PS05: การจำลองผลจากเครื่องโทคาแมค JET โดยรวมลักษณะขอบเขตการแพร่ด้านในและด้านขอบ

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บทคัดย่อ

งานวิจัยนี้เป็นการใช้โปรแกรมจำลองแบบ 1.5 มิติ ชื่อ BALDUR เพื่อจำลองผลการทดลองหมายเลข 40542 กับ 40847 ของเครื่องปฏิกรณ์ฟิวชั่น JET โดยได้รวมปรากฏการณ์ที่เกิดขึ้นสองอย่างเข้าไปด้วยคือ ขอบเขตการแพร่ด้านใน (Internal Transport Barrier, ITB) และด้านขอบ (Edge Transport Barrier, ETB) ซึ่งได้กำหนดขอบเขตของพลาสมาจากจุดสูงสุดของเพเดสทอล (pedestal) โดยทฤษฎีที่ใช้จำลอง ETB นั้นมีพื้นฐานมาจาก การจำลองอุณหภูมิที่เพเดสทอล โดยใช้การประมาณอัตราส่วนของความกว้างของเพเดสทอล ที่เป็นผลมาจาก โมเดลของการทำให้การไหลของสนามแม่เหล็กไฟฟ้าคงตัว และการจำลองความต่างของความดันด้วยทฤษฎีขีดจำกัดพลาสมาในรูปแบบบอลลูน (ballooning mode limit) ส่วนทฤษฎีที่ใช้จำลอง ITB นั้นมีพื้นฐานมาจากโมเดลการเคลื่อนที่กึ่งสัดส่วนชื่อ Mixed Bohm/gyro-Bohm (Mixed B/gB) ซึ่งใช้ในการคำนวณ การเปลี่ยนแปลงตามเวลาของปริมาณทางฟิสิกส์ในพลาสมา โดยในที่สุดทฤษฎีของ ITB และ ETB ทั้งสองนี้ ได้นำไปใช้ในการจำลองการเปลี่ยนแปลงตามเวลาของ อุณหภูมิและความหนาแน่นของพลาสมา สำหรับสองการทดลองที่ JET ดังได้กล่าวเบื้องต้น และได้มีการวิเคราะห์ทางสถิติเช่น หารากของค่าเฉลี่ยกำลังสอง ของผลการจำลองเพื่อเทียบกับผลการทดลอง

คำสำคัญ: เขตกั้นการแพร่ด้านใน เขตกั้นการแพร่ที่ขอบนอก โทคาแมค

JET Simulations with Edge and Internal Transport Barriers Included

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Abstract

A 1.5D BALDUR integrated predictive modeling code is used to simulate self-consistent two optimized shear JET experiments [discharge number 40542 and 40847] with the presence of both an edge transport barrier (ETB) and an internal transport barrier (ITB). The edge of the plasma is taken to be at the top of the pedestal. The pedestal temperature is obtained using the theory-based pedestal width scaling, which is based on a magnetic and flow shear stabilization model. The pedestal pressure gradient scaling is based on ballooning mode limit. Furthermore, a version of the semi-empirical Mixed Bohm/gyro-Bohm (Mixed B/gB) core transport model that includes ITB effects is used to compute the time-evolution of plasma profiles. In this model, the anomalous transport in the core is stabilized by the influence of $E_r xB$ flow shear and magnetic shear, which results in a formation of ITB. This Mixed B/gB transport model with ITB effects combined with the pedestal model is used to simulate the time-evolution of temperatures and density profiles for JET discharges. Statistical analysis, such as the calculation of root-mean square errors (RMSE) of both simulation and experimental data, is used to quantify the agreement.

Keywords: Internal transport barrier, Edge transport barrier, Tokamak

1. Introduction

Energy confinement concept in tokamaks is very important because it reflects nuclear fusion energy performance. It is known that the performance improvement is caused by formation of an edge transport barrier, called the pedestal. Additionally, a formation of an internal transport barrier inside the plasma also improves the performance. The presence of both transport barriers greatly improves plasma temperature and hence nuclear fusion power production. Therefore, it is very important to understand how both barriers are formed.

