Statistical Analysis of Ballistic Propagation Distance in Edge Turbulence

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The nonlinear simulation of resistive ballooning turbulence is performed in tokamak edge geometry. The spatiotemporal autocorrelation is calculated for the gradient of turbulent heat flux. The typical ballistic nature in the correlation plot is introduced by the "Lagrangian correlation," which has spatial and temporal dependence. Propagation distances of the ballistic pulses of the gradient of turbulent heat flux are quantified and are about four times the characteristic size of the front.

Keywords: edge turbulence, fluid simulation, ballistic dynamics, statistical analysis

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1. Introduction

Recently, the violation of local closure for transport relation has attracted considerable attention experimentally [1, 2] and theoretically [3–9]. For the integral formula [4] that may supplement the local closure, a detailed study of the ballistic propagation [5–8, 10] is mandatory. In particular, the radial penetration length of the fronts must be analyzed. In this study, we statistically examine the 3D fluid turbulence of edge plasmas and the penetration distance of the ballistic front.

The flux-driven nonlinear simulation of the resistive ballooning mode with edge geometry [11] is performed using the numerical code EMEDGE3D [9, 12]. Ballistic propagation in the radial direction is observed [8]. The basic equation and model we previously discussed [8] and are not reproduced here. The main simulation parameters are normalized as follows: $(r - r_0)/\xi_{\rm bal} \rightarrow x$, $r_0\theta/\xi_{\rm bal} \rightarrow y$, $R_0\varphi/L_{\rm s} \rightarrow z$, $t\tau_{\rm int} \rightarrow t$, $\tau_{\rm int}\phi\left(B_0\xi_{\rm bal}^2\right) \rightarrow \phi$, and $L_p p(\xi_{\rm bal}p_0) \rightarrow p$. with $\tau_{\rm int}^2 = R_0 L_p/\left(2c_{\rm s0}^2\right)$: resistive interchange time, $\xi_{\rm bal}^2 = m_i n_0 \eta_{\parallel 0} L_{\rm s}^2/\left(\tau_{\rm int}B_0^2\right)$: resistive ballooning length. Typical parameters on Tore Supra are $\xi_{\rm bal} = 1.4\,[\rm mm]$, $r_0 = 0.7\,[\rm m]$, $L_{\rm s} = R_0 = 2.5\,[\rm m]$, and $\tau_{\rm int} = 5\,[\mu\rm sec]$ [3]. Fluctuations with respect to averages $\tilde{\phi} = \phi - \bar{\phi}$ and $\tilde{p} = p - \bar{p}$ are introduced. $\bar{\Gamma}_{\rm turb}(x,t) = \left\langle -\tilde{p}\partial_y\tilde{\phi}\right\rangle_{y,z}$ corresponds to the turbulent radial heat flux. The symbol $\langle\cdots\rangle_{y,z}$ indicates the average over the (y, z) plane, i.e., magnetic flux surface.

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2. Simulation Results

The localized pressure gradient was found to move in a ballistic manner with the localized gradient of $-\nabla\bar{\Gamma}_{\rm turb}$ [8]. Thus, the ballistic motion of the front is most easily captured by observing $-\nabla\bar{\Gamma}_{\rm turb}$ because of the association of front with the steep gradient of the turbulent flux [6, 8]. Figure 1 illustrates the spatiotemporal autocorrelation function of gradient $-\nabla\bar{\Gamma}_{\rm turb}$. The reference position for the correlation function is set as follows: x_0 is the radial center and $t_0 = 8750\,[\tau_{\rm int}]$. At each radial point, the fluctuation part of the physical quantities is calculated by subtracting the time-averaged quantity from $t = 1500$ to $9000\,[\tau_{\rm int}]$. The temporal average is defined as $\langle g(t)\rangle = T^{-1}\int_{t-T}^{t} g(s)\,{\rm d}s$ with $T = 7000\,[\tau_{\rm int}]$.

We observe that strong correlation exists from $\Delta t \sim \pm 20$ to $\Delta t \sim \mp 20$ in the temporal range, and extends to nearly the whole system in the spatial range (Fig. 1). The contours of correlation represent the ballistic pulse propagation of the localized gradient of $\bar{\Gamma}_{\rm turb}$. We call this slanting correlation, which has both spatial and temporal dependence along the ballistic motion, "Lagrangian correlation" (red dashed lines in Fig. 1). On the other hand, we call the spatial correlation at $\Delta t = 0$ "Eulerian correlation" (blue dashed line in Fig. 1).

