Transport Simulation of Helical Plasmas
Using the TASK/TX Code

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It is widely accepted that the radial electric field strongly affects plasma confinement through the transport process. We have analysed the time evolution of the radial electric field and the radial transport in plasmas in a helical magnetic configuration by extending the TASK/TX code [M. Honda and A. Fukuyama, J. Comput. Phys. 227, 2808 (2008)]. TASK/TX is a one-dimensional dynamic transport code originally developed for axisymmetric plasmas. A set of flux-surface averaged fluid equations is solved simultaneously, rather than a set of diffusion equations based on the flux-gradient relations. TASK/TX consists of one-dimensional two fluids (electron and ion) equations, Maxwell’s equations and diffusion equations of neutrals. To apply TASK/TX to helical plasmas, we have included two additional effects: helical neoclassical viscosity force and diffusion due to magnetic braiding. Plasma transport simulation is carried out mainly using the LHD parameters. We obtained negative radial electric field (ion root) with ion heating and positive radial electric field (electron root) with electron heating. Effects of magnetic braiding are also studied.

Keywords: helical plasma, radial transport, radial electric field, transport simulation

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1. Introduction
In toroidal plasmas, the radial electric field $E_r$ strongly affects plasma confinement through the transport process. In helical plasmas, equations based on the ambipolar condition [1] have been widely used to determine the radial electric field. Some of the equations include an ambiguous electric diffusion coefficient $D_E$. In this paper, we present simulation results of the radial profile and the time evolution of radial electric field and radial transport in helical plasmas by extending the TASK/TX code [2]. The TASK/TX is a one-dimensional dynamic transport code, which can simulate time evolution of the plasma fluid quantities including $E_r$, by solving a set of fluid equations, rather than a set of diffusion equations based on the flux-gradient relations.

In section 2, we give a brief description of the TASK/TX and explain the specific helical terms added to the original TASK/TX. In section 3, after reviewing traditional ambipolar equations to determine $E_r$, the time evolution equation of $E_r$ derived from the equations of motion in TASK/TX is shown. The results of numerical simulations will be presented in section 4, and we conclude this paper in section 5.

2. Transport Models
2.1 TASK/TX code
The TASK/TX is the one-dimensional dynamic transport code originally developed for axisymmetric plasmas, which solves a set of flux-averaged two-fluid equations. TASK/TX consists of flux-averaged Maxwell’s equations, two-fluid equations for electrons and bulk ions, as well as diffusion equations for three groups of neutrals. By solving these equations simultaneously, radial profiles of the radial electric field, density, temperature, plasma rotation and so on are obtained. In order to apply TASK/TX to helical plasmas, we have introduced additional terms briefly described in the following subsections.

2.2 Helical neoclassical transport
The magnitude of the magnetic field $B = |B|$ in the helical configuration is expressed in an approximate form:

$$B(r, \theta, \phi) \approx B_0 \left[ 1 - \epsilon_T \cos \theta - \epsilon_H \cos(l \theta - m \phi) \right].$$

Here, $\epsilon_T$ and $\epsilon_H$ are toroidal modulation and helical modulation of the magnetic field, $l$ and $m$ are the poloidal and toroidal mode numbers. The helical ripple results in neoclassical viscosity in toroidal and poloidal directions, which leads to enhanced neoclassical diffusion in the low collisional regime. The helical neoclassical viscosity force $F_{HNC}^{\parallel}$ and $F_{HNC}^{\perp}$ are derived as follows for species $s$.

The position of a particle on a magnetic surface can be described by $\zeta = l \theta - m \phi$. If $\partial \zeta / \partial t = 0$ then the particle moves along the twisted magnetic surface, while in the case of $\partial \zeta / \partial t \neq 0$, the moving particle experiences the helical neoclassical viscosity force $F_{\text{hnc}}^s$ perpendicular to the...
3. Governing Equation for the Radial Electric Field

In the previous literatures, two methods have been used to determine the radial electric field [1]. The first is called as the algebraic ambiopolar relation, which is expressed using the radial ambiopolar particle flux \( \Gamma_{as} \) for species \( s \):

\[
\frac{\partial}{\partial t} \left( 1 + \frac{\epsilon_s^2}{\nu_s^2} \right) E_r = - \sum_s \epsilon_s \Gamma_{as}
\]

This equation has a difficulty that \( E_r \) can change discontinuously in the radial direction. This difficulty can be avoided by the formulation including derivatives of the electric field.

\[
\frac{\partial}{\partial t} \left( 1 + \frac{\epsilon_s^2}{\nu_s^2} \right) E_r = - \sum_s \epsilon_s \Gamma_{as}
\]

\[
+ \frac{1}{V'(r)} \frac{\partial}{\partial r} \left( V'(r) \left( \sum_s \epsilon_s \frac{B_s}{e} \right) \frac{\partial E_r}{\partial r} \right).
\]

where \( D_E \) is the electric diffusion coefficient given in [1].

