PS11: การศึกษาถึงผลของค่าความเป็นสามเหลี่ยมและกระแสพลาสมาต่อความสามารถของพลาสมาในโทคาแมคโดยผ่านรหัสคอมพิวเตอร์ BALDUR

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บทคัดย่อ

การศึกษานี้เป็นการใช้แบบจำลองพลาสมาเพื่อทำนายผลของปฏิกิริยาฟิวชันในเครื่องโทคาแมค ผลของค่าความเป็นสามเหลี่ยมของพลาสมาและกระแสพลาสมาภายในเครื่องโทคาแมค ได้ถูกศึกษาโดยใช้รหัสคอมพิวเตอร์ทำนายผลเชิงคณิตศาสตร์แบบรวม BALDUR โดยที่การส่งผ่านอนุภาคแบบแปลก (anomalous) ได้ถูกคำนวณโดยแบบจำลอง Multi-Mode Model 95 (MMM95) ส่วนการส่งผ่านแบบกระเจิงใช้แบบจำลอง NCLASS โดยใช้ค่าพารามิเตอร์ของเครื่องโทคาแมค ITER เป็นตัวตั้งมาตรฐาน จากการคำนวณได้พบว่าเมื่อค่าความเป็นสามเหลี่ยมเพิ่มสูงขึ้น ค่าความสามารถของพลาสมาจะลดลง โดยที่ค่าความเป็นสามเหลี่ยมต่ำสุด คำนวณได้ค่า Q สูงสุดอยู่ที่ประมาณ 7 นอกจากนี้ ได้พบว่าเมื่อกระแสพลาสมามีมากขึ้น ค่าความสามารถของฟิวชัน ก็ขึ้นสูงตาม

คำสำคัญ: พลาสมา แบบจำลองแบบรวม โทคาแมค อิเทอร์

Study of Triangularity and Plasma Current Effects on Tokamak Plasma Performance via BALDUR Code

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Abstract

This study investigates the fusion parameters inside a tokamak. Effects of plasma triangularity and plasma current on fusion power production in an ITER tokamak setup are investigated using the BALDUR integrated predictive modeling code. Transport of plasma particles can be divided into neoclassical part and anomalous part. Theoretical-based Multimode Model (MMM95) was used to model the anomalous flow of the plasma while NCLASS was used for the neoclassical flow. The machine parameters were based on ITER standard values. It was found that as triangularity increases, the simulations based on MMM95 model gave a steady falling trend of the fusion performance. At the lowest triangularity value (zero), the Q value is at a maximum, of about 7. Furthermore the Q value is also found get larger as the plasma current increases from the proposed value.

Keywords: plasma, integrated modeling, tokamak, ITER

1. Introduction

This study looks at the transverse shape effects on the magnetic fusion performance. Over the years predictive transport modeling has been used to predict behaviors of plasma inside a tokamak, where strong magnetic fields are used to confine nuclear fusion charged ingredients. The International Thermonuclear Experimental Reactor (ITER) [1], which is the largest tokamak to be built, aims to generate more energy output than it takes in by using deuterium-tritium fusion. In 1997, the current largest tokamak, the Joint European Torus (JET), proved that the physics of fusion is realizable by generating fusion power of 16 MW and energy of 22 MJ. ITER will increase the confinement time and the fusion power even more. With a large expansion of plasma volume and surface, the ITER tokamak scenarios will likely include unforeseen effects. 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).

Inside the toroidal geometry, the magnetic fields keep the charged particles bound in helical paths, each spinning about a guiding center with a centripetal force normal to both velocity and magnetic field vectors. Currents are generated from primary current loops and from the conducting plasma itself. However, producing fusion reactions inside tokamaks requires our ability to both heat and contain high temperature plasmas (of the order 100 million kelvins or 10 keV) for a long enough time at a high enough energy density. Heating can be done, for instance, via natural ohmic heating, neutral beam injection, and radio-frequency power. Containment is a more difficult challenge. Many processes tend to disrupt the fusion reactions. The plasma system itself is inherently unstable and many types of disruptions (loss of confinement) such as edge-localized modes (ELMs) [8], sawtooth crashes [10], or neoclassical tearing modes (NTMs) [9] can happen.

Plasma-wall interaction is prohibitive as the plasma will quickly cool off and the wall may get damaged.

