Impact of Toroidal Flow on ITB *H*-Mode Plasma Performance in Fusion Tokamak

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Abstract

A self-consistent 1.5D integrated predictive modeling code BALDUR is used to predict plasma performance of standard *H*-mode scenario in International Thermonuclear Tokamak Reactor (ITER). The core transport model used are NCLASS for calculation of neoclassical transport coefficients and semi-empirical Mixed Bohm/gyro-Bohm (Mixed B/gB) with inclusion of ITB effects for calculation of anomalous transport coefficients. In addition, the boundary condition is taken to be at the top of pedestal where its values are described using a theory-based pedestal model which is based on magnetic and flow shear stabilization pedestal width scaling and an infinite-n ballooning pressure gradient model. Theoretically, ITB is formed as a result of suppression in anomalous transport due to the effects of ω_{ExB} flow shear which can be computed from a combination of toroidal flow, poloidal flow and pressure gradient effects. In this work, an impact of toroidal flow is studied with respect to ITB formation, plasma profiles and plasma performance. The toroidal velocity is estimated using an empirical approach model in which it is directly proportional to local ion temperature. Time evolution of plasma profiles for standard type I ELMy *H*-mode ITER are simulated to study the impact of toroidal flow. Simulation results show that the central ion temperature, total fusion power output and alpha power are approximately 50 keV, 800 MW and 220 MW, respectively with evidence of ITB formation when toroidal rotation exists. In addition, the effect of toroidal velocity seems very crucial because it significantly enhances plasma performance.

***Keywords**:* Tokamak, Toroidal Velocity, BALDUR, Internal Transport Barrier

1. Introduction

Magnetic confinement fusion device based on Tokamak device is the most advance experimental machine in term of nuclear fusion energy production. ITER is an international collaboration with goals to demonstrate scientific and engineering feasibilities of nuclear fusion energy[1]. The machine will be ready for experiment around 2020 aiming to be a prototype reactor of electrical power production. Production of significant fusion reactions inside a tokamak requires high plasma temperature and density, as well as a sufficient energy confinement time. Since the high confinement mode (*H*-mode) plasmas in tokamaks generally provide high temperature and excellent energy confinement time, burning fusion experiment like ITER is designed to operate in the *H*-mode regime. It is commonly accepted that the performance of an *H*-mode discharge can be further improved with the formation of a transport barrier inside the plasma, called an internal transport barrier (ITB) [2].

The ω_{ExB} flow shear as well as magnetic shear *s* play significant roles in formation of ITB because they are the main mechanisms for the reduction of anomalous transport in the core of the plasma having low or negative magnetic shear [3]. Theoretically, the calculation of ω_{ExB} requires the toroidal velocity (v_{tor}) as one of the ingredients. The fusion research community is still attempting to calculate toroidal rotation. B. Chatthong has proposed an empirical scaling to estimate toroidal velocity that is simply directly proportional to local ion temperature [4-5]. However, it is expected that in such a large machine like ITER it would be quite difficult to rotate the plasma using external torque. The only possibility is to rely on intrinsic toroidal rotations such as rotation driven by temperature or density gradients. The mechanism is still under study so there is uncertainty to which extent the machine can rotate. This work focuses on the study of impact of toroidal flow with respect to ITER performance by using numerical simulations.

In this work, an effect of toroidal rotation in ITER will be studied and analyzed by using a 1.5D BALDUR integrated predictive modeling code to simulate the time-evolution profiles of density and temperature of electron and ion. The ETB model used in this paper is based on Ref. [6]. In this model, a transition to *H*-mode is developed according to a pedestal model, where pedestal temperature is explained using the theory based pedestal width model combining with pressure gradient limits by ballooning mode instability. The model for ITB used in this paper is a semi-empirical Mixed Bohm/gyroBohm (Mixed B/gB) core transport model which proposes that formation of ITB is caused by the suppression in anomalous transport due to ω_{ExB} flow shear and magnetic shear.

The paper is organized as follows: an introduction to BALDUR code along with important models used are presented in section 2; results of simulation and discussion are described in section 3; and a summary is given in section 4.

2. Simulation Procedures

All simulations in this works are carried out using BALDUR integrated predictive modeling code [7], which is a time-dependent one and half dimensional transport modeling code which is used to compute many physical quantities in tokamaks. The code itself simultaneously solves three diffusion equations of number density, energy density and poloidal magnetic field. As a result, it computes the plasma profiles such as time-evolution of electron density, electron and ion temperatures. Moreover, it can be used to compute other physical quantities like impurity and hydrogen densities, magnetic *q* and other gas densities. BALDUR code self-consistently computes these profiles by mixing many physical processes together in form of modules for example, transport, plasma heating, particle flux, boundary conditions, and sawtooth oscillations modules.

