§15. Dependence of Radial Thermal Diffusivity on Parameters of Toroidal Plasma Affected by Resonant Magnetic Perturbations (II)

Kanno, R., Nunami, M., Satake, S., Takamaru, H.
(Chubu Univ.)

In order to investigate fundamental properties of the radial thermal diffusivity χ_r in a quasi-steady state of a low-collisional toroidal plasma having a perturbed region, we apply the drift kinetic equation solver KEATS to the ion heat transport phenomenon in the circular tokamak field disturbed partly by the resonant magnetic perturbations (RMPs).[1)] The simulation conditions are as simplified as possible: (1) The perturbed region is wedged in between the regular closed magnetic surfaces; (2) Electric field, MHD activities, neutrals, and impurities are disregarded.

We evaluate the radial thermal diffusivity of ion from the radial heat flux given in the drift kinetic simulations. The important contribution to the radial heat flux originates from not only the untrapped particles but also the trapped particles affected by the RMP field. Here, the contribution of the "untrapped particles" to the radial heat flux is shown as the random spots in the regions of $|v_\parallel/v_\perp| > \sqrt{\epsilon_\mathrm{t}}$ in the contour maps of $\delta Q_{\mathrm{i}\,r}$, as illustrated in figure 1. Here, $v_\parallel$ and $v_\perp$ are the parallel and perpendicular velocities of the guiding center, respectively, ϵ_t is the inverse aspect ratio, and $\delta Q_{\mathrm{i}\,r}$ is evaluated by the following equation:

$$\delta Q_{\mathrm{i}\,r}(v_\parallel, v_\perp) = \left\langle \nabla r \cdot \overline{\int \mathrm{d}^3 v'\, I_{v_\parallel,\, v_\perp}(v'_\parallel, v'_\perp)\, \frac{m_\mathrm{i} {v'}^2 \boldsymbol{v}'}{2} \delta f} \right\rangle,$$

where $I_{v_\parallel,\, v_\perp}(v'_\parallel, v'_\perp)$ is the indicator function defined as $I_{v_\parallel,\, v_\perp}(v'_\parallel, v'_\perp) = 1$ if $v_\parallel - \Delta v_\parallel/2 \le v'_\parallel < v_\parallel + \Delta v_\parallel/2$ and $v_\perp - \Delta v_\perp/2 \le v'_\perp < v_\perp + \Delta v_\perp/2$, and $I_{v_\parallel,\, v_\perp}(v'_\parallel, v'_\perp) = 0$ otherwise. In figure 1, the domain of $v_\parallel$ is given as $-4v_\mathrm{T} < v_\parallel < 4v_\mathrm{T}$, the domain of $v_\perp$ is given as $0 < v_\perp < 4v_\mathrm{T}$, and both the domains are squarely divided by the constant widths, $\Delta v_\parallel = \Delta v_\perp > 0$, where v_T is the thermal velocity. Note that $\delta Q_{\mathrm{i}\,r}(v_\parallel, v_\perp)$ is given from the integral of $\nabla r \cdot I_{v_\parallel,\, v_\perp}(v'_\parallel, v'_\perp)\, (m_\mathrm{i} {v'}^2 \boldsymbol{v}'/2)\, \delta f$ taken over a reference surface labeled by r, and that the energy flux across the reference surface is given as $Q_{\mathrm{i}\,r} = \sum_{k_v,\, \ell_v} \delta Q_{\mathrm{i}\,r}(\{k_v + 1/2\}\Delta v_\parallel, \{\ell_v + 1/2\}\Delta v_\perp)$, where $k_v = \cdots, -2, -1, 0, 1, 2, \cdots$, and $\ell_v = 0, 1, 2, \cdots$.

The present study shows that the region of the toroidally trapped particles in the original tokamak field without RMPs is modified by the RMP field, as shown in figure 1, and that the contribution of the untrapped particles, which is caused by the RMP field, depends mainly on the strength of RMP field $\langle \|\delta B_r\|^2 \rangle^{1/2}$ and the collisionality $(\nu_\mathrm{eff}/\omega_\mathrm{b})$. Here, $\langle \|\delta B_r\|^2 \rangle^{1/2}$ is the strength of the RMPs in the radial directions, ν_eff is the effective collision frequency, and ω_b is the bounce frequency.

From the simulation results, the radial thermal diffusivity in the collisionless limit is expected as[1)]

$$\chi_r \sim \chi_r^\mathrm{NC} + \tilde{c}_0\, q R_\mathrm{ax} v_\mathrm{T} \frac{\langle \|\delta B_r\|^2 \rangle}{|B_\mathrm{t0}|^2}.$$

Here, χ_r^NC is the neoclassical thermal diffusivity, q is the safety factor, R_ax is the major radius of the magnetic axis, $|B_\mathrm{t0}|$ is the strength of the magnetic field on the magnetic axis, and $\tilde{c}_0$ is a positive coefficient. The value of the coefficient $\tilde{c}_0$ is evaluated as $\tilde{c}_0 \sim 10^{-4}$ from the simulation results; i.e., the value of $\tilde{c}_0$ is as small as satisfying $0 < \tilde{c}_0 \ll \pi$ in a quasi-steady state of δf, as contrasted with that the coefficient predicted by the field-line diffusion (FLD) theory[2)] is $\tilde{c}_0 = \pi$. While the simulation results in the present study employing the assumption of zero electric field are not appropriate to be directly compared to ordinary tokamak experimental results, we can expect from the results of the present study that the radial thermal diffusivity in the perturbed region in the ordinary tokamaks is significantly reduced as compared to the FLD theory because of the Coulomb collision.

There remain the questions how the coefficient $\tilde{c}_0$ is determined in a given RMP field and how it depends on geometry of flux surface, q-profile, etc. In the present study, a remarkable feature determining the coefficient $\tilde{c}_0$ is not found in the complicated distributions in the velocity space. Therefore, we expect that the physics behind the determination of $\tilde{c}_0$ is not simple but involves kinetic processes in the perturbed magnetic field. The questions above are topics in the future study.

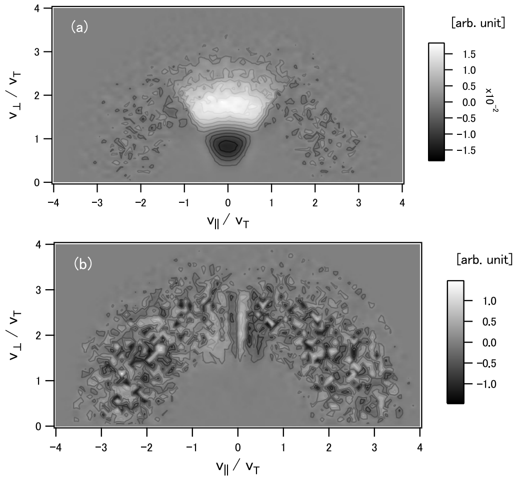

Fig. 1: The contour map of $\delta Q_{\mathrm{i}\,r}$ in the case: (a) without RMPs and (b) with RMPs, where $\delta Q_{\mathrm{i}\,r}$ is estimated at the center of the perturbed region.

1) R. Kanno *et al.*, Plasma Phys. Control. Fusion **55** (2013) 065005.

2) A.B. Rechester and M.N. Rosenbluth, Phys. Rev. Lett. **40** (1978) 38.