Because of a high cost of running a fusion reactor, an efficient operation is required. Simulations are used as the tools to understand plasma and develop the control scheme. Many groups develop different codes to help explain different aspects of tokamak plasma. For instance, the codes may focus on the confinement of energetic particles, transport barrier, stability, RF heating, NBI heating, plasma-wall interactions, and impurity transport. Integrated simulation combines different simulation codes to cover all the relevant areas of the plasma inside tokamaks. 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. Geometry of the plasma cross-section in tokamak is partly determined by the triangularity factor (δ). 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. Method

BALDUR integrated predictive modeling code [2] is used to carry out the simulations of ITER plasmas with the standard H-mode scenario. BALDUR is a transport code, written in FORTRAN, designed to simulate tokamak plasmas in various settings. It uses transport models to calculate numerical results from theories.

The aspect ratio of ITER is set as follows: major radius R = 6.2 m, minor radius a = 2.0 m. Consequently, the length of one poloidal loop is 12.6 m, while one toroidal loop is 39.0 m. Other parameters are: plasma current I_p = 15 MA (ramping), toroidal magnetic field B_T = 5.3 T, edge ion and electron temperatures 3.0 keV (the value obtained from empirical models in [6] is 2.74 keV), and line density = 1.0×10^{20} m-3. ITER will house 830 m^3 of D-T plasma. The volume is much larger than the current largest tokamak. JET contains 100 m^3 of plasma (3 m major radius and 1 m minor radius). A combination of 33 MW of NBI heating power and 7 MW RF heating power will be used to heat this large plasma volume. The plasma parameters are summarized in Table 1.

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 (keV)	T_e (keV)
15	5.3	1.0×10^{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. Time evolution of plasma properties can be investigated by using different models. In this work, the simulations are studied via the use of a theoretical based core transport model called the Multimode model (MMM95) [3] while the neoclassical transport between the plasma species is computed using the NCLASS module [5]. MMM95 consists of the Weiland model for ITG (ion temperature gradient) modes and TEM (trapped electron modes), the Guzdar-Drake model for drift-resistive ballooning modes, and smaller contributions from kinetic ballooning modes.

The Multi-Mode model is a linear combination of theory-based transport models. It is purely a gyro-Bohm model. MMM95 consists mainly of the Weiland model for the ion temperature gradient (ITG) and trapped electron modes (TEM), the Guzdar–Drake model for drift-resistive ballooning (RB) modes. There are also smaller contributions from kinetic ballooning (KB) modes and neoclassical transport. The Multi-Mode Model applies the philosophy to use the best transport theories available for different turbulence modes that dominate different parts of the plasma. The detailed description is given in [8].

The Weiland model in MMM95 uses the equation of continuity and includes the ExB drift in the flow velocity. The ITG and TEM drift modes of the Weiland model are usually the largest contributions 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. In the plasma, the electrons can either be free or trapped. The Weiland model includes many different physical phenomena such as effects of electrons, ion and electron temperatures, impurities, and fast ions.

The resistive ballooning model in MMM95 transport model is based on the 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 semiempirical 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.

Results have shown that MMM95 code accurately predicts temperatures and densities of experimental plasma data available [7], for both low-confinement and high-confinement modes at TFTR (US), DIII-D (US), and JET (UK).

Transport code calculates the movement of particles in the plasma volume. The continuity equation solved in MMM95 is

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}_i) = 0 \text{, with } \vec{v}_i = \vec{v}_E + \vec{v}_{*i} + \vec{v}_{Pi} + \vec{v}_{\pi i} + \hat{B}\upsilon_{par,i}$$

where $\vec{v}_E$ is E cross B drift ($\vec{E} \times \vec{B}$); $\vec{v}_{*i}$ and $\vec{v}_{\pi i}$ are off-diagonal element drift; $\vec{v}_{Pi}$ is polarization drift, and $\upsilon_{par,i}$ is the parallel ion motion. The electrons are classified as either trapped or free, each with different density.

Drifts depend on the Lorentz force $\frac{d\bar{p}}{dt} = q(\vec{E} + \bar{v} \times \vec{B})$, where p is the momentum. Fields E and B are caused by the current coil setup, and also by the charged particles that make up the plasma themselves. If the charged particles start off with some initial velocity, they will follow Larmor orbits. Assuming constant perpendicular drift velocity, $\frac{d\bar{p}}{dt} = 0$. Thus, $\bar{v} \times \vec{B} + \vec{E} = 0$,

$$\vec{B} \times (\bar{v} \times \vec{B}) + \vec{B} \times \vec{E} = 0$$

$$B^2 \bar{v} - \vec{B}(\bar{v} \cdot \vec{B}) + \vec{B} \times \vec{E} = 0$$

$$\bar{v} = \frac{\vec{E} \times \vec{B}}{B^2}$$

Two pressure-driven modes are included in MMM95. Both have a relative pressure gradient term ($\nabla p / p$) included.

