: Hahm, Burrell '94



- Other shearing effects (linear):

Response shift
and dispersion

  - spatial resonance dispersion: $\omega - k_\parallel v_\parallel \Rightarrow \omega - k_\parallel v_\parallel - k_\theta \langle V_E \rangle' (r - r_0)$
  - differential response rotation → especially for kinetic curvature effects

→ N.B. Caveat: Modes can adjust to weaken effect of external shear

(Carreras, et. al. '92; Scott '92)

Shearing II

- Zonal Shears: Wave kinetics (Zakharov et. al.; P.D. et. al. '98, et. seq.)

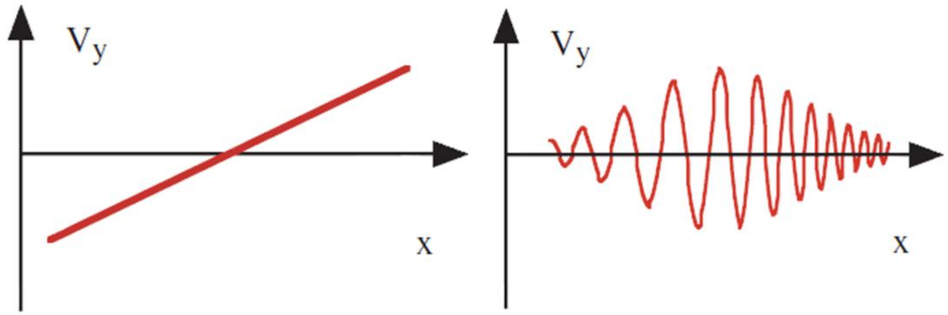
  Coherent interaction approach (L. Chen et. al.)

- $dk_r / dt = -\partial(\omega + k_\theta V_E)/\partial r \; ; \; V_E = \langle V_E \rangle + \tilde{V}_E$

  Mean shearing $: k_r = k_r^{(0)} - k_\theta V_E' \tau$

  Zonal Random shearing $: \langle \delta k_r^2 \rangle = D_k \tau$

  $$D_k = \sum_q k_\theta^2 \left| \tilde{V}'_{E,q} \right|^2 \tau_{k,q}$$



- Wave ray chaos (not shear RPA) underlies $D_k \rightarrow$ induced diffusion
- Induces wave packet dispersion
- Applicable to ZFs and GAMs

- Mean Field Wave Kinetics

$$\frac{\partial N}{\partial t} + (\vec{V}_{gr} + \vec{V}) \cdot \nabla N - \frac{\partial}{\partial r}(\omega + k_\theta V_E) \cdot \frac{\partial N}{\partial \vec{k}} = \gamma_{\vec{k}} N - C\{N\}$$

$$\Rightarrow \boxed{\frac{\partial}{\partial t}\langle N \rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r} \langle N \rangle = \gamma_{\vec{k}} \langle N \rangle - \langle C\{N\} \rangle}$$

Zonal shearing

Shearing III

- Energetics: Books Balance for Reynolds Stress-Driven Flows!
- Fluctuation Energy Evolution – Z.F. shearing

$$\int d\vec{k}\,\omega\left(\frac{\partial}{\partial t}\langle N\rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r}\langle N\rangle\right) \Rightarrow \frac{\partial}{\partial t}\langle \varepsilon\rangle = -\int d\vec{k}\, V_{gr}(\vec{k}) D_{\vec{k}} \frac{\partial}{\partial k_r}\langle N\rangle \qquad V_{gr} = \frac{-2k_r k_\theta V_* \rho_s^2}{\left(1+k_\perp^2\rho_s^2\right)^2}$$

Point: For $d\langle\Omega\rangle / dk_r < 0$, Z.F. shearing damps wave energy $\left(\langle N\rangle \sim \langle\Omega\rangle\right)$

- Fate of the Energy: Reynolds work on Zonal Flow

Modulational Instability

$$\partial_t \delta V_\theta + \partial\left(\delta\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle\right) / \partial r = -\gamma \delta V_\theta$$

$$\delta\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle \sim \frac{k_r k_\theta \delta\Omega}{(1+k_\perp^2\rho_s^2)^2}$$

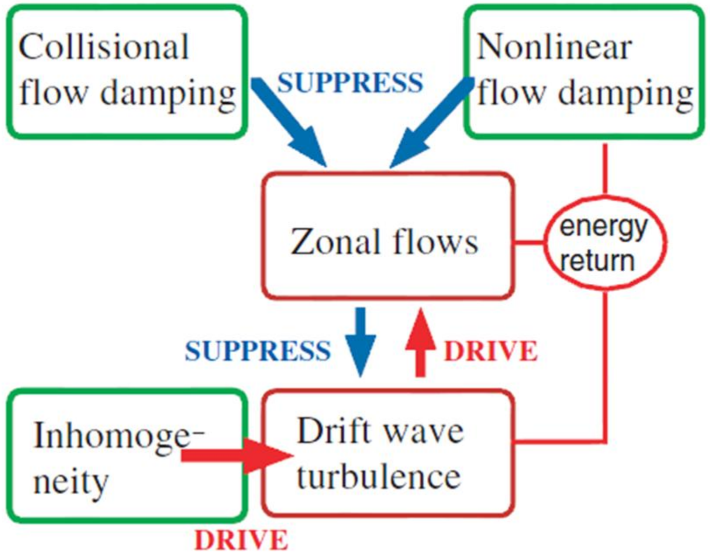
N.B.: Wave decorrelation essential: Equivalent to PV transport (c.f. Gurcan et. al. 2010)

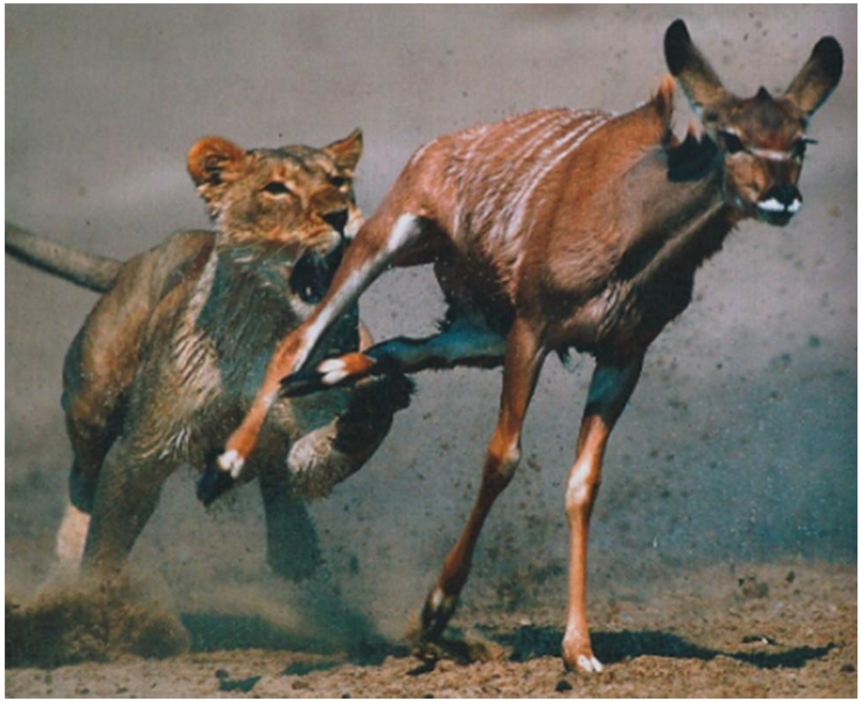
- Bottom Line:
  - Z.F. growth due to shearing of waves
  - “Reynolds work” and “flow shearing” as relabeling → books balance
  - Z.F. damping emerges as critical; MNR ‘97

