Formation of Internal Transport Barrier in Tokamak triggered by pellet injection

P. Klaywittaphat[1], N. Poolyarat[2], R. Picha[3], and T. Onjun[1]

[1]*Sirindhorn International Institute of Technology, TU, Pathumthani, Thailand*

[2]*Department of Physics, Thammasat University, Pathumthani, Thailand*

[3]*Thailand Institute of Nuclear Technology, Bangkok, Thailand*

1. Introduction

To obtain a high performance regime in tokamak by reducing of the radial transport in the plasmas is very important for fusion study. The control of a radial electric field, E_r, and its radial derivative, is required in order to significantly reduce the level of turbulence in the plasma. The injection of deuterium pellets has been investigated as a means of affecting various plasma quantities, such as the electron density and the toroidal rotation velocity. In this work, we consider an operation scenario with pellet injection density control and ITB formation in tokamak using the BALDUR simulation code.

2. Integrated predictive modeling code

2.1 Pellet injection model

The pellet injection can be described as two simultaneous processes, which are the pellet ablation and the mass relocation (plasmoid drift). In this work, the neutral gas shielding (NGS) model [1] is used for calculate ablation rate, which an ablation rate of this model can be expressed in terms of a power function as follows:

$$\frac{dN}{dt} = 5.2 \times 10^{16} n_e^{0.333} T_e^{1.64} r_P^{1.333} M_i^{-0.333} \tag{1}$$

where N, n_e (m^{-3}), T_e (eV), r_p (m), and M_i (u) are the number of particles in a pellet, the electron density, the electron temperature, the pellet radius, and the pellet mass, respectively and for the mass relocation model, a scaling model of pellet drift displacement, based on the grad-*B* induced pellet drift [2], has been taken into account couple with pellet ablation rate in the pellet injection module.

2.2. ITB Model

Internal transport barrier is defined as the region in the core plasma where anomalous transport is reduced or quenched, resulting in the steepening of the central plasma profiles [3]. The ITB model using in BALDUR was described in [4], in this model the conventional Bohm term is multiplied by a step function, which is set as zero when the condition is favorable for ITB formation. Hence, the Bohm term is effectively switched off. The expressions for the Bohm and gyroBohm terms are

$$\chi_{gb} = 5 \times 10^{-6} \sqrt{T_e} \left| \frac{\nabla T_e}{B_T^2} \right| \tag{2}$$

$$\chi_B = \chi_{B_0} \times \Theta(-0.14 + s - \frac{1.47\omega_{E\times B}}{\gamma_{ITG}}) \tag{3}$$

$$\chi_{B_0} = 4 \times 10^{-5} R \left| \frac{\nabla(n_e T_e)}{n_e B_\phi} \right| q^2 (\frac{T_e(0.8\rho_{\max}) - T_e(\rho_{\max})}{T_e(\rho_{\max})}) \tag{4}$$

respectively. Note that R is the major radius, B_T is the toroidal magnetic field, q is the safety factor, ϱ is the normalized minor radius, s is the magnetic shear, γ_{ITG} is the linear growth rate, and $\omega_{E\times B}$ is the shearing rate. The value of γ_{ITG} is calculated by

$$v_{th}/qR \tag{5}$$

where v_{th} is the electron thermal velocity. The value of $\omega_{E\times B}$ shearing rate is determined by the Hahm–Burrell model [5, 6] as

$$\omega_{E\times B} = \left| \frac{RB_\theta^2}{B_\varphi} \frac{\partial (E_r / RB_\theta)}{\partial \psi} \right| \tag{6}$$

Here, B_θ is the poloidal magnetic field, ψ is the poloidal flux, and E_r is the radial electric field, which can be calculated by

$$E_r = v_{\phi i} B_\theta - v_{\theta i} B_\phi + \frac{1}{Z_i e n_i} \frac{dp_i}{dr} \tag{7}$$

where Z_i, e, n_i, p_i, V_θ, B_θ and B_ϕ are charge number, electronic charge, ion density, ion pressure, poloidal rotation velocity, poloidal magnetic field and toroidal magnetic field, respectively.

