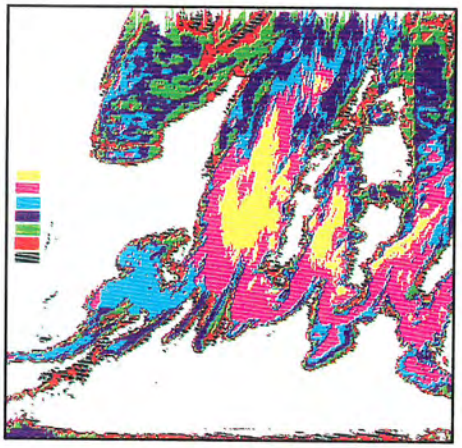
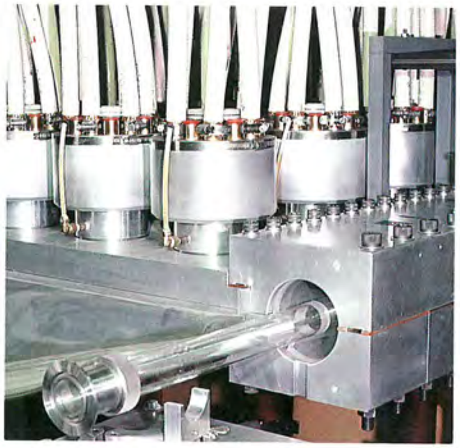
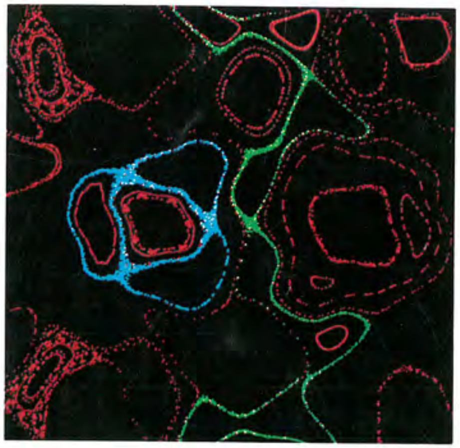
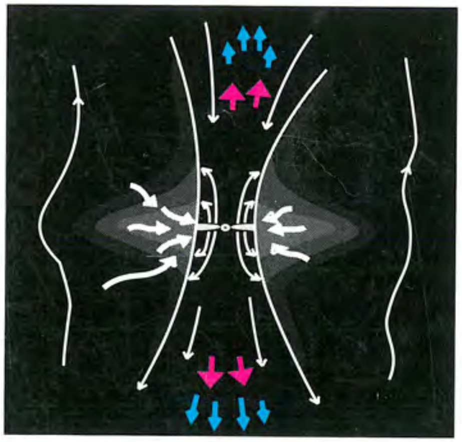
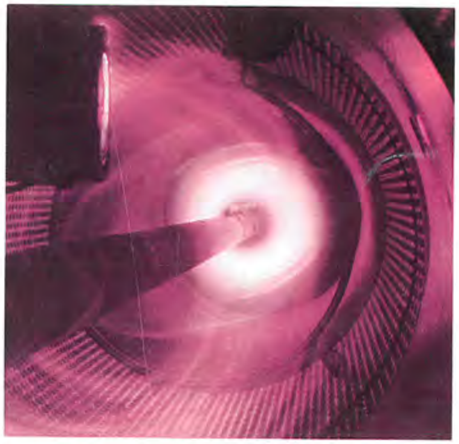
PLASMA STUDIES
at Cornell University





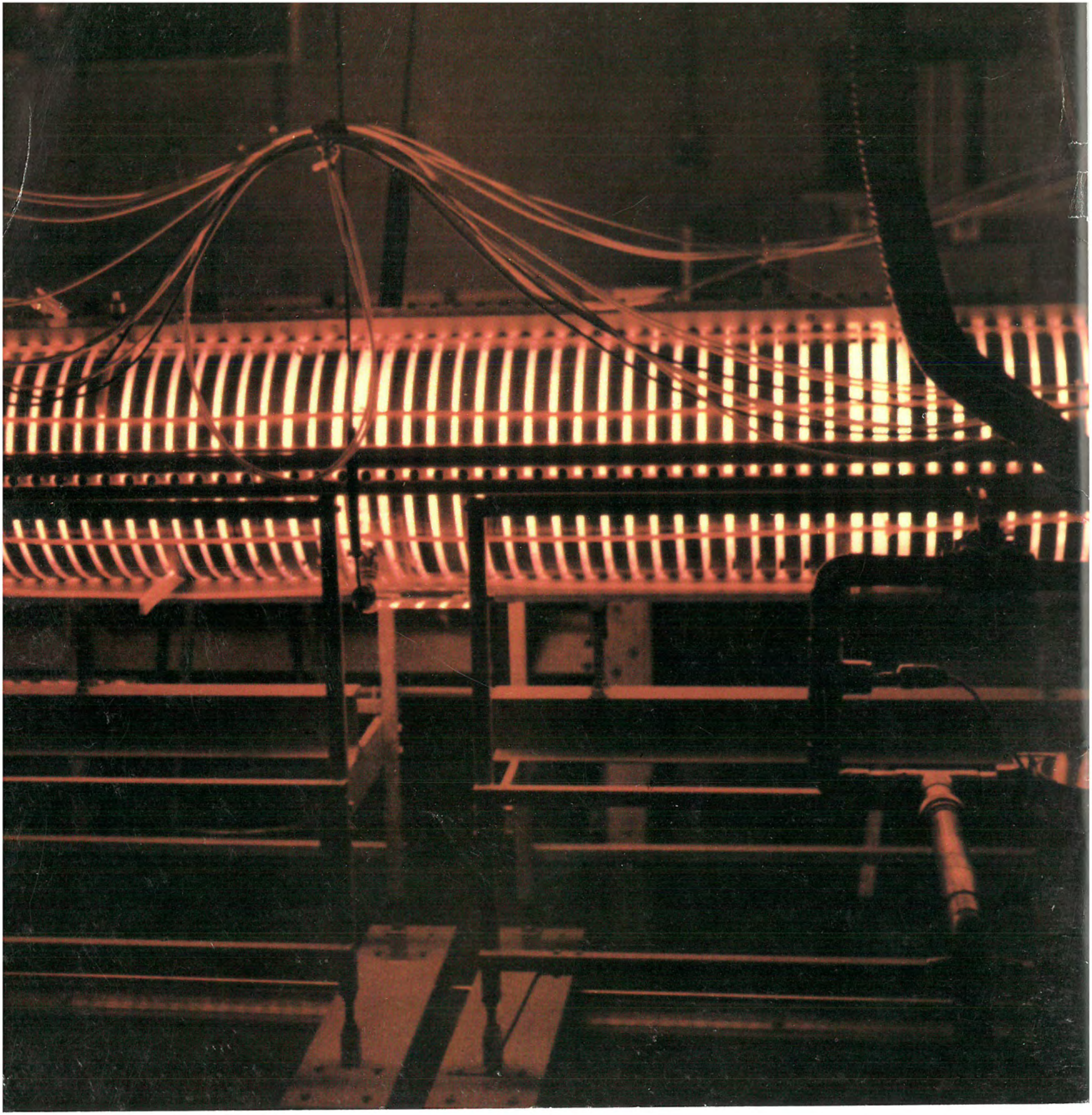






A Collection of Articles
Written in Connection
with the 20th Anniversary
of Cornell's Laboratory
of Plasma Studies

Autumn 1987



PLASMA STUDIES at Cornell University

edited by Gladys McConkey

College of Engineering
Cornell University
Ithaca, New York

Cover Illustrations

Inside front cover: Glowing plasma is magnetically confined in this 2.5-meter-long chamber in Professor David Hammer's laboratory. An ion-ring–plasma interaction experiment is in progress.

Outside cover: The computer-generated graph at top left displays data on the ionospheric plasma density irregularity called equatorial spread-F (see the article by Professor Charles Seyler, Jr.). Altitude and time are plotted on ordinate and abscissa; the colors represent intensities of echo power backscattered from radar signals. The data were collected at the Jicamarca observatory in Peru and processed at Cornell by Wesley Swartz.

The "theta-pinch" plasma device at top center is used in an ion-beam–plasma interaction experiment in Professor Bruce Kusse's laboratory. The plasma tube is contained within the massive two-million-ampere single-turn aluminum coil, which is powered by forty capacitors.

The computer image at top right is a simulation of charged-particle diffusion in a magnetic field, brought about by an electrostatic wave. The image was generated by Dana Longcope on Cornell's supercomputer as part of a study of resonance absorption directed by Professor Ravi Sudan.

The diagram at lower left illustrates the "black-hole pump" discussed by Professor Richard Lovelace (see page 50).

The photograph at center in the bottom row shows a field-reversing ring (the light area) in Cornell's RECE-Christa experiment, described by Professor Hans Fleischmann.

Inside back cover: This photograph of the Particle Beam Fusion Accelerator II at Sandia National Laboratories was taken during the second test shot in January 1986, as part of the research program for development of controlled thermonuclear fusion. In the photograph, the purplish areas are surface electrical flashovers resulting from magnetic fields produced by the 100-trillion-watt accelerator. Blue areas, which are underwater electrical arcs, show where electrical energy is switched for pulse-forming or is diverted after the main energy pulse.

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CONTENTS

THE FIRST TEN YEARS

A Personal Recollection of the Development of Cornell's Laboratory of Plasma Studies

by Peter Auer

The first ten years were easy—at least in retrospect. But then, we had a lot of help in starting up the Laboratory of Plasma Studies at Cornell.

Since this is a personal reminiscence of that time and of the people who made things happen, it is sure to be incomplete. Avoiding names in order to avoid omissions would take all the fun out of reminiscing, though, so with due apologies to those left out, I will set down my recollections.

I came to Cornell as a faculty member in 1966, almost twenty years after receiving a B.A. degree here. In the interim I had become interested in plasma physics—the physics of very-high-temperature gases that have become ionized and are thus good conductors of electricity, as in the interior of the sun or in a bolt of lightning or in an electrical discharge tube. Especially intriguing to me was the prospect of finding a way to produce limitless amounts of energy through nuclear fusion, a process similar to what takes place in the sun. For someone with these interests, Cornell was a good place to go because there was already considerable activity here in plasma physics and the related science of magnetohydrodynamics.

By the time I arrived, Henry Booker and Bill Gordon had left behind not only the giant radio telescope at Arecibo, but also a strong tradition in ionospheric plasma physics that has continued to this day in Cornell's School of Electrical Engineering. Some of the plasma physics problems associated with the ionosphere also attracted the interest of Ed Salpeter, who was in the process of establishing a strong school in theoretical astrophysics, along with Tommy Gold and others. In those days, Ravi Sudan straddled two camps with ease, just as he does today. His early work on ionospheric plasma waves was well known, but his interest in fusion and the theory of high-temperature plasmas was just beginning to reach the flood stage. John Nation was then a young assistant professor, carrying on some of the work on gaseous plasma devices that had been started by Connie Dalman and Les Eastman, while Richard Liboff was deeply involved in probing the kinetic theory of plasmas.

A number of faculty members in what was then the Graduate School of Aerospace Engineering were interested also in the sister science of magnetohydrodynamics (MHD), the study of electrically conducting fluids in the presence of magnetic fields. MHD became known largely through the early work of Hannes Alfvén in Sweden, and Alfvén had a number of admirers at Cornell. Bill Sears, the first director of the aerospace engineering school, and some of his students were attracted to this novel field of fluid dynamics. Even Don Turcotte became involved with MHD briefly before the sirens of the geophysical world called him away. But it was primarily Ed Resler who encouraged the development of MHD studies at Cornell. He had become enamored with high-temperature gas dynamics as a student of Arthur Kantrowitz, and during the years Resler directed the aerospace engineering school, he was a leading advocate for finding a way to unite the interests in MHD among his faculty with the interests in plasma physics elsewhere on campus.

SETTING UP THE LABORATORY OF PLASMA STUDIES

It was Resler who brought me into the aerospace engineering faculty, and soon we had an embryonic plasma physics program of our own.

Left: Simpson Linke was one of the early collaborators in building Cornell's first intense electron-beam source. Linke, a specialist in energy systems and high-voltage transmission, became professor, emeritus, last year.

Right: Early leaders at the Graduate School of Aerospace Engineering were William R. Sears (at right), the first director, and Edwin L. Resler, Jr. (at left), his successor. The photograph was taken in 1971 during the convocation celebrating the centennial of the College of Engineering.

The need to set up a special laboratory quickly became apparent. The catalyst for Cornell's Laboratory of Plasma Studies (LPS) was Alan Kolb, who a few years earlier had formed a plasma physics division at the Naval Research Laboratory (NRL) in Washington, D.C. It was Kolb's belief that the research of his group in new areas of plasma physics and lasers would profit considerably from close collaboration with university-based research groups having similar interests. He already had good working relations with Hans Griem at the University of Maryland and was exploring with Resler the possibility of forming similar arrangements at Cornell.

A program of joint funding and a three-way sharing of research was worked out: Cornell and Maryland would perform basic research in areas that would complement the somewhat more applied work at NRL. As a result, Cornell embarked on what eventually became an LPS specialty—studies of high-voltage, pulsed power and the production of intense relativistic electron beams—as well as work with molecular lasers.

Even at the earliest stages of the development, it was apparent that the joint program would require centralized facilities that could be provided more easily through an independent laboratory than through individual schools or departments. The laboratory was set up, therefore, as an interdepartmental unit attached to the College of Engineering. This helped in the recruitment of new faculty members: Hans Fleischmann, Art Kuckes, and Norm Rostoker joined both the applied physics faculty and LPS, and Bruce Kusse and Richard Lovelace followed the same path in due time. Similarly, Ed Ott and Chuck Wharton added their talents to the LPS program upon joining the electrical engineering faculty, and Charlie Seyler did the same some years later.

WORK ON PULSED POWER AND MOLECULAR LASERS

But I'm getting ahead of my story. Research on pulsed power and molecular lasers actually began even before LPS was in place.

Soon after I arrived, it became obvious that I needed help from an experienced electrical engineer, and I was most fortunate in obtaining this from Sam Linke. Sam and I—he more than I—along with some expert helpers, braved the unknown world of Marx generators and Blumlein lines to put together our first intense beam source so that we could begin to study the way in which very-high-voltage electron beams propagate.

There were two main reasons our initial attempt was a success. One was that we had two unusually talented graduate students to work on this project: Jack Clark and Dave Hammer. For reasons that have never been clear to me, Jack eventually left plasma physics to become dean of Cornell's School of Hotel Administration; Dave went on to get his Ph.D. here with Norm Rostoker and eventually, as head of LPS, got to worry about all the things I used to worry about. The second reason we succeeded so well from the start is that we had the world's master in pulsed-power technology as our tutor—namely, Charlie Martin from the Atomic Weapons Research Establishment in England.

Charlie was a patient teacher and an excellent provider. For example, at a crucial stage in our early efforts, a small but vital component was urgently needed. As it happened, Charlie could easily assemble this component in his laboratory, so

FORMER AND CURRENT CORNELL PROFESSORS CITED IN THIS ACCOUNT

Simon H. Bauer	Chemistry, 1939–77 (emeritus)
Henry Booker	Electrical Engineering, 1948–65; currently retired as head of the electrophysics department, University of California, San Diego
Terrill A. Cool	Applied and Engineering Physics, 1965–
Edmund T. Cranch	Theoretical and Applied Mechanics, 1952–78; dean 1972–78; currently president of Wang Institute
C. Conrad Dalman	Electrical Engineering, 1956–87 (emeritus)
Lester F. Eastman	Electrical Engineering, 1957–
Hans H. Fleischmann	Applied and Engineering Physics, 1967–
Thomas Gold	Astronomy, 1959–86 (emeritus)
William E. Gordon	Electrical Engineering, 1948–66; currently retired as emeritus professor, vice president, and provost of Rice University
David A. Hammer	Nuclear Science and Engineering, 1977–; currently director of LPS
Arthur Kantrowitz	Aeronautical Engineering, 1946–56; currently retired from Avco
Arthur F. Kuckes	Applied and Engineering Physics, 1968–86; currently at Vector Magnetics
Bruce R. Kusse	Applied and Engineering Physics, 1970–
Richard L. Liboff	Applied Physics and Electrical Engineering, 1964—
Simpson Linke	Electrical Engineering, 1949–86 (emeritus)
Richard V. E. Lovelace	LPS, 1970–74; Applied and Engineering Physics, 1974–
Ross McFarlane	Electrical Engineering, 1969–79; now at Hughes Research
John Nation	Electrical Engineering, 1965–
Edward Ott	Electrical Engineering, 1968–80; now at University of Maryland
Edwin L. Resler, Jr.	Mechanical and Aerospace Engineering, 1951–52, 1956–
Norman Rostoker	Applied and Engineering Physics, 1967–72; currently at University of California, Irvine
Edwin E. Salpeter	Physics, Astronomy, and Nuclear Studies, 1949–
Andrew Schultz, Jr.	Operations Research, 1941–80 (emeritus); dean 1963–72
William R. Sears	Aerospace Engineering, 1964–74; currently professor, emeritus, University of Arizona
Ravindra N. Sudan	Electrical Engineering, Applied and Engineering Physics, 1958–
Chung L. Tang	Electrical Engineering, 1964–
Donald L. Turcotte	Aerospace Engineering, 1959–73; Geological Sciences, 1973–
Charles B. Wharton	Electrical Engineering, 1967–
George J. Wolga	Electrical Engineering, Applied and Engineering Physics, 1961–

Hammer was dispatched to England over the Christmas holidays to help with the work and bring home the bacon. This he did, in a carefully packaged container covered with a replica of the Union Jack to help with the customs inspection. It all worked out according to plan. On another occasion, when progress was lagging, Charlie dispatched one of his helpers, George Herbert, who actually stayed at Cornell for six weeks; and later Phil Champney helped us for more than a month (he was here when our first beam of electrons was extracted).

Research on lasers was an integral part of the joint program. At Cornell the active participants were Sy Bauer, Terry Cool, Chung Tang, and George Wolga, to begin with. Ross McFarlane joined the group soon after its start. The sum total of the work done on lasers and quantum electronics at Cornell was far greater than the part sponsored through LPS, but even so, the LPS share resulted in some notable achievements. Among these were the demonstration of chemical lasing in the HF/DF system, and the precise study of vibrational excitation/relaxation processes in molecules.

Of course, the fields of lasers and plasma physics often overlap, as in the technology of laser fusion and inertial confinement—an approach in which high-power lasers are used to initiate the fusion reaction in tiny pellet targets. This is an area of research that was never directly pursued at LPS, but we followed it closely through contacts with the University of Rochester, where Moshe Lubin, one of Resler's former students, had organized what was to become the Laboratory for Laser Energetics. In time, LPS became involved with the inertial-confinement approach through joint research with the

Sandia National Laboratory at Albuquerque, where a group then headed by Gerry Yonas, a Cornell engineering physics graduate of 1962, was using energetic particle beams rather than lasers as the driver for pellet fusion.

SUPPORT FOR LPS ON AND OFF CAMPUS

Having gotten this far in my story, perhaps it is time to relate how LPS was formed. There is no way to get around it, I'm afraid; at some point the administration has to be involved in momentous decisions of such magnitude. Joking aside, we were most fortunate to have a very supportive engineering dean, Andy Schultz. With his help and blessing, Ed Cranch, who was then the associate dean, was able to obtain seed money from the New York State Science and Technology Foundation. It was this funding that enabled us to provide suitable housing in Upson Hall and to purchase equipment needed to relocate the research programs that Fleischmann, Kuckes, and Wharton had been carrying out before coming to Cornell. We also needed help from the dean, the university provost, and the president to make available the faculty positions that led to a rapid increase in our ranks.

The University of Maryland was also expanding its faculty in the area of plasma physics, and soon Nick Krall, who had obtained his Ph.D. with Ed Salpeter at Cornell, and Al Trivelpiece became participants in the joint program. When LPS was a few years old, Alan Kolb decided to leave NRL to devote his full energies to a private company that he founded. His replacement at NRL was Ramy Shanny, under whose direction our working relationship remained as effective as before. Eventually, Tim Coffey took over that job, and although he is now director of the entire NRL, our association with him and the plasma group remains strong.

During the formative years of LPS, it was crucial to obtain nongovernmental support as well as funding from the state. Our start in plasma-confinement experiments and the application of intense charged-particle beams to fusion got a big boost during those early years from two separate grants from groups of electric utilities. One of these groups funded us through the Edison Electric Institute; Bob Gilkeson, who at that time was a member of our Engineering College Council, was instrumental in establishing the contacts. Similarly, Joseph Swidler, then head of the Public Service Commission, acted on behalf of Governor Nelson Rockefeller to convince the New York group of utilities to give us the needed support. Eventually, the federally funded fusion program became the source of support for this research effort, but without the help of the utilities, I doubt that we could have gotten off the ground.

AFTER TWENTY YEARS: RETROSPECT AND EXPECTATION

In looking back at the accomplishments of LPS, whether for ten years or twenty, one can be proud of the work done here and of the ensuing scientific achievements of the students and post-docs who got their start at Cornell. I can't attempt a comprehensive accounting of these individuals, but I would like to mention a few of our "alums" from the early days.

Moshe Friedman and Mike Ury made valuable contributions at the beginning of the electron-beam program, and it would be difficult to forget the good work that Peter Korn did while he was here. Stan Humphries was instrumental in working

> *"...one can be proud of the work done here and of the ensuing scientific achievements of the students and post-docs who got their start at Cornell."*

with Ravi Sudan to start the ion-beam work that now represents such a large fraction of our program. Dave Morse was the principal contributor to the laboratory simulation of space-plasma phenomena. Tom Lockner gave up his lucrative job as an engineer in the lab to go back to school here, earn a Ph.D., and make a career of the beam business at Sandia. Bill Condit and Milt Johnson both got to run pieces of the fusion program out of Washington, while Ezra Heitowit spent years explaining technical matters to the Congress.

We did rather well in seeding the countryside with plasma physicists who practice our specialty. There is a healthy representation of them at NRL and at those "Beltway-Bandit" companies that have sprung up in the Washington area. The national laboratories at Sandia, Los Alamos, and Livermore all have significant particle-beam or laser programs in which our students are playing a leading role. And of course, some of our students have become university faculty members and are presumably carrying on the LPS tradition.

Actually, our influence extends well beyond the United States. I haven't even mentioned the lasting ties we have formed with several institutions in other countries, and the cooperative work these associations have promoted.

Brief though it has been, the history of LPS is rich in achievement and extensive in scope. And we haven't even "come of age" yet! After a promising start, we anticipate an auspicious maturity.

Peter L. Auer, a professor in the Sibley School of Mechanical and Aerospace Engineering, became the first director of the Laboratory of Plasma Studies at Cornell when it was formed in 1967. He continued as director until 1975.

Auer received his undergraduate education at Cornell with a major in chemistry, and then earned the Ph.D. in physics at the California Institute of Technology in 1951. His specialty fields are plasma physics and fusion power, and he has been active at the national level in energy policy analysis.

He worked as a physicist for the General Electric Research Laboratories in Schenectady, New York, from 1954 to 1961, and was head of the plasma physics research team at the Sperry Rand Research Center in Sudbury, Massachusetts, from 1961 to 1964. Just before coming to Cornell in 1966, he was director of Ballistic Missile Defense in the Office of the Secretary of Defense, and he has subsequently served as a consultant to that office.

He has also been a consultant to the General Electric Company, the Electric Power Research Institute, the Atomic Energy Commission, the Nuclear Regulatory Commission, the National Academy of Sciences, the Department of Energy, and the Institute for Energy Analysis.

A Guggenheim fellowship enabled him to spend 1960–61 as a visiting scientist in Frascati, Italy, and he spent 1972–73 at Oxford University, England. During his most recent sabbatical leave, last spring, he worked with the research group at the Bechtel Corporation in San Francisco.

Auer has published widely on technical subjects and energy-policy issues and has served as editor of Plasma Physics *and as associate editor of* Energy. *He is a fellow of the American Physical Society.*

THE SECOND DECADE
An Account of Developments at LPS

by Ravi Sudan

The early history of plasma physics at Cornell—the events that led to the formation of the Laboratory of Plasma Studies, and the excitement generated by the pioneering activities of LPS members—has been told by Peter Auer in the initial article in this special collection. I will pick up the thread of the chronicle in its second phase, after the departure of Norman Rostoker for sunny California and of Peter Auer for a well earned sabbatical at Oxford. My account will mention only those projects in which I was personally involved; the articles of other LPS faculty members will fill out the picture.

THE ADVENT OF ION BEAMS FOR PLASMA STUDIES

Most of the early experimental activity at LPS was focused on pulsed-power technology and its application to the generation of intense relativistic electron beams. It soon became apparent that this same successful technology could be used to produce intense beams of protons and other ionic species.

Two difficulties had to be overcome, however. One was that ions, unlike electrons, cannot be extracted from metallic electrodes except under impractically high electric fields. The second problem was that even if ions could be extracted from an anode surface, the electrons emitted from the cathode would provide almost all of the diode current because their mass is so much smaller than that of ions. This would make the diode very inefficient.

A simple means of avoiding the electron-current difficulty, we realized, would be to prevent the emitted electrons from reaching the anode by introducing a magnetic field into the gap. Richard Lovelace and I made a theoretical calculation which showed that such a scheme could be made to work, and in the spring of 1973 Stanley Humphries, Jr., a postdoctoral fellow, began experiments in a small room made available to us by Ed Resler, who was then director of the mechanical and aerospace engineering school. This was the beginning of the ion-beam laboratory at Cornell.

No ions were observed in the initial experimental device, but early the next year successful results were obtained with use of a different geometry—which we called the *reflex triode*—that did not require a magnetic field at all.

The ion-source problem was solved by replacing the metallic anode by an insulator: nylon wires stretched across a frame, as in a tennis racket. The voltage pulse across the diode caused a surface flashover on the insulating anode, ionizing gas released at the anode surface, and the ionized plasma layer became the source for protons and other ionic species. From nylon wires to mylar sheets was a small step. More elaborate anodes are now in use, but they function according to the same principle.

With the problem of an adequate ion source solved, the earlier suggestion of a magnetically insulated diode also turned out to be successful. A patent covering both diode types was granted to Humphries and me in 1976.

