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Kinetic Integrated Modeling of Toroidal Plasmas
トロイダルプラズマの運動論的統合モデリング

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In order to self-consistently describe heating and current drive and various influences of energetic particles in toroidal plasmas, we have been developing a kinetic integrated modeling code TASK-3G. This modeling is based on the behavior of the momentum distribution function of each particle species. The time evolution of the momentum distribution function is described by a Fokker-Planck component TASK/FP and the influence of energetic particles on global stability is studied by a full wave component TASK/WM. Self-consistent analysis of multi-scheme heating in a ITER plasma is demonstrated including radial transport and fusion reaction rate calculated from the modified momentum distribution function. The linear stability of global eigen modes in the presence of energetic particles is also discussed.

1. Introduction

In order to accurately predict the behavior of fusion plasmas and to develop reliable schemes controlling them, development of integrated simulation codes for burning plasmas is urgently needed. Fusion reactions and external plasma heating and control generate energetic particles and modify the momentum distribution functions of plasma species. The existence of these energetic particles may drive global instabilities, such as resistive wall modes, internal kink modes, Alfvén eigenmodes and so on. The occurrence of global instabilities usually redistributes the energetic particles. Previous analyses of momentum distribution functions usually assume background species with Maxwellian distribution and the temperature of the bulk component cannot be changed during the analyses. These assumptions are not satisfied in a strong heating case where the bulk temperature changes rapidly. Therefore integrated core-transport simulation based on the momentum distribution is required for.

2. Kinetic Integrated Modeling of Tokamak Plasmas

For these purposes, we have been developing a kinetic integrated simulation code, TASK-3G, based on the time evolution of the momentum distribution functions. It is an extension of the integrated tokamak modeling code TASK [1] which includes the components for MHD equilibrium, diffusive transport, ray tracing, full wave and the Fokker-Planck analyses. In TASK-3G, the Fokker-Planck component TASK/FP describes the behavior of the bulk component including the radial transport, and self-consistently simulates strong heating cases where the momentum distribution function is strongly modified. The modification is taken into account in the full wave component TASK/WM which describes the ICRF heating and low-frequency global instabilities.

3. Multi-species Fokker-Planck analysis

The relativistic bounce-averaged Fokker-Planck component TASK/FP [2] has been extended to describe the time evolution of the multi-species momentum distribution function $f_s(p,\theta,\rho)$ where s, p, θ and ρ are particle species, magnitude of momentum, pitch angle and normalized minor radius, respectively. In this modeling, axisymmetry, time scale longer than the particle bounce time, and zero bounce orbit width are assumed. The Fokker-Planck equation includes nonlinear Coulomb collision, quasilinear wave-particle interaction, parallel electric field acceleration, radial diffusion, and particle source.

Figs. 1, 2 and 3 show typical simulation results for multi-scheme heating in ITER plasma. We assumed a radial diffusion coefficient $D_{rr}(\rho) = 0.1(1 + 9\rho^2)\,[\mathrm{m^2/s}]$ and an inward pinch term to keep the initial density profile. The ICRF waves heat tritons by second-harmonic cyclotron damping and electrons by Landau damping. Deuterons are heated by NBI and alpha particles are generated by DT fusion reaction. Fig. 1 indicates the power transfer between different species. Fig. 2 illustrates the contours of f_s at various radial position, 1 s after heating starts. Initial electron density and temperature on the magnetic axis are $10^{20}\,\mathrm{m^{-3}}$ and 20 keV. Fig. 3 indicate the radial profiles at $t = 1\,\mathrm{s}$ of the absorbed power density of each particle species, average kinetic energy of electrons, D and T, collisionally transferred power density, and time evolution of collisionally transferred power. The distribution f_s is calculated on 50 magnetic surfaces by full-implicit parallel solver on 50 CPU cores. At $t = 200\,\mathrm{ms}$, the alpha particle density is only 0.5% of the electron density. The tritons produced by DD reaction affect f_T near the normalized momentum $p \sim 10$, about 1 MeV. Collisional power transfer between species is also calculated self-consistently by using the nonlinear collision operator which conserves momentum and energy with reasonable numerical accuracy.

