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Neoclassical Transport Analysis around An $m/n = 1/1$ Magnetic Island

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In order to analyze neoclassical transport phenomena in/around a magnetic field configuration with an $m/n = 1/1$ magnetic island, where m is a poloidal mode number and n a toroidal mode number, we are developing a new neoclassical transport simulation code KEATS. It is based on the δf method in Eulerian coordinates, i.e., a so-called helical coordinate system. Because the code does not assume existence of nested flux-surfaces, it has an advantage of treating the plasma transport phenomena in a three dimensional complicated magnetic field structure including islands. Radial profile of heat flux for ions is evaluated under effect of the Coulomb collisions in the magnetic field configuration. We find that because of the existence of the island the radial heat flux becomes larger than one in a magnetic configuration having nested flux surfaces.

Keywords: neoclassical transport, Large Helical Device, magnetic island, Monte-Carlo simulation

A conventional neoclassical transport simulation code assuming existence of nested flux surfaces is hard to treat transport phenomena in complicated magnetic field structure including magnetic islands. Recently, however, interesting experimental results in a magnetic field including islands have been reported. In the Large Helical Device (LHD) experiments, it is found that if width of a $m/n = 1/1$ magnetic island, which is generated by perturbation coils, exceeds the critical value ($15 - 20\%$ of minor radius), a plasma flow is observed along the magnetic flux surface inside the magnetic island in the direction to reduce the flow shear at the boundary of the island [1, 2]. In other researches of LHD, a self-healing phenomenon of the magnetic island is observed [3]. Bootstrap current around the island is expected to explain the healing [4]. To understand these experimental results, neoclassical analysis of transport phenomena around the island is required. In order to study neoclassical transport phenomena including convective flows in/around the island, we are developing a new neoclassical transport simulation code without the assumption of existence of nested flux surfaces, named "KEATS" (Kinetic EquATion Solver in the helical coordinate system). In this paper, we give a brief outline of the code and report a simulation result of analyzing transport phenomena in a magnetic field with an island.

The KEATS code is programed by using an Eulerian coordinate system, i.e., a so-called helical coordinate system [5], and is extended from a well-known Monte-Carlo particle simulation scheme based on δf method [6, 7]. In the δf method, the distribution function of plasma is separated into $f = f_{\rm M} + \delta f$, where $f_{\rm M}$ is a local Maxwellian background and δf is considered as a small perturbation from $f_{\rm M}$. In the neoclassical (or drift kinetic) framework, we solve the linearized drift kinetic equation of the first order,

$$\begin{aligned} \frac{D}{Dt}\delta f &\equiv \frac{\partial}{\partial t}\delta f + (\boldsymbol{v}_{\parallel} + \boldsymbol{v}_{\rm d}) \cdot \nabla \delta f - C_{\rm T}(\delta f) \\ &= -\boldsymbol{v}_{\rm d} \cdot \nabla f_{\rm M} + C_{\rm F} f_{\rm M}, \end{aligned} \tag{1}$$

where $\boldsymbol{v}_{\parallel}$ is the parallel velocity, $\boldsymbol{v}_{\rm d}$ is the drift velocity of guiding center motion and electric field is neglected. The test particle collision operator $C_{\rm T}$ is implemented numerically by random kicks in marker velocity space $(v_{\parallel}, v_{\perp})$, which represents

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the Coulomb scattering process. The operator C_{F} is the field particle collision term, which represents local momentum conservation. To solve Eq.(1) by Monte Carlo techniques, we adopt the two-weight scheme of the δf formulation [6, 7].

We are interested in transport phenomena in the magnetic structure having the $m/n = 1/1$ island. In this paper, a region composed of the magnetic island and the ergodic region is called the target region. We focus on the dependence of ion heat flux on temperature profile in the target region. For simplicity, we use a magnetic configuration which is formed by adding an $m/n = 1/1$ island component into a simple tokamak field, where the major radius of the magnetic axis $R_{\mathrm{ax}} = 3.6$ m, the minor radius of the plasma $a = 1.0$ m and the magnetic field strength on the axis $B_{\mathrm{ax}} = 3.0$ T. Hereafter, it is called the "test configuration." The Poincaré plots of magnetic field lines on a poloidal cross section in the test configuration is shown in Fig.1(a). To investigate neoclassical transport phenomena in the test configuration, we evaluate the radial profile of heat flux using KEATS code. In the evaluation, we use two types of temperature profile as shown in Fig.1(b). The one forms exponentially (red triangles), which is called "original" temperature profile T^{org}. The other one forms considering existence of the island using the technique referring the pressure relaxation algorithm in HINT code [5] (blue diamond), which is obtained by averaging pressures over each field line according to $p = \int (p^{\mathrm{org}}/B)\mathrm{d}\ell / \int (1/B)\mathrm{d}\ell$, where the pressure is defined by $p = nT$, $p^{\mathrm{org}} = n_0 T^{\mathrm{org}}$ is original pressure distribution and ℓ is length of field lines. It is called "modified" temperature profile T^{mod}. The density profile is set homogeneous, $n_0 = 1 \times 10^{19}$ 1/m^3. In KEATS code, we use the number of spatial grids $(N_R, N_Z, N_\phi) = (100, 100, 320)$ and the number of test particles $N_{\mathrm{TP}} = 16000000$.

