Development of hierarchy-integrated simulation code for toroidal helical plasmas, TASK/3D

Masahiko SATO, Shinichiro TODA, Yuji NAKAMURA[1)], Kiyomasa WATANABE, Atsushi FUKUYAMA[2)], Sadayoshi MURAKAMI[2)], Masayuki YOKOYAMA, Hisamichi FUNABA, Hiroshi YAMADA and Noriyoshi NAKAJIMA

National Institute for Fusion Science, Toki 509-5292, Japan

[1)]Graduate School of Energy Science, Kyoto University, Kyoto 611-0011, Japan

[2)]Graduate School of Engineering, Kyoto 606-8501, Japan

The present status of the development of the hierarchy-integrated simulation code for troidal helical plasmas, TASK/3D, is reported. The TASK/3D is based on the integrated modeling code for tokamak plasmas, TASK. In order to extend the TASK for two dimensional configuration to the TASK/3D for three dimensional configuration, new modules for the radial electric field and rotaional transform for a general toroidal configuration have been developed. Numerical simulations for the time evolution of temperature and electric field are done for an LHD experiment by the combination of the diffusive transport module and the electric field module. Improvement of the rotational transform module is also reported.

Keywords: integrated simulation, helical plasma, radial electric field, plasma current

1 Introduction

In order to systematically clarify confinement physics in toroidal magnetic confinement systems, a hierarchy-renormalized simulation concept is being developed under domestic and international collaborations with universities and institutes. The hierarchy-renormalized simulation model in toroidal magnetic confinement systems consists of a hierarchy-integrated simulation approach and a hierarchy-extended simulation approach. The former approach, which is mainly based on a transport simulation combining various simplified models describing physical processes in different hierarchies, is suitable for investigating whole temporal behavior of experimentally observed macroscopic physics quantities, and the latter approach, which includes fluid core plasma description, kinetic core plasma description, and peripheral fluid/kinetic description, is focused on the description of mutual interaction among neighboring hierarchies in a more rigorous way. The hierarchy-integrated simulation code (TASK/3D) is based on the integrated modeling code for tokamak plasmas, TASK[1], developed in Kyoto University. In order to extend the TASK code developed for two dimensional configuration to three dimensional, the transport equations for the rotational transform and the radial electric field have been reformulated in a general toroidal configuration. With this new formulation, temporal evolution of the net current in LHD has been analyzed [2,3]. In this research, present status of the first-stage development of TASK/3D is reported.

This paper is organized as follows. In section 2, numerical model equations and module structure of TASK/3D are described. In section 3.1, we show numerical simulation results obtained by the combination of the diffusive transport module and the electric field module. where the profile of the radial electric field is determined by the ambipolar condition. In section 3.2, we show simulation results of time evolution of current profile by using rotational transform module. The improvement of the rotational transform module is also reported. Finally, section 4 is devoted to summary.

author's e-mail: masahiko@nifs.ac.jp

2 Numerical model in TASK/3D

In order to extension the TASK for two dimensional configuration to three dimensional, we are developing and adding new modules into TASK as indicated by red character in Fig.1. As a first step, we will carry out simulations by using the diffusive transport module TR, rotational transform module EI and electric field module ER. In TASK/3D, the TR module is used for solving the following particle transport equation and heat transport equation;

$$\begin{aligned}\frac{1}{V'}\frac{\partial}{\partial t}(n_s V') &= -\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|\rangle n_s V_s \right.\\ &\left. -V'\langle|\nabla\rho|^2\rangle D_s\frac{\partial n_s}{\partial \rho}\right) + S_s, \qquad (1)\end{aligned}$$

$$\begin{aligned}\frac{1}{V'5/3}\frac{\partial}{\partial t}\left(\frac{3}{2}n_s T_s V'^{5/3}\right) &= -\frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|\rangle\frac{3}{2}n_s T_s V_{Es}\right.\\ &\left. -V'\langle|\nabla\rho|^2\rangle n_s\chi_s\frac{\partial T_s}{\partial \rho} + P_s\right), \qquad (2)\end{aligned}$$

where n is density、T is temperature、ρ is normalized radial coordinate、V is volume enclosed by a magnetic surface, s expresses species of particles, and the prime denotes the derivative with respect to ρ. $\langle\rangle$ is average value on magnetic surface. The rotational transform module EI can be used for analyzing inductive plasma current, where the equation of the rotational transform is solved;