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, $|\phi_q|^2$

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

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)

$$\frac{\partial}{\partial t} N = \gamma N - \alpha V^2 N - \Delta\omega N^2$$

$$\frac{\partial}{\partial t} V^2 = \alpha N V^2 - \gamma_d V^2 - \gamma_{NL}(V^2) V^2$$

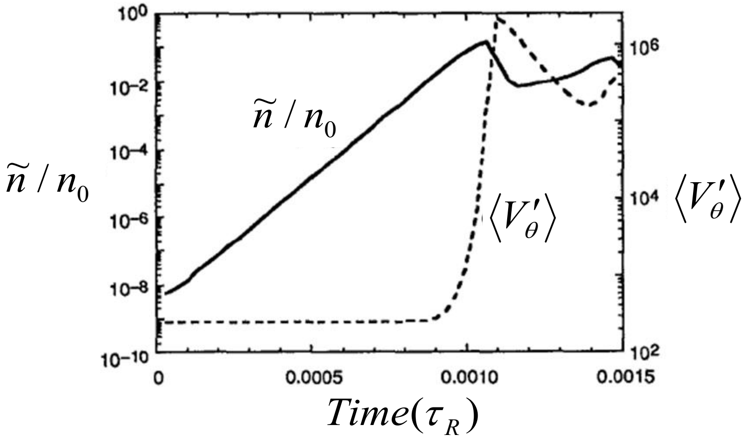
System States

State	No flow	Flow ($\alpha_2 = 0$)	Flow ($\alpha_2 \neq 0$)
N (drift wave turbulence level)	$\frac{\gamma}{\Delta\omega}$	$\frac{\gamma_d}{\alpha}$	$\frac{\gamma_d + \alpha_2\gamma\alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
V^2 (mean square flow)	0	$\frac{\gamma}{\alpha} - \frac{\Delta\omega\gamma_d}{\alpha^2}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
Drive/excitation mechanism	Linear growth	Linear growth	Linear growth Nonlinear damping of flow
Regulation/inhibition mechanism	Self-interaction of turbulence	Random shearing, self-interaction	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)	$\gamma > 0$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$

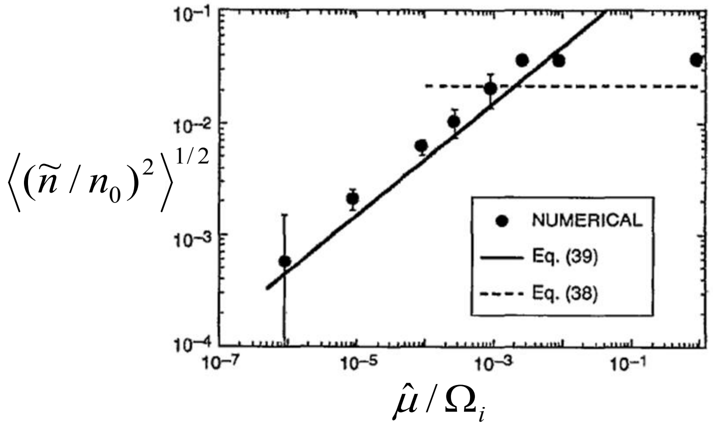
Feedback Loops III

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

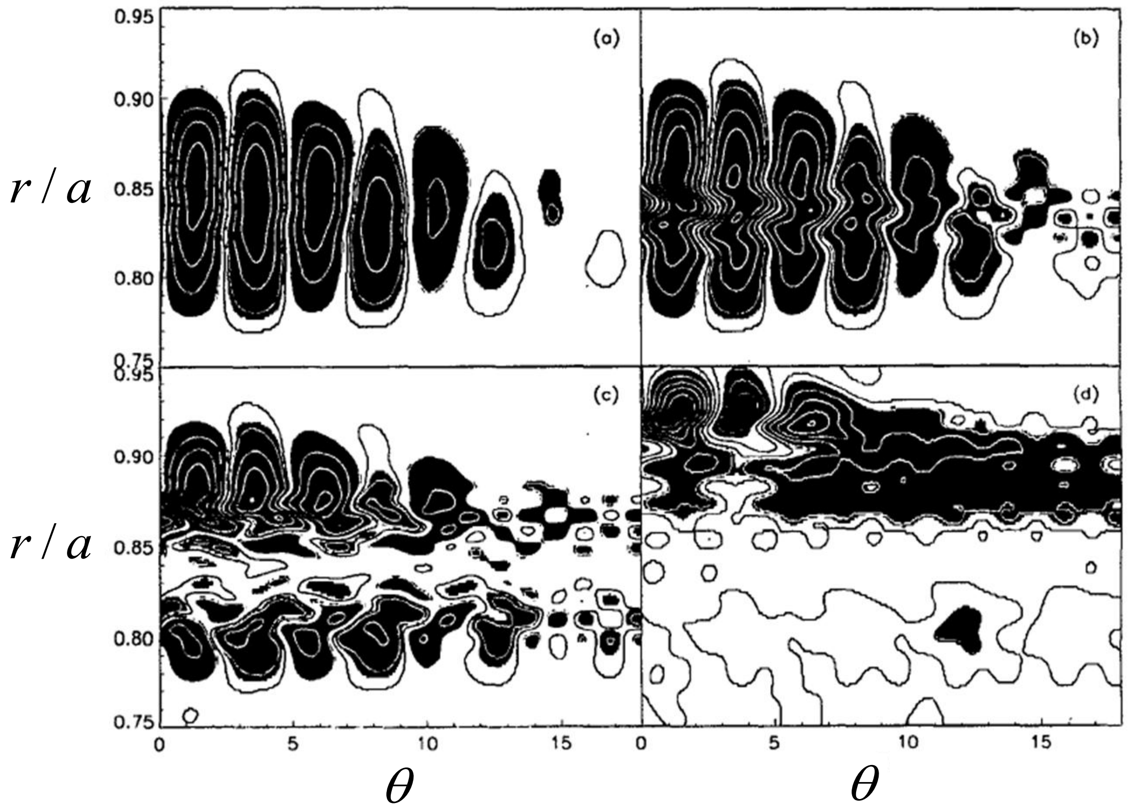
(L. Charlton et. al. '94)



