# Comparisons of the Plasma Performance of Future Thailand Tokamak using Various External Heating Schemes*)

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Simulations of future Thailand tokamak plasmas are carried out using a CRONOS integrated predictive modelling code. The design of the reactor is based on nominal parameters of HT-6 M tokamak. The code consists of a 1D transport solver with general 2D magnetic equilibria, and includes several heat, particle and impurities transport models as well as heat, particle and momentum sources. In this work, a combination of a mixed Bohm/gyro-Bohm anomalous transport model and an NCLASS neoclassical transport model are used to calculate plasma core diffusivities. The boundary condition of the simulations is taken to be at the top of the pedestal which is calculated based on an international multi-tokamak scaling. Sensitivity analyses on plasma performance of the future Thailand tokamak are investigated by varying plasma current, toroidal magnetic field and external heating schemes. It is found that the performance in $H$-mode plasmas such as transport barrier at plasma edge and central temperatures are found to be sensitive to heating schemes and their magnitudes. Additionally, ICRH and LH methods appear to be the most effective scheme of heating for ion and electron temperatures, respectively. Central ion temperature in the range of 120 - 750 eV and central electron temperature in the range of 1,100 - 2,750 eV with heating are expected.



Keywords: Tokamak, CRONOS, $H$-mode

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## 1. Introduction

HT-6 M, a donated small tokamak from China, was previously developed and operated by the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) in Hefei. This tokamak is planned to be installed at Thailand Institute of Nuclear Technology (TINT), under the collaborative work of the Center for Plasma and Nuclear Fusion Technology (CPaF). It is a small tokamak with major radius $R = 0.65$ m and minor radius $a = 0.20$ m [1]. Originally, tokamak operation was designed for studying the auxiliary heating (NBI, ICRH, ECRH and LH) and the transport of the impurity. Study for operation of this machine can be prepared by computer simulation using the CRONOS integrated predictive modeling code [2]. The code has both capabilities of predictive and analytic simulations. It has been used in several works such as to analyze electron power balance with experimental profiles due to LHCD on EAST [3], to study the transport modelling with ITB in JT-60U and JET tokamaks for the prediction of high-beta steady state scenario in JT-60SA [4] and to perform scenario analysis in DEMO [5]. Simulation work on preparation of HT-6 M installment in Thailand has been done previously by J. Promping *et al.* to predict temperature profiles using different turbulent transport models including Mixed Bohm/gyro-Bohm model and Multi-mode model without external heating using BALDUR code [6]. This work investigated plasma temperature profiles when several parameters are varied using simulation. The CRONOS code consists of a 1D transport solver with general 2D magnetic equilibria and includes of several heat, particle and impurities transport models as well as heat, particle and momentum sources. In this work, a combination of a mixed Bohm/gyro-Bohm anomalous transport model [7] and an NCLASS neoclassical transport model [8] are used to calculate plasma core diffusivities [9]. In past experiments in HT-6 M, it was found that $H$-mode were obtained by Lower hybrid external heating [1]. Therefore, the edge area is described by a pedestal model based on international scaling [10], which

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was not taken into account in the previous BALDUR simulations [6]. This set of code is used to predict plasma profiles including electron and ion temperatures. The parameters that are varied include plasma current, toroidal magnetic field and external heating magnitude and scheme. Because the HT-6 M device is about to be upgraded to Thailand Tokamak, the result from this work will be useful for that propose. The paper is organized as follows: In section 2, the main parameters of the HT-6 M tokamak are presented. Section 3 discusses on the setup of simulation code, CRONOS. The plasma performance without external heating is shown in section 4. In section 5, the ion and electron temperatures resulting from external heating scheme of the tokamak such as ICRH, ECRH and LH are reported. The summary is given in section 6.

