



Preliminary Testing of Integrated Simulation for *L*-mode Tokamak Plasma from consistent Core-Edge-SOL with BALDUR Code

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Abstract

An integrated predictive modeling code BALDUR based on transport model with neoclassical transport which calculated by NCLASS module and the anomalous transport Multi-Mode-Model version 2001 (MMM2001) is used to calculate for a core region of tokamak plasma. Moreover, the small amount of residual plasma between the edge of the plasma and the tokamak vessel named scrape-off-layer (SOL) is performed as boundary conditions of the edge and core region, it has been included to carry out self-consistent effects on low confinement mode (*L*-mode). Therefore, the experimental data of *L*-mode discharges from tokamak named TFTR and statistical analysis root mean square (RMS), and offset are used to calibrate and to validate the simulation data that carried out by BALDUR code. The results show good agreement of the simulation data compared to the experimental data for electron temperature, ion temperature, and electron density.

Keywords: tokamak, tokamak plasma, SOL, *L*-mode and BALDUR.

1. Introduction

The Low Confinement mode (*L*-mode) is one regime which is interested scenario for burning plasma experiments in the magnetic confinement fusion concept. However, the performance of *L*-mode plasma is lower than the High Confinement mode (*H*-mode) when the plasmas are heated with the same input power, but *H*-mode discharges are often perturbed by quasi-periodic bursts of energy and particles in

the region near the edge of the plasma. This activity is referred to "*Edge Localized Modes*" (ELMs); each ELM crash results in a rapid loss of particles and energy at the plasma boundary. Thus, if the understanding of *L*-mode plasmas is better, it could potentially improve the *L*-mode performance to be in a more desirable regime, because the *L*-mode has more stable and easy to control the plasma when compared to the *H*-

mode. Normally, the tokamak plasma can be divided into three main regions, shown in Fig. 1.

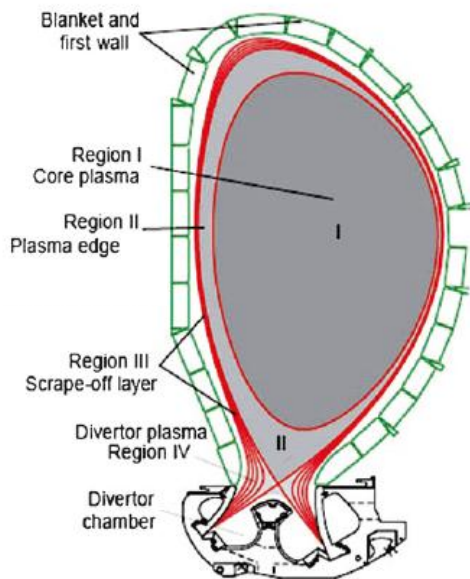


Fig. 1 Cross section of a tokamak, showing the three main regions. [1]

Core plasma region: It is the main part of the plasma, which extends from the center of the plasma up to the edge region that is close to separatrix. At here, the plasma is confined then it is produced the fusion energy from this zone.

Edge plasma region: It is a narrow region which is located between the core region and the separatrix. Normally, at this region the transport barrier will be occurred in *H*-mode plasma. The transport barrier is characterized by sharp temperature and density gradients as named "pedestal". However, when tokamak plasma is operated in *L*-mode, the pedestal does not formed because the total power is lower than the threshold power [2].

Scrape-off-Layer (SOL): It is the region outside of the last closed magnetic flux surface or separatrix, where magnetic field lines run into the limiter or divertor. The SOL plasma is essentially governed by two-dimensional effects,

such as the flows of heat and particles along magnetic field lines as well as across field lines. The physics of the SOL is dominated by atomic process and plasma wall interactions. This physics is obtained by the particle flow to material surfaces; it is primarily due to diffusion from the plasma core into the edge region. In the edge boundary layer the plasma flows along the magnetic field and then interacts with a solid surface. Ions which are incident at this surface may then be neutralized and backscattered or released in other ways to re-enter the plasma. This process is known as "recycling".

For the previous paragraph, the important of SOL is illustrated as "Sink and Source" of energy and particles of tokamak plasma, hence in this paper, the particle and heat-loss model at the SOL that has been developed by W. D. Langer and C. E. Singer [3] is used to predict the plasma profiles in SOL region then the plasma profiles are evolved to edge and core region with Multi-mode anomalous core transport model version 2001 (MMM2001).

Thus, this work is organized as follows: the details of a SOL model will be described in the next section, then brief information of the anomalous core transport MMM2001, and the integrated predictive modeling code BALDUR are described, respectively. In section5, the simulation results for standard *L*-mode will be validated by the statistical method compare to the experimental data from tokamak TFTR; they are presented and discussed. The final section is conclusion.

