A Mean Field Model of the L→H Transition in a Stochastic Magnetic Field

W.X. Guo[1*], M. Jiang[2**], P.H. Diamond[2,3], C.-C. Chen[3]

H.H. Li[1] and T. Long[2]

[1] HUST, Wuhan, China
[2] SWIP, Chengdu, China
[3] UCSD, San Diego, USA

Guo* and Jiang** are joint first authors.
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Outline

- **Motivation and Background**
- **Mean Field Model** (a work in progress)
  - What determines $\langle v_E' \rangle$?

    Key novelty: $\langle J_r \rangle$ induced by magnetic perturbation

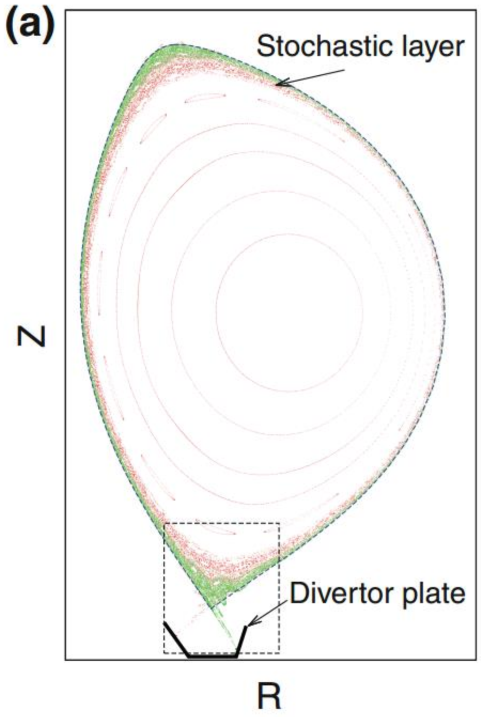
    → $\langle V_\theta \rangle$ and $\langle V_\phi \rangle$ evolution

    → Particle and heat flux

    Turbulence intensity
  - Modified 1D "Predator-Prey" model for $\langle E_r \rangle'$
- **Lessons learned, so far**
- **Conclusion and Open Issues**

Stochastic magnetic field

- The phenomenon of chaos of magnetic field lines is known as magnetic stochasticity (or magnetic chaos)
- In early studies, magnetic stochasticity is thought to be bad for confinement due to the enhanced radial transport of particles and energy along the chaotic field lines.
- However, at end of 1970s, magnetic stochasticity can be used to control the transport of energy and particles. → stochasticity as a positive: ergodic divertor concept



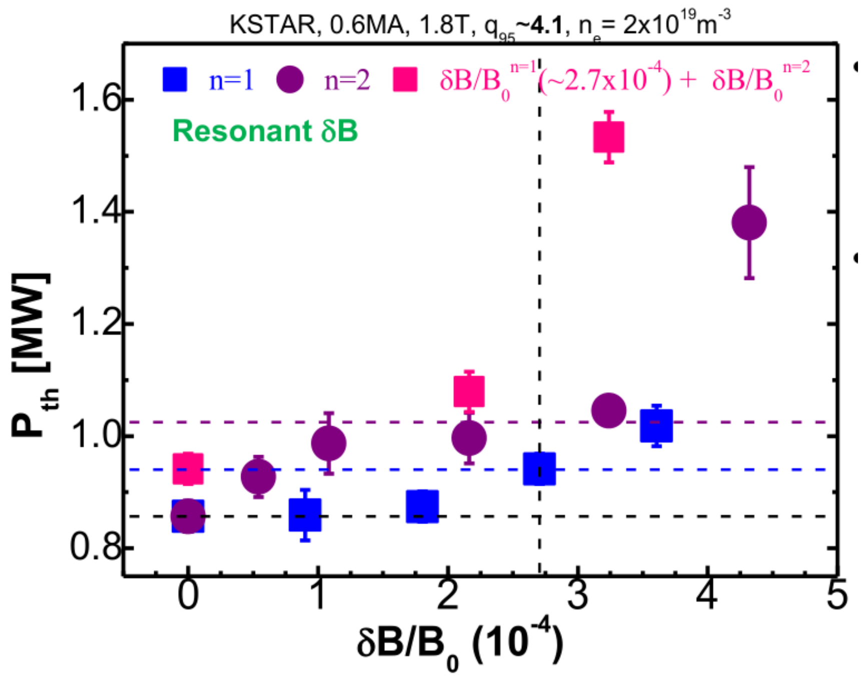
Typical Poincaré section of field lines in DIII-D like plasmas

Stochastic magnetic field induced by RMP

- Most of today's tokamaks need to use RMP (resonant magnetic perturbation) before L→H transition, in order to mitigate/suppress large ELMs, including first
- RMPs are thought to produce stochastic layer near separatrix
- The stochastic B field observed to influence
  — threshold and power
  — $V_{\boldsymbol{E}\times\boldsymbol{B}}$ and flows
  — fluctuations

Motivation (why?)

- RMPs increase P_{th} of L→H transition (experiments on DIII-D, MAST, AUG and KSTAR).