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

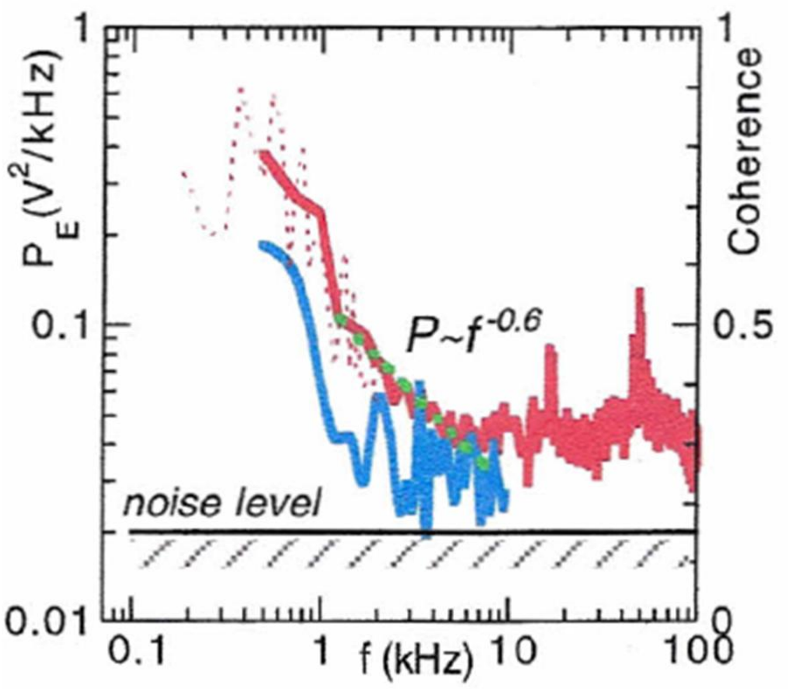


Generic picture of fluctuation scale reduction with flow shear

Feedback Loops IV

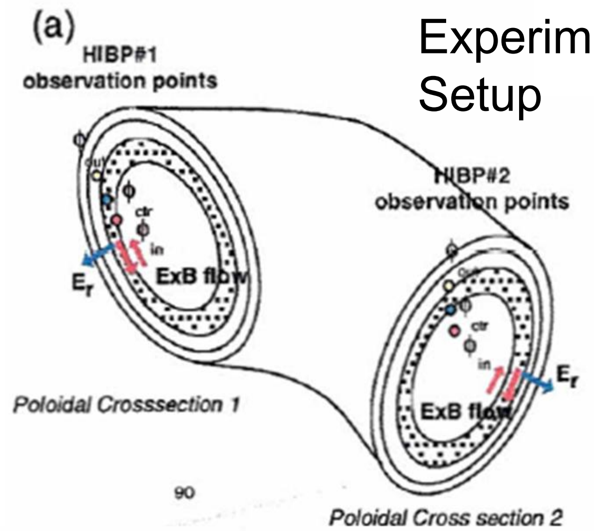
- Zonal Flows Observed in Toroidal Systems
  - Fujisawa, et. al. 2004: Correlated HIBP Scattering

Coherence PSD

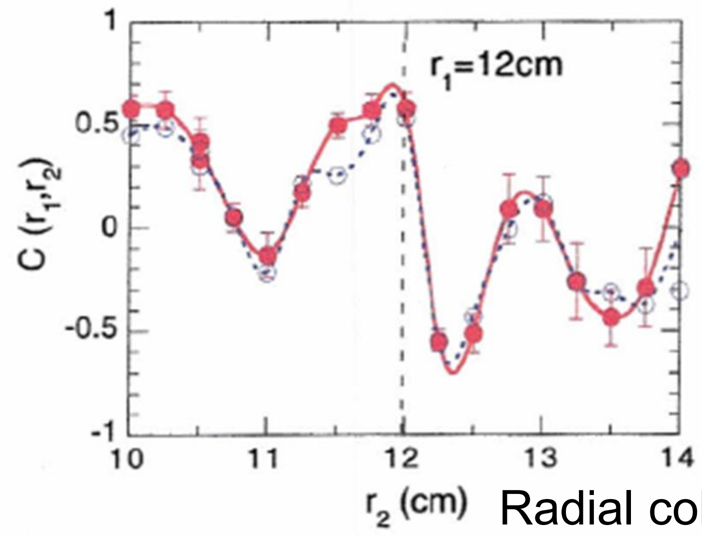


Potential Difference PSD

Red – PSD of difference
Blue - coherence



Experimental Setup



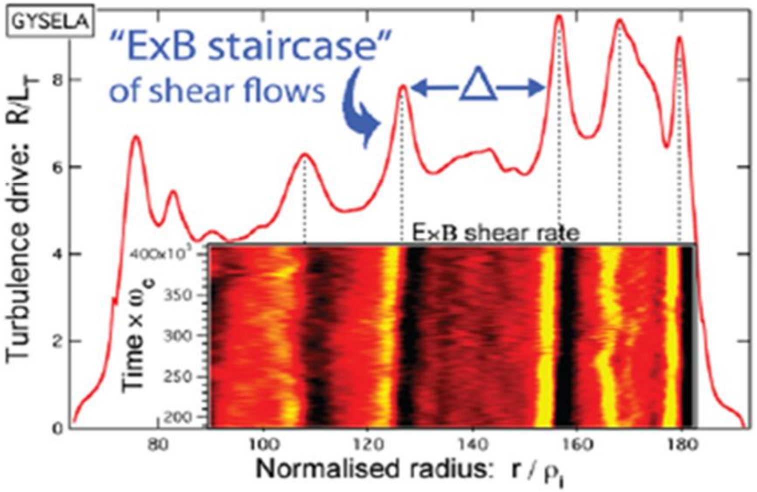
Radial Structure

Radial coherence C(r1,r2)

Forefront Topic

With G. Dif-Pradalier et. al.

Analogy with geophysics: the '**E** × **B** *staircase*'



- Quasi-regular pattern of shear layer and profile corrugations

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

- '**E** × **B** staircase' width ≡ kernel width Δ
- coherent, persistent, jet-like pattern
  ⇒ the '**E** × **B** staircase'
- staircase NOT related to low order rationals!

Dif-Pradalier, P.D. et. al., Phys Rev E. 2010

Forefront Topic, cont'd

- The point:
  - fit: $Q = -\int dr' \kappa(r,r') \nabla T(r')$ $\kappa(r,r') \sim \frac{S^2}{(r-r')^2 + \Delta^2}$ → some range in exponent
  - $\Delta >> \Delta_c$ i.e. $\Delta \sim$ Avalanche scale >> $\Delta_c \sim$ correlation scale
  - Staircase 'steps' separated by Δ ! → 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?

