Topic-TH

Study of ITER Performance Based on Different Plasma Geometry

R. Picha[1], K. Tharasrisuthi[2], T. Onjun[2], S. Suwanna[2], N. Poolyarat[3], and O. Onjun[4]

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

[2] *Sirindhorn International Institute of Technology, Thammasat U., Pathumthani, Thailand*

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

[4] *Department of Science Service, Ministry of Science and Technology, Bangkok, Thailand*

Abstract

Effects of plasma geometry on nuclear fusion power production in ITER tokamak are investigated using the 1.5D BALDUR integrated predictive modeling code. In this work, shaping parameters, which are elongation and triangularity, are varied, and their impacts on nuclear fusion power production are observed. These simulations are explored with two different anomalous core transport models: an empirical based Mixed Bohm/gyro-Bohm (Mixed B/gB) and a theoretical based Multimode model (MMM95). It is found that as elongation is increased, the simulations based on MMM95 model show a steady rise of the fusion performance until at the elongation of 1.9. On the other hand, the ITER performance decreases steadily with elongation when Mixed B/gB model is used. Regarding triangularity dependence, the simulations based on both MMM95 and Mixed B/gB models show a decrease in the nuclear fusion power production as the plasma becomes more triangulated. Furthermore, the simulations using MMM95 consistently yield higher plasma performance (approximately by a factor of 3) than those using Mixed B/gB. In addition, when MMM95 is used, it appears that the ion temperature gradient (ITG) and trapped electron modes (TEM) are the dominant modes. When the Mixed B/gB is used, it appears that the Bohm contribution is the most dominant term.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) [1] aims to generate more energy output than it takes in by using fusion process. Burning plasmas (sustained by the alpha particles from fusion) of deuterons and tritons are to be created and investigated, the understanding of which will lead to the development of the demonstration fusion power reactor (DEMO). Tokamaks are toroidal magnetic chambers which are currently the main device used in controlling fusion via magnetic confinement. Inside the toroidal geometry, the magnetic fields keep the charged particles bound in helical paths. There are currents from primary current loops and from the plasma itself. However, producing fusion reactions inside tokamaks requires our ability to both heat and contain high temperature plasmas for a long enough time at a high enough energy density. There are various instability modes which tend to disrupt the fusion reactions. Optimizing plasma performance via intensive computer simulations and obtaining reliable predictions are crucial to fusion experiments.

In this paper we explored the effects of plasma geometry on the fusion performance of the plasma via computational simulation codes. Geometry of the plasma cross-section in tokamak is mostly determined by the vertical elongation factor (κ) and triangularity factor (δ). Elongation is the major radius divided by the minor radius of the plasma cross-section. Low-κ plasmas are more circular in the cross sections. Triangularity is the horizontal offset factor, which equals to the horizontal distance from the tallest part of the plasma to the horizontal center divided by the minor radius. A large-δ plasma has a triangulated shape.

2. Methods

A BALDUR integrated predictive modeling code [2] is used to carry out the simulations of ITER plasmas with the standard H-mode scenario, as it is the reference scenario for ITER. The aspect ratio of ITER is set as follows: major radius R = 6.2 m, minor radius a = 2.0 m. Other parameters are: plasma current I_p = 15 MA, toroidal magnetic field B_T = 5.3 T, edge ion and electron temperatures 3.0 keV (the value obtained from empirical models based on magnetic and flow shear stabilization and infinite-n ballooning modes in [6] is 2.7 keV), and line density $n_l = 1.0\text{x}10^{20}$ m^{-3}. ITER will house 830 m^3 of DT plasma. A combination of 33 MW of NBI heating power and 7 MW RF heating power is used. The plasma parameters are summarized in Table 1. Time evolution of plasma properties can be investigated.

Table 1: Summary of relevant plasma parameters.

Plasma current (MW)	B_T (T)	Density (m^{-3})	NBI power (MW)	RF power (MW)	Total aux. power (MW)	$T_{i,\,ped}$ (keV)	$T_{e,\,ped}$ (keV)
15	5.3	$1.0\text{x}10^{20}$	33	7	40	3.0	3.0

When particles collide, they transfer energy and cause diffusion. Since these particles are charged, besides continuously losing energy via such collisions, they also radiate energy in the form of photons. In this work, the simulations are studied via the use of two different core transport models: a theoretical based Multimode model (MMM95) [3] and an empirical based Mixed Bohm/gyro-Bohm (Mixed B/gB) [4].