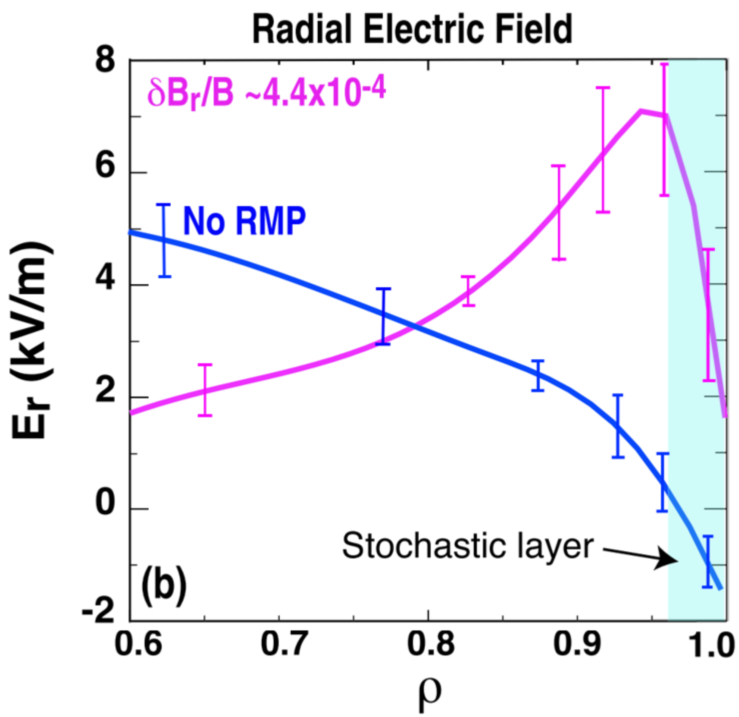


Here, stochastic B-field is thought to be caused by resonant δB.

Need model to elucidate the physical mechanism.

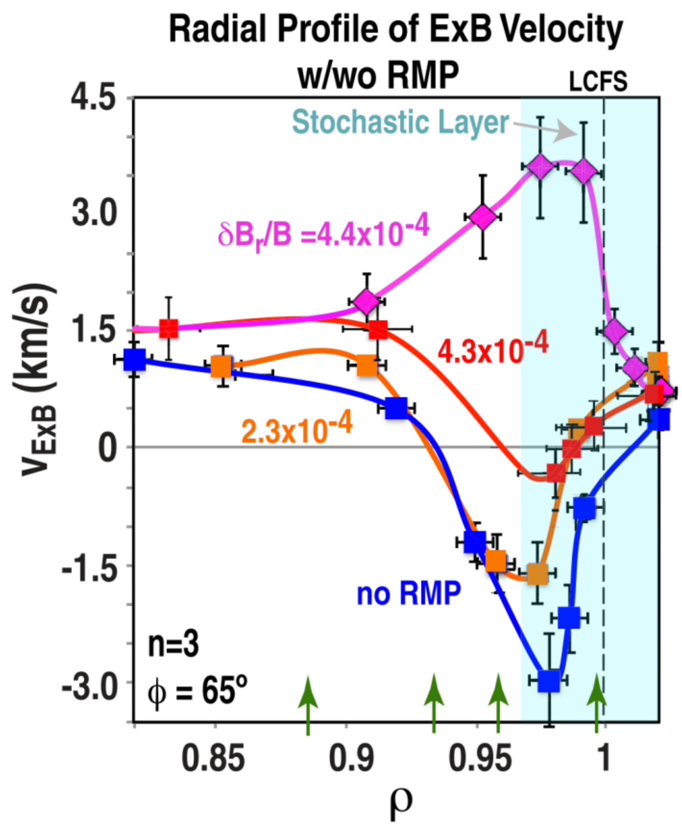
So, how stochastic B-field affects $\langle v_E' \rangle$?

$\langle E_r \rangle$ structure: reversal by RMPs



DIII-D
L-mode

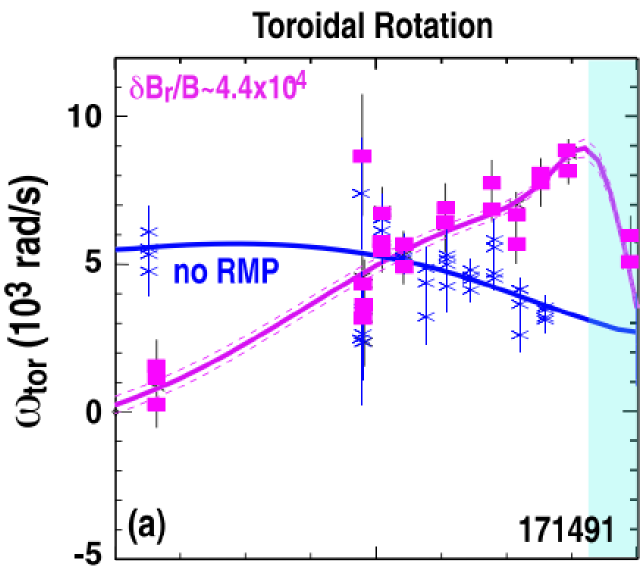
L. Schmitz et al NF 2019



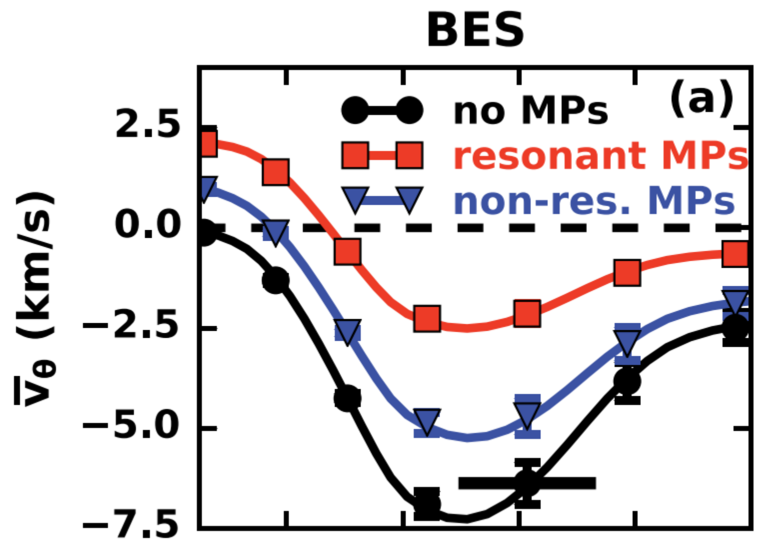
- ✓ E_r reversal or 'bifurcation' : E_r well reduced or inverted to E_r hill with increasing RMP. Edge E_r shear layer sits in stochastic field region.
- ✓ Clear Change in E_r' due to increase of RMP field

