Projected performance of ITER based on different theoretical based pedestal temperature models

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Abstract. Self-consistent modeling of the ITER has been carried out using the 1.5D BALDUR integrated predictive modeling code. In these simulations, the boundary is taken to be at the top of the pedestal, where the pedestal values are described using the theory-based pedestal scalings. These pedestal temperature scalings are based on three different pedestal width models: magnetic and flow shear stabilization, flow shear stabilization, and normalized poloidal pressure. The pedestal width scalings are combined with a pedestal pressure gradient scalings based on ballooning mode limit to predict the pedestal temperature. The developed pedestal temperature scalings are used together with a core transport model, which is a combination of an anomalous transport and a neoclassical transport. An anomalous transport is calculated either using the Mixed Bohm/gyro-Bohm (Mixed B/gB) core transport model or the Multimode (MMM95) core transport model, while a neoclassical transport is computed using the NCLASS model. At the reference design point (with 40 MW auxiliary heating: 33 MW NBI and 7 MW RF), it is found that the pedestal temperatures with different pedestal width scaling ranges from 2.4 keV to 2.8 keV. As a result, the performances with the same anomalous core transport model are almost similar. It is also found that the simulations using MMM95 yield better performance than those using Mixed B/gB. In addition, when the MMM95 is used, it appears that the ion temperature gradient (ITG) and trapped electron modes (TEM) are the most dominant modes. When the Mixed B/gB is used, it appears that the Bohm contribution is the most dominated term.

1. Introduction
The ITER project is an international collaborative effort with an aim to demonstrate the scientific and technological feasibility of fusion energy using magnetic confinement fusion concept [1]. Due to the fact that high confinement mode (H-mode) discharges in tokamaks generally provide excellent energy confinement and have acceptable particle transport rates for impurity control, burning fusion experiments such as ITER tokamak are designed to operate in the H-mode regime. The improved performance of H-mode mainly results from the formation of the edge transport barrier, called pedestal. Therefore, the performance of ITER depends sensitively on the pedestal values.

In the previous ITER performance study by G. Bateman and his colleagues [2], the BALDUR integrated predictive modeling code [3] with the Multi-mode (MMM95) anomalous transport model
[4] together with neoclassical transport, calculated using the NCLASS neoclassical model [5], 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 [6]. It is assumed that 40 MW of RF heating power is used as the auxiliary heating power, where 24 MW of RF heating power goes to thermal ions, and 16 MW of RF heating power 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 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 with both ion and electron pedestal temperature of 2.7 keV. In the later ITER performance study by T. Onjun and his colleagues [7], ITER simulations were carried out using the JETTO integrated predictive modeling code with the Mixed Bohm/gyro-Bohm (Mixed B/gB) anomalous transport model [8] with NCLASS neoclassical transport. In addition, the combination of 33 MW of NBI heating power and 7 MW RF heating power (similar to ITER reference design) was used. When a fix pedestal width of 6 cm (the ion and electron pedestal temperature of 4.9 and 4.4 keV, respectively) is 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 would occur in the second stability regime of ballooning modes. Therefore, the values at the top of the pedestal used in the JETTO simulations are higher than those used in the BALDUR simulations. It is worth noting that the dynamic of pedestal width is not included in the JETTO simulations; while it is included in the BALDUR simulations.

In this work, the BALDUR integrated predictive modeling code is used to carry out simulations of the ITER plasma with the standard $H$-mode scenario. Due to the design of BALDUR code, the BALDUR simulations are started from the top of the pedestal to the center of the plasma. As a result, several important edge physics may not be properly included and might be ignored such as the effects of ELM crashes. However, it is enough to properly describe the plasma core behaviors [9, 10].

