A COMPARATIVE STUDY OF CORE AND EDGE TRANSPORT BARRIER DYNAMICS OF DIII-D AND TFTR TOKAMAK PLASMAS

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Abstract

Confinement bifurcations and subsequent plasma dynamics in the TFTR core and the DIII-D core and edge are compared in order to identify a common physics basis. Observations suggest a framework in which E×B shear plays a dominant role in the barrier dynamics. In TFTR, bifurcations from the reverse shear (RS) into the enhanced reverse shear (ERS) regime with high power balanced neutral beam heating (above 25 MW at 4.8 T) resemble edge H mode transitions observed on DIII-D. In both, radial electric field (E_r) excursions precede confinement changes and are manifest as localized changes in the impurity poloidal rotation. Reduced transport follows the excursions, and in both cases strong E_r shear is reinforced by the plasma pressure. These characteristics are contrasted with DIII-D negative central shear (NCS) barrier evolution with unidirectional beam injection. There, the improved confinement region can develop slowly, depending on the neutral beam input power and torque. Rapid expansion and deepening of this region follows an increase in the neutral beam heating power. The initial formation phase is modulated by confinement steps and interruptions. An analog for these steps is found in TFTR RS plasmas. Although these do not dominate the TFTR plasma evolution during low power (7 MW) heating, they can represent significant transport reductions when additional heating is applied. In both devices, no strong excursion in E_r precedes these latter confinement bifurcations. The triggering event of these steps may be related to current profile relaxation, but it is not always connected with simple integral or half-integer values of the minimum in the q profile. Finally, variations of E_r and the E×B shear through the application of unidirectional injection on TFTR yielded plasmas with confinement characteristics and barrier dynamics similar to those of DIII-D NCS plasmas. The data underscore that the physics responsible for the enhanced confinement states is fundamentally the same in both devices.

1. INTRODUCTION

In the last several years, experiments worldwide have enjoyed success in generating dramatic reductions in thermal and particle transport of the cores of tokamak plasmas. These reductions join a long history of bifurcation phenomena that are pervasive in the edge of many plasma devices. Some elements of core and edge H mode barrier formation have common phenomenology, suggesting that common physics is involved in bifurcations in these distinct regions. While many elements of transport barrier behavior in the core appear to be similar between devices, however, close examination of barrier and fluctuation dynamics reveal differences that as yet are unexplained, and which serve as challenges to theories and models of barrier formation.

This paper presents results from a comparative study of core and edge transport barrier formation and dynamics between the DIII-D and the TFTR tokamaks. In addition to providing a description of the phenomenology of both devices, the work is aimed at identifying a common physics framework that can explain many of the similarities and differences in the barrier dynamics. Many aspects of the dynamics are consistent with E×B flow shear turbulence decorrelation and suppression playing a dominant role in both devices. Differences in the core of TFTR ERS and DIII-D NCS plasmas may be ascribed to different feedback loops at play between the flow shear and the plasmas' pressure and rotation in the different experimental configurations. Importantly, this framework accounts for the fact that turbulence reduction and confinement improvement can occur both for the negative E_r well seen in the core of balanced-injection TFTR ERS plasmas and for the E_r hill seen in the case of co-injection dominated DIII-D plasmas.