2.1. ITB model

As mentioned previously, it is assumed that the suppression of core anomalous transport due to ω_{ExB} flow shear and magnetic shear causes ITB formations [8]. This ω_{ExB} is calculated according to Hahm-Burrell model [3],

$$\omega_{ExB} = \left| \frac{RB_\theta^2}{B_T} \frac{\partial (E_r / RB_\theta)}{\partial \psi} \right|, \quad (1)$$

where R is the major radius, B_θ and B_T are the poloidal and toroidal magnetic fields, respectively, Ψ is the poloidal flux, and E_r is the radial electric field, which can be calculated from the force balance equation:

$$E_r = \frac{1}{Zen_i} \frac{\partial p_i}{\partial r} - v_\theta B_T + v_{tor} B_\theta \quad (2)$$

With $\frac{\partial p_i}{\partial r}$ is the pressure gradient, v_θ and v_{tor} are the poloidal and toroidal velocities, respectively, n_i is the ion density, Z is the ion charge number and e is the elementary charge. The calculation of toroidal velocity is discussed in the next section.

ITB formation and its dynamics are modelled through a semi-empirical core transport model called mixed Bohm/gyro-Bohm (Mixed B/gB) [9]. The Mixed B/gB transport model includes ITB effect by having a cut-off in Bohm term which is a step function of flow shear and magnetic shear. Here we discuss briefly on the details of the model, first of all the χ_e electron diffusivity and χ_i ion diffusivity, used to calculate temperature, are calculated as follows:

$$\chi_e = 1.0\chi_{gB} + 2.0\chi_B, \quad (3)$$

$$\chi_i = 0.5\chi_{gB} + 4.0\chi_B, \quad (4)$$

where χ_{gB} is the gyro-Bohm contribution and χ_B is the Bohm contribution for the Mixed B/gB model. They can be calculated from:

$$\chi_{gB} = 5\times10^{-6}\sqrt{T_e}\left|\frac{\nabla T_e}{B_T^2}\right|, \quad (5)$$

$$\chi_B = \chi_{B_0} \times \Theta\left(-0.14 + s - \frac{1.47\omega_{ExB}}{\gamma_{ITG}}\right), \quad (6)$$

With

$$\chi_{B_0} = 4\text{x}10^{-5} R \left|\frac{\nabla(n_e T_e)}{n_e B_T}\right| q^2 \left(\frac{T_e(0.8\rho_{max}) - T_e(\rho_{max})}{T_e(\rho_{max})}\right), \quad (7)$$

where ρ is normalized minor radius, T_e is the local electron temperature measured in keV, γ_{ITG} is the linear growth rate, and n_e is the local electron density. The linear growth rate γ_{ITG} is equal to v_{th}/qR, where v_{th} is the electron thermal velocity. For density simulations, note that here it is assumed that D_H particle diffusivity is the same as D_Z impurity diffusivity and they can be calculated as follows:

$$D_H = D_Z = (0.3 + 0.7\rho)\frac{\chi_e \chi_i}{\chi_e + \chi_i}. \quad (8)$$

2.2. Toroidal velocity model

The model for predicting toroidal velocity (v_{tor}) is assumed to be linearly proportional to local ion temperature (T_i) [4-5, 10] as follows:

$$v_{tor}[m/s] = cT_i[keV]. \quad (9)$$

The proportional constants c are varied according to statistical analysis when comparing the predicted values with experimental values from 10 JET discharges. These values are c_{med} = $1.43\text{x}10^4$ corresponding to the mean value of the distribution, c_{max} = $0.93\text{x}10^4$ corresponding to the value at one standard deviation below the mean, and c_{max} = $1.78\text{x}10^4$ corresponding to the value at one standard deviation above the mean. For details discussion on this please see Ref.

[4]. This toroidal velocity model was implemented in the BALDUR predictive integrated modeling codes and the simulations of 10 JET optimized shear discharges yield agreement with the average RMSs less than 30% for temperatures and density profiles and 40% for toroidal velocity profiles[4]. Note that this model is applied only in the *H*-mode phase while it is turned off during *L*-mode phase where no rotation is assumed.

