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PLASMA TURBULENCE CALCULATIONS ON SUPERCOMPUTERS*

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Fusion energy is the source of energy of the sun and the stars. This energy is released during a nuclear fusion reaction in which two light nuclei combine into a heavier nucleus.[1] In the sun, pairs of hydrogen nuclei react, producing deuterium and releasing 1.44 MeV. This reaction is not the most likely one to be used in a future commercial electricity production plant, because of the high temperature required. The "fuel" for the reactor is more likely to be deuterium and tritium, because their fusion reaction, producing helium, has the highest cross-section for temperatures between 10 keV and 100 keV. At lower temperatures there is no fusion reaction with a scattering cross section large enough to be relevant for energy production. At these high temperatures, matter exists only as a plasma. That is, the nuclei and electrons are no longer bonded, forming atoms and molecules.

The principal goal of fusion research has been to *contain*, or *confine*, plasmas for a long enough time. Of course, no material vessel can stand the high temperatures of a fusion plasma. One way to confine a plasma is with magnetic fields, because charged particles move mostly along magnetic field lines and only move across field lines if they collide with other particles. By carefully controlling the magnetic field, it is possible to confine a plasma away from the vessel. The plasma can be localized in a finite region by bending the field lines in a doughnut-shape, or toroidal, configuration. A magnetic field with a doughnut-shape configuration can be created solely by external conductors or by a combination of external coils and the magnetic field generated by a plasma current. The former type of device is called a stellarator and the latter a tokamak.[2]

Although the single-particle picture of magnetic confinement is helpful in understanding some basic physics of plasma confinement, it does not give a full description. Collective effects dominate plasma behaviour. Any analysis of plasma confinement requires a self-consistent treatment of the particles and fields. The general picture is further complicated because the plasma, in general, is turbulent. The study of fluid turbulence is a rather complex field by itself. In addition to the difficulties of classical fluid turbulence, plasma turbulence studies face the problems caused by the induced magnetic turbulence, which couples back to the fluid. Since the fluid is not a perfect conductor, this turbulence can lead to changes in the topology of the magnetic field structure, causing the magnetic field lines to wander radially. Because the plasma fluid flows along field lines, they carry the

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particles with them, and this enhances the losses caused by collisions. The changes in topology are critical for the plasma confinement.

In present magnetic confinement devices, classical transport theory based on particle collisions predicts electron and ion confinement times longer than those experimentally measured by factors of 3 to 10 for ions and up to 30 for electrons. Therefore, anomalous transport mechanisms that have not yet been identified are in operation. At the plasma edge, detailed measurements of fluctuations are possible using material probes. From these measurements, it has been inferred that anomalous losses in the edge can be explained by turbulence-induced transport.[3] Theoretical understanding of the anomalous transport mechanism would enable one to not only calculate size and scaling parameters for fusion reactors but also improve the confinement concept. The optimization of the reactor has an important impact on its overall cost.

The study of plasma turbulence and the concomitant transport is a challenging problem. Because of the importance of solving the plasma turbulence problem for controlled thermonuclear research, the high complexity of the problem, and the necessity of attacking the problem with supercomputers, the study of plasma turbulence in magnetic confinement devices is a Grand Challenge problem.

There are two main approaches for numerical calculations of plasma turbulence. One is based on particle pushing techniques. This approach starts from basic principles, but is formulated as a nonlinear problem in a six-dimensional space for a large number of particles. This approach is discussed in detail by J. Dawson.[4] The other approach is based on a fluid representation obtained by taking moments of the primitive kinetic equations. The problem is then reduced to the solution of a few fluid-like equations. This simplifies the computational problem, although it is not clear that the present computer capabilities are sufficient for this problem, but it misses some important physics.

Progress has been made by moving away from the two extremes. In particle techniques, the gyrokinetic approach[5] of averaging over the gyromotion eliminates one degree of freedom and the fastest time scale in the problem, both of which are probably irrelevant to the turbulent processes of interest. In the fluid approach, effects such as diamagnetic rotation, finite Larmor radius corrections, and closure schemes compatible with Landau damping[6,7] have already been included. This method is commonly called gyro-fluid with Landau closure and brings back into the fluid picture most of the relevant physics.

Furthermore, a hybrid fluid-particle code has been developed.[8] This code treats one particle species as a fluid and the other as particles. In this way, some of the relevant kinetic effects are brought into the problem. We are developing a variation on this approach for burning plasmas by treating the bulk plasma as a fluid and the alpha particles as particles. This method offers an intermediate step between fluid codes and full gyrokinetic computations.

