SIMULATION OF PLASMA DYNAMICS USING MANY PARTICLES

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SIMULATION OF PLASMA DYNAMICS USING MANY PARTICLES

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Almost anything that is hot enough is a plasma—the sun, stars, Van Allen belts, ionosphere, magnetosphere, lightning, arcs, discharges, and even the interior of the common fluorescent bulb. A hot plasma is an ionized gas which has many collective particle interactions. It is an electrical medium with currents, electric and magnetic fields, and pressure and density gradients. Since the electron and ion densities are nearly equal everywhere in them, most plasmas are nearly electrically neutral. The internal energy may range from 0.1 electron volts (eV) to above 10^5 eV, which for a gas would correspond to temperatures from 1000 K to about 10^9 K.

Ninety-nine percent of known matter is in the plasma state, and many plasmas have been studied for decades. However, there is great technological interest today in some new plasma applications: extremely high temperature plasmas for causing deuterium and tritium to fuse in a reactor designed to produce electrical power, and lower temperature plasmas for etching and

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depositing materials during integrated circuit manufacture.

Most laboratory plasmas exist inside vacuum vessels, are hard to probe and are full of waves and instabilities. Plasmas are simultaneously particle-like (kinetic theory applies) and fluid-like (magnetohydrodynamic theory applies). In mathematical terms they are inhomogeneous, nonlinear, and anisotropic. Plasma phenomena span a wide range of time and distance scales, forcing most plasma studies to be selective in scope. Thus, mathematical modeling of a plasma is difficult and challenging; some problems are only now becoming tractable with the advent of supercomputers with nanosecond cycle times and multimillion-word memories.

MODELING WITH SUPERPARTICLES

Features of plasma behavior are varied and numerous, yet nearly all of these—waves and oscillation, instabilities and turbulence, plasma heating, and particle and energy transport—are accessible by plasma simulation. Using suitable algorithms, we can observe whether and how a process starts, how it evolves, how it interacts with other processes, and what overall effect a process has on the plasma. When something new or unexpected happens, subsequent theoretical, computational, and experimental research benefits from the extensive diagnostics available through computer simulation.

How is this accomplished? In particle simulations, we use a manageably small number of marker (test) particles to represent the entire plasma and follow them; numbers range from a few thousand in one-dimensional simulations to 10^4 or 10^6 in two- or three-dimensions. That this is valid was shown long ago by Dawson, Eldridge, and Feix [1], who demonstrated that much of the kinetic behavior of a plasma could be simulated with a "few" particles in each plasma scale length—the Debye length—which is the distance over which a test charge causes appreciable fields. The computer is programmed to follow each of these particles, working from first physical principles.

Each marker particle is really a *superparticle*, consisting of perhaps 10^{12} electrons or ions, which behaves as a rigid but tenuous charged cloud. Each cloud may have the same charge-to-mass ratio as an electron or ion. Hence, each superparticle moves in the same way as a single electron or ion in an electric (**E**) or magnetic (**B**) field. We divide up the plasma-filled region into individual volumes or cells with a mathematical mesh or grid. The superparticles contribute source terms in each such cell—a density ρ and a current density **J**. These source terms are used to produce solutions of Maxwell's equations: that is, **E** and **B** due to the particles and any applied fields are obtained, and these fields accelerate the particles which are "moved" by integrating the Newton-Lorentz equation of motion over a short time step. New values of ρ and **J** are then obtained, leading to new values of **E** and **B**, and the cycle repeats, perhaps for a few thousand time steps [2]. Current supercomputers move more than a million particles per second (for example, in each second the computer moves 1000 particles through 1000 steps).

Even large number-crunching computers such as the CRAY computers can take several hours to run simulations of the magnetic and inertial confinement of plasmas in fusion power reactors and in certain space applications. In spite of the relatively large amount of computation required, we now simulate the essential physical phenomena of large-scale plasma experiments. These computer simulations consume only a small fraction of both the time and expense of actual plasma experiments, which for fusion plasmas are running over $300 million for each of the major experiments.

SIMULATION OF AN ELECTROMAGNETIC INSTABILITY

Plasmas may be confined for fusion within a magnetic "bottle" created by specially shaped coils carrying high currents. One design is the well-known doughnut-like tokamak, having closed magnetic field lines. In another design, plasma particles having certain initial velocities are reflected between "magnetic mirrors" with open field lines. If there are no instabilities in the plasma, the mirrors "leak" slowly, due to classical collisions and scattering of velocities. A crucial question is whether instabilities cause particle velocities to scatter much more rapidly and increase the rate of particle escape, which might prevent achieving sustained fusion.

