Doing physics with computers

Computations in plasma physics

Computers of all sizes are assisting in theoretical calculations of increasing sophistication and precision, and in the design, direction and analysis of experiments.

Bruce I. Cohen and John Killeen

Physicists around the world are today vigorously pursuing research in plasma physics, not only because nearly all matter in the Universe is in the plasma state, but because plasma physics has many important terrestrial applications. Researchers in the field quickly recognized the complexity of phenomena supported by collections of charged particles, and by using computers they have significantly accelerated the maturation of plasma science. Recent advances in computational models[1] and computer hardware have greatly improved the correspondence of computer calculations with experimental data.

Plasma experimentalists and theorists alike use computers—from microprocessors to the largest mainframes—to supervise experiments, manage the acquisition of data and perform calculations. They are using thousands of complex computer programs, or "codes," to design mammoth fusion reactors and to understand basic plasma phenomena on a microscopic level. However, to guarantee the feasibility of such fusion reactors and to maintain the vitality of plasma science, computers must become even more powerful and widely accessible.

Because of the long-range nature of the Coulomb interaction, plasmas are rich in collective phenomena. Similar in many respects to fluids, plasmas support waves, collective instabilities and turbulence. The discreteness of a plasma's constituent particles, and the effects of their kinetic energy, add another dimension to the scope of plasma phenomena. Particle descriptions of plasmas have much in common with n-body models in astronomy and statistical mechanics. Thus, it is not surprising that the numerical models employed extensively in plasma physics have close counterparts in many other fields, including fluid dynamics, meteorology, statistical mechanics, astrophysics and astronomy.

There is a great diversity of computational models in active use in plasma physics. The variety, number and sophistication of plasma computations have steadily increased as computer capability and the number of researchers have grown. In this article, we survey the use of computers in plasma physics. We will focus on the contribution of computers to research in magnetic- and inertial-confinement fusion, charged-particle-beam propagation and the space sciences. We will look first at the typical use of computers in the design and control of laboratory and spacecraft experiments, and in data acquisition. Then we will discuss the major plasma computational models and some of the important physics problems they address. Finally, we will comment on future directions in the use of computers in plasma research, giving attention to the increasing role of microprocessors and interactive high-speed graphics, and to the need for more-powerful computers.

Computers in experiments. The design and control of laboratory and spacecraft experiments require the heavy use of computers, as do the acquisition and real-time analysis of the data. To design experimental hardware, engineers and physicists make extensive use of computer codes and models. In the magnetic-fusion-energy program, for example, elaborate three-dimensional codes with names such as EFFI, MAFCO and GFUN help specify vacuum magnetic fields and help design coils and supporting structures for conventional and superconducting magnet systems. These codes allow the designer to "build" magnet systems—such as the one in figure 1—from elementary coil segments of various sizes, shapes and orientations. This design activity is often interactive, and is done in conjunction with calculations of the behavior of the plasma using models that we will discuss later.

Dedicated small or moderate-sized stand-alone computers are especially suited to schedule and synchronize the firing sequence in plasma-physics experiments, to control diagnostic hardware, and to coordinate the collection, storage and analysis of data. These computers, which analyze data in real time as well as after experiments, are frequently linked to a network of larger mainframe computers. The control rooms for major fusion and beam-propagation experiments are remarkably similar in appearance and function, and differ very little from accelerator and power-reactor control rooms.

The box on page 57 outlines the network of nine Perkin–Elmer 7/32 and 8/32 computers that will supervise the Mirror Fusion Test Facility now under construction at Lawrence Livermore National Laboratory. The apparatus for this large "tandem mirror" experiment will consist of a central solenoid section bounded on each end by a transition region, a high-field region and a magnetic mirror end plug. There will be neutral-beam injectors, gyrotrons that generate microwaves for electron resonance heating, and 50 to 100 diagnostic systems. A sophisticated computer-automated measurement and control system is essential to the operation of the experiment.

Physics models

In principle, we can compute the behavior of a plasma completely. We

Bruce I. Cohen is a research physicist in the Magnetic Fusion Energy Program at Lawrence Livermore National Laboratory, and is adjunct lecturer at the University of California, Berkeley. John Killeen is director of the National Magnetic Fusion Energy Computer Center at Livermore, and is professor of applied science at the University of California, Davis.

need only carry out the following sequence of steps:

▶ determine the dynamical evolution of the plasma by integrating either fluid, particle or kinetic equations

▶ compute the associated charge and current densities

▶ calculate the self-consistent electromagnetic fields by integrating Maxwell's equations.

In practice, however, even with the use of today's most powerful computers, this step-by-step computation is impractical. As figure 2 shows, plasma phenomena occur over enormous spatial and temporal ranges. To resolve the full span of time and space scales that exist in a real plasma might require perhaps 10^5 to 10^{10} spatial zones and a like number of time steps. In actual practice, we must either compress the range of time and space scales by a choice of artificial plasma parameters, or reduce the number or complexity of the equations by making an expansion in a small parameter. Let us look at seven important computational models and some of their applications, and then examine briefly some relevant advanced software.

Magnetohydrodynamic equilibria. Of particular interest in the design and operation of laboratory experiments are "equilibrium codes," which are programs used to compute and analyze equilibrium plasma configurations; in fact, the reliable and precise calculation of plasma equilibria has been a prerequisite to the success of major fusion experiments. The computation of magnetohydrodynamic equilibria requires the solution of elliptic partial differential equations, as does the calculation of "guiding center" equilibria, in which some orbital kinetics are taken into account.[3] Computer codes designed to do these calculations use a variety of iterative and direct methods.

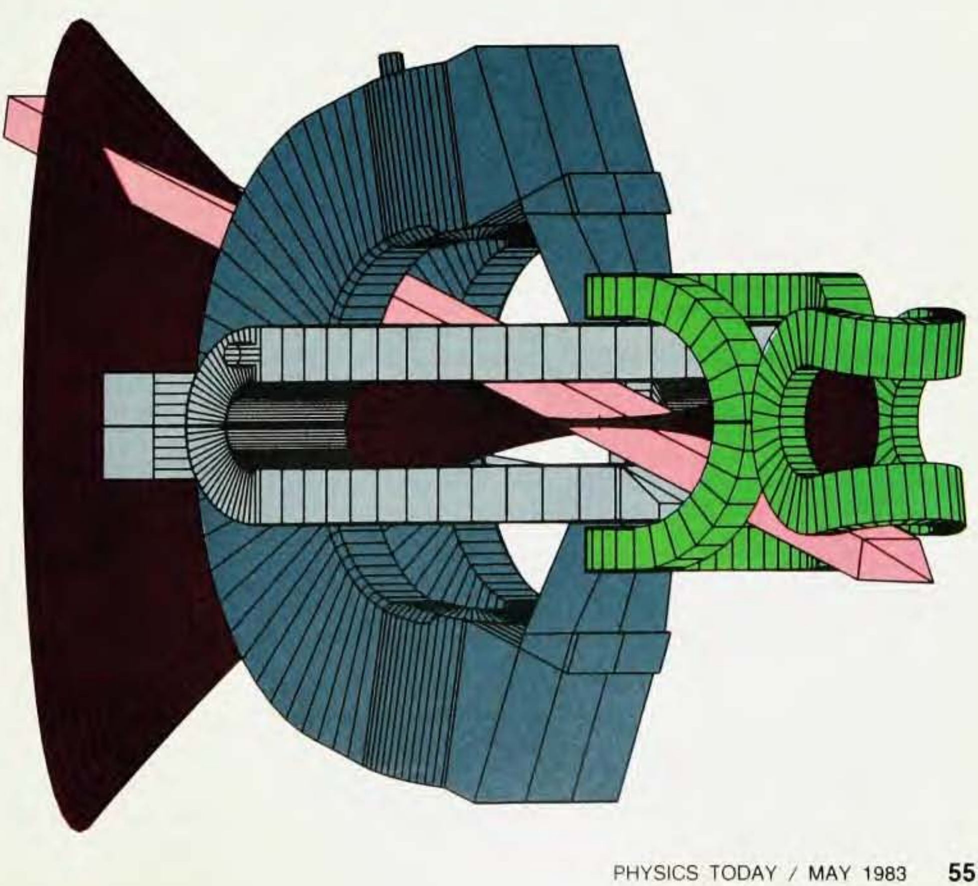
The simplest equations describing a plasma at equilibrium are