The geometry of the magnetic configurations relevant to fusion is intrinsically three-dimensional (3-D), with a finite range in the radial coordinate, and periodicity in the two angular coordinates. As is typical of turbulence studies, high resolution is needed to resolve all the scale lengths in the problem. Here, the longest scales are of the order of the minor radius, a, of the device, which can be several meters (from 0.3–1.0 m in present experiments to about 3–5 m in a reactor). The smallest scale lengths to be resolved are of the order of the ion Larmor radius, about a fraction of a centimeter. Hence, the ratio of scale lengths is of the order of 10^2 to 10^4. To study the development of steady-state turbulence, the plasma evolution must be followed for a few decorrelation times, that is, 2×10^4 to 10^5 time steps for present experiments. An increase of at least an order of magnitude is required for reactor conditions.

In a magnetic confinement device, it is important to distinguish between two plasma regions: the core and the edge. At the plasma edge, the dynamics of the plasma can be modeled by fluid-like equations; the fluctuations are, in general, large (of the order of the equilibrium quantities), and detailed measurements can be made with probes. These large fluctuation levels can only be modeled by including the atomic physics drives. Numerical results seem to provide a good description of present experimental measurements[9] (Fig. 1). The study of core plasmas requires a kinetic theory treatment; the core fluctuation levels are low (a few percent), and measuring them is difficult. At ORNL, we are following the gyro-fluid approach in modeling the plasma core turbulence.

For turbulence calculations based on fluid-like equations, we use KITE-type codes.[10] In these codes, all fields are written as a Fourier expansion in the angular variables. The components of these fields are functions of the radius, and they are represented on a finite-difference grid. Most of the CPU time used by these codes is spent in inverting matrices and doing convolutions. These calculations have been carried out mainly with the CRAY-II machines at the National Energy Research Supercomputer Center (NERSC) in Livermore, California. From the computational point of view, there are two constraints: (1) memory size, which is governed mainly by the size of the matrices, and (2) CPU time, which is dominated by the convolutions. On the CRAY-II, typical calculations take from 50 to 500 hours of CPU time. These times translate into many months of real time, and practical problems occur in stretching the work over such long periods of time. For jobs with memory size below 10^7 words, there is a factor of about 25 between real time and CPU time. This factor becomes much larger for larger memory sizes.

To improve the real-time efficiency, we have explored two main avenues: manual multitasking or macrotasking in the CRAY-II[11] and the use of massively parallel machines.[12,13] Each has required a different adaptation of the numerical scheme. In the CRAY-II, we separated the tasks in Fourier space, associating a task with each toroidal mode included in the calculation. This was done because of the block structure of the matrices in toroidal geometry. For jobs with more than 10 million words run on one eight-processor CRAY-II, an average of less than two processors is the most we are able to achieve. Therefore, it is seldom possible to effectively improve the efficiency of the calculations. The reason for this is the priority in scheduling at NERSC. The overhead of programming complexities associated with macrotasking makes this avenue of little practical use. The second approach was to use a parallel algorithm that we tested on several hypercubes, the most advanced being the 64-node Intel iPSC/860 (RX) at ORNL. The algorithm was modified to allocate a radial region to each node. In this way, convolutions at a fixed radius were performed in parallel, and communication was limited to the boundary values for each radial region. The effective memory configuration is a ring. Present results show that the number of steps for CPU time is the same for the iPSC/860 (RX) machine using 32 processors as for a single-processor CRAY-II (for 300 modes and 129 radial grid points). We have compared the efficiency of these two machines and are also examining the efficiency of workstations (Fig. 2). We have also started testing the same code on the CM-2 machine at Los Alamos National Laboratory.

While current computer technology and algorithms are deemed adequate to perform turbulence calculations for edge plasma parameters, the massively parallel mainframes of the next generation and new algorithmic developments appear to be needed to tackle the fluctuations at the core of present-day tokamaks. The toroidal nature of the geometry and the ability to model hotter plasmas, by adopting a fully kinetic approach, by extending the fluid-like models to include relevant kinetic effects, or by combining these techniques, present formidable analytical and computational challenges.

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Figure Captions

Fig. 1. Comparison of experimentally measured and numerically calculated potential fluctuation levels at the edge of the TEXT tokamak.

Fig. 2. Performance versus prices of different computers. The tests have been done with the KITE code for a plasma turbulence problem with a grid of 380 radial points and 147 Fourier components.

