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Impact of turbulence spreading on structure formation in toroidal plasma

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Turbulence spreading is a nonlinear coupling of fluctuation energy that redistributes the turbulence intensity field away from the regions where it is exciting. Turbulence spreading impacts the structure formation in the steady-state at the boundary between the region where turbulence is enhanced and the region where the turbulence is strongly suppressed. This talk discusses the impact of turbulence spreading on structure formation based on the various experimental observations in toroidal plasmas.

The internal transport barrier (ITB) is characterized by the radial temperature profile with a sharp gradient region, which appears in interior plasma [1]. In the ITB region, the turbulence is strongly suppressed (stable region), while the turbulence is enhanced (unstable region) outside the ITB region. The micro-scale turbulence in the unstable region spreads into the stable region through the nonlinear coupling with mesoscale and macro-scale turbulence. When the turbulence spreads weakly, the ITB has discontinuity of gradient, a so-called ITB foot. In contrast, this discontinuity disappears, and the ITB foot becomes unclear when the turbulence spreading becomes strong. Once the turbulence spreading occurs, the discontinuity of gradient (i.e., the second derivative of temperature) becomes weak, and the ExB shear also becomes weak. Since the ExB shear contributes to the block of turbulence spreading, further instances of it occur. This feedback process causes the bifurcation of the ITB structure with and without a clear foot point.

A magnetic island is a closed magnetic flux surface bounded by a separatrix (X-point), isolating it from the rest of the space. Since the radial heat flux perpendicular to the magnetic flux surface flows through the X-point, the temperature profile becomes almost flat (nearly zero temperature gradient) at the O-point of the magnetic island in the steady state. The O-point of the magnetic island becomes a stable region because the gradient is too small to generate turbulence. Therefore, the turbulence observed inside the magnetic island should not be driven turbulence but the spreading turbulence propagated from outside the magnetic island. The ExB shear layer, which contributes to the block of turbulence spreading, is weak near the X-point [2]. The X-point of the magnetic island is the possible root for turbulence spreading [3].

The scrape-off layer (SOL) is the region where the temperature gradient perpendicular to the magnetic field is smaller than the critical gradient for turbulence excitation (i.e., stable region) because the heat flux parallel to the magnetic field is dominant. Therefore, the turbulence observed in the SOL is mainly propagated from the pedestal region at the boundary by spreading turbulence. Turbulence spreading into the edge stochastic magnetic layer, induced by magnetic fluctuation, has been reported [4]. The turbulence spreading into the SOL region is blocked by the large second derivative of the pressure gradient. When the magnetic fluctuation appears at the boundary, the turbulence spreading is enhanced, and density fluctuation in the SOL region increases. The increase of density fluctuation in this layer broadens and reduces the peak divertor heat load. The reduction of the divertor heat load by turbulence spreading at the plasma boundary is a beneficial impact of turbulence spreading in nuclear fusion research.

Turbulence spreading plays a crucial role in structure formation. Finite turbulence spreading is necessary to smooth the staircase structure's curvature at the corners of the jump and step. However, the enhancement of turbulence spreading tends to wash out the pattern [5]. Mesoscale transport events, such as avalanches or turbulence pulses (i.e., spreading), drive inhomogeneous mixing and transport of potential vorticity. Recently, preceding propagation of turbulence pulses at avalanche events [6] was observed in a magnetically confined plasma [7]. The propagation speed of the turbulence pulse is six times faster than that of the heat pulse propagating. The heat pulse propagates at approximately the same speed as the theoretical prediction. In contrast, the turbulence pulse propagates one order of magnitude faster than that in the prediction, thereby providing essential insights into the physics of non-local transport [8].

References

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