Turbulence May Sink Titanic Reactor

The $10 billion International Thermonuclear Experimental Reactor project is meant to show that fusion is a practical energy source. But a new set of calculations says ITER will fizzle

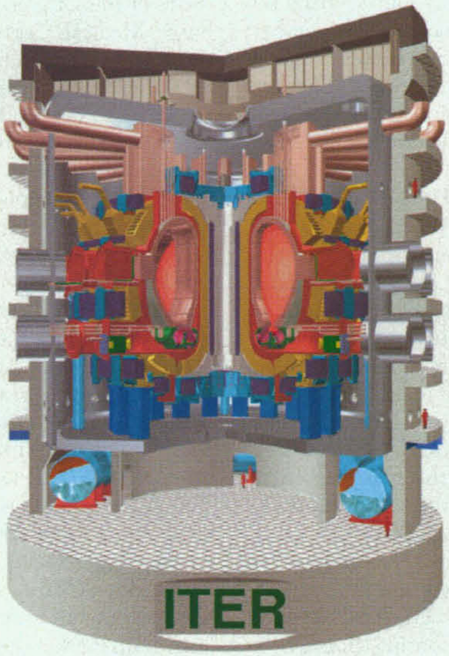
DENVER—For more than a decade, hundreds of fusion researchers around the world have been working toward an audacious dream: an enormous machine called the International Thermonuclear Experimental Reactor (ITER). A $10 billion megaproject sponsored by the United States, Russia, Europe, and Japan, ITER is envisioned as a building-sized, donut-shaped device called a tokamak that is threaded with spiraling magnetic fields. The fields would cage million-degree deuterium and tritium ions, long enough for them to fuse and generate abundant power—enough, designers hope, to kindle the world's first controlled, self-sustaining fusion burn. Scientists have struggled for decades to demonstrate that fusion could be a practical source of power. ITER, due to be up and running before 2010 if construction funds materialize, is supposed to prove the case.

But that grand vision may be colliding with physical reality, in the form of results that have been roiling the fusion community for months and were discussed publicly here at a November meeting of the American Physical Society's division of plasma physics. Two researchers at the Institute for Fusion Studies (IFS) of the University of Texas, Austin—William Dorland and Michael Kotschenreuther—have come up with what Marshall Rosenbluth, a physicist at the University of California, San Diego (UCSD), calls "a remarkable intellectual achievement": a new theory of how turbulence rattles hot, ionized gas caged within powerful magnetic fields in a tokamak. That theory may be bad news for ITER.

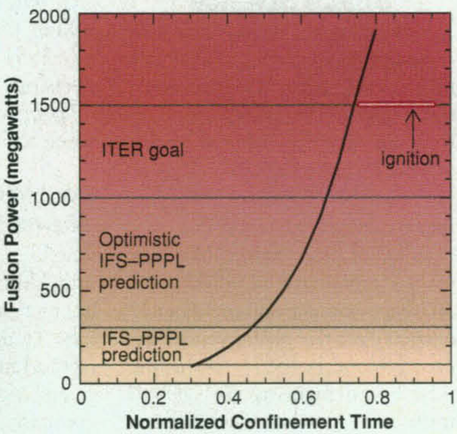
For decades, physicists designing new tokamaks have been forced to extrapolate from experiments to estimate how fast this complicated turbulence will cause heat to leak across such fields. Instead, the IFS work derives the rates directly from basic physics principles. "This differs from all previous attempts to understand [plasma] turbulence," says IFS director Richard Hazeltine, who was not involved in the work. According to computer models based on the theory, turbulent heat conduction in ITER will likely be strong enough to seriously undermine its performance.

ITER's power output, like any tokamak's, will depend in an exquisitely sensitive way on how well it can confine thermal energy. *Science* has learned that since March of last year, Dorland and Kotschenreuther have been telling ITER scientists and officials that turbulence could shorten the energy confinement time in ITER to the point where, far from generating the 1.5 billion watts in fusion power that ITER's official documents project, it may give back no more than a few times the energy used to heat the plasma in the first place—much too little to ignite a fusion burn.

Dorland and Kotschenreuther say their analysis shows that, because of its size, ITER will be more prone to turbulence than the smaller, existing tokamaks on which the optimistic projections for ITER's performance are based (see box). And it won't benefit from



ITER



SOURCE: DORLAND AND KOTSCHENREUTHER (IFS); HAMMETT (PPPL)

No fire in its belly? ITER's 16-meter donut would dwarf existing tokamaks, but calculations *(right)* based on the new turbulence theory show that ITER's energy confinement and power output may fall far short of its goals. The fusion curve assumes 100 megawatts of heating power—until ignition, when the heating could be turned off. The upper prediction allows for optimistically high temperatures near the edge of the fusion plasma.

stabilizing influences at work in the smaller machines. These devices, for example, are often heated by beams of fast particles that race around the donuts and create "velocity shear"—spinning plasma flows that stretch and rip apart turbulent eddies. But the ITER plasma—too large for beams to penetrate and too massive to spin—would be heated mainly by fusion reactions, which would impart little velocity shear. Because of these shortcomings, says Kotschenreuther, ITER "wouldn't work, and by a substantial margin."

