J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Integrated Modeling for Control of Advanced Tokamak Plasma

Takahisa OZEKI, Nobuhiko HAYASHI, Mitsuru HONDA, Nobuyuki AIBA, Kiyotaka HAMAMATSU, Katsuhiro SHIMIZU, Hisato KAWASHIMA, Kazuo HOSHINO, Tomonori TAKIZUKA and Shinji TOKUDA

Japan Atomic Energy Agency, Naka Fusion Research Institute, Naka-city, Ibaraki 311-0193 Japan

(Received: 1 September 2008 / Accepted: 19 December 2008)

Integrated modeling on areas of plasma core, edge-pedestal and scrape-off-layer (SOL)-divertor progressed based on the researches in JT-60U experiments. An anomalous transport model of fast particles due to the Alfvén eigenmode is proposed in the core plasma and a new one-dimensional core transport code, which can describe the radial electric field and plasma rotations self-consistently, is developed. The integrated code TOPICS-IB is improved in the edge pedestal region, and effects of the pressure profile inside the pedestal and the collisionality dependence on the ELM energy loss are clarified. The impurity Monte Carlo code is incorporated to the integrated divertor code SONIC. Simulation of impurity behavior at X-point MARFE successfully produced the complete detached plasma, where a part of sputtered carbon penetrates into the main plasma and contributes to the enhanced radiation near the X-point.

Keywords: integration, modeling, burning plasma, edge-pedestal, SOL-divertor, advanced tokamak, simulation

1. Introduction

In order to realize a steady–state tokamak fusion reactor, establishment of a robust control method of advanced tokamak plasma is a critical issue. Since the advanced tokamak plasma consists of high values of normalized beta, a fraction of self-generated bootstrap current, and a confinement enhancement factor, the plasma has an autonomous property through the strong coupling of profiles of plasma pressure, current density, rotation and so on. To predict and control the advanced plasma with a large gain of fusion power, it is necessary to simulate the property of these complex plasmas with a real time scale and a real spatial scale. For this purpose, the modeling of the various physics in tokamak plasmas and the integration of models are useful and an effective means. In Japan Atomic Energy Agency (JAEA), integrated models of 1) core, 2) edge-pedestal and 3) scrape-off-layer (SOL)-divertor were developed based on the researches in JT-60U experiments, and complex features of reactor relevant plasmas are clarified [1,2]. Investigations of the integrated modeling are progressing with some projects of National Transport Code Collaboration (NTCC) [3], Fusion Simulation Project (FSP) [4], Burning Plasma Simulation Initiative (BPSI) [5], Integrated Tokamak Modeling (ITM) task force on EFDA task [6], and so on.

In this paper, the progress on the integrated modeling for burning plasmas is presented. 1) The integrated core plasma model including an anomalous transport of fast particles due to the Alfvén eigenmode indicated a degradation of the fusion burning. A new one-dimensional core transport code, which can describe the radial electric field and plasma rotations, is developed [7]. 2) The core integrated code with the transport and the stability TOPICS-IB is developed for the edge pedestal model [8,9], and the pressure profiles and collisionality dependence on the energy loss due to edge-localized-mode (ELM) are clarified. 3) The integrated SOL-divertor model SONIC (Divertor/Neutral/Impurity) progressed [10] and the complete detached plasma is obtained by the integrated simulation with impurity behavior. Success in these consistent analyses using the integrated code indicates that it is an effective means to investigate complex plasmas and to control the integrated performance.

2. Integrated Model of Core plasma

The influence of the alpha particle related instability on the plasma confinement is important issues. A model of the radial transport of alpha particles or energetic ions due to neutral beam injection (NBI), including the anomalous radial transport due to the Alfvén eigenmode, is proposed [11], and the model solves the Fokker-Planck equation for the integrated simulation based on the transport code, TOPICS-IB.