Initial parameters in these simulations are set based on ITER values. Notation: Te = electron temperature; Ti = ion temperature; ne = electron density; ni = ion density; (0) means the value at initial time.

- Toroidal magnetic field: 5.3 T, toroidal current: 2.0 megaampere
- Temperatures : Te(0) = 3.0 keV, Te(a) = 0.2 keV. Initial temperature profile is set by Te(r)-Te(a) prop. to (1-(r/a)** 2.00)** 1.00
- Ti(0): 3.0 keV, Ti(a): 0.2 keV. As for electron, Ti(r)-Ti(a) prop. to (1-(r/a)** 2.00)** 1.00

- Electron density: ne(0) = 2.680E+13 particles per cubic cm, ne(a) = 1.432E+13 particles per cubic cm
- Ion density: ni(0) = 2.620E+13 particles per cubic cm, ni(a) = 1.408E+13 particles per cubic cm
- Deuterium density: n(0) = 1.300E+13 particles per cubic cm, n(a)= 7.000E+12 particles per cubic cm, 49.65 0f plasma, atomic wt= 2.0, charge= 1
- tritium n(0)= 1.300E+13 particles per cubic cm, n(a)= 7.000E+12 particles per cubic cm, 49.65 0f plasma, atomic wt= 3.0, charge= 1
- carbon n(0)= 9.999E+10 particles per cubic cm, n(a)= 4.000E+10 particles per cubic cm, 0.35 0f plasma, atomic wt= 12.0, charge= 6
- helium-3 n(0)= 9.999E+10 particles per cubic cm, n(a)= 4.000E+10 particles per cubic cm, 0.35 0f plasma, atomic wt= 4.0, charge= 2

4. Results and Discussions

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.

The triangularity (defined in Fig. 1) value can be set as a BALDUR input. In Fig. 2, we see the time evolution profiles of the electron and ion core temperatures, calculated using different triangularity parameter. As the triangularity increases, the temperature decreases and, in the case of ions, eventually the thermal stability is lost around triangularity of 0.4 and beyond.

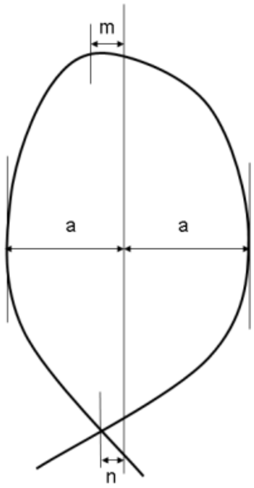

Figure 1: Plasma cross section (poloidal view). Triangularity is defined to be (m+n)/2a.

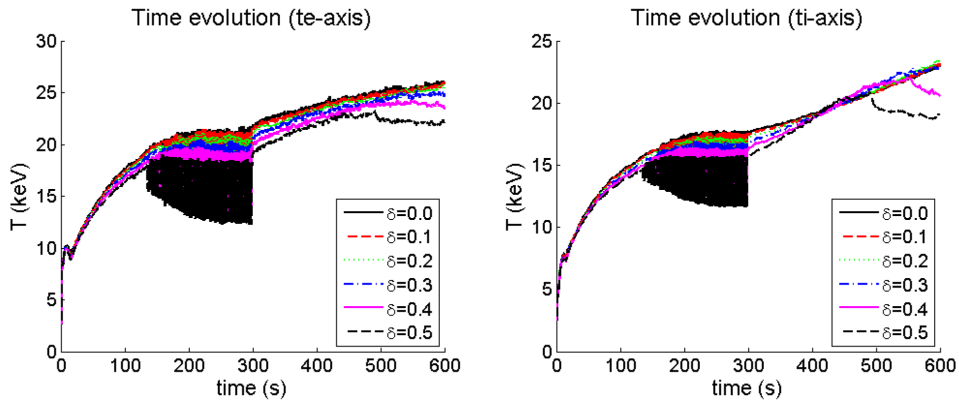

Figure 2: Time evolution of the electron (left) and ion (right) temperatures at the plasma core. Sawtooth time is from 15.07 to 298.00 s.

