GLOBAL DISPERSION AND NONLINEAR DYNAMICS IN PLASMAS MODELED FOR JT-60U STRONGLY REVERSED MAGNETIC SHEAR CONFIGURATION EXHIBITING A SIGNATURE OF ITBS FROM L-MODE CHARACTERISTICS

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We investigate the global dispersion of unstable drift modes and associated turbulent transport using δf-based global gyro-kinetic simulations, modeled for JT-60U strongly reversed magnetic shear (RS) plasmas, which exhibits L-mode characteristics with constrained profiles dominated by large scale avalanches [1]. A notable feature is the separate nature between ion/electron temperatures and that of the density, where the density is localized in the inner region with negative magnetic shear ($\hat{s} < 0$) at $r \sim r_{in}(\sim 0.4)$, while the ion/electron temperatures are localized in outer region around the minimum safety factor q surface at $r(= r_{min}) \sim 0.7$. Note that the radius is normalized by the minor radius a_0. Reflecting such configurations, we identified two different branches with respect to the toroidal mode number n, which is mapped to the radius r. One is the density gradient driven *trapped electron modes* (∇n-TEMs) in the inner region with lower n values. As n increases, they transit to *ubiquitous modes* and then to toroidal *ion temperature gradient* (ITG) modes [2,3], one other is slab-like *non-resonant ITG modes* with higher n values, all localized at the minimum q (q_{min}) surface. Here, the maximum growth rates in each branch are almost the same, i.e. $\gamma_{max}^{in} \sim \gamma_{max}^{out}$, indicating that unstable free energy sources are configured to be globally balanced so as not to cause unbalanced transport between the inner and outer regions [4]. Correspondingly, the turbulence is initiated from both inside ($r \sim r_{in}$) and outside ($r \sim r_{min}$). Then, each of them spread to both sides coupled with geodesic acoustic modes (GAMs), generating three regions, i.e. [A] the intermediate region ($r_{in} \le r \le r_{min}$), [B] the outside region of the q_{min} surface ($r_{min} \le r$) and [C] the inside region ($r \le r_{in}$). In region [A], two types of turbulent spreading coexist, one is from inside to outside ($r_{in} \to r_{min}$), the other is from outside to inside ($r_{min} \to r_{in}$), followed by the coalescence and mixing, leading to a new type of turbulent state coupled with counter propagating GAMs. In the outside region [B], the turbulence energy excited around q_{min} surface is transferred to propagating GAMs [5]. The associated oscillating E_r (the radial electric field) and $\partial E_r/\partial r$ (the shearing counterpart) are advected outside the q_{min} surface and dissipated to the plasma, by which the turbulence is suppressed. The similar process is found to take place in the inside region [C]. These results show the signature that two ITBs can be triggered, one is the outside of the q_{min} surface, the other is inside of the maximum density gradient, which is consistent to that observed JT-60U discharge [1].

1. INTRODUCTION

Reversed magnetic shear (RS) plasmas, where the safety factor profile q has a minimum value q_{min} at a certain radius $r = r_{min}$, have attracted attentions, leading to internal transport barriers (ITBs) [1,6]. However, even with such non-monotonic q-profiles, plasmas are found to exhibit L-mode characteristics with strongly constrained profiles dominated by large scale avalanches, as studied in JT-60U [1]. This leads to the conjecture that L-modes are universal without strictly depending on the magnetic structure. Given that the mode distribution is regulated by the q profile via the resonance, $nq \sim m$, it is important to unravel the underlying physics. Here, we revisit the properties of instability free energy sources for plasmas with strongly RS q profiles, modelled for those in JT-60U, as shown in Figs. 1(a) (b), and their nonlinear dynamics based on the simulations using the global gyro-kinetic code (GKNET) [6]. An interesting feature is that ion/electron temperature scale lengths L_T and the density scale length L_n are separated, i.e. the density is localized in the inner region with negative magnetic shear ($\hat{s} < 0$) at $r \sim r_{in}(\sim 0.4)$, while temperatures are localized in outer region around the q_{min} surface with $\hat{s} \sim 0$ at $r \sim r_{min}(= 0.7)$. Due to the presence of different instability free energy sources in different radial locations, multiple branches and associated eigen-modes are thought to exist, which make the transport process more complicated.

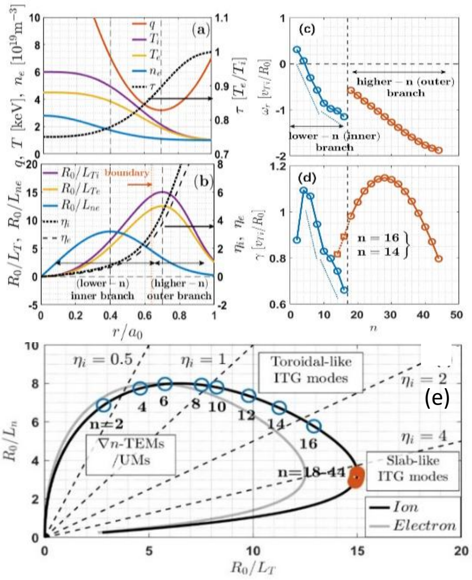

Fig. 1 (a) Equilibrium profiles of the safety factor q, ion temperature T_i, electron temperature T_e, electron density n_e, and τ; (b) Scale length profiles of T_i, T_e, n_e; (c), (d) The relation between real frequency ω_r, growth rate γ to the toroidal mode number n. (e) Mode location in the plain of $(R_0/L_T, R_0/L_n)$.

