Gyrokinetic Global Analysis of Ion Temperature Gradient Driven Mode in Reversed Shear Tokamaks

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Abstract: A new toroidal gyrokinetic particle code has been developed to study the ion temperature gradient driven (ITG) turbulence in reactor relevant tokamak parameters. We use a new method based on a canonical Maxwellian distribution $F_{CM}(P_\varphi, \varepsilon, \mu)$, which is defined by three constants of motion in the axisymmetric toroidal system, the canonical angular momentum P_φ, the energy ε, and the magnetic moment μ. A quasi-ballooning representation enables linear and nonlinear high-*m*,*n* global calculations with a good numerical convergence. Conservation properties are improved by using the optimized loading method [2]. From comprehensive linear global analyses over a wide range of an unstable toroidal mode number spectrum (n=0~100) in large tokamak parameters (a/ρ_{ti}=320~460), properties of the ITG modes in reversed shear tokamaks are discussed. In the nonlinear simulation, it is found that a new method based on F_{CM} can simulate a zonal flow damping correctly, and spurious zonal flow oscillations, which are observed in a conventional method based on a local Maxwellian distribution $F_{LM}(\psi, \varepsilon, \mu)$, do not appear in the nonlinear regime.

1. Introduction

For the purpose of studying the ion temperature gradient driven (ITG) turbulence, we have developed a new gyrokinetic toroidal particle code for a 3D nonlinear global simulation (GT3D). This code, which has been developed based on a finite element PIC method [1], has several new features which are essential for studying the ITG turbulence in reactor relevant tokamak parameters. Firstly, we have developed a new method based on a canonical Maxwellian distribution $F_{CM}(P_\varphi, \varepsilon, \mu)$, which is defined by using three constants of motion in the axisymmetric toroidal system, the canonical angular momentum P_φ, the energy ε, and the magnetic moment μ. In the system with F_{CM}, a free energy related to $\partial_{P\varphi} F_{CM}$, which corresponds to the density and temperature gradients, does not drive any axisymmetric perturbations including zonal flows. However, in the system with a conventional local Maxwellian $F_{LM}(\psi, \varepsilon, \mu)$, which is defined by a flux label ψ, spurious driving effects on axisymmetric perturbations exist. Although this driving effect is a higher order correction compared with the linear driving term for the ITG mode with n>0, it significantly affects on axisymmetric perturbations or zonal flows, where this ordering does not hold, and spurious zonal flow oscillations grow in simulations using F_{LM}. Therefore, use of F_{CM} is important especially for studying zonal flows, which are closely related to the suppression of the ITG turbulence. Secondly, the conservation property of GT3D is greatly improved using the optimized loading [2]. An improvement of the conservation property not only demonstrates the validity of the simulation, but suppresses spurious $E\times B$ flows which are generated also from a breakdown of the particle conservation. Thirdly, we use a quasi-ballooning representation, which enables linear and nonlinear global high-*m*,*n* calculations. This technique is important to study transport properties in recent advanced tokamak configurations, where the conventional kinetic ballooning theory breaks down around a transport barrier region or a weak magnetic shear region. Of course, in case of the nonlinear simulation, we can not use the kinetic ballooning theory. Finally, GT3D has been implemented successfully on the JAERI Origin3800 system. The code is highly scalable and it operates with 40% of processing efficiency up to 512 processors. GT3D has a capability of simulating large tokamak parameters such as a/ρ_{ti}~500.

2. Linear Gyrokinetic Global Analysis of ITG Modes in Reversed Shear Tokamaks

From comprehensive global analyses over a wide range of an unstable toroidal mode number spectrum (n=0~100) in large tokamak parameters (a/ρ_{ti}=320~460), it is found that especially in reversed shear tokamaks, properties of the ITG mode are drastically changed through ion heating and density peaking processes. When the ion temperature is sufficiently high, most unstable high-n modes are excited in the outside of the q_{min} region. Residual low-n global modes in the q_{min} region show slab like feature, and their growth rates decrease by a peaked density profile. In the present study, we have assumed a circular concentric tokamak; deuterium plasma, R_0=2.6m, a=0.94m, B_0=4.6T. Peak density and temperature gradients at r/a~0.5 are given as L_{ti}/R=0.1, L_{te}/R=0.5, and L_n/R=0.5.

