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MECHANISMS FOR ELECTRON TRANSPORT BARRIER FORMATION IN THE DIII–D TOKAMAK

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*Lehigh University, Bethlehem, Pennsylvania.
†University of California, Los Angeles, California.

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ABSTRACT

The $E\times B$ shear stabilization paradigm explains much of the phenomenology of ion thermal transport in tokamaks. Behavior in the electron channel, however, has continued to challenge our understanding. Recent experiments in DIII–D and elsewhere produce regions where electron thermal transport is almost completely eliminated with intense, localized, direct electron heating. Simulations of DIII–D discharges identify $\alpha$-stabilization, local magnetic shear stabilization due to the Shafranov shift, as the dominant turbulence reduction mechanism in these experiments and may point the way toward regimes with simultaneous electron and ion internal transport barriers.
INTRODUCTION

Discharges with internal transport barriers (ITB), or regions of reduced transport, in the ion thermal, particle and/or angular momentum transport channels have been developed which exhibit high fusion performance in many tokamaks. Behavior of the electron channel is not as well controlled: although some such discharges exhibit reduced electron thermal diffusivity $\chi_e$, it can be unchanged or even increased in others. Identification of the conditions for electron thermal transport reduction has become a major challenge in fusion experiments. Recently, several tokamaks have demonstrated barrier formation in the electron channel in the presence of intense, localized, direct electron heating. Such a regime has now been demonstrated in discharges heated primarily by electron cyclotron heating (ECH) in the DIII–D tokamak.

Reduced ion thermal transport is often a consequence of suppression of long wavelength turbulence, such as the ion temperature gradient (ITG) mode, by a sheared $E \times B$ flow. However, the electron temperature gradient (ETG) mode acts over much shorter scale lengths, so that $E \times B$ shear is not expected to measurably reduce these modes. In plasmas where ITG modes are suppressed, the electron temperature gradient is often calculated to be limited by ETG stability.

It will be shown that transport modeling of electron internal transport barrier (e-ITB) formation in DIII–D has identified $\alpha$-stabilization as a dominant mechanism for suppression of the ETG mode, where the Shafranov shift parameter $\alpha$ is defined as

$$\alpha = -\mu_0 p'\psi V'\psi (V/4\pi R_0)^{1/2}$$

where $p$ is the plasma pressure, $V$ is the volume enclosed by the magnetic surface enclosing the poloidal flux $\psi$, $R_0$ is the major radius of the flux surface center and $'$ indicates a derivative with respect to $\psi$. The transport models reproduce most characteristics of these discharges only when the effects of $\alpha$-stabilization and $E \times B$ shear are included. Although $\alpha$-stabilization has previously been identified theoretically, this marks the clearest demonstration to date of a case where it has been shown necessary to explain experimental observations from DIII–D.
**EXPERIMENTAL RESULTS**

The e-ITB appears promptly in the early phase of discharges operated at low density \(n_e < 1 \times 10^{19} \text{ m}^{-3}\), when ECH is applied 0.1 s after the beginning of the current ramp (Fig. 1). The discharge shown is heated by the output of a single gyrotron, which provides 0.5 MW of heating power to the electron component of the plasma. Although the ECH is phased to generate electron cyclotron current drive (ECCD) in the direction opposite to the main plasma current (counter-ECCD), nearly identical results have been achieved in DIII–D with both co-ECCD and pure heating (waves launched radially into the plasma so as to drive no net current). This contrasts with experience in other devices where similar effects were seen only with counter-ECCD. The plasma is also subjected to approximately 0.5 MW of neutral beam power (time averaged) applied in short, discrete pulses for diagnostic purposes [charge exchange recombination (CER) for ion temperature, carbon impurity density and rotation and motional Stark effect (MSE) for the current profile]. Calculations with the TRANSP code indicate that most of this neutral beam power is lost from the plasma, primarily due to the large beam ion orbits associated with the small poloidal field produced at low plasma current.

The electron temperature profile responds almost immediately to the onset of ECH (Figs. 1 and 2). A steep temperature gradient, which can exceed 150 keV/m in an approximately 3 cm wide region, forms near the heating location calculated by TORAY-GA. Central temperatures reach 4 keV in the first 37 ms of the ECH pulse, and 6 keV in less than 100 ms. This barrier appears to expand ahead of the heating location as that location is Doppler shifted outward due to increasing electron density and temperature. A small increase is seen in the ion temperature as well, but the ions remain relatively cold, with \(T_e/T_i \approx 10\) in the core.

