Dynamics of Core Fluctuations and Poloidal Rotation During Formation of Core Transport Barriers

C.L. Rettig, K.H. Burrell,[*] C.M. Greenfield,[*] B.W. Rice,[§]
M.E. Austin,[‡] E.J. Doyle, and W.A. Peebles

Department of Electrical Engineering, UCLA, Los Angeles, California 90024

[*]General Atomics, P.O. Box 85608, San Diego, California 92186, U.S.A.
[§]Lawrence Livermore National Laboratory
[‡]University of Texas, Austin, TX

Introduction

Internal transport barriers (ITBs) in tokamak plasmas present an important pathway to achieving fusion energy gain and a more reasonable tokamak power plant designs. However, details of a comprehensive theoretical model for the dynamics and scaling characteristics have not been experimentally confirmed or completely tested. Measurements have shown that core turbulence reduces and the E×B turbulence shearing rate increases during the period of the discharge that the ITB forms, especially when the q-profile is inverted [1]. Therefore, great attention has been paid to models incorporating microscopic instabilities and E×B shear as part of the dynamics responsible for the ITB performance enhancement.

A prominent theoretical model able to explain the dynamics of ITB formation and evolution is centered around a feedback cycle involving turbulence, transport, and E×B shear driven by plasma rotation and pressure [2,3]. The model postulates that (1) weak or negative central magnetic shear suppresses sawteeth, avoids ballooning modes, and reduces the E×B shear threshold necessary to quench core turbulence, (2) with turbulence suppressed, the core rotation and pressure gradients increase to larger values, greatly increasing the ExB shearing rate, and (3) E×B shear in the plasma interior further suppresses microturbulence and associated transport allowing still greater gradients to build. Thus, the model is comprised of a feedback loop whose final state is a highly sheared, low transport plasma. Various features of this model have been predicted in a numerical simulation of the barrier dynamics [3] and have been observed in experiments [1,4,5]. The dynamics of the barrier development, E×B shearing rate profile, and turbulence are critical to the ultimate development of a high performance ITB discharge. To test this model, it has become imperative to characterize and understand dynamics of the internal transport barrier. This paper describes aspects of the stepwise development observed in the formation of internal transport barriers in DIII–D.

Barrier and Turbulence Dynamics

In DIII–D, internal transport barriers are most readily formed if the q-profile is flat or inverted. This is achieved by simple yet effective current profile control techniques that keep the peak current density away from the magnetic axis. Such a configuration possesses greater MHD stability and has in general resulted in greater values of beta [6]. Another feature that is always found in the core region of ITB discharges is significant E×B shear, resulting in a strong turbulence suppression rate. Experimental evidence from DIII–D and other tokamaks indicates that turbulent fluctuations decrease significantly during high performance ITB discharges. Large plasma rotation velocity and internal pressure are measured in ITB discharges indicating the presence of a large and highly sheared radial electric field, which is able to reduce turbulence through nonlinear decorrelation and linear stabilization [7]. Although the ITB typically forms locally and expands on a timescale of hundreds of milliseconds, in DIII–D the formation and expansion proceeds in a stepwise fashion. For example, transient

jumps in the local electron temperature have been observed in the low power phase of DIII–D NCS discharges and are often correlated with transient reductions in the density fluctuations [1].

In DIII–D, when NBI is initiated within 100 ms of breakdown the stepwise formation of the ITB has been particularly pronounced. NBI initiated this early allows very little of the inductively driven current to diffuse into the core, so that almost all of the plasma current is driven off-axis. The resultant q-profile is very large on axis (>10) and has a minimum at a flux coordinate outside 0.7, prior to excitation of an MHD instability which re-distributes the current within approximately 100 ms. The subsequent q-profile remains strongly inverted for up to 1 second into the current ramp. During the strongly sheared phase of the discharge, an abrupt increase in the poloidal plasma rotation has been measured. Figure 1 displays the vertical (poloidal) plasma rotation velocity evolution measured at various locations within the core during the low power phase of a discharge possessing strong negative central shear. As shown, the poloidal rotation at r = 0.31 increases abruptly at approximately 750 ms into the discharge, nearly doubling within 50 ms. However, the rotation velocity measured closer to the magnetic axis changes only slightly, and the velocity measured further out reduces on a slower timescale following the step. Thus, the rotation has rapidly developed a localized peak near $\rho = 0.31$. Evidence that the rotation jump is not merely an artifact of changing cross sections associated with the rising ion temperature can be seen in the ion temperature evolution shown in Fig. 2. The ion temperature change is similar at both $\rho = 0.23$ and $\rho = 0.31$, while the poloidal rotation changes only at the outer location.

