ENGINEERING

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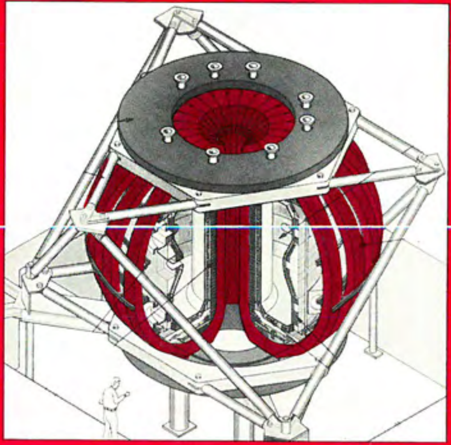

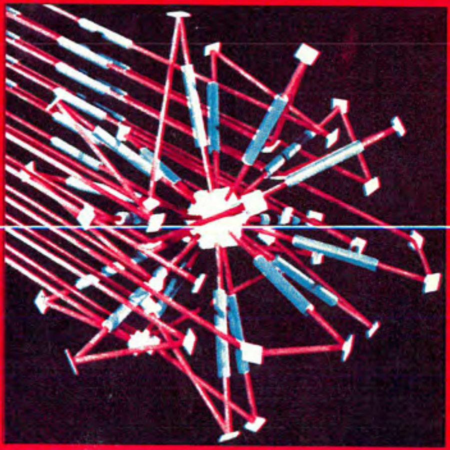

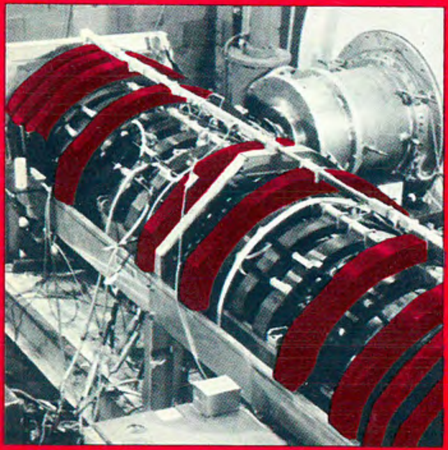

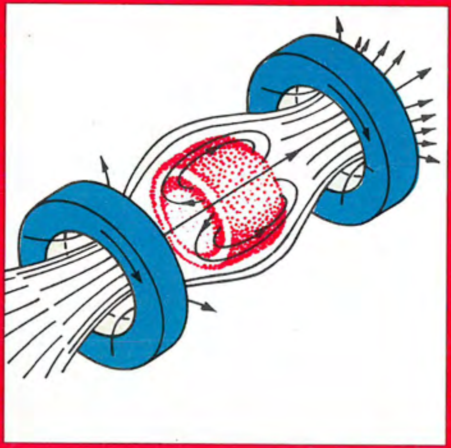

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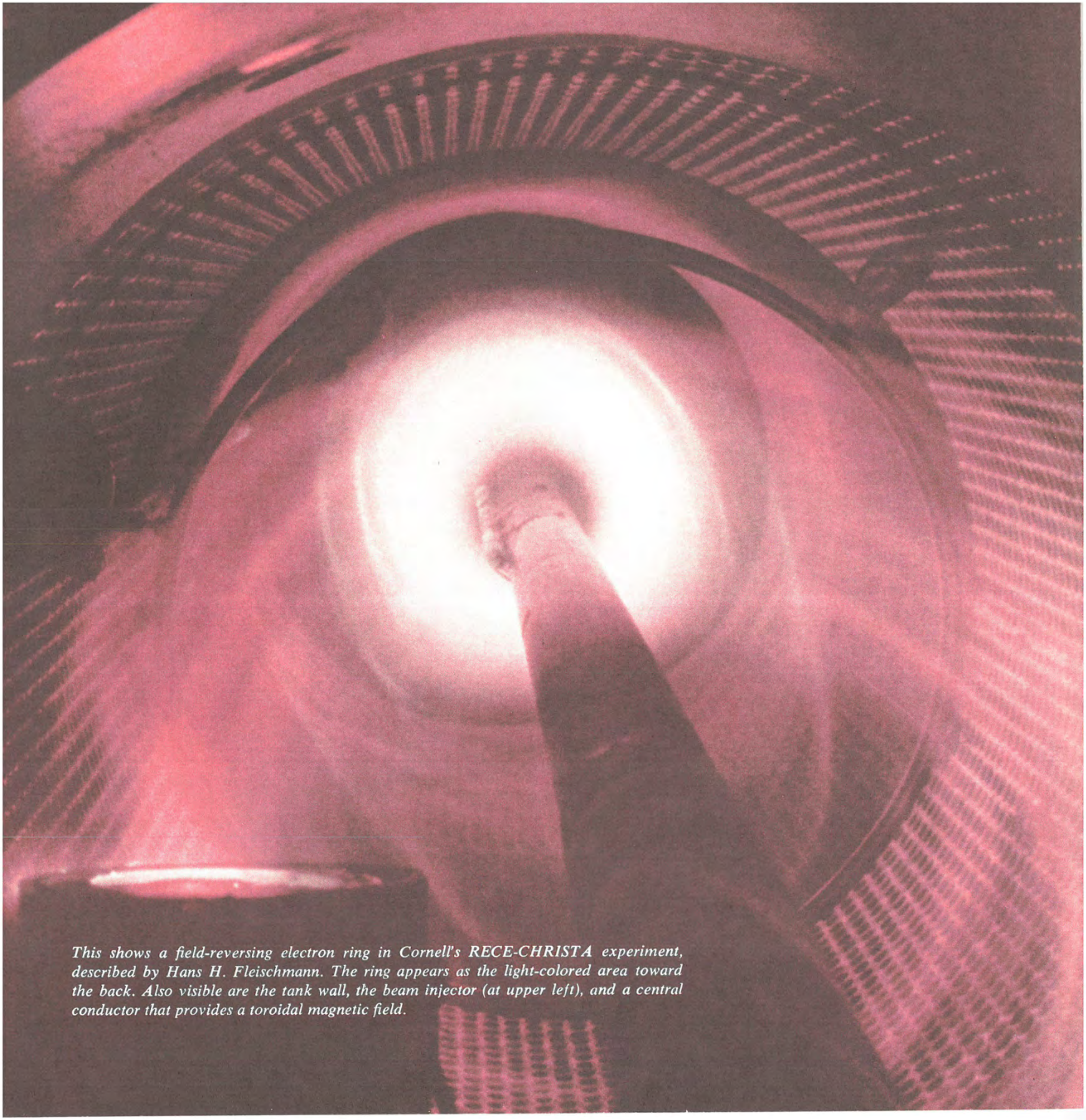
PROSPECTS FOR FUSION POWER



This shows a field-reversing electron ring in Cornell's RECE-CHRISTA experiment, described by Hans H. Fleischmann. The ring appears as the light-colored area toward the back. Also visible are the tank wall, the beam injector (at upper left), and a central conductor that provides a toroidal magnetic field.

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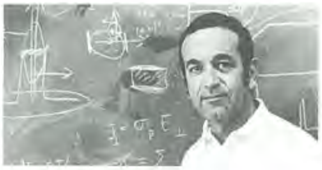

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Outside cover illustrations (clockwise): Model of Doublet III fusion experiment; model of target area of 20-chain laser system for the Lawrence Livermore facility; diagram illustrating ion-ring experiments at Cornell; electron-beam machine at Cornell.

A DECADE OF PIONEERING RESEARCH IN PLASMA STUDIES AT CORNELL

by Ravindra N. Sudan

The Laboratory of Plasma Studies at Cornell was founded exactly ten years ago. This is an appropriate time to consider what we have accomplished, the place our program has in the national research effort, and where we are going from here.

Magnetohydrodynamics, the science of electrically conducting fluids, and plasma physics, its sister science of high-temperature ionized gases, evolved rapidly in the 1950's, partly because they are basic to an understanding of astrophysical, ionospheric, and space phenomena. The main impetus, though, came from the world-wide interest in controlled thermonuclear fusion as a potential source of energy. At Cornell, interest in these two sciences grew in the schools of aerospace and electrical engineering and soon spread to applied and engineering physics. By 1967 the need for coordinating the dispersed research activity led to the establishment of the Laboratory of Plasma Studies with Peter L. Auer as its first director.

Now, a decade later, the personnel at the laboratory includes twenty-six faculty members, eight research or postdoctoral associates, and twenty-seven graduate research assistants. Facilities include an off-campus building for large-scale experimental work, additional laboratories in Upson and Grumman Halls on the engineering campus, and access to large computing centers for fusion research. The laboratory's operating budget for the current year is more than 1.5 million dollars.

The specialty of the Cornell laboratory has been the development of the technology of high-powered electron and ion beams and their applications, especially to fusion research. Some of the earliest work in electron-beam research was accomplished here, and Cornell has continued in the forefront of developments. For example, pulsed intense ion beams were first developed at Cornell, and currently Cornell researchers are exploring new techniques of utilizing collective processes in electron beams to generate high-power microwave pulses and to accelerate high-energy ions. In recognition of the pioneering work in these areas by members of the Laboratory of Plasma Studies, the Second International Topical Conference on High Power Electron and Ion Beam Research and Technology was held at Cornell this past October.

PULSED POWER FROM INTENSE ELECTRON AND ION BEAMS

The early years of the Laboratory of Plasma Studies were devoted to the development of technology to supply large amounts of electrical power at high voltages. The machines that were assembled can deliver between a few hundred kilovolts and 5 megavolts of electrical pulses about 100 nanoseconds in duration. Basically, they consist of a cascaded sequence of electrical energy reservoirs that charge slowly but discharge rapidly (see Figure 1). Such machines are now available commercially; the largest one at Cornell, CREB 5, can deliver 75×10^{10} watts for about 70 nanoseconds. When these electrical pulses are applied to a diode, high-powered 10^{12}-watt electron beams can be extracted. The early work at Cornell on pulsed-power machines and electron-beam physics was done by Professors Simpson Linke, Norman Rostoker (now

> *"The specialty of the Cornell laboratory has been the development of the technology of high-powered electron and ion beams"*

at the University of California, Irvine), John A. Nation, Hans H. Fleischmann, and Bruce R. Kusse, with the assistance of research associates and graduate students.

In 1973 I suggested, in a paper coauthored by my Cornell colleague, Professor Richard V. E. Lovelace, how pulse-power technology could also be used to produce intense beams of ions. This possibility, of potentially greater usefulness in fusion research than the direct application of electron beams, was experimentally demonstrated in 1974 in my laboratory by Stanley Humphries, Jr., and a patent on the invention was recently granted to us. After practical problems of ion emission from a plasma anode and electron current suppression from the cathode had been resolved, we succeeded in designing efficient ion diodes; and when these diodes were powered by a pulsed power machine, Neptune, proton beams of about 100,000 amperes (100 kA) at 300,000 electron volts (300 keV) could be produced routinely. Following this Cornell work, other laboratories, including the Naval Research Laboratory in Washington, D.C., Sandia Laboratories in Albuquerque, New Mexico, Physics International Company in San Leandro, California, and the Lawrence Livermore Laboratory in Livermore, California, also initiated ambitious programs of research on intense ion beams.

Most of the research programs in the Laboratory of Plasma Studies at Cornell are now concerned with applications of this new technology of high-powered charged particle beams. These programs are outlined here and discussed in more detail in the articles that follow.

THE CHALLENGE AND PROMISE OF CONTROLLED FUSION

One of the most challenging projects of this century is to harness the energy released in the fusion reaction between the nuclei of hydrogen isotopes. One of these isotopes, deuterium, is present in water at the level of about one part in six thousand, which means that the supply is practically unlimited; the other isotope, tritium, can be produced by nuclear reaction from abundant supplies of lithium. A successful solution to the problem of how to tap this fusion energy would help meet the long-range energy requirements of developed nations and ensure that a lack of energy does not limit the development of technologically less advanced countries.

Two conditions must be met if controlled fusion reactions are to be technologically useful: (1) the temperature of the fuel in the reactor must be high enough to initiate thermonuclear burn; and (2) the energy output must exceed the energy input necessary to bring the reacting mixture up to the ignition temperature. At the very high temperature of ignition and, indeed, even well below it, the atomic electrons are all stripped away and the reaction mixture consists of positively charged nuclei and free electrons. This mixture is known as *plasma*, a word coined by Langmuir in 1929 to describe its jelly-like properties. In order for a fusion reaction to occur, the plasma must have sufficient thermal energy to permit the positively charged nuclei to interact.

On the basis of known fusion reaction rates, it has been deduced that the optimum temperature is in the range

Figure 1

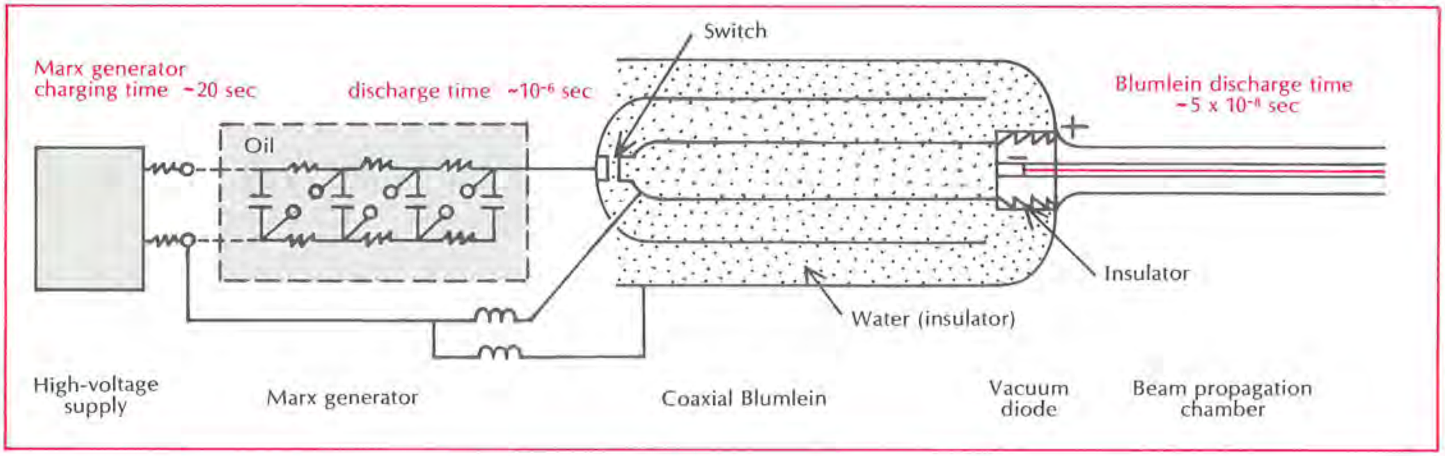

Figure 1. Schematic electrical circuit of a high-power electron-beam machine.

of 100 million degrees Celsius. (As a comparison, we can note that the temperature at the surface of the Sun is only about six thousand degrees.) The requirement that energy output must exceed energy input is known as the *Lawson criterion,* which may be expressed as $n\tau > 10^{14}$, where n is the density of the mixture in particles per cubic centimeter and τ is the length of time, in seconds, for which the heat energy is expected to be retained.

In current research, two entirely different approaches are being pursued to achieve thermonuclear burn conditions. One is *magnetic confinement,* in which the hot plasma is kept away from the vessel walls by means of magnetic fields, and the other is *inertial confinement,* in which plasma fuel in the form of pellets of solid deuterium–tritium ice is ignited before the pellets can disassemble. Research at Cornell is concerned with some of the problems arising from these disparate approaches.

MAGNETIC CONFINEMENT IN FUSION REACTORS

If the charged particles in the plasma fuel were allowed to strike the walls of a containing vessel, they would quickly lose energy. One way of preventing this is to employ magnetic fields to confine and insulate the hot plasma. In actual reactors, superconducting magnetic coils will be used so that power losses in the coils will be reduced to a minimum.

The ability of the magnetic field strength to confine plasma is easily calculated. The pressure exerted by the field on the plasma is proportional to the square of its magnitude; 5 kilogauss, for example, is equivalent to a pressure of one atmosphere. Present-day superconducting technology limits field strengths in the plasma to about 80 kilogauss. The plasma pressure that must be counteracted is equivalent to nT, the product of density and temperature. It follows that at ignition temperature, a density of the order of 10^{15} particles per cubic centimeter is the most that could be confined. This is only 10^{-5} or one-hundred-thousandth of the atmospheric density at ordinary temperatures.

With a density n of this magnitude, the Lawson criterion for ignition requires that confinement time τ must exceed one-tenth of a second. In practical terms, τ must be of the order of a few seconds. Values of $n\tau$ that have been achieved so far by fusion laboratories are indicated in Figure 2 of the *Commentary* by Professor Auer that appears in this issue.

The most successful device for magnetic plasma confinement to date is the tokamak, a "magnetic bottle" conceived by the late Soviet physicist Lev Artsimovich. In the tokamak, the main field is toroidal; that is, the magnetic lines of force are closed within a finite volume. Because of the high $n\tau$ values achieved, the tokamak has been adopted by the Energy Research and Development Administration (ERDA) as the "mainline approach" to fusion in this country. Construction of the Tokamak Fusion Test Reactor (TFTR), a $250 million facility for achieving the Lawson criterion, was begun this fall at the Princeton Plasma Physics Laboratory.

1

2

Scientists from around the world visit Cornell's Laboratory of Plasma Studies.

1. The Soviet-American Workshop on Beam Pellet Fusion, held last April, was attended by a Soviet delegation and representatives of United States laboratories. This group, photographed in the ion-beam laboratory, are, left to right: Eduard Kruglyakov of the Institute of Nuclear Physics, Novosibirsk, Siberia; Ravindra N. Sudan of Cornell; Leonid Rudakov of the Khurchatov Institute of Atomic Energy, Moscow, leader of the Soviet delegation; Edmund T. Cranch, dean of engineering at Cornell; Matthew McHugh, United States Congressman from New York; Stanley Humphries, Jr., assistant professor at Cornell last year, now at Sandia Laboratories; Oleg Gusev of Efremov Institute, Leningrad; Vitaly Korzhavin of the USSR's State Committee on Atomic Energy; and John A. Nation of Cornell.

2. Some 220 delegates registered for an international conference held at Cornell this past October.

3. The keynote speaker at the conference was Valentin Smirkov of the USSR.

4. Conference events included informal discussions as well as about seventy scheduled talks.

The toroidal configuration of the reactor creates formidable engineering problems in both design and maintenance, however, and in recognition of some of the potential difficulties with tokamaks, ERDA is also supporting the "magnetic mirror" approach (see Figure 2), which recently has produced some very promising results at Livermore. The main difficulty with mirrors is the plasma leakage at the two ends of the machine. Although this leakage can be recovered by some clever techniques, the required recirculating power is high

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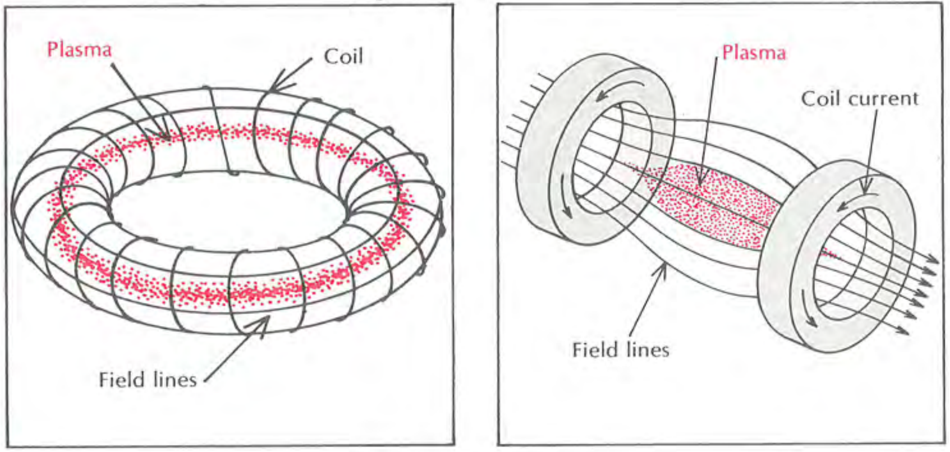


Figure 2a

Figure 2b

Figure 2. The two main types of devices for magnetic confinement of plasma. The sketch at left shows a closed system in which the magnetic field is generated by a coil in the shape of a torus; lines of force and therefore plasma particles are confined to a finite volume. Tokamaks are examples of this kind of system. The sketch at right shows a simple magnetic mirror system. Note the possibility of plasma leakage at the two ends. A way of controlling this leakage is illustrated in Figure 3.