Alfvén Ion Cyclotron Instability

In a plasma located in a magnetic field, energetic ions and electrons circle around the magnetic field lines at their so-called cyclotron frequencies, ω_{ci} and ω_{ce}. One instability that we have studied by computer simulation is the Alfvén ion cyclotron (AIC) instability that occurs when the ions in the plasma have a larger temperature associated with velocities $v_\perp$ perpendicular to **B**, than with the velocity $v_\parallel$ parallel to **B**. This instability arises from electromagnetic interaction between the shear Alfvén wave and the ion cyclotron wave.

Figure 1 shows how this instability behaves for one set of plasma conditions. In our model, the wave fields initially grow exponentially in time (over all space), starting from a small perturbation of the particles in the plasma. The initial exponential growth ultimately slows (as the particles interact nonlinearly with the wave) and then stops; simultaneously, the temperature imbalance relaxes.

The particle simulation is an essential tool for studying the complex nonlinear kinetic behavior that leads to saturation of this instability. Figure 2 shows that as saturation occurs, the ion motion is directed increasingly toward the axis of the magnetic mirror system, causing eventual loss of particles out the ends of the magnetic containment bottle. Furthermore, the deleterious effects of the AIC wave turbulence have been confirmed in experimental observations on the TMX tandem mirror experiment at Lawrence Livermore National Laboratory

[3]. Hence, this instability is a disaster for magnetic confinement. However, from the understanding of the AIC instability provided by theory and simulations, researchers have designed subsequent experiments on TMX-U that have avoided the AIC instability; AIC-stable parameters have been proposed or implemented in other tandem mirror experiments in the U.S. and Japan.

CONCLUSIONS

Particle simulations are now well established in plasma research and development work for controlled fusion, space physics, and high-powered charged-particle beams. Simulations greatly aid in developing theories, and in designing and analyzing experiments. Methods are continuously being developed for speeding up computation. One new method accommodates accurately the disparity in time scales between electron motion (short) and ion motion (long) [4]. Furthermore we are now seeing an increase in the use of particle simulations outside fusion plasmas where they were initially applied, such as in the plasma-assisted processing of materials.

The AIC simulation example illustrates the value of particle simulation in giving a comprehensive look at plasma collective and kinetic nonlinear behavior. Because particle simulations rely on first principles, only a few underlying assumptions are required. The simulation can come very close to mimicking the actual experimental situation, and permits us to probe details of plasma behavior not generally available to the experimentalist.

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FIGURE CAPTIONS

Fig. 1. Plot of AIC instability wave magnetic field, with a single wave, showing exponential growth with time initially, up to end of growth, saturation. The inserts show $v_\parallel$ of the 12,032 particles used as a function of the gyrophase in the wave frame, displaying the development of particle trapping in the wave.

Fig. 2. Effect of the AIC instability with 100,000 particles and many waves on the ion distribution function in $v_\perp$, $v_\parallel$ space (density contours). The initial distribution (a) is within the magnetic mirror loss cone (solid line); particles are mirror trapped. The instability saturates at (b), with many particles transported across the loss cone and, hence, out the mirror ends. At later time (c), beyond saturation, there is much larger particle loss and temperature relaxation.

