36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-4.163 (2009)

TSC Simulation of ITER Plasma Termination Scenario with Stable H-L Mode Transition and Avoidance of Radiation Collapse

Y. Nakamura[1)], S. Miyamoto[2)], S. Toshimitsu[2)], T. Sugie[2)], Y. Kusama[2)] and R. Yoshino[2)]

1) Nippon Advanced Technology Co., Ltd., Ibaraki, 319-1112, Japan
2) Japan Atomic Energy Agency, Ibaraki, 311-0193, Japan

1. Introduction

Development of reliable plasma termination scenario in ITER requires proven operations with high performance capabilities to ramp-down the plasma density and current while keeping the plasma in divertor magnetic configuration. Because the current ramp-down rate in H mode is too slow to avoid advancing the inductive flux state, stable transition control from H to L mode is required. In DIII-D, a ramp-down experiment was performed to reproduce and verify the terminating operation equivalent to ITER [1]. Excellent controls of the plasma shape and internal inductance were achieved, retaining the vertical stability. Turning off of auxiliary heating power demonstrated a stable H to L mode transition. Besides the ITER equivalent experiments, numerical modeling approaches to predict the plasma termination dynamics have been adopted with simulation codes, while taking performance capability of the PF power supplies into account. The codes, commonly comprised of two-dimensional free boundary plasma equilibria and one-dimensional transport model, describe time-evolution of the plasma shape and profile dynamics of the plasma current I_p and temperatures [2, 3].

This paper presents self-consistent simulations of the ITER inductive termination scenario 2 [4] with TSC code [3], comprised of newly developed D-T fuelling and pumping-out system. With particular attention to the stable H to L mode transition, the transition dynamics, *e.g.* reduction in the plasma density while building-up of the in-vessel neutral gas, disappearance of the non-inductive edge BS current and consequent jump in the internal inductance $l_i(3)$, were investigated to assess the performance of the ITER pumping system.

2. Simulation modeling

By solving the momentum equation along with Faraday's law and Ohm's law, the TSC provides axisymmetric MHD fluid dynamics as well as time-evolution of the PF coil currents. We use the energy transport coefficients as a sum of the turbulent term χ_{CDBM} [5] and the neoclassical term χ_{NC}, *i.e.*, $\chi_{CDBM} + \chi_{NC}$. When the plasma is in H-mode, the neoclassical transport was assumed in a prescribed edge-region ($\rho > 0.9$), making up edge transport barrier (ETB). The particle transport was solved with the diffusion coefficient by $D = 0.1 \times (\chi_{CDBM} + \chi_{NC})$. The plasma density was controlled by feedback on neutral gas puff.

To solve transient of the plasma density when the H to L mode transition occurs, we newly developed a numerical model of D-T fuelling and pumping-out system, comprised of two sub-models each for determining neutral density profile in plasma region and for solving accumulation and pumping-out dynamics of fuelling gas in vacuum vessel. Using one-dimensional slab geometry of the plasma region, the neutral density profile was determined taking atomic process into account, *i.e.*, ionization and charge-exchange. Starting with Franck-Condon neutral, the charge-exchanged neutral was considered with multi-generation of up to 5th. It was shown that the neutral density profile is remarkably sensitive to the pedestal structure of the plasma density in H mode.

The following model equation provides the accumulation and pumping-out dynamics of fuelling gas, n_0, in vacuum vessel:

$$\frac{d}{dt}(n_0 V_v) = \left(\Gamma^p{}_{out} - \Gamma^p{}_{in}\right) - n_0 S_p^* + \Gamma_{feed}$$

Here, V_v means volume (m^3) of vacuum vessel. Γ^p_{out}, Γ^p_{in} and Γ_{feed} are out-flux from, in-flux to plasma and feeding flux of neutral gas (s^{-1}), respectively. S_p^* means effective pumping-speed ($m^3 \bullet s^{-1}$) including dynamic retention to and release from vessel wall. Property of this wall-retention/release is heavily dependent on various factors such as wall material, temperature and history of exposure to plasma particle. Therefore, identification of S_p^* is difficult and uncertain. For convenience of modeling, we use S_p^* as an adjustable parameter in this work.

Deposition profile of NB heating was prescribed. Regarding self-consistent EC H/CD model with 170 GHz O-mode wave, ray-tracing calculation under ITER EC injector geometry was performed using fully relativistic Fokker-Planck code. BS current was provided by Hirshman and Sigmar. 0.8% neon with uniform distribution was considered as impurity to get the same value of Z_{eff} = 1.7 as the representative 15 MA ITER scenario.

