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Non-local Structure and Transport in Toroidal Flux-Driven ITG Turbulence

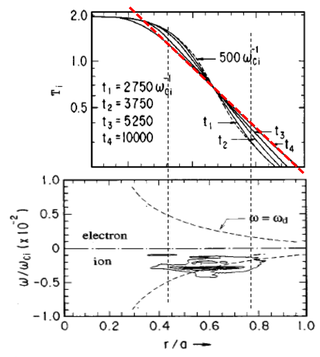
Kenji Imadera[1)], Yasuaki Kishimoto[1,2)]
Kevin Obrejan[1)], Takuya Kobiki[1)], Jiquan Li[1)]

[1)] Graduate School of Energy Science, Kyoto University
[2)] Institute of Advanced Energy, Kyoto University

E-mail address: imadera@center.iae.kyoto-u.ac.jp

1. Background: Self-organized criticality in toroidal ITG turbulence

Profile-driven simulation (without ZF/MF)



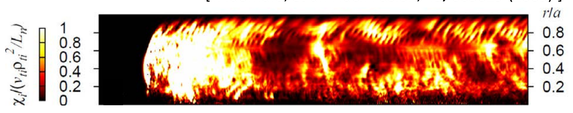
- A radially extended structure imposes a strong constraint on the functional form of temperature profile.
- Two-scale relaxation process provides a self-organized transport.

[Y. Kishimoto, *et.al.*, Phys. Plasmas **3**, 1289 (1996).]

Flux-driven simulation (with ZF/MF)

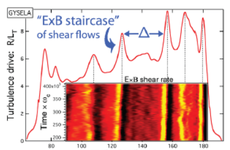
- Recent flux-driven full-f GK simulations revealed that stiff ion temperature profiles are sustained with a critical gradient, and a significant part of the heat flux is carried by avalanches.

[Y. Idomura, *et al.* Nucl. Fusion, **49,** 065029 (2009).]



- Such a type of simulation captured a new class of flow pattern called as $E \times B$ staircase, which is a localized $E \times B$ shear flow and steepens temperature profiles.

[G. Dif-Pradalier, *et.al.* Phys. Rev. E, **82**, 025401 (2010).]

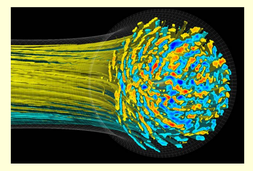


✓ Why self-organized critical transport is dominant even in flux-driven turbulence with mean/zonal flows?
✓ What is the role of *flow* (mean/zonal flows and $E \times B$ staircase) to such a self-organized critical transport?

2. Purpose of our research

- We newly developed a 5D toroidal global gyrokinetic code and checked the validity through several benchmark tests (neoclassical, R-H, linear, nonlinear ITG tests). Main features are

  Vlasov solver ($r, \vartheta, \varphi, v_{//}, \mu$) : 4th-order Morinishi scheme
  Field solver ($r, \vartheta, \varphi, \mu$): 4th-order FDM ($r$) + FFT ($\vartheta, \varphi$)
  -> Real space filed solver is also developed (see poster 15)
  Time integration : 4th-order Runge-Kutta-Gill scheme
  Parallelization: 3D(r-ϑ-μ) MPI decomposition
  Collision and heat source/sink are implemented

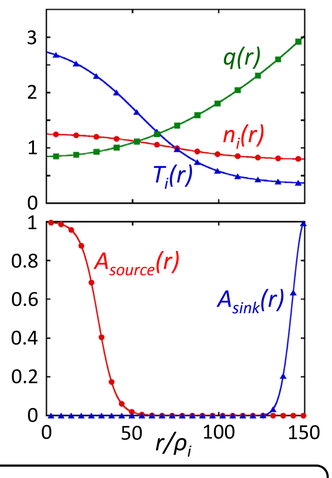


- Based on this code, we investigated the prominent non-local characteristics of flux-driven ITG turbulence and transport coupled with neoclassical physics. In particular, we focus on

  (A) Dominant turbulent transport process in flux-driven ITG turbulence
  (B) Role of mean/zonal flows in explosive global transport
  (C) Profile stiffness/resilience in power scan test

