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Formation and Sustainability of *H*-mode Regime in Tokamak Plasma via Sources Perturbations Based on Two-Field Bifurcation Concept

(Pembentukan dan Kelestarian Rejim *H*-mod pada Plasma Tokamak melalui Pengusikan Sumber Berdasarkan Konsep Dua-Bidang Dwicabang)

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ABSTRACT

A set of coupled particle and thermal transport equations is used to study a formation and sustainability of an edge transport barrier (ETB) in tokamak plasmas based on two-field bifurcation. The two transport equations are numerically solved for spatio-temporal profiles of plasma pressure and density. The plasma core transport includes both neoclassical and turbulent effects, where the latter can be suppressed by flow shear mechanism. The flow shear, approximated from the force balance equation, is proportional to the product of pressure and density gradients, resulting in non-linearity behaviors in this calculation. The main thermal and particle sources are assumed to be localized near plasma center and edge, respectively. It is found that the fluxes versus gradients regime illustrates bifurcation nature of the plasma. This picture of the plasma implies hysteresis properties in fluxes versus gradients space. Hence, near marginal point, the perturbation in thermal or particle sources can trigger an L-H transition. Due to hysteresis, the triggered H-mode can be sustained and the central plasma pressure and density can be enhanced.

Keywords: ETB; fusion; L-H transition; plasma; tokamak

ABSTRAK

Satu set gandingan zarah dan persamaan angkutan terma digunakan untuk mengkaji pembentukan dan kelestarian halangan angkutan pinggiran (ETB) dalam plasma tokamak berdasarkan dua medan dwicabang. Dua persamaan angkutan diselesaikan secara berangka untuk profil ruang-masa tekanan plasma dan ketumpatan. Teras plasma mengangkut kedua-dua kesan neoklasik dan turbulens, dengan turbulens boleh disekat melalui mekanisme aliran ricih. Aliran ricih, penghampiran daripada persamaan keseimbangan daya, adalah berkadaran dengan produk tekanan dan kecerunan ketumpatan yang mengakibatkan tingkah-laku yang tak linear dalam pengiraan ini. Sumber utama terma dan zarah masing-masing adalah diandaikan setempat berhampiran pusat plasma dan pinggiran. Didapati bahawa rejim kecerunan menggambarkan dwicabang semula jadi plasma. Gambaran plasma ini membayangkan sifat histeresis dalam fluks berbanding ruang kecerunan. Oleh yang demikian, berhampiran titik marginal, pengusikan di dalam sumber terma atau zarah boleh mencetuskan peralihan L-H. Oleh sebab histeresis, pencetus H-mod dapat dikekalkan dan ketumpatan tekanan tengah plasma boleh dipertingkatkan.

Kata kunci: ETB; lakuran; plasma; peralihan L-H; tokamak

INTRODUCTION

In tokamak experiment, a high confinement mode (*H*-mode) is highly desirable because in this mode, as oppose to a low confinement mode (*L*-mode), the plasma yields high density, high temperature and sufficient energy confinement time. These are crucial factors used for measuring plasma performance, which can indicate the fusion energy output. Future burning plasma experiments, like the ITER project, aim to operate in *H*-mode (Aymar et al. 2002). It is known that the enhanced plasma performance of *H*-mode is a result of an edge transport barrier (ETB) formation (Hubbard 2000). Experimentally, tokamak plasma makes an abrupt transition from *L*-mode to *H*-mode, called *L-H* transition, once external heating surpasses a power threshold (Ryter et al. 1998). This means a certain amount of power is needed in order to improve fusion output. Hysteresis phenomena at the transition has been found in several tokamak experiments (Thomas et al. 1998). It was found that after achieving *H*-mode, the heating power can be reduced while maintaining *H*-mode characteristics. The heating power can be reduced as large as a factor of two (Snipes et al. 2000; Thomas et al. 1998; Wagner 2007). Therefore, investigation on hysteresis depth is very important because it could increase the window of tokamak operation. The existence of hysteresis in plasma transition implies that the same heating power that would only allow the plasma to be in *L*-mode could potentially be used to sustain the plasma in *H*-mode as well. This work explores the possibility to trigger the *L-H* transition using perturbations in thermal and particle sources so that after the perturbations are removed, the plasma can remain in *H*-mode.

