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# Implementation of NBI heating module FIT3D to hierarchy-integrated simulation code TASK3D

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TASK3D is an hierarchy-integrated simulation code for toroidal helical plasmas. For the further development of the TASK3D, new module for neutral beam injection (NBI) heating, FIT3D, has been implemented to the TASK3D. In order to check the applicability of the FIT3D module, test simulation for the FIT3D module has been performed together with MHD equilibrium VMEC module, one-dimensional diffusive transport TR module, radial electric field ER module and neoclassical transport database DCOM/NNW module.

Keywords: integrated simulation, helical plasma, NBI heating

## 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 [1]. The hierarchy-renormalized simulation model in toroidal magnetic confinement systems consists of a hierarchy-integrated simulation approach and a hierarchy-extended simulation approach. The hierarchy-integrated approach is mainly based on a transport simulation combining various simplified models describing physical processes in different hierarchies. This approach is suitable for investigating whole temporal behavior of experimentally observed macroscopic physics quantities. For the hierarchy-integrated simulation approach, the integrated modeling code for three dimensional configurations (TASK3D) is being developed on the basis of an integrated modeling code for tokamak plasmas, TASK (Transport Analyzing System for tokamaK) [1], which was developed in Kyoto University. In order to extend the TASK code to be applicable to three dimensional configurations, the transport equations for the rotational transform and the radial electric field have been reformulated by taking the three-dimensional nature of configurations into account. With this new formulation, new modules for the rotational transform (EI module)[2-4] and radial electric field (ER module) [5] have been developed and implemented. The TASK3D has also been extended to read LHD experimental data in Ufile format[5].

The TASK3D has a modular structure as shown in Fig.1. The modular structure of the TASK3D allows us to conduct simulations using an individual module or combination of some modules according to the user's objective. For example, in ref[2-4], calculations on the temporal evolution of the rotational transform and non-inductive current for an LHD experiment have been performed by using the combination of VMEC module for MHD equilibrium, EI module for rotational transform and BSC/FIT module for bootstrap current and Ohkawa current. In ref[6], the MHD stability beta limit in LHD has been analyzed by using VMEC module for MHD equilibrium and TR module for diffusive transport. In this analysis, a linear stability module was used together with these modules to include the effect of MHD instabilities. From the analysis, it is found that the volume average beta value is expected to be beyond 6% in LHD.

In this paper, the further development of the TASK3D, implementation of the NBI (Neutral beam injection) heating module (FIT3D module), is reported. In order to check the applicability of the FIT3D module, test simulations have been performed by using the combination of VMEC module, TR module, ER module, DCOM/NNW module and FIT3D module.

This paper is organized as follows. In Section 2, the numerical scheme of the test simulation for the application of the FIT3D module and the modules used here are explained. In Section 3, we show the numerical result of the test simulation for an NBI heating plasma in LHD. Finally, Section 4 is devoted to brief summary.

## 2 Numerical scheme of test simulation on application of FIT3D module

The FIT3D is an neutral beam injection (NBI) heating module. The FIT3D has been developed based on three simulation codes[7]: HFREAYA, MCNBI and FIT, where HFREYA evaluates beam ion birth points using Monte-Carlo method and MCNBI calculates radial redistribution