3. Results and Discussions

In these simulations, the anomalous transport is calculated using the MMM95 transport model [3], while the neoclassical transport between the plasma species is computed using the NCLASS module [5]. The Mixed B/gB anomalous transport model was also used for comparisons. The performance of the plasma is measured in the term of fusion Q, which is the power extracted from each fusion reaction divided by the externally supplied power. Using the known energy fraction of the alpha particle (20%) in each fusion reaction, we can calculate the fusion power.

In Fig. 1, we see the time evolution profiles of the electron and ion core temperatures, calculated using different elongation parameters. MMM95 is used. The electrons have a higher temperature than the ions by about 35% at t = 300s. The profile shapes are the same for different elongation settings. The profiles are also relatively unchanged as triangularity is varied. As the elongation increases, the temperature decreases. In each simulation, the pedestal temperature seems to continue rising beyond the time limit studied here.

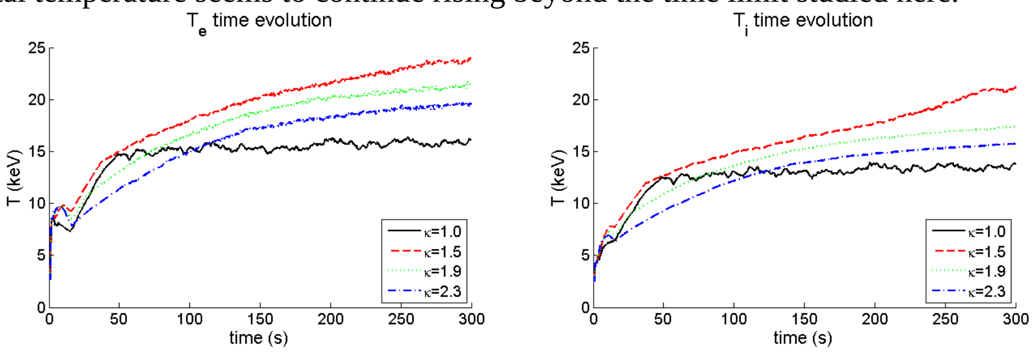

Figure 1: Time evolution of the electron (left) and ion (right) temperatures at the plasma core. MMM95 model is used.

The ratio of the power output to the power input changes over time. Time evolutions of Q are studied as functions of elongation and triangularity. Figure 2 shows time evolution profiles of fusion Q as elongation is varied. In MMM95 results, the perfectly symmetric plasma has low Q. The increase in Q seems to cease around the elongation of 1.9. In Mixed B/gB, as the elongation gets too large, Q loses its peak shape profile. The circular plasma also does not have a well defined Q peak.

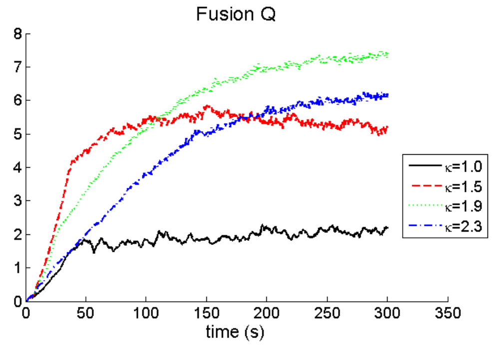

Figure 2: Elongation dependence of fusion Q, shown as time evolution profiles. MMM95 model is used.

The triangularity dependence is shown in Fig. 3 Whereas MMM95 gives Q profiles which generally flatten out with time, Mixed B/gB yields Q values that peak around 40 seconds and then drop to lower values. The triangularity sensitivity of the Mixed B/gB results is less radical than the elongation sensitivity. The results seem to suggest better fusion performance in low-triangularity plasma.

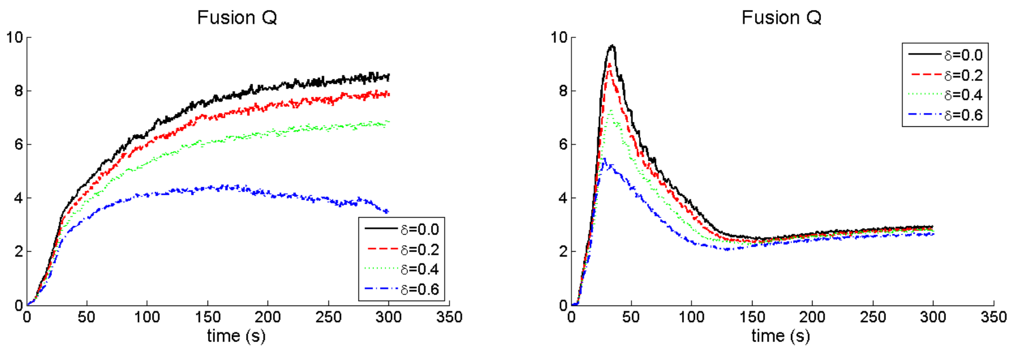

Figure 3: Triangularity dependence of fusion Q, shown as time evolution profiles. MMM95 model is used in the left panel. Mixed B/gB model results are shown on the right panel.

