



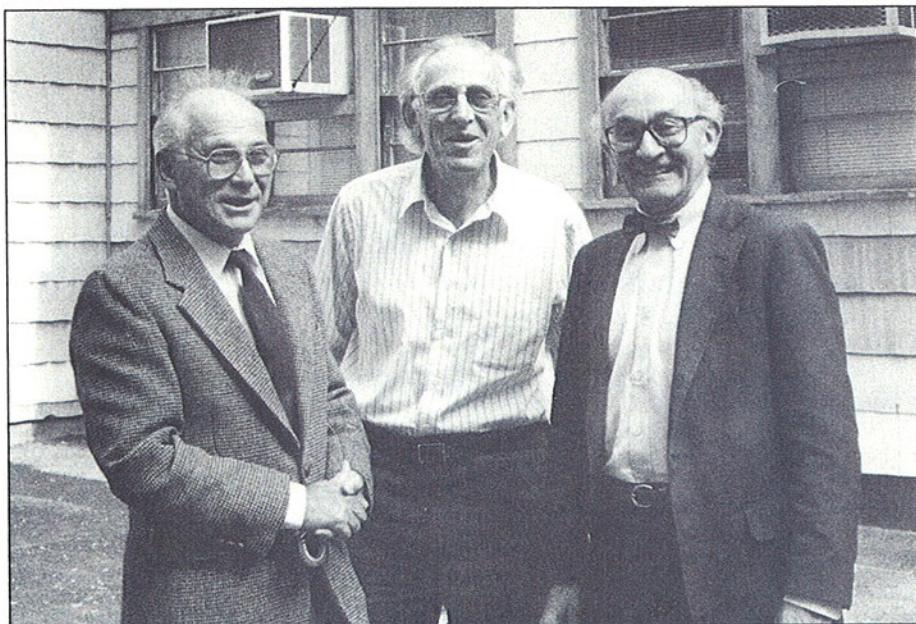
# RLE

# currents

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The Research Laboratory of Electronics at the Massachusetts Institute of Technology

## Discovering the Universal Importance of Plasmas at RLE



*Senior faculty members of RLE's Plasma Physics Group reunite where it all began—at MIT's Building 20. With almost a century of MIT experience between them, Professors Bruno Coppi, George Bekefi, and Abraham Bers take a moment to reflect on the group's success and what is still to come in plasma science research. (Photo by John F. Cook)*

In our universe, it is estimated that plasmas make up 99% of all the states of matter. The plasma state is most abundant in space, where interstellar and galactic plasmas comprise many of the stars and other heavenly phenomena in this and other galaxies. The sun (itself a star) is literally a hotbed of plasma activity with its seemingly limit-

less heat and light energy generated by potent atomic fusion reactions.

Sunspots, solar prominences and flares, and the solar wind are all products of the sun's fusion process that affect the Earth's environment 150 million kilometers away. While the Earth's ionosphere is most sensitive to solar activity, our magnetosphere and its

Van Allen belts also provide a rich geomagnetic environment for plasma activities that are visible in spectacular light and thermal energy reactions, including lightning bolts and breathtaking atmospheric auroras. Spaceborne objects entering Earth's atmosphere, such as space vehicles and satellites, also generate plasmas hot enough to melt their surfaces.

On Earth itself, plasma activity can be observed in the flames of a fire and from the glow of man-made neon and fluorescent lights. Imitating the sun's generation of powerful and abundant fusion energy on Earth has been the focus of many basic scientific studies and complex experiments since the start of the nuclear age. These investigations continue as both theorists and experimentalists seek to overcome the formidable difficulties associated with extremely high-temperature plasmas necessary to achieve one of the principal goals of plasma physics research—to create a thermonuclear fusion reactor that will produce electricity and serve as a source of plentiful energy.

### From Gas to Plasma

The heating of a solid or liquid substance leads to events known as *phase transitions*. Molecules or atoms with enough energy to overcome what is called the *binding potential* will evap-

*(continued on page 2)*

## Director's Message

Plasma physics is an excellent example of the evolution of research focused within a particular field over the life of RLE. Interest in plasmas started in MIT's Radiation Laboratory with a strong emphasis on gas discharge tubes and their use in radar. Over the years, a great deal of theoretical understanding and experimental characterization of plasmas has built up, ranging from large plasmas in space to those confined magnetically with a view toward future energy sources based on fusion. Exceedingly complex "codes" have been developed to facilitate the design of plasma confinement systems, and RLE has also used a small research tokamak to gain fundamental insight into plasma heating.

Recently, free-electron lasers have emerged as high-power, tunable sources in high-frequency regimes and new ideas for ignition in fusion reactors have been proposed. Not surprisingly, some plasma phenomena have been modeled using notions of chaos,



*Professor Jonathan Allen, Director  
Research Laboratory of Electronics*

and a detailed understanding of these nonlinear effects can be obtained and insightfully displayed with the use of today's powerful computing technology. The future will undoubtedly see the continued, rapid growth in the understanding of basic plasma phenomena and the aggressive application of this knowledge to a wide variety of both natural and synthetic systems.

### PLASMAS AT RLE

*(continued)*

orate. At temperatures hot enough to impart this energy to almost all particles, the substance then becomes a gas. Gas particles are in constant, random motion and follow the principles of Newtonian laws. Under normal conditions, gas particles travel at break-neck speeds (43,000 centimeters per second). The distance that each particle travels, or its *mean free path*, is interrupted only by collisions with other particles on the average of 5 billion times a second. The volume of all these moving particles is actually a small fraction of the space that the entire gas occupies. Because the parti-

cles are in constant motion, the gas takes up more space than if the particles were motionless. Forces, such as those due to magnetic fields, do not exist between the particles except when they collide. During these countless collisions, no energy is lost, but it can be transferred between particles. Thus, the energy distribution of the gas can change, but the total amount of energy stays constant.

Further heating of a gas results in additional transitions. For example, a molecular gas dissociates, or separates, gradually into an atomic gas (known as an inert or noble gas) if the thermal energy of some particles exceeds the molecular binding energy. An even more drastic change occurs as soon as the gas's temperature is high enough

for some of its electrons to overcome the atomic binding energy. The electrical bonds that hold the orbiting electrons in place are broken. Electrons escape from their orbits and the remaining central nuclei become ions. As the temperature increases, more atoms are stripped of their electrons until the gas is ionized and becomes a mixture of freely moving electrons and nuclei. The substance is now a plasma.

The transition from an un-ionized gas to a plasma occurs gradually as the temperature increases, beginning with a weakly ionized medium and progressing to a fully ionized substance composed of electrically charged ions and electrons. It is not strictly a phase transition in the usual thermodynamic sense (for example, water suddenly changing to steam), but the medium it creates has been referred to as the fourth state of matter.

A plasma does not behave like a solid, liquid, or cold gas. Unlike gases, which are electrical insulators, plasmas can conduct electricity, and their particles are free to interact or collide with



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any other particle. These novel properties stem from an internal force between a plasma's electrically charged particles; an electromagnetically repulsing Coulomb force that decreases gradually as the distance between the particles increases. Thus, a given particle can interact not only with its immediate neighbors, but also with many other particles that are far away. This so-called *collective behavior* is the basis for fascinating plasma phenomena. However, it is also the source of plasma instabilities, the uncontrolled and disruptive oscillations within a plasma, that remain a major challenge for scientists and engineers today.

### Gaseous Electronics

In 1879, Sir William Crookes was the first to use a glow discharge tube to study electrical effects in gases and the properties of gas particles. His discovery focused on the gas inside a glass tube that was partially evacuated and brought to a very low pressure. An electrical current was made to flow between two electrodes in the tube which broke the gas down into a rarefied gas that emitted a colorful glow. From his observations, Crookes proposed that the electrified gas was a fourth state of matter. The phenomenon in Crookes' tube was studied by many scientists who used weakly ionized glow discharges to probe the new field of gaseous electronics. The glow discharge tube also became the basic apparatus used in early plasma experiments and in early investigations of atomic structure.