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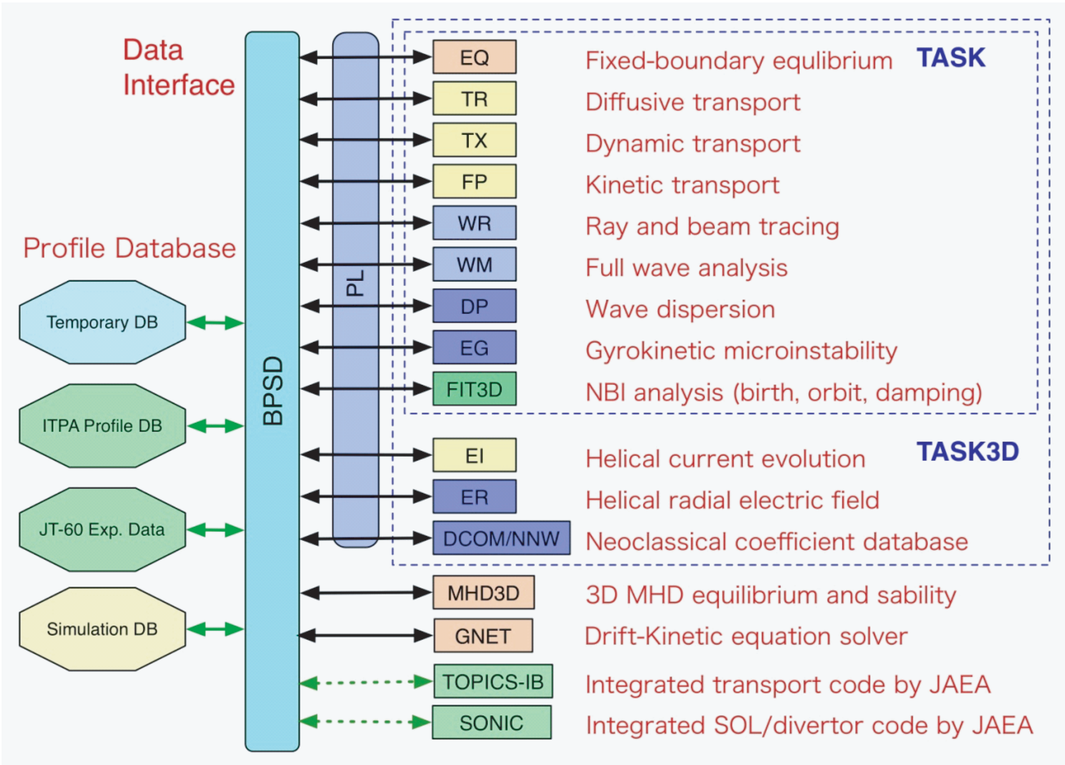


Fig. 1 Module structure of TASK3D.

of beam ions due to prompt orbit effects. Then, heating profiles are obtained by FIT code solving the Fokker-Planck equation. In order to check the applicability of the FIT3D module, test simulation has been performed by using the combination of VMEC module, TR module, ER module, DCOM/NNW module and FIT3D module. The numerical scheme of the test simulation on application of the FIT3D module is shown in Fig.2. The TR module is a one-dimensional diffusive transport module for solving particle transport and heat transport equations. In this test simulation, the density profile is fixed. Hence, the following heat transport equation is solved;

$$\frac{1}{V'^{5/3}}\frac{\partial}{\partial t}\left(\frac{3}{2}n_sT_sV'^{5/3}\right) = -\frac{1}{V'}\frac{\partial}{\partial\rho}\left(V'\langle|\nabla\rho|\rangle\frac{3}{2}n_sT_sV_{Es} - V'\langle|\nabla\rho|^2\rangle n_s\chi_s\frac{\partial T_s}{\partial\rho}\right) + P_s, \quad (1)$$

where $n_s$ is density, $T_s$ is temperature and $s$ expresses species of particles. $V_{Es} = V_{Ks} + \frac{3}{2}V_s$, where $V_{Ks}$ is a heat pinch velocity and $\chi_s$, $V_s$ are a thermal diffusion coefficient, and a particle pinch velocity which consist of neoclassical part and anomalous part. $t$, $\rho$, $V$ are time, minor radius variable of magnetic surface and volume enclosed by the magnetic surface, respectively. The prime denotes the derivative with respect to $\rho$, and $\langle\rangle$ represents the magnetic surface average. $P_s$ is the energy source (or sink). The NBI heating power is included in the energy source

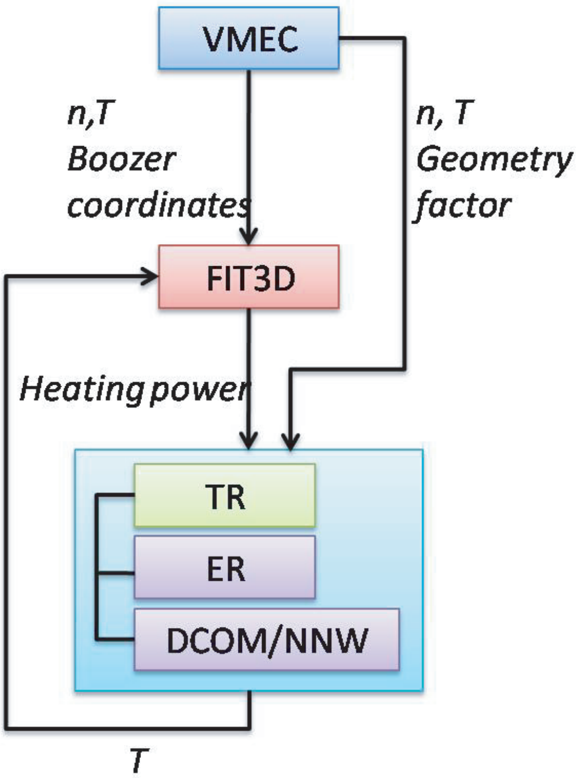


Fig. 2 Numerical scheme of test simulation on application of the FIT3D module, where $n$ is density and $T$ is temperature.