2. E×B FLOW SHEAR AND ITS INTERACTION WITH BACKGROUND PROFILES

There are many discussions in the literature about possible interplay between E×B flow shear and turbulent transport [cf. recent reviews [1,2,3]]. Reference is generally made to the force balance equation, valid for any plasma species. The radial force balance equation can be used to solve for the radial electric field, $E_r = \nabla p/(nZe) + V_\phi B_\theta - V_\theta B_\phi$, where n is the density of the species in question, p is its pressure, Z is the charge number, e is the electronic charge, V_θ is its poloidal rotation, V_ϕ is its toroidal rotation, B_θ is the poloidal magnetic field, and B_ϕ is the toroidal field. A characteristic rate for shearing turbulence can be written as $\omega_{E\times B} = \left| \frac{\Delta\Psi_0}{\Delta\phi}\left[\frac{\partial}{\partial\Psi}\left(\frac{E_r}{RB_\vartheta}\right)\right]\right|$, where Ψ is the poloidal magnetic flux, $\Delta r_0 \equiv \Delta\Psi_0/RB_\theta$ is the radial correlation length, and $\Delta\phi$ is the toroidal correlation angle [4]. The framework of E×B shear decorrelation and stabilization of turbulence has the attractive character that it provides a mechanism whereby increased background gradients in the plasma pressure and velocity result in reduced turbulent transport levels. Improved energy and momentum transport that results then leads to a further increase in gradients, resulting in a confinement improvement scenario that is self-reinforcing. As a result, bifurcations in confinement may also result: several modeling efforts have revealed the possibility of both fast and slow bifurcations [5,6,7,8,9] when considering these positive feedback loops. This relation between transport and the background gradients also suggests that modification in these gradients by some external means (e.g. core heating to increase ∇p and its gradient, or strong injected neutral beam torque to increase the gradient in V_ϕ) or by plasma self-generated events (e.g. Reynolds stress induced poloidal flows [10,11]) can have a profound influence on the plasma dynamics. Finally, there is also the possibility of interplay between the different elements in the force balance equation, yielding the possibility that a wide and rich range of plasma behavior can result from E×B flow shear effects.

3. ELECTRIC FIELD BIFURCATIONS IN THE DIII-D H MODE EDGE AND THE TFTR ERS CORE

One of the hallmarks of many transitions to enhanced confinement in the edge is the spontaneous development of increased electric field strength and its gradient that precedes a confinement change. On some devices, this first becomes apparent in the plasma poloidal rotation [12,13,14]. On DIII-D, this appears as a localized impurity poloidal rotation excursion in the electron diamagnetic drift direction just inside the separatrix (Fig. 1(a)). This increase in shear in the poloidal rotation and radial electric field E_r precedes any measurable changes in the other background plasma profiles, pointing to a threshold character of the confinement bifurcation and indicating that the change in electric field shear is a causal element of the transport reduction. The change in confinement is identified by the rapid change in the electron density near the radius of changes in E_r'. After the initial change in confinement, ∇p increases and takes over the role of V_θ in dominating the determination of E_r in the impurity force balance equation.

Recent measurements of carbon poloidal rotation made in the core of TFTR ERS plasmas [15] indicate that this description of the H mode formation process can be extended to core barrier formation in the case of TFTR ERS plasmas. Considering the force balance equation, the E_r evolution in this case generally consists of a poloidal rotation precursor, followed by a continued significant role of V_θ and an increasing role of ∇p in the determination of E_r (Fig. 1). The precursor is located close to and just inside the minimum in the q profile. Like the H mode measurements on DIII-D, the change in V_θ precedes any change in local confinement characteristics by many tens of milliseconds. Near or at the peak of the carbon poloidal flow excursion, an increase in the local confinement, as represented by the local carbon pressure, takes place. Recent direct measurements of the local electric field [16] are consistent with the spectroscopic determination that the V_θ excursion is the dominant component of the electric field early in time, as is found in the H mode. Like the H mode edge, an electric field well develops near the radius of the steep pressure gradient. The ∇p term in the carbon force balance equation plays an increasingly important role in the determination of E_r as the plasma pressure increases in both cases. In the TFTR core, V_θ remains important after the confinement transition and deviates significantly from values predicted by neoclassical theory, and is responsible for the positive electric field seen near the TFTR magnetic axis.