This technology was soon picked up by the Naval Research Laboratory (NRL) in Washington and the Sandia National Laboratories in Albuquerque. A West German laboratory was also interested; Hans Bluhm and Klaus Zieher of the Kernforschungzentrum in Karlsruhe (KFK) each spent a year with us at LPS and as a result, a strong group in ion-beam physics and technology was formed at KFK. Visitors from the Soviet Union (A. Didenko), France (Noel Camarcat), Israel (Zeev

Zinamon and Yitzhak Maron) and Japan (Y. Nakagawa and K. Imasaki) also spent time with us and returned to their laboratories to establish programs based on the intense-ion-beam technology.

THE TECHNOLOGY OF INTENSE ION AND ELECTRON BEAMS

Many strides in the technology of pulsed, intense ion beams have been made since that modest beginning. The parameters of the first Cornell experiment—500 amperes at 100 kilovolts for 100 nanoseconds—have been pushed in present-day experiments at Sandia to more than one million amperes at over 1,000 kilovolts for 50 nanoseconds, an increase in power of over a factor of 10^5 in a decade.

People at Cornell who participated in the very early stages of this program, in addition to Humphries and me, were J. J. Lee, a postdoctoral associate; Carl Eichenberger, our versatile technician; and a number of dedicated graduate students—Phil Dreike, John Maenchen, Jesse Neri, and Larry Wiley. As the project developed, Mike Greenspan and Ken Busby joined the group as postdoctoral associates.The experimental effort, involving a number of graduate students and postdoctoral associates, is now being led by faculty members David Hammer and Bruce Kusse and LPS senior research associate John Greenly.

As the LPS program developed, Cornell became increasingly recognized as one of the world's leading centers of research in beam plasma physics, and in the fall of 1977, the second International Conference on Intense Electron and Ion Beams was held here. These biennial conferences, which were initiated by Gerry Yonas at Sandia in 1975, are the dominant professional meetings in that field of science and technology.

ION BEAM TECHNOLOGY FOR FUSION RESEARCH

The main application of intense ion beams has been in controlled thermonuclear fusion research, in both its magnetic and inertially confined manifestations.

In 1971 Hans Fleischmann and his group at Cornell had successfully created "field-reversed" rings of electrons by using the newly developed electron-beam technology. The concept of "field-reversed" magnetic configuration with relativistic electrons was the brainchild of Nicholas Christofilos, who pointed out its many potential advantages for plasma confinement, but had been unable to create it at Livermore because of the inadequate technology available at the time.

Later Christofilos realized that in a fusion reactor, relativistic electrons would lose their energy at an unacceptable rate through synchrotron radiation, and he suggested that protons or deuterons be used instead. Since LPS had now developed an adequate source of protons, in 1977 a DOE-funded program was launched to investigate, both experimentally and theoretically, the formation and stability of proton rings.

Soon Phil Dreike, John Greenly, and Dave Hammer were able to produce proton rings in the laboratory. These rings were not strong enough to bring about field reversal; indeed, only 5 to 10 percent of the required strength was achieved because NEPTUNE, the laboratory's pulsed-power supply, had insufficient output. However, we were able to set a very significant milestone: two-thirds of the output that was available was converted into energetic 400-kV protons circulating in a ring. This program continues to this day, but with more modest objectives, since it still lacks a big enough power supply.

"Cornell became increasingly recognized as one of the world's leading centers of research in beam plasma physics."

IONS INSTEAD OF LASERS FOR INITIATING FUSION

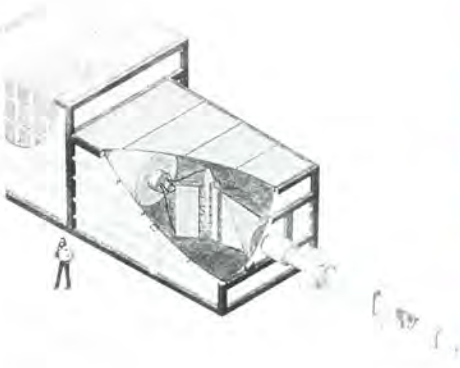
While we were developing ion-beam technology, it did not escape our notice that these high-powered beams could, in principle, replace lasers as the means to implode pellets of deuterium-tritium for inertial fusion.

Experiments were designed by Humphries, Wiley, and me to test whether intense ion beams at current densities approaching kiloamperes per square centimeter could be focused. By early 1976 we had results that encouraged Sandia National Laboratories to mount a major program on ion-beam fusion, and ultimately, a joint program operated by LPS and Sandia was funded by DOE.

One of the highlights of this joint program was the acquisition, in 1981, of a Light Ion (LION) fusion facility. This came about through the offices of Gerry Yonas, who was then director of the pulsed power division at Sandia. This machine is rated at 2 MV, 400 kA, and 40 ns—in other words, it can deliver nearly a trillion watts of power in 40 billionths of a second.

Recent work in the field of ion-beam fusion is discussed in the article by David Hammer and in the forthcoming article by Bruce Kusse.

The joint program with Sandia is similar to the one formed earlier with the Naval Research Laboratory (NRL). These two joint programs have been very valuable in sustaining the intellectual vitality of LPS, facilitating the exchange of ideas, equipment, and occasionally personnel.



Left: The LION (light-ion fusion facility) at LPS was provided by Sandia National Laboratories. The large structures house the power-generating and pulse-forming components; extending to the right is the magnetically insulated transmission line.

Below: Those who attended the 1981 dedication and inspection of the LION included (left to right) Gerold Yonas of Sandia, and Cornellians Bryce D. McDaniel, nuclear studies; Joseph M. Ballantyne and Donald T. Farley, electrical engineering; Andrew Schultz, Jr., former engineering dean; Boris W. Batterman, applied and engineering physics; and William B. Streett, engineering dean.

THEORETICAL STUDIES OF ION BEAMS, RINGS, AND PLASMAS

In addition to work associated with the development and physics of charged-particle beams, our theoretical studies have included research in three major areas: (1) the equilibrium and stability of ion rings; (2) the nonlinear interaction physics of beams with a background plasma; and (3) strong turbulence in plasma.

In developing a theoretical framework for examining the stability of ion rings, the main difficulty is that the orbits of the ions span the size of the entire plasma configuration. This is in sharp contrast to the conditions of ordinary fluid dynamics and even magnetohydrodynamics, in which the mean free path (or the gyroradius) is much smaller than any macroscopic scale length. Marshall Rosenbluth and I, and Richard Lovelace independently, solved this problem by extending conventional "energy-minimizing principles" to this regime. Further progress was made in conjunction with John Finn, Christof Litwin, Dieter Pfirsch, and Alan Turnbull.

One of the byproducts of this work was the realization that a population of very energetic particles could provide a stabilizing influence in other magnetic plasma configurations. A workshop devoted to this important theme was convened at Cornell in the spring of 1982.

THE IMPACT OF SUPERCOMPUTING ON NONLINEAR PHYSICS

The rapid development of computers into supercomputers and their impact on science also took place in the 1970s. The year (1970–71) I had spent at NRL had reinforced in my mind the potential of the computer revolution.

Cornell's computing facilities were then somewhat primitive, so in 1974 Geoffrey Chester, Ed Salpeter, Ken Wilson (all of the physics faculty) and I banded together to set up, in the basement of Clark Hall, a computer terminal that could access the different computing centers around the country. Fortunately, the National Magnetic Fusion Computing Center was established at Livermore in 1976, and soon LPS was linked to Livermore via dedicated telephone lines and a satellite link.

Thus began an era of serious computing in LPS. A long and happy collaboration with Jacques Denavit led to the development of many useful codes and the training of a sequence of talented graduate students—Lester Thode, Nino Pereira, Michael Keskinen, Alex Friedman, Alan Mankofsky, Larry Sparks, Michael Desjarlais, Greg Ginet, Peter Lyster, and Jon Krall—in the science of computation. Not all of my graduate students were oriented toward the computer, of course; Richard Lutomirski, Milton Johnson, Roswell Lee, Jabayo Akinrimisi, and Gerson Ludwig did excellently without its help.

The availability of powerful computers, which made an immediate contribution to the whole field of nonlinear physics, was particularly important to LPS in studies of plasma turbulence. Important progress was made in understanding the interaction of electron beams with plasma, and in understanding high-frequency plasma-wave (Langmuir) turbulence. New computing capabilities helped enormously in developing the theory of solitons and the concept of soliton turbulence. The results of computations made it possible to visualize plasma behavior and thereby to get at the truth through bold approximations.

One particular investigation illustrates what a powerful tool supercomputing can be. This work grew out of observations, made over a period of many years by Don Farley and his colleagues in electrical engineering, of electron-density irregularities in the lower ionosphere. One type of irregularity had been understood in terms of the Farley-Buneman instability, driven by the equatorial electrojet current, but other types could not be understood in terms of a linearized theory of small-amplitude waves. It appeared to Farley and me that many of the observations could be explained only by considering the interaction of two or more waves.

To test this hypothesis, we needed a large-scale numerical analysis based on the fundamental equations of the problem. I called on Tim Coffey at NRL (the joint program was useful in providing the ready connection) to arrange for the development of a suitable numerical code. This was done, and the results of the analysis not only verified the notion that wave interaction can explain the observed electron-density irregularities, but provided an insight into the physical phenomena behind the observations. An improved version of the NRL code was developed at Cornell by Richard Ferch and Michael Keskinen, and the insights gained from the numerical calculations allowed Keskinen, Russell Kulsrud, Dieter Pfirsch, and I to develop a theory of turbulence that predicted the power spectrum of the irregularities. Recent observations by Don Farley, Mike Kelley, and their collaborators confirm several aspects of this theory.

The outstanding unsolved theoretical problem in plasma physics concerns strong plasma turbulence and the transport of matter and heat in the turbulent state. The heat conductivity observed in large tokomaks—such as the Joint European Torus (JET) at Culham, England, and the Tokamak Fusion Test Reactor (TFTR) at Princeton University—is two orders of magnitude greater than the conductivity calculated according to classical theory. Any successful theory of the very complex and highly nonlinear phenomena that occur in the high-temperature plasmas of tokamaks will have to rely on massive numerical simulations. State-of-the-art graphics are also necessary to allow the torrent of data from supercomputers to be visualized.

We are fortunate to have on campus the resources needed to make a concerted effort in the field of turbulence and turbulent transport: the Cornell National Supercomputer Facility (CNSF), a unit of the National Center for Theory and Simulation in Science and Engineering (usually called the Theory Center). The work will be carried out by an LPS research group that includes Philippe Similon, a senior research associate; Jay Albert, a postdoctoral associate; and several graduate students. The problem we will be studying is a fundamental one because it is central to the understanding not only of plasma behavior in controlled-fusion machines, but of the heating processes that occur in the solar corona, the solar magnetic cycle, solar flares and x-ray emissions, the fluctuations in the solar wind, Earth's magnetosphere, and the auroral and equatorial regions of the ionosphere.

AN INTERNATIONAL CENTER FOR PLASMA STUDIES

During these years at LPS, we have had visits from many distinguished scientists from the United States and overseas—from many European nations, the Soviet Union, Japan, China, and India. Of all the people with whom we have exchanged information and ideas, a few are particularly memorable because they collaborated with us so often that they are almost a part of the LPS family: Russell Kulsrud of Princeton University, Dieter Pfirsch of the Max Planck Institüt für Plasma Physik in Munich; and Marshall Rosenbluth, who was an Andrew Dickson White Professor-at-Large at Cornell from 1976 to 1982.

Some of the participants in the Laboratory of Plasma Studies are represented in this book, but there are others who should be recognized also. Edward Ott, who was a faculty member here and is now at the University of Maryland, was a key researcher. Postdoctoral research associates with whom I have been privileged to work include Christian Dum (now at the Max Planck Institut für Physik und Astrophysik), S. Hamasaki (now at Jaycor), Michael Gerver (now at the Massachusetts Institute of Technology), Alan Reiman (now at Princeton University), Göran Schulte (now at Lausanne, Switzerland), and A. Surjalal Sharma (now at PRL in Ahmedabad, India). I also want to acknowledge the unfailing support, through the years, of office staff members Rosemary Saltsman, Jackie Discenza, and Joyce Oliver.

LPS has developed rapidly and dramatically throughout its relatively brief history through the efforts of the faculty, research staff, and graduate students. The coming years, too, will mark a period of challenge, excitement, and achievement.

Ravi Sudan, the IBM Professor of Engineering at Cornell, served as director of the Laboratory of Plasma Studies from 1975 to 1985. At that time he became deputy director of the Theory Center, which operates the national supercomputing facility at Cornell. He is a faculty member in both electrical engineering and applied and engineering physics.

Sudan was educated in India and England and worked as an engineer in both countries before coming to Cornell in 1958. His degrees are the B.A. from the University of Punjab, the D.I.I.Sc. from the Indian Institute of Science, the D.I.C. from Imperial College, London, and the Ph.D. from the University of London.

He has held visiting appointments in plasma and fusion physics in England and Italy, as well as the United States; he has been an invited lecturer in the Soviet Union, France, and West Germany; and he has chaired several international conferences. He has served as head of the theoretical plasma physics section at the U.S. Naval Research Laboratory and later as a scientific adviser there, and he is a consultant to a number of other government, industrial, and university laboratories.

Sudan is co-editor of volumes I and II of the Handbook of Plasma Physics *and is an editor of several professional journals. He is a fellow of the American Physical Society and of the Institute of Electrical and Electronics Engineers.*

INTENSE ION BEAMS
A Major Research Area in Plasma Studies at Cornell

by David Hammer

High-power beams of electrons or ions are powerful tools, potentially capable of producing high-power microwave radiation, initiating fusion reactions, modifying the surfaces of materials, or generating intense pulsed lasers. Producing these beams, understanding their properties, and developing the technology to put them to use has been a research specialty of Cornell's Laboratory of Plasma Studies since its founding in 1967.

In this article, I describe some major achievements of LPS in intense ion-beam research, and discuss the ongoing work and future possibilities.

THE TECHNOLOGY AND ITS DEVELOPMENT

The basic technique for generating an intense electron or ion beam is to store energy in high-voltage capacitors over a period of 10 to 100 seconds, and then deliver it to a load at even higher voltage in very short pulses, only a microsecond or less in duration.

Typically, this is done by charging the capacitors in parallel and discharging them in series. One or more pulse-shaping circuit elements may be added. The voltage, current, pulse duration, and pulse shape that are desired depend upon the specific application.

These "pulsed power generators" in our laboratory provide voltages up to 1.5 million volts (MV), currents up to a few hundred kiloamperes (kA), and pulse durations from a small fraction (0.04) of a microsecond to about 1 microsecond.

In the early years of LPS, our research effort was devoted to intense electron beams exclusively because although ion beams were potentially more useful, a technique for generating them efficiently had not been developed. In 1973, however, Professors Ravi Sudan and Richard Lovelace suggested a technique by which the same pulsed-power apparatus being used to generate electron beams could be used to generate ion beams.

By 1977, when I joined the Cornell faculty, intense pulsed ion beams were an experimental reality as a result of pioneering work by Stanley Humphries, Jr., Sudan, and their associates. The magnetically insulated diode this group invented is now the device most commonly used in the United States to produce intense ion beams for research and applications.

SPECIAL PROBLEMS AND HOW THEY WERE SOLVED

In order to efficiently generate an intense ion beam, a way must be found to inhibit the flow of electrons from the cathode to the anode of a high-voltage accelerating gap. If this is not accomplished, the electrons, which are much lighter than the ions, will dominate the current flow in the gap and therefore account for most of the power delivered by the high-voltage source. In the magnetically insulated diode, this problem is solved by the method illustrated in Figure 1. A magnetic field applied parallel to the electrodes (that is, perpendicular to the applied electric field) causes an electron to move in a semicircular orbit that has a radius smaller than the gap spacing. Since the ions are much heavier, they are affected only slightly by this magnetic field, and are extracted from the diode through apertures in the cathode.

The other major problem in generating ions rather than electrons is to provide a source. Since ions are very difficult to extract from a metal electrode, there must be a plasma on the high-voltage electrode (the anode) from which the ions can be drawn.

Figure 1

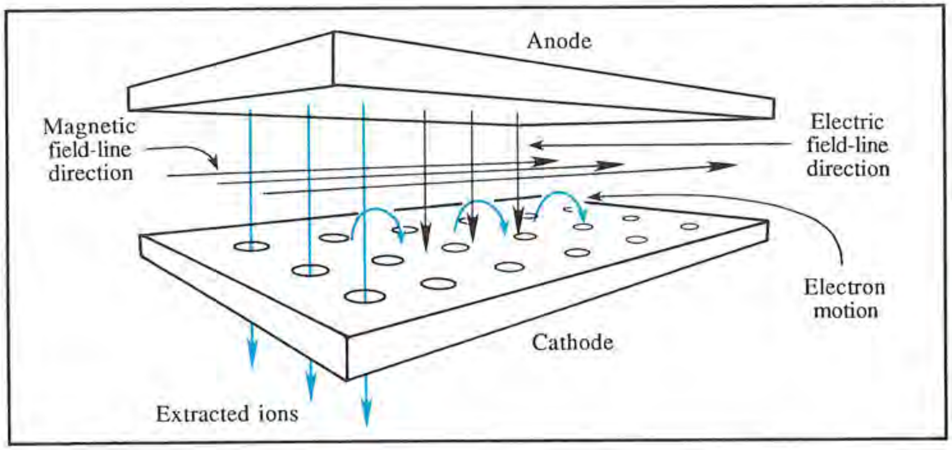


Figure 1. The magnetically insulated diode for generating ion beams. The applied electric field accelerates ions from the high-voltage anode to the cathode. A magnetic field applied parallel to the electrodes keeps electrons from reaching the anode, since such a flow would reduce the efficiency of the diode. (The magnetic field affects the ions only slightly.) Ions are drawn from a plasma at the anode and are extracted through apertures in the cathode.

The method most commonly used to produce this anode plasma is to cover the metal anode with a dielectric and produce a plasma on that surface by a process called *surface flashover*.

This method, which was used in some of the earliest experiments at Cornell, has been significantly improved over the past twelve years so that the plasma can be generated more quickly and uniformly upon the arrival of the voltage pulse at the accelerating gap.

The technique is to prepare the anode of the magnetically insulated diode by mounting on it a sheet of dielectric material—such as polyethylene or epoxy—that has metal pins or holes in it. An alternative method is to fill grooves in the surface of a metal anode with epoxy. When the electric field is applied, a surface breakdown is initiated near the edges of the holes or pins or grooves because of fields distortions that occur at those places. The plasma that is generated quickly spreads over the anode surface, but is prevented by the insulating magnetic field from filling the entire accelerating gap. By adjusting the hole spacing and size, or the groove spacing and depth, reasonably uniform ion emission can be achieved over areas as large as 1,000 square centimeters.

Beams of a variety of different ions can be generated by using different dielectric materials. For example, a few years ago one of my graduate students, Jesse Neri, used Teflon —$(CF_2)_n$—to produce a beam that was mostly carbon ions, and barium fluoride to produce a barium beam.

The beam that is generated by the surface flashover technique generally contains a variety of ion species, however. Furthermore, the plasma takes a finite time to produce—a drawback because the driving pulses can be quite short, especially for inertial confinement fusion. For these reasons, we decided to develop a diode containing an independently produced anode plasma. This has been accomplished using LONGSHOT, a 1-microsecond, 180-kV pulser.

The technique is illustrated in Figure 2. Except for the fact that the symmetry is cylindrical instead of planar, the diode schematic for this new source is not very different from the schematic shown in Figure 1, once the anode plasma has been generated. The main difference is that the plasma is actually produced a few centimeters away, in the region marked *gas puff*, and is driven into its final position by a rapidly increasing magnetic field produced by a fast coil.

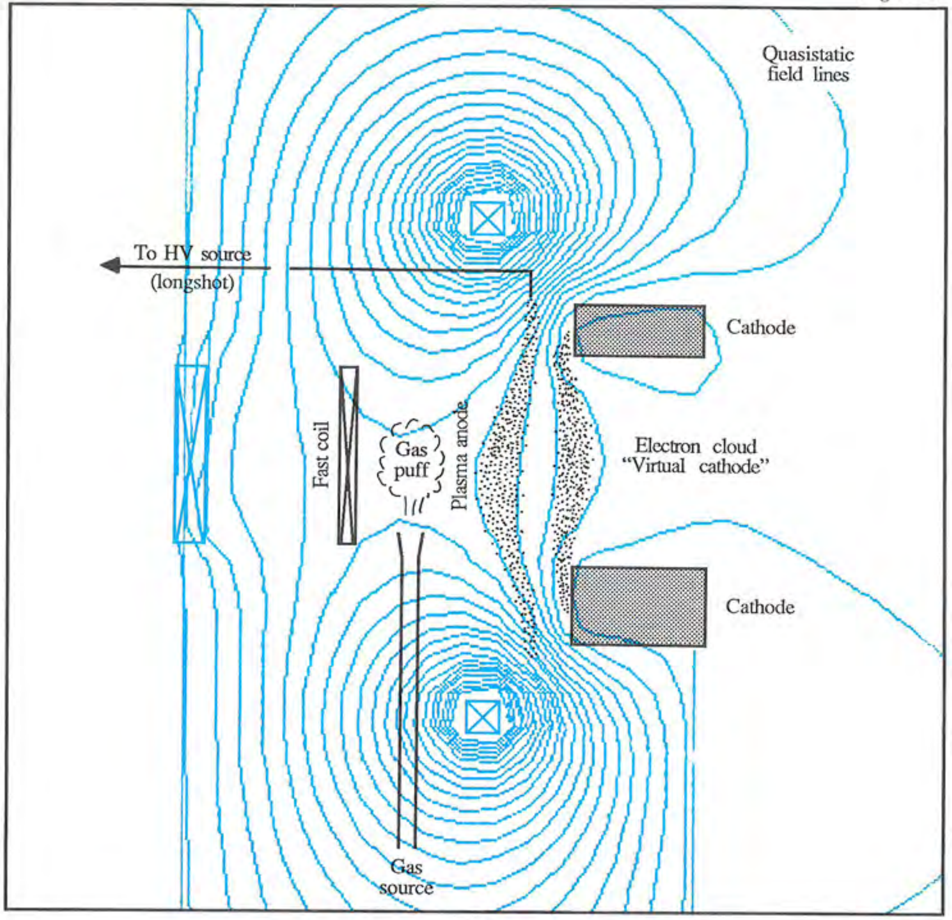
The apparatus shown in Figure 2 has several advantages. First, the position of the anode plasma at the time the high-voltage pulse is applied can be varied by adjusting the strength of the magnetic field that pushes the plasma. This has a major impact on the current density and quality of the ion beam. The second advantage is that there are no material electrodes on either side of the gap. This is because the ions are drawn from a plasma that merely contacts the anode, and the cathode is formed by electrons moving freely along magnetic field lines that lead from the metal cathode out into the region in front of the anode plasma. The diode actually consists of an anode that is a plasma and a cathode that is an electron cloud (called a virtual cathode). This diode has the possibility of a very long pulse life if everything works as anticipated, since the two components normally most subject to damage—the anode and the cathode—are not solid material. Currently, a graduate student doing research on magnetic-confinement fusion is using the

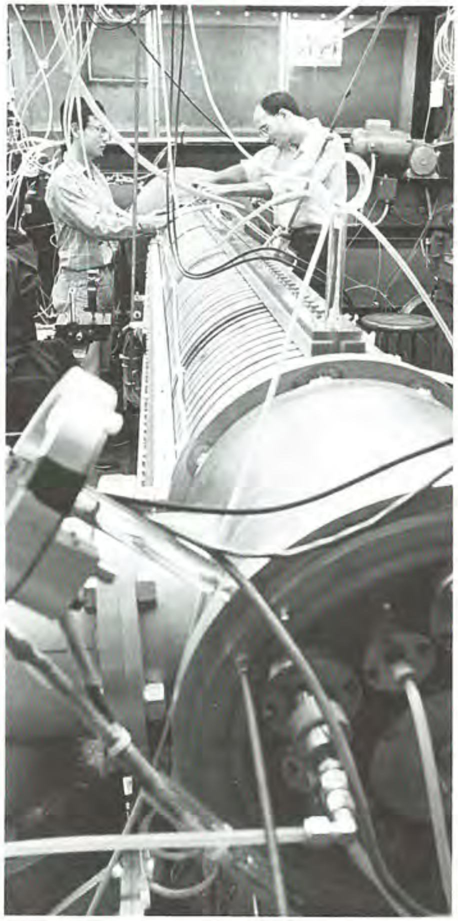
Figure 2. The diode with an independent source of anode plasma. The diagram shows a cutaway view of the upper half of the cylindrically symmetric device. The plasma is generated from a gas puff, and a rapidly increasing magnetic field drives it to the desired position. The ions are extracted from this plasma layer rather than having to be obtained from a dielectric mounted on a metal anode.

The plasma generation process is as follows. A fast-acting valve injects a gas puff into the region indicated. Spark gaps around the gas puff are then pulsed, bathing the gas in ultraviolet light, and this ionizes a small percentage of the gas. The fast coil behind the gas puff is then energized very rapidly, inducing a current to flow in the plasma. This current causes more ionization as well as a rapidly rising magnetic field behind the plasma. This magnetic field drives the plasma to the accelerating gap, where it is stopped by a pre-existing magnetic field. The field lines from this initial field, and the slow coils that generate them , are in color.

Right: This 2.5-meter-long z-pinch apparatus is used in magnetic fusion research. The LONGSHOT pulsed-power generator is at the rear. The researchers are Niansheng Qi, a postdoctoral associate (at left), and Edl Schamilglu, a graduate student.

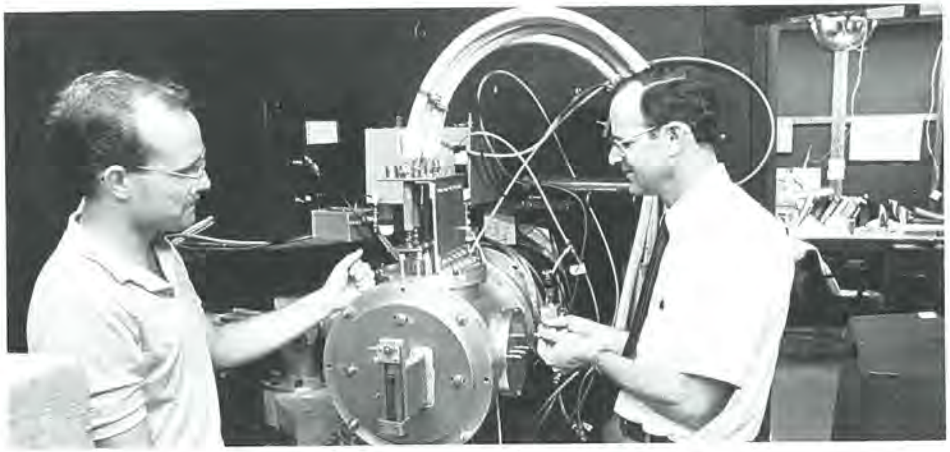
Figure 2





LONGSHOT pulsed-power generator and the modified diode to produce ion beams of about 100 amperes per square centimeter at 100–200 kV.

