MHD Turbulence in a Prescribed Stochastic Magnetic Field

P.H. Diamond[(1)], M. Cao[(1)], M. Choi[(2)], J.M. Kwon[(2)]

U.C. San Diego, USA
KSTAR Team and KFE, RoK

Stochastic Approaches to Turbulence
in Hydrodynamical Equations, 2022

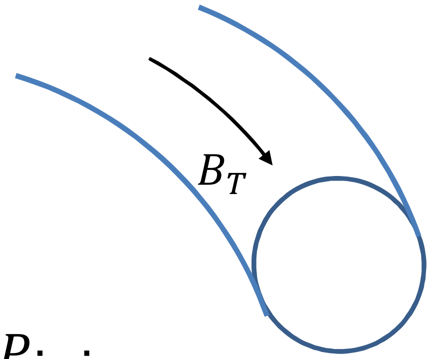
This research was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DEFG02-04ER54738.

Outline

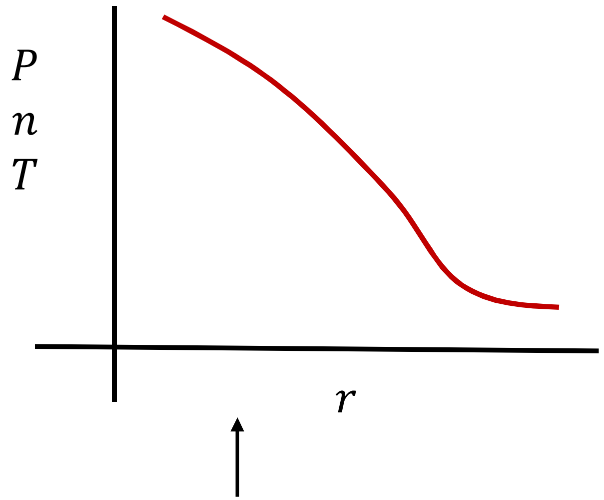
- Why this? → Confinement is too good…
  - the H-mode
  - Boundary control, RMP and trade-off
- Some Evidence → KSTAR fluctuation analysis
  - Complexity and Bi-coherence
  - Implications
- Beginnings of a Theory
  - Resistive interchange(s) in stochastic field
  - Novelties: ‘Micro-cells’ and ‘Locking-on’
- Outlook

Why this Problem ?

What is a tokamak ?



$$\tau_E = W/P_{\text{inj}}$$



Profiles → energy content

- Crucial element – plasma boundary
  - Profile gradient at separatrix key indicator of confinement state

Evolution of MFE Theory

Prehistory: 3D

- Beginnings: 60's ~ 1980

Trieste	T3
Micro-stability	Alcator A
Neoclassical theory	PLT
Disruption models	TFR
Taylor Relaxation	

- Understanding Good Confinement: 1980 ~ 2010

[Self-Organization]

ExB shear, ZF's	ASDEX → H-mode
Transport Bifurcations	Alcator C, C-Mod → pellet, n-limit
Gyrokinetics, Simulation	TFTR, JET → D-T
AE modes	DIII-D → ETBs, ITBs
Intrinsic Rotation	JT-60U → ETBs, ITBs

Evolution of MFE Theory

- Good Confinement + Good Power Handling → ITER:
  2010 – Present, and beyond

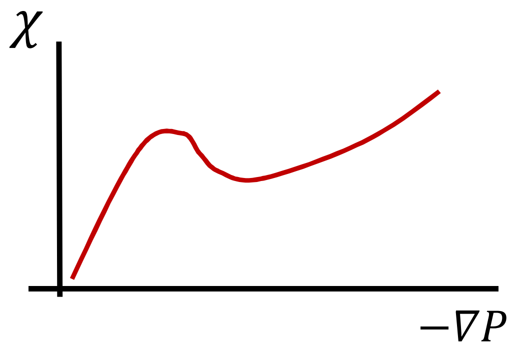
ELMs, Peeling-Ballooning	DIII-D, AUG
RMP, QH-mode	Alcator C-Mod
Multi-scale problems	LHD
Core-Edge coupling,	W7X
Turbulence Spreading	RFX-QSH
Disruptions (?)	EAST, KSTAR
SOL Heat Loads (?)	...
	...

N.B.:
Return to 3D !

➔ Theory must address trade-offs

Theoretical Problem: L→H Transition

- What of L→H ? → Converging, though still open questions



- Fundamentals:
  - Transport bifurcation
  - Bistability essential – S curve
  - Robust feeadback channel – ExB shear flows
  - Insulation layer at the edge...

$$\chi_T = \chi_T(V'_{E\times B}/\omega)$$

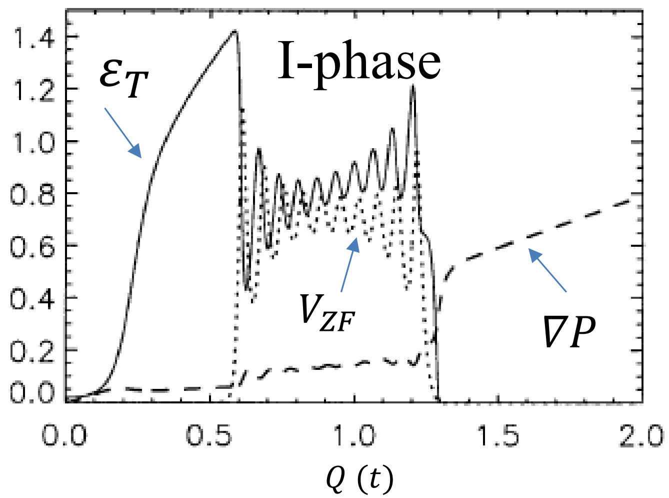
$$V_{E\times B} = \nabla P/n + \cdots$$

$\chi_T \downarrow$ for $V'_{E\times B}/\omega$ > crit.

- Subtleties
  - What is the "trigger"? → i.e.,
  - What physics allows ∇P to steepen?
- Coupling of energy to edge zonal flow
  - Interplay of $\varepsilon_T, V_{ZF}, \nabla P$
  - $P_{Reynolds}$ crit. needed,

    measured (Tynan)
  - Crucial to note <u>$E \times B$ flow</u>

Kim, PD, PRL'03



40 Years of H-mode - Lessons

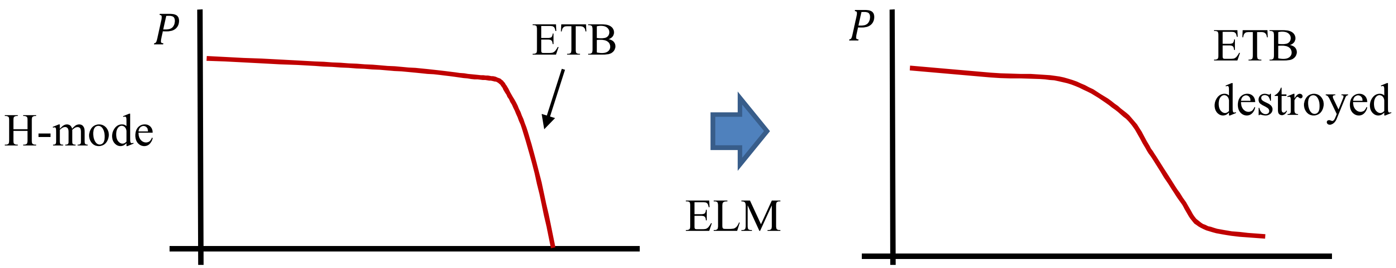
- Saved MFE from Goldston scaling

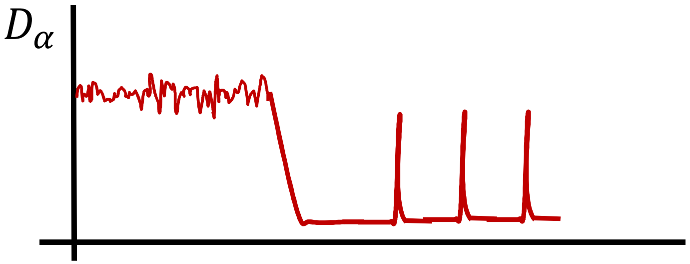
Also:

- Introduced transport barrier, bifurcation → state 'phases' and transitions
- Role of flow profile in confinement (BDT '90)
- Dynamical feedback loops → Predator-Prey cycles, Zonal flows, etc. (PD+'94,05; K-D '03)
- Consequences of marked transport reduction
- ➡ Need for transport regulation, not transport elimination

ELMs and RMP – A Primer

- ELM = Edge Localized Mode (Mode ?!)