$$\frac{\partial \iota}{\partial t} = \left(\frac{\partial \Phi_T}{\partial \rho}\right)^{-1} \frac{\partial \iota}{\partial \rho}\frac{\partial \Phi_T}{\partial t} + \left(\frac{\partial \Phi_T}{\partial \rho}\right)^{-1}\frac{\partial}{\partial\rho}\left\{\eta_\parallel \left(\frac{\partial \Phi_T}{\partial \rho}\right)^{-2}\frac{\partial V}{\partial \rho}\left\{\langle B^2\rangle \frac{\partial}{\partial\rho}[(S_{11}\iota + S_{12})\Phi_T'] + \frac{\partial\Phi_T}{\partial\rho}\frac{\partial P}{\partial\rho}(S_{11}\iota+S_{12}) - \frac{\partial \Phi_T}{\partial\rho}\langle \mathbf{J}_s\cdot\mathbf{B}\rangle\right\}\right\}, \quad (3)$$

where Φ_T is toroidal magnetic flux, $\eta_\parallel$ is resistivity, $\mathbf{J}_s$ is noninductive current, $\mathbf{B}$ is magnetic field and P is plasma pressure. The elements of susceptance matrix, S_{11} and S_{12} are given by

$$S_{11} = \frac{V'}{4\pi^2}\left\langle \frac{g_{\theta\theta}}{g}\right\rangle \quad (4)$$

$$S_{12} = \frac{V'}{4\pi^2}\left\langle \frac{g_{\theta\zeta}}{g}\right\rangle . \quad (5)$$

In eq.(3) $\langle B^2\rangle$ and P' are entered instead of other elements of susceptance matrix, S_{21} and S_{22}, by using the MHD equilibrium condition. In helical plasmas, off diagonal element of susceptance matrix, S_{12} appears due to nonaxisymetry.

For electric field module ER, the equation of the electrostatic potential Φ_0 is solved;

$$\epsilon_0\epsilon_r\langle|\nabla\psi|^2\rangle\frac{\partial}{\partial t}\frac{d\Phi_0}{d\psi} = \sum_{a=e,i}\langle \mathbf{B}_x\cdot\nabla\cdot\mathbf{\Pi}_{a1}\rangle - \sum_{a=e,i}\langle\mathbf{B}_x\cdot\mathbf{S}_{a1}\rangle + e_f\langle n_{f1}\mathbf{u}_{f1}\cdot\nabla\psi\rangle, \quad (6)$$

where $\psi = \Phi_T/2\pi$. The second term and the third term of R.H.S. are source term and fast particle term due to NBI etc., respectivly. A relative permittivity ϵ_r is given by

$$\epsilon_r = 1 + \frac{c^2}{\langle|\nabla\psi|^2\rangle}\left\{\left\langle\frac{|\nabla\psi|^2}{v_A^2}\right\rangle + \left\langle\frac{(g_2)^2}{v_A^2}\right\rangle - \frac{\langle g_2\rangle^2}{\langle v_A^2\rangle}\right\}, \quad (7)$$

where v_A is Alfvén velocity. g_2, which describes Pfirsch-Schluter current, is given by

$$\mathbf{B}\cdot\nabla\left(\frac{g_2}{B^2}\right) = \mathbf{B}\times\nabla\psi\cdot\nabla\left(\frac{1}{B^2}\right). \quad (8)$$

In the current stage of the development of the TASK/3D, the electric field module has been added to the TASK/3D, where the radial electric field is determined by ambipolar condition which is obtained by considering steady state of eq.(4). In the electric field module, replacing the ambipolar condition to the equation of time evolution for electric field is a future work. On the other hand, the rotational transform module EI has not been added to TASK/3D yet, although temporal evolution of the plasma current in LHD has been analyzed [3] by using the combination of the EI module, the VMEC MHD equilibrium module, and BSC/FIT module, where BSC/FIT modules are used for calculating non-inductive current. Adding the EI module into TASK/3D is underway.

