Creation and Dynamical Co-evolution of Electron and Ion Channel Transport Barriers[*]

D.E. Newman 1), B. A. Carreras 2), Daniel Lopez-Bruna 3), P.W. Terry 4)

1) Department of Physics, University of Alaska at Fairbanks, Fairbanks, Alaska, USA
2) Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee
3) Asociación Euratom-CIEMAT, Madrid, Spain
4) Univ. of Wisconsin, Madison, WI

e-mail contact of main author: ffden@uaf.edu

Abstract. A wide variety of magnetic confinement devices have found transitions to an enhanced confinement regime. Simple dynamical models have been able to capture much of the dynamics of these barriers however an open question has been the disconnected nature of the electron thermal transport channel sometimes observed in the presence of a standard ("ion channel") barrier. By adding to simple barrier model an evolution equation for electron fluctuations we can investigate the interaction between the formation of the standard ion channel barrier and the somewhat less common electron channel barrier. Barrier formation in the electron channel is even more sensitive to the alignment of the various gradients making up the sheared radial electric field then the ion barrier is. Electron channel heat transport is found to significantly increase after the formation of the ion channel barrier but before the electron channel barrier is formed. This increased transport is important in the barrier evolution.

1. Introduction

One of the more important and exciting recent advances in the physics of confined plasmas has been the production and concomitant developing understanding of enhanced confinement regimes. If controllable, these operating regimes offer the promise of an easier path to the economic production of fusion energy. Over the last 10 years a wide variety of magnetic confinement devices have found transitions to such an enhanced confinement regime [1-8]. These regimes include edge transport barriers and internal transport barriers as well as combinations of both. A simple model incorporating the nonlinear interactions between the low-k turbulent fluctuations and the sheared radial electric field coupled to a transport model has been able to capture much of the observed dynamics[9-11] of ion transport barriers and has even been able to suggest barrier control strategies. However, an open question which remains is the nature and dynamics of the active electron thermal transport channel which is sometimes observed in the presence of a standard ("ion channel") barrier. An understanding of the electron channel is important not only because it can become the dominant energy flow channel when in the presence of an ion channel barrier, but also because in devices in which $T_e \geq T_i$ this channel is always important. This, of course, is likely to be the case for reactor relevant regimes. By adding to the simple model mentioned above an evolution equation for electron fluctuations, such as a simplified version of the ETG model, one can investigate the interaction between the formation of the standard ion channel barrier and the somewhat less common electron channel barrier. While it has previously been found that the ion channel barrier is sensitive to the alignment of the various gradients that make up the sheared radial electric field, we now find that the barrier formation in the electron channel is even more sensitive. It should be remembered that these gradients include both the first and second derivatives of the temperature and density as well as the gradients of the toroidal and poloidal flows. This sensitivity has significant implications for operating scenarios in which barrier control plays an important part. It also highlights the importance of having a variety of real

time profile modification tools to facilitate the initiation of barrier formation and its subsequent control. The electron channel heat transport is found to significantly increase after the formation of the ion channel barrier but before the electron channel barrier is formed. This increased transport is important in the ion barrier evolution, the electron barrier initiation and the final "steady state" profiles if an electron barrier does not form.

2. The Extended Model

The basic model consists of a set of transport equations for the density(n), electron temperature(T_e) and ion temperature(T_i) plus a nonlinear dynamical envelope equation for the fluctuations(ε).The fluctuation evolution equations are coupled to the transport equations through the transport coefficients and the profiles as well as through the radial electric field via the force balance equation. While the basic model and many of its features are explained in detail in ref 1 and 2 we will give a brief overview of some of the terms.

