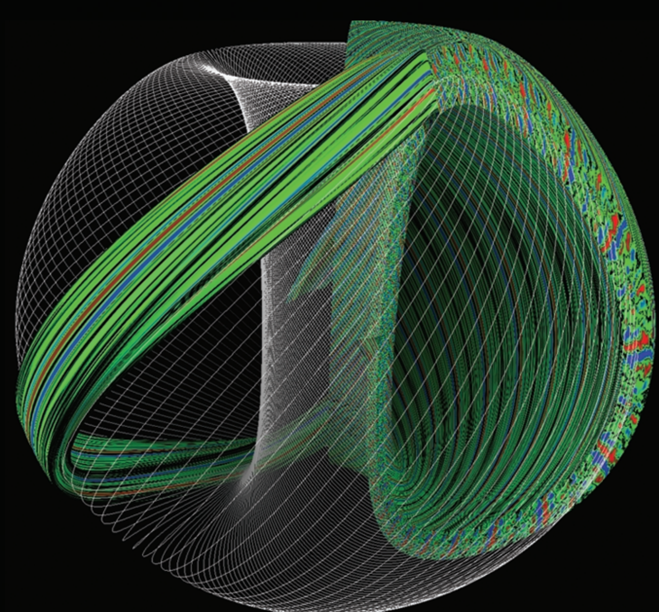
Simulating Turbulence in Magnetic Fusion Plasmas

Microturbulence, a long-time nemesis of magnetic fusion energy experiments, is being understood in unprecedented detail thanks to new three-dimensional simulations.



This Livermore simulation shows a magnetic field line (white) wrapping around a torus, or doughnut-shaped configuration of plasma. Magnetic field lines are embedded within the plasma, with individual particles traveling along each field line. The color contours indicate microturbulent fluctuations in the plasma density. Regions with similar density—microturbulent eddies indicated by regions of similar color—stretch along the field lines, while varying rapidly across the field lines. These microturbulent eddies transport heat from the plasma's superhot core to the cold outer edge.

SINCE the 1950s, Lawrence Livermore has been one of the world's leading centers of magnetic fusion energy research. Magnetic fusion uses intense magnetic fields to confine an extremely hot gas of electrons and positively charged ions called a plasma. Under the right conditions, the plasma ions undergo fusion reactions, the energy source of the Sun and other stars.

The long-standing goal of fusion researchers has been to duplicate the cosmos's means of producing energy to provide a virtually inexhaustible source of reliable and environmentally benign energy on Earth. Despite the immense technical challenges involved in making magnetic fusion a source of commercial electrical power, important progress has been made in the past decade as researchers nationwide have collaborated on experiments and computer simulations.

Lawrence Livermore's Fusion Energy Program carries out magnetic fusion energy research in two complementary thrusts. The first thrust is performing advanced fusion experiments. Livermore researchers are collaborators at the national DIII-D tokamak experiment at General Atomics in San Diego, California.

Laboratory scientists are also pursuing novel designs for magnetic fusion reactors, such as the spheromak experiment dedicated in 1998. (See *S&TR*, December 1999, pp. 18–20.)

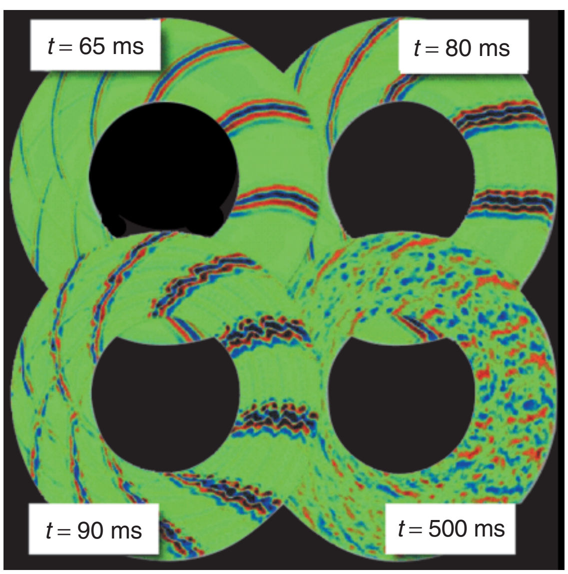
Complementing the experimental work is an effort to accurately simulate the extraordinarily complex physics involved in magnetically confined plasmas. Lawrence Livermore scientists have developed a number of codes for simulating different aspects of magnetic fusion energy experiments. Its PG3EQ program, developed by physicists Andris Dimits, Dan Shumaker, and Timothy Williams, for example, is one of the most advanced programs available for simulating plasma turbulence. Another Livermore code, called CORSICA, goes a step further and links individual programs that model different aspects of magnetic fusion energy physics. (See *S&TR*, May 1999, pp. 20–22.)

