Development of Integrated Transport Code, TASK3D, and Its Applications to LHD Experiment*)

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The integrated transport code for helical plasmas, TASK3D, has been developed both by modifying modules in TASK to be applicable to three-dimensional magnetic configurations, and by adding new modules for stellarator-heliotron specific physics and incorporating three-dimensional equilibria. In this paper, these module developments so far are collectively introduced, and recent progress on the applications of TASK3D to heat transport analyses of LHD plasmas is introduced.

Keywords: integrated model, TASK3D, TASK, stellarator-heliotron physics, three-dimensional equilibrium, heat transport, neoclassical diffusion, anomalous transport, predictive and interpretive analyses, LHD

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1. Introduction

The Large Helical Device (LHD) experiments have steadily expanded the parameter regime of helical plasmas such as electron and ion temperatures, density, beta value, pulse length and total input energy to plasma in a long-pulse operation as summarized in Ref. [1]. Thereby physics understandings have substantially been increased on the plasmas confined in torus magnetic configurations. In order to deepen and further increase the physics understandings, the integral simulation code applicable to LHD experiments is indispensable. We, therefore, are developing an integrated transport code, TASK3D, by modifying modules in TASK [2]. For the development of the integrated code, the wide-range applicability is required, and, in the mean time, validation of each module and its integration should be performed. The simulation code is designed to predict the overall time evolution of observable physics quantities in the plasma core, based on the diffusive transport equation with fluxes and source/sink terms for the particle and heat incorporating the three-dimensional (3D) nature of magnetic configurations. Followings are of vital importance: the increase in the accuracy of predictions, the validation and improvements of established theory-based models, the introduction of the database-approach through the extension of theory and large-scale simulations, and applications to the LHD experiments for their validation.

2. Outlook and Present Status of TASK3D Development

Figure 1 shows the overview of module components of TASK and TASK3D to show how TASK3D has been

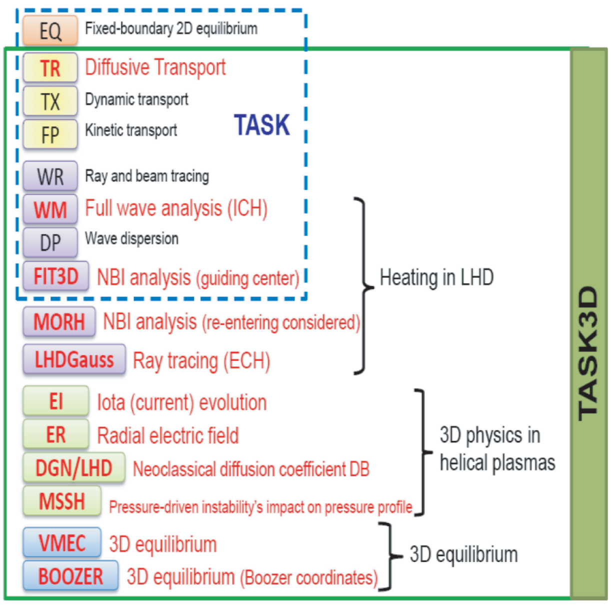

Fig. 1 An overview of module components of TASK and TASK3D. Modules, utilized/will be utilized for TASK3D, are denoted in bold characters. They are categorized to heating modules for LHD (NBI, ICH and ECH), stellarator-heliotron specific physics and 3D equilibrium. They have been developed piece-by-piece basis.

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extended and will try to deal with stellarator-heliotron specific physics issues and 3D equilibrium. The integration and packaging of these modules have been progressing, as will be described in Sec. 3.

The radial transport aspect of TASK3D employs the diffusive transport equation [module: TR] with the local diffusivity (particle and heat) and the particle and heat source/sink terms. Main focus of module modification/supplement in TASK3D development is to take 3D configuration's impacts into account to such quantities. In the following, a few modules of such developments are described in brief.

