Kinetic Integrated Modeling of Heating and Current Drive in Tokamak Plasmas

A. Fukuyama 1), H. Nuga 1), S. Murakami 1)

1) Graduate School of Engineering, Kyoto University, Kyoto, Japan

e-mail contact of main author: fukuyama@nucleng.kyoto-u.ac.jp

Abstract. In order to self-consistently describe heating and current drive and various influences of energetic particles in tokamak plasmas, we have been developing a kinetic integrated modeling code TASK3G. 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 newly-extended 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 for the first time including radial transport and fusion reaction rate calculated from the 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 redistribute 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, TASK3G, 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 TASK3G, 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.

Figure 1 illustrates the present structure of the integrated code, TASK, and associated codes. The TASK3D is an extension to the analysis of three-dimensional (3D) helical configurations, composed of TASK components and three additional transport components. They are designed to exchange predefined standard data through unified application interface.

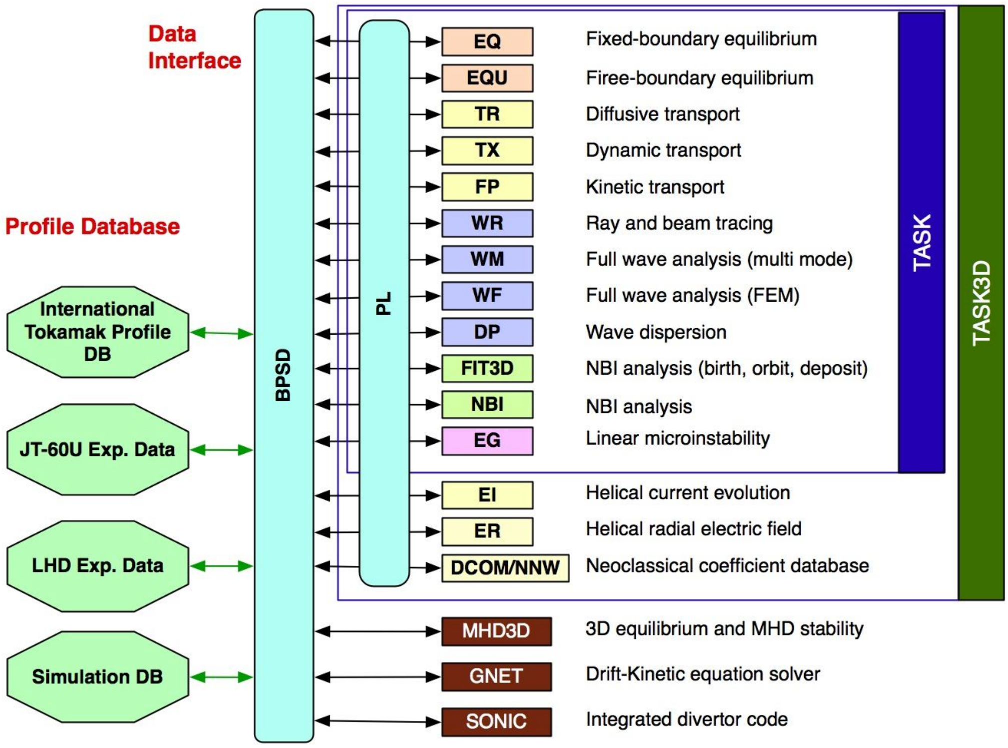

Fig. 1. Present structure of TASK and TASK3D

The core transport phenomena have been simulated by various levels of transport modeling as shown in Fig. 2. The TASK code includes three kinds of components for transport analysis. The conventional transport component TASK/TR is based on the diffusive transport equations for densities, toroidal momentum, temperature, and poloidal magnetic flux. TASK/TX [2] is based on dynamic transport modeling which solves flux-surface-averaged multi-fluid equations including the equations of motion. It describes the time evolution of the radial electric field and plasma rotation profiles self-consistently. The Fokker-Planck code TASK/FP has been extended for the kinetic integrate modeling; the radial transport is included and high performance is obtained by parallel processing. The higher dimensional kinetic modelings usually describe plasma turbulence and require much more computer resources.

3. Multi-species Fokker-Planck analysis The relativistic bounce-averaged Fokker-Planck component TASK/FP [3] has been newly 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, quasi-linear wave-particle interaction, parallel electric field acceleration, radial diffusion, and particle source.

