PHYSICS OF TURBULENCE CONTROL AND TRANSPORT BARRIER FORMATION IN DIII-D[*]

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This paper describes the physical mechanisms responsible for turbulence control and transport barrier formation on DIII–D as determined from a synthesis of results from different enhanced confinement regimes, including quantitative and qualitative comparisons to theory. A wide range of DIII–D data support the hypothesis that a *single underlying physical mechanism, turbulence suppression via **ExB** shear flow* [1–5] is playing an essential, though not necessarily unique, role in reducing turbulence and transport in all of the following improved confinement regimes: H–mode, VH–mode, high-ℓ_i modes, improved performance counter-injection L–mode discharges and high performance negative central shear (NCS) discharges. DIII–D data also indicate that synergistic effects are important in some cases, as in NCS discharges where negative magnetic shear also plays a role in transport barrier formation. This work indicates that in order to control turbulence and transport it is important to focus on understanding physical mechanisms, such as **ExB** shear, *which can regulate and control entire classes of turbulent modes*, and thus control transport. A more detailed description of recent results follows, grouped by type of operating regime:

Edge L-H Transition Data. In fast L-H transitions detailed edge Langmuir probe measurements indicate *quantitative agreement* with **ExB** shear flow theories. The spatial dependence of the edge turbulence reduction is consistent with shear suppression for negative E_r shear, while for positive E_r shear the turbulence suppression is consistent with the effect of E_r curvature for modes for which an E_r well is destabilizing [6]. Phenomenologically distinct “fast,” “dithering,” and “slow” types of L-H transitions previously reported on DIII–D can all be explained by **ExB** shear suppression of turbulence and transport. An additional type of “very slow” transition has been observed on DIII–D in which the edge D_α emission can take more than 50 ms to evolve from L– to H–mode levels. Within the edge negative E_r well density turbulence levels do not reduce until near the end of the D_α drop. Further out, in the vicinity of the separatrix, density and potential fluctuations are not reduced in H–mode, and may even increase. In this region the phase angle is responsible for a reduction in broadband turbulent driven flux. That the phase angle can play such a role in reducing transport has been observed previously [6], and has also been suggested by theoretical modeling [2,4]. Unlike fast transitions, SOL profiles remain unchanged from L– to H–mode.

High-ℓ_i and VH–mode Discharges. Magnetic braking of toroidal rotation in high-ℓ_i enhanced confinement discharges reduces the **ExB** shearing rate, leading to an increase in turbulence and transport which demonstrates that **ExB** shear plays a causal role in the reduced turbulence and transport normally observed in these plasmas. Similar results indicating causality have been obtained with the magnetic brake in VH–mode discharges [7]. Controlling the current profile can directly affect the **ExB** shear mechanism as the magnitude of the shearing rate is proportional to the shear in E_r/RB_θ [8], and in high-ℓ_i discharges the modified current profile increases the shear in E_r/RB_θ, resulting in enhanced turbulence suppression.

Counter-injection L–mode Data. Reduced fluctuation levels have been observed in counter-injection L–mode plasmas, correlating with increasing **ExB** shear. These measure-

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ments may explain observations of improved L–mode confinement in counter-injection plasmas in ASDEX and JFT-2M.

Negative Central Shear (NCS) Discharges. There are several reasons to believe that **ExB** shear effects are playing an essential role in controlling turbulence and transport in these discharges: (a) A power threshold has to be exceeded before turbulence and transport are reduced, in agreement with **ExB** shear theory [5]. (b) NCS is not necessary for the maintenance of high performance; performance is maintained in discharges where the current profile evolves such that the core magnetic shear becomes low or near zero. However, high levels of **ExB** shear are maintained. (c) As in high-ℓ_i discharges, the modified current profile in NCS discharges changes the central poloidal field profile such that shear in E_r/RB_θ in the core of these discharges can be an order of magnitude higher than in a VHmode discharge with similar toroidal rotation rates. (d) After transport barrier formation the **ExB** shearing rate clearly exceeds the trapped electron η_i mode linear growth rate in the region of reduced transport, whereas the two rates are comparable immediately before barrier formation. This indicates that the **ExB** shear rate is quantitatively sufficient to suppress turbulence such as η_i modes, and hence reduce transport [9]. (e) Negative magnetic shear is predicted to locally lower the threshold for turbulence suppression via **ExB** shear [10]. However, negative magnetic shear also contributes to the formation of high performance NCS discharges and such shear is predicted to suppress some curvature driven microinstabilities. Thus, DIII–D data support a picture in which the enhanced performance in the NCS regime is obtained via a combination of *both magnetic and **ExB** shear effects.* As a result, very low levels of turbulence and transport are observed in NCS discharges; BES measurements indicate $\tilde{n}/n$ levels of <0.1% in the core of NCS L–mode plasmas, while scattering measurements indicate low levels of turbulence *everywhere* in high performance NCS H–mode plasmas. The core transport barrier is often observed to form in the initial low power heating phase (which generates the magnetic shear reversal), before the main heating beams are applied. The barrier formation has the nature of a bifurcation, and both the rate of barrier formation and the radial extent of the reduced turbulence/transport region increase with increasing NBI power, in accord with theoretical predictions [5]. Finally, the residual turbulence in high performance NCS plasma often exhibit a regular bursting character in time, reminiscent of the limit-cycle behavior predicted in Ref. [4].

In conclusion, a synthesis of data from DIII–D indicates that sheared **ExB** flow is playing an essential role in the formation and maintenance of a wide range of transport barriers and reduced transport regimes. The evidence for this conclusion can be summarized under the following headings: *1. Causality.* Edge measurements at the L-H transition provide evidence for a causal role for **ExB** shear, as do magnetic braking experiments in VH– and high-ℓ_i modes. *2. Quantitative tests of theory.* Edge measurements across the L-H transition show quantitative agreement with theory, and also indicate that the measured reduction in turbulence driven flux is sufficient to account for the observed transport improvement. In NCS plasmas the **ExB** shearing rate exceeds the η_i mode growth rate, indicating that such turbulence should be suppressed. 3. *Qualitative tests of theory.* Measurements in all reduced transport regimes indicate a spatial and temporal correlation between the development of **ExB** shear and reduced turbulence and transport. The observed **ExB** shearing rates in all regimes are of sufficient magnitude that turbulence reduction can be expected. Other processes, such as magnetic shear effects on turbulence are also important, and can operate in parallel in a synergistic fashion. Finally, experimental measurements continue to find new results that extend our understanding of transport barrier formation, a good example of this being the new “very slow” type of L-H transition.

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