2.3. ETB model

The plasma makes a transition from *L* to *H* mode with a development of an ETB which is also called a pedestal. For these simulations, the boundary condition of the plasma is set to be at the top of pedestal [11]. The pedestal region is located at the steep gradient right near the edge of the plasma. It is assumed that the pressure gradient ($\partial p/\partial r$) within this region is constant so the pedestal temperature can be calculated as follows [6]:

$$T_{ped} = \frac{1}{2kn_{ped}} \Delta \left| \frac{\partial p}{\partial r} \right|, \qquad (10)$$

where n_{ped} (m^{-3}) is pedestal density, k is the Boltzmann's constant, and Δ is the pedestal width. So in order to calculate pedestal temperature one must obtain pedestal density, pedestal width and pedestal gradient. With the pressure gradient based on ballooning mode and the pedestal width based on magnetic and flow shear stabilization, the temperature at the top of the pedestal can be estimated as

$$T_{ped} = C_1^2 \left(\left(\frac{4.57x10^{-3}}{4\mu_0 (1.6022x10^{-16})} \right)^2 \left(\frac{B_T^2}{q^4} \right) \left(\frac{A_H}{R^2} \right) \left(\frac{\alpha_c}{n_{ped}} \right)^2 s^4 \right). \qquad (11)$$

The constant C_1 is chosen to minimize the RMSD with 533 experimental data points from four large tokamaks obtained from ITPA pedestal database and from Ref. [6], it is found to be 2.42. In this work, n_{ped} is calculated from experimental data (all JET discharges), while the pressure gradient and width of the pedestal region can be estimated as described below.

The pedestal density, n_{ped}, is obtained by an empirical model which is based on the fact that n_{ped} is a fraction of line average density, n_l, that can be taken from experimental data, as shown:

$$n_{ped} = 0.71 n_l . \qquad (12)$$

This pedestal density empirical model agrees with the data from the International Tokamak Physics Activity (ITPA) pedestal database with 12% RMSE [12].

3. Simulation Results and Discussion

Standard type I ELMy *H*-mode ITER simulations are carried out in this study using BALDUR integrated predictive modeling code. The design parameters are shown in table 1.

Table. 1 Engineering design parameters for ITER

Parameters	***unit***	***Full-current***
R	m	6.2
a	m	2.0
I_p	MA	15.0
B_T	T	5.3
κ	-	1.7
δ	-	0.33
RF	MW	7.0
NBI	MW	33.0
n_l	m^{-3}	$1.0x10^{20}$

3.1. Impact of toroidal rotation on ITER

Figure 1 illustrates plasma profiles of ITER for ion temperature (T_i) (top left), electron temperature (T_e) (top right), deuterium density (n_D) (middle left), tritium density (n_T) (middle right), beryllium density (n_{BE}) (bottom left), and helium density (n_{HE}) (bottom right) as a function of plasma major radius at the time of 2,900 seconds. Note that at this time, plasma reaches quasi-steady state condition.

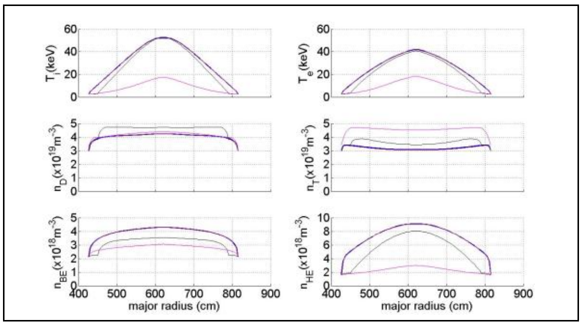

Fig. 1 Plasma profiles at steady state (t=2900 s): red line (c_{med}), blue line (c_{max}), black line (c_{min}), and pink line (no v_{tor})

In Figure 1, the red line represents simulation result using the toroidal flow model according to eq. (1), the blue and black lines represent the similar model with different proportional constants according to maximum and minimum values for the standard deviation from value in eq. (1), please see section 2.2 for discussion on these values. The pink line stands for simulations with no toroidal flow included. Evidently, it can be easily observed that both the temperature profiles are much higher when toroidal flow is included. The values are roughly the same for different proportional constants used implying that there is not so much sensitivity in the constant value. This result agrees with theoretical and experimental understanding that the shear flow is the suppression mechanism for reduction of transport. When there is no toroidal flow, the heat can transport out much easier leading to having lower temperature profiles.

It can also be seen that both temperatures are high near the center and lower toward the edge, while the densities of all species remain roughly the same throughout the plasma except Helium density in ITB simulation which accumulates more near plasma center. The temperature profiles indicate the existence of ITB formations which is shown by significant improvements of plasma temperature over those results without ITB. Evidently, when ITB effects are included in the run, the central temperature for both ion and electron increase significantly, from 12 keV to 49 keV and from 13 keV to 39 keV, respectively. Yet, the temperatures near the edge of plasma remain approximately the same. This implies that ITB formations result in better plasma confinement for the plasma temperature, hence energy. For other profiles, impurities (beryllium and helium) accumulates more in the plasma core for simulation with ITB included, which means that ITB formations also prevent transport of impurity species. Beryllium is an impurity from the first wall outside of the plasma, the concentration is slightly higher in plasma with the presence of ITB run as expected because there are more beryllium trapped in the core. The situation is similar for helium species, except that the concentration in the run with ITB effect is much higher than the run without ITB effect.

