Self-consistent Integrated Modelling of Core and SOL/Divertor Transports and Simulation Study on Transient Behavior of Heat Load on Divertor Targets

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Abstract. We have developed a self-consistent integrated modelling of core and SOL/divertor transport. Thereby it enables us to investigate operation scenarios to be compatible with high confinement core plasma and detached divertor plasmas. To integrate a 1.5D core code (TOPICS-IB, TASK) and a 2D divertor code (SONIC), we introduce a new Multiple Program Multiple Data parallel computing system. For an integrated code including Monte-Carlo calculations, this system makes it possible to perform efficient simulations. The predictive simulation studies are carried out for JT-60SA with the integrated code (TOPICS-IB/SONIC).

1. Introduction

Control of the power and particle exhaust is one of the most critical issues to achieve the fusion reactors, such as ITER and DEMO [1,2]. In the SOL-divertor regions, there are many interactive processes among fuel plasmas, impurities, neutral particles, and plasma-facing components with intricate configurations. In order to study these complicated SOL-divertor plasmas and to establish reliable control methods, numerical simulations are really indispensable and comprehensive divertor codes have been developed worldwide [1]. We too have developed a 2D divertor code, SONIC [3-5]. The SONIC suite of integrated divertor codes consists of the 2D plasma fluid code (SOLDOR), the neutral Monte-Carlo code (NEUT2D) and the impurity Monte-Carlo code (IMPMC) (Fig. 1). The feature of SONIC is that Monte-Carlo approach with flexibility of modelling is applied to impurity transport [3].

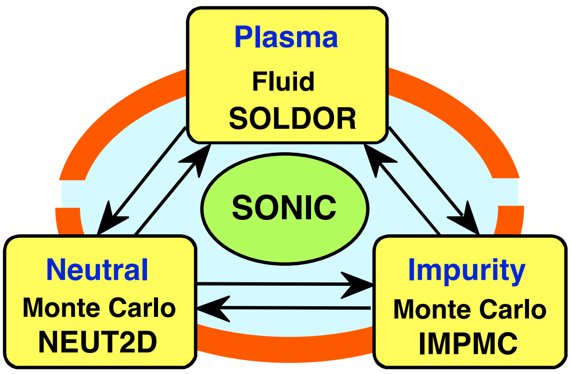

FIG. 1 Schematic of the SONIC suite of integrated divertor codes.

The dynamic evolution of X-point MARFE observed in JT-60U was investigated with SONIC code. It was found that the hydrocarbons sputtered from the dome contribute to the enhanced radiation near the X-point. These divertor simulations have been performed by giving the boundary condition of particle and heat fluxes at a certain magnetic surface in the core plasma near the separatrix. Since the core confinement and the SOL-divertor characteristics are significantly affected each other, above core boundary condition could not simply be given as input parameters. Recently several projects to combine a 1.5D core transport code and a 2D SOL/divertor code have started, such as JINTRAC [6] and FACETS [7]. In this paper, we exhibit our project of the self-consistent integrated modelling of core and SOL/divertor transports.

2. Model of core and SOL/divertor coupling

In the SONIC code, as well as other many divertor codes, the particle flux Γ, the electron heat flux Q_e, and the ion heat flux Q_i are given on the core edge boundary $\rho = \rho_c$ (usually normalized minor radius ρ_c = 0.90~0.95) at fixed values as input parameters. In actual tokamak plasmas, however, above fluxes to the edge region are essentially determined by the plasma transport in the core region. On the other hand, the core plasma transport is significantly affected by edge plasma conditions of the ion density n_i, the electron temperature T_e, and the ion temperature T_i, due to the temperature profile resilience for example. In addition to the boundary condition effect, SOL/divertor plasmas have strongly influence the core edge plasma through the particle source, the charge exchange loss and the impurity radiation.

In order to further study the power and particle control in tokamak plasmas including the above interactions between core and SOL/divertor plasmas, SONIC has been consistently coupled to a 1.5 D tokamak transport code (TOPICS-IB [8-10] or TASK [11-13]). From the 1D core transport unit the fluxes (Γ, Q_e, Q_i) at $\rho = \rho_c$ are sent to 2D SONIC unit, while the plasma quantities (n_i, T_e, T_i) at $\rho = \rho_c$ are sent to the 1D core unit from 2D SONIC unit vice-versa. The 2D MHD equilibrium is relied on TOPICS-IB or TASK. Figure 2 shows an example of MHD equilibrium of JT-60SA tokamak plasma for the coupling between core and peripheral transports. In the present work, the TOPICS-IB suite of codes is being coupled to the SONIC at the setout. The TOPICS-IB contains various physics modules for a free-boundary MHD equilibrium, the diffusive transport including several turbulent transport models, RF and NB heating and so on.