Hysteresis phenomenon can be depicted using bifurcation of a system because in a bifurcation regime, the same values of controlled parameters can yield different state of the system. In tokamak plasma, the controlled parameters correspond to thermal (plasma heating) and particle (particle influx) sources. Whereas, the responding plasma profiles like pressure and density gradients exhibit sudden change, resulting in a transition of plasma modes. The *L-H* transition can be viewed, within the framework of bifurcation theory, as a phase transition in flux (heat/particle) versus gradient (pressure/density) regime (Toda et al. 1996). The heat/particle flux represents the heating/particle influx, respectively. An example of bifurcation diagram can be seen in Figure 1. The non-monotonic behavior in this graph allows possibility to study hysteresis nature of the plasma. Previously, it was found that the increase or decrease of heat and particle fluxes can influence the plasma mode (Chatthong et al. 2015). In other word, as the heat is increased, the plasma transits to H-mode as soon as the heating power exceeds *L-H* power threshold. Meanwhile, if the heat is reduced from *H*-mode condition, the plasma can remain in *H*-mode as long as the heat is still above the *H-L* back transition power threshold. Because of the back transition threshold is less than that of the forward transition, hysteresis exists.

The aims of this works were to investigate *L-H-L* transitions and hysteresis behaviors and explores the possibility to trigger and sustain the H-mode using two-field bifurcation model. This approach on analyzing the *L-H* transition has been done in several previous works (Carreras et al. 1994; Chatthong et al. 2016; Diamond et al. 1995; Hinton 1991; Itoh 1994, 1988; Jhang et al. 2012; Lebedev et al. 1997; Malkov et al. 2009, 2008; Shaing et al. 1989). The analysis is based on the work on bifurcation concept discussed by Malkov and Diamond (2008). A bifurcation diagram, as shown in Figure 1, is used to illustrate what happens at the transitions. It is typically expressed as an s-curve graph on pressure/density gradients versus thermal/particle fluxes space. According to the model, the transitions are assumed to be intrinsic properties of the plasma where the state can suddenly alter once some kind of threshold has been satisfied. Previously, the bifurcation approach was used to analyze energy and particle confinements in tokamak plasmas (Hinton et al. 1993). Hysteresis behavior was found in the work of Lebedev et al. (1997) based on one field model. The model was later improved to include the second field and hyper-diffusion effect (Malkov et al. 2008). Recently, the model was extended to also explain the formation of an internal transport barrier (ITB) (Chatthong et al. 2016). This work numerically and simultaneously solves the coupled thermal and particle transport equations. The plasma transport is composed of a combination of neoclassical and anomalous effects. The flow shear suppression, acting solely on the anomalous transport, is based on a critical gradient model. The small perturbations in thermal and particle sources are given in addition to the main sources, which are localized based on Gaussian distribution at plasma center for thermal source and plasma edge for particle source.

The paper is organized as follows: the bifurcation model and bifurcation diagram are explained in the next section; numerical results and discussion are presented in next; and the summary is given in the last section.

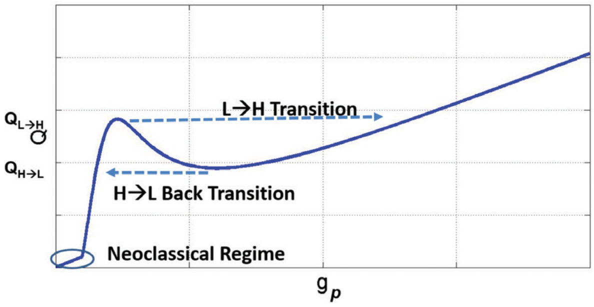

FIGURE 1. Bifurcation diagram of heat flux versus pressure gradient illustrating *L-H* transition and *H-L* back transition