In 1928, American physicist Irving Langmuir, working with gas discharge tubes and heated gases, observed a certain phenomenon in his experiments that he compared to the behavior of plasma in blood. His findings confirmed earlier scientific speculation on a fourth state of matter. By identifying these rarefied, glowing, electrically conducting gases, Langmuir introduced the term "plasma" for gases whose particles ionize at extremely high temperatures. Research in gaseous electronics was motivated by the need to develop vacuum tubes that could carry large currents. Today, plasmas of this nature are found in devices such as the mercury rectifier, the thyatron, fluorescent and neon lights, welding arcs, and radar transmit-receive tubes. In a fluo-

## Brief History of Plasma Physics at RLE

PERIOD	ACTIVITY	SOME "FIRSTS" AT RLE
1940s - 1950s	Microwave breakdown in gases  Gaseous electronics	First accurate measurement of electron-atom collision cross sections by microwave techniques
1960s	Wave propagation  Wave instabilities  Beam-plasma interactions and plasma heating  Radiation from plasmas  Gyrotrons (cyclotron masers)	New classification of waves in anisotropic plasma media First identification scheme for instabilities First systematic theory and experiments First quantitative measurements of bremsstrahlung and cyclotron emission; first complete theory First correct dispersion relation
1970s	Nonlinear wave-plasma interactions Relativistic magnetrons Plasma turbulence	First nonlinear theory  First prediction and experiment First prediction of "clumps"
1980s - present	Magnetohydrodynamics of toroidal plasmas Radio frequency-driven current in tokamaks Stabilization of instabilities in mirror machines Cyclotron autoresonance maser amplifiers Free-electron laser with reversed guide magnetic field	First high-field compact tokamak design First theoretical prediction; first definitive experiment First successful experiment  First experiment  First experiment

rescent tube, for example, radiation from a gaseous discharge plasma reacts with fluorescent material coating inside the glass tube which causes the material to emit light. The highly visible glow of a neon light is the direct radiation of plasma inside the glass tube.

### Plasmas in Space

In the early 1900s, Oliver Heaviside and other scientists realized that long-distance radio communications could benefit from using the reflective, "electrified layer" of Earth's upper atmosphere. This discovery prompted

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research in wave propagation in an ionized medium, and later, wave studies in other media interacting with magnetic fields. Space exploration has provided a better understanding of the near-Earth environment which contains highly active and well-ionized plasmas. As a spacecraft passes through this environment, scientists can measure the solar wind's activity and its interaction with the Earth's magnetosphere as

the wind undergoes a variety of magnetic reconnection events and spawns magnetospheric substorms. Over the last twenty years, missions to other planets have identified and explained electromagnetic emissions from their magnetospheres as plasma instabilities. In the study of astrophysics, the occurrence of matter in the plasma state is almost universal—from the low-density, low-temperature interstellar medi-

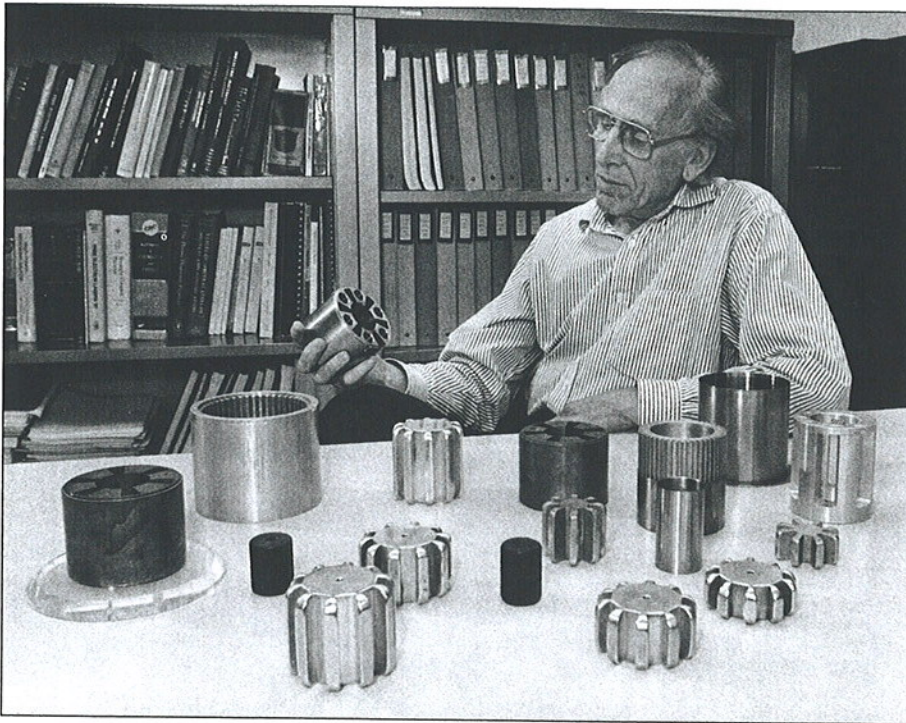
um to the high-density, high-temperature cores of stars. Intense emissions from quasars, pulsars, and other astrophysical phenomena are also thought to involve collective plasma instabilities.

### Controlled Thermonuclear Fusion

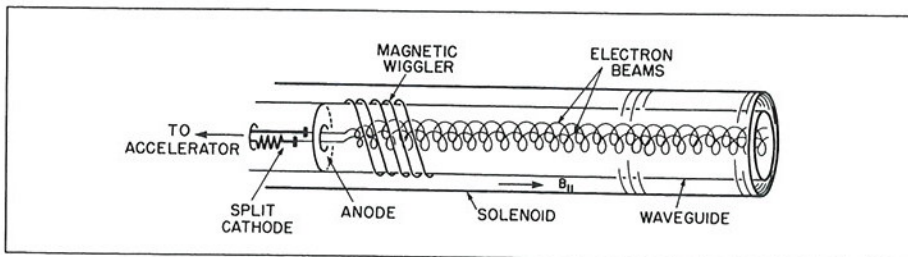
In 1938, physicists Hans Bethe and Carl von Weizsacker independently determined that a star's energy is produced by atomic fusion. In this process, lightweight atoms join together to form heavier ones. The fusion reaction results in a loss of weight, which is converted to impressive amounts of energy. In the sun, the nuclei of hydrogen atoms, aided by carbon, fuse after a sequence of reactions to form helium. These reactions require several million years to convert one gram of hydrogen into helium.

Since the explosion of the first hydrogen bomb, scientists have proposed methods to control fusion reactions and to construct fusion reactors. Hydrogen gas is commonly used for fuel in these fusion experiments since it is abundant and easy to work with. In order to produce a higher yielding, energy producing reaction, heavy hydrogen isotopes such as deuterium and tritium are used. They have the same properties as hydrogen but a different atomic nucleus. Deuterium is abundant in seawater, and when extracted from a gallon of seawater, its energy is equivalent to that produced by 300 gallons of gasoline. By itself, deuterium would provide an almost infinite fuel supply, but it is difficult to ignite. Mixtures of deuterium and tritium are easier to ignite, but tritium is rare and must be produced by nuclear reactors from another plentiful seawater element, lithium.

Compared to the hydrogen on the sun, hydrogen on Earth is rarefied and evanescent, so only a minimal amount of energy can be produced from it. Scientists do not have the sun's massive weight of hydrogen, its temperature, or the pressure density that effectively holds its blazing plasmas together. In a controlled fusion reaction, difficulties center around the fact that plasma particles must stay within a close proximity long enough for the short-range nuclear forces to fuse them together. On Earth, the conditions for deuterium and tritium ions to fuse and give off their excess energy become possible



Professor George Bekefi examines a relativistic magnetron, one of the world's most powerful microwave sources. On display are his original designs of devices which include inverted magnetrons, relativistic magnetrons, and circular free-electron lasers. Professor Bekefi's research focuses on the physics of various free-electron lasers that range in wavelength from microwave to visible light for use in heating fusion plasmas, novel particle accelerators, and communication. (Photo by John F. Cook)



The double-stream cyclotron maser is a novel source of coherent electromagnetic radiation developed by Professor George Bekefi. The advantage of a double-stream system over a conventional one-beam cyclotron maser is that a much higher frequency can be achieved for the same magnetic field and electron energy. The maser, which uses two co-propagating beams with different velocities that gyrate in a uniform axial magnetic field, has been proposed as a source of millimeter wavelength radiation. Professor Abraham Bers and his collaborators have also carried out a linear instability analysis of this maser and are currently conducting further numerical studies that may be applicable to either space plasma physics or coherent electromagnetic amplifying devices.

only at temperatures above 100 million degrees Kelvin. Only at these temperatures can the interacting particles (which normally repel each other because of the Coulomb force) come close enough to fuse to one another. Plasma can be heated to very high temperatures by passing high current (*ohmic heating*) through it. Supplemental heating is often needed, and can be provided by injecting the plasma with high-power microwaves (*radio-frequency* or *RF heating*) and/or high-intensity neutral particle beams (*neutral particle heating*). The injection of high-power microwaves also has a beneficial effect on the plasma since it helps to drive more current around the containment machine. This increased current (*RF current drive*) is needed for better plasma confinement and control.