2. Particle and Heat-loss model at SOL



Plasma transport models of radial flow in tokamaks with a divertor or pumped limiter must include particle and heat-loss terms due to flow along magnetic-field lines in the scrapeoff. The plasma entering the scrapeoff flows along open field lines until it reaches the neutralizer plate. The resulting neutral gas interacts with the incoming plasma and modifies its properties and flow. The greatest effect occurs when there is a large recycling of the neutral gas. This happens when the neutrals are ionized by the plasma near the neutralizer and are swept back to the neutralizer with the cycle repeated a number of times. This enhancement of the plasma flow near the neutralizing surface serves to amplify the particle flux and reduce the temperature, thereby minimizing erosion. The amplification of particle flux due to recycling also reduces the upstream plasma flow velocity along the field lines in the scrapeoff, thus changing the edge density of the main plasma region. To solve the flow of material entering the scrapeoff into a high-recycling region, the model ignores all radial flows in the scrapeoff and considers only parallel flow along the field lines. The fluid equations, including sources, have been derived in arbitrary coordinates. When cross-field transport near the mid-plane is sufficient to give broad profiles of density and temperature, only flow along the field lines need be considered near the divertor. Assuming a constant ratio of poloidal to total magnetic field B_θ/B , the fluid equation for the flows of ions, total momentum, and total energy can be written:

$$\frac{d}{ds}(nu) = S_i \quad (1)$$

$$\frac{d}{ds}(mnu^2 + n(T_e + T_i)) = 0 \quad (2)$$

$$\frac{d}{ds} \left[q^e + \left(\frac{5}{2} n(T_e + T_i) + \frac{1}{2} mnu^2 \right) u \right] = W \quad (3)$$

where; u is a fluid velocity, m is a ion mass, S_i is a ion source due to ionization of neutrals, W is energy source, q^e is a parallel electron heat conduction, S is the distance along a magnetic field line, and T_e and T_i is electron and ion temperature, respectively.

3. Anomalous core transport model

The Multi-Mode Model version 2001 (MMM2001) is a combination of theory-motivated transport models used to predict plasma profiles in tokamaks. It consists of the Weiland model for the ion temperature gradient (ITG) and trapped electron modes (TEM) [4], the Guzdar-Drake model for drift-resistive ballooning modes [5, 6], and kinetic ballooning modes [7]. Usually, the Weiland model for drift modes provides the largest contribution, followed by drift-resistive ballooning mode and kinetic ballooning mode, respectively. The Weiland model $\chi_{Weiland}$ 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 quasi-linear approximation for the thermal and helium transport fluxes. The Weiland model includes many different physical phenomena such as effects of trapped electrons, unequal ion and electron temperatures, impurities, fast ions, finite β and collisions. The resistive ballooning model χ_{RB} in MMM2001 transport model is based on the 1993 $E \times B$ 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. The kinetic ballooning model χ_{KB} is a semi-empirical model, which usually provides a small contribution to the total diffusivity throughout the plasma, except near the magnetic axis. However, the kinetic ballooning model plays quite a significant role in the region near the plasma core up to a radius. This model is an approximation to the first ballooning mode stability limit. All the anomalous transport contributions to the MMM2001 transport model are multiplied by κ^{-4} since the models were originally derived for circular plasmas. The expressions of transport coefficients in MMM2001 are:

$$\chi_i = 0.8\chi_{i_{ITG\&TEM}} + 1.0\chi_{i_{RB}} + 1.0\chi_{i_{KB}}$$

$$\chi_e = 0.8\chi_{e_{ITG\&TEM}} + 1.0\chi_{e_{RB}} + 1.0\chi_{e_{KB}}$$

$$D_H = 0.8D_{H_{ITG\&TEM}} + 1.0D_{H_{RB}} + 1.0D_{H_{KB}}$$

$$D_z = 0.8D_{z_{ITG\&TEM}} + 1.0D_{z_{RB}} + 1.0D_{z_{KB}}$$

where, χ_e is the electron diffusivity, χ_i is the ion diffusivity, D_H is the particle diffusivity, D_z is the impurity diffusivity, $\chi_{ITG\&TEM}$ is the thermal diffusivity of ion temperature gradient and trapped electron mode, χ_{RB} is resistive ballooning thermal diffusivity and χ_{KB} is kinetic ballooning thermal diffusivity.

4. Code descriptions

The transport models, which used in BALDUR, integrated predictive modeling code. It 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 overall agreement of 10% RMS deviation [8, 9]. 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. 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. The brief details of these transport models are described below.

5. Simulation Results and Discussions

5.1 Profile Comparison

The predicted plasma profiles are carried out using the anomalous core transport model (MMM2001) to couple with the SOL model for the L-mode discharge from TFTR, which represents the gyro-radius (ρ^*) scan (discharge number 50904). In this discharge, the engineering parameters compose of major radius (R) = 2.45m, minor radius (a) = 0.80m, toroidal magnetic (B_T) = 2.86T, plasma current (I_p) = 1.19MA, line average density ($\overline{n_e}$) = $2.58 \times 10^{19} \text{ m}^{-3}$, auxiliary heating power (P_{aux}) = 7.17MW, and diagnostic time = 3.95sec. These parameters are used as boundary conditions for BALDUR simulation and the SOL temperature

and density are set at 1eV and $1 \times 10^{17} \text{ m}^{-3}$, respectively.