Most practical applications of intense ion beams, from fusion to material-surface modification, will require ion-beam sources that can be operated with pulse repetition rates ranging from one pulse per second (pps) to 1,000 pps. Accordingly, the major technological step we are now undertaking is to operate a modified version of the plasma-anode diode as the load of a pulser capable of generating pulses repeti-



Michael Coleman (at left), a graduate student, works with Professor Hammer on an ion-diode spectroscopy experiment.

tively. The power source we are using, on loan from the Lawrence Livermore National Laboratory, is capable of generating from 1 to perhaps 1,000 pps in a few-pulse burst. Our first step will be to develop a long-lived version of the plasma-anode diode at the 1-pps repetition rate, and then we plan to build one with very high vacuum-pumping speed in order to find out how rapidly such a diode can be pulsed without degrading the quality of the beam.

We will also be testing a version of the diode at 500–600 kV, since many possible uses, including applications in controlled fusion, will ultimately require ion diodes at that voltage level or even higher.

EXPERIMENTS IN ION DIODE PHYSICS

Optimizing the operation of an intense ion-beam diode for any application requires that we understand the physics of the operation of these diodes.

In a recently completed experiment, we used the technique of analyzing the light emitted by aluminum and carbon ions accelerating in the diode to learn something about the detailed conditions of the accelerating gap. For example, because an electric field can affect the precise wavelength of certain visible-light ion emission lines, we were able to determine the electric field as a function of position in the accelerating gap. We were also able to learn about the ion velocity distribution perpendicular to the acceleration direction (an important factor in determining how well the beam can be focused) from the width of certain ion emission lines.

These results, especially the electric-field measurements, have been compared in detail with the predictions of analytic theory and computer modeling, and have forced the adoption of a view of the operation of ion diodes that is significantly different from the simple picture presented in the mid-1970s by two Cornellians, Tom Antonson and Ed Ott (both now at the University of Maryland). In their analytic theory, the electrons in the cathode cloud are confined to a sheath region, whereas the experiments show the electrons to be spread throughout the accelerating gap, in line with the results of a model recently developed by Michael Desjarlais, who at that time was a graduate student working with Sudan.

We are continuing these experiments on the physics of ion diodes using visible-light emission with a plasma-anode diode. Our goals are to understand the physics of this diode better, and to improve the accuracy of our earlier experiments.

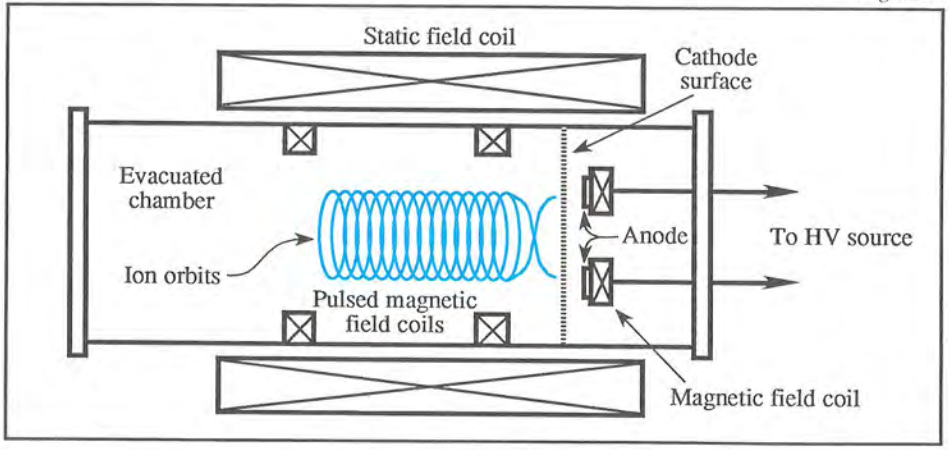
STUDYING THE PHYSICS OF ION-BEAM PROPAGATION

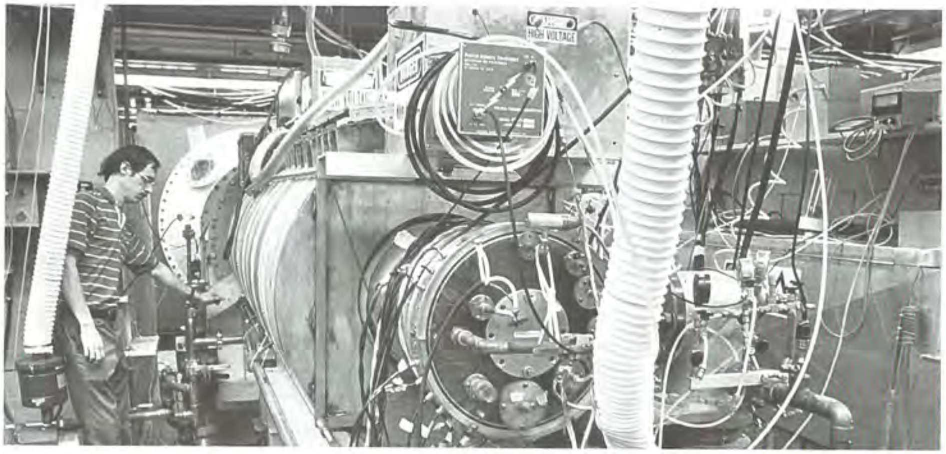
For most applications, intense ion beams must propagate at least a few centimeters, and in some cases several meters, to their "target." We are concerned, therefore, with the physics of ion-beam propagation.

A straightforward calculation shows that the space charge in an intense ion beam must be nearly completely charge-neutralized, because otherwise the self-electric field would cause rapid beam expansion. Many experiments conducted in the past ten years have verified that this deduction is correct. Accordingly, an ion beam propagates along with an equal number of co-moving electrons, or else it propagates in a dense plasma in such a way that the plasma electrons can shift their position so as to eliminate the beam electric field.

When the ion beam propagates *along* a magnetic field, the physical picture is still simple. This is because co-moving elec-

Figure 3





trons can move freely along a magnetic field, and plasma electrons can shift readily along magnetic field lines. However, if the magnetic field has a component perpendicular to the propagation direction, the situation changes: electrons can no longer move along freely with the ions, and therefore cannot bring about the required charge neutralization.

Such a perpendicular magnetic field component is present, for example, in experiments that are part of our magnetic fusion research. We make ion rings by injecting a proton beam across a transverse

Figure 3. The ion-ring experiment. In this apparatus, a magnetic field causes an intense proton beam (injected by the high-voltage pulse source) to rotate around the field lines, thereby producing a rotating proton beam or ion ring. An increasing magnetic field (a magnetic mirror) reflects most of the protons back toward the injector, where they encounter and are trapped by a pulsed magnetic mirror field that is generated after the initial passage of the ion ring.

Above: John Greenly, a senior research associate, works on the ion-ring experiment. The static field coils surrounding the vacuum chamber are in the foreground; the high-voltage pulser is in the background.

"We make ion rings by injecting a proton beam across a transverse magnetic field of sufficient length to cause the protons to rotate around the magnetic field lines."

magnetic field of sufficient length to cause the protons to rotate around the magnetic field lines (see Figure 3). The rotating protons propagate a linear distance of 1.5 meters before they encounter an increasing magnetic field that reflects most of them back toward the injector. Many of these reflected ions become trapped near the injector by an increased magnetic field generated in that region by a pulsed coil.

We have performed such trapping experiments in vacuum, with static fills of hydrogen or nitrogen at pressures of 0.005–0.3 Torr (atmospheric pressure is about 760 Torr at sea level), with low-density plasmas, and with puffs of gas in various regions of the experiment chamber.

What we have learned is that ion-beam propagation is disrupted unless certain conditions exist wherever the electrons encounter a magnetic field gradient or a transverse magnetic field. Either there must be enough pre-ionized plasma there to eliminate the self-electric field of the ring, or else there must be enough neutral gas to allow the beam to generate its own plasma very quickly. In other words, the electric fields required to drag electrons up magnetic field gradients are enough to spoil efficient ion-beam propagation unless a plasma much more dense than the ion beam is either already present or is quickly generated by the ion beam itself.

APPLICATIONS TO RESEARCH ON MAGNETIC FUSION

The ultimate goal of these "proton ring" and trapping experiments is to contribute to one of the lines of research on controlled thermonuclear fusion: the research on compact toroids, a class of magnetic-confinement reactor configurations. Compact toroids will be discussed by Hans Fleischmann in the next *Quarterly* issue.

Studies of an advanced switching technique for pulsed-power generators are being conducted by Lynne Adler, a graduate student working with Professor Hammer. Devices such as the "plasma opening switch" Adler is working on are expected to be key to the development of ion-beam generation technology for light-ion fusion.

So far, we have generated and trapped ion rings that contain a few hundred joules of energy and last for a few microseconds. Both of these numbers must be larger by a factor of perhaps 100 if ion rings are to help stabilize and heat a compact toroid plasma of the size that might serve as a proof-of-principle experiment, demonstrating that the compact toroid could be scaled to a fusion reactor. It may be necessary to inject several megajoules of ion energy in order to heat and stabilize a reactor-size plasma, but this energy could be injected by many ion-beam pulses over many milliseconds.

Inertial confinment fusion, which will be discussed by Bruce Kusse in the forthcoming issue, also requires a multi-megajoule ion beam. In this case, the energy must be delivered in a time of not more than perhaps 0.03 microsecond, which implies 10^{14} watts. A pulsed power generator capable of delivering a pulse of such high power is being tested at the Sandia National Laboratories, Albuquerque.

MODIFYING THE SURFACE PROPERTIES OF MATERIALS

An application that requires much lower power and much less energy than inertial confinement fusion is the modification of the surface properties of materials.

The annealing of implant-damaged semiconductors is one such application. Experiments along this line were carried out a few years ago in a collaborative effort by our group and by Rod Hodgson and John Baglin of IBM. A key property of ion beams at a few hundred kilovolts is the short range of the ions—only a few microns for protons and even less for heavier species. This means that less than one joule per square centimeter is required to melt the surface of most materials, and even less is required to anneal a semiconductor. So long as the energy is delivered in a microsecond or less, heat conduction does not play an important role during the pulse, and the necessary beam power density is only 10^{6} watts per square centimeter—eight orders of magnitude less than for inertial confinement fusion.

Our IBM collaborators have also worked with Professor James Mayer and his group in the Department of Materials Science and Engineering in a study of the unique materials that can be formed by melting multilayer coatings on a silicon substrate. An intense ion beam is used to melt the coatings, and the melt quenches on a time scale of a few microseconds—long enough for interlayer mixing of atoms, but too short for much mixing into the substrate. Mayer and a student, Richard Fastow, recently studied controlled metal/silicon interfacial reactions, the crystallization of amorphous silicon, and the formation of metastable alloys. Intense ion beams for materials research is being continued by Professor Michael Thompson and his students. Once we can produce repetitive pulses of pure beams of a variety of ions, it should be possible to effectively implant them in surfaces and thereby modify such properties as surface hardness and resistance to wear.

POSSIBILITIES FOR RESEARCH WITH INTENSE ION BEAMS

Exciting high-pressure gap lasers with ion beams is another possibility we have investigated. Some of the most powerful pulsed lasers involve the excitation of high-pressure gases by the injection of intense electron beams; ion beams offer the prospect of better operation for certain gases. The efficiency of converting electrical energy into laser light may be limited by a poor match between the size of the gas column and the relatively long range of the electron. Ions at a few hundred kV have a range about two orders of magnitude shorter than that of electrons at the same energy, and therefore gases that are nearly transparent to electrons can be efficiently excited by ions.

A few years ago one of my students, Larry Wiley, used proton-beam pumping in an argon/nitrogen laser and achieved the highest power density ever obtained in this type of laser. Experiments of this kind were carried out a few years ago at the Naval Research Laboratory—where proton-beam-excited gas lasers were first achieved—as well as at Cornell, but to our knowledge, such work is now in progress only in the Soviet Union.

Since experimental work with intense ion beams dates only to 1974, the field is still young and we can expect new applications to come to the fore as capabilities improve. For example, if there is a nuclear test ban treaty, one of the fields we can expect to see grow—though not at Cornell—is the simulation of effects of nuclear weapons. Intense ion beams could be used to launch shock waves in materials, or to perform other tests in which a high energy density must be deposited in a material. Of course, the size of objects that could be tested with an ion beam from a pulsed-power generator is small compared to the size of objects that could be tested using an underground explosion, but many more tests could be performed. Another application that has been suggested is an anti-ballistic-missile weapon using an energetic ion beam. We rather doubt that such a weapon is possible, and we are certain that tests of such a system would not be done at Cornell!

For virtually the entire first decade of LPS history, electron-beam research dominated our laboratories. During the second ten years, research with positive ion beams became equally important. At the time of our thirtieth anniversary, will we be studying negative-ion or neutral beams and their applications, or will the emphasis be on something completely different? The one certainty is that the research will provide us with interesting challenges in both technology and physics.

David Hammer, a professor of nuclear science and engineering, has been director of Cornell's Laboratory of Plasma Studies since 1985. He has been on the faculty here since 1977.

Hammer received the B.S. degree from the California Institute of Technology in 1964 and the Ph.D. from Cornell in 1969.

After receiving his doctorate, Hammer worked for seven years as a research physicist at the Naval Research Laboratory. His work there was mainly on the physics and applications of intense pulsed electron beams. His current interests are in plasma physics, nuclear fusion, and high-power ion-beam physics.

Before joining the Cornell faculty, he taught at the University of Maryland and at the University of California at Los Angeles. In 1983–84 he was a visiting senior fellow at Imperial College, London, under the joint sponsorship of the National Science Foundation and the Science and Engineering Research Council.

He is a fellow of the American Physical Society and a senior member of the Institute of Electrical and Electronics Engineers.

THE POWER OF ELECTRONS
What Intense Relativistic Electron Beams Can Do for Technologies of the Future

by John A. Nation

The development of such future devices as fusion reactors or free-electron lasers requires new ways of accelerating intense beams of ions or electrons. The generation of microwave pulses for applications such as deep-space communication requires comparable new technology. At Cornell, in the Laboratory of Plasma Studies, we are working on novel ways of using powerful electron beams to achieves these goals.

The object of this work, which began in 1969, has two aspects: how to generate high-power microwave pulses, and how to accelerate particle beams. Both concepts are based on a useful property of electron beams: they behave as a whole rather than as individual particles. This is called *collective behavior*.

The research I discuss in this article is in the area of accelerator physics. In particular, I restrict attention to the class of accelerators that use radio frequency waves.

USING ELECTROMAGNETIC WAVES TO ACCELERATE PARTICLES

Modern high-energy accelerators, such as the Stanford Linear Collider, use electromagnetic waves in a disk-loaded waveguide to accelerate the load particles. The particle acceleration is achieved by designing the cavity in such a way that the phase velocity of the wave can be matched to the electron velocity; under these circumstances, particles traveling with the wave can continuously extract energy from the electromagnetic wave.

In these devices, the radio frequency waves are generated using klystrons and are fed via microwave circuitry to the accelerator. In a sense, a high-current, low-energy electron beam (in the klystron) is used to accelerate the low-current, high-energy beam of the accelerator. What has been built is a transformer to increase the electron energy at the expense of the beam current.

In our work we consider a new class of accelerators. In this class the two beams are in the same enclosure and are tightly coupled to each other without the use of external circuitry.

The low-energy, high-current beam is a weakly relativistic electron beam that has an energy of, say, 0.5 MeV and a current of a few thousand amperes. (The eV, or electron volt, is the unit of particle energy, representing the energy gained by an electron in falling through a potential difference of one volt; 1 MeV = 10^6 eV.) Waves are excited on the beam as it propagates through a cylindrical waveguide. These waves, which can only exist in the presence of the beam, are eigenmodes of the beam-guide system and may be used to accelerate other electrons or ions if the phase velocity of the wave is matched to the particle velocity. Since the electrons in the low-energy beam behave collectively, the wave is described as a collective mode of the system. When it is used for particle acceleration, what we have is a collective wave accelerator.

THE CONCEPT OF COLLECTIVE WAVE ACCELERATORS

Many of the characteristics of electron-beam modes may be identified using a dispersion diagram such as the one in Figure 1. This is a plot of the wave frequency against wavenumber.

The ratio of the wave frequency to the wavenumber gives the phase velocity of the wave at that point. For acceleration we need to match the wave-phase velocity to the particle velocity and then change the velocity at a rate that keeps the particles trapped in the wave. This is exactly analogous to what a surfer tries to do when riding an ocean wave.

Four beam modes are shown in the figure. Two of them have phase velocities that exceed the electron velocity in the high-current beam; two have slow waves that travel with velocities less than those of the electrons. In addition, the figure shows an electromagnetic wave that has a phase velocity greater than the speed of light.

A question we must be concerned with is whether external energy would be required to grow a wave. This is indicated by the sign of the wave energy: the slow waves are negative-energy modes and the fast waves have a positive energy. Negative-energy waves have a very attractive feature, however. They can interact with positive-energy waves in such a way that both may grow in amplitude, each increasing in the magnitude of their energy density while conserving the total energy in the system.

We use this feature to grow the required modes. For collective acceleration we propose to use slow waves; for ion acceleration, either cyclotron or space-charge waves; and for electron acceleration, fast cyclotron waves. The fast cyclotron, or upper hybrid, mode is the only beam mode that cuts the light line; it can be used for accelerating particles to ultrahigh energies.

GROWING SLOW WAVES FOR ION ACCELERATION

Our current research is mostly on the study of fast hybrid modes, but much of the work we have accomplished during the course of the program has focused on the growth of slow space-charge waves.

This kind of wave has been grown using two techniques. In one of these techniques the wave is coupled to positive-energy electromagnetic waves in a traveling-wave tube or cavity configuration. When the

Figure 1

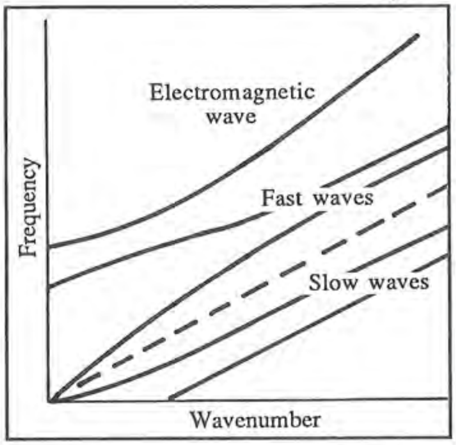
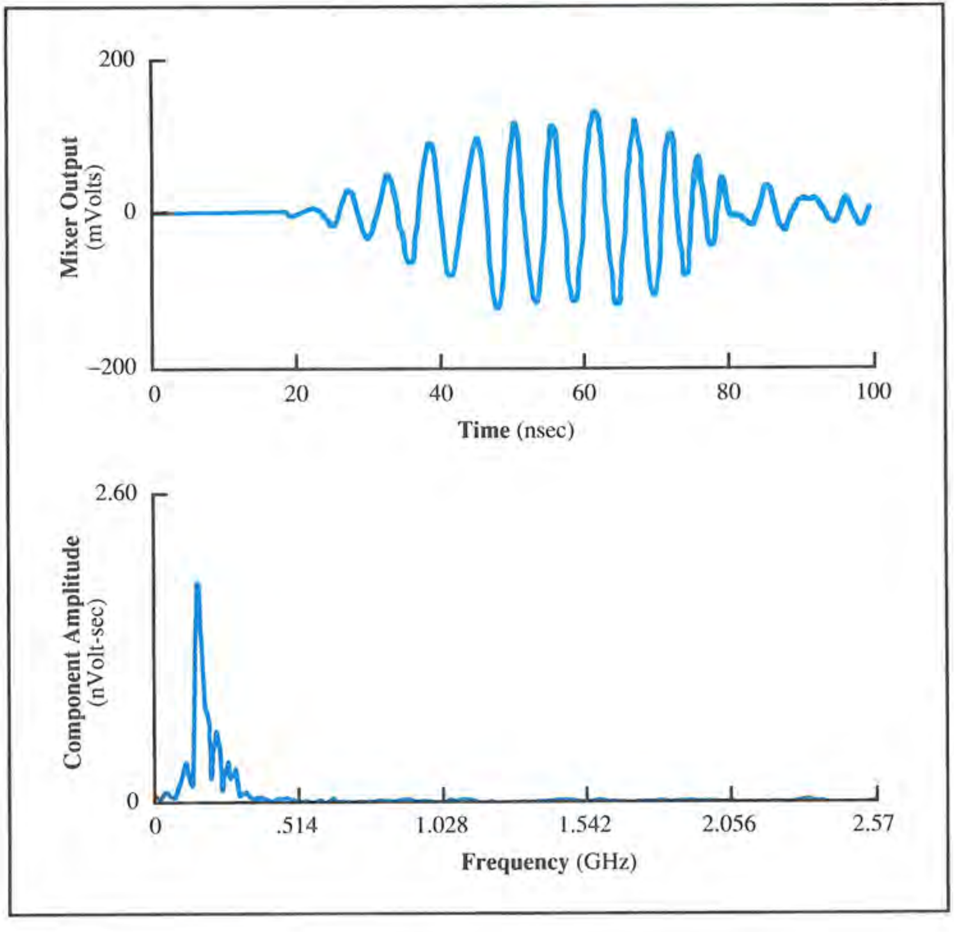


Figure 1. Dispersion relations for electron beams in a uniform pipe. Phase velocity is given by the ratio of frequency (the vertical scale) to wavenumber (the horizontal scale). The solid lines, top to bottom, are for an electromagnetic wave, a fast hybrid or cyclotron wave, a fast space-charge wave, a slow space-charge wave, and a slow hybrid wave.

Figure 2. Growth of slow space-charge waves. The upper trace shows a frequency-downshifted wave train excited by an electron beam propagating through a series of coupled cavities. The lower trace shows the wave spectrum.

Figure 2



Right: Work on the growth of slow space-charge waves excited by an electron beam is carried out in the laboratory pictured here. The photograph shows a Marx generator (at lower left) and pulse lines (the cylindrical tubes).

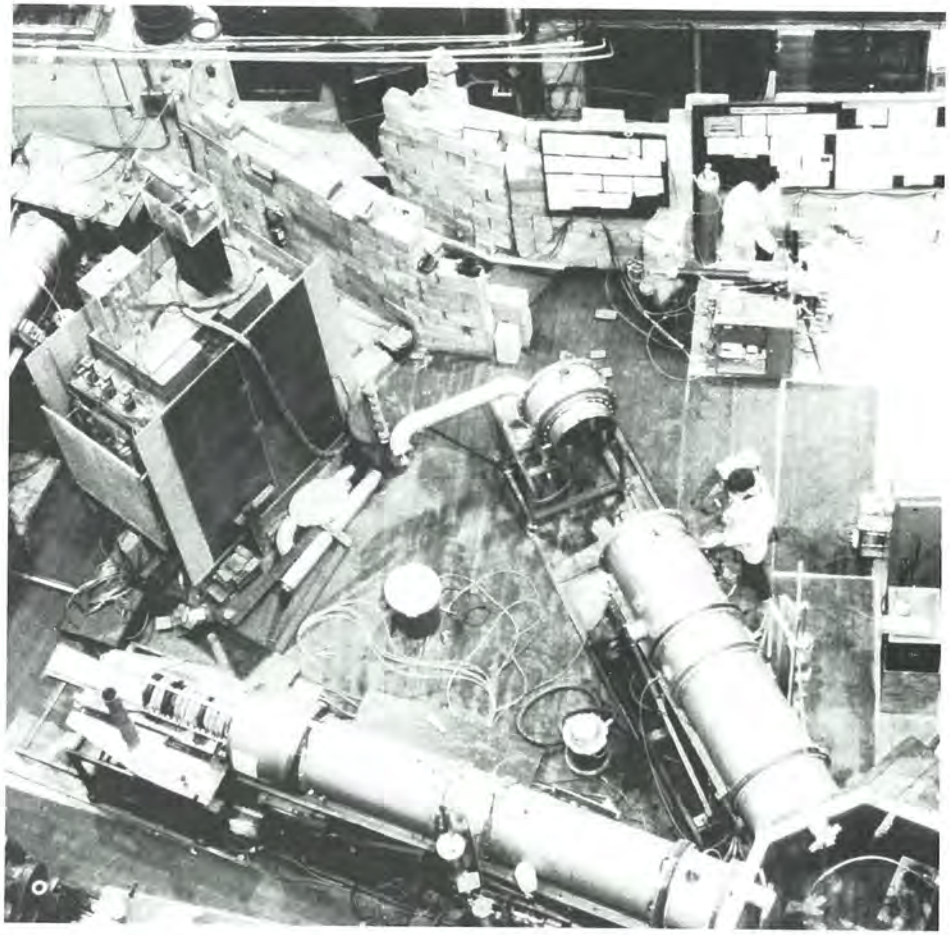
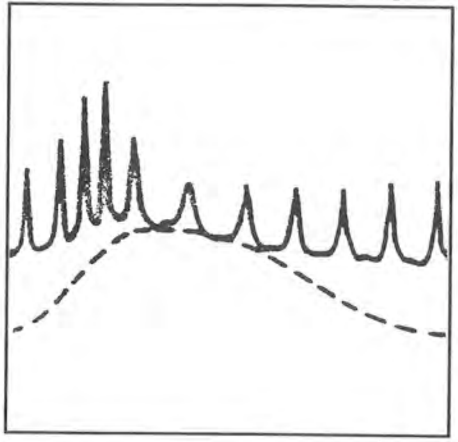


Figure 3. Wave propagation in a nonuniform tube. The length of the tube is 128 centimeters. The dotted line indicates the tube envelope and the upper plot shows the wave amplitude as a function of position.

The wavelength is a measure of wave velocity. Note that the wave slows down as the tube diameter increases.

Figure 3



electromagnetic wave is extracted from this structure, we have a high-power microwave generator.

