การศึกษาประสิทธิภาพของเครื่องโทคาแมคอีเทอร์ โดยใช้แบบจำลองทางคณิตศาสตร์แบบรวม

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บทคัดย่อ

พลังงานนิวเคลียร์ฟิวชันเกิดจากการรวมตัวของธาตุที่มีน้ำหนักเบา เช่น ดิวเทอร์เรียมและตริเตรียม กลายเป็นธาตุที่มีน้ำหนักมากขึ้นเช่น ฮีเลียม เครื่องควบคุมการเกิดปฏิกิริยานิวเคลียร์ฟิวชันโดยใช้สนามแม่เหล็กที่เรียกว่า เครื่องโทคาแมค นั้นสามารถที่จะควบคุมการเกิดเกิดปฏิกิริยานิวเคลียร์ฟิวชันได้อย่างต่อเนื่อง การศึกษาและวิจัยทางด้านพลังงานนิวเคลียร์ฟิวชันโดยใช้เครื่องโทคาแมคได้เกิดขึ้นในหลายประเทศทั่วโลก และมีความก้าวหน้าอย่างต่อเนื่อง โครงการระดับนานาชาติที่ชื่อว่า โครงการอีเทอร์ เป็นก้าวที่สำคัญในการพัฒนาพลังงานนิวเคลียร์ฟิวชันมาเป็นพลังงานในอนาคต ในการวิจัยนี้ได้ทำนายประสิทธิภาพของการเกิดปฏิกิริยานิวเคลียร์ฟิวชันโดยใช้แบบจำลองทางคณิตศาสตร์แบบรวม โดยจะทำนายประสิทธิภาพของการเกิดปฏิกิริยานิวเคลียร์ฟิวชันในสภาวะที่ถูกออกแบบไว้ นอกจากนี้จะศึกษาผลกระทบต่อประสิทธิภาพของการเกิดปฏิกิริยานิวเคลียร์ฟิวชันจากการเปลี่ยนค่าของพลาสมาเช่น ความหนาแน่นของพลาสมาและพลังงานที่ให้ เป็นต้น

คำสำคัญ: พลาสมา, เอชโมด, โทคาแมค, นิวเคลียร์ฟิวชัน

Self-consistent predictions of ITER with integrated predictive modeling code

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Abstract

Self-consistent modeling of the International Thermonuclear Experimental Reactor (ITER) has been carried out using the BALDUR integrated predictive transport modeling code. In these simulations, the plasma core transport is described by the combination of anomalous and neoclassical transports. An anomalous transport is calculated either using the Mixed Bohm/gyro-Bohm (Mixed B/gB) model or using the Multi-mode (MMM95) model; while a neoclassical transport is computed by the NCLASS model. The boundary conditions used in these simulations are prescribed by using the predictions of a pedestal temperature model based on magnetic and flow stabilization width scaling and an infinite-n ballooning mode limit [T. Onjun *et al*. 2002 *Phys. Plasma*s **12** 5018]. It is found that the simulations carried out using the MMM95 transport model yield more optimistic performance of ITER than those using the Mixed B/gB transport model. When the MMM95 model is employed for the core transport, the fusion Q of 6.2 (with the lower and upper bound of 5.4 to 6.8, respectively) can be obtained. For the simulation carried out using the Mixed B/gB model, the simulation yields a lower fusion Q of 2.3 (with the lower and upper bound of 0.9 to 3.7, respectively).

Keywords: Plasma; H-mode; ELMs; Pedestal; Modeling; ITER

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) is an international collaborative effort with the aim to demonstrate the scientific and technological feasibility of fusion energy using the magnetic confinement fusion concept [1]. Because of good energy confinement and acceptable particle transport rates for impurity control in high confinement mode (*H*-mode) plasma, *H*-mode is one of the possible scenarios that will be used in burning plasma experiments like ITER. It is interesting to know the performance of ITER with the standard *H*-mode scenario, which will lead to a way to optimize or to improve the performance in order to have a better chance of success.