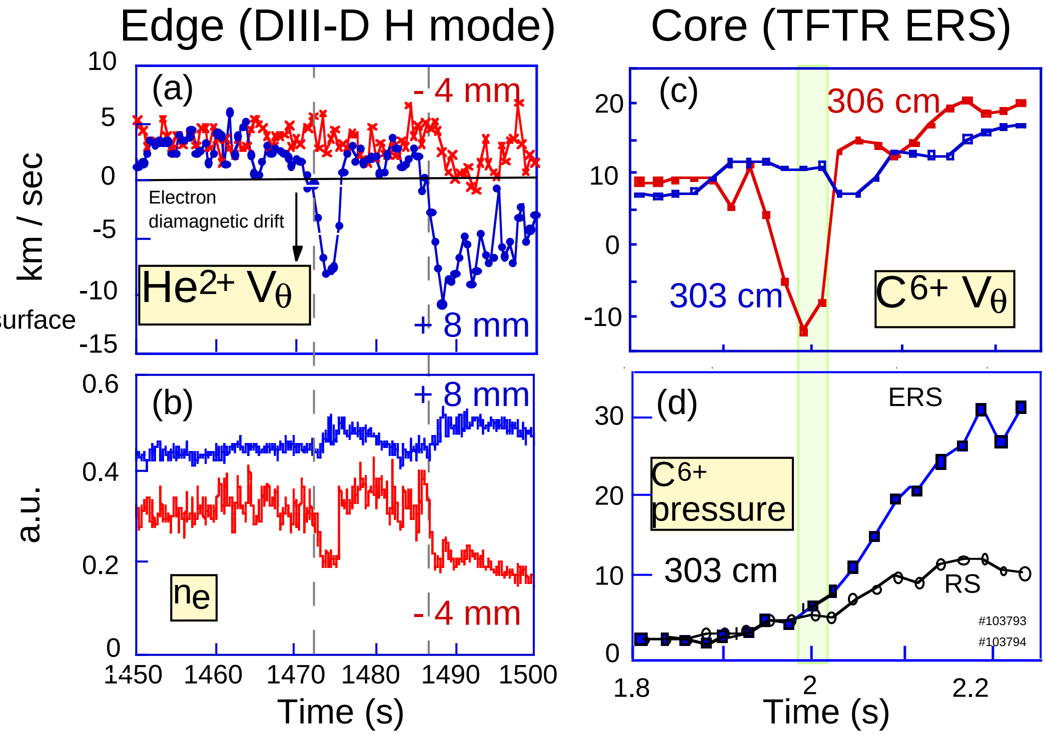

Figure 1. Characteristics of local parameters of the L-H transition on DIII-D and an ERS transition on TFTR. (a) Helium impurity poloidal rotation V_θ for the DIII-D H mode [17,18]. The change in V_θ is just inside the separatrix and begins slightly before the bifurcation in confinement. (b) The local electron density, as measured by a lithium beam diagnostic, for two locations near the separatrix. (c) Carbon V_θ for a TFTR ERS plasmas [Bell, 1998]. The excursion in V_θ is located just inside the minimum in the q profile, and occupies a region no wider than a few cm. The excursion begins before the transition to enhanced confinement, as illustrated by (d), the change in the local carbon pressure. For both plasmas, the changes in V_θ represent spontaneously generated, localized E_r shear. In the early stages of the bifurcation, the $V_\theta B_\phi$ term dominates the force balance equation. Later in time, the ∇p term for each impurity has an increasingly important role governing E_r in the force balance equation, and especially its shear.

In both cases, the confinement bifurcation is rapid compared to a transport time scale. Fluctuation characteristics change quickly with the confinement change as well [3]. The transition also exhibits a threshold character when the heating power is varied at a fixed set of external control parameters. These local measurements in the edge and the core suggest that developing predictive capability regarding this threshold amounts to understanding the local physics required for establishing a nonlinear bifurcation in the local plasma electric field. Further common physics is suggested by noting that the excursions in V_θ and E_r in both the edge and the core are well localized: in the ERS core, the E_r shear layer occupies ~2 cm, and a smaller radial extent is found in the H mode edge. The origin of this precursor in E_r shear evolution, already a subject of active consideration regarding the H mode for many years, is now reemphasized with these observations in the core. There are recent efforts [19] to explain the ERS core E_r behavior as a sustained neoclassical poloidal viscosity bifurcation similar to that proposed for H mode transitions [20]. A continuing challenge for this work is to develop a self-consistent picture that accounts for the decay of V_θ after the confinement bifurcation. The rapid decay is consistent in many respects with a fluctuation-driven flow generation which is terminated when the fluctuations are suppressed [8,10,11]. However, a difficulty with reconciling this particular picture with the data is that the present 2-D models [9] intrinsically conserve momentum; it remains to be seen if the monopolar features observed in the TFTR ERS core and the H mode edge can be reproduced with a more complete treatment.