Reduced toroidal/poloidal flow by RMPs

L. Schmitz et al NF 2019



Kriete, PoP 2020



- ✓ RMP increased toroidal (co)rotation and shear at separatrix
- ✓ RMP reduces mean turbulence poloidal velocity

➡ **Clear effect on flows, and would further affect**

$$E_r = \frac{1}{enB}\frac{\partial}{\partial r}P_{\mathrm{i}} + v_\phi B_\theta - v_\theta B_\phi .$$

Fluctuations point: RMPs degrade energy transfer to mean flows prior to L-H transition

Energy balance between turbulence and mean flow[1,2]

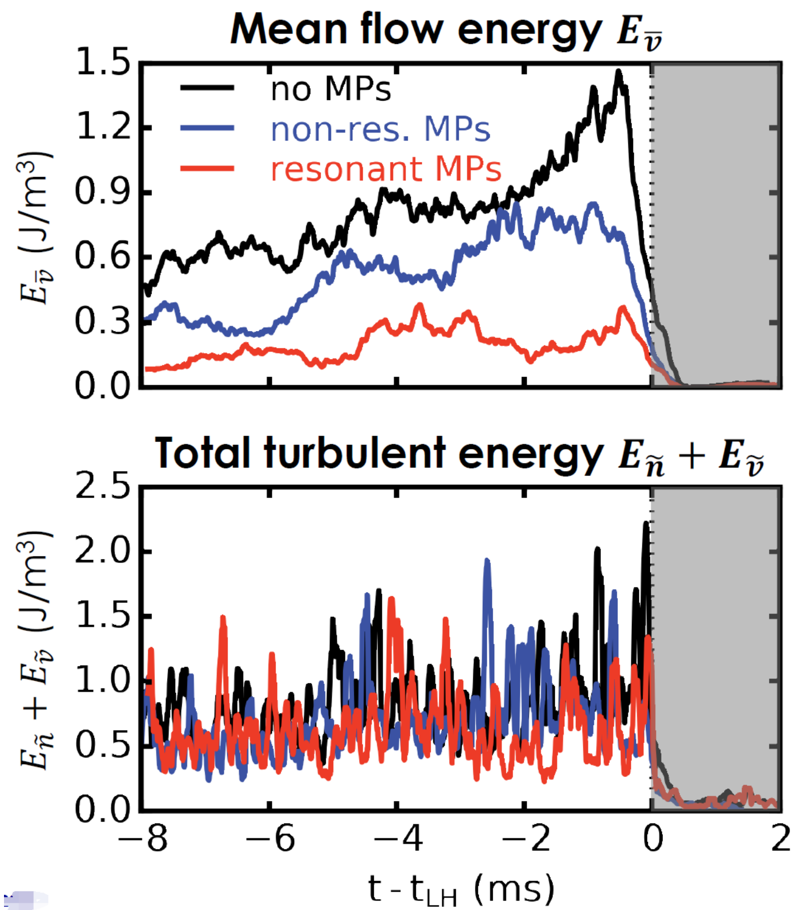
Mean flow energy: $E_{\bar{v}} = \frac{1}{2} n_0 m_i \langle \bar{v}_\theta \rangle^2$

Turbulent flow energy: $E_{\tilde{v}} = \frac{1}{2} n_0 m_i \left(\langle \tilde{v}_r^2 \rangle + \langle \tilde{v}_\theta^2 \rangle \right)$

Thermal free energy: $E_{\tilde{n}} = \frac{1}{2} n_0 T_{e0} (\tilde{n}_e / n_0)^2$

- ✓ $E_{\bar{v}}$ **increases** prior to L-H in axisymmetric case
- ✓ $E_{\bar{v}}$ **decreases** due to RMPs, but total turbulent energy only changes slightly
- ✓ Power transfer to zonal flow decreases