In Fig. 4, the fusion Q at the end of the time cycle is plotted as a function of elongation. The triangularity sensitivity is shown in Fig. 5. From the elongation range studied (1.0-2.3), MMM95 simulation shows the increase of Q with elongation, peaking around elongation of 1.9. The Q calculated from Mixed B/gB shows a steady decline as the plasma becomes more elongated. The effect of elongation was empirically found to extend the duration of confinement therefore the Multi-Mode model anomalous transport contributions were multiplied by $1/\kappa^4$ [3]. (κ is the local elongation coefficient.) Mean values of Q are 5.6 (MMM95) and 2.9 (Mixed B/gB). The increasing triangularity generally seems to decrease the plasma performance in both MMM95 and Mixed B/gB models. The mean values of Q are 6.9 (MMM95) and 2.8 (Mixed B/gB).

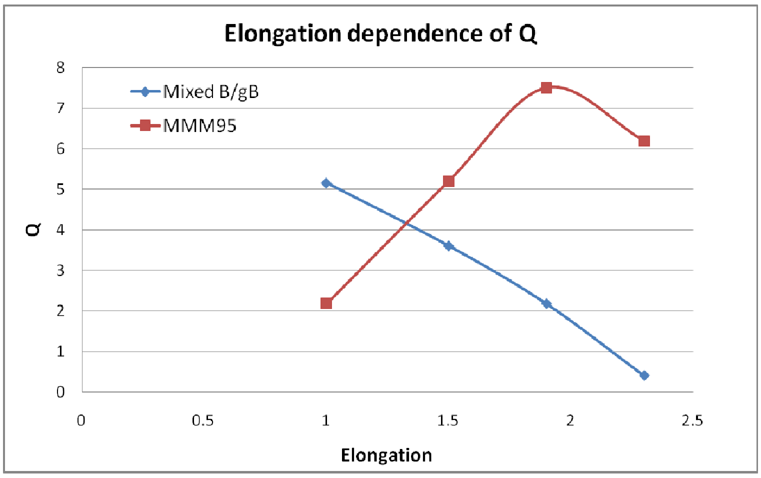

Fig. 4: Elongation dependence of fusion Q at the end of the cycle, computed by the Multi-Mode Model and the Mixed Bohm/gyro-Bohm.

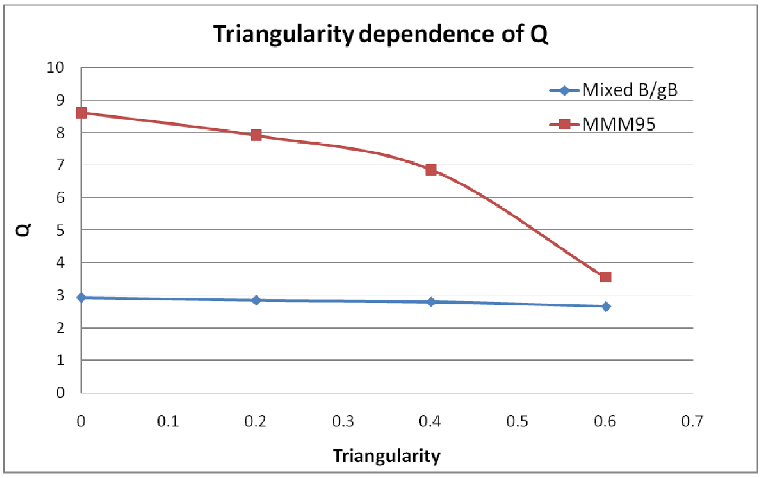

Fig. 5: Triangularity dependence of fusion Q at the end of the cycle, computed by the Multi-Mode Model and the Mixed Bohm/gyro-Bohm.

Transport of particles and their energy is also an important determining factor of plasma performance. Figure 6 shows the ion thermal diffusivity as a function of minor radius at the time 300 sec calculated by MMM95 model. It can be seen that the ion temperature (ITG) and trapped electron mode (TEM) contributions are the dominant contributions to the ion thermal diffusivities. The exception, however, is at the center of the plasma, where the density is highest. In this region, the neoclassical contribution dominates the ion transport. For the electrons, the neoclassical contributions are negligible. The thermal transport from the kinetic ballooning mode is significant in the region between normalized minor radius of 10% to 50%, whereas the resistive ballooning mode is small almost everywhere. In the region from the center of the plasma to the edge of plasma, the resistive ballooning contributions are quite small (less than 1 m^2/s) for both the ions and the electrons. For the Mixed B/gB, shown in Fig. 7, the Bohm term dominates the gyro-Bohm term except the very center of the plasma. The electron gyro-Bohm term seems to have higher contributions to the total diffusivity than that of the ion.