We know it difficult to integrate large code systems which contains a number of physical modelling, i.e. TOPICS-IB, TASK and SONIC in parallel with improvement of physical modelling. Because each code is being developed independently by different researcher/group and the substantial change of code is not allowed without understanding the whole code. So far a single load module of the integrated code has been executed. On the parallel computer, the integrated code, which consists of multiple load modules, can be executed with exchanging data between load modules. We have developed a new MPMD (Multiple Program Multiple Data) computing system, as shown in Fig. 3. In this system [14], the grand master PE (processing element) issues commands to control each load module via MPI (Massage Passing Interface). The mutual interface between codes is limited to exchange data through MPI_Send/MPI_recv routines. The loose coupling based on MPMD makes it possible to improve independently each component of the integrated code without interference in each other. At least there is no need of considerable adjustment for code integration.

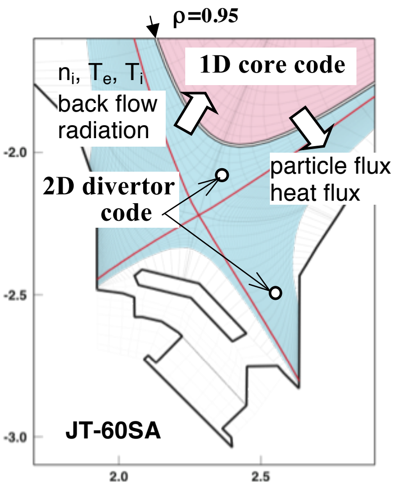

FIG. 2 Coupling between 1D core transport and 2D SOL/divertor transport in JT60SA tokamak. Plasma quantities (n_i, T_e, T_i) and fluxes (Γ, Q_e, Q_i) are connected at the core boundary at $\rho = \rho_c$.

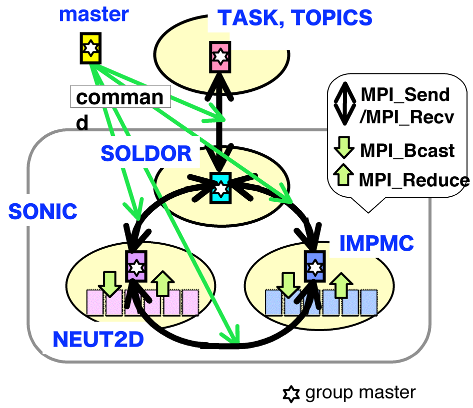

FIG. 3 MPMD parallel computing system for the integrated modelling of 1.5D core transport (TOPICS-IB, TASK) and 2D SOL/ divertor transport (SONIC).

3. Transient behavior of JT-60SA divertor after H-mode transition

To demonstrate the advantage of coupling of SONIC to TASK, we investigated how the dynamic change in fluxes affects divertor characteristics. Predictive simulations were carried out for a high current operation of JT-60SA (I_p=5.5 MA, B_T=2.25 T, P_{in}=41 MW). The simulations consisted of the following three steps.

Step 1: The TOPICS-IB simulation, where the boundary condition at $\rho = 1.0$ was given as input parameters, was carried out. Figure 1 shows the time evolution of NBI power. After NB injection with P_{NBI} = 15 MW, the L-H transition is assumed to take place at t=3.452 s. The scaling of power threshold of the H-mode transition predicts that the heat flux at the core edge $\rho = 0.95$ exceeds some critical value of ~10 MW for the JT-60SA operation. The timing of the H-mode transition corresponds to this condition. We employed the anomalous heat diffusivities of $\chi_i(\rho) = \chi_e(\rho) = 0.288\cdot(1+2\rho^2)\times\sqrt{1+P_{NB}/P_{OH}}\ m^2/s$ for Ohmic phase, L-mode phase and H-mode phase. The particle diffusion was assumed be $D_i(\rho) = 0.5\times\chi_i(\rho)$. The H-mode transition was modelled by a sudden reduction in diffusion coefficients in the periphery $0.9 < \rho < 1.0$ to the ion neoclassical level ($D_i = 0.1\ m^2/s$, $\chi_i = \chi_e = 0.2\ m^2/s$). The density and temperature at the plasma centre oscillated due to the simple sawtooth mixing model as shown in Fig. 1.