The second wave-growth technique uses parametric scattering to simultaneously grow slow and fast space-charge waves. This interaction requires a third wave—often a zero-frequency electrostatic wiggler. Our wiggler consists of the electrostatic fields produced by conducting rings arranged so that grounded rings alternate with rings at a high voltage. To the beam electrons, this looks like an electromagnetic wave propagating toward them.

Both of these techniques work well, as Figure 2 shows.

In order to accelerate the particles in the high-energy beam, we need to increase the velocity of the slow wave. (This is not required with the fast cyclotron or hybrid wave because the accelerating electrons have a velocity bounded by the speed of light, and therefore gain energy at a constant velocity.) This change in the phase velocity of the wave is accomplished by changing the diameter of the waveguide. As the pipe size is reduced, the velocity increases to an upper limit set by the drift velocity of the electrons. This process has also been demonstrated in the laboratory and is nicely shown in a simulation carried out by Charles Seyler and one of his former graduate students, Dan Fenstermacher.

The speeding up of the wave is seen in Figure 3 as an increase in the wavelength of the space-charge wave as the guide size decreases. It is believed that accelerating field gradients in excess of 100 MV/m can be achieved using these technqiues with the proper electron-beam parameters. This is greater than the field gradient in any existing electron accelerator, although propos-

"A principal driving force in these investigations is the desire . . . to make accelerators more compact and therefore less expensive."

als for new devices project accelerators with comparable gradients.

APPLICATIONS OF THE RESEARCH TO PARTICLE ACCELERATORS

A principal driving force in these investigations is the desire to achieve higher field gradients to make accelerators more compact and therefore less expensive. This will be an economic necessity for high-energy physics accelerators of the future—beyond the superconducting supercollider now proposed.

The collective devices I envision have the advantage that their design is simple. The absence of internal structures will enhance the prospect of achieving high field gradients. It will also eliminate wake field effects, which degrade the quality of the beam. (The wake fields arise from the electromagnetic radiation generated by the accelerating particles as they traverse the cavity structure; the beam degradation is caused by feedback of the radiation on the beam itself.)

In addition, we can show that it is possible to achieve higher particle currents in collective accelerators than in more conventional devices. This is an important consideration for applications, such as the free-electron laser, in which the reaction is density-dependent.

In its present status, pulsed-power technology makes possible the production of high-repetition-rate electron beams, which in turn may be used for the development of new devices. This capability of pulsed power was achieved only in the last few years with the production of new amorphous magnetic glasses, which are used to generate the ultrashort pulses typical of pulsed-power systems.

Further development of novel accelerator concepts will be augmented by this new magnetic switching technology, and also by improved techniques for generating ultrahigh-power radio frequencies by means of pulsed-power-driven intense electron beams.

The combination of all these technologies provides an opportunity for rapid and substantial advances in the development of high-energy accelerators.

John A. Nation is a professor of electrical engineering and is currently director of the school. He has also served as associate director of the Laboratory of Plasma Studies.

Nation was educated at Imperial College, London. After receiving his doctoral degree in 1960, he joined the plasma physics group at Frascati, Italy, where he worked on a theta pinch fusion device. Subsequently he worked at the Central Electricity Research Laboratories in England, and in 1965 he came to Cornell.

He is a fellow of the American Physical Society.

INTENSE RELATIVISTIC ELECTRONS

Their Interactions with Matter and with Waves

by Charles B. Wharton

What happens when a powerful beam of electrons encounters matter or electromagnetic waves? Finding out has been a focus of research at Cornell's Laboratory of Plasma Studies ever since it was started twenty years ago. The answers are of great interest from a fundamental scientific point of view, and they are central to the development of important technologies.

In my laboratory, my associates and I conduct experiments of three types. We are working on plasma heating for fusion reactors; on electron-positron plasmas, until now unknown on Earth; and on high-power beams of microwaves. But as the following discussion will show, these three investigations have a common base: They all involve pulsed electron beams that have megavolt energies and kiloampere currents, and they all involve *collective* interactions, in which electrons behave as coherent groups rather than as separate units and thereby greatly amplify the coupling power of the beam.

PLASMA HEATING: A NECESSITY FOR NUCLEAR FUSION

The fusion reactions that must occur in a controlled thermonuclear reactor require very hot plasma. Many methods of heating—some slow, some rapid—have been proposed and developed.

We have found that magnetically confined plasma can be heated to high temperatures very rapidly by injecting a pulse of a high-power electron beam. The pulse we use has a voltage of 0.5 MeV (500,000 electron volts) and a current of 60 kiloamperes lasting about 40 nanoseconds (billionths of a second); the plasma has a density of 10^{13} electron-ion pairs per cubic centimeter. The system is sketched in Figure 1.

The coupling between the electrons of the plasma and the electrons in the beam was found to be very strong. This seemed remarkable, since we had expected that the mean free path of the beam electrons—the distance they travel between collisions—would be much longer than our two-meter

Figure 1

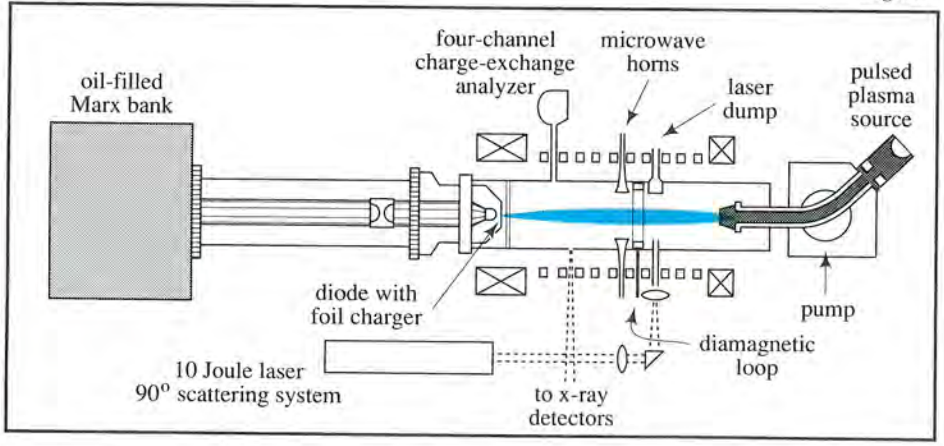


Figure 1. A simplified diagram of the highly instrumented system used to heat plasma by means of a high-intensity pulsed electron beam. The high-voltage pulse is impressed by the coaxial line from the left, and the electron beam emitted by the cathode penetrates the anode foil separating the diode vacuum from the plasma column.

"We are working on plasma heating for fusion reactors; on electron-positron plasmas, until now unknown on Earth; and on high-power beams of microwaves."

column. In our machine the interaction length was only 10 to 20 centimeters.

The explanation involves the collective, or wavelike, behavior of the electron plasma and the penetrating electron beam—a phenomenon that is somewhat analogous to ocean waves driven by a steady wind. The waves subsequently "break" (as waves do on a beach) producing particle thermalization, and the plasma is heated to temperatures as high as 7 or 8 keV (81 to 93 million degrees Celsius).

The presence of the waves was verified by experiments in which microwave probing beams, with wavelength in the millimeter range, were scattered from the plasma column. Measurements were made of the magnitude and scattering angle of the maximum signal, and these data allowed determinations of wave amplitude, scale size, and identity. We concluded that at least two types of waves, arising from streaming instabilities, were present: ion-acoustic waves, which are similar to sound waves but have frequences of hundreds of megahertz, and electron plasma waves.

The temperature of the electrons was measured with a laser, using a technique called Thomson scattering. It is based on the fact that when light photons are reflected from plasma electrons, their frequencies are shifted by a Doppler effect caused by the thermal velocities of the electrons. The velocities and thus the temperature of the electrons is obtained by analysis of the wavelengths of the scattered light. The method relies on the use of a high-power laser and very sensitive light detectors in a high-quality optical system. We measured electron temperatures as high as 3 keV during and slightly after the electron-beam pulse, but these levels decayed to less than 1 keV during the confinement period of a few milliseconds.

The total bulk plasma heating was determined by measuring the increase in plasma diamagnetism with a special magnetic loop. This measurement, together with a determination of plasma density by microwave interferometry (a method originally developed by the author) yields the energy gain per particle and thus the temperature.

Direct measurements of ion temperature were made using a technique called charge-exchange analysis. In this procedure, plasma ions are neutralized and allowed to escape across the confining magnetic field lines, and then they are energy-analyzed. This measurement revealed that the ion energy distribution resulting from electron-beam heating was nonthermal, as evidenced by the presence of a high-energy "tail", seen in Figure 2.

This distribution is advantageous for controlled fusion applications, since the nuclear fusion reaction rates are much higher at large ion energies. Unfortunately, the charge-exchange process also drains energy from the plasma, and in our experiments that was the major loss mechanism, limiting the energy-confinement time to just a few milliseconds.

TOWARD THE CREATION OF AN ELECTRON-POSITRON PLASMA

A kind of plasma that up to now has been contemplated as existing only in deep space is made up of electron and positron pairs, which are created by the interaction between high-energy gamma rays and dense matter. Such plasmas would have unique properties because of the absence of ions, and we hope to create and study them in the laboratory.

In our experiment, we generated gamma rays by bombarding a tantalum plate with

Figure 2

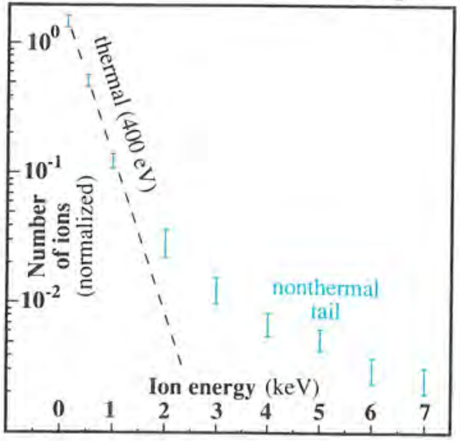


Figure 3

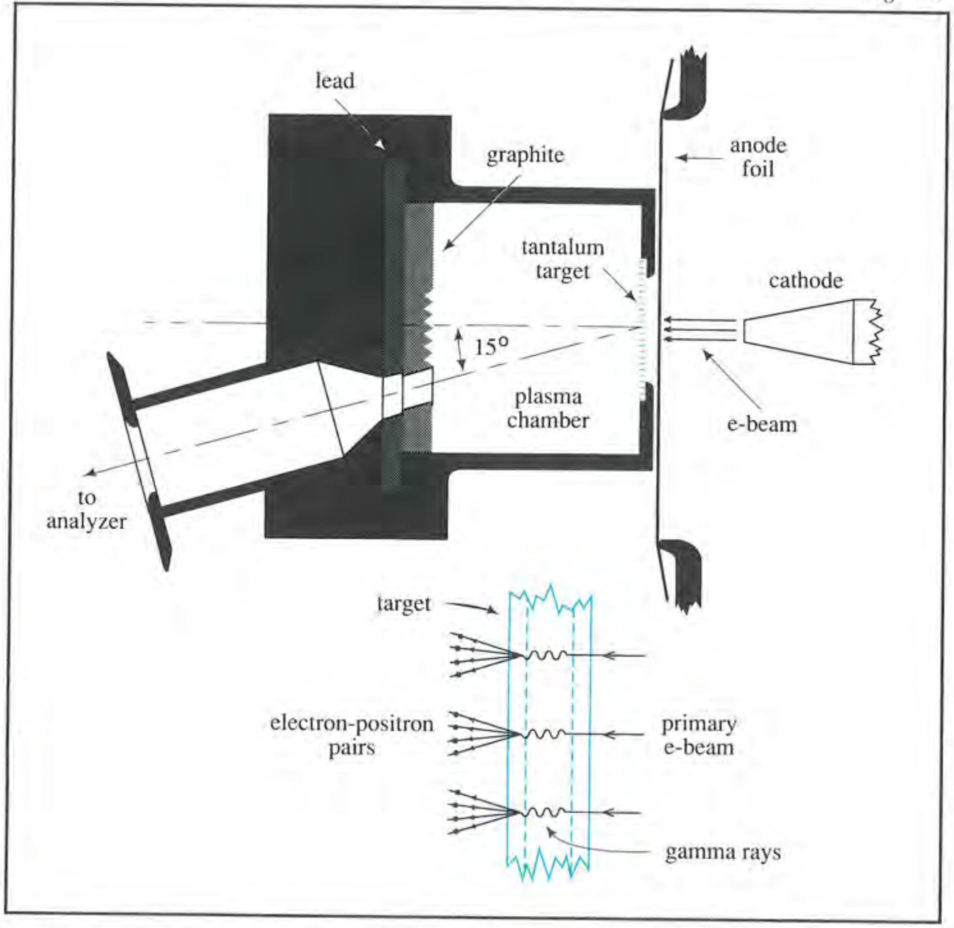


Figure 2. The energy distribution of plasma ions after heating by the method illustrated in Figure 1. The data were obtained from the four-channel analyzer indicated in Figure 1. This type of distribution, with a high-energy "tail," is favorable for nuclear-reactor fusion.

Figure 3. Generating energetic positrons. Gamma rays are produced by bombarding a 1-millimeter tantalum plate with high-energy electrons; the electron-positron pairs that are created emerge from behind the plate.

A high-current accelerator powers the electron beam to 4 MeV at a current of 60 kiloamperes in 80-nanosecond pulses. Each pulse produced 40 amperes of positrons with an average energy of 0.5 MeV, but extending up to nearly twice the energy of the primary beam.

pulses of high-energy electrons. The gamma rays, in turn, created electron-positron pairs, which emerged from the back side of the plate, as indicated in Figure 3. The tantalum target was destroyed with every pulse, but 40 amperes of positrons were produced and accelerated before the disassembly took place.

The positrons reached energies nearly twice that of the 4-MeV primary beam. The high-energy tail points to a collective acceleration mechanism, possibly collapsing solitary wave trains. Electrostatic acceleration could not give energies higher than that of the primary beam. In order to create an electron-positron plasma, the energetic particles must be trapped in a strong magnetic well long enough for them to heat and be cooled, either by radiation or with a moderator.

Because of the absence of ions, this is a very unusual plasma, especially in regard to waves. In such a plasma, nonlinear phenomena would predominate over linear phenomena in wave-wave and wave-particle interactions—just the converse of the situation in a normal plasma.

The positron energy analysis was made with a four-channel magnetic analyzer, calibrated with both protons and electrons of known properties. Essentially only the secondary particles reached the analyzer; the primary electrons were rejected by the combined effects of the thick plate, the large angle used for extraction and acceleration, and the magnetic filters.

These experiments have been set aside for the time being, but we hope to return to them.

USING E-BEAMS TO GENERATE HIGH-POWER MICROWAVES

We have recently initiated experiments in which metallic slow-wave structures, rather than a plasma, interact with the high-power electron beam. The process produces high-power microwaves.

We are investigating beam interactions with both forward waves—in travelling wave amplifiers (TWAs)—and backward waves—in backward wave oscillators (BWOs). Figure 4 shows a sketch of the vital parts of a BWO, and Figure 5 shows conditions under which oscillation occurs.

The dashed-line dispersion curve in Figure 5 pertains to "cold" conditions, when there is no beam; the solid lines show coupling with the slow space-charge wave of the beam. The coupling excites an absolute instability that oscillates at a frequency determined by the geometry of the slow-wave structure and the energy of the beam. Because the power carried by the beam is very large, typically at gigawatt levels, the microwave power outputs are also very large.

These experiments are similar and complementary to those discussed by John Nation in his article in *Plasma Studies at Cornell University* (an article published earlier in the Autumn 1987 issue of *Engineering: Cornell Quarterly*). Our approaches and goals are slightly different, however. Our primary purpose is to investigate the relativistic-electron TWA and the phase stability of multiple amplifiers driven by a BWO. We are also interested in the fundamental problems of beam-wave interactions.

We have now begun a study of the spatial growth of the beam-wave interaction as a function of beam temperature (energy spread), to see whether the temperature is the chief effect leading to non-

Figure 4

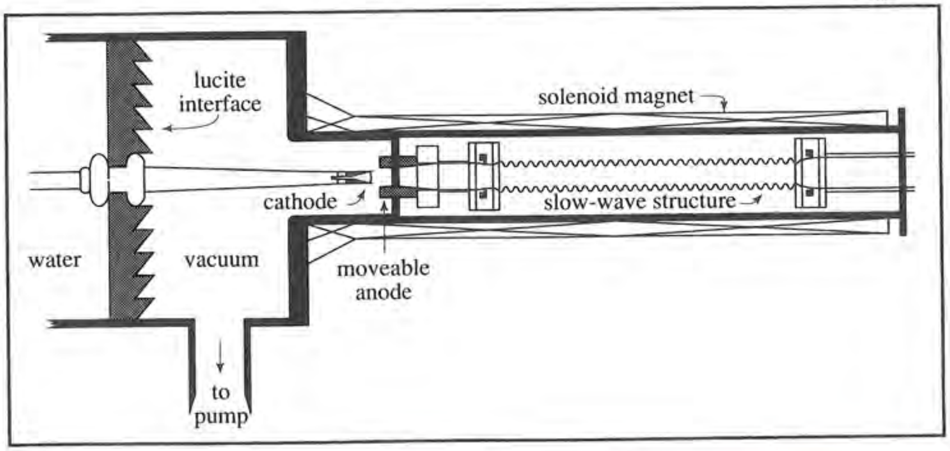
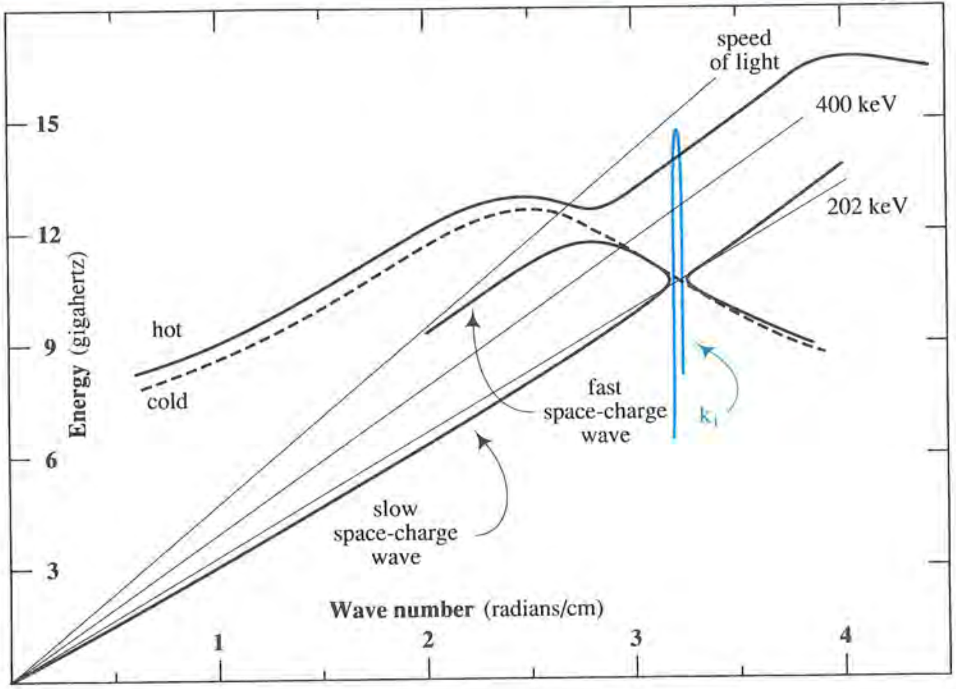


Figure 4. A backward wave oscillator (BWO) used to generate high-power microwave pulses. A pulsed high-power electron beam is injected into a rippled-wall slow-wave metal structure. The microwave power that is generated flows to the left and is reflected back to the right.

Figure 5. Dispersion curves of a BWO, showing beam-wave coupling and space-charge wave from the 5-kA beam. The dashed line is for "cold" dispersion (without beam); solid lines show the lowest TM mode; k_i (with values in the range 0.05–0.02) is the imaginary part of the dispersion, indicating oscillation.

Figure 5



linear saturation of growth, or whether there are additional causes, such as trapped particles or factors as yet unsuspected. If we can determine the causes of the nonlinear saturation, we may be able to take corrective measures that will permit waves to grow larger, thus increasing the ultimate power output and efficiency of the microwave-generating devices.

DIAGNOSTIC INSTRUMENTS FOR THE MICROWAVE RESEARCH

In our program the development of diagnostic instruments is almost equal in importance to the production of the high-power microwaves.

These instruments are necessarily very specialized, since they must be able to handle the large pulsed power and electromagnetic fields, and yet be sensitive to the small total energies of a few joules in each pulse. Multiple data must be collected from each pulse without averaging, since the pulses occur only once every few minutes. Two instruments developed by our group will be discussed here.

The directional coupler sketched in Figure 6 permits waves to be sampled in the large circular waveguides used in high-power experiments. It measures the forward power transmitted to a load, and any reflected power due to mismatched loads or to electrical breakdowns such as window flashovers.

The coupling in this instrument is through a series of holes spaced to enhance the forward wave going to each respective arm, but to cancel the reverse wave. The pickup arms are made from a section of coaxial cable whose TEM-mode fields match the TM-mode fields of the main waveguide. (TEM signifies transverse electromagnetic field; TM signifies transverse magnetic field.)

Figure 6

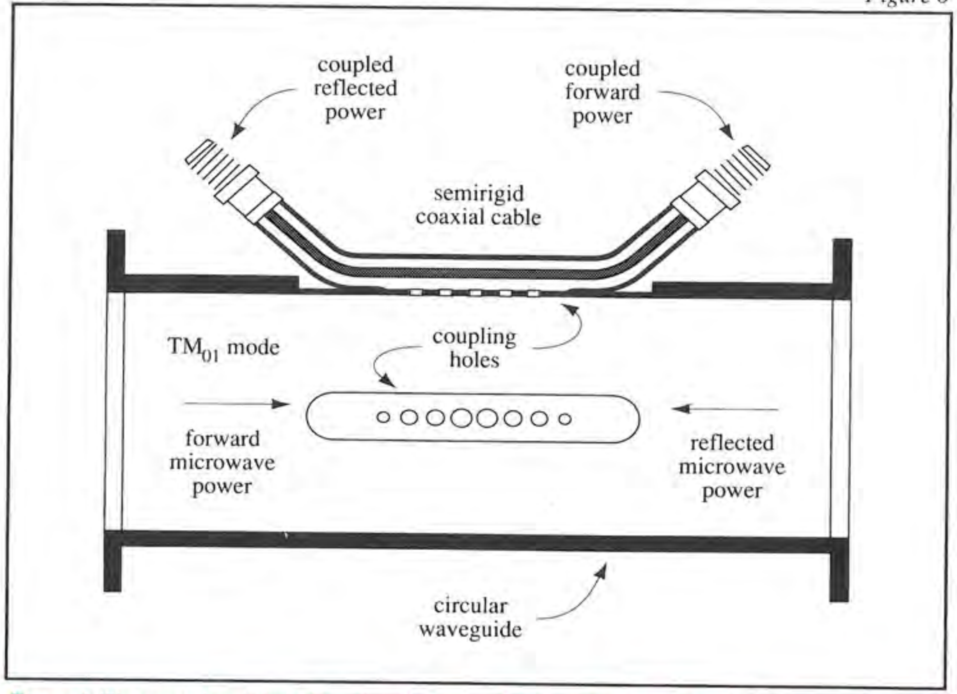
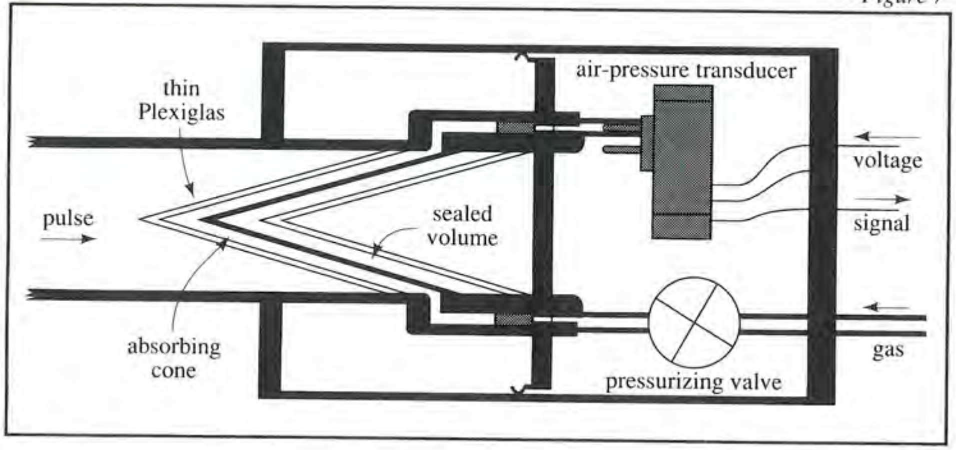


Figure 6. The special multihole directional coupler for large circular waveguides carrying TM waves. Very small coupling (-50 to -80 dB) is needed to sample microwave powers at hundred-megawatt levels; 26 dB of directivity permits reflection coefficients as small as 5 percent to be measured. Chebycheff-array coupling holes give 25 percent bandwidth.

Figure 7. The broadband calorimeter for power measurements in circular TM-mode waveguides. The resistive cone absorbs microwave power, heating the trapped air. The pressure transducer measures the increase in pressure due to the heating, giving a voltage output that is proportional to the microwave power.

Figure 7



Right: Working with the backward wave oscillator used for the research on high-power microwaves are Professor Wharton and two of his graduate students, S. Furukawa (at left) and Jennifer Butler.

Coupling coefficients of -50 to -80 dB are required to sample the waves, which are normally at levels of hundreds of megawatts. Signals are detected with conventional silicon microwave detectors, with response times of 5 to 10 nanoseconds, and are recorded on an oscilloscope to show the power as a function of time.

The second instrument is a calorimeter, used to measure the total energy contained in each microwave pulse. The device sketched in Figure 7 is unique in that the microwave power is converted to an electrical signal by means of an air-pressure transducer. The microwave absorber is positioned within a sealed-off enclosure, so that as it is heated by the microwaves, the trapped gas expands to increase the pressure. The instrument is broadband, in our case 8 to 13 gigahertz, and has a broad range, from millijoules to tens of joules, with a response time of a few milliseconds.

The pulse-energy data obtained with this instrument, together with the time-dependent amplitude information obtained from the directional coupler, provide a way of measuring peak microwave power.

Our research demonstrates the complexity that develops when a new area of science and technology is opened up. Before new technology is actually put to use, the fundamental physics must be understood, devices must be designed and analyzed, and sometimes new diagnostics must be devised. Our work is pioneering the way for several future applications of high-power beams.