To investigate the radial transport and the slowing down process of energetic particles, a two-dimensional distribution function f(v, ρ, t) is introduced, where v is the velocity and ρ is the radial coordinate in the direction of the minor radius. The time evolution is assumed to the following extended Fokker-Planck equation;

author's e-mail: ozeki.takahisa@jaea.go.jp

$$\frac{\partial f(v,\rho,t)}{\partial t}+\frac{1}{\rho}\frac{\partial}{\partial\rho}\left[\rho\left(-D(v,\rho)\frac{\partial f}{\partial\rho}+V_{AN}(v,\rho)f\right)\right] \qquad (1)$$
$$=S(v,\rho)+\sum_j C_j(f)-L(f),$$

where S is the particle source due to the fusion reaction and NBI, $C_j(f)$ is the Coulomb collision term colliding off bulk plasma species j. The loss term of

$$L(f)=\frac{f(v,\rho,t)}{\tau_{th}(\rho)}\exp\left[-\frac{m_\alpha v^2}{\lambda T_{ash}(\rho)}\right] \qquad (2)$$

shows the slowing down alpha particle as helium ash, where $\tau_{th}(\rho)$ is the thermal collision time. The velocity range of removed particles is expressed by the constant λ. The radial transport of energetic particles is expressed by the second term in the left hand side of the equation (1). The diffusion D is composed of the neo-classical part D_{NC} and an anomalous part D_{AN}. The neo-classical diffusion coefficient is assumed by $D_{NC}(v,\rho)=((1+\varepsilon)/2\varepsilon)^{1/2}\Delta_b^2(v,\rho)/\tau_\perp(v,\rho)$, where ε is the local aspect ratio, $\Delta_b(v,\rho)$ is the banana width, and $\tau_\perp(v,\rho)$ is the pitch angle scattering time.

Model of the anomalous transport caused by instabilities with large amplitude MHD activities like the TAE-mode is developed. Anomalous radial flux Γ_ρ can be assumed as

$$\Gamma_\rho=-D_{\mathrm{MHD}}\frac{\partial f_{res}(v,\rho)}{\partial\rho}+V_{\mathrm{MHD}}f_{res}(v,\rho) \qquad (3)$$

where f_{res} is a part of f resonated with the MHD mode. To evaluate f_{res} and the transport coefficients D_{MHD} and V_{MHD}, the structure of the MHD mode and the interaction between particles and MHD field are needed. In the case of TAE mode, particles are resonated at the velocity $v_\parallel=v_A$, where v_A is the Alfvén velocity. The population of resonant particle decreases with decreasing of v from the birth velocity $v_\alpha=(2\mathrm{x}3.5\mathrm{MeV}/m_\alpha)^{1/2}$. The transport coefficients due to the MHD-mode are related to an envelope of fluctuated MHD field, which is assumed to be $\langle\delta B/B\rangle\propto\xi(\rho)=\exp[-((\rho-\rho_{MHD})/\Delta\rho_{MHD})^2]$, where ρ_{MHD} is a peaked position and $\Delta\rho_{\mathrm{MHD}}$ is a width of the fluctuated MHD field. From the items mentioned above, we assume that $D_{AN}(v,\rho)=D_{AN0}\eta(v,\rho)\xi^2(\rho)$ and $V_{AN}(v,\rho)=V_{AN0}\eta(v,\rho)\,\xi(\rho)\,\rho/a$, where D_{AN0} and V_{AN0} are constant factors as given parameters. The developed model shows the slowing down of the fast particle and the enhancement of the radial transport due to the TAE [11].

Plasma rotation has a significant effect on the transport and the stability and it is therefore important to integrate the rotation effect to the integrated code TOPICS-IB. A new one-dimensional multi-fluid transport

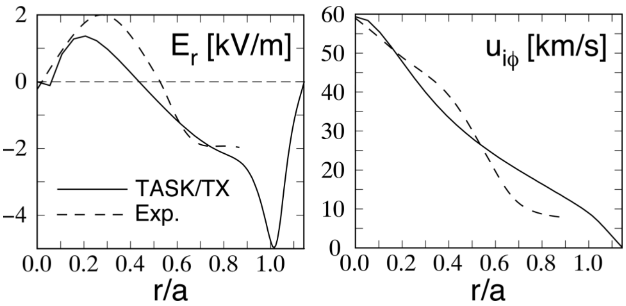

Fig.1 Comparison of the radial profiles of the radial electric field and the ion toroidal velocity in a steady state between the simulation results and the experiment on JFT-2M.

code TASK/TX has been developed [7] to describe dynamic behavior of tokamak plasmas, especially the time-evolution of the radial electric field and the plasma rotations. TASK/TX is an independent code at present, but it will be incorporated in TOPICS-IB as a time-advancing transport module with momentum transport.

