3 Plasma Theory

3.1 Plasma theory and simulation research activities

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Abstract: In 2010, we study the effects of parallel electron viscosity on double tearing mode, the properties of edge density in single-null diverted plasma, the ETG and GAM instabilities in HL-2A tokamak plasmas, the instability driven by barely passing energetic ions, zonal flows, resistive wall mode (RWM), and ballooning mode. In addition, we establish and find the relations between the heat transport coefficients, the turbulent dissipations, and the zonal flow and electric field. Furthermore, the designs on the error field coils and the control coils of edge local mode in HL-2A(M) are carried out.

Key words: Plasma theory; Numerical simulation; Related research

1 Effects of parallel electron viscosity on double tearing mode

In this work, the double tearing modes (DTMs) induced by plasma resistivity have been studied adequately. The numerical simulations based on the reduced magnetohydrodynamic (RMHD) model in a cylindrical geometry are performed to investigate systematically the linear behaviors of the DTMs induced by anomalous electron viscosity. The DTMs mediated by electron viscosity are found enhanced by plasma resistivity which is in such a range that the growth rate of the mode induced by the latter alone is comparable with that mediated by the former alone, and vice versa. Otherwise, the growth rate of the mode is equal to the higher of the modes mediated by resistivity or electron viscosity alone when both resistivity (See Fig. 1).

![Fig. 1. The growth rate vs R are plotted for different D_e.](image)

2 Pedestal density profile in single-null diverted tokamak plasma

The structures of the density and temperature profiles in the tokamak edge region have long been attracted interests since they are closely related with physics for confinement mode transition [from the low (L) to the high (H) mode and vice versa]. The pedestal density is also related with the density limit problem. Transport processes of particle and heat are always important and many studies are devoted to this respect. According to a recent analysis on the DIII-D edge pedestal experiments, it seems that the particle pinch is important for explaining the pedestal density structure. A common trend to represent the tokamak radial particle flux is to use a diffusive-convection model as \( \Gamma = -D \nabla n + n_\text{v_y} \) while the mechanisms for producing the convection are multiple, including some unknown ones due to turbulences.

Recently, Stacey and Greifner have found formalism based on continuity equation and force balance equation for some H-mode shots. They find that there is a very large pinch velocity (its absolute peaked value can be over 200 m \cdot s^{-1} for some special cases) in edge region for some H-mode shots. Motivated by this study partly, we want to add a suitable inward convection into the original diffusion model of edge pedestal density study.

In this work, we find that the density pedestal structures for large convection case mainly depend on the width of this large convection itself while the neutral penetration only has weak effect on it. This is qualitatively different from the diffusion dominant case originally studied in that indicated the puffing and recycling neutral particles have significant effect on the density pedestal structure, especially in high density regime.

3 Transport coefficients, turbulent dissipations, and zonal flow

Physically, the resistivity mainly dissipates the electric field while the viscosity largely does the flow. Hence, Eq. can be qualitatively written as the following two parts:
\[ E_{\text{z}} = \eta' J_\theta \]
\[ V_{\text{z}} \times B_0 = \nabla \cdot \mathbf{R}/e n \]

Eqs. for the first time give the linear relation between the zonal electric field \( E_{\text{z}} \) and turbulent resistivity \( \eta' \) and that between the zonal flow \( V_{\text{z}} \) and turbulent viscosity \( \nu' \), respectively.

It is well known that the plasma resistivity heats electrons mainly while the plasma viscosity heats ions mainly. Thus, the turbulent resistivity can be regarded as a heat source of electrons. The radial scale length of the heat source is the electron temperature gradient scale length \( L_{e} \). The power of the heat source is \( < \eta' J_{\theta}^{2} > \). If \( \chi_{e}^{\eta'} \) is the conventional electron heat transport coefficient of electrons, including the collisional and the anomalous and so on, the effective heat transport coefficient of electrons is qualitatively

\[ \chi_{e}^{\eta'} = \chi_{e}^{\eta'} - < \eta' J_{\theta}^{2} > / L_{e}^{2} \]

Similarly, we obtain the effective heat transport coefficient of ions after the plasma turbulent viscosity is considered

\[ \chi_{e}^{\nu'} = \chi_{e}^{\nu'} - < \nu' \nabla V \cdot \nabla V > / L_{i}^{2} \]

Eqs. indicate that \( \eta' \) makes \( \chi_{e}^{\eta'} \) reduce and \( \nu' \) does \( \chi_{e}^{\nu'} \) decrease, respectively. Furthermore, due to the linear relation between \( \eta' \) and \( E_{\text{z}} \), and that between \( \nu' \) and \( V_{\text{z}} \), the previous arguments show that electromagnetic micro-turbulence can induce the significant turbulent resistivity \( \eta' \) and turbulent viscosity \( \nu' \) at or near rational surface. Thus, they strongly heat the ions and electrons at or near rational surface so that the \( \chi_{e}^{\eta'} \) and \( \chi_{e}^{\nu'} \) decrease to form the thermal transport barriers of ions and electrons there.