2.1 Relation between Radial Eigenmode Structure and *n* Spectrum

In Fig.2, growth rates are plotted for the following three cases of equilibrium configurations; (a) normal shear, a/ρ_{ti}~320 (T_{i0}=26keV, T_{e0}=8keV), (b) reversed shear, a/ρ_{ti}~320, and (c) reversed shear, a/ρ_{ti}~460 (T_{i0}=13keV, T_{e0}=4keV) (see Fig.1). For the above devise size, the growth rate spectrum spreads over very high-n (n~100) region. From a detailed study of the eigenmode structure, it is found that the higher-n modes are excited at the outer magnetic surface. This is because a radial position where the mode is excited is determined from a competition between the following two conditions; local gradient parameters and a destabilization condition in a wave number space, $k_\theta\rho_i=nq(r)/r\rho_i(r)$~0.5. Especially in the latter condition, a geometry effect $1/r$ and the finite Larmor radius effect $\rho_i(r)$ are involved. In the reversed shear configuration, where q is almost constant in the q_{min} region, these effects become distinct and the high-n modes with n>20 are excited in the outside of the q_{min} surface. On the other hand, in the normal shear configuration, where q increases monotonically as a function of r, these effects are cancelled by a change of q. In the lower ion temperature case (case (c)), the unstable region with $k_\theta\rho_i$~0.5 is shifted into the inner magnetic surface. Accordingly, only in the high temperature reversed shear plasma (case (b)), a low-n dominant growth rate spectrum is produced in the q_{min} region or r/a~0.5.

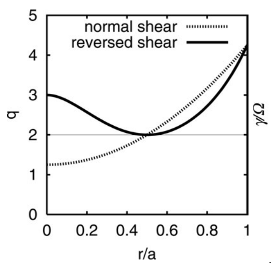

Fig.1: Safety factor profiles of normal and reversed shear configurations.

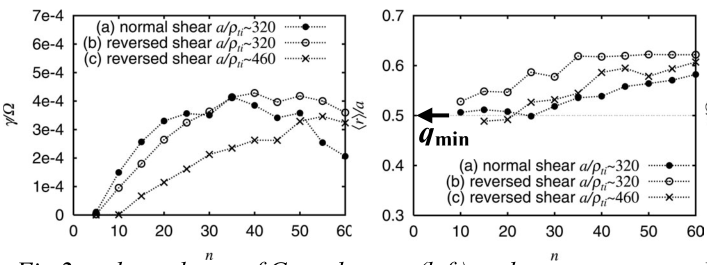

Fig.2: n dependence of Growth rates (left) and average positions of the eigenfunction (right). In the reversed shear configuration with a/ρ_{ti}~320 (case (b)), the high-n modes with n>20 are excited at the outer magnetic surface.

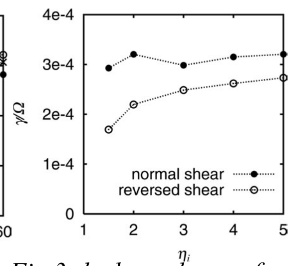

Fig.3: h_i dependence of the growth rate for n=20 mode. Here, L_{ti} is fixed and a/ρ_{ti}~320.

2.2 Slab like ITG Mode

The ITG mode in the normal shear configuration shows a typical toroidal mode structure (see Fig. 4(a)). On the other hand, low-n global modes in the q_{min} region show a coupled mode structure between the slab and toroidal ITG modes (see Figs. 4(b) and 4(c)). A similar mode structure has been observed also from a global gyrokinetic eigenvalue code [3]. Since the eigenmode structure contains significant double rational surface (m=nq+1) and nonresonant (m=nq-1) components around the q_{min} surface, this slab like feature shows a contribution from a reversed shear slab ITG mode [4,5]. It is noted that a gap mode structure, which was observed in a quasilinear saturation phase of a global PIC simulation [6], is not obtained as a linear eigenfunction. Since the slab ITG mode is sensitive to η_i ($=L_n/L_{ti}$), we have studied the η_i dependence of the growth rate in Fig.3, where a driving effect on the toroidal ITG mode L_{ti} is fixed. In the normal shear case, where the toroidal ITG mode is dominant, the growth rate is almost constant for η_i=1.5~5. However, in the reversed shear case, the growth rate is reduced by a peaked density profile or a small η_i parameter.