Figures 4 and 5 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

Fluid model

Diffusive transport equation: $n(\rho, t), v_\phi(\rho, t), T(\rho, t)$	**TR**
Dynamic transport equation: $n(\rho, t), \boldsymbol{u}(\rho, r), T(\rho, t)$	**TX**

Kinetic model

Bounce-averaged drift-kinetic equation: $f(p, \theta_\mathrm{p}, \rho, t)$	**FP**
Axisymmetric gyrokinetic equation: $f(p, \theta_\mathrm{p}, \rho, \chi, t)$	**XGC0**
Gyrokinetic equation: $f(p, \theta_\mathrm{p}, \rho, \chi, \zeta, t)$	**GT5D, GKV**
Full kinetic equation: $f(p, \theta_\mathrm{p}, \phi_\mathrm{g}, \rho, \chi, \zeta, t)$	**PARASOL**

Fig. 2. Level of transport modeling

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. Figure 4 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. Figures 5 indicate the radial profiles at $t = 1$ 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. The total absorbed power is 8.4 MW for electrons, 18.17 MW for T, 31.6 MW for D and 61.3 MW for alpha particles. The fusion reaction rate is calculated with f_s of reacting particles. At $t = 200$ 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.

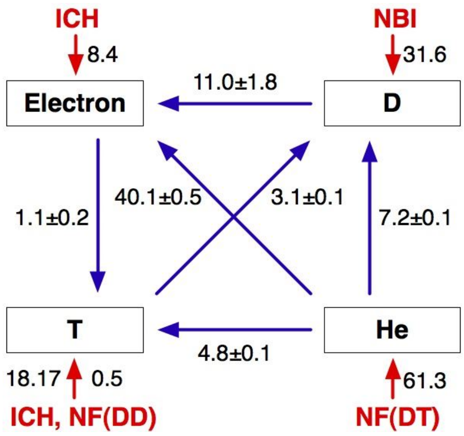

Fig. 3. Power transfer among plasma species

In the calculation shown in Fig. 4, the radial diffusion broadens the collisional power transfer profile, 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