The present results indicate that the effective resistivity and viscosity should be much larger than collisional resistivity and viscosity especially at or near rational surface during or after the formation of transport barrier, which waits to be tested by experiments.

### 4 Instability driven by barely passing energetic ions

In this work, the instability driven by barely passing energetic ions is numerically studied according to the dispersion equation derived previously. We consider a NBI experiment (injection energy \( E_{\text{n}} = 60 \text{ keV} \)) on the HL-2A tokamak with a circular cross section equilibrium configuration. The other parameters are the toroidal magnetic field \( B_{t} = 1.68 \text{ T} \), the Alfvén frequency \( \omega_{A} = 4.31 \times 10^{4} \text{ s}^{-1} \), \( \omega_{b} = 0.72/0.25 \), the major radius \( R = 165 \text{ cm} \), the minor radius \( a = 40 \text{ cm} \), the magnetic shear \( s = 0.003 \), and \( \delta W_{b} = 0.003 \) (i.e. MHD is stable).

It is found that the modes with frequency comparable to the toroidal precession frequency of the ELs are resonantly excited. Positive and negative density gradient dominating cases, corresponding to off- and near-axis depositions of neutral beam injection (NBI), respectively, are analyzed in detail. The most interesting and important feature of the modes is that there exists a second stable regime in the higher \( B_{t} \) \( (= \text{pressure of ELs / toroidal magnetic pressure}) \) range (See Fig. 2).

![Fig. 2. The Nyquist diagrams plotted in complex D.](image)

The dashed, dashed-dotted, and dashed lines are, respectively, for the first and second regime, and unstable regime.

### 5 Simulation research on edge instabilities in HL-2A plasma

On the basis of the work of last year, we use the gyrokinetic toroidal code (GTC) to study furthermore the linear and nonlinear development of the drift instabilities, such as ion/electron temperature gradient (U/ETG) driven modes and trapped electron mode (TEM), as well as generation the GAM (and low/zero frequency zonal flows) and its interaction with the turbulence for realistic parameters, including steep pressure gradients, in edge plasmas of the HL-2A tokamak. (See Fig. 3)

The preliminary results indicate that that TEM is strongly unstable and the main driven turbulence in the edge plasma of HL-2A. In addition, the geodesic acoustic mode zonal flow structure, its generation and interaction with the turbulence are all observed by the nonlinear simulation. The results are compared with and show reasonable agreement with the experimental observation.

![Fig. 3. Spectrum for the growth rate and real frequency of TEM.](image)
6 Finite Larmor radius effects on high n ballooning modes

In this paper, the finite Larmor radius (FLR) effects on the high n ballooning modes are studied numerically on the basis of the FLR magnetohydrodynamic (FLR-MHD) model, which is derived previously in a “$\hat{\alpha} - \alpha$” type equilibrium of circular-flux-surfaces. Here it is found that at high magnetic shear region ($\hat{\alpha} \geq 0.8$) the critical pressure gradient ($\alpha_{c,FLR}$) of ballooning mode is larger than the ideal one ($\alpha_{c,MHD}$) and becomes larger and larger with increase of FLR parameter $b_n$ (See Fig. 4). However, at low magnetic shear region, the FLR ballooning mode is unstable than the ideal one, and the $\alpha_{c,FLR}$ is much lower than the $\alpha_{c,MHD}$. Moreover, the present results indicate that there exists some weaker new instability branches near the second stability boundary (obtained from ideal MHD theory), which means the second stable region becomes narrow.

![Image](image.png)

Fig. 4. Growth rate and real frequency vs the FLR parameter $b_n$ for the different radial wavenumber.

7 Effects of turbulent viscosity on resistive wall mode

We derive a model for the resistive wall mode (RWM) in 2009, including the turbulent viscosity effect. In the present work, the model is improved and the numerical study, based on the model, is carried out. The value of $\chi$ in this study is estimated based on the experimental measurements. The numerical results indicate that the growth rate of the RWM decreases quickly with increase of $\chi$ for the case without the plasma rotation frequency. Furthermore, in the presence of the plasma flow the numerical results show that the mode is completely suppressed as the plasma rotation frequency exceeds a critical value $\Omega_c$. Thus, we have a conclusion that the turbulent viscosity $\chi$ reduces significantly the threshold flow velocity required for RWM stabilization.

In addition, the effects of the turbulent viscosity and the plasma rotation frequency on the stability window have also been investigated. For a given $\eta_0$ and a proper choice of $\Omega_b$, we calculate the growth rate of the mode varying the wall distance $b$ for various $\chi$. It is found that, when the turbulent viscosity reaches a certain value, the stability window first appears in the wall position. A further increase in $\chi$ widens the stability window toward the plasma boundary.

In addition to the works stated above, in 2010 we study the zonal flow and the quasi-linear diffusion, and theoretically analyze the SMBI in HL-2A plasma. Furthermore, the designs on the error field coils, and the control coils of edge local mode in HL-2A(M) are carried out.