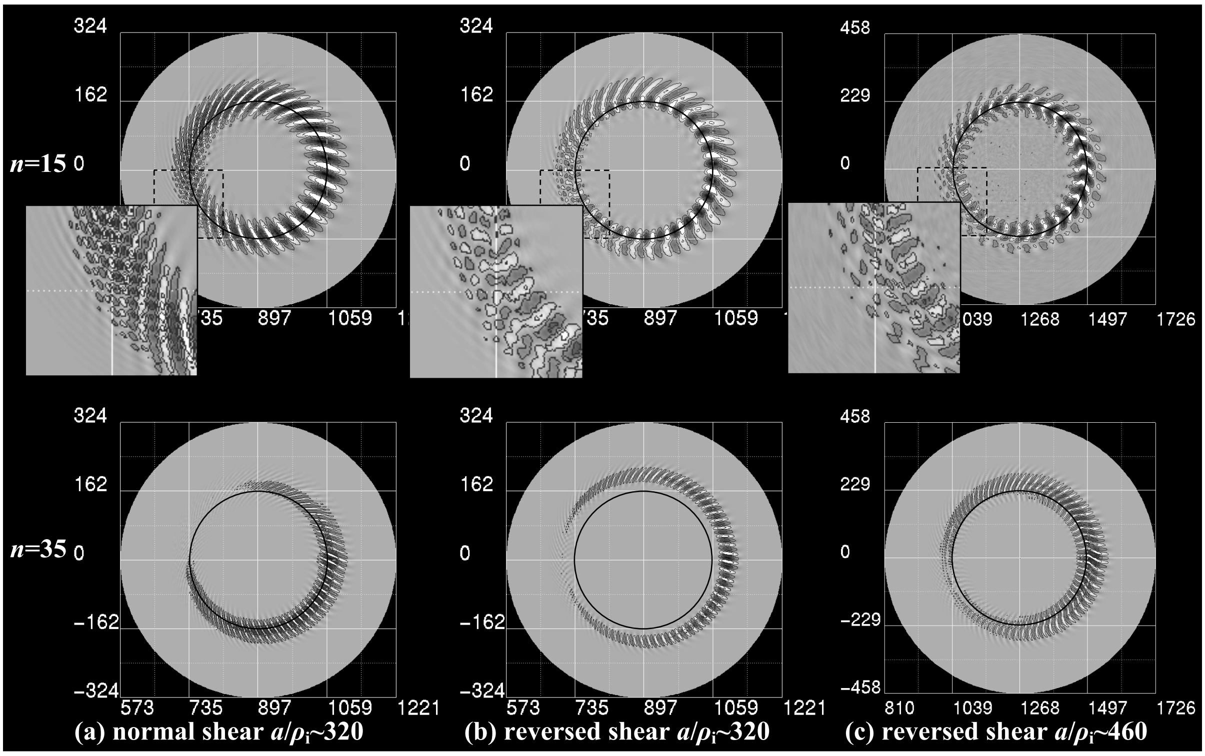

Fig.4: Typical eigenfunctions of the low-n and high-n modes in the normal and reversed shear configurations. In the q_{min} region, the low-n global mode shows a coupled mode structure between the slab and toroidal ITG modes. In the case (b), the high-n mode (n=35) is excited in the outside of the q_{min} surface.