    → spatial, domain decomposition, ala' spinodal decomposition?

Flow Chart

Self-Organization of Profiles

Layer 1 : L→H Transition as Transport Bifurcation

Intermezzo: Zonal Modes

Layer 2 : Multi-shear Interaction

Layer 3 : Challenge of Prediction and Control

Layer 4 : Do we really *want* the H-mode?

Multi-Scale Flow and Feedback

- Awareness of zonal flow importance begged the question of ZF role in transition
- Realization: Since zonal flow is fluctuation driven, ZF can trigger transition but cannot sustain it.
- Transition is intrinsically a 2 predator + 1 prey problem
- Mean shear impacts Reynolds correlation as well as intensities.

Feedback Loops

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

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

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

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

$\mathcal{E} \equiv$ *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)

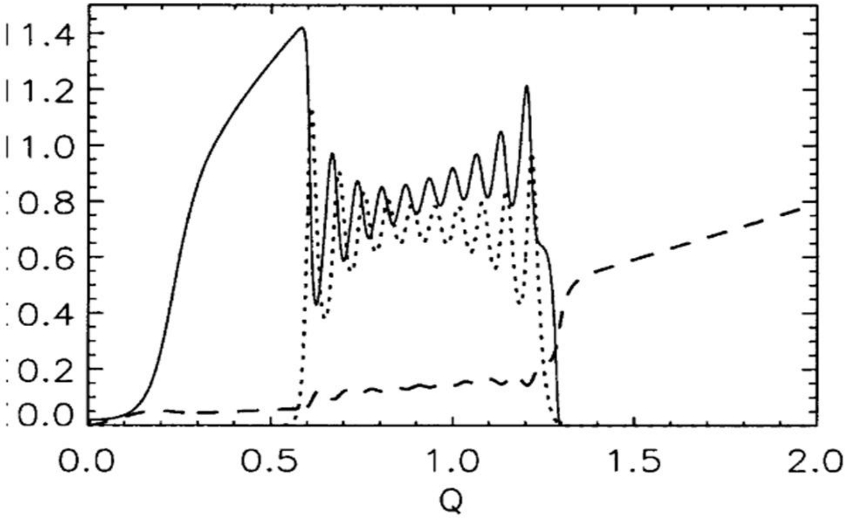
i.e. prey sustains predators
predators limit prey } usual feedback

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

L→H Transition, cont'd

- 

Solid - $\mathcal{E}$

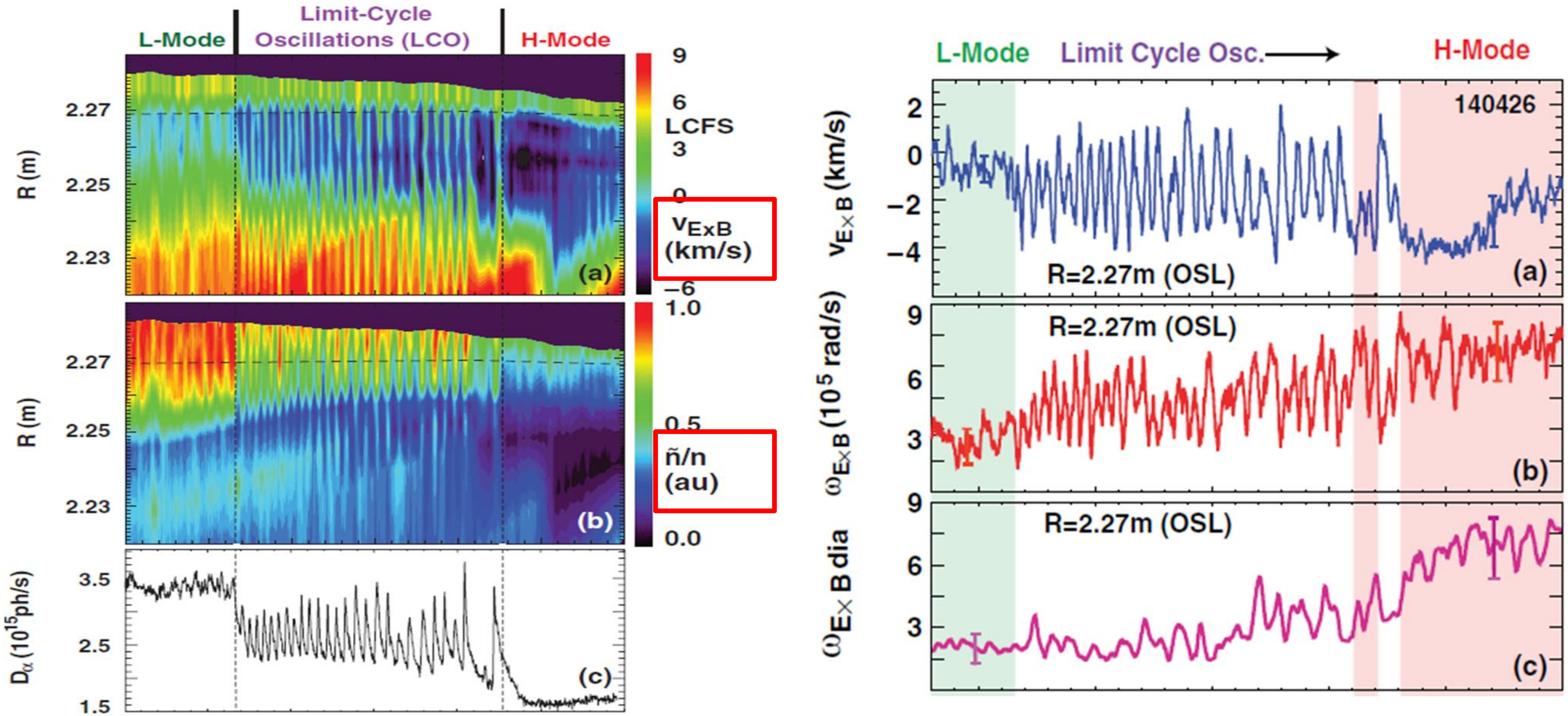
Dotted - V_{ZF}^2

Dashed - $\nabla\langle P\rangle$

- Observations:
  - ZF's trigger transition, $\nabla\langle P\rangle$ and $\langle V_E\rangle'$ lock it in
  - Period of dithering, pulsations .... during ZF, $\nabla\langle P\rangle$ oscillation as $Q\uparrow$
    $\Rightarrow$ "I-phase"
  - Phase between $\mathcal{E}$, V_{ZF}^2, $\nabla\langle P\rangle$ varies as Q increases
  - $\nabla\langle P\rangle$ $\Leftrightarrow$ ZF interaction $\Rightarrow$ effect on wave form