## 2. The HT-6 M Tokamak

The HT-6 M tokamak was a small tokamak with a full poloidal limiter. Previously, the main purposes were to study the high power auxiliary heating, investigation of edge plasma behavior and confinement improvement. It has a major radius of 0.65 m and minor radius of 0.20 m. There are 23 coils of the magnetic system, which consists of 16 toroidal field coils and 9 poloidal field coils. Material of vacuum vessel for HT-6 M is stainless steel. There were 10 diagnostics systems, which consist of the magnetic diagnostics, Far-infrared HCN laser interferometer, optic diagnostics, soft x-ray diagnostic, Langmuir probe, soft x-ray pulse height analyzer, absolute extreme ultraviolet radiation, electron cyclotron emission, hard x-ray emission and visible light camera [11]. The experiments done on HT-6 M were as follows:

- Experiments on pumping limiter
- Experiments on impurity transport
- Experiments on edge ohmic heating and confinement
- Experiments on ion cyclotron resonance heating
- Experiments on lower hybrid waves current drive and heating
- Experiments on electron cyclotron resonance heating
- Experiments on wall conditioning

Mainly, this work study plasma environment similar to that of a small HT-6 M tokamak using integrated predictive code based on the design parameters as shown in the Table 1. These are the basic inputs for all simulations in this work. Note that the parameters shown in the table depended on specification and experimental campaign.

Table 1 Design HT-6 M parameters [1].

| | |
|---|---|
| Major radius (m) | 0.65 |
| Minor radius (m) | 0.20 |
| Plasma current (kA) | 100 |
| Toroidal magnetic (T) | 1.5 |
| Central electron density ($m^{-3}$) | $2.0 \times 10^{19}$ |
| ICRF power (MW) | 0.1 - 0.5 |
| ECRH power (MW) | 0.1 - 0.5 |
| LH power (MW) | 0.1 - 0.5 |

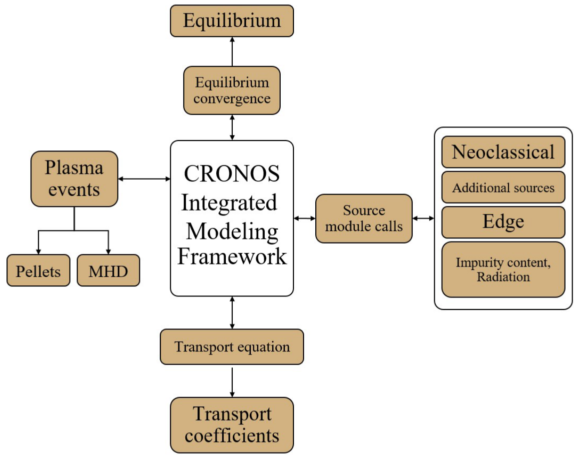


Fig. 1 Global CRONOS workflow with the main sophisticated physics modules around the core transport equation solver.

## 3. The CRONOS Suite

This work simulates tokamak plasma by using CRONOS suite which has capacities to predict experimental results. The core of CRONOS is a numerical code which solves the transport equations for various plasma fluid quantities, i.e. particle and impurities density, ion and electron temperatures, current density, plasma momentum, etc. The CRONOS workflow is shown in Fig. 1. A user of the CRONOS suite can control using a graphical interface, including access to experimental data for generating the input, multi-diagnostic profile fitting, visualizing the results and comparing with experimental databases or other simulations. In addition, CRONOS is also used for data validation, analysis of experiments, model validation, diagnostic studies, and predictive simulations.

The code solves the equation describing the conservation of the thermal energy flowing through the electron and ion as derived for the neoclassical theory in Ref. [2]:

$$V'^{\frac{5}{3}} Q_{\mathrm{j}} = \frac{3}{2}\frac{\partial}{\partial t}\left(P_{\mathrm{j}} V'^{\frac{5}{3}}\right) + V'^{\frac{2}{3}} \frac{\partial}{\partial \rho}[V' \langle |\nabla \rho|^2 \rangle (q_{\mathrm{j}} + \lambda T_{\mathrm{j}} \Gamma_{\mathrm{j}})], \quad (1)$$