The model for ITB used in this paper is based on literature review of ITB (both theoretical work and experimental work). It is called semi-empirical Mixed Bohm/gyroBohm (Mixed B/gB) core transport model which proposes that formation of ITB is due to E_rxB flow shear and magnetic shear[1]. While a temperature scaling model based on magnetic and flow shear stabilization and pressure gradient scaling model based on ballooning limit are used to describe how ETB is formed.

In this paper, a 1.5D BALDUR Integrated Predictive Modeling Code is used to simulate the time-evolution profiles of electron density, electron temperature and ion temperature. Impliment the models above into the code, the results are compared with experimental results of two optimized shear JET (Joint European Torus) discharges [40542 and 40847]. Statistical analysis such as root-mean square error is applied to quantify the agreement. Acceptable results imply the models used are valid.

An introduction to BALDUR code is presented in section 2, along with ITB (Mixed Bohm/GyroBohm) and ETB (Scaling pedestal width and pressure gradient) models. In section 3, experimental data are presented and statistical analysis is discussed. Results of experiment and discussion are explained in section 4. And in the section 5, summary is given.

2. Theory and Modelling

This section introduces theories and models used in calculation of plasma profile, the BALDUR predictive code is also introduced here.

2.1 1.5D BALDUR Integrated Predictive Modeling Code

BALDUR is a time-dependent one and half dimensional transport modelling code which is used to compute many physical quantities in tokamaks. The code simulates the plasma profiles such as time-evolution of electron density, electron and ion temperatures[2] as in this paper. It can also be used to compute other physical quantities like impurity densities, magnetic q and other gas components densities[3].

BALDUR code compute these profiles by mixing many physical processes together which includes transport, plasma heating, particle flux, boundary conditions, and sawtooth oscillations[3]. It is accepted widely that results from BALDUR yield results that are reasonably in agreements with experimental profiles.

2.2 ITB Models

ITB is defined as a separation of temperature at two neighbouring radial locations at some instant of time[4]. The physical mechanism of the ITB formation has not yet been clearly identified. However, it is found that ω_{ExB} flow shear and magnetic shear have played role on forming ITB[1].

ITB formation and dynamics is modelled through a semi-empirical transport model called mixed Bohm/gyro-Bohm[5]. It includes the effect of suppression of core anomalous transport due to

ω_{ExB} flow and magnetic shear[6]. This model is an empirical because it was first a local transport model with Bohm scaling which means the diffusivities are proportional to the gyro-radius times thermal velocity. The model then was modified to additionally describe ion transport and called gyro-Bohm, in order to simulate both smaller and larger size tokamaks. Gyro-Bohm scaling thus means the diffusivities are proportional to square of the gyro-radius times thermal velocity divided by plasma major radius[3]. The model can be expressed as following[5]

$$\chi_e = 1.0\chi_{gB} + 2.0\chi_B, \tag{1}$$

$$\chi_i = 0.5\chi_{gB} + 4.0\chi_B, \tag{2}$$

$$D_H = D_Z = (0.3 + 0.7\rho)\frac{\chi_e \chi_i}{\chi_e + \chi_i}, \tag{3}$$

where

$$\chi_{gB} = 5\times10^{-6}\sqrt{T_e}\left|\frac{\nabla T_e}{B_T^2}\right|, \tag{4}$$

$$\chi_B = \chi_{B_0} \times \Theta\left(-0.14 + s - \frac{1.47\omega_{E\times B}}{\gamma_{ITG}}\right), \tag{5}$$

with

$$\chi_{B_0} = 4\times10^{-5} R \left|\frac{\nabla(n_e T_e)}{n_e B_T}\right| q^2 \left(\frac{T_e(0.8\rho_{max}) - T_e(\rho_{max})}{T_e(\rho_{max})}\right) \tag{6}$$

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, χ_{gB} is the gyro-Bohm contribution, χ_B is the Bohm contribution, ρ is normalized minor radius, T_e is the local electron temperature, B_T is the toroidal magnetic field, R is the major radius, n_e is the local electron density, υ_{th} is electron thermal velocity, and γ_{ITG} is the linear growth rate.

