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Numerical Tokamak Wins Support

Physicists Simulate Fusion Plasmas

The Numerical Tokamak Project is one of six "Grand Challenge" proposals that has been chosen for support by the Department of Energy High Performance Computing Program, according to Stephen Jardin, Deputy Head of the PPPL Physics Department.

"The fact that this project was one of six chosen out of 50 proposals submitted to DOE reflects both the quality of the science and the high priority status of fusion research."

The support, which will last for up to five years, will include access to the high performance computers at the Los Alamos Advanced Computing Laboratory and an additional PPPL staff member. Two groups at the Laboratory will receive support—the Gyrokinetic Simulation group, led by Theoretical Physicist W.W. Lee, and the Gyrofluid Modeling group led by TFTR Physicist Greg Hammett.

The goal of the Numerical Tokamak Project is to make a complete computer model of a tokamak plasma and to use this model to do experiments on the computer instead of in the laboratory. At present, this computer modeling can approximate a one to ten millisecond interval of a plasma in a tokamak about one-third the size of TFTR. The next generation of computers will enable modeling of plasmas simulating those in machines as large as TFTR for much longer time intervals. (See "Parallel Computers," page 4.)

Says Jardin, "A comprehensive computer model of a tokamak plasma will save us millions of dollars in the development of a fusion reactor by allowing us to design and fine-tune experiments without building and operating as much expensive hardware."

The Grand Challenges program was developed by the Federal High Performance and Communications Program of the Office of Science and Technology Policy. The Numerical Tokamak Project was chosen because it fit the Grand Challenge criteria as a fundamental problem in science and engineering whose solution could be advanced by applying high performance computing techniques and resources.

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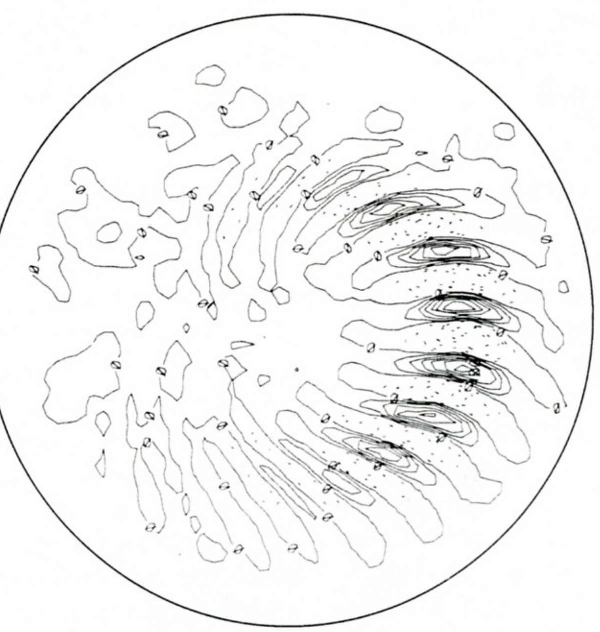


A cross section of the density contours in a plasma depicting the patterns of turbulence. It was calculated using the gyrokinetic particle simulation code for the numerical tokamak.

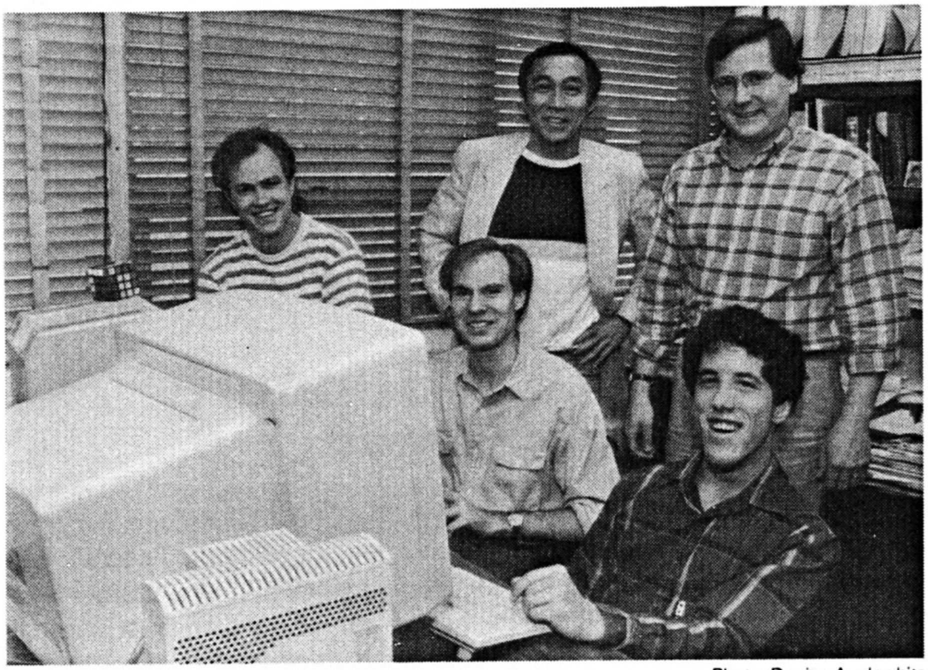


Photo: Denise Applewhite

The Gyrokinetic Particle Simulation Group includes: (left to right) standing, Principal Research Physicist Dr. Wei-li Lee and DOE Fellow Dr. Scott Parker; seated, graduate students John Reynders, Robert Santoro, and Julian Cummings.

to DOE reflects both the quality of the science and the high priority status of fusion research." The other five proposals chosen were related to: lattice gauge theory—elementary particles in the supercollider; petroleum reservoir models; development of chemical compounds through computation; structural biology as related to the DNA molecule; and fluid dynamics for aircraft design and global climate modeling.