Focus on Tokamak

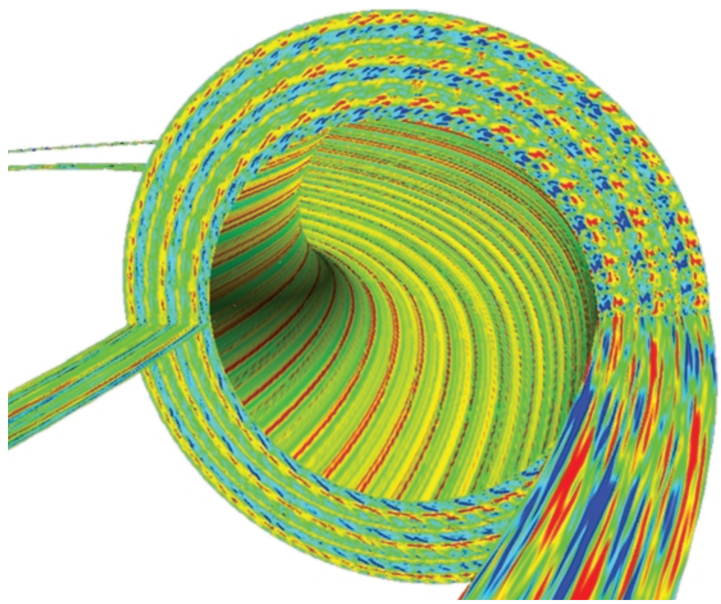
A national team of researchers led by Laboratory physicist Bill Nevins is developing advanced simulation codes running on supercomputers to deepen scientific understanding of the plasma turbulence that occurs inside a tokamak, a magnetic confinement device. Tokamaks use powerful magnets to confine plasmas of fusion fuel on the toroidal, or doughnut-shaped, magnetic "surfaces" defined by individual magnetic field lines as they wind about within a vacuum chamber.

Plasma turbulence causes thermal energy to leak across the magnetic surfaces faster than it can be replaced by fusion reactions. This lost energy must be replaced by external sources to prevent the plasma from cooling below the 100-million-degree temperatures needed to optimize the rate of fusion reactions. However, current tokamak experiments are close to the major goal of breakeven, that is, the point at which the energy produced by the fusion reactions equals the energy applied from an external source to heat the fuel. A better understanding of plasma turbulence may allow researchers to reduce the rate of energy loss so that energy breakeven could be achieved in the current generation of tokamaks.

The national collaboration is called the Computational Center for the Study of Plasma Microturbulence. It is funded by the Department of Energy's Office of Fusion Energy Sciences, a part of DOE's Office of Science. The work is part of the Office of Science's Scientific Discovery through Advanced Computing (SciDAC) program, which was launched in late 2000. SciDAC's goal is to develop the scientific computing hardware and software needed for terascale (trillion-operations-per-second) supercomputing. The effort is similar to the National Nuclear Security Administration's Accelerated Strategic Computing Initiative, which is making



This simulation, done by Livermore collaborator General Atomics of San Diego, California, with the GYRO code, shows a cross section of a tokamak over time (*t*) in microseconds (ms). The color contours indicate microturbulent fluctuations in the plasma density. The center sections have been removed to facilitate comparison.



Part of the cross section of a tokamak plasma. The color contours indicate microturbulent fluctuations in the plasma density. Livermore's PG3EQ code, which was used to produce this simulation, models a "tube" of magnetic flux as it wraps once around the tokamak poloidally, or the short way around. Toroidal symmetry was then used to displace this flux tube and fill the annulus.

available terascale computers for the nation's Stockpile Stewardship Program.