$$\mathbf{j} \times \mathbf{B} = c\nabla \cdot \mathbf{p}$$
$$c\nabla \times \mathbf{B} = 4\pi \mathbf{j}$$
$$\nabla \cdot \mathbf{B} = 0$$

where $\mathbf{j}$ is the current density, $\mathbf{B}$ is the magnetic field and $\mathbf{p}$ is the pressure tensor. One matches the number of unknowns and the number of equations by providing a relation between the pressure, the magnetic field and the total magnetic flux ψ. For systems with closed magnetic field lines, such as tokamaks and toroidal pinches, a scalar pressure $p(\psi)$ is often sufficient. Open-ended systems, such as magnetic mirrors, typically support anisotropic plasmas, and a tensor pressure is required. One can use guiding-center theory[3] to calculate the pressure tensor $\mathbf{p}(\psi,\mathbf{B})$.

Designers of magnetic field-coil systems in tokamaks now use equilibrium codes on a routine basis. The ISX-B tokamak at Oak Ridge National Laboratory is a good example of the use of equilibrium codes to improve the design of poloidal coils. Considerable expense in power supplies and control circuitry was saved by combining the ohmic heating coils, the vertical field coils, and the coils that force the plasma's cross section into the desired shape. The optimization of the coil design not only cut the required current in half, but resulted in a very flexible field system, which can produce plasmas of various shapes for stability studies.

Tandem-mirror plasma equilibria are in some respects more complicated than those usually encountered in toroidal devices. Anisotropic pressure, the coexistence of several distinct plasma components, and the three-dimensional nature of these equilibria all increase the difficulty of computing realistic configurations. To these difficulties one must add the complicated structure of the magnetic and electric fields that arise form the various segments of the tandem mirror system—the central cell, transition regions, thermal-barrier cells (which prevent

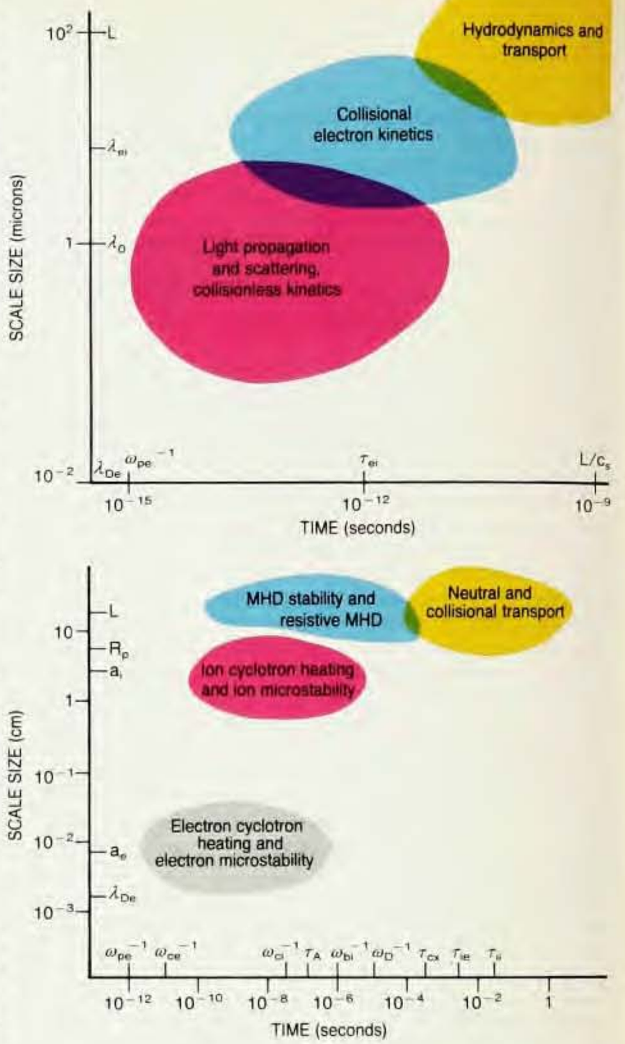


Magnet system consisting of various coils designed by computer. This perspective drawing shows one end of the tandem-mirror plasma confinement device now under construction at Lawrence Livermore Laboratory. The coils on the left (blue) act as a magnetic-mirror end plug; the other coils generate a magnetic field for the transition region between the end plug and the central solenoid section of the device. The cross-hatched region (magenta) represents a plasma surface enclosed by magnetic-field lines. This surface is 30 cm in diameter in the central solenoid section. The diagonal shaft denotes the path of an injected neutral beam. (Drawing courtesy of Gary Yamaguchi.) Figure 1 the mixing of hot electrons in the end plugs with cooler electrons in the central cell), and end-plug mirrors—all of which influence the equilibrium configuration.

Calculations of three-dimensional magnetohydrodynamic equilibria vary from analytical treatments of idealized low-beta plasmas (beta is the ratio of the plasma pressure to the energy density of the confining magnetic field) to more realistic, numerical treatments of high-beta plasmas. The analytical calculations of plasma equilibria in tandem mirrors with quadrupole symmetry, even in the limit of plasmas that are geometrically long and thin, yield complicated formulae that must be evaluated numerically if they are to be applied to the solution of stability and transport problems. Without the approximation of long and narrow plasmas, one must solve much more complicated three-dimensional equations.

Magnetohydrodynamic stability. Plasma physicists want to be able to predict the circumstances under which a plasma will be stable, and they have developed magnetohydrodynamic stability codes for this purpose. These time-independent codes calculate the magnetohydrodynamic stability of equilibrium configurations of plasmas by solving the appropriate linearized, perturbed equations for their normal modes.[4] The stability codes are based on the assumption of "ideal" magnetohydrodynamic conditions, under which the plasma behaves as a simple fluid showing no resistivity and no effects of finite particle orbits. Stability calculations determine the ranges of parameters for which plasmas will be stable, and they predict the frequency spectrum of the normal modes of spatial and temporal oscillation of the plasma's particles and fields. These calculations are useful in interpreting the measured spectra of fluctuating electric and magnetic fields, and in analyzing the heating of plasmas by electromagnetic waves, particularly Alfvén waves.