$$\frac{\partial n}{\partial t} = S_{NBI} + S_{gp} + \frac{1}{r}\frac{\partial}{\partial r}\left[rD_n\frac{\partial n}{\partial r}\right]$$

$$\frac{3}{2}\frac{\partial nT_i}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\chi_i n\frac{\partial T_i}{\partial r} + \frac{5}{2}D_n T_i\frac{\partial n}{\partial r}\right)\right] - D_n\frac{1}{n}\frac{\partial n}{\partial r}\frac{\partial nT_i}{\partial r} + Q_{NBI}^i + Q_{ei}(T_e - T_i)$$

$$\frac{3}{2}\frac{\partial nT_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\chi_e n\frac{\partial T_e}{\partial r} + \frac{5}{2}D_n T_e\frac{\partial n}{\partial r}\right)\right] + D_n\frac{1}{n}\frac{\partial n}{\partial r}\frac{\partial nT_i}{\partial r} + Q_{NBI}^e + Q_{Ohm} + Q_{ie}(T_e - T_i)$$

$$\frac{\partial \varepsilon}{\partial t} = \left\{\gamma - \alpha_1\varepsilon - \alpha_2\left[\frac{r}{q}\frac{\partial}{\partial r}\left(\frac{q}{r}\frac{E_r}{B_\phi}\right)\right]^2\right\}\varepsilon + \frac{1}{r}\frac{\partial}{\partial r}\left[rD_\varepsilon\frac{\partial \varepsilon}{\partial r}\right]$$

$$E_r = -V_\theta + V_\varphi\frac{B_\theta}{B_0} + \alpha\left[\frac{\partial T}{\partial r} + \frac{T}{N}\frac{\partial N}{\partial r}\right]$$

The growth rate γ in the fluctuation equation has a external component due to magnetic shear considerations as well as the more self-consistent profile related form common to eta-i models. The magnetic shear component is important for internal transport barrier investigations as we do not evolve current profiles in this model. The fluctuations in turn dynamically adjust the profiles through the D and χ terms in the transport equations. Finally, the fluctuation equation is coupled a second time to the profiles through the radial electric field. This is via the third term on the right hand side of the fluctuation equation. This suppression term is of the Hahm Burrell form [12] and it is very important for the dynamics and that the electric field shear has all of the pressure gradient terms as well as the velocity gradient terms. The model has evolution equations for the poliodal and toriodal flows however for simplicity in this paper we have turned those equations off. All of the coefficients in the model are described in detail in ref 1. In order to investigate the electron channel, we add a new equation to this model. That is an envelope evolution equation for the electron scale fluctuations (ε_e).

$$\frac{\partial \varepsilon_e}{\partial t} = \left\{\gamma_e - \alpha_{1e}\varepsilon_e - \alpha_{2e}\left[\frac{r}{q}\frac{\partial}{\partial r}\left(\frac{q}{r}\frac{E_r}{B_\phi}\right)\right]^2\right\}\varepsilon_e + \frac{1}{r}\frac{\partial}{\partial r}\left[rD_{\varepsilon e}\frac{\partial \varepsilon_e}{\partial r}\right]$$

This equation has a form identical to that of the ion scale fluctuation equation however the

various coefficients are changed to those for an electron scale turbulence model. For this paper we use an eta-e model however the basic idea is valid with the model of your choice with only the growth rate and other coefficients changing. For the eta-e model we replace the ion temperature with the electron temperature in the appropriate places and most importantly change α_{2e} and χ_e. Because the electron fluctuation scale is much smaller then the ion fluctuation scale the coefficient in front of the suppression term is reduced by the ratio of the mean turbulent wavenumbers for the two systems. This is because a larger shear is required to suppress smaller scale fluctuations. For this paper the ratio is taken to be between 20 and 100 (though once again the exact number is not important to these results). The electron temperature equation is also modified through χ_e, which has a term with the same form as the ion fluctuation level term but now proportional to the electron fluctuation level squared added to it. This term is however reduced from the ion fluctuation level term by the ratio of the mean wavenumbers because of the reduced step size intrinsic to the smaller scale fluctuations.