Corresponding equation can be derived from the equations of motion in TASK/TX. Keeping the Lorentz forces, the perpendicular viscosity force and the neoclassical viscosity force in the poloidal and toroidal equations of motion, we obtain

\[
\frac{\partial}{\partial t} \left( 1 + \frac{\epsilon_s^2}{\nu_s^2} \right) E_r = - \sum_s \epsilon_s \Gamma_{as}
\]

\[
+ \frac{1}{V'(r)} \frac{\partial}{\partial r} \left( V'(r) \left( \sum_s \epsilon_s \frac{B_s}{e} \right) \frac{\partial E_r}{\partial r} \right).
\]

Here, \( F^{NC}_{\omega} \) is the axisymmetric neoclassical viscosity force in poloidal direction, which is valid in banana-plateau regime, defined as [5]:

\[
F^{NC}_{\omega} = - \sqrt{\pi q_s n_s m_s} v_{\| s} \frac{v'_{\| s} u_{\| s} + \nu_{\| s} q_R}{q_R 1 + \nu_{\| s} u_{\| s}}.
\]

\[
F^{NC}_{\omega} \text{ and } F^{HNC}_{\omega} \text{ are poloidal and toroidal components of the helical neoclassical viscosity defined in Eqs. (1)-(2). Observing Eq. (5), we find that the balance of neoclassical viscosity forces corresponds to the traditional ambiopolar relation.}

Solving equations of motion directly, we can describe the time evolution of the radial electric field more consistently than conventional ambipolarity equations.

4. Numerical Simulation

In the following simulation, we adopted typical parameters of the Large Helical Device (LHD):

\[ R = 3.7 \text{ m}, \quad a = 0.60 \text{ m}, \quad b = 0.65 \text{ m}; \]

\[ l = 2, \quad m = 10, \quad \epsilon_{l1} = \epsilon_{l0} \rho^2, \quad \epsilon_{l0} = 0.2. \]
Here, \(l\) and \(m\) are the poloidal and toroidal pitch number, \(R\) is the major radius, \(a\) and \(b\) are the minor and wall radius. Initial conditions were set as follow:

\[
\begin{align*}
n_e(0) &= n_e(0) + [n_e(0) - n_e(1)](1 - \rho^2), \\
n_i(0) &= 1.0 \times 10^{19} \text{ m}^{-3}, \\
T_e(0) &= 1.0 \times 10^{18} \text{ m}^{-3}, \\
T_i(0) &= 0.30 \text{ keV}, \\
q_0(0) &= q_0(0) + [q_0(0) - q_0(1)](1 - \rho^2), \\
q_0(0) &= 2.0, \\
q_0(1) &= 1.0.
\end{align*}
\]

For comparison of the effect of magnetic braiding, we also used parameters of a typical small helical device:

\[
\begin{align*}
R &= 1.3 \text{ m}, \\
a &= 0.35 \text{ m}, \\
b &= 0.38 \text{ m}, \\
l &= 2, \\
m &= 5, \\
\epsilon_l &= \epsilon_{lo} = 0.1, \\
n_e(0) &= 4.0 \times 10^{19} \text{ m}^{-3}, \\
T_0(0) &= 5.0 \times 10^{18} \text{ m}^{-3}, \\
q_0(0) &= 3.0, \\
q_0(1) &= 2.0.
\end{align*}
\]

For anomalous transport coefficients, particle diffusivity \(D\), perpendicular viscosity \(\mu_s\) and thermal diffusivity \(\chi_s\), empirical fixed profiles are used in the present analysis:

\[
\begin{align*}
D(\rho) &= D(0) + [D(1) - D(0)] \rho^3, \\
D(0) &= 0.1 \text{ m}^2/\text{s}, \\
D(1) &= 0.3 \text{ m}^2/\text{s}, \\
\mu_s(\rho) &= \mu_s(0) + [\mu_s(1) - \mu_s(0)] \rho^2, \\
\mu_s(0) &= 3 \text{ m}^2/\text{s}, \\
\chi_s(\rho) &= \mu_s(\rho).
\end{align*}
\]

### 4.1 Ion-root confinement with ion heating

First we examined the dependence of plasma fluid quantities on the ion heating power \(P_i^{RF}\) in the case of \(P_i^{RF} = 0.2\text{ MW}, 0.4\text{ MW}, 0.6\text{ MW}\). Figure 1 shows the radial profiles of (a) radial electric field \(E_r\), (b) electron density \(n_e\), (c) safety factor \(q\), (d) electron temperature \(T_e\), (e-f) electron plasma rotation \(n_{\theta e}\) and \(u_{\phi e}\), (g) ion temperature \(T_i\), (h-i) ion plasma rotation \(n_{\theta i}\) and \(u_{\phi i}\) at \(t = 0.1\) s.