TASK/TX self-consistently solves a set of flux-surface averaged equations in the cylindrical coordinates; Maxwell's equations, continuity equations, equations of motion, heat transport equations, momentum transfer equations for fast particles, and two-group neutral diffusion equations.

The finite element method with a piecewise linear interpolation function is employed. The Streamline Upwind Petrov–Galerkin method is also incorporated for numerically robust calculation. Despite solving the very nonlinear equations, the code shows a good convergence performance.

Modification of a density profile during neutral beam injection (NBI) is presented. We found the density peaking for the counter-NBI and the density broadening for the co-NBI. The balance between neoclassical and turbulent effects defines the status of the density profile. We compared profiles of the radial electric field and the ion toroidal velocity in a steady state between simulated by TASK/TX with those observed in the JFT-2M experiment [12] with R=1.3m, a=0.35m, B_T=1.3T I_p=0.2MA and P_{co}=0.5MW [7], and we confirmed that TASK/TX is capable of qualitatively reproducing the overall tendencies of the experimental profiles, as shown in Fig.1.

In the presence of ion orbit losses, the code predicts the generation of the intrinsic (spontaneous) rotation in the counter direction with the inward radial electric field. The non-ambipolar loss breaks quasi-neutrality and the plasma instantaneously generates the inward radial current near the periphery to compensate the ion loss current, inducing the more negative radial electric field and the torque toward the counter direction. Other conventional transport codes assuming the quasi-neutrality cannot follow these processes. It is the very special characteristic of the TASK/TX code that there is no need to impose an explicit quasi-neutrality condition.

3. Integrated Model of Edge Pedestal

The plasma on the edge-pedestal consists of the transport improvement, the edge stability and the interaction with the SOL and divertor. The structure of the pedestal is thought to determine the plasma performance and to induce the instability near the edge, i.e. ELM, that makes the heat load on the divertor plate. Therefore, the integrated modeling on the edge-pedestal region is developed by using the integrated simulation code TOPICS-IB based on a 1.5 dimensional core transport code with a stability code for the peeling-ballooning modes and a transport model for SOL and divertor plasmas [8]. Transient behaviors of H-mode plasma are simulated and a mechanism of the collisionality dependence of the ELM energy loss is clarified with the fixed density profile for simplicity.

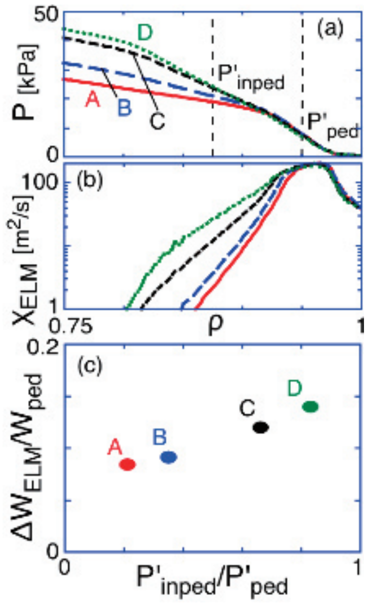

Fig.2 (a) Pressure profiles at ELM onset and (b) χ_{ELM} for cases A-D. (c) Dependence of $\Delta W_{ELM}/W_{ped}$ on P'_{inped}/P'_{ped}. Definition positions of P'_{inped} and P'_{ped} are shown in (a).