3. Barrier Formation and Evolution

With in the model, a broad central beam deposition profile (shown in Figure 1a) can lead to a narrow ion channel transport barrier (Figure 2a) due to the decreased flux through a given radial location. With a narrow deposition profile (Figure 1b) the converse is true and a broad barrier in the Ion channel can form (Figure 2b).
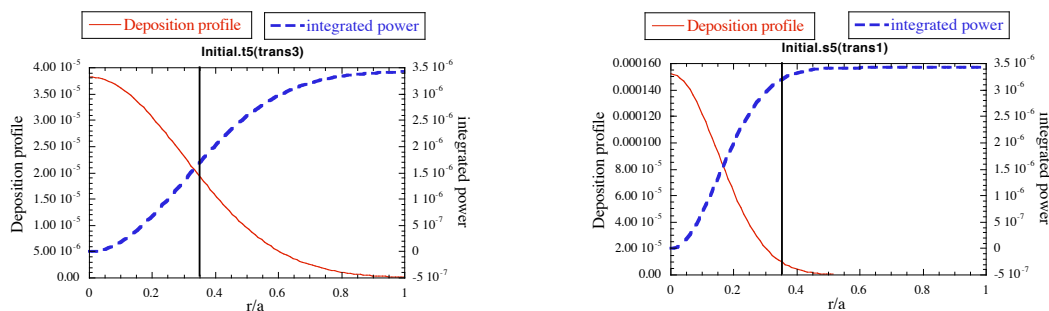

Fig. 1. Integrated power for two deposition profiles each with the same total power. a) A broad deposition profile leads to only half the total power through r/a=.35 while b) a narrow deposition profile leads to almost the total power through r/a=.35

In general, initial formation of the ion channel barriers is facilitated by a narrower deposition profile (for a fixed total power) because of the larger flux through the critical radial surface.
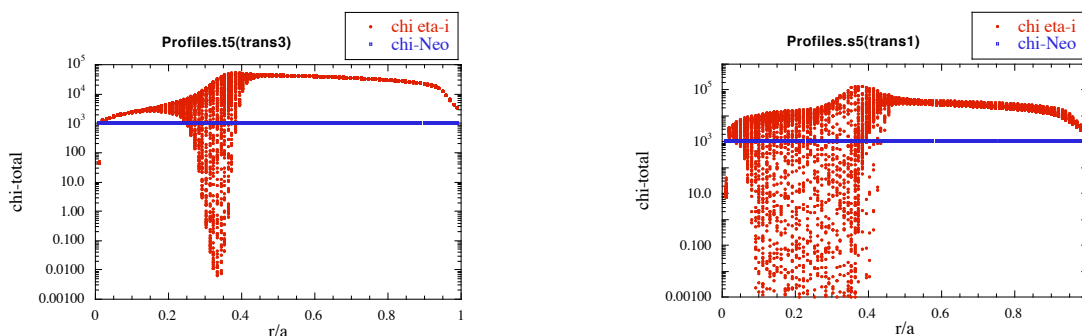

FIG. 2. Thermal transport coefficients from η_i fluctuations and neoclassical component for a) broad deposition profile showing narrow barrier and b) for narrow deposition profile showing broad barrier

However after the ion channel barrier is formed, the width of the barrier is instrumental in setting the profile shape and in turn, this barrier width is determined in part by the beam

deposition profile. Inside the actual barrier the profile is flatter and in the case of the narrow barrier (broader deposition profile) the second derivative of the pressure profile constituents is usually found to be larger at the top and bottom of the barrier region then in the case of the broad barrier (narrow deposition profile) (Fig 4b vs Fig. 3).

When the evolution equation for electron fluctuations is added, the details of the post ion channel transition profiles become important. The narrow barrier in the ion channel leads to a sharper change in the temperature and density profiles, which in turn can lead to a well aligned and large gradient in the radial electric field. This in turn can lead to a barrier forming in the electron channel. Formation of this barrier requires a larger radial field shear due to the higher k involved in the fluctuations. With the broader ion channel barrier (from the narrow deposition profile) the less sharp profile features leads to a much higher power threshold for the electron channel barrier. In the case of the narrow deposition profile a broad peaked barrier in the ion channel can form at lower power (Fig. 3) while still having an active electron channel.
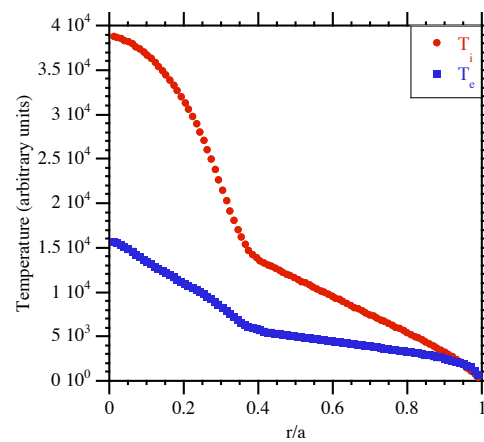