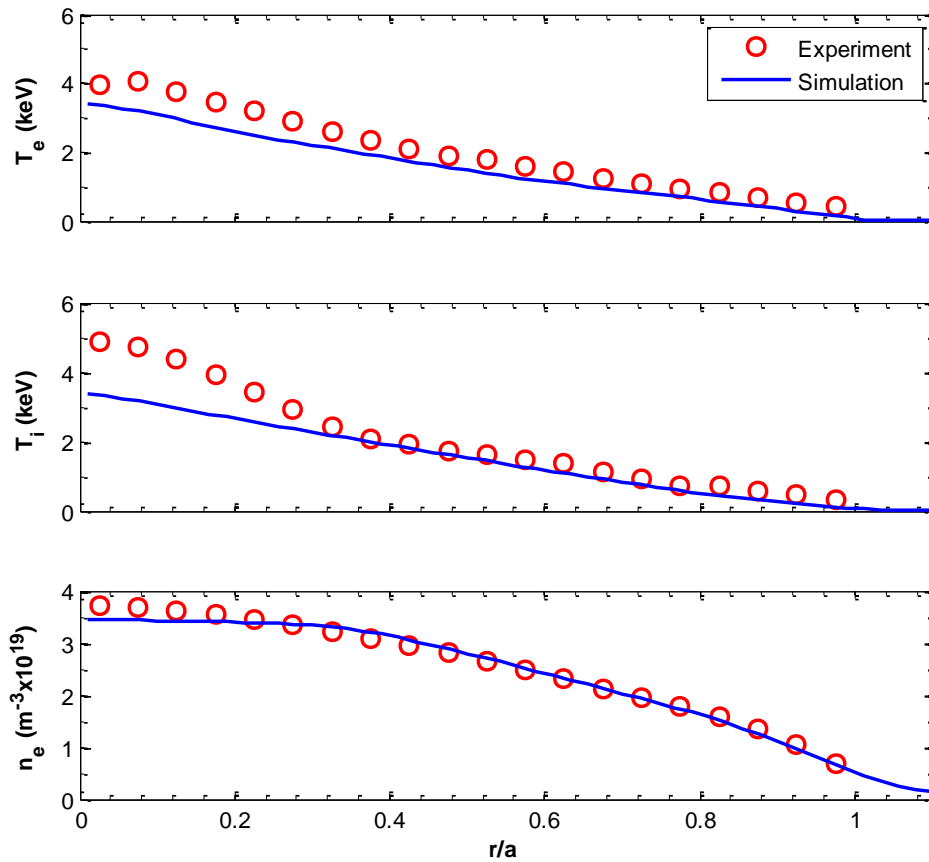


Fig. 2 The profile of electron temperature, ion temperature, and electron density as a function of normalized minor radius. The simulation result is carried out by BALDUR with an anomalous core transport model MMM2001 that couples with a SOL model. This simulation data compares to the TFTR tokamak experiment data discharge 50904 at a diagnostic time.

The comparison result is shown in Fig.2. In the case of electron temperature and ion temperature, the simulation can fit the experiment well at the core to the edge area ($r/a = 0.3-1.0$). However, at the center of plasma ($r/a = 0.0-0.3$) the simulation shows underpredict the experiment in both cases. For electron density, the simulation fit very well to the experiment along the minor radius of plasma.

5.2 Statistical analysis

To quantify the comparison between simulations and experiments, the percentage of root-mean-square (%RMS) deviation is computed based on the difference between simulation profiles and experimental data. In this paper, the %RMS is defined as Eq. (4).

$$\%RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{X_{exp_i} - X_{sim_i}}{X_{exp_0}} \right)^2} \times 100 \quad (4)$$



$$\text{Offset} = \frac{1}{N} \sum_{i=1}^N (\ln(X_{exp_i}) - \ln(X_{sim_i})) \quad (5)$$

where, X_{exp_i} is the i th data point of the experimental profile, X_{sim_i} is the corresponding data point of the simulation profile and X_{exp_0} is the maximum data point of the experimental profile of X as a function of radius, which has N points in total.

It shows RMS of electron temperature and ion temperature equal to 11.86% and 14.22%, respectively as well as RMS of electron density equals to 2.87%. Moreover, the offset values of electron temperature, ion temperature, and electron density equal to -0.11, -0.10, and -0.00, respectively. These can be indicated the minus sign of offset for all profiles; most of the simulation predicted lower than the experiment.

6. Conclusions

The simulation results that carried out from BALDUR with the multi-mode anomalous core transport model version 2001 (MMM2001) and it couples with the sink and source particles in SOL region. It shows the capability of the precision prediction of experiment along a minor radius to the wall of a TFTR tokamak for L -mode regime.

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8. References

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