# The Radial Electric Field and Transport Barriers in Tokamak Plasmas

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The pathway to plasma regimes with reduced transport and improved confinement has been greatly advanced by understanding the important role of the radial electric field $E_r$ in the formation of transport barriers in tokamak plasmas. More specifically, the transport reduction results from the nonlinear decorrelation and linear stabilization of turbulent eddies by the $E \times B$ velocity shear. Increased local gradients in the radial profile of $E_r$ have led to the formation of transport barriers from the plasma edge to the plasma core. For instance, the dramatic increase in the absolute derivative of $E_r$ just inside the plasma separatrix can explain the transport barrier formed at the transition from L–mode to H–mode plasmas. The radial extension of the region of increased shear in $E_r$ further into the plasma core can explain the even greater confinement improvement observed in VH–mode plasmas. Further changes in the radial derivative of $E_r$ in the plasma core are associated with the core or internal transport barrier formed in plasmas with low or negative central magnetic shear. The reduction in transport is substantial. A combination of both core and edge transport barriers, as produced in DIII–D negative magnetic shear plasmas with H–mode plasma edges, has led to decreases in the ion thermal transport to below the conventional neoclassical levels across the whole plasma cross-section [1].

The underlying mechanism of $E \times B$ velocity shear stabilization of turbulence is evident from the experimental results on transport barriers in both the plasma core and the plasma edge. There is both qualitative and quantitative agreement between the experimental results and theoretical work on nonlinear decorrelation and linear stabilization of turbulence. In nonlinear turbulence decorrelation theory [2,3], the $E \times B$ velocity shear causes phase changes between the density and velocity fluctuations and reduction in the fluctuation amplitudes leading to an overall decrease in the radial transport. In linear stabilization theory [4–6], $E \times B$ velocity shear can couple unstable turbulent modes to stable modes thereby resulting in an aggregate improvement in stability, although the coupling itself may be mode dependent. For $E \times B$ velocity shear decorrelation of turbulence, $\omega_{E \times B}$ must be comparable to $\Delta\omega_D$, where $\omega_{E \times B}$ represents the $E \times B$ shearing rate for flute-like modes [7] and $\Delta\omega_D$ is the nonlinear turbulence decorrelation rate in the absence of $E \times B$ velocity shear [2]. Similarly, for $E \times B$ shear stabilization of turbulence, $\omega_{E \times B}$ must be comparable to $\gamma_{max}$, which is the maximum linear growth rate of all the unstable modes [8]. Due to limitations and uncertainties in the theoretical predictions, the above inequalities can lie within factors of 2–3 in comparing experimental results with theoretical predictions.

The merit of the model of $E \times B$ velocity shear stabilization of turbulence is most clearly evident from the formation of the edge transport barrier in H–mode plasmas. The absolute gradient in $E_\mathrm{r}$ just inside the plasma separatrix increases abruptly at the transition from L–mode to H–mode [9,10]. In the same region where $E_\mathrm{r}$ steepens, the amplitude of density fluctuations decreases significantly and the density and temperature profiles steepen. There is both a temporal and spatial correlation between the region of increased $E \times B$ shear, the region of reduced density fluctuations, and the region of reduced transport. The value of $\omega_{E\times B}$ is significantly greater than $\Delta\omega_\mathrm{D}$ in the region of the transport barrier in the H–mode [11,12]. The well-like structure in the $E_\mathrm{r}$ profile formed at the plasma edge at the L–H transition persists into the H–mode and is an intrinsic aspect of H–mode plasmas. The width of the $E_\mathrm{r}$ well is remarkably invariant to a large range of plasma parameters and conditions at the L–H transition, although the absolute value of the minimum in the $E_\mathrm{r}$ well is observed to vary for different plasma parameters [12]. Even though the $E \times B$ velocity shear at the plasma edge changes from negligible to substantial at the L–H transition, it can be very different from the value of the poloidal rotation of the main ions and the impurity ions, which can be in opposite directions to each other [13]. The value of $E_\mathrm{r}$ (as determined from the lowest order force balance equation) is dominated by the main ion diamagnetic term or pressure gradient as soon as 3.5 ms after the start of the L–H transition [14] and even later (in the order of 10s of ms) by the impurity ion pressure gradient [10]. The physics behind the bifurcation in the edge $E_\mathrm{r}$ for spontaneous L–H transitions is as yet undetermined.