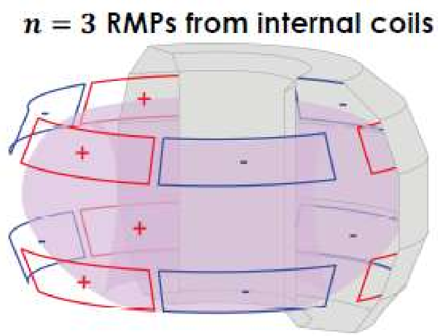


← ELM cycle

ITER: $\Delta W_{ELM} \sim 20\ MJ$!

→ Heat loads on PFC !?

- RMP = Resonant Magnetic Perturbation - δB
  - Stochastic edge layer
  - Pump out - density
  - Mitigate, suppress ELMs, with good confinement



to ITER

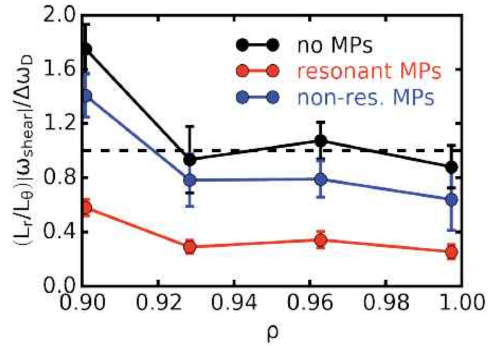
Resonant Magnetic Perturbations Disrupt Shear Suppression of Turbulence, Increasing the L-H Power Threshold

- RMPs reduce flow shear rates ω_{shear} and raise turbulence decorrelation rates $\Delta\omega_D$ in L-mode

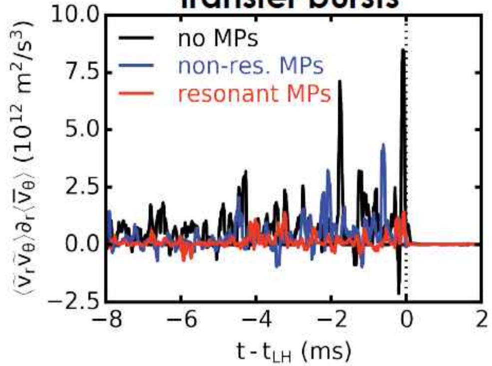
* Shear suppression parameter $\omega_{shear}/\Delta\omega_D$ is reduced significantly below 1
  - More shear flow must be driven to access H-mode

* RMPs disrupt nonlinear energy transfer from turbulence to flows that can trigger L-H transition

Shear suppression parameter



nonlinear energy transfer bursts

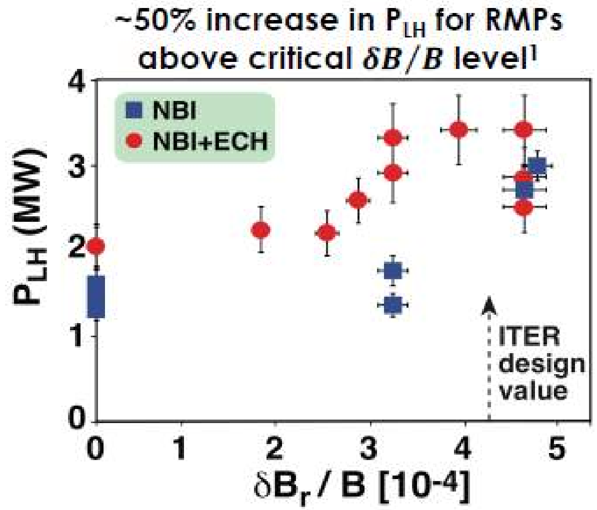


Benefit and Cost

- Need make L→H Transition with RMP !
- Increase in P_{th} for L→H !?
  - $(\delta B/B)_{crt}$ for

    L→H Power increase
  - Significant !
- Issues:
  - Why L→H threshold ↑ due RMP
  - What physics defines $(\delta B/B)_{crt}$?
  - Turbulence in stochastic magnetic field!

"First ELM the largest"



(resonant vs. non-resonant)

Kriete et. al. DIII-D

The Problem:

➔ **MHD turbulence in ambient stochastic magnetic field**

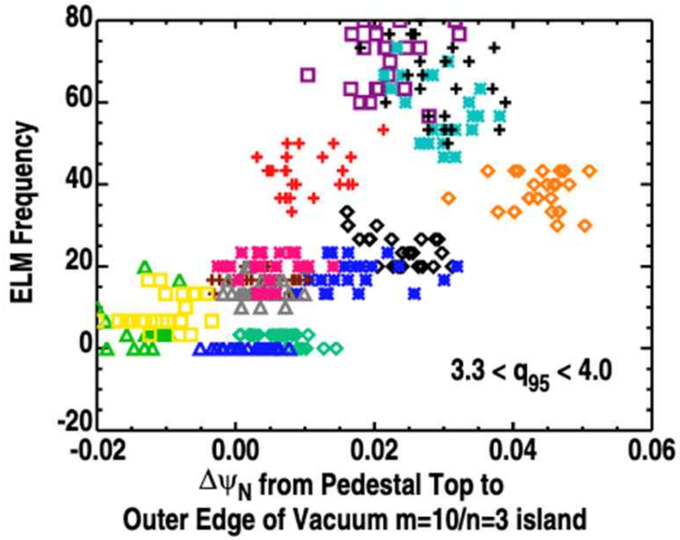
Some Evidence –

KSTAR Fluctuation Studies

Key Question: Stochasticity of Applied Field?

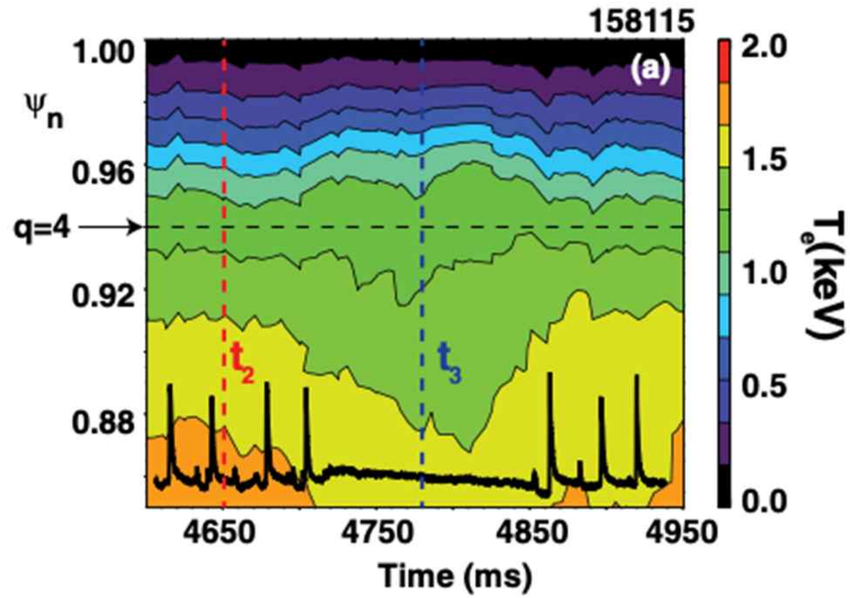
Previous exp. observations implying a stochastic layer

- RMP ELM suppression was achieved when the resonant rational surface is close to pedestal top (R_{top})



[Wade, Nucl. Fusion 55, 023002 (2015)]

- Localized temperature flattening near R_{top} during the RMP ELM suppression



[Nazikian, PRL 114, 105002 (2015)]

- Another way to identify a stochastic layer?