3. TSC simulation of ITER 15MA/200s plasma termination

The representative plasma termination, started at 500 s and performed in divertor magnetic configuration, has two phases with the duration 100 s each [4]: (1) the plasma cooling current ramp-down in H mode from 15 MA to 10 MA (500 s < t < 600 s); (2) the I_p ramp-down in L mode from 10 MA to 1.5 MA (600 s < $t \leq$ 700 s). During the first phase, the plasma density is decreased consistently with the I_p ramp-down. Fusion power is reduced by turning down NB heating power, ceasing the fusion burn. At 600 s the NB heating is switched off, leading to the H to L mode transition. In DINA simulation, evolution of the plasma density was prescribed and assumed as its linear decrease from 0.5 x 10^{20} m^{-3} at 600 s to 0.3 x 10^{20} m^{-3} at 604 s. During the second phase of plasma termination, the plasma current is reduced linearly from 10 MA at 600 s to 1.5 MA at 704 s, whereas the plasma density is reduced keeping $\langle n_e \rangle / n_G = 0.35$. In what follows, we review the representative ITER termination scenario by self-consistent simulations with the TSC code, comprised of newly developed D-T fuelling and pumping-out system.

3.1. Termination with pumping-performance enhanced and stable H to L mode transition

Figure 1 shows evolutions of fusion power P_α, NB heating power P_{NB}, the total heating power P_{tot} (= $P_\alpha + P_{NB}$), ohmic heating power P_Ω and radiation power P_R, as well as evolutions of the volume-averaged plasma density n_e, reference plasma density n_e^{ref} and neutral density n_0 in vacuum region. Turning down operation of the NB heating power from P_{NB} ~ 60 MW got started at 500 s of EOB, leading to gradual decrease in P_α. Meanwhile, n_e reduced by feedback control of n_0, while feeding the fuel Γ_{feed} and pumping S_p^* with performance enhanced. The fusion power dropped to P_α ~ 10 MW at 600 s. At the same time, the NB heating power of P_{NB} ~ 35 MW was switched off to trigger the H to L mode transition, which was intentionally caused by removing the ETB ($\rho > 0.9$). After the H to L mode transition, P_Ω ~ 10 MW domimated P_{tot}, while P_R remained small. The TSC simulation demonstrated that the plasma termination with pumping-performance enhanced was well performed as expected, *i.e.*, a stable H to L mode transition. However, at 600 s, a 20 % reduction in n_e was obtained in the TSC simulation, whereas a 40 % reduction was assumed in the representative termination scenario with DINA code [4]. It can be construed that when the H to L mode transition occurred, the burst of n_0 attributed to degradation of the plasma particle confinement increases backward influx Γ^p_{in} into plasma. Additionally, the density pedestal of H mode plasma, which hinders the neutral particle from penetrating into plasmas, got lost in L mode plasma, hence enhancing the penetration of the neutral particle.

Figure 2 shows control performance of the I_p ramp-down and evolution of $l_i(3)$. Time-evolution of the plasma current profile is also shown. During the first phase of the plasma cooling in H mode, the I_p ramp-down was well performed with an I_p feedback control, while the edge BS current decreased in accordance with a gradual reduction of the plasma β_p. After