In this work, ω_{ExB} shearing rate is calculated according to Hahm-Burrell model[7,8]

$$\omega_{ExB} = \left|\frac{RB_\theta^2}{B_T}\frac{\partial(E_r/RB_\theta)}{\partial\psi}\right|, \tag{7}$$

where $B\theta$ is the poloidal magnetic field, Ψ is the poloidal flux, and E_r is the radial electric field, which is calculated as follows:

$$E_r = \frac{1}{Zen_i}\frac{\partial p_i}{\partial r} - v_\theta B_T + vB_\theta \tag{8}$$

where $\partial p_i/\partial r$ is the pressure gradient, v_θ and v are the poloidal and toroidal velocities, respectively, and, n_i is the ion density, Z is the ion charge number and e the elementary charge. Note that the toroidal velocity is taken directly from the experiment.

2.3 ETB Models

In this study, the boundary condition of the plasma is set to be at the top of pedestal, which is where transport barrier is observed[3]. The pedestal is a region of steep gradient, shown in Fig. 1.

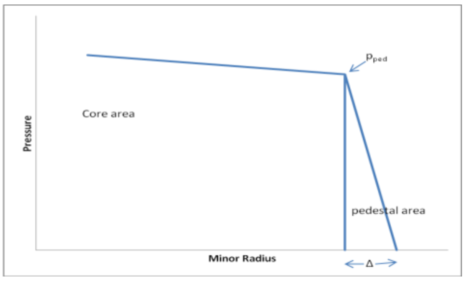


Fig. 1: Plot of pressure profile near edge of plasmas.

It is assumed that the pressure gradient ($\partial p/\partial r$) within this region is constant so the pedestal temperature (T_{ped}) in keV unit can be calculated as the following[9].

$$T_{ped} = \frac{1}{2kn_{ped}} \Delta \left| \frac{\partial p}{\partial r} \right| \tag{8}$$

Where n_{ped} (m^{-3}) is pedestal density, k is the Boltzmann's constant, and Δ is the pedestal width. n_{ped} is obtained from experimental data (all JET discharges), while width of the pedestal region and the pressure gradient are estimated using models in this paper.

The pedestal pressure gradient scaling is limited by the ballooning mode instability[10]. It is based on the assumption that there exists maximum normalized pressure gradient with critical pressure gradient[9], α_c

$$\alpha_c(s,\kappa s,\kappa) = -\frac{2\mu_0 Rq^2}{B_T^{\ 2}} \left(\frac{\partial p}{\partial r} \right)_c \tag{10}$$

Here, s is magnetic shear, κ is elongation, δ is triangularity, μ_0 is permeability of free space, R is tokamak major radius, q is safety factor, and B_T is vacuum toroidal magnetic field. Rewrite this relation and substitute pressure gradient into equation (10) to obtain

$$T_{ped} = \frac{\Delta}{2kn_{ped}} \frac{\alpha_c B_T^{\ 2}}{2\mu_0 Rq^2} \tag{11}$$

The pedestal width scaling model is based on magnetic and flow shear stabilization[9]. There is an assumption that the transport barrier is formed in the region where the turbulence growth rate is balanced by a stabilizing $E_r xB$ shearing rate. The scaling width is derived in paper [9] to be

$$\Delta = c_1 \rho s^2 = c_1 \left(4.57 \times 10^{-3} \frac{\sqrt{A_H T_{ped}}}{B_T} \right) s^2, \tag{12}$$

where C_1 is the constant of proportionality and A_H is the average hydrogenic mass. Combine this scaling with previous pressure gradient scaling, the final T_{ped} is as

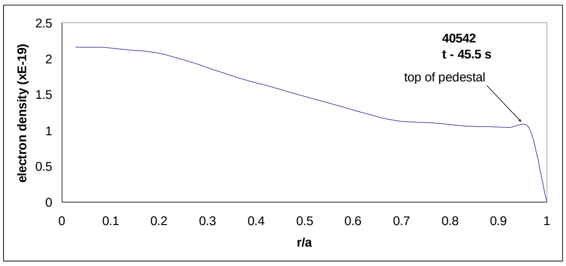
$$T_{ped} = c_1^2 \left(\left(\frac{4.57 \times 10^{-3}}{4\mu_0 \left(1.6022 \times 10^{-16}\right)} \right)^2 \left(\frac{B_T^{\ 2}}{q^4} \right) \left(\frac{A_H}{R^2} \right) \left(\frac{\alpha_c}{n_{ped}} \right)^2 s^4 \right) \tag{13}$$

This result will be used in BALDUR code for calculation of plasma profiles. The constant C_1 is chosen to optimize the agreement and from reference [9], it is found to be 2.42.