After several collision times, the heat flux becomes saturated sufficiently. We estimate the radial heat flux by taking time average after satulation in three cases; i.e., in a configuration with (a) no island under the original temperature profile, (b) the $m/n = 1/1$ island under the original temperature, and (c) the $m/n = 1/1$ island under the modified temperature profile. Because we have no unified magnetic coordinate systems including several magnetic field structures as the island and the core region, the heat fluxes are evaluated neglecting the existence of the island, that is averaged over concentric circular shell region in the whole toroidal angles as if there were nested flux surfaces.

The simulation results are shown in Fig.2. From the results, we find that the heat flux is strongly affected by the magnetic island and temperature profile in the target region. Note that the distance between the magnetic axis and the O-point of the island varies with a toroidal angle and that the width of the target region is changed for the poloidal and toroidal directions, then the width of the region projected onto a poloidal cross section becomes broad compared with the width of the island in Fig.1. At first, in the simple tokamak field as in the case (a), the heat flux has a gentle profile (green circles). This result is agreed with "FORTEC-3D" code [8] which uses magnetic coordinate system. In the case (b), we see that there are obvious difference compared with the case (a) in the target region. In the region, we obtain that the flux has a steeple peak (red triangles). This result suggests that the flux arises to make the temperature flat in the region. In the case (c), the result differs from former two cases. The flux has two peaks near boundaries of the target region while the flux is flat in the region (blue diamonds). The heat flux seems to arise to relax the temperature profile strongly around island separatrix and ergodic region where the temperature has strong gradients shown in Fig.1(b).

Of course, when more detailed analysis in a specific magnetic structure, e.g., the magnetic island, is required, we should average appropriately over the corresponding magnetic flux surface in the island. Then, we need to label magnetic surfaces using our labeling technique of flux surfaces [9]. Moreover, when we concentrate the target region, we should restrict the calculation region to improve the resolution of the simulation. In that case, some proper boundary condition is required. We develop a new numerical technique to set the boundary condition by fixing the δf distribution at the boundary of the target region from a rough result which is already obtained as in Fig.2. Now we are going on the detailed analysis. These results will be reported in near future.

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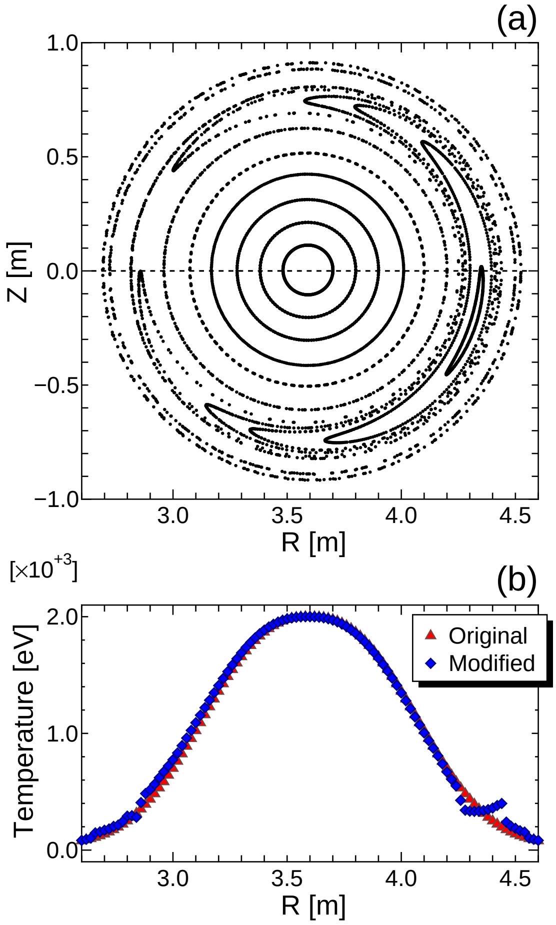

Fig. 1 (a) Poincaré plots of magnetic field lines on a poloidal cross section in the test configuration. (b) Radial profiles of temperature on the line of $Z = 0$. Original profile $T^{\rm org}$ forms exponentially, and modified profile $T^{\rm mod}$ is calculated by the pressure relaxation algorithm in HINT code [5].

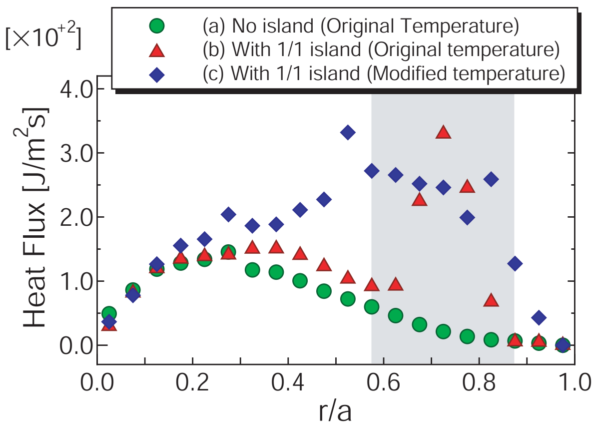

Fig. 2 Radial profiles of ion heat flux for three cases, where $r = \sqrt{(R - R_{\rm ax})^2 + Z^2}$. Hatched region shows the target region, that is the region including the island and ergodic region.