Consortium Developed

In order to produce a proposal with the greatest chance for success, PPPL formed a consortium with nine other fusion laboratories, according to Jardin, who played a major role in the formation of the consortium.

During the course of the Numerical Tokamak Project, fusion theory, simulation, and computing communities will be collaborating closely to develop the simulation models and computer facilities that will result in the ability to simulate a large tokamak plasma.

In addition to PPPL, those involved are: California Institute of Technology/Jet Propulsion Laboratory; Cornell University; General Atomics; Institute for Fusion Studies/University of Texas; Lawrence Livermore National Laboratory; Los Alamos National Laboratory; National Energy Research Supercomputing Center; Oak Ridge National Laboratory; and University of California, Los Angeles.

Advanced Plasma Research Meets Advanced Computers

The Numerical Tokamak Project has grown out of two fortuitous circumstances coming together—the development of gyrokinetic particle theory over the last ten years and the explosion in the speed of computers within the last five years.

According to Lee, over the last decade, a small group of PPPL physicists have been working on this gyrokinetic theory. He notes, "Through years of intensive research, we have reduced the Vaslov-Maxwell equations to a new gyrokinetic formulation yielding a new set of equations. Because this was brand new work, there have been no road maps to follow, so it has been a long and painful process."

However, this research is proving very useful because, as Lee explains, "We have now eliminated unwanted time and spatial scales from the simulation plasma, thereby improving our technique by several orders of magnitude."

Gyrokinetic particles can be viewed as "sampling" (ring) particles—each of which represents billions of ordinary particles in the plasma. By following the gyrokinetic particles, physicists can now learn how billions of particles interact without following them individually, thus reducing an overwhelming task to more manageable size.

However, even *with* the comparative reduction in task size, the numbers of computations to be made are gigantic. This is where the supercomputers come into the picture. For example, to simulate core transport of particles in a TFTR-size tokamak plasma, by following approximately 16 million particles for a few milliseconds of a discharge would take one to two weeks on the Cray 2 or the CM2—today's fastest computer. With the newest machine being released by the Thinking Machines Company, the CM5, the same task would take only a few hours.

Plasma Turbulence

One major goal of the Numerical Tokamak Project is to develop more complex, complete, efficient models for describing turbulent transport in plasmas. In practical terms, this would enable more accurate predictions of how large a tokamak plasma must be for ignition and ultimately might lead to the design of a cheaper fusion reactor.

The phenomenon of turbulence still puzzles scientists, whether it is water turbulence, turbulence in aerodynamics, weather turbulence, or turbulence in plasmas. With super-computers, turbulence can now be modelled to help design ships and airplanes and to help predict weather and climate patterns.

Supercomputers have already reduced the need for physical hardware in important ways. For example, until these computers became available, wind tunnels were used to test new aircraft designs. Now, these tests can be simulated in "numerical windtunnels" via massively parallel computers.

Of all turbulence problems, those in plasma are by far the most complex because of its electromagnetic nature, according to Lee. Nevertheless, he is optimistic that with gyrokinetic theory to simplify computations, such turbulence can be simulated via supercomputer.

Understanding how plasma turbulence affects energy confinement is crucial to the ultimate success of the fusion program. Turbulence causes the plasma to leak out of the "magnetic bottle" or tokamak, faster than if there were no turbulence, necessitating larger-sized tokamaks. By understanding turbulence better, scientists believe they will be able to minimize its harmful effects.

The Plasma—Particles or Fluid?

Both Lee and Hammett are interested in describing the turbulence in the plasma with the help of supercomputers, and both start with basic gyrokinetic theory. However, they look at the plasma in two different ways.