During this time period, the q-profile continues to evolve on a slow timescale, such that the minimum and central values of q(r) reduce, passing through various low-order rational and integral values. The abrupt rotation increase occurs in the same general region of the minimum value of q, however, q_{min} passes through 2.2 at the time of the change, a value which is neither low-order rational nor integral. Though this may not be true of all types of core barrier discharges, it is consistently observed in this and similar discharges. The accuracy
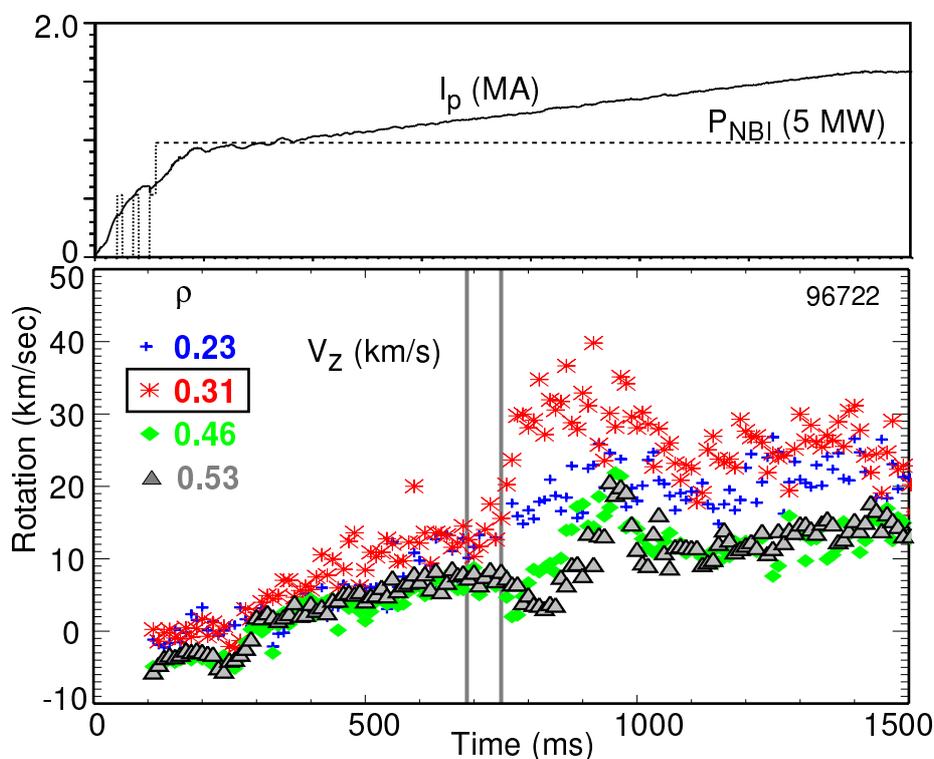

Fig. 1.. *Vertical line of sight velocity measured at various radii during the low power phase of a ITB discharge created with NBI initiated at 100 ms into the current ramp.*

with which the safety factor is determined effectively rules out the possibility that the measurement is in error enough to shift the value of q_{min} to 2.0. The current profile is measured via the motional start effect (MSE) diagnostic and uncertainties in the associated equilibrium fit are insignificant for this conclusion.