BIFURCATION MODEL

The study in this work is based on simplified thermal and particle transport equations similar to what introduced by Malkov and Diamond (2008):

$$\frac{3}{2}\frac{\partial p}{\partial t}-\frac{\partial}{\partial x}\left[\chi_{neo}+\frac{\chi_{ano}}{1+\alpha v_E'^2}\right]\frac{\partial p}{\partial x}=H(x,t), \tag{1}$$

$$\frac{\partial n}{\partial t}-\frac{\partial}{\partial x}\left[D_{neo}+\frac{D_{ano}}{1+\alpha v_E'^2}\right]\frac{\partial n}{\partial x}=S(x,t), \tag{2}$$

where p is the plasma pressure; n is the plasma density; χ_{neo} is neoclassical thermal transport coefficient; χ_{ano} is anomalous thermal transport coefficient; D_{neo} is neoclassical particle transport coefficient; D_{ano} is anomalous particle transport coefficient; is the flow shear; and H and S are the heat and particle sources, respectively. The parameter α is proportional to the square root of the turbulence correlation time. Typically, the turbulent transport has a correlation time on the order of tens to hundreds of milliseconds (Itoh et al. 1999; Malkov et al. 2008). It is widely accepted that the suppression on anomalous transport using the flow shear can result in ETB formation (Pankin et al. 2005). In this model, the neoclassical transport coefficients are simply set to be just constant. The anomalous transport coefficients can be calculated based on critical gradient models (Dimits et al. 2000; Garbet et al. 2004) with the forms:

$$\chi_{ano}=c_x\,(g_p-g_{pc})\;\theta\,(g_p-g_{pc}), \tag{3}$$

$$D_{ano}=c_D\,(g_n-g_{nc})\;\theta\,(g_n-g_{nc}), \tag{4}$$

where and are proportional constants representing the strengths of anomalous transport, $g_p = -\frac{\partial p}{\partial x}$, $g_n = -\frac{\partial n}{\partial x}$, $g_{pc} = \left(-\frac{\partial p}{\partial x}\right)_c$ and $g_{nc} = \left(-\frac{\partial n}{\partial x}\right)_c$ are the critical gradients for pressure and density fields, respectively and θ represents a Heaviside step function. Note that the results in this work are only applicable to the plasma with diffusion as a dominating transport. This is because the particle pinch effect is neglected in the model. It was found by Iguchi et al. (1994) that in some case the pinch can be related to the thermal gradient. At steady state, the two transport equations are in the forms:

$$\begin{aligned} \chi_{neo} g_p &= Q, & g_p &< g_{pc} \\ \chi_{neo} g_p + \frac{c_\chi \left(g_p - g_{pc}\right)}{1 + \alpha v_E'^2} g_p &= Q, & g_p &\geq g_{pc} \end{aligned} \tag{5}$$

$$\begin{aligned} D_{neo} g_n &= \Gamma, & g_n &< g_{nc} \\ D_{neo} g_n + \frac{c_D \left(g_n - g_{nc}\right)}{1 + \alpha v_E'^2} g_n &= \Gamma, & g_n &\geq g_{nc} \end{aligned} \tag{6}$$

respectively, where $Q = \int_0^x H(x',t)\,dx'$ is the heat flux and $\Gamma = \int_0^x S(x',t)\,dx'$ is the particle flux. These yield fluxes versus gradients relations, in which an example is shown in Figure 1. The thermal and particle anomalous diffusivities are assumed to be one to two order of magnitude over their neoclassical counterparts. In addition, the particle diffusivities are assumed to be one fourth of thermal diffusivities (Wesson 2004). Specifically, $\chi_{neo} = 1$, $c_\chi = 10$, $D_{neo} = 0.25$, $c_D = 2.5$, and $\alpha = 0.1$. The flow shear suppression can be approximated from the force balance equation as:

$$v_E' = c\frac{E_r'}{B} \cong -\frac{c}{eBn^2} p'n' \propto g_p g_n. \tag{7}$$

In this approximation, the curvature, the toroidal and poloidal rotation contributions are neglected.