The collaboration involves researchers from Lawrence Livermore, the Princeton Plasma Physics Laboratory, the University of California at Los Angeles, the University of Colorado, the University of Maryland, and General Atomics. These institutions were part of previous DOE magnetic fusion energy simulation efforts, including the Numerical Tokamak Turbulence Project (1993 to 1999), led by Livermore physicist Bruce Cohen, and the Plasma Microturbulence Project (2000 to 2001), led by Nevins.

The simulations are focused on microturbulence, a long-time nemesis of achieving breakeven conditions in magnetic fusion energy experiments. Microturbulence is one of two forms of plasma turbulence observed in magnetic confinement experiments. Macroturbulence, on the scale of centimeters to meters, has been largely tamed in advanced tokamak designs. Microturbulence, on the scale of tenths of millimeters to centimeters, has not.

Fluctuating Plasma Soup

Microturbulence is an irregular fluctuation in the plasma "soup" of electrons and ions. The fluctuations are caused by gradients of density and temperature. The fluctuations, a collective phenomenon, form unstable waves and eddies that transport heat from the superhot core across numerous magnetic field lines out to the much cooler plasma surface and, ultimately, to the tokamak's walls. Energy researchers call this phenomenon energy transport.

Nevins notes that a tokamak's plasma will undergo fusion reactions only if it is hot enough, dense enough, and kept away from the much colder reactor walls. By causing heat to be lost from the plasma core, microturbulence helps to degrade confinement and prevent breakeven conditions. "We want plasma at about 100,000,000°C in the center and below 1,000°C at the walls, so they don't melt," says Nevins. "We obviously need good thermal insulation, and that's provided by the confining magnetic field. If we can minimize microturbulence, we can prevent heat leaking out faster than the fusion reactions can generate heat."

Controlling microturbulence will be immensely important in determining whether an advanced experiment, currently in the early planning stages, will be a success. Nevins says that the largest tokamaks cost several hundred million dollars to build. Constructing an experimental device that would go beyond breakeven for a net production of energy would cost about $2 billion. If a way were found to control microturbulence, construction costs could decrease significantly.

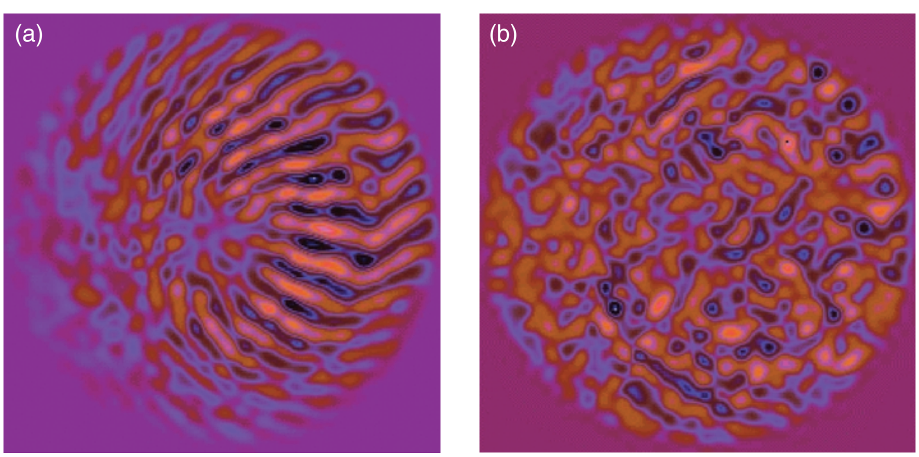
Says Cohen, "If we had better energy confinement, we could build the next generation device at a much lower cost. To do that, we need to understand better the nature of plasma microturbulence."

Simulation Focus

The collaboration's current focus is on advanced codes, algorithms, and data analysis and visualization tools. Nevins says that simulating microturbulence has proved difficult because of the enormous range of time and space scales that occur in magnetic fusion plasmas. Indeed, scientists within the national magnetic fusion energy program have worked to model microturbulence for more than two decades.

