M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering,
Jeju, Korea, April 16-20, 2017, on USB (2017)

Operation scenario modeling of non-activation phase in ITER

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Abstract – *The non-activation phase of operation in ITER research plan has two important roles. The first is commissioning of the system related to plasma control and safety including magnetic control, all installed heating, fueling and diagnostic systems with plasma. The second is the validation of the present models for predicting ITER operation. In this paper, the reasonable H/He plasma operational window for these purpose is discussed. As a result, the He operation has more extensive operational window because it has the lower density to avoid the excessive NBI shine-through limit and the higher critical density calculating by the L-H transition threshold power scaling. In that operational domain, the non-activation phase ITER scenario modeling is conducted by the robust integrated simulation based on the ASTRA transport code. The temperature profiles are calculated by the GLF model and the pedestal parameters are calculated by the statistical model with ITER EPED1 database.*

I. INTRODUCTION

The first step operation phase in the present ITER research plan is the non-activation phase which has two distinct purposes. The first purpose is commissioning of the systems related to plasma control and safety, including magnetic control, all installed heating, fueling and diagnostic systems – with plasma. The second purpose is the validation of the present models for predicting ITER operations. To achieve the first purpose, previous surveys have attempted to assess the feasible H&CD (Heating and Current Drive) schemes at various toroidal fields (2.65 – 5.3 T) for H/He operations and address several critical operational issues, such as H-mode access [1]. For modeling H-mode access in the non-activation phase of ITER operation, experiments with the ITER-like plasma conditions have been conducted in JET [2, 3] and ASDEX Upgrade [4].

This paper deals with assessment H&CD scheme, H-mode access and the plasma parameters such as pedestal parameters and temperature in the non-activation phase of ITER operation by using knowledge which has been built by experiments with ITER-like plasma condition in the present devices.

II. DESCRIPTION OF THE ACTUAL WORK

1. The updated ITER configuration and operational specifications

The previously developed scenarios could be improved by taking into account the updated ITER configuration and operational specifications such as the availability of H&CD systems and schemes, achievable ranges of plasma density, pedestal parameters and plasma confinement, and anticipated impurity behaviors [5]. In this study, the scaling law of L-H mode transition is improved by considering the recent experiments in ITER-like plasma condition on present devices [2 - 4]. The pedestal model is improved by using the recent EPED1 database for ITER operation.

2. The possible domain for non-activation phase ITER operation

Previous study proposed the several scenarios for full commissioning of the systems in non-activation phase of ITER operation. These scenarios can be distinguished by plasma parameters such as plasma current, toroidal magnetic field, and plasma density. However, these previous investigations have been limited by the lack of the diversity of the plasma parameters. This work can propose the possible domain of continuous plasma parameters for safe operation, and the possible target H-mode for commissioning all installed heating systems by using several constraints such as excessive shine-through limit, Greenwald limit, and scaling law of L-H mode transition power.

3. The robust integrated simulation for the non-activation phase of ITER operation

As a first step, the operational input parameters, such as plasma current, toroidal field, and electron density, can be decided for both hydrogen and helium discharge respectively. The core plasma parameters can be calculated using an integrated simulation package coupling plasma equilibrium, transport, and heating and current drive [6] based on the ASTRA transport code [7]. In many previous researches, the boundary conditions are fixed in time or the evolution of the boundary conditions is assumed. In this study, the boundary condition is calculated by the pedestal model with the EPED1 database. As shown in Fig. 1, the input of the pedestal model is provided from the ASTRA transport code. This makes it possible to simulate the plasma evolution with time, self-consistently. The ASTRA transport code runs recursively by exchanging the information by each step.

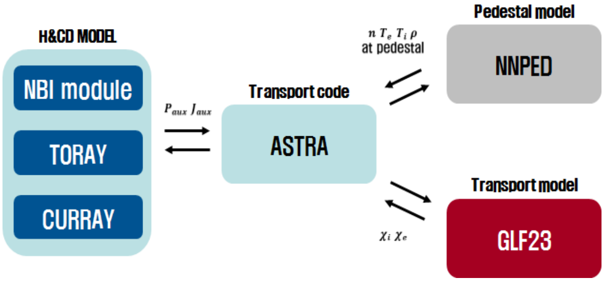

Fig. 1. A diagram of the robust integrated simulation including H&CD model, transport model and pedestal model for tokamak plasmas.