Figure 1 illustrates the graph between the heat flux and the pressure gradient, exhibiting a non-monotonic behavior which characterizes the bifurcation nature of the plasma. This graphical interpretation can be used to identify the locations of *L*-*H* and *H*-*L* back transitions. Taking heat/particle fluxes as independent parameter, at low fluxes with low gradients, the anomalous transport is not yet turned on so only neoclassical transport plays role. The increase of the fluxes also increases the gradients, once the critical gradients are achieved the anomalous effects starts to grow. While the gradients are still relatively low, the plasma is in *L*-mode. Within the bifurcation ranges, according to stability analysis, the plasma remains in *L*-mode (Chatthong et al. 2015). It makes an abrupt transition to *H*-mode as soon as the heat flux exceeds *L*-*H* transition threshold for heat flux $Q_{L \to H}$. On the other hand, if the fluxes are reduced from *H*-mode, the plasma remains in the mode within the bifurcation range. Eventually, the plasma makes a back transition to *L*-mode when the heat flux is below $Q_{H \to L}$. This explanation illustrates hysteresis phenomena of the plasma because the thresholds for forward and backward transitions are different. It is possible that in some case the high gradients in *H*-mode cannot be achieved because of stability violation. This kind of instability like ELM effect is not included in this work. Nonetheless, the results in this work only focus near the marginal points close to the transitions. Therefore, assuming that the *H*-mode can be achieved, the stability violation can be avoided. The transport (1) and (2) are solved numerically and self-consistently based on discretization method for spatio-temporal evolution profiles of plasma pressure and density in this simplified system. The thermal and particle sources, respectively, are defined as:

$$H(x, t) = H_0(x, t) + \tilde{H}(x, t), \tag{8}$$

$$S(x, t) = S_0(x, t) + \tilde{S}(x, t), \tag{9}$$

where H_0 and S_0 are the main sources localized at plasma center and edge, respectively, as seen in Figure 2. The localization is given by Gaussian distribution where 90% of the source is located within 10% of location around the peak of the distribution. As in the burning plasma, majority of heating comes from alpha heating at the center of plasma and particle influx comes from plasma edge, the main plasma sources are given as mentioned. The $\tilde{H}$ and $\tilde{S}$ terms represent the small perturbation in the main thermal and particle sources, respectively.

RESULTS AND DISCUSSION

PERTURBATION IN THERMAL SOURCE

In this section, a scenario is given for triggering of the *L*-*H* transition via perturbation in thermal source. Initially, in the first phase (1st), the plasma is setup with a heating power at the marginal point just below the *L*-*H* threshold so the plasma is in *L*-mode. In second phase (2nd), the perturbation effect on the heat source is simulated by adding random noise to the main source. Physically, this could represent small fluctuation in plasma heating, which includes heating by neutral beam injection (NBI), radio frequency heating (RF) or alpha heating. In the third phase (3rd), the same condition as in the first phase is given, i.e. the fluctuation in heat source is removed. The simulation results show that, as seen in Figure 3, during the second phase the plasma enters the *H*-mode with sudden increases of central pressure and density. This implies that at a time within the second phase the fluctuation is large enough that the total heat flux surpass an *L*-*H* threshold. As the heat flux is defined as an integration of the total heat source, a positive average of the fluctuation that is large enough can trigger the transition. After the *H*-mode has been reached

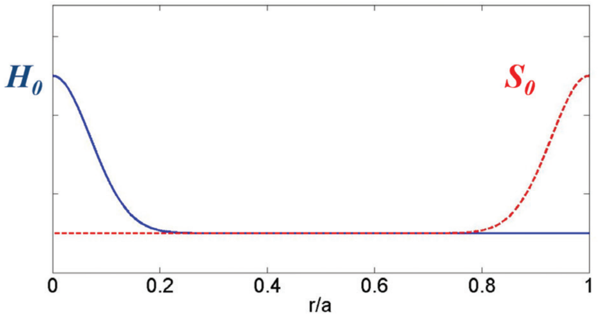

FIGURE 2. Main thermal source (H_0), localized near plasma center and main particle source (S_0), localized near plasma edge as functions of normalized minor radius (r/a)