3. Simulation condition

$$\begin{cases} \rho_* = \dfrac{\rho_{ti}}{a} = \dfrac{1}{150} & (N_r, N_\theta, N_\varphi, N_{v_{//}}, N_\mu) \\ \varepsilon = \dfrac{a}{R_0} = 0.36 & = (128, 128, 64, 32, 16) \\ \dfrac{R_0}{L_T} = 10 & (L_r, L_\theta, L_\varphi, L_{v_{//}}, L_\mu) \\ \dfrac{R_0}{L_n} = 2.22 & = \left(150\rho_{ti}, 2\pi, \pi, 12v_{ti}, 18v_{ti}^2 / B_0\right) \\ & P_{in} = 4[MW], 16[MW] \\ & \tau_{snk}^{-1}\dfrac{R_0}{v_{ti}} = 0.25,\ \nu_*\dfrac{R_0}{v_{ti}} = 0.5 \end{cases}$$



Source/Sink operator

$$S_{src} = A_{src}(x)\tau_{src}^{-1}\left\{f_M(2\bar{T}_0) - f_M(\bar{T}_0)\right\}$$
$$S_{snk} = -A_{snk}(x)\tau_{snk}^{-1}\left\{f(t) - f(t=0)\right\}$$

[Y. Idomura, *et. al.*, Nucl. Fusion **49**, 065029 (2009).]

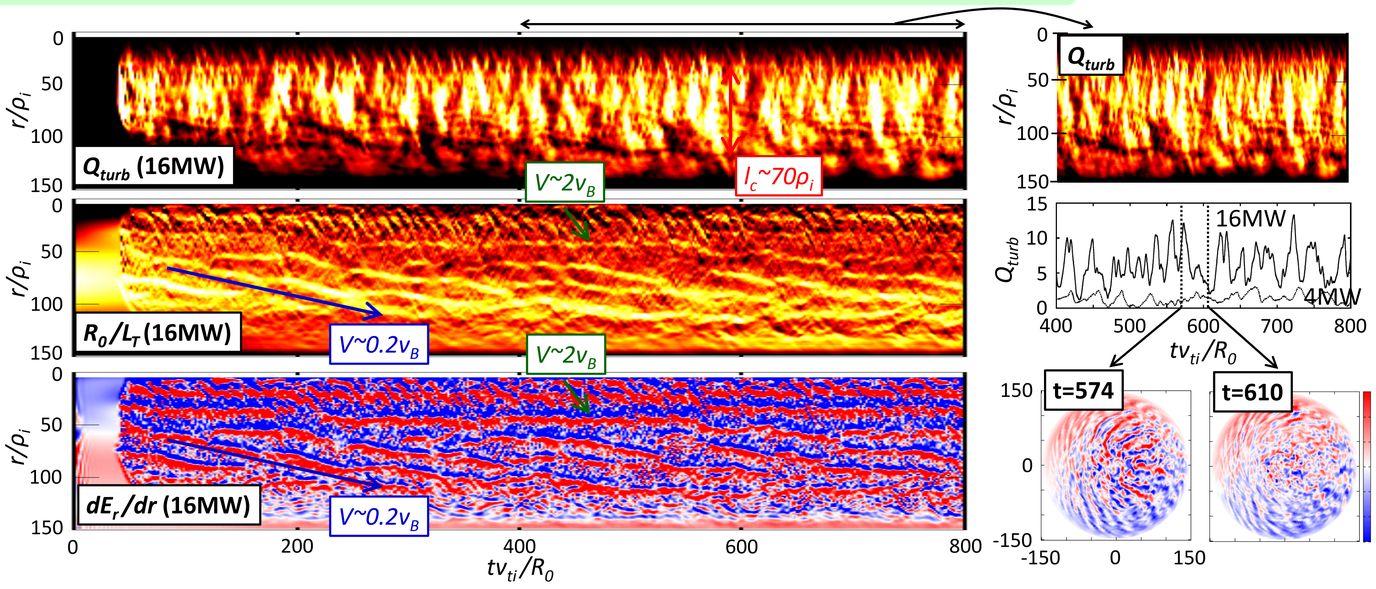
Collision operator

$$C_{coll}(f) = \frac{\partial}{\partial u}\left[\frac{3\sqrt{\pi}}{2}\frac{n}{v_{th}}\frac{\Phi(v)-\Psi(v)}{2v}\frac{\varepsilon^{3/2}}{q_0 R_0}\nu_*\left(\frac{\partial f}{\partial u} + \frac{u}{v_{th}^2}f\right)\right] - \frac{1}{n}\left[aF(x) + bG(x)\xi + cH(x)\right]f_M$$

$$\Phi(v) = \frac{2}{\sqrt{\pi}}\int_0^v e^{-x^2}dx,\ \Psi(v) = \frac{\Phi(v) - v\Phi'(v)}{2v^2} = \frac{1}{2v^2}\left(\frac{2}{\sqrt{\pi}}\int_0^v e^{-x^2}dx - \frac{2v}{\sqrt{\pi}}e^{-v^2}\right)$$