Charles B. Wharton, a professor in Cornell's School of Elctrical engineering, began work with microwaves and high-energy ion accelerators as a graduate student at the University of California, Berkeley.

After receiving the M.S. degree in 1952, he joined a new group at Berkeley that was investigating the possibility of making a controlled-fusion reactor. When this group moved to Livermore, Wharton headed the diagnostics development program. In 1962 he joined the experimental physics group at the General Atomic Company, and in 1967 he came to Cornell.

Wharton has been a visiting scientist at the Max Planck Institute in Germany, the Atomic Energy Research Establishment at Harwell, England, and the Physical Research Laboratory at Ahmedabad, India. He serves as a director of the International School of Plasma Physics in Varenna, Italy.

He is a fellow of the American Physical Society and of the Institute of Electrical and Electronics Engineers. In 1973 he received the prestigious von Humboldt Prize.

COMPACT-TOROID FUSION AND HIGH-ENERGY PARTICLE RINGS

by Hans H. Fleischmann

Intense beams of electrons and ions have been a major focus of Cornell research on plasmas from the time the program began twenty years ago. Since various aspects and applications of these studies are described in other articles in this series, I will concentrate on my group's research in the area of large-orbit particle rings. This work, which started in 1969, is concerned mainly with potential applications of such rings in the compact-toroid area of fusion research, and in the development of novel, very intense high-energy particle accelerators.

Since the Laboratory of Plasma Studies is currently celebrating its twentieth anniversary, I will include some of the history of the program.

MAGNETIC FUSION RESEARCH AND COMPACT TOROIDS

Over the past twenty years, fusion research in the United States and worldwide has made tremendous and often not fully recognized progress. Plasma temperatures have been increased from around 100 electron volts (eV) to near-fusion levels of about 10 keV. Plasma lifetimes have gone from less than a millisecond to seconds. Energy break-even (the point at which the energy generated by fusion equals the energy used to heat the plasma) is expected to be achieved within a few years in at least one of the three large experimental machines now in operation.

These machines—the Tokamak Fusion Test Reactor (TFTR) at Princeton University, the Joint European Torus (JET) in Culham, England, and the JT-60 in Tokyo—have achieved conditions equivalent to an overall energy-gain ratio, Q, of 0.25, with $Q = 1$ representing break-even.

For various reasons, including an early concentration of resources, the main thrust in fusion research has been development of the tokamak concept (see the article by Richard L. Liboff in this series). The three large machines in the United States, England, and Japan are all tokamaks.

With break-even approaching, the goal of the fusion community has expanded; the current aim is to find the optimum technological and economic parameters of potential fusion machines. In addition to the tokamak concept, a number of "alternative" plasma-confinement concepts, including three variations of compact toroids, are being investigated.

Figure 1

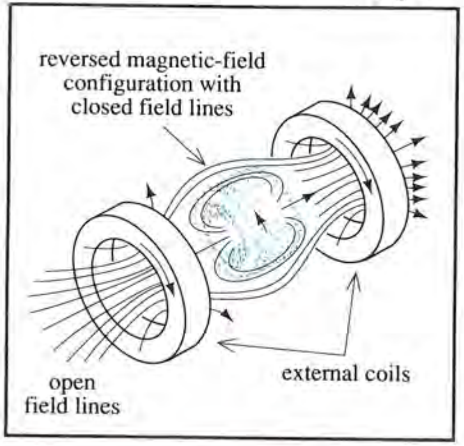


Figure 1. The basic idea of the compact toroid. The plasma is magnetically confined in a doughnut-shaped ring, which is kept in place by a simple axial magnetic field.

In a compact toroid, as in a tokamak, a doughnut-shaped plasma is surrounded and confined by a toroidal system of closed magnetic field lines. In contrast to a tokamak, however, the externally applied magnetic field of a compact toroid consists simply of a homogeneous field parallel to the ring axis (see Figure 1). Assuming gross stability of the rings, they could be included in a simple reactor design: ini-

Figure 2

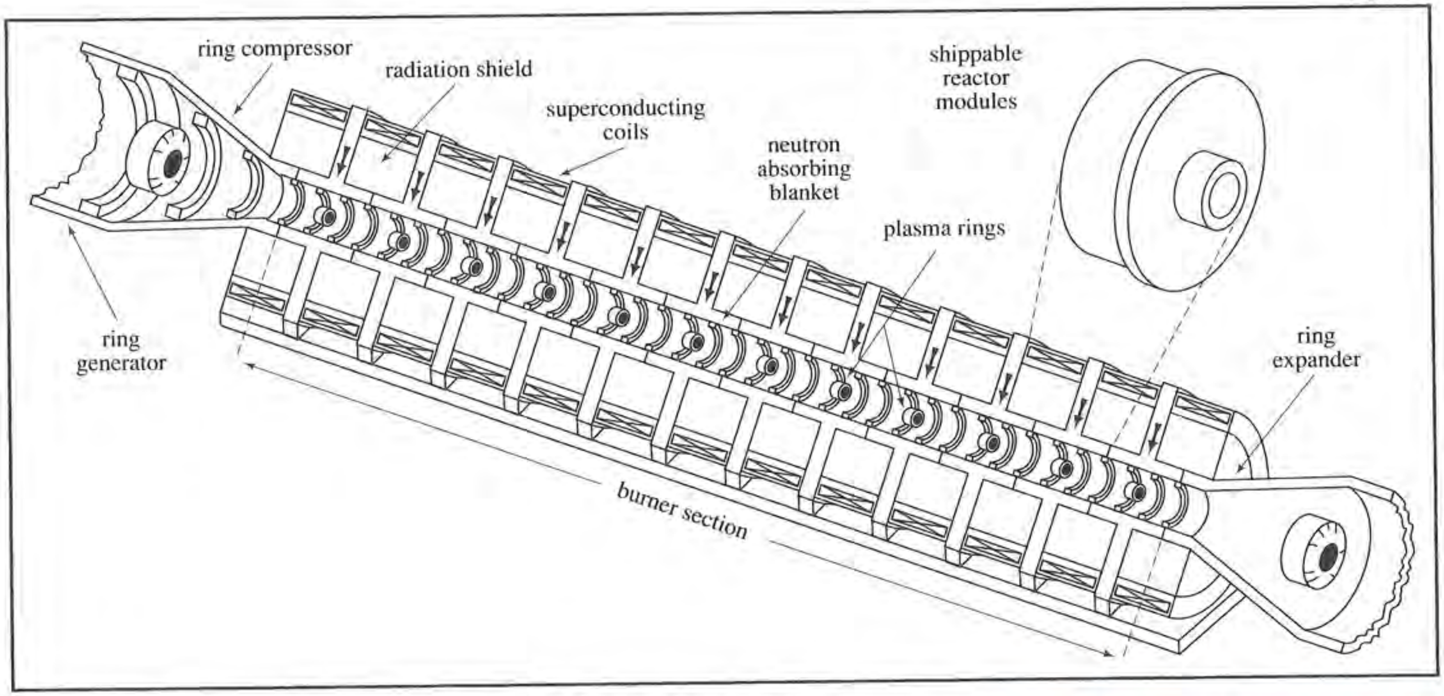


Figure 2. The compact toroid concept as it might be used in a fusion reactor. The plasma rings, after generation and compression heating (at left), would "burn" while moving through a straight burn chamber, and ultimately be discarded (at right).

tially cold low-energy compact-toroid rings could be heated efficiently by magnetic compression, then percolated along a straight burn chamber during energy production, and finally cooled by magnetic expansion (see Figure 2).

Compact-toroid schemes vary mainly in how the required ring current would be carried in the plasma. The schemes referred to as Spheromak and FRX call for the current to be carried directly by the confined plasma; in our Ion Ring Compressor (IRC) concept, the current is assumed to be carried by high-energy ions having Larmor orbit sizes comparable to the ring diameter.

Because of funding limitations, experiments based on these compact-toroid schemes have not yet yielded plasma parameters comparable to those obtained with tokamaks. Considerable progress has been made over the past few years, however, and more is expected in the near future.

THE ASTRON IDEA AND THE EXPERIMENT AT LIVERMORE

The IRC concept, which I developed in 1972–74, is an expansion of the earlier Astron idea of the very inventive and energetic Nicholas Christofilos at Lawrence Livermore Laboratory.

Christofilos, in his original 1958 proposal, envisioned the use of a large-orbit ring "E-layer" of relativistic electrons (50 to a few hundred MeV). The build-up and maintenance of this ring would be accomplished by stacking (injecting and trapping) sequential bursts of electrons in a nearly homogeneous axial magnetic field. Closed magnetic field lines would be generated when enough fast electrons accumulated to reverse the direction of the total magnetic field at the ring axis—that is, when *field reversal* was achieved. The sizable Astron experiment based on this idea was started at Livermore in the early 1960s.

By 1967 it was realized that relativistic electrons are not suitable for a fusion reactor and would have to be replaced by high-energy protons. Still, electron-ring experiments could serve as a scalable test for ion rings. However, in spite of an expenditure of about 30 million dollars, the Livermore group was not able to make stacking work so as to obtain field reversal, and the experiment was shut down after the sudden death of Christofilos in 1973. Unfortunately, many people in the fusion community tended to ascribe this failure to basic instabilities of the rings (including a tilt instabil-

". . . fusion research in the United States and worldwide has made tremendous and often not fully recognized progress."

ity resulting from the opposing alignment of the ring field in the external field)—that is, to a basic flaw of the concept itself.

RELATIVISTIC ELECTRON COIL EXPERIMENTS AT CORNELL

My work with intense beams began on my arrival at Cornell in the fall of 1967. Dave Hammer (then a graduate student and now director of the Laboratory of Plasma Studies) had just returned from England, where he had been sent to consult with Charlie Martin at the Atomic Weapons Research Laboratory. With Charlie's help, we then built Cornell's first beam generator, part of which is still in use. (It is discussed by Peter Auer in his article in this series.)

After that we earned our keep by "transporting calories in tubes"—that is, by investigating the propagation of electron beams for our Navy sponsors. But the application of beams to fusion appeared most interesting to me, especially since our single beam pulses contained many times the electrons needed for Astron field reversal. In 1969 a postdoctoral researcher, Merrill Andrews, and others worked with me in designing and building our first ring experiment (later dubbed Alphie) and by early summer we had achieved field reversal. However, because the ring currents were carried mostly by plasma currents without trapping fast electrons, the ring lifetime was limited to about 200 nanoseconds (1 nanosecond = 10^{-9} second).

Actual relativistic electron coil (RECE) experiments got underway a year later, when our new RECE-Berta device, built with the help of Dave Woodall (and some funding from the college), succeeded in generating field-reversing electron rings. These rings had a lifetime of about 20 microseconds, which corresponds to about 10^4 fast-electron orbits. This was a big success in comparison with the Livermore experiment. Since then we have repeated this with other devices: RECE-Cusp, which was built in collaboration with a visiting professor, Robert Kribel, and RECE-Christa, which postdoctoral researchers Clark Swannack and Bob Meger worked on. (Later, I also worked with Swannack and Chip Smith on a similar device at Los Alamos National Laboratory.) The electron rings generated in these devices were highly stable; in RECE-Christa, for example, ring lifetimes of a few milliseconds, corresponding to 10^6 orbits, were achieved.

Since then, over the past twelve years, graduate students and postdoctoral researchers have worked on a long string of studies involving detailed measurements and related quantitative calculations. This work has included studies of the decay of ring strength and electron energy (which is simply collisional); the radial stabilization of the rings by conducting walls and various magnetic fields; the axial transport of ring over a distance of about two meters; a radial compression of rings; and even a stacking of two rings (which had not worked at Livermore).

In all these experiments, conducted under a variety of conditions, the rings proved very stable and well behaved—in good quantitative conformance with relatively simple model calculations. Anomalously fast electron losses were observed only at unrealistically low background densities (due to micro-instabilities) or—in two cases—when resonances in the fast-electron orbits led to enhanced diffusion of the electrons.

These experimental results are consistent with theoretical studies performed in our group by Richard Lovelace and his students. These include studies of the for-

Right: Working with the new MICE device are Professor Fleischmann and two of his graduate students—Bill Podulka at left and Steve Jones at right.

(The sketch above, which has been painted on the MICE machine by graduate students, suggests the hoped-for fate of the large TFTR machine at Princeton.)

mation of large-orbit electron or ion rings, of their basic equilibria, stability, and scaling laws, of their behavior under compression, and of their particle orbits. All these studies indicate that such rings are stable.

Since our goal of demonstrating ring stability had evidently been reached, we decided that the electron experiments had served their purpose, and over the past two years we have converted our RECE-Christa device to an ion-ring experiment.

MICE: THE NEW MEGAVOLT ION COIL EXPERIMENT

In the early 1970s, when I. Nebenzahl did the first calculations on magnetic insulation of diodes, I began to consider experiments with ion beams and ion rings. There was a delay in initiating such a program, however, because of the serious misgivings about the Astron scheme, and because the equipment that would be required for ion experiments was much heavier and more costly than that required for work with electrons.

The first ion experiments conducted by our group were carried out in 1975 by Stan Luckhardt. He made some measurements of magnetically insulated ion diodes, which appeared to us particularly promising for future ion-ring experiments. The goal was to demonstrate ion-beam densities of at least 2–400 A/cm^2, and pulse times of at least 1–200 nanoseconds—values comparable to those required for a really significant first-stage proton-ring experiment. These hopes were satisfied.

In addition, the actual results broke important new ground in ion-beam generation by demonstrating larger-than-anticipated beam densities and pulse times. The values obtained for ion-beam density were $j_{\text{proton}} \leq 300$ A/cm^2—larger by a factor of nearly 10 than what would be expected from normal space-charge considerations—and $t \leq 400$ microseconds—considerably larger than the 50–100 nanoseconds that were usual at the time.

Another contribution was the introduction of a "virtual" cathode created by injecting electrons along the magnetic field. Virtual cathodes, which are now a standard feature of magnetically insulated diodes, eliminated the need for physical cathodes, which are not only cumbersome, but subject to damage by the ion beam.

Figure 3

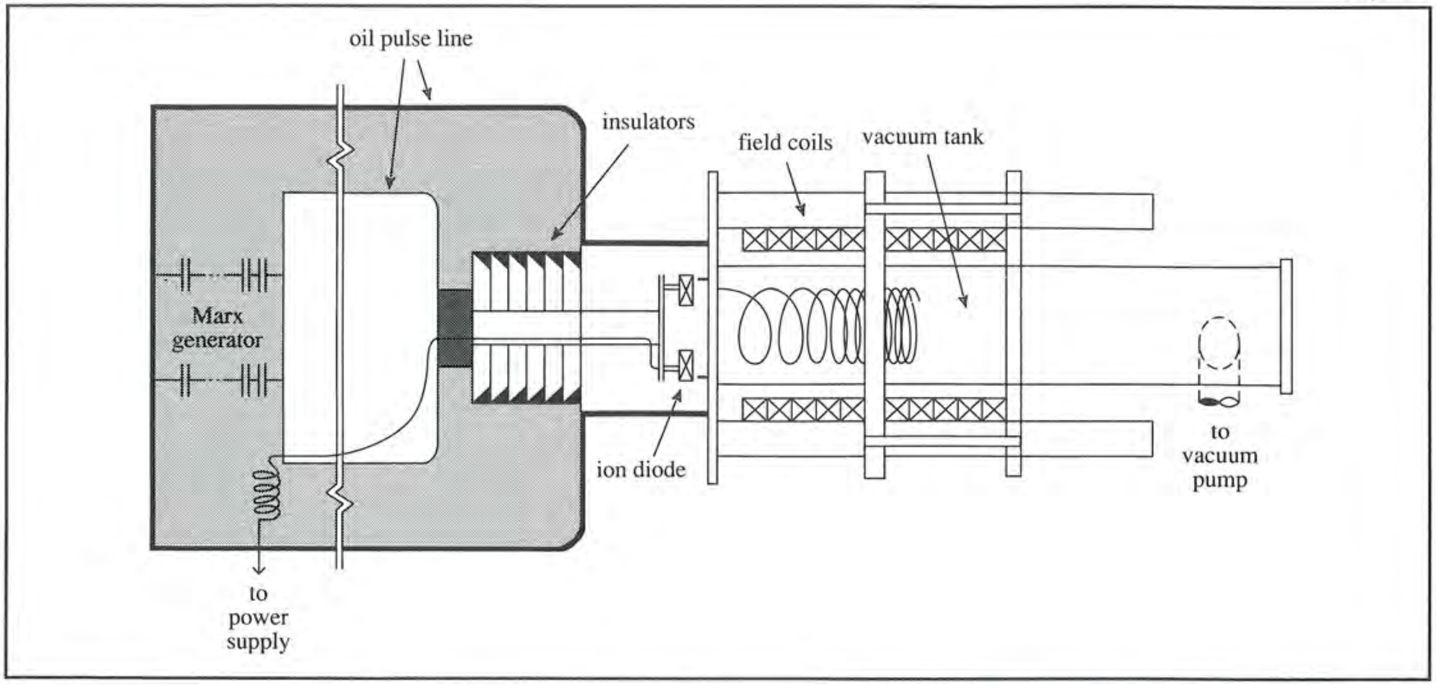


Figure 3. The Megavolt Ion Coil Experiment (MICE). The high-velocity ions are generated in a ring-shaped diode and directed mostly along the axis. The ions are then injected into the confinement tank through a cusp-like magnetic field which redirects them perpendicular to the field.

The ion diode consists of a ring-shaped anode containing a pulsed field coil and a plasma-generating plastic "flashover" surface which acts as proton source. The pulsed magnetic field provides magnetic insulation by strongly reducing the otherwise dominating electron current, and also acts as part of the cusp field. A positive 1-megavolt pulse, for accelerating the ions, is supplied to the anode from an oil-insulated Marx generator.

In the near future, this generator will be complemented with a less inductive water pulse line, which will permit a further enhancement of the available ion currents. After penetrating the cusp field, the protons will spiral—and, it is hoped, be trapped—in the rising field (6–8 kilogauss) of the main confinement tank.

Our new Megavolt Ion Coil Experiment (MICE) (see Figure 3) is based on these results and on the ring diode proposed by us at that time. Experiments with this facility have begun recently. Initially, they are focusing on the generation of strong ion beams and on the behavior and physics of these beams in the cusp (see the figure) and in the main field. Subsequently, the focus will shift to the generation and trapping of strong rings.

The significance of these experiments is that for the first time, ion rings will be investigated in detail under conditions in which the ring-generated magnetic field is comparable to the external field, so that the ring's self-field will seriously influence the orbits of a wide range of single ions. Comparable experiments have been performed in the ion-ring experiment (IREX) at Cornell, but so far the beam-generated field changes have been limited to only a few percent. In an earlier experiment at the Naval Research Laboratory, very promising strong beam-generated fields (including field reversal!) were generated for a few hundred nanoseconds, but unfortunately, the time could not be extended before the experiment was terminated.

FUTURE APPLICATIONS OF ION RINGS

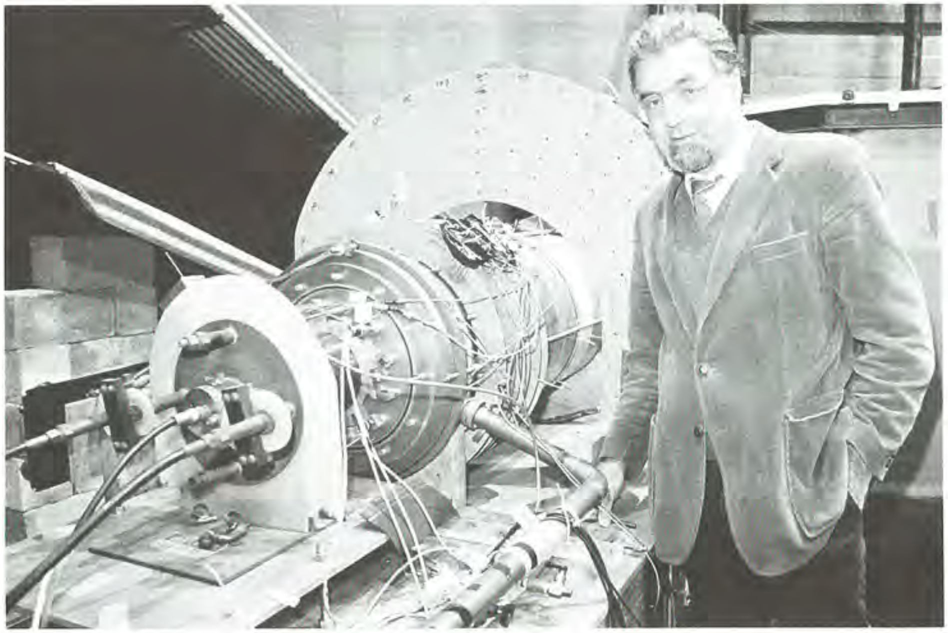
The basic ion-ring compressor (IRC) scheme I have described constitutes one leg of the compact-toroid triad; the Spheromak and the FRX are the others. Although good progress in plasma confinement has been made with these other two concepts, they face a major problem: their rings have a tendency to tilt so that the magnetic dipole moment becomes aligned parallel to the external field. With Spheromaks, this problem was theoretically predicted and also observed experimentally. Stabilization would require external coil arrangements that would seriously reduce the attractiveness of a such a reactor. This tilt has not yet been observed in FRX experiments, but it is expected in more advanced models.

Since our ion rings have never shown such tilts, I proposed (in 1979) hybrid systems in which part of the ring current in the Spheromak and FRX configurations would be carried by high-energy ions. If really tilt-stable, such hybrid compact toroids could be used in a technologically very attractive moving-ring reactor arrangement. Such rings could also have some advantages with respect to the simple IRC concept.

Very rough theoretical estimates predict that a fast-ion current of only 10–30 percent of the total current may be needed for stabilization. In that case, experiments could be performed within a few years on one of the planned larger Spheromak or FRX devices. One of the goals of our MICE research is to develop the technology and the physics base for such an experiment.

Ion ings also have potential use for very-high-current accelerators. A ring such as the one in our IRC, produced only once per second, would correspond to an accelerator with an average current of about 300 mA. This is larger by nearly two orders of magnitude than the currents in existing accelerators in the comparable energy range (400 MeV). Moreover, such an ion-ring accelerator would have much better cost and energy efficiency.

A related and even more attractive possibility is a betatron-type acceleration of our ring ions. If an axial flux coil were placed along the ring axis, the ions would be accelerated by the electric field produced by its changing flux. We performed similar experiments with electrons in our RECE-Christa device and were able to accelerate rings of 2 kA, an order of magnitude larger than the currents previously attained.



The progress made in my laboratory during nineteen years of research has come about mainly because of the work of students and postdoctoral associates. In addition to those I have noted, I particularly want to mention John Bzura and David Phelps on RECE-Berta; Don Rej, Mark Parker, Hal Davis, Michel Tuszewski, "Jay" Jayakumar, and Daniel Taggart on RECE-Christa; and, recently, Bill Podulka, Steve Jones, and R. Behrouz Amini on MICE. Also, a number of visitors have contributed advice and work; they include Tom Fessenden (Livermore), Professor Henk Hopman (Amsterdam, The Netherlands), Professor Kyoshi Yatsui (Nagaoka, Japan), and Professor Akihira Mohri (Nagoya, Japan).

The potential of our work is far from realized, of course. It provides basic knowledge and experience that will contribute to important future applications of plasma science and technology.

Hans H. Fleischmann, professor of applied and engineering physics, came to Cornell in 1967 at the start of the plasma studies program. He had worked with General Atomic in San Diego on controlled fusion research, and at Cornell he has maintained a program in this field.

He studied at the Technische Höchschule in Munich, earning his doctoral degree in 1962. He has been a visiting scientist or professor at the University of Maryland, the Plasma Physics Laboratory at Princeton University, and the McDonnell Douglas Corporation, and he has served as a consultant to many industrial and government laboratories, including the national laboratories at Oak Ridge and Los Alamos.

He is a fellow of the American Physical Society and the Institute of Electrical and Electronics Engineers, and currently he is president of the University Fusion Association.

INERTIAL CONFINEMENT FUSION

And Cornell's Part in its Development

by Bruce R. Kusse

The prospect of producing clean energy from a virtually inexhaustible source has motivated the research in controlled thermonuclear fusion. The reactants could be isotopes of hydrogen. The end products could be helium, neutrons, and a large amount of energy.

Initially it was hoped that the development of fusion reactors would follow the development of fission reactors as a straightforward next step, but that has not happened. Controlled fusion has turned out to be extremely difficult, involving many problems in physics and technology.

THE TWO APPROACHES TO CONTROLLED FUSION

The quest for this ideal source of energy has proceeded along two fundamental lines of approach: magnetic confinement and inertial confinement. Both entail the same basic requirements. The reactants, in the form of plasma particles, must reach the extremely high energy levels at which their nuclei can fuse, and this state must be sustained long enough to allow a net gain in energy. In more technical terms, the requirement is that the plasma must reach ignition temperature, approximately 10^8 degrees Celsius, and the ignited plasma must be confined long enough to satisfy the *Lawson condition:*

$$n\tau > 10^{14} \text{ sec/cc}$$

where n is the plasma density and τ is the particle-confinement time.

The two fusion-reactor approaches address the Lawson requirement differently. In the magnetic-confinement approach the idea is to have modest densities and strive for long confinement times through the use of magnetic traps. The inertial approach uses higher plasma densities and very short confinement times determined only by the inertia of the ions. I will discuss inertial fusion and the research efforts in this area at Cornell.

In the inertial scheme, the plasma starts out as a small solid pellet of thermonuclear fuel, most likely a combination of the hydrogen isomers deuterium (D) and tritium (T).

The fuel pellet is irradiated by an energetic beam to produce the ignition condition and initiate the fusion reaction:

$$\text{D} + \text{T} \;\; > {}^4\text{He} + \text{neutron}.$$

Both laser beams and beams of particles (electrons or light ions) have been proposed as drivers. Laser beams have the advantage of being relatively easy to transport and focus, but the disadvantage of being inefficient. Particle beams can be produced efficiently, but are more difficult to propagate and focus. At the present time, lithium beams are considered the most appropriate kind of particle-beam driver.

CORNELL RESEARCH ON THE USE OF LIGHT-ION BEAMS

The Laboratory of Plasma Studies at Cornell has pioneered in the development of intense charged-particle beams and at the present time is collaborating with Sandia National Laboratories on the application of light-ion beams for inertial confinement fusion.