L→H Transition, again

- LCO / Intermediate Phase Now Observed in Many Experiments (L. Schmitz, et. al. 2012)



- Zonal shearing LCO during I-phase allows $\langle V_E \rangle'$ to grow
- At transition, turbulence and ZF decay, mean shear locks in H-mode

L→H Transition

- Spatio-Temporal Evolution:

  5-field, *k*-*ε* Type Model

  (with K. Miki)

Predator-prey model

Turbulence intensity: $\gamma_L \sim \gamma_{L0}\frac{c_s}{R}\sqrt{\frac{R}{L_T}-\left(\frac{R}{L_T}\right)_{crit}}$ ← from *p*,*n* profile

$$\partial_t I = (\gamma_L - \Delta\omega I - \alpha_0 E_o - \alpha_V E_V)I + \chi_N \partial_x (I\partial_x I)$$

Driving term; Local dissipation; ZF shearing; MF shearing; Turbulence spreading

Zonal flow energy: $E_0 = V_{ZF}^2$ $\quad \alpha_0 \sim \alpha_V \sim \tau_{ac0}\frac{\sqrt{a\rho_i}}{c_s}$ $\quad (\tau_{ac} << 1)$

$$\chi_N \sim \chi_{N0}\chi_{GB} \sim \chi_{N0}\frac{\rho_i^2 c_s}{a}$$

$$\partial_t E_0 = AE_0\alpha_0(I/(1+\zeta_0 E_V) - I_*)$$

Screening factor; Reynolds stress drive; MF/ZF competition; ZF collisional damping

$$I_* = \gamma_{damp}/\alpha_0$$

$$\gamma_{damp} \sim \nu_{ii}/R$$

Mean flow shearing:

$$E_V = (\partial_x V_{E\times B})^2$$

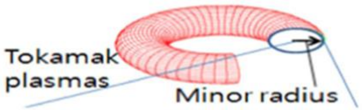
→ by radial force balance

Short time scale normalization $\omega_*(\sim c_s/a)t \to t$ $\quad$ Small spatial scale $\rho_i \sim 0.01a$

Long time scale τ_{ii} $(=1/\nu_{ii}) \sim 600(a/c_s)$ $\quad$ Long spatial scale normalization $r/a \to r$

1D transport model

x: radial direction



pressure $\quad \partial_t p(x) + \partial_x \Gamma_p = \partial_x H$

density $\quad \partial_t n(x) + \partial_x \Gamma_n = \partial_x S$

$$\Gamma_p = -(\chi_{neo} + \chi_o)\partial_x p$$

$$\Gamma_n = -(D_{neo} + D_o)\partial_x n - Vn$$

Pinch term

TEP pinch; Thermoelectric pinch

$V = (v_{0,TEP} + v_{0,TE})$ Inward pinch

$$\simeq \left(\frac{D}{R} - \frac{D}{L_T}\right) \quad (\propto I,\ L_T < 0)$$

$$n \sim \exp\left(-\frac{V}{D}r\right)$$

→density peaking

Neoclassical transport term

Banana regime

$$\chi_{neo} \sim \chi_{Ti} \sim \varepsilon_T^{-3/2} q^2 \rho_i^2 \nu_{ii}$$

$$D_{neo} \sim (m_e/m_i)^{1/2}\chi_{Ti}$$

Turbulent transport term

$$D_0 \sim \chi_0 \sim \frac{\tau_c c_s^2 I}{(1+\alpha_t V_E'^2)}$$

→*Predator-prey model*

A la' Hinton

Poloidal momentum spin-up

- Coupling radial and parallel momentum force balance equations, we obtain

Eq. of poloidal rotation

Turbulence drive obtained from stress tensor [McDevitt, PoP '10]; Neoclassical effects

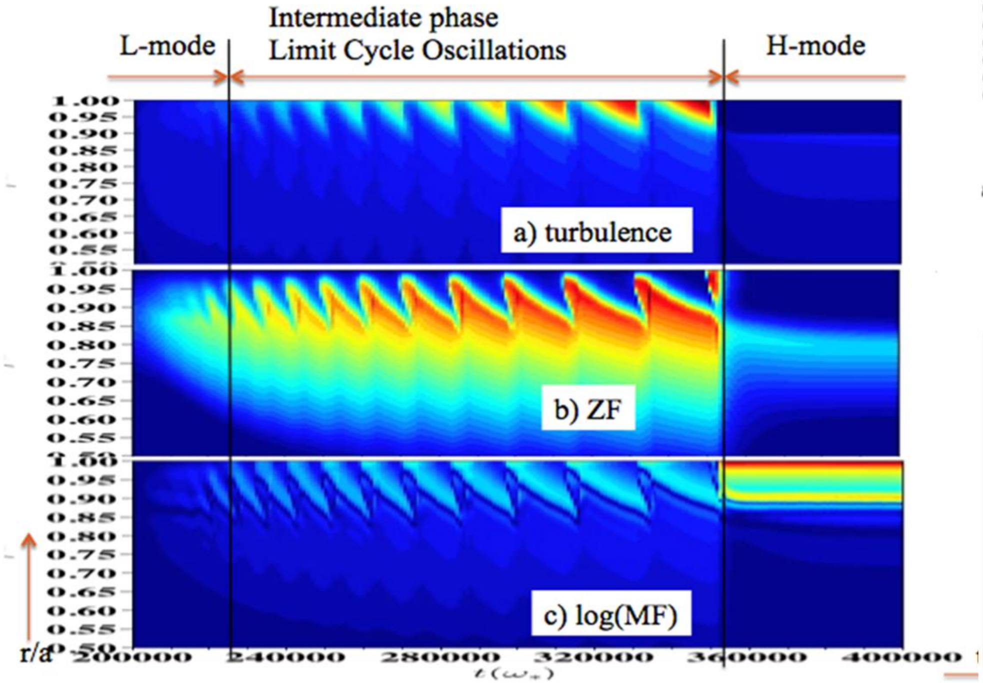
$$-\frac{\partial u_\theta}{\partial t} = \frac{1}{nm}\left\langle \nabla\cdot(\hat{e}_y \vec{\Pi}_{turb})\right\rangle + \mu_{ii}^{(neo)}(u_\theta - u_\theta^{(neo)})$$