4. DEVELOPMENT OF IMPROVED TRANSPORT IN THE DIII-D NCS CORE AND COMPARISON TO TFTR REVERSE SHEAR PLASMAS

The rapid bifurcations in E_r and confinement found in the DIII-D H mode edge and the TFTR core are to be contrasted to the slow development of the core transport barrier region in DIII-D NCS plasmas. As reported in [21], development of the improved transport region that is slow compared to an energy confinement time scale is observed throughout the early heating period of these plasmas (Fig. 2). Typically, the region of reduced transport expands to about $\rho = 0.4$, where $\omega_{E\times B}$ is found to be approximately equal to the local linear growth rate for the fastest growing mode. Upon an increase in the unidirectional neutral beam heating power, there is a rapid improvement in the confinement that takes place on the time scale of the toroidal rotation spinup. The local shearing rate increases with increasing toroidal rotational shear, and the region of reduced transport increases in radial extent. Unlike the DIII-D H mode edge and the TFTR ERS core, the toroidal rotation plays an important if not dominant role in determining $\omega_{E\times B}$ in these plasmas. Rather than yielding an E_r well in the region of large plasma pressure, as is the case for the ERS core and the H mode edge, a positive E_r hill is generated with neutral beam injection in the direction parallel to the plasma current (co-injection).

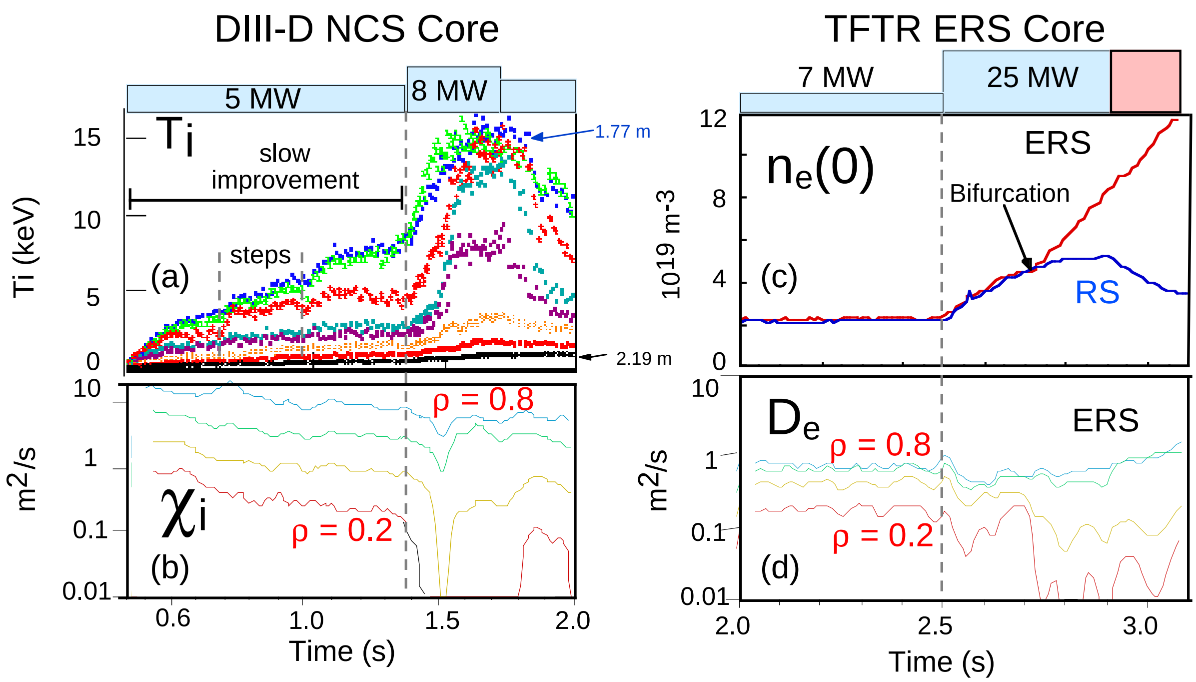

Figure 2. (a) The ion temperature evolution in a DIII-D NCS plasma. (b) The ion thermal conductivity χ_i for the same plasma. In the early heating phase before the beam power step just before 1400 ms, the improved confinement develops slowly. Upon the increase in the heating power, the improvement is rapid. This is apparent not only χ_i but in the rapid change in slope in $T_i(t)$ upon the increase in heating power. (c) The central electron density for two TFTR RS plasmas, one of which undergoes a transition to the ERS regime. (d) The particle diffusivity D_e for the ERS plasma. The ERS bifurcation is rapid and may be considerably delayed with respect to the beam power increase. The sudden onset is to be contrasted with the slower development of the improved transport region in the NCS case.