Thus, the goal in a controlled fusion reaction is to hold a plasma long enough at fusion conditions. In confinement, plasma densities are kept low to better control the plasma, but denser plasmas require shorter confinement times. Contact with any solid material, such as the wall of a container, would cool the plasma and stop the fusion reaction.

### Building a Better Magnetic Bottle

In contrast with the sun, where fusion products are confined by tremendous gravity, plasma confinement here on Earth requires potent electromagnetic forces because the Earth's gravitational forces are negligible. The quest for a reliable "magnetic bottle" that could effectively contain plasmas began with the first cyclotrons and particle accelerators in the 1930s and 1940s. These devices used magnetic fields to confine a small number of electrons and protons, but the particles were generally too isolated or far apart. Later attempts in the 1950s resulted in leaking, diffused, and kinked plasmas that were not hot enough or close enough for a sufficient period of time to release any useful level of fusion power.

In 1957, British physicist J.D. Lawson calculated the requirements needed so that a fusion reaction could produce more energy than it used to get started. The Lawson criteria ( $n\tau$ ) stated that this net power production depended on the plasma's density (where  $n$  = number of particles per cubic centimeter) multiplied by con-



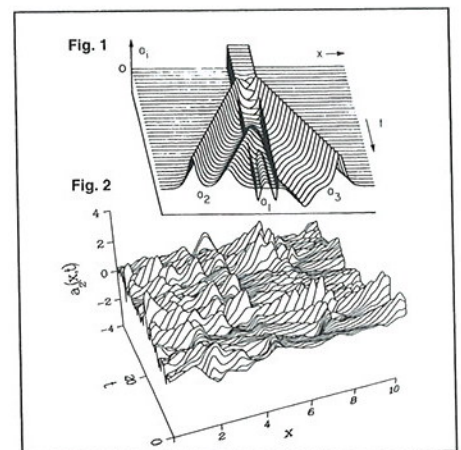
*Professor Abraham Bers studies nonlinear wave theory in plasmas related to radio-frequency heating and current generation. He has modeled and analyzed problems that involve coupling, propagation, energy, and momentum deposition, as well as induced transport in the interaction of electromagnetic fields with plasmas. Studies in radio-frequency current drive, which Professor Bers pioneered with his students, also indicate its possible use in stabilizing certain magnetohydrodynamic instabilities that are driven by ohmic currents, and may lead to new current drive applications.*

(Photo by John F. Cook)

finement time (where  $\tau$  = number of seconds the particles were together). Scientists had a long way to go in achieving the product of the Lawson criterion, which was calculated at a hundred thousand billion ( $10^{14}$ ). In addition, American David Bohm found that the hotter the plasma and the more powerful the magnetic force, the faster the plasma particles would separate. These were just two of the problems in handling plasmas that needed solutions.

Plasmas also have many ways of leaking and diffusing out of any force field or container that tries to hold them. Over the years, a variety of different schemes and geometries have been used in the design of magnetic bottles. *Pinch effect* devices have been used, where the plasma current generates its own magnetic field and squeezes itself into a thin thread. Similar devices called *stellarators* could change these pinched threads into a

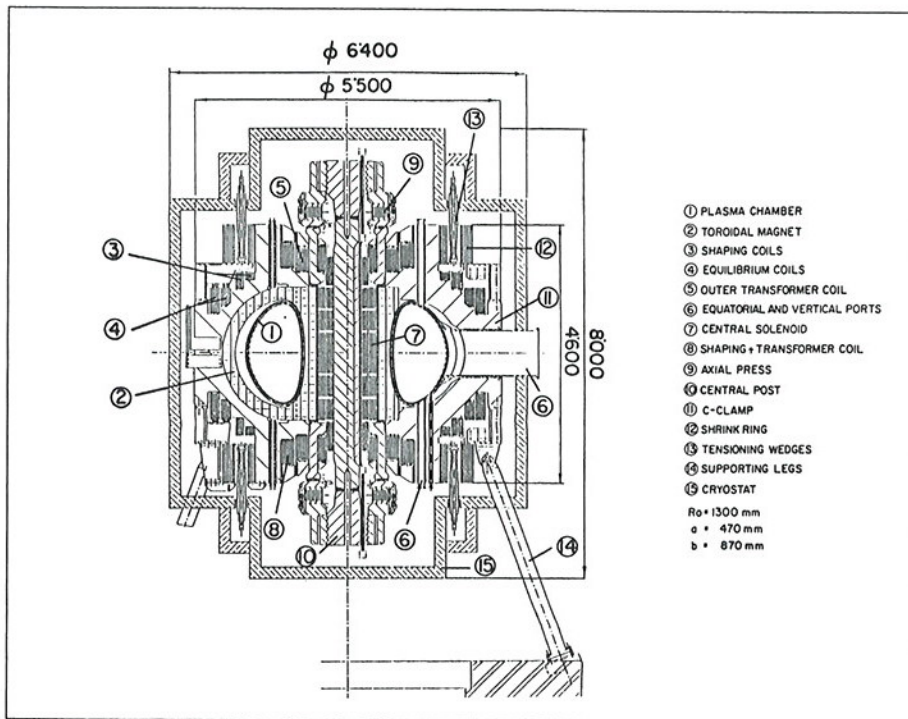
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*The space-time evolution of the nonlinear interaction of three wavepackets into solitons is the focus of research by Professor Abraham Bers. In figure 1, the conservative interaction of three undamped wavepackets is integrable. The soliton generation in the lower frequency wavepackets ( $a_2$  and  $a_3$ ) by the high-frequency, middle group velocity wavepacket ( $a_1$ ) is shown. Spatiotemporal chaos results in figure 2, when the high-frequency wavepacket is unstable and the other two are damped. The time-asymptotic  $a_2(x,t)$  exhibits the chaotic dynamics of quasi-soliton structures.*



Professor Bruno Coppi is "confined" by one of the innovative steel components of Alcator A, the first high-field toroidal plasma machine constructed in 1972. Steel plates were placed between the machine's copper plates to keep them from breaking apart under the tokamak's operating pressure of 5,700 pounds per square inch. Professor Coppi and his collaborators were first to propose and design experiments that demonstrated ignition conditions in magnetically confined fusion reacting plasmas. He is currently designing experiments to demonstrate the feasibility of so-called "clean fusion," based on the possibility of burning a deuterium-helium 3 mixture. (Photo by John F. Cook)



A cross section of major components of the Ignitor toroidal confinement experiment designed by Professor Bruno Coppi and his collaborators. The Ignitor is used to investigate deuterium-tritium ignition conditions in a plasma.

spiral using the shape of the confinement tube or extra magnetic coils. But the pinch effect did not provide enough confinement time and kinks formed in the plasma. It seemed the tighter the self-induced pinch, the more unstable the plasma became. To overcome these instabilities, another method called the *magnetic mirror* was designed. Magnetic mirror devices generate magnetism outside the device to confine a plasma within a cylinder- or doughnut-shaped chamber. In cylinder-shaped devices, outside magnetic coils wrap around the length of the cylinder with more powerful magnets at each end to reflect plasma particles. As particles approach the ends of the device, strong magnetic field lines make them reverse direction back to the center. Instabilities still occurred since the particles tended to drift out from the ends and the center of the device. This caused a separation of ions and electrons, called a *flute* or *interchange instability*, that was eventually overcome by the addition of a magnetic well in the center of the device created by *Ioffe bars*.