On the face of it, the calculations are "pretty worrying for ITER," says Rosenbluth, a member of the ITER Joint Central Team, although he thinks they are still far from conclusive enough to seal ITER's fate. "The theory's [predictions] should be taken at least as seriously as—and probably more seriously than—other scalings," adds Diethelm Düchs of the Max Planck Institute for Plasma Physics in Garching, Germany, and the former head of theory at the Joint European Torus in the United Kingdom, in a response to *Science* written with his Max Planck colleague Dieter Pfirsch. "Undoubtedly, this would, and should, affect the present timetable for ITER," say Düchs and Pfirsch.

Düchs and Pfirsch aren't the only fusion physicists saying ITER should be delayed. But officials of the project, which has already arrived at a basic design and is spending about $55 million a year in the United States alone—roughly 20% of the overall U.S. fusion budget—aren't ready to change course. "I'm still personally feeling fairly confident that ITER's designs will achieve ignition," says Anne Davies, director of the Department of Energy's (DOE's) office of fusion energy. The IFS researchers, says Davies, "have done a nice piece of work—but I believe people's view of it is that it's not a complete piece of work yet. It's not the last word."

Davies and her colleagues are taking the challenge seriously, however. John Sheffield of Oak Ridge National Laboratory, chair of DOE's Fusion Energy Sciences Advisory Committee, says that both Dorland and Kotschenreuther will be asked to serve on committees

Behind the Official Optimism, Flawed Projections

A new, physics-based theory of turbulence that has grim implications for the performance of the International Thermonuclear Experimental Reactor (see main text) isn't the only thing shaking confidence in plans for this huge fusion-energy test-bed. The same physicists who developed the new theory have also examined the ITER project's own optimistic projections of the machine's performance—and found them wanting.

ITER physicists arrived at these projections by scaling up data from existing and defunct fusion machines. But the methods they used have serious mathematical deficiencies, say William Dorland and Michael Kotschenreuther of the Institute for Fusion Studies (IFS) at the University of Texas, Austin. Other fusion scientists—even some in ITER—say that Dorland and Kotschenreuther have put the spotlight on uncertainties that should have been highlighted much earlier. Marshall Rosenbluth, a member of the ITER Joint Central Team in San Diego, calls the new analysis "a serious issue." Adds Richard Hazeltine, director of the IFS, "I've looked at it, and I think it's what ITER should have done."

The work, which has been presented at roughly half a dozen scientific meetings since it was first shown to ITER scientists 14 months ago, casts a harsh light on the rosy picture of ITER's likely performance painted in ITER's Interim Design Report. This July 1995 description of the project has been circulated to officials of the countries taking part in the multinational endeavor. The report declares that ITER has a good chance of achieving self-sustaining fusion ("ignition") and a virtual certainty of producing a large surplus of power, saying, "The probability for pure ignition … is equal to 67%. With 100 megawatts of injected power, the probability to obtain 1.5 gigawatts [billion watts] of fusion power is 99.5%." Says Rosenbluth, "That was an absurd statement that never should have been in there—even [considering what was known] at the time. I don't think any of us would ever have thought the confidence was that high."

"The probability to obtain 1.5 [billion watts] of fusion power is 99.5%."

—ITER Interim Design Report

"That was an absurd statement that never should have been in there."

—Marshall Rosenbluth

He's not the only ITER scientist disavowing these figures. "I think that [statement] was most unfortunate," says Paul Rutherford of the Princeton Plasma Physics Laboratory and chair of the ITER Technical Advisory Committee. Even the ITER director, Robert Aymar, says, "I will not back these exact values."

Rosenbluth says that somehow "caveats got lost" when the statistical analyses "got transmitted to the higher levels" within ITER. Ultimately, say both Rosenbluth and Rutherford, reviewers within ITER then simply overlooked the two errant sentences within the lengthy report.

Dorland began to have doubts several years ago when he looked at the database underlying the ITER performance projections. It contains measurements of how energy confinement time—a crucial factor for tokamak performance—varies in six different tokamaks as a function of eight parameters, such as magnetic-field strength, plasma density, plasma current, and machine size.

ITER, at 16 meters across, would dwarf even the biggest machine in the database—the 6-meter Joint European Torus (JET) in the United Kingdom—and it would carry many times more current. But the ITER physicists believed that in the existing machines, the confinement time showed a so-called power-law relation with each variable: It seemed to increase in roughly a straight line when plotted against each variable on a logarithmic scale. If so, the line could be extended all the way to ITER, where it implied encouragingly long confinement times. But Dorland noticed that slight changes in how the fit was obtained, for example, had large effects on the extrapolation. "I filed that thought away," he says.