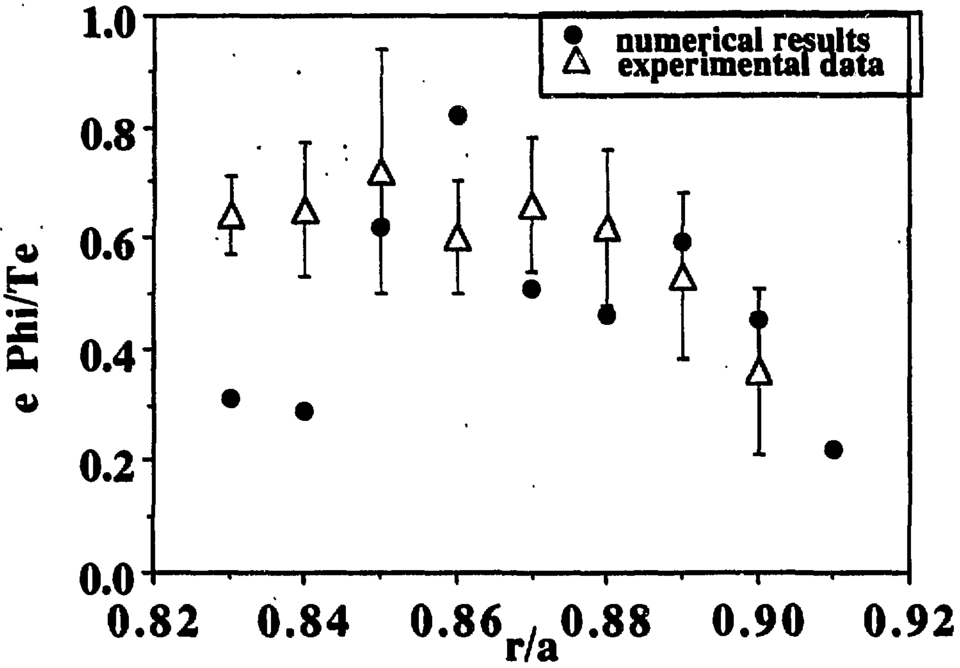
numerical results
experimental data
e Phi/Te
1.0
0.8
0.6
0.4
0.2
0.0
0.82
0.84
0.86
0.88
0.90
0.92
r/a

Fig.1

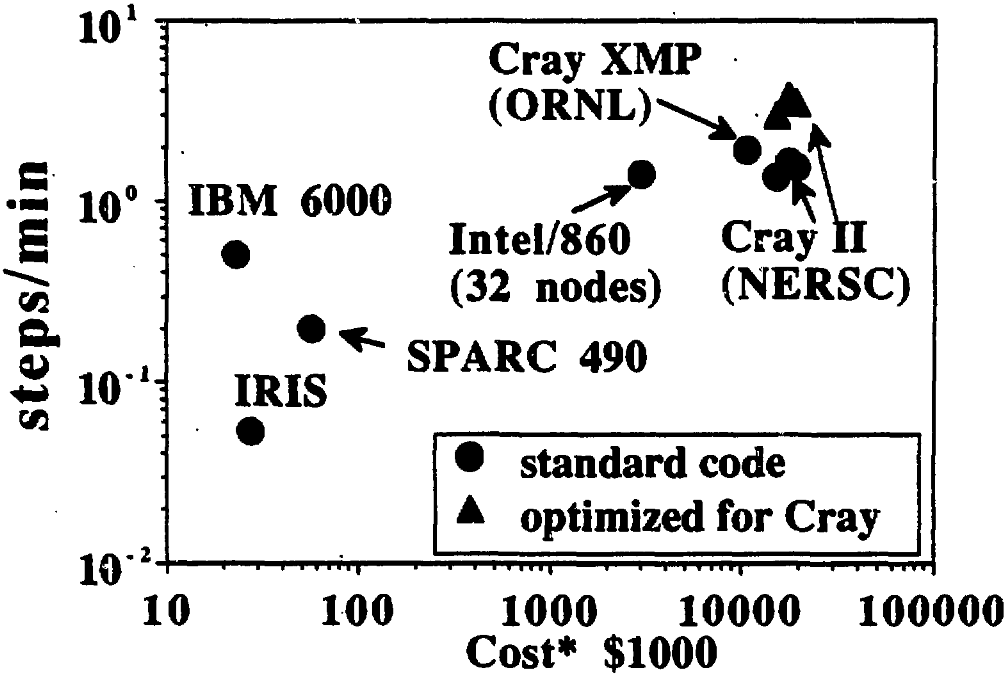
Cray XMP
(ORNL)
IBM 6000
Intel/860
(32 nodes)
Cray II
(NERSC)
SPARC 490
IRIS
standard code
optimized for Cray
steps/min
10¹
10⁰
10⁻¹
10⁻²
10
100
1000
10000
100000
Cost* $1000

Fig.2