The core electron density evolution as calculated by BALDUR is shown in Fig. 3. The electrons have a higher temperature than the ions. Using $\langle KE \rangle = \frac{3}{2}kT$, we can calculate the root-mean-square speed of each species. Sawtooth effect is triggered via BALDUR with an arbitrary time span. It is seen that the amplitude of the temperature fluctuation during sawtooth oscillation goes up to around 5 keV for electrons, and 3 keV for ions. Although the initial core electron densities of various triangularity settings appear similar, after the sawtooth oscillation period the core electron density decreases with triangularity.

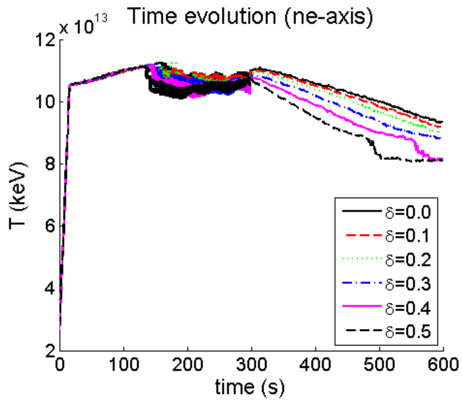

Figure 3: Time evolution of the electron density at the plasma core. Sawtooth time is from 15.07 to 298.00 s.

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 4 shows time evolution profiles of fusion Q as triangularity is varied. MMM95 gives Q profiles which generally peak around 300 s and slowly decrease as time increases.

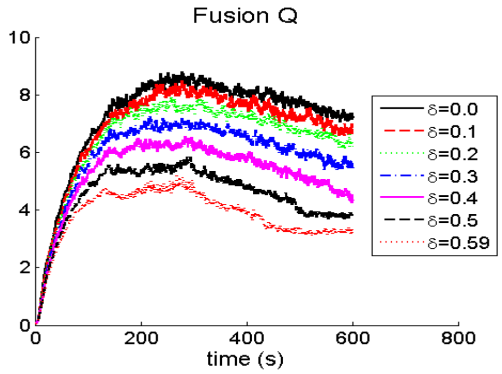

Figure 4: Triangularity dependence of fusion Q, shown as time evolution profiles.

In Fig. 5, the fusion Q (defined to be P_{fusion} / P_{aux}) at the end of the time cycle is plotted as a function of triangularity. It can be seen that an increased triangularity causes a decrease the plasma performance.

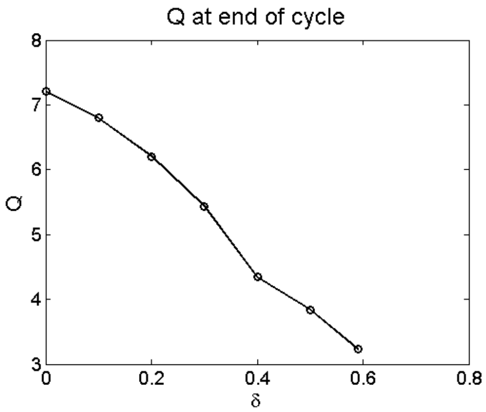

Figure 5: Triangularity dependence of fusion Q at the end of the cycle.

Radial profiles of temperatures are shown in Fig. 6. As triangularity is increased, the temperature gradually drops.

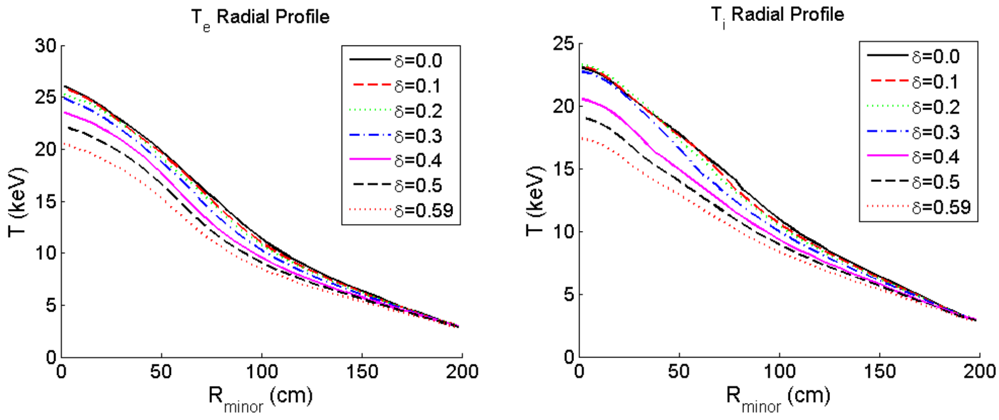

Figure 6: Radial profiles of temperatures at time of 600 s.