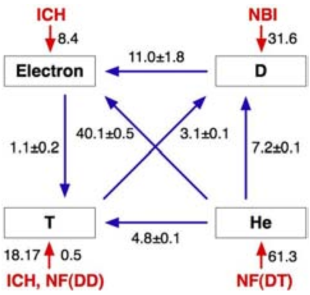

Fig. 1. Power transfer among plasma species

In the calculation shown in Fig. 3, the radial diffusion broadens the kinetic energy density, especially T heated by ICRF waves. The region of triton temperature increase becomes broader and is shifted inward due to the inward pinch. We found that the heating and current drive profiles are sensitive to the radial transport model. We have introduced several kinds of turbulent diffusion coefficient and inward pinch, without energy dependence, with $1/\sqrt{1+p^2}$ dependence, fixed radial profile. Validation of the radial transport model with experimentally observed radial profiles of energetic particles is under way.

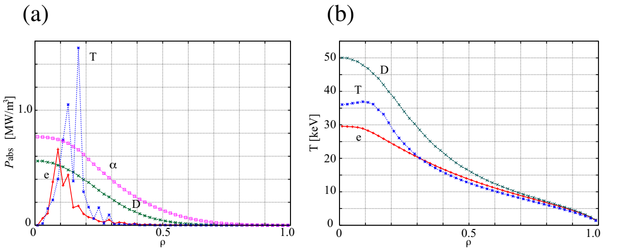

Fig. 3. Radial profiles of (a) absorbed power density and (b) average kinetic energy

4. Full wave analysis including the influence of energetic particles The ICRF wave electric field is calculated by the full wave component TASK/WM [3] in the case shown in Fig. 1. Using the kinetic dielectric tensor calculated by numerical integration in momentum space, TASK/WM can deal with arbitrary f_s in analyzing ICRF heating and current drive. The energetic particles also affect the stability of Alfvén eigen modes and low-frequency global eigen modes. The analysis of global eigen mode usually studied with MHD model, e.g. resistive wall modes and internal kink modes, is planned including the influence of energetic particles.

Acknowledgments

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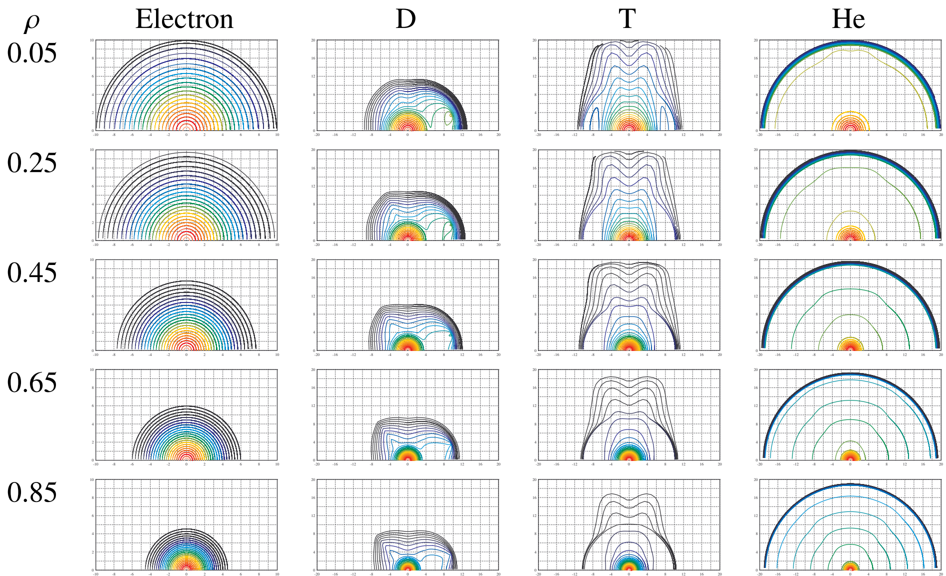

Fig. 2. Radial dependence of momentum distribution functions for electron, D, T, He.