[G. Dif-Pradalier, *et.al.* Phys. Plasmas, **18**, 62309 2011).]
[S. Satake , *et.al.* Comput. Phys. Comm. **181**, 1069 (2010).]

4. Non-local heat transport - avalanches and explosive global transport -



Various types of transport

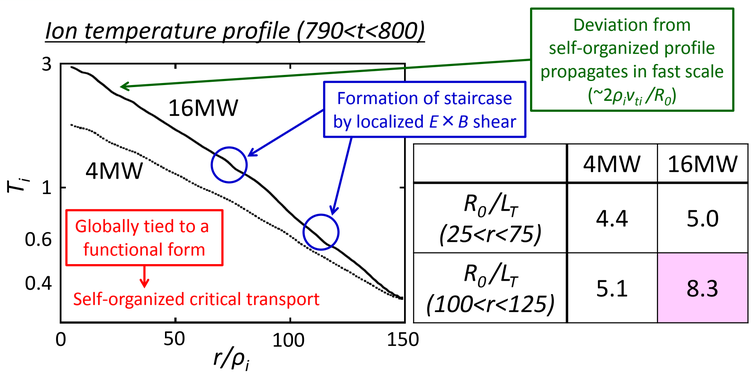
(1) Fast-scale avalanches
- Meso-scale
- Radially propagate to both in and outwards
- $V \sim 2v_B \sim C_s\rho_i$*

(2) Explosive global transport
- Meso-Macro scales
- Simultaneous event
- Coupled with radially extended vortices

(3) Slow-scale propagation of $E \times B$ staircase
- Meso-scale
- Radially propagate to outward
- $V \sim 0.2v_B$

5. Profile resilience/stiffness

Ion temperature profile (790<t<800)

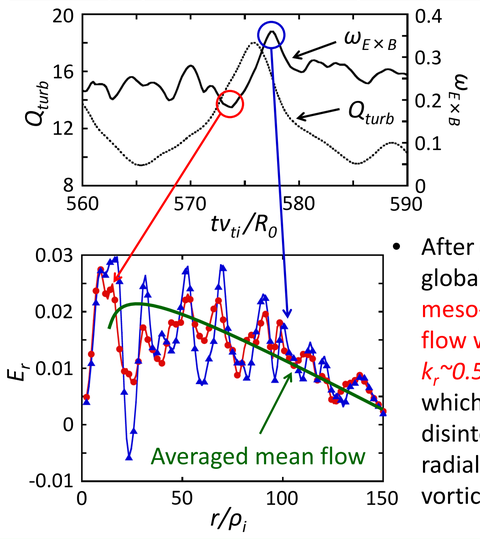


	4MW	16MW
R_0/L_T (25<r<75)	4.4	5.0
R_0/L_T (100<r<125)	5.1	8.3

- While temperature corrugation propagates in fast-scale(~$2\rho_i R_0/v_{ti}$), global temperature profile is tied to a functional form.
  -> Self-organized critical transport
- $E \times B$ shear propagates in slow-scale(~$0.2\rho_i R_0/v_{ti}$) to outer region, where a break of resilience is observed.

6. Role of zonal/mean flow shear to explosive global transport

Radial Er profile just before and after explosive event



- After explosive global transport, meso-scale zonal flow with $k_r \sim 0.5\rho_i^{-1}$ grows, which quickly disintegrates radially extended vortices.