A large facility called PBFA-II (Particle Beam Fusion Accelerator) has been constructed at Sandia (see Figure 1) and is being used for an experiment in which a high-power pulsed lithium beam is focused on a deuterium-tritium pellet, resulting in compression and heating. The device is designed to raise the pellet to ignition temperature and possibly "break-even," with an energy gain of 1.

Figure 1

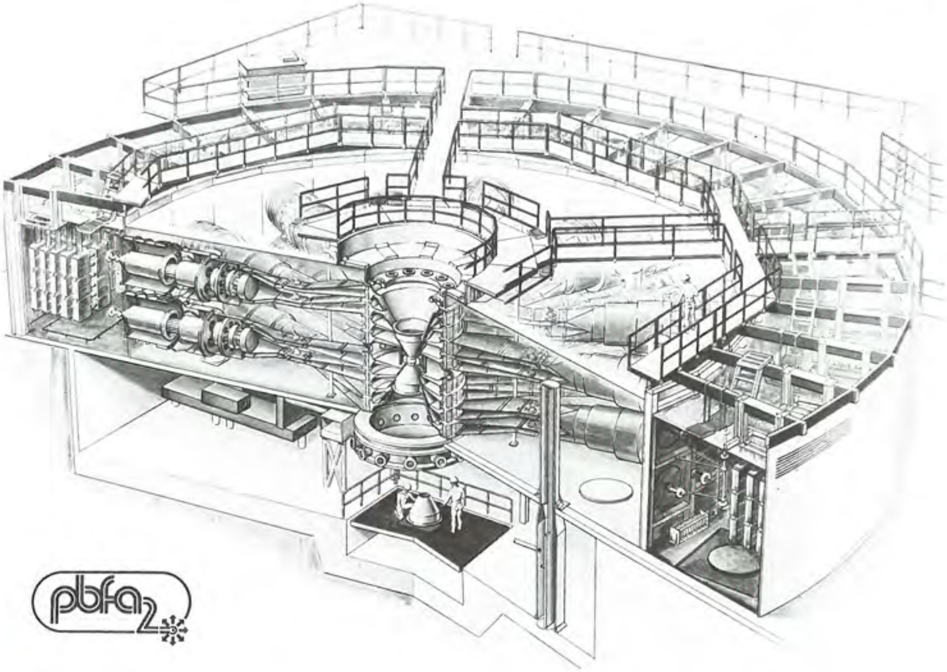
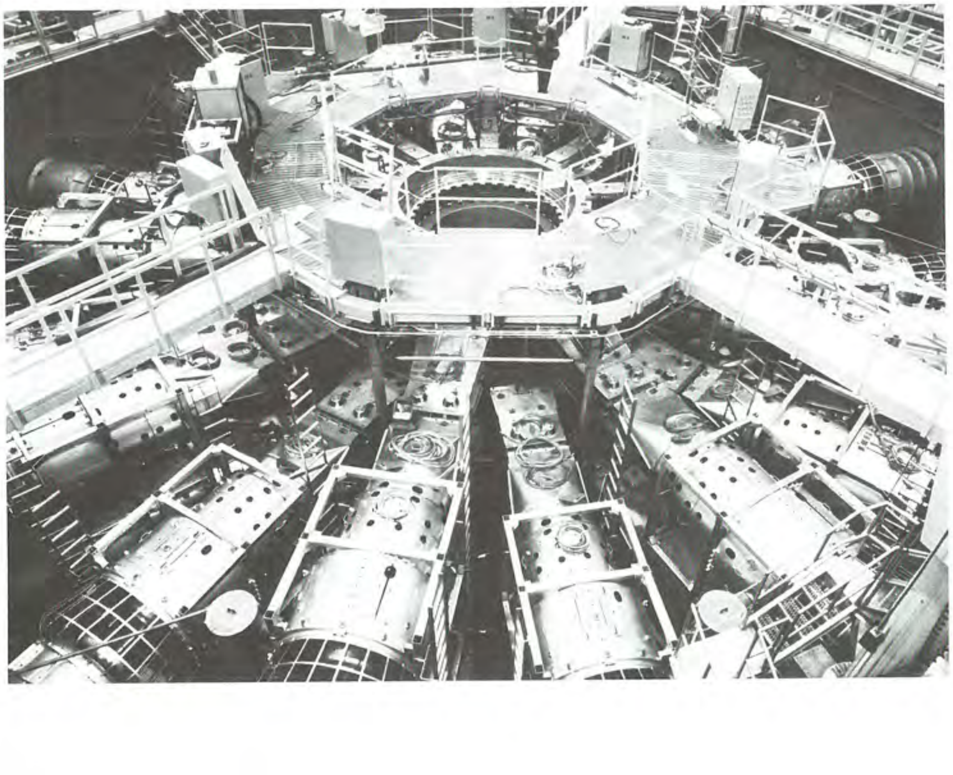


Figure 1. PBFA-II, the Particle Beam Fusion Accelerator at Sandia National Laboratories. This large facility is designed to focus a light-ion beam on a deuterium-tritium pellet for experimentation in controlled thermonuclear fusion. The PBFA-II has the potential of achieving ignition and possibly energy "break-even".

The current experiment uses a pulsed lithium beam with a power of 150 terawatts (TW), which is equivalent to the electrical generating power of the entire United States. The ratings are 30 million electron volts (30 MeV) and 5 million amperes (5 MA). The beam is capable of delivering pulses of energy at a level of about 1 million joules (1 MJ).

The cutaway drawing shows the capacitors in the outer annulus and the multimodule pulse-forming network extending toward the center where the pellet is located.

Right: This photograph of PBFA-II shows the pulse-forming section in the foreground.



The pulsed-power components of this large experiment are, for the most part, working, and at the present time attention is concentrated on the production, propagation, and focusing of the lithium beam.

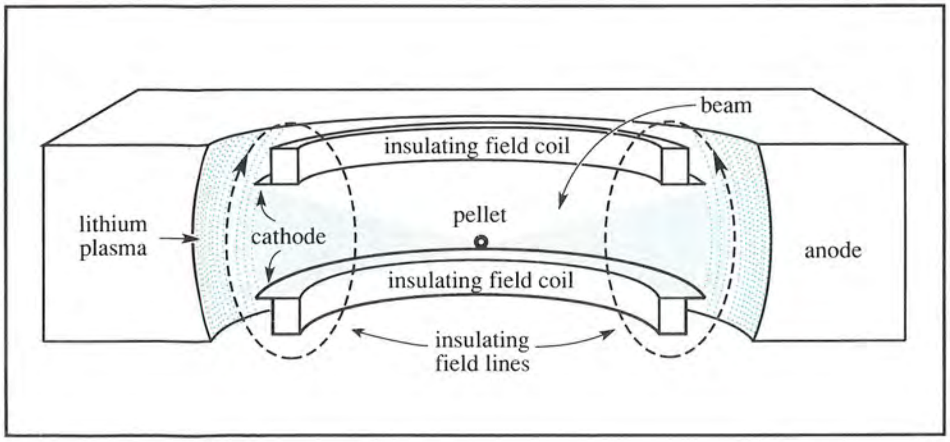
Cornell is collaborating in this effort by conducting a series of experiments on our LION accelerator.

Left: Working at the LION diode are Conrad Stuckman (at left), a graduate student, and Gary Bordonaro, a technician. The facility is used in fusion research conducted in cooperation with Sandia National Laboratories .

Below: Surrounded by a maze of cables, Jim Longfellow works on an experiment that is part of a study of lithium-beam charge exchanges. Longfellow, a senior in applied and engineering physics, is participating in the project under the auspices of a new College of Engineering program that gives undergraduates the opportunity to take part in ongoing research.

Figure 2. A cutaway view of the inertial fusion diode under study at Cornell. This diode is designed to focus the ion beam on the pellet target.

Figure 2



USING A LION TO TAME A HIGH-POWER ION BEAM

Cornell's Light Ion Fusion Facility (LION) was provided in 1981 by Sandia for work on the cooperative project. A beam source similar to the one on PBFA-II has been installed on our LION accelerator, and we will use the specially designed diode diagrammed in Figure 2 to investigate ways of manipulating the lithium beam.

The accelerator produces a 1.2-MeV, 400-kA, 40-nanosecond pulse; in other words, it supplies nearly 500 billion watts of power in 40 billionths of a second. The

"The production, propagation, and focusing problems associated with the lithium beam must be solved...."

beam is applied to the cylindrically symmetric anode-cathode gap of the diode, and the curvature of the anode and the magnetic fields allow it to focus on the pellet target. An applied magnetic field is used to insulate the gap against electron flow while permitting the ions to cross.

The focusing is complicated by the presence of the applied insulating magnetic field, the self electric and magnetic fields of the beam, and any charge exchange that can occur as the lithium beam propagates from the gap to the target. To a large degree, these problems have been solved for a proton beam by proper adjustment of the anode curvature and the applied magnetic field. For a lithium beam, however, production, propagation, and focusing are more difficult and many problems remain to be solved.

Producing a lithium beam is more difficult than producing a proton beam because a hydrogen-free source is needed at the anode. Focusing is made more difficult by the fact that the charge state of lithium can change as the beam propagates. If the charge state of the beam does not change, focusing is achieved when the magnetic flux through the anode-cathode gap is equal and opposite to the flux between the cathode and the pellet. If, however, the beam can change its charge state during propagation to the pellet, the equal-but-opposite flux condtion must be modified. The ratio of the two fluxes that is required in order to allow focusing depends on where the charge exchange occurs.

The production, propagation, and focusing problems associated with the lithium beam must be solved, and are under study in our laboratory as well as at Sandia. If these problems can be overcome and the PBFA-II made to meet the goals of ignition and near-break-even, we will have made a big step toward the realization of a practical fusion reactor.

Bruce R. Kusse, a professor of applied and engineering physics, came to Cornell in 1970 as a research associate in the Laboratory of Plasma Studies and joined the faculty the following year.

After receiving the S.B. degree in electrical engineering from the Massachusetts Institute of Technology in 1960, he served in the navy for three years and then returned to MIT for graduate study in electrical engineering. He received the S.M. in 1964 and the Ph.D. in 1969, and then spent a year and a half as a senior scientist at EG&G, Inc., and as a research associate at MIT.

In 1976 he was a visiting scientist at MIT's Plasma Fusion Center, and in 1986 he was a visiting scientist at the Lawrence Livermore National Laboratories.

PLASMA PHYSICS: A PURE AND APPLIED FIELD

by Charles E. Seyler, Jr.

For those who are inspired by the complexity and the beauty of plasma and have devoted their lives to its study, it is fortunate that plasma physics is not only a pure science, but also an integral part of several applied fields.

The most grand application is to controlled thermonuclear fusion. The promised economic and environmental payoffs have been the reason plasma physics has been studied to the extent it has. In the coming decade, the major challenge of magnetic-containment controlled fusion, the main approach, will be to understand confinement scaling—that is, to understand the processes by which the plasma and its thermal energy escape to the confining vessel and thereby limit the effectiveness of the confinement. Fusion by means of inertial confinement, initiated by an extremely high-powered laser or ion beam impinging upon a tiny fuel pellet, has an entirely different set of difficulties to contend with. Here progress will be largely dependent upon the development of more powerful and efficient lasers and particle beams.

Another area of application that involves plasma physics in a fundamental way is the physics of intense relativistic electron beams. A technique that shows considerable promise is the acceleration of charged particles by means of plasma waves in the electron beam. This is called *collective acceleration* because it utilizes the electric field associated with the collective motion of the electrons to accelerate other charged particles (and possibly electrons). With this technique it may be possible to achieve very high energies within a relatively short distance (as compared to distances in accelerators such as synchrotrons or linacs). The enormous cost of the proposed superconducting supercollider has encouraged the development of other ways of accelerating particles.

A relatively new field that has already provided some very useful technology is plasma processing of silicon for integrated circuits. Semiconductor materials are either etched from or deposited onto a chip in order to create a circuit on a semiconductor substrate. Advances will come about through a better understanding of plasma chemistry and plasma-surface interaction.

The two major fields of pure science in which plasmas play a significant role are astrophysics and geophysics.

Many kinds of astrophysical phenomena—including solar flares, radio bursts, sun spots, and prominences—are manifestations of plasma dynamics. Cosmic rays are believed to have their origin in plasma processes, and exotic entities such as neutron stars, the accretion disks about white dwarfs, and black holes have been proposed as galactic sources of x-rays and gamma rays.

Below: Prominences visible above the surface of the sun are streams of plasma trapped in magnetic fields.

Geophysical plasma is considered to extend from about 100 kilometers above the surface of the earth, where the ionosphere begins, out to the magnetosphere. The most beautiful and commonly known of the many ionopsheric and magnetospheric phenomena is the aurora. A more thoroughly understood type of event, though it is not visible to the eye, is equatorial spread-F.

Research in space plasmas, both astrophysical and geophysical, has been growing rapidly in the past few years. This is partly because of a slowdown in the magnetic-fusion program, but it is also because funding agencies are recognizing the intrinsic importance of understanding our environment *in toto*. In the next decade space-plasma physics will be a leading field of plasma study. Experimental observations made with satellites, sounding rockets, and radar will provide data about our local plasma environment. Astrophysical plasma observations will rely upon the next generation of orbiting observatories and very-long-baseline astronomy.

THE IMPORTANCE OF LARGE-SCALE COMPUTING

Plasma physics is one of the most diffficult fields in classical physics, partly because it simultaneously involves electrodynamics and the classical mechanics of many bodies. Often a statistical mechanical description is necessary. But the chief reason for the difficulty is that the most interesting and important characteristics of plasmas are nonlinear. Only within the past ten years or so has there been a real appreciation of the complexity of even simple nonlinear systems—and plasmas are not simple by any standard.

A significant advance in the theory of plasmas will be contingent on progress on three separate fronts: the invention of new analytical tools for the study of nonlinear systems, a refinement of diagnostics for experimental investigations, and the development of computational hardware and software for large-scale numerical simulation of plasma dynamics. The three-pronged approach involving the synthesis of theory, experiment, and simulation has been highly successful and will become more so as techniques of numerical simulation are developed.

"The three-pronged approach involving the synthesis of theory, experiment, and simulation has been highly successful and will become more so. . . ."

Numerical simulation has been particularly fruitful for plasma studies because of the establishment in the 1970s of the National Magnetic Fusion Energy Computation Center at Livermore, California. Much of the dramatic progress in controlled nuclear fusion can be attributed to advancement in numerical simulation.

Direct simulation is a powerful tool for plasma studies because it provides a means of following the motion of a large number of interacting charged particles. A numerical simulation is much like an experiment; in fact, it is in principle a perfect experiment, since one can derive in almost perfect detail the plasma characteristics.

In practice, however, there are major limitations of two kinds. The limited power of present-day computers restricts computational speed and memory capacity, and software inadequacies make it difficult to implement complex numerical algorithms. The other kind of limitation stems from our ignorance of precisely what to look for in the prodigious volume of information that a simulation produces. Without some theoretical or experimental guidance, a numerical simulation is only capable of producing interesting pictures whose meaning is a mystery.

The combination of experiment, theory, and simulation is not only helpful, but essential. Experiments tell us what happens in the physical world. Theory expresses our understanding of the processes. Simulation reinforces that understanding, giving us confidence that would otherwise be lacking because of the limitations of both theory and experiment.

Large-scale computing is vital also as a tool for solving the equations that emerge from theoretical analysis of plasmas. The model equations, which are usually in the form of partial differential equations, almost invariably require numerical solution because they are nonlinear. This kind of numerical solution—of a set of equations arising from a theory that is not fundamentally a first-principles approach—is often called simulation, but is more appropriately referred to as computer-assisted theory. It is a valuable approach because it helps one understand and refine the essential features of a mathematical model, which is the essence of any physical theory.

THEORETICAL STUDIES UNDERWAY IN LPS

Most of the theoretical work in the Laboratory of Plasma Studies is carried out by faculty members Richard L. Liboff, Richard V. E. Lovelace, R. N. Sudan, and myself, along with senior research associate Philippe Similon, postdoctoral associate Jay Albert, and graduate students. Outside collaborators are also involved.

Liboff is interested in the kinetic theory of solid-state plasmas and strongly coupled matter (see his article in this volume).

Lovelace, also a contributor to this volume, is interested primarily in relativistic magnetohydrodynamics of astrophysical jets and accretion disks around black holes; the equilibrium and stability of ion-ring/spheromak systems for possible use in fusion reactors; and electromagnetic wave propagation in turbulent media.

Sudan's work centers on controlled fusion and plasma turbulence. It includes studies of the equilibrium and stability of ion-ring compact torus fusion reactors, the physics of magnetically insulated diodes as sources of intense ion beams for driving inertial fusion, and the physics of plasma opening switches for pulsed-power generators. He is also working on the application of mapping techniques in nonlinear dynamics to cyclotron resonance heating in a plasma. His work in the area of plasma turbulence includes study of turbulent transport due to drift-Alfvén wave fluctuations, which may lead to anomalous electron heat transport in magnetic-confinement geometry. And he is developing numerical magnetohydrodynamic codes for the detailed study of solar convection.

Similon's interests also span several areas. He is currently investigating ponderomotive force theory, which involves the stabilization of magnetically confined plasma, with use of high-frequency electromagnetic or plasma waves to create a stabilizing potential well. He is working with Sudan on renormalized group theory techniques to provide a fundamental approach to a statistical description of turbulence. They are also studying the heating of the solar corona through the absorption of Alfvén waves.

Similon, Sudan, and Albert are collaborating on a study of plasma turbulence that is almost two-dimensional. In this kind of turbulence, the length scales, along the direction of a strong applied magnetic field, are much longer than the scales perpendicular to the magnetic field.

In January Niels Otani, who is currently at the Courant Institute of Mathematical Sciences of New York University, will join Cornell's electrical engineering faculty and the Laboratory of Plasma Studies. Otani, a specialist in the numerical simulation of plasmas, uses both direct methods (particle simulation) and indirect methods (partial differential equations). He will make full use of the resources in the new national supercomputing center at Cornell.

My own research is in two areas—collective acceleration and the nonlinear dynamics of ionospheric and magnetospheric plasma.

COLLECTIVE ACCELERATION OF HIGH-ENERGY ELECTRON BEAMS

A particular plasma wave, the so-called *upper hybrid wave*, appears to be a promising candidate for the acceleration of electrons. It has two especially useful properties: (1) since the waveguide is conducting, there is a component of the electric field along the axis of the guide, and (2) for a specific wavelength, which depends upon the guide and beam parameters, the phase velocity of the wave is equal to the speed of light.

These two properties make it possible to use the upper hybrid wave to accelerate electrons to ultrahigh energies—provided

The singularly beautiful phenomenon of the aurora, or "Northern lights", is seen as twisting, swirling, and glowing bands of light in the night sky. This display was photographed in Alaska.

that the wave can be excited by a feasible mechanism and that its nonlinear properties do not destroy its desirable linear features. My group is studying this problem. Our approach is to first formulate an appropriate dynamical model, and then solve the resulting nonlinear partial differential equations numerically.

This theoretical work is being performed in close coordination with experiments directed by Professor John Nation. The hope is that the theory can give some guidance as to which experimental regimes may be optimal, and also provide interpretation of the experimental results.

STUDY OF EQUATORIAL SPREAD-F AND THE AURORA

The aspects of plasmas that I find most intriguing are associated with the nonlinear dynamics of the fluid-like motion, and the many mathematical models used to describe this motion. Space-plasma physics is rich in fascinating dynamical phenomena and in the diversity of plasma models.

One project we are working on concerns equatorial spread-F, which results when the bottom side of the ionospheric plasma recombines in the evening to form an unstable configuration in which denser plasma is on top. This configuration is described by a generalized form of the Rayleigh-Taylor instability, which occurs when a light fluid is on top of a heavier fluid relative to gravitational acceleration.

Equatorial spread-F is reasonably well understood, at least for weak or only moderately strong events. Under certain conditions, however, the Rayleigh-Taylor instability is so strong that the plasma density structures (bubbles) attain an altitude at which the plasma becomes collisionless. In this regime, the plasma dynamics is not so well understood.

As one can see in the figure reproduced on the cover, there is much detail in the structure of this extremely strong event. We would like to understand the hierarchy of the spatial scales in the turbulent structure; Shahrokh Zargham is doing doctoral research on this problem. Our approach is to solve numerically the two-dimensional nonlinear partial differential equations that describe the instability. We consider the full range of plasma collisionality—from completely collisional (friction-dominated) to collisionless (inertia-dominated). With the insight gained from the numerical solution of the model equations, we hope to develop a physical picture of the high-altitude dynamics of equatorial spread-F.

At high latitudes, the primary ionospheric plasma structuring is evident in the spectacular aurorae. These occur when fast-moving electrons from the magnetosphere precipitate into the ionospheric E-region.

The complex motion of the aurora is not well understood because it is not an isolated event, but it is believed that the energetic flux of charged particles comprises a current aligned with the magnetic field and carried via a plasma wave called a *kinetic Alfvén wave*. Since the bottom-side ionosphere is conducting perpendicular to the magnetic field, it acts as a resistive load to the field-aligned current.

A discrete auroral event is called an *auroral arc* because the magnetospheric voltage source produces, by means of the kinetic Alfvén wave, a potential difference across the base of the conducting ionosphere (the E-region), and this subsequently generates an electrical arc. Our research on the complicated plasma physics of auroral arcs is aimed at comprehending the important subprocesses that affect the global structuring of the discrete arc.

I believe there are at least four classes of plasma phenomena that determine auroral arc dynamics. These are: the kinetic Alfvén waves, which carry the current; ion cyclotron waves, which dissipate current parallel to the earth's magnetic field; inertial two-dimensional flows, which convect the parallel currents and plasma density; and the conducting E-region plasma waves (gradient-drift and Farley-Buneman), which dissipate currents across the magnetic field.

These phenomena are involved in several current projects. A study of two-dimensional shear-driven turbulence in auroral arcs is being carried out in collaboration with Professor Michael Kelley and graduate student Greg Earle. Nonlinear ion cyclotron waves generated by intense field-aligned currents in auroral arcs is being studied in a collaborative effort with research associate Jason Providakes. He and I are also studying kinetic Alfvén waves associated with the coupling of the magnetosphere and the ionosphere. A study of nonlinear plasma waves in the E-region ionosphere is being pursued in collaboration with graduate student John Sahr.

Charles E. Seyler, Jr., an associate professor of electrical engineering, has been at Cornell since 1981.

He holds B.A. and M.A. degrees from the University of South Florida and a Ph.D. in physics, granted in 1975, from the University of Iowa. He did postdoctoral research at the Courant Institute of Mathematical Sciences at New York University and then spent four years at the Los Alamos National Laboratory.

PLASMA STUDIES: A BROAD FIELD OF RISING INTEREST

Collaboration between theoreticians and experimentalists is natural in the field of plasma physics because all investigations, both pure and applied, have a theoretical component. The close working relationship between our group and the Space Plasma Physics observational group headed by Professors Farley, Kelley, and Kintner is an example.

Cooperative work is prevalent also because plasma itself is so widespread. Most of the observable matter in the universe is in the form of plasma, and researchers in many disciplines are concerned with it.

The inherent beauty of plasma dynamics, combined with recognition of the importance of plasma physics as both a pure and an applied field, has brought about a growing interest and enthusiasm. The 1990s should be an exciting time for plasma physics on all fronts.

THE EXPANDING WORLD OF SPACE PLASMA PHYSICS

by Donald T. Farley

A "back-of-the-envelope" calculation, that legendary source of important scientific discovery, probably marked the beginning of the current era of ionospheric and space research at Cornell.

The calculation was carried out at a seminar in Phillips Hall in 1958. William Gordon (then a professor of electrical engineering at Cornell and now retired as vice president and provost at Rice) told the small group of graduate students (among them Donald Farley) and faculty members that the ionosphere could be probed with radar.

The idea of trying to detect a pinhead at a distance of 300 kilometers or more sounded hopeless at first. The technique makes use of scatter from individual electrons, which is incredibly weak: each electron has a cross section of about 10^{-28} square meter, and the total cross section, representing all the electrons in a volume of 10 cubic kilometers at an altitude of 300 kilometers—where the electron density in the ionosphere is the greatest—is only about 1 square millimeter.

Gordon, however, said that the feat was quite feasible with equipment then available. All you needed was a *really big* radar, one with an antenna area of many acres and a transmitter power of a few megawatts.

The idea was tested within a few months by Kenneth Bowles, who had recently received his Ph.D. in electrical engineering at Cornell. Then, in a remarkably short time (funds were easier to raise in those days, it seems), two major observatories were built close to the earth's equator—one in Arecibo, Puerto Rico, and one near Lima, Peru.

EARLY RESEARCH AND CURRENT WORK IN RADIO ASTRONOMY

At the time Gordon made his deceptively simple calculation, Cornell already had an active program of ionospheric research in the School of Electrical Engineering.

This began shortly after World War II, when Charles Burrows, who came as director of the school in 1945, brought Henry Booker into the faculty. Booker, a specialist in electromagnetic theory and radar, introduced ionospheric studies and radio astronomy into the research program.

The *ionosphere*, as the name implies, is the ionized portion of the upper atmosphere. Of course, the entire atmosphere is at least slightly ionized by cosmic rays, but the lower boundary of the ionosphere is usually placed at an altitude of 60 to 70 kilometers, where ionization by the sun's ultraviolet radiation begins to seriously affect the propagation of radio waves.

The upper boundary is also hard to define, but at altitudes of several hundred to several thousand kilometers, depending upon latitude, the plasma of terrestrial origin gives way to plasma of solar origin—the so-called solar wind, which is really the constantly expanding solar corona. The two regions are kept separate, to a large extent, by the earth's magnetic field. The outermost part of the terrestrial plasma is usually called the *magnetosphere*.

In the 1950s the research emphasis was primarily on radio propagation effects, especially scattering phenomena in both the ionosphere and the lower atmosphere. One branch of this program was concerned with the "twinkling" of radio stars, or radio star scintillation, caused by the irregular refraction in the ionosphere of the radio waves emitted by certain stars. This program was in some sense the forerunner of Cornell's present very strong radio astronomy program in the Department of Astronomy of Cornell's College of Arts and Sciences.

Left: The world's largest radio-radar telescope at Arecibo, Puerto Rico, is operated by Cornell. The spherical reflector has a diameter of 305 meters. The 600-ton feed support structure is suspended 150 meters above the reflector surface.

Below: Also administered by Cornell is the Jicamarca Radio Observatory, located very close to the magnetic equator in Peru.