FIG. 3. Temperature profiles after an ion channel barrier forms from a narrow deposition profile

Before an electron channel barrier forms (or in cases that only an ion barrier forms) the increased gradients leads to an increase in the electron fluctuation level (Fig. 4a). This increase can partially compensate for the reduced (or eliminated) transport in the ion channel. The increase in the electron scale fluctuations therefore can cause a local decrease in the slope of the T_e profile (Fig. 4b) which can prevent the formation of the electron barrier at the footpoint of the ion channel barrier.
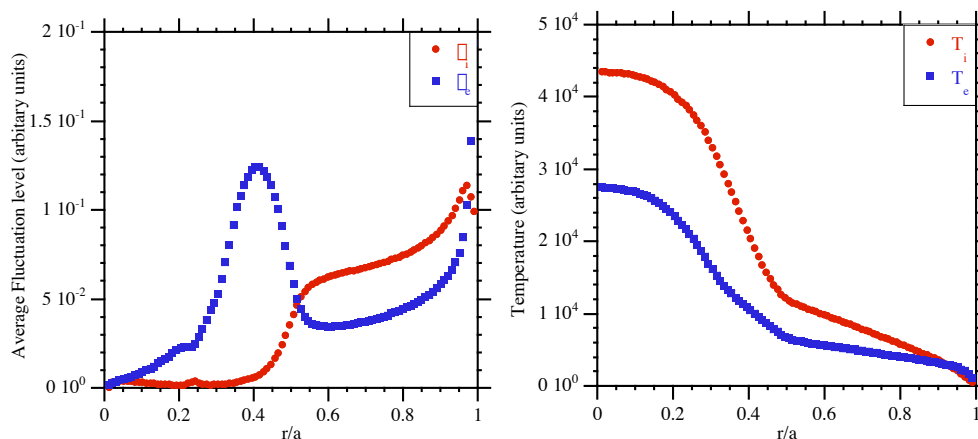

FIG. 4. a) η_e fluctuation level increases after ion channel barrier forms but before electron channel barrier forms b) Temperature profiles showing a flattened region in the electron temperature profile and a broader flat core due to a broader deposition profile

When an electron barrier does form, it tends to form near the steep curvature region at the top of the ion barrier (Fig. 5) and can grow outward from there. For all of the cases studied with this model, the electron barrier footpoint remains inside the ion barrier footpoint.
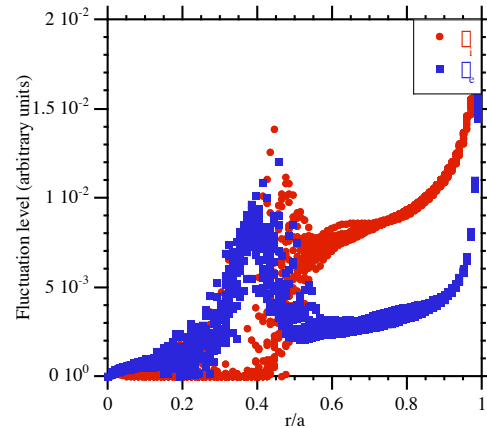

FIG. 5. η_e and η_i fluctuation levels showing both ion and electron channel barriers in a broad deposition profile case with the electron barrier forming near strong curvature region at the top of the ion barrier.

The formation and evolution of an electron transport channel barrier in the presence of and ion transport channel barrier allows for very complex dynamics. Oscillations often found at the transition point now can have multiple characteristic frequencies that can also interact either helping or hindering the barrier propagation depending on their amplitude. This complex interrelated dynamics between the two channels allows for a number of potential control schemes such as utilizing the electron channel as a profile control valve.

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