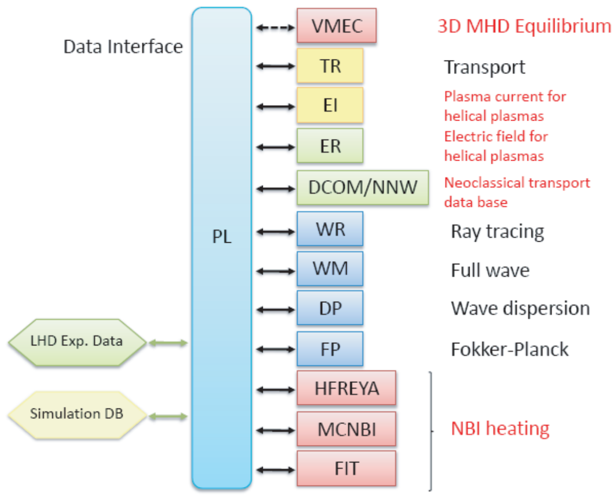

Fig. 1 Module structure of TASK/3D.

3 Numerical Results

3.1 Radial electric field module

In order to check the combination of TR module and electric field module, transport simulations are done for an LHD plasma, where the plasma is heated by NBI and the steady state is achieved. In the simulations, the time evolution of the temperature profile is calculated by using the heat transport equation (2) in the TR module and the radial electric field is determined by ambipolar condition in the ER module. The density and rotational transform profiles are fixed. For neoclassical transport model, the single helicity model proposed by Shaing[4] is used. We carried out simulations for two different anomalous transport models, a constant model and a parabolic model. Figure 2 shows time evolution of electron and ion temperatures obtained from the simulation, where the anomalous transport coefficient is chosen as $\chi_a = 1+\rho^2(m^2/s)$. In this simulation, the profiles of the density and rotational transform are fixed. The density profile is also plotted in Fig.2. The positive electric field initially appears around $\rho = 0.6$ in Fig.3. This is mainly due to the positive gradient of the density. As the electron temperature decreases, the positive electric field disappears. We also carried out the simulation for the constant anomalous model, where the anomalous coefficient is chosen as $\chi_a = 1(m^2/s)$. The behavior of teperature and electric field for $\chi_a = 1(m^2/s)$ is qualitatively same as the case for $\chi_a = 1 + \rho^2(m^2/s)$ The dependence of temporal evolution of profiles on the transport model is currently under investigation.