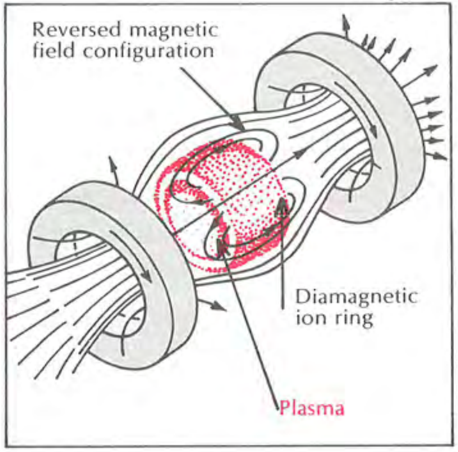


Figure 3

Figure 3. The Astron configuration, invented by Christofilos, which aims to generate a strongly diamagnetic region with closed lines of force within a conventional mirror such as illustrated in Figure 2. Ion rings are expected to provide the circulating current to create diamagnetism.

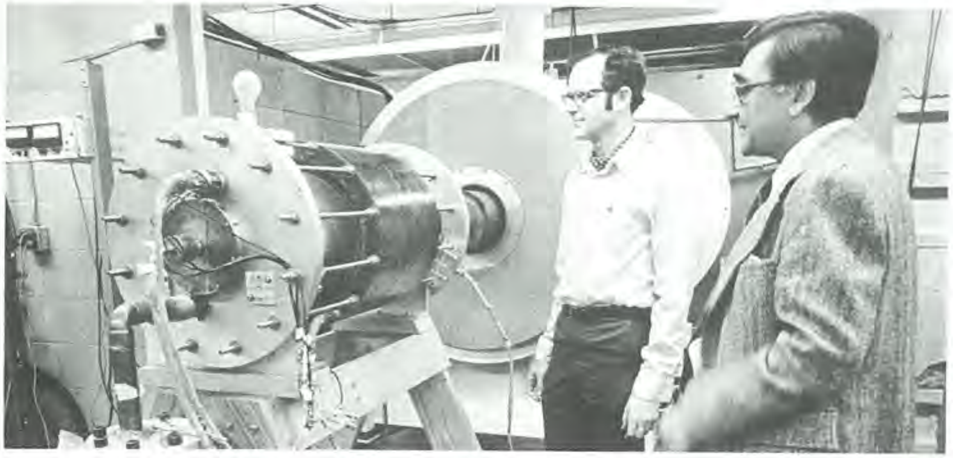
Below: A pilot experiment at the Laboratory of Plasma Studies tests the injection of ion beams into a magnetic mirror to form ion rings. Omnipulse II is a pulsed-power machine designed and built at Cornell. Shown are Philip Dreike, graduate student, and Carl Eichenberger, technician.

enough to make the prospects for development of a magnetic mirror fusion reactor only marginal.

One way of overcoming this inherent deficiency of magnetic-mirror bottles is now being investigated at Cornell. The scheme (see Figure 3) is to inject an intense ion beam to produce a circulating current of ions which create a magnetic field opposed to the field produced by the external coils. The result is a configuration of closed lines of force nested within the open lines. The hot plasma stays within the closed-line region, and the end losses are replaced by much smaller losses across the field lines, as in a toroidal system. Actual experimental work on this Ion Ring scheme has begun with funding from a recently announced $420,000 contract with ERDA.

Professors David A. Hammer, who joined the Cornell faculty this fall, and Bruce R. Kusse, who is now on sabbatic leave at the Massachusetts Institute of Technology, will be heavily involved in the planning and experimental work of this project.

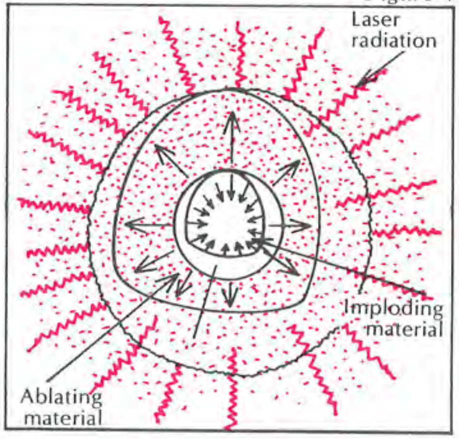
The concept of reversing the field by



Left: This apparatus is used for ion-beam focussing experiments (as diagrammed in Figure 5). Those working on the project are Michael Greenspan, a postdoctoral associate; Professor David Hammer (at left); and author Sudan (at right).

Figure 4. Cutaway view of an imploding pellet of fuel strongly irradiated by powerful lasers.

Figure 4



injection of charged particles was originally proposed by the late Nicholas Christofilos of Livermore. Such field reversal was first achieved at Cornell several years ago by Professor Hans H. Fleischmann and his collaborators by injecting relativistic electron beams; this program is discussed in his article.

INERTIAL CONFINEMENT: AN ALTERNATE APPROACH

In a more recently proposed approach to the achievement of thermonuclear burn, no effort is made to confine the reacting plasma. Instead, the fuel is contained in small pellets and ignition is achieved before the plasma becomes dispersed. This approach is referred to as *inertial confinement* because inertial forces control the speed with which the pellets disassemble during the time required to achieve ignition. Because of the small but finite time required for plasma dispersal—about 1 to 10 nanoseconds (10^{-9} seconds)—the Lawson criterion can be satisfied if the density is very high. The density needed is at least one hundred to over one thousand times the solid density, and therefore enormous pressures, ranging from 10^6 to 10^{11} atmospheres, are required for compression.

A scheme for realizing inertial confinement is indicated in Figure 4. A small pellet, a few millimeters in diameter, of solid deuterium and tritium is irradiated with very powerful lasers. The surface layer heats and ablates and, in accordance with Newton's third law, exerts a compressive force which heats and compresses the central region. While simple in concept, this approach would require tremendous advances in laser technology; the laser power required for thermonuclear burn is in the range of 10^{15} watts.

High-powered focussed beams of electrons or protons are being considered as alternatives to lasers because of their greater efficiency. Proton beams in the energy range of 10 million electron volts (MeV) would have significant advantages over electron beams for pellet ignition provided that it is possible to focus the required power on the small pellets. As a first step in developing this capability, recent experiments at Cornell demonstrated that such beams can be focussed (see Figure 5). Further work to scale up the power is under way.

Another suggestion is to use a beam of high-energy heavy ions, such as 50-billion-electron-volt uranium ions; because of their very high energy, the required number of particles per pulse would be much lower. Such ions can be generated by conventional high-energy accelerators, but the cost gets prohibitive. Acceleration techniques using the space charge of electron beams are currently being investigated at Cornell by Professor Nation.

Figure 5a

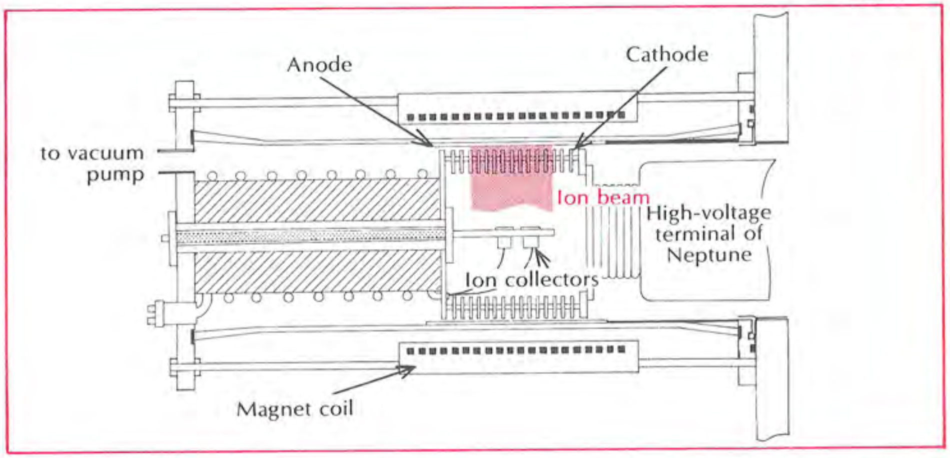


Figure 5b

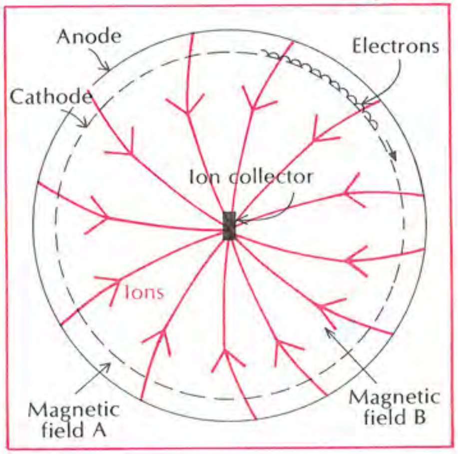


Figure 5. Layout of a Cornell experiment (a) to demonstrate the generation and focussing of intense proton beams. The anode and cathode are made in the form of coaxial cylinders. Ions accelerated by the electric field in the diode gap pass through slots in the cathode and converge onto the axis as shown in the end-on view (b). A 10:1 convergence is achieved on the line focus where the ion current density is about 0.5 kA per cm². Magnetic field A in the gap prevents electrons emitted by the cathode from reaching the anode. A much weaker bias field, B, corrects ion trajectories. Ion pulses of 100 kA at 300 kV have been generated.

Left: In this experiment, ion beams are focussed by magnetic lens. Graduate students Larry Wiley (pictured) and John Maenchen are involved in this project.

PLASMA HEATING AND OTHER BEAM EFFECTS

High-powered beams are also capable of heating plasma and, therefore, are a potential source of the additional heat needed in fusion reactors to raise the plasma to ignition temperature. In a scheme under study at Cornell, the heating effect is obtained by the indirect process of creating waves in the plasma, much as a boat creates a trail of waves when it moves on the surface of a lake; the plasma waves are dissipated as heat energy. Details of the experimental program are given in the article by Charles B. Wharton.

Of course, in order to use beams to heat a plasma confined by a magnetic field, it is first necessary to demonstrate that such beams can indeed be injected into the fields. The toroidal fields of tokamak reactors present special difficulties, but successful techniques have been developed at Cornell and are described in the article by Bruce R. Kusse.

Other ways in which high-powered beams can be put to use are also under investigation in the Laboratory of Plasma Studies. These include the acceleration of ions and the generation of very powerful bursts of microwaves, both of which occur as a result of collective processes in high-energy electron beams (see the article by John A. Nation elsewhere in this issue). Nation was the first to apply high-power electron-beam technology to the generation of intense microwave signals; now research on high-power microwave sources has spread to many other laboratories, both within and outside the United States.

LOOKING AHEAD TO THE NEXT DECADE

Cornell has been active in the relatively new area of plasma research almost from the beginnings. Many of the achievements of the Laboratory of Plasma Studies have been the work of theorists in the faculty research groups—among them Auer, Lovelace, Edward Ott, Richard Liboff, and myself—who predict new phenomena and suggest experiments to verify them. And although space physics forms only a small part of the total Laboratory effort, many theoretical studies of ionospheric, magnetospheric, and astrophysical phenomena that can be understood in terms of plasma physics have been undertaken. Now, as the field of plasma studies is expanding rapidly into areas of direct application, especially in controlled thermonuclear fusion, the Laboratory is proceeding not only with experimental projects but with more computational work to complement the theoretical research. This becomes necessary because calculations to predict the quantitative behavior of plasma in actual devices are extremely complex and require the use of the largest existing computers. The Laboratory now operates terminals on the campus that are linked by telephone to large fusion computing centers at the Lawrence Livermore Laboratory in California and at ENCAR in Boulder, Colorado.

We anticipate a second decade of fruitful research in plasma studies at Cornell, a decade in which we hope to make substantial contributions to the success of fusion.

Ravindra N. Sudan has been director of Cornell's Laboratory of Plasma Studies since 1975. He is the IBM Professor of Engineering and a member of the electrical engineering and applied physics faculties.

In addition to research on pulsed high-power electron and ion beams and high-temperature plasmas, his work has included theoretical studies of very low-frequency radio emissions from Earth's magnetosphere and of turbulence in the equatorial electrojet in the ionosphere. He has published more than ninety papers on these subjects.

Sudan received the B.A. degree from the University of East Punjab in 1948 and the D.I.I.Sc. degree in electrical technology from the India Institute of Science in Bangalore in 1952. He was awarded the J. N. Tata Endowment Scholarship for graduate study in England, and in 1955 received both the D.I.C. degree from the Imperial College in London and the Ph.D. in electrical engineering from the University of London. After working for several years as an engineer in England and India, he came to Cornell in 1958 as a research associate and was appointed to the faculty the following year.

Sudan is a consultant to the Naval Research Laboratory in Washington, D.C., the Lawrence Radiation Laboratory, Livermore, California, and several industrial organizations. He has lectured on plasma physics around the world and has held visiting appointments at the United Kingdom Atomic Energy Authority Culham Laboratory in England, the Center of Theoretical Physics in Trieste, Italy, the Institute for Advanced Study at Princeton, and a number of other American universities. In 1974–75 he spent a sabbatic leave at the Naval Research Laboratory as scientific adviser to the director of research; during an earlier leave, in 1970–71, he was head of the theoretical plasma physics group at that laboratory.

He served as chairman of the organizing committee for the international conference on electron- and ion-beam research held at Cornell this past October, and he has been an active participant in other recent international workshops and conferences.

He is a fellow of the American Physical Society (APS) and has served on the executive committees of the Plasma Physics Division of APS and of the Nuclear and Plasma Physics Society of the Institute of Electrical & Electronics Engineers. He is currently on the editorial boards of Nuclear Fusion *and* Comments on Plasma Physics.

HOTTER THAN THE SUN

Reaching Ignition Temperature in a Controlled Thermonuclear Reactor

by Charles B. Wharton

At ignition the fusable material in a controlled thermonuclear reactor will be several times hotter than the interior of the Sun. How to reach this extremely high temperature, around 100 million degrees Celsius, is one of the chief concerns of fusion research today.

The fuel in a fusion reactor is in the plasma state—a highly energized, completely ionized gas—but a large amount of additional heating energy is required to allow the positively charged nuclei to overcome their mutual repulsion and interact to initiate fusion reactions. A number of ways of providing this extra heating have been proposed, but although experimental machines have come very close to meeting the temperature requirement, ignition has not yet been achieved.

At Cornell we have explored the problem of plasma heating for the past ten years and two techniques that promise to be applicable on the reactor scale are under development.

The first approach we investigated is *turbulent heating,* a technologically simple and highly efficient method of producing significant temperature elevation in dense plasma. (A plasma is "dense" when its concentration is in the range of 10^{13} to 10^{15} particles per cubic centimeter, a near-vacuum by atmospheric standards.) The idea is to cause microturbulence in the plasma through application of a microsecond-long high-voltage pulse; as the turbulence decays, the particles interact and are heated. Later the program was expanded to include a second approach, which is to heat the plasma by injection of a *relativistic electron beam* (E-beam). (Such beams are also used to provide magnetic confinement of a plasma column in other projects described in this issue.) At the present time, either heating technique, or a combination of both, can be studied.

TURBULENT HEATING IN A PLASMA COLUMN

What is turbulent heating and how does it occur? The technique (see Figure 1) is to apply a short pulse of high voltage across a plasma column in such a way that electrons in the plasma flow along the confining magnetic field, creating a large current. What happens is that as the electrons flow past plasma ions, they generate intense microinstabilities, which thermalize and thereby raise the temperature of the plasma. In experiments in our laboratory, we found that a one-microsecond, 100-kilowatt pulse could induce currents up to 25,000 amperes and heat the plasma to 1.5 kiloelectron volts (keV), which is equivalent to about 18 million degrees Celsius. The turbulent levels dropped off quickly and the hot plasma remained stably confined.

The first results of this work were published in 1969: we reported that we had detected the microinstabilities as regions of anomalous resistivity, measured their time dependence, and obtained a turbulence frequency spectrum. The next step was to measure the spatial distribution of the anomalous resistivity. We also studied the plasma ions and found that although their energy distribution was not the normal Maxwellian type (it had a high-energy tail), it was essentially isotropic.

Matters of technical as well as scientific interest were studied in the project.

Figure 1

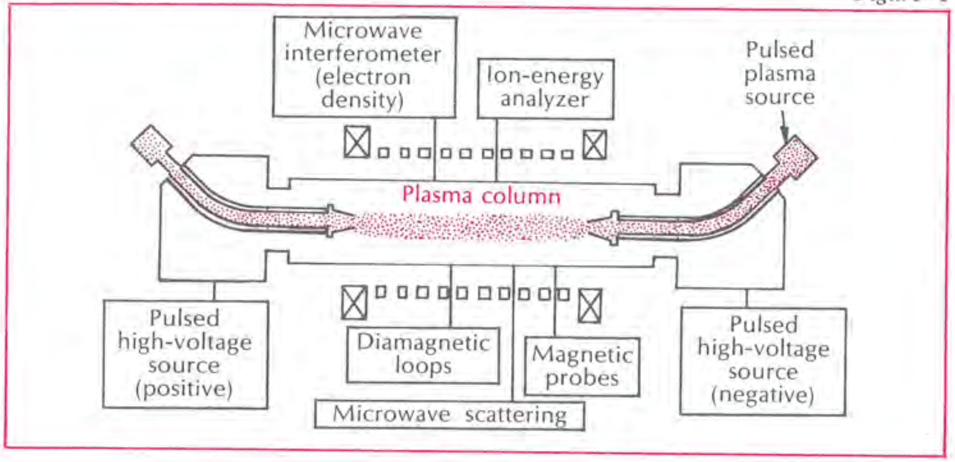


Figure 2

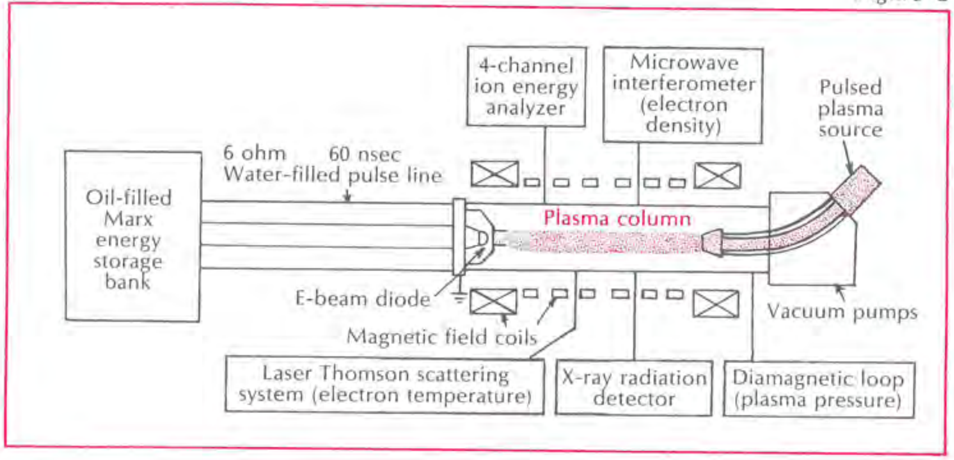


Figure 1. The Cornell facility for experiments in turbulent heating of plasmas by the application of high-voltage pulses. Plasma electrons flowing along the confining magnetic field interact with plasma ions to produce the heating effect.

Figure 2. The facility for experiments in plasma heating by injection of a relativistic electron beam.

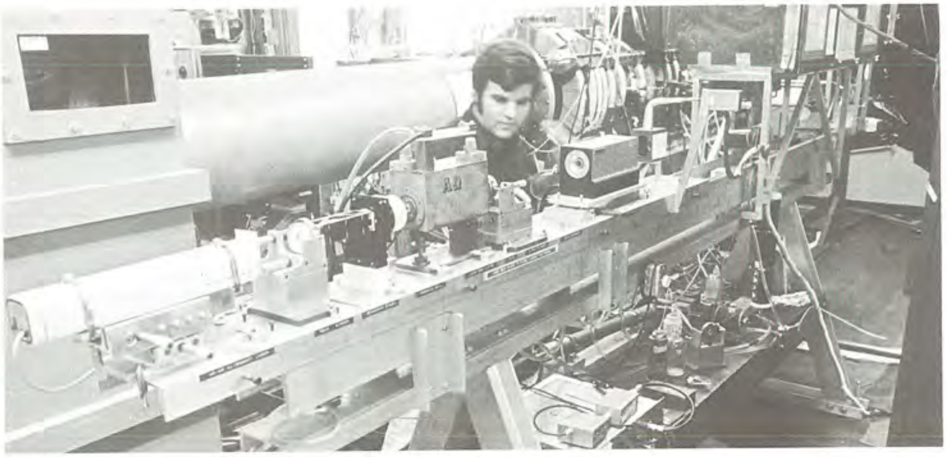
For example, we showed that there are no "runaway" electrons, even when the applied electric field is very high—above the critical value for a "collisionless" plasma (one in which the particle–particle collisions do not dominate the energy distribution). We investigated the *skin effect*, in which electrons flow only on the outer skin of a highly conducting current channel, and found that it does not impede heating rates when the applied voltage is very high. We worked on the serious problem of plasma impurity, which greatly reduces the efficiency of turbulent heating, and developed a technique, called *clean turbulent heating*, that has enabled us to achieve a twenty-fold reduction of contaminants and thereby appreciably increase the containment time of the heated plasma.