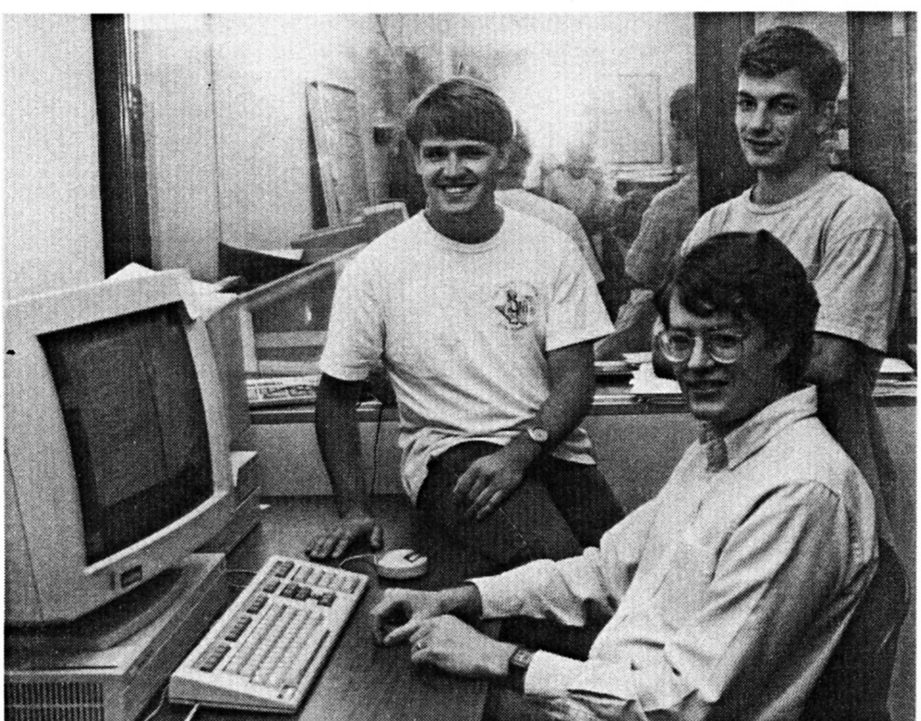
Like air, plasma can be treated either as millions of *particles* or as a *fluid.* Lee, and his group (sometimes dubbed particle pushers), follow millions of gyrokinetic *particles* in the plasma. Lee, Scott Parker, and graduate students Julian Cummings, John Reynders, and Bob Santoro use this approach. Lee also gives credit to Liu Chen, T.-S. Hahm, John Krommes, William Tang, and other members of the Theory Division for their efforts in support of gyrokinetic theory.

By contrast, Hammett and graduate students Bill Dorland and Mike Beer focus on the plasma as a *fluid,* and their model is called the gyrofluid model. They follow the mass density, fluid velocity, and pressure of the plasma. Two new graduate students, Steve Smith and Steven Kauffman, have recently joined the group.

In the past, it had been difficult to treat plasma turbulence with a fluid approximation because particles may travel hundreds of times around the torus before colliding with other particles. In 1990, Hammett and PPPL Theorist Francis Perkins published a paper showing how to model this mixing of particles in the fluid approach.

Dorland and Hammett began working with gyrofluid computer simulations in 1990. Beer has recently joined the group and is extending the turbulence simulations to toroidal geometry using a nonlinear ballooning mode theory developed by PPPL Physicist Steve Cowley.

Says Hammett, "The gyrokinetic particle approach is more rigorous, but the gyrofluid approach is simplified and therefore may be faster. Our work is complementary with that of Lee's group, and we compare notes so that we can learn from each other. We all have the goal of developing a computer program that will fully simulate a tokamak so that we can design the optimum fusion reactor in the most economical way possible."



TFTR Physicist Greg Hammett (front right) works with graduate students Bill Dorland (left) and Mike Beer on a gyrofluid modeling problem. Photo: Dietmar Krause

Parallel Computers

Just how are parallel computers different from ordinary personal computers? Let's imagine you have a very long calculation to make that requires billions of additions and multiplications. To do this on a single PC might take hours.

However, if you had 1,000 PCs working on the job, it might take a few seconds, or even less. Simply put, this is what is meant by "parallel." All the computer units work *simultaneously* on various aspects of the larger problem. Therefore, they can complete the calculation much faster.

John Reynders, a graduate student who has been working on parallel computers as part of his Ph.D. thesis, compares them to checkout lines in the grocery store. Explains Reynders, "It would take a rather long time to buy one's groceries if only one checkout counter were available, but with several checkouts, consumers can pay quickly and be on their way—the more counters available, the less standing in line!"

He adds, "Likewise, computers with only a single processor must operate on each piece of a problem separately—one piece after another. By contrast, a parallel computer with many processors can operate on many pieces of the problem simultaneously—the more processors in the computer, the more quickly the problem is solved."

Terms like *massively parallel* and *supercomputer* are being used to describe the ultrafast computers now appearing. The Cray 2 computer, which had been the fastest, could complete 500 million floating operations per second (MFLOPs) on a single processor.

By fall, the CM5 supercomputer will be installed and ready for use at the Advanced Computing Laboratory at Los Alamos, New Mexico. Calculations that would take a single processor on the Cray 2 over 200 hours to complete can be done by 1,000 processors on the CM5 *in under an hour*. This massively parallel computer will perform over 100 *billion* operations per second.

Says Reynders, "To put this in perspective, if you could perform 100 multiplications on a piece of paper in one minute, it would take you almost 2,000 years and over two tons of paper. To do the same calculation, the CM5 would take only *one second*. But thanks to parallel computers, our forests are safe, and we can begin to tackle problems that should provide greater insight into the complex nonlinear plasma dynamics of fusion devices."