The First TSME International Conference on Mechanical Engineering
20-22 October, 2010, Ubon Ratchathani

Simulation of ITER plasma during pellet injection

P Klaywittaphat[1], T Onjun[1*], R Picha[2], N Poolyarat[3] and S Suwanna[1]

[1] School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Pathumthani, Thailand
[2] Thailand Institute of Nuclear Technology, Bangkok, Thailand
[3] Department of Physics, Thammasat University, Pathumthani, Thailand
*Corresponding Author: thawatchai@siit.tu.ac.th, Tel. 66(2)564-3221-9, Fax. 66(2)986-9112-3

Abstract

In this work, MMM95 and NCLASS core transport models in BALDUR integrated predictive modeling code, together with NGS pellet ablation and pellet grad-B drift models, are used to simulate the time evolution of plasma current, ion and electron temperatures, and density profiles for ITER standard type I ELMy H-mode discharges during the pellet injection either from high field side or from low field side of tokamak. It is found that the injection of pellets from the high field side result in a rapid increase of plasma density than that from low field side. In addition, the pellets from high field side can penetrate much deeper into plasma than those from low field side. Moreover, the pellets from high field side yield an improved fusion performance while the pellets from low field side result in degradation of plasma performance.

Keywords: Plasma, Fusion, Tokamak, ITER, Pellet, Fueling.

1. Introduction

The injection of hydrogenic pellets has been demonstrated in many tokamaks for various purposes of efficient fuelling, confinement improvement and diagnosis in tokamak plasmas. However, the physics of pellet injection and associated plasma responses has not yet been completely understood in spite of a variety of such experimental demonstrations in the past three decades. This paper aims to demonstrate the simulation of plasma during pellet injection from the high field side (HFS) comparative to that from the low field side (LFS). It has been proposed from many tokamaks that pellet injection from the high field side can penetrate deeper into the plasma core than that from the low field side due to grad-B effect. Owing to ITER tokamaks having a large minor radius, grad-B effect would be significant when the pellet is injected. This paper aims to investigate the plasma behavior during and after the pellet injection. It is organized as follows : brief description of relevant component of the BALDUR code [1], which is used for the simulation of pellet injection in ITER, including the MMM95 anomalous transport model, a pellet ablation model, a pellet drift model, are presented in section 2; simulation results and discussion are described in section 3;and the conclusion is given in section 4

2. BALDUR code

BALDUR integrated predictive modeling code is a multifluid transport code which solves time-dependent one-dimensional radial diffusion equations for plasma profiles including electron and ion temperatures, deuterium and tritium densities, helium and impurity densities, safety factor, neutrals, and fast ions. These time-evolving profiles are computed in the BALDUR code by combining the effects of many physical processes self-consistently, including the effects of transport, plasma heating, particle influx, boundary conditions, the plasma equilibrium shape, and sawtooth oscillations. Fusion heating and helium ash accumulation are also computed self-consistently. BALDUR simulations have been intensively compared with a wide variety of plasma experimental data, which yield an overall agreement, with about a 10% relative RMS deviation. In BALDUR code, fusion heating power is determined by the nuclear reaction rates together with a Fokker Planck package used to compute the slowing down spectrum of fast alpha particles on each flux surface in the plasma. The fusion heating component of the BALDUR code also computes the rate of the production of thermal helium ions and the rate of the depletion of deuterium and tritium ions within the plasma core.

2.1 Plasma transport model

BALDUR transport code can be described by the linear combination of neoclassical and anomalous transport. The anomalous transport model called MMM95 is a linear combination of theory-based transport models which consists of the Weiland model for the ion temperature gradient (ITG) and trapped electron modes (TEM), the Guzdar–Drake model for drift-resistive ballooning modes, as well as a smaller contribution from kinetic ballooning modes. The Weiland model for drift modes such as ITG and TEM modes usually provides the largest contribution to the MMM95 transport model in most of the plasma core. The Weiland model is derived by linearizing the fluid equations, with magnetic drifts for each plasma species. Eigenvalues and eigenvectors computed from these fluid equations are then used to compute a quasi-linear approximation for the thermal and particle transport fluxes. The Weiland model includes many different physical phenomena such as effects of trapped electrons, $T_i \neq T_e$, impurities, fast ions, and finite β. The resistive ballooning model in MMM95 transport model is based on the 1993 *ExB* drift-resistive ballooning mode model by Guzdar–Drake, in which the transport is proportional to the pressure gradient and collisionality. The contribution from the resistive ballooning model usually dominates the transport near the plasma edge. Finally, the kinetic ballooning model is a semi-empirical model, which usually provides a small contribution to the total diffusivity throughout the plasma, except near the magnetic axis. This will be discussed in Section 3. This model is an approximation to the first ballooning mode stability limit. MMM95 model gives the diffusion coefficients in the following forms:

$$\chi_e = \chi_e^{ITG/TEM} + \chi_e^{RB} + \chi_e^{KB} \qquad (1)$$

$$\chi_i = \chi_i^{NEO} + \chi_i^{ITG/TEM} + \chi_i^{RB} + \chi_i^{KB} \qquad (2)$$

All the anomalous transport contributions to the MMM95 transport model are multiplied by κ^{-4}, where κ is elongation factor, since the models were originally derived for circular plasmas.

2.2. Pellet ablation and pellet drift models

The pellet injection module is integrated with the core transport code to calculate pellet ablation rates and drift displacements in the major-radius direction. A neutral gas shielding model [2] is applied to calculate the ablation rates of the injected pellet during its passage through the background plasma, and the ablation rate is expressed in terms of power functions as follows:

$$\frac{dN}{dt} = 1.12 \times 10^{16} n_e^{0.333} T_e^{1.64} r_p^{1.33} M_i^{-0.333} \qquad (3)$$

where T_e and n_e are the electron temperature in eV and the electron density in cm^{-3}, respectively, r_p is the pellet radius in cm and M_i is the atomic mass of pellet material (M_i = 2 is used for deuterium in this modeling). There exist several models to calculate the pellet drift motions, such as the simplified MHD pellet displacement model [5] and the PRL model [6]. In BALDUR, the NGS [3] scaling model which is based on the grad-B induced pellet[4] is taken into account as a pellet drift model to calculate the drift displacement of the ablated plasma particle:

$$\Delta_{drift} = c_1 v_p^{c_2} r_p^{c_3} n_{e0}^{c_4} T_{e0}^{c_5} \left(\left| \|\theta\| - c_6 \right| + c_7 \right)^{c_8} \times (1-\Lambda)^{c_9} a_0^{C_{10}} R_0^{c_{11}} B_t^{c_{12}} k^{c_{13}} \qquad (4)$$

where n_{e0} and T_{e0} are the electron density and temperature at the plasma core axis, respectively. This drift model scales the drift displacement drift with pellet velocity v_p, injection angle θ, minor radius a_0, major radius R_0, toroidal magnetic field strength at the axis B_t and plasma elongation κ. The impact parameter Λ of the pellet trajectory is normally ignored in the drift calculation. The coefficients and power parameters c_s (s = 1, 2,...,13) in equation (4) are described in [4].

Using the two models described above for the pellet injection module, the deposition of pellet fuel can be estimated with the background plasma profiles. The 1.5 dimensional equilibrium configurations of the background plasma are calculated by an equilibrium solver coupled with the core transport code. In the numerical calculation, cell positions, pellet path lengths between neighboring cells, and magnetic field strength are set as the initial conditions before injecting a pellet. The path and velocity of the pellet that determine its time spent in each cell are assumed to be straight and constant, respectively, during its penetration through the plasma. The density and temperature profiles of the background plasma are self-consistently calculated by coupling the pellet model with the core transport code. Once a pellet enters the plasma, the pellet ablation rate and the drift displacement at each cell are computed by equations (3) and (4). The time evolution of the pellet ablation rate is governed by the fourth-order Runge–Kutta method.

3. Simulation results and discussion

BALDUR code is used to carry out simulations of ITER with the design parameters for full-current standard type I ELMy H-mode discharges (R = 6.2 m, a = 2.0 m, I_p = 15 MA, B_T = 5.3 T, κ_{95} = 1.7, δ_{95} = 0.33, $Z_{eff,\ edge}$ = 1.4, and n_l = 1.0×10^{20} m^{-3}). In these simulations, deuterium pellet is applied. The pellet description here is the deuterium pellet's size of 3 mm with a velocity of 300 m/s and a frequency of 8 Hz. It is assumed in this work that there are only four plasma species considered: two working gas species (deuterium and tritium) and two impurity species (helium and beryllium). It is worth noting that the effect of ELMs is not considered in this work.