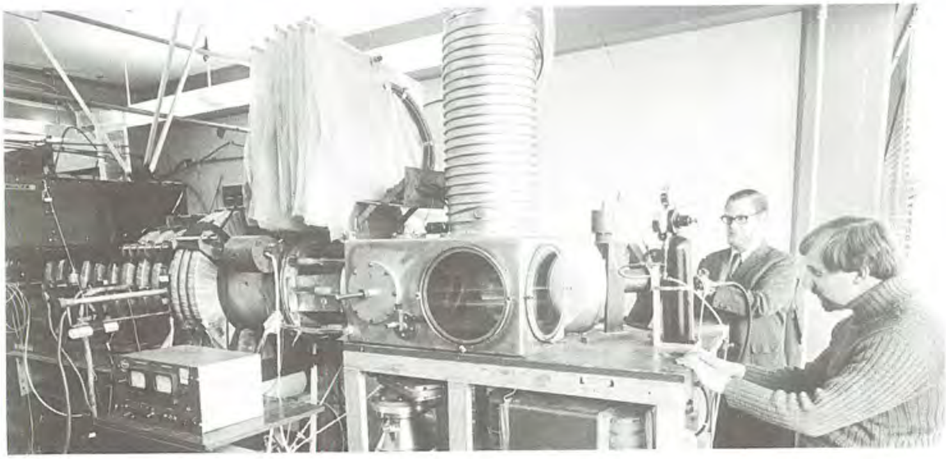
Our research on turbulent heating has shown that it is an effective means of heating plasma to kilovolt temperatures and that it can also be used to prepare a collisionless plasma for further heating by alternative means. Such alternatives include two effects achieved in our laboratory: heating with an electron beam and heating by an ion-cyclotron resonance technique.

HEATING WITH RELATIVISTIC ELECTRON BEAMS

Since we expanded our program to include E-beam experiments, we have been able to obtain energy density levels five to ten times higher than those obtained with turbulent heating alone.

In the E-beam technique, illustrated in Figure 2, a 60-nanosecond pulse of a 500-keV, 60,000-ampere electron beam is shot along the plasma column. The electron beam, generated by a cold-cathode diode, generally passes through a thin-foil anode and enters the plasma along magnetic field lines. Strong microinstabilities are generated and plasma heating occurs rapidly.





Right above: This view shows the relativistic electron-beam apparatus connected to the plasma heating experiment. Graduate student John Sethian (who has since received his doctorate and is now at the Naval Research Laboratory) is shown adjusting the laser-scattering equipment used to measure the plasma electron temperature and density.

Right: The plasma source is being adjusted by Professor Wharton while graduate student Jerry Ferrentino observes the injection region of the plasma-heating experiment. Numerous diagnostic instruments can be seen attached to the vacuum chamber in the left of the picture.

The major emphasis in this work has been on determining the mechanisms of heating. Extensive diagnostic instruments have been developed and applied, and at least three heating processes have been identified and found to have good correspondence with theory.

THE HEATING MECHANISM OF TWO-STREAM INSTABILITY

The dominant mechanism at low and moderate currents, up to 40,000 amperes, is collective interaction caused by a relativistic two-stream instability (see the article in this issue by John A. Nation for a discussion of collective interaction). Energy coupling occurs between beam and plasma electrons, and subsequently a similar coupling energizes the plasma ions. We found that the heating efficiency is high (30 percent) when the beam electrons have very little perpendicular energy (a "cold" beam), but degrades as the beam electrons get scattered, either by the anode foil as they pass through or in the turbulence caused by the instability itself. As the beam penetrates the plasma column, the scattering increases and the interaction is therefore self-limiting: in our experiments, intense heating was confined to the first 20 to 40 centimeters of the plasma column. The "hot" beam then travels the remaining 100 centimeters with only a small loss of energy. The scattering of beam electrons is so intense that at least 20 percent of them gain enough perpendicular energy to become trapped in the magnetic mirror confinement system.

These experimental results on relativistic two-stream instability substantiate theoretical work conducted at Cornell by Lester Thode and Ravindra N. Sudan; the overall work constitutes an important contribution to the understanding of rapid heating by intense collective interactions. These results are important also in the design of long solenoidal systems that will be technically unsophisticated if they can be scaled up to reactor conditions. In such a reactor, break-even conditions (when the energy produced is equivalent to that used, a minimal requirement) would involve, for example, plasma at a density of 10^{17} particles per cubic centimeter, contained in a 150,000-gauss magnetic solenoid 300 meters long and heated by a 200-kiloampere, 8-megaelectron volt electron beam. The beam energy would have to be deposited slowly and uniformly over the length of the plasma column, not all at the near end, and beam tailoring would be required.

THE RETURN-CURRENT HEATING MECHANISM

At high beam currents, the dominant heating mechanism was found to arise in the return current induced by the beam head. The beam-current column generates a circumferential magnetic field whose magnitude varies with the current. As the beam head approaches, the magnetic field strength in a region increases rapidly and induces an electromagnetic force that acts on the surrounding plasma electrons, accelerating them in the direction opposite to that of the beam current. This induced current generates instabilities in a process very much like that of turbulent heating, but at a much higher energy level. The subsequent coupling is directly to the plasma ions, and ion waves similar to acoustic waves are generated. The heating effect is caused by the damping of these waves.[5] This mechanism was predicted by Sudan and Richard Lovelace at Cornell.

The heating efficiency we determined for this mechanism is not as high as the efficiency measured for the relativistic two-stream interaction, but the resulting plasma temperatures are higher —up to 2 or 3 keV—because there is more energy in the electron beam for this mode.

These experiments are significant because they have shown that dense plasmas can be heated to thermonuclear conditions by interactions with relativistic electron beams and that the heated plasma can be stably contained in a magnetic confinement geometry. We are actively working on further applications to reactor systems.

THE OVERALL PROGRAM IN PLASMA HEATING RESEARCH

The experimental program I have discussed was begun when funds from the New York State Science and Technology Foundation enabled us to establish the turbulent heating facility in 1967. In 1973 it was modified to provide the option of plasma heating by an E-beam. Over the years, grants from the Atomic Energy Commission, the Office of Naval Research, and the Army have supported research and student training.

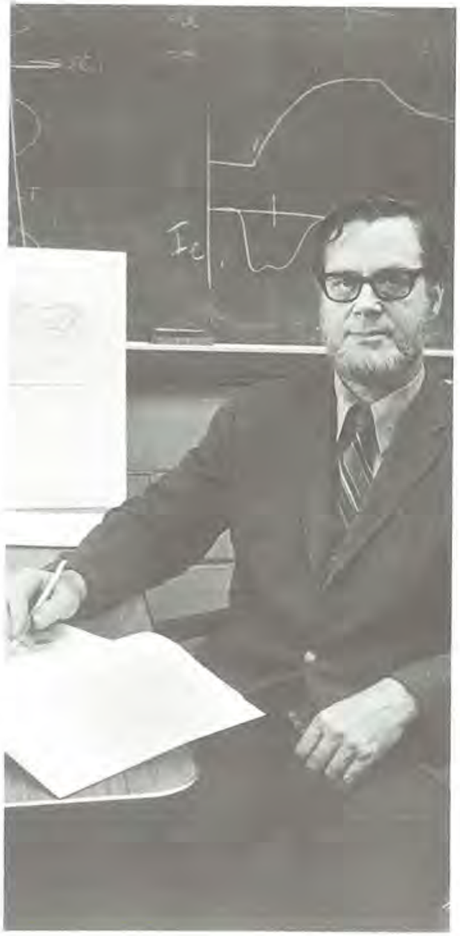
The primary goal was to create a dense, heated plasma in a clean magnetic-confinement geometry using collective interactions. This we have succeeded in doing; now we are working toward the achievement of reactor

"…dense plasmas can be heated to thermonuclear conditions by interactions with relativistic electron beams"

conditions. Another objective has been the necessary one of devising plasma diagnostic methods. We have developed or adapted a great many techniques, including microwave scattering for measuring turbulence spectra, conductivity probes for measuring spatial variations in resistivity, X-ray measurements to indicate electron energies, laser scattering to measure the electron energy distribution, and charge-exchange analysis to measure the ion energy distribution.

In addition to technical achievements such as these, the scope of our program includes theoretical and experimental investigation of processes that occur in thermonuclear systems. The major emphasis, of course, is the exploration of heating mechanisms in fusion systems. Also involved are studies of the propagation of relativistic electrons and other particles in vacuum and in matter.

From the beginnings, then, the program has had both scientific and technological interest, contributing to the understanding of plasma physics and to the development of fusion reactor design.



Charles B. Wharton, professor of electrical engineering, has conducted research in plasma physics for more than twenty-five years. His experience includes twelve years as a staff member of the University of California's Lawrence Radiation Laboratory, where he headed the diagnostics development group in the controlled fusion program; five years at General Atomic in the experimental physics department; and ten years at Cornell, where he has been associated with the Laboratory of Plasma Studies since its inception.

He has also spent several years on leave at the Max Planck Institute for Physics in Munich, Germany; the most recent occasion was in 1973–74, when he received a Humboldt Prize in physics from the Alexander von Humboldt Foundation of Bonn. In addition, he has conducted research at the Atomic Energy Research Establishment at Harwell, England.

Wharton has been a lecturer at the International School of Plasma Physics in Italy, the International Summer Course in Plasma Physics in Denmark, the International Autumn School in Plasma Physics in the Soviet Union, the Summer School on Plasma in France, and the Summer Workshop in Plasma Properties at the University of Maryland. He headed a United States research specialist team that visited the Soviet Union in 1970.

He has published widely in professional journals and technical volumes and is coauthor of Plasma Diagnostics with Microwaves *(Wiley, 1965). His professional activities include service as a consultant to the McGraw-Hill Information Systems Division, the United States Naval Research Laboratory, and the Lawrence Livermore Laboratory.*

Wharton holds the degrees of B.S. and M.S. from the University of California, Berkeley.

HEATING TOROIDAL PLASMA WITH ELECTRON BEAMS

by Bruce R. Kusse

Beams of electrons so energetic that they travel at relativistic speeds can be used to heat the fusable material in a controlled thermonuclear reactor, possibly to the extremely high temperature required for ignition.

There is a difficulty, however, in using such a beam in a *tokamak,* the type of fusion reactor now being developed most intensively. The reactor fuel consists of hydrogen isotope nuclei in the highly energized plasma state, and in a tokamak (see Figure 1) the plasma is confined by a strong poloidal magnetic field. The basic problem in using an electron beam for heating is that of injecting it into the toroidal plasma column.

This problem is being investigated at Cornell in a project sponsored by the National Science Foundation and carried out in the Laboratory of Plasma Studies.

THE PROMISE AND PROBLEMS OF TOKAMAK REACTORS

Tokamaks have come very close to satisfying the two chief requirements for an operable fusion reactor. The first is that ignition temperature must be reached: a reasonable goal is 10 kiloelectron volts (keV), equivalent to over 100 million degrees Celsius. The second requirement is that more energy must be produced from subsequent reactions than is used for initiating reaction: this places a requirement on the minimum value for the plasma density–confinement time product, $n\tau$, called the *Lawson criterion.*

Tokamaks currently under construction are expected to reach the Lawson condition by appropriate scaling of induced current, toroidal field, and physical size. The conditions necessary to increase plasma temperature do not scale as straightforwardly, however, because the fundamental ohmic or resistive heating becomes ineffective at high temperatures where the plasma electrical resistivity decreases. It is commonly accepted that tokamak reactors will require heating beyond that which can be provided ohmically.

One of the schemes for providing this additional heating is being investigated at the University of Nagoya in Japan and at Cornell. This scheme makes use of the relatively new intense relativistic electron beam technology, which has made available beams with energies as high as one megajoule per pulse of 50 to 100 nanoseconds. This is a very promising capability: in experiments in open-ended plasma machines, with use of more modest beams (on the order of one kilojoule per pulse), the transfer of approximately 30 percent of the beam energy to the plasma has been observed. These experiments were conducted at Cornell (see the preceding article by Charles B.

Figure 1

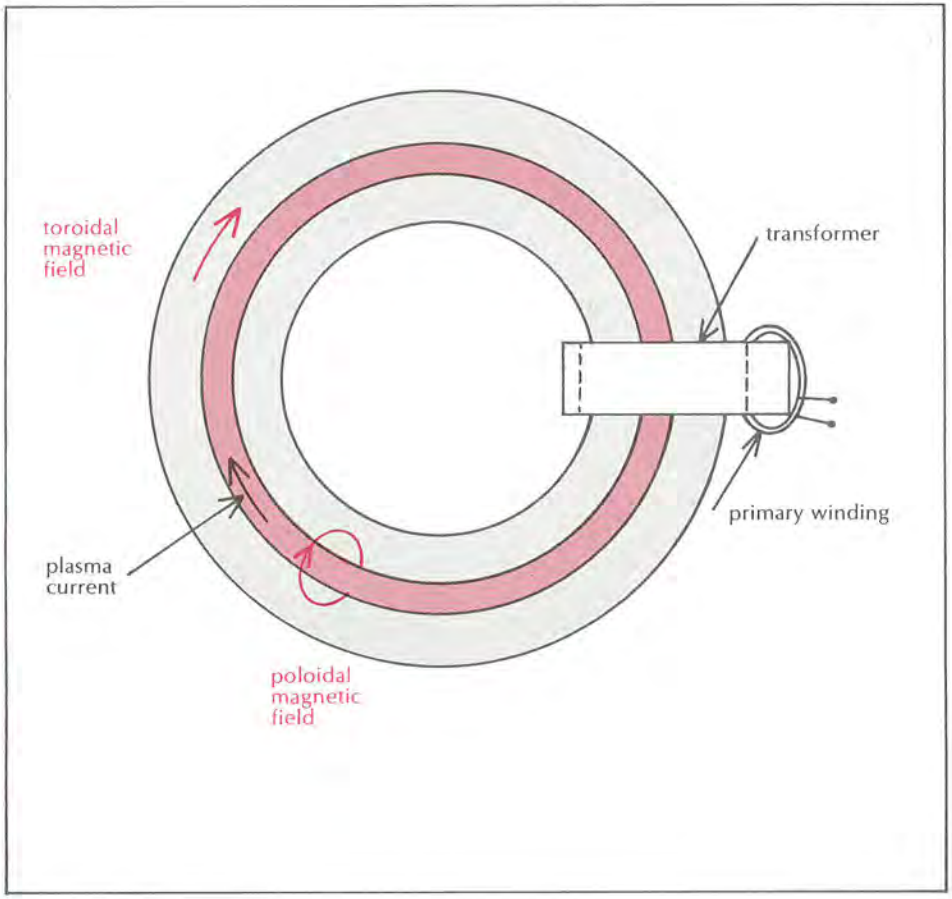


Figure 1. Schematic of a tokamak, showing the magnetic confinement system. A strong toroidal magnetic field (50 to 100 gauss for a reactor) is produced by external coils. The discharge is struck and a toroidal plasma current is induced by making the plasma column the secondary turn of the transformer. This induced current (several megamperes for a reactor) produces a poloidal magnetic field which provides plasma equilibrium, stability, and ohmic heating. The ohmic heating effect of the plasma current most probably will need to be augmented if the plasma is to be heated sufficiently for a nuclear fusion reactor (see Figure 2).

Wharton) and in other laboratories in this country and in the Soviet Union.

Using these beams to heat tokamaks is quite different from using them in open-ended plasma systems, however. In the linear machines it is possible to inject the beam directly into the plasma column, but in toroidal systems it is not. Problems not encountered in the linear experiments occur in three areas —*injection, propagation,* and *beam–plasma interaction.* As might be expected, these areas are not completely independent. For example, the strength of the beam–plasma interaction depends upon the beam propagation and vice versa. Also, the particular trajectories that the beam follows are dependent on the condition of the beam immediately after injection. In our project at Cornell, we have addressed the first two problem areas and are beginning to look into the third.

PROBLEMS IN INJECTING THE ELECTRON BEAM

At reactor field strengths and beam energies, the beam would penetrate only a few millimeters or, at most, centimeters into the toroidal plasma column if it were fired directly across the magnetic field. According to the heating mechanisms identified in the linear experiments (see Wharton's article), the interaction should be strongest when the beam is inside the plasma column; however, there still should be significant energy transfer if the beam is outside but close, particularly if it makes several passes.

Injection of a beam in this manner has been accomplished in our labora-

Figure 2

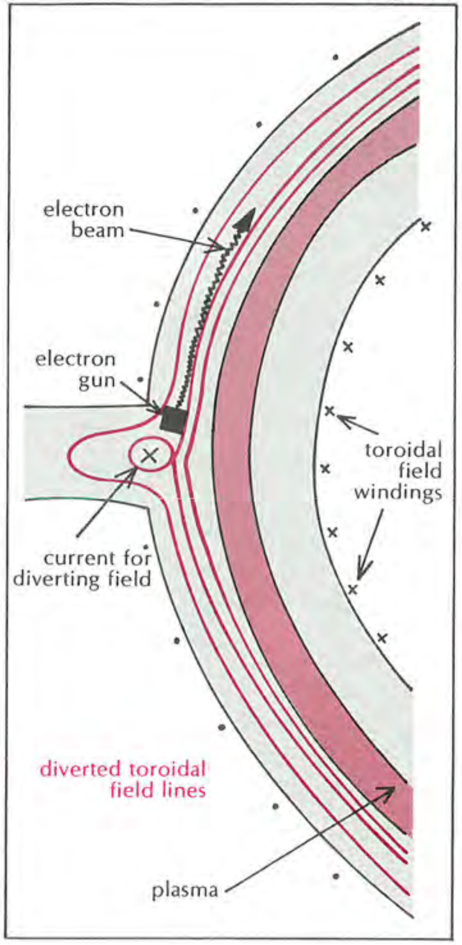


Figure 2. Sectional view showing how the Cornell beam injector works in a tokamak or similar device. Normally the strong toroidal magnetic field would prevent the penetration of an electron beam, but here the field is temporarily diverted so that the high-intensity beam does not have to cross magnetic lines but can enter along a magnetic surface. The purpose is to allow the beam to quickly establish a trajectory close to the plasma column where it can be effective in heating the plasma.

Figure 3. Three classes of beam trajectories. The sketch shows two-dimensional projections of the spiral electron-beam orbits. The type of trajectory that spirals close to the plasma column permits the strongest interaction between the beam and the plasma. These classes of trajectories were predicted theoretically and observed experimentally in the laboratory at Cornell (see Figure 4).

Figure 4. A computer prediction of electron beam trajectories. Experimental results confirming these trajectories were obtained in the Cornell laboratory with use of a metal conductor to represent the conducting plasma of a reactor.