Magnetohydrodynamic stability calculations often use an energy principle together with the Lagrangian associated with perturbations about an equilibrium configuration to formulate an eigenvalue problem. Setting the variation of the time integral of the Lagrangian equal to zero leads to the Euler–Lagrange equations—a set of partial-differential equations that one can solve numerically, if not analytically. These equations describe the evolution of the plasma. One approach to solving the equations employs a set of carefully selected expansion functions, which reduce the problem to one of minimizing an algebraic quadratic form with respect to certain variational parameters.



Space and time scales showing the large range of plasma behavior of interest in inertial confinement fusion (top) and magnetic confinement fusion (bottom). The upper diagram indicates the range of phenomena in a plasma generated by a neodymium–glass laser of wavelength λ_0. Other parameters characterize the plasma: electron mean-free-path before encountering an ion λ_{ei}, electron Debye length λ_{De}, plasma dimension L, plasma frequency ω_{pe}, electron–ion mean collision time τ_{ei} and speed of sound c_s. The diagram below is for a representative deuterium plasma confined by a magnetic mirror. Parameters include electron and ion Larmor radii a_e and a_i, plasma radius and length R_p and L, electron- and ion-cyclotron frequencies ω_{ce} and ω_{ci}, ion bounce and drift frequencies ω_{bi} and ω_D, mean ion–electron and ion–ion scattering times τ_{ie} and τ_{ii}, Alfvén-wave transit time τ_A, and the mean neutral-beam charge-exchange time τ_{cx}. (Reference 2.) Figure 2

Important examples of magnetohydrodynamic stability codes are PEST at the Princeton Plasma Physics Laboratory, ERATO at Ecole Polytechnique in Lausanne, Switzerland, and GATO at GA Technologies Inc. in San Diego; these codes have been used in designing and analyzing the stability of major toroidal magnetic confinement experiments.

Plasma physicists have applied linear magnetohydrodynamic stability codes to the study of kink, sausage, hose, interchange and ballooning instabilities in magnetically confined plasmas. One recent result of extensive computer calculations using such codes was the recognition that ballooning modes of low azimuthal mode number can from large radial channels that connect the interior of a plasma column to its edge. Ballooning modes grow like aneurisms in regions where the curvature of the confining magnetic field is concave to the plasma. For a given configuration of magnetic field and conducting walls, these instabilities determine the greatest stable plasma pressure.

Techniques developed in studies of ballooning modes in the limit of ideal magnetohydrodynamics are now being used to study resistive ballooning modes, again with close interaction between analysis and computation. This understanding of ballooning has already had a strong influence on machine design. The design of the present generation of tokamaks of noncircular cross section, such as Princeton's Poloidal Divertor Experiment and General Atomic's Doublet, is based largely on the prediction that such devices are stable against the ballooning instability at higher pressures than are circular devices. Furthermore, studies of the three-dimensional magnetohydrodynamic stability of plasmas in exploratory devices, such as the "spheromak," have influenced the design of coils and the positioning of conducting walls. In the case of the spheromak—a compact toroidally shaped device with no inner wall—studies predicted a tilting instability, which was subsequently observed experimentally.

Time-dependent MHD. The detailed comparison of theory and experimental data from magnetic-confinement devices, laser-driven pellet implosions, and spacecraft measurements of Earth's magnetosphere depends on the application of two- and three-dimensional magnetohydrodynamic codes. Time-dependent magnetohydrodynamic calculations can simulate the development of equilibrium and stability on short time scales—nanoseconds to microseconds in most laboratory experiments. One application exciting interest today is in the study of the early stages of tokamak discharges and the formation and destruction of magnetic surfaces. Other important examples are the evolution of Rayleigh–Taylor instabilities in laser-fusion ablative implosions (figure 3) and bubble formation in the magnetosphere of the Earth.[5]

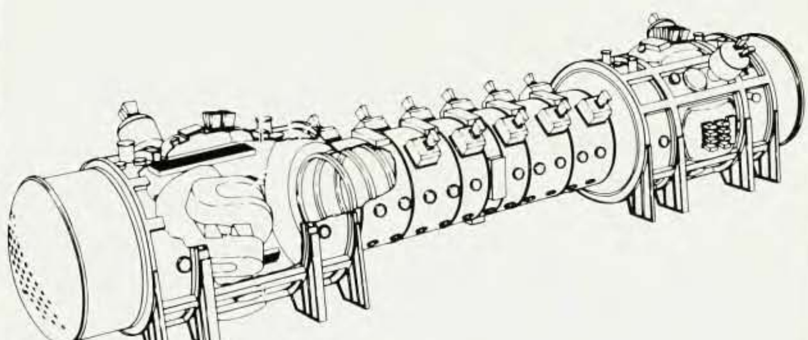
Codes that calculate short-time-scale magnetohydrodynamic evolution are typically used to investigate the time-dependent linear and nonlinear behavior of instabilities. The main question to be answered is whether or not a particular magnetohydrodynamic mode is unstable, and if so, how fast does it grow, what is its structure, and how destructive is it? Although linear magnetohydrodynamic stability problems are often amenable to analytical solution, nonlinear problems, including the effects of resistivity, rely almost totally on computers.

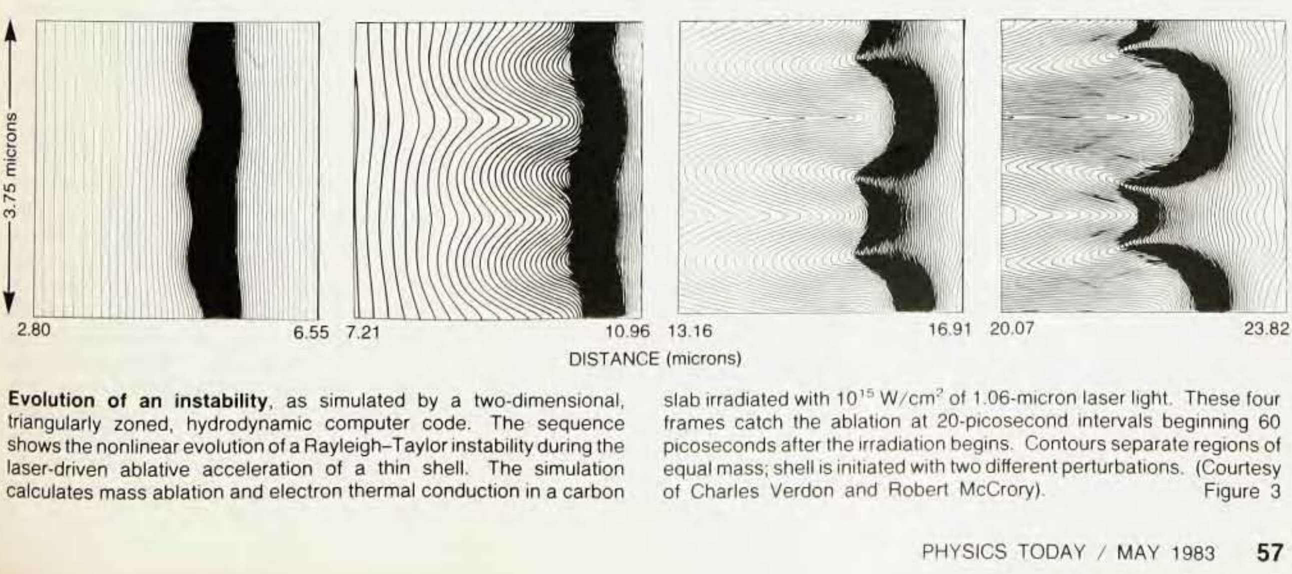
To analyze nonlinear resistive instabilities, one must solve the time-dependent magnetohydrodynamic equations of motion. These comprise a coupled system of eight time-dependent, nonlinear, partial-differential equations, whose three-dimensional solution is a formidable task on any computer system. To follow the flow of the plasma and the development of the fields, one combines the fluid equations for conservation of mass, momentum and energy with Maxwell's equations, neglecting the displacement current. One must give a prescription for the heat flux to close the system of equations, and this is usually done by considering particle kinetics or by giving a phenomenological description of the heat flow. Finally, one typically reduces the equations in number or complexity to make the computations more tractable. Despite the difficulty of the problem,

