Robustness of self-organized criticality behaviors in flux driven full-f gyrokinetic simulations

Y. Asahi[1,2], V. Grandgirard[1], Y. Idomura[2], X. Garbet[1], G. Latu[1], Y. Sarazin[1],
G. Dif-Pradalier[1], P. Donnel[1], C. Ehrlacher[1]
[1] *CEA, IRFM, F-13108 Saint Paul-lez-Durance cedex, France*
[2] *Japan Atomic Energy Agency, 178-4-4 Wakashiba, Kashiwa, Chiba, Japan*

Introduction

Due to the non-equilirium characteristics, magnetic confined plasmas are likely to generate structures through complex interactions between plasma turbulence and equilibrium profile. This complex system can be modeled by flux-driven full-F gyrokinetic simulations which allow one addressing several important transport issues such as self-organized criticality (SOC) like behaviors of bursty transport, stiff temperature profiles, momentum transport processes leading to intrinsic rotation, and influences of radial electric fields on turbulent transport. In addition, full-F gyrokinetic codes deal with the radial transport driven by collisions and turbulence consistently. Taking advantages of full-F gyrokinetic codes, we investigate the SOC like behaviors and interactions between neoclassical and turbulence transport channels.

In the present work, we employ two different gyrokinetic codes GYSELA [1] and GT5D [2]. The main differences in these codes lie in numerics where GYSELA uses semi-Lagrangian method to solve vlasov equation and GT5D uses finite difference method. Another important difference is the boundary condition applied at the magnetic axis in their Poisson solvers. In order to keep the boundary condition as close as possible between the codes, we avoid to apply the boundary condition in GYSELA at the magnetic axis following the procedure in Ref. [3]. This approach is quite similar to the natural boundary condition used in the Poisson solver in GT5D. By benchmarking of these two codes, we show the robustness of self-organized criticality behavior and profile formation processes.

Avalanche like transport

To investigate the SOC like behavior, we performed flux-driven simulations with Cyclone Base Case (CBC) [4] profile. Input power is set as 2 MW and Krook-type sink term is applied for $\rho = r/a > 0.9$. Figure 1 shows the spatio-temporal evolutions of the ion heat flux Q_i, the normalized ion temperature gradient R_0/L_{ti} and the radial electric field shear $\mathrm{d}E_r/\mathrm{d}r$. In a source free region ($r/a = 0.5-0.9$), the turbulent heat transport shows the avalanche like feature in both codes, as shown in Figs. 1 (a) and (d). The similar avalanche like behaviours are found in

Figs for R_0/L_{ti} (b, e) and dE_r/dr (c, f).