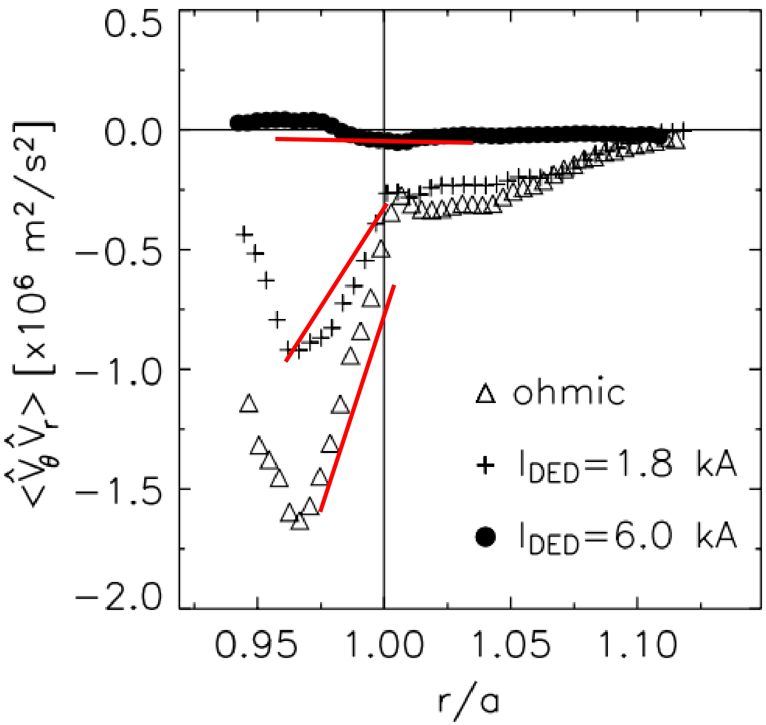
Kriete, PoP 2020



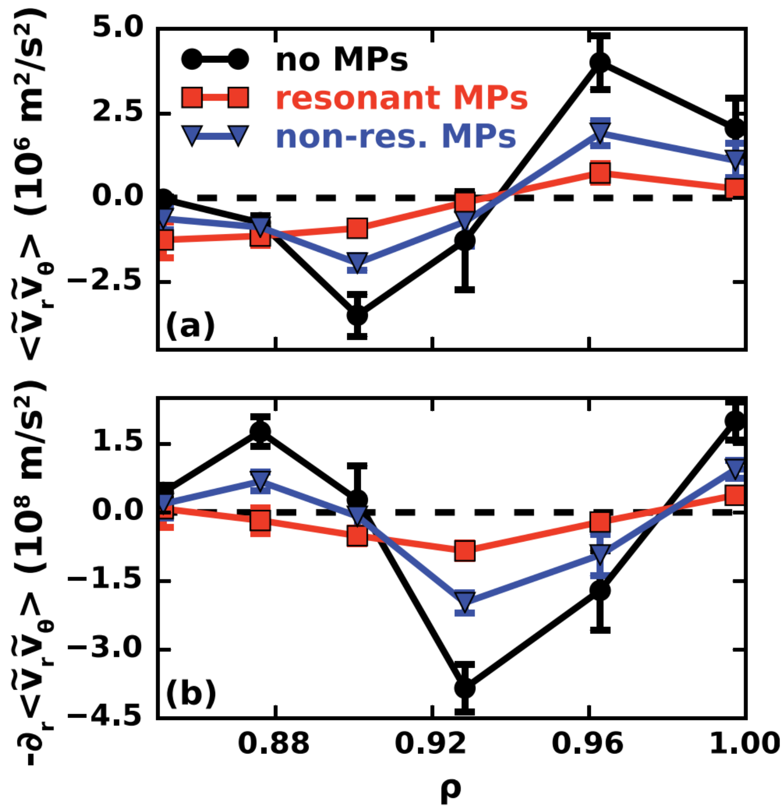
Need more power to supply sufficient energy to the mean flow

Reduced Reynold stress/force by RMP

Y. Xu, 2007 NF



Kriete, PoP 2020



- ✓ Increase I_{DED} reduces Reynold force.
- ✓ RMP reduces Reynold force in L-mode, thus increasing power required for H-mode.

➡ Effects of RMP on transition? ↔ Model !

Model – $\langle E_r \rangle$ as critical

- **Goal:** ascertain change due to RMP
  mean field model for $\langle E_r \rangle$ and $\langle v_E' \rangle$

— Radial force balance equation: $\langle E_r \rangle$ is determined by

$$\langle E_r \rangle = \frac{\langle \nabla P_i \rangle}{ne} - \langle V_\theta \rangle B_\phi + \langle V_\phi \rangle B_\theta$$

Diamagnetic drift Poloidal rotation Toroidal rotation

$\Gamma_e,\ Q_i$

$$\underbrace{\text{Poloidal rotation} \quad \text{Toroidal rotation}}_{\langle J_r \rangle \leftrightarrow \langle \tilde{b}_r \tilde{b}_\theta \rangle}$$

—Direct effect of $|\tilde{b}_r|^2$ on turbulence discussed later. Take turbulence as electrostatic in L-mode.

—Prescribe stochastic B-field

$\langle J_r \rangle$ is key to L→H trigger mechanism

- L→H transition: V_E' shearing feedback (mainly ∇P) + "trigger" due to $\langle J_r \rangle$

- Several candidates for $\langle J_r \rangle$

—Radial flux of polarization charge → turbulence intensity gradient scale

$$\rho_s^2 \langle \tilde{v}_r \nabla_\perp^2 \tilde{\phi} \rangle \rightarrow \frac{\partial}{\partial r} \langle \tilde{V}_\theta \tilde{V}_r \rangle$$: Reynolds force

Critical Reynolds work criterion [Rich literatures: Diamond, Tynan et al]

—neoclassical polarization → $\rho_{\theta i}$ scale [S-I. Itoh, et al PRL, 60 (1988) 2276]

—orbit loss → $\rho_{\theta i}, \ldots\ldots$ [K.C.Shaing, PoF B: Plasma Physics 4 (1992) 171]

— New player here: $\langle J_r \rangle = \frac{\langle \tilde{J}_\parallel \tilde{B}_r \rangle}{B}$

stochastic field intensity profile scale, how enters?

Common element: $\langle J_r \rangle$ induced by stochastic B-field

- Ambipolarity breaking due to stochastic field $\Rightarrow \langle J_r \rangle$

$$\langle J_r \rangle = \left\langle \vec{J}_{\parallel} \cdot \vec{e}_r \right\rangle = \frac{\langle \tilde{J}_{\parallel} \tilde{B}_r \rangle}{B} \qquad \langle J_{\parallel} \rangle = \langle J_{\parallel,e} \rangle + \langle J_{\parallel,i} \rangle$$

- From Ampere law: $\tilde{J}_{\parallel} = -\dfrac{c}{4\pi} \nabla^2 \tilde{A}_{\parallel}$

