Roles of driven current locations on ETB and ITB based on three-field bifurcation concept

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Abstract. This work investigates the roles of external current source on the formation and effectiveness of an internal transport barrier (ITB) and an edge transport barrier (ETB) in fusion plasma using bifurcation approach. Thermal, particle and toroidal momentum transport equations are solved simultaneously for the spatiotemporal profiles of plasma pressure, density and toroidal velocity, respectively. The transport effects include neoclassical and turbulent terms with constant coefficients assumption. The turbulent suppression, leading to intrinsic formation of transport barriers, is driven by the magnetic shear and the flow shear. Residual stress effect is included in this work. Thermal, particle and torques sources are locally provided based on Gaussian shape distribution at plasma center, plasma edge and plasma center, respectively. The effects of off-axis driven current locations on ITB and ETB formations are investigated. In particular, width and height of ETB and ITB are shown to be affected by the source. It is found that off-axis of driven current can increase plasma temperature, density and toroidal velocity at its core because ITB is formed and expanded. However, size of ETB pedestal is slightly affected by the location of driven current. When the location of driven current is changed from $r = 0.00$ to $r = 0.60$, ITB width changes from $r = 0.00$ to $r = 0.12$ of plasma profile and ITB top formation location changes from $r = 0.00$ to $r = 0.80$.

1. Introduction
Nowadays, human try to create fusion energy to solve energy problem and to replace fossil energy. One possible way is magnetic confinement fusion based on a device called tokamak. However, one of the biggest issues of magnetic confinement device is how to battle plasma turbulence. The turbulence has an effect to decrease performance of plasma at the core i.e. temperature, density and confinement time. But fusion reaction needs a lot of energy to overcome Coulomb force, so turbulence is a big obstacle. In magnetic confinement device, plasma has high turbulence caused by both electromagnetic wave and thermodynamic effects. Turbulence of plasma effects on confinement and the plasma is said to be in low confinement mode ($L$-mode) when the turbulence is high. However, loss from plasma turbulence can be suppressed resulting in two types of transport barrier. First, an edge transport barrier (ETB) can be observed at the edge of plasma, its formation causes the plasma to transit to high confinement mode ($H$-mode) [1]. Once entering $H$-mode, the performance of plasma is greatly improved [1-3]. However, the $H$-mode also has disadvantage from instability like an edge localize mode (ELM), which can destroy both first wall in fusion reactor and divertor [4]. Many experiments and theories explain formation of ETB by using effect of flow shear to suppress turbulence at the edge [1,3,5]. Second, an internal transport barrier (ITB) can be observed at plasma core. Its formation can occur in both $L$ - mode and $H$ - mode plasma. Similar to an ETB, it can increase plasma performance at the core and more importantly can
avoid effect of instability induced in $H$-mode. Until recently, the physics of ITB is still not clear but many experimental observations found ITB to be related to magnetic shear because location of ITB coincides with location of reverse magnetic shear induced by off-axis plasma current [2]. This work tries to investigate effects of driven current location on plasma profiles in the present of ITB and ETB by using three-field transport equations base on bifurcation concept [3,6-8]. Bifurcation idea was used to study $L$-$H$ transition by Malkov and Diamond to explain effect of flow shear on turbulence with energy and density transport at steady state [3]. Later, Jhang et. al. used similar method Malkov and Diamond to investigate bifurcation of ITB with energy and toroidal momentum transports at steady state and combined residual stress from Gürcan’s work [6,8]. In addition, Chatthong’s work studied about suppression ETB and ITB based on bifurcation model [5]. This current work uses model adapted from bifurcation concepts proposed by Malkov and Diamond, Jhang et. al., Gürcan et. al. and Chatthong et. al., to solve three-field transport equations, simultaneously, for time evolution profiles of plasma pressure, density and toroidal velocity [3,5,6,8].

2. Models for ETB and ITB formations

This work is based on three-field transport model similar to what proposed by Gürcan’s work [6]. Thermal, particle and toroidal momentum transport equations are written, respectively, as:

$$\frac{3}{2} \frac{\partial p}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \left( \chi_0 + \chi_1 \frac{\partial \phi}{\partial r} \right) \right) = H(r), \quad (1)$$

$$\frac{\partial n}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \left( D_0 + D_1 \phi \right) \right) = S(r), \quad (2)$$

$$\frac{\partial \nu_0}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \left( \frac{\partial \nu_0}{\partial r} + \pi_{\text{res}} \right) \right) = \chi(r), \quad (3)$$

Where $r$ is normalize plasma radius. $\chi_0$, $D_0$ and $\nu_0$ are neoclassical transport coefficients, assumed to be constant. $\chi_1$, $D_1$ and $\nu_1$ are turbulence transport coefficients, also assumed to be constant. $H(r)$, $S(r)$ and $\chi(r)$ are Gaussian distribution representing heat, particle and torque sources, respectively [5]. $\pi_{\text{res}} = \kappa \sigma (1 - \frac{\partial \phi}{\partial r})$ represents residual stress effect with $\kappa$ and $\sigma$ as coefficients of the model. $p$, $n$ and $\phi$ are plasma pressure, density and toroidal velocity, respectively. $\nu_0$ is suppression term based on flow shear ($\nu_{E<B}$) and magnetic shear ($s$). It has the form $\nu = \frac{\nu_0}{1 + \alpha_0 r^\beta}$ similar to the function proposed in Chatthong’s work to investigate ITB and ETB formations, with $\nu_0$ is suppression coefficient, $\alpha$ and $\beta$ are ad-hoc parameters for focus and control ETB and ITB formation [5]. The flow shear can be calculated from the force balance equation as:

$$\nu_{E<B} \approx \frac{1}{B_B^2} \frac{\partial}{\partial r} \frac{\partial}{\partial r} + \frac{B_B^2 \partial B_B}{B_B^2 \partial \phi} + \frac{B_B \partial B_B}{B_B^2 \partial \phi}$$

