The Initiation and Dynamical Evolution of Electron and Ion Channel Transport Barriers in Self-heated Plasmas

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Enhanced confinement regimes and the "transport barriers" often intrinsic to them have been studied and recognized as of fundamental importance to the control and sustained access to fusion relevant conditions in magnetically confined plasmas for over 30 years. With burning plasma conditions getting nearer, control of these barriers with the self-heating from the fusion alpha particles is critical both for access to the required conditions and for control of the gradients (for stability etc) and ash accumulation. Over the last 2 decades, simple dynamical models have been able to capture a remarkable amount of the dynamics of the transport barriers found in many devices [1,2], however an open question has been the often disconnected nature of the electron thermal transport channel sometimes observed in the presence of a standard ("ion channel") barrier. By adding to this rich though simple dynamic transport 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 has been found to be even more sensitive to the alignment of the various gradients making up the sheared radial electric field then the ion barrier is [3]. 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 formation and evolution. Because of this sensitivity and coupling of the barrier dynamics, the dynamic evolution of the self-heating profile in fusion plasmas can have a significant impact on the barrier location and dynamics. To investigate this, self-heating has been added this model and the impact of the self-heating on the formation and controllability of the various barriers will be explored.

The basic model for the ion transport barrier consists of a set of transport equations for the density (n), ion temperature (T_i) and electron temperature (T_e) plus a nonlinear dynamical envelope equation for the fluctuations (ε).

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

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

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

$$\frac{\partial \varepsilon}{\partial t} = \left\{ \gamma - \alpha_1 \varepsilon - \alpha_2 \left[\frac{r}{q}\frac{\partial}{\partial r}\left(\frac{q}{r}\frac{E_r}{B_\phi} \right) \right]^2 \right\} \varepsilon + \frac{1}{r}\frac{\partial}{\partial r}\left[rD_\varepsilon \frac{\partial \varepsilon}{\partial r} \right] \tag{4}$$

$$E_r = -V_\theta + V_\varphi \frac{B_\theta}{B_0} + \alpha \left[\frac{\partial T_i}{\partial r} + \frac{T_i}{n}\frac{\partial n}{\partial r} \right] \tag{5}$$

To this model an electron scale fluctuation equation was added in order to deal with electron scale dynamics [3]

$$\frac{\partial \varepsilon_e}{\partial t} = \left\{ \gamma_e - \alpha_{1e} \varepsilon_e - \alpha_{2e} \left[\frac{r}{q}\frac{\partial}{\partial r}\left(\frac{q}{r}\frac{E_r}{B_\phi} \right) \right]^2 \right\} \varepsilon_e + \frac{1}{r}\frac{\partial}{\partial r}\left[rD_{\varepsilon e} \frac{\partial \varepsilon_e}{\partial r} \right] \tag{6}$$

This six equation model and many of its features are explained in detail in refs [1-2] and [3], however, briefly, the growth rate γ in the fluctuation equation, Eq. (4), is based on the toroidal η_i model of Biglari el al [4]. It includes a term responsible for magnetic shear stabilization as well as the more self-consistent profile related form common to ion temperature gradient driven turbulence models (ITG), while for the electron fluctuation equation Eq. (6) we use ETG like parameters.

To these we have now added self-heating as source/sink terms in the temperature and density equations (equation 1-3). The rate is given by [Hively 83]:

$$\langle \sigma v \rangle_{\mathrm{DT}} = 9.10 \times 10^{-16} \exp\left(-0.572 \left| \ln \frac{T}{64.2} \right|^{2.13} \right) \ \mathrm{cm}^3/\mathrm{s},$$

The fraction going into the ions vs. electrons through the alpha slowing given by [Kikuchi 2012]

$$F_i(x) = \frac{1}{x}\left[\frac{1}{3}\ln \frac{1 - x^{1/2} + x}{(1 + x^{1/2})^2} + \frac{2}{\sqrt{3}}\left(\tan^{-1}\frac{2x^{1/2} - 1}{\sqrt{3}} + \frac{\pi}{6} \right) \right]$$

First, using ITER like parameters but no self-heating, the system exhibits a great deal of stiffness in the formation of internal transport barriers. This is due to large bursty fluctuations at the transition point which transport very effectively and make access to the barrier regime much more difficult. For a large enough neutral beam power with a moderately wide on axis deposition profile (gaussian width of r/a=0.20) an internal barrier can form, first in the ion cannel and then in the electron channel. Figure 1 shows the fluctuation suppression in the 2 channels and as the temperatures rise and a transient density hole develops. In this case profile control is difficult.