III. RESULTS

1. The possible domain for non-activation phase of ITER operation

Three constraints are used to propose the possible domain for non-activation phase of ITER operation. Firstly, the ratio of plasma current and toroidal field is fixed so to provide $q_{95} = 3$ for the full-bore reference ITER operation. Secondly, the Greenwald density limit is used as upper density limit. Thirdly, to limit the NBI shine-through power to the first wall below $4\ \mathrm{MW/m^3}$, the minimum densities are set to be $4.5 \times 10^{19}\ m^{-3}$ for hydrogen and $3 \times 10^{19}\ m^{-3}$ for helium, respectively at 870 keV of beam energy. Fourthly, the maximum input power depends on the toroidal field because the RF system is strongly related with the toroidal field. ECH operations are possible at the first harmonic in the range of $B_t = 2.3 - 2.8\ T$ and for the second harmonic in the range $B_t = 4.7 - 5.3\ T$. ICH in hydrogen plasmas is possible in the range of $B_t = 3.7 - 5.3\ T$. ICH in helium plasmas is possible in the range $B_t = 2.5 - 5.3\ T$ [8]. Because the input power depends on the toroidal field, the critical density which is the value at the power loss required for the transition from the L- to H- mode depends on the toroidal field. In the calculation of the critical density at a certain toroidal field, the modified H-mode threshold power scaling, equation (1), is used.

$$P_{th} = P_{th,D}(Martin) \cdot \left(\frac{2}{A_{eff}}\right) \cdot f_w \cdot f_{He} \qquad (1)$$

where, Pth is the threshold power of the L-H transition, $(2/A_{eff})$ is the factor of the isotopic effect [2], f_w is the factor of the tungsten wall [3] and f_{He} is the factor of helium [4]. To predict the L-H mode transition in the non-activation phase, we need to modify the Martin's power scaling law [9], which is for deuterium plasmas with carbon walls, by considering the experiment in present devices such as JET and ASDEX Upgrade.

As you can see in the Fig. 2, the scenario of the full commissioning is hard to be achieved in hydrogen discharges. Blue regime, which can be target H-mode, is very narrow. However, we can extent this condition by reducing the beam energy. On the other hand, in Fig. 3, the scenario of the full commissioning is easy to be achieved in helium discharges.

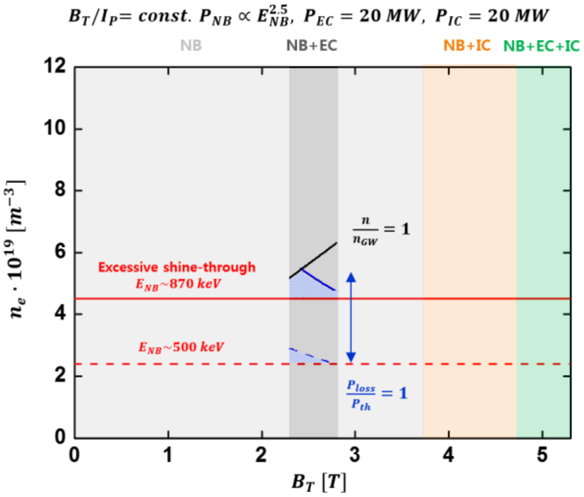

Fig. 2. Operation regime $<B_t - n_e>$ for hydrogen plasmas. The excessive shine through limit (red), the Greenwald density limit (black), the H-mode power scaling (blue); at 870 keV of NB energy (solid) and 500 keV of NB energy (dotted). Blue regime means the accessible range of H-modes.