3. Experimental Data

The experimental data used in this study are taken from two JET discharges [40542 and 40847]. The top of the pedestal is identified from experimental electron density profile, shown in Fig. 2. It can be that ETB was formed.

In this experiment, the values of toroidal velocity v are taken from the real experiment in order to calculate the ω_{ExB} shearing rate. Fig. 3 illustrates their plots as a function of normalized minor radius at time t = 47 s for discharge 40542, which is when ITB formation was found (please see section 4).



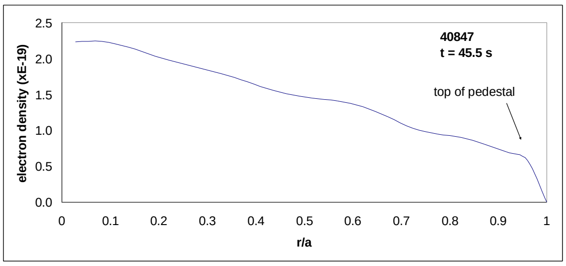
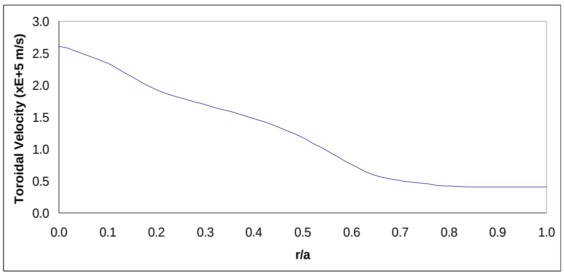


Fig. 2: Electron density profiles are plotted as a function of normalized minor radius for JET discharge 40542 (left) and 40847 (right)



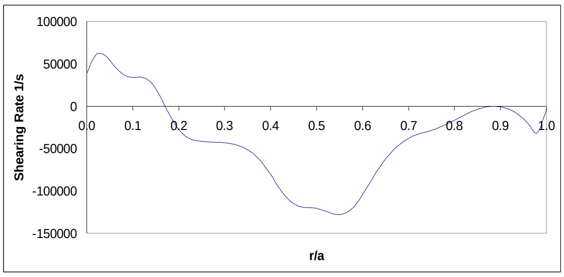


Fig. 3: Toroidal velocity (left) and ω_{ExB}(right) shearing rate are plotted as a function of normalized minor radius for JET discharge 40542 at t = 47 s (when ITB found)

To quantify the comparison between the predictions of electron density, electron and ion temperatures, and experimental data, the root mean-square error (RMSE) is computed[9]. The RMSE and offset are calculated as follows:

$$\mathrm{RMSE}(\%) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{T_{\exp_i} - T_{\mathrm{mod}_i}}{T_{\exp,0}}\right)^2} \times 100 \qquad (14)$$

$$\mathrm{Offset} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{T_{\exp_i} - T_{\mathrm{mod}_i}}{T_{\exp,0}}\right), \qquad (15)$$

where N is total number of data, T_{expi} and T_{modi} are the i^{th} experimental and model results of temperature, and $T_{exp,0}$ is experimental temperature at centre of tokamaks. Calculations for electron density are similar.

4. Results and Discussions

The BALDUR code is used to carry out simulations of two optimized shear JET discharge number 40542 and 40847. In discharge 40542, the plasma was initiated with a fast current ramp, 0.5 MW of ICRH (Ion cyclotron resonance heating) was used for pre-heating. Then NBI (neutral beam injection) was stepped up from 0 to 10 MW at 45.0 seconds and then to 18 MW at 45.4 seconds. Experimentally, ITB was formed at 45.4 seconds and it persisted throughout the run. Plasma remained in L-mode until 46.15 seconds then transition to an ELMy (Edge localized mode of instability) H-mode occurred. Parameters used in simulation are R = 2.73 m, a (minor radius) = 0.98 m, I_p (current) = 1.99 MA, and B_T = 35.7 T.