Coincident with the abrupt rotation step, the electron and ion temperature profiles change abruptly as well. Shown in Fig. 2, the ion temperature increases at radii near $\rho = 0.37$ and 0.27 whence the rotation increased at $\rho = 0.3$, but T_i evidences only a delayed increase at $\rho = 0.5$. The radial extent of the affected zone is distinct and relatively small. Also shown, the electron temperature increases abruptly and significantly at locations near the poloidal rotation peak, at $\rho = 0.35$ to 0.5. Prior to the poloidal rotation increase, the electron and ion temperatures begin reducing at radii near the outer edge of the poloidal rotation zone, increasing the local thermal gradient.

At the start of the low power phase, electrostatic fluctuations in the core and edge exhibit the broad wavenumber and frequency dependence that is characteristic of turbulence. The peak wavenumber and the bandwidth are in a range closely associated with drift modes such as the ITG instability. The fluctuation level dynamics during this period are shown in Fig. 3. Coincident with or slightly before the rotation increase, fluctuations with the largest Doppler shift, which are associated with the deepest location, begin decreasing. After the rotation step, the integrated fluctuation level shown in Fig. 3 begins to reduce. A strong increase in fluctuations with negative frequency, associated with rapid propagation in the electron drift direction, is also observed coincident with the rotation step. The electron feature is somewhat coherent, i.e. $\Delta f/f \approx 0.1$, and may be related to a fast particle driven mode (TAE, BAE, etc.).
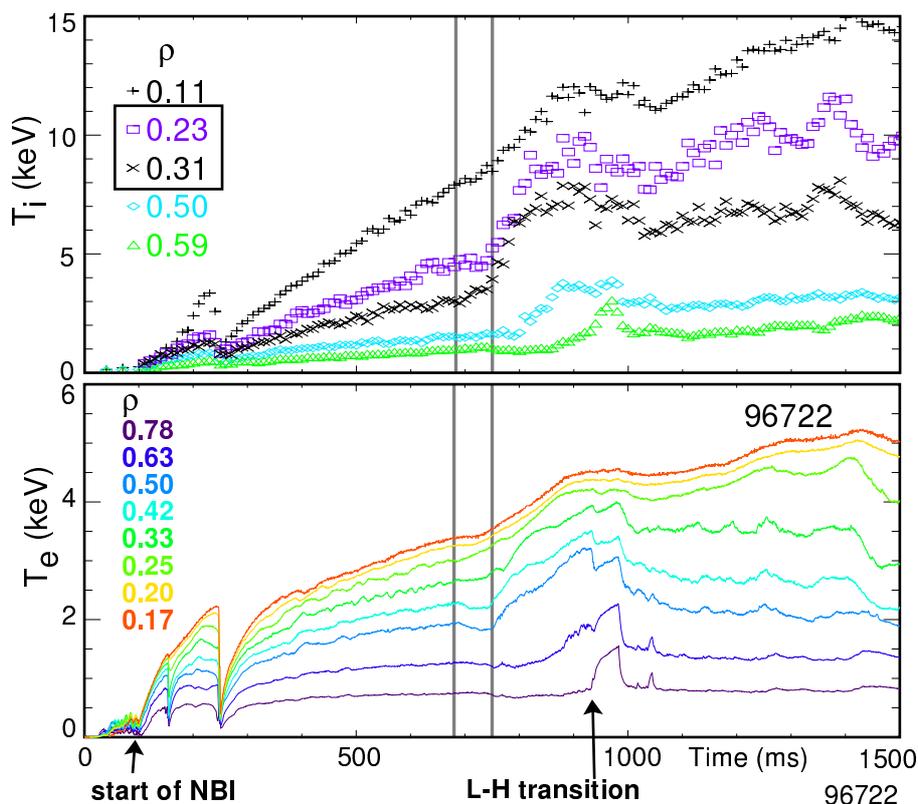