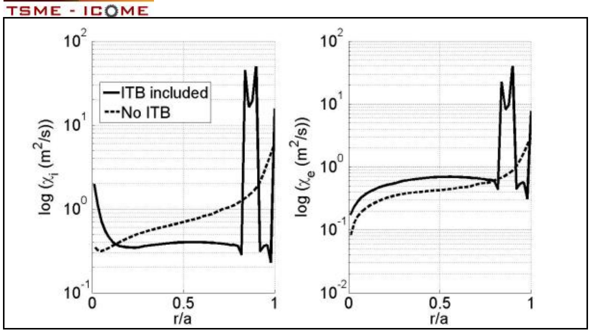

Fig. 2 diffusion coefficient profiles during steady state for ion (left) and electron (right)

To demonstrate the ITB region, χ_i(ion diffusivity) and χ_e(electron diffusivity) are plotted as shown in Fig. 2. Both profiles reach similar conclusion that two ITB regions are formed, the first one extends from plasma center to *r/a* about 0.82, and the second one, much smaller region, is a bit further out toward plasma edge. Note that the diffusivity for ion are higher than that of electron in non ITB region but lower in ITB region, this corresponds to ion temperature being slightly higher than electron temperature.

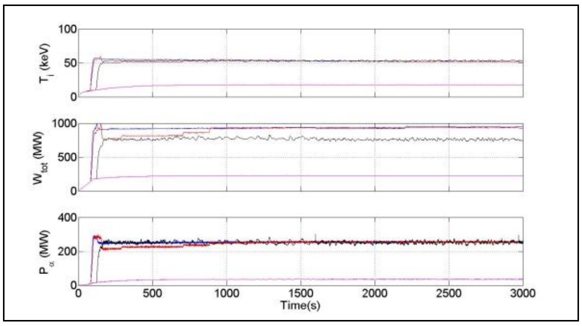

Fig. 3 Time evolution profiles of plasma temperature, total energy and alpha power: red line (c_{med}), blue line (c_{max}), black line (c_{min}), and pink line (no v_{tor}).

As stated earlier, transport barriers improve plasma energy confinement and power production, which mean the fusion reaction rate is enhanced as well. This is confirmed by Fig. 3 in the bottom panel which shows time-evolution profile of alpha power. During quasi-steady state, the alpha power of ITB simulation is almost 10 times higher than that when no ITB formed. These alpha particles have charges so they are trapped with the magnetic field inside the tokamak. The energy is then used to reheat the plasma, transferring back to deuterium and tritium by way of collision. More alpha power means more alpha particles produced from fusion reaction so more helium density is observed. This result is further confirmed by deuterium and tritium densities plots. Since both species are starting particles of fusion reaction, higher reaction rate means more fuel burn and hence less density accumulated for both. As observed in Fig. 1, ITB simulation shows less deuterium and tritium concentrations.

In summary, to see what is happening at the center of the plasma, the central ion temperature is plotted as functions of time (Fig. 3) along with total fusion power output and alpha power of the plasma profile plots. As expected, they are higher in simulations with ITB formation. During steady state, ion temperature reaches on value of 50 keV, the total power output of the plasma is slightly lower than 800 MW, and the alpha power is around 220 MW.

4. Conclusions

Self-consistent simulations of ITER with the presence of both ITB and ETB are done using the BALDUR code. The combination of Mixed B/gB transport model together with pedestal model based on magnetic and flow shear stabilization pedestal width scaling and an infinite-n ballooning pressure gradient model, and with empirical toroidal velocity model based on local ion temperature, is used to simulate the time-evolution profiles of plasma temperature, density, and current for ITER standard type I Elmy *H*-mode operation. The presence of toroidal flow is very crucial because it results in great improvement in plasma energy confinement over standard run without the flow. The impact of toroidal velocity causes both ion and electron temperatures to be higher, especially at the center. However, it only slightly affects the densities of deuterium, tritium, and beryllium. Helium concentration is higher in simulations with toroidal velocity because of larger fusion reaction rate. Therefore, this is a critical issue for ITER because of the machine's size it will be difficult to drive the rotation using external torque. Therefore, most of rotation must come from intrinsic flow of the plasma.

5. Acknowledgement

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6. References

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