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Simulations Predict Favorable Confinement Trend for Reactor-Scale Plasmas (2001)

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Fusion research reached a milestone in 2001 with the first simulation of turbulent transport in a full-sized reactor plasma by researchers at the Princeton Plasma Physics Laboratory. This breakthrough full-torus simulation was made feasible by a new generation of software and hardware—better physics models and efficient numerical algorithms, along with NERSC's 10 teraflop/s IBM SP. The new simulation produced a result that was as welcome as it was surprising—as the size of the plasma increased, the turbulent transport reached a plateau and leveled off. This "rollover" from one scaling mode to another is an important topic of current research.

Most people do not think about turbulence very often, except when they are flying and the captain turns on the "Fasten Seat Belts" sign. The kind of turbulence that may cause problems for airplane passengers involves swirls and eddies that are a great deal larger than the aircraft. But in fusion plasmas, much smaller-scale turbulence, called microturbulence, can cause serious problems—specifically, instabilities and heat loss that could stop the fusion reaction.

In fusion research, all of the conditions necessary to keep a plasma dense and hot long enough to undergo fusion are referred to as confinement. The retention of heat, called energy confinement, can be threatened by microturbulence, which can make particles drift across, rather than along with, the plasma flow. At the core of a fusion reactor such as a tokamak, the temperatures and densities are higher than at the outside edges. As with weather, when there are two regions with different temperatures and densities, the area between is subject to turbulence. In a tokamak, turbulence can allow charged particles in the plasma to move toward the outer edges of the reactor rather than fusing with other particles in the core. If enough particles drift away, the plasma loses temperature and the fusion reaction cannot be sustained.

One troublesome result of tokamak experiments to date is that as the size of the plasma increases, the relative level of heat loss from turbulent transport also increases. Because the size (and therefore cost) of a fusion experiment is determined largely by the balance between fusion self-heating and turbulent transport losses, understanding this process is of utmost importance for the design and operation of fusion devices such as the multi-billion-dollar ITER project. ITER (Latin for "the way"), a multinational tokamak experiment to be built at Cadarache in southern France, is one of the highest strategic priorities of the DOE Office of Science.

ITER is expected to produce 500 million thermal watts of fusion power—10 times more power than is needed to heat the plasma—when it reaches full operation around the year 2016. As the world's first production-scale fusion reactor, ITER will help answer questions about the most efficient ways to configure and operate future commercial reactors.

The growth of the microinstabilities that lead to turbulent transport has been extensively studied over the years, not only because understanding this process is an important practical problem, but also

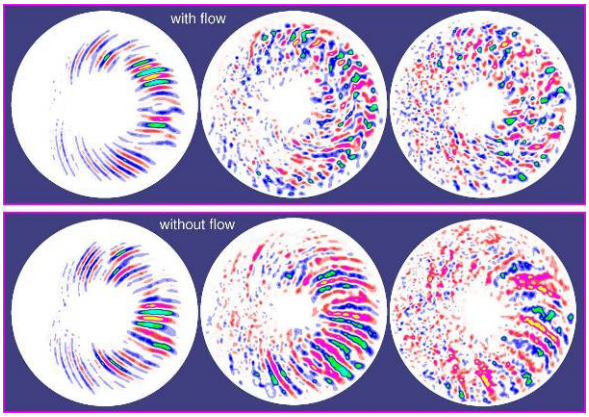

Figure 1. Turbulence reduction via sheared plasma flow compared to case with flow suppressed.

because it is a true scientific grand challenge which is particularly well suited to be addressed by modern terascale computational resources. And the latest news, confirmed by multiple simulations using different codes, is good: in reactors the size of ITER, heat losses caused by plasma turbulence no longer follow the empirical trend of increasing with the size of the plasma. Instead, the rate of heat loss levels off and stabilizes.