By the 1970s, extensive theoretical studies coupled with the development of novel devices and improved international cooperation brought a clearer understanding of plasmas. The limits set by Bohm's equation were eventually surpassed. A breakthrough came in 1968 with the success of Russian *tokamak* devices that could confine hot, dense plasmas longer than before. The tokamak (a Russian acronym for toroidal plasma chamber) has a large, doughnut-shaped vacuum chamber, more scientifically termed as toroidal or a torus. The first magnet design on these devices featured closely spaced hoop-shaped electromagnets around a long cylinder which prevented the plasma from contacting the walls of the chamber. To limit confinement, the design was eventually changed to a toroidal or doughnut shape, where the ends of the cylinder met. Tokamaks now appear to be the most promising approach to fusion reactor design.

Today, split-second research experiments called "shots" are carried out in several different classes of tokamaks. Powered by motor-generators, the tokamak's curved copper bars conduct powerful currents to generate magnetic fields through magnetic coils. A steel framework holds powerful magnetic conductors in place. In a typ-

ical shot experiment, titanium vapors are released in the tokamak to coat its inside walls. The titanium absorbs impure atoms in the plasma which can prevent it from heating up. A powerful electric current in the copper coils creates a strong magnetic field. Puffs of hydrogen gas are introduced into the vacuum chamber. Another large current is injected into the gas, which heats the gas to extremely high temperatures, thus freeing the electrons from their atomic nuclei. The hydrogen is now a plasma, glowing livid purple inside the vacuum chamber, much like a lightning bolt. The purplish color comes from plasma impurities and partially ionized atoms. The plasma current establishes a magnetic field to confine the hot plasma and to prevent it from losing heat by touching the chamber walls. High-energy neutral hydrogen atomic beams are then applied to increase the plasma's temperature. When the plasma darkens in the center, the temperature for total ionization is reached and all impure atoms have freed up their electrons. As the plasma cools, it glows more brightly again as electrons reattach themselves to nuclei.

Scientists are now attempting to achieve *ignition* conditions, where the plasma fusion reaction would produce enough energy to become self-sustaining. At 350 million degrees, a plasma produces so much energy from fusion reactions that it needs no further heating from outside sources. In this process, nuclear collisions occur on a mass scale, and the nuclei fuse to release their potent energy. Many basic research projects in plasma physics do not seek to achieve this actual fusion process, simply the proper conditions needed to produce it. Other more ambitious projects, such as the Joint European Torus in the United Kingdom and Princeton University's Tokamak Fusion Test Reactor are attempting to achieve *breakeven*, a condition where the fusion energy produced by a plasma equals the energy fed from outside sources, such as neutral beams, to heat the plasma.

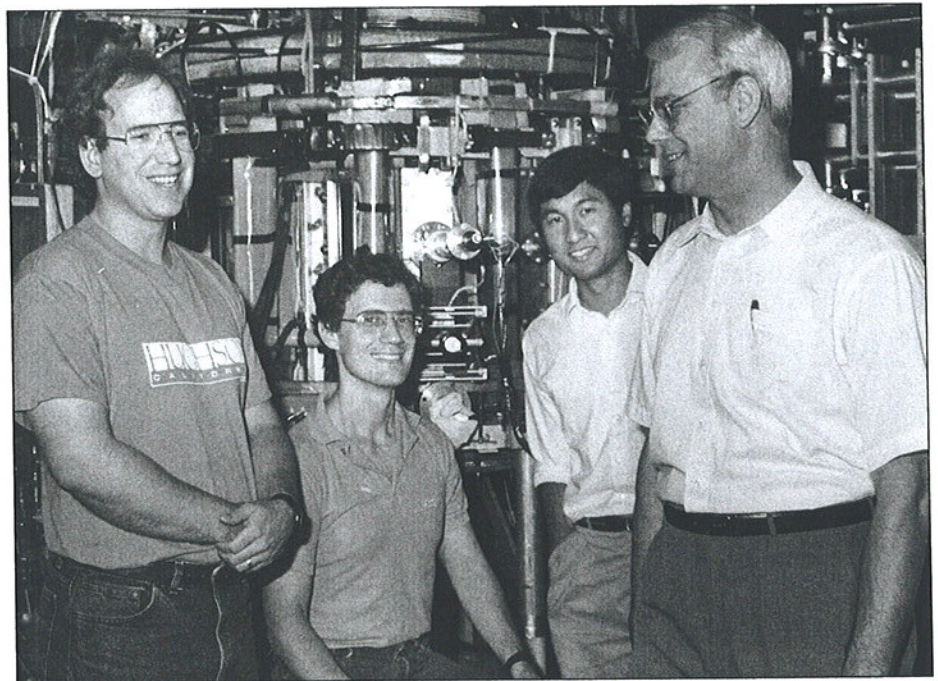
The conversion of thermal plasma fusion reactions to electricity is the ultimate goal of controlling a thermonuclear reaction. One conversion method involves *magnetohydrodynamics* (MHD). To unlock the tremendous energy of plasmas, their fast-moving, conductive currents are coupled with

powerful magnets. MHD generators can directly convert heat energy to electricity without mechanical devices or moving parts; only the plasma current moves. Scientists continue to investigate the three factors needed for MHD generation: plasma conductivity, magnetic field strength, and plasma flow speed.

Other issues concerned with the generation of fusion power include the wave-particle micro-instabilities that result from the shared energy between plasma particles and electromagnetic forces. Shock waves and escaping plasma in controlled research experiments cause the plasma to lose some of its mass. All containment devices experience these instabilities and oscil-

also continue to study the use of different metals with low radioactivation properties. These metals will be used in future containment devices to prevent the fusion products of gaseous helium and electrically neutral nuclei from changing the atomic structure of the vessel and causing radioactivity in containment equipment.

Finally, the advent of *cold fusion* has entered not only the scientific arena, but the political arena as well. Still hotly debated, physicists and other scientific investigators continue to search for answers behind the phenomena associated with a simple electrochemical tabletop experiment that was initially conducted in 1989. Its unconventional results have been



*The research tokamak Versator (background) is used by Professor Miklos Porkolab (right) and graduate students Jared P. Squire, Jeffrey A. Colburn, and Joel N. Villaseñor to study a variety of plasma phenomena. Their primary emphasis is on basic investigations of radio-frequency plasma interactions, including heating and noninductive current drive, as well as studies of plasma stability and the development of novel diagnostics. (Photo by John F. Cook)*

lations that affect how long a plasma can be contained. Physicists are trying to understand the nature of these instabilities and plasma loss, and studies focus on the collective behavior of charged particle groups in electric and magnetic fields, as well as the design of containment machines. Scientists

claimed to produce nuclear fusion conditions at room temperature. Further experiments seek to understand this puzzling interaction between deuterium gas and palladium metals.

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## Lasers and Plasmas

Conventional plasmas contain almost an equal amount of free positive-charge ions and free negative-charge electrons, thus a plasma is overall electrically neutral. However, nonneutral plasmas, composed of particles with a single polarity charge, can be readily produced and confined not only by electric and magnetic fields, but also by laser beams. These systems exhibit the collective behavior found in neutral plasmas and allow detailed studies to be made on inexpensive, table-top experimental devices.