Fortunately, massively parallel computers, which use thousands of microprocessors in tandem, are well-suited to this simulation task. These machines are ideal because the collective behavior of trillions of electrons and ions is complex, but the underlying physics—and the equations that describe it—are relatively straightforward.

Most computing is done remotely at the Department of Energy's National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley



The UCAN code, developed by Livermore collaborators at the University of California at Los Angeles, produced these two images of tokamak plasmas. (a) Early in the development of the microturbulence, small-amplitude, radially elongated turbulent eddies form. (b) Fully developed microturbulence exhibits smaller, disordered structures.

Fusion for the Future

Fusion combines the nuclei of light elements to form a heavier element. For example, two nuclei of hydrogen isotopes, deuterium and tritium, will overcome the natural repulsive forces that exist between such nuclei and combine under enormous temperature and pressure. The fusion reaction produces a single nucleus of helium, a neutron, and a significant amount of energy.

A device that creates electricity from fusion must heat the fuel to a sufficiently high temperature and then confine it for a long enough time so that more energy is released than must be supplied to keep the reaction going. To release energy at a level required for electricity production, the fusion fuel must be heated to about 100,000,000°C, more than 6 times hotter than the interior of the Sun. At this temperature, the fuel becomes a plasma, an ionized gas of negatively charged electrons and positively charged ions. Although rare on Earth, plasmas constitute most of the visible universe.

The challenge for scientists is how to confine the plasma under extreme temperatures and pressures. One solution is to use powerful magnetic forces. In the absence of a magnetic field, a plasma's charged particles move in straight lines and random directions. Because nothing restricts their motion, the charged particles can strike the walls of a containing vessel, thereby cooling the plasma and inhibiting fusion reactions. In an appropriately designed magnetic field, the particles are forced to follow spiral paths about the magnetic field lines so they do not strike the vessel walls. The plasma is thus confined to a particular magnetic field line. The magnetic field line itself can be confined within a vacuum chamber if its path is restricted to a toroidal, or doughnut, shape.

A bundle of such magnetic field lines forms a doughnut-shaped magnetic "bottle" called a tokamak, an acronym derived from the Russian words meaning toroidal chamber and magnetic coil. In the tokamak, the stable magnetic bottle is generated both by a series of external coils, which are wrapped around the outside of the doughnut, and by a strong electrical current, up to several million amperes, that is induced in the plasma itself.

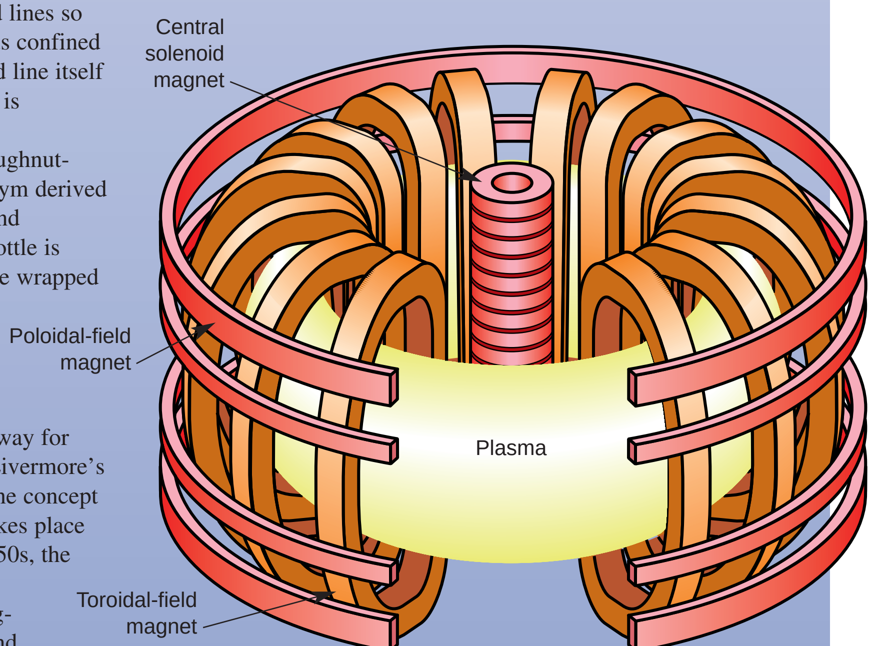
Half Century of Research

Magnetic fusion energy research has been under way for more than a half century and was one of Lawrence Livermore's original programs. The idea was classified because the concept uses the energy released by the same reaction that takes place in a hydrogen or thermonuclear bomb. In the late 1950s, the research program, called Project Sherwood, was partially declassified because it was viewed as a long-term effort without immediate military application and one that would benefit greatly from international cooperation.