2.3 Toroidal velocity model

In this model, the toroidal velocity results from two different mechanisms: the toroidal momentum due to auxiliary heating and the neoclassical theory, which can be described in the following expression[7]:

$$V_{tor} = V_{neo} + V_{J\times B} + V_{LH} \tag{8}$$

3. Simulation results

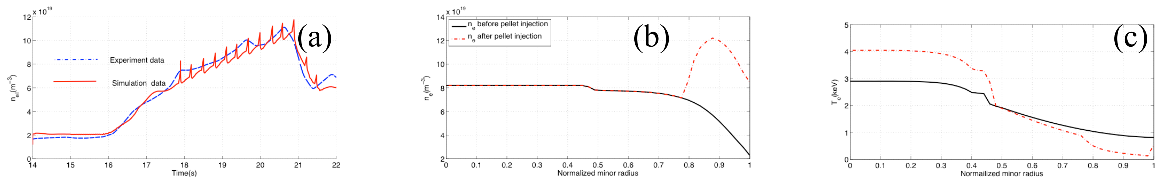

Figure 1 a) time evolution of plasma line average density b) plasma electron density as a function of Normalized Minor radius c) plasma electron temperature as a function of Normalized Minor radius.

In this work, density control and internal transport barrier (ITB) formation due to pellet injection have been simulated in tokamak using 1.5D BALDUR integrated predictive modeling code with a combination of NLCASS neoclassical transport and Mixed Bohm/gyro-Bohm turbulent transport model. The pellet ablation is described by NGS model, in which the effect of grad-B drift is included. Figure 1 (a) shows the time evolution of plasma line average density, in which a series of pellets is injected at 17.87 sec.. The simulation agrees well with experiment data JET 53212 and pellet injection could provide a high target plasma density. A peak density profile is obtained after pellet injection in Figure (b) and the plasma temperature is decreased in the region that the pellets ablate, shown in Figure (c). Noting that 2 mm pellets are injected from HFS with velocity of 100 m/s. The detail of ablation process and the plasma behavior can be seen in [8].

3.1 ITB formation

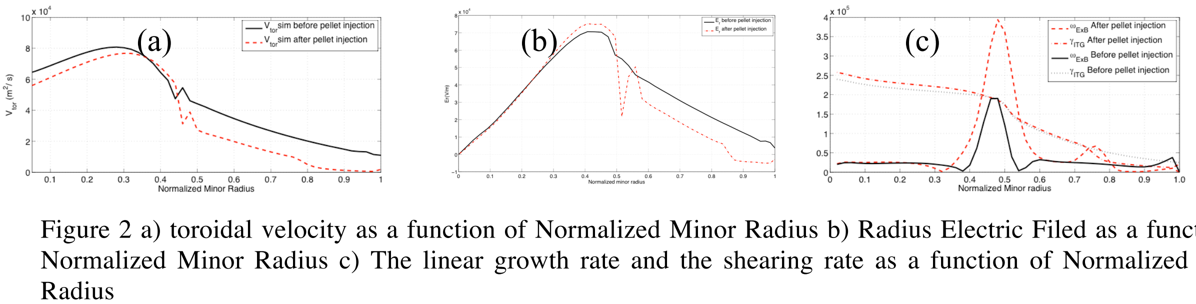

Figure 2 a) toroidal velocity as a function of Normalized Minor Radius b) Radius Electric Filed as a function of Normalized Minor Radius c) The linear growth rate and the shearing rate as a function of Normalized Minor Radius

Figure2 a) show the reduction in the toroidal rotation speed due to the increase of plasma density [9] (Figure 1 a)) in causes a decrease in the radial electric field in Figure 2 b) as can be seen from equation (7). In this simulation, ITB formation is determined by two parameters, $\omega_{E\times B}$ and γ_{ITG}. The γ_{ITG} is reduced in the region which pellet is ablation (plasma temperature is reduced) can be seen in Figure 1 c). Nothing that the suppression occurs when $\omega_{E\times B}$ exceeds γ_{ITG} and with the criteria in equation (3) γ_{ITG} is the linear growth rate, and $\omega_{E\times B}$ is the shearing rate. The value of γ_{ITG} is calculated by equation (5) and The value of $\omega_{E\times B}$ shearing rate is determined by equation (6) the result of $\omega_{E\times B}$ and γ_{ITG} before and after pellet injection is shown in Figure 2 c),.which can used determine location of ITBs.