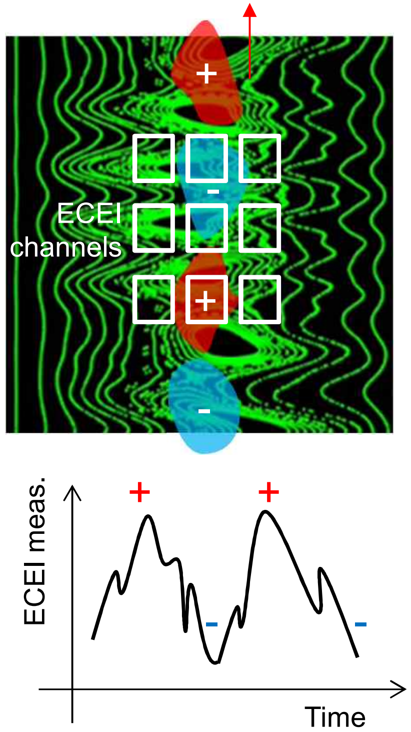
Pedestal T_e fluctuation diagnostics & analysis methods

- Localized T_e fluctuation near the pedestal top can be measured using the 2D electron cyclotron emission imaging (ECEI) diagnostics
  [Yun, Rev. Sci. Instrum. 85, 11D820 (2014)]

- Spectral methods
  - Cross power spectrum, frequency/wavenumber power spectrum (two-points method), [Beall, J. Appl. Phys. 53, 3933 (1982)] wavelet bicoherence [van Milligen, Phys. Plasmas 2, 3017 (1995)]

- Statistical method
  - The Complexity-Entropy analysis
    [Rosso, Phys. Rev. Lett. 99, 154102 (2007)]

Background figure copied from [Hu, Nucl. Fusion 60, 076001 (2020)]



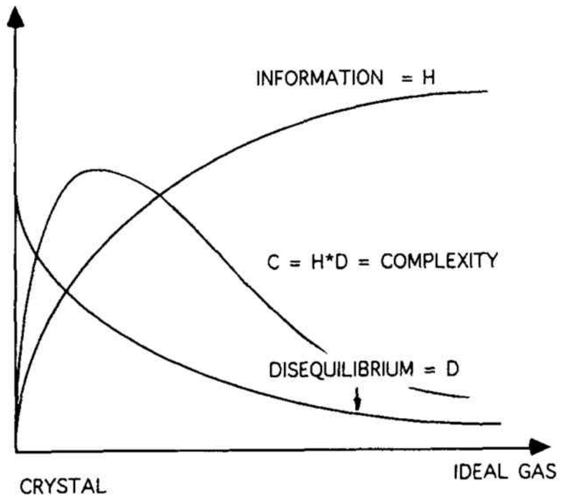
(Information theoretic) meaning of Complexity and Entropy

- Meaning of Entropy : a measure of missing (unknown) information
  - Shannon Entropy $S[P] = -\sum_i p_i \ln p_i$ where $P = \{p_i\}_{i=1,\ldots,N}$
  - Normalized Shannon Entropy $H = S/S_{\mathrm{max}}$ where $S_{\mathrm{max}} = \ln N$ for the equiprobable distribution

- Meaning of Complexity : disequilibrium (D) x information (H) [Lopez-Ruiz, Phys. Rev. A 209, 321 (1995)]
  - Disequilibrium : distance from the equiprobable distribution ($P_e = \{p_i = 1/N\}$)

Two examples of a "simple" (not complex) system in physics : a perfect crystal or ideal gas

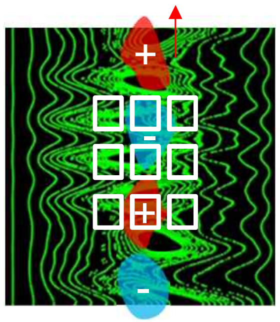
	Information	Disequilibrium	Complexity
Perfect crystal	Small	Large	Small
Ideal gas	Large	Small	Small

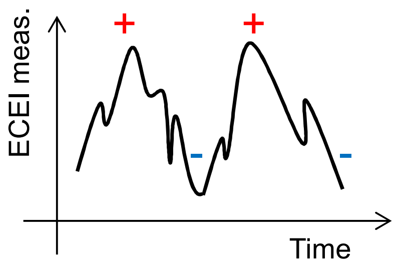


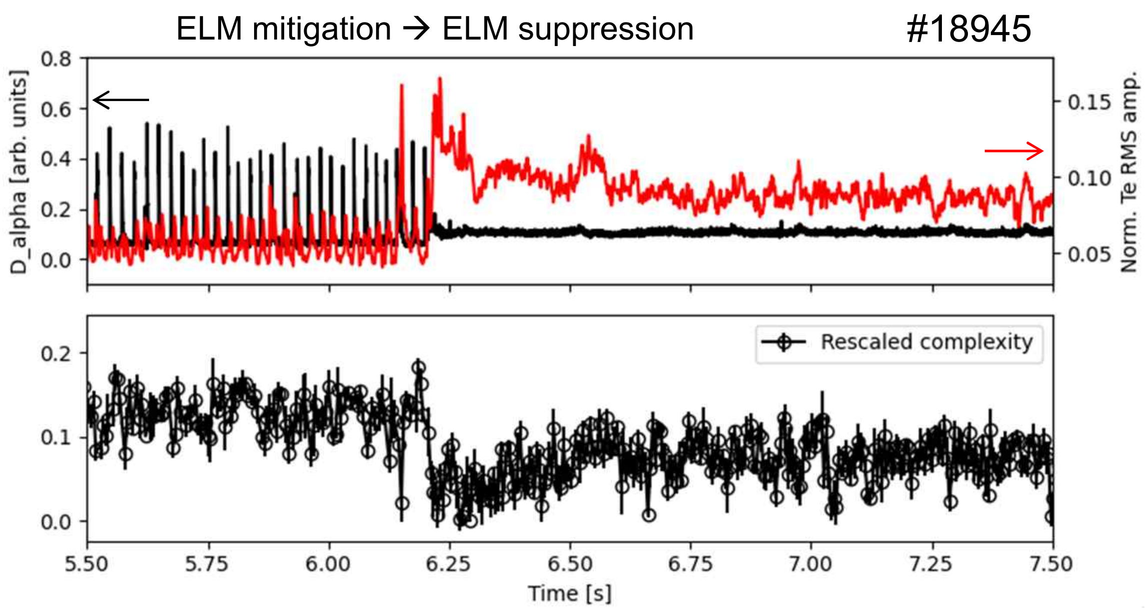
- What state for P? How to measure D?

Rescaled complexity of T_e fluctuation at the pedestal top

- T_e fluctuation amplitude increases with ELM mitigation-suppression transition
  - It has a broad wavenumber range ($k_\theta \rho_i < 0.4$)
  - It is larger than the inter ELM period level
- Parameters to calculate P_{BP} & $\hat{C}$
  - Time step between points = 2 us
  - Size of each segment = 5 points (10 us ~ $\frac{\text{cm}}{\text{km/s}}$)
    - Structures of 10—100 kHz
  - 2500 (>> 5!) segments to calculate one BP PDF