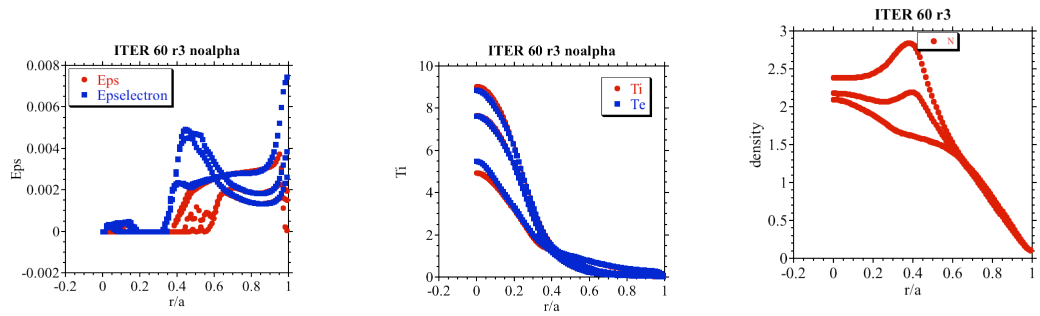

Fig. 1 Without self-heating both barriers can be formed with appropriate parameters, Left panel shows ion and electron scale fluctuation suppression in barrier region. The middle panel show the central temperatures rising with Ti~Te. The right panel shows a transient hollow density profile.

With self-heating and the same parameters and beam power, a barrier forms in both channels, then, due to the development of the density hole, the self-heating profile dominantly in the electrons, moves off axis leading to the collapse of the electron channel barrier (Fig. 2).

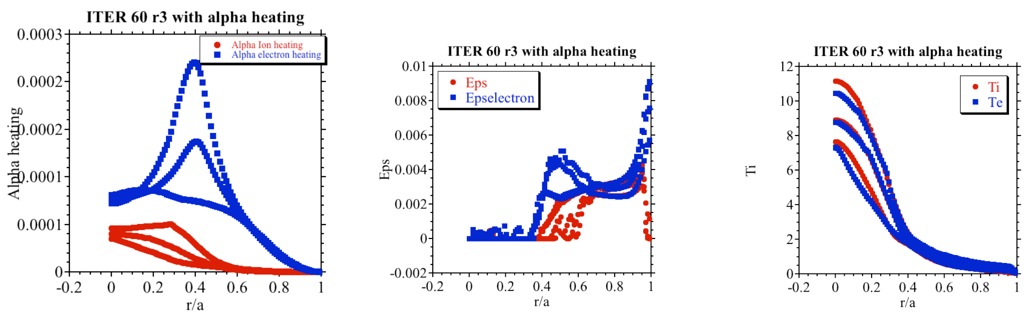

Fig. 2 With self heating and same NBI power, as density hole grows, heating profile moves off axis electron channel barrier is broken, Left panel shows the self –heating energy profiles into the electrons and ions as the barrier forms and the density hole develops. The middle panel show shows ion and electron scale fluctuation suppression in barrier region followed by a recovery of the electron scale fluctuations while the right panel shows the central temperatures rising with Ti becoming larger then Te.

Figure 3 shows time traces of the electron scale and ion scale fluctuations at 3 radial locations. The suppression and recovery of the fluctuations can be seen in the electron channel at all locations while the barrier can be seen to be maintains (though reduced in extent in the ion channel).

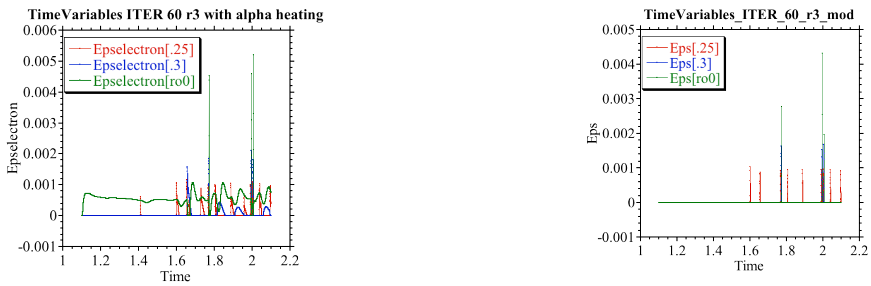

Fig. 3 Time traces of fluctuations at different radial locations. Transient electron channel barrier formed then it collapses with enhanced transport. Left panel, electron scale and right panel ion scale.

This barrier collapse is not entirely bad as it allows for the possibility of control of the profiles in a system that is intrinsically very stiff. With control of the NBI source (which is at this point a sub-dominant power source) the barrier might be controllable. Figure 4 shows the evolution when the beam is turned off. This leads to a potential control knob for the profiles including the energy deposition profile which could help optimize the burning volume.

Fig. 4 Which NBI turned off, electron barrier is fully removed but ion barrier persists, density profile smooths out and heating moves inward. Left panel shows the fluctuation profiles for the electron scale and ion scale fluctuations while the right panel shows the self-heating profiles.

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