Mirror Fusion Test Facility control hierarchy

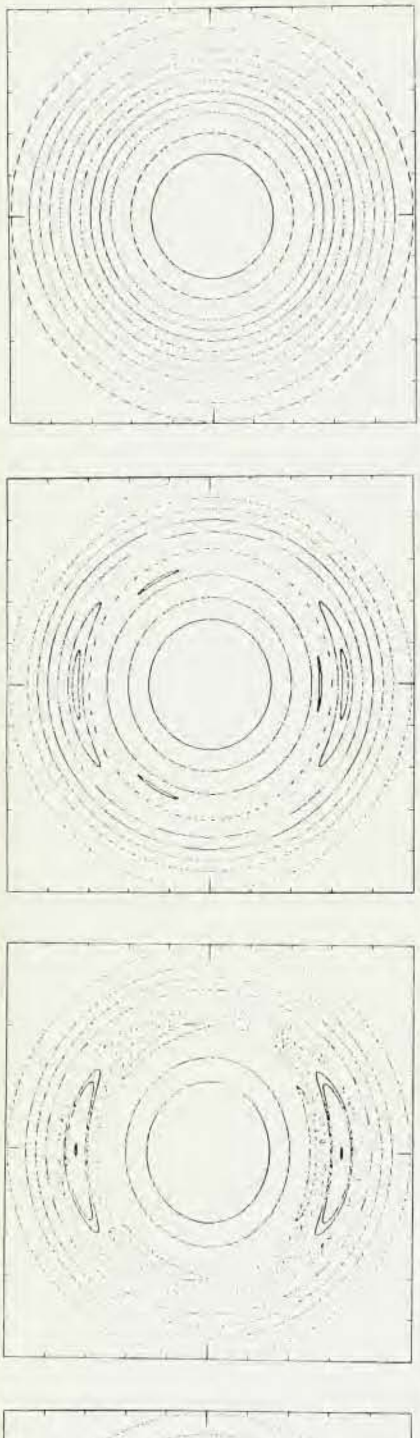
Supervisory computer

- Facility computer
  - 230-kV-pulse power substation
  - Magnets
  - Safety interlocks
- Vessel-systems computer
  - Cryogenic system
  - Vacuum system
  - Getters
- Injector computer
  - Plasma streaming gun control computer
  - Startup neutral-beam computer
  - Sustaining neutral-beam computer
- Plasma diagnostics computer
- Data-base management computer





Evolution of an instability, as simulated by a two-dimensional, triangularly zoned, hydrodynamic computer code. The sequence shows the nonlinear evolution of a Rayleigh–Taylor instability during the laser-driven ablative acceleration of a thin shell. The simulation calculates mass ablation and electron thermal conduction in a carbon slab irradiated with 10^{15} W/cm^2 of 1.06-micron laser light. These four frames catch the ablation at 20-picosecond intervals beginning 60 picoseconds after the irradiation begins. Contours separate regions of equal mass; shell is initiated with two different perturbations. (Courtesy of Charles Verdon and Robert McCrory). Figure 3



Simulated major disruption of a plasma in a tokamak, as calculated by time-dependent, three-dimensional, resistive magnetohydrodynamic equations. The simulation traces the nonlinear evolution of the tearing of magnetic flux surfaces that have differing helical pitches. As viewed in a minor cross section, the tearing leads to the formation of island-shaped perturbations. When islands associated with flux surfaces of two or more distinct pitches overlap, the magnetic-field-line trajectories become random and plasma confinement deteriorates dramatically. (Courtesy of Oak Ridge National Laboratory). Figure 4

there have been notable advances in three-dimensional resistive mangetohydrodynamic codes in recent years.[6,7]

Progress in calculating the magnetohydrodynamics of resistive plasmas in tokamaks has been especially dramatic, and comparison with experiment has been increasingly favorable. Detailed calculations at Princeton, Oak Ridge, Fontenayaux-Roses in France, and Culham in England have given a credible picture of the major instabilities that disrupt plasmas in tokamaks.[7] Figure 4 gives an example.

Macroscopic plasma transport. To simulate the flow, or "transport," of particles and energy in a plasma, one must solve a set of partial-differential equations of the diffusion type. Typical dependent variables are the number densities and temperatures of each particle species, the current densities and the magnetic field. The equations require transport coefficients, that is, coefficients of diffusion, thermal conductivity and electrical resistivity; these are obtained from the best available theories. Physicists have made considerable progress in obtaining numerical solutions of the transport equations for magnetically and inertially confined plasmas, and they have made detailed comparisons of experiments and theory,[8] as we shall see.