Figure 3

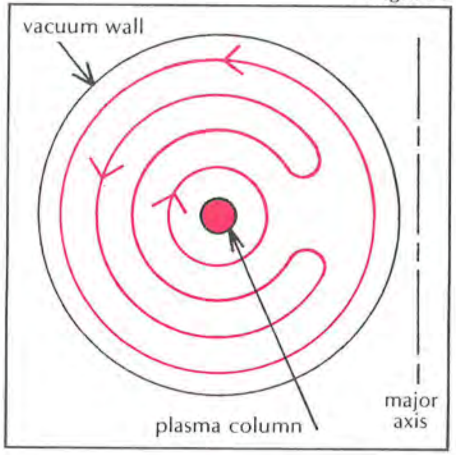
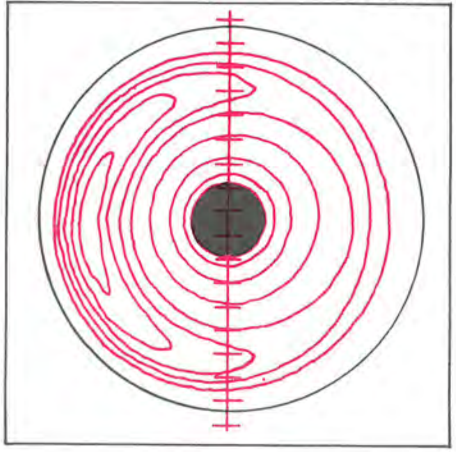


Figure 4



tory by diverting the toroidal magnetic field onto the electron gun, as shown in Figure 2. The diversion is achieved by superimposing a magnetic field produced by currents in the electron gun onto the original toroidal field. Because the plasma column is a good electrical conductor, toroidal field lines in the column are frozen and cannot be diverted (this is the reason the beam cannot be launched directly into the plasma column); therefore, only toroidal field lines outside the plasma column are affected. When the diverting field is applied (this is done during beam emission only), electrons do not have to cross magnetic field lines, but instead are able to flow along a magnetic surface. By controlling the ratio of diverting field to toroidal field, it is possible to launch the beam at predetermined positions between the vacuum wall and the plasma column.

BEAM TRAJECTORY AND PROPAGATION AFTER LAUNCH

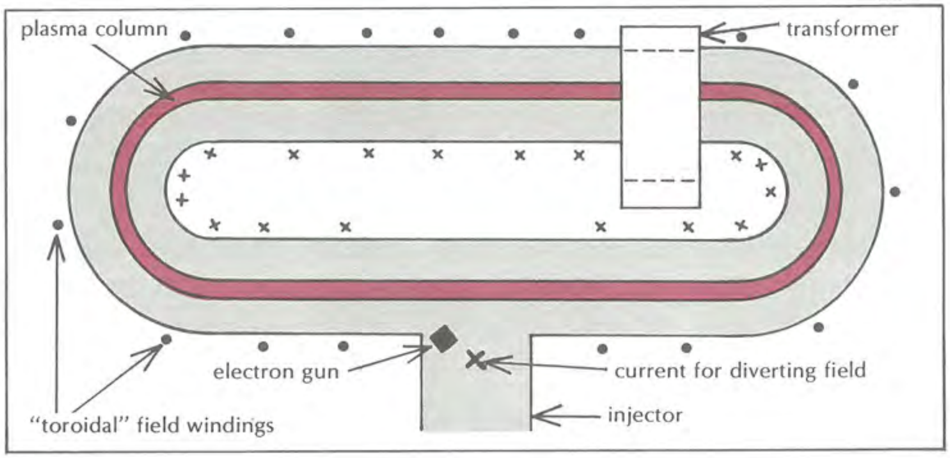
Although an electron beam can be launched arbitrarily close to the plasma column, its subsequent propagation may be along trajectories that carry the beam back toward the vacuum wall. The nature of the trajectories therefore has a large effect on the strength of the beam–plasma interaction. The beam trajectories are influenced by the launch position, the radius and conductivity of the plasma column, the transformer-induced plasma currents, and the location of the outer wall. Knowledge of how these factors control the trajectories allows us to inject and propagate the beam so as to maximize the beam–plasma interaction.

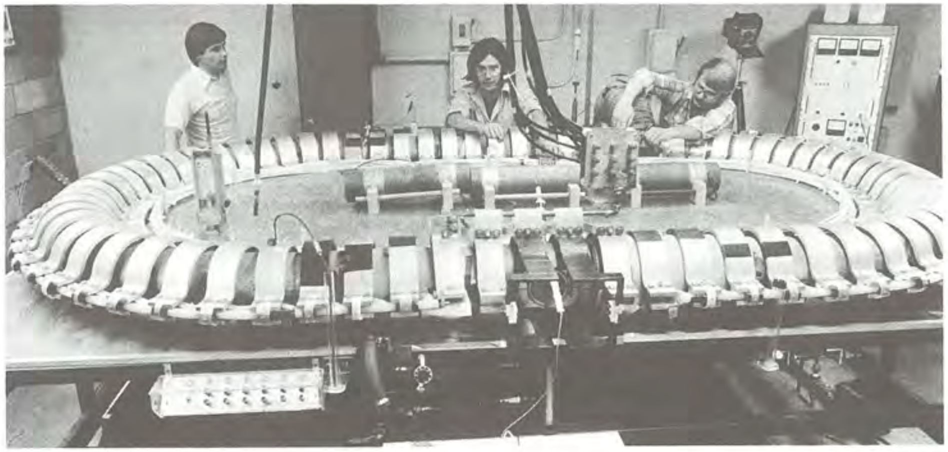
Three classes of trajectories have been predicted analytically and observed in our laboratory experiments. Projections of these orbits onto a poloidal plane (a plane containing the major axis and a major radius of the torus) are shown in Figure 3. One class of trajectories spirals tightly around the plasma column; this type results in the strongest interaction between the beam and the plasma. A second class of trajectories spirals close to the outer wall and results in essentially no interaction between the beam and the plasma. A

Figure 5. Cornell's race track. This device is similar to a tokamak, but has a larger ratio of major to minor circumference. It is used in an investigation of interaction between the plasma and injected high-intensity electrons.

Photograph below: Shown with the actual race track experimental device (located in Upson Hall) are, left to right: Professor Kusse, David Sing, and George Proulx. Sing and Proulx are doctoral candidates in applied physics.

Figure 5





"Our hope is to demonstrate the possibility of supplying the . . . additional heating necessary for a tokamak fusion reactor."

third class, described by the banana-shaped orbits in Figure 3, results in plasma interaction over part of the trajectory and wall interaction over the other part.

These kinds of trajectories were predicted on the assumption that the plasma is a perfect electrical conductor. With the plasma modeled experimentally by a metal conductor, we have been able to observe all three types of orbits (see Figure 4).

EFFECTS OF STRONG BEAM–PLASMA INTERACTION

If there is strong interaction between the plasma and the electron beam, the assumption of small plasma resistivity is no longer valid. Anomalous resistivity in the plasma will modify the trajectories, and analysis indicates that the beam could spiral into the plasma column, where it would be most effective in increasing the plasma temperature.

Experiments to look for these interactions in toroidal geometry are under way in Japan at the University of Nagoya and at Cornell. The Nagoya experiment is being carried out in a conventional tokamak device. The experiment at Cornell is being performed in the "race track" device shown in the accompanying photograph and diagrammed in Figure 5. Results from both these experiments indicate that the beam appears to penetrate the plasma column eventually. Under this condition, the transfer of energy from the beam to the plasma should be more efficient than in the linear experiments because the beam would be making more than one pass through the plasma.

In our current experiments, we are using beams with energies of 0.5 to 1 kilojoule per pulse, which should be able to add approximately 1 keV of thermal energy to the plasma. If satisfactory results are obtained, the next step will be a scaling experiment to investigate the feasibility of using more intense beams.

Our hope is to demonstrate the possibility of supplying the roughly 10 megajoules of additional heating necessary for a tokamak fusion reactor and thereby overcome one of the major obstacles to the realization of controlled thermonuclear fusion technology.

Bruce R. Kusse, associate professor of applied and engineering physics, is currently on sabbatic leave at the National Magnet Laboratory at the Massachusetts Institute of Technology (MIT), where he is working with the Alcator fusion reactor experiment. He came to Cornell in 1970 as a research associate in the Laboratory of Plasma Studies and was appointed to the faculty the following year.

His initial research here was with Professor Hans H. Fleischmann on field reversal in an Astron configuration. More recently, he has focused on the subject of this article: how to inject relativistic electron beams into a toroidal plasma configuration.

Kusse received his university education at MIT. After earning the B.S. degree in electrical engineering in 1960, he spent three years in the Navy and then began graduate study in plasma physics. He received the S.M. degree in 1964 and the Ph.D. in 1969. He spent the following year as a research scientist at E.G.G., Inc., and as a research associate at MIT. He has also served as a consultant to H/K Systems, Inc.

NEW SOURCES OF VERY HIGH POWER

by John A. Nation

New sources of extremely high power now under study at Cornell may make controlled thermonuclear fusion workable, provide a means of communication over long distances in space, or find application in technologies of the future. Ions accelerated by high-energy electron beams or pulses of microwaves generated by them are capable of providing power in magnitudes not available from any other source.

Both of these power sources require powerful electron beams, and they are being studied as part of the overall program in electron-beam research at Cornell's Laboratory of Plasma Studies. Current project work is concerned with the physics and also the technological feasibility of intense ion beams and microwave pulses.

COLLECTIVE PROCESSES AND THEIR CAPABILITIES

The common feature of both ion acceleration and high-power pulse generation is a dependence on collective processes in powerful electron beams. Groups of high-energy beam electrons can be caused to interact *as units* with each other, with ions, or with electromagnetic waves to produce forces millions of times stronger than those associated with single-particle interactions. An alternate way of viewing the collective interaction process is to consider the effect of generated waves on an electron beam. If a wave is excited on a powerful beam, the electromagnetic fields associated with the wave will exert an influence back on the beam electrons; this causes a bunching of the electrons (see Figure 1), which in turn augments the wave growth. The process continues until the particles are lost or a saturation point is reached.

How much power could be produced? The electron beam generator used in our study (see Figure 2) has an output of one million volts and can deliver electron beam currents of 60,000 amperes. The peak power output is 60 gigawatts (a gigawatt is 10^9 watts). In principle, this power is available for conversion to electromagnetic waves or for ion acceleration. The largest beam accelerators now being developed will have a peak power capability of about 80 terawatts (a terawatt is 10^{12} watts), which is about 80,000 times the output of an ordinary one-gigawatt power station.

APPLICATIONS OF HIGH-POWER ION BEAMS AND MICROWAVES

Possible applications of these beam systems are mainly in the area of controlled fusion. For example, high-power microwaves might be used in fusion reactors for the radiofrequency heating of plasma to thermonuclear ignition. Accelerated ion beams might find application in pellet-fusion reactors. (See the introductory article in this issue by Ravindra N. Sudan for a discussion of pellet fusion.)

A proposed regime for particle-beam pellet fusion employs intense proton beams of the type studied and developed by Sudan at Cornell. An alternate approach, employing collective acceleration techniques, would use ion species of high atomic number. The higher the atomic number, the lower the beam current needed, although the greater the beam energy required; one possibly attractive ion for pellet fusion is carbon, for which the requirement would be

Figure 1

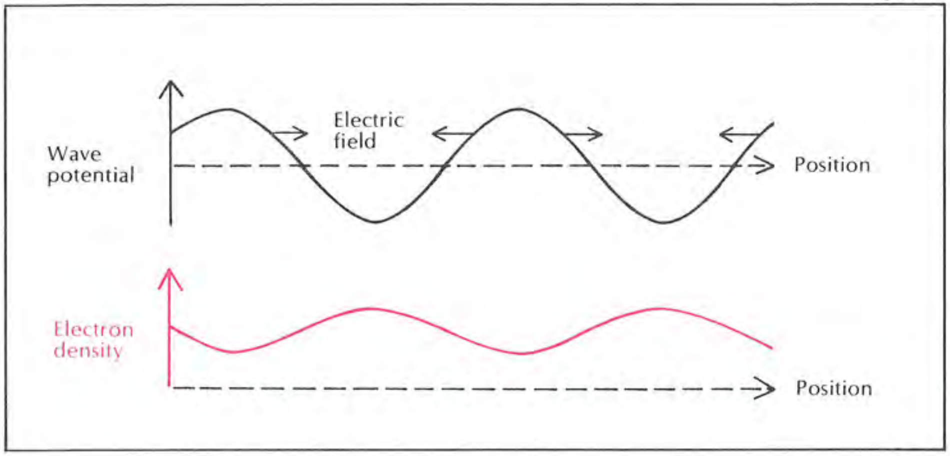


Figure 1. The bunching of electrons in an electron beam as a result of the field of an electromagnetic wave. This phenomenon is a manifestation of the collective processes that can be used to amplify the immense power available in high-current electron beams. Proton beams with energies of the order of a few GeV appear possible, and microwave pulses in the gigawatt (10^9 watts) range have already been obtained in experiments at Cornell.

Figure 2

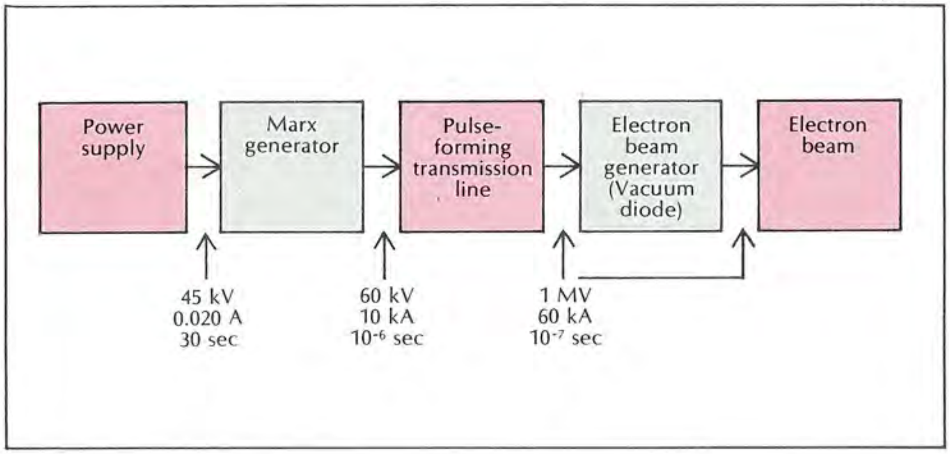


Figure 2. Schematic of the electron beam generator used in the experimental work on collective interactions. The power gain accomplished with this machine is about 100 million. Typical pulse times and signal levels at the various points are indicated.

The instrumentation consists of a power supply, a Marx generator, a pulse-forming network, and a vacuum diode to supply the final voltage pulse; the accelerated electrons pass into an evacuated tube used for the collective interaction. The power supply delivers up to 100 kV and 35 mA. The Marx generator has fourteen capacitors, each with a 100-kV rating, which are charged in parallel and discharged in series via a switching circuit. The diode has an anode of thin foil through which the electrons pass, and an anode-cathode gap of about one centimeter. (Other details of this machine are indicated in the schematic diagram shown on page 4).

Most of the power gain occurs in the Marx generator, although some occurs as a result of pulse compression achieved in the pulse line. Because the pulses are so short, about 0.1 microsecond, the total energy stored in the machine is only about 6 kilojoules.

ions with energies of about 100 megaelectron volts (MeV) and a current of about one million amperes.

We are now starting an ion-beam program in which we shall attempt to accelerate heavy ions by exposing them to the fields of a high-current electron beam. A long-range objective in such research would be to generate beams with currents of up to a few thousand amperes at gigaelectron-volt (GeV) energies. This type of beam would be directly useful in fusion pellet devices. A more modest objective, feasible for a university research program, would be to accelerate the heavy ions to an energy of several tens of MeV. Such a beam would provide a suitable injector for a more conventional accelerator, which would produce the final multi-GeV beam.

In addition to possible use in thermonuclear fusion reactors, microwave and ion-beam high-power sources have other potential applications. High-power microwaves might be used for deep space communication, which requires very strong signals because the power

Figure 3

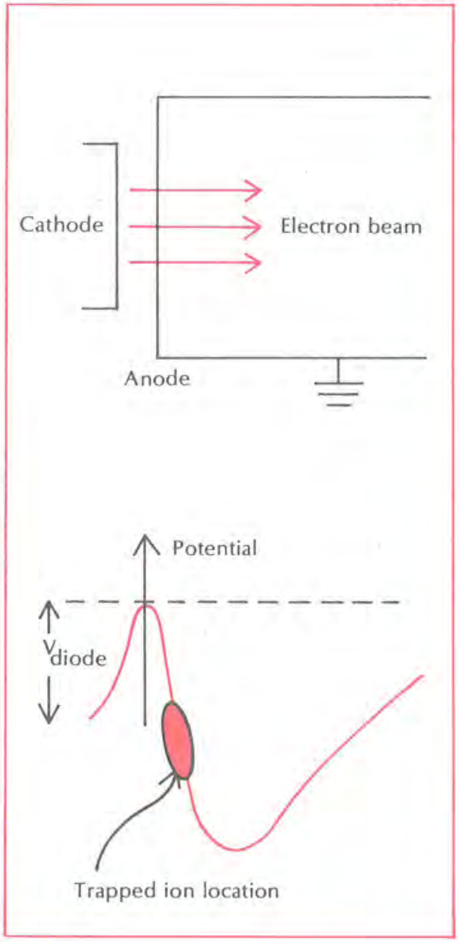


Figure 3. Potential well at the head of an electron beam entering an evacuated tube. This well, with negative polarity, can trap positively charged ions; as the well propagates down the tube, the ions are accelerated. This is the basis of the simplest type of ion beam accelerator.

density of a transmitted signal decreases with the square of the distance between the source and the receiver. Ion beams provide a possible approach to heavy-ion fusion, or to the commercial preparation of radioactive material. Applications such as these are fairly far away, however, since collective acceleration physics is far from well understood and certainly not yet optimized.

COLLECTIVE ACCELERATORS FOR POWERFUL ION BEAMS

The possibility of accelerating ions to the velocities of electrons in a high-current relativistic beam is very attractive because the ions would acquire energies many times greater than those of the electrons. Even with only one percent efficiency, ion beams with powers approaching a terawatt become a possibility.

In a collective accelerator, the object is to get the collective field of an electron bunch to drag along a much smaller bunch of ions. At the velocity of the electrons, the ions would have energies higher by the factor of their greater mass; for example, if one suc-

Figure 4

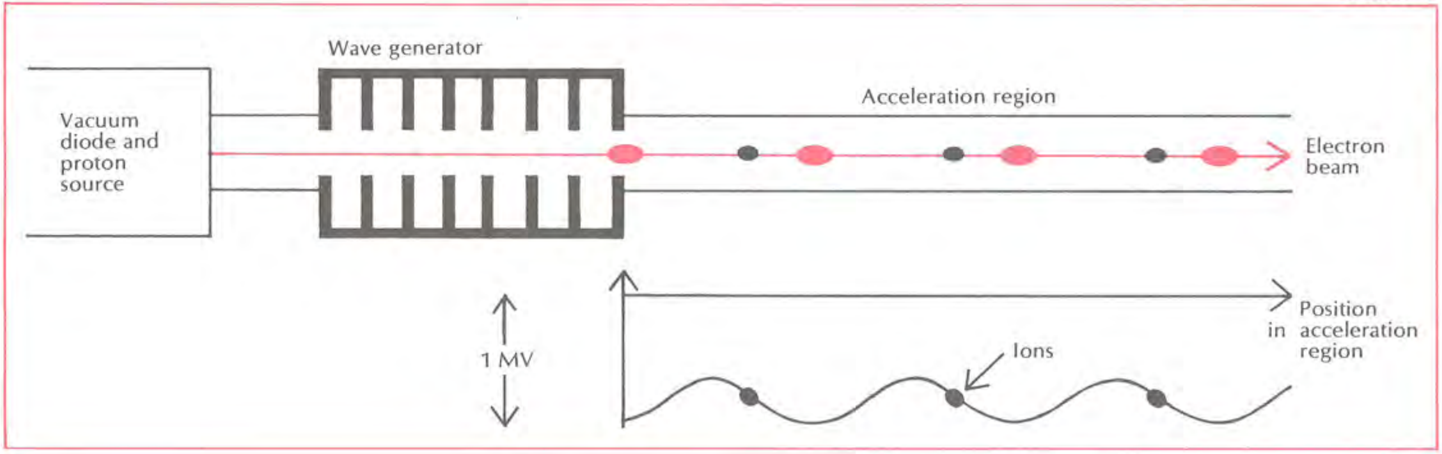


Figure 4. Experimental arrangement used in growing a wave train. Ions are trapped in each of the potential wells of the wave and are accelerated to high energy as the velocity of the wave is increased in the acceleration region. Proton energies anticipated in the wave accelerator are comparable to those obtained with conventional particle acceleration. Beam current levels would be millions of times greater.