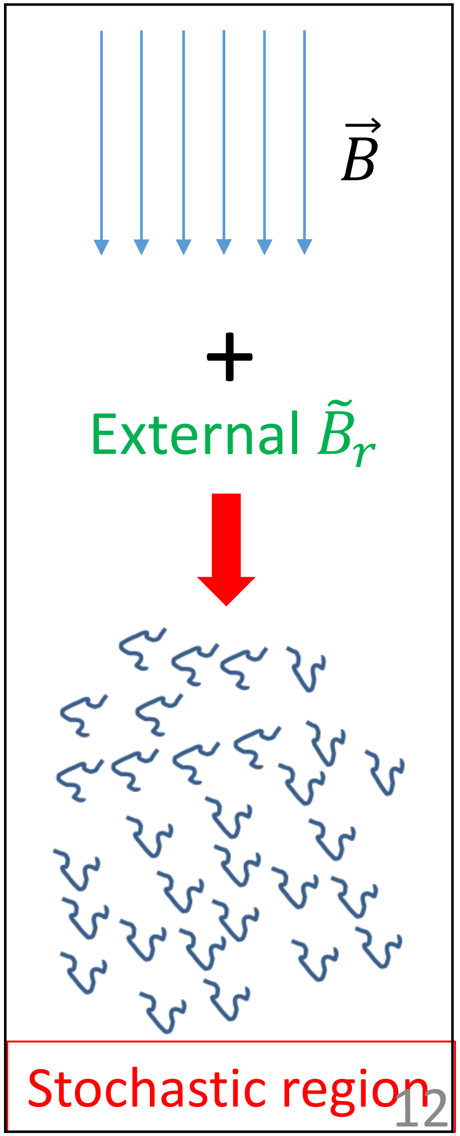
Stochastic field produces currents in plasmas

$$\langle J_r \rangle = \frac{\langle \tilde{J}_{\parallel} \tilde{B}_r \rangle}{B} = -\frac{c}{4\pi B} \left\langle \frac{\partial}{\partial y} \tilde{A}_{\parallel} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \tilde{A}_{\parallel} \right\rangle$$

$$= -\frac{c}{4\pi B} \frac{\partial}{\partial x} \left\langle \left(\frac{\partial}{\partial x} \tilde{A}_{\parallel} \right) \left(\frac{\partial}{\partial y} \tilde{A}_{\parallel} \right) \right\rangle = \frac{c}{4\pi B} \frac{\partial}{\partial x} \langle \tilde{B}_x \tilde{B}_y \rangle$$

$$= \frac{cB}{4\pi} \frac{\partial}{\partial x} \langle \tilde{b}_x \tilde{b}_y \rangle \Rightarrow \frac{cB_0}{4\pi} \frac{\partial}{\partial r} \langle \tilde{b}_r \tilde{b}_\theta \rangle \quad \boxed{\text{Maxwell Force}}$$

Note: $\langle J_r \rangle$ tracks momentum, not heat transport.



Phase in Maxwell stress

- Maxwell stress $\langle \tilde{B}_r \tilde{B}_\theta \rangle = \sum_k |\tilde{A}_k|^2 \langle k_x k_y \rangle$
  - $\tilde{A}_k$ tilted by developing $\boldsymbol{E} \times \boldsymbol{B}$ flow

$$\frac{\partial A}{\partial t} + V \cdot \nabla A = \eta J$$
$$\frac{\partial A}{\partial t} + V_E' \frac{\partial A}{\partial y} + \tilde{V} \cdot \nabla A = \eta J$$

$$k_x = k_x^{(0)} - k_y V_E' \tau_c$$
$$\tau_c : \left\{ \begin{array}{c} shear \\ fluctuations \end{array} \right\}$$

  - Thus, $\langle \tilde{B}_r \tilde{B}_\theta \rangle = -\sum_k |\tilde{A}_k|^2 \langle k_y^2 V_E' \tau_c' \rangle$
- Hence, Reynolds and Maxwell cross-phase closely linked.

F-I9 30min	**Chang-Chun Chen** University of California, San Diego	On How Decoherence of Vorticity Flux by Stochastic Magnetic Fields Quenches Zonal Flow Generation

Stochastic B-field affects $\langle V_\theta \rangle$

- For V_θ:
  Poloidal momentum balance

Turbulence Reynold stress

Maxwell stress of stochastic field perturbation

$B_\phi \langle J_r \rangle$

$$\frac{\partial \langle V_\theta \rangle}{\partial t} = -\mu(\langle V_\theta \rangle - V_{\theta,neo}) - \frac{\partial}{\partial r}\left(\langle \tilde{V}_\theta \tilde{V}_r \rangle - \frac{1}{4\pi\rho} \langle \tilde{B}_r \tilde{B}_\theta \rangle \right)$$

- For SS: $\langle V_\theta \rangle = V_{\theta,neo} - \frac{1}{\mu}\frac{\partial}{\partial r}\left(\langle \tilde{V}_\theta \tilde{V}_r \rangle - \frac{1}{4\pi\rho} \langle \tilde{B}_r \tilde{B}_\theta \rangle \right)$

$$= V_{\theta,neo} - \frac{1}{\mu}\frac{\partial}{\partial r}\left(\frac{1}{B^2}\tau_c V_E' \frac{I}{1+\alpha V_E'^2} - \frac{B^2}{4\pi\rho}\tau_c' V_E' |\tilde{b}_r|^2\right)$$

with

$$\mu = \mu_{00}\left(1 + \frac{\nu_{CX}}{\nu_{ii}}\right)\nu_{ii} q^2 R^2 \quad V_{\theta,neo} \approx -1.17\frac{\partial T_i}{\partial r} \qquad \tau_c' = \left(\frac{k_\theta^2 V_E'^2 D_T}{3}\right)^{-1/3}$$

- V_E' phasing via tilt tends to align turbulence and stochastic B-field, which counteracts the spin-up of $\langle V_\theta \rangle$.
- $\frac{\partial}{\partial r}|\tilde{b}_r|^2$ not only $|\tilde{b}_r|^2$, plays arole.

