Analysis of Off-Axis Driven Current Effects on ETB and ITB Formations based on Bifurcation Concept

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Abstract. This research study plasma performance in fusion Tokamak system by investigating parameters such as plasma pressure in the presence of an edge transport barrier (ETB) and an internal transport barrier (ITB) as the off-axis driven current position is varied. The plasma is modeled based on bifurcation concept using a suppression function that can result in formation of transport barriers. In this model, thermal and particle transport equations, including both neoclassical and anomalous effects, are solved simultaneously in slab geometry. The neoclassical coefficients are assumed to be constant while the anomalous coefficients depend on gradients of local pressure and density. The suppression function, depending on flow shear and magnetic shear, is assumed to affect only on the anomalous channel. The flow shear can be calculated from the force balance equation, while the magnetic shear is calculated from the given plasma current. It is found that as the position of driven current peak is moved outward from the plasma center, the central pressure is increased. But at some point it stars to decline, mostly when the driven current peak has reached outer half of the plasma. The higher pressure value results from the combination of ETB and ITB formations. The drop in central pressure occurs because ITB stats to disappear.

Keywords: bifurcation, flow shear, magnetic shear

1. Introduction

To improve plasma performance is an aim for Tokamak experiment. Experimental observations have revealed that the formation of transport barriers can improve plasma performance significantly. There are two types of transport barrier, an edge transport barrier (ETB) which is the phenomenon of plasma confinement changing from low plasma confinement mode (*L-mode*) to high plasma confinement mode (*H-mode*) at the edge of plasma [1].Second one is an internal transport barrier (ITB), which at the core plasma region[2]. Both of their occurrences are result of turbulence suppression involving flow shearand magnetic shear. Some research described this phenomenon (i.e.*L-H transition*) based on bifurcation concept which illustrated nonlinear flux ofthe plasma including both stable and unstable plasma states in gradient space. Malkov*etal.*applied this concept to analyze pressure gradient and particle density gradient versus heat flux and density flux to show that the *L-H transition phenomenon*follows Maxwell's equal area when hyper diffusion effect is included[3]. Later Chatthong*et al.* improved this model by adding magnetic shear term to describe both ETB and ITB[4]. They demonstrate that the plasma could abruptly transit from *L-* to *H-* mode once the heating power surpasses a threshold. Additionally, an ITB can form when the plasma current is driven off-axis or off-centre. Nevertheless, the work did not address the situation where ETB and ITB could interact with each other. This could allow an additional plasma operating regime, providing that any gradient-limited instability is not violated. This work explores bifurcation concept by solving simple plasma transport model to investigate ETB and ITB formations at various local position in tokmak plasma.

2. Models for ETB and ITB Formations

In this work, the model used is similar to what describe in Ref. [4]. The steady state thermal and particle transport equations are written, respectively, as:

$$-\left[x_{neo} + x_{ano} f\left(v'_E, s\right)\right]\frac{\partial p}{\partial x} = Q(x) \quad (1)$$

$$-\left[D_{neo} + D_{ano} f\left(v'_E, s\right)\right]\frac{\partial n}{\partial x} = \Gamma(x) \quad (2)$$

where x_{neo} and D_{neo} are heat and particle neoclassical transport coefficients , x_{ano} and D_{ano} are heat and particle anomalous transport coefficients, $f\left(v'_E, s\right)$ is a term representing suppression mechanism, $\frac{\partial p}{\partial x}$ is the pressure gradient, $\frac{\partial n}{\partial x}$ is the density gradient, $Q(x)$ is heat flux, and $\Gamma(x)$ is particle flux.The heat flux is calculated as Q= $\int_0^x H(x')\,dx'$, where the heat source H(x) is given as Gaussian distribution with some background as: $H(x) = H_0 \mathrm{e}^{-\frac{x^2}{0.01}} + \frac{H_0}{2}$, localized at plasma center. H_0 is a constant.The particle flux is calculated as $\Gamma(x) = \int_0^x S(x')\,dx'$, where the particle source S(x) is given as Gaussian distribution with some background as: $S(x) = S_0 \mathrm{e}^{-\frac{(x-1)^2}{0.01}} + \frac{S_0}{2}$, localized at the plasma edge. S_0 is a constant.

Note that the suppression function consists of flow shear (v'_E) and magnetic shear(s), the main mechanisms for turbulent suppression. Generally, the turbulence causes particles loss and decrease of plasma performance. In this work, the suppression has the form [4]:

$$f(v'_E, s) = \frac{\beta|s|}{1+\alpha {v'_E}^2}\frac{1}{1+\gamma s^2}. \quad (3)$$

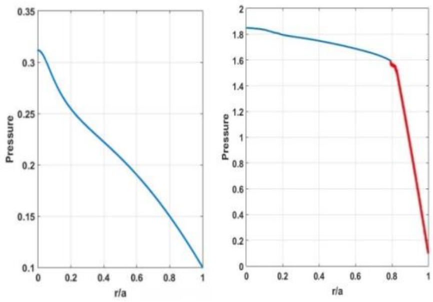
In this work, the neoclassical coefficients are assumed to beconstant and anomalous termsdepend on their respective gradients (pressure/density) [5]. Equation (1) and (2)are solved simultaneously and self-consistently using discretization method. The constants are chosen arbitrarily but they correspond to physical observation and theoretical expectation. The details are given in Ref.[4].

The magnetic shear (s) is a result of the twist angle of magnetic field linesin the torus. It is defined as the radial gradient of the rotational transform which relates to safety factor(q),s= $\frac{x}{q}\frac{\partial q}{\partial x}$,with $q = \frac{x}{R}\frac{B_\emptyset}{B_\theta}$, where $B_\emptyset$ and B_θ are toroidal and poloidal magnetic fields, respectively.