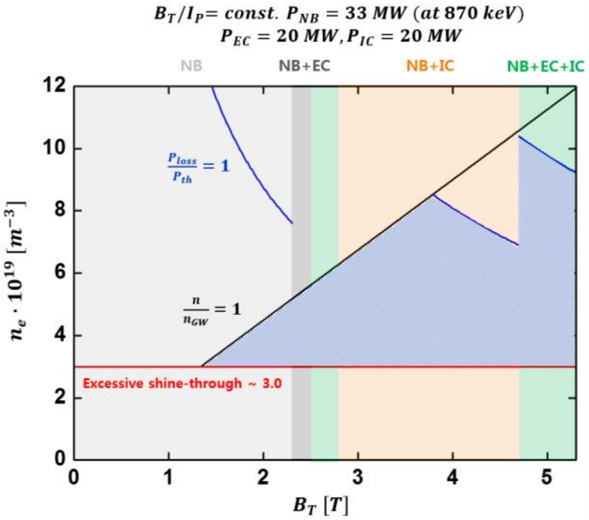

Fig. 3. Operation regime $<B_t - n_e>$ for helium plasmas. Excessive shine through limit (red), the Greenwald density limit (black), the H-mode power scaling (blue). Blue regime means the accessible range of H-modes.

2. Pedestal model by using EPED1 database for ITER operation

To predict the ITER pedestal height and width, the EPED1 predictive model [10] was adopted. The input parameters of the EPED1 predictive model are the plasma current, the electron density at pedestal, the effective ion charge, the normalized beta, the toroidal field, elongation, triangularity, the mass of the main ion species, major radius and minor radius. The pedestal height and the width are the outputs of this model. We have about 8500 sets of EPED1 database, available in International Tokamak Physics Activity (ITPA) database which have the various input parameters in the range of the ITER operation.

Neural network, a statistical approach [11], which is useful to deal with nonlinear problems, is used to fit this database. In this work, the neural network consists of the one hidden layer of 10 neurons. Randomly selected 20 % of dataset is used for testing. The 50 % of dataset is used for training and the rest of 30 % of dataset is used for validation. The Levenberg-Marquardt algorithm [12] is employed for the training algorithm. In this specification of neural network, high R-square value can be achieved (Fig. 4, 5).

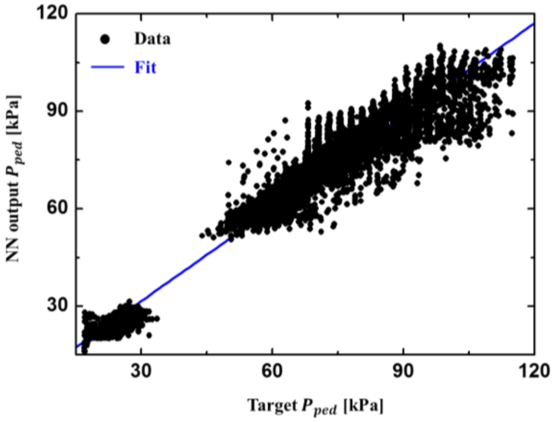

Fig. 4. Fitting result of the statistical method for Pedestal pressure where R-square is about 0.94

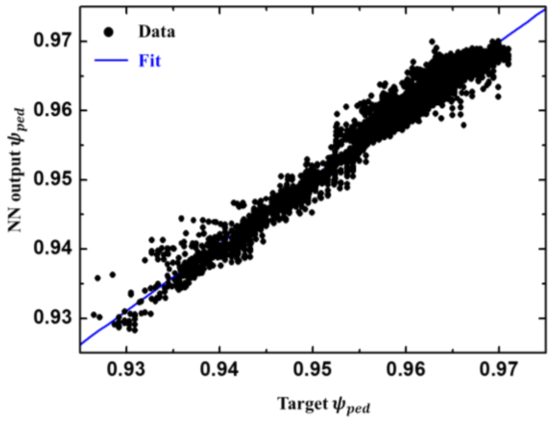

Fig. 5. Fitting result of the statistical method for pedestal psi where R-square is about 0.97