In a previous ITER study by G. Bateman and his co-workers [2], the BALDUR integrated predictive modeling code with the Multi-mode (MMM95) anomalous transport model together with neoclassical transport, calculated using the Cheng-Hinton neoclassical model [3], was used to predict the plasma core profiles of ITER and, consequently, the performance of ITER. In that work, the boundary conditions, which were taken to be at the top of the pedestal, were obtained from a predictive pedestal model based on magnetic and flow shear stabilization width model and first stability regime of infinite-*n* ballooning modes pressure gradient model [4]. It is also assumed that 24 MW of the RF heating power goes to thermal ions and 16 MW goes to thermal electrons. Fast ions resulting from auxiliary heating are not considered. The heating produced by fusion reactions and the resulting fast alpha particles are added to the ohmic and auxiliary heating. The performance of ITER was evaluated in term of fusion *Q*. Note that fusion *Q* is the ratio of a fusion power with an applied heating power. An optimistic performance of ITER was obtained in that simulation with fusion *Q* of 10.6. In the later ITER study by T. Onjun and his co-workers [5], ITER simulations were carried out using the JETTO integrated predictive modeling code with the Mixed Bogm/gyro-Bohm (Mixed B/gB) anomalous transport model with NCLASS neoclassical transport [6]. In addition, the combination of 33 MW of NBI heating power and 7 MW RF heating power was used. An optimistic performance of ITER with fusion *Q* of 16.6 was found. It was also found that the JETTO code predicts the strong edge pressure gradient, which is in the second stability regime of ballooning modes. In other words, the values at the top of the pedestal in the JETTO simulations are higher than those used in the BALDUR simulations.

In this work, the BALDUR integrated predictive modeling code is used to simulate the core profiles in ITER standard *H*-mode scenario. Two different core transport models — the Mixed B/gB core transport model (Mixed B/gB) [7] or the multimode core transport model (MMM95) [8] — are employed in the BALDUR code to carry out simulations of ITER. Then, the results will be compared. In addition, the neoclassical transport, calculated using the NCLASS module, is added to the core transport to fully describe the transport in the plasma core. In addition, 40 MW of heating power used in these simulations is divided into 33 MW of NBI heating power and 7 MW of RF heating power. This paper is organized as follows: Brief descriptions of a BALDUR integrated predictive modeling code, core transport models, and pedestal model are given in Sec.2. The ITER prediction using a BALDUR integrated predictive modeling code is described in Sec. 3, while conclusions are given in Sec. 4.

2. BALDUR integrated predictive modeling code

The BALDUR integrated predictive modeling code [9] is used to compute the time evolution of plasma profiles including electron and ion temperatures, deuterium and tritium densities, helium and impurity densities, magnetic q, neutrals, and fast ions. These time-evolving profiles are computed in the BALDUR integrated predictive modeling 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 computed self-consistently. The BALDUR simulations have been intensively compared against various plasma experiments, which yield an over all agreement of 10% RMS deviation [10, 11]. In BALDUR code, fusion heating power is determined using the nuclear reaction rates and a Fokker Planck package to compute the slowing down spectrum of fast alpha particles on each flux surface in the plasma [9]. The fusion heating component of the BALDUR code also computes the rate of production of thermal helium ions and the rate of depletion of deuterium and tritium ions within the plasma core. In this work, two core transport models in BALDUR will be used to carry out simulations of ITER. The brief details of these transport models are described below.

2.1 Mixed B/gB core transport model

The Mixed B/gB core transport model [7] is an empirical transport model. It was originally a local transport model with Bohm scaling. A transport model is said to be "local" when the transport fluxes (such as heat and particle fluxes) depend entirely on local plasma properties (such as temperatures, densities, and their gradients). A transport model is said to have "Bohm" scaling when the transport diffusivities are proportional to the gyro-radius times thermal velocity over a plasma linear dimension such as major radius. Transport diffusivities in models with Bohm scaling are also functions of the profile shapes (characterized by normalized gradients) and other plasma parameters such as magnetic q, which are all assumed to be held fixed in systematic scans in which only the gyro-radius is changed relative to plasma dimensions.