Negative \(E_r\) is formed in all radial region, whose magnitude \(|E_r|\) is almost proportional to the heating power. The electron density \(n_e\) became lower as the heating power became stronger. In all cases, the density has decreased linearly as time advances.

### 4.2 Electron-root confinement with electron heating

Next we examined the dependence of radial profiles on the electron heating power \(P_e^{RF}\) in the case of \(P_e^{RF} = 0.2\text{ MW}, 0.4\text{ MW}, 0.6\text{ MW}\). Figure 2 (a-i) shows the radial profiles of \(E_r, n_e, q, T_e, u_{\theta e}\) and \(u_{\phi e}\) at \(t = 0.5\) s as same as Fig. 1.

Contrast to the case of ion heating, positive \(E_r\) peaking at \(\rho \approx 0.1\) is observed in the case of higher electron heating power. The peak value of \(E_r\) becomes larger as the heating power increases. Particle confinement becomes better with higher heating power. A hollow density profile where the density gradient becomes positive is observed at \(\rho \leq 0.2\).

We have also examined the time evolution of the radial electric field \(E_r\) in the case with \(P_e^{RF} = 0.4\text{ MW}\). Figure 3 shows the time evolution of (a) \(E_r\) profile, (b) temperatures on magnetic axis \(T_i(0)\) and averaged temperatures \(\langle T_e\rangle\), (c) density on magnetic axis \(n_e(0)\) and averaged density \(\langle n_e\rangle\).

At the beginning of heating \(E_r\) is negative in all region but the transition to \(E_r > 0\) occurs near \(\rho \approx 0.1\). We observed the same behavior in the case of \(P_e^{RF} = 0.2\text{ MW}\) and \(0.6\text{ MW}\), but the time of transition was earlier in the case of higher heating power and vice versa.

### 4.3 Effect of magnetic braiding

First we analysed the effects of destroyed magnetic surfaces in a typical small helical plasma. The radial profile of the magnetic diffusivity \(D_m(\rho)\) is defined as Eq. (4). The lower and the upper bound of the braided region are set to \(\rho_{\text{min}} = 0.85\) and \(\rho_{\text{max}} = 1.02\), respectively, and the maximum value of \(D_m(\rho)\) is \(D_m = 1.0 \times 10^{-8}\). The heat-
of (a) profiles of (a) than ions since (4) that in the ergodic region electrons di
gion. This can be understood as follow. It is clear from eq.
ing power is $P_{RF}^e = 0.036$ MW. Figure 4 shows the radial profiles of (a) $E_r$, (b) $n_e$ and (c) $T_e$ at $t = 0.15$ s.

Sharp increase in $E_r$ is observed near the ergodic re-
region. This can be understood as follow. It is clear from eq.
(4) that in the ergodic region electrons diffuse more quickly
than ions since $v_{Te} > v_{Ti}$, which results in the increase of $E_r$. Although the density slightly decreases inside the er-
godic region, the temperature profiles are not affected. The
difference may be explained by large heat transport mainly
driven by the anomalous transport.

We also examined the effects of destroyed magnetic
surfaces using the LHD parameters. The profile of $D_m(\rho)$
was set as same as in the previous calculation. The heating
power is $P_{RF}^\rho = 0.2$ MW. Figure 5 shows the radial profile
of (a) $E_r$, (b) $n_e$ and (c) $T_e$ at $t = 0.5$ s.

For LHD plasmas, remarkably large positive $E_r$
appeared in the ergodic region, while density and tempera-
ture profiles were not affected. The reason why the results
which differ from the case of typical small helical plasma
were obtained are not clear and left for our future work.

5. Conclusion
In this study, we simulated the radial transport and the
time evolution of the radial electric field in helical plasmas
by extending the TASK/TX code. By changing the ion and
electron heating power, the ion root and the electron root
transport were obtained. In the case of the ion heating,
only the ion root was observed. In the case of the electron
heating, electron root has appeared near the magnetic axis.
Effect of magnetic braiding was also studied for typical
small helical plasmas and LHD plasmas.

A future work includes: 1) Comparison of the radial
electric field which is obtained from TASK/TX and the
usual ambipolar relation. 2) Study of parameters depend-
ence of the existence and performance of electron root
(anomalous transport model, density et al.) 3) Theory-
based model for turbulence transport, such as current-
diffusive interchange mode (CDIM) model instead of the
fixed spacial profile.

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