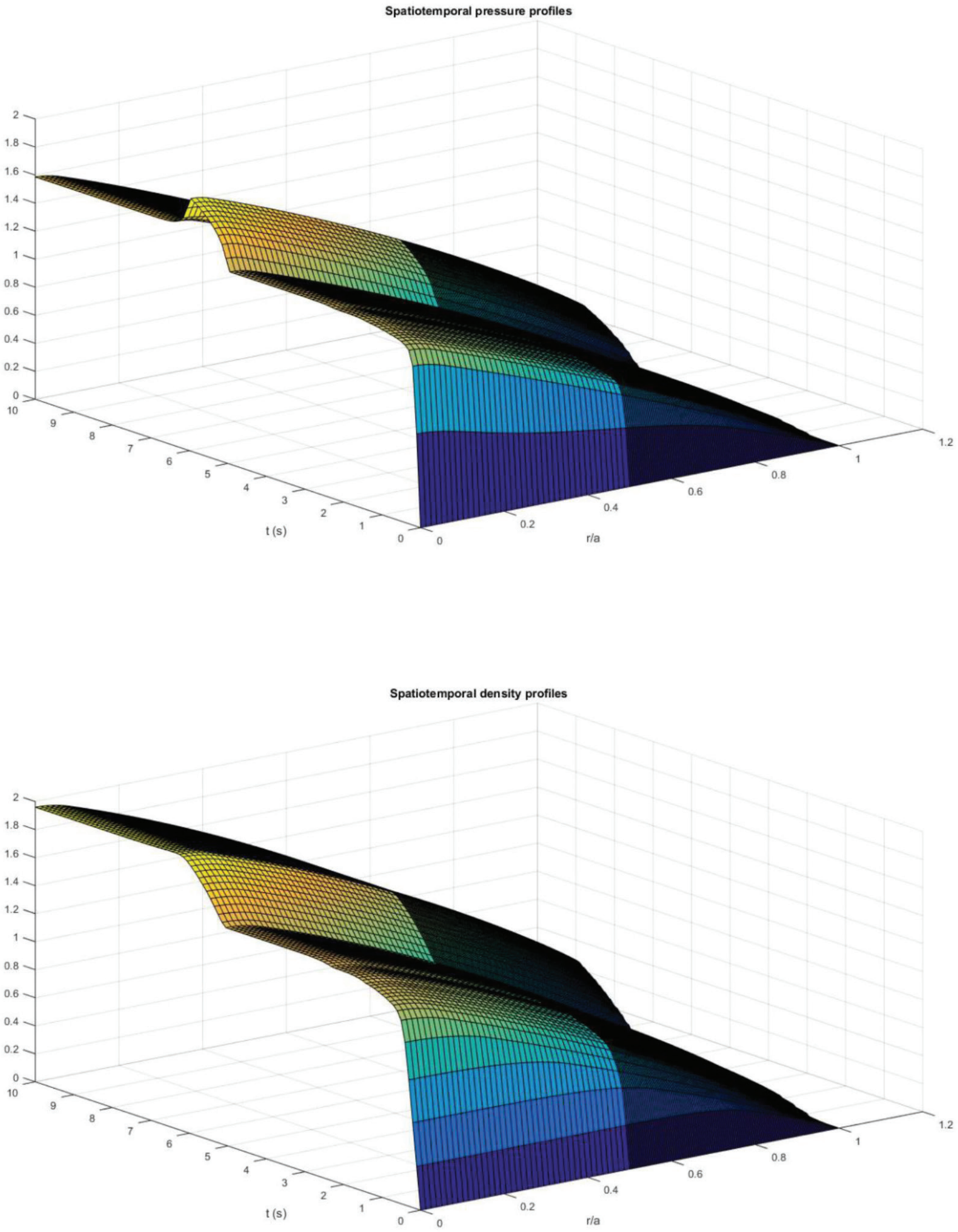

FIGURE 3. Spatio-temporal evolution profiles of plasma pressure (top) and plasma density (bottom) illustrating a triggering of an *L*-*H* transition via perturbation in heat source

both central pressure and density increase shortly before the third phase arrives.