The original JET model was subsequently extended to describe ion transport, and a gyro-Bohm term was added in order for simulations to be able to match data from smaller tokamaks as well as data from larger machines. A transport model is said to have "gyro-Bohm" scaling when the transport diffusivities are proportional to the square of the gyroradius times thermal velocity over the square of the plasma linear dimension. The Bohm contribution to the JET model usually dominates over most of the radial extent of the plasma. The gyro-Bohm contribution usually makes its largest contribution in the deep core of the plasma and plays a significant role only in smaller tokamaks with relatively low power and low magnetic field.

2.2 Multimode core transport model

The MMM95 model [8] 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 quasilinear 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 b. The resistive ballooning model in MMM95 transport model is based on the 1993 **E**x**B** 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 model is an approximation to the first ballooning mode stability limit. All the anomalous transport contributions to the MMM95 transport model are multiplied by κ^{-4}, since the models were originally derived for circular plasmas.

2.3 Pedestal Models

A model used to predict the temperature and density at the top of the pedestal of type I ELMy H-mode plasmas is described in this section. This model is used in this paper to provide boundary conditions in the integrated predictive simulations of burning plasma experiments. The width of the temperature pedestal, Δ, is assumed to be determined by a combination of magnetic and flow shear stabilization of drift modes [12],

$$\Delta = C_W \rho s^2 , \tag{1}$$

where C_W is a constant, s is the magnetic shear and ρ is the ion gyro-radius at the inner edge of the steep gradient region of the pedestal. In the steep gradient region of the pedestal, the pressure gradient is assumed to be constant and to be limited by the ideal, short wavelength, MHD ballooning mode limit. This first stability ballooning mode limit is approximated by

$$\alpha_c = 0.4s\left(1+\kappa_{95}^2\left(1+5\delta_{95}^2\right)\right). \tag{2}$$

where κ_{95} and δ_{95} are the elongation and triangularity at the 95% magnetic surface, respectively.

The pedestal pressure is taken to be the product of the pedestal width and the critical pressure gradient. After some algebra, the following expression is obtained for the pedestal temperature, T_{ped},:

$$T_{ped} = 0.323 C_W^2 \left(\frac{B}{q^2}\right)^2 \left(\frac{A_H}{R^2}\right)\left(\frac{\alpha_c}{n_{ped,19}}\right)^2 s^4 , \tag{3}$$

where B is the toroidal magnetic field, q is the safety factor, A_H is the average hydrogenic ion mass in atomic mass units, R is the major radius and $n_{ped,19}$ is the electron density at the top of the pedestal in units of 10^{19} m^{-3}. In Ref. [3], the C_W was found by optimizing the agreement with the pedestal data obtained from the ITPA Pedestal Database [13], in which the value of C_W = 2.42 yield the RMSE of 32% with 533 pedestal data points.

The pedestal density, n_{ped}, is described by a simple pedestal density model. Since the pedestal density is usually a large fraction of line average density, n_l, the pedestal density can be calculated as:

$$n_{ped} = 0.71 n_l \,. \tag{4}$$

This pedestal density model agrees with the pedestal data obtained from the ITPA pedestal database with 12% RMSE.

3. ITER simulations using BALDUR code

The BALDUR integrated predictive transport modeling code is used to carry out the simulations of ITER with the designed parameters shown in Table 1. In this work, an anomalous transport is calculated either using the Mixed B/gB transport model or using the MMM95 transport model, while the neoclassical transport is computed using the NCLASS module. The boundary conditions are provided at the top of the pedestal by the pedestal model described above. It is assumed that the electron and ion pedestal temperatures are the same values. Three different values of the pedestal constant C_w are used in these simulations. When the simulation is carried out with the value of C_w = 2.42, it shows the actual prediction. When the simulation is carried out with the value of C_w = 1.16, the lower bound of the prediction is found. When the simulation is carried out with the value of C_w = 4.86, the upper bound of the prediction is predicted. The auxiliary heating power of 40 MW, which is a combination of 33 MW NBI heating power with 7 MW of RF heating power, is used in these simulations,.