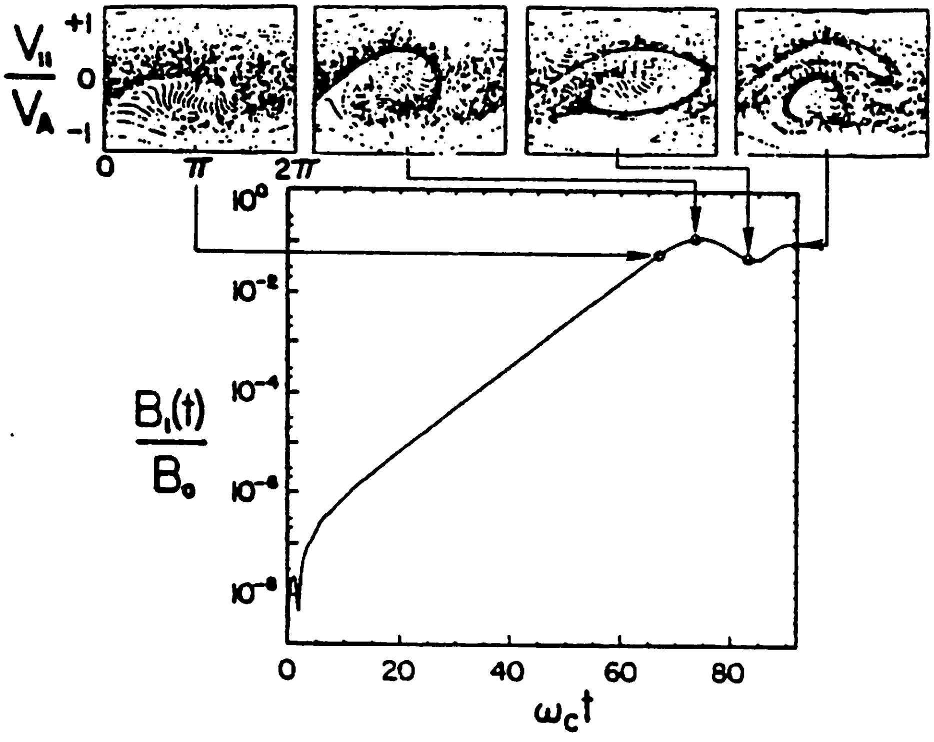
$\frac{V_{\parallel}}{V_A}$
+1
0
−1
0
π
2π
$\frac{B_1(t)}{B_0}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
20
40
60
80
$\omega_c t$

Figure 1

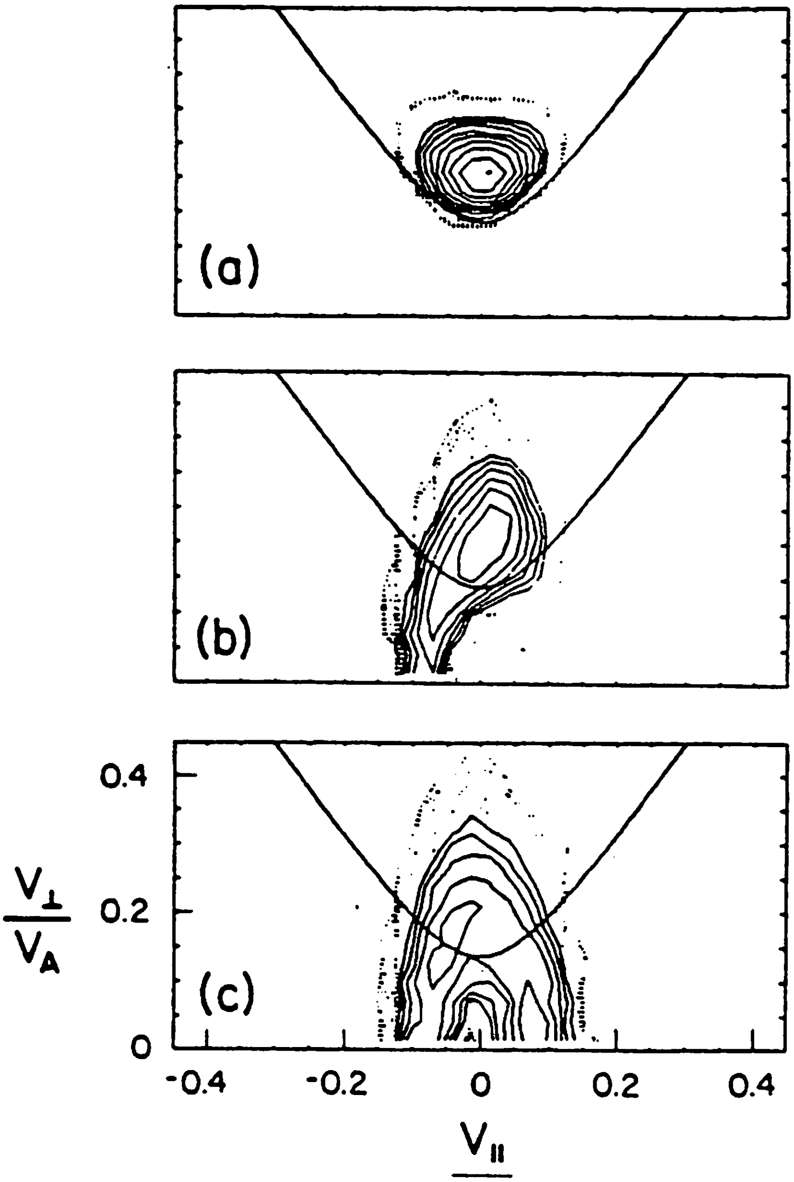

Figure 2