The toroidal magnetic field is assumed to be constant so safety factor depends only on the poloidal magnetic field. The equation $B_\theta = \frac{\mu_0 I}{2\pi x}$ can be substituted in safety factor equation. The equation becomes $q = \frac{2\pi x^2 B_\emptyset}{\mu_0 I R}$. The term $\frac{2\pi B_\emptyset}{\mu_0 R}$ is constant so q depends only on $\frac{x^2}{I}$. The current I can be calculated using Ampere's law $I = \int j\,dA$, where j is current density of the form: $j(x) = j_0\left(1 - \frac{(x-x_0)^2}{a^2}\right)^2 + j_b$, where x_0 is the location of the current density peak, a is the plasma normalized minor radius and j_b is the bootstrap current which is generated by trapped particles in plasma.

3. Effects of Driven Current Peaking Position

L-mode H-mode (ETB)



ITB

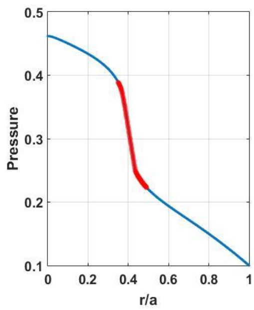


Figure1 shows pressure profile

Figure 1 illustrated examples of simulation results. The top left panel shows the plasma pressure in *L*-mode. The top right panel shows the plasma pressure in *H*-mode, where the red line indicates ETB zone. The bottom panel shows the plasma pressure with ITB formation, where the red line indicates ITB zone.These results show that the model can confirm what found in experiments and those previously concluded in Ref.[4], in which an ETB can occur when plasma is heated over a threshold power heating and an ITB can occur when the current peaking location is shifted from the plasma axis or centre.

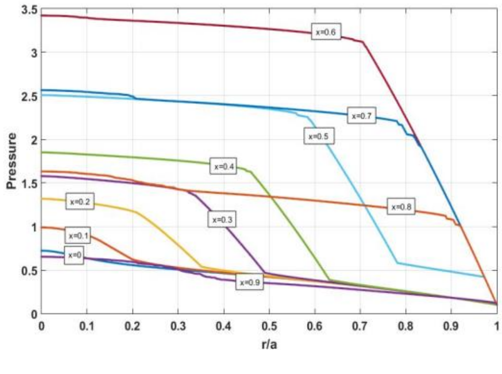


Figure2 shows pressure profile at various driven current peaking position

The effect of driven current peaking position(x_0) on plasma pressure and transport barrier formations is investigated. As seen in figure2,ITB starts to form in the position which is near plasma core ($x_0 = 0.2$). Note that if x_0 is lower than that ITB becomes weaker and disappears. This result agree with what found in work of Ref.[4].This is because the suppression is not enough to form the barrier. When the driven current peaking position is varied, moving out from plasma core to plasma edge, the central pressure is increased and ITB location also follows that of the current peaking. At some driven current peaking position, ITB moves out to plasmaedge and combine with ETB resulting in central pressure enhancement. This can be seen in figure2 at $x_0 = 0.6$. This event results in the highest central pressure among all conditions. At some point, central pressure is decreased because ITB starts disappear and ETB region is decreased. ITB and ETB are formed because of turbulent suppression so we can conclude that the turbulence can be high from core to edge of plasma and has smaller values in the edge and ITB regions of plasma.

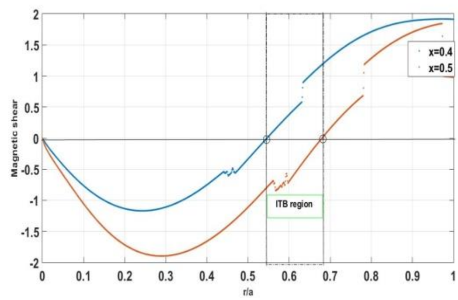


Figure3 shows magnetic shear profile in all tokamak position with different drivencurrent peaking position.

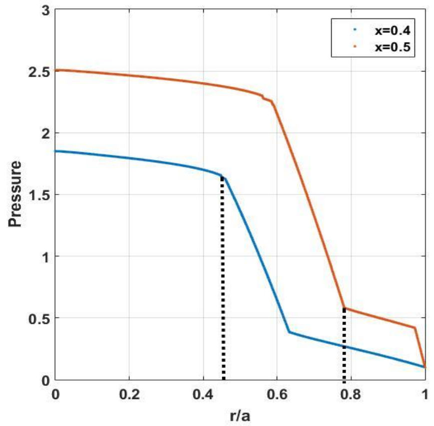


Figure4 shows pressure profile

Figures (4) and (5) show that an ITB can occur at region where magnetic shear has a small value, which is close to zero. This implies that if a magnetic field line is parallel to the vicinity lines, turbulence has small value and ITB is formed.

4. Conclusion

This work investigates ITB and ETB formations by using transport equation which consists of neoclassical term and anomalous term. The result shows that ITB and ETB formation can be investigated by supplying efficient heat flux and proper location of current peaking position. ITB and ETB are formed by turbulent suppression. ITB is formed inside plasma while ETB is formed at plasma edge. Driven current peaking position influences the position of ITB formation because when driven current peaking position is moved out from plasma core to plasma edge, the position of ITB formation is also moved out too. And the driven current peaking positions that are suitable for ITB formation are from 0.3-0.4. ITB formation was found although heat flux is changed. Central pressure is increased when ITB formation moves out to plasma edge and the highest of central pressure occurs when ITB and ETB are combined. After that region, central pressure starts to drop because ITB starts to disappear. Magnetic shear is a reason for ITB formation because ITB occurs near position where its value is close to zero.

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