Figures 1 and 2 show the profiles for ion (top) and electron (middle) temperatures and electron density (bottom) as a function of major radius at a time of 300 sec for different values of the pedestal constant C_w. It is found in these simulations that the predicted pedestal temperatures are about 3 keV (with the lower and upper bound of 2.6 keV and 4.1 keV, respectively). It can be seen in both figures that the temperature profiles are peak profiles. For the density profiles, the simulation with the Mixed B/gB transport model tends to be flat with a smaller peak at the region close to the center of the plasma than that in the simulation with the MMM95 transport model. The temperature profiles in the simulation with the MMM95 model are higher than those in the simulation with the Mixed B/gB model. The central temperatures in the simulation with the Mixed B/gB model are in the range between 10 keV to 15 keV, while those in the simulation with the MMM95 model are in the range between 15 keV to 20 keV. Note that the central temperatures obtained in the ITER simulation in the previous study [2] are higher than the results obtained in this work. This can be explained by the difference in the auxiliary heating used in the simulations. In the previous ITER simulation, the auxiliary heating power was assumed to be 40 MW of RF heating power mainly applied in the plasma core region by employing a parabolic heating profile. This is an effective heating profile for burning plasma experiments since most of the power will be available at the center of the plasma. On the other hands, the combination of NBI and RF heating power is used in this work. Because ITER plasma density is high, the broader heating profile is obtained, which results in lower temperature profiles, especially at the plasma center.

In Fig. 3, the alpha power production of ITER is plotted as a function of time. It can be seen that the alpha power production from the simulation with the MMM95 model is significantly higher than that from the simulation with the Mixed B/gB model. The higher alpha power production results from the higher temperature prediction in the simulation with the MMM95 model. The fusion performance can be evaluated in term of Fusion Q, which can be calculated as

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

where $P_{\alpha,\text{avg}}$ is an average alpha power and P_{AUX} is an auxiliary heating power (equal to 40 MW for these simulations). Therefore, the fusion Q in ITER is predicted to be 6.2 (with the upper and lower bound of 6.8 and 5.4, respectively) in the simulation with the MMM95 transport model. For the simulation with the Mixed B/gB transport model, the fusion Q of 2.3 (with the upper and lower bound of 1.1 and 3.7, respectively) can be obtained.

4. Conclusions

Self-consistent simulations of ITER have been carried out using the BALDUR integrated predictive modeling. Simulations are carried out either using the MMM95 transport model or using the Mixed B/gB transport model. It is found that the simulations carried out using the MMM95 model yield more optimistic results than those using the Mixed B/gB model. When the Mixed B/gB model is used, the simulation yields fusion Q of 2.3 (with the lower and upper bound of 0.9 to 3.7, respectively). For the simulation carried out using MMM95, the fusion Q of 6.2 (with the lower and upper bound of 5.4 to 6.8, respectively) is obtained.

5. Acknowledgements

Authors are grateful to Prof. Suthat Yoksan and Prof. Arnold H. Kritz for their helpful discussions. This work is supported by Commission on Higher Education and the Thailand Research Fund (TRF) under Contract No. MRG4880165, National Research Council of Thailand, and the Thammasat University Research Fund.