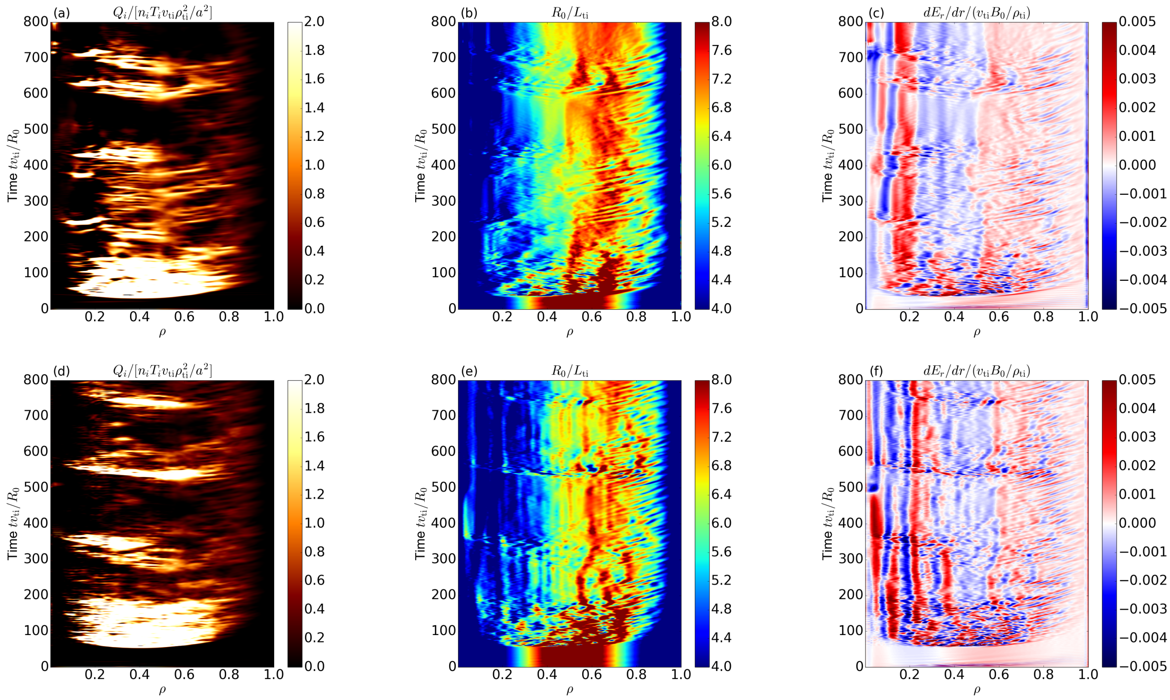

Figure 1: Spatio-temporal evolutions of the ion turbulent heat flux $Q_i/\left[n_i T_i v_{ti} \rho_{ti}^2/a^2\right]$ (a, d), the normalized temperature gradient R_0/L_{ti} (b, e) and the radial electric field shear $dE_r/dr/(v_{ti}B_0/\rho_{ti})$ (c, f) in GYSELA (upper row) and GT5D (lower row).

From the view point of self-organized criticality, it is important to investigate the frequency Fourier spectrum and compare it with the so-called 1/f decay [5]. Figure 2 shows the frequency Fourier spectra of the turbulent heat flux Q_i and the normalized temperature gradient R_0/L_{ti}. In both Figures, we found $1/f$ type spectra and transitions to $1/f^3$ type spectra. These findings are non-trivial since they confirm that this SOC-like behavior is robust and not dependent on numerics.

Toroidal momentum transport and flow profile formation

Formation of the parallel flow profile, the intrinsic rotation is of great interest. We first compared the time averaged parallel flow profile to find a dipole structure (one positive peak and one negative peak) in both codes (see. Figure 3 right bottom). We also find that the rotation is rather small. In order to investigate the flow generation process, we analysed the momentum fluxes. Firstly, we decompose the parallel momentum fluxes into the one driven by $E \times B$ drift

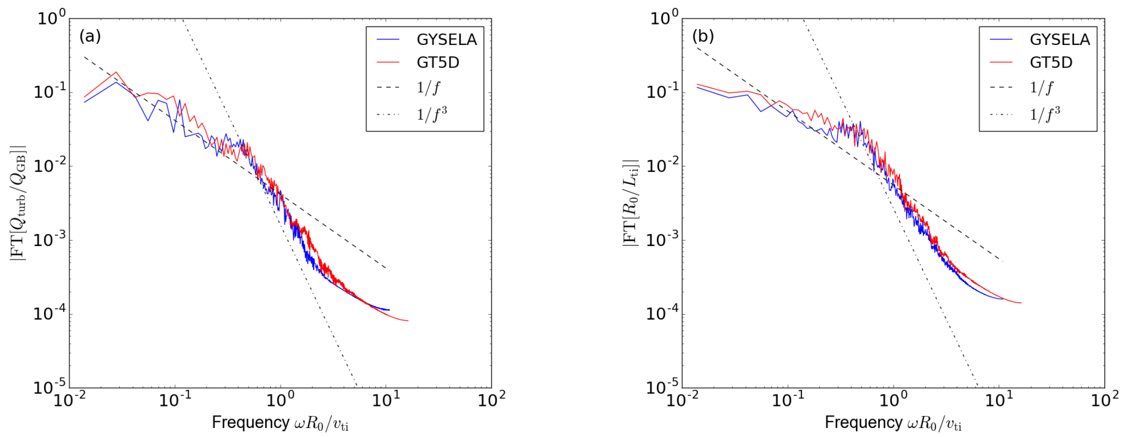

Figure 2: The frequency spectra of (a) the turbulent heat flux Q_i and (b) the normalized temperature gradient $R_0/L_{\rm ti}$ which are evaluated for $300 \leq tv_{\rm ti}/R_0 \leq 750$ with radial average in source free region ($0.5 \leq \rho \leq 0.8$).

and the magnetic drift as follows:

$$\Pi^E_{r\parallel} = \int_0^{2\pi} \frac{d\varphi}{2\pi} \int d^3\mathrm{v} F v_{Er} v_\parallel \tag{1}$$

$$\Pi^D_{r\parallel} = \int_0^{2\pi} \frac{d\varphi}{2\pi} \int d^3\mathrm{v} F v_{Dr} v_\parallel \tag{2}$$