[Neoclassical diffusion and radial electric field: DGN/LHD, ER] The presence of the ripple transport (so called $1/\nu$ diffusion) is specific feature in non-axisymmetric magnetic configurations. The ambipolarity of neoclassical particle fluxes has been demonstrated to well describe the bifurcation nature of the radial electric field (E_r) in LHD and also in other helical plasmas [3, 4]. Thus, it is of a great importance to accurately calculate the neoclassical radial fluxes, and then ambipolar E_r. For this purpose, the diffusion coefficient database, DGN/LHD [5], has been prepared for a wide-range of equilibria in LHD by utilizing advantages of neoclassical transport codes, DCOM [6] and GSRAKE [7]. It has covered for vacuum conditions of $3.45\,\mathrm{m} < R_{ax} < 3.90\,\mathrm{m}$, and for volume averaged beta up to about 3% for $R_{ax} = 3.60\,\mathrm{m}$ configuration. Here R_{ax} denotes the magnetic axis position at vacuum condition. This establishment of the highly-accurate and fast neoclassical transport evaluation module has made it possible to compare with the power-balance analysis to elucidate anomalous transport contribution based on accurate neoclassical contribution to the radial heat flux [8].

[Time evolution of iota (current) profile: EI] The impact of 3D magnetic configuration on the current evolution is formulated through the susceptance matrix components [9]. The evolution of the rotational transform profile evaluated through this current evolution equation is compared to show the same trend (even quantitatively) with Motional Stark Effect (MSE) measurement in LHD. Recent extension of MSE measurement in a wide-range of plasma conditions [10] provides further opportunities to validate/improve the module by its application.

[NBI deposition analysis: FIT3D, MORH] As for the NBI deposition analyses, FIT3D code [11] has been routinely employed in LHD experimental analysis. FIT3D has been included in TASK, and then TASK3D as the indispensable module for heating analysis. Recently, it has also provided the torque input attributed to NBI, to perform momentum transport analyses [12]. To examine the impact of re-entering particles (passing in and out through the last closed flux surface) on NBI heating efficiency, especially for high-beta and/or low magnetic field conditions, a new module MORH has been developed [13]. Experimental validation has been in progress.

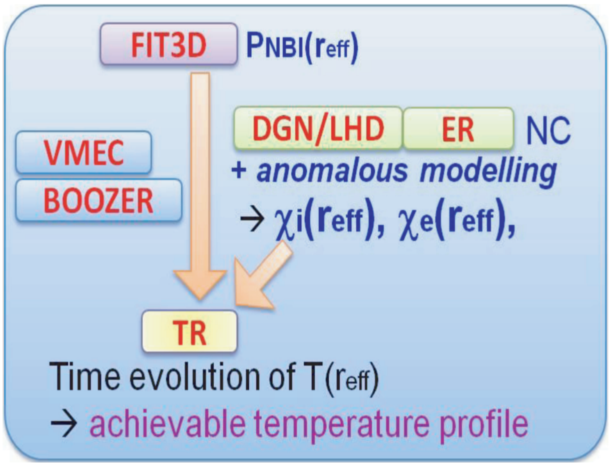

Fig. 2 A schematic view of modules used for "predictive" analyses.

3. Recent Progress on Applications to LHD Experiments

The applications of TASK3D to LHD experiments are of great importance. It should increase physics understandings, accurate discussion and scientific systemization for phenomena observed in LHD experiment. On the other way, it will provide significant opportunities to improve the models/extend the modules through the validation and falsification process. Based on such progresses, predictive capability of TASK3D can be increased.

Recently, one of emphases for the application of TASK3D to LHD experiment has been put on the heat transport analyses. It consists of two aspects: one is the predictive, and the other is interpretive analysis. This has been performed by packaging modules, TR, DGN/LHD, and FIT3D, along with 3D equilibrium modules, VMEC and BOOZER. Throughout the examples described below, the density profile is fixed for simplicity as initially assumed one or the experimentally measured one.