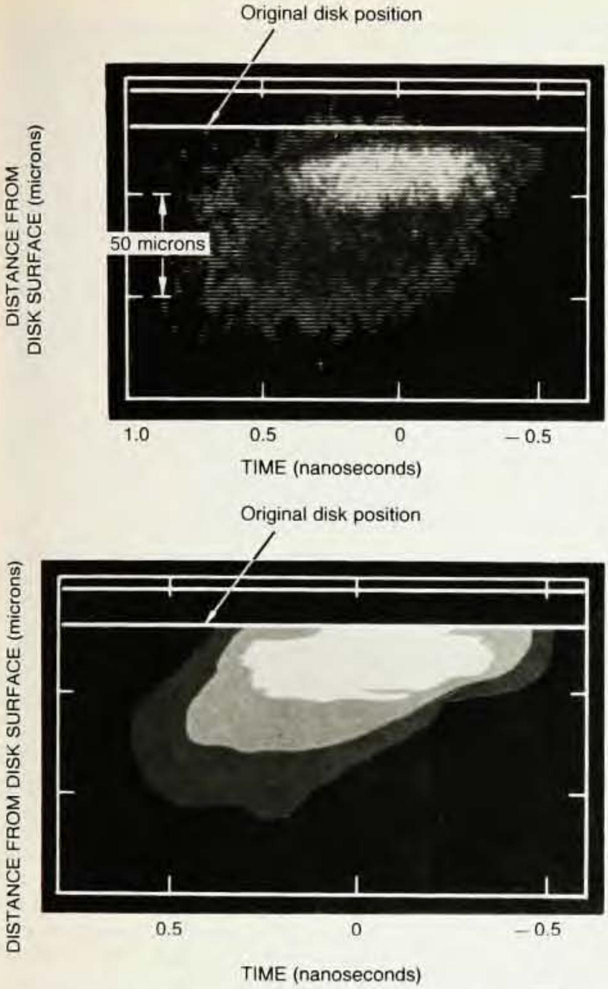
One calculates different quantities when analyzing an existing experiment than when simulating a future experiment. When the goal is analysis, it is sometimes convenient to specify measured density and temperature profiles and then deduce empirical transport coefficients. By contrast, for simulations one specifies the transport coefficients, which are typically based on previous analyses, and then calculates the densities and temperatures.

Whether they are doing analysis or simulation, transport codes generally model many physical phenomena in addition to transport. For example, tokamak transport codes also calculate the evolution of equilibrium, taking into account radiation losses due to impurities, the reflux of material from the chamber walls back into the plasma, sawtooth temporal oscillations in x-ray emission and loop voltage, the programmed injection of neutral gas to replenish the plasma, auxilliary heating of the plasma by the injection of a neutral beam or microwaves, and, of course, fusion over the 10- to 100-msec lifetime of the discharge. Whereas transport is typically treated as one-dimensional, namely perpendicular to the surfaces of magnetic flux, some of the subsidiary calculations often employ more refined geometric models. For example, the equilibrium calculation is customarily two-dimensional, whereas the auxiliary heating models may be three-dimensional. Although inclusion of such refinements allows more realistic modeling, it requires increased computer capacity and capability.

Transport codes, now used routinely in the analysis of data from all major tokamak and mirror experiments, have also proven to be quite useful in experimental design and in the exploration of new operating regimes. For example, transport calculations for Princeton's Tokamak Fusion Test Reactor predicted that large levels of impurity radiation could cause temperature profiles that peak off the principal toridal axis, and such profiles were subsequently observed in the Princeton Large Torus experiment.

Plasma researchers use fluid and Monte Carlo codes to address axial and radial transport in tandem-mirror devices. These calculations, which consider detailed axial and radial profiles and include the effects of collisions, determine electron and ion loss rates as well as confinement properties. In a tandem-mirror device, transverse losses can exceed classical losses because the magnetic field is not symmetric about the main axis. In such a situation, ions satisfying certain resonance conditions experience progressive radial displacements that can be further increased by collisions. Quantitative calculation of the consequences of this phenomenon requires transport codes to represent the plasma both axially and radially. These codes must also model neutral-beam injection, radio-frequency heating and atomic physics processes.

In inertial-confinement fusion research, sophisticated one- and two-dimensional hydrodynamic transport codes have become invaluable in the design and analysis of experiments. The most successful of these codes is the two-dimensional hydrodynamic-transport code LASNEX, which employs a coordinate grid that moves with the plasma. Developed by George Zimmerman and his coworkers at Livermore, LASNEX models hydrodynamics, radiation transport and multi-energy-group electron transport; it then calculates the fusion yield and simulates the



Experiment and simulation of emission from an aluminum disk driven by the Shiva laser at Livermore. The simulation (below) was done with the computer code LASNEX. Shown in each frame is a streaked image of the x-ray self-emission for a 600 picosecond pulse at 5.8×10^{14} W/cm^2. The code was able to accurately model the blow-off and the complex radiation phenomena that occured. (Courtesy of Robert Price and Mordecai Rosen.) Figure 5

dignostic measurements performed in experiments.[9] (See figure 5.) Codes such as LASNEX are unique in that they describe macroscopic transport but also contain some kinetic detail.

Particle and Vlasov codes. Particle codes use first principles to compute the motion of particles under the influence of their self-generated electric and magnetic fields as well as externally imposed fields. Ideal for providing microscopic information on the growth and saturation of strong instabilities and the effect of turbulence, these codes give phase-space distribution functions, fluctuation and wave spectra, and trajectories of individual particles.

Particle codes are usually classified as either "electrostatic" or "electromagnetic." In the first type, one computes only the electric field, and this is done with Poisson's equation; the magnetic field is either absent or constant in time. The second type of code is either relativistic and fully electromagnetic—that is, the equations of particle motion are relativistic and the electric and magnetic fields are obtained from the full Maxwell equations—or it assumes the nonradiative limit, in which the equations are nonrelativistic and transverse displacement currents are neglected.[10]

Particle codes calculate the trajectories of individual particles in serial fashion by integrating equations of motion such as

$$\mathrm{d}\mathbf{x}_i/\mathrm{d}t = \mathbf{v}_i \qquad (1)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(m\gamma\,\mathbf{v}_i) = q(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}/c)$$

where $\gamma = (1 - v^2/c^2)^{-1/2}$, and the electric and magnetic fields $\mathbf{E}$ and $\mathbf{B}$ must be interpolated from a grid to the instantaneous location of particle i. The codes collect charge and current densities ρ and $\mathbf{j}$ from the particles and assign them to nearby points on the grid:

$$\rho(\mathbf{x}) = \sum_i qS(\mathbf{x}_i - \mathbf{x})$$

$$\mathbf{j}(\mathbf{x}) = \sum_i q\mathbf{v}_i S(\mathbf{x}_i - \mathbf{x})$$

The distribution factor S is zero beyond a certain distance from each particle i. The summation extends over the full range of the 10^3 to 10^5 particles in typical simulations. Solution of Maxwell's equations using these sources yields values of the electric and magnetic fields that correctly reflect the fields generated by the particles themselves. These large-scale particle simulations often require several hours of running time on a Cray computer.

Instead of integrating the equations of motion for a collection of particles using equation 1, one can integrate a kinetic equation for the phase-space distribution function $f(\mathbf{x}, \mathbf{v}; t)$. For example, one can solve the collisionless Boltzmann or Vlasov equation

$$\mathrm{d}f/\mathrm{d}t = (\partial/\partial t + \mathbf{v}\cdot\nabla_{\mathbf{x}} + \mathbf{a}\cdot\nabla_{\mathbf{v}})f = 0 \quad (2)$$

Velocity moments of the phase-space distribution function determine the charge and current densities, which one can then use in Maxwell's equations as sources for the fields. Overall, Vlasov simulation gives the same kind of information as particle simulation.

Particle simulation codes have grown from simple one-dimensional electrostatic models to three-dimensional electromagnetic models, although the three-dimensional models are still quite limited. Grid resolution in all particle codes has improved, but not dramatically. However, ion–electron mass ratios are now much more realistic. With recent advances in numerical methods,[11] time steps need not be limited by the resolution of time scales based on the plasma frequency or the cyclotron time. This refinement is important because stability and transport phenomena are often much slower and demand large time steps. However, the simultaneous resolution of very fine and very coarse time scales remains limited.

