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§13. Set of Model Equations for the Analysis of the Resistive Drift Wave Turbulence in Cylindrical Plasmas

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Turbulent plasmas form a variety of structures, and researches have been carried out to clarify their role in plasma transport. Recently, plasma experiments in a simple linear configuration have been revisited for quantitative understandings of the structural formation mechanism by turbulence [1]. These results motivate the detailed simulation study of plasma turbulence in a linear device. We have been developing a three-dimensional numerical simulation code called 'Numerical Linear Device' (NLD), which simulates the drift wave turbulence in a linear device [2]. Turbulence characteristics obtained from the numerical simulation are compared with experiments to give comprehensive understanding of plasma transport. The model used in NLD for the analysis of the resistive drift wave turbulence is described here.

Turbulence measurements in linear devices, such as LMD in Kyushu University [3] and CSDX in University of California San Diego [1] are compared with our simulation. The plasma has a simple cylindrical shape. The plasma boundary is given at $r = a$. In this model, we do not solve the vacuum region, simply assuming that a background density profile has a fixed nonzero value at $r = a$. The magnetic field has only the component in the axial direction z with the uniform intensity B. According to experiments, high density ($n_e > 1\times10^{19}$[m^{-3}]) and low temperature ($T_e < 5$ [eV]) plasmas in an argon or neon discharge are analyzed. Only monovalent ions are considered, and the density of neutral particles is high even in the plasma core region, so the effect of neutral particles should be taken into consideration.

For describing the resistive drift wave turbulence in a linear device, the fluid model including the continuity equation, the momentum conservation equation of electrons and the charge conservation equation are used [2]:

$$\frac{\partial n}{\partial t} + \vec{\nabla}\cdot(n\vec{v}_e) = 0\,, \tag{1}$$

$$nm_e\frac{d\vec{v}_e}{dt} = -\nabla p - ne\left(\vec{E} + \vec{v}_e\times\vec{B}\right) + n\nu_{ei}m_e\left(\vec{v}_i - \vec{v}_e\right) - n\nu_{en}m_e\vec{v}_e\,, \tag{2}$$

$$\vec{\nabla}\cdot\vec{J} = 0\,, \tag{3}$$

where $d/dt = \partial/\partial t + [\varphi,\ ]$ is the convective derivative, φ is the electrostatic potential, $n = n_e = n_i$ is the density, m_e is the mass of electron, $p = nT$ is the pressure, $\vec{J}$ is the current, $\vec{v}_e$ and $\vec{v}_i$ are the velocity of electron and ion, ν_{ei} and ν_{en} are the electron-ion and electron-neutral collision frequency, respectively. Quasineutrality holds for the dynamics of our interests, so that the charge conservation gives the form of Eq. (3). This set of equations gives an extension of the Hasegawa-Wakatani equations [4] by (i) inclusion of an inertial term of electron and a resistive term caused by neutrals in Eq. (2), and (ii) consideration of three-dimensional dynamics. The current in Eq. (3) is divided into components perpendicular and parallel to the magnetic field, and the perpendicular current is given to be

$$\vec{J}_\perp = en\left(v_{i\perp} - v_{e\perp}\right) = \frac{Mn}{B^2}\left(-\frac{d}{dt}\nabla_\perp\phi - \nu_{in}\nabla_\perp\phi\right), \tag{4}$$

where M is the mass of ions, and ν_{in} is the ion-neutral collision frequency. The first and second terms of Eq. (4) come from the polarization current and the Pederson current, respectively. Equations (1) - (3) are written to be

$$\frac{dN}{dt} = -\nabla_{/\!/}V - V\nabla_{/\!/}N + \mu_N\nabla_\perp{}^2N\,, \tag{5}$$

$$\frac{dV}{dt} = \frac{M}{m_e}\left(\nabla_{/\!/}\phi - \nabla_{/\!/}N\right) - \nu_e V + \mu_V\nabla_\perp{}^2V\,, \tag{6}$$

$$\frac{d\nabla_\perp{}^2\phi}{dt} = \nabla N\cdot\left(-\nu_{in}\nabla_\perp\phi - \frac{d\nabla_\perp\phi}{dt}\right) - \nu_{in}\nabla_\perp{}^2\phi - \nabla_{/\!/}V - V\nabla_{/\!/}N + \mu_W\nabla_\perp{}^4\phi \tag{7}$$

by assuming $v_{i/\!/} \ll v_{e/\!/}$, substituting Eq. (4) into Eq. (3), and using normalization $N = \ln(n/n_0)$, $V = v_{/\!/}/c_s$, $\phi = e\varphi/T_e$, where n_0 indicates the value of density at $r = 0$, $v_{/\!/}$ is the electron velocity parallel to the magnetic field, $c_S = \sqrt{T_e/M}$ is the ion sound velocity and T_e is the electron temperature. Note that the time and distance are normalized by the ion cyclotron frequency $\Omega_{ci} = eB/M$ and Larmor radius (at the electron temperature) $\rho_S = c_S/\Omega_{ci}$, respectively. The collision frequencies are normalized by Ω_{ci} and $\nu_e \equiv \nu_{ei} + \nu_{en}$. The effects of neutrals are taken into account by ν_{in} and ν_{en} in Eq. (6) and (7). Artificial viscosities μ_W, μ_N and μ_V are added in Eqs. (5) - (7) for the purpose of numerical stability in nonlinear simulation.

Equations (5) - (7) compose the set of model equations for analyzing the resistive drift wave turbulence in NLD. The boundary condition in the radial direction r is set to $\tilde{f} = 0$ at $r = 0$, a when $m \neq 0$, and $\partial\tilde{f}/\partial r = 0$ at $r = 0$, $\tilde{f} = 0$ at $r = a$ when $m = 0$, where $r = a$ gives an outer boundary of the plasma column and f implies $\{N, \phi, V\}$. The periodic boundary conditions in the azimuthal θ and axial z directions are assumed, and the Fourier spectral expansion in θ and z directions is adopted. To obtain $\tilde{N}$, $\tilde{\phi}$ and $\tilde{V}$, the terms in equations (5) - (7) are divided into linear and nonlinear parts. The linear parts are solved implicitly, and the nonlinear terms are advanced in time by using predictor-corrector method. The background density N_{bg}, potential ϕ_{bg} and parallel velocity V_{bg} also affect the stability of the drift wave. Giving these quantities as the initial conditions, numerical simulations are carried out.

References

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