The effect of the pressure gradient inside the pedestal top, P'_{inped}, on the ELM energy loss is examined [9]. Figure 2(a) shows pressure profiles which are obtained by given various thermal diffusivities. The thermal diffusivities are assumed as the ion neoclassical level in the pedestal region, and assumed as additionally higher values inside the pedestal top for cases A-D. As a result, pressure profiles, P, with different pressure gradients inside the pedestal top are simulated just before the ELM onset (Fig. 2(a)). The pedestal top is located at $\rho = 0.925$ for all cases and P'_{inped} becomes larger in order of A, B, C and D. Even for the lower pressure gradient case of A, P'_{inped} is larger than that of observed in JT-60U. The steep pressure gradient broadens eigenfunctions of unstable modes and the region of the ELM enhanced diffusivity, χ_{ELM}, is widened for the cases B-D, as shown in Fig. 2(b). The ELM energy loss, ΔW_{ELM}, normalized by the pedestal energy, W_{ped}, increases as a function of $P'_{\mathrm{inped}}/P'_{\mathrm{ped}}$ where P'_{ped} is the pedestal pressure gradient (Fig. 2(c)). In the case A, the ELM energy loss is less than 10% of the pedestal energy and is comparable with those in JT-60U. The steep pressure gradient inside the pedestal top enhances the ELM energy loss. The density collapse, which is not considered here, enhances the value of $\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$ by about 50% under the assumption of the similar collapse to the temperature one. The ELM energy loss in the simulation becomes larger than 15% of the pedestal energy, as is shown in the database of multi-machine experiments.

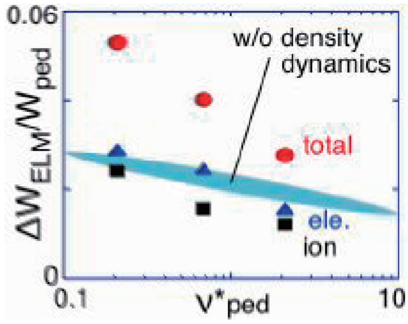

Fig.3 Collisionality (ν^*_{ped}) dependence of $\Delta W_{ELM}/W_{ped}$ and its electron and ion components. Shaded region denotes ΔW_{ELM} without density dynamics.

Next, density dynamics effect on the ELM behavior and the resultant particle and energy losses are investigated [13]. The density collapse enhances the ELM energy loss through the convective heat transport. The dynamics of the pedestal density strongly connects with the neutral recycling. Thus, the integration of the neutral model is necessary for the density dynamics. For this purpose, we newly integrate a 2D Monte Carlo code for core neutrals and a simple integral model for neutrals in SOL-divertor regions with TOPICS-IB. The TOPICS-IB successfully simulates the behavior of the whole plasma with the density dynamics. The collisionality dependence is investigated by varying the density and the temperature instead of artificially enhancing the collisionality in the previous study [8]. Figure 3 shows the normalized ELM energy loss $\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$ as a function of normalized collisionality at the pedestal top and at the ELM onset, ν^*_{ped}. In the electron energy loss, the conductive loss is larger than the convective one and decreases with increasing the collisionality while the convective loss is almost constant. The constant electron convective loss is caused by the independence of the ELM particle loss of the collisionality, which was also observed in experiments. The collisionality dependence of the electron conductive loss is caused by the bootstrap current and the SOL transport, as the same as in the previous study [8]. On the other hand, for lower collisionality, the ion temperature becomes higher than the electron one due to the ineffectiveness of the equipartition proportional to the collisionality. As a result, ion convective and charge-exchange losses bring the collisionality dependence of the ion energy loss, which could not be found without the density dynamics. The collisionality dependence becomes strong, and it is comparable with that in experiments.

4. Integrated Model of Scrape-off-layer (SOL) – divertor

Divertor of tokamak reactors has four major functions: heat removal, helium ash exhaust, impurity retention, and density control. Such divertor performance strongly depends on the various physics, i.e. plasma transport, kinetic effects, atomic processes, and plasma-wall interactions.

To predict the heat and particle controllability in the divertor of tokamak reactors and to optimize the divertor design, comprehensive simulations by integrated modeling allowing for various physical processes are indispensable. SOL-divertor codes have been developed in JAEA for the interpretation and the prediction on behavior of SOL-divertor plasmas, neutrals and impurities [10]. The code system consists of the 2D fluid code SOLDOR, the neutral Monte-Carlo (MC) code NEUT2D, and the impurity MC code IMPMC. Their integration code "SONIC" is mostly completed and examined to simulate self-consistently the SOL-divertor plasmas in JT-60U. In order to establish the physics modeling used in fluid simulations, the particle simulation code PARASOL has also been developed [14].