Particle and Vlasov simulations, by giving a detailed and complete picture of the kinetic behavior of plasmas, are the most reliable tests of nonlinear kinetic theory. They are frequently used to simulate the linear and nonlinear evolution of microinstabilities (instabilities dependent on the details of the particle velocity distribution function). At Princeton, researchers have used two- and three-dimensional electrostatic simulations to analyze low-frequency drift waves that contribute to an anomalous confinement of energy in tokamaks. At Livermore, simulations have verified linear and nonlinear theories of ion-cyclotron instabilities in magnetic-mirror configurations. These theories and simulations have contributed importantly to the strategy on which current tandem-mirror experiments are based. A number of groups are using particle simulations to study the heating of magnetically confined plasmas by electromagnetic waves tuned to the lower hybrid and electron- and ion-cyclotron frequencies. They are doing this computer work in support of various experimental devices—the Princeton Large Torus, the Elmo Bumpy Torus at Oak Ridge, Alcator C at MIT and Doublet at GA Technologies.

Particle simulation plays a dominant role in the design and analysis of electron and ion beam-propagation experiments. Two- and three-dimensional relativistic electromagnetic codes, such as CCUBE, in use at Los Alamos and Mission Research Inc., MASK, in use at the Naval Research Laboratory and at Science Applications Inc., model the performance of diodes, klystrons, linacs, beat-wave accelerators and free-electron lasers. These codes reveal the efficiency of beam extraction, the stability, positioning and strength of guide fields, the amount of focusing, and other propagation characteristics (figure 6).[12]

Particle simulation is also used extensively in inertial-confinement-fusion research, particularly at Livermore and Los Alamos. The most important codes are two-dimensional electromagnetic and relativistic. These codes simulate fundamental laser–plasma interactions, including the following: the microscopic details of simulated Raman and Brillouin scattering, the generation of hot electrons, resonant absorption, the steepening of the plasma density gradient, the cratering of the laser-absorption layer of the plasma, the self-generation of megagauss magnetic fields by currents induced by the laser, the two-plasmon decay instability in which laser photons decay into pairs of electron plasma waves, and concomitant effects on heat transport by electrons. These simulations have not only predicted and explained the phenomena observed in experiments, but they have also supplied transport codes with phenomenological transport coefficients.

Other applications of particle codes are diverse. Particle simulations have elucidated the role of "double layers"—sharp steps in electrostatic potential often caused by current-driven microinstabilities—in mechanisms of auroral acceleration, and have been used in the study of collisionless shocks in the Earth's bowshock. Researchers under Defense Department contract have performed three-dimensional particle simulations of the exposure of satellites to x rays and gamma rays.

Kinetic transport codes. In various plasmas, the assumption of a Maxwell–Boltzmann distribution of electron or ion velocities is inadequate, and one must solve kinetic equations to find the distribution functions. For example, at number densities and energies typical of quiescent plasmas in mirror experiments, the end losses are caused primarily by the classical Coulomb scattering of charged particles into the velocity-space loss cones. The kinetic equation describing this process is the Boltzmann equation with Fokker–Planck collision terms[13]

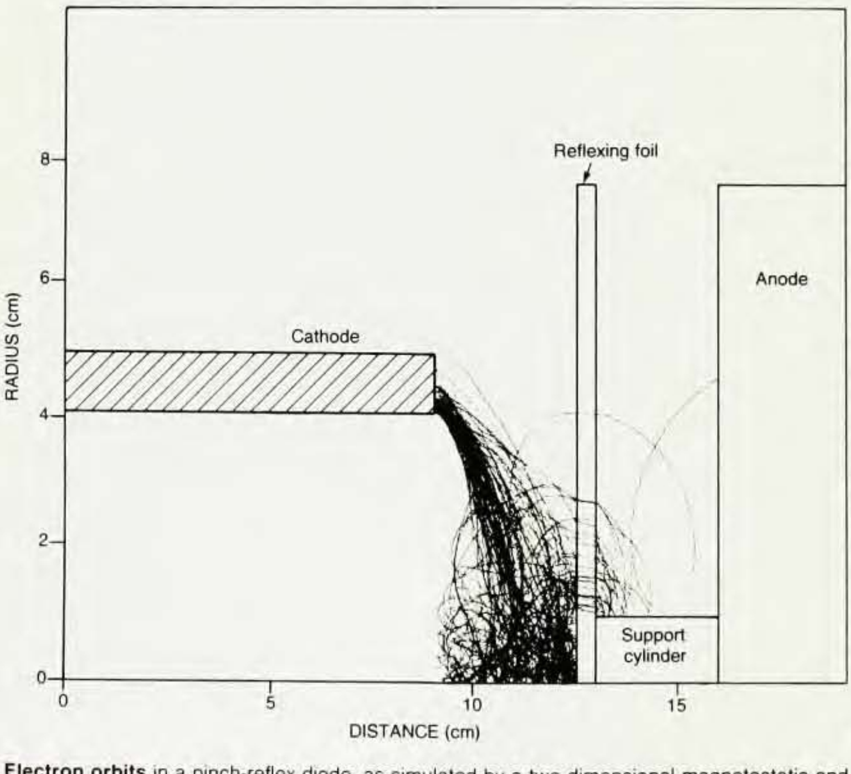
$$\frac{df}{dt} = \sum_i \frac{\partial}{\partial v_i} \left\langle \frac{\Delta v_i}{\Delta t} \right\rangle f + \frac{1}{2}\sum_{i,k} \frac{\partial^2}{\partial v_i \partial v_k} \left\langle \frac{\Delta v_i \Delta v_k}{\Delta t} \right\rangle f$$

The angular brackets indicate that the dynamic friction and diffusion coefficients are determined by an average over many scattering events; df/dt is defined in equation 2. One must solve this equation to study the thermalization of α particles in deuterium–tritium plasmas, to study runaway electrons and ions in tokamaks, to analyze superthermal-electron energy transport in laser fusion, to evaluate the performance of two-energy-component fusion reactors, and to understand the heating of plasmas by energetic neutral beams, microwaves or lasers. Physicists used results from kinetic transport codes in designing the Princeton Tokamak Fusion Test Reactor to obtain fusion breakeven with deuterium–tritium burning.

