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FIRST HIGH-FIDELITY COMPUTATIONAL DEMONSTRATION OF SPONTANEOUS TRANSITION TO HIGH-CONFINEMENT PLASMA REQUIRED BY ITER

Extreme-scale computer code for the first time shows spontaneous bifurcation of turbulence to high-confinement mode (H-mode) at the edge of the plasma. This feat has been achieved by XGC, a first principles-based code.

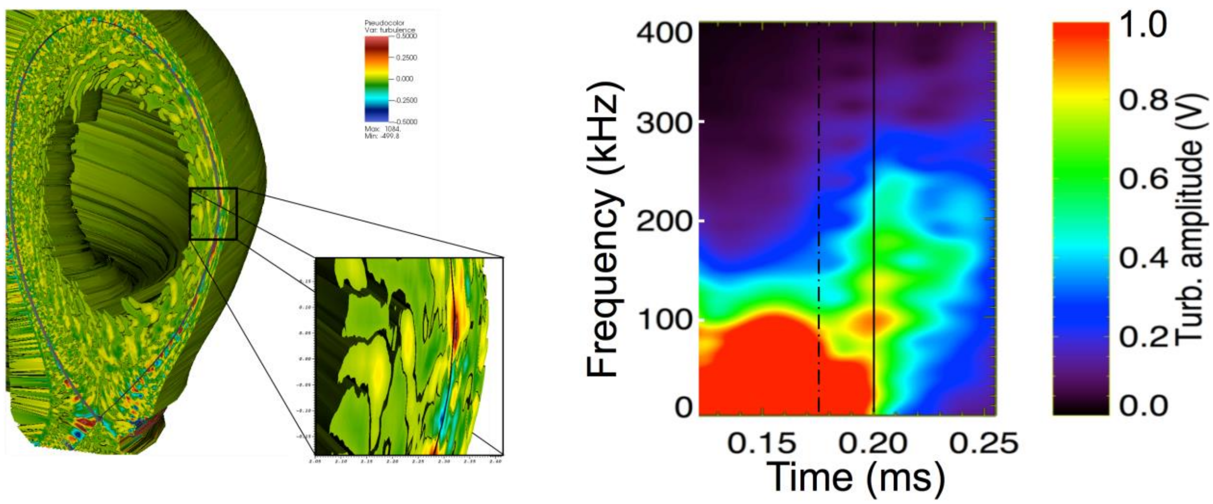

Image caption: (Left) A typical plasma-density-fluctuation pattern from edge turbulence in a realistic tokamak geometry. The black line shows the magnetic separatrix surface with the magnetic X-point at the bottom. (Right) Contour plot of bifurcation of turbulence to H-mode at the plasma edge in sub-milliseconds. The suppression of high amplitude turbulence (red) starts around 0.175 ms, at the vertical dash-dot line, and completes around 0.2 ms, at the vertical solid line, followed by the suppression of lower amplitude turbulence (shades of green and blue) . The suppression of the lower frequency, high amplitude turbulence is accompanied by an increase in higher frequency, lower amplitude turbulence, showing the transformation of the large size eddies into smaller ones in the process.

The Science

Successful operation of ITER with 10-fold energy production depends upon achievement of high-confinement mode (H-mode) operation, which suppresses turbulence at the edge of the plasma. After 35 years, the fundamental physics of the bifurcation of turbulence into the H-mode state has now been simulated thanks to the rapid development of the computational hardware and software capability.

The Impact

Resolving the longstanding question of how and why the plasma bifurcates into high-confinement mode enables ITER to predict the heating power required to achieve its goal of 10-fold energy production. Since ITER conditions will be very different from those in today's tokamaks, any non-physics-based projection of required heating power from present data could well have large uncertainty.

Summary

To achieve its goal, ITER's core ion temperature must be around 15 keV, or over 10 times hotter than in the core of the sun. At the same time, the ions in contact with the tokamak wall must remain cold. However, the cold edge will not allow the core to reach 15 keV unless the distance between the core and the edge is unreasonably large, given the invariability of the steep radial slope of the ion temperature. For more than 35 years it has been known that the edge temperature can spontaneously bifurcate into a high pedestal, or transport barrier, in a layer whose width is only a few percent of the total plasma size. This happens as the heating power is increased above a critical level, and enables the core ion temperature to rise above 15 keV following the same invariable radial slope.

Experiments have verified that the spontaneous buildup of the edge pedestal results from a spontaneous suppression of its turbulence. Numerous simple, speculative theories attempt to explain this bifurcation in one of two different ways. One school of thought focuses upon turbulent Reynolds-stress generated sheared-flow. The other relies on a non-turbulent generated sheared-flow.

The reason that only these simple, speculative theories exist has been the multiscale, multiphysics, kinetic nature of the edge plasma physics and the lack of computing power. The multiscale edge gyrokinetic code XGC, utilizing 90% of the 27 petaflop Titan supercomputer for three days, achieved the edge turbulence bifurcation for the first time at a first-principles level. The simulation revealed that the turbulence bifurcation is achieved through synergistic effects between the turbulent Reynolds-stress generated sheared flow and the non-turbulent generated sheared flow, also called the "X-point orbit loss-driven" sheared flow. The discovery represents a significant implication for the operation of ITER. If the X-point orbit loss-driven sheared flow is not as strong in ITER as in the present tokamaks, the bifurcation to high-mode may require higher plasma heating power than what is presently planned. On the other hand, the heating power need may be lower if the X-point orbit loss-driven sheared flow proves stronger in ITER.

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