For the predictive analysis, the sum of the neoclassical heat diffusivity estimated by DGN/LHD and assumed anomalous transport contribution to the heat diffusivity, $\chi(r_{\mathrm{eff}})$, is given to TR module so that the profile evolution is solved in a time-dependent manner along with the NBI deposition profiles, $P_{\mathrm{NBI}}(r_{\mathrm{eff}})$, calculated by FIT3D with assumed beam information. A schematic structure for such calculations is described in Fig. 2. One-dimensional transport is analyzed in the direction of effective minor radius r_{eff}. A wide range of anomalous transport models has been implemented in TR module, so that the variety of validation studies and predictive analyses are available as reported in Ref. [8]. This has been made possible through the fast and accurate evaluation of neoclassical contribution by equipment of DGN/LHD. Estimated neoclassical ambipolar E_r (by module ER) is also taken into account for the estimate of the neoclassical heat diffusivity in DGN/LHD. So far, the equilibrium is fixed throughout the evolution of

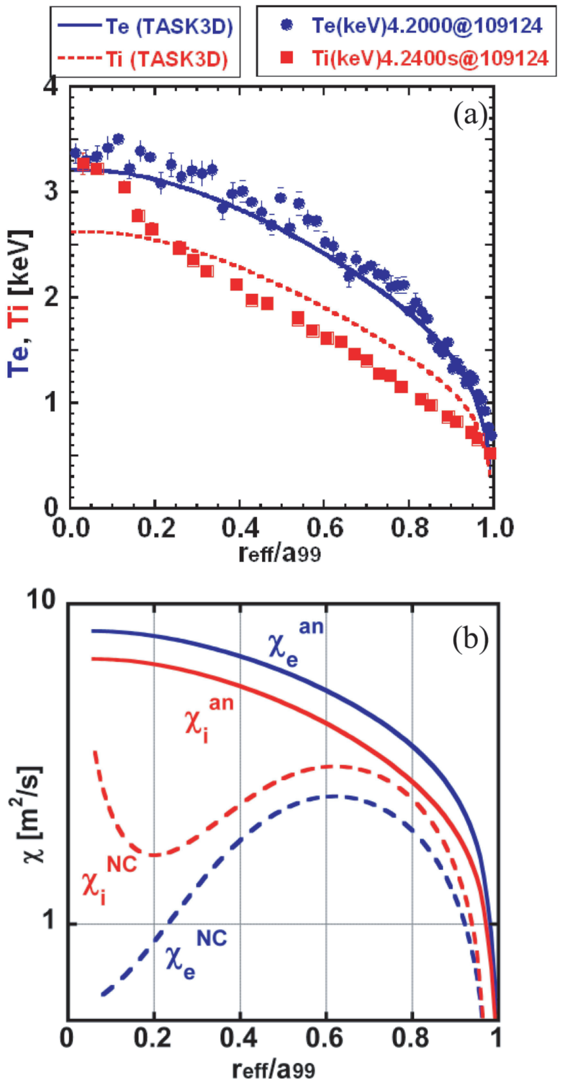

Fig. 3 (a) An example of predictive temperature profiles (curves), and measured profiles (closed symbols with error-bar) for a corresponding discharge 109124, based on (b) assumed anomalous heat diffusivity in addition to the neoclassical heat diffusivity provided by module DGN/LHD.