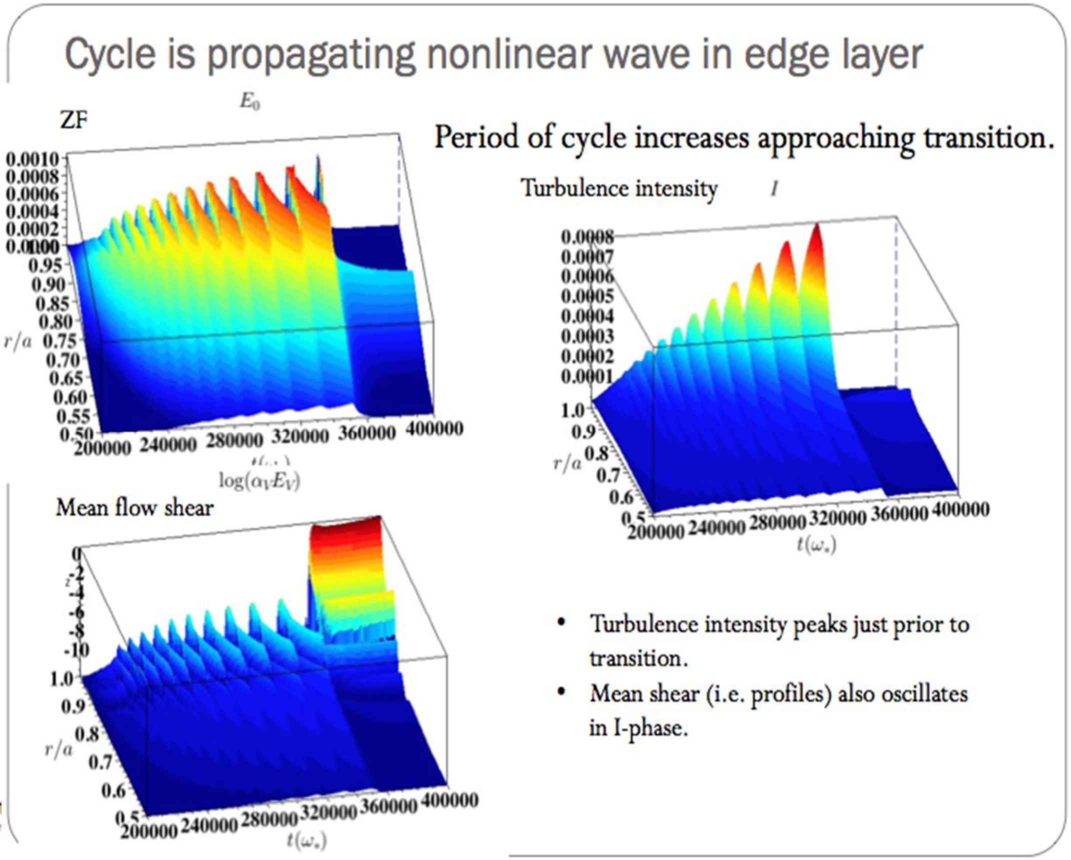
$$\sim \alpha_5 \frac{\gamma_L}{\omega_*} c_s^2 \partial_x I + \nu_{ii} q^2 R^2 \mu_{00}(u_\theta + 1.17 c_s \frac{\rho_i}{L_T})$$

Totally, time-evolving 5-fields (n, p, I, E_0, and u_θ) are solved numerically.

Reduced Model Captures Many Features of L → I → H Transition

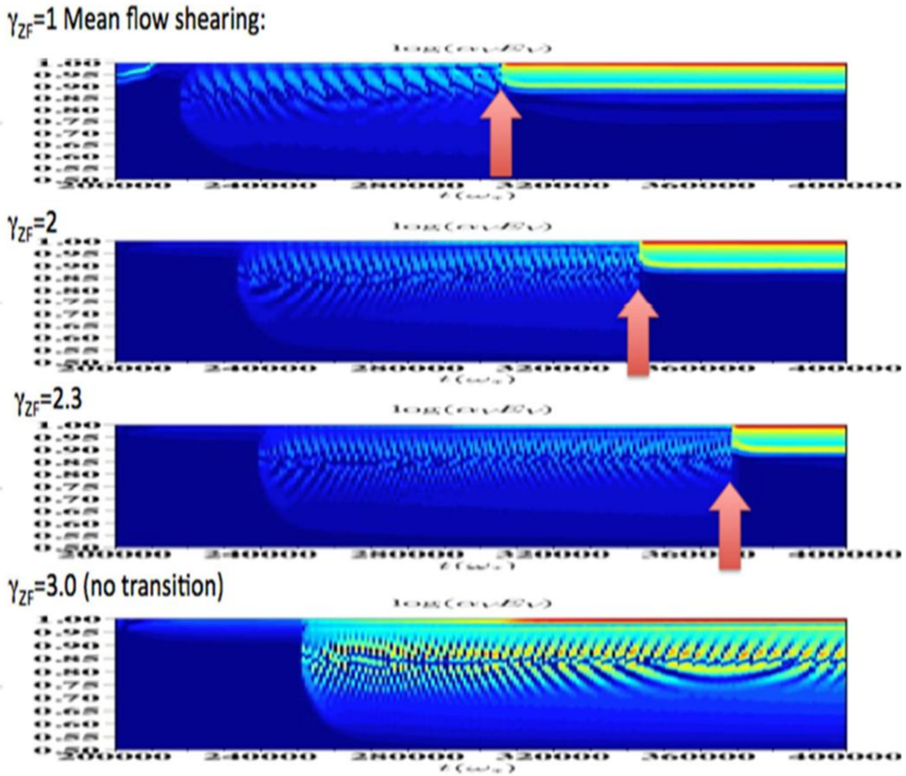
Slow Power Ramp Indicates
L → I → H Evolution