Considerable progress has been made in the last 20 years at Livermore and other research centers in meeting the scientific challenges of attaining the combination of temperature, density, and confinement time necessary to promote fusion reactions. At one point, several different types of devices, including Livermore's magnetic "mirror" design, were pursued within the national program. Budget constraints, however, led to the adoption of the tokamak as the principal design for the U.S. program, with other approaches being explored at lower levels of resources.

The long-standing goal of magnetic fusion energy is to produce abundant, environmentally acceptable electric energy from a fusion-powered reactor. In fusion power plants, the heat from deuterium–tritium fusion reactions would be used to produce steam for generating electricity. Deuterium is abundant and easily extracted from ordinary water (about one water molecule out of every 6,000 contains deuterium). Tritium can be made from lithium, a plentiful element in Earth's crust.

One kilogram of deuterium–tritium fusion fuel would produce the same energy as 30 million kilograms of coal. Other major advantages include no chemical combustion products and therefore no contribution to acid rain or global warming, radiological hazards that are thousands of times less than those from fission, and an estimated cost of electricity comparable to that of other long-term energy options.



In a tokamak, magnetic fields from surrounding magnets confine a plasma fuel of hot, ionized gas within a hollow, doughnut-shaped vacuum chamber.

National Laboratory. In fact, the collaboration is the biggest user of NERSC facilities. The current simulations typically require from 10 to 20 hours to complete using NERSC's most powerful machines.

With the latest generation of supercomputers, says Cohen, "We can do bigger pieces of the simulation, with more physics." Nevertheless, no computer yet built can perform simulations requiring six orders of magnitude in spatial size, eight to nine orders of magnitude in time scale, and three dimensions in space. As a result, "We have to be clever about reducing the scales and still obtaining accurate results," says Cohen.

The hardware advances have been accompanied by the equally impressive development of efficient algorithms with which to solve the equations that form the basis of plasma simulation. The algorithms are of two kinds, particle-in-cell (PIC) models and continuum models, depending on how they track simulated electrons and ions in space and time. PIC models track individual electrons and ions; continuum models solve equations that do not involve individual particles.

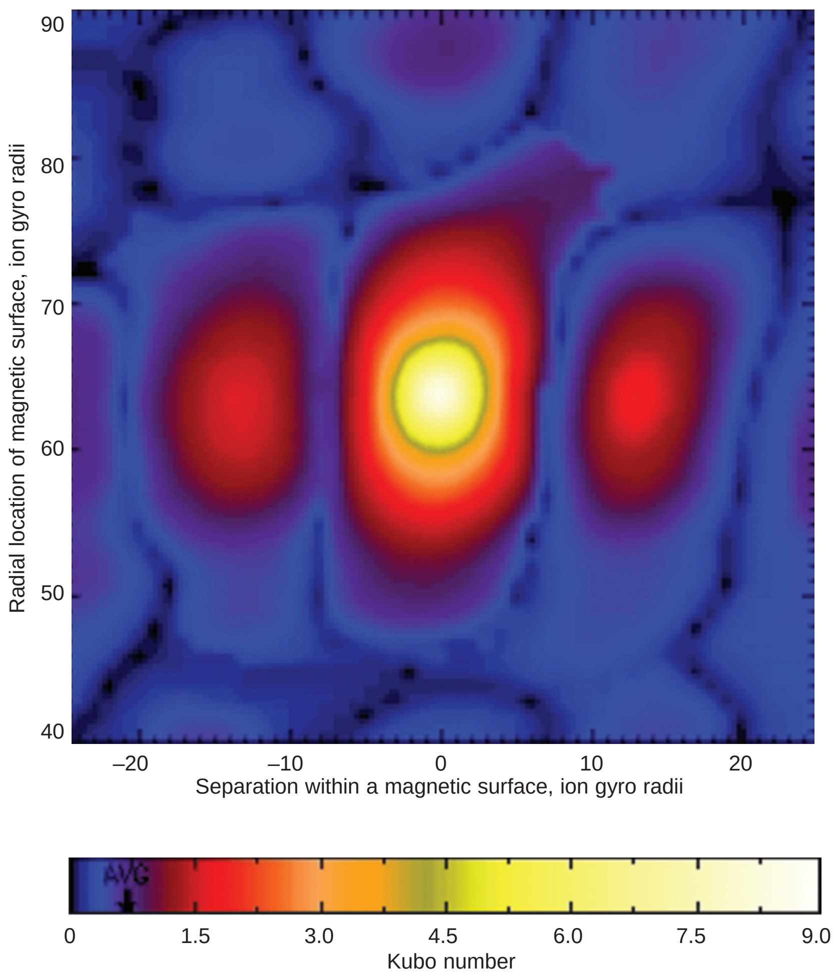
The national effort is developing both kinds of algorithms because they offer a valuable means of verifying new codes. "Together, the two kinds of algorithms provide a balanced scientific approach to understanding microturbulence," says Nevins. Each approach, however, pushes the limits of current supercomputer capability.

