Kinetic Integrated Modeling of Tokamak Plasmas

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Introduction

Integrated modeling of tokamak plasmas is indispensable for predicting the performance of burning plasmas and developing control schemes in ITER and future fusion reactors. Conventional approach to integrated modeling is based on diffusive transport equations and MHD stability analyses. In fusion plasmas, however, energetic particles are generated by external heating, current drive, and fusion reactions, and they affect global instabilities, such as resistive wall modes, internal kink modes, and Alfvén eigenmodes. In order to describe the behaviour of energetic particles and their influence on global stabilities self-consistently, we have been developing a kinetic integrated modeling code, TASK3G [1], based on the time evolution of the momentum distribution functions. It is an extension of the integrated modeling code TASK as shown in Figure1. TASK3G has two main components, TASK/FP and TASK/WM. The Fokker-Planck component TASK/FP describes the time evolution of the momentum distribution functions, and the full wave component TASK/WM describes not only ICRF wave heating but also Alfvén eigenmodes and low-frequency global eigenmodes. These two components are coupled with anisotropic MHD equilibrium analysis, ray tracing analysis for EC and LH waves, and edge plasma analysis.

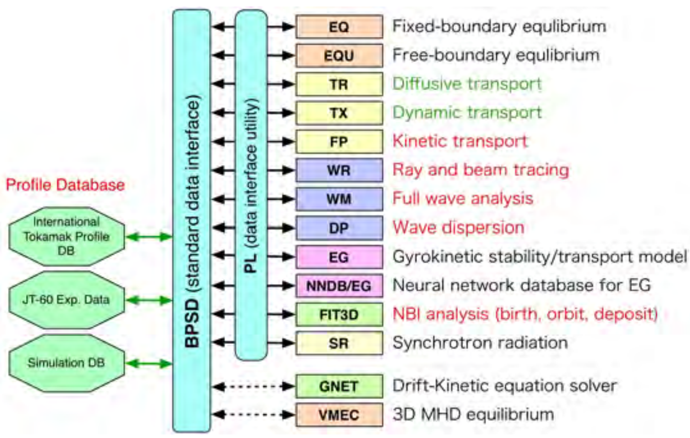

Figure 1: Present structure of the TASK code

Kinetic transport component: TASK/FP

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 on the outer mid plane 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.

Simulation of multi-scheme heating in ITER plasma

TASK/FP was applied to multi-scheme heating in ITER plasma. The plasma is composed of electron, deuteron, triton and Helium ions. 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. Figure2 shows the radial dependence of the momentum distribution functions of the four species in $(p_\parallel, p_\perp)$ space at 1 sec after the heating starts. Energetic particles generated in the core region diffuse to the lower density outer region. It should be noted that 1 MeV trirons are generated by DD fusion reaction and accelerated by second harmonic cyclotron resonance though the particle density is very low. At 1 sec, ion cyclotron heating power goes to triton 18.2 MW and to electron 8.4 MW, NBI heating power to deuterons 31.6 MW, and DT fusion power to He 61.3 MW. Dominant collisional power transfer processes are 40.1 MW from He to electron and 11.0 MW from deuteron to electron.

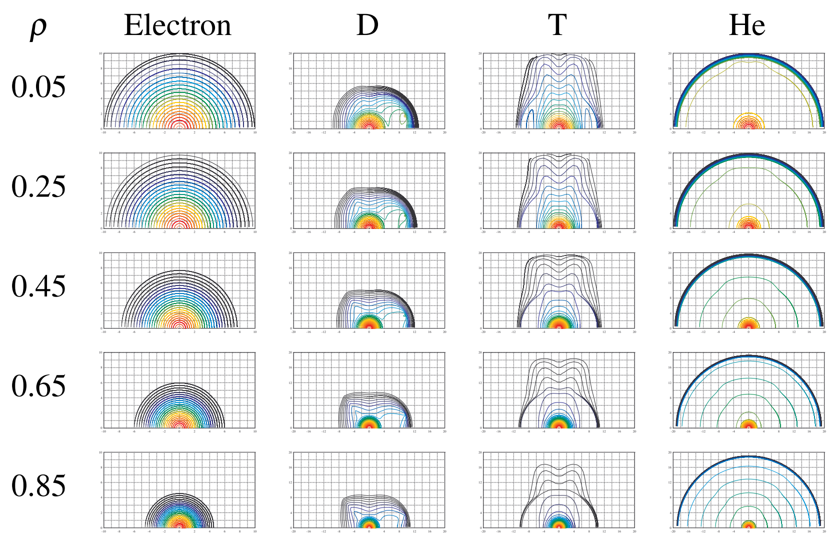

Figure 2: Radial dependence of momentum distribution functions

Dependence on radial diffusion model

The radial diffusion coefficient D_{rr} is considered to depend on the momentum p through the finite orbit size effects. We assume the form $D_{rr}(p,\rho) = D_0(\rho)p'^{-\mu}$ where $p' = \sqrt{p^2 + p_{\mathrm{th0}}^2}$ and p_{th0} is the thermal momentum. The radial profiles of average kinetic energy density and bulk temperature for $\mu = 0$, $\mu = 1/2$, $\mu = 1$ and $D_0 = 0$ are shown in Figure3. The bulk temperature is evaluated from the gradient of the momentum distribution function in the low energy region. The radial diffusion broadens the profile of average kinetic energy density, especially for T heated by ICRF waves. The μ dependence of global quantities, volume averaged kinetic energy density, bulk temperature, He density, and total absorbed power are shown in Table. With the increase of μ, the heating power of the ion cyclotron waves and the fusion power increases due to the stronger interaction of energetic ions.