Two issues have been investigated for ITER. The first issue is the sensitivity of the ITER performance on the model for predicting pedestal temperature. Three different theoretical based pedestal temperature models are used in this investigation. These pedestal temperature models were developed using three different pedestal width concepts: magnetic and flow shear stabilization width scaling [11], flow shear stabilization width scaling [6], and normalized poloidal pressure width scaling [12]. These pedestal width scalings are combined with a pedestal pressure gradient model based on first stability regime of infinite n ballooning mode. It was found in reference [6] that these pedestal temperature models could yield equally well agreement with the pedestal data obtained from the ITPA pedestal database [13]. This exploration will provide more confidence in the BALDUR predictions. Due to the fact that ITER is designed to operate with high triangularity, low collisionality and high bootstrap current, the plasma is likely to obtain an access to second stability regime of ballooning modes. However, since the pedestal temperature models used in this work do not include effects of an access to second stability regime of ballooning modes and peeling mode instability, the results can be treated only as a low bound of the ITER performance projection. Secondly, the sensitivity of core transport prediction is explored. The BALDUR simulations are extended to be carried out with two different anomalous core transport models: the Multimode (MMM95) core transport model or the Mixed Bohm/gyro-Bohm (Mixed B/gB) core transport model. Both core transport models were derived from different approaches: MMM95 is a theoretical based anomalous transport model; while Mixed B/gB is an empirical based anomalous transport model. The brief details of both models can be found in section 2. It is worth mentioning that the simulations using both core transport models yield about 10% RMS deviation with experimental data for both $L$-mode [9] and $H$-mode plasmas [10]. This exploration will also provide a confidence on the predicted performance of ITER tokamak. In addition
with those issues, there are several minor modifications on these simulations comparing with those simulations carried out in reference [2] — such as the auxiliary heating power (using 33 MW of NBI heating power and 7 MW RF heating power) and the sawtooth model (using Porcelli sawtooth triggering model [14] and modified Kadomtsev magnetic reconnection model [15]).

This paper is organized as follows: brief descriptions for a BALDUR integrated predictive modeling code, anomalous transport models, and pedestal models are given in section 2. The ITER prediction using a BALDUR integrated predictive modeling code is described in section 3, while conclusions are given in section 4.

2. BALDUR integrated predictive modeling code

The BALDUR integrated predictive modeling code 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 also computed self-consistently. The BALDUR simulations have been intensively compared against various plasma experiments, which yield an over all agreement with 10% relative RMS deviation [9, 10]. In BALDUR code, fusion heating power is determined by 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 [3]. The fusion heating component of the BALDUR code also computes the rate of the production of thermal helium ions and the rate of the 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 [8] 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 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.

The version of the MixedB/gB model that is used in this paper can be briefly described below. Both the electron and ion thermal diffusivities consist of two terms. One term has Bohm scaling

$$\chi^B = \rho_e g^2 \frac{a(dp_e/dr)}{p_e} \Delta T_e,$$  \hspace{1cm} (1)

while the other term has gyro-Bohm scaling.
where \( r_s \) is the ion gyroradius, \( c_s \) is the sound speed, \( q \) is the safety factor, \( p_e \) is the electron pressure, \( a \) is the minor radius and \( T_e \) is the electron temperature. In the Bohm diffusivity expression, \( DT_e \) is a finite difference approximation to the normalized temperature electron temperature difference at the plasma edge

\[
\Delta T_e = \frac{T_e(r/a = 0.8) - T_e(r/a = 1)}{T_e(r/a = 1)}.
\]

The resulting anomalous ion and electron thermal diffusivities are constructed from the sum of these Bohm and gyro-Bohm terms, with empirically determined coefficients

\[
\chi_i = 1.6 \times 10^{-4} \chi^B + 1.75 \times 10^{-2} \chi^B,
\]

\[
\chi_e = 8.0 \times 10^{-5} \chi^B + 3.5 \times 10^{-2} \chi^B,
\]

and the hydrogenic and impurity charged particle diffusivity is given by

\[
D \propto \frac{\chi_i \chi_e}{\chi_i + \chi_e}.
\]

### 2.2. Multimode core transport model

The MMM95 model [4] 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 \( \beta \). The resistive ballooning model in MMM95 transport model is based on the 1993 E×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. However, for the ITER case in this work, it is surprisingly found that the contribution from the kinetic ballooning mode plays quite a significant role in the region near the plasma core up to a radius of 1.0 m. This will be discussed in section 3. 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 \( \kappa^4 \), since the models were originally derived for circular plasmas.