He and Kotschenreuther returned to the database last year, puzzled by the discrepancy between their own analysis of ITER's performance and the optimistic figures in the design report. They did standard statistical tests, such as removing one tokamak and checking how well its performance is predicted by the other five, and testing how well the data points determine a single extrapolation to ITER.

The results, says Kotschenreuther, were "astonishing." In the five-tokamak test, removing data on one variable, plasma density, actually improved predictions of the performance of the sixth tokamak. But disregarding density lowered the performance extrapolation to ITER by almost a third. The two physicists also found that, in critical "cuts" through the eight-dimensional space defined by the eight variables, the data looked more like an amorphous blob than like points scattered about a line. Says Hazeltine, "If I worked on ITER, I would be very embarrassed that this had to be pointed out by people in the [general fusion] community. It says it's very difficult to predict what ITER will do."

Dorland and Kotschenreuther went further, checking to see whether a "curved" line in the eight-dimensional space might fit the data better than a straight one—as their turbulence theory suggested it might. The curve seemed to fit the data, but it also cut the best extrapolation to ITER by as much as 60%. "With almost anything you do, the prediction goes down," says Dorland. Finally, they verified what most fusion researchers already knew: The projections fail to predict the performance of two other tokamaks from which data only recently became available: the large Japanese tokamak JT-60U and the much smaller Alcator C-Mod, at the Massachusetts Institute of Technology.

Some ITER physicists defend the standard projections. J. G. Cordey, a JET physicist who is chair of the ITER expert group on confinement, says the curved fits are "statistically questionable." He and other ITER physicists add that JT-60U's performance may be an anomaly because of a problem peculiar to that machine, and presumably irrelevant to ITER: an undesirable rippling in the applied magnetic field, which allows energy to leak out. For others, however, the Texas researchers have crystallized long-standing unease about projections of ITER's performance. In a joint response to *Science*, Diethelm Düchs and Dieter Pfirsch of the Max Planck Institute for Plasma Physics in Garching, Germany, who have done their own analysis of such projections, wrote: "We can only join in these authors' urgent call for caution."

Now, Dorland, Kotschenreuther, and many physicists within ITER are wondering whether the project will revise its official projections to reflect the uncertainty. A new design document, the Detailed Design Report, is scheduled to be reviewed by Rutherford's committee early this month, then sent to the ITER Council for provisional approval before being circulated to participating countries. In a draft copy obtained by *Science*, the optimistic projections were still unchanged. –J.G.

to review the next phase of ITER's design, the Detailed Design Report, due out in December. "The fat lady hasn't sung yet," says Sheffield of the theory's consequences for ITER. "The fat lady hasn't gone on stage yet."

Turmoil in a tokamak

The problem Dorland and Kotschenreuther have taken on—how turbulence grows within the caged plasma—sounds deceptively simple. Charged particles streaming along a tokamak's curved magnetic field lines feel a centrifugal force that tends to push the plasma outward, across the field lines. Like honey oozing through the grooves of a honey dipper, the plasma develops ripples that help it escape through the bars of its magnetic cage. Temperature gradients in the plasma—the hottest ions are at its center, the coolest at its edge—strengthen this instability, turning the ripples into full-blown eddies called ion-temperature-gradient (ITG) waves along the outside of the donut. The eddies do most of their damage by scattering energetic particles that would otherwise be snugly confined by the magnetic field. Diffusing outward, the particles carry heat out of the plasma.

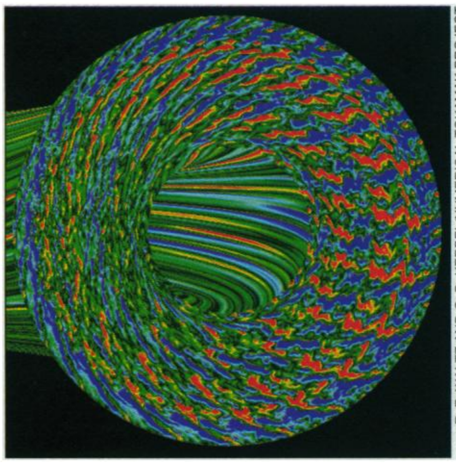
In spite of the problem's apparent simplicity, actually computing the growth of the instabilities, their interactions, and their effects on the caged particles is fiendishly difficult. Calculating turbulence in an ordinary fluid is one of the great challenges of computational physics, and plasmas have the additional wicked subtleties of electric and magnetic fields, along with all their associated energies and forces, thrown into the mix. Directly solving the equations describing the sloshing and swirling that take place in a full-sized tokamak is out of the question, says Martin Greenwald, a plasma physicist at the Massachusetts Institute of Technology. "You're trying to bridge huge scale [differences] in temporal and spatial dimensions"—from tiny eddies to the whole machine, for example.