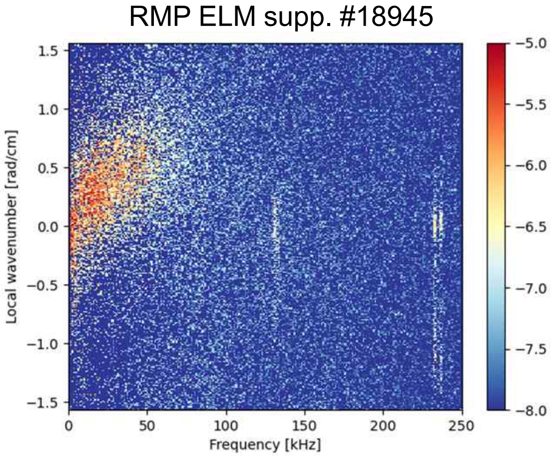


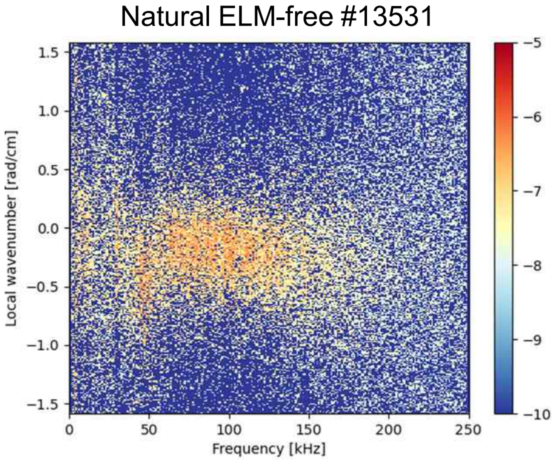


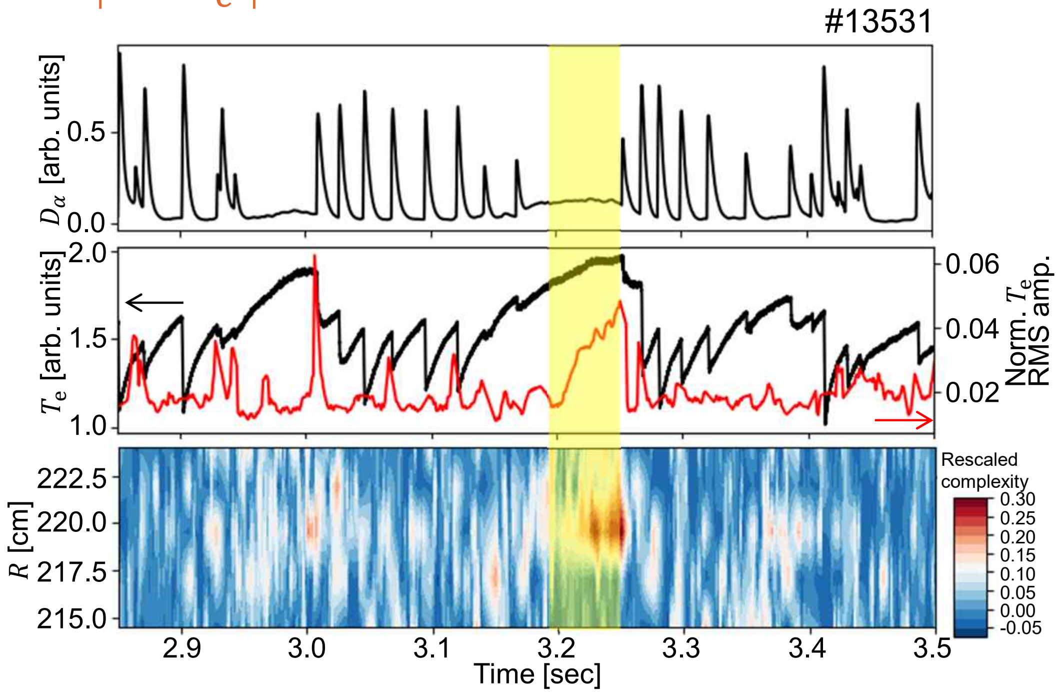
- Rescaled complexity of T_e fluctuation decreases with the ELM suppression
  - T_e becomes less complex (more stochastic)
- Result of stochastic fields?

Comparison with a natural ELM-free case

- The natural ELM-free phase
  - The broadband T_e fluctuation increases and its rescaled complexity also increases
  - Turbulence w/o RMP field develops to have a complex T_e pattern rather than to be stochastic

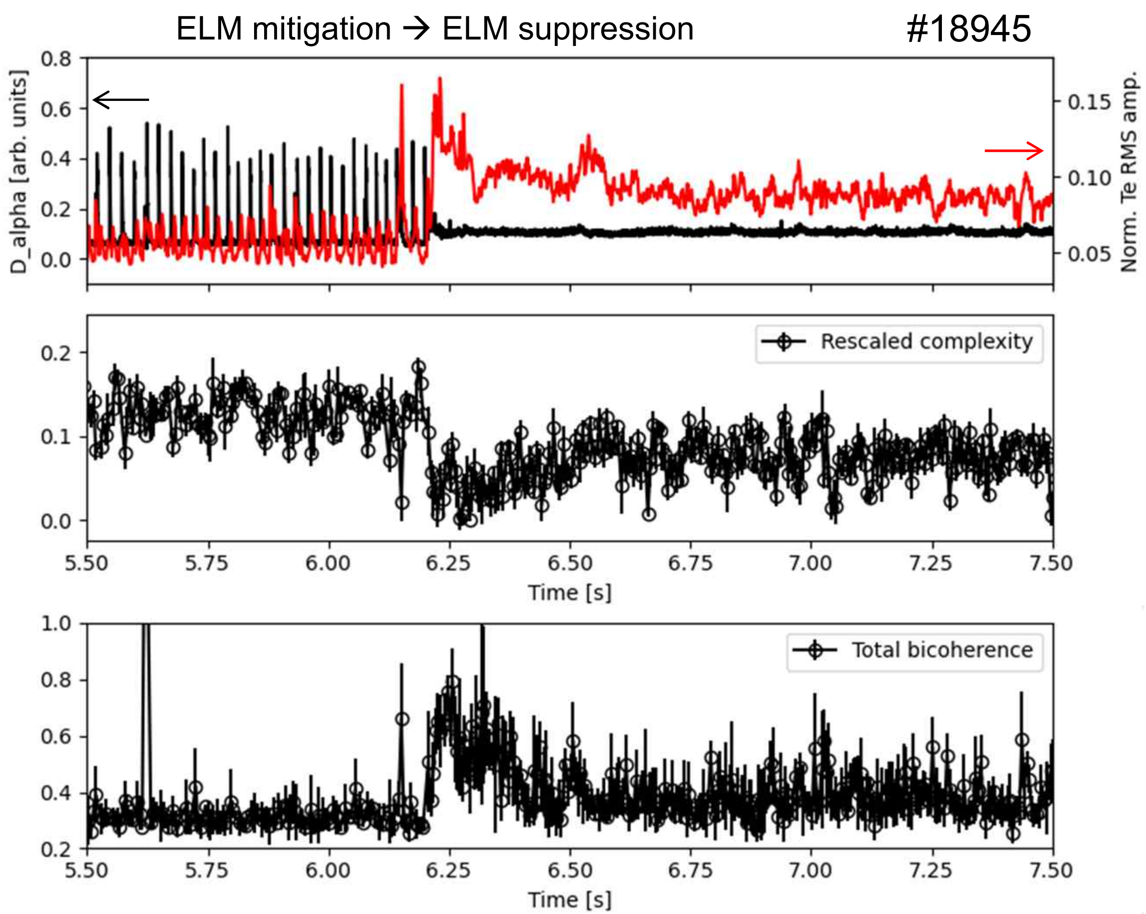






Bicoherence analysis of T_e fluctuation at the pedestal top

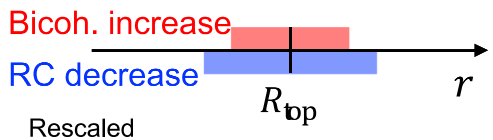
- T_e fluctuation amplitude increases with ELM mitigation-suppression transition
  - It has a broad wavenumber range ($k_\theta \rho_i < 0.4$)
  - It is larger than the inter ELM period level
- Rescaled complexity of T_e fluctuation decreases with the ELM suppression
  - T_e becomes less complex (more stochastic)
- Bicoherence of T_e fluctuation increases
  - Triad coupling between $f_1, f_2, f_3 = f_1 + f_2$
- Contradictory result?



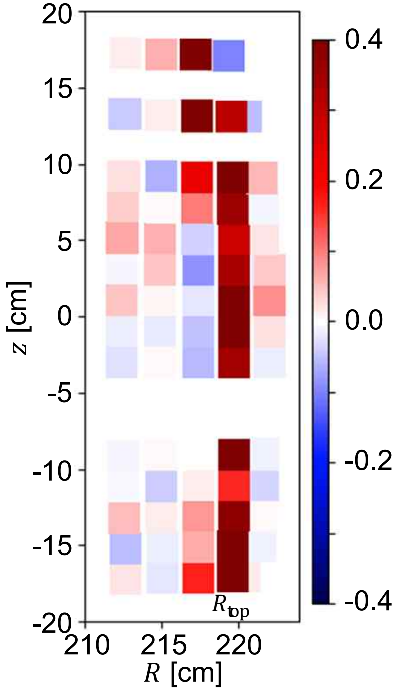
Distinguished in real and frequency space