where j is the notation for ion (i) and electron (e), $P_{\mathrm{j}}$ is the pressure, $\rho$ $(= r/a)$ is normalized minor radius defined by toroidal flux, $V$ is the volume enclosed inside the magnetic surface of flux coordinate $\rho$, $\lambda$ is the coefficient depending on the formulation of the transport model, $T_{\mathrm{j}}$ is the temperature, $q_{\mathrm{j}}$ is the heat flux flowing through ion or electron and $\Gamma_{\mathrm{j}}$ is the particle flux. The source term $Q_{\mathrm{i}}$ is the sum of the following contributions:

$$Q_i = Q_{ei} - Q_{neo} + Q_{i,LH} + Q_{i,NBI} + Q_{i,ICRH} + Q_{i,ECRH} + Q_{i,n0} + Q_{i,ext} + Q_{i,fus} + Q_{i,rip}, \quad (2)$$

where each respectively represents electron-ion collisional energy transfer, neoclassical contribution (opposite sign with respect to electron heat equation), LH, NBI, ICRH, ECRH, charge exchange, optional additional source 'EXT', fusion reactions and energy losses induced by toroidal magnetic field ripple. The source term $Q_e$ is the sum of the following contributions:

$$Q_e = -Q_{ei} + Q_{\Omega} + Q_{neo} + Q_{e,LH} + Q_{e,NBI} + Q_{e,ICRH} + Q_{e,ECRH} + Q_{e,n0} + Q_{e,ext} - Q_{rad} - Q_{brem} - Q_{cyclo} + Q_{e,fus} + Q_{e,rip}, \quad (3)$$

where each respectively represents the similar parameters as for the ion source. In addition, ohmic, line radiation (rad), bremsstrahlung (brem) and synchrotron radiations (cyclo) are included. The ion and electron heat flux can be calculated as the sum of a diffusive and a convective term:

$$q_j = -K_j \frac{\partial T_j}{\partial \rho} - P_j V_j^q, \quad (4)$$

where $K_j$ is the ion or electron conductivity, $V_j^q$ is the convective term, which is a pinch term (positive value means inward flux). The ion particle flux $\Gamma_i$ is linked to $\Gamma_e$, which guarantees electroneutrality in the assumption of diffusivity and convective velocity equality for all species (ions and electrons):

$$\Gamma_i = \alpha_e \Gamma_e - D_e n_e \frac{\partial \alpha_e}{\partial \rho}, \quad (5)$$

$$\Gamma_e = -D_e \frac{\partial n_e}{\partial \rho} - n_e V_e^{\Gamma}, \quad (6)$$

$$\alpha_e = \frac{n_i}{n_e} = \frac{\sum_{j=species} n_j}{n_e}, \quad (7)$$

where $n_i$ is the sum of the density of all ion species and $D_e$ is the electron diffusion coefficient. Note that the model used to predict electron and ion conductivity is a combination of Mixed Bohm/gyro-Bohm and NCLASS transport models.

In this simulation work, only stationary states of ion and electron temperatures profiles are predicted with fully relaxed current profile. Hydrogen is used for main ion species. The electron density is assumed to be fixed with its value at center equal to $2.0 \times 10^{19}\,m^{-3}$ as shown in Fig. 2. Impurity species used in this simulation consist of carbon dioxide and oxygen, resulting in $Z_{eff} = 1.5$. Plasma rotation is assumed to be zero, though in actual experiments certain degree of intrinsic and LH driven rotational sources are to be expected. Effects of ICRH, ECRH and LH sources and their magnitude on HT-6M like tokamak plasma are investigated. Additionally, the pedestal top is described by an international scaling law [10]. Width of pedestal is fixed from $\rho = 0.95$ to the edge of plasma.

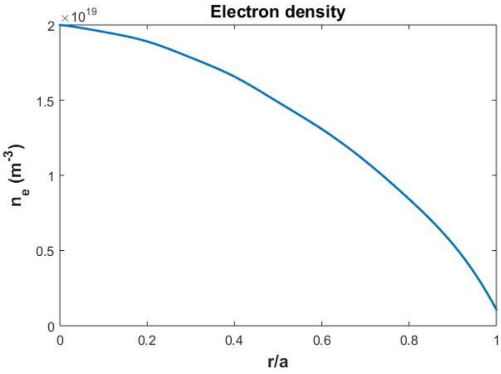


Fig. 2 Density profile.