PIC and continuum algorithms can be used in two geometric representations: global and flux tube. Global simulations model the entire plasma core of a tokamak, whereas flux tube simulations represent a more limited area. Here again, says Nevins, the two geometric approaches serve as a useful cross-check on the results obtained from each other.

With the increased speed of microprocessors, additional memory, massively parallel supercomputers, and advanced algorithms, important progress has been made in the past few years in modeling microturbulence. Nevins points to significant improvements in the comparisons of simulations to experiment results, in the agreement of results from codes developed by collaborators from different centers of magnetic fusion energy research, and in the increasingly thorough and accurate physics content of the models.

An important aspect of the code work is developing new tools to analyze and visualize the simulation results. Data analysis and visualization provide the bridge between the microturbulence simulation and experimental research. Nevins has developed GKV, a program that allows the user to easily compute, analyze, and display results (in presentation-quality form) easily from microturbulence simulation data. The program is used by researchers nationwide.

A strong numerical model of microturbulence, combined with better



Livermore's GKV program allows users to interactively compute, analyze, and display data from microturbulence simulations. This GKV image displays the Kubo number, or the number of times an ion circulates around a turbulent eddy before that eddy dissipates, versus the separation within a magnetic surface and the radial location of the magnetic surface. Distances are measured in ion gyro radii, that is, the radius of a typical ion's orbit as it gyrates about a magnetic field line.

data analysis and visualization tools, is aiding the interpretation of experimental data and the testing of theoretical ideas about microturbulence and how to control it. The simulations are also helping scientists to plan future experiments. In addition, continued progress in code development may stimulate advances in the understanding of astrophysical plasmas and turbulence in fluids.

Theorists Now Getting Respect

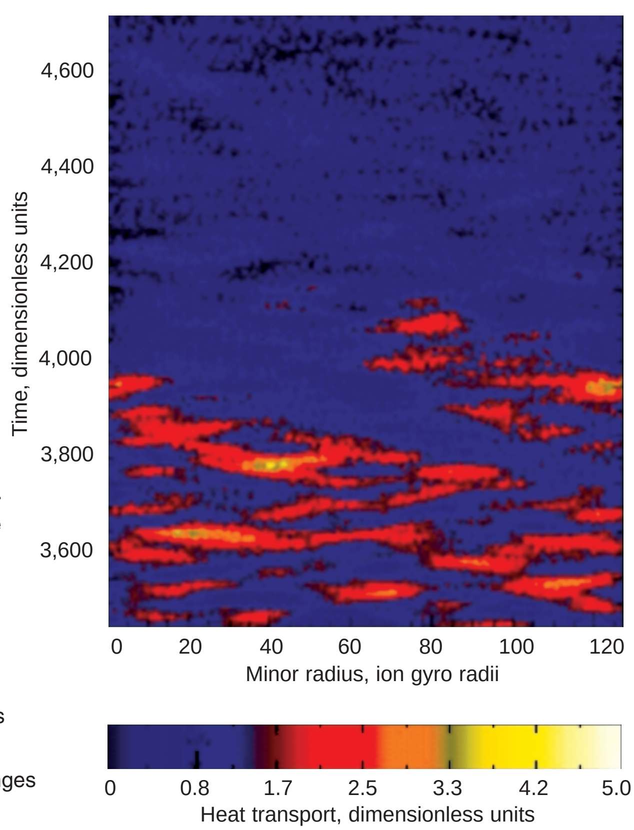
Cohen recalls that five years ago, experimentalists paid much less attention to theorists regarding plasma turbulence. Today, however, simulations do such a good job in predicting experimental results that “experimentalists are really paying attention to the codes.” Simulations, he says, have achieved such a level of fidelity to the underlying plasma physics that they can often be used as a tool for experiments regarding plasma microturbulence.