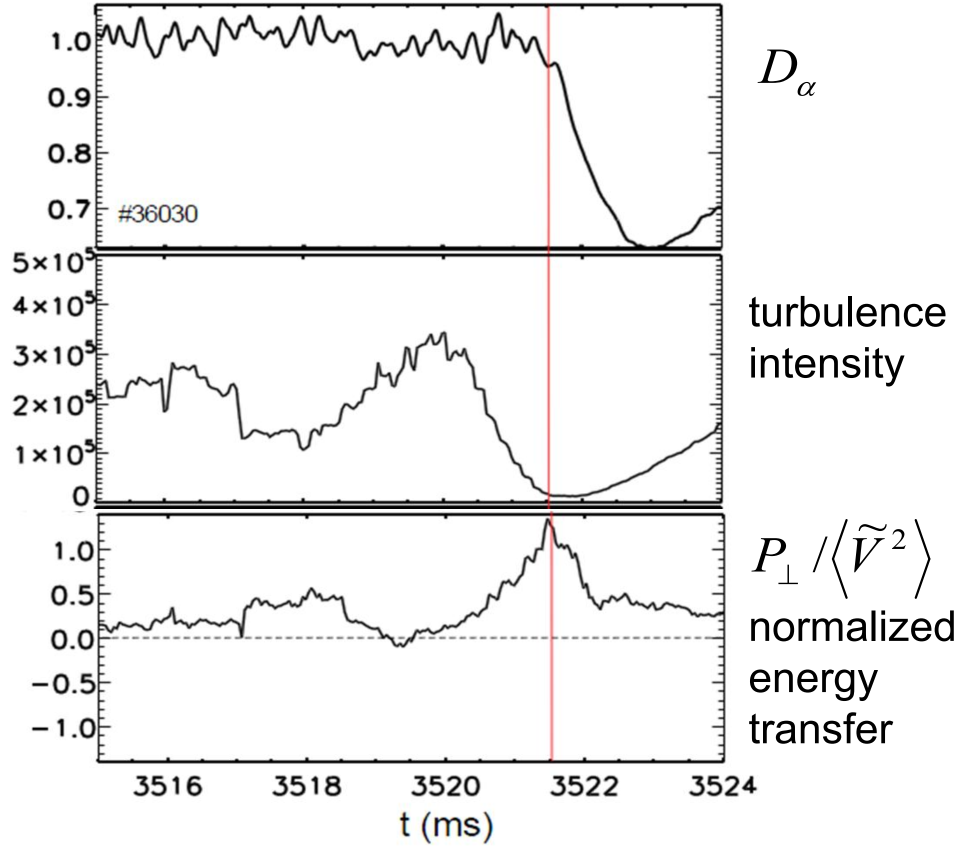


L→H Transition

- Is the zonal flow the ‘trigger’ of the L→H transition?
- Model
- Experiment – EAST (P. Manz, et. al. 2012)



Increasing ZF damping can delay or suppress transition



L→H Transition

- Partial Conclusions
  - Dynamics of L→H transition effectively captured by multi-shear predator-prey model
  - Theory and experiment both strongly suggest that zonal flow is the trigger of L → H transition
  - Remaining Issue:
    - Connection of P_{thresh} scalings to micro-dynamics,

      i.e. Zonal flow damping should enter P_{thresh}

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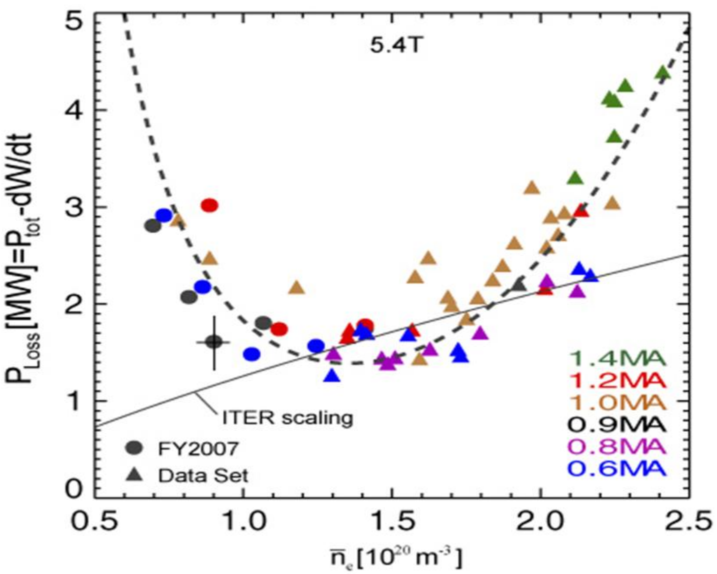
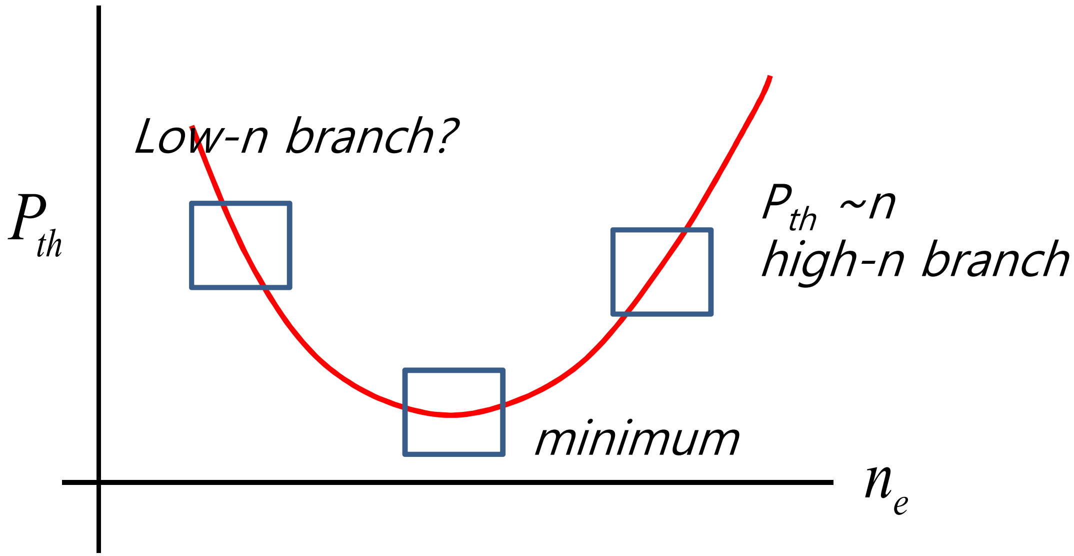
Problem in H-mode Physics: A Selected List

- What sets $P_{th}\,(n)$?

  Strength of hysteresis?



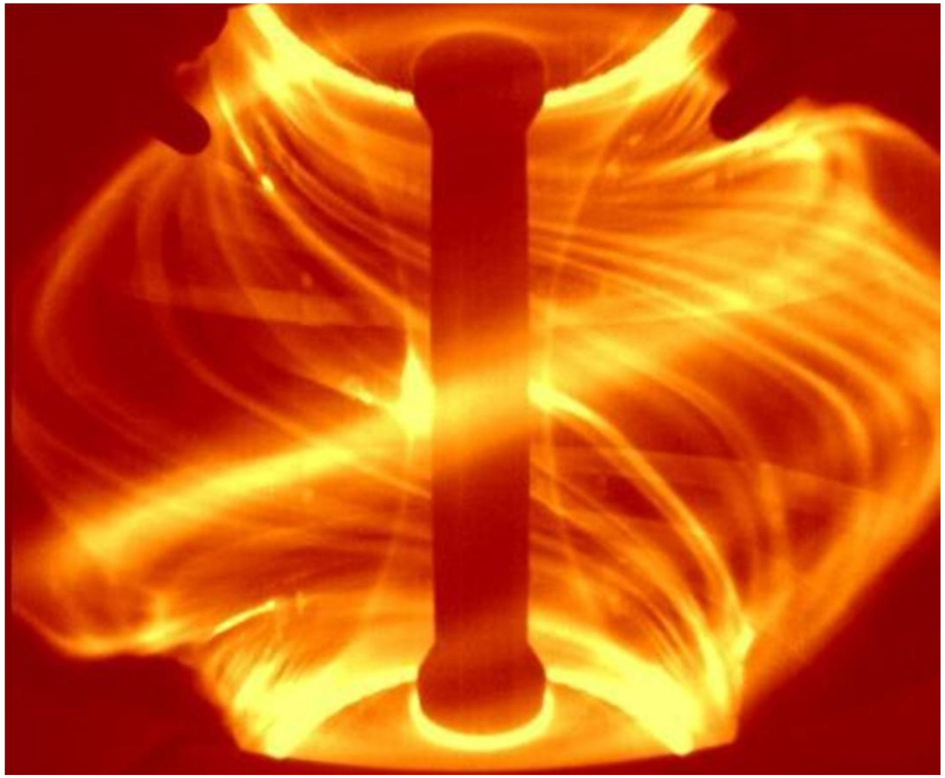


  - $P_{th}\,(n)$ scaling at high density due zonal flow collisional damping
  - Understanding of low-n branch remains elusive ➔ electron-ion coupling for low-n ECH