Transport analysis with TRANSP indicates that both the electron and ion thermal diffusivities are reduced immediately upon application of ECH. The electron diffusivity becomes extremely small in a narrow region near the ECH heating location. The ion diffusivity, although larger, is still below the neoclassical level calculated by NCLASS [Fig. 2(d)]. Despite the reduced ion thermal diffusivity, the ion temperature remains low due to the relatively small amount of power entering the ion channel [Fig. 2(c)].

During this period, low-\(k\) fluctuations measured by reflectometry are reduced (Fig. 3) in the region where the e-ITB forms. This indicates suppression of long wavelength turbulence \(k_\theta \approx 0–6 \text{ cm}^{-1}\) such as the ITG or trapped electron (TEM) modes. As
Fig. 1. Time history of a discharge exhibiting an e-ITB shortly after ECH is applied. Neutral beam pulses are applied for diagnostic purposes during the steady ECH pulse. $T_e$ is measured by electron cyclotron emission (ECE) at several different positions in the plasma. The shaded region is near the ITB “foot”. The dotted vertical lines represent collapses attributed to the resistive interchange mode. The vertical dashed line denotes the time where transport coefficients are shown in Fig. 2 (99696).

Fig. 2. Profile evolution of e-ITB. (a) Electron temperature profiles from ECE and Thomson scattering measurements. Crosshatched profiles are ECH deposition profiles calculated by TORAY-GA. (b) Ion temperature profile from CER. (c) Electron, ion and electron ion coupling power densities calculated by TRANSP at $t = 0.2$ s. (d) Calculated thermal diffusivities from TRANSP at $t = 0.2$ s (99696).
discussed below, this does not indicate stabilization of shorter wavelength modes such as ETG turbulence. A measurement of turbulence at submillimeter scales is not currently available on DIII–D and is under study for future implementation.

Shortly after the times shown in the figures, the electron temperature profile collapses due to the first of a series of repetitive reconnection events believed to be associated with the resistive interchange mode\textsuperscript{17} (Fig. 1, collapses marked by vertical dotted lines). The barrier reforms between these events.
SIMULATIONS

Stability of the e-ITB region to both low- and high-\(k\) turbulence was calculated by a linear gyrokinetic stability code\(^{18}\) with non-circular geometry\(^{19}\) and fully electromagnetic dynamics\(^{20}\) (GKS). Although these results indicate that the low-\(k\) modes, in this case calculated to be the TEM, are only partially stabilized by the small E×B shearing rate, the growth rate is shown to be very sensitive to the magnitude of \(\alpha\) [Fig. 4(a)].

Also shown is the normalized electron temperature gradient \(a/L_{Te}\) (\(a\) is the minor radius of the plasma and \(L_{Te} = T_e/\nabla T_e\) is the electron temperature gradient scale length) compared to the calculated critical temperature gradient for the onset of the ETG mode, \(a/L_{Te}^{\text{crit}}\) [Fig. 4(b)]. As is frequently observed in DIII–D,\(^{11}\) \(a/L_{Te} = a/L_{Te}^{\text{crit}}\) in the region where electron thermal transport is reduced. This result is also sensitive to the value of \(\alpha\), so that if \(\alpha\) is set to zero, the gradient is well in excess of the calculated critical value. Note that the calculated growth rate for the ETG mode becomes extremely large when \(a/L_{Te} > a/L_{Te}^{\text{crit}}\), so that if the ETG mode can drive sufficient transport, it becomes self-limiting and the electron temperature profiles become “stiff.”

![Graph](image.png)

Fig. 4. (a) The maximum linear growth rate \(\gamma_{\text{max}}\) to low-\(k\) turbulence (TEM) calculated by GKS is highly sensitive to \(\alpha\). (b) The e-ITB region is near marginal stability for the ETG mode with \(\alpha\)-stabilization, and well above it without (99696 0.2s).
For both high- and low-$k$ turbulence, we noted a dependence on $\alpha$, $\alpha$-stabilization, often referred to as Shafranov shift stabilization, is a well known phenomenon\textsuperscript{12,13} which is calculated to be a stabilizing effect on turbulence over a wide range of scales (including the ITG, TEM and ETG modes) in the presence of weak or negative magnetic shear, as is the case in these discharges (with ECCD, there are typically neighboring regions with both positive and negative magnetic shear).

Simulations have also been done using the GLF23\textsuperscript{21} model, which can dynamically simulate profile evolution, approximating the transport due to ITG, TEM and ETG turbulence. In these simulations, the temperature and rotation profiles evolve according to the model with the density and current profiles, sources and sinks fixed according to TRANSP analysis of the discharge. Boundary conditions are also imposed on each of the simulated profiles at $\rho=0.9$.

