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Turbulence and Sheared Flow

In the quest for fusion energy using magnetic confinement, a continuing theme is the search for ways to improve energy confinement by eliminating the effects of plasma instabilities. Early workers developed magnetic field configurations which eliminated the gross, large-scale magnetohydrodynamic (MHD) instabilities. When present, these global MHD instabilities can typically tear apart in microseconds a plasma whose energy containment time can be several seconds. Even when the magnetic configuration suppresses these gross instabilities, most fusion plasmas still retain a significant level of small-scale turbulent eddies, so-called microturbulence, which dominates the loss of energy from the plasma.

One of the scientific success stories of magnetic fusion research over the past decade is the intertwined development of techniques to reduce microturbulence-driven transport and the simultaneous development of the **E**×**B** velocity shear stabilization model discussed below to explain how those techniques work. A continuing interplay between experimental discovery and theoretical insight has guided this development. One achievement using these techniques is tokamak plasmas with fusion-relevant ion temperatures of 20 to 30 keV, where the energy loss through the plasma ions has been reduced by more than an order of magnitude — to the level caused simply by interparticle collisions. Indeed, in some cases the measured loss rates are so low that the once-moribund field of collisional transport calculations is again an active field of research, as workers strive to determine whether even the collisional rates are too high to agree with experiment for the precise magnetic configuration used in the experiments.

The improvement due to **E**×**B** shear stabilization in magnetized plasmas is a fascinating basic physics result; it is not often that a turbulent system self-organizes to a higher energy state with reduced turbulence and transport when an additional source of free energy is applied to it. Usually, turbulent media like neutral fluids or plasmas become more turbulent and lose energy faster with increased heating or fueling. Although there are a few cases where neutral fluids exhibit velocity shear stabilization [1], the interplay of electric and magnetic fields in magnetized plasmas helps overcome the usually detrimental effect of increased velocity gradients in driving turbulence [2]. In addition to its intrinsic physics interest, the transport decrease which is associated with **E**×**B** velocity shear has significant practical consequences for magnetic fusion research. For example, the best fusion performance to date in the DIII–D [3], JT–60U [4] and TFTR [5] tokamaks has been obtained under conditions where transport reduction through **E**×**B** velocity shear stabilization of turbulence is almost certainly taking place.

The **E**×**B** phrase in the name of this type of shear stabilization comes from a basic motion of charged particles in an electric field **E** and magnetic field **B**. In addition to the usual cyclotron motion around the magnetic field and motion parallel to it, a particle moves with a velocity $\mathbf{v_D} = \mathbf{E}\times\mathbf{B}/B^2$. This velocity does not depend on the charge or the mass of the particle, so that all particles share this component of their velocity. This common speed is one of the reasons why the **E**×**B** velocity shear is the most fundamental shear. While shear in individual species' velocities or in turbulent wave propagation speeds can, in principle, affect the microturbulence through shear in those specific velocities, the ubiquitous character of sheared **E**×**B** flow makes it the most fundamental effect [2].

The basic physics involved in transport reduction is the effect of **E**×**B** velocity shear on the growth and size of turbulent eddies in the plasma. Although both nonlinear [6,7] and linear [8,9] effects have been considered, there is now a general consensus that the nonlinear effects must be included in the complete picture [6,10]. More complete references to the theory are in Ref. 2. The basic shearing effect is the reduction in transport due to a decrease in the size of the turbulent eddies and due to a change in the relative phase between turbulent oscillations in the density, temperature, and electrostatic potential.

A greatly simplified illustration of the effect of **E**×**B** shear on turbulence and transport is given in Fig. 1, which is based on work by Carreras [11]. The colored ovals in Fig. 1(b) show the surfaces of constant turbulence-driven particle flux in a cylindrical plasma for the case of no **E**×**B** velocity shear while the distorted ovals in Fig. 1(d) show how this quantity changes in the presence of the velocity shear. Figures 1(a) and (c) are plots showing how the particle flux varies with position across the middle of the turbulent eddies. Although this simplified model is for particle flux, similar effects hold for energy flux. A key point in the theory is that there must be a change in the **E**×**B** velocity with position (i.e., shear) in order to affect the turbulent transport. Notice that the twisting of the eddies caused by the spatially varying velocity makes them shrink in the radial direction, which is the direction of heat flow toward the wall of the container holding the plasma. In addition, although the peak particle flux in the two cases in Fig. 1 is the same, the total flux is greatly reduced by the **E**×**B** velocity shear. This total flux is given by the area under the curves in Figs. 1(a) and (c). Much more elaborate numerical calculations [12,13] have shown the same qualitative features; indeed, the color plots in these two papers give wonderfully intuitive illustrations of the effects of **E**×**B** velocity shear on turbulence in the experimentally relevant toroidal geometry.

