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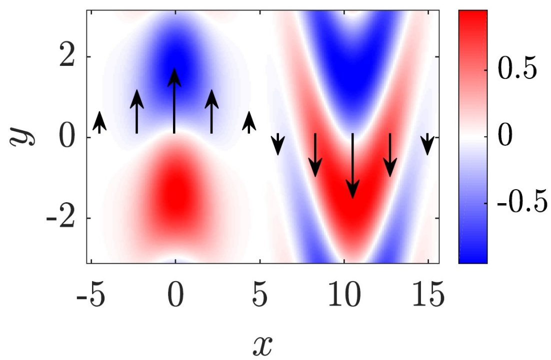
The Primary, Secondary, and Tertiary Instabilities Determine the Onset of Turbulence in Fusion Plasmas

Subtitle:

An analogy between turbulence and quantum particles provides a better understanding of an advanced confinement regime in fusion plasmas.



Localization of turbulent modes (the fluctuating field is shown in color) near minima and maxima of the zonal velocity (shown with arrows). In a tokamak, *x* is the radial coordinate and *y* is the poloidal coordinate.

The Science

Successful operation of future magnetic fusion devices will rely on taming turbulence in the plasmas that fuel fusion reactions. Such turbulence can significantly degrade plasma confinement. Turbulence is driven by "primary" micro-instabilities that arise, for example, when the pressure gradient in plasma exceeds a certain threshold. Once that happens, a "secondary" instability may follow and cause the turbulence to to lose energy into spontaneously formed plasma flows known as zonal flows. In the so-called Dimits regime, this development can suppress turbulence completely. But there also exists a "tertiary" instability, which can disrupt zonal flows and reinstate the turbulence, thus posing a limit to the Dimits regime. Discovered two decades ago, these fundamental processes have not been sufficiently understood. Now, a new theory has emerged that explains them in simple terms.

The Impact

To reduce or to eliminate turbulence completely, researchers must first understand the basic physics of turbulence. The new theory changes the paradigm of understanding an important piece of this physics — specifically, how zonal flows suppress turbulence and how the Dimits regime is produced. This improved understanding opens a new path toward better optimization of future fusion devices.

Summary

Zonal flows are "sheared" flows, which means that their velocity changes in the direction perpendicular to the velocity itself. It was thought, as in the classic Kelvin-Helmholtz instability, that zonal flows

destabilize when the average steepness of the flow profile, or shear, becomes too large. However, researchers at the Princeton Plasma Physics Laboratory have shown that the average shear itself is not that important, because as shown in the figure, turbulence tends to localize in regions where the shear vanishes in any case. Instead, stability of localized plasma fluctuations depends on the local concavity of the flow profile. This dependence explains the famous "Dimits shift," or the shift of the stability threshold relative to the threshold without zonal flows. The researchers have been able to develop a generic model of this shift by drawing an analogy between the localized turbulent fluctuations and quantum harmonic oscillators, whose properties are well known.

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Publications

Hongxuan Zhu, Yao Zhou, and I. Y. Dodin, "Theory of the Tertiary Instability and the Dimits Shift from Reduced Drift-Wave Models." Physical Review Letters **124**, 055002 (2020), https://doi.org/10.1103/PhysRevLett.124.055002