- 2D structures of bicoherence and rescaled complexity change are different

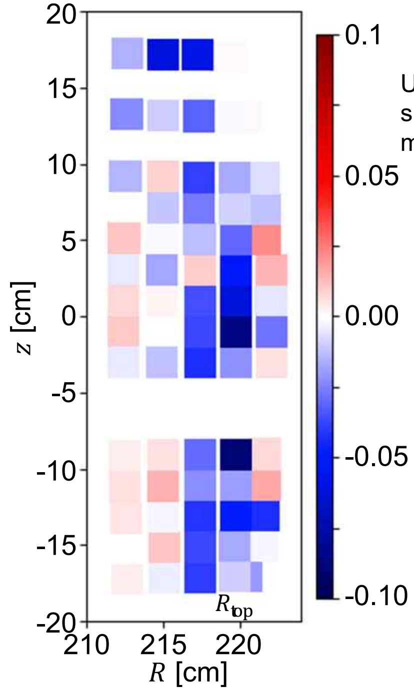
From mitigation to suppression



Summed tot. bicoherence change



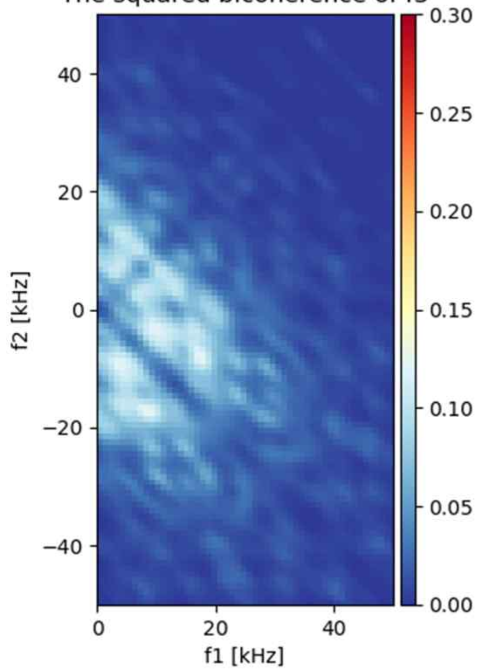
Rescaled complexity change



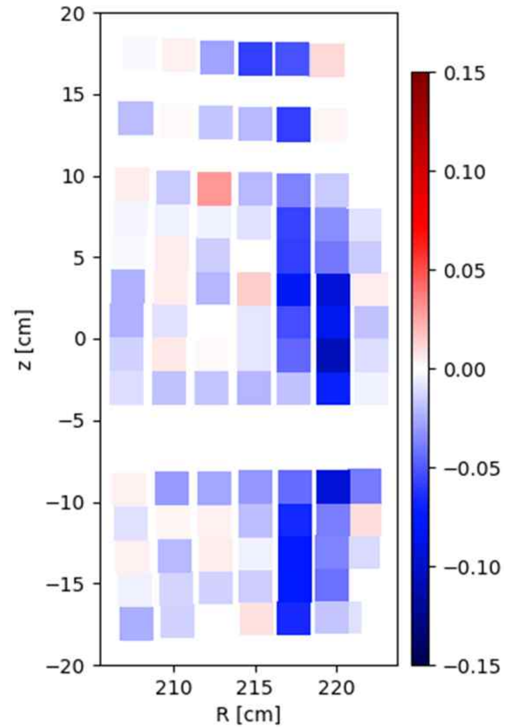
Upper channels suffer from more noise

- Bicoherence exists in < 25 kHz, and RC analysis is sensitive to higher frequency fluctuation (~100 kHz)

The squared bicoherence of f3

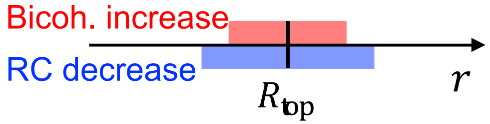


Rescaled complexity change with 25—100 kHz fluctuations



Our interpretation and a clue for origin of fluctuation incr.

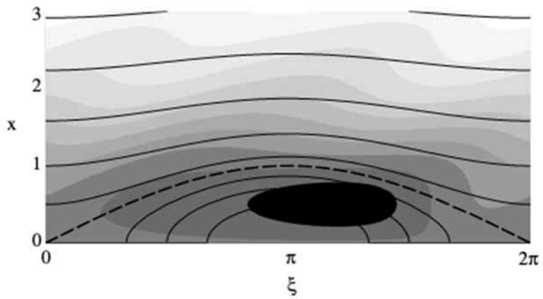
- A partially stochastic island at the pedestal top can explain both bicoherence and rescaled complexity changes



- – Low-k and low-f nonlinear coupling between a magnetic island and fluctuation → Bicoherence increase
- – The nonlinear resonance condition for drift wave emission might be satisfied in the RMP ELM suppression experiment

$W_{island} \sim$ a few ρ_is

$\omega_E < \omega_{island} < \omega_{*e}$

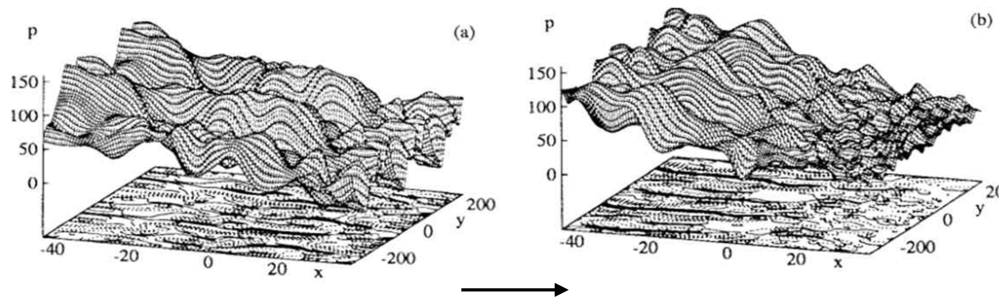


[Waelbroeck, Phys. Rev. Lett. 87, 215003 (2001)]

- – High-k stochastic fields around the island change fluctuation characteristics → Rescaled complexity decrease
- – Enhancement of high-k (high-f) fluctuation
- – Turbulence can lock on to stochastic fields, i.e. $\langle \tilde{v}_r \tilde{b}_r \rangle \neq 0$

[Cao & Diamond, APTWG 2021]

[Beyer, Phys. Plasmas 5, 4271 (1998)]



Summary

Preprint at https://arxiv.org/abs/2102.10733

- Analysis of characteristics of plasma turbulence/transport with the RMP field
  - Previous analyses : kinetic profiles (transport), fluctuation spectra (turbulence intensity, dispersion)
  - In this work, the Complexity-Entropy analysis is adopted to identify/distinguish a state of plasma turbulence/transport and to improve understanding of the state

- Main Results of our analyses
  - CH analysis shows that both pedestal top T_e fluctuation and particle flux at the divertor striking point become less complex (more stochastic) with a RMP field
    - Response of the former seems to be more nonlinear
  - Turbulence dynamics with a RMP field is suggested based on CH and bicoherence analyses
    - Low-k island onset at pedestal top → island drives low-k turbulence nonlinearly → high-k turbulence generated by stochastic fields around islands

[Cao & Diamond, APTWG 2021]

[Waelbroeck, Phys. Rev. Lett. 87, 215003 (2001)]

Towards a Theory →

Resistive Interchange (Turbulence)