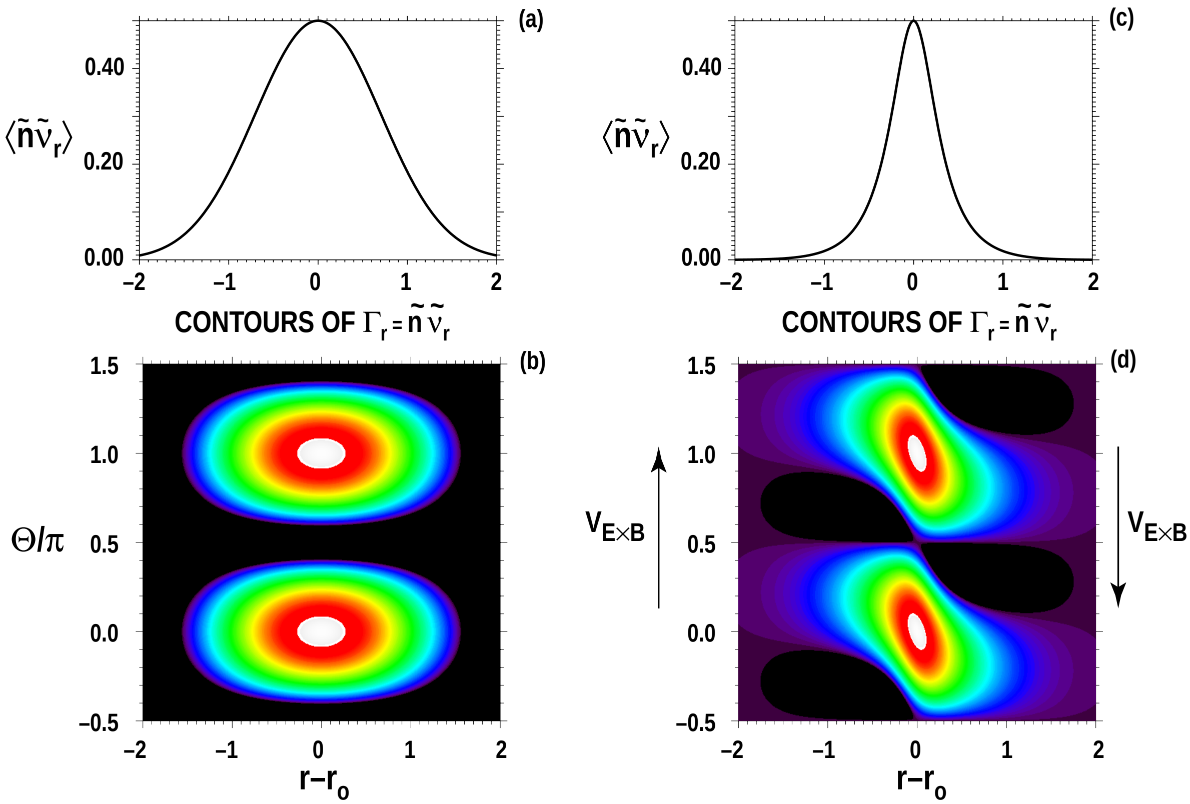

Fig. 1. The radial fluctuation-driven particle flux $n\,\mathbf{V}_r$. The (a) and (b) plots are for no shear in the average velocity while (c) and (d) are for the sheared case. The (b) and (d) plots are color coded contours of the radial flux in the cylindrical (r, θ) plane while the (a) and (c) plots are the radial flux averaged over the θ coordinate. The distortion of the eddies in (d) compared to (b) shows the effect of velocity shear on the radial flux. In addition, at points away from the maximum, the radial flux decreases strongly in the sheared case. The net radial flux [the integral under the curves in (a) and (c)] decreases significantly as a result of the velocity shear.