Where $B_B$ is poloidal magnetic field calculated from plasma current using Ampere’s law, it can be written as $B_B \sim B_{0\phi} \delta(r, r_{j,\text{peak}})/r$ when $I_p(r, r_{j,\text{peak}}) \sim \int r_j \int 0 \int_0^r \left[ 1 - \left( r' - r_{j,\text{peak}} \right)^2 \right]^{15} r' dr'$ is plasma current and $r_{j,\text{peak}}$ is peak of driven current density. $B_B$ is toroidal magnetic field depending on radius of torus device $(R \sim R_0/a \pm r)$, it can be written as $B_B \sim B_0 (R_0/a \pm r)^{-1}$ when $R_0$ is major radius, $a$ is minor radius, positive plasma radius mean outer region and negative mean inner region of torus device.

Magnetic shear represents twist of magnetic fields in radial direction: $\sim \frac{1}{q} \frac{\partial q}{q \partial r}$, where safety factor $(q)$ can be calculated as $q \sim r B_B/RB_0$. Experimentally, turbulence transport at the core appears to depend on location of minimum of safety factor [2].

Plasma profiles as a function of position and time are solved from three-field transport equations using finite difference method. Relations of driven current locations on ETB and ITB widths and heights are illustrated in the next section.
3. Effect of driven current locations

Figure 1 illustrates possible conditions of plasma mode as results of solving the three-field transport equations. Figure 1(a) shows plasma pressure versus normalized radius at steady state. It is found that the plasma transits to $H$-mode once the heat source surpasses the threshold. This result agrees with previous work of bifurcation model as well as experimental observations [1-3,5-8]. Additionally, ITB is formed when the $r_{\text{peak}}$ moves away from plasma center, as equals to 0.40 in this case for both $L$- and $H$-mode plasmas. This also agrees with experimental observations [2,5]. In short, the results imply that ETB and ITB can occur both individually and simultaneously as found in several fusion devices. Figure 1(b) shows plasma pressure at center ($r = 0.00$) versus simulation time. Clearly, simultaneous formations yield highest plasma pressure, with central pressure of about 573 % enhancement from that of $L$-mode no ITB plasma case. Meanwhile single ETB formation appears to yield higher plasma pressure (268 %) than single ITB formation (78 %). Note that plasma density and toroidal velocity profiles also yield similar results but not shown here.

Figure 2. Effects of $r_{\text{peak}}$ on plasma pressure, $L$-mode (a) and $H$-mode (b) at steady-state

Effect of peak driven current, hence reverse magnetic shear, is illustrated in figure 2 by changing $r_{\text{peak}}$ from 0.00 to 0.60. Figure 2(a) shows variation in $L$-mode plasma, demonstrating that as $r_{\text{peak}}$ is varied, the location of ITB top shifts from 0.00 to 0.80 and ITB width increase from 0.00 to 0.12. Moreover, central pressure is increased by up to 197 % from its lowest value when no ITB occurs. More details of the percentage increased for all three fields parameters are shown in table 1. Figure 2(b) shows variation in $H$-mode plasma, which shows that location of ITB top shifts from 0.00 to 0.80, same with
$L$-mode results but ITB foot location is different resulting in ITB width increases from 0.00 to 0.16. Interestingly, the ETB appears to be affected by driven current location as well. Its width is increased from 0.02 to 0.03 and its height is increased from 0.05 to 0.08. In $H$-mode, the central pressure is increased by up to 206 %. Similar behavior is found in density and toroidal velocity profiles. Effect of $r_{j,\text{peak}}$ can change state of plasma from $L$-mode to $H$-mode if $r_{j,\text{peak}} > 0.60$ based on results in this work.

**Table 1.** Percentage increase of central pressure, density and toroidal velocity from their lowest values at driven current density peak at plasma center.

| Plasma profile (%) | Peak of driven current density ($r_{j,\text{peak}}$) |
|-------------------|----------------|
|                   | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 |
| $p_0$             | L    | H    | L    | H    | L    | H    |
|                   |      | 27   | 30   | 52   | 78   | 125  |
| $n_0$             |      | 11   | 19   | 28   | 38   | 42   |
|                   |      |      |      |      |      |      |
| $v_{\phi,0}$      |      | 18   | 22   | 51   | 47   | 79   |

4. Conclusion

ITB and ETB formations in fusion plasma are investigated based on three-field transport equations for both time and position of plasma pressure, density and toroidal velocity profiles. It was found that plasma profiles depend on location of peak of driven current density. In particular, shifting of top and foot ITB were observed when peak of driven current density was off-axis and moved away from center of plasma. Both transport barriers width and height are also found to be increased. ITB width and height are increased by changing plasma state from $L$ to $H$-mode. Time evolution profiles show that the plasma has reached steady-state faster in $L$-mode.

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