mission will lead to more powerful space interferometers. Indeed, a bold mission to place a radio telescope in a 75,000-km orbit is being carried out in Russia (Radioastron), a second-generation Japanese telescope with higher frequency and higher sensitivity operation (VSOP-2) is being planned, and a much larger 25-m-diameter telescope project (ARISE) is being explored by NASA. Although we may never be able to see down to the very edge of the black hole, because of high opacity near the hole and instrumental limitations, VSOP and future space interferometers will certainly lead to great advances in our understanding of these amazing objects.

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PERSPECTIVES: PLASMA PHYSICS

Turbulence and Sheared Flow

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In the quest for fusion energy, a continuing theme is the search for ways to improve energy confinement by eliminating the effects of plasma instabilities. Early workers in magnetic confinement fusion developed field configurations that eliminated 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 otherwise be several seconds. Even when gross instabilities are suppressed, most fusion plasmas still have small-scale turbulent eddies, so-called microturbulence, which dominate the loss of energy from the plasma.

One of the 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 what is called the **E** × **B** shear stabilization model (discussed below) to explain how those techniques work. The continuing interplay between experimental discovery and theoretical insight has guided this development. Some of the latest, most detailed numerical simulations in this area are reported on page 1835 of this issue (*1*). With these techniques, tokamak plasmas have been created with ion temperatures of 20 to 30 keV, the range relevant for fusion. Moreover, 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 active, 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 (*2*), the interplay of electric and magnetic fields in magnetized plasmas helps overcome the usually detrimental effect of increased velocity gradients in driving turbulence (*3*). In addition to its intrinsic physics interest, the transport decrease associated with **E** × **B** velocity shear has important practical consequences for magnetic fusion research. For example, the best fusion performance to date in the DIII-D (*4*), JT-60U (*5*), and TFTR (*6*) tokamaks has been obtained under conditions at which transport reduction through **E** × **B** stabilization is almost certainly taking place.

The "**E** × **B**" 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 $\mathbf{v}_D = \mathbf{E} \times \mathbf{B}/\mathbf{B}^2$. This velocity does not depend on the charge or the mass of the particle, so all particles share this component of their velocity. This common motion is one of the reasons why the **E** × **B** velocity shear is the most fundamental shear. Although shear in individual species' velocities or in turbulent wave propagation speeds can, in principle, affect the microturbulence, the ubiquitous character of sheared **E** × **B** flow makes it the most fundamental effect (*3*).

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 (*7*, *8*) and linear (*9*, *10*) effects have been considered, there is now a general consensus that the nonlinear effects must be included in the complete picture (*7*, *11*). [More complete references to the theory are given in (*3*)]. 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 the figure, which is based on work by Carreras (*12*). The colored ovals in panel B show the surfaces of constant turbulence-driven particle flux in a cylindrical plasma for the case of no **E** × **B** velocity shear, whereas the distorted ovals in panel D show how this quantity changes in the presence of the velocity shear. Panels A and C show 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 (that is, a shear) 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 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 panels A and C. Much more elaborate numerical calculations (*13*), including those of Lin *et al.* (*1*), have shown the same qualitative features; indeed, the color plots in these two reports give wonderfully intuitive illustrations of the effects of **E** × **B** velocity shear on turbulence in the experimentally relevant toroidal geometry.

One of the strengths of the **E** × **B** shear stabilization idea is its ability to explain a wide range of results (*3*, *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

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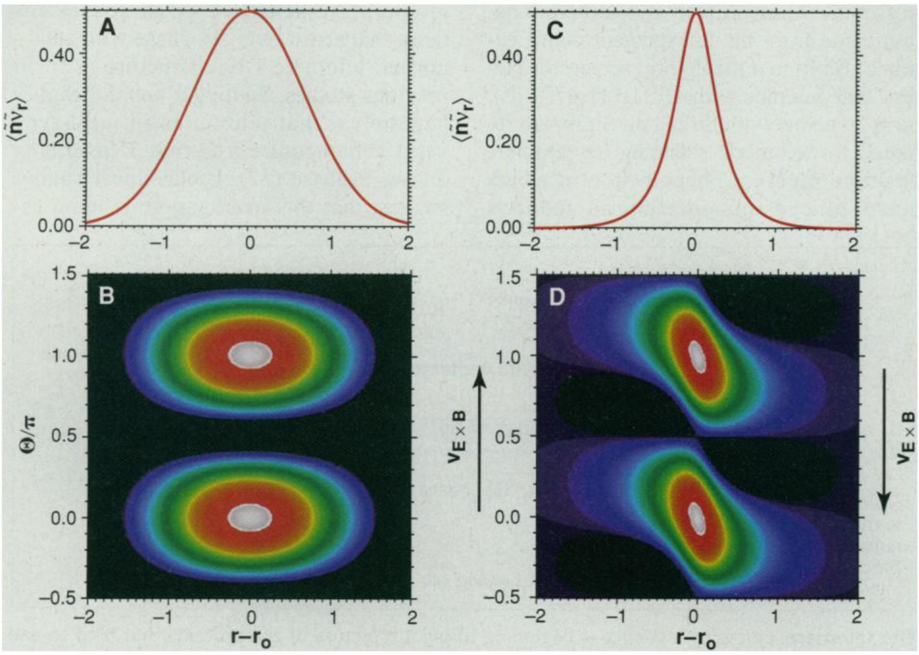
the electric field interact. The equilibrium force balance in the plasma relates **E** to density, pressure gradient, and plasma velocity **v**. Because plasma transport influences the density, pressure, and velocity and because the **E** × **B** shear can affect transport, there are a multitude of feedback 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 (*3*, *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. Clear spatial and temporal correlations between changes in sheared **E** × **B** velocity, fluctuation amplitudes, and local transport rates were first seen with an extensive set of spatially resolved diagnostic measurements to determine local plasma density, temperature, and velocity as well as density fluctuations. Over the past 4 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 (*3*, *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 to test causality by changing **E** directly by changing **v**.

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** × **B** shear (*15*, *16*). This has recently led to the idea of regulation of the turbulent transport through its own self-generated **E** × **B** shear (*1*, *17*). Properly describing this self-regulation is crucial to accurate predictions of turbulent energy transport in all confinement regimes (*1*).



Shear improvement. Different views of the radial fluctuation-driven particle flux $\tilde{n}\tilde{v}_r$. (**A**) and (**B**) show plots for zero shear in the average velocity, and (**C**) and (**D**) show plots for the sheared case. (B) and (D) show color-coded contours of the radial flux in the cylindrical (r, θ) plane, whereas (A) and (C) show the radial flux averaged over the θ coordinate. The distortion of the eddies in (D) compared with (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. [Adapted from (*3*)].

The development of improved confinement in magnetic fusion devices and its explanation through **E** × **B** shear has generated enormous excitement among fusion researchers and has given them new tools in the search 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 (small-scale, high-frequency, self-generated **E** × **B** shear) and what experimentalists can measure. New diagnostics to measure this and improved calculations under 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 at which the transition to improved confinement can become self-sustaining. 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 (rf techniques, for example) 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 optimization to fully exploit 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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