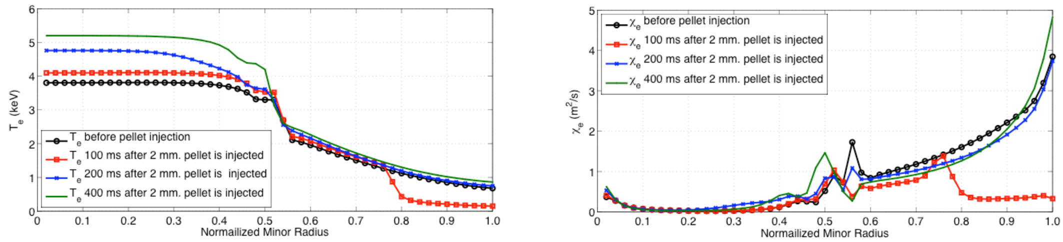

Figure 3 a) The time evolution of plasma temperature as a function of Normalized Minor Radius b) The time evolution of plasma electron thermal diffusivities as a function of Normalized Minor Radius

The time evolution of plasma temperature and electron thermal diffusivities, $\chi_{i,e}$, given by the mixed Bohm/gyro-Bohm model are shown in Figure 3a) and b) the reduced of electron thermal diffusivities according to a criterion which takes into account the magnetic shear s and the ratio $\omega_{E\times B}/\gamma_{ITG}$ between the shear of the $E \times B$ velocity and the growth rate of the ITG modes. It has been observed on a statistical basis [10] that in general a barrier is formed where the condition $z = -0.14+s-1.47\omega_{E\times B}/\gamma_{ITG} < 0$ is satisfied, for that reason the Bohm diffusion term in the mixed Bohm/gyro-Bohm transport model is multiplied by $\Theta\ (z)$, where Θ is the Heaviside step function. It is worth noting that the expression used in this work for γ_{ITG} has the simplified form $\gamma_{ITG} = v_{th,i}/qR$, where $v_{th,i}$ is the ion thermal velocity.The ITBs located at 0.75 and 0.5 Normalized minor radius can be used Figure 2 c). to find the location of ITBs

3.2 Sensibility analysis

In the previous section, we show that pellet injection could modify E_r and can be use to formation of ITB. Here, we consider an operation scenario with different pellet radius and velocity to see the relation of pellet parameter with ITB formation.

3.2.1 Vary pellet radius

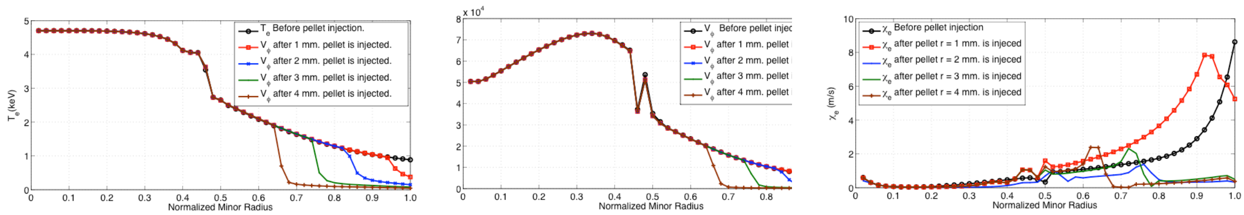

Figure 4 a) a) The time evolution of plasma temperature as a function of Normalized Minor Radius b) The time evolution of toroidal velocity as a function of Normalized Minor Radius c) The time evolution of plasma electron thermal diffusivities as a function of Normalized Minor Radius.