A significant feature of the early plasma evolution in NCS plasmas is the appearance of confinement steps and sometimes interruptions in the otherwise monotonic development of the improved transport region [21,22] (Fig. 2). In the low power (7 MW) early heating phase of TFTR RS plasmas, steps and drops in the ion and electron temperature are observed as well, but they at best serve as small perturbations to an otherwise steady-state early heating phase. However, at about 14 MW of NBI at 4.8 T on TFTR, the steps often result in a significant reduction in transport, primarily in the ion thermal and momentum channels, and in the electron particle diffusivity. In contrast to the picture discussed in Section 3, measurements made in the core of DIII-D and in these TFTR plasmas across these steps do not indicate the presence of a strong carbon poloidal rotation precursor prior to measurable confinement changes. This suggests that the criteria for initiating a confinement step in these cases has been met by some other means. Some role of the current profile is suggested by the extraordinary reproducibility of the timing of the steps from one plasma discharge to the next. Many devices, including RTP [23] and JET [24], have cited correlations between transport steps and the emergence of simple integer values of the q profile in the plasma. On DIII-D, however, similar correlations are often, but not always, found [22]. It should be noted, however, that on TFTR significant increases in confinement are in fact correlated with q_{min} passing through 2 [25].

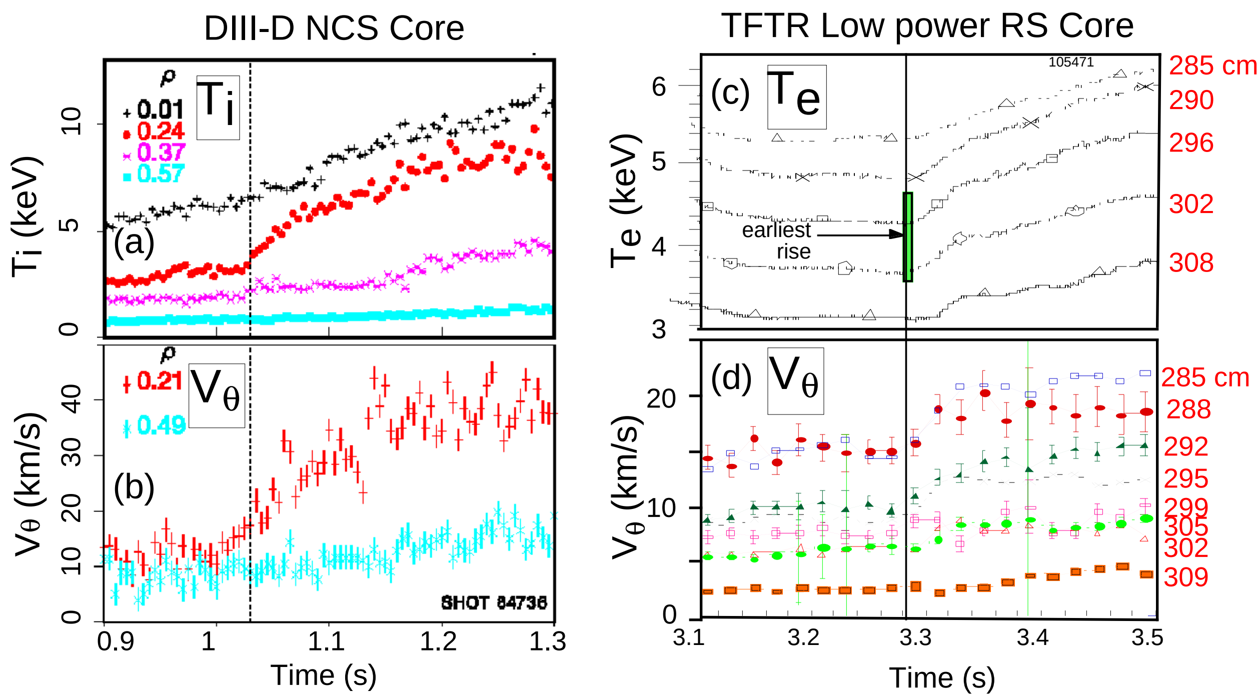

Figure 3. (a) The ion temperature in the core and across a confinement step during the early heating phase of a DIII-D NCS plasma. (b) The carbon poloidal velocity V_θ across the same step. (c) The core electron temperature across a confinement step in a TFTR RS plasma. ECE data reveals the highly localized nature of the step and that it propagates both radially inward and outward. (d) The inverted carbon V_θ data for the same TFTR plasma. For both (b) and (d), there is not a strong signature of spontaneous E_r shear development like that seen in the core of TFTR ERS plasmas.

