Investigation of ETB Formation, Pedestal Width and Dynamics Based on Bifurcation Concept

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Edge transport barrier (ETB) formation, pedestal width and dynamics are analyzed within the framework of the bifurcation concept similar to that introduced in Ref. [1]. This model conceptually describes that the *L*-*H* transition phenomenon is an intrinsic property of the plasma where its confinement mode abruptly changes once certain criteria are satisfied. It is graphically depicted in the bifurcation diagram representing an *S*-curve line of pressure or density gradients versus heat or particle fluxes, respectively. Namely, at low flux, plasma points are mapped onto the low gradient branch of the *S*-curve implying that the plasma is in *L*-mode. Whereas, at high flux, the points are mapped onto both low and high gradient branches of the curve meaning that the plasma is in *H*-mode with a considerable jump in the gradient. In an intermediate range of flux, there coexist three possible equilibria of the plasma state: one of which is unstable and the other two are stable; one has low gradient (*L*-mode); and the other one has high gradient (*H*-mode). This range falls into a bifurcation regime where the plasma can be in one of the two stable states depending on the direction of flux ramping, exhibiting a hysteresis loop. According to the model, simplified versions of heat and particle transport equations are utilized in slab geometry, which can be expressed in these forms: $\frac{3}{2}\frac{\partial p}{\partial t}-\frac{\partial}{\partial x}\left[\chi_0+\frac{\chi_1}{1+\alpha v_E'^2}\right]\frac{\partial p}{\partial x}=H(x)$ and $\frac{\partial n}{\partial t}-\frac{\partial}{\partial x}\left[D_0+\frac{D_1}{1+\alpha v_E'^2}\right]\frac{\partial n}{\partial x}=S(x)$, where p is the plasma pressure, n is the plasma density, χ_0 and D_0 represent the neoclassical transport coefficients, χ_1 and D_1 represent the anomalous transport coefficients, v_E' is the flow shear suppression, α is a positive constant representing strength of the suppression, and H(x) and S(x) are the thermal and particle sources, localized at plasma center and edge, respectively. The main ingredient for the stabilization of the anomalous transport is the flow shear v_E', which accounts for the known reduction of turbulent transport by sheared radial electric field [2]. It couples the two transport equations according to the force balance equation

$v'_E = c\frac{E'_r}{B} \simeq -\frac{c}{eBn^2}p'n'$. Note that the curvature, the toroidal and poloidal rotation contributions are neglected here.

Throughout this work, the two transport equations are solved simultaneously using discretization method. Heat and particle sources are given as described previously and they are constant in time. The numerical results yield time evolution of plasma profiles i.e. pressure, density, and their gradients. The neoclassical transport coefficients are simply set to be constant while the anomalous transport coefficients follows critical gradient transport model similar to that described in Ref. [3]: $\chi_1 = c_\chi \left(p' - p'_c\right)\mathrm{H}\left(p' - p'_c\right)$ and $D_1 = c_D \left(n' - n'_c\right)\mathrm{H}\left(n' - n'_c\right)$, where c_χ and c_D are proportional constants, p'_c and n'_c are the critical gradients for pressure and density fields, respectively, and θ represents a Heaviside step function.

Pedestal Dynamics

This section illustrates the pedestal growth in the plasma. The crucial assumption to be noted here is that the pedestal is allowed to grow without any constraint, like MHD instability. Thus, these results presumably predict what would happen to the plasma and its pedestal if loss mechanism like ELM can be controlled. First of all, the two criteria (minimum flux and minimum diffusivities ratio) for possibility of *L-H* transition according to bifurcation model are satisfied [4] so the plasma is ensured to reach *H*-mode at steady state. Figure 1 demonstrates the growth of pedestal width after it is formed. The growth of pedestal is initially fast, and then it slows down and eventually reaches its steady state. It appears that the pedestal growth is categorized as superdiffusive behaviour ($\Delta_{ped} \propto t^b, b > 0.5$), agreeing with the turbulent nature of the plasma because in this phase the suppression effect is still low, thus turbulent transport still plays a dominant role. Later, wider region of the plasma is suppressed so only the neoclassical transport takes effect in the pedestal region resulting in slower pedestal growth (subdiffusion or even lower). There is an interesting point worth mentioning here, which is the time it takes the plasma to evolve during *H*-mode is around one order of magnitude slower than the time it takes for the plasma to evolve from *L* to *H* mode. This characteristic of the model is doubtful because, in the real tokamak plasma, instabilities at the edge cannot yet be controlled fully and efficiently. Moreover, one has to make sure that plasma loss via transport is the sole mechanism in order to observe this behaviour.