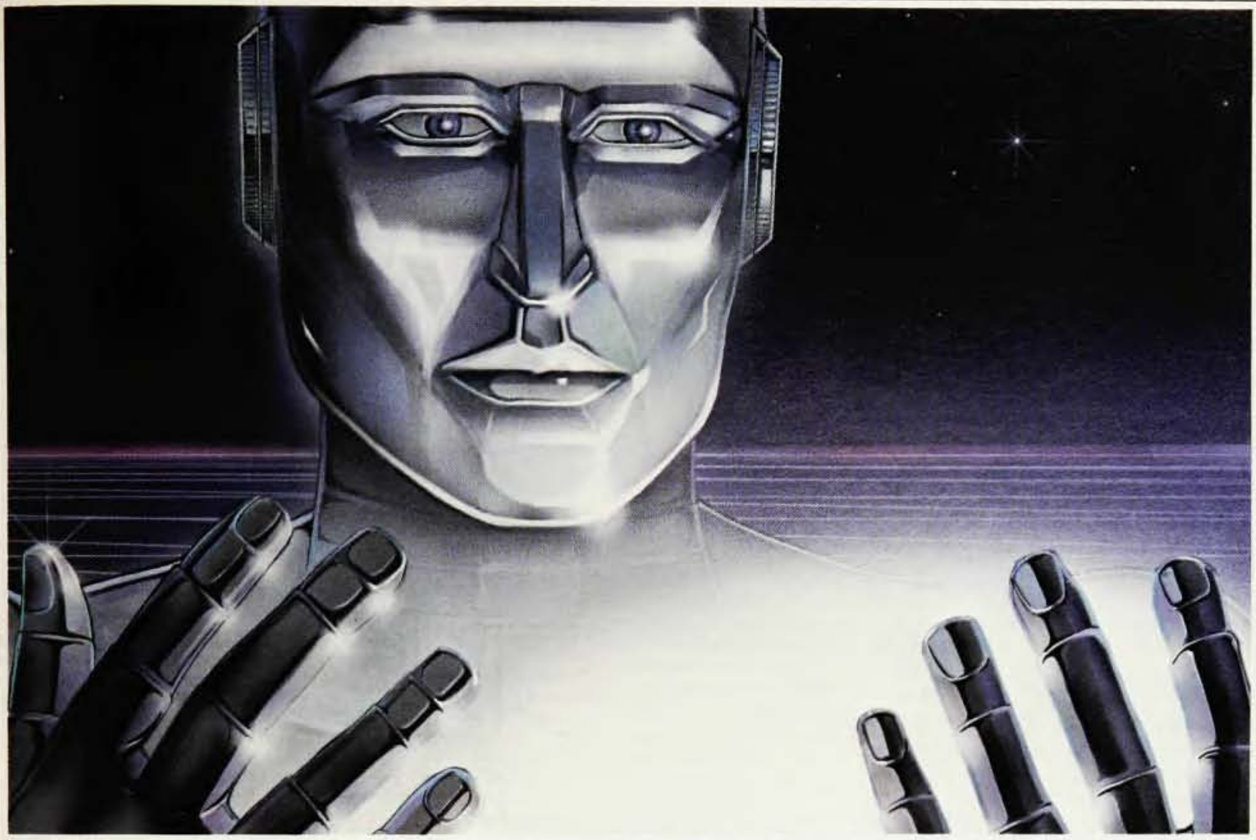
Hybrid codes. A "hybrid code" is one that combines two or more basically different models, and hence, two or more basically different techniques of computation. The most prominent example is a combination particle–fluid code.

The advantage of a particle code alone is that it contains the most complete treatment of the physics. Its disadvantage, which stems from this same feature, is that it is forced to follow the development of the plasma on the shortest time and space scales at which significant plasma phenomena occur. Unfortunately, these scales are typically much shorter than the time and space scales associated with confinement and transport. Fluids codes are attractive because they treat the plasma on coarser scales, and hence need many fewer time steps and spatial points. When the motion of certain classes of particles is important, we must treat those particles kinetically; we may treat the remainder of the plasma with fluid equations. Another useful hybridization is the coupling of a kinetic transport model to a macroscopic plasma transport code, which is the case with LASNEX.

Particle–fluid hybrid models have become increasingly important in the last five years. A typical hybrid model used in magnetic fusion work represents the ion components as kinetic species and the electrons as a fluid; this eliminates some or all electron frequencies and short length scales. Freed from the limitations imposed by



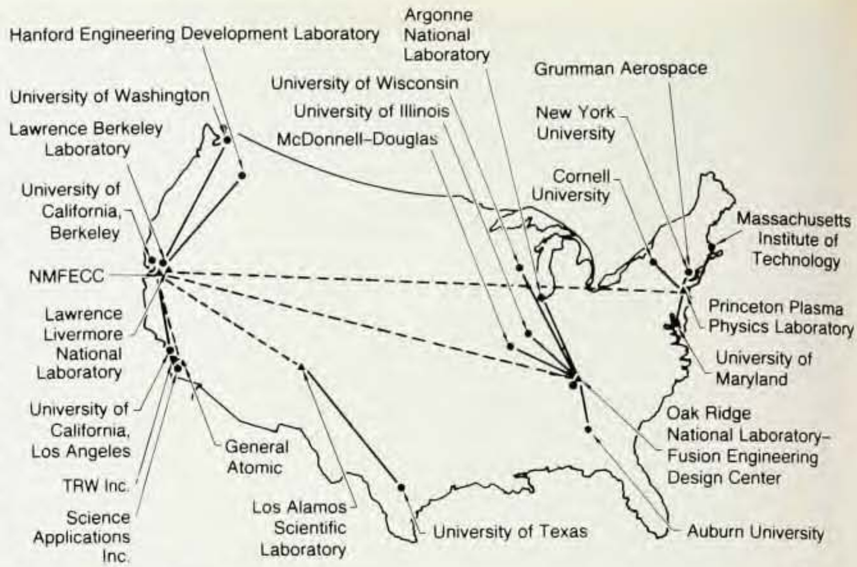
Electron orbits in a pinch-reflex diode, as simulated by a two-dimensional magnetostatic and electrostatic computer code. The horizontal axis is an axis of revolution. Electron emission is limited to the face of a cylindrical cathode. The reflexing foil is an ion source, behind which is the back plate of the anode. The computer code considers diode voltages up to 5 MV, which produce electron currents up to 165 kA. These simulations model the Aurora experiment performed by the Naval Research Laboratory. (Courtesy of Adam Drobot.) Figure 6

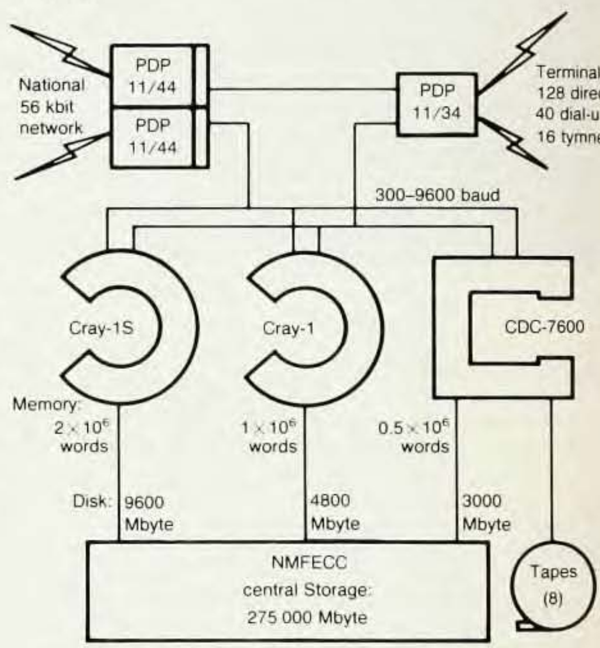


the electrons, one can model the kinetic ion effects on macroscopic, almost magnetohydrodynamic, time and length scales, which are considerably more relevant to experiments. For example, researchers have used hybrid codes to study the ion-temperature-gradient drift instability in a tokamak, and they have applied these codes to the analysis of the formation and stability of field-reversed and toroidal pinches. In beam-propagation research, hybrid models describe the beam itself with a particle model, and the propagation medium—plasma or air—with fluid equations. Laser-fusion researchers are simulating superthermal-electron energy transport and electron-heat-flux inhibition by modeling energetic electrons with kinetic equations and the rest of the plasma with fluid equations.