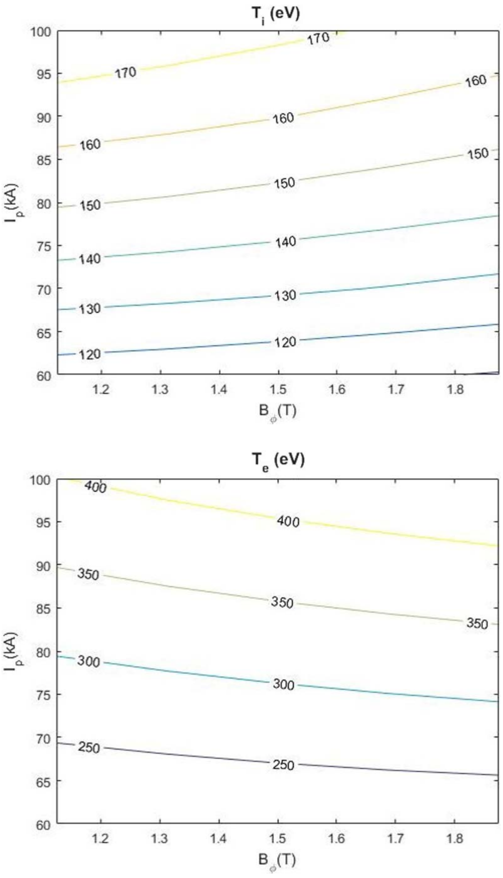


Fig. 3 Contour plots of central ion (top) and electron (bottom) temperatures at various plasma currents and toroidal magnetic fields.

# 4. Ohmic Phase Investigations

This part investigates the effects of plasma current and toroidal magnetic fields on ion and electron temperatures profiles. The plasma current ranges from 60 to 100 kA, less than 70% increase. While, the toroidal magnetic field ranges from 1.125 to 1.875 T, about the same percentage increase. Figure 3 illustrates the contour plots of central electron and ion temperatures. It can be seen that both ion and electron temperature profiles are more sensitive to the changes of plasma current. The central value of electron temperature is increased from around 200 to 410 eV, about two times improvement, when plasma current is varied. Meanwhile, the central value of ion temperature is increased from 120 to 170 eV, about 40% increase. As the magnetic field is increased, the electron temperature is slightly enhanced because of better plasma confinement. On the contrary, the ion temperature is slightly reduced because the decrease of energy exchange rate, this will be illustrated more detailed in the next section. In summary, the results show that in this regime of plasma, it is more desirable to increase plasma current instead of the magnetic field. This trend is similar to the predictions using BALDUR code made by J. Promping *et al.*, though the temperatures are different because of the difference in electron densities and temperature boundary conditions used [6]. This simulation result is also close to the experimental set-up in Li Jian-gang *et al.*, ($T_{\rm i}$ = 200 eV, $T_{\rm e}$ = 500 eV when $B_\phi$ = 1 T and $I_{\rm P}$ = 60 ∼ 100 kA) [1]. As the tokamak is intrinsically a pulsed machine because it is relying so much on inductive current. Non-inductive current drive scheme is needed so that the tokamak can be run continuously. A lower hybrid current drive is a possible solution for this. An advanced plasma scenario with ITB and ETB formations are also desired because of the high bootstrap current generation [12].