Figure 5

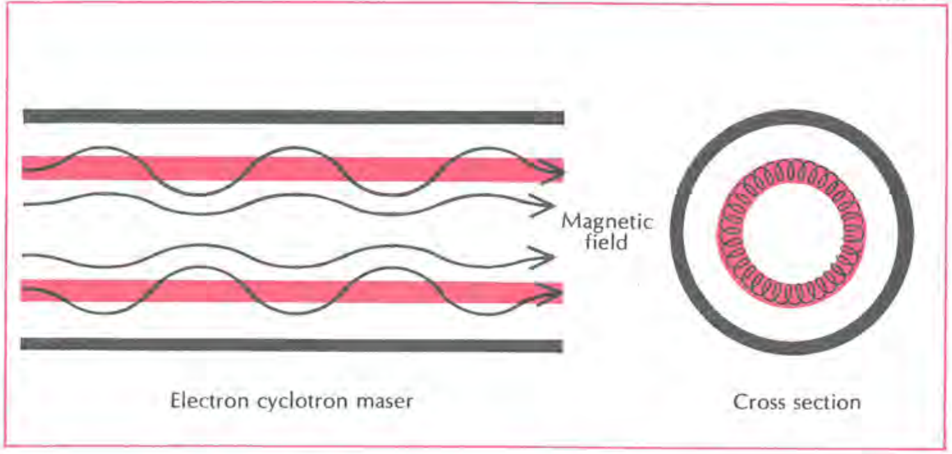


Figure 5. Schematic showing the configuration of an electron cyclotron maser. An electron beam (color) propagates through a periodically rippled magnetic field. The cross sectional view of the tube shows the rotational motion of electrons about the magnetic field. This type of maser is used in Cornell research on high-power microwave generation.

ceeded in dragging some protons along with the electrons, the proton energies would be 1,843 times greater than the electron energies. With an electron beam of one MeV, the maximum proton energy achieveable in a collective accelerator is 1.84 GeV, but with electron beams of greater strength or ions of greater mass, much greater beam energies are possible, at least conceptually. Of course, the requirements of conservation of momentum and energy keep the ion current considerably smaller than the electron current, but such ion beams would be far more intense than any attainable with existing technology.

There are a number of ways in which the electron beam can be bunched so as to be an effective accelerator for an ion beam. The simplest of these methods depends on the "potential well" that exists at the head of the beam. As the electrons enter an evacuated tube, electric fields are developed at and ahead of the beam head. The potential, which is zero in advance of the beam head, is depressed to a large negative value (two or three times larger than the injector potential) at the electron beam location. This configuration is sketched in Figure 3. A potential well is possible only in a transient region such as that at the beam head, and will propagate down the tube as the beam head advances. The well has the correct polarity to trap positively charged ions, and if ions are successfully injected, they will move down the tube along with the well. Accelerators of this kind actually have been constructed, and proton beams with energies of up to twenty-two times the electron energy have been achieved. With the heavier ion of fluorine, an ion energy of 135 MeV has been accomplished with a 2-MeV electron beam.

A development of this kind of accelerator is being investigated at Cornell. In these experiments, the objective is to generate a wave train—a wave with a large number of periodically spaced clumps of charge—on the electron beam (see Figure 4) and to accelerate bunches of ions by changing the phase velocity of the waves. Conventional microwave techniques are used to generate the wave train, but this is probably the first time that such waves have been grown on very intense beams.

We have succeeded in growing waves with potential wells of a few hundred kilovolts and propagating them through the accelerator region. The next step is to inject and accelerate ions. The principal problem is that low-energy ions can be trapped efficiently only in a slowly moving wave; a very close analogy is that of the surfer who is picked up by a sea wave only when his speed matches that of the wave. We must learn how to slow down the potential well propagation sufficiently to allow ions to be "picked up" and then to accelerate the well gradually enough so that the heavy ions will not be lost.

The potential capabilities of this kind of accelerator make its development an exciting area of research, and it is the basis of expanding research activity in many countries. It should be pointed out, of course, that the wave-train accelerator has not yet been proved and that there are several potential difficulties. Two questions that must be resolved are (1) How long

"... we are now ... learning how to use these powerful beams rather than simply studying what they do if left to themselves."

can ions be trapped in the wave? and (2) How many ions can be trapped? These questions should be answered in the next few years.

THE STATE OF HIGH-POWER MICROWAVE GENERATION

The first high-power microwave generation experiments using intense relativistic electron beams were carried out at Cornell several years ago. Since that time, large groups have been formed in the United States, the Soviet Union, and France to develop these sources. As a result of this activity, the capabilities in single-power sources have been extended by more than two orders of magnitude over the levels attainable prior to 1970. These results have been accomplished over a range of frequency from one gigahertz (GHz) up to about 400 GHz.

The Cornell work has been concentrated in two areas: experiments using the cyclotron maser, and experiments exploring the interaction of conventional microwave circuits with high-current beams.

In the cyclotron maser (see Figure 5), a periodically rippled magnetic field causes the electrons to rotate about the field lines and, under certain conditions, to acquire a large amount of rotational energy. The distribution of rotational velocity is such that a density inversion is exhibited in the momentum distribution; when this relaxes to an equilibrium Maxwellian distribution, radiation is generated and becomes coupled to the waveguide modes. This interaction process is similar to that in a laser (which was originally developed in the 1950's). The greatest power attained so far with this kind of system is in the range of one gigawatt, obtained at a frequency of about 10 GHz. These results were achieved in a joint experiment carried out at Cornell with researchers from the Naval Research Laboratory.

The interaction of slow wave circuits with high-current beams produces clumps of space charge, as described above in the discussion of collective acceleration processes. This kind of interaction has been explored at the Lebedev Institute in the Soviet Union and at Cornell. With use of waves in the frequency range of 10 GHz, power outputs of up to 300 megawatts have been achieved with conversion efficiencies greater than 10 percent.

Recent work in this field, especially in a program at the Naval Research Laboratory, has been concerned with the reflection of microwave signals from relativistic electron beams. The frequency of the reflected wave is greater than that of the incident wave because of the Doppler effect: the electron beam acts like a moving "mirror," reflecting the initial wave back toward its source. Pulses larger than one megawatt have been detected at wavelengths of less than one millimeter. The process causing this upconversion of frequency is not a direct reflection from the beam head, although this has also been observed, but it is a more complicated process involving a scattering of the radiation from coherent density fluctuations in the beam.

THE PROGRESS OF WORK IN A NEW AREA OF RESEARCH

Research with intense electron beams was begun in the United States in 1965

Left: The author's laboratory is pictured with him in the foreground. The cylindrical tube is the water-dielectric pulse-forming line; it is connected to the oil-filled Marx generator to the left. The electron beam is extracted through the vacuum diode located at the far right of the pulse line. (See also Figure 2.)

The large tank visible at the rear is part of the 5-MeV electron accelerator described in the articles by Ravindra N. Sudan and Hans H. Fleischmann.

and at Cornell the following year. The first studies of collective interactions in these beams were conducted here in 1969, and the program continues as an important part of the electron-beam research at the Laboratory of Plasma Studies. Funding for the Cornell experimental work I have described has been provided by the National Science Foundation, the Air Force Office of Scientific Research, and the Army. The research described currently involves the following graduate students: Richard Adler, George Gammel, George Providakes, and Ronald Williams. Technical support is provided by James Ivers and Frank Redder.

Tremendous achievements have been made since the beginnings of research on relativistic electron beams, and we are now in a phase of learning how to use these powerful beams rather than simply studying what they do if left to themselves. As electron-beam research progresses from fundamental investigation toward technological applications, Cornell continues in the forefront of activity. It is an exciting place to be.

John A. Nation is an associate professor of electrical engineering at Cornell and assistant director of the Laboratory of Plasma Studies. Since joining the faculty here in 1965, he has worked on the development and application of high-current relativistic electron beams.

Nation studied at Imperial College, London, for the B.Sc. and Ph.D. degrees in physics, awarded in 1957 and 1960, respectively. After receiving the doctorate, he joined the plasma physics group at Frascati, Italy, and worked on a theta pinch fusion device. In 1962 he returned to England where he worked at the Central Electricity Research Laboratories in the magnetohydrodynamics power-generation program.

During a sabbatic leave from Cornell, Nation conducted research at Imperial College as a senior visiting fellow of the Science Research Council.

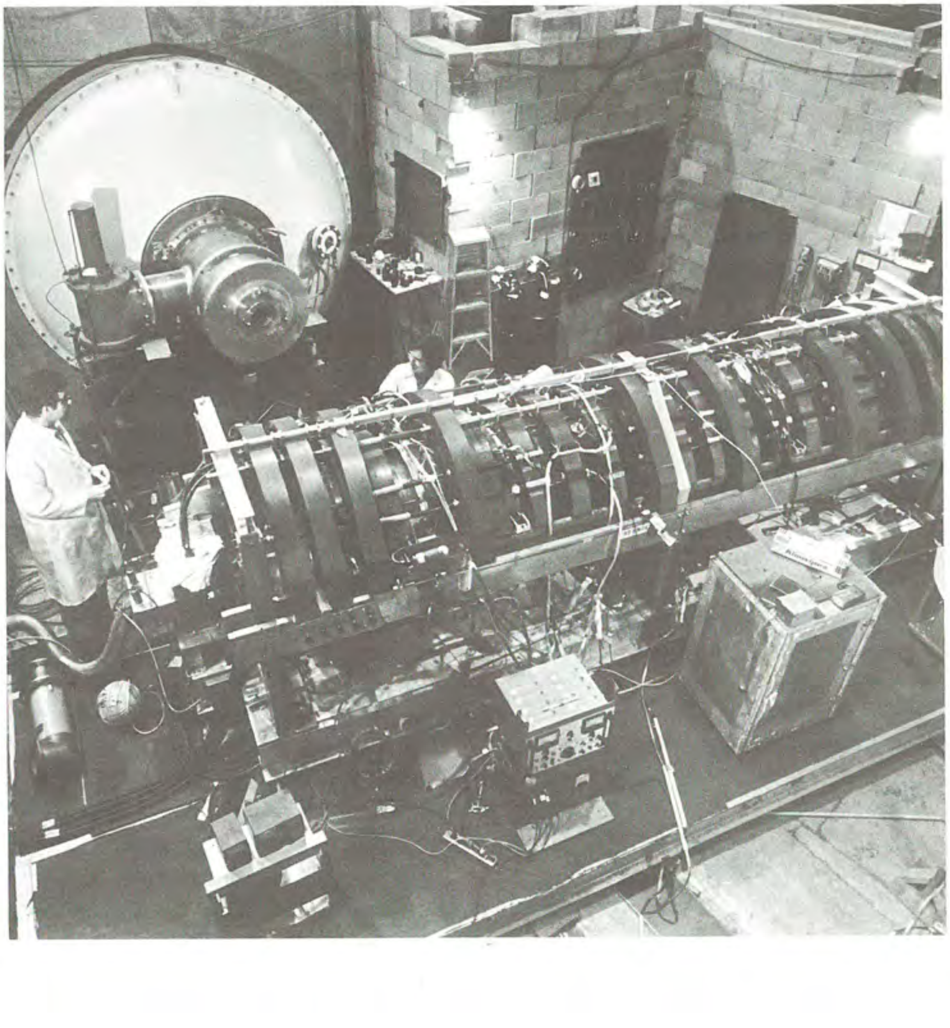
He is a consultant to several industrial and government research laboratories and has served as a reviewer for agency research proposals and for various professional journals. He is a member of the American Physical Society and a senior member of the Institute of Electrical & Electronics Engineers.

AN ION RING BOTTLE FOR A FUSION REACTOR

by Hans H. Fleischmann

Thermonuclear fusion is generally considered a long-term option for energy production: although not yet adequately developed, it is attractive because of the essentially unlimited supply of fusion reactor fuel and the relatively benign environmental impact such a reactor would have. In this country, annual governmental expenditures for research and development in controlled thermonuclear fusion have risen from about \$30 million in the early 1970's to more than \$400 million in the current fiscal year.

The major part of these funds is dispensed through ERDA, the Energy Research and Development Administration (now incorporated into the recently created Department of Energy), with most of the money going to support research on magnetic confinement schemes and devices. The main emphasis at the present time is on the development of *tokamak* and *mirror* de-



Right: The RECE-CHRISTA electron-ring experiment uses a 5-MeV electron beam generator and a containment system consisting of a large vacuum tank surrounded by magnetic field coils.

"The basic strategy is to study first the behavior of field-reversing electron rings."

vices (see Figures 1 and 2), but work on a number of other "exploratory" magnetic fusion concepts is supported on a smaller scale. These alternative approaches are seen as a backup in case of the unexpected failure of the two major lines of research and development, and are also intended to keep the way open for ideas that might offer cheaper or otherwise more attractive paths to the controlled generation of thermonuclear energy.

The field-reversing ion-ring reactor described in this article is one of these alternative concepts. Results of Cornell research in this area have led to very significant advances in recent years.

MAJOR FUSION SCHEMES WITH MAGNETIC CONFINEMENT

In a fusion reactor, a plasma that will most likely be composed of heavy hydrogen isotopes will have to be heated to one hundred million degrees or more and kept confined long enough for sufficient thermonuclear burn to occur. In magnetic confinement systems, in which plasma density is limited by the available magnetic field strength, the necessary confinement time is expected to be in the range of 0.01 to 10 seconds. The aim of current research is to achieve both of these objectives—high enough temperature and long enough confinement time—in a manner that will satisfy the technological reliability requirements and also the economic constraints imposed on all large-scale power systems.

The achievement of the necessary conditions is hindered mainly by the tendency of the plasma to exhibit instabilities that lead to energy loss either from collision of the charged particles with the vessel wall or from the diffusion of energy or particles through the magnetic field lines. These instabilities are strongly affected by the design of the plasma-confining field. With the two major types of device, the tokamak and the mirror, plasma temperatures and confinement times close to the required values have been achieved, although not yet simultaneously. Theorists predict that some additional instabilities will occur before the final goal of an operable reactor is achieved, but the fusion community shares a strong belief that at least one of these two approaches will lead to significant energy production in the next few years.

THE FIELD-REVERSED ION RING REACTOR CONCEPT

The ion-ring reactor concept (see Figure 3) we are investigating can be considered a mixture of the two main schemes. As envisioned by its inventor, Nicholas Christofilos, a large-orbit ring of many high-energy ions is trapped in the magnetic mirror field between two external field coils. The magnetic field component generated by the orbiting fast ions has a polarity that is opposite in direction to that of the externally applied field. If there is a sufficient number of trapped fast ions, the direction of the total magnetic field (that is, the external field plus the ring field) on the axis may be reversed. The result is a toroidal system of closed field lines that confines the thermonuclear plasma in a doughnut-shaped ring. In addition, a toroidal field could be generated around the plasma ring by means of a conductor positioned along the axis.

This scheme can be considered a relative of both the mirror and the toka-

Figure 1

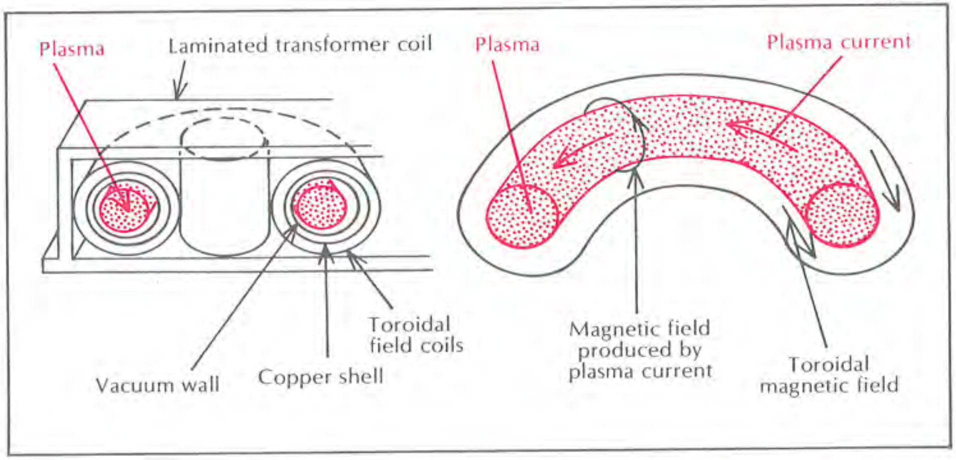


Figure 2

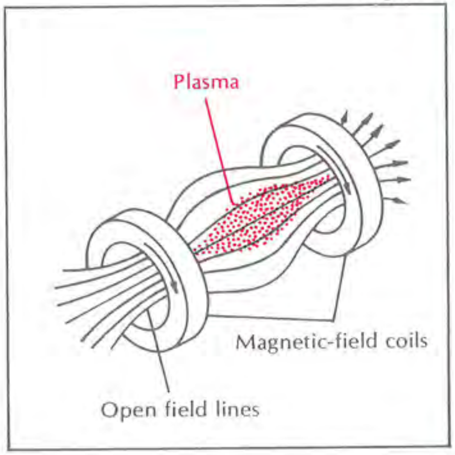
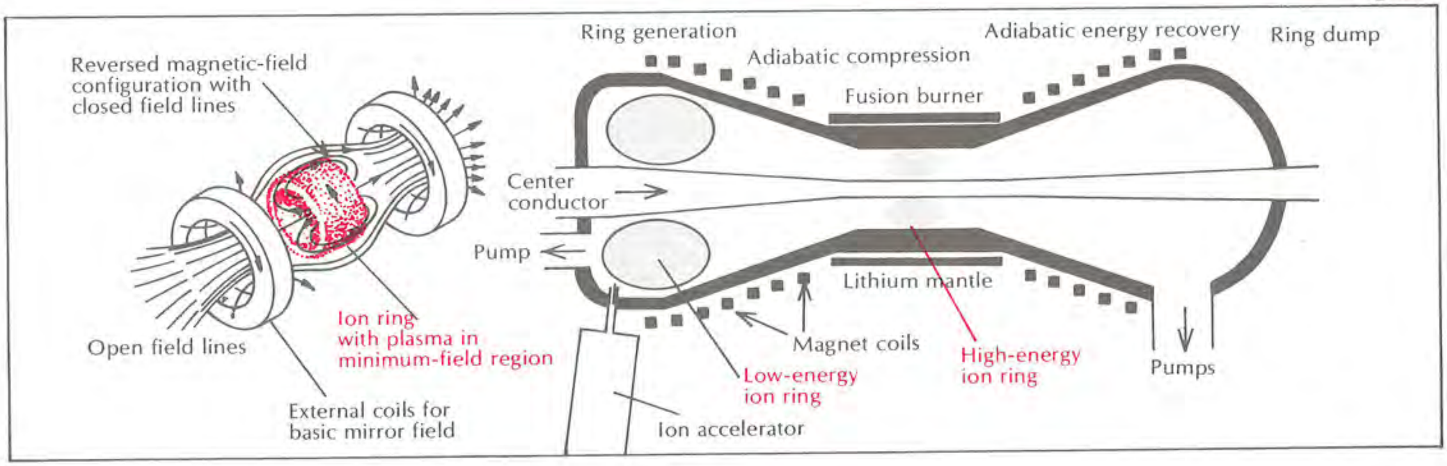


Figure 1. Tokamak scheme showing the doughnut-shaped plasma ring confined in an externally applied toroidal magnetic field. To provide sufficient "equilibrium," an additional toroidal current is driven in the plasma ring by using the ring as the secondary winding of a transformer. Because of ohmic resistance, the current also contributes to plasma heating.

Figure 2. Magnetic mirror scheme, in which plasma is confined in the low-field region between two magnetic field coils. The generation and heating of the plasma is generally accomplished by injecting highly energetic atoms or ions that have been accelerated through electrostatic potentials of 10 to 100 kV.

Figure 3. Basic field-reversal scheme (at left) and the proposed Ion Ring Compressor (IRC) for a reactor. The reactor diagram shows, on the left, a ring of low-energy ions generated by a low-energy ion accelerator. Subsequently, this ring is compressed and moved to the right into the burn chamber. After sufficient fusion burn has occurred, the ring remnants are moved farther to the right and cooled by adiabatic expansion. The purpose of the lithium mantle is to recover the fusion energy and to regenerate the spent tritium.

Figure 3



mak schemes. In terms of the mirror concept, it simply closes some of the otherwise "open" field lines (the lines leading to the vessel walls) that cause very serious plasma losses in the normal mirror design. When compared with a tokamak, the ion-ring scheme is distinguished mainly by the fact that the ring current is carried by the fast ions rather than by the confined plasma itself, and by the fact that it requires much smaller toroidal magnetic fields and so avoids the extra costs associated with the higher tokamak fields.

The main advantage of these ion ring systems is that they are expected to provide exceptionally good plasma confinement. The strength of the total magnetic field has a minimum within the plasma doughnut and increases everywhere toward the doughnut surface, a favorable configuration according to both theory and experiment. In particular, these systems are expected to be able to sustain comparatively large plasma pressures for a given strength of the externally applied field, and therefore permit a comparatively high plasma density. This would allow a smaller overall reactor size and thus again reduce the cost.