Advanced software. All scientific disciplines have seen a staggering increase in the development and use of sophisticated computer software. Plasma physicists have been particularly interested in the utilization of automated algebra and the development of structured and automated programming. The MACSYMA system for symbolic manipulation, developed by the Laboratory for Computer Science at the Massachusetts Institute of Technology, has been applied widely in the complicated and often tedious algebraic manipulations that frequently arise in plasma physics. The MACSYMA program also generates its own Fortran coding to numerically evaluate roots, integrals, derivatives and the like for expressions it has already obtained by symbolic manipulation.

To relieve the burden of certain tedious and repetitive programming tasks, plasma theorists have developed automated FORTRAN programming packages, such as OLYMPUS at Culham Laboratories and derivative packages at Livermore.[14] These packages require the user to provide subroutines that both define the particular calculation and are compatible with the structured format of the master program contained in the package.





Network. Map outlines the national magnetic-fusion-energy computer network. Dashed lines represent 56-kilobit/sec satellite links; solid lines denote land links, which are somewhat slower. Schematic diagram shows the hardware configuration of the National Magnetic Fusion Energy Computer Center at Livermore. The center serves 2000 remote users across the country on a time-sharing system. Figure 7

Future directions

Advances in computations derive from improvements in numerical and mathematical techniques as well as from the introduction of more sophisticated computers. To make the most powerful computers accessible to the largest number of people, users have established pools. For instance, the groups working on magnetic-fusion research in the United States have established a national computer network, outlined in figure 7. The National Magnetic Fusion Energy Computer Center at Livermore currently houses two Cray-1 computers and a CDC-7600. Remote users around the country are connected to the center by telephone lines and satellite links. As large mainframe computers have improved, faster computers featuring vector processing and larger fast memories have joined shared networks. The next generation of computers will have multiple central processors and will make possible more realistic and more complex plasma simulations. Calculations will be faster by factors of 4 to 10, and grid resolution will be increased by a factor of 10 or more.

Improvements and cost reductions in peripheral equipment have accompanied improvements in mainframes. Microprocessor technology has invaded plasma physics laboratories, physicists' desktops and plasma experiments flown on spacecraft.[15] In the future, experiments will make greater use of microprocessors for supervision and data management. "Smart" terminals and high-speed interactive graphics, now more common, are especially valuable in the design of laboratory experiments and in processing data collected in experiments and in computer simulations. Special-purpose computers that have been optimized for a specific class of calculations are being introduced as cost-effective alternatives to large mainframe computers.

Plasma computations have evolved from rudimentary one-dimensional models that were performed on the earliest computers to sophisticated three-dimensional simulations that run on today's state-of-the-art mainframes. However, as physicists continue their efforts to analyze and predict plasma behavior, the complexity of the problems will demand further advances in both model building and computer capability.

* * *

We wish to thank the many physicists and engineers who generously contributed resource materials to this endeavor. We are particularly grateful to Steve Auerbach, Carol Gerich, Betsy Sanger and Janet Wikkerink for their expert scientific, technical and editorial assistance in the preparation of this article. Out work is supported in part by United States Department of Energy contract number W-7405-ENG-48 at Lawrence Livermore National Laboratory.

References

1. *Methods in Computational Physics*, B. Alder, S. Fernbach, M. Rotenberg, J. Killeen, eds., Academic, New York (1976), volume 16.
2. B. McNamara, Proc. IEEE **69**, 1043 (1981).
3. B. McNamara in reference 1, page 211.
4. R. C. Grimm, J. M. Greene, J. L. Johnson in reference 1, page 253.
5. C. P. Verdon, R. L. McCrory, R. L. Morse, G. R. Baker, D. I. Meiron, S. A. Orszag, Phys. Fluids **25**, 1653 (1982); S. T. Zalesak, S. L. Ossakow, P. K. Chaturvedi, J. Geo. Res. **87**, 151 (1982).
6. J. U. Brackbill in reference 1, page 1; T. Sato, T. Hayashi, Phys. Rev. Lett. **50**, 39 (1983).
7. R. B. White, D. A. Monticello, M. N. Rosenbluth, Phys. Rev. Lett. **39**, 1618 (1977); B. Carreras, H. R. Hicks, J. A. Holmes, B. V. Waddell, Phys. Fluids **23**, 1811 (1980).
8. J. T. Hogan in reference 1, page 131; D. F. Düchs, D. E. Post, P. H. Rutherford, Nucl. Fusion **17**, 565 (1977).
9. G. B. Zimmerman, W. L. Kruer, Comments Plasma Phys. Cont. Fusion **2**, 85 (1975); M. D. Rosen, D. W. Phillion, V. C. Rupert, W. C. Mead, W. L. Kruer, J. J. Thomson, H. N. Kornblum, V. W. Slivinsky, G. J. Caparaso, M. J. Boyle, K. G. Tirsell, Phys. Fluids **22**, 3020 (1979).
10. A. B. Langdon, B. F. Lasinski in reference 1, page 327; C. W. Neilson, H. R. Lewis in reference 1, page 367.
11. R. J. Mason, J. Comp. Phys. **41**, 233 (1981); A. Friedman, A. B. Langdon, B. I. Cohen, Comments Plasma Phys. Contr. Fusion **6**, 225 (1981); B. I. Cohen, R. P. Freis, J. Comp. Phys. **45**, 367 (1982).
12. R. J. Faehl, B. S. Newberger, B. B. Godfrey, Phys. Fluids **23**, 2440 (1980); R. A. Meger, F. C. Young, A. T. Drobot, G. Cooperstein, S. A. Goldstein, D. Mosher, S. E. Graybill, G. A. Huttlin, K. G. Kerris, A. G. Stewart, J. Appl. Phys. **52**, 6084 (1981).
13. J. Killeen, A. A. Mirin, M. E. Rensink in reference 1, page 389.
14. K. V. Roberts, Comput. Phys. Commun. **7**, 237 (1974); J. P. Christiansen, K. V. Roberts, Comput. Phys. Commun. **7**, 245 (1974); B. McNamara, P. A. Willmann, Lawrence Livermore National Laboratory report UCRL-88387 (1982).
15. F. Mozer, R. B. Torbert, U. V. Fahleson, C. G. Falthammar, A. Gonfalone, A. Pedersen, IEEE Trans. Geo. Elect. **GE-16**, 258 (1978). □