Effect of Er on ballooning structure

$$E_r = \frac{1}{n}\frac{\partial p}{\partial r} - v_\theta B_\varphi + v_\varphi B_\theta = \frac{1}{n}\frac{\partial p}{\partial r} - k\frac{\partial T}{\partial r} + \frac{rU_{//}}{qR} = -\left(\frac{1}{L_n} + \frac{1-k}{L_T}\right)T + \frac{rU_{//}}{qR}$$

Neoclassical poloidal flow

$$\left\langle \dot{\theta} \right\rangle = \iint \frac{d\theta}{dt} f_0 dv_{//} d\mu = \frac{1}{B}\left[-\frac{2}{R}\cos\theta + \left(\frac{1}{L_n} + \frac{1-k}{L_T}\right)\right]nT$$

$$\frac{\partial}{\partial r}\left\langle \dot{\theta} \right\rangle = \underbrace{-\frac{2}{R_0}\cos\theta\left(\frac{1}{L_n} + \frac{1}{L_T}\right)nT}_{\partial\omega_r/\partial r} + \underbrace{\left(\frac{1}{L_n} + \frac{1-k}{L_T}\right)\left[\frac{\cos\theta}{R_0} + \frac{R}{R_0}\left(\frac{1}{L_n} + \frac{1}{L_T}\right)\right]nT}_{\partial\omega_f/\partial r}$$

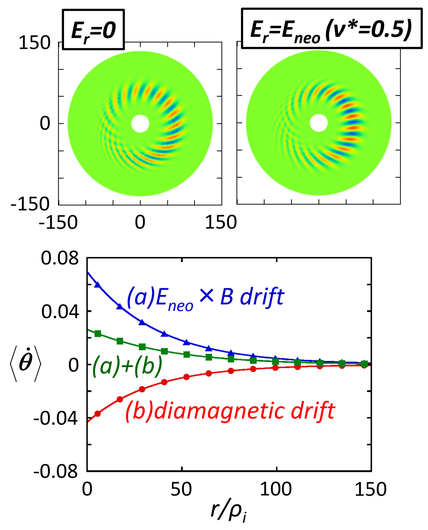
Ballooning mode width/angle

$$\Delta r \cong \left|\frac{2\gamma_0 \sin\theta_0}{k_\theta \hat{s}\left(\frac{\partial\omega_r}{\partial r} + \frac{\partial\omega_f}{\partial r}\right)}\right|^{1/2} \cong \left|\frac{2\sin\theta_0}{k_\theta\rho_i}\left(\frac{\gamma_0}{\omega_d}\right)\left(\frac{L_T\rho_i}{\hat{s}}\right)\right|^{1/2}$$

$$(\Delta\theta_0)_{max} \cong \mp\left|\frac{\left(\frac{\partial\omega_r}{\partial r} + \frac{\partial\omega_f}{\partial r}\right)}{2k_\theta\gamma_0\hat{s}}\right|^{1/3} \cong \left|\left(\frac{\gamma_0}{\omega_d}\right)\frac{1}{2\hat{s}k_\theta L_T}\right|^{1/3}$$

$$\gamma(\theta_0) \sim \gamma_0 \cos\theta_0$$

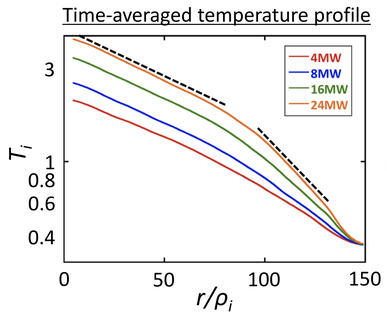
[Y. Kishimoto, *et.al.*, Plasma Phys. Controlled Fusion **41**, A663 (1999).]



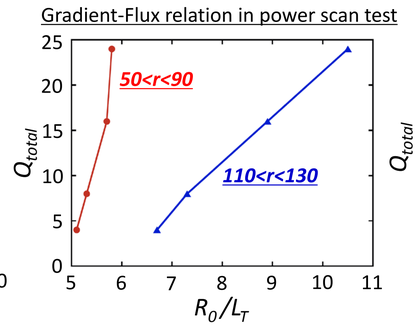
- The neoclassical mean flow shear can cancel the global profile variation effect, i.e. diamagnetic shear.

