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

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Abstract. This research studies 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 the 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 outwards 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 the 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.

1. Introduction

One of the aims for tokamak experiments is to improve the performance of plasma operation. Experimental observations have revealed that the formation of transport barriers can improve plasma performance significantly. Two types of transport barriers have been observed so far. One is Edge Transport Barrier (ETB). Another one is Internal Transport Barrier (ITB). ETB 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], while ITB is located at the core plasma region [2]. Both of their occurrences are results of turbulence suppression involving flow shear and magnetic shear. Some research described this phenomenon (i.e. *L-H transition*) based on the bifurcation concept which illustrated nonlinear flux of the plasma including both stable and unstable plasma states in gradient space. Malkov *et al.* 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 demonstrated 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 positions in tokamak plasma.

2. Models for ETB and ITB Formations

In this work, the used model is described in Reference [4]. The steady state thermal and particle transport equations are written, respectively, as:

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

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

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, $f(v'_E, s)$ 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: $H(x) = H_0 e^{-\frac{x^2}{0.01}} + \frac{H_0}{2}$, 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: $S(x) = S_0 e^{-\frac{(x-1)^2}{0.01}} + \frac{S_0}{2}$, localized at the plasma edge. S_0 is a constant. 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 be constant and anomalous terms depending on their respective gradients (pressure/density) [5]. Equations (1) and (2) are solved simultaneously and self-consistently using the 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 lines in the torus. It is defined as the radial gradient of the rotational transformation 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 the 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: $j(x) = j_0 (1 - \frac{(x-x_0)^2}{a^2})^2 + j_b$, where x_0 is the location of the current density peak, a is the plasma normalized minor radius, j_0 is the external current density and j_b is the bootstrap current which is generated by trapped particles in plasma.

3. Effects of Driven Current Peaking Position

These results show that the model can investigate ITB and ETB formations.
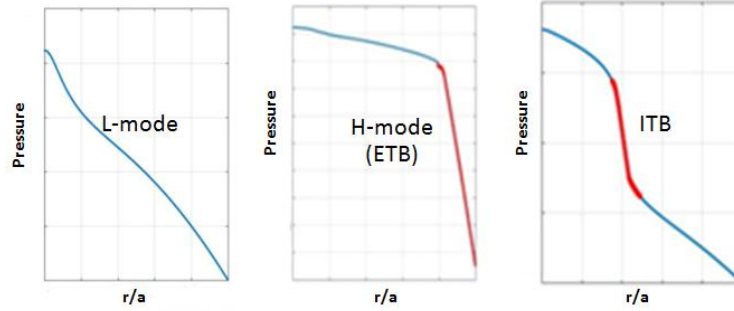

Figure 1. Trends of the formations in plasma profile with normalized plasma radius corresponding to those report in ref.[4]

Figure 1 illustrates examples of simulation results. The left panel shows the plasma pressure in *L*-mode. The middle panel shows the plasma pressure in *H*-mode, where the red line indicates ETB zone. The right panel shows the plasma pressure with ITB formation, where the red line indicates ITB zone. These results show that the model can confirm what was 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 peak position is shifted from the plasma axis or centre.
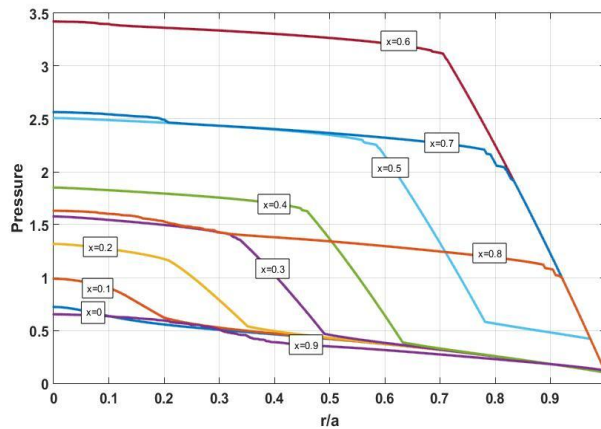

Figure 2. Pressure profile at various driven current peak positions

The effect of driven current peaking position (x_0) on plasma pressure and transport barrier formations is investigated. As seen in Figure 2, ITB starts to form in the position near the plasma core $(x_0 = 0.2)$. Note that if x_0 is lower than that ITB becomes weaker and disappears. This result agrees with what was found in the work of Ref.[4].This is because the suppression is not enough to form the barrier. When the driven current peak position is varied, from plasma core to plasma edge, the central pressure is increased and the ITB location also follows the current peak. At some driven current peak position, ITB moves out to plasma edge and combines with ETB resulting in central pressure enhancement. This can be seen in Figure 2 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 to disappear and

the 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 at the edge and in ITB regions of plasma.
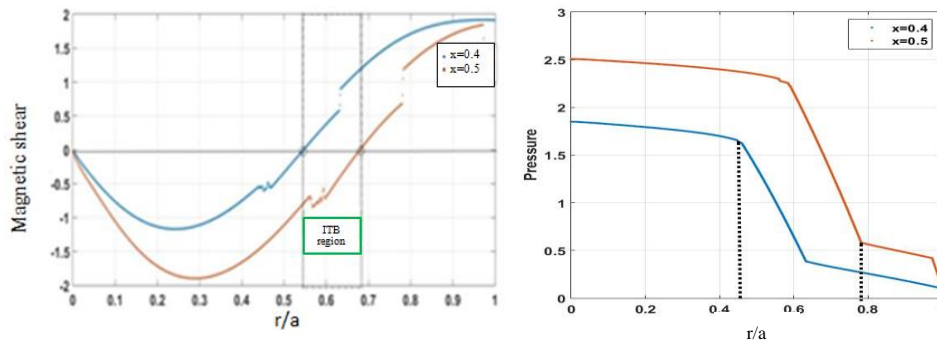

Figure3. In panel 1 and 2 show magnetic shear and plasma profile, respectively with driven current at $x_0 = 0.4$ and $x_0 = 0.5$

An ITB can occur in a region where magnetic shear has a small value, 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 the transport equation which consists of neoclassical term and anomalous term. The results show that ITB and ETB formation can be investigated by supplying efficient heat flux and proper location of current peak position. ITB and ETB are formed by turbulent suppression. ITB is formed inside plasma while ETB is formed at plasma edge. Driven current peak position influences the position of ITB formation because when driven current peak position is moved out from plasma core to plasma edge, the position of ITB formation is also moved out. Driven current peak positions that are suitable for ITB formation range from 0.3 to 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, central pressure starts to drop because ITB starts to disappear. Magnetic shear is a reason for ITB formation because ITB occurs at a position with a value close to zero.

References

[1]   Wagner F 2007 A quarter-century of H-mode studies. Plasma Physics and Controlled Fusion **49** B1

[2]   Connor J W *et al* the ITB DatabaseGroup, the ITPA Topical Group on Transport and Internal Barrier Physics 2004 A review of internal transport barrier physics for steady-state operation of tokamaks. *Nucl.Fusion* **44** R1

[3]   Malkov M A and Diamond P H 2008 Analytic theory of L-H transition, barrier structure, and hysteresis for a simple model of coupled particle and heat fluxes *Phys. Plasmas* **15** 122301

[4]   Chatthong B and Onjun T 2016 Understanding roles of E × B flow and magnetic shear on the formation of internal and edge transport barriers using two-field bifurcation concept *Nucl. Fusion* **56** 016010

[5]   Garbet X Mantica *et al* 2004 Profile stiffness and global confinement *Plasma Phys. Control. Fusion* **46** 1351