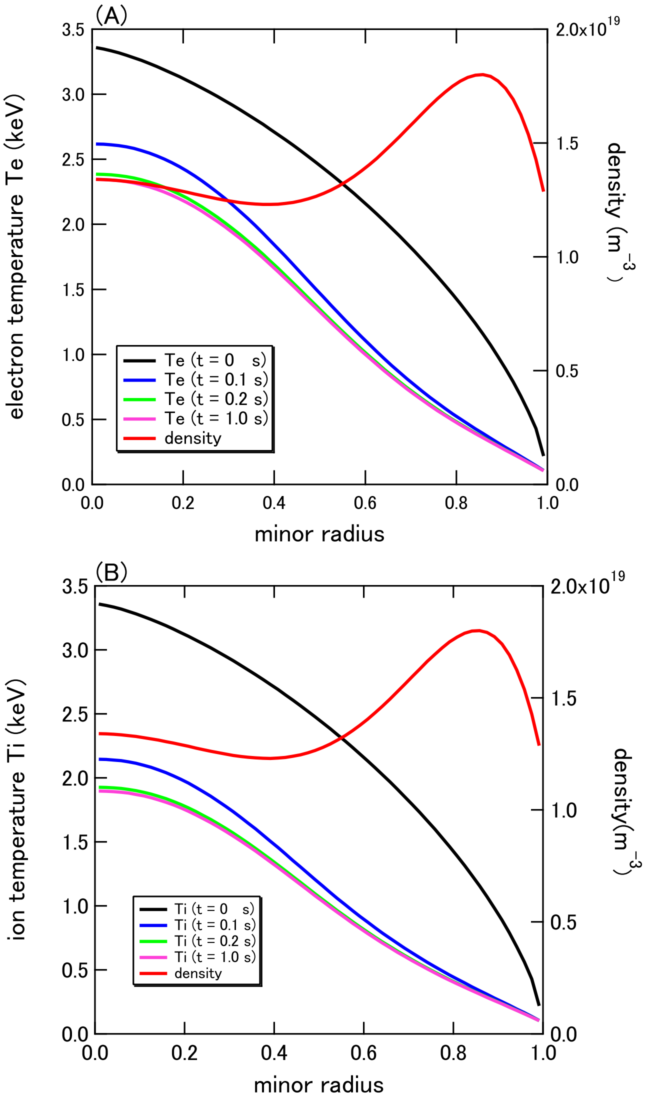

Fig. 2 Time evolution of radial profiles of (A) electron and (B) ion temprature calcurated by the combination of the diffusive transport module TR and the electric field module ER. The anomalous coefficent is chosen as $\chi_a = 1 + \rho^2(m^2/s)$. The profiles of the temperature and density observed in an LHD experiment are used for initial profiles in the simulation. In this simulation , the density profile indicated by red line is fixed.

3.2 Rotational transform module

The rotational transform module EI can be used for analyzing the plasma current in helical plasmas. As is shown in refs.[2] and [3], Fig.6 shows a waveform of the discharge

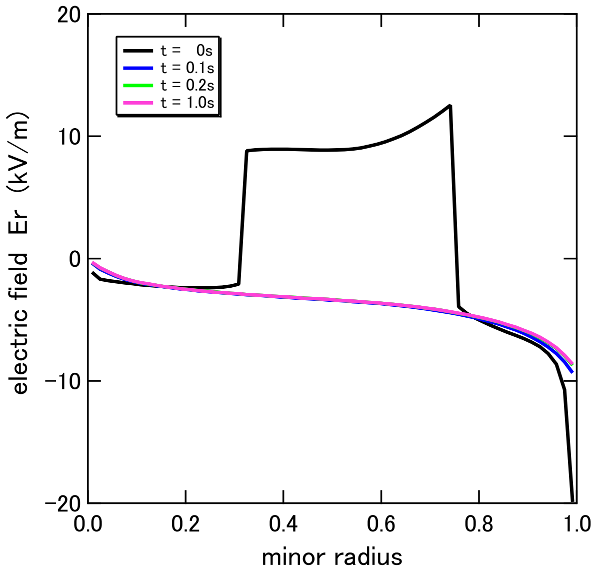

Fig. 3 Time evolution of radial profile of electric field corresponding to Fig.2.

with 2 neutral beam (NB) injection. The 1st NB is injected to the counter-direction from $t \sim 0.7s$ and the 2nd NB to the co direction from $t \sim 1.2s$. The blue line denotes the observed net toroidal current by Rogowski coils. Numerical simulations are done for the LHD neutral beam heated plasma shown in Fig.6. In this simulation, non-inductive current (bootstrap current and Ohkawa current) is calculated by BSC/FIT module. We use the time evolution of the plasma density and temperature profiles observed in the experiment. The equilibrium profile is calculated by the VMEC code at some time interval which is longer than the time interval for the EI module.

The earlier version of the EI module uses the square root of the normalized toroidal magnetic flux as radial coordinate ρ and the rotational transform is discretized at half mesh points. In this case, the calculated noninductive current becomes negative around $r = 0.9$ at t=4.5s as shown Fig.7(A). The problem is mainly due to the disagreement between the plasma boundary and the half mesh point. In order to solve this problem, the EI module has been updated. The new version of the EI module uses the normalized toroidal magnetic flux as radial coordinate s and the rotational transform is discretized at full mesh points. Figure 7(B) shows numerical results obtained by the updated EI module. In this case, the noninductive current does not become negative around $r = 0.9$ at t=4.5s.

It is important to decide appropriate time interval for recalculation of equilibrium profile by VMEC. We are investigating the dependence of numerical results on the time interval for recalculating equilibrium profile.

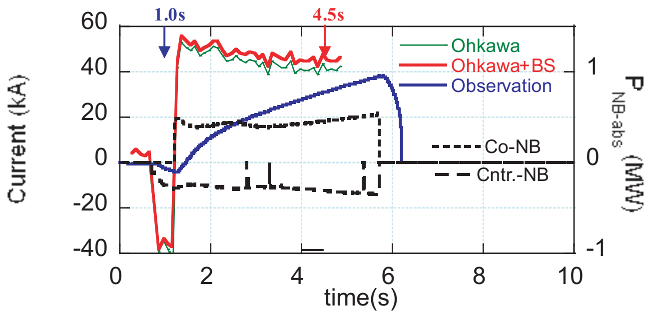

Fig. 4 Waveform of the discharge with 2 NB-injection. blue is observed current, red is calculated Ohkawa and bootstrap current , green is calculated Ohkawa current.Dotted line and dashed line are absorbed beam power.