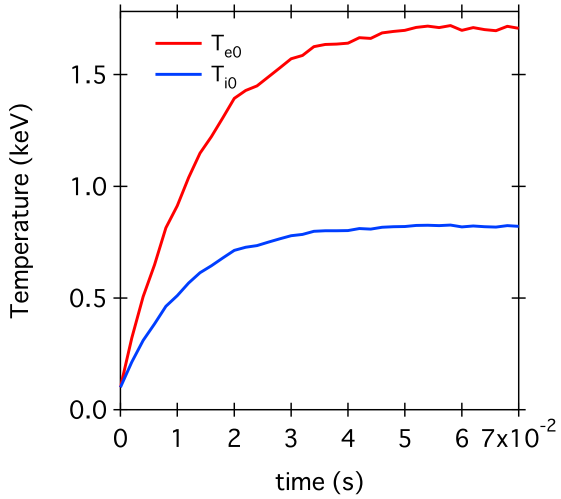


Fig. 3 Time evolution of electron ($T_{e0}$)and ion ($T_{i0}$) temperature at the plasma center.

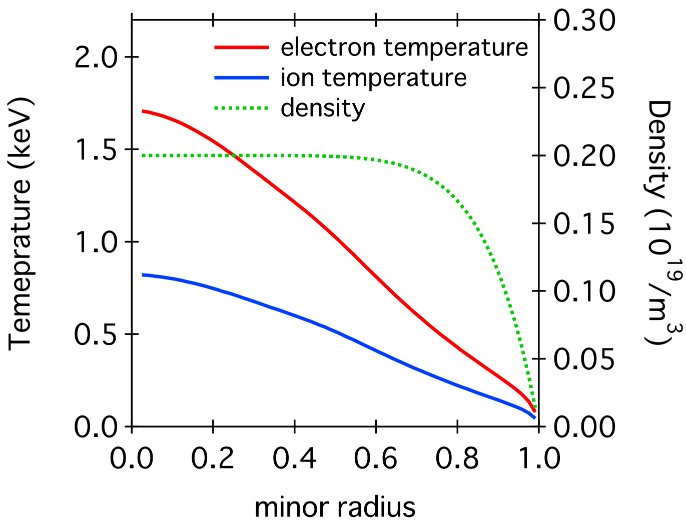


Fig. 4 Radial profiles of electron and ion at t=0.07[s]. The density profile (green line) is fixed.)

term $P_s$, which is calculated by the FIT3D module. The geometry factors $V'$, $\langle|\nabla\rho|\rangle$, $\langle|\nabla\rho|^2\rangle$ in eq.(1) are calculated by the VMEC module. In the test simulation, the profiles of the geometry factors are fixed after the MHD equilibrium is calculated for the initial state by the VMEC module.

Since the ambiplolar condition is not satisfied intrinsincally due to the non-axisymmetry of helical plasmas and the radial electric field $E_r$ is determined by neoclassical transport. For this purpose, ER module is calculated the radial electric field from the ambipolar condition $\Gamma_e = \Gamma_i$, where $\Gamma_e$ and $\Gamma_i$ are electron and ion neoclassical particle flux, respectively. For the evaluation of the neoclassical transport flux, DCOM/NNW module is used. The DCOM/NNW is the database of the neoclassical diffusion coefficients being constructed by the DCOM/NNW (Diffusion Coefficient Calculator by Monte Carlo Method / Neural NetWork) [8], based on the Monte-Carlo code, DCOM.

By the TR module, the profiles of the temperature of the electron and ion are updated and then the updated profiles are used for input parameters of the FIT3D module. Then, the heating power is recalculated for new temperature profiles.