Sawtooth effects are a kind of instabilities found in plasma. Figs. 7 and 8 show the computed sawtooth effects. Time span is arbitrary. The oscillation temperature amplitude is around 2-3 keV.

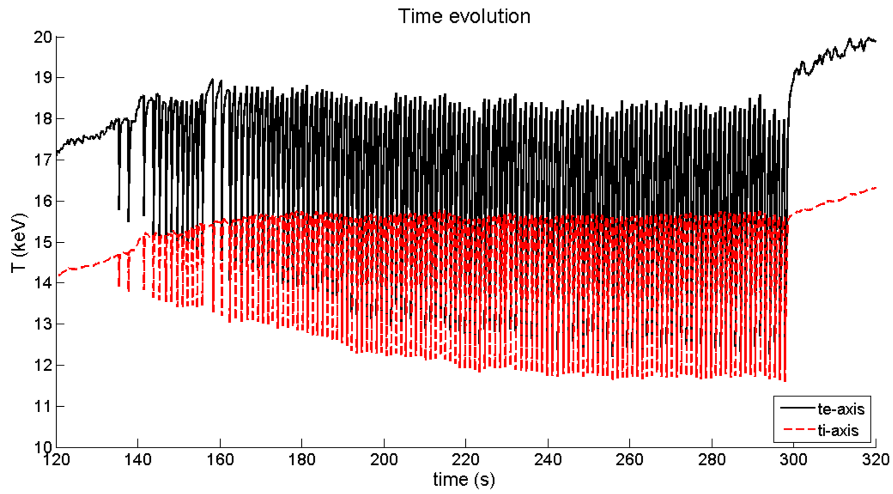

Figure 7: Sawtooth profiles of central plasma temperature.

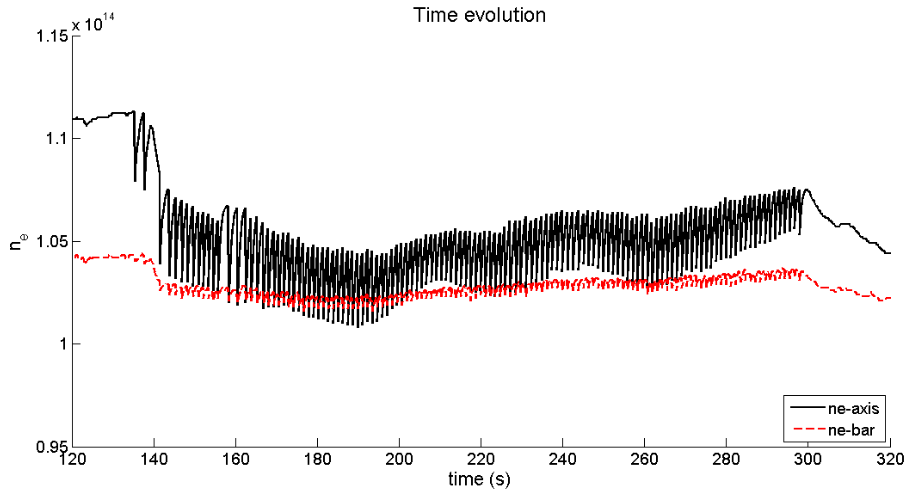

Figure 8: Sawtooth profile of central electron density and average electron density.

From the results, it is observed that BALDUR simulations using MMM95 and NCLASS have given fusion performance that is highly dependent on triangularity. Fig. 9 shows the contributions of different diffusivity terms in MMM95.

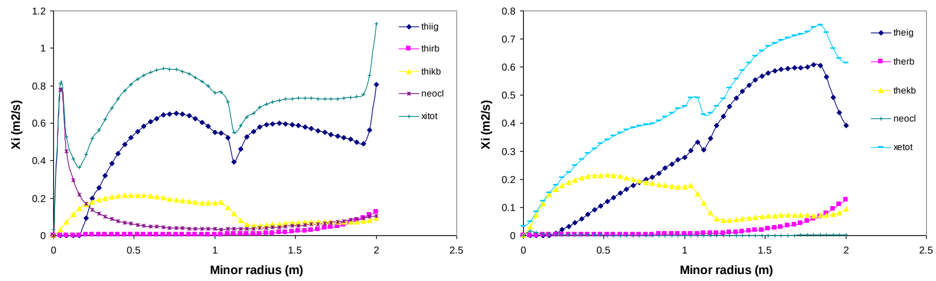

Fig. 9: Ion (left) and electron (right) diffusivities from the MMM95 transport model are shown as a function of minor radius at the time of 300 s. Standard geometry is used (elongation 1.7, triangularity 0.33). Ion diffusivity includes ITG and TEM contribution, resistive ballooning contribution, and kinetic ballooning contribution. The neoclassical contribution is also shown. Electron diffusivity includes the similar terms.