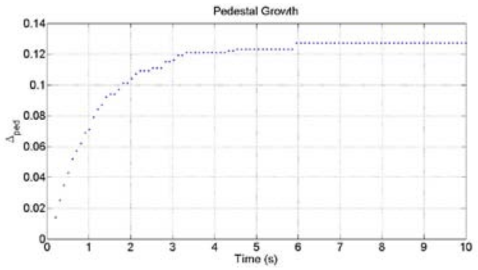

Figure 1: Pedestal width in normalized minor radius (*r/a*) unit as a function of time

Pedestal Width

This section focuses on the pedestal width analysis at steady state. Here, the relationship between the pedestal and various plasma parameters is shown in figure 2.

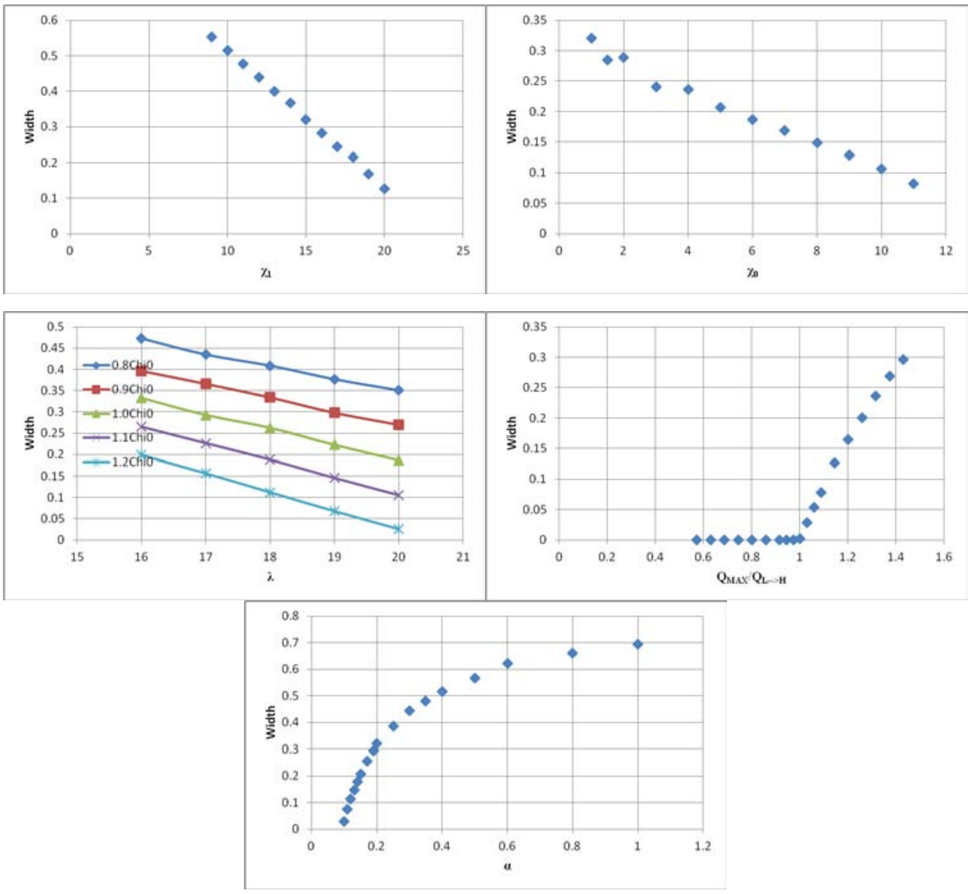

Figure 2: Pedestal width at steady state as a function of various parameters.

Firstly, it can be observed that the width is inversely proportional to the transport diffusivities (both neoclassical and anomalous). These are not surprising results because if the transport is increased, it is expected that the plasma loss is enhanced hence reduction in plasma confinement. It is safe to assume that the pedestal width is correlated to the plasma confinement. Also it can be seen that at a heat flux lower than the critical value the pedestal cannot yet form, but after the critical flux is reached the pedestal width is growing proportionally to the heat given to the plasma. In the last graph, it is showed that once the suppression strength is increased the pedestal width is theoretically allowed to grow even up to *r/a* = 0.7. This shows the possibility to obtain the VH mode or even higher mode.

Conclusions

Numerical method is used to solve the coupled heat and particle transport equations. The transport effects included are neoclassical transport which is assumed to be constant and anomalous transport which is inspired by the critical gradient transport model. The suppression mechanism is the flow shear approximating from the sheared radial electric field equation. It is found that without gradient limiting instability, the pedestal width can expand initially superdiffusively and later subdiffusively. The time the plasma takes for pedestal expansion is much longer than it takes to transit from *L*- to *H*-mode. Furthermore, the pedestal width at steady state appears to be proportional to the heat flux and the suppression strength but inversely proportional to the transport diffusivities.

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