in a Stochastic B-field

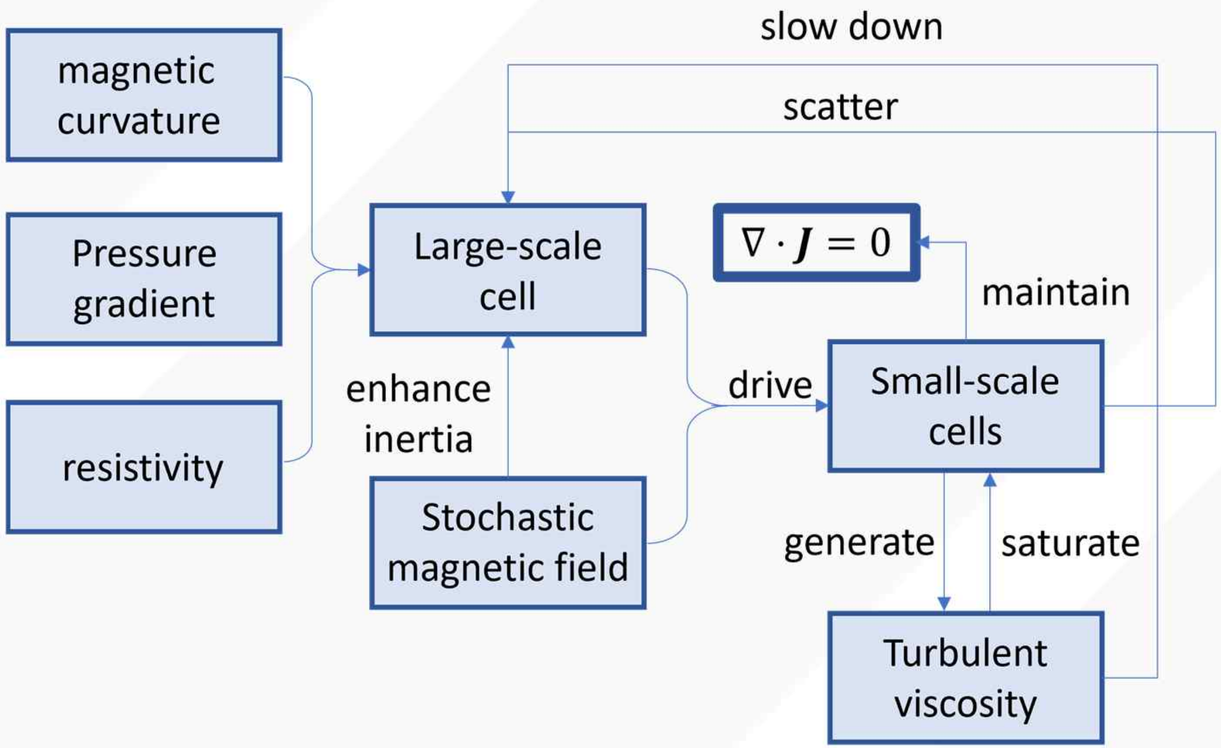
→ Single Cell Problem and Beyond

N.B.: After FKR and Braginsky-Meytlis

INTRODUCTION OF MODEL

Model must:

- **maintain $\nabla \cdot \boldsymbol{J} = 0$ at all scales**
- **connect micro and macro scales**
- **be tractable** → **resistive interchange mean field**



Key point: small scale potential fluctuations are generated due to stochastic magnetic field

INTRODUCTION OF MODEL

Where we start:

1. Classical resistive interchange:

- Linearized vorticity equation

$$\underbrace{-(\rho_0/B_0^2)\partial_t\nabla_\perp^2\varphi}_{\nabla_\perp\cdot J_{pol}}\underbrace{-(g/B_0)\partial_y p}_{\nabla_\perp\cdot J_{PS}}+\underbrace{\boldsymbol{b_0}\cdot\nabla J_\parallel}_{\nabla_\parallel J_\parallel}=0$$

$\nabla\cdot\boldsymbol{J}=0$

- Electrostatic Ohm's law of resistive MHD

$$E_\parallel=-\nabla_\parallel\varphi=\eta_\parallel J_\parallel$$

- Linearized pressure equation

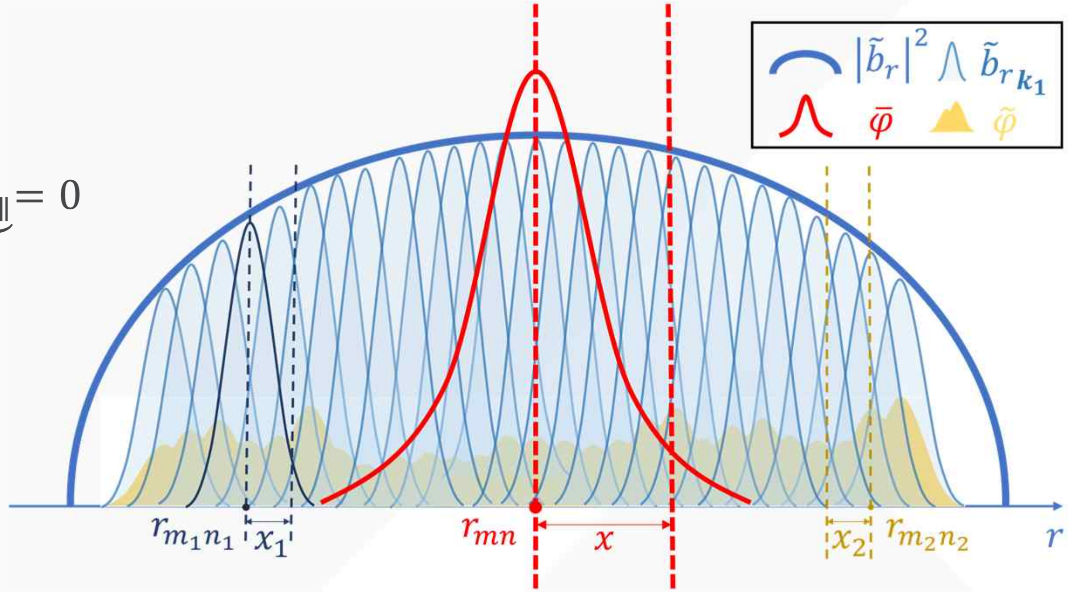
$$\partial_t p-(\nabla\varphi\times\hat{\boldsymbol{z}})/B_0\cdot\nabla p_0=0$$

2. Magnetic perturbations:

$$\widetilde{\boldsymbol{b}}=\widetilde{\boldsymbol{B}}_\perp/B_0=\sum_{m,n}\widetilde{\boldsymbol{b}}_{m,n}(x')e^{i(m\,\theta-n\phi)}$$

Since $\boldsymbol{B_{tot}}=\boldsymbol{B_0}+\widetilde{\boldsymbol{B}}_\perp$, now the parallel gradient is $\nabla_\parallel=\nabla_\parallel^{(0)}+\widetilde{\boldsymbol{b}}\cdot\nabla_\perp$.

Compared to mode, the profile of stochastic field evolves much slowly in space.



Sketch of the mode and stochastic magnetic field

INTRODUCTION OF MODEL

Need maintain: we want to keep $\nabla \cdot \boldsymbol{J} = 0$ at all scales.

If there are only $\tilde{\boldsymbol{b}}$ and $\bar{\varphi}$, $\nabla \cdot \boldsymbol{J} = 0$ is not guaranteed!

At micro scale:

$$\tilde{\boldsymbol{J}}_\parallel = \tilde{\boldsymbol{J}}_{\parallel 0} + \tilde{\boldsymbol{J}}_\perp = -\frac{1}{\eta_\parallel}(\tilde{\boldsymbol{b}} \cdot \nabla_\perp)\bar{\phi}\boldsymbol{b_0} - \frac{1}{\eta_\parallel}\nabla_\parallel^{(0)}\bar{\phi}\tilde{\boldsymbol{b}}$$

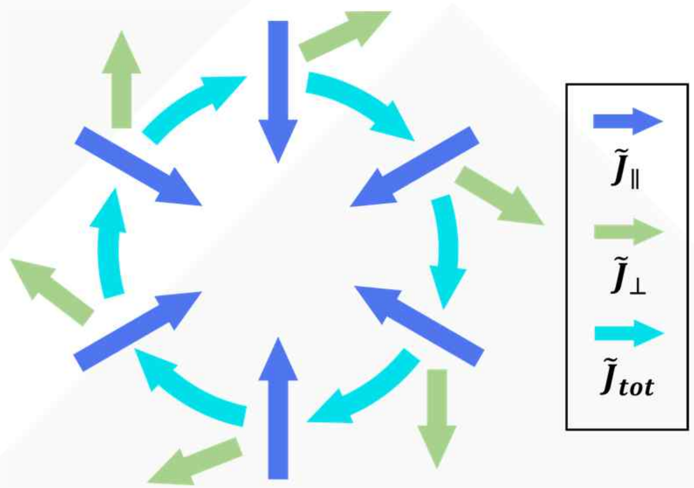
$$\widetilde{\nabla_\parallel \boldsymbol{J}_\parallel} = -\frac{1}{\eta_\parallel}\left\{\nabla_\parallel^{(0)}\left[(\tilde{\boldsymbol{b}} \cdot \nabla_\perp)\bar{\phi}\right] + (\tilde{\boldsymbol{b}} \cdot \nabla_\perp)\nabla_\parallel^{(0)}\bar{\phi}\right\} \neq 0$$

Insights from a classic: Kadomtsev and Pogutse'78[1]:

Electron heat flux is divergence free at all scales → $\nabla \cdot \boldsymbol{q} = 0$

Analogy	K&P	C&D
Goal	$\langle q_r \rangle_{NL}$	$\gamma_{\boldsymbol{k}}^{(1)}$
Base State	$\bar{T}$	$\bar{\varphi}$
Stochastic quantity	$\tilde{\boldsymbol{b}}$	$\tilde{\boldsymbol{b}}$
Constraint	$\nabla \cdot \boldsymbol{q} = 0$	$\nabla \cdot \boldsymbol{J} = 0$
Resulting Fluctuations	$\tilde{T}$	$\tilde{\varphi}$