## 3 Numerical result of test simulation on application of the FIT3D module

In order to check the applicability of the FIT3D module, test simulation has been performed for an LHD plasma according to the numerical scheme shown in Fig.2. In this section, numerical result of the test simulation is shown. In the test simulation, the initial temperature profiles of electron and ion are chosen as $T_s = (T_{s,0} - T_{a,s})(1 - \rho^2) + T_{a,s}$, where $T_{s,0}$ = 0.1[keV] and $T_{a,s}$ = 0.01[keV]. We set the density profile as $n = (n_0 - n_a)(1 - \rho^8) + n_a$, where $n_0$ =

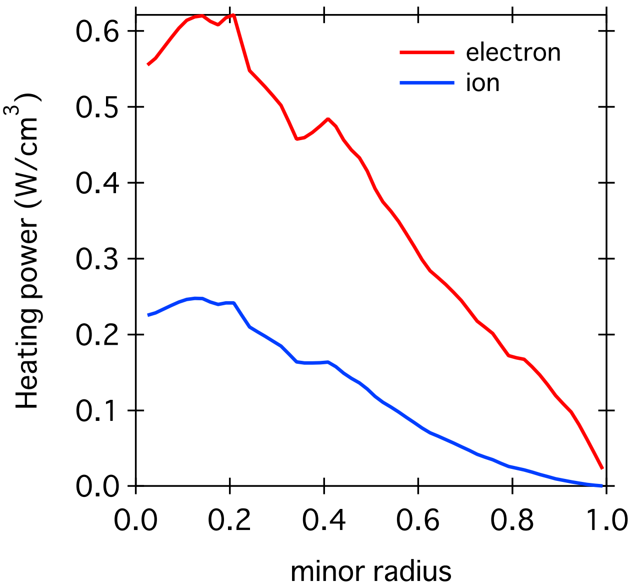


Fig. 5 Radial profiles of electron and ion heating power at t=0.07[s].

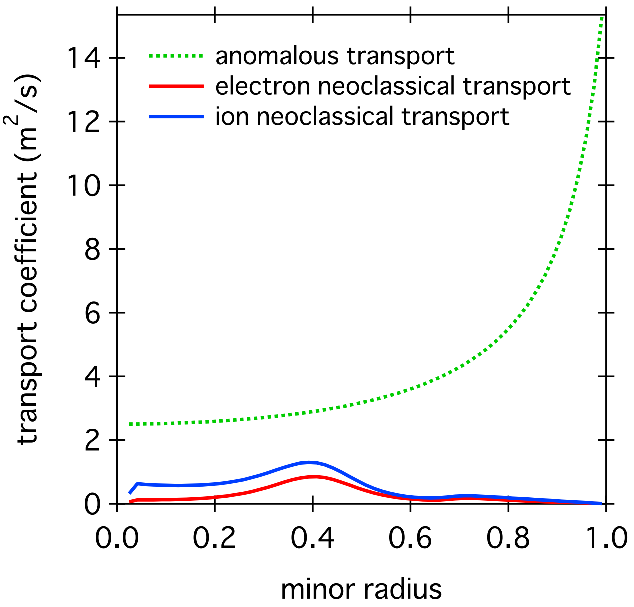


Fig. 6 Radial profiles of electron and ion neoclassical transport coefficient and anomalous transport coefficient at t=0.07[s].

2[$10^{19}$/m$^3$] and $n_a$ = 0.01[$10^{19}$/m$^3$]. Anomalous transport coefficient is assumed to be $\chi^{an} = 2/(1 - 0.85\rho^2)$ [m$^2$/s]. The profiles of the density and the anomalous transport coefficient are fixed. The magnetic field strength is set to be B=2.5[T]. For the NBI heating, three tangential NBI in LHD are considered. Their injection beam ion energy $E_b$ and beam power $P_b$ are set to be $(E_b, P_b)$ = (170 [keV],3.45 [MW]), (150 [keV],2.75 [MW]),(148 [keV], 2.75 [MW]), respectively. Figure 3 shows time evolution of the temperatures of the electron ($T_{e0}$) and the ion ($T_{i0}$) at the plasma center. The temperatures $T_{e0}$ and $T_{i0}$ are saturated at about t=0.05[s]. The profiles of the temperature, heating power and transport coefficient at t=0.07[s] are shown in Figs.4, 5 and 6, respectively. The heating power for the electron is about three times that of the ion as shown in Fig.5. On the other hand, the temperature of the electron is about twice that of the ion as shown in Fig.4.

## 4 Summary

The NBI heating module, FIT3D, has been implemented to TASK3D. In order to check the applicability of the FIT3D module, test simulation of a NBI heating plasma for LHD has been performed by the combination of VMEC, FIT3D, TR, ER and DCOM/NNW modules. From the test simulation, the applicability of the FIT3D module and the linkage of essential modules for analysis of the transport phenomena in LHD have been confirmed. In this paper, the anomalous transport coefficient is fixed for simplicity. The evaluation of the energy confinement time for various anomalous transport model is a future work.

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