5. AN EXPERIMENTAL DEMONSTRATION OF A CONTINUOUS CONNECTION BETWEEN THE TFTR ERS AND DIII-D NCS CONFINEMENT REGIMES

Both devices exhibit strong similarities in the magnitude of the transport reduction, the predominance of improvements in the ion channel as compared to the electron channel, and a facilitating role of magnetic shear reversal in achieving these reductions. However, significant differences in the dynamics of the reduced transport region in the plasma core between DIII-D and TFTR challenge any single physics picture that might be used to describe these plasma states. Such differences include the following. First, if the theoretical description involves the radial electric field, such a theory has to account for the fact that TFTR ERS plasmas with balanced neutral beam injection have a negative E_r well near the region of steepest pressure gradient, while in the core of DIII-D, a positive E_r hill exists as a result of the strong unidirectional injection parallel to the plasma current. Second, the development of the reduced transport region of DIII-D NCS plasmas can be slow when the neutral beam heating power and the associated input torque is low (5 MW and below). More rapid deepening and expansion of the reduced transport region occurs at higher powers, on the time scale of the toroidal rotation spinup upon application of a neutral beam power step. This is to be contrasted to

TFTR ERS plasmas, which have a clear bifurcation character, and such bifurcations are rapid compared to a transport time. The family of TFTR ERS plasmas also exhibits a threshold in the heating power for a given set of external device parameters and wall conditions [26], like the H mode.