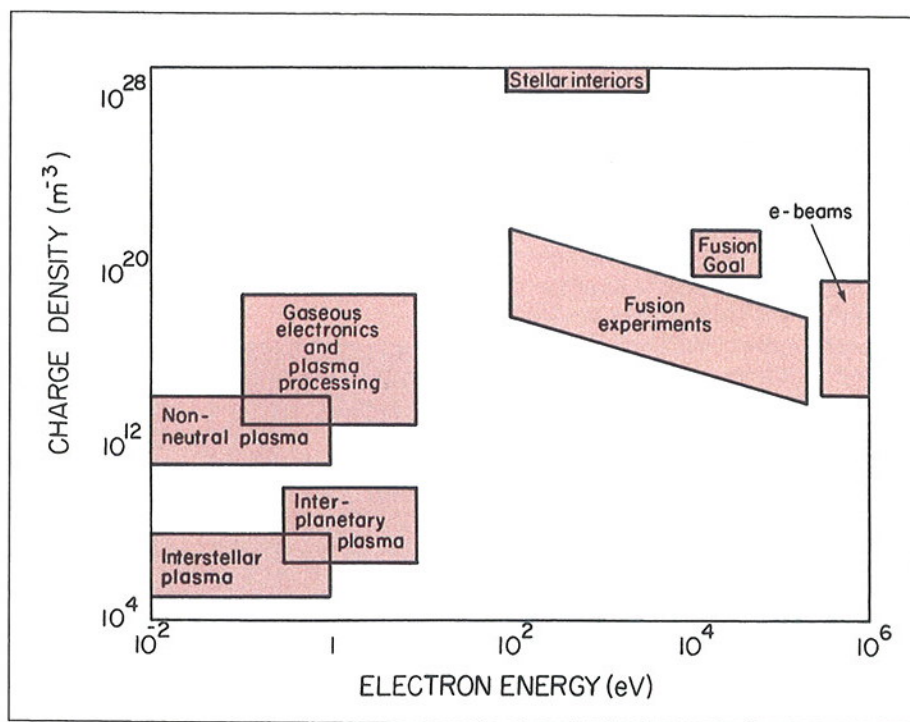
Another example of nonneutral plasmas is charged ion or electron beams. In this type of fusion, intense ion beams travelling almost as fast as the speed of light are used to compress and heat pellets of fusion fuel to induce reactions. The beam's energy explodes the pellet's outer layer while imploding its central core. Containment is not required since the atoms' inertia in each pellet holds together long enough for the fusion reaction to occur. This is known as *inertial confinement*, and similar attempts using laser beams are also being made.

Intense electron beams can also be used to generate *coherent electromagnetic radiation*. Coherent radiation is generated when phase relationships between different points in a cross section of the beam are maintained. The promise of developing lasers and masers where the active medium is an actual stream of free electrons has evoked great interest in recent years. Advantages to this approach include continuous frequency tuning, the variation of electron energy, and very high-power operation without damage to the lasing medium which can occur in more conventional lasers. These novel energy sources and their underlying mechanisms are quite similar to the early sources of coherent electromagnetic radiation, particularly the early microwave devices. The klystron, magnetron, and traveling wave tube, all developed in the 1940s and 1950s, are early examples of free-electron sources capable of generating coherent microwave radiation. In the decimeter and centimeter wavelength ranges, these devices can emit power levels as high as tens of megawatts with good efficiencies exceeding sixty percent.

The new generation of free-electron radiation sources aims to extend

the electromagnetic spectrum from the microwave to the millimeter, infrared, visible, and ultraviolet regimes with previously unattainable intensities and efficiencies. These sources include the gyrotron, the *cyclotron autoresonance maser* (CARM), the *free-electron laser* (FEL), and the relativistic magnetron

in entirely new ways. Gone were the familiar electrodes in glass discharge tubes. They were replaced by electrodeless microwave cavities driven by high-power magnetrons. These cleaner and simpler structures led to a detailed understanding of radio-frequency (RF) breakdown and to new ways of mea-



Plasmas are classified by their charge density and their electron energy. The accompanying illustration shows the vast range of densities and energies for plasmas in their natural state as well as for plasmas used to benefit humankind. Plasma physics is a rich and challenging field of interdisciplinary research that encompasses atomic and nuclear physics, space and astrophysics, fluid and statistical mechanics, and electrodynamics.

and klystron. A wide range of promising applications includes spectroscopy for condensed matter physics and in atoms and molecules, isotope separation, the development of novel accelerators, millimeter and submillimeter radar and communication, plasma heating for thermonuclear fusion, biomedicine, and lithography.

## Plasma Physics at RLE

The microwave instrumentation and technology that was developed at MIT's Radiation Laboratory during World War II enabled physicists to explore ionization phenomena in gases

ensuring atomic processes in ionized gases. The effects of an external magnetic field on RF breakdown led to the discovery of electron cyclotron resonance.

When RLE was established in 1946, the microwave gas discharge group, led by Professor Sanborn C. Brown, began to probe the behavior of electrons in gases. Using high electric fields, the group overcame the deleterious effects of positive ions in discharges by separating them from electrons. With this new technique, many questions about the nature of gas discharges were answered and new phenomena associated with microwave frequencies were discovered. The

development of novel microwave methods to measure gas discharge breakdown, controlled only by electron diffusion, enabled better precision. Studies of plasma resonance, a similar phenomenon where radio-frequency or microwave electromagnetic waves are reflected or absorbed at high plasma densities, also contributed to a better understanding of high-frequency radio transmissions in the ionosphere.

The innovative studies of Professors William P. Allis and Sanborn C. Brown established RLE as a major research center for gaseous electronics in the late 1940s and early 1950s. In

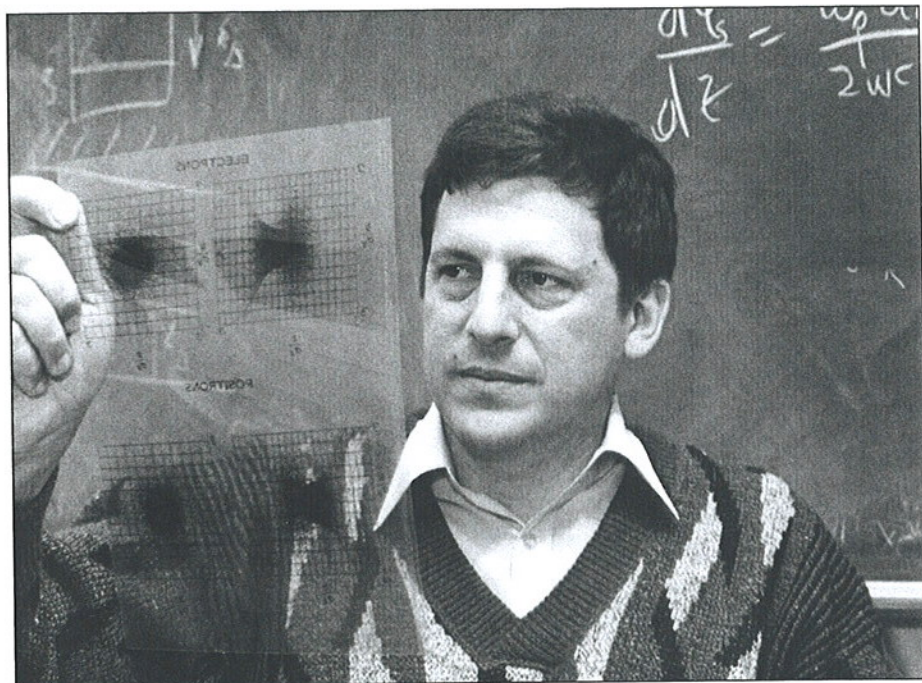
Bers led to a topological classification known as the *Clemmow-Mullaly-Allis diagram*. Concerns about plasma cooling caused by emissions of electromagnetic radiation from the medium stimulated Professor George Bekefi and his students to investigate the basic processes involved in *bremssstrahlung*, cyclotron, and synchrotron radiation. Measurements of these emissions also became useful diagnostic tools of the plasma state. The first fundamental theoretical analysis of these phenomena was developed by Professor Thomas H. Dupree. The collective oscillations of the almost collisionless plasmas made the study of related

monuclear fusion can sometimes be used to generate coherent electromagnetic radiation and to create new microwave and millimeter-wave devices. Initial work in solid-state plasmas was led by Professors Bers and Bekefi in the early 1960s. As scientific attention turned to lasers and the new area of quantum electronics, this work was interrupted, but resumed in the 1970s by Professor Bekefi using relativistic electron beams. The first narrow-band free-electron laser, tunable over a wide range of frequencies, was achieved by this group.