A key aspect in the model of $E \times B$ shear stabilization of turbulence is the issue of causality. Observations of significant changes in $E_\mathrm{r}$ shear prior to the L–H transition on the DIII–D tokamak present evidence for causality [14,15]. In cases of externally generated $E_\mathrm{r}$ produced by biasing the plasma edge, experimental results from TEXTOR indicate that increases in local density and confinement are spatially and temporally correlated with the radial derivative of the applied $E_\mathrm{r}$ (and not $E_\mathrm{r}$ itself) prior to the actual bifurcation of the radial current [16]. Further evidence of causality is seen in experiments on magnetic braking in the VH–mode plasmas on DIII–D. The VH–mode results after a transition from H–mode conditions as the region of predominant $E \times B$ velocity shear established in H–mode penetrates deeper into the plasma core. When magnetic braking is applied to VH–mode plasmas, the resultant decrease in the $E \times B$ shearing rate is spatially correlated with an increase in the amplification of density fluctuations and an increase in local transport [17]. Similar results are observed on applying magnetic braking to high $\ell_\mathrm{i}$ discharges produced by vertical elongation ramps [18].

The highest improvements in confinement and greatest reduction in transport have occurred with transport barriers created in the plasma core. Again, the $E \times B$ velocity shear is the dominant mechanism for the reduction in transport. Although core transport barriers are facilitated by the presence of negative central magnetic shear, the negative shear alone is not sufficient to form the transport barrier. This is seen in reverse shear (RS) and enhanced reverse shear (ERS) discharges on TFTR, which have near identical $q$ profiles with $q' < 0$ in the plasma core, but the transport barrier is absent in the RS discharge [19]. In the transition to the ERS phase, some observations of the core carbon poloidal rotation $v_\theta$ indicate an abrupt and substantial change in $v_\theta$ and hence $E_r$, which is dominated by the $v_\theta$ term [20,21]. The $E_r$ change occurs prior to any increase in local confinement. The subsequent improvement in local confinement results in an increase in the carbon pressure gradient which maintains the changed $E_r$ value, even as the value of $v_\theta$ decreases after the initial bifurcation. Data from TFTR [22] and DIII–D [23] indicate spatial correlation between the regions where turbulence is substantially reduced and where $\omega_{E\times B}$ exceeds $\gamma_{max}$. Furthermore, the turbulence exhibits poloidal asymmetry, as in DIII–D, where higher levels of turbulence are observed in the inboard high toroidal field side where $\omega_{E\times B}$ is lower than on the outboard low field side [11].

Further proof of causality has been seen on TFTR by varying the angular momentum input during the postlude phase of ERS discharges. Changes to the $E_r$ profile and, hence, the $E \times B$ shearing rate as a result of changing the toroidal rotation reveal clear spatial and temporal correlation between changes in $\omega_{E\times B}$ and transport [19]. As $\omega_{E\times B}$ is made to decrease, the density fluctuations increase coincident with an increase in transport thereby resulting in a back transition to the RS phase. In cases where $\omega_{E\times B}$ is maintained at higher values in the postlude phase, the reduction in transport and the back transition are delayed.

Threshold power requirements exist for the formation of both edge [24] and core transport barriers [25,26]. This behavior is consistent with the need to drive $E_r$ and $\omega_{E\times B}$ to sufficiently high levels to be effective in turbulence suppression. High $\beta_p$ experiments on JT–60U indicate that power deposition specifically into the plasma core is critical for the formation of the core transport barrier [27]. Furthermore, results from DIII–D indicate that the core barrier expands radially outward as the input power is increased and, conversely, the barrier contracts radially inward as the power is decreased and the $\omega_{E\times B}$ rate gradually decreases into the plasma interior [11,28].

Future advances require methods to be developed to actively control and modify the $E_r$ profile in the plasma core and edge to affect changes in the local $E \times B$ velocity shear.

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