One of the strengths of the **E**×**B** shear stabilization idea is its ability to explain a wide range of results [2,14]. Turbulence stabilization and associated transport reduction have been seen in a number of different magnetic configurations (tokamak, stellarator, and mirror machine) at a number of different locations in these plasmas. The source of this breadth of effects is the multitude of ways that the plasma transport and the electric field interact. A fundamental equilibrium relation in the plasma is the radial force balance equation for the ions $E_r = (Z_i e n_i)^{-1} \nabla P_i - (\mathbf{v} \times \mathbf{B})_r$ where $Z_i e$ is the ion charge, P_i is the plasma ion pressure, n_i is the ion density, **v** is the ion velocity and E_r is the component of **E** that is perpendicular to **B**. Because plasma transport influences the density, pressure, and velocity and since the **E**×**B** shear can affect transport, there are a multitude of feedback loops whereby the plasma can bootstrap itself into an improved confinement state. Different ones have been seen to be operational in different machines and at different times during a single discharge [2,14].

Because the **E**×**B** shear, turbulence and transport are all intimately intertwined in multiple feedback loops, devising experiments to test whether **E**×**B** shear causes a change in turbulence and transport has been a major challenge for experimentalists. Experimentalists first established clear spatial and temporal correlations between changes in sheared **E**×**B** velocity, fluctuation amplitudes, and local transport rates by using an extensive set of spatially resolved diagnostic measurements to determine local plasma density, temperature, and velocity as well as density fluctuations. Over the past four years, there have been four clear demonstrations of causality performed in tokamak plasmas, both at the plasma edge on DIII–D and TEXTOR and further into the plasma core on DIII–D and TFTR [2,14]. One of the most elegant was the recent work on TFTR [14], where external momentum input was used to spin the plasma in different directions, thus changing E_r through the equilibrium relation by changing **v**. Great care was taken to keep the total power input to the plasma constant so that initially only E_r charged. Once the change in E_r was big enough, the expected changes in turbulence and transport were seen [14].

The initial work on **E**×**B** shear considered primarily the quasi-static portion of the electric field; indeed at present, in the core of tokamak plasmas, time resolution for electric field measurements is 0.5 ms at best. The theoretical community has moved on to consider the effects of self-generated electric fields in which the plasma turbulence itself generates E_r [15,16]. This has recently led to the idea of regulation of the turbulent transport through its own self-generated **E**×**B** shear [13,17]. Properly describing this self-regulation is crucial to accurate predictions of turbulent energy transport in all confinement regimes [13].

The development of improved confinement regimes in magnetic fusion devices and their explanation through **E**×**B** shear has generated enormous excitement among fusion researchers and has given them new tools to help in their quest for controlled fusion energy. However, there are still a number of outstanding issues. Experimentally, reduction of ion transport is easier to achieve than reduction of energy loss caused by electrons, although reduction of electron loss has been seen under some conditions. Accordingly, the electron transport problem is one major outstanding issue. A second major issue is the continuing, more detailed comparison between theory and experiment. Part of the difficulty in this area is a mismatch between what theory can now calculate (e.g., small scale, high frequency self-generated **E**×**B** shear) and what experimentalists can measure. New diagnostics to measure this and improved calculations under more experimentally relevant conditions are both needed. A third key problem is how to create the needed **E**×**B** shear in future devices. All cases of transport reduction by sheared **E**×**B** velocity require some external drive to push the plasma to the point where the transition to improved confinement can become self-sustaining.

Examples of these drives are heat and particle inputs to change the pressure or momentum inputs to change the ion velocity **v**. Some novel magnetic configurations, such as the compact spherical tokamaks now under construction in the United States and United Kingdom, should naturally have high **E**×**B** shear because of the large pressure gradient allowed by that magnetic configuration. For larger machines, present techniques will either have to be adapted to the larger size or new ones (e.g., rf techniques) will have to be developed. Finally, sheared **E**×**B** velocity allows confinement good enough that the global MHD stability is again an issue, requiring further configuration optimization to allow full exploitation of the improved confinement. If the research needed to confront these issues can be carried out, the new tools provided by sheared **E**×**B** velocity stabilization of turbulence should allow development of new, innovative ways to create fusion power.

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