## 5. External Heating Effects

In this section, ion and electron temperatures profiles are shown as functions of position in form of normalized minor radius defined by toroidal flux location of plasma $r/a$. Each line represents steady-state simulation results using different magnitude of the heating power. The external heating types used for investigation consists of ICRH, ECRH and LH. The plasma current ($I_{\rm p}$) is set at 100 kA. The toroidal magnetic field is assumed to be 1.5 T on its axis. The heating power of range 0.1 - 0.5 MW is used as it was shown in the experiment of HT-6 M that *L-H* transition could be achieved [1]. Ion and electron temperatures profiles with the ICRH power varied is shown in Fig. 4. It can be clearly seen that ion and electron temperature are increased when ICRH power is increased. As the power ICRH source is increased, shown in Fig. 5, more energy is transferred to the electron than ion in the plasmas, which results in higher increase in electron temperature than ion. Thus, at core of plasma, ion and electron temperature is directly proportional to ICRH power. Additionally, it is found that both temperature profiles at the edge of the plasma can form a transport barrier in case of ICRH equals to 0.2 - 0.5 MW, signifying by steep raising of the temperature profiles. This transition agree with HT-6 M experiments [1].

The effect of ECRH on ion and electron temperatures is demonstrated in Fig. 6. It can be seen that electron temperature is increased due to energy is transferred to electron in the plasmas when ECRH power is increased. On the

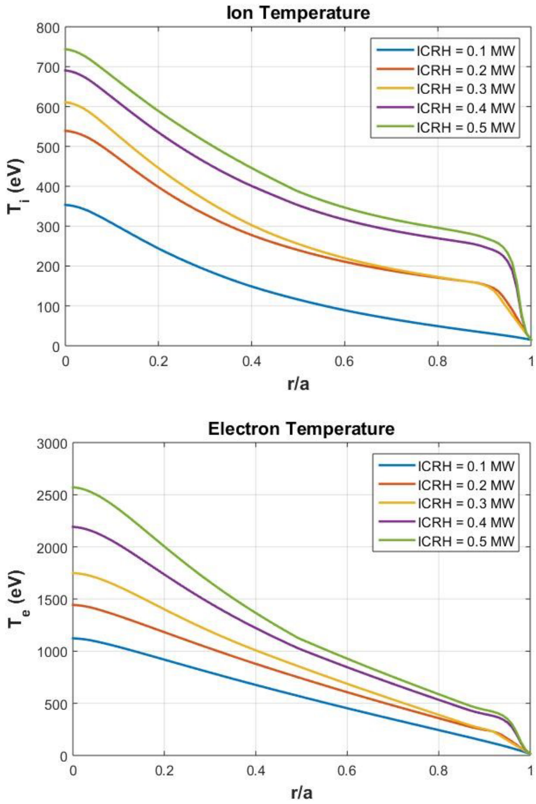


Fig. 4 Ion and electron temperatures as functions of normalized minor radius defined by toroidal flux of plasma when $I_{\rm P}$ = 100 kA, $B_\phi$ = 1.5 T and ICRH power was varied.

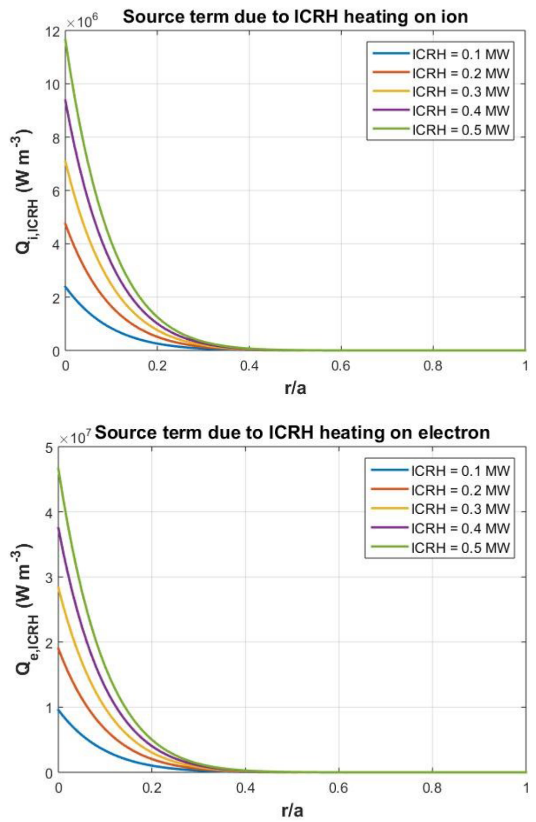


Fig. 5 Source term due to ICRH heating on ion and electron.