Simulations initialized with temperature profiles as measured prior to the onset of ECH clearly predict the dynamic formation of the observed e-ITB. However, this result strongly depends on the value of $\alpha$. In this simulation, $c_\alpha$ was set to 1.35, where

$$\alpha = c_\alpha \alpha_{\text{calc}}$$

(2)

where $\alpha_{\text{calc}}$ is the value of $\alpha$ calculated directly from the profiles used in the simulation. No barrier forms if $c_\alpha < 1.35$ in the simulation.

In simulations initialized with the measured profiles after the barrier had already developed, the barrier was maintained with $c_\alpha = 1.0$ (Fig. 5). The e-ITB is rapidly lost when $\alpha$-stabilization is removed.

![Fig. 5. Dynamic simulations with the GLF23 model maintain the e-ITB when the effects of $\alpha$-stabilization are included (99696 0.2s).](image)
DISCUSSION

These calculations clearly establish the crucial role of \( \alpha \)-stabilization in determining electron thermal transport. Small changes in \( \alpha \) can produce major changes in both low- and high-\( k \) stability, and within reasonable uncertainties, are capable of providing the level of turbulence suppression required to reproduce the experimental results. \( \mathbf{E} \times \mathbf{B} \) shear appears insufficient: it is too small to completely suppress the low-\( k \) modes outside \( \rho = 0.32 \) (Fig. 4) and would have to be orders of magnitude larger to suppress the ETG mode due to its small spatial scales.

In calculations with both GKS and GLF23 (dynamic simulation), it was found that the values of \( \alpha \) required to produce the observed results are larger than indicated by the profiles (\( c_\alpha > 1 \)). The uncertainties involved in calculating \( \alpha \) are, however, large. A calculation based on experimental profiles requires accurate knowledge of the details of the equilibrium (i.e. safety factor, \( q \)). This is rather uncertain in these discharges, largely due to the extremely small poloidal field in the core during the early phase of the plasma current ramp. Furthermore, since the simulations only predict the temperature and rotation profiles, they are not fully self-consistent (e.g. \( q \) is held fixed in time), resulting in some uncertainty. Thus, the requirement of increased \( c_\alpha \) appears acceptable.

The simulation starting with the fully developed barrier covers an interval where the \( q \) and heating profiles are nearly constant, so that the simulation remains more self-consistent despite not evolving these profiles. Here, there was no requirement to increase \( c_\alpha \) above unity.

A common concern about ETG turbulence and its stabilization as a mechanism for determining transport in the electron channel is that this instability is often believed incapable of driving sufficient transport. However, with a sufficiently large temperature gradient, ETG turbulence should be capable of driving the observed transport as evidenced by the simulations.

Another mechanism proposed to allow ETG turbulence to drive strong transport is the formation of ETG streamers,\(^{22}\) or large scale radial structures. Although this process would drive considerable transport, calculations indicate that streamers only occur where the magnetic shear is significantly positive, which is not believed to be the case here. This issue will be addressed by future studies.
All of these results taken together with previous studies of core barriers mainly affecting the ion thermal channel\(^{23,24}\) point toward a working model of turbulence, transport and their suppression (Fig. 6). Several different turbulence mechanisms are active, each over a particular range of spatial scales, in particular ITG, TEM and ETG turbulence. Ion internal transport barriers are relatively easy to produce, since they require suppression of turbulence of relatively long spatial scales, so that all known stabilization mechanisms are effective. In particular, \(E \times B\) shear is known to be associated with most ITBs in DIII–D. Conversely, electron thermal transport is very difficult to reduce if ETG modes are present, since \(E \times B\) shear is not effective. Previous results in DIII–D\(^{11}\) and JT–60U\(^3\) have indicated that reduced transport in the electron channel is more likely under conditions of strongly negative magnetic shear. In experiments with direct electron heating, including the present experiments, it appears most likely that \(\alpha\)-stabilization is the dominant mechanism in reducing transport.

One implication of these results is that a prerequisite for creating an e-ITB is the suppression of turbulence at all scale lengths, including those that affect the ion channel. This is consistent with the experiment, where the ion thermal diffusivity (Fig. 2) and low-\(k\) turbulence intensity (Fig. 3) were both reduced. Under these conditions, core barriers affecting both the ion and electron temperature profiles should be accessible by applying heating power to the ions after the e-ITB has already formed provided that the loss of \(T_i/T_e\) stabilization can be compensated for. In fact, this may have already occurred in ASDEX-U\(^5\). Experiments are planned to test this hypothesis in DIII–D by applying high power neutral beam injection to the e-ITB described in this letter.

![Fig. 6](image-url)
REFERENCES

\(^a\)Lehigh University, Bethlehem, Pennsylvania, USA.
\(^b\)University of California, Los Angeles, California, USA.
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