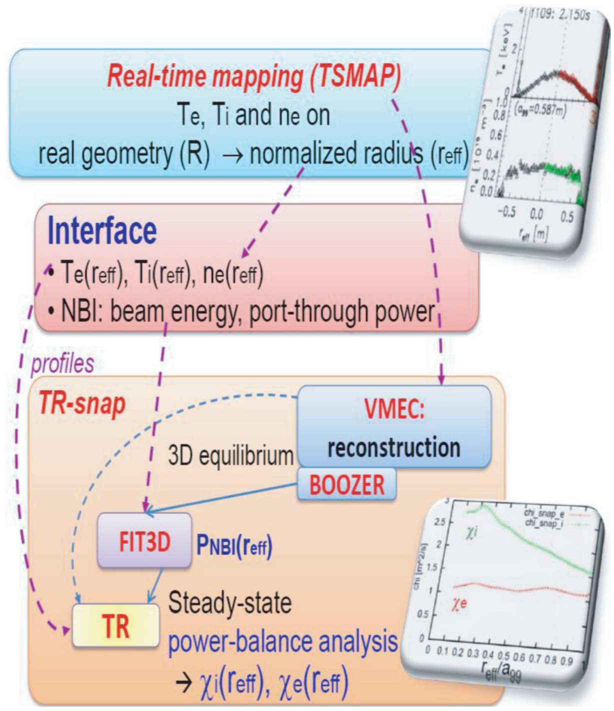

Fig. 4 A schematic structure of TR-snap and its interface to real-time mapping system (TSMAP) for "interpretive" analyses.

the temperature profiles. NBI power deposition is repeatedly evaluated by FIT3D during the evolution of temperatures. Then the temperatures reach steady-state profiles. The steady-state profiles calculated here are considered to be a "prediction" of the achievable temperature profiles under an assumed NBI heating condition and an anomalous transport model. Figure 3 (a) shows an example of such a prediction (curves) for the assumed density about $1.4 \times 10^{19}\,\mathrm{m}^{-3}$. An experimental discharge corresponding to the employed conditions, such as the density range and NBI input power, is conducted: profiles of electron and ion temperatures are shown in Fig. 3 (a) for the prediction and for an experiment (shot 109124 with port-through $P_{\mathrm{NBI}} \sim 25\,\mathrm{MW}$). Here, a_{99} denotes the effective minor radius (r_{eff}) corresponding to that of the flux surface within which 99% of the plasma stored energy is confined. The gyro-Bohm transport model is applied for this example, whose value of the heat diffusivity exceeds the neoclassical one as shown in Fig. 3 (b). The differences between the prediction and measurement provide several clues for the modification of assumption of the anomalous transport contribution, along with such as the detailed comparison with absorbed power from NBI heating, and impact of equilibrium change on the heat transport. Such systematic study will be performed with the predictive analyses by TASK3D and comparisons with measurement in corresponding discharges. In this way, anomalous transport modelling appropriate for LHD plasmas is anticipated to be elucidated, to provide the reliable basis for the predictive capability towards further extension of plasma parameters.

On the other hand, the "interpretive" analyses are based on the measurement (so called, in general, power balance analyses). For this purpose, a module package, TR-snap [14], has been established. It has included modules, TR and FIT3D, along with the implementation of equilibrium geometry information from VMEC equilibria. Recent progress of its application to LHD experiments is to establish the interface to the real-time magnetic coordinate mapping system [15]. This system (so called TSMAP) has provided a mapping from the real coordinates to the effective minor radius (r_{eff}) using based on wide-range of pre-calculated VMEC equilibrium database. Thus, establishing the interface between TSMAP and TR-snap has significantly enhanced the capability of quick interpretive analyses. The interface includes the functions as follows: to prepare a VMEC input by utilizing "best-fitted" equilibrium parameters (for VMEC equilibrium reconstruction, and then transformed into the Boozer coordinates for providing equilibrium information to other modules), to describe measured temperature and density profiles as a function of r_{eff}, and to acquire NBI energy/port through power. A schematic structure of TSMAP_TR-snap integration is shown in Fig. 4. TR-snap is currently extending for implementing modules to be applicable to ECH (LHDGauss) and ICH (WM) heating in LHD. Thus, comprehensive analyses for a wide range of heating scenario in LHD experiments should become possible as its extension proceeds.

4. Concluding Remarks

The development of integrated transport code, TASK3D, and applications of combined modules to LHD experiments have been steadily progressed. As a recent example of TASK3D applications to LHD experiment, the predictive and interpretive analyses for the heat transport are described in this paper. Close link between TASK3D and LHD experiments in this way should increase the accuracy of TASK3D analyses and its predictive capability for future experiments and for reactor plasmas.

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