In the Cornell-proposed Ion Ring Compressor (IRC) scheme (illustrated in Figure 3) it is envisioned that the ion ring will be made of protons having an energy of a few hundred MeV and that these rings will be generated by adiabatic compression of rings made up of lower-energy ions. In a "small-orbit" version of this scheme, it may be possible to retain the good stability characteristics if the ring current is carried by ions with orbital sizes of one-third to one-fifth the overall ring radius.

RESEARCH EFFORTS IN OTHER LABORATORIES

This basic ion-ring scheme entails a number of questions and potential problems pertaining to the generation of the rings, the stability of both rings and plasma, and the quality of plasma confinement. These matters are being investigated at Cornell and in other laboratories, notably the Lawrence Livermore Laboratory in California.

The effort at Livermore started with the Astron experiment supervised by Christofilos. In an intensive effort stretching over the decade from 1962 to 1972, and with the help of nearly $40 million, the Livermore researchers tried to generate field-reversing rings using 6-MeV electrons to simulate high-energy ions. Unfortunately, the accelerator used, although one of the strongest conventional linear accelerators available at that time, did not have a sufficient number of electrons per pulse to cause field reversal. Thus, the trapping or "stacking" of a series of pulses was needed. This stacking did not appear to work, and following Christofilos' death in 1972, the Astron experiment was terminated.

Recently, "small-orbit" field-reversal experiments using neutral atom injection have been performed at Livermore. In this work, the Mirror Experiment 2XIIB, rings close to field-reversal strength have been obtained. Unexpected particle losses have been observed, however, and these are now being investigated.

CORNELL EXPERIMENTS WITH ELECTRON AND ION RINGS

The Cornell investigations of field-reversing rings were an outgrowth of our earlier work on intense electron-beam devices, which started at the time I came to Cornell in 1967. (The respective beam physics and technology were developed to a considerable extent by a Cornell group including Norman Rostoker, Simpson Linke, John Nation, and myself.) Originally, these devices had been intended primarily for flash X-ray generation needed, for example, in military simulation work. After three years spent mainly in obtaining the necessary know-how and equipment, we were finally ready, in 1970, to begin work on other applications, including the generation of field-reversing electron rings for fusion reactors.

A short pilot experiment indicated a good chance for success and led to significant funding for the developing project RECE (Relativistic Electron Coil Experiments). The Empire State Atomic Development Agency, later renamed the Empire State Electric Energy Research Corporation, provided support for the initial experiments and for additional equipment, including a large 5-MeV electron beam accelerator. The

Experiments with relativistic electron beams are conducted by Professor Fleischmann's research group.

Right: Timothy Renk, a graduate student, works with the RECE-BERTA, with which it was shown for the first time that field-reversing rings of high-energy particles could exist in an Astron-type thermonuclear fusion reactor.

Below: Donald Rej, a graduate student, and Michel Tuszewski, a postdoctoral research associate, are shown with the larger RECE-CHRISTA.

Naval Research Laboratory, which had supported a sizable part of the earlier beam experiments, also provided some funds. Since about 1973, ERDA has provided steadily increasing funds, presently about $280,000 a year, for this work and our related ion-generation experiments.

The overall aim of this effort is to assess the chances for success of the ion-ring scheme and to build such a reactor if this appears feasible. The basic strategy is to study first the behavior of field-reversing electron rings: basic considerations indicate that most of the characteristics of electron rings are similar and can be scaled to those of the envisioned ion rings. Because of the physics involved, significant ion-ring experiments cannot be performed on a small scale. The much smaller required magnetic fields and energies make experiments with electron rings faster and much more flexible than comparable ion-ring experiments, and cheaper by one to two orders of magnitude. The experiments with electron rings will help determine not only whether a much larger effort on ion rings should be undertaken, but also how such an experiment should be designed.

Following this concept, three separate electron-ring experimental machines, RECE-BERTA, RECE-CHIP, and the larger RECE-CHRISTA, have been constructed and several measurements of ion generation have been performed by our group. In the electron-ring experiments, the intense electron beam is injected into a magnetic mirror field and a small portion of the beam is trapped in the form of a ring. The main difference between this and the Astron experiments at Livermore is that a much larger number of electrons is available in our beam pulses; the trapping of only a few percent of the injected electrons is sufficient to cause the field reversal.

These experiments have been fully successful: field-reversing rings were first observed in RECE-BERTA in 1972 and in RECE-CHIP in 1973. An important observation was that these rings decayed quite smoothly as fast electrons scattered because of collisions with the background gas. Further investigation shows that although instabilities can occur, they are apparently manageable. In particular, it was shown that the "precessional mode" (corresponding to a wobble of the ring around the system's axis), which had already been observed in the earlier Astron experiments, can be stabilized. In addition to instabilities, interesting fast-electron losses have been observed by one of my students, Stanley Luckhardt. These losses appear to be caused by an insufficient confinement of some single-particle orbits in the ring when certain perturbation fields are applied. It appears that such orbital perturbations may be important in explaining why the field-reversal experiments on the much larger 2XIIB at Livermore have not yet been successful.

In our earlier, small-scale experiments, the collisional decay of the electron rings limited the ring lifetime to about 10 to 20 microseconds. The significantly larger RECE-CHRISTA experiment with the higher-energy 5-MeV accelerator was designed to remedy this situation. Harold Davis, a postdoctoral research associate, and graduate students Bob Meger and Don Rej have succeeded in generating electron rings with lifetimes of more than a millisecond. They were also able to show that a stacking of weaker rings, if properly executed, can lead to the generation of field-reversing rings.

CURRENT AND PROJECTED RESEARCH EFFORTS

In current experiments, the ring lifetime is being extended by trapping the electron ring in a temporary gas cloud in the vicinity of the beam injector and then rapidly moving it along the tank axis into a region of low-density gas. A further extension of ring lifetime will be attempted by compression of the electron ring (see Figure 3). These experiments, which will be conducted by Michel Tuszewski, a postdoctoral research associate, will increase the energy of the electrons and thereby lengthen the ring lifetime. Even more importantly, they should prepare the way for further experiments in which we intend to actually test for the first time the theoretical predictions of good plasma confinement. As in the past, an important part in the planning and execution of the experiments will be played by theoretical analyses. In particular, recent equilibrium calculations of Professor Richard Lovelace and his student David Larrabee indicate that the magnetic field configurations now available in RECE-CHRISTA are significantly better for plasma confinement than the simpler Astron configurations.

In addition to the electron-ring experiments, our research group has performed some experiments on the generation of high-current ion beams. I expected, subsequent to some suggestions made in 1970 by Friedwardt Winterberg and some preliminary calculations made at Cornell by Morton Nebenzahl, that the very large amounts of ions needed for ion-ring experiments, as well as for a final reactor, could be produced by simply repolarizing the available electron-beam machine. Indeed, such experiments have been performed successfully both at Cornell and elsewhere (see the introductory article by Ravindra N. Sudan). My research group has concentrated its efforts on a diode design in which magnetic fields are used to suppress unwanted electron currents. In recent experiments, Stanley Luckhardt and Robert Kribel (a visiting professor from James Madison University) succeeded in generating time-integrated pulse densities of over 100 microampere-seconds per square centimeter, significantly higher than any density previously achieved and approximately the level needed for ion-ring experiments.

Obviously, many questions remain to be answered before an ion-ring fusion reactor can become reality, but if it does, our work at Cornell will have made a significant contribution to its development.

Hans H. Fleischmann, an associate professor in the School of Applied and Engineering Physics, has been a member of the Laboratory of Plasma Studies since he came to Cornell in 1967. He has worked on the development of the electron beam effort since its inception and holds several patents on related devices.

Fleischmann studied physics at the Technische Hochschule in Munich, Germany, for the Dipl.Phys., which he received in 1959, and the Dr.rer.nat., awarded in 1962. After a year as a research associate at the Munich institution, he became a staff member of General Atomic in San Diego, where he worked for five years before coming to Cornell.

He has served as a consultant to several industrial firms and government laboratories and spent a summer with the thermonuclear division at Oak Ridge National Laboratory.

A specialist in both atomic and plasma physics, he has published numerous papers on research in these areas and has contributed to many conferences in this country and abroad.

COMMENTARY

Fusion Power—Its Promises and Prospects

The following is an abstract of a talk given last February by Peter L. Auer, Cornell professor of mechanical and aerospace engineering, as a Public Lecture at the annual meeting of the American Association for the Advancement of Science. Auer's scientific specialty is plasmadynamics, and he is active in the area of controlled-fusion and energy-policy studies. He is a former director of Cornell's Laboratory of Plasma Studies.

The world-wide effort to understand and develop nuclear fusion is approaching a transition stage. The underlying scientific discipline, plasma physics, hardly existed twenty-five years ago, but very rapid advances have taken place. Now, although a number of important scientific issues remain to be resolved to satisfaction, increasing attention is being given to the difficult engineering and technological problems that must be solved before fusion can become a practical reality.

A number of fairly large and somewhat expensive scientific experiments are now in various stages of planning, construction, and operation. The objective is to lay the groundwork for the design and construction of a series of fusion power-producing reactors on the pilot-plant scale, during the next decade, in order to begin exploring all the significant questions associated with the development of a commercial fusion reactor. If fortune continues to smile on the plasma physicists and fusion engineers involved in this effort, it is quite possible that some time early in the next century fusion power will start to become available to society.

THE BRIEF HISTORY OF FUSION RESEARCH

The discovery of what we now term fusion reactions dates back to the early thirties, actually preceding the discovery of fission by a few years. The initial discoveries were made by Rutherford and his co-workers, and not long afterward Bethe* used fusion reactions to explain the origin of energy production in the stars, a process of particular interest to us in connection with our own star, the Sun. But we had to wait for the impetus of wartime research on nuclear explosives before work on controlled fusion aroused serious interest within scientific circles. In the early fifties, groups of scientists in this country, Great Britain, and the Soviet Union embarked, more or less independently, on the development of fusion power for peaceful purposes. Today, in addition to the original three, nations with major fusion programs include the Federal Republic of Germany, France, Italy,

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**Nobel laureate Hans A. Bethe, the John Wendell Anderson Professor of Physics, emeritus, at Cornell.*

Deuterium fusion reactions:

$$\mathrm{D} + \mathrm{D} \begin{cases} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} & +3.27\ \mathrm{MeV} \\ \rightarrow \mathrm{T} + \mathrm{p} & +4.03\ \mathrm{MeV} \end{cases}$$

$$\mathrm{D} + {}^{3}\mathrm{He} \longrightarrow {}^{4}\mathrm{He} + \mathrm{p} \qquad +18.4\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{T} \longrightarrow {}^{4}\mathrm{He} + \mathrm{n} \qquad +17.6\ \mathrm{MeV}$$

Net theoretical reaction:

$$3\mathrm{D} \longrightarrow {}^{4}\mathrm{He} + \mathrm{p} + \mathrm{n} \qquad +21.6\ \mathrm{MeV}$$

Proposed fuel cycle:

$${}^{6}\mathrm{Li}\ (7\%) + \mathrm{n}\ (\mathrm{slow}) \longrightarrow \mathrm{T} + {}^{4}\mathrm{He} \qquad +\ 4.8\ \mathrm{MeV}$$

$${}^{7}\mathrm{Li}\ (93\%) + \mathrm{n}\ (\mathrm{fast}) \longrightarrow \mathrm{T} + {}^{4}\mathrm{He} + \mathrm{n} \qquad -\ 2.5\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{T} \longrightarrow {}^{4}\mathrm{He} + \mathrm{n} \qquad +17.6\ \mathrm{MeV}$$

Figure 1. Reactions of interest in the development of fusion power.

Deuterium (D), an abundantly available natural isotope of hydrogen, reacts with itself in one of two branching modes with nearly equal probability at modest energies. The reaction yields a neutron plus nuclei of hydrogen (which is a proton); of tritium (T), a radioactive isotope of hydrogen with a relatively brief halflife; and of ordinary helium. The theoretical net reaction yields helium, hydrogen, neutrons, and a large amount of energy.

Of these reactions, only the one between D and T has a high enough probability to be practical in a fusion reactor, and it is necessary to devise a means of producing tritium. This may be done by breeding tritium from lithium, using fast neutrons from the deuterium fusion reactions. In the fuel cycle shown, the isotopic composition of natural lithium is indicated (by the percentages in parentheses), along with the fact that tritium production from ${}^{6}Li$ is exothermic, while from ${}^{7}Li$ it is endothermic.

and Japan. More modest efforts are being made in many other countries.

The reason for this widespread interest is fairly evident. The original purpose remains: to supply humankind with an energy source that is virtually inexhaustible and benign. The original questions also remain: when and at what cost? The pursuit of fusion power has turned out to be one of the most challenging technological endeavors of modern times.

THE BASIC REACTIONS OF FUSION SCHEMES

Let me begin a consideration of the prospects for fusion power with a brief description of what fusion is all about.

Fusion involves nuclear rearrangement reactions among the light elements in the periodic table and is accompanied by the release of copious amounts of energy. It is useful to think of fusion as the nuclear analog of chemical combustion; for example, we speak of the Sun as "burning" hydrogen, to describe the chain of fusion reactions that ultimately transform hydrogen nuclei into helium nuclei, positrons, and neutrinos. There are great differences between the two types of reactions, however. Fusion releases energy in amounts many orders of magnitude greater than chemical combustion, and requires temperatures of at least 60 million to 100 million degrees (well in excess of temperatures in the Sun's interior) and even higher for fuels other than the isotopes of hydrogen. Fortunately for those who occupy this planet, the fusion processes in the Sun proceed at a very slow rate, and we must look toward other reactions if we are to develop thermonuclear power of terrestrial origin.

The reactions of interest (see Figure 1) involve the nuclei at the light end of the periodic table, principally the isotopes of hydrogen, deuterium (D), which occurs in nature, and tritium (T), which must be created artificially since it has a relatively brief radioactive lifetime. Deuterium reacts with itself to yield neutrons and protons (the nuclei of ordinary hydrogen) plus nuclei of tritium and of the light isotope of helium. These nuclei also undergo fusion, or rearrangement reactions, with deuterium to yield ordinary helium nuclei. Thus, were it possible to "burn" deuterium and its intermediary reaction products to completion, the net reaction would be the transformation of deuterium into helium and hydrogen plus a neutron, accompanied by a large release of energy.

Unfortunately, it would be quite difficult to make such a scheme practical. Fusion events involve the collisions between nuclei, each of which carries positive electrical charge. Only energetic nuclei, traveling at high velocity, have a reasonable chance of penetrating the barrier of coulomb repulsion and passing close enough to each other to achieve a fusion encounter. In order to have a large enough population of energetic nuclei to be of practical interest, the reactants must be heated to high temperatures. (At these temperatures, matter will be in the gaseous state, molecules will be dissociated, and the resulting atoms will be stripped of their outer electrons. Thus, the medium for fusion reactions is a high-temperature ionized gas, usually termed a *plasma*.)

The probability that a specific nuclear reaction will take place is measured by the event's *cross section*. Of the reactions involving deuterium shown in Figure 1, only the D-T reaction has a large enough cross section at anticipated reactor conditions to be practical; other fusion reactions would require higher operating temperatures or better energy-conversion efficiencies. For these reasons, most attention to date has centered on the possibilities of developing a D-T fusion reactor.

DEUTERIUM-TRITIUM AS A REACTOR FUEL

For a fusion reactor operating with a D-T mixture as its fuel, it is necessary to devise a means for producing tritium. This is relatively straightforward, since the fast neutrons (14 MeV) resulting from the fusion reaction can be used, in part, to breed tritium from lithium (see Figure 1). In effect, the D-T-Li fusion breeder would use deuterium, which occurs in the proportion of 1:6,500 with ordinary hydrogen and is in virtually unlimited supply, and lithium, which, while not nearly as abundant as deuterium, is still quite plentiful (estimates show there is enough to satisfy the world's electricity needs through fusion power for many hundreds and even thousands of years).

There are some complications, however. Tritium is radioactive, and while relatively small amounts may be required in the fusion core itself, the total amount present in a fusion plant will be sufficient to require careful leakage control. In addition, the neutron flux can be expected to be somewhat higher than in a fission reactor of comparable power rating, and the resulting radioactivity induced in the reactor's structural material poses problems in design. It also creates somewhat of a waste-disposal problem, although perhaps not on the scale of a fission reactor, and a potential safety hazard in the case of, for example, uncontrolled chemical fires in the plant. (The chance for nuclear excursions is absent in the case of a fusion reactor, and the control of loss-of-coolant accidents is less demanding than in the case of a fission reactor.)

Some have argued for skipping the D-T-Li generation of fusion reactors, thereby avoiding the problems of tritium breeding and handling. The idea would be to go directly to an "advanced" fuel cycle, such as the one shown in the top three equations of Figure 1, in which neutron fluxes and attendant radiation problems would be less severe. Some have even argued that pure fusion should aim at "ideal" fuel cycles involving proton bombardment of lithium or boron isotopes, which would produce no neutrons but only charged particles that would lend themselves to direct conversion schemes at high efficiency. Unfortunately, fuel cycles other than D-T-Li appear impractical on the basis of our present understanding of the properties of plasmas.

PROSPECTS FOR FUSION POWER TECHNOLOGY

Two fundamental approaches to fusion power are being pursued throughout the world: *magnetic confinement*, historically the first and now the conventional approach, and *inertial confinement*, using lasers or intense beams of electrons or ions to cause ignition of small pellets of D-T fuel. (These approaches are discussed in other articles in this issue.)

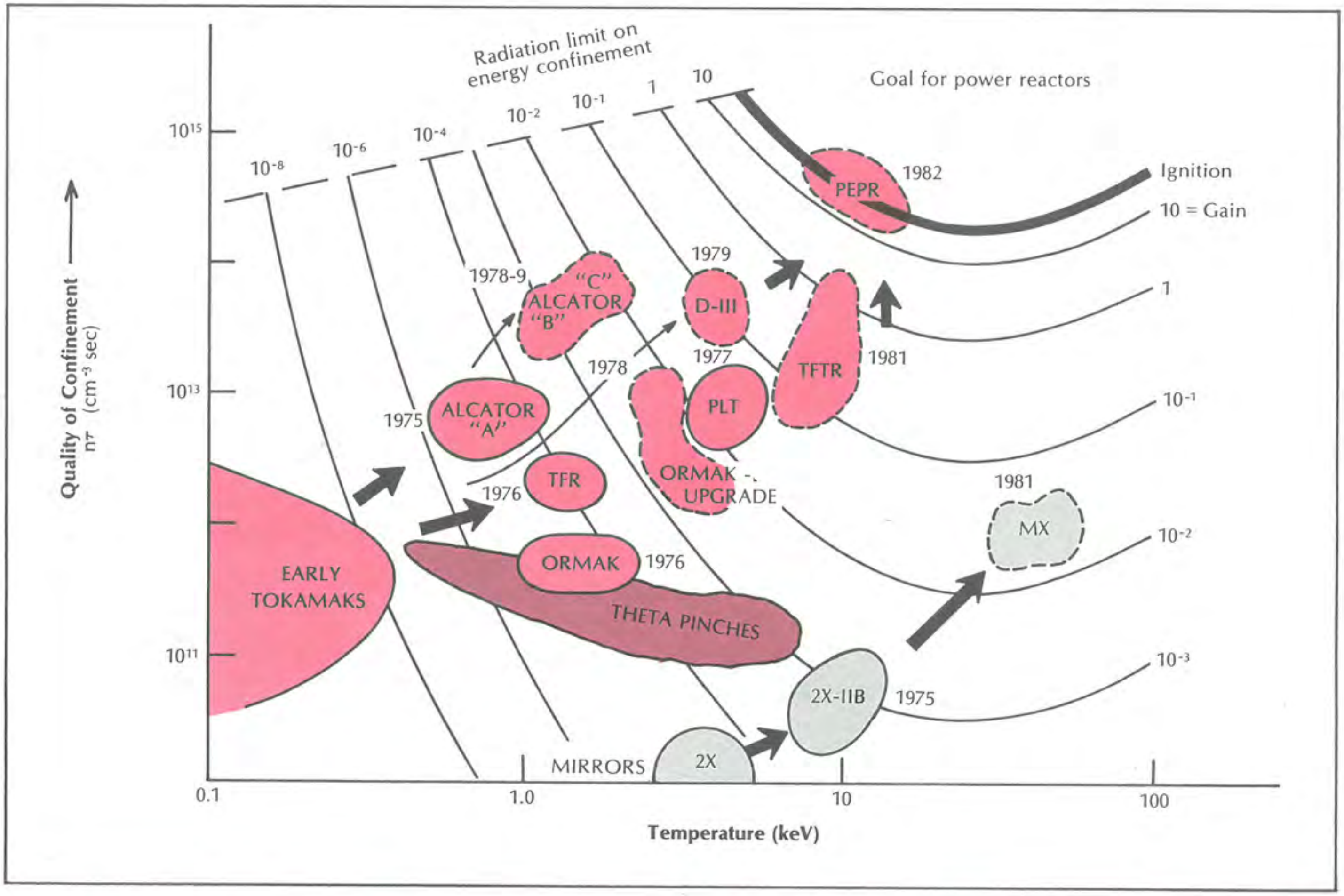


Figure 2. Achieved and projected results of experiments in magnetic confinement in the United States. Ignition, the goal for power reactors, is expected to be achieved in the Prototype Experimental Power Reactor (PEPR), planned for 1982. Quality of confinement is expressed as the product of density and energy confinement time, $n\tau$. The contours represent levels of thermonuclear energy gain. (Source: Division of Magnetic Fusion, Energy Research and Development Administration).