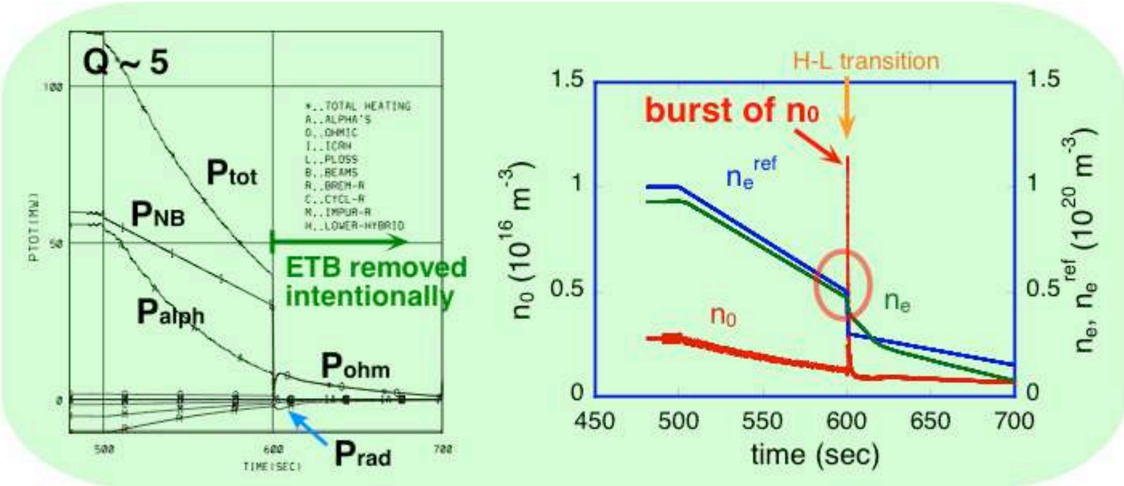

Fig. 1 Termination with pumping-performance enhanced. (1) Fusion power P_α, NB heating power P_{NB}, total heating power P_{tot} (= P_α + P_{NB}), ohmic heating power P_W and radiation power P_R; (2) volume-averaged plasma density n_e, reference plasma density n_e^{ref} and neutral density n_0 in vacuum region.

the H to L mode transition, the I_p feedback control was switched off. At 600 s, $l_i(3)$ jumps by ~ 0.18 due to an abrupt loss of the edge I_{BS}. During the second phase, $l_i(3)$ continued to increase to ~ 1.4 at 700 s. When the I_p feedback control is switched on, the $l_i(3)$ jump at the H to L mode transition was reduced to ~ 0.1. Subsequently, $l_i(3)$ continued to increase to ~ 1.6 at 700 s, while consuming the inductive PF magnetic flux. The plasma shape control was well performed along with keeping a desired divertor configuration over the plasma termination.

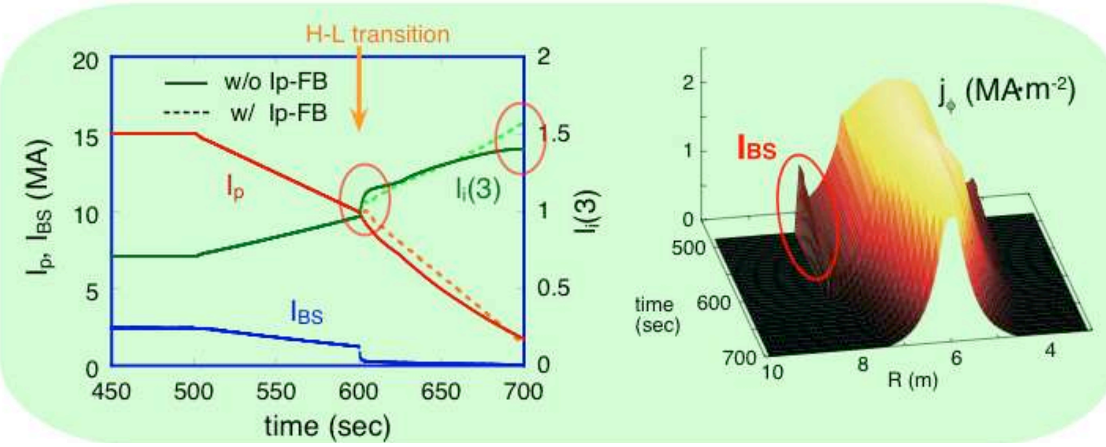

Fig. 2 Termination with pumping-performance enhanced. (1) control performance of I_p ramp-down and evolution of $l_i(3)$; (2) plasma current profile

3.2. Termination with pumping-performance degraded and avoidance of radiation collapse

A plasma termination scenario with pumping-performance degraded by half was investigated. Figure 3 shows evolutions of n_e, n_e^{ref} and n_0. Control performance of the I_p ramp-down and evolution of $l_i(3)$ is also shown. The plasma density reduced by feedback control of n_0 with a pumping-performance degraded S_p^*, while turning NB heating power down and feeding the fuel Γ_{feed}. After the H to L mode transition, n_e remained at a higher level than the density with the pumping-performance enhanced. After a while, n_e turned to an upsurge in concert with a sharp increase in n_0. Simultaneously, the radiation power P_R primarily originating from the plasma edge increased. When P_R increased to P_Ω ~ 10 MW, a radiation collapse was triggered at 660 s.