The benchmark test of SOLDOR/NEUT2D code with B2/EIRENE code was attempted. The simulation study of JT-60SA divertor was carried out with B2/EIRENE and the difference between single-null and double-null configurations was confirmed [15].

Simulation of impurity behavior at X-point MARFE was carried out. The contamination process of carbon impurity into the main plasma is investigated in JT-60U detached divertor plasmas. In the IMPMC, the carbon out fluxes due to physical and chemical sputtering are determined self-consistently taking account of sputtering yields and incident fluxes of deuterium ions and neutrals onto the target plates and the walls. For the neutral-beam heated divertor discharge (I_p=1.5MA, B_T=3T, P_{NB}=15MW), the heat flux and the particle flux from the core edge (r/a=0.95) are specified, Q_i=Q_e=7MW, Γ_i=3x$10^{21}$$s^{-1}$. The attached divertor plasma is obtained in a steady state before the gas puff, where the radiation of carbon concentrates near both strike points (Fig. 4). After a strong gas puff of Γ_{puff}=6x$10^{22}$$s^{-1}$, the radiation profile changes temporally from the strike points to the X-point. In the complete detached plasma, a part of carbon sputtered from the dome penetrates into the main plasma, and such carbons contribute to the enhanced radiation near the X-point. In the present simulations, the complex dissociation processes of CD_4 are simplified in an ionization process of C with a low energy (~1eV). The prompt re-deposition of fragments (CD_n) and the cross-field movement of neutral hydrocarbons are effectively taken into account in this model [16].

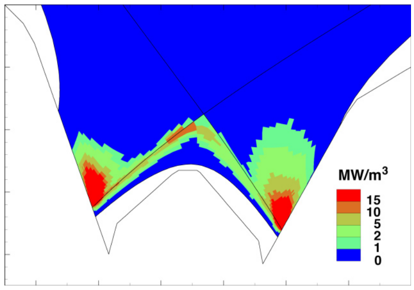

Fig.4 Radiation profiles calculated with SOLDOR/NEUT2D/IMPMC for attached plasma before strong gas puffing.

However, the carbon influx into the main plasma depends strongly on the dissociation processes and the interactions between various fragments and the walls. The MC code EDDY can treat minutely such dynamics of hydrocarbons near the targets [17].

IMPMC Code is extended toward time evolution simulation. As a self-consistent modeling of divertor plasma and impurity transport, the development of the integrated code SONIC is in progress. The key feature of this integrated code is to incorporate with IMPMC code. The MC approach is suitable for modeling of interactions between impurities and walls, including kinetic effects, and the complicated dissociation process of hydro-carbons. The MC modeling, however, has the disadvantage for long computational time, large MC noise, and assumption of steady state. The first and second difficulties were solved by developing a new diffusion model [18] and by optimizing with a Message Passing Interface (MPI) on the massive parallel computer. The third subject is solved by extension of IMPMC code toward time evolution simulation. In time-dependent simulation with the MC code, a serious problem to increase number of test particles. The particle reduction method consisting of sorting the weights, pairing and Russian roulette has been proposed [18]. Sorting of the weights is indispensable to suppress the MC noise.

The divertor configuration in JT-60SA has been optimized from a viewpoint of the neutral recycling with SOLDOR/NEUT2D. In the near future, it will be further optimized from a viewpoint of the impurity control with the SONIC code package coupled with the above extended IMPMC.