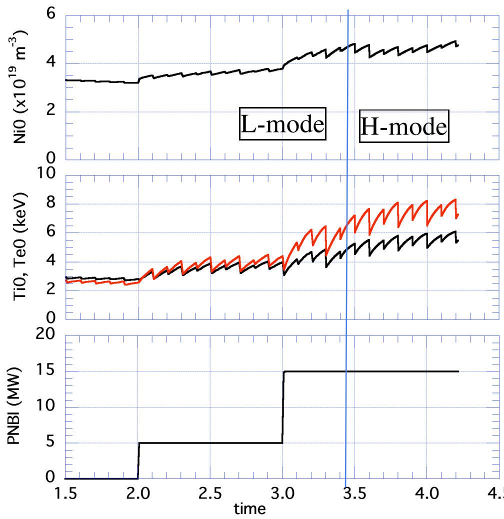

FIG. 4 Discharge waveform obtained with TOPICS-IB code. H-mode is assumed to start at t=3.452 s. Density and temperature at the plasma centre oscillate due to the simple the sawtooth mixing model.

Step 2: The calculation of the quasi-steady state of

L-mode phase at t=3.400 s was performed with the SONIC code, using the particle and heat fluxes (Γ, Q_e, Q_i) at $\rho = \rho_c$, obtained at t=3.400 s in the previous step calculation. The diffusion coefficients in the core edge region (ρ>0.9) were the same as those in the TOPICS-IB. The diffusion coefficients in the SOL/divertor regions were assumed to be $D_i = 0.3\,m^2/s$, $\chi_i = \chi_e = 1\,m^2/s$ throughout the simulation. For continuity of fluxes and plasma parameters at the boundary in TOPICS-IB, several iterations were required. The connection radius ρ_c is chosen to be 0.82 to avoid the effect of the significant change in the diffusion coefficient after H-mode transition.

Step 3: The dynamic simulation was performed with the integrated code (TOPICS-IB/SONIC). The calculation started from the initial distributions in the main plasma and the peripheral region obtained at the second step. The boundary conditions were exchanged every 0.1 ms.

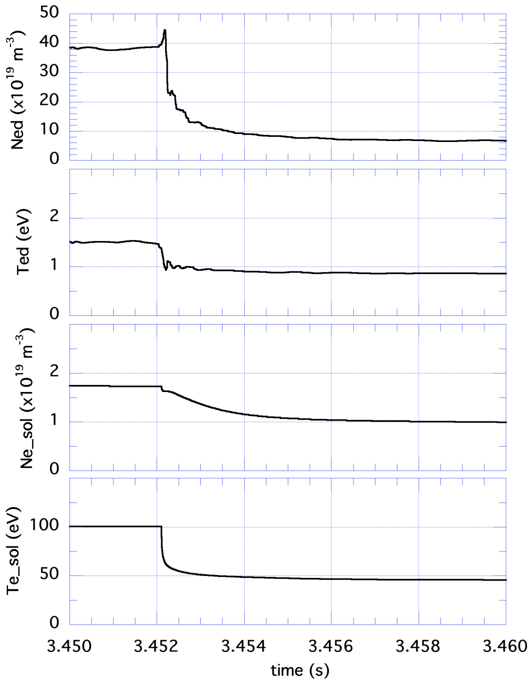

FIG. 5 Time evolution of electron density and temperature at inner divertor strike point and at outer mid-plane after H-mode transition.

Figure 5 showed the time evolution of electron density and temperature at inner divertor strike point (n_{ed}, T_{ed}) and at the outer mid-plane (n_{esol}, T_{esol}) just after the H-mode transition. The particle and heat fluxes into the SOL region reduced just after the transition from $(\Gamma_i = 7.0\times10^{21}\ m^{-3}, Q_i = 4.9\ MW,\ Q_e = 5.8$ MW) at t=3.452 s to $(4.4\times10^{21}\ m^{-3}, 1.2\ MW, 1.3\ MW)$ at t=3.454 s. The electron density at the strike point reduced rapidly from $3.8\times10^{20}\ m^{-3}$ to $1.2\times10^{20}\ m^{-3}$ after 1 msec of the H-mode transition. And then it gradually reduced to $7\times10^{19}\ m^{-3}$. Though the electron density was not so high, the electron temperature remained around 1 eV due to low heat flux across the separatrix. The electron density and temperature at the mid-plane also reduced from $(1.8\times10^{19}\ m^{-3}, 100\ eV)$ to $(1.0\times10^{19}\ m^{-3}, 50\ eV)$.