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Table 1: The basic parameters for ITER design

Parameters	**Values**
Major radius	6.2 m
Minor radius	2.0 m
Plasma current	15 MA
Toroidal magnetic field	5.3 T
Elongation	1.70
Triangularity	0.33
Line average density	$1.0\text{x}10^{20}$ m^{-3}
Auxiliary power	40 MW

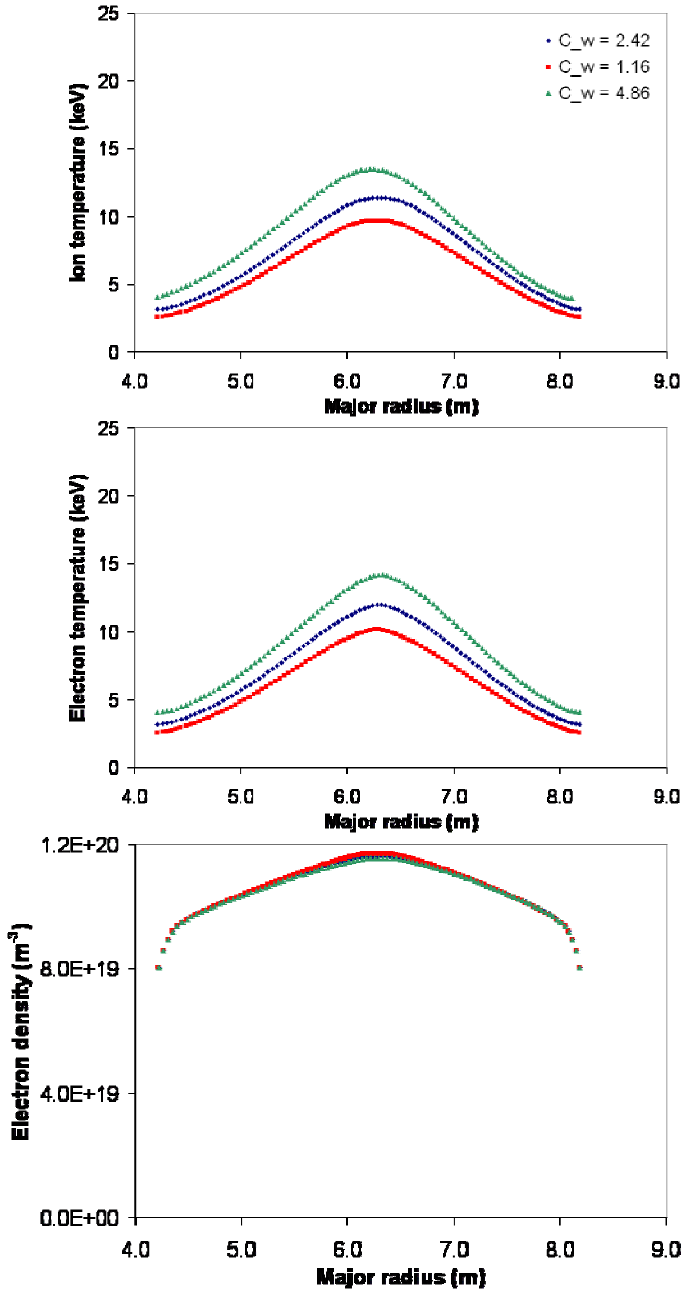

Fig. 1: Profiles for ion (top) and electron (middle) temperatures and electron density (bottom) are shown as a function of major radius at a time of 300 sec. These BALDUR simulations are carried out using Mixed B/gB core transport model for different values of pedestal width constant C_w. The simulation with C_w = 2.42 (blue) represents the actual prediction, while the simulations with C_w = 1.16 (red) and C_w = 4.86 (green) represent the lower and upper bound of the prediction, respectively.