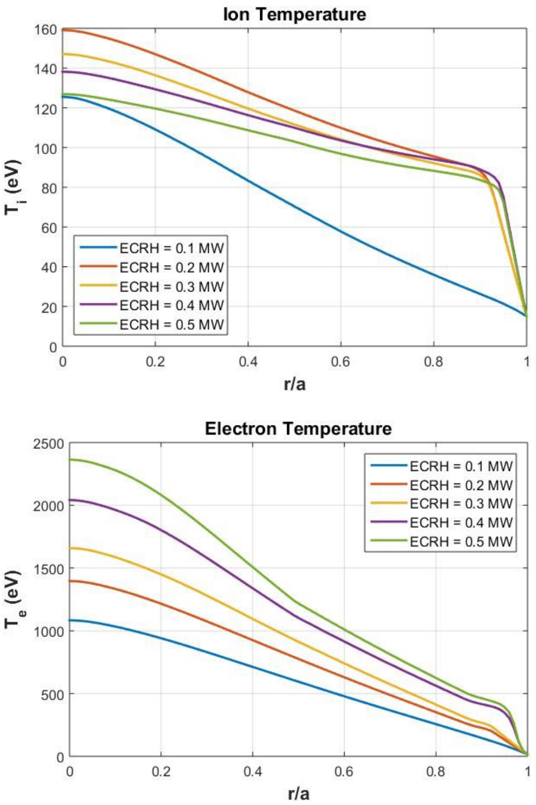


Fig. 6 Ion and electron temperatures as functions of normalized minor radius defined by toroidal flux of plasma when $I_P$ = 100 kA, $B_\phi$ = 1.5 T and ECRH power was varied.

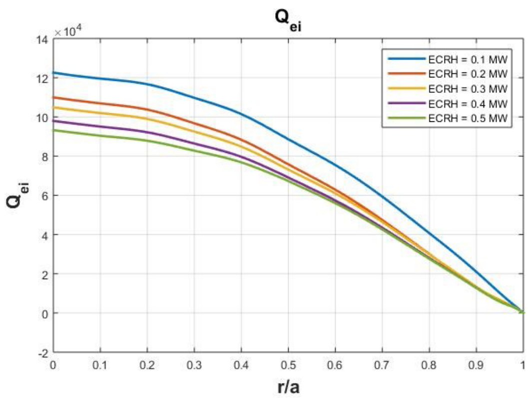


Fig. 7 The electron-ion energy exchange in ECRH power.

other hand, ion temperature decrease when ECRH power increase in case of 0.2 - 0.5 MW. This behavior is due to the fact that energy source term due to ECRH contributing to ion equals to zero. That means the electron-ion energy exchange, shown in Fig. 7, is the only main source in ion heat transport equation. Hence, the decrease of the electron-ion energy exchange results in ion temperature reduction. This energy exchange can be enhanced by the difference between electron and ion temperatures, which increases with the power. Thus, the reduction in the energy exchange is due to the reduction of electron-ion collision with in-