### 2.3. Pedestal model

In the development of the pedestal temperature models described in reference [6], two ingredients are required: the pedestal width (D) and the pressure gradient (\( \partial p / \partial r \)). If the pedestal density (\( n_{ped} \)) is known, the temperature at the top of the pedestal (\( T_{ped} \)) can be estimated as
The pedestal temperature, $T_{\text{ped}}$, is given by:

$$T_{\text{ped}} = \frac{1}{2n_{\text{ped}}k} \left[ \frac{\partial p}{\partial r} \right] \Delta,$$

where $k$ is the Boltzmann constant, $\mu_0$ is the permeability of free space, $\alpha_c$ is the normalized critical pressure gradient, $B_T$ is the magnetic field, $R$ is the major radius and $q$ is the safety factor. In this work, three pedestal temperature models in reference [6] are selected. These pedestal temperature models yield equally well agreement with the pedestal data from the ITPA Pedestal Database. These pedestal models are based on either the magnetic and flow shear stabilization width scaling ($\Delta \propto \rho s^2$) [9], the flow shear stabilization width scaling ($\Delta \propto \sqrt{\rho R q}$) [6], or the normalized poloidal pressure width scaling ($\Delta \propto R \sqrt{B_{\theta,\text{ped}}}$) [10], where $\rho$ is the ion gyro radius, $s$ is the magnetic shear, and $B_{\theta,\text{ped}}$ is the normalized poloidal pressure. The pedestal pressure gradient calculation is normally complicated and required a lot of details. For simplicity, the pedestal gradient is assumed to be uniform throughout the pedestal region and the pedestal gradient is limited by the first stability limit of infinite $n$ ballooning mode, so that the normalized critical pressure gradient for the pedestal region is estimated by

$$\alpha_c = 0.4 s (1 + \kappa_{95}^2 (1 + 5 \delta_{95}^2)),$$

where $\kappa_{95}$ is the elongation at the 95% flux surface, and $\delta_{95}$ is the triangularity at the 95% flux surface. The further details of these pedestal temperature models can be obtained from reference [6]. It is worth noting that these pedestal temperature models were derived from different pedestal width scalings. The pedestal width constant in each model was chosen to minimize the RMS deviation with 533 experimental data points from 4 large tokamaks obtained from the ITPA pedestal database. So, in this work the pedestal models with the chosen width constant in reference [6] are used. These pedestal temperature models include the effect of edge bootstrap current, which has an impact on magnetic shear and safety factor. This inclusion results in a non-linear behavior in the pedestal temperature model. The scheme to deal with the calculation of magnetic shear and safety factor was addressed in reference [6]. Note that the descriptions for magnetic shear and safety factor in the pedestal model are different from the rest of the code.

The pedestal density, $n_{\text{ped}}$, 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:

$$n_{\text{ped}} = 0.71 n_l.$$

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

### 3. Simulation results and discussion

The BALDUR integrated predictive transport modeling code is used to carry out the simulations of ITER with the designed parameters ($R = 6.2$ m, $a = 2.0$ m, $I_p = 15$ MA, $B_T = 5.3$ T, $\kappa_{95} = 1.85$, $\delta_{95} = 0.33$ and $n_l = 1.0 \times 10^{20}$ m$^{-3}$). In this work, the plasma parameters are ramped up to the target values within 15 sec, which is a faster ramp-up than that used in the ITER simulations in reference [2]. It is found that the plasma reaches the $H$-mode phase at the time of 4 sec. It is worth noting that even though the plasma current reaches its flat top with in 15 sec, complex interactions within the plasma itself — such as the self plasma heating by the alpha particle and redistribution of heating power after sawtooth crash — still occurs and lead to interesting observation. Note that the sawtooth oscillation is considered during the time of 15 sec to 297 sec. For each simulation, 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 of the same values. In most simulations, 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. The effect of sawtooth oscillation is also included, where a Porcelli sawtooth model [14] is used to determine a sawtooth crash and a modified Kadomtsev magnetic reconnection model [15] is used to describe the effects of sawtooth crash.