Nevins points out that the cost of doing simulations is nearly negligible compared with the cost of building and running a new fusion ignition experiment (around $1 billion to $2 billion). “Inexpensive but increasingly realistic simulation capability will continue to have immense leverage on relatively expensive experiments,” he says.

He also points out that numerical simulation has a distinct advantage over experimental observations of microturbulence: The simulations give users access to virtually any portion of the plasma in time or space. Simulations use “synthetic” diagnostic tools, which mimic the signal that an experiment would be expected to produce on an experimental diagnostic.

Says Nevins, “We can put in better diagnostics on a computer code than we can during an experiment.” What’s more, the physics underlying observed microturbulence can often be ambiguous. “With a simulation, we can turn different physics on and off to isolate what is driving the microturbulence observed in the experiment.”

Not only have recent simulations produced a clearer understanding of microturbulence, but they have also provided a few surprises as well. For example, scientists have long puzzled over large but transient bursts of heat that are transported out of the core plasma by microturbulence eddies. “We would have expected the transfer of heat from the plasma core out to the walls to be homogeneous because of the small eddies caused by microturbulence. Instead, we’ve seen large, intermittent bursts 10 times the size of the eddies,” Nevins says.



Tokamak experiments have detected puzzling bursts of heat produced by microturbulence. Recent simulations show the same phenomenon, where the heat pulses are indicated by bright regions. Researchers have noticed the similarity between these heat pulses and other instances of self-organized criticality, which resemble the sudden occurrence of avalanches as grains of sand are slowly added to the top of a sandpile. The simulation also shows the spontaneous transition in time from a state of high heat transport, with many heat pulses, to a state of low heat transport, in which the heat pulses are largely absent. This transition was caused by microturbulence-induced changes in the plasma’s flow shear.

Learning from Sandpiles

Nevins and others have noticed that these intermittent spikes are characteristic of “self-organized criticality,” a phenomenon that occurs in a system when certain key parameters reach critical values. Self-organized criticality is responsible, for example, for the occurrence of sudden avalanches as grains of sand are slowly added to the top of a sandpile. The Livermore simulation team is using the insights derived from self-organized criticality to account for these unexpected bursts of heat, which apparently are the combination of many turbulent eddies.

An important recent addition to the simulation codes is a phenomenon called flow shear that works to dampen microturbulence and thereby improve plasma confinement. The plasma rotates (flows) within each of the nested magnetic surfaces defined by individual magnetic field lines. The term flow shear describes spatially localized changes in the rate of plasma rotation. The flow shear sharply reduces the rate at which heat is transported out to the cold plasma edge by stretching and tearing apart the microturbulence eddies.

Nevins explains that heat must travel to the outer plasma edge across many nested magnetic surfaces. When the magnetic surfaces rotate relative to each other, the eddies transporting the heat tend to dissipate. He offers the analogy of a busy freeway, with each lane of cars (magnetic surface) at a different speed. If a driver must hand a rubber band (microturbulence eddy) to a driver in another lane passing by at a much faster rate, the rubber band will soon break and not be passed to the driver in the faster lane.