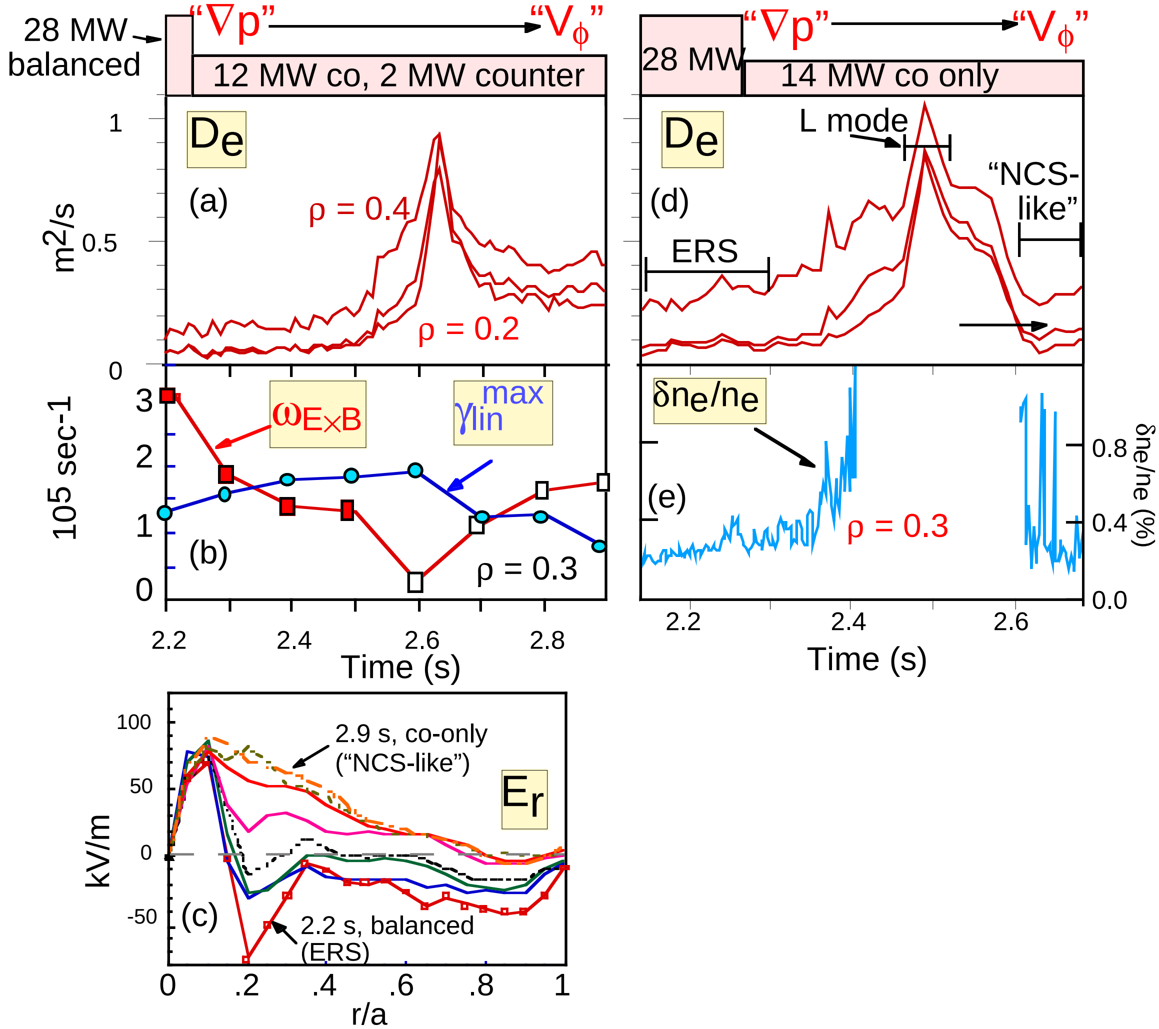

Figure 4. (a) The particle diffusivity, inferred from TRANSP analysis, for a plasma with an ERS transition in the balanced injection period near 2 s. After 2.25 s, most of the remaining injected power is parallel to the plasma current. The entry into the second enhanced transport phase is slow compared to the original ERS bifurcation (Fig. 2) (b) The shearing rate and the maximum linear growth rate [Beer, 1995] evaluated near the foot of the pressure profile of the initial ERS phase. As the toroidal rotation increases in the co-direction, the E_r well is eliminated and $\omega_{E\times B}$ is driven to low values. For $\omega_{E\times B}$, the shaded boxes correspond to times when E_r is negative, and open boxes correspond to times when E_r is positive. Maximum transport occurs when $\omega_{E\times B} \sim 0$, not when $E_r \sim 0$. The confinement improves again as V_ϕ begins to dominate $\omega_{E\times B}$ as the positive E_r hill steepens. (c) E_r at different times for the plasma illustrated in (a) and (b). All terms in the carbon force balance equation were measured. (d) Same as (a), except this plasma had all of the power injected parallel to the plasma current in the rotating phase, as in DIII-D NCS plasmas. The transport trends are the same as in the plasma shown in (a), but the final transport levels are lower. At the same time, the toroidal rotational shear is larger, owing to the additional applied torque. (e) The density fluctuation level for the plasma shown in (d) (Mazzucato, 1996), measured by reflectometry. Fluctuations are reduced in both enhanced confinement states. The measurements have an estimated spatial resolution of 1 - 2 cm, and sample a wave number range of $0.5 < k < 2.0\ \mathrm{cm}^{-1}$.

Previous work indicates that E×B flow shear likely plays an important role in the core barrier dynamics of both devices (cf. [1,22,26,27,28,29]). That DIII-D NCS and TFTR ERS plasmas represent confinement regimes that are dominated by E×B shear effects but which exercise different feedback loops in getting to a state of enhanced confinement is suggested by examination of a single discharge type on TFTR. These experiments drew on the capability of TFTR to vary the sign of E_r through the application of a variety of torques with co- and counter-directed neutral beam injection. Previously, such an procedure was used to demonstrate the necessary role of E×B shear in sustaining enhanced confinement in TFTR ERS plasmas [26,29]. In those experiments, E_r and its shear were varied by changing the toroidal rotation while keeping other quantities that might stabilize turbulence, such as strong Shafranov shift gradients and density peaking, constant. Below, efforts to extend these experiments are described to examine the possibility that different feedback loops might account for the different evolutions of the improved confinement regions between DIII-D NCS and TFTR ERS plasmas.