Stochastic B-field affects $\langle V_\phi \rangle$

- For V_ϕ: $$\frac{\partial \langle V_\phi \rangle}{\partial t} + \nabla \cdot \langle \tilde{V}_r \tilde{V}_\phi \rangle = \frac{1}{\rho c} \langle J_r \rangle B_\theta + S_M$$

$$\langle \tilde{V}_r \tilde{V}_\phi \rangle = -\chi_\phi \frac{\partial}{\partial r} \langle V_\phi \rangle, \quad \chi_\phi = \chi_T = \frac{\rho_s^2 c_s}{L_T}, \quad S_M = S_a \exp\left(-\frac{r^2}{2L_{M,dep}^2}\right)$$

Only consider diffusive term. G.B. Momentum source tracks heat (from core).

$$\Rightarrow \frac{\partial \langle V_\phi \rangle}{\partial t} = \frac{\partial}{\partial r}\left(\chi_\phi \frac{\partial}{\partial r} \langle V_\phi \rangle\right) + \frac{1}{4\pi\rho} \frac{B_\theta}{B} \frac{\partial}{\partial r} \langle \tilde{B}_r \tilde{B}_\theta \rangle + S_M$$

- For SS: $$\frac{\partial}{\partial r}\left(\chi_\phi \frac{\partial}{\partial r} \langle V_\phi \rangle\right) = -\frac{V_{T_i}^2}{\beta} \frac{B_\theta}{B} \frac{\partial}{\partial r} \langle \tilde{b}_r \tilde{b}_\theta \rangle - S_M$$

Stochasticity edge toroidal velocity, shear

$$\boxed{\frac{\partial}{\partial r} \langle V_\phi \rangle|_{r_{sep}} = -\frac{1}{\chi_\phi} \int_0^{r_{sep}} S_M dr - \frac{V_{Ti}^2}{\beta \chi_\phi} \frac{B_\theta}{B} \langle \tilde{b}_r \tilde{b}_\theta \rangle|_{r_{sep}}}$$

$B_\theta \langle J_r \rangle$

Integrated external torque

- ✓ Force through radial current across separatrix.
- ✓ Shear affected by stochasticity.

With $\langle \tilde{b}_r \tilde{b}_\theta \rangle = k_y^2 V_E' \tau_c' |\tilde{b}_r|^2$

Stochastic B-field affects electron density flux

- For electron density : $\dfrac{\partial n_e}{\partial t} + \dfrac{1}{r}\dfrac{\partial}{\partial r}(r\Gamma_e) = S_p$

with $\Gamma_e = -(D_{neo} + D_T)\dfrac{\partial n}{\partial r} + \Gamma_{e,\,stoch}$ $\longleftarrow$

- $D_{neo} = (m_e/m_i)^{1/2}\chi_{i,neo}$
- $D_T \sim bD_{GB}$ with b<1

$$S_p = \Gamma_a \frac{a - r + d_a}{L_{dep}^2}\exp\left(-\frac{(a + d_a - r)^2}{2L_{dep}^2}\right)$$

- The stochastic field can induce particle flux ($n_e = n_i$):

$$\Gamma_{e,\,stoch} = \frac{c}{4\pi e}\langle \tilde{b}_r \nabla_\perp^2 \tilde{A}_\parallel \rangle + n\langle \tilde{V}_{\parallel,i}\tilde{b}_r\rangle$$

$\langle \tilde{b}_r \tilde{J}_\parallel \rangle$ $\qquad$ $\langle \tilde{b}_r \tilde{J}_{\parallel,i} \rangle$

with

- $\langle \tilde{b}_r \tilde{b}_\theta \rangle$ phasing via V_E' tilt.

✓ $\dfrac{c}{4\pi e}\langle \tilde{b}_r \nabla_\perp^2 \tilde{A}_\parallel \rangle = -\dfrac{c}{4\pi e}\dfrac{\partial}{\partial r}\langle \tilde{b}_r \tilde{b}_\theta \rangle = -n\dfrac{D_B}{\beta}\dfrac{\partial}{\partial r}\langle \tilde{b}_r \tilde{b}_\theta \rangle$

✓ $n\langle \tilde{V}_{\parallel,i}\tilde{b}_r\rangle$: parallel ion flow along tilted field lines

Stochastic B-field affects electron density flux

- The stochastic field can induce particle flux :

$$\Gamma_{stoch} = \frac{c}{4\pi e}\langle \tilde{b}_r \nabla_\perp^2 \tilde{A}_\parallel \rangle + n\langle \tilde{V}_{\parallel,i} \tilde{b}_r \rangle$$

- And from $\nabla_\parallel V_\parallel \cong 0,$ $\tilde{v}_{\parallel,i} \sim -\tilde{b}_r \frac{\partial \langle V_{\parallel,i} \rangle}{\partial r} \Big/ (ik_\parallel)$

$$\rightarrow \quad \langle \tilde{b}_r \tilde{V}_{\parallel,i} \rangle = -D_{M,\,eff} \frac{\partial \langle V_{\parallel,i} \rangle}{\partial r} = -\sum_k \langle \tilde{b}_r^2 \rangle_k \, l_{ac,eff} \frac{\partial \langle V_{\parallel,i} \rangle}{\partial r}$$

Modify l_{ac} due to $\boldsymbol{E} \times \boldsymbol{B}$ shear

$$l_{ac,eff} = \frac{l_{ac} l_{V_E'}}{l_{ac} + l_{V_E'}}, \; l_{ac} = qR, l_{V_E'} = \frac{C_s}{|k_\theta \Delta V_E'|} \sim \frac{C_s}{|V_E'|}$$

✓ V_{pinch} is not diffusive, induced by stochastic B field

✓ Flow gradient drives particle flux.