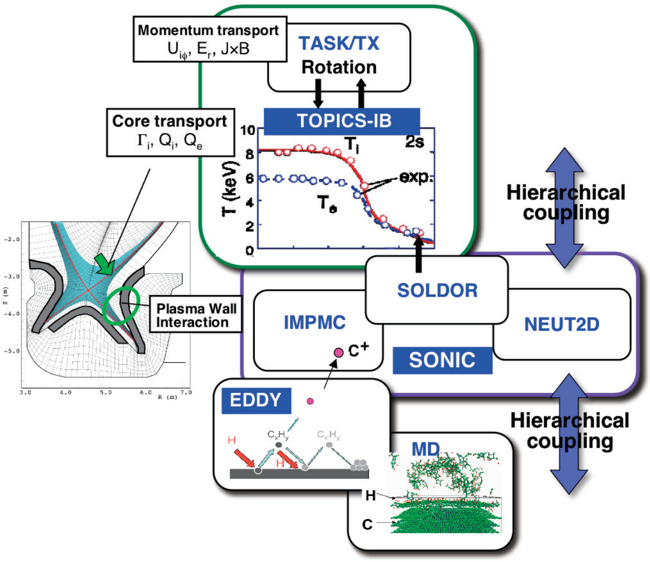

Fig.5 Schematics of an integrated model of a whole tokamak plasma by hierarchical coupling.

5. Summary

To investigate the complex burning plasma, the modeling and the integration of the model progressed. In the plasma core, an anomalous transport model of fast particles due to the Alfvén eigenmode is proposed. It will be bases to investigate the burning control issues. The transport model of the flow is developed. The flow is one of the key issues for the transport and the stability, and the self-consistent analysis of the developed code is useful to clarify the mechanism and it would be the platform of the integrated code.

The significant progress on the integrated edge pedestal code is obtained and understanding of the mechanism of the ELM energy loss through effects of the pressure profile inside the pedestal and the collisionality of the main plasma. The impurity Monte Carlo code IMPMC is incorporated to the integrated divertor code SONIC and the integration of divertor plasma model is in progress. Simulation of impurity behavior at X-point MARFE successfully produced the complete detached plasma. Also, IMPMC Code is extended toward the time evolution simulation.

These developed codes are planed to be integrated to simulate a whole tokamak plasma, including the plasma-wall interaction, as shown in Fig.5. The SOL-divertor code, SONIC, is connected to the core integrated code with the core transport and MHD stability, TOPICS-IB, which is connected to the momentum transport. It also links to the plasma surface interaction. The whole tokamak modeling leads to the further effective investigation of complex plasmas and the method to control the burning advanced tokamak plasma.

Acknowledgements

This work is partly supported by the Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science (JSPS).

References

[1] T. Ozeki, *et al.*, Fusion Sci. Technol. **50**, 68 (2006).
[2] T. Ozeki, *et al.*, Phys. Plasmas **14**, 056114 (2007).
[3] NTCC project, http://w3.pppl.gov/ntcc/
[4] FSP project, http://www.lehigh.edu/~infusion/
[5] BPSI project, http://bpsi.nucleng.kyoto-u.ac.jp/bpsi/en/
[6] Task force of EFDA, http://www.efda-taskforce-itm.org/
[7] M. Honda, *et al*., J. Comput. Phys. **227**, 2808 (2008).
[8] N. Hayashi, *et al.*, Nucl. Fusion **47**, 682 (2007).
[9] N. Hayashi, *et al.*, Contrib. Plasma Phys. **48**, 196 (2008).
[10] H. Kawashima, *et al.*, Plasma Phys. Control. Fusion **49**, S77 (2007).
[11] K. Hamamatsu, *et al.*," Radial Transport Model of Alpha Particles based on Fokker-Planck equation", proc in 10th IAEA Technical Meeting on "Energetic Particles in Magnetic Confinement Systems", P19 (2007).
[12] K. Ida, *et al*., Phys. Rev. Lett. **68**, 182 (1992).
[13] N. Hayashi *et al.*, J. Phys. Conf. Series **123**, 012025 (2008).
[14] T.Takizuka, *et al*., Trans. Fusion Tech. **39** 111 (2001).
[15] Y. Suzuki, *et al*., Contrib. Plasma Phys. **48**, 169 (2008).
[16] K. Shimizu, *et al*., J. Nucl. Mater. **363-365**, 426 (2007).
[17] K. Ohya, *et al*., J. Nucl. Mater. **363-365**, 78 (2007).
[18] K. Shimizu, *et al*., Contrib. Plasma Phys. **48**, 270 (2008).