Tokamaks are the leading type of experimental device. The largest of these now operating in this country is the Princeton Large Torus (PLT). The record $n\tau$ value to date is held, however, by the mighty little Alcator at the Massachusetts Institute of Technology. Under construction or in stages of design are larger tokamak experiments: Ormak-Upgrade at Oak Ridge will be equipped with powerful neutral beam sources to study plasma heating under near reactor-like conditions; Doublet III at General Atomic will extend earlier work on noncircular cross-section tokamaks which promise to improve the power density capabilities of toroidal devices; and finally, the Tokamak Fusion Test Reactor (TFTR) at Princeton is expected to achieve break-even conditions in energy gain.

Work on magnetic mirror devices, now a backup to tokamaks, also shows progress. The early experiments with simple mirror devices, where confinement was based on principles resembling those that account for the trapping of high-energy solar particles in Earth's magnetic field, have evolved into rather sophisticated configurations in which the plasma is confined to regions of minimum field strength. A larger mirror experiment at Livermore, the MX, is designed to verify the scaling laws. Despite the problem of energy losses at the ends of mirror devices, there may be offsetting advantages to mirrors in designing actual reactors.

The demonstration of scientific feasibility is the purpose of the present generation of facilities for the United States research program on controlled thermonuclear fusion. The leading type of experimental device is the tokamak, which features a toroidal configuration of magnetic lines of force for plasma confinement. The Princeton Large Torus (PLT), shown at right, is the largest tokamak facility now operating in this country. Other facilities now in operation, under construction, or planned include magnetic-mirror and laser-driven devices.

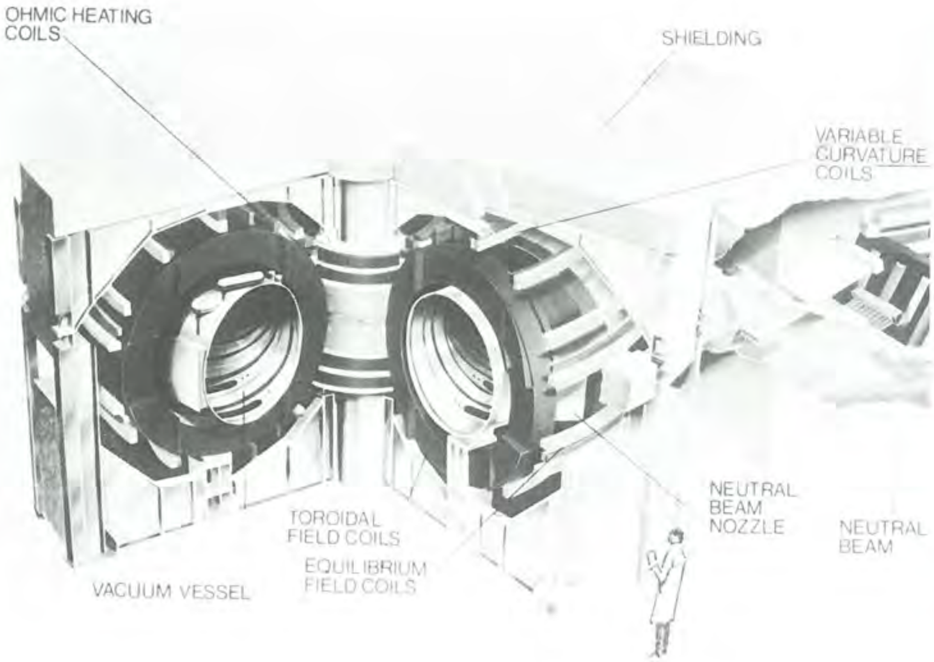
While a great deal more remains to be known about various facets of plasma behavior, there is a prevailing mood of optimism within the fusion community. Expectations are high that within the next five or so years one or more approaches will have yielded successfull demonstrations of scientific feasibility, putting the fusion development program on a par with where the fast-breeder program stood when the first Experimental Breeder Reactor lit a light bulb at the Idaho Test Station.

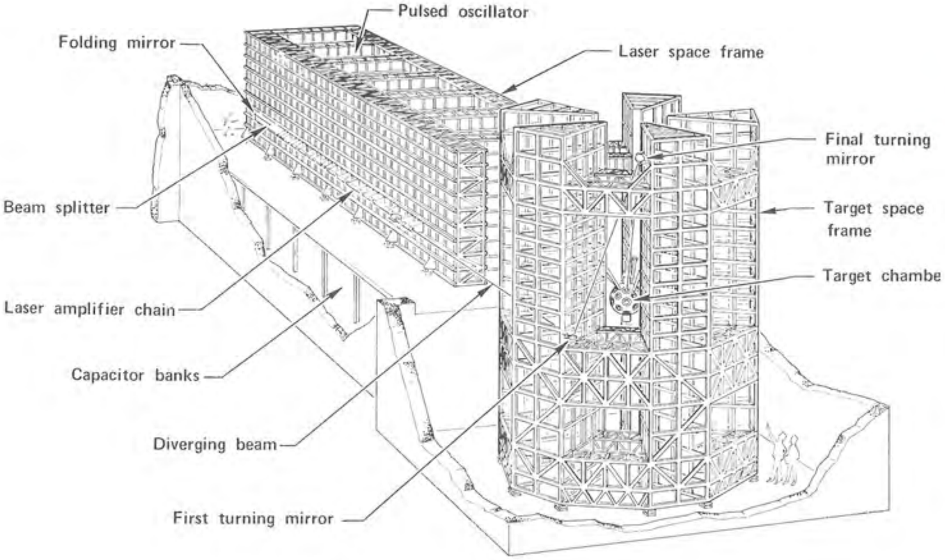
The prospects for commercial fusion power are far more uncertain, however, since a variety of engineering and technological problems remain to be solved. Auxiliary power must be supplied for ignition and (in the case of systems that require extra energy during the entire thermonuclear burn) for driving magnetically confined plasma; in the case of inertial confinement systems, an adequate driver system is not yet even on the drawing boards. A high degree of impurity control must be maintained to prevent energy losses from radiation. Techniques must be developed for removing helium "ash" and other residues, and for introducing fresh fuel. Materials problems arising from high levels of radiation, particularly neutrons, must be met. A series of problems concerned with tritium breeding and handling, heat removal and transfer, and thermal conversion remain to be solved. The large superconducting magnet systems required for magnetic confinement entail problems in mechanical design, force containment, and protection against sudden quench or other transients. In addition, there is the matter of final disposition of radioactive material.

A number of paper design studies of fusion reactor concepts have been made already. These have served and are continuing to serve a very useful function in that they have uncovered many of the engineering and technological problems I have mentioned. On the other hand, it is possible to take the results of these paper studies literally, unjustifiably so in my opinion, and draw discouraging conclusions. I suppose it is only natural that as feasibility approaches rapidly, the criticism becomes more acute.

Several knowledgeable people have looked at tokamaks, for example, extrapolated them to reactor size, and concluded that they didn't like what they saw. The capacity was too large; unlike nuclear reactors which initially came in small units and grew in size gradually, these fusion reactors would be difficult for an individual utility to accommodate during the "learning" phase. In addition, a torus is a cumbersome object from an engineering point of view, even while it may be elegant scientifically. But all the results aren't in yet and future toroidal reactor designs may shrink in size and shed some of their ugly-duckling features.

There is also a certain degree of impatience. It's taking far too long to develop fusion power and the anticipated R & D costs are rather large, some fifteen to twenty billion non-inflated dollars over the course of the next twenty or so years, according to certain estimates. There are two extreme schools of thought that have been expressed, neither of which is wise in my opinion. One would have us hurry and select the most promising

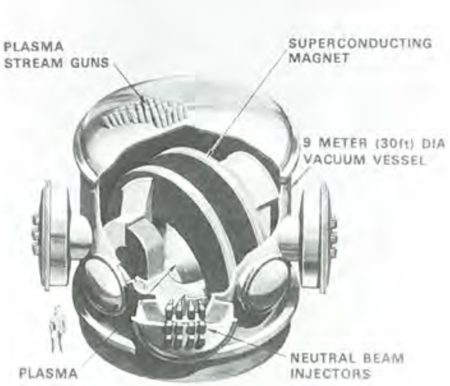




Left: Construction began a few months ago on the Tokamak Fusion Test Reactor (TFTR) at Princeton. This is expected to achieve break-even conditions (in which the fusion energy produced is equivalent to the energy invested in the plasma and the balance of the plant; for a practical reactor, of course, as large an energy gain as possible is sought). Another experimental tokamak is the Doublet III at General Atomic (see a picture of the model on the cover of this magazine).

Left below: A facility for experimentation in the alternate approach of inertial confinement is under construction at the Lawrence Livermore Laboratory. This High Energy Laser Facility (HELF), which features a powerful Nd doped glass laser system, is expected to achieve significant thermonuclear burn. The facility includes both a 10-kilojoule subnanosecond laser (SHIVA) and its building. The laser chain and target-chamber components will be mounted in a space frame of steel tubing.

Below: A large magnetic mirror experiment, the MX, is being planned for Livermore. This type of device is considered the chief "backup" to tokamaks for fusion plasma confinement.



"...it is quite possible that some time early in the next century fusion power will start to become available."

approach and then concentrate our effort on a relatively narrowly defined program aimed at building a demonstration reactor. I think it's premature to adopt such a policy. The other extreme view would have us divert greater attention to shorter-term objectives, namely the fusion–fission hybrid.

A fusion reactor is, after all, a copious source of neutrons. Each one of these neutrons could be used to produce not only the tritium atom needed for replacement, but also up to five fissile atoms in a suitably designed blanket containing uranium and/or thorium. Each of these fissile atoms, when fed to a nuclear converter (fission reactor), could produce about 300 MeV of energy if recycling is permitted. Instead of 17 to 20 MeV of energy released per fusion event, it seems we can have nearly one hundred times more if the fusion reactor is somehow coupled to fission reactors. This, in turn, would allow fusion reactors to become economical under far less stringent conditions than if the fusion plant had nothing to sell but electricity.

The argument in favor of the fusion–fission hybrid is that it could become a practical reality earlier than fusion by itself, provide a cheaper way to the ultimate development of fusion power, and ease the operational requirements to begin with, since it would be "off-line" (not necessarily connected to a utility grid). The argument against fusion–fission is that it combines the worst possible features of both fusion and fission. I don't believe fusion–fission can be dismissed out of hand; it deserves to be looked at carefully and periodically. But I see little reason at this time for making it the principal immediate objective of the fusion program.

The principal immediate objective of the fusion program needs to be: to learn more about the behavior of plasmas under reactor-like conditions, with plasma densities and temperatures comparable to those required for a reactor, to explore in greater depth the promising new concepts scientists are forever inventing because there is lots of room for a good new invention, and to learn how to solve the many difficult engineering tasks that lie ahead. I doubt that it's possible to begin assembling now all the elements that will be needed for the design and construction of a successful demonstration reactor for the simple reason that we just don't know enough. On the other hand, we know reasonably well what additional experiments must be done to acquire some of that knowledge.

The cost of the fusion program is hardly insignificant any more. It could easily approach the billion-dollar-a-year level within the next few years. Surely it will be asked whether we can afford that level of commitment when the way to reach the final goal is only dimly perceived and the promised benefits are off in some imprecisely defined future.

My own assessment is that although we might get along without fusion power for fifty or perhaps even one hundred years, a full commitment to the fusion program is a choice our nation cannot afford to give up.

REGISTER

New School and Department Heads Named in Four Engineering Units

Professors in four academic units of the College have been appointed to terms as school or department administrators. Those who assumed their new responsibilities this fall are *Albert R. George,* director, and *John F. Booker,* assistant director of the Sibley School of Mechanical and Aerospace Engineering; *George L. Nemhauser,* director of the School of Operations Research and Industrial Engineering; and *Juris Hartmanis,* chairman of the Department of Computer Science. *Norman R. Scott* will become head of the Department of Agricultural Engineering in February.

■ George, the new director of the Sibley School, had served as assistant director for the past five years. He has been a member of the Cornell faculty since 1966 and a full professor since last January.

George holds three degrees from Princeton University: the B.S.E. in aerospace engineering, granted in 1959; and the A.M. and Ph.D. in aerospace and mechanical sciences, awarded in 1961 and 1964, respectively. Before coming to Cornell, he had been a research associate at Princeton and spent a year as a faculty member at the University of Washington. During a sabbatic leave in 1972-73, he was a senior visiting fellow in aeronautics at the University of Southampton, England.

His recent research has been in the areas of helicopter rotor noise, sonic boom, and high-speed aerodynamics, and he has published a number of papers on these subjects. In addition, he has served as a consultant to the Aeronautical Research Council (Great Britain) and to several industrial organizations, including Hamilton Standard, in this country.

He is active in the American Institute of Aeronautics and Astronautics (AIAA) as a member of the aeroacoustics technical committee, and last year served on the technical program committee for the organization's international meeting. He is also a member of several other professional societies.

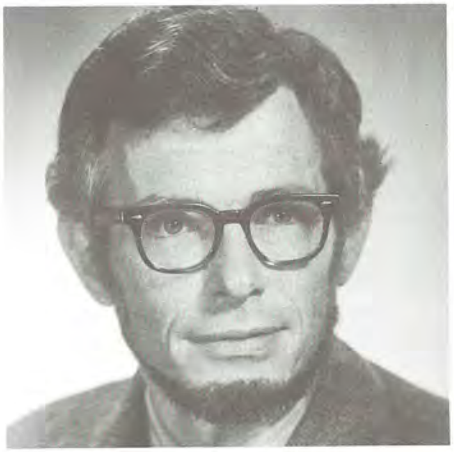
George was the 1970 recipient of the Ralph E. Teetor Award of the Society of Automotive Engineers, and was selected as an AIAA Outstanding Faculty Adviser in 1967, 1968, and 1977.

■ Booker, a specialist in lubrication, finite-element methods, and computer-aided simulation and design, is an associate professor of mechanical and aerospace engineering. He has been a faculty member here since he received his Cornell doctorate in mechanical engineering in 1961.

He studied at Yale University for the B.E. degree, granted in 1956, and spent two years as an engineer with the Chrysler Corporation before beginning graduate study.

In 1974-75 Booker spent a sabbatic leave at the University of Leeds, England, where he was a senior visiting fellow of the British Science Research Council. In this post he conducted research on elasto-hydrodynamic lubrication in human joints as part of a bioengineering group at the Institute of Tribology. During a previous sabbatic leave, in 1967-68, he was a Ford Foun-

George



Booker

dation Resident at the International Business Machines Corporation. His professional activities have included consulting for the General Motors Research Laboratories and other industrial organizations. He is currently an associate editor of the *Journal of Lubrication Technology.*

In 1965 he received the Henry Hess Award of the American Society of Mechanical Engineers. In 1969 a paper coauthored by Booker won the Starley Premium Prize of the Institution of Mechanical Engineers (British).

Nemhauser

■ Nemhauser, a specialist in mathematical programming, has been a professor in the School of Operations Research and Industrial Engineering since 1969 and served as acting director during the 1973-74 academic year. He assumed the directorship after a two-year leave spent at the University of Louvain, Belgium, where he was research director of the Center of Operations Research and Econometrics.

He studied at City College of New York for the B.Ch.E. degree, granted in 1958, and at Northwestern University for the M.S. in 1959 and the Ph.D. in 1961. Before coming to Cornell, he spent eight years on the faculty of The Johns Hopkins University, where he was named three times by a student group as one of the best eight teachers in the arts and sciences school.

In 1969 he was awarded a National Science Foundation senior faculty fellowship and returned to Louvain as a visiting research professor. He has also been a visiting lecturer at the University of Leeds, England.

In addition to publishing numerous papers in professional journals, he is

Hartmanis

Scott

the author of *Introduction to Dynamic Programming* (Wiley, 1966) and coauthor of *Integer Programming* (Wiley, 1972). He is editor of *Operations Research* and has served on the editorial boards of four other professional journals. He has served on the council of the Operations Research Society of America and is a member of several other professional societies.

■ Hartmanis came to Cornell in 1965 as professor of computer science and chairman of the department, and continued as chairman until his sabbatic leave in 1971-72.

He received the degree of Cand.Phil. from the University of Marburg, Germany, in 1949, the M.A. in mathematics from the University of Kansas City in 1951, and the Ph.D. in mathematics from the California Institute of Technology in 1955. After receiving the doctorate, he taught mathematics at Cornell for two years and at Ohio State University for one year, and then served as a research mathematician at the General Electric Research Laboratory for seven years prior to his Cornell appointment in computer science. His sabbatic leave was spent at the Gesselschaft für Mathematik und Datenverarbeitung in Bonn.

Hartmanis has published some seventy papers in his specialty fields and is coauthor of a book, *Algebraic Structure Theory for Sequential Machines* (Prentice-Hall, 1966). He is an editor of the *SIAM Journal on Computing* and the *Journal of Computer and System Sciences,* and is on the editorial board of *Mathematical System Theory.* He is also editing *Lecture Notes in Computer Science,* to be published by Springer-Verlag.

In other professional activities, he has served as program committee member for several international conferences and on various university and government committees working on problems related to computer science.

■ Scott, a Cornell Ph.D. in agricultural engineering, joined the faculty here after receiving the degree in 1962. He has been a full professor since 1976.

His research interests are in the areas of biomathematical modelling of animal systems, agribioengineering, animal calorimetry, environmental physiology, thermal environment, and structural systems. He has participated in Cornell projects on earth–air heat exchange, thermoregulation of chickens, mechanics of milking, estrus detection of cattle, bond-slip in concrete reinforced members, environmental systems for livestock housing, and solar heating and cooling of greenhouses and residences.

Scott studied at Washington State University for the B.S.A.E. degree (with honors), granted in 1958. In 1970-71 he spent a sabbatic leave in the Biomedical Engineering Department of Case Western Reserve University.

Honors he has received include the 1971 Paper Award of the American Society of Agricultural Engineers (ASAE) and the 1977 Outstanding Faculty Award of the student branch of ASAE at Cornell.

President, Distinguished Professors Among New Engineering Colleagues

Cornell's new president, Frank H. T. Rhodes, has been granted his wish "to be allowed in the classroom to give an occasional lecture in geology" and is now a professor of geology and mineralogy as well as chief administrative officer of the university. For people at the College of Engineering, there is the agreeable prospect of getting to know Rhodes as colleague and teacher as well as president.

Before coming to Cornell, Rhodes was professor of geology and mineralogy and vice president for academic affairs at the University of Michigan. He received his scientific education at the University of Birmingham in his native England, earning the baccalaureate degree with first-class honors in 1948 and the doctorate two years later.

He came to the United States in 1950 as a postdoctoral fellow and Fulbright scholar at the University of Illinois. During the 1950's he was a member of geology faculties at the University of Durham, at Illinois, and at the University of Wales, Swansea. He served as head of the department there and in 1967 was named dean of the faculty of science. He joined the Michigan faculty in 1968 as professor of geology and mineralogy, became dean of the university's College of Literature, Science and the Arts in 1971, and was named to the vice presidential post in 1974.

Rhodes is the author of more than sixty scientific papers many of them on a group of microscopic fossils called conodonts, which are important as indicators of geologic age. He has also written a number of more general articles and books on the earth sciences, including *The Evolution of Life* (1962), which has been translated into several foreign languages, and *Evolution* (1974). Since 1962 he has been editor of the Commonwealth and International Library series on geology. He was senior author of a monograph on undergraduate education published by the American Geological Institute in 1971. He has also participated in several educational radio and television programs.