Figure 1 shows the profiles for ion and electron temperatures and electron density as a function of minor radius at a time of 300 sec using Mixed B/gB and MMM95 core transport models. In these figures, these simulations are carried out using a pedestal temperature model based on the magnetic and flow shear stabilization width model. It can be seen that the ion and electron temperature profiles are peak profiles. For the density profiles, the simulation with the MMM95 transport model is quite an unusual profile. There is a small humps in the region about 60% of the plasma and contain a smaller peak at the region close to the center of the plasma. However, this type of density profile is often observed in plasma simulations with the MMM transport model [9, 10]. When different pedestal temperature model is used, it is found that the pedestal temperatures and central temperatures in the simulation using the pedestal temperature based on normalized poloidal pressure width model is the highest, while those in the simulation using the pedestal temperature based on flow shear stabilization is the lowest. The results are summarized in table 1. It is worth noting that the central temperatures obtained in the ITER simulation using the BALDUR code in reference [2] are higher than the results obtained in this work. This might due to the change of auxiliary heating and sawtooth model. A full investigation must be taken to resolve this issue. At this moment, we rather leave the issue for a future work.

The results of the ion pedestal temperature and the corresponding central ion temperature are summarized in table 1. It can be seen that the pedestal temperature ranges from 2.4 keV to 2.8 keV, where the central temperature ranges from 10.3 keV to 16.5 keV. The values of ion pedestal temperature are not much different, but the central ion temperature is significantly different among the simulations using the Mixed B/gB core transport and the MMM95 core transport models. It is worth noting that these pedestal temperature models were derived from different pedestal width scalings. The pedestal width constant in each models was chosen to minimize the RMS deviation with the experimental values obtained from the ITPA pedestal database [6].

Table 1 Summary of pedestal values and central ion temperature in the simulations for different pedestal temperature models using either Mixed Bohm/gyro-Bohm or Multi-mode transport model

| Pedestal model | Pedestal width | Mixed Bohm/gyro-Bohm model | Multi-mode model |
|----------------|----------------|---------------------------|-----------------|
| 1              | \( \Delta \propto \rho \) | \( T_{i,\text{ped}} \) (keV) | \( T_{i,0} \) (keV) | \( T_{i,\text{ped}} \) (keV) | \( T_{i,0} \) (keV) |
| 2              | \( \Delta \propto \sqrt{\rho R_q} \) | 2.6 | 10.8 | 2.7 | 16.3 |
| 3              | \( \Delta \propto R \sqrt{\beta_{\text{\theta,ped}}} \) | 2.8 | 11.5 | 2.9 | 16.5 |
Figure 1. Profiles for ion temperature (top), electron temperature (middle) and electron density (bottom) are shown as a function of minor radius at a time of 300 sec. These BALDUR simulations are carried out using Mixed B/gB model (solid line) and MMM95 model (dotted line). The pedestal temperature model based on magnetic and flow shear stabilization is used to provide the temperature boundary conditions.
Figure 2 shows the ion thermal diffusivities as a function of minor radius from simulations using the Mixed B/gB transport model. Note that the ion temperature and density profiles for this simulation are shown in figure 1. The pedestal model based on magnetic shear and flow shear stabilization width model is used for predicting boundary conditions. The “effective” thermal diffusivity, for example, is defined as the heat flux divided by the density times temperature gradient—with no separate contribution for convection. The total thermal diffusivities shown in figure 2 are the contributions from the Bohm and gyro-Bohm terms in the Mixed B/gB model as well as neoclassical transport, which has gyro-Bohm scaling. It can be seen in figure 2 that the Bohm contribution to the Mixed B/gB transport model is the dominant contribution to the ion thermal diffusivities everywhere in the plasma, except in the region closed to the center of the plasma, where the neoclassical transport is the most dominant. It can be seen that the ion thermal diffusivity is less than 1 m$^2$/s in the region from the center of the plasma to the radius of 80% of minor radius. This result for the transport is observed in all simulations with Mixed B/gB in this work. It is worth mentioning that the dominance of the Bohm contribution is similar to those results with the Mixed B/gB transport model reported in references [9, 10].

![Figure 2](image)

**Figure 2.** Ion diffusivities from the Mixed B/gB transport model are shown as a function of minor radius at a time of 300 sec. This simulation is carried out using the pedestal temperature model based on magnetic and flow shear stabilization width model. The blue line shows the Bohm contribution, the pink line shows the gyro-Bohm contribution, the red line shows the neoclassical contribution, and the green line shows the total ion thermal diffusivity.