2. LINEAR EIGEN-MODE DYNAMICS AND DISTRIBUTION

From the series of simulation, we found qualitatively different two branches and associated modes, as shown in Fig. 1(c) for real frequency ω_r and (d) for growth rate γ with respect to n, one is ballooning type resonant modes with lower-n values for $2 \leq n \leq 16$ lying in the inner negative magnetic shear region ($\hat{s} < 0$), exhibiting highly localized structure in the poloidal direction, the other is non-resonant modes with higher-n values for $18 \leq n \leq 44$ lie in the outer region, which are all localized around the q_{min} surface. The former branch is identified as the density gradient driven trapped electron modes (∇n-TEMs), which show the largest growth rate at $n = 4$ with positive real frequency ($\omega_r > 0$) rotating the electron diamagnetic direction. As n increases, the real frequency crosses $\omega_r = 0$ and becomes negative values, i.e. the ion-diamagnetic direction, indicating that the TEMs are thought to transit to ubiquitous modes, which is the non-resonant counterpart of TEMs, but rotate in the ion diamagnetic direction. Furthermore, they tend to pure toroidal ITG modes. Meanwhile, the latter branch is the slab-like ITG modes, which show the largest growth rate at $n = 28$. The radial location of each mode is mapped in the plain of $(R_0/L_T, R_0/L_n)$ as shown in Fig. 1(e). The boundary of inner and outer branches can be seen in the region of $\eta_i = 2 \sim 4$, which is mapped inside the q_{min} surface at $r = 0.6$. It is noted that each branch is found to have nearly the same maximum values for the growth rate in inner and outer regions, indicating that linearly unstable free energy sources are organized to be globally balanced so as not to cause unbalanced transport between inner and outer regions. This is considered to be a global version of such marginal stability.

3. NONLINEAR TURBULENCE SIMULATION

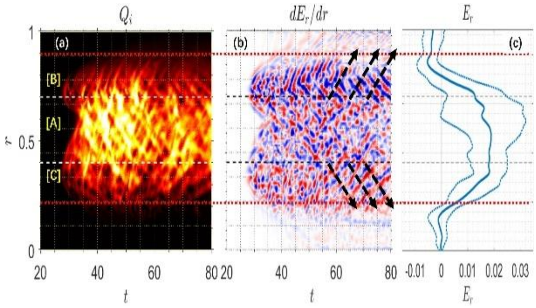

Fig. 2 The time evolution of (a) ion heat flux Q_i and (b) E_r shear; (c) Averaged E_r profile. Locations of the maximum density gradient (r=0.4) and q_{min} surface (r=0.7) are indicated by two lines.

Figure 2 shows the time evolution for the radial distribution of (a) ion heat flux Q_i, (b) the radial gradient of the electric field $\partial E_r/\partial r$, which includes GAM component, and (c) quasi-static (averaged) E_r. The mode for $n = 4$ and $n = 28$, which exhibit largest growth rate in each inner and outer branch, grow from $r = r_{in}(= 0.34)$ and $r = r_{min}(= 0.7)$ almost at the same time, developing to the turbulence coupled with GAMs, and spread both inward and outward. They are then coalesced and mixed around the boundary of inner and outer branches, i.e. $r = 0.6$. Here, we classify three regions, i.e. [A] the intermediate region, [B] the outside region of the q_{min} surface and [C] the inside region, as shown in Fig. 2. A strong burst happens and sustains from $t \sim 35$ to $t \sim 50$, accompanied with a mesh-like avalanche structure with the opposite phase velocities. In region [B] and [C], the self-generated E_r shear profile (dE_r/dr) owes two local maxima at $r_{in} \sim 0.2$ and $r_{out} \sim 0.9$, as the Fig. 2(c) shows. This is due to the fact that the turbulence energy excited around q_{min} surface is transferred to propagating GAMs [5]. The associated oscillating E_r (the radial electric field) and $\partial E_r/\partial r$ (the shearing counterpart) are advected outside q_{min} surface and dissipated to the plasma, by which the turbulence is suppressed. Correspondingly, the poloidally $E \times B$ shear flow with two maxima in both inside and outside limits the heat flux spreading in those two regions, forming certain heat flux boundaries of $r_{in} \sim 0.2$ and $r_{out} \sim 0.9$ in Fig. 2(a) and (b). In this process of transport, the system comes into a quasi-stationary state, which is characterized by the profile semi-globally relaxation. These results reveal a signature that two ITBs are ready to be trigger, one is from outside the q_{min} surface, the other is from inside of the maximum density gradient, i.e. double barrier, when the input power is sustained.

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