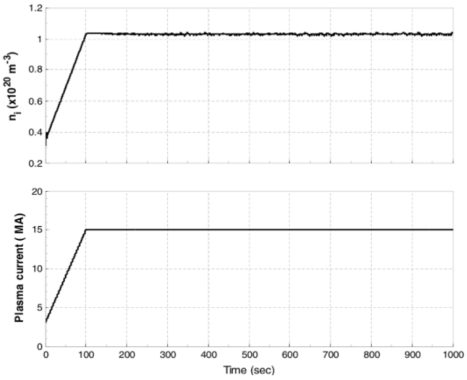

Figure 1: Time evolution of line average density (top) and plasma current (bottom) are shown.

In operation of tokamaks, an auxiliary heating is used, in this simulation 33 MW of NBI and 7 MW of ICRF and 15 MA ohmic heating is applied. For a fueling system in ITER, a gas puff system is used to maintain a density of fuel. In this simulation deuterium and tritium gas is applied with density 1.0×10^{20} m^{-3} (shown in Figure 1)

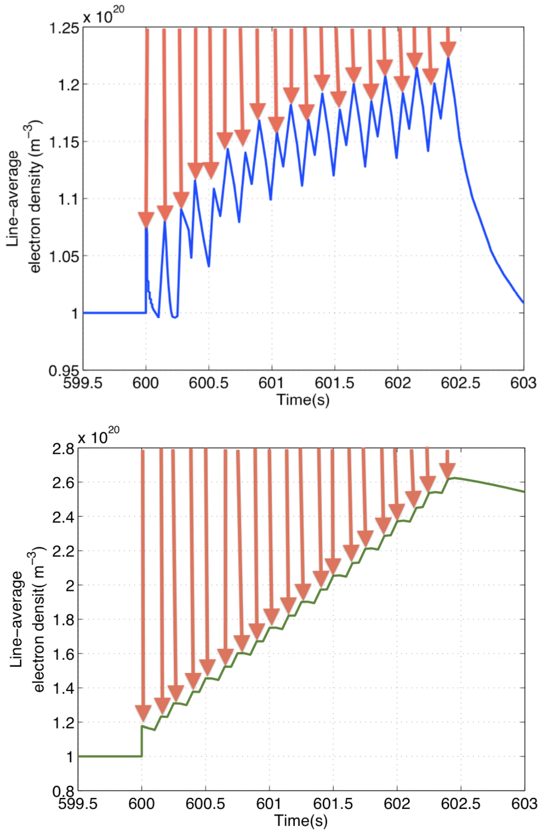

Figure 2: Electron line-average density during the injection of each pellet (indicated by arrow) obtain from the simulations with LFS (top) and HFS pellet injection (bottom).

After the plasma reaches its quasi-steady state for long enough time, 20 consecutive pellets are injected into the plasma. The impact of LFS and HFS injections is studied under the same target plasma condition. Figure 2 shows the time evolutions of line-averaged densities during the periodic injections of deuterium pellets of 3.0 mm in radius at 300 m/s of injection velocity from LFS and HFS, respectively. It can be seen from Figure 2 that line-averaged electron density rapidly increases after each pellet is launched. The ionized particles from the pellet diffuse and eventually drift, both inwardly and outwardly, from their ablated positions depending on the injection direction.

From Figure 2, line-averaged electron densities in the simulation with LFS and HFS pellet injections increased by up to 20% and 160%, respectively after 20 pellets are injected. This indicates that the injection from HFS is more efficient for fueling in the tokamak than the one from LFS, which can be explained by deeper pellet penetration in the HFS injection [6, 7].

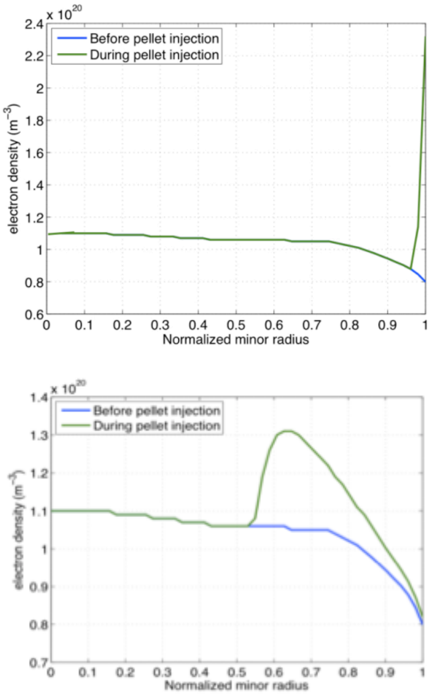

Figure 3: Profiles of electron density of LFS pellet injection (top) and HFS pellet injection (bottom) are shown.