Ion heat flux with stochastic field

- For ion temperature : $n\frac{\partial T_i}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(rQ_i)=S_H$

with

Electrostatic

$$Q_i=\boxed{-n\left(\chi_{i,neo}+\chi_{i,T}\right)\nabla T_i}+Q_{i,stoch}$$

$$S_H=Q_a\exp\left(-\frac{r^2}{2L_{h,dep}^2}\right)$$

- $\chi_{i,neo}=\varepsilon^{-3/2}q^2\rho_s^2\nu_{ii}$
- $\nu_{ii}=\frac{n_0Z^4e^4\ln\Lambda}{\sqrt{36}\pi\varepsilon_0^2m_i^{1/2}T_{i0}^{3/2}}$
- $\chi_{i,T}=\left(\frac{C_s^2\tau_c}{1+\alpha V_E'^2}\right)*I$

  $\sim\chi_{GB}*I$

- The stochastic field affects ion heat flux :

$$Q_{i,stoch}=\int V_\parallel\langle\tilde{B}_r\delta f\rangle\left(V_\parallel^2+V_\perp^2\right)=-\frac{\partial\langle T_i\rangle}{\partial r}\sqrt{\chi_{\parallel,i}\chi_{\perp,i}}\langle\tilde{b}_r^2\rangle l_{ac}k_\perp$$

$$=-v_{th,i}D_{M,eff}\frac{\partial\langle T_i\rangle}{\partial r}\simeq-D_{B,i}D_M\sqrt{\bar{k}_\perp^2}\frac{\partial\langle T_i\rangle}{\partial r}$$

✓ Potentially important as threshold power is directly related to heat flux.

✓ Power uptake determines turbulence and Reynolds force

Turbulence intensity

- For turbulence intensity :

$$\frac{\partial}{\partial t} I = \frac{\gamma_L}{(1+\alpha V_E'^2)^\sigma} I - \beta I^2 \rightarrow I = \frac{\gamma_L}{(1+\alpha V_E'^2)^\sigma} \frac{1}{\beta}$$

(γ_L − growth rate, β − nonlinear decay rate, V_E' − $E \times B$ shear rate)

$$\frac{\gamma_L}{(1+\alpha V_E'^2)^\sigma} \sim \beta \qquad \alpha = \frac{1}{\alpha_0 (C_s/(\mathrm{qR}))^2},$$ α_0 and σ are adjustable.

$$\gamma_L = \gamma_{L0}\left(\frac{C_s}{R}\right)\sqrt{\frac{R}{L_T} - \underbrace{\left(\frac{R}{L_T}\right)_{crit}}_{\text{threshold}}} \sim \gamma_{L0}\left(\frac{C_s}{R}\right), \gamma_{L0} \approx 0.01$$

So, mean field "Predator-Prey" model

- RFB equation: $\langle V_E \rangle' = \frac{1}{eB}\frac{\partial}{\partial r}\langle \nabla P_i / n \rangle - \frac{\partial}{\partial r}\langle V_\theta \rangle + \frac{B_\theta}{B}\frac{\partial}{\partial r}\langle V_\phi \rangle$

- Five field model:

① $\frac{\partial}{\partial t} I = \frac{\gamma_L}{(1+\alpha V_E'^2)^\sigma} I - \beta I^2$ Turbulence intensity

② $n\frac{\partial T_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r Q_i) = S_H$ Ion temperature

③ $\frac{\partial n_e}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r \Gamma_e) = S_p$ Electron density

$|\tilde{b}_r|^2$ — T_i, n_e, $\langle V_\theta \rangle$, $\langle V_\phi \rangle$

④ $\langle V_\theta \rangle = V_{\theta,neo} + \frac{1}{\mu}\frac{\partial}{\partial r}\left(\frac{1}{B^2}\tau_c V_E' \frac{I}{1+\alpha V_E'^2} - \frac{B^2}{4\pi\rho}\tau_c' V_E' |\tilde{b}_r|^2\right)$

Poloidal flow

⑤ $\frac{\partial}{\partial r}\langle V_\phi \rangle|_{r_{sep}} = -\frac{1}{\chi_\phi}\int_0^{r_{sep}} S_M dr - \frac{V_{Ti}^2}{\beta \chi_\phi}\frac{B_\theta}{B}\langle \tilde{b}_r \tilde{b}_\theta \rangle|_{r_{sep}}$

Toroidal flow

$\langle J_r \rangle$ directly related to Γ_e and Maxwell stress in flows

The sources

$$S_H = Q_a \exp(-\frac{r^2}{2L_{h,dep}^2})$$ $L_{h,dep} = 0.15a$ Heat source

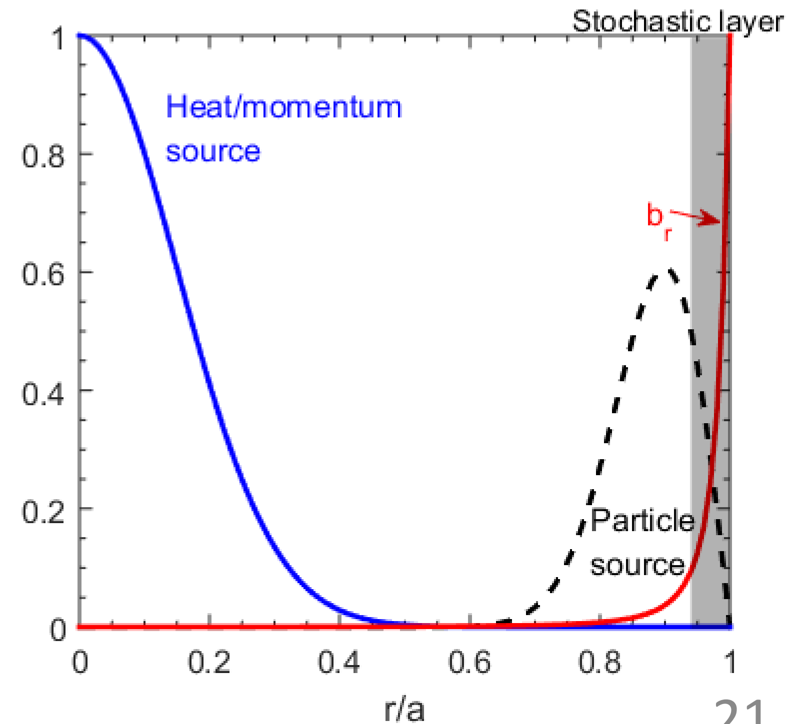
$$S_p = \Gamma_a \frac{a - r + d_a}{L_{dep}^2} \exp(-\frac{(a + d_a - r)^2}{2L_{dep}^2})$$ $L_{dep} = 0.1a$, $d_a = 0$ Particle source