The ERS enhanced confinement state of these plasmas was initiated in the usual way with a net torque of nearly zero applied via neutral beam heating ("balanced injection"), like the plasma described in Fig. 1. Following this balanced stage, the power was reduced from 28 MW, and injected power at the 14 MW level was applied predominantly but with varying fractions parallel to the plasma current. As the plasma toroidal rotation increases, E_r changes from negative to positive in the region near the steep pressure gradient (r/a ~ 0.3, Fig. 4). In the process, the negative E_r well was eliminated and replaced by an E_r hill, much like those routinely measured on DIII-D. As the E×B shear is minimized during the transition from negative to positive E_r, a collapse from the initial enhanced confinement state is observed. The maximum linear growth rate [30], evaluated at this radius without including E×B shear effects, is comparable to $\omega_{E\times B}$ at the start of the rotating phase. The difference in the two rates increases with increasing rotation and is maximized near the time of maximum transport. Since the plasma pressure is kept constant up to the time of the barrier collapse while E_r is varied, this loss of good confinement can be ascribed to a reduction in E×B shear resulting from the modification of the toroidal rotation term in the force balance equation. Recent measurements of the poloidal rotation confirm this general picture, and these results are included in the evaluation of $\omega_{E\times B}$ presented here. The necessary role of flow shear is emphasized by noting that the transient loss of E×B shear during the switch from balanced to strong co-injection corresponds to the time of minimum global confinement, and maximum transport levels.

The subsequent TFTR plasma spinup and development of an positive electric field hill results in a plasma whose performance, dynamics, and electric field behavior have many similarities to those observed in DIII-D NCS plasmas. After the back transition, the plasma transport for a brief period is comparatively rapid as transport rates approach L mode levels. After the L mode period, however, the toroidal rotational shear continues to increases, overtaking the now diminished contribution from the pressure gradient, and the radial electric field shear grows. It is during this period that a region of good core confinement is reestablished. The return of small transport rates occurs as the ratio of the linear growth rate to the shearing rate decreases. At the later times, however, the shearing rate is determined by a positive radial electric field corresponding to strong co-rotation, not a negative electric field determined by the pressure gradient in the carbon force balance equation. As in DIII-D NCS plasmas, the entry into this second enhanced confinement state is slow compared to the fast TFTR ERS bifurcations. Both the DIII-D case and these TFTR rotating cases develop enhanced confinement over a period of several hundred milliseconds, a time scale comparable to the rotational spinup time. This correlation of the generation of E×B shear through a positive E_r hill and transport and fluctuation reductions is analogous to the phenomenology observed on DIII-D, and is consistent with turbulence stabilization of E×B flow shear effects playing a dominant role in turbulence suppression in both devices. It is inconsistent with theories that require E_r have a particular sign for a confinement improvement. When reverse shear plasmas of similar powers are compared, the magnitude of the confinement improvement is strongly correlated with the fraction of power injected parallel to the plasma current and thus the magnitude of the E×B shear developed through toroidal rotation. With the largest applied torques, the lowest core transport levels are far below the L mode values and rival those of the 14 MW balanced injection ERS regime that was present earlier in the same discharge. Density fluctuation levels also fall to the low values observed in the ERS phase [27]. The final level of the transport reduction depends on the input torque applied: 14 MW of co-only injection yielded lower transport levels than did the simultaneous injection of 12 MW of co-injection and 2 MW in the direction antiparallel (counter) to the plasma current.

6. MEASUREMENT NEEDS AND TRANSPORT CONTROL STRATEGIES

The above discussions highlight that many aspects of the plasma dynamics in both devices can be explained within the framework of E×B shear stabilization and decorrelation of turbulence. However, many features are as yet unexplained. The origin of the electric field bifurcation in the high power

TFTR ERS core and the DIII-D H mode edge is still a subject of debate, and resolution of this question would be greatly assisted by diagnosis of the relevant fluctuation characteristics that might lead to turbulence-driven flows..

It has been argued that the size scaling of E×B shear stabilization effects on turbulence to reactor scale devices may be unfavorable. However, the localized E_r bifurcations in the H mode edge and the high power ERS core demonstrate that plasma confinement over a broad region in the core in a large device can be dramatically influenced by plasma flows that begin on a considerably smaller spatial scale. The data presented here emphasizes the need to consider local nonlinear dynamics in assessing the viability of exploiting this physics in a reactor. As suggested by results from IBW heating experiments on the PBX-M tokamak [31], the large scale impact of small-scale flow shears opens the possibility that modest manipulation of the plasma's radial electric field on a small spatial scale may provide significant leverage on the confinement characteristics and control prospects of the core plasma as a whole.

7. ACKNOWLEDGMENTS

The support of the research and technical staffs at both General Atomics and the Princeton Plasma Physics Laboratory is gratefully acknowledged. This work supported by U.S. DOE contracts DE-AC02-76CH03073 and DE-AC03-89ER51114.

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