In Figure 3 the profile of the electron density is plotted as a function of normalized minor radius at the line before and during the injection of pellet. It can be seen that the pellet injected from HFS can penetrates deeply into the plasma, reaching *r/a* ∼ 0.6 while the pellet injected from LFS cannot reach below *r/a* ∼ 0.9. LFS injection provides relatively shallow depth of pellet mass deposition and thus is a poor fueling method. These simulation results reasonably agree with the previous experimental results of other reports [6, 7].

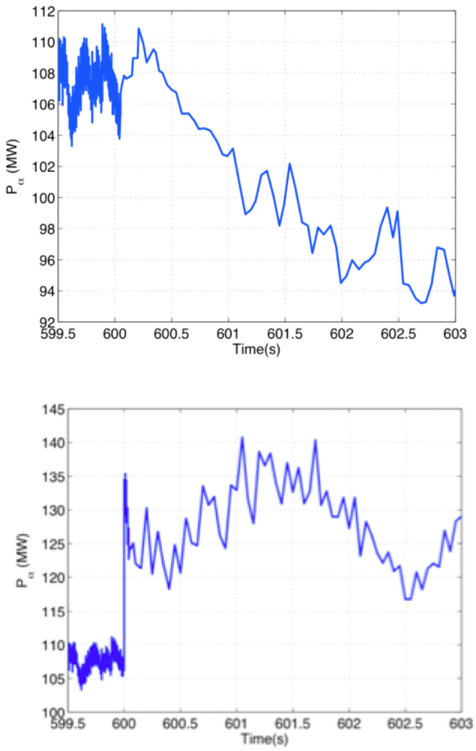

Figure 4: Time evolution of alpha power during pellet injection of LFS pellet injection (top) and HFS pellet injection (bottom) are shown.

The key parameter of ITER performance is fusion Q which is defined as

$$\text{Fusion } Q = \frac{5 \times P_{\alpha,\text{avg}}}{P_{\text{AUX}}}$$

where $P_{\alpha,avg}$ is a time-average of the alpha power and P_{AUX} is the auxiliary heating power (equal to 40 MW for these simulations). In Figure 4 alpha power is increased when pellet is injected from HFS, on the other hand injection from LFS is decreased alpha power, which means the degradation of fusion performance.

6. Conclusions

Simulations of ITER plasma during the injection of pellet are carried out using BALDUR code. It is found that the injection of pellets from the high field side results in a more rapid increase of plasma density than that from the low field side. In addition, the pellets from the high field side can penetrate much deeper into plasma than those from the low field side. Moreover, according to the alpha power results, the pellets from the high field side yield an improved fusion performance while the pellets from the low field side result in degradation of plasma performance.

7. Acknowledgement

This work is supported by Thailand Toray Science Foundation and Thailand National Research University Project.

8. References

[1] B Pégourié (2007). Pellet injection experiments and modelling, Plasma Phys. Control. Fusion 49 (2007) R87.

[2] C. E. Singer, et al (1988) Baldur: A one dimensional plasma transport code, Comput. Phys. Commun, 49 (1988) 399.

[3] P.B. Parks and R.J. Turnbull (1978). Effect of transonic flow in ablation cloud on a solid hydrogen pellet in a plasma, Phys. Fluids 21 (1978) 1735.

[4] F. Köchl, D. Frigione, L. Garzotti, G. Kamelander, H. Nehme, B. Pégourié, et al., Proc. 35th EPS Conf. Plasma Phys. 32D P-4.099, 9–13 June 2008, Hersonissos, Greece, 2008.

[5] P.B. Parks, W.D. Sessions, and L.R. Baylor (2000), Improved core fueling with high field side

pellet injection in the DIII-D tokamak, Phys. Plasmas 7 (2000) 1968.

[6] L.R. Baylor, T.C. Jernigan, P.B. Parks, G. Antar, N.H. Brooks, S.K. Combs, et al.,(2007) Comparison of deuterium pellet injection from different locations on the DIII-D tokamak, Nucl. Fusion 47 (2007) 1598.

[7] P.T. Lang, G.D. Conway, T. Eich, L. Fattorini, O. Gruber, S. Gunter, et al.,(2004) ELM pace making and mitigation by pellet injection in ASDEX Upgrade, Nucl. Fusion 44 (2004) 665.