7. Power scan test

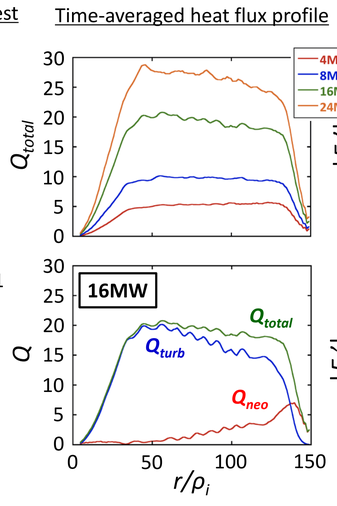
Time-averaged temperature profile



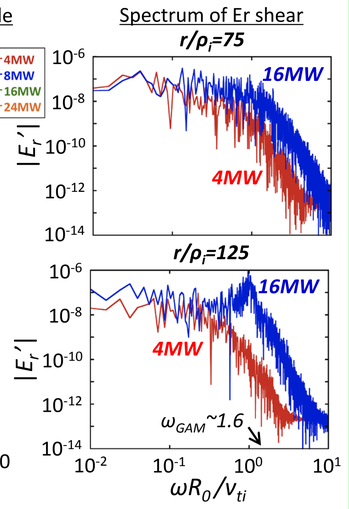
Gradient-Flux relation in power scan test



Time-averaged heat flux profile



Spectrum of Er shear

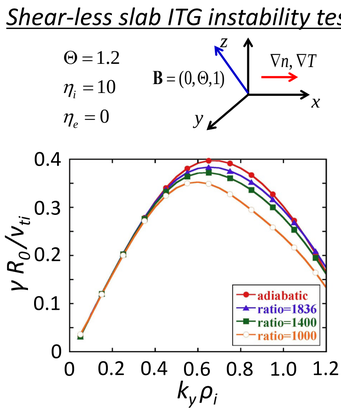


- Temperature profile is tied to an exponential functional form, while temperature scale length largely changes in outer region.
- In outer region, (1) neoclassical heat flux increases due to the effect od sink opearator and (2) E_r shear spectrum is piled up especially in $\omega v_{ti}/R_0 \sim 1$.

8. Implementation of kinetic electron (on going)

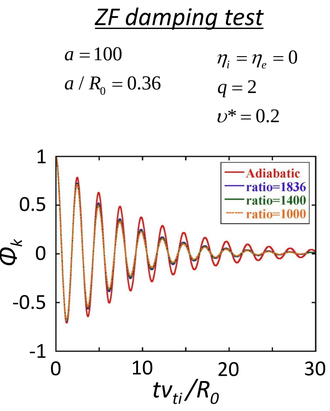
Shear-less slab ITG instability test

$\Theta = 1.2$
$\eta_i = 10$
$\eta_e = 0$
$\mathbf{B} = (0, \Theta, 1)$

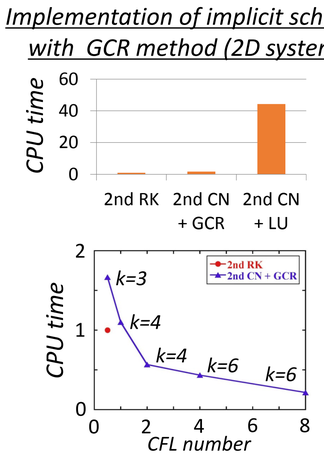


ZF damping test

$a = 100$
$a/R_0 = 0.36$
$\eta_i = \eta_e = 0$
$q = 2$
$\upsilon^* = 0.2$



Implementation of implicit scheme with GCR method (2D system)



- Growth rate decreases as mass ratio becomes smaller.
- Implicit scheme with GCR method can reduce CPU time.
- Toroidal collision-less simulation always numerically diverges…

9. Conclusion and future plans

- Flux-driven turbulent transport is dominated by three process; (1) fast-scale avalanches, (2) explosive global transport and (3) slow-scale propagation of $E \times B$ staircase.
- Explosive global transport is triggered by the instantaneous formation of radially extended potential vortices, which is enhanced by the neoclassical mean flow shear through the cancelation of global profile variation effect, i.e. diamagnetic shear.
- A self-organized resilient profile keeping the exponential function form is established even in the presence of zonal/mean flow. Such a resilience is also confirmed from step-up/down switching test for heat input power (not shown in this poster).
- A break of resilience is observed in outer region, where radial convection of temperature corrugation coupled with $E \times B$ staircase occurs, exhibiting a weak transport barrier formation in high power regime.

Future plans

- Implementation of general magnetic configuration -> Edge boundary effect
- Implementation of kinetic electron -> ITG-TEM mode
- Study of transport barrier formation in flux-driven ITG turbulence