The antenna covers an area 300 meters square and consists of 18,432 dipoles arranged in a grid pattern. The photograph shows a section of dipoles supported by posts. The people are, left to right, Walter Camacho, an engineer at the facility; Erhan Kudeki, who was then a graduate student and is now on the faculty of the University of Illinois at Urbana; Professor Farley; and Ron Woodman, a research associate.

This is the chief facility used in Cornell research on plasma instabilities in the equatorial ionosphere.

THE BIG RADAR OBSERVATORIES AND OTHER RESEARCH FACILITIES

The Arecibo Observatory was constructed under the direction of Gordon. It is now called the National Astronomy and Ionosphere Center and is administered by Cornell with funding from the National Science Foundation. The current director is Tor Hagfors, professor of astronomy and electrical engineering.

Nestled in the rugged hill country of Puerto Rico, the huge observatory is a spectacular sight, especially at night. It is now probably more famous for its astronomical program than for the perhaps less glamorous field of ionospheric research that was its original reason for being.

The radar in Peru, located in a desolate, dry valley near Lima, was built under Bowles' direction. It is now part of the Geophysical Institute of Peru, but most of

Below: This rocket launch took place at Sondre Stromfjord, Greenland, in February 1987. Professor Kelley was NASA campaign scientist for this three-year project to study the aurora.

Above: the antenna for the portable radar system is erected at the observational site, with the van containing the control equipment positioned nearby. This photograph was taken in Sweden in March, 1985.

The Winnebago has been transported to the Kennedy Space Center, as well as to Sweden. Before the portable system was installed in the van, it was used at sites in Manitoba, Canada; St. Croix in the Virgin Islands; Greenland; and North Carolina.

Left: A view of the interior of the van shows researchers Wesley Swartz (at left) and Jason Providakes at the controls.

its funding comes from the National Science Foundation of the United States and, like Arecibo, it is administered by Cornell.

There are now three other similar large radar facilities, one in Massachusetts, one in Greenland, and one in the northernmost part of Norway.

Our Space Plasma Physics group has carried out experiments at all these radar observatories. The group consists of Professors Farley, Hagfors, Michael Kelley, and Paul Kintner, plus a number of research associates, engineers, and technicians, and ten or twelve doctoral students.

And these are not the only facilities we use. The large radars are very powerful tools for studying the dynamics of ionospheric plasmas, but they cannot measure everything of interest; for some investigations we need in-situ measurements from rockets or satellites or even balloons—if possible, in combination with simultaneous complementary radar experiments.

Rocket and satellite research, directed by Kelley and Kintner, has been an important component of the Cornell program since about 1975. Rocket experiments have a faster "turn-around" time from conception to data reception than satellite measurements (for which the typical delay is now about a decade) and so they are better suited to graduate student research, but some phenomena can be studied only with satellites.

Our most recently added research tool, which we built to facilitate some of our combined, multi-experiment campaigns, is a rather sophisticated portable radar system that is housed entirely (except for the antenna) in a Winnebago van.

Needless to say, travel is a major item in our grant budgets! Some of us manage to make our winter trips to the congenial climates of Peru and Puerto Rico, but others brave the arctic winter nights.

IONOSPHERE-MAGNETOSPHERE ENERGY COUPLING

One of the reasons for heading north to the latitudes of the aurora, or northern lights, is to study how energy is coupled from the solar wind to the magnetosphere, to the lower ionosphere, and eventually to the atmosphere. The aurora is the spectacular visual manifestation of this interaction.

In the last three years, seven rockets have been fired by Cornell researchers through the aurora from a temporary NASA launch base in Greenland. One purpose is to study the violent turbulent motions in the plasma, and their associated electric fields and plasma waves. Our results so far give tantalizing evidence that the interactions may follow the predictions of two-dimensional turbulence theory. If so, we have a convenient laboratory, large and with no walls, in which to investigate this important topic.

The interactions are complicated and often spectacular because the plasma regions have very different properties. The solar wind is very tenuous and fairly cool, but it flows supersonically outward from the sun until it encounters the earth, passes through a shock wave front, and interacts with the outer edge of the magnetosphere in complex and only partially understood ways.

Drops in potential amounting to tens of kilovolts develop across the magnetosphere, and these drive large-scale convection processes. They help energize particles that precipitate and collide with other atoms and molecules in the atmosphere, producing the auroral displays that we see, sometimes even in Ithaca.

Left: These photographs of the aurora were taken from a satellite at an altitude of 800 kilometers. The lower (equatorial) edge of the diffuse aurora sometimes displays complex scalloped patterns, as can be seen in these two examples. The total area covered in the photographs is about 5 million square kilometers.

The convection processes may at times sweep out most of the ionospheric plasma during the night, producing what is called the *ionospheric trough*, at latitudes just south of the auroral zone and not far north of Ithaca. Some of the highest ionospheric convection velocities ever recorded, more than 7 kilometers per second, were measured in this region.

The associated velocity shears and density gradients generate various plasma instabilities, just as velocity shears in a river cause whirlpools and vortices. But in the ionosphere the scales are often very large: a scalloping effect on the edge of the auroral zone can be seen in photographs of the aurora taken from above with satellite cameras. This phenomenon was first observed from the ground, as well, during a campaign organized by Cornell in 1985. We collected radar and satellite data and scientists from Boston University used their image-intensified all-sky camera to record the optical emissions.

RESEARCH ON LOW-LATITUDE PLASMA INSTABILITIES

For a long time we have been interested in ionospheric plasma processes that occur only at latitudes close to the magnetic equator, where the earth's magnetic field is horizontal.

At altitudes of 100 to 110 kilometers in this region, currents of the order of 10^{-5} ampere per square meter—strong by ionospheric standards—flow and often generate plasma instabilities, just as do the far stronger currents in plasma fusion devices. These instabilities cause waves, similar to sound waves in the neutral atmosphere, to grow spontaneously, and these plasma waves can be studied easily with the large radar in Peru.

The small density variations associated with the waves cause even smaller variations in the refractive index, but these are nevertheless large enough to scatter back to the radar receiver a tiny, but easily detectable, fraction of the transmitted radar pulse. Furthermore, since the waves are moving, the frequency of the received signal will be slightly shifted from the transmitted frequency. By studying the spectrum of these Doppler shifts, we can learn surprisingly much about the physics of the instability processes.

The main emphasis these days is on the study of nonlinear "turbulent" interactions

"The main emphasis these days is on the study of nonlinear 'turbulent' interactions which couple waves together and cause energy to flow. . . ."

which couple waves together and cause energy to flow—generally from long wavelengths to short, but sometimes the other way around. Some of these coupling processes have also been simulated numerically, using large computers. (See the graph on the front cover.) These simulations then provide a way of doing "experiments" in the ionosphere to test our understanding of the physics. Conversely, the ionosphere provides a "clean" laboratory for testing simulation algorithms that may then be used to study the more complicated problems of high-energy plasmas.

Another interesting class of plasma instability is observed at the equator at higher altitudes, usually above 300 kilometers. These are much the same as the instability that develops at the interface when a heavy fluid is on top of a lighter one. The smallest ripple will grow, steepen, and develop fingers in which the heavier fluid flows downward until it is all below the lighter one, or, from another viewpoint, the lighter fluid bubbles up through the heavier one.

In the equatorial ionosphere, regions of low-density plasma bubble up through denser plasma above and, as the bubbles rise, all sorts of small-scale "froth" develops on the sharp edges. It is this froth that the radar sees. The physics of the froth is of interest in itself; in addition, the froth acts as a tracer to reveal the large-scale structure. The observed wavelengths range from hundreds of kilometers to a few centimeters.

Both the low-altitude and the high-altitude instabilities were studied intensively in Peru in 1983 in a joint radar and NASA rocket campaign in Peru that was organized through a Cornell initiative. By making use of real-time displays of the radar data, we were able to launch the rockets into particularly interesting events. The simultaneous rocket and radar observations provide far more information than either could alone. And here again, numerical simulations are becoming an important research tool.

SWEDEN'S VIKING SATELLITE: A COOPERATIVE VENTURE

Since the 1960s, members of the Cornell Space Plasma Physics group have collaborated with Swedish scientists, to the benefit of both research programs. For example, when Sweden decided to build its first satellite in 1981, we were asked to participate in the design, and this gave us an opportunity to launch into space a Cornell experiment.

The instrument was the first plasma wave interferometer, a device that enabled us to measure wavelengths directly rather than deducing them from point measurements taken on a satellite. The indirect method is not easy to accomplish when the satellite is moving at a velocity comparable to that of the waves, whose velocity and direction of propagation are unknown.

The Swedish Viking satellite was launched successfully in 1986 and so far the quality of the data has been excellent, exceeding all expectations. Cornell scientists have participated in the field operations in Sweden and are now digging into the data.

PERFORMING ACTIVE EXPERIMENTS IN SPACE

In recent years it has become possible to perform active experiments in space. The idea is to perturb the medium with a chemical release, or perhaps with powerful radio waves, and watch what happens.

Cornell scientists participated in an attempt to trigger the aurora by disturbing part of the magnetosphere so that it would dump some of its trapped high-energy particles into the lower ionosphere. A plasma jet was launched from a rocket, and we believe that this initiated a train of events. Waves excited by the plasma jet (Alfvén waves) traveled up into the magnetosphere until they reached a location where they interacted strongly with trapped particles, some of which were accelerated and then precipitated into the lower ionosphere: a complicated scenario, to be sure.

In another active experiment, an explosion generated plasma waves, which were detected by our small portable radar set up in Florida. The waves were not where we expected them to be, however, and we are now trying to solve the puzzle. It appears to be related to the generation of Alfvén waves and their propagation away from the explosion.

Experiments in which the space plasma is perturbed by powerful radio waves are performed regularly at Arecibo and at the observatory in northern Norway, and Cornell faculty members and graduate students have been active at both locations. When the impinging radio waves are strong enough, the resulting electron motions are so large that nonlinear effects are important, and the interactions become exceedingly complicated and interesting. Similar interactions are important in laser fusion experiments, in which the object is to heat a small pellet to fusion temperature with intense laser irradiation. Since the ionospheric interactions are considerably less violent and take place more slowly, it is a little easier to sort out what is going on.

Recently the Cornell group developed a new and very ingenious way to improve the spatial resolution of the radar diagnostic techniques used in these experiments. Not surprisingly, the technique has revealed some new phenomena that we do not yet understand. In particular, we sometimes apparently see "cavitons", small depleted regions.

OUT IN SPACE, AROUND THE GLOBE, AND INDOORS AT HOME

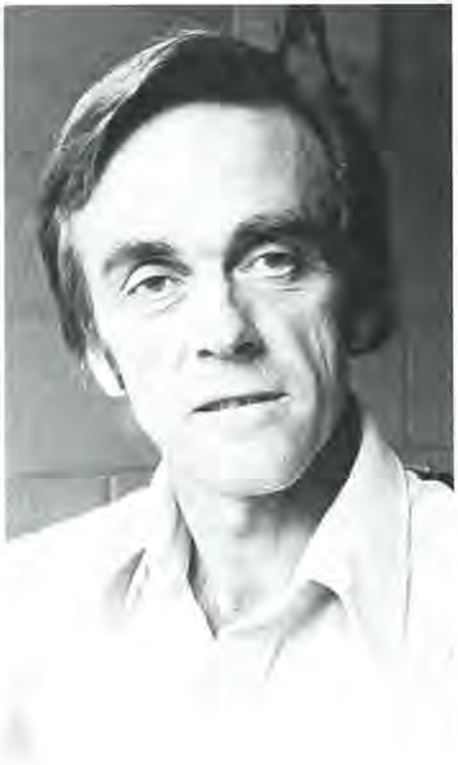
Our research program grows increasingly varied and exciting.

The radar, rocket, and satellite experimental programs will continue to take us all over the globe, from Antarctica in the south to Sweden, Norway, Greenland, Alaska, and Canada in the north.

On the theoretical side, we anticipate growing emphasis on nonlinear problems and the physics of plasma turbulence. We hope to improve our already close ties with the "indoor" plasma program at Cornell; the recent move of our offices to the new Upson Hall addition, above the LPS offices, should encourage more informal contact.

Computer simulation promises to become more important in our research, and we expect to make good use of the advanced facilities available at the new national supercomputing center at Cornell.

As we prepare to participate in the twentieth anniversary of the Laboratory of Plasma Studies, we find that looking back on years of achievement is gratifying, but looking ahead—and up—is better.



Donald T. Farley is a professor of electrical engineering and also a Cornell alumnus—he earned a bachelor's degree in engineering physics in 1956 and a doctorate in 1960.

Before joining the faculty in 1967, he spent a year at Cambridge University in England, a year at Chalmers University in Sweden, and six years as a physicist and then director of the Jicamarca Radio Observatory in Peru. (For his work at Jicamarca on incoherent scattering of radio waves, he received the Gold Medal of Merit from the United States Department of Commerce.) He returned to Sweden in 1985–86 as a visiting professor at the Uppsala Ionospheric Observatory.

Farley is a senior member of the Institute of Electrical and Electronics Engineers and a member of the American Geophysical Union, the International Scientific Radio Union (URSI), and the American Association for the Advancement of Science.

BLACK-HOLE PUMPS

by Richard V. E. Lovelace

With the recent rapid development and improvement of astronomical instruments, spectacular physical phenomena not anticipated theoretically have been seen and analyzed. Photons from distant astronomical objects can be detected and imaged at frequencies ranging from the radio ($\lesssim 10^7$ hertz) to the gamma-ray (10^{27} hertz). The new information greatly enhances the possibilities for theoretical work.

During the past decade, part of my research in plasma theory has been concerned with plasma phenomena in active galaxies. Problems suggested by observations of such galaxies have been the subject of doctoral research by eight of my graduate students. We are trying to understand and model observed phenomena such as the narrow plasma jets associated with black holes.

ACTIVE GALAXIES AND THEIR BLACK HOLES

Typical galaxies are made up of a diffuse distribution of stars, gas, plasma, and dust spread out over a region of many thousands of parsecs (1 parsec $\approx$ 3 light years $\approx 3 \times 10^{18}$ centimeters). The matter is, of course, held together by gravitational attraction.

A small percentage of galaxies are *active galaxies*, which exhibit spectacular phenomena involving an enormous power output from a tiny central region. The size of this nuclear region is comparable to that of our solar system (about 10^{14} centimeters), and the power output (more than 10^{47} ergs per second or 10^{40} watts) is larger in some cases than that of many thousands of normal galaxies. A wide variety of activity has been catalogued, and the taxonomy includes quasars (most of which are at extremely large, cosmological distances), Seyfert galaxies, BL-Lac objects, and radio galaxies.

The power output of a typical active galaxy is in broadband electromagnetic radiation covering the radio, infrared, optical, ultraviolet, x-ray, and gamma-ray bands. The source of the power is now generally thought to be the gravitational accretion of matter by a massive *black hole* at the center of the galaxy. (The term derives from the fact that not even light can escape because of the strength of the gravitational field.)

The basic idea of power from an accreting black hole is simple: A rock dropped from a tall building gains kinetic energy in falling, while its gravitational energy becomes more negative; on impact, the kinetic energy is released as heat. Correspondingly, in the accretion of matter by a black hole, clumps of infalling matter collide with each other and heat up before disappearing into the black hole. Processes that may lead to the formation of massive black holes are now under study at Cornell by Professors Stuart L. Shapiro and Saul A. Teukolsky.

The black-hole masses are deduced to be in the range of 100 million to 1,000 million solar masses (the solar mass is about 2×10^{33} grams); the rate of accretion can be as large as one to ten solar masses per year. A variety of observations suggests that a smaller black hole, about 10^6 solar masses, is at the center of our galaxy.

The heating up of galactic matter as it moves toward the black hole is limited by radiation; $T \sim 10^5$ K. But while radiation easily carries off energy, it carries off only a tiny amount of angular momentum, and the distributed matter in a galaxy—stars, gas, plasma, and dust—usually has at least a small amount of net angular momentum about some axis—say, $\mathbf{L} = L_z\mathbf{z}$. In order for the matter to continue to move inward,

Figure 1

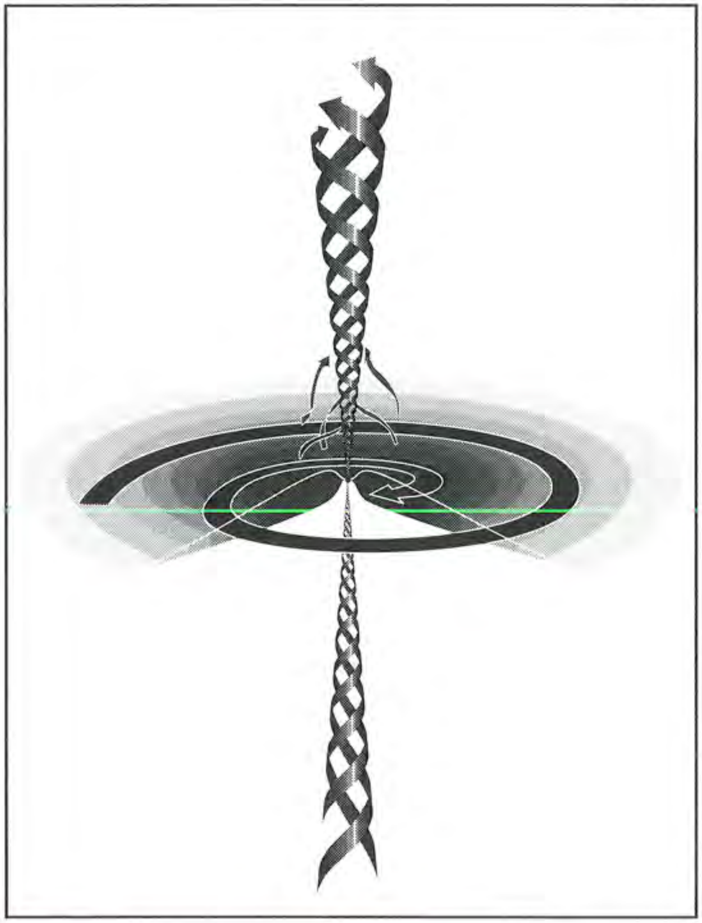


Figure 1. The geometry of a central engine of a galaxy. The features shown are the central black hole, the surrounding accretion disk, and the outward-propagating (±z) jets. The twisting lines on the jets represent magnetic field lines.

Figure 2

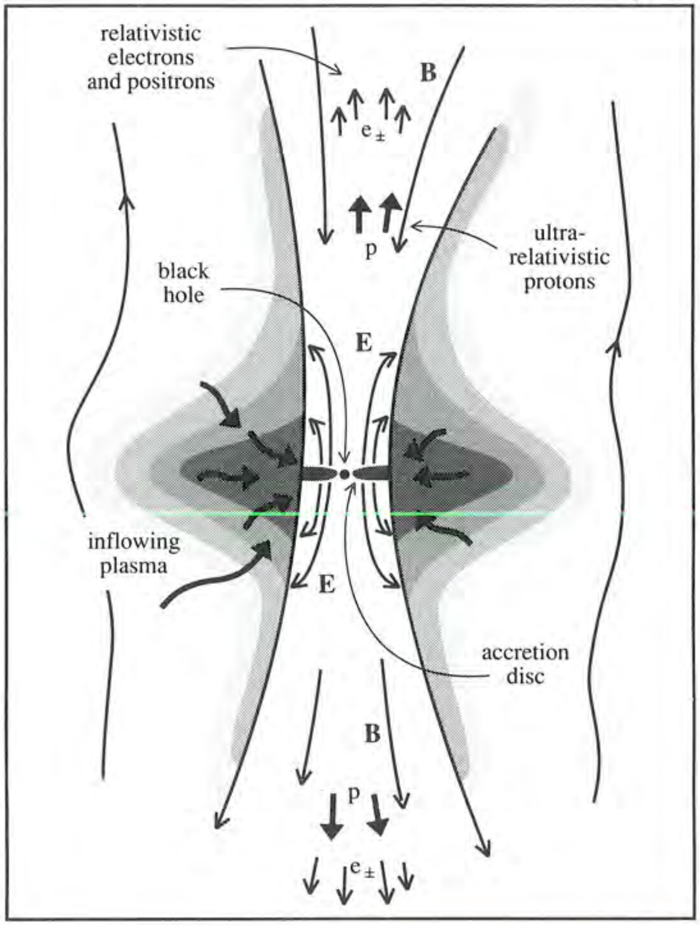


Figure 2. A schematic drawing of an electrodynamic black-hole pump. (Adapted from the author's article in Nature *262:649, 1976.)*

some of that angular momentum must be lost—that is, transported outward. This loss could occur as a result of turbulent viscosity in the flow or as a result of electromagnetic field stresses (discussed below).

Because of the angular momentum, the accreting matter takes on a disk-like configuration (see Figure 1).

PLASMA JETS AND BLACK-HOLE PUMPS

The remarkable properties of active galaxies go well beyond their high power and small size. In some cases, the nuclei of these galaxies produce collimated jets—single or oppositely directed—of high-velocity plasma. An accreting black hole that also produces jets has been referred to as a *black-hole pump*.

The jets are seen at radio and sometimes optical and x-ray frequencies, and this emission is believed to be synchrotron radiation from a low-density population of highly relativistic electrons (and possibly also positrons). The particles have Lorentz factors of about 10^3 and move in a weak magnetic field ($\sim 10^{-5}$ gauss).

Sometimes, the jets show a spectacular collimation maintained over enormous distances, of the order of mega-parsecs. This corresponds to jet lifetimes longer

PHYSICAL DOMAINS IN PLASMA PHYSICS

by Richard L. Liboff

Do the plasma in the sun's core and the electron-conduction plasma in a semiconductor behave in the same way?

This question is both fundamental and practical, for plasma physics plays a role in a vast area of natural phenomena and in many engineering devices. Understanding the cosmos, or designing a computer chip or a thermonuclear fusion reactor, requires first of all a realization of equations of motion that are appropriate to the particular problem.

As an elementary example, consider a free macroscopic particle compared to the electrons around the nucleus of an atom. The free particle obeys Newton's laws of motion; the motion of the electrons is quantum mechanical, described by the Schroedinger equation.

Similar physical differences occur in engineered structures. The plasmas in most thermonuclear fusion devices are basically like the plasma in the core of the sun: weakly coupled and classical—that is, obeying Newton's laws and Maxwell's equations. The conduction electrons in a semiconductor, on the other hand, obey the laws of quantum mechanics.

Figure 1

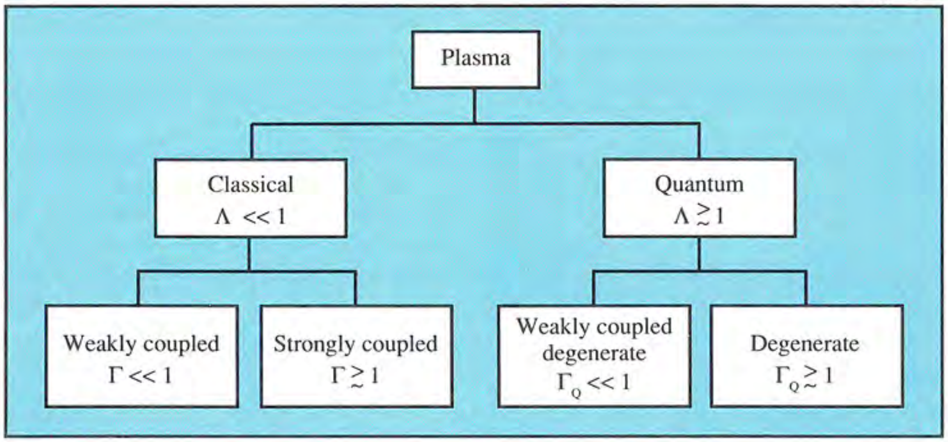


Figure 1. The division of plasma domains according to the quantum degeneracy parameter Λ. In all domains different equations of motion apply.

The pertinent parameters are the plasma parameter Γ and the quantum plasma parameter Γ_Q.

CHARACTERIZING PLASMAS: CLASSICAL OR DEGENERATE?

In classifying the various domains of plasma physics (see Figure 1), the first division is into *classical* or *quantum* (also called *degenerate*) domains.

The separation of these domains is given in terms of the quantum degeneracy parameter, Λ:

$$\Lambda = n\lambda_d^3 \qquad (1)$$

where n is the number density of charge carriers in the plasma, and λ_d is the thermal deBroglie wavelength:

$$\lambda_d^2 \equiv \frac{h^2}{2\pi m k_B T}\,. \qquad (1a)$$

Here h is Planck's constant, m is the charge-carrier mass, and T is temperature.

STRONG VERSUS WEAK COUPLING

In strongly coupled plasmas, the mean interparticle potential energy dominates the mean particle kinetic energy. In weakly coupled plasmas, it is the kinetic energy that dominates.

The mean Coulomb interaction energy in a plasma may be written (here and hereafter all formulas are written in cgs units):

$$\langle V \rangle \simeq \frac{e^2}{a} \tag{3}$$

where a^3 is a measure of the mean occupation volume per particle. In terms of n, the number density of charge carriers:

$$\frac{4}{3}\pi a^3 = n^{-1}. \tag{3a}$$

Mean particle kinetic energy is given by

$$\langle E_K \rangle \simeq k_B T. \tag{4}$$

Thus, when $\langle V \rangle << \langle E_K \rangle$, particles in the plasma become statistically independent and the plasma is termed *weakly coupled.*

The plasma parameter Γ (see Figure 1) is related to the preceding variables:

$$\Gamma^{\frac{2}{3}} \simeq \frac{\langle V \rangle}{\langle E_K \rangle}. \tag{5}$$

Substituting (3) and (4) into this equation gives:

$$\Gamma = (a/\bar{\lambda}_D)^3 \propto \frac{1}{n\lambda_D^3} \tag{6}$$

where

$$\bar{\lambda}_D = \left(\frac{k_B T a^3}{e^2}\right)^{\frac{1}{2}} \tag{7}$$

represents the Debye distance. The canonical expression of λ_D is given by

$$\lambda_D^2 = \frac{k_B T}{4\pi n e^2}. \tag{7a}$$

With reference to (6) one often says that a plasma is weakly coupled if there are many particles in a Debye sphere.