In the 1970s, investigations continued to probe various plasma phenomena such as nonlinear wave-plasma interactions and the properties of plasma turbulence. Professor Thomas Dupree established the first fundamental understanding of nonlinear theory and developed the notion of "clumps," fluctuations of local phase density in turbulent plasmas. Professor Bruno Coppi introduced the study of the magnetohydrodynamics of hot toroidal fusion plasmas and developed many concepts behind the design of high-field tokamaks. Professor Coppi's first tokamak design, the *Alcator A*, was built in 1972 at MIT's Francis Bitter National Magnet Laboratory under the supervision of Professor Ronald R. Parker. (The National Magnet Laboratory, established in 1960 as the first high-magnetic field laboratory in the U.S., has designed and constructed some of the world's most powerful magnets that have produced world-record magnetic fields.) Today, research in RLE continues on the *Alcator C* tokamak, which is being constructed at MIT's Plasma Fusion Center. In 1977, Professor Bekefi and his students designed and built a small research-size tokamak, the *Versator II*. Experimental research on hot, magnetized plasmas continues in RLE on this machine.

Another issue in thermonuclear fusion research is supplemental plasma heating. RLE interests in this area have focused on radio-frequency (RF) heating. In the mid-1970s, the first prediction of RF-driven current in tokamaks was proposed by graduate student Nathaniel J. Fisch in Professor Bers' group, and the first demonstration of this phenomenon was carried out by Professor Miklos Porkolab and

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*Professor Jonathan S. Wurtele checks a transparency with the results from a simulation of beam-beam interaction in a tera-electron volt electron-positron linear collider, which is part of his research on the physics of charged particle beam coherent radiation sources and advanced accelerator concepts. He and his collaborators have developed nonlinear models of the free-electron laser and cyclotron resonance maser, and have made detailed comparisons between theory and experiment. (Photo by John F. Cook)*

the early 1960s, following the Second International Conference on the Peaceful Uses of Atomic Energy in Geneva, interests in RLE turned toward the investigation of more highly ionized, warm plasmas confined by strong magnetic fields. The need to understand wave propagation in such magnetized plasmas by Professors Allis, Solomon J. Buchsbaum, and Abraham

instabilities a high priority. The classification of these instabilities was put on a firm theoretical basis by Professors Richard J. Briggs and Abraham Bers. Plasma heating by injecting electron beams into the ionized medium was studied experimentally by Professor Louis D. Smullin and his collaborators.

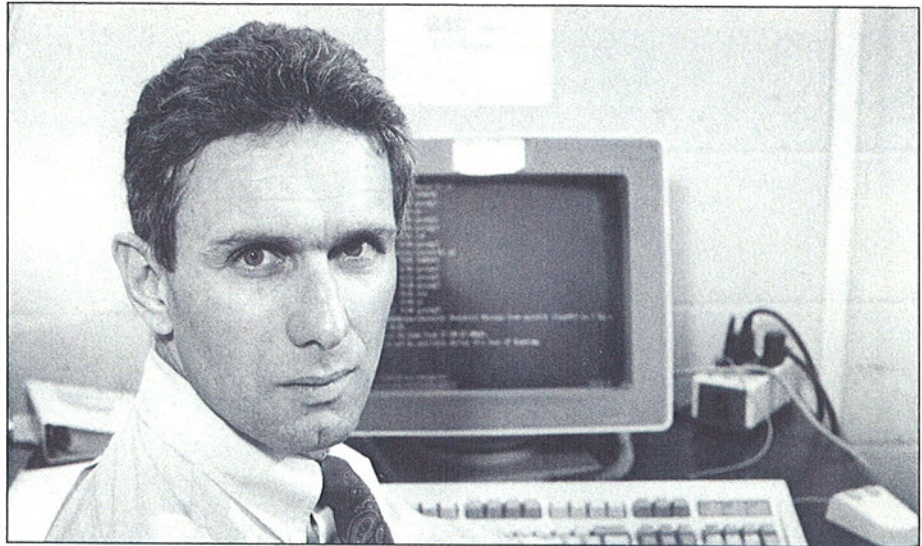
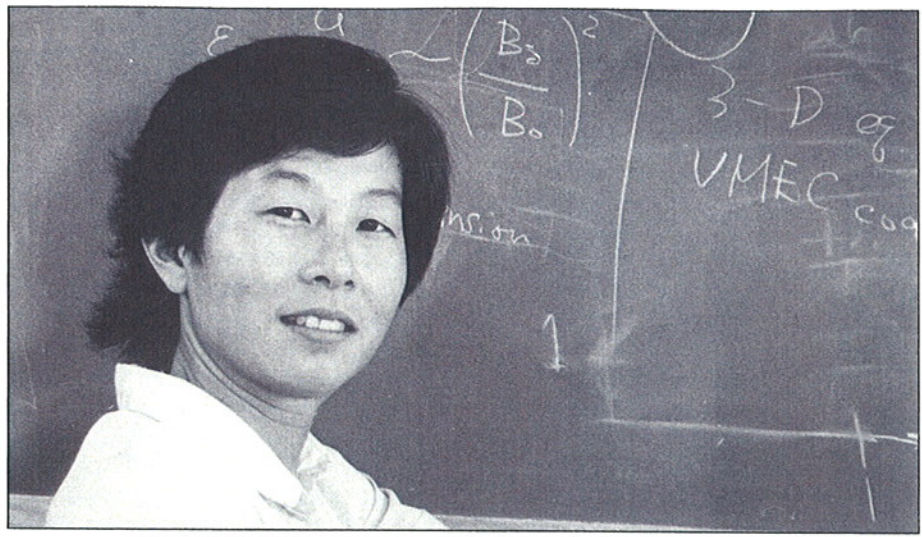
These same instabilities that adversely affect conditions for ther-

Research Scientist Stanley C. Luckhardt on the *Versator II* tokamak.

Today in RLE, Professors George Bekefi and Jonathan Wurtele carry out research to generate coherent millimeter and submillimeter electromagnetic radiation by converting the energy produced by using intense relativistic electron beams (operating at 0.5-1.5 megavolt voltage and 1-20 kiloampere current) as the lasing media. The focus of their work involves experiments with free-electron lasers and relativistic klystrons. They and their group of collaborators have discovered a novel magnetic field configuration for free-electron lasers. In this configuration, the cyclotron rotation of the electrons in the uniform axial guide magnetic field opposes the rotation in the helical magnetic wiggler field. Known as a *reversed field free-electron laser*, it differs from the conventional free-electron laser geometry where the two fields reinforce each other. This new laser has yielded unprecedented output power (60 megawatt) in the millimeter-wave range with a 27% conversion efficiency. The reversed field free-electron laser has also produced an unexpected physics phenomenon called "antiresonance," which has been attributed to the motion of off-axis electrons. Theoretical investigations continue to examine the phenomenon of frequency upshift from the input driver frequency of the free-electron laser's amplifier discovered by the group. A possible reason may be the rapid temporal changes of the effective refractive index of the pulsed electron beam.

To generate light using electron beams with moderate energies requires very short-period *magnetic wigglers*. A novel, permanent magnet, tunable "microwiggler" has been designed and constructed in Professor Bekefi's group. It is now being installed in the Brookhaven National Laboratory's 50-megaelectron volt radio-frequency linear accelerator, where it is expected to produce 10 megawatts of radiation at a 530-nanometer wavelength.

In the next generation of particle accelerators, novel high-power (100 megawatts), high-frequency (10-30 gigahertz) drivers will be needed to replace the conventional klystron. Although the cyclotron autoresonance maser (CARM) has undergone extensive theoretical study and numerical simulations, its capabilities as a source



*Research Scientists Dr. Linda E. Sugiyama and Dr. Stefano Migliuolo conduct investigations into the theory and modeling of plasma instabilities and transport behavior observed in toroidal confinement systems. As part of Professor Bruno Coppi's research group, their work contributes to the understanding of tokamak plasma physics and the advancement of magnetic fusion research in plasma reactors. (Photo by John F. Cook)*

of coherent millimeter wavelength radiation have not been thoroughly tested under laboratory conditions. Professor Bekefi's group is the first to have designed, constructed, and tested a CARM amplifier. Measurements are carried out at a frequency of 35 gigahertz with a relativistic electron beam (1.5 mega-electron volt, 260 amperes) that is generated by a field emission electron gun. Then, an emittance selector removes the hot outer electrons. Energy is imparted to the electrons by a bifilar helical wiggler. Measurements have yielded a small signal gain of 60 dB/m and a saturated power output

of 12 megawatts. By improving electron beam quality and tapering the guide magnetic field, continuing experiments on CARMs and FELs seek to optimize power output and radio-frequency efficiency.