Figure 3 shows the parallel momentum flux driven by $E \times B$ drift $\Pi^E_{r\parallel}$ (left top) and that by magnetic drift $\Pi^D_{r\parallel}$ (right top) and their normalized cross correlation [6] as defined in Eq. (3).

$$\gamma(u,v) = \frac{\sum_{x,y}\left(f(x,y) - \overline{f}_{u,v}\right)\left(t(x-u,y-v) - \bar{t}\right)}{\sqrt{\sum_{x,y}\left(f(x,y) - \overline{f}_{u,v}\right)^2 \left(t(x-u,y-v) - \bar{t}\right)^2}} \tag{3}$$

Intuitively, it can be found that the spatio-temporal evolutions of momentum fluxes driven by $E \times B$ drift and magnetic drift have opposite signs. More accurately, using the normalized cross correlation of these two fluxes, it can be shown that these are highly anti-correlated (large negative value at the center indicates the strong anti-correlation). Due to the latest theoretical work [7], this anti-correlation process can be explained by the poloidal symmetry breaking of electrostatic potential induced by turbulence. The anti-correlation of these two tensors may play a role in the relatively small rotation speed that is seen in simulations.

Summary

Flux driven full-F gyrokinetic simulations can tackle several important transport issues such as self-organized criticality (SOC) like behaviors of bursty transport, stiff temperature profiles, momentum transport processes leading to intrinsic rotation, and influences of radial electric

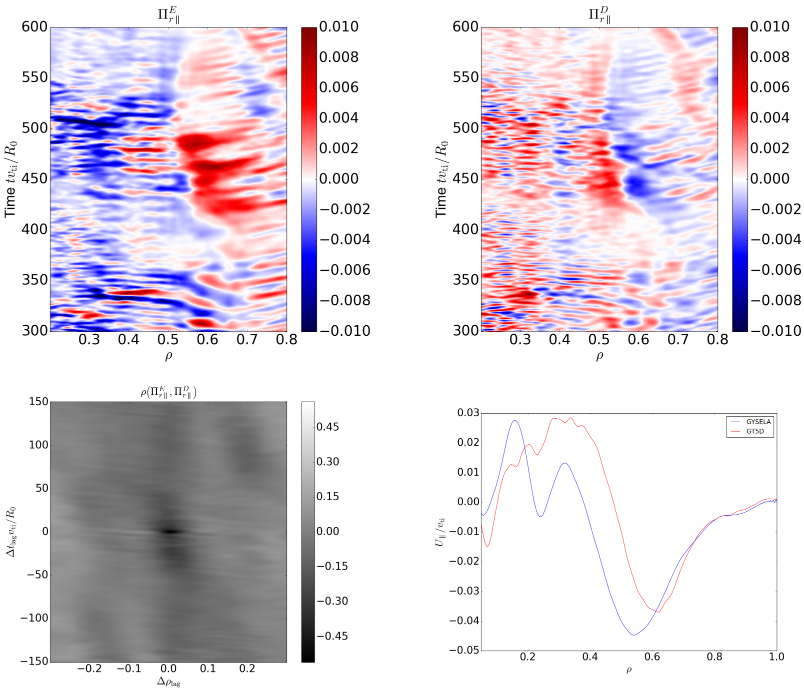

Figure 3: The parallel momentum flux driven by $E \times B$ drift $\Pi^E_{r\parallel}$ (left top), the parallel momentum flux driven by magnetic drift $\Pi^D_{r\parallel}$ (right top), their normalized cross correlation (left bottom) and radial parallel flow profile averaged for $tv_{\mathrm{ti}}/R_0 = 600 - 750$ (right bottom).

fields on turbulent transport. In the present study, we focus on two self-organization processes, namely the avalanching heat transport and the formation of parallel flow, that is the intrinsic rotation. Firstly, we found evidence of SOC-like behaviors of bursty transport in both codes. These simulations confirm that this SOC-like behavior is robust and independent of numerics. Secondly, we investigate the toroidal momentum fluxes so as to explain the relatively small rotation speed. By comparing the parallel momentum fluxes driven by $E \times B$ drift and magnetic drift, we found that these two values are anti-correlated. An anti-correlation is also confirmed by estimating the normalized cross correlation coefficient, which shows clear anti-correlation of these values. The result is also consistent with recent theoretical work.

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