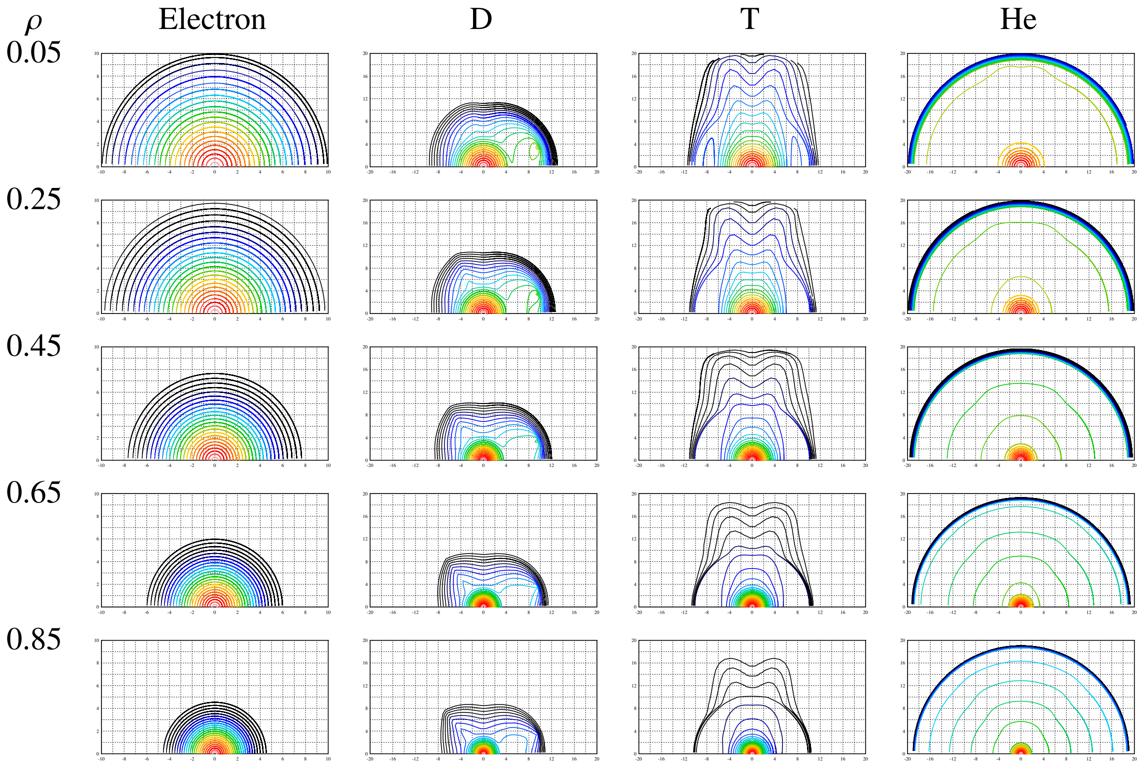

Fig. 4. Radial dependence of momentum distribution functions for electron, D, T, He.

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, and turbulent transport models used in transport simulations. Validation of the radial transport model with experimentally observed radial profiles of energetic particles is under way.

4. Full wave analysis including the influence of energetic particles The ICRF wave electric field is calculated by the full wave component TASK/WM [4] 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. Since the present kinetic dielectric tensor model assumes a uniform plasma, modes coupled with drift waves cannot be correctly described. Therefore we have developed a drift-kinetic dielectric tensor model for arbitrary f_s. Using this newly-developed model, we have analyzed the linear stability of low-frequency Alfvén eigen modes coupled with drift waves driven by energetic particles. The analysis of global eigen mode usually studied with MHD model, e.g. resistive wall modes and internal kink modes, is also under way including the influence of energetic particles.

Acknowledgments

This work is supported in part by Grant-in-Aid for Scientific Research (S) (20226017) from JSPS.

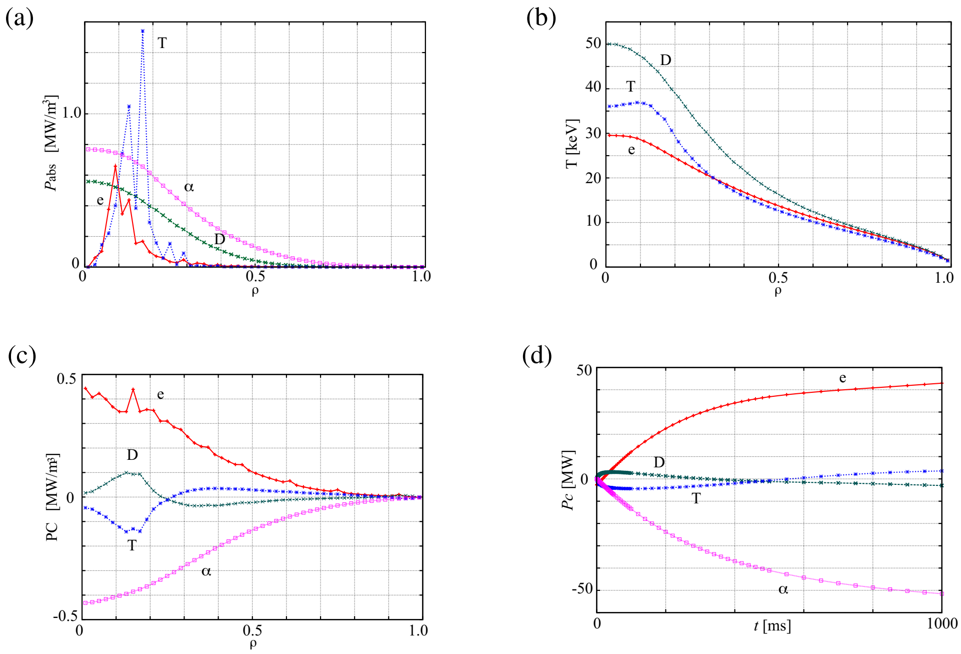

Fig. 5. Radial profiles of (a) absorbed power density, (b) average kinetic energy, (c) collisionally transferred power density, and time evolution of collisional power transfer

References

[1] FUKUYAMA A et al., Proc. of 20th IAEA FEC (Villamoura, 2004) IAEA-CSP-25/CD/TH/P2-3.
[2] HONDA M, FUKUYAMA A, J. Comp. Phys., 227, 2808 (2008).
[3] NUGA H, FUKUYAMA A, J. Plasma and Fusion Res. Series, 8, 1125 (2009)
[4] FUKUYAMA, A., et al.: Proc. of 21th IAEA FEC (Chengdu, 2006) IAEA-CN-149/TH/P6-10.