The change in central plasma pressure and density can be seen more clearly in Figure 4. The sharp increase of their values start around 5 s. Interestingly, after the fluctuation is removed, the central pressure is reduced by around 10% but the plasma still remains in *H*-mode even though the same heating is used as in the first phase. This confirms the hysteresis behaviour of this plasma. Therefore, the triggered *H*-mode can be sustained with ratio of central pressure of the third phase over that of the first phase is as large as 1.15. Additionally, it appears that the response to the change of sources are different. Evidently, when the heat perturbation is removed in the third phase, the central pressure is reduced more significantly than that of the density. In fact, as shown in the right panel of Figure 4, the central density increases slightly. The ratio of central density of the third phase over that of the first phase is about 1.27. The formation of an ETB is categorized with the abrupt change in plasma gradients. Figure 5 illustrates the plasma pressure (middle panel) and density (right panel) gradients for the first, second and third phase. There is no abrupt change in the first phase, while in the second and third phase, the plasma gradients abruptly and significantly increase near the edge of plasma. This is a clear indication of an ETB formation. The left panel of this figure shows the

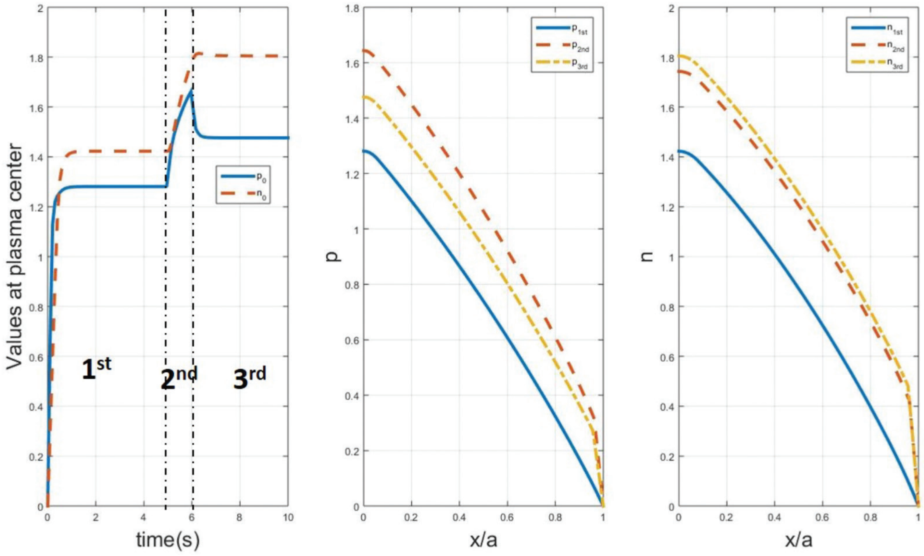

FIGURE 4. Effects of change in heat source on time evolution of central pressure and density (left) and profiles of pressure (middle) and density (right) at different time