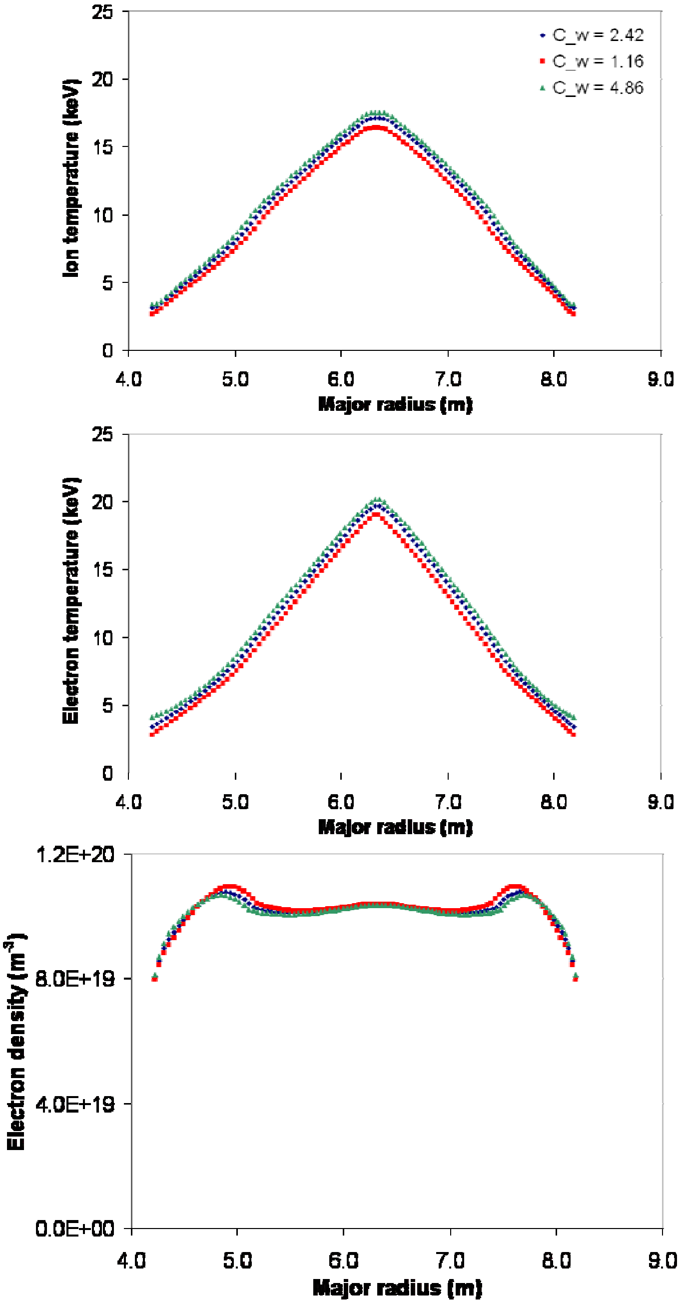

Fig. 2: Profiles for ion (top) and electron (middle) temperatures and electron density (bottom) are shown as a function of major radius at a time of 300 sec. These BALDUR simulations are carried out using MMM95 core transport model for different values of pedestal width constant C_w. The simulation with C_w = 2.42 (blue) represents the actual prediction, while the simulations with C_w = 1.16 (red) and C_w = 4.86 (green) represent the lower and upper bound of the prediction, respectively.

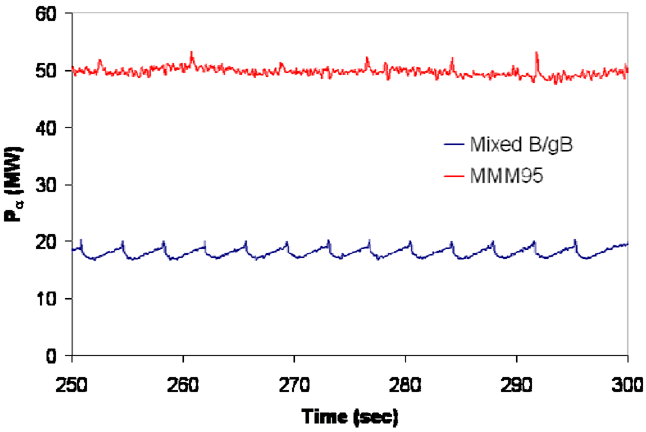

Fig. 3: The alpha power production is plotted as a function of time. The blue line is the result obtained from the simulation using the Mixed B/gB core transport code and the pedestal model with $C_w = 2.42$. The red line is the result obtained from the simulation using the MMM95 core transport code and the pedestal model with $C_w = 2.42$.