3 Nonlinear Gyrokinetic Global Simulations using Canonical Maxwellian Distribution

In this section, we show the nonlinear simulation using a new scheme based on a canonical Maxwellian distribution $F_{CM}(P_\varphi, \varepsilon, \mu)$. Use of F_{CM} is important because of the following reasons. Firstly, in the canonical coordinates, the linear gyrokinetic equation is given by

$$\frac{d\delta F}{dt} = \frac{\partial\langle\phi\rangle}{\partial\varphi}\frac{\partial F_0}{\partial P_\varphi} - \frac{\partial\langle\phi\rangle}{\partial t}\frac{\partial F_0}{\partial\varepsilon}, \quad (1)$$

where $\langle\phi\rangle$ is the gyroaveraged electrostatic potential, and φ is the toroidal angle. When a canonical Maxwellian F_{CM} is used as the equilibrium distribution F_0, axisymmetric perturbations including zonal flows are not driven by $\partial_{P\varphi}F_{CM}$, which corresponds to the density and temperature gradients [7]. But, when we use a local Maxwellian $F_{LM}(\psi, \varepsilon, \mu)$, zonal flows, which are not subject to the Landau damping, are significantly affected by spurious driving effects. Secondly, in a conventional δf method based on F_{LM} which is not an exact equilibrium solution of the gyrokinetic equation, a variation of F_{LM} along the unperturbed characteristics, $d\boldsymbol{R}/dt|_0\nabla F_{LM}+dv_{//}/dt|_0\partial_{v//}F_{LM}$, is artificially assumed to be zero. This treatment violates the conservation properties of the system. However, in a new δf

method using F_{CM} which is an exact equilibrium solution, the method is constructed without using this kind of artificial assumptions. In the present convergence study using the Cyclone base case [8], we compare results obtained from the new and conventional methods.

3.1 Linier Stability and Conservation Properties

In Fig.5, the growth rate spectrum of the ITG mode. As is understood from the linear gyrokinetic theory, a difference between F_{LM} and F_{CM} provides only a minor correction for the ITG mode. And, both results agree well with the previous linear benchmark calculations [8]. In Fig. 6, the energy conservation property of the new code is compared between the conventional Maxwellian particle loading and the optimized particle loading. In GT3D, a 2D particle distribution function, which is optimized in the r and $v=\varepsilon^{1/2}$ space, is used for an initial particle loading. The convergence tests have been performed using 40 million marker particles, 32 toroidal modes, 32 poloidal meshes with a quasi-ballooning representation, and 76 nonuniform radial meshes. In the case with the optimized loading, the energy conservation property is improved due to a reduction of a particle noise. As for the early nonlinear stage, similar improvements are observed also by using F_{LM}. However, long time behaviour of the conservation property becomes quite bad because of spurious zonal flow oscillations.

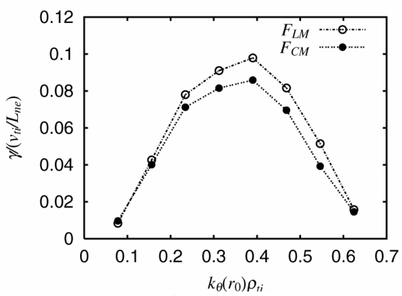

Fig.5: Growth rate spectrum plotted for the Cyclone base case; $R_0/a=0.36$, $a/\rho_{ti}\sim152$, $R_0/L_{ti}=6.9$, $\eta_i=3.12$, and $q=1.4$ at $r=0.5a$.

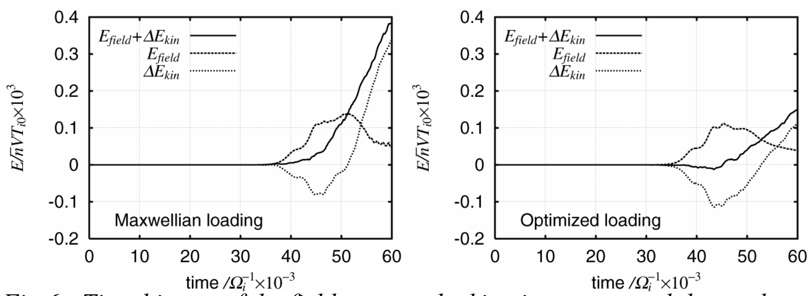

Fig.6: Time history of the field energy, the kinetic energy, and the total energy in the Cyclone base case with a Maxwellian particle loading (left) and an optimized particle loading (right). The energy conservation property is improved by using the optimized particle loading.