President Rhodes inspects a specimen in the "rock park" outside Kimball Hall. With him is Jack E. Oliver, chairman of the Department of Geological Sciences.

During his visit to the engineering campus, Rhodes (at the wheel) took a spin in the electric car, a student project. Onlookers from the College included (left to right) Edmund T. Cranch, dean; John F. McManus, associate dean; Joseph L. Rosson, faculty adviser for the electric car project; and G. Conrad Dalman, director of the School of Electrical Engineering.

Rhodes has received numerous awards from the Geological Society of London. He was a Gurley Lecturer at Cornell in 1960 and director of the National Science Foundation–American Geological Institute First International Field Studies Conference the following year. In 1964 he undertook a lecture tour, sponsored by the British Council, of universities and geological surveys in India, Pakistan, Thailand, Turkey, and Iran.

He is a member of a number of professional societies in the field of geological sciences and has served as chairman of the curriculum panel of the Council on Education in the Geological Sciences.

■ A leading theoretical plasma physicist, Marshall N. Rosenbluth, has been named Andrew D. White Professor-at-Large of the University. He is professor of physics at the Institute for Advanced Study, Princeton, and also a faculty and Plasma Physics Laboratory staff member at Princeton University.

The White professorships bring outstanding specialists in various fields to Cornell for periods of residency throughout the six-year terms of appointment. Rosenbluth made his first visit to the campus in April.

Rosenbluth

He recently received the 1976 James Clark Maxwell Prize in Plasma Physics, awarded by the American Physical Society. He was cited for his analyses of the behavior of plasma and his contributions to plasma theory in the areas of stability, transport processes, interaction of radiation with plasma, fluctuations, and wave phenomena. Previous awards Rosenbluth has received are the E. O. Lawrence Award (1964) and the Albert Einstein Award (1967).

Rosenbluth earned his doctorate at the University of Chicago in 1949, taught at Stanford University for a year, and then became a staff member at the Los Alamos Scientific Laboratory. In 1956 he joined the General Atomic Laboratories as senior research adviser and subsequently received a joint appointment as professor of physics at the University of California, San Diego. He joined the Institute for Advanced Study in 1967.

He is a fellow of the American Physical Society and was elected a member of the National Academy of Sciences in 1968. He is a consultant to NASA and the Maxwell Laboratories, Inc.

Lumley

Dick

The College faculty has been augmented this fall by the appointment of two chaired professors, both internationally recognized experts in their fields of engineering. *John L. Lumley,* a specialist in studies of turbulent flow, has been named the first Willis H. Carrier Professor of Engineering in the Sibley School of Mechanical and Aerospace Engineering. *Richard I. Dick,* an expert in water pollution control engineering, is the Joseph P. Ripley Professor of Engineering in the School of Civil and Environmental Engineering.

■ Lumley, previously a professor in a named chair at the Pennsylvania State University, is recognized for both theoretical and experimental work in turbulent flow. He has devised electronic circuitry for processing complex data signals in turbulence experiments, for example, and has developed computer programs for the analysis of his theoretical models and experimental results. Studies of turbulent flows have practical applications in such areas as turbomachinery, combustion, communications, atmospheric pollution, and local climatic conditions. At Cornell Lumley's work is expected to strengthen research programs in related areas such as aerodynamics, atmospheric sciences, combustion, and radio physics.

Lumley received the A.B. degree from Harvard University in 1952 and took his graduate work at The Johns Hopkins University, earning the M.S.E. degree in mechanical engineering in 1954 and the Ph.D. in aeronautics in 1957. He joined the Pennsylvania State faculty in 1959 after two years of postdoctoral research at Johns Hopkins.

Lumley has held a Guggenheim fellowship for research at the Universities of Aix-Marseilles II and Claude-Bernard (Lyon) in France and a Fulbright senior lectureship at the University of Liege in Belgium, and he has served as a visting professor at universities in Belgium, France, and England.

He is a fellow of the American Academy of Arts and Sciences and the American Physical Society and is active in a number of professional organizations. In addition to publishing extensively in professional journals, he is author or coauthor of several widely used books on turbulence, has served as an editor of several professional publications, and has edited the translation of a two-volume Russian treatise on turbulence.

■ Dick, who came to Cornell from the University of Delaware, is best known for his research on solids separation and the properties and processing of residues produced in wastewater treatment. He has investigated the properties of suspensions produced in the biological treatment of organic wastes, for example, and analyzed factors controlling the performance of solids separation processes so as to improve the quality of treated effluents, increase the capacity of biological treatment processes, and reduce waste sludge disposal problems.

In 1968 Dick was awarded the Harrison Prescott Eddy Medal of the Water Pollution Control Federation for his research. He has published numerous papers in his field and serves on the editorial boards of *Water Research* and *Progress in Water Technology.*

He received the B.S. degree in civil engineering from Iowa State University in 1957, the M.S. in sanitary engineering from the State University of Iowa in 1958, and the Ph.D. in environmental engineering from the University of Illinois in 1965. He is registered as a professional engineer in Illinois and Delaware.

Dick worked with the United States Public Health Service in Kansas City, Missouri, and with a private consulting firm in Illinois before joining the Illinois faculty in 1965. He was a visiting engineer at the Water Pollution Research Laboratory in Steveage, Herfordshire, England in 1970-71 and joined the faculty at Delaware the following year. He has been active as a consultant to the World Health Organization, federal agencies, municipalities, industries, and legal and engineering firms, and he serves on committees of the International Joint Commission and the National Research Council.

Dick is a past-president and member of the board of directors of the Association of Environmental Engineering Professors. He serves on the executive committee and the governing board of the International Association on Water Pollution Research and is chairman of that organization's National Committee in the United States.

In addition to two chair professorships, appointments in the College this fall included a senior professor in the area of nuclear science and engineering and plasma studies, assistant professors in various schools and departments, and a number of visiting and adjunct professors.

■ *David A. Hammer,* a Cornell Ph.D., has returned as an associate professor of nuclear science and engineering in the Laboratory of Plasma Studies, where he worked as a graduate student during the Laboratory's formative years. His research is in the field of intense electron and ion beams and their applications. Hammer received the B.S. degree in physics from the California Institute of Technology in 1964, began graduate study at the University of Leeds in England as a Fulbright fellow, and completed his doctoral work at Cornell in 1969. Subsequently he became a research physicist at the Naval Research Laboratory, where he started the program in intense electron beam research. During those years he also served as a visiting associate professor at the University of Maryland, and last year was an associate professor at the University of California, Los Angeles.

■ A new assistant professor in the School of Chemical Engineering is *Claude Cohen,* a Princeton University Ph.D. whose area of research is physical studies of polymer solutions and bulk polymers. Cohen was graduated from the American University in Cairo in 1966 with a degree in chemistry. In 1972 he received both his doctorate in chemistry and his United States citizenship. Since then he has been a research associate and instructor in chemistry at Brown University; conducted research in the polymer department of the Weizmann Institute of Science in Rehovot, Israel, as an Aharon Katzir-Katchalsky Fellow; and served as a research fellow in chemical engineering at the California Institute of Technology.

■ In the School of Civil and Environmental Engineering, two assistant professors have joined the Department of Environmental Engineering and one has been named to the Department of Structural Engineering.

Gerhard H. Jirka, a specialist in environmental hydraulics, came to Cornell from the Massachusetts Institute of Technology. After completing his doctoral studies there in 1973, he served as a research engineer and program manager for environmental research in the Energy Laboratory and as a lecturer in the Department of Civil Engineering. His undergraduate Dipl. Ing. (with honors) was awarded in 1969 by the Hochschule für Bodenkulter in his native Austria.

Jery R. Stedinger is a specialist in environmental systems engineering. In his doctoral thesis, written at Harvard University, he developed models to analyze the effectiveness of forest-insect-management policies for the spruce budworm in Maine and New Brunswick. His undergraduate degree, in applied mathematics, was awarded in 1972 by the University of California at Berkeley. When an undergraduate, Stedinger held a work-study position at Sandia Laboratories in Livermore, California, and after graduating, he spent a year as a mathematical programmer at Lawrence Livermore Laboratory in Livermore, California. During his graduate years, he was a summer employee at the Los Alamos Scientific Laboratory in New Mexico and also worked as a consultant in environmental modeling for the Energy Resources Company, Inc., in Cambridge, Massachusetts.

Anthony R. Ingraffea joined the Department of Structural Engineering after earning the Ph.D. at the University of Colorado and completing a term there as a postdoctoral researcher. His specialty area is structural mechanics. He received the B.S. degree in aerospace engineering from the University of Notre Dame in 1969 and worked for several years at the Grumman Aerospace Corporation, Bethpage, New York, before earning the M.S. degree in civil engineering at the Polytechnic Institute of New York in 1971. Before beginning his doctoral studies, he spent two years as a county engineer with the Peace Corps in Bejuna, Venezuela. In that job he was responsible for all technical services for 40,000 people. He is a licensed professional engineer in the State of Colorado.

■ A new assistant professor in the School of Electrical Engineering is *Daniel W. Hammerstrom,* a specialist in computer architecture, multi-processing, microcomputer design and application, system performance evaluation, and systems programming. He is also interested in research on alternative energy sources. Hammerstrom completed his doctoral study this past summer at the University of Illinois, where he was a research assistant in the Coordinated Science Laboratory. His experience also includes several years as a computer systems design engineer with the United States Air Force Electronic Systems Division at Hanscom Air Force Base in Massachusetts. He was graduated with distinction from Montana State University in 1971, and received the M.S. in electrical engineering from Stanford University in 1972.

■ In the Department of Geological Sciences, *Larry D. Brown* was appointed assistant professor after earning his Cornell Ph.D. in geophysics in 1976 and serving for a year as a postdoctoral research associate. He received the B.S. degree in physics, with highest honors, from the Georgia Institute of Technology in 1973. As an undergraduate he held part-time jobs in plastic products manufacture and chemical analysis. At Cornell he has worked with Professors Jack E. Oliver and Sidney Kaufman in seismic data processing, deep seismic reflection studies of continental crust, and studies of recent crustal movement, and he has published several papers on these subjects.

■ Four assistant professors have joined the faculty of the School of Mechanical and Aerospace Engineering.

Said Jahanmir, a specialist in materials processing, did his graduate work in mechanical engineering at the Massachusetts Institute of Technology, earning the M.S. in 1973 and the Ph.D. in 1976. For the past year he has been a lecturer at the University of California at Berkeley. His B.S. degree, also in mechanical engineering, was granted by the University of Washington in 1971. Jahanmir has already published sixteen papers on materials research, mostly on wear of metals. He is an Iranian citizen.

Another MIT graduate new to the mechanical engineering faculty is *Ronald L. Levin,* whose research interests are in biomechanics and thermodynamics. Levin received the S.B. and S.M. degrees in 1973 and the Sc.D., with a major in mechanical engineering and a minor in nuclear engineering, in 1976. During the next year he served as a research fellow in biophysics at the Harvard Medical School and as a research affiliate in thermodynamics at MIT. His publications include papers on the permeation of metals by hydrogen and hydrogen isotopes, and on diffusion in biological membranes.

Predrag T. Radulovic, an instructor in the School last year, was appointed assistant professor. His specialty field is holography and laser optics as applied to heat transfer and fluid mechanics. Radulovic received the Dipl. Ing. in mechanical engineering from the University of Belgrade in his native Yugoslavia in 1965, and then worked for five years as a systems engineer with the Energoproject Consulting and Engineering Company in Belgrade. During this time, he shared the first prize for professional achievement in the field of power generation. In 1970 he was awarded a Fulbright scholarship and entered graduate school at the University of Pittsburgh, where he earned the M.S. degree in 1972. He studied at the University of Michigan for the Ph.D., granted last summer.

New in the aerospace engineering group is *Zellman Warhaft,* a specialist in turbulence and atmospheric physics. Warhaft, an Australian, received a baccalaureate degree in electrical engineering from the University of Melbourne in 1967 and the Ph.D. in electrical engineering from the University of London in 1975. In Australia he conducted research on microwave telecommunications for the postal department; subsequently, in England, he worked with the Science Research Council (where he collaborated in some research with Cornell Professor Ralph Bolgiano); and after he completed his doctorate, he was a senior project associate in aerospace engineering at the Pennsylvania State University.

■ The Department of Theoretical and Applied Mechanics has two new assistant professors this year.

Philip J. Holmes comes from England, where he has most recently been a postdoctoral fellow at the Institute of Sound and Vibration Research at the University of Southampton. He holds the B.A. degree, with honors, from Oxford University (1967) and the Ph.D. from Southampton (1974). His research interests are in sound and vibration, nonlinear mechanics, dynamical systems, stability, and bifurcation theory.

Peter Dashner has returned to New York State from Virginia, where he taught engineering science and mechanics last year. He studied at the State University of New York at Buffalo for three degrees in engineering science: the B.S. in 1973, the M.S. in 1975, and the Ph.D. in 1976. His specialty fields are continuum mechanics and inelastic behavior of materials.

■ New visiting and adjunct professors augment the regular faculty in a number of academic areas.

In the School of Applied and Engineering Physics, *Jene A. Golovchenko,* a specialist in synchrotron radiation and the structure of solids, is serving as an adjunct associate professor this year. He is from the Bell Telephone Laboratories in Murray Hill, New Jersey. Visitors during the spring term will be *Jerry Gollub,* professor at Haverford College and specialist in turbulence, and *Eric Siggia,* assistant professor at the University of Pennsylvania, whose research interests are in phase transformations and nonlinear fluctuations and instabilities in condensed matter. Siggia will be working in the Laboratory of Applied and Solid State Physics and the Laboratory of Nuclear Studies as well as the School of Applied and Engineering Physics.

In the School of Chemical Engineering, *Robert W. F. Tait,* a specialist in coal utilization and desalination, is a visiting professor from the University of Adelaide, Australia, for the fall term. *Arthur Einsele* from the Swiss Federal Institute of Technology in Zurich is a visiting assistant professor; he is working on mixing and gas dispersion in fluids for biochemical production processes. *William B. Streett* of the United States Military Academy, West Point, is participating in research on polyatomic liquids and their mixtures as an adjunct professor for the year.

In the School of Civil and Environmental Engineering, *Charles A. Moore* from Ohio State University is a visiting professor in geotechnical engineering and *Anthony J. Richardson* from Monash University in Clayton, Victoria, Australia, has been appointed visiting assistant professor in transportation studies for the spring term.

Chula naRanong is a visiting assistant professor in the School of Electrical Engineering. A specialist in circuit theory and control and computer systems, he is from Footscray Institute of Technology, Victoria, Australia.

A visiting associate professor in the Department of Materials Science and Engineering this year is *Edward Lilley,* a faculty member of the University of Sussex, England. His specialty areas are ceramics and ionic materials.

Three visitors are here for the year in the School of Operations Research and Industrial Engineering. *David Gilat,* a specialist in probability from the University of California at Berkeley, is a visiting associate professor. Visiting assistant professors are *Abraham Neyman* from Hebrew University, Jerusalem, Israel, whose research interest is game theory, and *Meir J. Rosenblatt,* a recent Ph.D. from Stanford University, who has specialized in management science.

FACULTY PUBLICATIONS

The following publications and conference papers by faculty and staff members and graduate students of the Cornell College of Engineering were published or presented during the period April through June 1977. Earlier publications inadvertently omitted from previous listings are included here in parentheses. The names of Cornell personnel are in italics.

AGRICULTURAL ENGINEERING

Albright, L. D., and *Scott, N. R.* 1977. Diurnal temperature fluctuations in multispaced buildings. *Transactions of the ASAE* 20(2):319–326.

Chowdhury, A. A.; White, R. N.; and *Scott, N. R.* (1977). Small scale models for reinforced concrete structures. *Transactions of the ASAE* 20:132–137, 144.

Haith, D. A., and *Chapman, D. C.* 1977. Best practicable waste treatment screening model. *ASCE Journal of the Environmental Engineering Division* 103(EE3):397–412.

Hillman, P. E.; Scott, N. R.; and *van Tienhoven, A.* 1977. Impact of centrally applied biogenic amines upon the energy balance of fowl. *American Journal of Physics* 232: R137–R144.

Irwin, L. H. 1977. Determination of pavement layer moduli from surface deflection data for pavement performance evaluation. In *Proceedings, IV international conference on the structural design of asphalt pavements*, pp. 575–590. Ann Arbor: University of Michigan.

———. (1977). Frost Heave in Pavements: Reasons and Remedies. Paper read at 66th Annual Winter Meeting, New York State County Highway Superintendents Association, 19–21 January 1977, in Rochester, New York.

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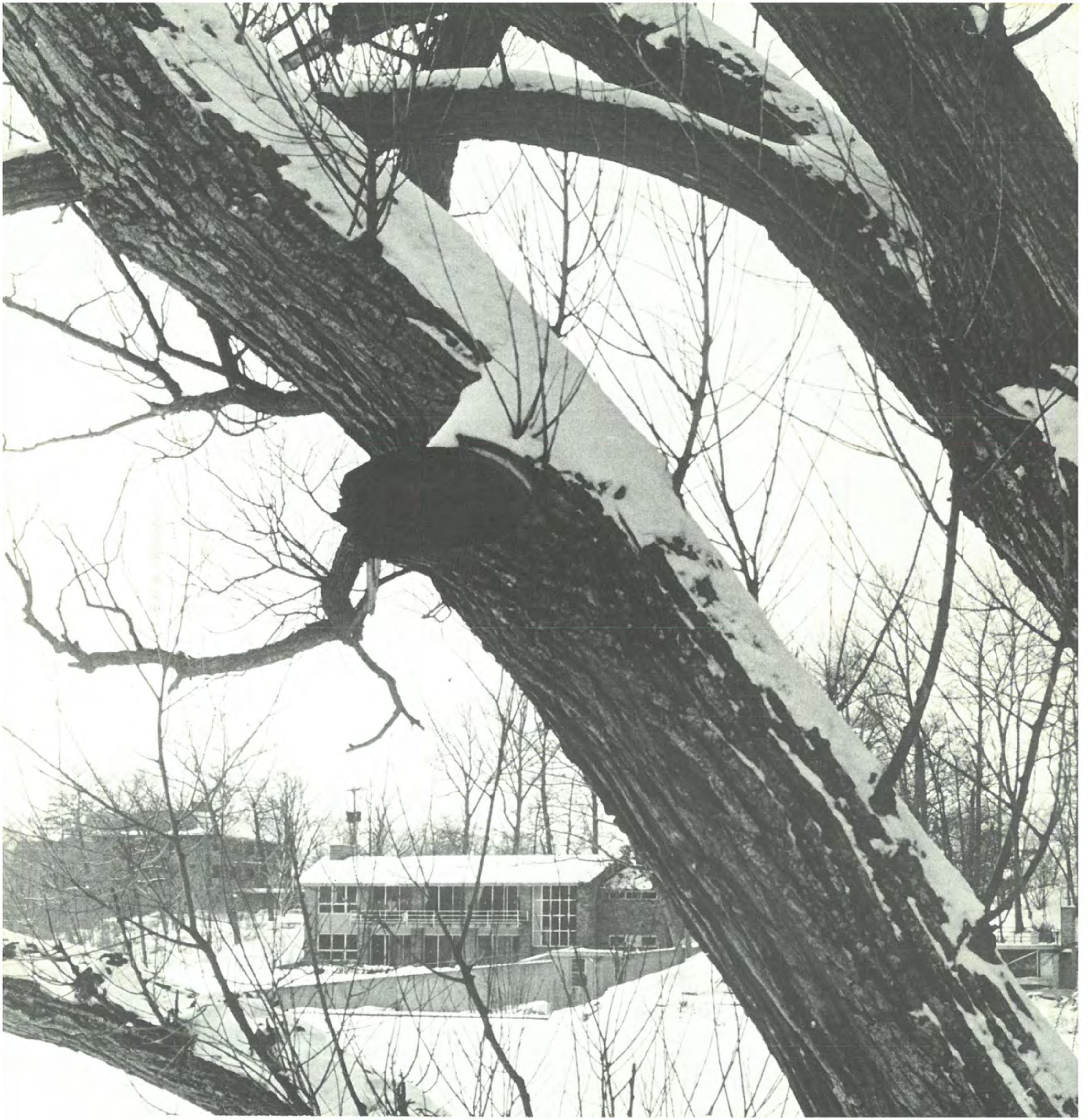

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