The projections of the Lagrangian and Eulerian correlations on the radial axis are presented in Fig. 2. The Lagrangian correlation peaks at the radial center of the simulation domain with Full-Width-Half-Maximum (FWHM) of ~ 0.01 in units of r/a. The FWHM indicates the size of the pulse of pressure gradient. We see broader peaks for

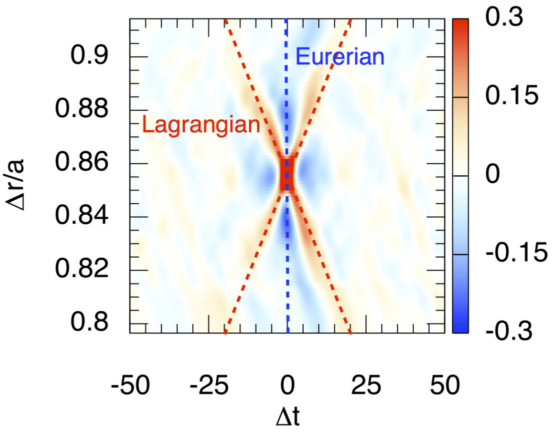

Fig. 1 Two-point, two-time autocorrelation function of the radial gradient of the turbulent heat flux. The reference point in space is the radial center and in time is $t = 8750$. The integral range in time is $T = 7000$.

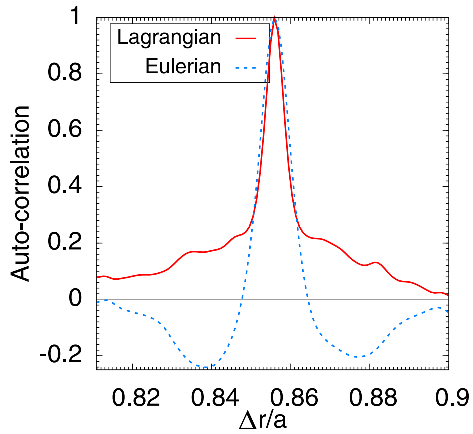

Fig. 2 Red line denotes the Lagrangian path of ballistic propagation phenomena in the spatiotemporal correlation of the radial gradient of the turbulent heat flux (Fig. 1). The blue dashed line denotes the Eulerian path in Fig. 1.

FWHM ~ 0.04. The width of the FWHM of the broader peak indicates the propagation distance of the fronts. The propagation of fronts has been studied [6] as a generalization of turbulence spreading. The FWHM of the broader peak is around four times that of the higher peak. The propagation distance of the pulse is around four times of its size. The absolute correlation value of the broader peak is ~ 0.3, which denotes the necessary level of statistical accuracy in experimental observations of the Lagrangian correlation of pulses. Compared to the Lagrangian correlation, the Eulerian correlation has negative values in the broader peak region. This negative dip in the Eulerian correlation is because of the solitary structure that propagates in space; that is, when the front is at the reference position, the fronts are less plausible to exist at the radial locations. If one projects the Lagrangian correlation on time, the FWHM for time is represented by the spatial FWHM length decided by the propagation velocity of the fronts.

The dependence of the Lagrangian correlation length on the heat flux was also studied. For various radial integrals of the pressure source, $\Gamma_{\mathrm{inp}} = 4$, 8, 12, and 20, it was confirmed that the Lagrangian correlation length l_{Lag} is about 0.04 r/a, as defined by the FWHM, and is weakly dependent on the source. On the other hand, the radial length of the heat pulse Δ_{pulse}, (FWHM of the Eulerian correlation length) shows weak dependence on $\Delta_{\mathrm{pulse}} \sim {\Gamma_{\mathrm{inp}}}^{-0.23}$. The ratio $l_{\mathrm{Lag}}/\Delta_{\mathrm{pulse}}$ depends on $\sim {\Gamma_{\mathrm{inp}}}^{0.23}$. The Lagrangian correlation length is determined by the stability of the heat pulse propagation. The theoretical study of the radial length of the ballistic propagation of heat flux modulation has just been initiated [13]. This simulation illustrates the dependence of l_{Lag} and Δ_{pulse} on the source and flux; therefore, it serves as the basis for theoretical modeling of the radial length of ballistic propagation.

We have studied convergence on the integral range T, and confirmed the $T = 7000$ case converged.

3. Summary

The nonlinear simulation of resistive ballooning turbulence was performed in tokamak edge geometry. The typical ballistic nature in the correlation plot is named "Lagrangian correlation," with spatial and temporal dependences. The propagation distance of the ballistic front of turbulent heat flux was also quantitatively estimated. The propagation distances are essential in understanding the role of ballistic pulses in the transport. The analysis results are verified by statistical convergence.

The Lagrangian correlation might be influenced by the size of the simulation domain. We also have performed analysis for the case of wider domain. The preliminary results confirm the present results is. The details will be reported in a forthcoming article.

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