Figure 3 shows the ion thermal diffusivities as a function of minor radius from a simulation using the MMM95 transport model for ITER. Note that the temperature and density profiles for this simulation are shown in figure 1. The pedestal model based on magnetic shear and flow shear stabilization width model is used for predicting boundary conditions. Note also that the Multi-mode ion thermal transport model consists of the ion temperature gradient and trapped electron modes, the drift-resistive ballooning modes, and the kinetic ballooning modes. It can be seen in figure 3 that the contribution from the ITG and TEM modes is the main contribution to most of the region of the plasma, except the region closed to the center of the plasma, where the neoclassical transport is the most dominant. The thermal transport from the kinetic ballooning mode plays a significant role in the region between normalized minor radius of 10% to 50%, whereas the resistive ballooning mode is small almost everywhere. This behavior of the kinetic ballooning mode is quite surprising since the...
contribution from this mode is normally small. It is worth mentioning that in the region from the center of the plasma to the edge of plasma, the ion thermal diffusivity is less than 1 m$^2$/s, except at the last grid point that the ion thermal is slightly above 1 m$^2$/s. Because of stronger thermal transport in the region near the edge of plasma when the Mixed B/gB transport model is used, the lower temperature profile is found. This result for the transport is observed in all simulations with MMM95 in this work. It is worth noting that there is a large drop in the kinetic ballooning mode transport and a notch in the ITG/TEM transport at the minor radius of about 1.1 m. This probably associates with the inverse density gradient because of the density hump at around that radius. This issue requires a further study. At this moment, we will leave this issue for future work.

![Figure 3](image)

**Figure 3.** Ion diffusivities from the MMM95 transport model are shown as a function of minor radius at a time of 300 sec. This simulation is carried out using the pedestal temperature model based on magnetic and flow shear stabilization width model. The blue line shows the ITG and TEM contribution, the pink line shows the RB contribution, the violet line show the KB contribution, the red line shows the neoclassical contribution, and the green line shows the total ion thermal diffusivity.

There are two types of auxiliary heating used in the ITER simulation. The total amount of neutral beam injection heating power, $P_{\text{NBI}}$, is 33 MW. Another source of auxiliary heating is the RF heating. The total amount of RF heating power is 7 MW. For simplicity, the RF heating profiles are taken to be a parabolic shape, although it is recognized that the physics of RF heating might be more complicated in the ITER plasma. Note that Ohmic heating is small compared to other types of heating. The alpha heating power is also shown in figure 4. It is found that the alpha heating power is about 49.4 MW.

In figure 5, the deuterium and tritium density profiles are plotted as a function of minor radius at the time of 300 sec. In this simulation, the anomalous core transport is described by MMM95 model. It can be seen that the shape of both profiles is similar to the shape of electron density profile. There is a small humps in the region about 60% of the plasma and contain a smaller peak at the region close to
Figure 4. The heating power density profiles are plotted as a function of minor radius. In this simulation, 40 MW of auxiliary heating is used (33.0 MW of NBI heating power and 7.0 MW of RF heating power). The alpha heating power from the fusion reaction is about 49.4 MW. This simulation is carried out using MMM95 model and the pedestal temperature model based on magnetic and flow shear stabilization width model.

Figure 5. The deuterium and tritium density profiles are plotted as a function of minor radius. This simulation is carried out using MMM95 model and the pedestal temperature model based on magnetic and flow shear stabilization width model.

the center of the plasma. This type of density profiles can not yield good alpha power production. If this is a case, a consideration of density peaking might be required. It is also found that in the simulation with MMM95 model, the particle transport and impurity transport is the same up to the minor radius of 0.6 m. On the other hand, in the simulations with Mixed B/gB, the impurity transport is set to be the same with the particle transport.
In figure 6, the central ion temperature and alpha power is plotted as a function of time during time of 250 sec to 300 sec for the simulations using the Mixed B/gB and MMM95 models. Note that the pedestal model based on magnetic shear and flow shear stabilization width model is used for predicting boundary conditions in this simulation. It can be seen that the central ion temperature and alpha power production oscillate due to the effects of sawtooth crashes. It is found that during a sawtooth crash, the central ion temperature drops about 26% and 24% for the simulations using Mixed B/gB and MMM95 models, respectively. On the other hands, it is found that during a sawtooth crash,