Fig. 2. *Time evolution of the ion and electron temperature measured at several radii across the plasma. The vertical bars coincide with the times in Fig. 1 when the poloidal rotation abruptly increases*
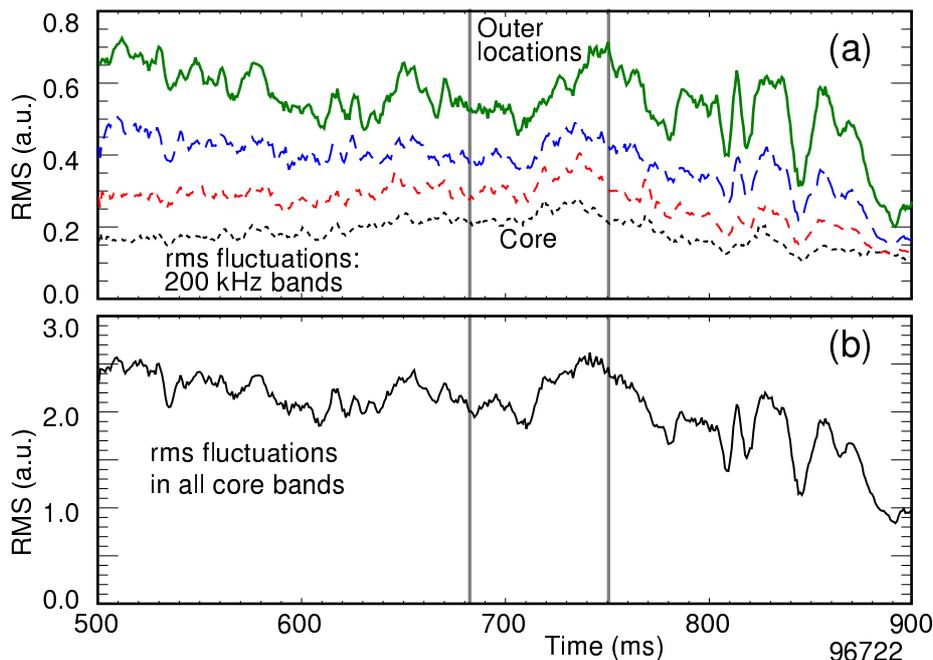
Fig. 3. *Fluctuation level measured via FIR coherent scattering during the abrupt poloidal rotation increase. (a) Fluctuations are integrated over contiguous 200 kHz frequency bands, associated with the core and further out respectively. (b Fluctuations are integrated over entire positive frequency band associated with the plasma interior. Note that the fluctuation level reduces after the rotation step, possibly earlier for deeper locations.*

Discussion

In DIII–D ITB discharges, the core barrier typically forms locally and expands during the period of low power auxiliary heating, in a stepwise fashion. In discharges with very early NBI and strongly inverted q-profiles, the step formation is particularly evident, and is concentrated in a single step This occurs coincident with a rapid, localized, and spontaneous increase in core poloidal rotation. The phenomenology is not unlike that observed in the edge at an L to H–mode transition or in the core at the ERS transition in TFTR [8], though the source is likely different entirely. In these discharges, neither the minimum value nor the central value of the safety factor is in proximity to either a low-order rational value or an integral value. Owing mostly to the large and highly localized change in the poloidal rotation, the electric field becomes very strongly sheared and the E×B turbulence shearing rate increases by a factor of ~2, in the region where the temperature profiles develop an inflection. Steps in the poloidal rotation associated with the stepwise formation of the barrier may therefore be another mechanism of triggering the feedback cycle described in the theoretical model, and represents an important class of discharges for elucidating the physics of barrier formation.

[1] C.L. Rettig, et al., Phys. Plasmas **5**, 1727 (1998).

[2] P.H. Diamond, et al., Phys. Rev. Lett. **78**, 1472 (1997).

[3] D.E. Newman, et al., Phys. Plasmas **5**, 938 (1998).

[4] C.M. Greenfield, et al., Phys. Plasmas **4**, 1596 (1997).

[5] E.J. Synakowski, et al., in Proc. of the 24th Euro. Conf. on Contr. Fusion and Plasma Phys., Vol. 3 (European Physical Society, Petit-Lancy, Switzerland, 1998) p. 1065.

[6] E.J. Strait, et al., Phys. Rev. Lett. **75**, 4421 (1995).

[7] K.H. Burrell, Phys. Plasmas **4**, 1499 (19097).

[8] E.J. Synakowski, et al., Phys. Plasmas **4**, 1736 (1997).