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高エネルギー粒子挙動解析のための統合モデリング
Integrated modeling of high-energy particle transport in Tokamak

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After starting the neutral beam (NB) injection during a plasma ramp-up phase in burning plasmas, not only the plasma heating and the current driven by NB, but also the internal heating by alpha particles and an associated bootstrap current, affect the evolution of the plasma and the equilibrium. Therefore, analysis of the plasma evolution consistent with high-energy ions generated from NB and alpha particles is indispensable for the design of the operation scenarios. Toward this end, we have integrated the bounce-averaged Fokker-Planck code (BAFP) [1] for the high-energy particles into the 1.5D transport code TOPICS [2].

TOPICS solves the transport equations, i.e., the continuity equation for the bulk ion density, the power balance equations for the electron and the bulk ions and the magnetic diffusion equation, with the Grad-Shafranov equation iteratively. BAFP solves the bounce-averaged Fokker-Planck equation for the high-energy ions on the bulk plasma profile and the equilibrium given by TOPICS, and calculates particle/heat sources and current terms for the transport equations of TOPICS. TOPICS evolves the plasma and the equilibrium taking into account these terms, passes the updated plasma and equilibrium to BAFP. The two codes evolve time steps alternately throughout a calculation.

In BAFP, the collision term and the field related parameters, i.e., the orbit length and the bounce time of the high-energy particles, are updated along with the variation of the bulk plasma and the equilibrium. These updates are, however, not enough to take into account the change of the distribution function caused by the variation of the magnetic field. When the magnetic field varies, the particle assemblage in the phase space moves conserving the number of particles, $N = f\mathrm{d}\boldsymbol{v}\mathrm{d}\boldsymbol{r}$, where $\mathrm{d}\boldsymbol{v}\mathrm{d}\boldsymbol{r}$ is the volume in the phase space. We have fixed the volume during the calculation for convenience of computation. Therefore, the movement of the particle assemblage has to be evaluated as the flux across the surface of the fixed volume. Since the flux is convective, the flux is expressed in the form of $\boldsymbol{\Gamma} = N\boldsymbol{u}$, where $\boldsymbol{u}$ is the velocity across the surface in the phase space. The velocity $\boldsymbol{u}$ is evaluated numerically via the orbit following calculation. The divergence of the flux $\boldsymbol{\Gamma}$ is added on the bounce-averaged Fokker-Planck equation. This scheme allows BAFP to reflect the variation of orbits due to the variation of the equilibrium in the distribution function.

Self-consistent calculation of the bulk and the high-energy particles has been undertaken for the ramp-up phase shortly after starting the NB injection via the integrated code. Result of the calculation and the contribution of the flux due to the variation of the equilibrium will be discussed in the presentation.

[1] K. Hamamatsu, J. Plasma Fusion Res. SERIES 8 (2009) 1134-1137.
[2] M. Honda, Comput. Phys. Commun. 181 (2010) 1490-1500.