3. The non-activation phase ITER scenario simulation

1) The ITER hydrogen operation scenario simulation

The ITER hydrogen operation 7.5 MA/2.65 T scenario simulation is conducted by the robust integrated simulator. As shown in Fig. 6. (a), the total plasma current is assumed to ramp up to 7.5 MA in 30 s. The electron density ramps up to $4.5 \times 10^{19}\ m^{-3}$ by 30 s in L-mode to avoid the excessive shine-through limit. At 30 s, 33 MW of NBI and 20 MW of EC are injected simultaneously, which triggers an L-H transition. The L-H transition occurs in a narrow window as shown in Fig. 6. (b), which strongly depends on the modified L-H transition power scaling (equation (1)). Therefore, in case factors such as the factor of the isotopic effect, the tungsten wall, and the helium are changed by the new empirical evidences, the results can be turned upside down. The density and temperature profiles evolve from L- to H- through the pedestal parameters calculated by the pedestal model with EPED1 database as seen in Fig. 10. At about 450 s, the pedestal pressure calculated by the pedestal model is 23.2 kPa and the electron temperature calculated by the pedestal model is 2.85 keV in Fig. 7.

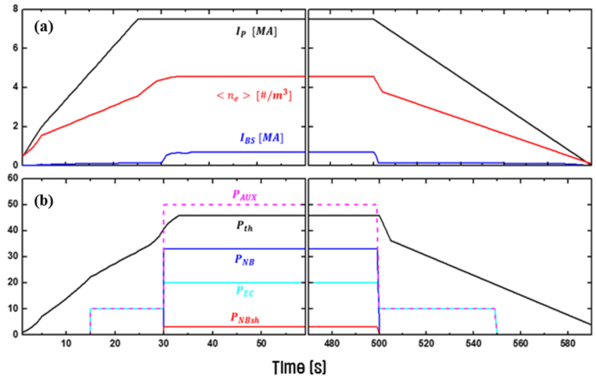

Fig. 6. Overview of the H operation scenario simulation. (a) Time evolution of the total plasma current (black), the volume averaged electron density (red) and the bootstrap current (blue). (b) Time evolution of the L-H transition threshold power (black), the total auxiliary heating power (dotted - magenta), the NBI heating power (blue), the EC heating power (cyan) and the shine-through power (red).

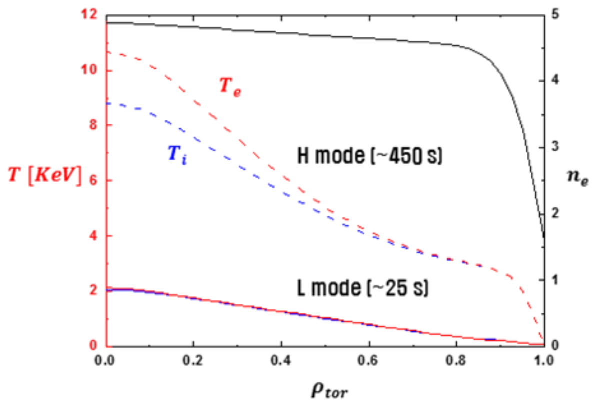

Fig. 7. The profile of the electron density at about 450 s (black) in H operation scenario. The profile of the electron temperature (red) and the ion temperature (blue) at about 25 s (solid) and about 450 s (dotted)

2) The ITER helium operation scenario simulation

The ITER helium operation of 7.5 MA/2.65 T is simulated by the robust integrated simulator. As shown in Fig. 8. (a), the total plasma current is assumed to be ramped up to 7.5 MA in 30 s. The electron density ramps up to $3 \times 10^{19}\ m^{-3}$ by 30 s in L-mode to avoid the excessive shine-through limit. At 30 s, 33 MW of NBI, 20 MW of EC and 20 MW of IC are injected, which triggers an L-H transition. At about 450 s, the pedestal pressure calculated by the pedestal model is 23 kPa and the electron temperature calculated by the pedestal model is 3.15 keV as shown in Fig. 9. The commissioning for H-mode in the helium operation is easier than that in the hydrogen one as seen in Fig. 8. (b). Therefore, the helium operation scenario is more flexible in the heating scenario.