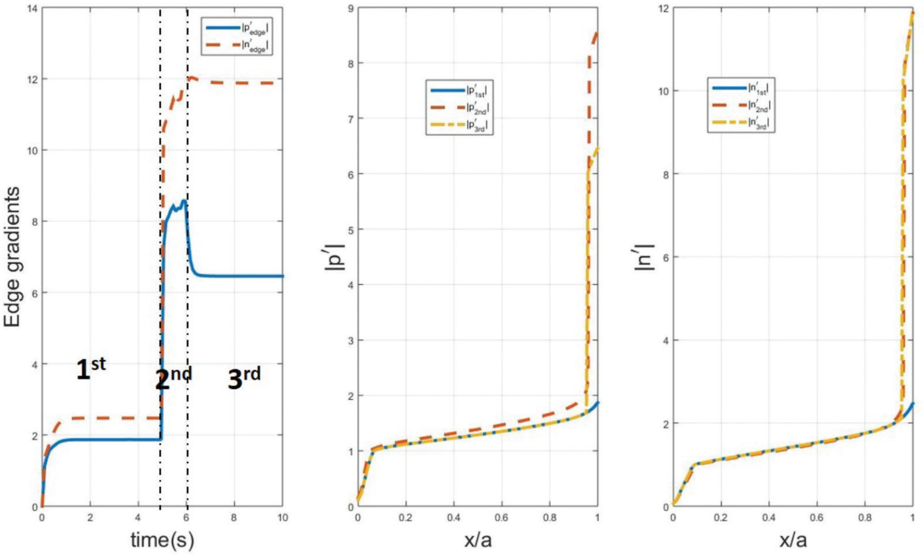

FIGURE 5. Effects of change in heat source on time evolution of edge pressure and density gradients (left) and profiles of pressure (middle) and density gradients (right) at different time

edge gradient as a function of time. The results are similar to what has been found already that the *H*-mode can be triggered in the second phase and retained in the third phase. Similarly, the reduction in edge density gradient is very small compared to that of the pressure gradient.

PERTURBATION IN PARTICLE SOURCE

In this section, a scenario is given for triggering of the *L-H* transition via perturbation in particle source. Initially, in the first phase (1st), the plasma is setup with a heating power at the marginal point just below the *L-H* threshold so the plasma is in *L*-mode. In second phase (2nd), the perturbation effect on the particle source is simulated by adding a peak profile to the main source. Physically, this could represent a pellet injection, which is used commonly as plasma fuelling and heating. It was found in some experiments that the pellet injection can also trigger formations of transport barrier. In the third phase (3rd), the same condition as in the first phase is given, i.e. the pellet injection source is removed. Similar to the previous case, the simulation results show that a perturbation in particle source can also trigger the *H*-mode where sudden increases of central pressure and density occur, as seen in Figure 6. Nevertheless, the required condition is that the particle source derived from pellet injection must be large enough for the total particle flux to surpass the *L-H* transition threshold. In addition, after the perturbed particle source is removed, the central density is reduced by around 20%, while the central pressure is only slightly affected but the plasma still remains in *H*-mode. Hence, the triggered *H*-mode can be sustained with ratio of central density and pressure of the third phase over that of the first phase are around 1.48 and 1.28, respectively. Note that as mentioned earlier, these ratio was found in experiment to be at maximum a factor of two so the simulation results can obtain similar values. It also appears that the response to the change of sources are different. Figure 7 illustrates the formation of an ETB where abrupt changes in plasma gradients are clearly shown. There is no abrupt change in the first phase, while in the second and third phase, the plasma gradients abruptly and significantly increase near the edge of plasma. This is a clear indication of an ETB formation. The left panel of this figure shows the edge gradient as a function of time. The results are similar to what has been found already that the *H*-mode can be triggered in the second phase and retained in the third phase. Similarly, the reduction in edge pressure gradient is very small compared to that of the density gradient.

CONCLUSION

A coupled 2-fields bifurcation model is used to investigate the possibility to trigger an *L-H* transition and *H*-mode sustainment via perturbation in thermal and particle sources in tokamak plasmas. The transport equations for heat and particles with simplified form of *ExB* flow shear effect included are numerically and self-consistently solved for describing the relation between local plasma gradients and corresponding fluxes, in order to examine the ETB formation. The heat source is perturbed in the form of fluctuations in heating and the particle source is perturbed in the form of pellet injection. It is found that in a marginal point just below *L-H* transition threshold, the ETB formation can be triggered using both type of perturbations. Due to hysteresis nature of the plasma, once triggered the *H*-mode can be sustained. Furthermore, the plasma appears to respond faster to the change of source perturbation in its own field.