Flow shear can appear spontaneously during a magnetic fusion energy experiment. When that happens, says Cohen, "We get it for free." Flow shear can also be created experimentally by applying a twisting force (torque) to the plasma using, for example, intense beams of neutral hydrogen atoms. The force pushes on the center of the plasma core to create barriers to heat transport.

"We want to understand much better how flow shear functions so we can know how much to apply to effectively control microturbulence," says Cohen. Precisely applying flow shear could increase plasma confinement and significantly decrease the cost of new experimental facilities.

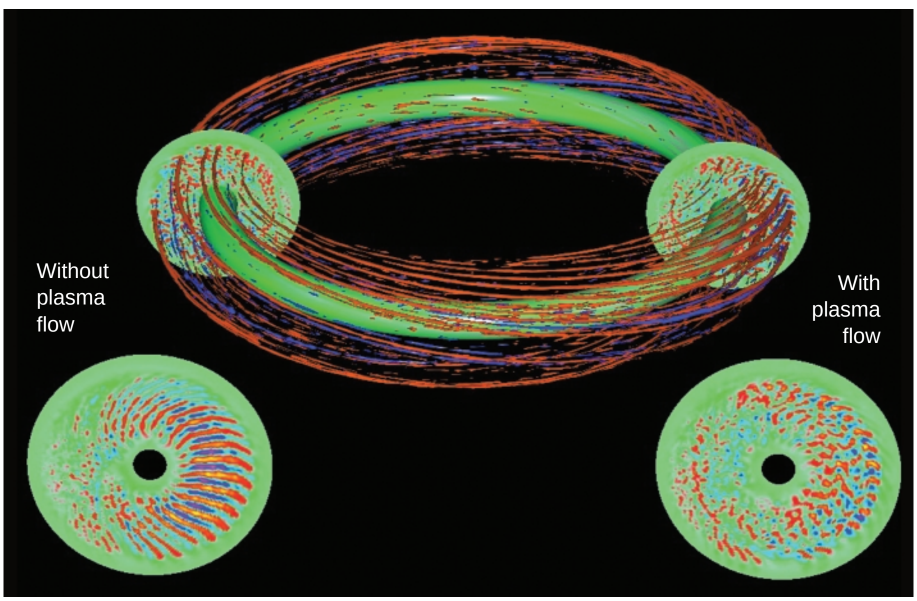
The national collaboration is working to provide a suite of modular, complementary computer programs, each with an identical user interface. Together, the modules will constitute a comprehensive code for microturbulence simulation, data analysis, and visualization. The modular architecture will enable physics simulations on diverse computer architectures with much less effort than current software approaches demand. Says Nevins, "We want to revolutionize the fusion community's ability to interpret experimental data and test theoretical ideas. The result will be a much deeper understanding of microturbulence."

As for the codes themselves, the collaborators are working on consolidating programs developed by individual research groups. Another area of activity is improving the physics simulated by the codes, for example, by refining the simulated diagnostic instruments and more accurately modeling the role of electrons involved in microturbulence.

Nevins is hopeful that by making the simulations easier to run and analyze, even more experimenters will choose to use them. "It was a heroic feat to make the codes work, but now we need to make them available to the experimental community," he says. "We want these tools to be used more widely so that we expand the use of microturbulence simulation well beyond the existing small group of code developers. Our goal is to have experimentalists run the codes and understand the results much faster."

Better simulation tools could bring dependable fusion energy much closer to reality. That would be welcome news for a nation recently reminded about the fragility of steady energy supplies and prices.

—Arnie Heller



Simulation of a tokamak and two plasma cross sections. In the simulation that produced the plasma cross section on the left, the flow shear was suppressed, while the self-generated flow shear was retained in the simulation that produced the cross section on the right. These cross sections illustrate the role of flow shear in suppressing plasma microturbulence and thereby forming barriers to unwanted heat transport. This simulation was created using the GTC code developed at the Princeton Plasma Physics Laboratory.

Key Words: fusion, macroturbulence, magnetic fusion, microturbulence, National Energy Research Scientific Computing Center (NERSC), plasma, Scientific Discovery through Advanced Computing (SciDAC), tokamak, turbulence.

For further information contact Bill Nevins (925) 422-7032 (nevins1@llnl.gov).