For discharge 40847, the parameters used are similar; R = 2.89 m, a = 0.96 m, I_p = 1.37 MA, and B_T = 35 T. The discharge also began with initiated fast current ramp, 1 MW of ICRH was used for pre-heating from 43.0 – 45.0 seconds. NBI was stepped up from 0 to 10 MW at 45.0 seconds and to 18 MW at 45.4 seconds. ITB was found to form at 45.3 seconds. The plasma was in L-mode until 46.76 seconds before the transition to ELM-free H-mode occurred.

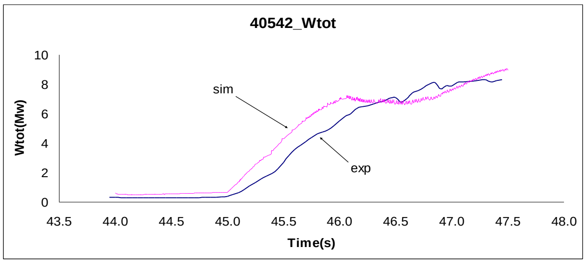


Fig. 4: Total plasma energy of discharge 40542 experimental and simulation results

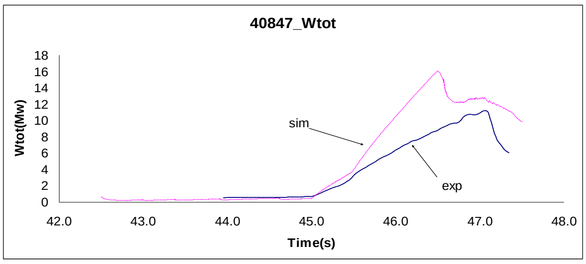


Fig. 5: Total plasma energy profiles of discharge 40847 experimental and simulation results

Figures 4 and 5 show W_{tot} (total plasma energy) as a function of time. Comparing between experimental and simulation results, both exhibits same trend even though the simulations over-predict by small amount. The 40542 simulation over-predict maximum W_{tot} by about 1 MW, while the 40847 simulation over-predict maximum W_{tot} more than 3 MW.

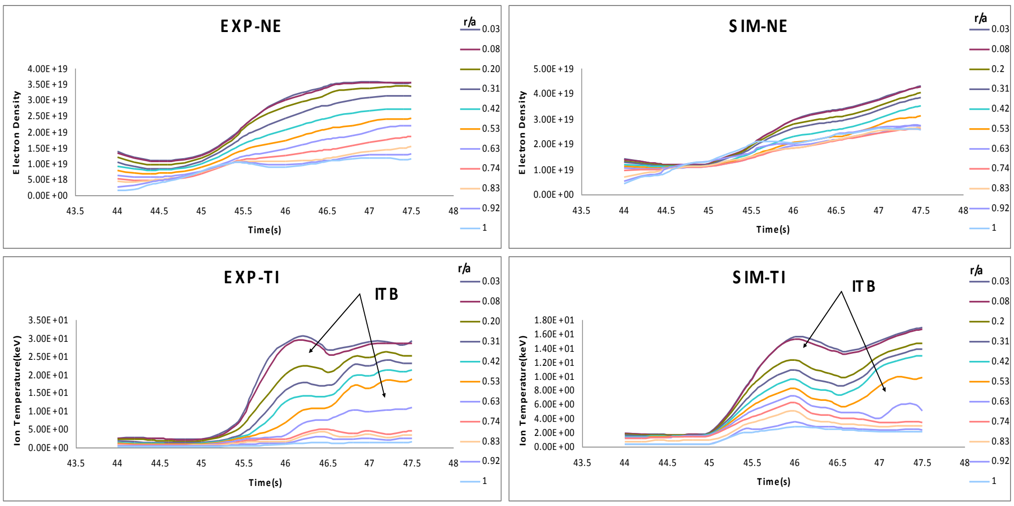


Fig. 6: NE and TI results for 40542 discharge, ITB formation identified.