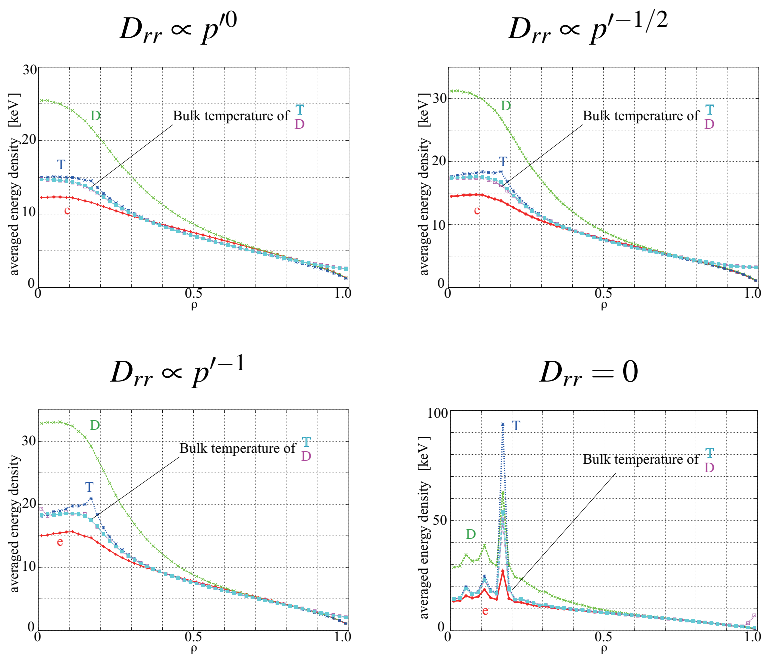

Figure 3: Radial profiles of average kinetic energy for various momentum dependence

Full wave analysis in the presence of energetic particles

The full wave component TASK/WM [2] calculates the ICRF wave electric field and low-frequency global modes. Since the kinetic dielectric tensor is calculated by numerical integration in momentum space, TASK/WM can describe wave excitation and absorption for arbitrary f_s. It has been applied to the self-consistent analysis of the ICRF heating and the analysis of global eigen mode usually studied with MHD model in the presence of energetic particles.

Table 1: Volume-averaged kinetic energy, bulk temperature, He density, and total absorbed power for various momentum dependence

		$D_{rr} \propto p'^0$	$D_{rr} \propto p'^{-1/2}$	$D_{rr} \propto p'^{-1}$	$D_{rr} = 0$
$E_{\mathrm{K,ave}}$ [keV]	e	7.13	7.63	7.74	8.18
	D	9.57	10.61	10.82	11.72
	T	7.18	8.00	8.15	9.44
	He	471.70	527.12	558.28	622.75
$T_{\mathrm{bulk,ave}}$ [keV]	e	7.16	7.64	7.80	8.18
	D	7.18	8.03	8.06	8.95
	T	7.13	7.98	7.98	8.87
	He	9.88	12.48	12.96	17.88
n_{ave} [$10^{16}\mathrm{m}^{-3}$]	He	6.45	8.36	8.64	9.65
P_{abs} [MW]	IC (e)	7.94	9.24	9.68	10.79
	IC (T)	8.95	10.34	10.87	15.28
	NB (D)	31.68	31.69	31.68	31.69
	$\mathrm{NF_{DT}}$	23.36	30.77	32.70	36.88

Remaining issues in kinetic transport modeling

There still remain several important issues in kinetic transport modeling. First we have to analytically formulate the turbulent transport coefficients with momentum dependence. Second the finite orbit size effects are essential for neoclassical transport and interaction of energetic ions. Third the coupling with inductive toroidal electric field will strongly affect the transient behavior of current drive. Finally the charge neutrality cannot be hold in the present formulation. The influence of the radial electric field on the particle transport has to be taken into account. By solving these issues, more consistent kinetic transport modeling will be available and simulation results will be compared with the results of conventional diffusive transport analysis.

Acknowledgments

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References

[1] A. Fukuyama et al., Proc. of 20th IAEA FEC (Villamoura, 2004) IAEA-CSP-25/CD/TH/P2-3.

[2] H. Nuga, A. Fukuyama, J. Plasma and Fusion Res. Series, 8, 1125 (2009)

[3] A. Fukuyama et al.: Proc. of 21th IAEA FEC (Chengdu, 2006) IAEA-CN-149/TH/P6-10.