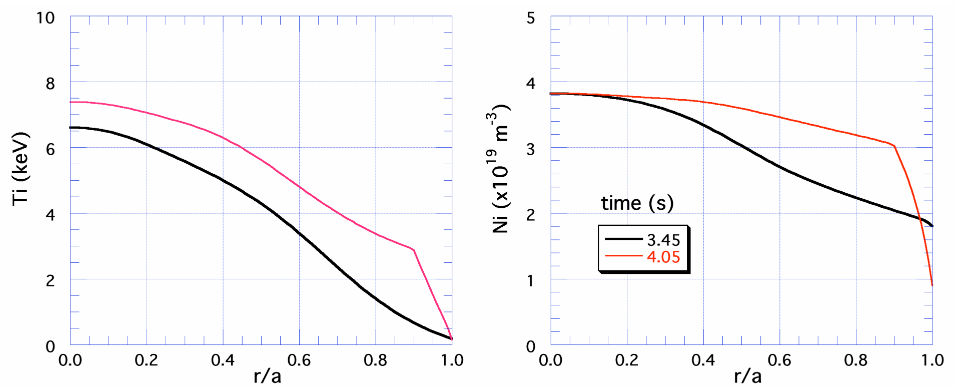

FIG. 6 Time evolution of ion density and temperature profile in the main plasma after H-mode transition at t=3.452 s. The pedestal is formed within 0.2 s. The particle and heat fluxes across the separatrix gradually increase due to the growing of steep density and temperature gradients at the pedestal.

The time scales for the main plasma and the SOL plasma are very different, 0.5~1 s and 1~20 ms, respectively. The SONIC divertor code demands computaional time. Thereby it is hard to execute a full simulation with the integrated code from the H-mode transition till a quasi-steady state. The simulation was performed with the TOPICS-IB from t=3.50 to 3.70 s. We resumed the simulation with the integrated code from 3.70 s and obtained a divertor plasma parameter durning H-mode phase t≈3.90 s. Figure 6 shows the ion density and temperature profiles before and after a H-mode transition. Due to increase in the particle and heat fluxes across the separatrix, the recycling was enhanced and the high density at the divertor was formed. Then the denisity at the SOL also increased.

Figure 7 shows the electron density, electron and ion temperature at the divertor plate. The particle and heat flux across the separatrix are $\Gamma_i = 5.1\times10^{21}\ s^{-1}$, $Q_i = 4.3\,MW$, $Q_e = 4.2\,MW$. The heat flux onto the divertor plate is shown. The peaked densities at the strike points are low compared with those obtaind in the steady state simulations [5]. The peaked heat flux, which consists of the conduction and convection power and recombination, is around 8.2 MW/m^2.

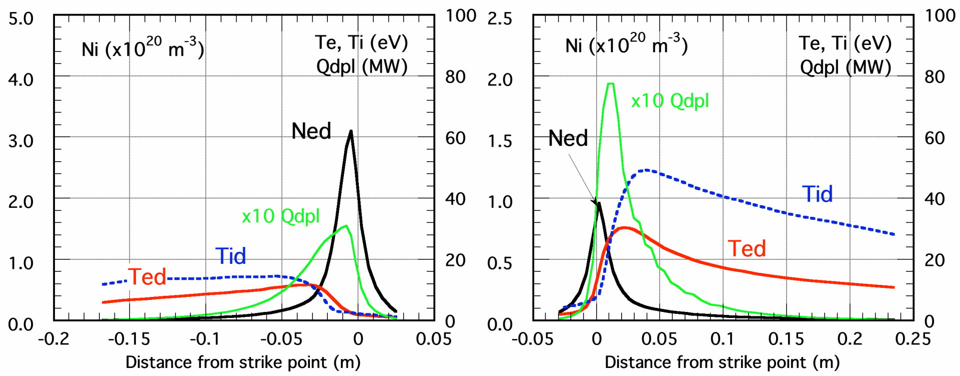

FIG. 7 Plasma parameters at the divertor plates. Left figure is of the inner divertor and right is of the outer.

4. Summary and discussion

We have developed a self-consistent integrated modelling of core and SOL/divertor transport. Thereby it enables us to investigate operation scenarios to be compatible with high confinement core plasma and detached divertor plasmas. To integrate a 1.5D core code (TOPICS-IB, TASK) and a 2D divertor code (SONIC), we introduce a new Multiple Program Multiple Data parallel computing system. For an integrated code including Monte-Carlo calculations, this system makes it possible to perform efficient simulations. The predictive simulation studies are carried out for JT-60SA with the integrated code (TOPICS-IB/SONIC). Dynamic change in particle and heat fluxes into the SOL region after an H-mode transition has a significant influence on divertor characteristics even in a subsequent steady state. We also discuss about the temporal behavior of divertor characteristics after an ELM crash.

Acknowledgments
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