§8. Monte-Carlo Simulation of Transport in Islands and 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.[1)] 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).[2)] 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 transport in magnetic islands and ergodic regions. Recently, we develop a new transport simulation code without the assumption of nested flux surfaces; the code is named "KEATS."[3)] 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, and discuss the interpretation of the simulation results. Here, because of a limited computational-time we treat ions (protons) for our first numerical study of the transport in the ergodic region.

For the investigation of the radial transport in the ergodic region, we use a magnetic configuration which is formed by adding RMPs into a simple tokamak field having concentric circular flux surfaces, where the major radius of the magnetic axis $R_{\rm ax} = 3.6$ m, the minor radius of the plasma $a = 1$ m, and the magnetic field strength on the axis $B_{\rm ax} = 4$ T. The unperturbed magnetic field is approximately given as $B_R = -(B_{\rm ax}R_{\rm ax}/q)Z/R^2$, $B_\varphi = -B_{\rm ax}R_{\rm ax}/R$, and $B_Z = (B_{\rm ax}R_{\rm ax}/q)(R-R_{\rm ax})/R^2$, where q is the safety factor and $q^{-1} = 0.8-0.78(r/a)^4$, and $r = \sqrt{(R-R_{\rm ax})^2+Z^2}$. The RMPs causing resonance with, for example, the rational surfaces of $q = m/n = 2/1, 3/1, 4/1, \ldots$ are numerically given by using the perturbation field generated by the island control coils of LHD,[4)] and order of the strength is $\mathcal{O}(|\delta B_{\rm r}/B_{\rm t}|) \sim 10^{-3}$. The Poincaré plots of the magnetic field lines on a poloidal cross section are shown in the left picture of Fig. 1. The ergodic region appears in $r/a \approx 0.7 \sim 1$. In the KEATS code, the number of marker particles is $N_{\rm MP} = 16{,}000{,}000$. The evaluation of the ion energy flux is carried out in the configuration having higher edge temperature $T_{\rm edge} \sim 1$ keV at a center of the ergodic region. The temperature profile is given as $T_{\rm i} = T_{\rm ax}\{0.02 + 0.98\exp[-4(r/a)^{7.86}]\}$ with $T_{\rm ax} = 2$ keV, which neglects the existence of the ergodic region. The density profile is set homogeneous, $n_{\rm i} = {\rm const.} = 1 \times 10^{19}$ m^{-3}. The radial profile of the energy flux estimated from the KEATS computations is shown as red closed-circles in the right picture of Fig. 1; the maximum value of the effective radial-thermal-diffusivity $\chi^{\rm i}_{\rm eff}$ is estimated as $\chi^{\rm i}_{\rm eff} \approx 0.9$ m^2/s at $r/a \approx 0.8$, where $\chi^{\rm i}_{\rm eff} = Q_{\rm r}^{\rm (KEATS)}/(n_{\rm i}|\partial T_{\rm i}/\partial r|)$ and $Q_{\rm r}^{\rm (KEATS)}$ the radial energy flux evaluated by the KEATS code. For simplicity, the radial energy fluxes are given by neglecting the existence of the ergodic region, because we have no magnetic coordinate system including several magnetic field structures as the core and ergodic regions. The energy flux $\boldsymbol{Q}_{\rm i}$ is averaged over concentric circular shell region in the whole toroidal angles as if there were nested flux surfaces.

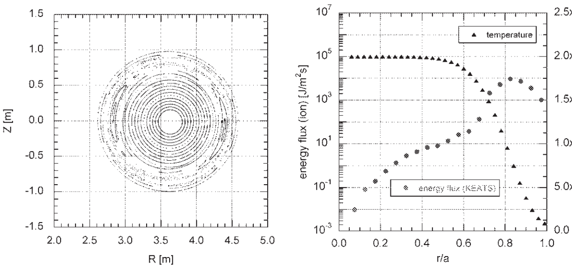

Fig. 1: [Left] Poincaré plots of the magnetic field lines on a poloidal cross section. [Right] Radial profile of the ion energy flux $Q_{\rm r}^{\rm (KEATS)}$ (red closed-circles), where $r = \sqrt{(R-R_{\rm ax})^2+Z^2}$. The temperature is shown by black closed-triangles.

We have been developing the drift kinetic equation solver, KEATS, to study the transport phenomena in the islands and ergodic regions. We apply the code to the edge disturbed by resonant magnetic perturbations under the assumption of neglecting effects of an electric field and neutrals. The detailed comparison between the simulation and the stochastic diffusion theory is needed, but it is left in future study.

1) Y. Nagayama *et al.*, Nucl. Fusion **45**, 888 (2005).

2) T.E. Evans *et al.*, Nature Phys. **2**, 419 (2006).

3) M. Nunami *et al.*, Research Report NIFS Series No. NIFS-871 (2007); R. Kanno *et al.*, Contrib. Plasma Phys. **48**, 106 (2008).

4) A. Komori *et al.*, in *Proc. 15th International Conf. on Plasma Physics and Controlled Nuclear Fusion Research 1994*, Vol.2 (IAEA, Vienna, 1995) p.773.