Multi-Scale Microturbulence



Small-scale current

1. B. B. Kadomtsev, and O. P. Pogutse, 1979.

INTRODUCTION OF MODEL

The full set of equations is

$$① \left[\frac{\partial}{\partial t} + \widetilde{\boldsymbol{v}} \cdot \nabla\right] \nabla_\perp^2 \bar{\varphi} = -\frac{S}{\tau_A}\Big[\nabla_\parallel^{(0)^2} \bar{\varphi} + \underbrace{\left(\nabla_\perp \cdot \langle \tilde{\boldsymbol{b}}\tilde{\boldsymbol{b}} \rangle\right) \cdot \nabla_\perp \bar{\varphi}}_{(a)} + \underbrace{\left\langle \nabla_\parallel^{(0)} \tilde{b} \cdot \nabla_\perp \tilde{\varphi} \right\rangle}_{(b)} + \underbrace{\left\langle \left(\tilde{b} \cdot \nabla_\perp\right) \nabla_{\parallel'}^{(0)} \tilde{\varphi} \right\rangle}_{(c)}\Big] - \frac{gB_0}{\rho_0}\frac{\partial \bar{p}_1}{\partial y},$$

$$② \left[\frac{\partial}{\partial t} + \widetilde{\boldsymbol{v}} \cdot \nabla\right] \nabla_\perp^2 \tilde{\varphi} = -\frac{S}{\tau_A}\Big[\nabla_\parallel^{(0)^2} \tilde{\varphi} + \underbrace{\left(\tilde{b} \cdot \nabla_\perp\right) \nabla_\parallel^{(0)} \bar{\varphi}}_{(\alpha)} + \underbrace{\nabla_\parallel^{(0)} \left(\tilde{b} \cdot \nabla_\perp\right) \bar{\varphi}}_{(\beta)}\Big] - \frac{gB_0}{\rho_0}\frac{\partial \tilde{p}_1}{\partial y},$$

→ Relate $\tilde{\varphi}$ to $\widetilde{\boldsymbol{b}}$

$$③ \left[\frac{\partial}{\partial t} + \widetilde{\boldsymbol{v}} \cdot \nabla\right] \bar{p}_1 - \frac{\nabla \bar{\varphi} \times \hat{\mathbf{z}}}{B_0} \cdot \nabla p_0 = 0,$$

$$④ \left[\frac{\partial}{\partial t} + \widetilde{\boldsymbol{v}} \cdot \nabla\right] \tilde{p}_1 - \frac{\nabla \tilde{\varphi} \times \mathbf{z}}{B_0} \cdot \nabla p_0 = 0,$$

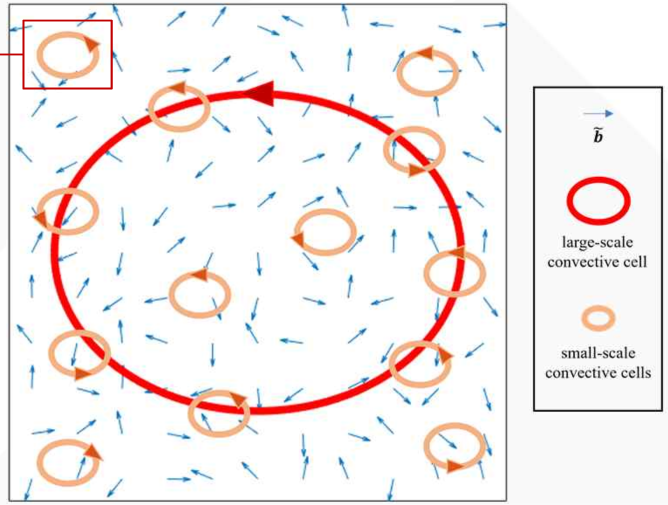
$\widetilde{\boldsymbol{v}} \cdot \nabla$ replaced by $-\nu_T \nabla_\perp^2$ or $\chi_T \nabla_\perp^2$

Turbulent viscosity
Turbulent diffusivity

$$\langle A \rangle = \bar{A} = \frac{1}{(2\pi)^2} \iint d\theta d\phi \; e^{-i(m\,\theta - n\phi)} A$$

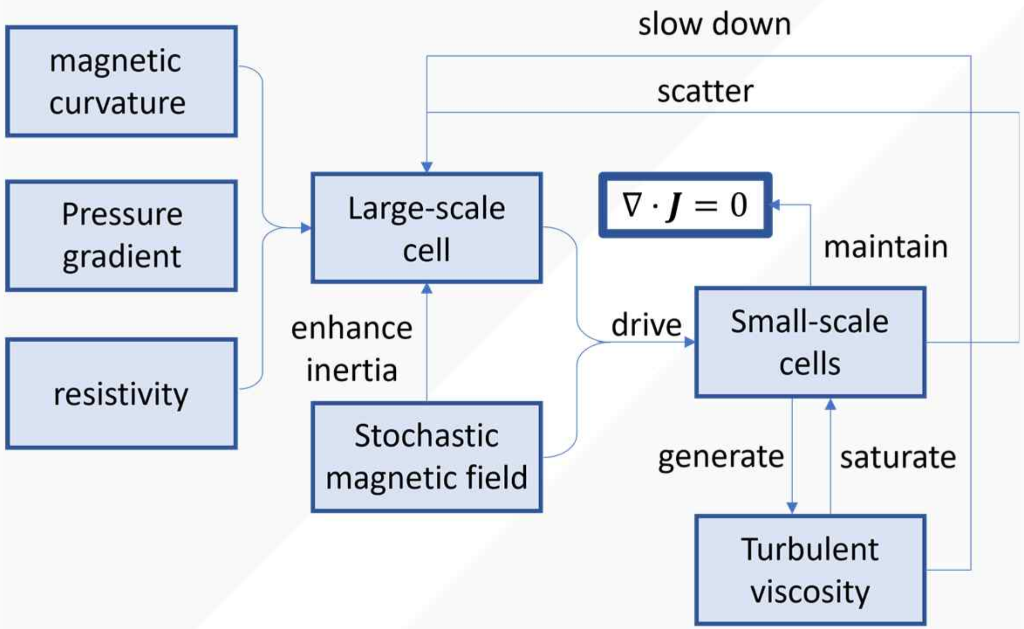
Some observations:

- $\bar{\varphi}$: low $\boldsymbol{k}$, slow interchange approximation $\left(1/w_{\boldsymbol{k}}^2 \gg k_y^2\right)$
- $\tilde{\varphi}$: high $\boldsymbol{k}'$, fast interchange approximation $\left(1/w_{\boldsymbol{k}'}^2 \ll {k'_y}^2\right)$
- The beat of $\widetilde{\boldsymbol{b}}$ and $\bar{\varphi}$ serves as the drive of $\tilde{\varphi}$ while $\tilde{\varphi}$ modifies $\bar{\varphi}$, thus small scale and large scale are now connected.
- Feedback loop: $\bar{\varphi}, \tilde{b} \rightarrow \tilde{\varphi}$



Three players: $\widetilde{\boldsymbol{b}}$, $\bar{\varphi}$, and $\tilde{\varphi}$