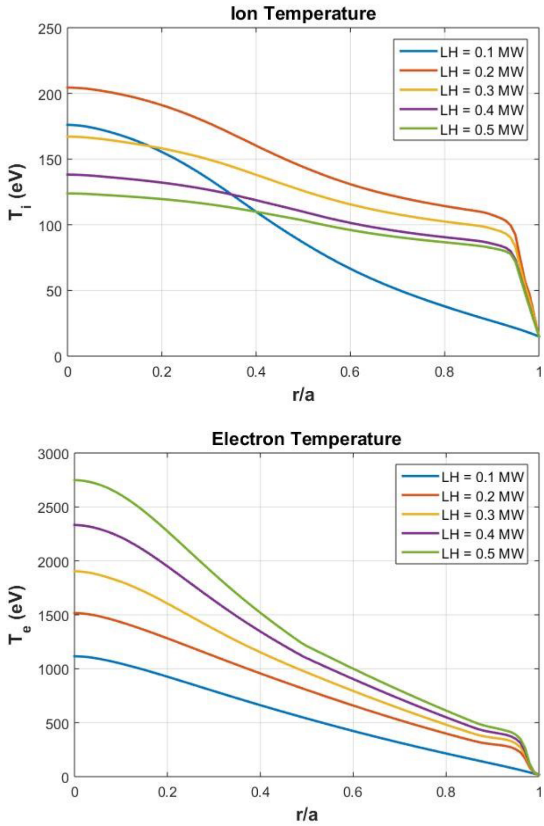


Fig. 8 Ion and electron temperatures as functions of normalized minor radius defined by toroidal flux of plasma when $I_P$ = 100 kA, $B_\phi$ = 1.5 T and LH power was varied.

crease in electron temperature. Similarly, it appears that a formation of transport barrier at the edge of the plasma can form in case of ECRH equals to 0.2 - 0.5 MW in both ion and electron channels. Thus, central ion temperature is inversely proportional to ECRH power in case of 0.2 - 0.5 MW, electron temperature is directly proportional to ECRH power in case of 0.1 - 0.5 MW.

Figure 8 shows effect of LH power on ion and electron temperatures. Evidently, electron temperature is directly proportional to LH power but ion temperature is inversely proportional to LH power in case of 0.2 - 0.5 MW power. The reason is the same as that in the case of ECRH heating. In addition, the formation of an edge transport barrier can be found as well when LH power is above 0.2 MW. Therefore, at core of plasma, ion temperature is inversely proportional to LH power in case of 0.2 - 0.5 MW, electron temperature is directly proportional to LH power in case of 0.1 - 0.5 MW.

Considering in case of 0.2 - 0.5 MW of all external heating, it can be seen that the edge temperature profiles exhibit steep gradients. This behavior can be explained by the theory for *L-H* transition, the change in profile at the edge of the plasma where there is a rapid increase in the temperature gradient, which is a characteristic of an edge transport barrier, ETB. This work uses international scaling law to estimate the threshold power [10]:

$$P_{\mathrm{Th}} = 1.38(n/10^{20})^{0.77} B_{\phi}^{0.92} R^{1.23} a^{0.76}\ \mathrm{MW}. \quad (8)$$

The transition to $H$-mode requires that the heating power must be above a certain threshold. With $2.0 \times 10^{19}\ \mathrm{m}^{-3}$ of electron density, 1.5 T of toroidal magnetic field, 0.65 m of major radius and 0.20 m of minor radius, the calculation shows that the transition will occur at 0.100541 MW heating power. The typical ohmic heating power based on parameters used in simulations is around 17.5 kW, which is around 20% comparing to the transition power.

## 6. Conclusions

This work predicts the temperature profiles of ion and electron in the plasma based on HT-6 M tokamak which will be installed in Thailand in the near future. The simulations are carried out using a 1.5D integrated predictive simulation code CRONOS. The transport model includes both anomalous and neoclassical effect. The $H$-mode pedestal model is included based on an international scaling law. The plasma remains in $L$-mode when there is no external heating given so it is solely heated by Ohmic. The simulation results provide us to understand the relation between the temperatures with several parameters, which can be concluded as; increase of the plasma current directly increases the ion and electron temperatures. Whereas, increase of the toroidal magnetic field decreases the ion temperature and increases the electron temperature. The central electron temperature ranges from 200 to 410 eV, whereas ion temperature ranges from 120 to 170 eV. When external heating is given, the results show that the ion and electron temperature at the core of plasma is directly proportional to ICRH power. Increase of the ECRH and LH decreases the ion temperature, whereas these two sources increases electron temperature at the core of plasma. The calculated ranges of central ion temperature from 120 to 750 eV, while central electron temperature ranges from 1,100 to 2,750 eV. The transition to $H$-mode requires total heating power to be above 0.1 MW, approximately. In summary, ICRH power yields the highest ion temperature for all of range 0.1 - 0.5 MW and LH power yields the highest electron temperature for range of 0.2 - 0.5 MW.

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