Professor Abraham Bers and his research group conduct studies on the nonlinear electrodynamics of plasmas. The nonlinear space-time dynamics of coherent waves can be either integrable (and exhibit solitons, for exam-

ple), or it can lead to a chaotic state. A paradigm for such interactions to lowest order in nonlinearity is the interaction of three *wavepackets*, which occurs not only in plasma dynamics but also in fluid dynamics and optics.

In the mid-1970s, Professor Bers' group showed that the conservative nonlinear interaction in space-time of three wavepackets exhibited the generation of solitons and the exchange of solitons between wavepackets. This problem was found to be integrable by the mathematics of *inverse scattering transforms* (IST). The group showed that even in an inhomogeneous plasma this conservative nonlinear interaction of three wavepackets was exactly solvable by IST.

In contrast, and more recently, his group demonstrated that the nonconservative space-time interaction of an unstable wavepacket nonlinearly coupled to two damped wavepackets leads to a state of spatio-temporal chaos. This state is characterized by the chaotic dynamics of well-defined space-time structures (in this case, *quasi-solitons*), and is distinct from either fully developed turbulence or chaos in low-dimensional systems. The results of this study show a new description of the nonlinear evolution and saturation of coherent instabilities. The spatio-temporal chaotic state also entails an anomalous transport which

is very different from the one described by usual plasma turbulence models.

Another major effort of Professor Bers' research group is related to studies of plasma heating and current drive for fusion plasmas. Fusion energy generation in a plasma requires very high temperatures (in excess of one hundred million degrees), and the magnetic confinement of the plasma in toroidal geometry requires plasma currents of ten to twenty million amperes. Some of the modern, fundamental means of heating a high-temperature plasma and generating an electron current in it, with externally applied power in coherent electromagnetic fields, have been developed in Professor Bers' group. A little over fifteen years ago, the group showed that the ions in a plasma could be heated by coherent fields that induced chaotic dynamics in the ion motion. At about the same time, the group worked out the idea and means of efficiently driving a current in a tokamak plasma with microwaves. This has become known as *lower hybrid current drive*.

In addition, a different effective way to heat the ions in a plasma is known to be by means of *ion-cyclotron resonance fields*. The energy deposition in the plasma by ion-cyclotron heating is a complex problem in kinetic wave propagation and mode conversion. Professor Bers'

group has developed a mode-reduced analytic description of these processes that will further the understanding of this heating process and help to determine the best design for such heating.

More recently, the group has been looking at the effects of heating and current drive on plasma transport. The large amounts of power required to bring plasma temperatures to the regime needed for an energy-producing reactor may affect the confinement of the particles which are directly acted upon by the heating and current drive fields. A first comprehensive, analytic description of such transport for lower hybrid current drive has now been completed.

Two new directions of applied research in Professor Bers' group are concerned with problems in space and astrophysical plasmas and in intense laser-plasma interactions. The theory and analysis of absolute and convective instabilities—established and developed in this group over several years—is being applied to understand the detailed spectra of intense radiation from space plasmas. In particular, relativistically energetic distributions of electrons in a magnetic field are subject to maser-type electromagnetic instabilities (which are also used in electron devices for generating and/or amplifying coherent electromagnetic signals), and were studied by this group in the mid-1960s. Professor Bers' group has recently shown that the bandwidth of observed radiation can be correlated to the absolute or convective nature of such instabilities, and can then allow the properties of the energetic electron distributions to be determined. In the area of intense laser-plasma interactions, much of this group's work on the nonlinear coupling of wavepackets is directly applicable to ongoing efforts in laser-pellet fusion. Of particular interest are the nonlinear processes that lead to backscattering of light from such plasmas and how to minimize it for short-pulse (picosecond), high-intensity (terawatt) incident laser light.

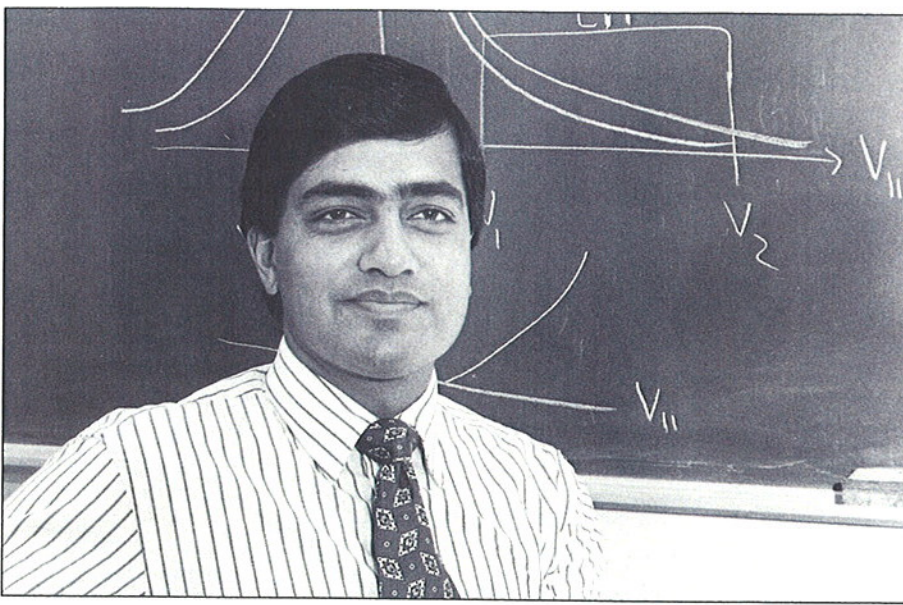


Professor Bruno Coppi and his collaborators were the first to propose and design experiments that demon-

(continued on page 12)



Research Specialist Ivan Mastovsky (foreground) assists graduate student Palmyra E. Catravas in the construction of a relativistic klystron amplifier. Students participating in the project are (from left): David L. Sisson, Palmyra, Pavel S. Volfbeyn, and Todd A. Hay. (Photo by John F. Cook)



Dr. Abhay K. Ram, Research Scientist with MIT's Plasma Fusion Center, works closely with Professor Abraham Bers' group in plasma electrodynamics. His current research in the area of nonlinear plasma dynamics in intense and coherent fields covers a variety of applications such as plasma heating and current drive methods in magnetic confinement fusion, laser-plasma interactions, and space plasma physics. He has made important contributions to the relativistic analysis of absolute and convective instabilities and their use in identifying electromagnetic emissions from space plasmas. (Photo by John F. Cook)

strate how ignition conditions could be reached in magnetically confined plasmas. The main focus of his program is the theoretical study of magnetically confined plasmas in the thermonuclear regime. The basic physical processes of thermonuclear plasmas such as equilibrium, stability, and transport are being investigated.

Professor Coppi's group has proposed and developed the physics and engineering ideas behind the design of the *Ignitor* as part of an ongoing program into ignition experiments. Future experiments will involve ignited plasmas, such as those planned for the deuterium-tritium burning *Ignitor*, and will attempt to attain advanced physical regimes where low-neutron-yield fuels can be "burned." Professor Coppi's proposed experiments could demonstrate the feasibility of so-called "clean fusion," based on the possibility of burning a mixture of deuterium-helium 3. Ongoing studies investigate the basic physics involved in deuterium-tritium ignition and conditions that influence plasma confinement.

Theoretical investigations are also conducted by Professor Coppi on the plasma processes involved in a phenomenon called *magnetic reconnection*.

Magnetic reconnection has been observed in the study of solar flares and the dynamics of the planets' magnetospheres. Fusion experiments on high-energy plasmas have also produced magnetic reconnection as a result of instabilities that provoke a "crash" in temperature in the central part of a confined plasma column. These instabilities, known as *sawtooth oscillations*, can prevent a magnetically confined plasma from reaching the ignition conditions. Professor Coppi and his collaborators have provided an extensive theoretical explanation of this phenomenon and their investigations in this area are ongoing.