Dorland and Kotschenreuther "bridge that gap with several small boards instead of one big board," says Greenwald, aided by recent developments including faster computers, clever computational algorithms, advances in the mathematics of turbulence, and their own decision to merge their separate lines of research into a single computer code. The team divides the donut into a series of rings, which they treat separately, then splice back together at the end of the calculation. They also split the analyses up according to the amplitude of the ITG waves.

Concentrating on small amplitudes lets Kotschenreuther simplify the equations and determine whether the slope of the temperature profile—how fast it is dropping from center to edge at any point—is enough to make eddies grow. By using several numerical tricks, such as tailoring the algorithms to the architecture of Cray supercomputers, he puts all this together to find unstable eddies very quickly and accurately.

Dorland contributes another piece of the puzzle by calculating just how these eddies interact at larger amplitudes, drawing on mathematics devised by Gregory Hammett of the Princeton Plasma Physics Laboratory (PPPL) and Francis Perkins, who is now the head of physics integration at the ITER work site in San Diego. The overall package also relies on work by UCSD's Patrick Diamond and collaborators, who showed how any velocity shear can tear apart the eddies and limit their growth, and by PPPL's Michael Beer.

It all meshes together as Kotschenreuther computes the instabilities and Dorland follows how the eddies interact, knocking particles around and conducting heat out of the plasma. The result is that heat transport can be handily calculated from first principles for any given set of conditions—say, a certain profile of plasma density, and so much beam heating to stir the brew. "For the first time, there is a physics-based transport model for tokamaks," says Steven Cowley of the University of California, Los Angeles.



Twist and shake. A simulation of turbulence in a tokamak, based on the new theory.

Bigger isn't better

The model has already proven to be "essential" to understanding many results in present tokamaks, says Ed Synakowski, an experimentalist at PPPL. And when the team applied it to ITER, they discovered two effects that would undermine the machine's performance. They found that turbulent eddies would strengthen, conducting heat out of the plasma, at somewhat smaller temperature gradients than in existing tokamaks. More important, they found that a related instability would develop at the very edges of the plasma, keeping them unexpectedly cool. The combination of a shallow temperature gradient and cool boundaries means that the center of the plasma would be cool as well, and unable to produce much fusion power.

ITER's size is largely to blame. The spiraling magnetic field lines in a tokamak normally act as a stabilizing influence, suppressing both the turbulent eddies and the edge instability: As particles follow the field lines around from the outside of the donut to the inside, the same centrifugal force that generated the instabilities now pushes them back toward the plasma. It's like spinning a honey dipper to keep the honey from oozing through it, say the researchers. But ITER's size reduces the stabilizing influence of the spiraling lines, because the particles have a longer journey from the unstable outside of the donut to the stable inside, as if the honey dipper were being twirled more slowly. Added to that geometric effect is the lack of velocity shear in ITER, which means that its more vigorous instabilities have less to rein them in.

Some physicists think that verdict may not be final. Rosenbluth suggests that recently discovered magnetic field configurations, which unexpectedly stanched heat loss from some tokamaks (*Science*, 28 July 1995, p. 478), might be a way out of the woods for ITER. And Derek Robinson, director of fusion at the U.K. Atomic Energy Authority and a member of ITER's Technical Advisory Committee, says that the complexity of the physics taking place at the edges of tokamaks casts doubt on the team's prediction of cool temperatures there. But Dorland and Kotschenreuther reply that ITER falls so far short that even if they have overlooked something, the picture is unlikely to change much.

One way to rescue the existing design, say Hammett and others, might be to look for a new way to generate turbulence-suppressing velocity shear—perhaps by using radio frequency waves beamed into the tokamak to push the plasma around. Experiments to test this idea are scheduled at PPPL's Tokamak Fusion Test Reactor, but will be cut short, says Hammett, when it is shut down next March.

But if it turns out that ITER does have to be radically redesigned, the new analysis may be a valuable predictive tool. Dorland and Kotschenreuther are already using their code to search for tokamak configurations that have low turbulent heat transport even without velocity shear. The key, their early results suggest, may lie in radically reshaping the tokamak cross section—perhaps by making it very oblate. Such a radical redesign would be likely to stretch out the timetable of ITER or point to an entirely different, smaller machine. Dorland and Kotschenreuther believe, however, that whatever happens to the ITER concept, the dream of a fusion power plant will still take the form of a donut. "Right now, the tokamak's still the leading concept in magnetic confinement fusion," says Dorland, "and these results don't change that. They just suggest new directions."

–James Glanz