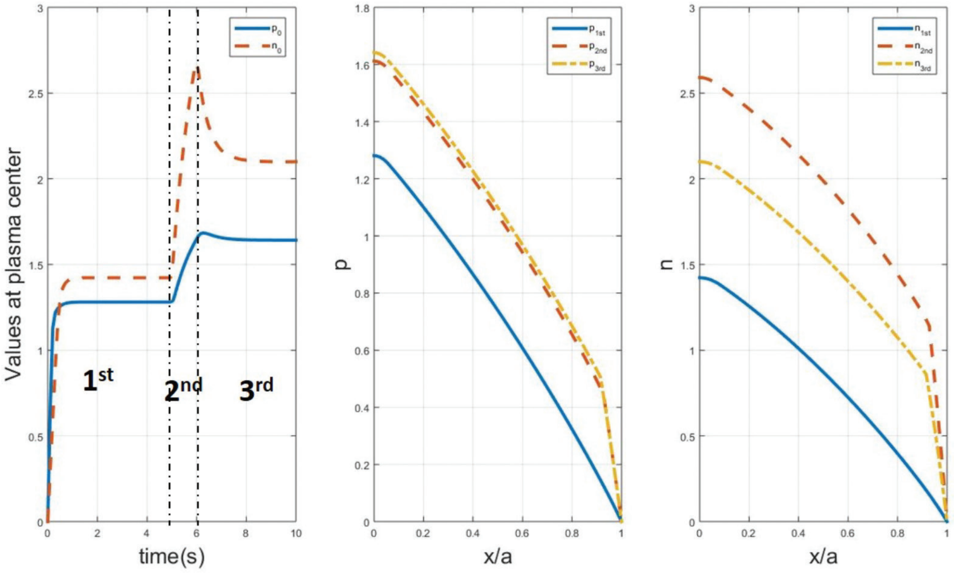

FIGURE 6. Effects of change in particle source on time evolution of central pressure and density (left) and profiles of pressure (middle) and density (right) at different time

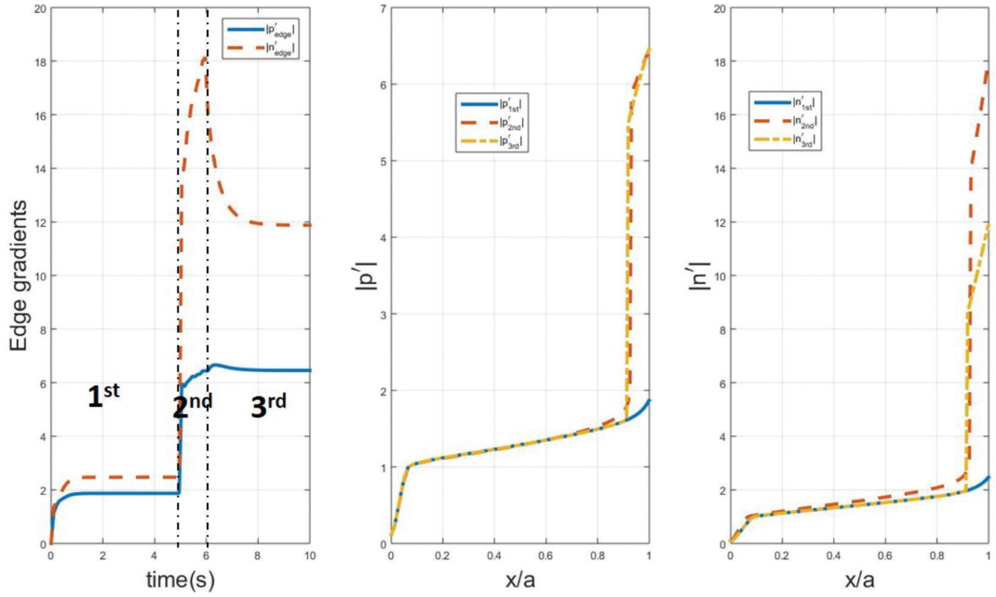

FIGURE 7. Effects of change in particle source on time evolution of central pressure and density gradients (left) and profiles of pressure (middle) and density gradients (right) at different time

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