![Graph showing central ion temperature and alpha power as a function of time for simulations using Mixed B/gB and MMM95 models.](image)

**Figure 6.** Central ion temperature (top panel) and alpha power (bottom panel) are plotted as a function of time. This simulation is carried out using the pedestal temperature model based on the magnetic and flow shear stabilization width model. The red line shows the simulation using Mixed B/gB and the blue line shows the simulation using MMM95.
the alpha power production suddenly increases about 7% in both simulations. The results was reported and explained in reference [2]. Note that the Porcelli model is used for calculating when sawtooth crash occurs and a modified Kadomtsev magnetic reconnection model is used to describe the effects of sawtooth crash. The details of the sawtooth triggering model and the Kadomtsev magnetic reconnection model can be found in references [14, 15]. It is found in all simulations that almost all of sawtooth crashes are triggered by the trapped of fast ion (equation 13 in reference [14]). It is found that the frequency of the sawtooth oscillation is almost the same for both transport model (0.8 Hz for Mixed B/gB and 0.7 Hz for MMM95 during the last 20 sec). The sawtooth mixing radius in the simulation using Mixed B/gB tends to be larger than that using MMM95 (116.1 cm for Mixed B/gB and 109.2 cm for MMM95 during the last 20 sec). It can be seen that the mixing radius of sawtooth oscillation in ITER is about half of the minor radius. This is an important issue for ITER and further investigation must be taken.

The fusion performance can be evaluated in term of Fusion $Q$, which can be calculated as

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

(10)

where $P_{\alpha, \text{avg}}$ is an average alpha power and $P_{\text{AUX}}$ is an auxiliary heating power (equal to 40 MW for these simulations). The results of average alpha power and fusion $Q$ are summarized in table 2. The higher alpha power production and fusion $Q$ in the simulation using MMM95 results from higher temperature prediction. Note that the average alpha power is taken during the time of 250 sec to 300 sec.

Table 1 Summary of pedestal values and central ion temperature in the simulations for different pedestal temperature models using either Mixed Bohm/gyro-Bohm or Multi-mode transport model

| Pedestal model | Pedestal width | Mixed Bohm/gyro-Bohm model | Multi-mode model |
|---------------|----------------|---------------------------|-----------------|
|               | $\Delta \propto \rho s^2$ | $P_{\alpha}$ (MW) | Fusion $Q$ | $P_{\alpha}$ (MW) | Fusion $Q$ |
| 1             | $\Delta \propto \rho \sqrt{P R q}$ | 13.9 | 1.7 | 49.4 | 6.2 |
| 2             | $\Delta \propto R \beta_{\alpha, \text{ped}}$ | 16.3 | 2.0 | 51.2 | 6.4 |

4. Conclusions
Self-consistent modeling of the International Thermonuclear Experimental Reactor (ITER) has been carried out using the 1.5D BALDUR integrated predictive modeling code. In these simulations, the boundary is taken to be at the top of the pedestal, where the pedestal values are described using the theoretical-based pedestal model. These pedestal temperature models are based on three different pedestal width scalings: magnetic and flow shear stabilization, flow shear stabilization, and normalized poloidal pressure. These pedestal width scalings are combined with a pedestal pressure gradient model based on ballooning mode limit to predict the pedestal temperature. The developed pedestal temperature models are used together with a core transport model, which is a combination of an anomalous transport and a neoclassical transport. An anomalous transport is calculated either using the Mixed Bohm/gyro-Bohm (Mixed B/gB) core transport model or Multimode (MMM95) core transport model, while a neoclassical transport is computed using the NCLASS model. At the reference design point, it is found that the pedestal temperatures in all simulations with different pedestal width scaling are nearly the same. As a result, the performances with the same transport model are similar. It is also found that the simulations using MMM95 yield more fusion power than those using Mixed B/gB. When the MMM95 is used, it appears that the ion temperature gradient
(ITG) and trapped electron modes (TEM) are the most dominant modes. When the Mixed B/gB is used, it appears that the Bohm contribution is the most dominant term.

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