The pellet is injected with velocity 100 m/s, different radius 1mm., 2 mm., 3 mm., 4 mm., to see the effect of pellet size with the ITB formation the simulation show that small pellet with radius 1 mm. cannot penetrate deeply to the plasma core or we can say that deep pellet penetration plays an important role in ITB formation, with this reason [11] HFS pellet injection is considerably effective as a technique for confinement improvement, however a very small pellet cannot reduce the electron diffusivity even is injected from HFS.

3.2.2 Vary pellet velocity

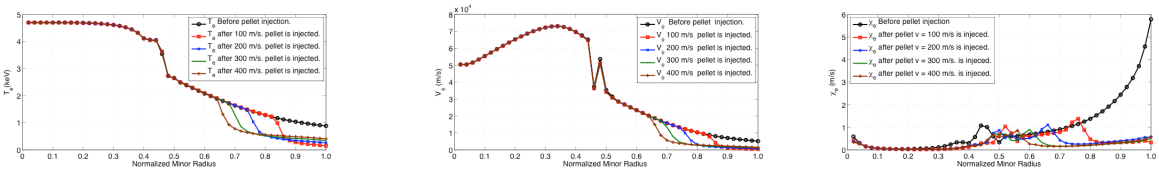

Figure 5 a) a) The time evolution of plasma temperature as a function of Normalized Minor Radius b) The time evolution of toroidal velocity as a function of Normalized Minor Radius c) The time evolution of plasma electron thermal diffusivities as a function of Normalized Minor Radius.

The pellet is injected with 2 mm., different velocity 100 m/s., 200 m/s., 300 m/s., 400 m/s., to see the effect of pellet velocity with the ITB formation the simulation show that all of pellet with radius 2 mm. can decreased the electron diffusivity and high velocity pellet (500 m/s) can penetrate deeply to the plasma core or we can say that deep pellet penetration plays an important role in ITB formation, with this reason [11] we can control the ITB formation or modify E_r with the pellet parameter that have high effective for confinement improvement.

4. Conclusions

The simulation pellet injection using 1.5D BALDUR integrated predictive modeling code with a combination of NLCASS neoclassical transport and Mixed Bohm/gyro-Bohm turbulent transport model and the pellet injection model shown that deuterium pellets can be used and able to significantly reduce the toroidal rotation velocity of the plasma where the pellet mass is ablation and deposited. The reduction in toroidal velocity leads to a local reduction in E_r through the radial force balance and hence a change in the shear damping rate. This capability to change E_r makes it desirable to use pellet injection to actively control the E_r profile at specific radii for the formation of transport barriers.

Reference

[1] Parks P.B., Turnbull R. J. *Phys. Fluids*. 1978. V. 21. P. 1735.
[2] Kochl F., Frigione D., Garzotti L., Kamelander G., Ne hme H., Pegourie B., and JET EFDA contributors *Proc. 35th EPS Conf. Plasma Phys*. Hersonissos, Greece. 2008. 32D, P 4.099.
[3] J.W. Connor et al 2004 *Nucl. Fusion* 44 R1
[4] B. Chatthong et al 2010 *Nucl. Fusion* 50 064009
[5] Pankin A.Y. et al 2005 *Plasma Phys. Control Fusion* 47 483
[6] Zhu P. et al 2000 *Phys. Plasmas* 7 2898
[7] T. Onjun et al., IAEA-FEC 2014.
[8] P. Klaywittaphat ., T.Onjun *Plasma Physics Reports* June 2012, Volume 38, Issue 6, pp 496-502
[9] B.P. Duval et al 1992 *Nucl. Fusion* 32 1405
[10] T J J Tala et al 2001 *Plasma Phys. Control. Fusion* 43 507
[11] Y Higashiyama et al 2008 *J. Phys.: Conf. Ser*. 123 012032