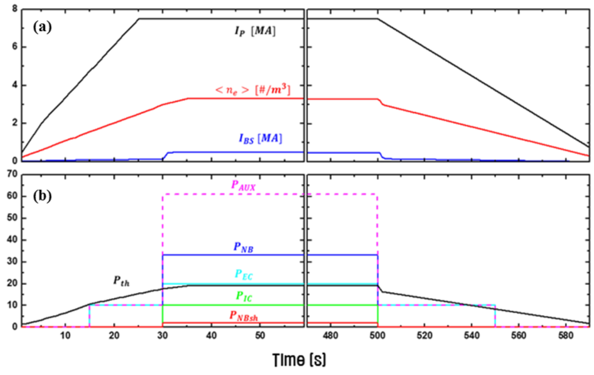

Fig. 8. Overview of He operation scenario simulation. (a) Time evolution of the total plasma current (black), the volume averaged electron density (red), the bootstrap current (blue). (b) Time evolution of the L-H transition threshold power (black), the total auxiliary heating power (dotted - magenta), the NBI heating power (blue), the EC heating power (cyan), the IC heating power (green) and the shine-through power (red).

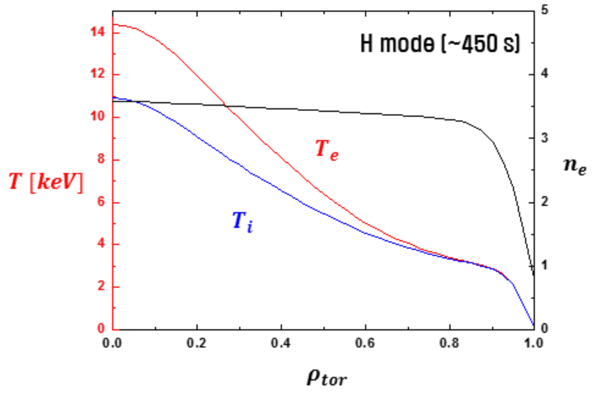

Fig. 9. The profile of the electron density at about 450 s (black) in He operation scenario. The profile of the electron temperature (red) and the ion temperature (blue) at about 450 s (solid)

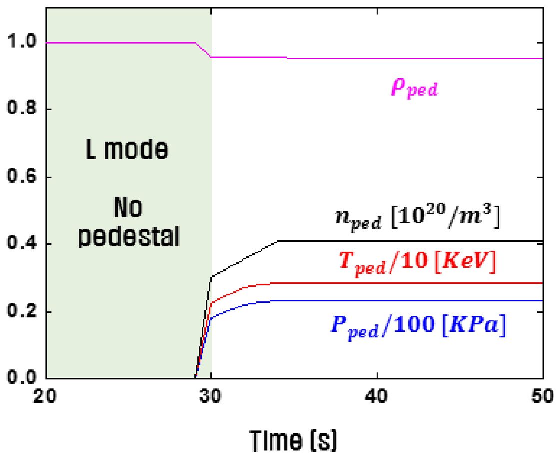

Fig. 10. Time evolution of the pedestal parameters including the width (magenta), electron density (black), electron temperature (red), and total pressure (blue).

IV. CONCLUSIONS

The operational window in H/He ITER scenario is proposed within the four constraints including the ratio of plasma current and toroidal magnetic field, the Greenwald density limit, the density to avoid the excessive NBI shine-through and the L-H transition power limit. In the operational domain, the H/He ITER operation scenarios have been successfully simulated by the robust integrated simulator coupling equilibrium, H&CD, transport, and pedestal model. The pedestal parameters and temperature in the non-activation of ITER operation are assessed. As a result, the helium operation turns out to be more feasible candidate for the non-activation phase due to the flexibility of the heating scenario and plasma parameters including plasma current, toroidal magnetic field, and density.

APPENDIX

$$P_{th} = P_{th,D}(Martin) \cdot \left(\frac{2}{A_{eff}}\right) \cdot f_w \cdot f_{He} \qquad (1)$$

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NOMENCLATURE

$\mathrm{I_P}$ = plasma current
$\mathrm{B_t}$ = toroidal field
$\mathrm{n_e}$ = electron density
$\mathrm{P_{th}}$ = the H-mode threshold power
$(2/A_{eff})$ = the factor of isotopic effect
$\mathrm{f_W}$ = the factor of tungsten wall
$\mathrm{f_{He}}$ = the factor of helium

ENDNOTES

ACKNOWLEDGMENTS

This work was supported by the Ministry of Science, ICT and Future Planning of the Republic of Korea under Korean ITER project contract.

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