$$S_M = S_a \exp(-\frac{r^2}{2L_{M,dep}^2})$$ Momentum $L_{M,dep} = 0.15a$

- Now momentum source tracks heat, but with different coefficients
- Try to change the direction of rotation

$$|\tilde{b}_r| = |\tilde{b}_0| \frac{1}{(L_{dep} - r)^3}$$ Perturbed magnetic field $L_{dep} = 1.05a$

- Adjust $|\tilde{b}_0|$, now use $10^{-4} \sim 10^{-3}$, may broaden the width of stochastic layer by changing profile



Lessons learned

- Novel $\langle J_r \rangle$ enters due to Stochastic field
  - ✓ Generates Maxwell stress/force, which competes with Reynolds stress/force
  - ✓ Effects on

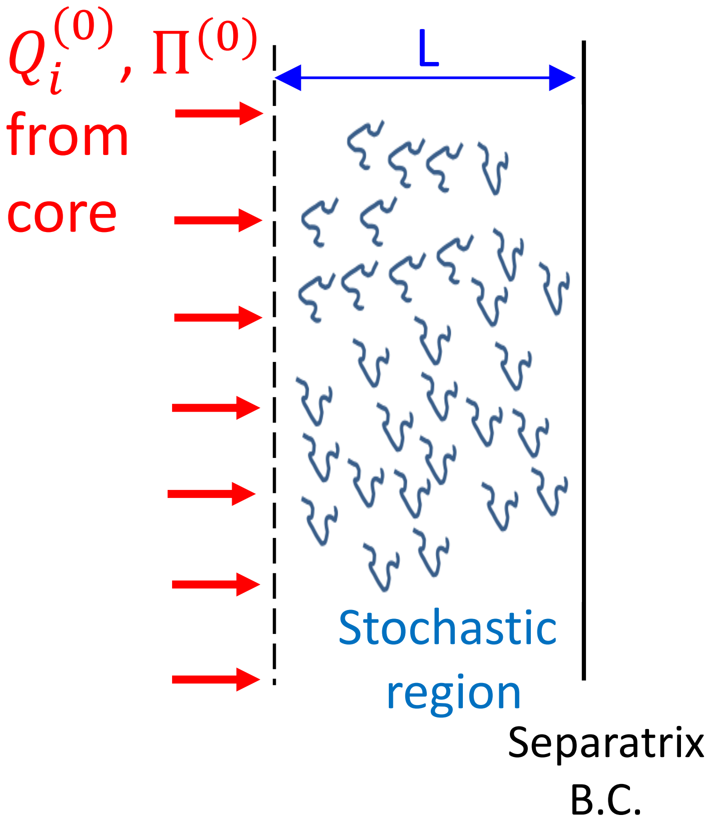
    —flow (poloidal and toroidal velocity)

    — phase

    — transport (particle and thermal)
  - ✓ Reynolds and Maxwell phases linked by shearing

$$\langle \tilde{b}_r \tilde{b}_\theta \rangle = k_y^2 V_E' \tau_c' |\tilde{b}_r|^2$$

Ongoing: toward to 1D solution



Reduced model as before, the model with:

- $|\tilde{b}_r|^2$
  Amplitude; scale
- Reduced RS in $\langle V_\theta \rangle$
  Quenching the spin-up of V_θ
- Intrinsic torque in $\langle V_\phi \rangle$
- Effect of $|\tilde{b}_r|^2$ on Q_i, Γ_e

Goals:

- Output the time evolution of *I*, V_ϕ, V_E', *n*, T_i for L→H physics modified by stochastic B-field.
- $Q_{i,crit}(|\tilde{b}_r|^2, \frac{\partial}{\partial r}|\tilde{b}_r|^2 \dots \dots)$

Conclusions

- Ambipolarity breaking $\Rightarrow \langle \tilde{b}_r \tilde{b}_\theta \rangle$, contribute to $\langle \boldsymbol{J_r} \rangle$
- Both amplitude and profile of $|b_r|^2$ matter.
- V_E' phasing $\Rightarrow$ stochastic $\langle \tilde{b}_r \tilde{b}_\theta \rangle$ opposes turbulence $\langle \tilde{V}_r \tilde{V}_\theta \rangle$

  phase linked
- Intrinsic toroidal torque, such that reversal or spin-up of edge $\langle V_\phi \rangle$ occur with RMP, $\langle \tilde{b}_r \tilde{b}_\theta \rangle$ enters edge $\langle V_\phi \rangle$
- $|b_r|^2$ can modify T_i and n_e profiles
- ……

Open issues

- Direct effect of stochasticity on turbulence (l_K v.s. $l_\parallel$ v.s. l_{mfp})

  Mode length

- Collisionality scaling
- Cost of P_{th} to obtain H-mode with $E_r > 0$ (E_r hill) ⇒Trade-off for particle control?
- RMP→island + stochastic region
- ……

Thank you very much !

G . T. Katt
(UCSD, USA)