3.2 Zonal Flow Damping in Axisymmetric Toroidal System

Figure 7 shows the time history of the fluctuation energy in the new and conventional codes. In the case with F_{LM}, spurious zonal flow oscillations grow after the saturation of the ITG mode. Since this oscillation is strongly excited only for $(m,n)=(0,0)$ component, it is not a geodesic acoustic mode, which often appear as a damping mode with $m=1$. On the other hand, in the case with F_{CM}, such spurious oscillations are not observed, and the zonal flow energy keeps a quasi-steady state. In order to understand these results, we have performed a zonal flow damping test, which was proposed by Rosenbluth and Hinton [9]. In the test shown in Fig. 8, we have solved only $n=0$ component by preparing an axisymmetric initial perturbation, which produces initial $E\times B$ flows with $v_{E\times B}\sim0.01v_{ti}$. In the case with F_{CM}, zonal flows are damped rapidly with $m=1$ damping oscillations and the residual zonal flow level agrees well with the theoretical prediction. This result is also consistent with the linear gyrokinetic theory, which predicts no driving effect on axisymmetric perturbations including zonal flows. However, in the case with F_{LM}, spurious zonal flow oscillations are excited. It is noted that in the large aspect ratio limit, both results agree well with each other, and zonal flow damping is recovered also by using F_{LM} [10]. However, for realistic or small aspect ratio configurations, a difference between F_{LM} and F_{CM} becomes large, and use of F_{CM} is essential to simulate a correct response of a plasma against zonal flows.

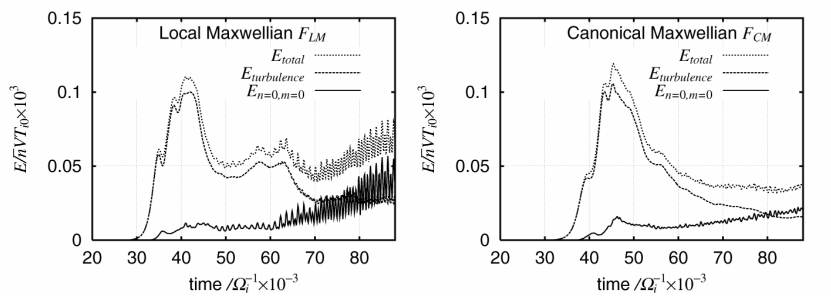

Fig.7: Time history of the fluctuation field energy in the Cyclone base case with the local Maxwellian F_{LM} (left) and the canonical Maxwellian F_{CM} (right). After the saturation of the ITG mode, spurious zonal flow oscillations grow in the case with F_{LM}.

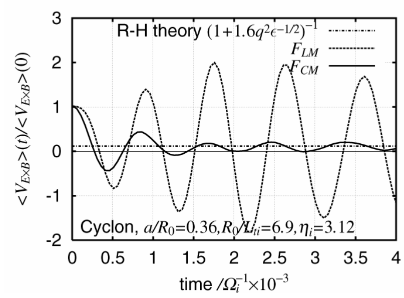

Fig.8: Time history of flux surface average zonal flows in zonal flow damping tests. Rosenbluth-Hinton theory is recovered by using F_{CM}.

4 Summary

From the linear global analysis using GT3D, it is found that most unstable high-n modes are excited in the outside of the $q_{\min}$ region in high temperature reversed shear tokamaks. Since the growth rate of low-n slab like modes in the $q_{\min}$ region is much smaller than that of high-n toroidal modes, the reversed shear configuration has an effective stabilizing effect on the ITG mode in the maximum R/L_{it} or η_{i} region. In the nonlinear simulation, an improved energy conservation property has been confirmed by using the optimized loading. From the nonlinear simulations using the local (F_{LM}) and canonical (F_{CM}) Maxwellian distributions, it is found that a choice of an equilibrium distribution function is a critical issue especially for studying zonal flows, since they are easily excited by a spurious driving effect of F_{LM}. Therefore, use of F_{CM}, which simulate a correct zonal flow damping, is essential for a gyrokinetic simulation.

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