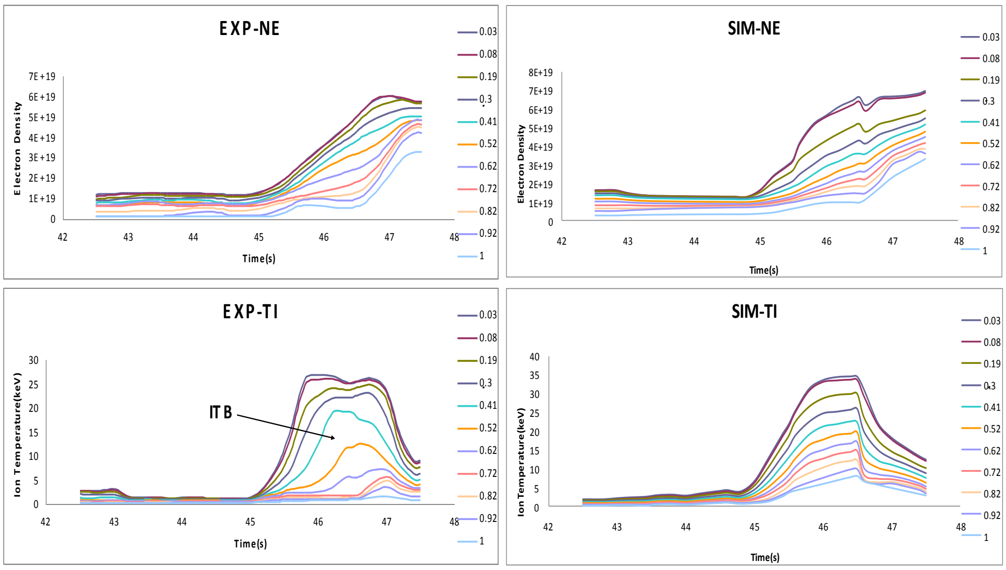


Fig. 7: NE and TI results for 40847 discharge, ITB formation identified.

Figures 6 and 7 illustrate the time evolution profiles of electron density and ion temperature for both discharges, comparing between experimental (left) and modelling (right) results. For these plots, x-axis represents time, y-axis represents corresponding density or temperature. Note that the plot began from time greater than 40 seconds which is after when full-heating was applied to the tokamaks and densities started to increase. Each line corresponds to fraction of tokamaks minor radius (r/a). They are in order from the topmost one being 0.03 (plasma’s core) to the bottommost one being 1.00 (plasma’s edge). The model successfully simulates formation of ITB for TI profiles of discharge 40542. According to the simulation, at time 45.6 seconds, ITB started to form close to the plasma’s core (r/a between 0.08-0.2). Later at time 46.7 seconds, it shifted toward the plasma’s edge (r/a between 0.4–0.6).

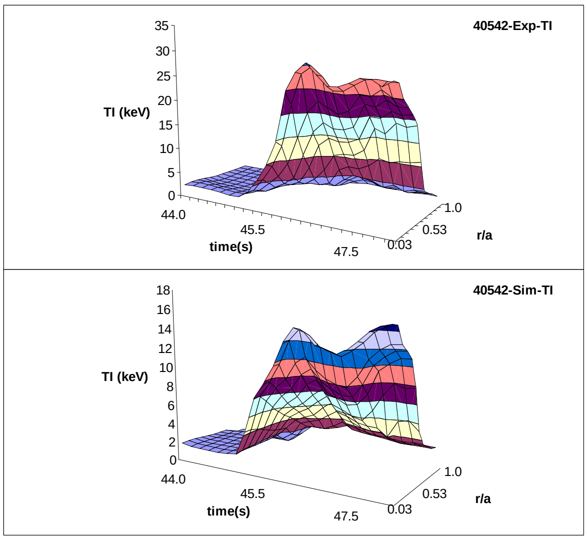


Fig. 8: TI 3-D plots of 40542 discharge, experiment (top) and simulation (bottom)

Two 3-D plots of this temperature profile is showed in figure 8, comparing between experimental and simulation results. As oppose to the first discharge, ITB formation did not appear in the modelling of discharge 40847. This is caused by sudden loss in W_{tot} at time 46.5 seconds as seen in Figure 4. Consequently, an abrupt drop in NE and TI can be observed during that time, see figure 6.

To verify formation of ITB of 40542 result as described previously, TI are plotted as a function of r/a at two different times, 46.2 seconds and 47.0 seconds (figure 9). First graph shows ITB formation near core of the tokamak and the second graph shows ITB formation further away toward the edge.