As also shown in Fig. 3, an avoidance scenario of the radiation collapse was examined by means of EC heating following the H to L mode transition. Starting with O-mode ECH of P_{EC}

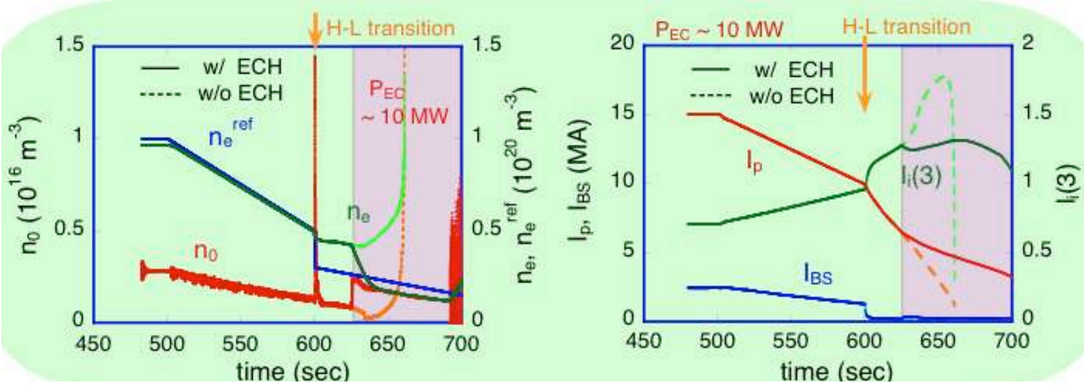

Fig. 3 Termination with pumping-performance degraded and avoidance of radiation collapse by means of O-mode ECH of P_{EC} ~ 10 MW (solid lines). (1) n_e, n_e^{ref} and n_0. (2) control performance of I_p ramp-down and evolution of $l_i(3)$ ECH

~ 10 MW at 625 s, the increase in n_e ceased, while increasing n_0. P_R from the plasma edge dramatically dropped. As a consequence, the radiation collapse was avoided. The sidestepping mechanism of the radiation collapse can be summarized as follows: ECH raises the electron temperature of the L mode plasma, and hence the radiation from the plasma edge is substantially reduced. Consequently, the plasma current channel remained without undergoing shrinkage, preserving the plasma volume large. Figure 3 also shows the dramatic ECH effect in achieving a desired I_p ramp-down after 625 s while preventing the disruptive, fast I_p ramp-down. Additionally, ECH broadened the plasma current profile while keeping $l_i(3)$ ~ 1.2, even though $l_i(3)$ without ECH proceeded to go up to ~ 1.8.

Furthermore, a combined use of O-mode ECH and inductive feedback of the plasma current was investigated. The inductive I_p feedback was switched on over the termination, while a lower power of P_{EC} ~ 6 MW was applied from 25 s after the H to L mode transition. The $l_i(3)$ jump at the H to L mode transition was reduced to ~ 0.1, and $l_i(3)$ never went beyond ~ 1.45. During the L mode phase, the control of n_e was performed well. It thus follows that a combined use of O-mode ECH and inductive I_p feedback makes the termination scenario more secure against the H to L mode transition

4. Summary

Self-consistent simulations of the ITER 15MA/200s termination scenario were performed with TSC code, comprised of newly developed models for D-T fuelling and density pumping-out. The H to L mode transition dynamics in particular was investigated in detail to discuss performance capability of ITER pumping system. Terminating operation under pumping-performance enhanced ensures stable H to L mode transition. It was newly shown that when pumping-performance suffers degradation, the forced H to L mode transition might trigger a radiation collapse, consequently terminating the discharge. It was also demonstrated that horizontal EC heating with 170 GHz O-mode wave after the H to L mode transition provides an effective control means to hedge risk of the radiation collapse. Furthermore, a combined use of ECH with P_{EC} ~ 6 MW and inductive I_p feedback provides a reliable means of safe, robust ITER terminating operation without causing radiation collapse. Experimental validation of the present model of the density pump-out is needed for practical use of the present model in studying ITER termination scenarios.

[1] T.C. Luce, 2nd IOS Topical Group Meeting, JAEA, Naka, Japan (2009).
[2] V. Lukash, et. al., Plasma Devices and Operations **15** (2007) 283.
[3] S.C. Jardin, N. Pomphery and J. Delucia, J. Comput. Phys. **66** (1986) 481.
[4] A.A. Kavin et. al., Progress report of plasma startup/termination, ITER_D_2F55U5, 2008.
[5] A. Fukuyama, et. al., Plasma Phys. Control. Fusion **37** (1995) 6611.