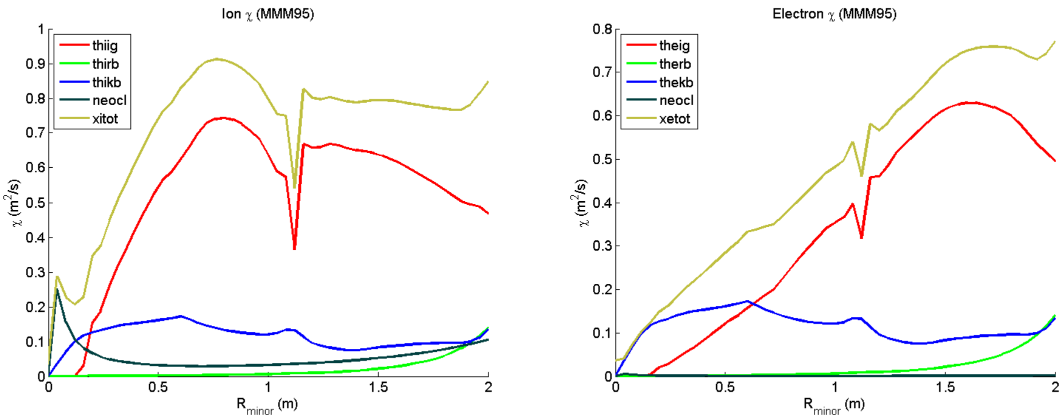

Figure 6: Ion thermal diffusivity and electron diffusivity (in m^2/s) plotted as functions of minor radius at 300 sec. The transport is calculated using MMM95 model. The ITG and TEM contributions for the ions are labeled “thiig,” kinetic ballooning “thikb”, neoclassical “neocl,” total “xitot.” For the electron the “i” is replaced with “e.”

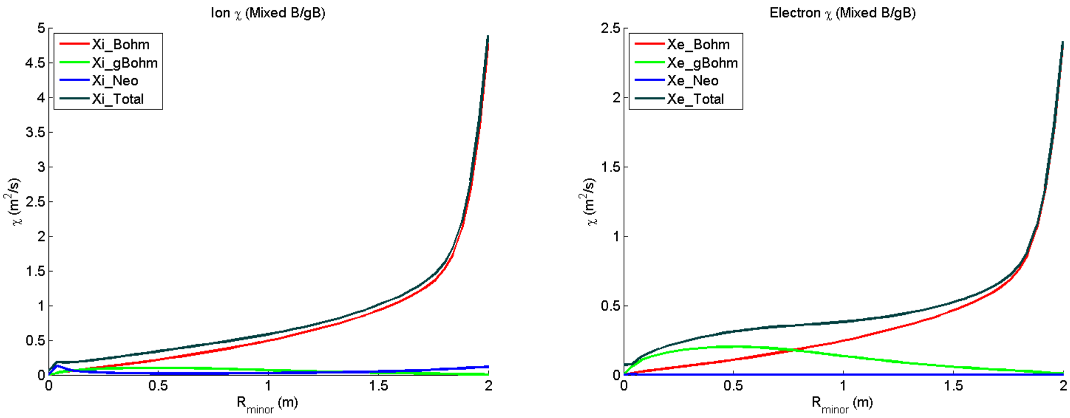

Figure 7: Ion thermal diffusivity and electron diffusivity (in m^2/s) plotted as functions of minor radius at 300 sec. The transport is calculated using Mixed B/gB model. For the ion, the Bohm contributions are labeled “Xi_Bohm,” gyro-Bohm “Xi_gBohm”, neoclassical “Xi_Neo,” total “Xi_Total.” For the electron the “i” is replaced with “e.”

4. Conclusions

Self-consistent modeling of ITER has been performed using BALDUR integrated code with Multimode Model and Mixed Bohm/gyro-Bohm used to calculate anomalous transport. Geometry of the plasma is found to affect the performance of the plasma. Fusion Q increases with elongation when MMM95 is used, peaking around elongation of 1.9. Electrons have higher temperature than ions. Higher performance is obtained from MMM95 than from Mixed B/gB. Plasma performance tends to favor plasma with small triangularity. At the current setting, the predicted value of Q is well above 1, satisfying the most basic requirement of burning plasma. Regarding transportation, the Bohm term dominates in Mixed B/gB while ITG and TEM dominate in MMM95. Pedestal temperature seems unsteady for the time period studied. In the future, simulations beyond t=300 s should be investigated.

Acknowledgements

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