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Plasma blobs and filaments -- fusion scientists discover secrets of turbulent edge transport

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Plasma blobs and filaments – fusion scientists discover secrets of turbulent edge transport

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Fusion plasmas must be heated to over 100 million degrees Celsius/Kelvin in their core, and yet transition to much cooler temperatures at the edge which must be withstood by material surfaces. This sharp edge transition in plasma temperature and pressure is made possible in tokamak plasmas by strong magnetic fields. While the magnetic fields help to confine the plasma, the strong gradients still give rise to turbulence that results in slow leakage of the hot plasma. Understanding and controlling this turbulence and subsequent interactions between the plasma and wall are critical for practical fusion energy. Turbulence that is too strong not only ruins the good core confinement required for fusion, but also can result in excessive erosion of the material surfaces that comprise the fusion vessel walls. Plasma physicists are making progress in understanding turbulent edge plasmas in work reported at the 54th APS Division of Plasma Physics conference.

Advances in measurement and experimental analysis techniques and have revealed that the edge plasma is characterized by filamentary features, which tend to align themselves along the magnetic field. High divertor heat loads from plasma blobs and filaments are an important issue for the ITER fusion experiment. The formation of blobs and filaments in edge turbulence and the sensitivity of global confinement predictions on edge turbulence highlight the importance of accurate edge turbulence models for development of fusion energy. Scientists on the National Spherical Torus Experiment (NSTX) have undertaken an effort to measure edge turbulence characteristics and validate edge turbulence simulations for NSTX plasmas. The spherical torus parameter regime compounds the inherent challenges of edge turbulence simulations and provides a rigorous test of edge turbulence models. The properties of NSTX edge turbulence are imprinted in visible emission from a deuterium heating beam, and scientists at the University of Wisconsin-Madison and Princeton Plasma Physics Laboratory designed a diagnostic system that measures plasma turbulence in NSTX by imaging beam emission. The measurements indicate large edge turbulence structures correlate with large density gradients, and turbulence characteristics are sensitive to plasma pressure and collisionality.

Accompanying the new measurement techniques, advanced computer codes can now simulate many aspects of the experimental measurements. Computer simulations of the strong gradient edge region of fusion plasmas pose daunting challenges, even for today's most advanced massively parallel computers. Turbulence exists on spatial scales ranging from the mm or smaller particle Larmor-radius in the magnetic field up to the several-meter size scale of the tokamak. Turbulence also occurs on very short time scales of only a few micro-seconds, yet predictions of plasma evolution are required over a fraction of a second and even longer. Thus present studies employ a number of different models designed to capture different aspects of the plasma dynamics.

Scientists at the University of Colorado-Boulder performed gyrokinetic simulations of NSTX edge turbulence and found enhanced turbulence at higher density gradients in qualitative agreement with measured turbulence properties. In the most fundamental gyrokinetic models, plasma dynamics are described by following the positions and velocities of billions of particles. These simulations using some of the world's fastest supercomputers clearly identify two instabilities in the edge region that determine the density and width of the edge boundary layer. Edge turbulence validation efforts will continue as scientists identify additional edge turbulence properties and push the limits of challenging turbulence simulations.

Other, so-called fluid models do not attempt to follow the motion of individual plasma particles, but rather capture the bulk motion of the plasma as a whole. These types of models have yielded additional information on the amplitude of the turbulence and rate at which this turbulence carries plasmas particles and energy outward towards the wall. The fluid models describe the plasma dynamics in terms of a limited number of macroscopic attributes of the plasma, e.g., space and time-dependent particle density, flow velocities, temperatures or pressures, and currents in realistic 3D tokamak geometry. The macroscopic fluid quantities evolve in response to self-consistent electromagnetic fields. The time evolution tracks the growth of the turbulence from small-amplitude initial conditions to steady-state in some examples and to transient large- amplitude relaxation oscillations in other examples. In the fluid simulations performed by researchers at the Lawrence Livermore National Laboratory reported at this conference, detailed comparisons are made to experimental data from the DIII-D tokamak at General Atomics, San Diego, CA. There are significant points of agreement between the fluid simulations and the experimental data, and insight is provided into the fundamental mechanisms driving the turbulence.

Turbulence in the edge plasma is not necessarily steady. Rather, much like turbulence encountered by an airplane in bad weather, there can be occasional strong bursts of high or low pressure. The turbulence that occurs in the edge plasma forms elongated filament structures called blobs that propagate towards the wall. These structures have been observed in all tokamak experiments. As with hurricanes and tornados in weather patterns, blob-like filaments can carry a great deal of potentially damaging plasma energy, so understanding their motion is very important. Fluid and statistical models that further simplify the plasma description are used for this task.

When the filaments cross the extreme edge of the plasma, sudden changes in the magnetic field and plasma parameters affect their motion in systematic ways, and can cause flows to develop out of the turbulent background. A set of new data analysis tools that can track these changes was applied by researchers at Lodestar Research to data on both the NSTX (Princeton Plasma Physics Laboratory) and Alcator C-Mod (MIT) tokamaks and to recent computer simulations, showing good agreement. Understanding the interaction of turbulence structures and flows is important both for plasma interaction with the wall, and for improving plasma confinement.

Work at MIT's Plasma Science and Fusion Center investigates fluctuations in the tokamak scrape-off layer where cross-field transport of particles and heat is dominated by radial motion of blob-like plasma filaments. This leads to time series of the particle density dominated by large- amplitude bursts. The researchers have succeeded in formulating a stochastic model that elucidates the role of the blob motion for large average plasma densities and fluctuation level in the scrape-off layer. The model predicts the statistics for the fluctuations in the particle density, which is shown to compare favorably with experimental measurements. Three numbers, the average burst amplitude, duration and waiting time, completely characterize the process. This may provide a powerful tool for validating first-principles based edge turbulence models.

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YI3.00001: Intermittent fluctuations in the Alcator-C-Mod scrape-off layer – O. E. Garcia
YI3.00002: Edge Sheared Flows and Blob Dynamics – J. R. Myra
YI3.00003: BOUT Simulations of Drift Resistive Ballooning L-Mode Turbulence in the Edge of the DIII-D Tokamak – B. I. Cohen
YI3.00004: Assessing low wavenumber pedestal turbulence in NSTX with measurements and simulations – David Smith
YI3.00006: Global Gyrokinetic Simulations of the Dominant High-n and Intermediate-n Instabilities in the H-Mode Tokamak Edge Pedestal – Scott Parker

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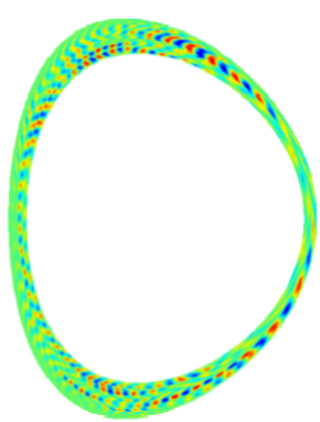

Fig. 1 Cross-section of annular region showing edge pedestal turbulence due to instabilities found using first-principle, five-dimensional kinetic simulations.