Our criteria for strongly and weakly coupled plasmas may be written

$$\Gamma << 1 \quad \underline{\text{Weakly coupled}} \tag{8a}$$

$$\Gamma \gtrsim 1 \quad \underline{\text{Strongly coupled}} \tag{8b}$$

The criteria are that a plasma obeys classical physics if

$$\Lambda << 1 \quad \underline{\text{(Classical)}} \tag{2}$$

and it is degenerate if

$$\Lambda \gtrsim 1 \quad \underline{\text{(Quantum)}} \tag{2a}$$

The physical meaning of these criteria is that the plasma is classical if the mean distance between charge carriers ($n^{-1/3}$) is large compared to the deBroglie wavelength, but that quantum physics comes into play when these quantities are of the same order.

In the case of the sun's core region, which is predominantly a hydrogen plasma, $T = 1.5 \times 10^7\ °K$, and $n = 9.44 \times 10^{25}$ cm^{-3}; accordingly, we find that Λ has a value of about 0.09 for the electron plasma, and is even less for the proton plasma. We may conclude that the plasma in the core of the sun is nondegenerate.

The situation in n-type GaAs is quite different. The concentration n is about 10^{17} cm^{-3}, and Λ turns out to be about 0.77. We may conclude that in this case the charge-carrier plasma is degenerate, obeying quantum mechanical laws.

STRONGLY COUPLED VERSUS WEAKLY COUPLED PLASMAS

Whether a medium is strongly or weakly coupled depends on the relation between the mean potential and kinetic energies.

When the potential energy between particles dominates, the plasma is strongly coupled; when kinetic energy dominates, the plasma is weakly coupled. The distinction is expressed in terms of the plasma parameter, Γ: if $\Gamma << 1$, the plasma is weakly coupled, and if $\Gamma \gtrsim 1$, it is strongly coupled. The mathematical development is shown in the chart.

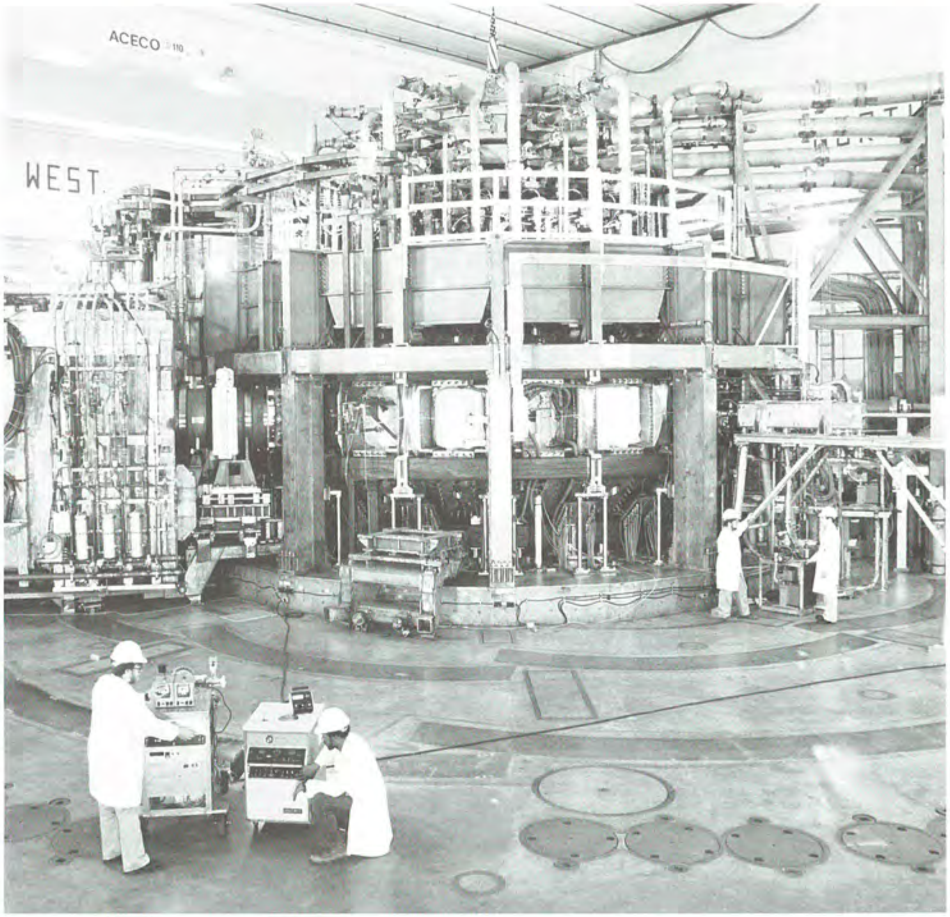
In the case of the sun's core, for example, a calculation gives $\Gamma = 0.04$. In spite of the very high density, the extreme temperature renders the plasma not only classical, but weakly coupled, like a rare gas. Neutron stars, on the other hand, are extremely dense (10^{15} g/cm^3 compared to 10^2 g/cm^3 for the core region of the sun) and are purely degenerate.

In thermonuclear fusion devices also, the extreme temperatures make the plasmas weakly coupled and classical. An exception is the plasma in laser or ion-beam implosion devices; there the extreme density renders the plasma degenerate.

Two examples of weakly coupled, classical plasmas are those in the interior of the sun and those in most thermonuclear fusion devices.

The experimental reactor shown in the photograph below is the Tokamak Fusion Test Reactor at Princeton University.

"In spite of the very high density [of the sun's core], the extreme temperature renders the plasma not only classical, but weakly coupled. . . . Neutron stars, on the other hand, are extremely dense . . . and are purely degenerate."



WEAKLY COUPLED AND DEGENERATE

To apply to solid-state plasmas, we write the expression for the Coulomb interaction energy in terms of the dielectric constant ϵ:

$$\langle V \rangle \simeq \frac{e^2}{\epsilon a}. \tag{9}$$

We wish to consider the ratio of the mean potential energy (9) to mean quantum uncertainty energy

$$\langle E_Q \rangle = \frac{\hbar^2}{m^* a^2} \tag{10}$$

where m^* denotes effective mass. Constructing the said ratio gives:

$$r_s \equiv \frac{\langle V \rangle}{\langle E_Q \rangle} = \frac{a}{a_o} \tag{11}$$

where a_o is the effective Bohr radius

$$a_o = \frac{\epsilon \hbar^2}{m^* e^2}. \tag{11a}$$

Substituting (3a) and (11a) into (11) gives the explicit form:

$$r_s = \left(\frac{3}{4\pi}\right)^{\frac{1}{3}} \frac{me^2}{\epsilon h^2 n^{\frac{1}{3}}}. \tag{12}$$

Thus we have the criterion:

$r_s \lesssim 1$ Weakly-coupled degenerate. (13)

An alternate description of a weakly coupled degenerate plasma is given in terms of the Thoms-Fermi length:

$$\lambda_{TF} = \left(\frac{\epsilon E_F}{6\pi n e^2}\right)^{\frac{1}{2}} \tag{14}$$

where

$$E_F = \frac{\hbar^2}{2m^*}(3\pi^2 n)^{\frac{2}{3}} \tag{15}$$

is the Fermi energy. Introducing the quantum plasma parameter

$$\Gamma_Q^2 = \left(\frac{8}{3\pi}\right)^2 r_s^3 \tag{16}$$

permits the equality

$$\Gamma_Q = \frac{1}{6\pi n \lambda_{TF}^3}. \tag{17}$$

This identification is seen to be analogous to the classical plasma parameter Γ given by (6). Thus we may write the criteria

$\Gamma_Q << 1$ Weakly-coupled degenerate (18*a*)

$\Gamma << 1$ Weakly-coupled classical (18*b*)

WEAKLY COUPLED DEGENERATE PLASMA

Since the quantum degenerate parameter Λ is proportional to the number density n, it is evident that at a given temperature, a plasma will grow degenerate with an increase in number density.

At extreme values of n, another phenomenon comes into play: the degenerate medium becomes weakly coupled. This occurs because kinetic energy associated with uncertainty in momentum grows large with a decrease in interparticle spacing, thereby overcoming the interaction energy between particles.

This has a bearing on solid-state plasmas. In many semiconductors, the effective mass, m^*, is less than the actual particle mass, m, and the dielectric constant, ε, is greater than 1. In such cases, the quantum plasma parameter, Γ_Q, may be less than unity at standard conditions (see the chart). An example is the semimetal bismuth, for which $n = 10^{18}\,\text{cm}^{-3}$, $\varepsilon = 10^2$, and $m^* = 0.1\,m$. These values give $\Gamma_Q = 0.1$, which indicates that the plasma is weakly-coupled degenerate.

COLLECTIVE PLASMA BEHAVIOR

Collective motion of a plasma is described in terms of the plasma frequency ω_p:

$$\omega_p^2 = \frac{4\pi n e^2}{m}. \tag{19}$$

Note the useful relation

$$\omega_p^2 \lambda_D^2 = C^2 \tag{19a}$$

where C is the thermal speed

$$mC^2 \equiv k_B T. \tag{19b}$$

Let ν denote the dominant collision frequency of plasma constituents. When

$$\nu >> \omega_p \tag{20}$$

the plasma acts fluid dynamically.

Figure 2

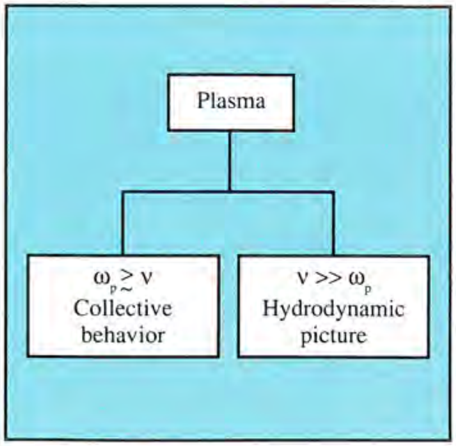


Figure 2. The division of plasmas into collective and fluid dynamic domains according to the plasma frequency ω_p, and the collision frequency ν.

BEHAVIOR AS A FLUID OR AS A COLLECTIVE PLASMA

Another useful way of classifying plasmas is according to whether they behave collectively or as a fluid. This classification is depicted in Figure 2.

The difference shows up in the way the plasma reacts to a disturbance. If a plasma is in the collective domain, it oscillates collectively when it is perturbed. In the fluid domain, perturbation results in hydrodynamic-type waves.

Mathematically, the situation is expressed by the relation between ν, the frequency with which collisions between plasma constituents occur, and ω_p, the frequency of the collective motion of the plasma (see the chart). When ω_p is greater than or about the same as ν, the plasma behaves collectively, but when ν is much greater than ω_p, collisions diminish collective plasma behavior and fluid phenomena occur.

Figure 3

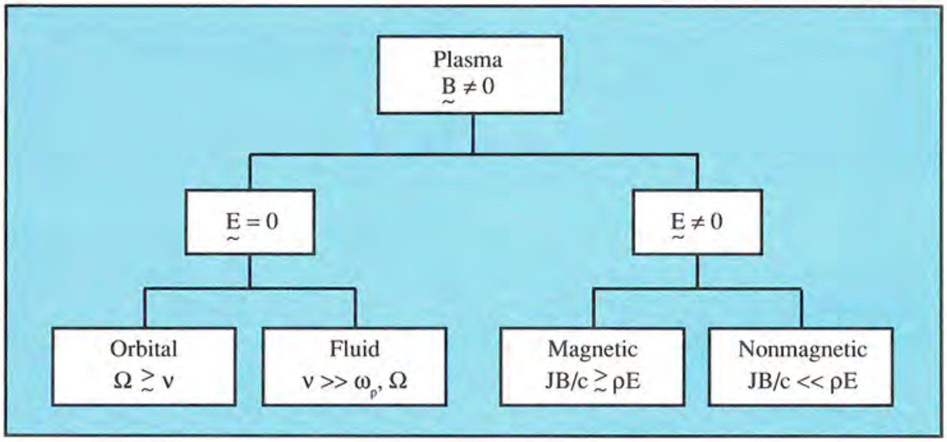


Figure 3. The division of plasma domains for plasmas immersed in electric (E) and magnetic (B) fields. The determining parameters are plasma frequency ω_p, collision frequency ν, Larmor frequency Ω, and charge density ρ. J is the current density and c is the speed of light.

THE INFLUENCE OF A MAGNETIC FIELD

If a magnetic field permeates the plasma, additional criteria come into play. What happens depends on whether or not there is also an electric field present and on the relative strength of the fields.

A plasma under the influence of a magnetic field has orbital motion if the Larmor frequency, Ω, of particles is greater than the collision frequence ν. But if ν is much greater, the circular motion is lost to collisions and the motion is fluid-like. Furthermore, fluid dynamics is observed in a plasma if ν is much greater than ω_p, the plasma frequency. Plasmas with $\nu \gtrsim \Omega$ are typically called magnetohydrodynamic (MHD).

When an electric field is also present, the criteria for magnetic and nonmagmetic plasmas involve, in addition, the current density and the electric field strength.

Figure 3 summarizes the situation and the accompanying chart gives the pertinent equations.

Below: The earth, a sphere with a magnetic field, might look like this if it were photographed as it moves through the plasma emitted by the sun. Actually, the photograph—taken in a Cornell laboratory—is of a small sphere moving through plasma at supersonic speed, where magnetohydrodynamic equations apply.

The experiment was part of a study of shock waves in plasma, conducted in the 1960s by Dale B. Henderson, a graduate student in aerospace engineering who was working with Professor Edwin L. Resler, Jr. A possible application of research of this kind is in the design of reentry vehicles.

MAGNETOHYDRODYNAMICS

In a magnetic field a free particle of charge *e* and mass *m* undergoes circular motion at the *Larmor frequency*

$$\Omega = \frac{eB}{mc} \qquad (21)$$

where *B* is the magnetic field and *c* is the speed of light. But in a plasma the motion is fluid-like if the collision frequency $\nu >> \Omega$ or if $\nu >> \omega_p$ (the plasma frequency).

If an electric field *E* is also present, then Ohm's law is written

$$\mathbf{J} = \sigma[\mathbf{E} + \frac{\mathbf{J} \times \mathbf{B}}{\rho c}] \qquad (22)$$

where J is current density, σ is conductivity, and ρ is charge density. The latter relation implies the following criteria for a nonmagnetic plasma:

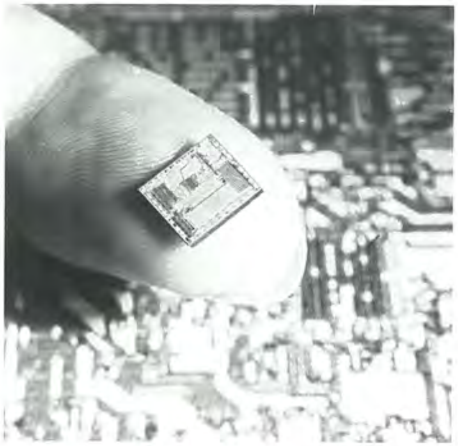
$JB/c << \rho E$ Nonmagnetic plasma (23)

MACROSCOPIC EQUATIONS IN QUANTUM PLASMAS

A question relevant to work with some kinds of quantum plasmas, including those in semiconductors, is under what circumstances it is appropriate to use classical macroscopic equations.

The answer may be found in an early work of Irving and Zwanzig in which classical macroscopic equations of motion were shown to follow from a purely quantum mechanical formulation. It was established that equations of continuity, momentum transport, and energy transport maintain their classical structure in the degenerate domain. This is akin to Ehrenfest's principle, which states that classical dynamical equations result when expectations are constructed of corresponding equations in quantum mechanics.

There is one contingency, however: Macroscopic equations for mean values are



When dimensions are very small, a full quantum analysis is necessary to describe transport properties in microdevices.

meaningful only if fluctuations away from the mean values are small compared to the mean. This observation is particularly relevant to submicron devices. Take gallium arsenide, for example. It was recently demonstrated by the author that classical macroscopic equations apply only under certain conditions. For example, for a cubical sample of n-type GaAs of volume L^3 at room temperature, classical macroscopic equations apply provided that $L > 0.15$ micrometer. If this criterion is violated, a full quantum analysis is necessary to describe the dynamics of the device.

As this example illustrates, the first requirement in all work with plasmas is to establish which equations apply. The success of design and analysis in applications ranging from semiconductor devices to schemes for thermonuclear fusion reactors depends on getting this fundamental picture right.

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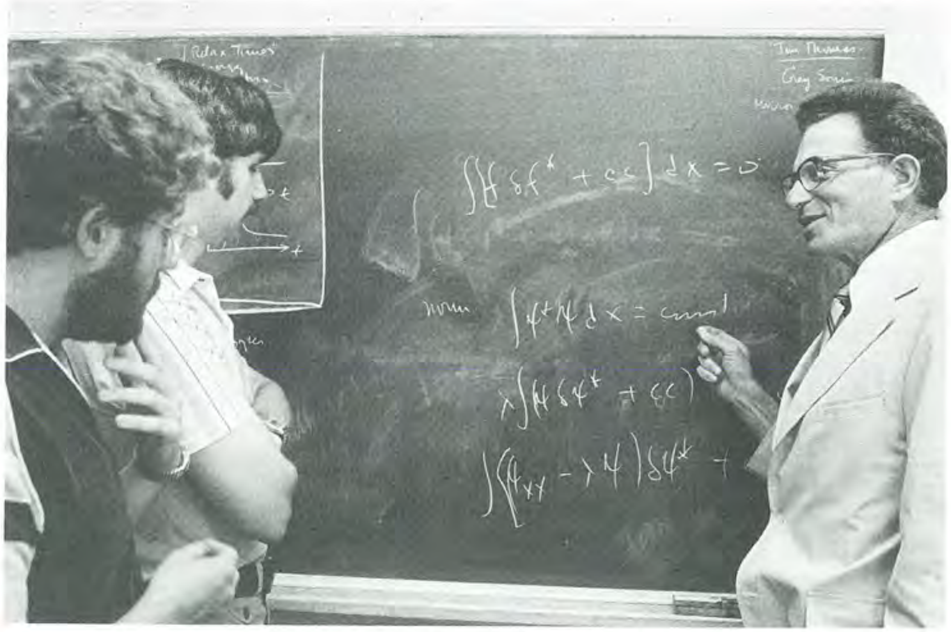
His present research is in two fields. One study, concerning the theory of strongly coupled matter, is relevant to so-called recombination x-ray lasing, as well as to plasmas encountered in electromagnetic propulsion devices.

The second investigation concerns the kinetic theory of charge transport through a semiconductor in the presence of very large electric fields. Such work is directly related to the design of micro field-effect transistors. This research is supported by the Army Research Office.

Liboff's publications include textbooks in the areas of waveguides, kinetic equations, and quantum mechanics. A sixth printing of the quantum text is soon to be issued by Addison-Wesley, and a new work on kinetic theory is to be published by Prentice-Hall.

Liboff holds the A.B. degree from Brooklyn College and the Ph.D. from New York University, where he taught for three years before coming to Cornell in 1964. He has been a visiting professor at the Université de Bruxelles, the Université de Paris—Centre d'Orsay, and Tel Aviv University, and has held Fulbright and Solvay fellowships. He is a fellow of the American Physical Society and a senior member of the Institute of Electrical and Electronics Engineers.

Below: Professor Liboff confers with two of his graduate students—Brian Jones (at left), who is now with the Peace Corps in Africa, and Ken Gardner, who is now in his last year of Ph.D. study.



A GREAT SEND-OFF FOR DECADE 3 AT CORNELL'S LAB OF PLASMA STUDIES

It was a time for reminiscence and for greeting old friends and colleagues. It was a time for taking stock of plasma physics today, and where it may be heading. And it was a time for thinking about the science and the technologies in the context of national and international events and priorities. It was the Symposium on Plasma Physics in the 1990s, held on campus October 15 and 16 in celebration of the twentieth anniversary of Cornell's Laboratory of Plasma Studies (LPS).

One participant, a researcher with fifteen years of experience in working on fusion-reactor experiments, commented that he particularly enjoyed the chance to "wipe the grease off my hands and contemplate the large picture of plasma physics." A young Ph.D.who is teaching at a nearby college said she had come mainly to absorb and discuss some "real physics." On his way outside into the sunny October splendor with his box lunch, another visitor remarked that this convocation was unusually eclectic for a scientific meeting—refreshing, stimulating, *great.*

The one hundred or so participants came from all over the United States and from five foreign countries. They included Cornell faculty members and graduate students; people who had been at LPS for some period during the past two decades or who had helped start it up or keep it going; and representatives of national, industrial, and university laboratories, some of whom have interacted over the years with the Cornell program.

The first two directors of LPS, Peter Auer and Ravi Sudan, were there, of course. So were many of the people they mentioned in their accounts (the first two articles in this volume) of the first two decades. These visitors included J. C. ("Charlie") Martin of Britain's Atomic Weapons Research Establishment, and Chiyoe Yamanaka of Osaka, Japan, who directs the largest laser-beam fusion program outside the United States.

The roster of speakers included many of the world's leaders in plasma research. How did LPS manage to get so many top people to give talks? one delegate asked David Hammer, the current director, who organized the symposium. "We simply called them up and asked them and they said yes," Hammer replied.

The symposium opened with remarks by Joseph Ballantyne, Cornell vice president for research and advanced studies, and proceeded to a session on the current status of pulsed-power technology and plasma physics and their prospects for the 1990s.

Alan Kolb, chairman and CEO of Maxwell Laboratories, Inc., surveyed the evolution of the technology in the areas of magnetic-confinement fusion, inertial fusion, and simulation, and made some assessments of future applications in power production, weapons development, and space technology. Kolb is well known at Cornell; he fostered the establishment of the LPS while he was at the U.S. Naval Research Laboratory, and initiated a long-standing and continuing program of joint funding and research collaboration.

The second speaker was Norman Rostoker, professor at the University of California at Irvine, who had come to Cornell as one of the early faculty members in LPS. He discussed current efforts in the development of high-power beams and pulsed plasmas.

Marshall Rosenbluth, professor at the University of California at San Diego, talked about the physics of free-electron lasers, which he described as tunable, potentially highly efficient, and coherent from

Symposium participants included (1) LPS director David Hammer and Norman Rostoker from the University of California at Irvine. Photographed at registration and coffee breaks were (2) Sidney Ossakow of NRL and Gerhard Haerendel of the Max Planck Institute; (3) Cornell's Ravi Sudan and John Dawson of the University of California at Los Angeles; and (4) Charles B. Wharton of Cornell, Stephen O. Dean of Fusion Power Associates, and John Sethian of NRL.

The more than one hundred people at the banquet included (5) Chiyoe Yamanaka from Japan and David Crandall of DOE. Alan Kolb and Charlie Martin (6) were among those who reminisced about the early years of LPS. The banquet speaker (7) was Alvin W. Trivelpiece.

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microwaves to x-rays. Free-electron lasers, which will require advanced electron accelerators and optics, are likely to be the lasers of the future, he said, both for military applications and for fusion technology. Rosenbluth's association with LPS and Cornell has included a term from 1976 to 1982 as an Andrew D. White Professor-at-Large, an appointment regarded as one of the highest distinctions accorded by the university.

Applications of plasma physics to high-energy physics was the first topic that afternoon. John Dawson, professor at the University of California at Los Angeles, described how intense laser beams might generate extremely strong electric fields in a plasma. Such fields could be used to accelerate charged particles to the extremely high energy needed for particle physics experiments.

The status and prospects for the two main lines of fusion development were discussed by researchers from two of the nation's primary laboratories in these fields. John Lindl (a 1968 Cornell B.S. graduate) of the Lawrence Livermore National Laboratory talked about inertial confinement fusion research. Harold Furth, director of the Princeton Plasma Physics Laboratory, discussed progress with tokamaks. On the basis of recent results, both speakers presented optimistic outlooks for their respective approaches.

The question posed for a panel discussion, "Is There Life after Fusion for Plasma Physics?" was answered in the affirmative by the panelists. In addition to Yamanaka, the panelists were Thomas Antonsen, Jr. (who holds B.S., M.S., and Ph.D. degrees from Cornell) of the University of Maryland, George Miley of the University of Illinois, and Gerhard Haerendel of the Max Planck Institüt für Physik und Astrophysik. Sudan served as moderator. The discussion was both broad and technically specific, bringing out strengths and needs in the scientific and technological areas.

The needs, Rosenbluth commented, include "another generation after the pioneers, people who can sell dreams." Others pointed out the need for recognition that plasma physics is not confined to controlled-fusion technology, which has been the "main engine" driving the research. Space exploration could be the leading motivation in the coming decade.

Space plasma physics was, in fact, the general topic at the Friday morning session. Haerendel talked about plasma physics of the aurora borealis, illustrating features of the beautiful and dynamic phenomenon with slides and a video tape. Although auroral plasma acceleration occurs so close to Earth and is so intriguing, he said, it is not well understood. Few appropriate measurements have been made, either in the source region or in the "fracture zone" where the particles precipitate and create the visible display. He described a multinational project, IMPACT, planned for 1993, in which the Soviets are to launch two satellites instrumented by Western scientists. The project is supported by Russia, the United Kingdom, West Germany, and the United States (though not through NASA). Cornell's experimental group in space plasma physics (headed by Professors Donald Farley, Michael Kelley, and Paul Kintner) have been invited to participate in the project.

A talk on plasma astrophysics was given by Edwin Salpeter, Cornell physics professor, who effectively expanded the scope of the symposium to considerations of galaxies as well as atomic nuclei and time scales of millions of light years as well as trillionths of a second.

The final presentation brought the symposium to earth with an address by Gerold Yonas (a 1962 Cornell graduate) that focused on the Strategic Defense Initiative, for which he was chief scientist for eighteen months. Yonas, who is now president of Titan Technolgies, Inc., also spent many years at Sandia National Laboratories as head of the pulsed power directorate (and in that capacity worked closely with LPS). The pertinent question about SDI, he said, is not whether it will work—as he is often asked—but what *is* it? Is it an astrodome, a bargaining chip, a military plan, a military-industrial scheme for profit, or what? He recommended that SDI be broken up into components for separate assessment and development, and he called for more interaction among universities, industry, and government, perhaps through consortia.

National and international politics as they impinge on scientific research was a theme also of the dinner address on Thursday evening. Alvin W. Trivelpiece, executive officer of the American Association for the Advancement of Science, described some background workings of the Reagan-Gorbachev summit at which groundwork was laid for cooperative work on fusion. Trivelpiece was at the Department of Energy from 1981 until this year. The banquet, the social highlight of the conference, also included reminiscences of the early days of LPS.

A tour of LPS facilities wound up the events on the final afternoon, and attention turned from the past to the present and the future. The consensus was that the third decade of plasma studies at Cornell promises to be as eventful and significant as the first two.—GMcC