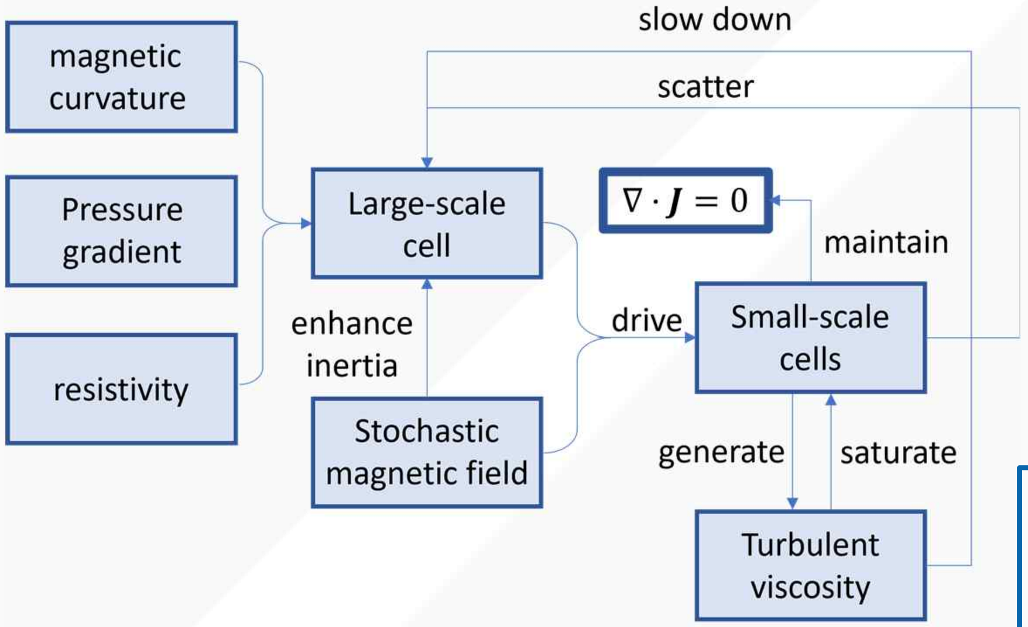
BIG PICTURE I



Multi-scale feedback loops

- $\nabla \cdot \boldsymbol{J} = 0$ is maintained at all scales, which reveals that electrostatic convective cells must be driven by $\tilde{\boldsymbol{b}}\bar{\varphi}$ beat. This indicates a turbulent background is generated, even in ‘single mode’ idealization
- Large scale and small scale interact. As small-scale convective cells are modulated by large-scale mode, large-scale mode is modified by small-scale cells through turbulent viscosity and electrostatic scattering.
- N.B.: Electrostatic ‘micro-bursts’ recently reported in DIII-D RMP experiments

BIG PICTURE II



Multi-scale feedback loops

- Stochastic magnetic field produces a magnetic braking effect, which enhances the effective inertia and exerts a drag on large-scale mode. This is similar in structure to Rutherford's nonlinear $\boldsymbol{J} \times \boldsymbol{B}$ forces[1], but in our case, it's produced by stochastic magnetic perturbations.

- We calculate a non-trivial $\langle \tilde{b}_r \tilde{v}_r \rangle$. The velocity fluctuations $\tilde{\boldsymbol{v}}$ 'lock on' to the magnetic perturbations $\tilde{\boldsymbol{b}}$.

→ **Complexity reduction result ?!**

1. P. H. Rutherford, 1973.

QUANTITATIVE RESULTS I

Specific results of this work are as follows:

- The increment in the growth rate of the large-scale mode is calculated:

$$\gamma_{\boldsymbol{k}}^{(1)} = -\frac{5}{6}\hat{\nu}\left(\frac{\tau_p \tau_\kappa}{\tau_A^2}\right)^{\frac{1}{3}} S^{\frac{2}{3}} \tilde{k}_\theta^{\frac{2}{3}} - \frac{1}{3}\frac{S}{\tau_A}\left|\tilde{b}_r\right|^2 - \frac{2\sqrt{2}}{3}\frac{\hat{I} S^{\frac{4}{3}} \tilde{k}_\theta^{\frac{4}{3}}}{\left(\tau_p \tau_\kappa \tau_A^4\right)^{\frac{1}{3}}}.$$

  As $\gamma_{\boldsymbol{k}}^{(1)}$ is negative definite, the net effect of $\tilde{\boldsymbol{b}}$ is to reduce resistive interchange growth.
  ←→ contrary to expectation of enhanced breaking of Alfven Thm

- The scaling of the turbulent viscosity (or turbulent thermal diffusivity) is calculated:

$$\nu = \left[\pi^{\frac{1}{2}} \frac{R r_m}{B_0^2} \frac{n \tilde{k}_\theta^2}{L_s^5}\left(\frac{S}{\tau_A}\right)^2 \bar{\varphi}_{\boldsymbol{k}}^2(0) \int dk_{2\theta} \frac{c^2 Z^2 w_{\boldsymbol{k}_2} o_{\boldsymbol{k}_2}^2}{|k_{2\theta}|^5 \gamma_{\boldsymbol{k}_2}^{(0)}}\right]^{\frac{1}{3}}.$$

QUANTITATIVE RESULTS II

- The criterion when magnetic braking effect becomes significant is given. When the width of magnetic islands satisfies

$$O_{\boldsymbol{k}_2} \sim \left[\frac{k_\theta^2}{k_{2\theta}^2}(\Delta x)^4\right]^{\frac{1}{4}}.$$

  Unlike Rutherford's result, extra factor $(k_\theta/k_{2\theta})^2$, which reflects the multi-scale nature of this problem.

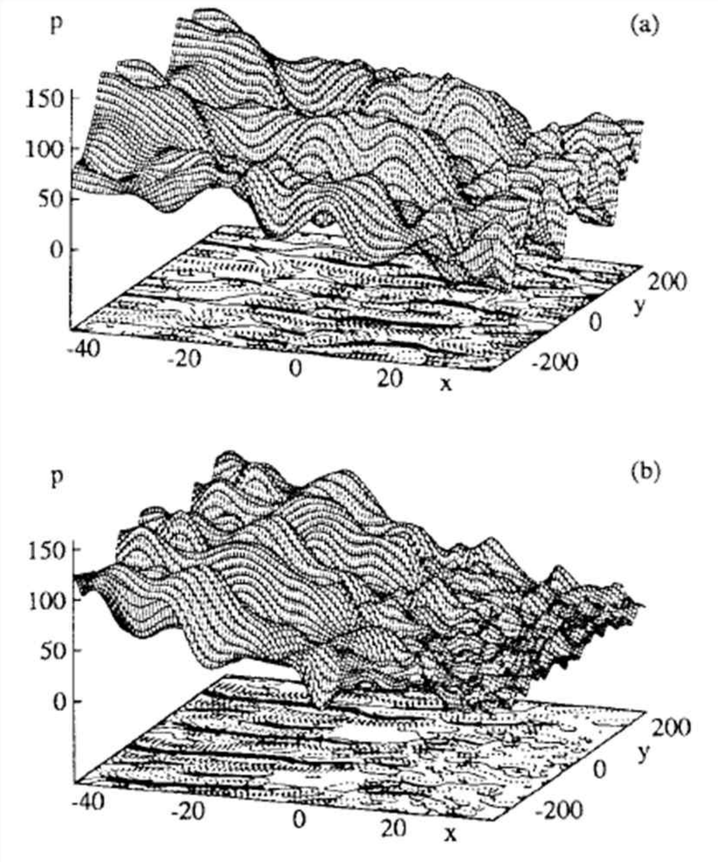
- Correlation $\langle \tilde{b}_r \tilde{v}_r \rangle$ is calculated explicitly:

envelope

$$\left\langle \tilde{b}_r \tilde{v}_r \right\rangle = \pi^{\frac{1}{2}} \frac{\tilde{k}_\theta R r_{mn}}{L_s^3 B_0} \frac{S}{\tau_A} \bar{\varphi}_{\boldsymbol{k}}(0) \times \int dk_{2\theta} \left|k_{2\theta}\right| k_{2\theta} \frac{c^2 Z^2 \left(k_\theta - k_{2\theta}\right) w_{\boldsymbol{k}_2} o_{\boldsymbol{k}_2}^2}{\Lambda_{\boldsymbol{k}_2}^0 - \Lambda_{\boldsymbol{k}_2}}$$

COMPARISON: SIMULATIONS & EXPERIMENTS

- **Previous simulation by Beyer, et al[1]:**
  - Electrostatic resistive ballooning modes in a stochastic magnetic field.
  - With RMP, large-scale structures are stabilized, and spatial roughness increases.
  - Testable prediction: $\langle \tilde{b}_r \tilde{v}_r \rangle$, comparison
- **Recent experimental studies by Choi, et al[2]:**
  - Change in pedestal temperature fluctuation predictability with RMP switched on and off.
  - Stochasticity reduces the predictability of the pedestal turbulence
  - Explanation: $\langle \tilde{b}_r \tilde{v}_r \rangle \neq 0$, generation of $\tilde{\varphi}$.



plasma pressure in a sector at the low field side without (a) and with (b) RMP[1]

1. P. Beyer, X. Garbet, and P. Ghendrih, 1998
2. M.J. Choi, et al., 2021.

Discussion

- Stochastic field + Resistive Interchange → 'micro-bursts', etc.

  → multi-scale, turbulent state

- Fluctuations 'lock-on' to imposed magnetic perturbations $\langle \tilde{b} v_r \rangle \neq 0$

➔

How understand resistive interchange <u>turbulence</u> in this system?

←→ competing mechanisms