§9. Monte-Carlo Simulation of Neoclassical Transport in Ergodic Region

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It is shown in Large Helical Device (LHD) experiments that the transport modeling based only on the fluid description is not sufficient for expressing edge transport phenomena in/around a magnetic island with lower-collisionality. For example, the healing of the $m/n = 1/1$ magnetic island observed in the edge of the LHD plasma is not explained by simulations based on the fluid equations neglecting kinetic effects when solving the relaxation process, where m and n are the poloidal and toroidal mode numbers respectively, and the temperature is $T_{\mathrm{edge}} > 500$ eV and the plasma density $n_{\mathrm{edge}} \sim 10^{19}$ m^{-3} in the island region in the experiments. On the other hand, in recent tokamak experiments it is found that so-called stochastic diffusion theory based on the "field line diffusion" overestimates the radial energy transport in the edge added resonant magnetic perturbations (RMPs). In collisionless edge ergodized plasma, the experimental thermal-diffusivity χ_{ex} is inconsistent with the prediction of the stochastic diffusion theory $\chi_{\mathrm{ql}} = v_{\mathrm{th}} D_{\mathrm{mag}}$; $\chi^{\mathrm{e}}_{\mathrm{ex}}/\chi^{\mathrm{e}}_{\mathrm{ql}} \ll 1/10$ for the electron thermal diffusivity. Small RMPs cause the complete suppression of the ELM events, and have negligible effect on the energy confinement.

The above experimental results in the torus plasmas imply that the conventional modeling of edge transport in magnetic islands and ergodic regions should be reconsidered for a lower-collisionality case, and kinetic modeling is required for understanding stochastic transport in the ergodic region. In order to understand fundamental properties of the collisionless edge plasma in magnetic islands and ergodic regions, and to take a new look at the modeling of the transport from the viewpoint of the kinetic treatment, we attempt a simulation study of neoclassical transport in magnetic islands and ergodic regions. Here, even in the field line structure disturbed by the RMPs, the Coulomb collision causes the transition between a passing particle orbit and a trapped particle orbit in toroidal and helical ripples (localized and/or blocked particle orbits); in the present paper we call it the neoclassical effect on transport phenomena. Recently, we develop a new transport simulation code without the assumption of nested flux surfaces; the code is named "KEATS." The code is programmed by expanding the well-known Monte-Carlo particle simulation scheme based on the δf method. By using the KEATS code, it is possible to execute the investigation. We apply the KEATS code to a torus plasma having the ergodic region in the edge. Here, because of a limited computational-time we treat ions (protons) for our first numerical study of the transport in the ergodic region.

To investigate effect of the existence of the ergodic region on the transport phenomena, we evaluate the energy flux of ions (protons) $\boldsymbol{Q}_{\mathrm{i}}$ for our first numerical study of the transport, because the evaluation of electron energy flux is highly time-consuming. The evaluation of the ion energy flux is carried out in the configuration having higher edge temperature $T_{\mathrm{edge}} \sim 1$ keV at a center of the ergodic region. The temperature profile is given as $T_{\mathrm{i}} = T_{\mathrm{ax}}\{0.02 + 0.98\exp[-4(r/a)^{7.86}]\}$ with $T_{\mathrm{ax}} = 2$ keV, which neglects the existence of the ergodic region. The density profile is set homogeneous, $n_{\mathrm{i}} = \mathrm{const.} = 1 \times 10^{19}$ m^{-3}. The radial profile of the energy flux estimated from the KEATS computations is shown as closed-circles in Fig.1; the maximum value of the effective radial-thermal-diffusivity $\chi^{\mathrm{i}}_{\mathrm{eff}}$ is estimated as $\chi^{\mathrm{i}}_{\mathrm{eff}} \approx 0.9$ m^2/s at $r/a \approx 0.8$, where $\chi^{\mathrm{i}}_{\mathrm{eff}} = Q^{(\mathrm{KEATS})}_{\mathrm{r}}/(n_{\mathrm{i}}|\partial T_{\mathrm{i}}/\partial r|)$ and $Q^{(\mathrm{KEATS})}_{\mathrm{r}}$ the radial energy flux evaluated by the KEATS code. The energy flux $\boldsymbol{Q}_{\mathrm{i}}$ is averaged over concentric circular shell region in the whole toroidal angles as if there were nested flux surfaces.

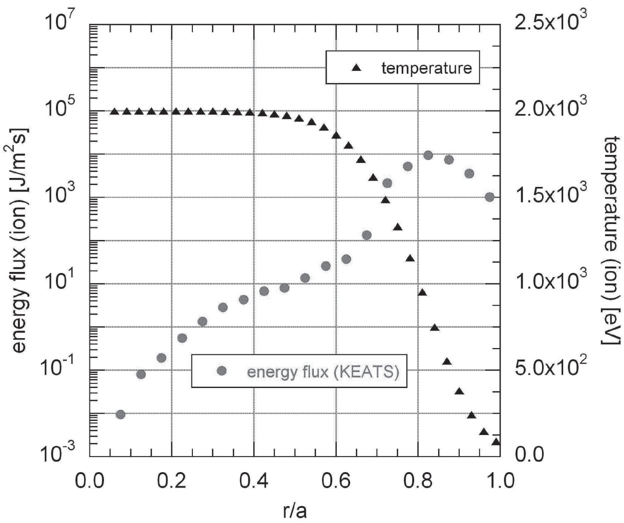

Figure 1: Radial profile of the ion energy flux $Q^{(\mathrm{KEATS})}_{\mathrm{r}}$ for higher edge temperature, where $r = \sqrt{(R - R_{\mathrm{ax}})^2 + Z^2}$. The center of the ergodic region is located at $r/a \approx 0.8$.