Progress in understanding plasma ion dynamics has been impressive. For example, studies show that electrostatic ion temperature gradient (ITG) driven turbulence can be suppressed by self-generated zonal flows within the plasma. The suppression of turbulence is caused by a shearing action that destroys the finger-like density contours which promote thermal transport (Figure 1).

This simulation is a good example of the effective use of powerful supercomputers (in this case, the 10 teraflop/s Seaborg IBM SP at NERSC). Typical global particle-in-cell simulations of this type have used one billion particles with 125 million grid points over 7000 time steps to produce significant physics results. Simulations of this size would not be feasible on smaller computers.

Large-scale simulations have also explored key consequences of scaling up from present-day experimental fusion devices (around 3 meters radius for the largest existing machines) to ITER-sized reactors (about 6 meters). For the reactor-scale plasmas of the future, these simulations suggest that the relative level of heat loss driven by electrostatic ITG turbulence does not increase with plasma size (Figure 2). This transition from “Bohm” (linear) scaling to “gyro-Bohm” (quadratic) scaling is a positive trend, because simple empirical extrapolation of the smaller system findings would produce much more pessimistic predictions for energy confinement. Since neither experiments nor theory and simulations have previously been able to explore such trends in an ITER-sized plasma, these results represent a significant scientific discovery enabled by the SciDAC program.

Exploration of the underlying causes for the transition in the rate of heat loss that simulations show around the 400 gyroradii range has inspired the development of new nonlinear theoretical models based on the spreading of turbulence. Although this predicted trend is a very favorable one, the fidelity of the analysis needs to be further examined by investigating additional physics effects, such as kinetic electromagnetic dynamics, which might alter the present predictions.

Publications:

Z. Lin, S. Ethier, T. S. Hahm, and W. M. Tang, “Size scaling of turbulent transport in magnetically confined plasmas,” Phys. Rev. Lett. **88**, 195004 (2002).

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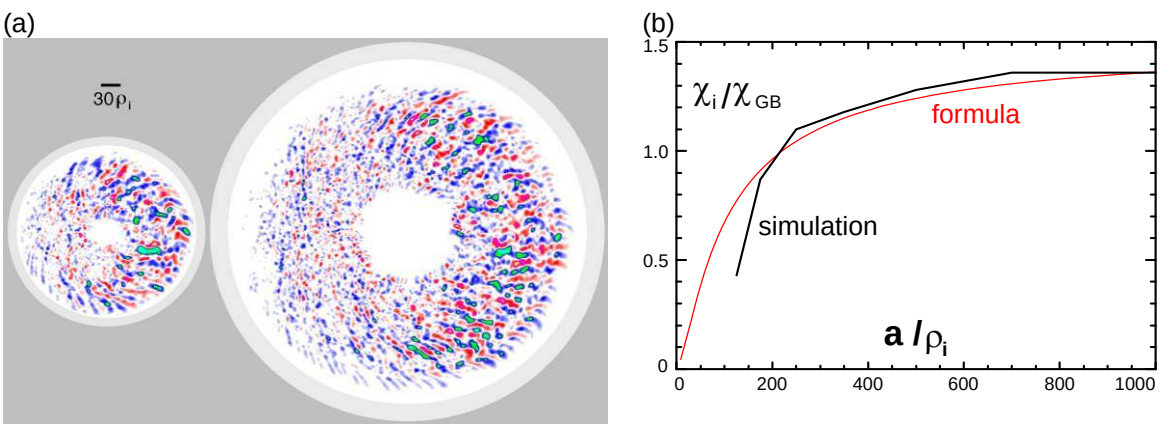

Figure 2. Full torus particle-in-cell gyrokinetic simulations (GTC) of turbulent transport scaling. (a) The granular structures represent the scales of the turbulence in a typical plasma which need to be included in realistic plasma simulations. (b) The horizontal axis expresses the plasma size, and the point at 1000 represents ITER’s size. The vertical axis represents the thermal diffusion, or heat loss.