In the tokamak, the current coils wrapped around the plasma volume produce a toroidal magnetic field. Additionally, a poloidal magnetic field is produced by the toroidal plasma current. The magnitude of the magnetic field increases with the current. At ITER, the plasma current value is designed to be 15 MA, which is a large increase over JET (7 MA). From the simulation it was found that the current affects the core temperatures of the plasma. Plasma current effects can be seen in

Fig. 10. As current increases, so does the temperature. Q value is shown in Fig. 11. It was found that, like temperature, Q also goes up with the plasma current.

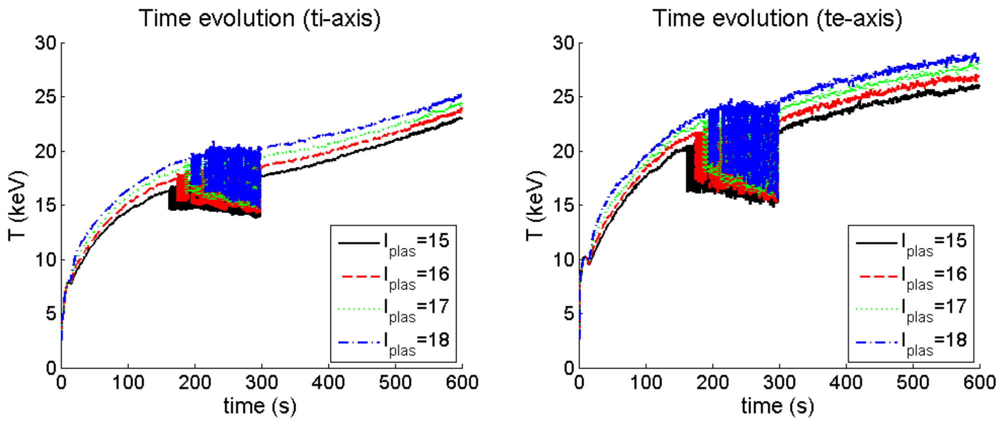

Figure 10: Time evolution of plasma temperatures as the plasma current is varied.

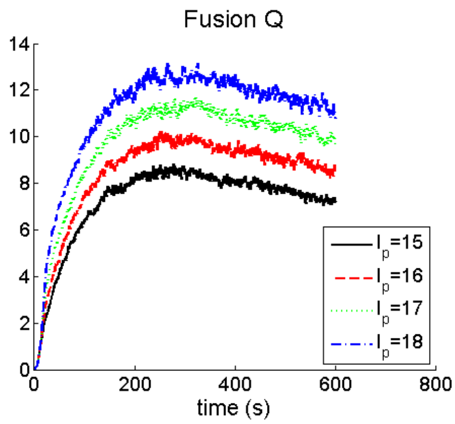

Figure 11: Time evolution of plasma Q as the plasma current is varied.

5. Summary

To gain a basic understanding of geometric effects on D-T fusion performance, self-consistent modeling of ITER was performed using BALDUR integrated code to study the evolution of plasma parameters as triangularity is varied. To quantify the energy efficiency, we use the Q ratio which is calculated from the alpha power and the external power, using the known fraction of alpha energy. Geometry of the plasma is found to affect the performance of the plasma. 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 a burning plasma. The simulations predict that the plasma tends to lose the stability of its pedestal temperature as the triangularity gets too large. Data at current large tokamaks will provide important knowledge to the impact that plasma geometry has on fusion power production before ITER commences operation. More work, both theoretical and experimental, will be required to understand the plasma behavior better.

6. Acknowledgments

The authors are grateful to Prof. Arnold H. Kritz and Dr. Glenn Bateman at Lehigh University for their support. We thank the members of Plasma and Fusion Research Unit (PFRU) at Sirindhorn International Institute of Technology for useful discussions. This work is supported by National Research Council of Thailand (NRCT).

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