4 Summary

The hierarchy-integrated simulation code for toroidal helical plasmas, TASK/3D, is being developed by based on TASK for two dimensional configuration. In the current stage, radial electric field module has been combined with the TR module, where the electric field is determined by the ambipolar condition and the single helicity model proposed by Shaing is chosen as neoclassical transport model. In order to check the electric field module ER, we carried out numerical simulations for an LHD experiment, assuming anomalous transport coefficient is a constant or a parabolic function. In the simulations, the density and rotational transform profiles are fixed.

For analyzing temporal evolution of the current profile in LHD, numerical simulations are done for an LHD experiment by using the combination of EI, VMEC, BSC/FIT modules, where experimental data is used for time evolution of the density and temperature profiles. By using full mesh points for discretization points, the updated EI module allows us to carry out reliable simulations.

In the next step, we will combine the EI module with the TASK/3D. Then, we can calculate temperature, density, radial electric field and rotational transform, simultaneously. Next, for neoclassical transport model, DCOM/NNW[5] will be added to TASK/3D, which is a neoclassical transport database for LHD plasmas constructed using the neural network method. Next, the ambipolar condition for determining electric field is replaced to the equation of time evolution of electric field, eq.(4). In this stage, nonlinearity of transport equations becomes stronger so that the present solver in TASK may not be suitable for solving such equations with strong nonlinearity. Hence, new stable and fast solver will be needed. For solving a set of nonlinear equations, Newton method is generally used. In the Newton iteration procedure, it is needed to solve large matrix problem, where the CPU time is consumed. We are trying to solve the problem by domain-decomposition method. After the stable and fast

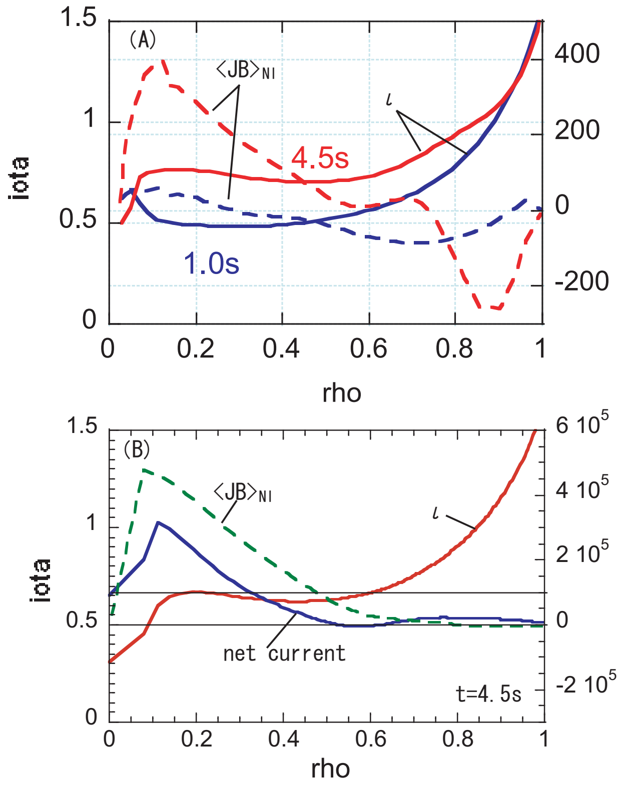

Fig. 5 Numerical results obtained from (A) earlier version of EI module and (B) updated version of EI module. In (A), solid lines are rotational transform profiles and dashed lines are non-inductive current profiles. The blue corresponds to result at $t = 1.0s$ and the red at $t = 4.5s$. In (B), the red solid line is rotational transform profile at $t = 4.5s$. The green dashed line and the blue solid line are non-inductive current profile and net current profile at $t = 4.5s$, respectively.

Newton solver is completed to develop, impurity module and heating modules will be added to TASK/3D in order to further develop the hierarchy-integrated simulation code for toroidal helical plasmas.

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