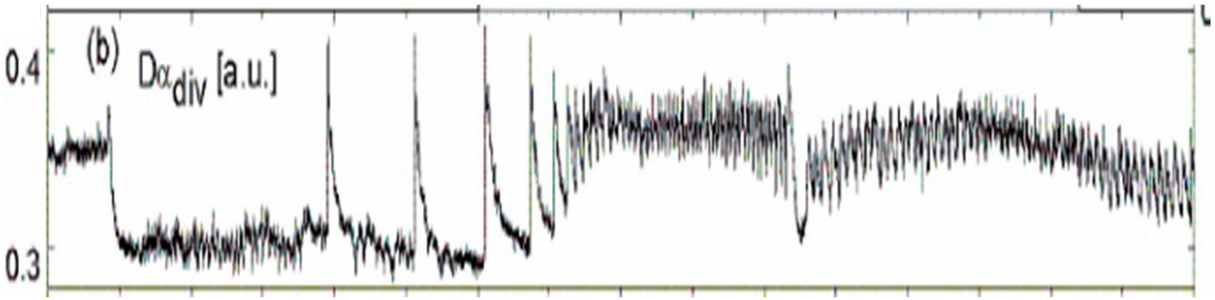
- Little understanding of $\frac{P_{LH}}{P_{HL}} > 1$ trends, even empirically

ELMs (Edge Localized Modes)

- ELMs are quasi-periodic edge relaxation bursts observed in H-mode and ∇P steepens and turbulence suppressed
- ELMs are (likely) related to localized macroscopic MHD instabilities, possible only in states of good confinement
- ELMs produce unacceptably LARGE transient heat load on plasma facing materials

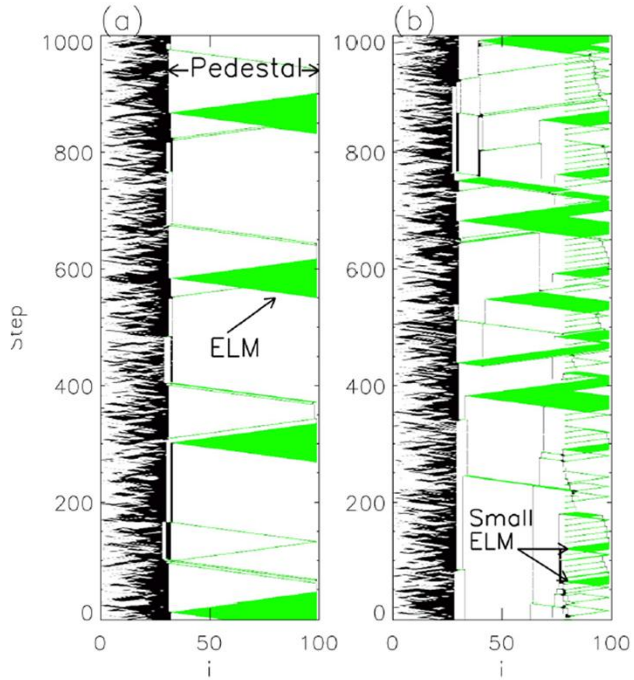


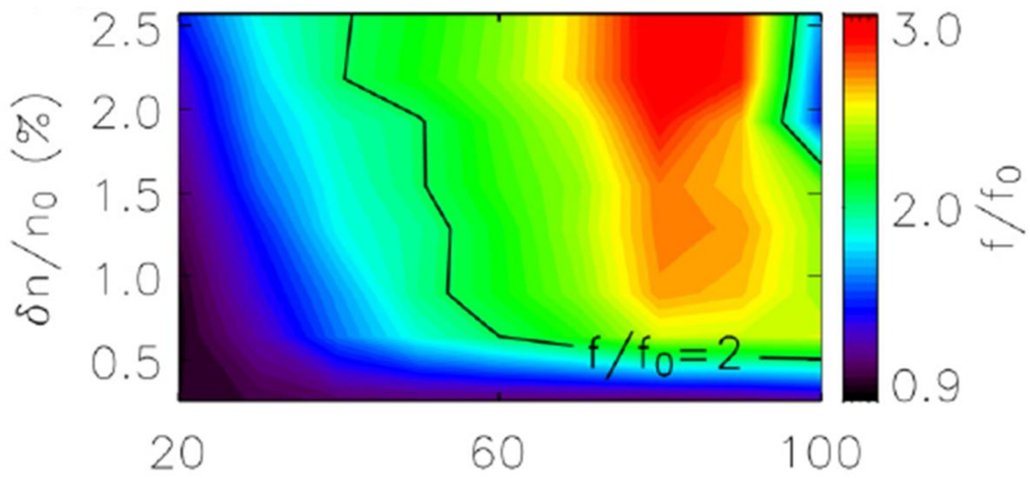
D_α



How control ELMs?

- RMP (cost >> $MB) (RMP pioneered at GA, San Diego by Todd Evans)
- Small pellets, SMBI (cost $\leq \$10\ KB$) (SMBI pioneered and developed at SWIP, Chengdu by Weiwen Xiao, L. Yao)
- Seeks to prevent formation of large transport events by perturbing $\nabla n, \nabla P$ in pedestal by injection
- How does SMBI work? (see also T. Rhee, this meeting)





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Is the H-mode really THE desirable mode of operation?

(see also M. Kikuchi, this meeting)

i.e.

- ELM control
- ITER W divertor
  - High Z impurity accumulation
  - Need ELMs to avoid radiative collapse
  - But plasma facing loads?
- SOL power e-folding length (R. Goldston, et. al.)
- ECH-driven intrinsic rotation and RWM control?

…… …..
…… …..

Open questions, and alternatives exist but not well explored…

Summary

What Lessons have we learned?

- Fusion plasma dynamics is rich in problems in complexity, nonlinear dynamics, self-organization, multi-scale phenomena

- The quest to understand the L→H transition has triggered much of the progress in fusion physics during past 30 years

- Much progress, but open questions remain

⇒ Outlook of the Past:

"What is the optimal configuration within which to contain the plasma?"

⇒ Outlook of the Future:

"What is the optimal means by which to achieve the self-organized state of the plasma?"