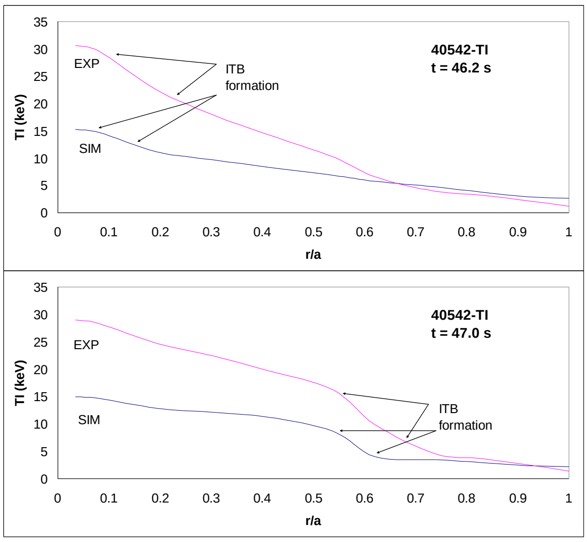


Figure 9: ITB formation at different times (top t = 46.2 s, bottom t = 47.0 s)

Table 1 summarizes the RMSE [Eq. (13)] results of NE (Electron Density), TE (Electron Temperature), and TI (Ion Temperature) of the two discharges. The errors range from 6.8% to 53.3% with less than 1% offset (table 2). Overall it demonstrates that discharge 40542 yields better result than discharge 40847. Statistically, RMSE of 40542 for TI is 27.3%, while it is 42.0% for 40847. This result agrees with previous conclusion that the simulation only found ITB formation for the first discharge.

Table 1: RMSE Results (%)

Discharge Number	**NE**			**TE**			**TI**		
	core	**edge**	**all**	**core**	**edge**	**all**	**core**	**edge**	**all**
40542	9.8	40.2	20.9	29.4	20.5	19.3	42.4	9.4	27.3
40847	40.3	6.8	19.2	9.3	41.2	24.4	53.3	22.7	42.0

Table 2: Offset Results

Discharge Number	**NE**			**TE**			**TI**		
	core	**edge**	**all**	**core**	**edge**	**all**	**core**	**edge**	**all**
40542	0.0	0.4	0.2	0.3	0.2	0.2	0.4	0.1	0.2
40847	0.4	0.1	0.1	0.0	0.4	0.2	0.4	0.2	0.3

5. Conclusion

Simulations of electron density, ion temperature and electron temperature profiles using BALDUR code has been conducted in order to compare results with experimental data. The run are with ITB and ETB effects included. Models for both transport barriers are taken into account. A version of the semi-empirical Mixed Bohm/gyroBohm is used to model formation of ITB. In addition, pedestal width scaling based on magnetic and flow shear stabilization and pressure gradient scaling based on ballooning limit instability are used to simulate ETB formation. The results are compared with two optimized shear JET discharges [40542 and 40847] and RMSEs are computed to be in the range of 19.2%-42.0%. ITB formation can be found in discharge 40542, the model demonstrates its characteristic in a satisfactory level. Overall, the models represent formation of transport barriers reasonably well.

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7. References

1. T J J Tala et al, Plasma Phys. Control. Fusion **43** (2001) 507.
2. A. Pankin, Lehigh U., BALDUR/Introduction http://physics.physics.lehigh.edu/baldur/backing.htm, May 17, 2000.
3. T. Onjun et al, 2008 TH/P8-2.
4. J.W.Connor et al, Nucl. Fusion **44** (2004) R1-R49.
5. T J J Tala et al, Plasma Phys. Control. Fusion **44** (2002) A495-A500.
6. M Erba et al, Plasma Phys. Control. Fusion **39** (1997) 261.
7. A.Y.Pankin et al, Plasma Phys. Control. Fusion **47** (2005) 483-504.
8. P. Zhu et al, 2000 Phys. Plasmas **7** 2898.
9. T. Onjun et al, 2002 Phys. Plasmas **9** 5018.
10. J. Connor, Plasma Phys. Controlled Fusion **40**, 191 (1998).