Professor Miklos Porkolab works with his students on the *Versator II*, a small research tokamak facility used for the fundamental study of the interactions of electromagnetic waves with fully ionized, nearly collisionless plasmas. Three investigations are being conducted which focus on radio-frequency plasma interactions (including heating and noninductive current drive), studies of plasma instability,

and the development of novel diagnostics.

Experiments are being conducted using x-ray spectrometer arrays to measure the bremsstrahlung emission from the energetic electrons that carry current in plasmas. These studies found that current could be driven equally well in the heating mode (by injecting waves symmetrically) or by

### Landmark Books on Plasma Physics by RLE Researchers

Allis, W.P., S.J. Buchsbaum, and A. Bers. *Waves in Anisotropic Plasmas*. Cambridge: MIT Press, 1963.

Bekefi, G., ed. *Principles of Laser Plasmas*. New York: Wiley, 1976.

Bekefi, G. *Radiation Processes in Plasmas*. New York: Wiley, 1966.

Briggs, R.J. *Electron-Stream Interaction with Plasma*. Cambridge: MIT Press, 1964.

Brown, S.C. *Basic Data of Plasma Physics*. Cambridge: MIT Press, 1959.

Brown, S.C. *Basic Data of Plasma Physics*. 2nd edition. New York: Wiley, 1966.

Brown, S.C., ed. *Electrons, Ions and Waves, Selected Works of W.P. Allis*. Cambridge: MIT Press, 1966.

Brown, S.C. *Introduction to Electrical Discharges in Gases*. New York: Wiley, 1966.

McDonald, A.D. *Microwave Breakdown in Gases*. New York: Wiley, 1966.

Rose, D.J., and M. Clark, Jr. *Plasmas and Controlled Fusion*. Cambridge: MIT Press, 1961.

normal current drive mode (injecting waves asymmetrically). Using x-ray emission analysis, evidence of *bootstrap current generation* may have been found in this experiment. Although predicted theoretically, there have been few experimental verifications of this phenomenon, which

could help attain a steady-state tokamak fusion reactor.

Fast wave current drive experiments focus on the feasibility of fast wave lower hybrid current drive using a dielectrically loaded waveguide array. If successful, this arrangement would be useful in maintaining the necessary equilibrium in future tokamak-based reactors. In further studies, nonlinear phenomena are being investigated which may explain the lack of complete wave penetration and efficient current generation in the plasma's center.

Current-drive experiments using electron cyclotron waves and lower hybrid waves have also been carried out. The analysis of a two-parallel-temperature superthermal tail observed in the electron distribution function during lower hybrid current drive has improved understanding of wave-induced particle diffusion in velocity space. The efficiency of electron cyclotron current drive was also studied and the efficiency was found to be greater than theoretical predictions. The combined efficiency of electron cyclotron and lower hybrid waves was significantly less than theoretically predicted, apparently as a result of radial particle loss caused by magnetic turbulence which is enhanced by electron cyclotron heating.

Plasma research at RLE has always forged close ties between theorists and experimentalists from several different academic departments as well as the National Magnet Laboratory and the Plasma Fusion Center. The Plasma Fusion Center (PFC) was established in 1976 to bring together all plasma research and technology related to fusion power. Its broad nature encompasses efforts ranging from basic plasma theory and experiments to fusion power system technology and design. PFC is recognized as one of the leading university research laboratories in the area of physics and the engineering aspects of magnetic confinement fusion. RLE's interests continue to focus on basic plasma phenomena and their theoretical properties, whether or not they are fusion-related. Although a major part of RLE's earlier effort in plasmas has moved to the Plasma Fusion Center, the emphasis on fundamental research in this area has remained at RLE.

by Dorothy A. Fleischer



## RLE Collegium

The RLE Collegium was established in 1987 to promote innovative relationships between the laboratory and business organizations through research projects and special partnerships. Its goal is to increase interaction and communication between RLE researchers and outside professionals in electronics and related fields. Collegium members have the opportunity to develop close affiliations with the laboratory's faculty, research staff, and students, and can quickly access emerging results and scientific directions. This kind of professional interaction provides RLE Collegium members with the most up-to-date technical information, often in areas not fully addressed by business and industry.

Collegium benefits include access to a wide range of RLE publications, personalized seminars and laboratory visits, and other opportunities for technology transfer. RLE also hosts visiting scientists from collegium companies. Individual research projects and special partnerships may develop with mutual technical interests and the appropriate external sponsorship.

The RLE Collegium membership fee is \$20,000 annually. Members of MIT's Industrial Liaison Program can elect to transfer 25% of their ILP membership fee to the RLE Collegium. Collegium fees will encourage new research initiatives within RLE.

RLE welcomes inquiries regarding the laboratory's research. To request an RLE *Progress Report*, an RLE *Collegium Prospectus*, or for more information on other RLE publications, please contact:

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Massachusetts Institute of Technology  
77 Massachusetts Avenue  
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Collegium: (617) 253-2509/2510  
Publications: (617) 253-2566  
Fax: (617) 258-7864

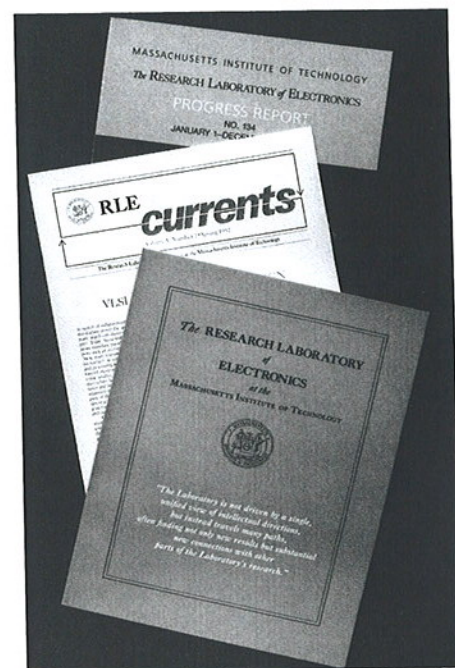
## Publications



RLE has recently published the following technical reports:

***Multi-Channel Signal Separation Based on Decorrelation***, by Ehud Weinstein, Meir Feder, and Alan V. Oppenheim. RLE TR No. 573. March 1992. 25 pp. \$9.00.

***Theoretical and Practical Aspects of Parallel Numerical Algorithms for Initial Value Problems, with Applications***, by Andrew Lumsdaine. RLE TR No. 574. August 1992. 85 pp. \$17.00.



***Speech Group Working Papers***, Vol. 8, July 1992. 158 pp. No charge.

In addition, *RLE Progress Report No. 134*, which covers the period January through December 1991, provides extensive information about the research objectives and projects of RLE's research groups. It also lists faculty, staff, and students who participated in each research project, in addition to current RLE personnel, and identifies funding sources. The *Progress Report* is available at no charge.

# FACULTY PROFILE:

## William P. Allis

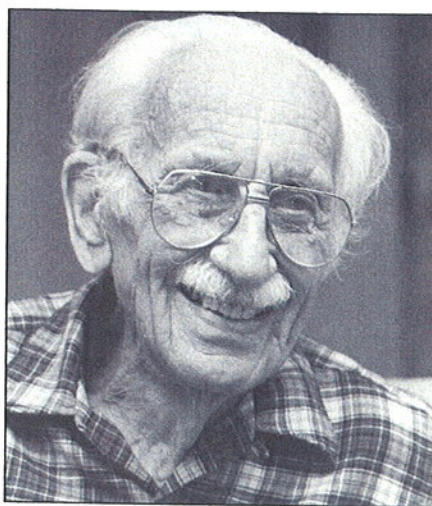
Many MIT faculty members and students have been guests of Professor Emeritus William P. Allis at his Dublin, New Hampshire retreat. Last July, far from MIT's frenetic urban campus, the 200-acre Yonder Farm provided an idyllic setting for this issue's "Faculty Profile," where **currents** interviewed its gracious host.

Professor Allis was born in Menton, France, in 1901. Home-educated, he came to MIT and quickly graduated in three years with a Master's of Science degree in 1924. His postgraduate studies involved research at the University of Nancy in France, Princeton University, and the University of Munich. His affiliation with MIT continued as a research associate (1925-29) and instructor (1931-34) in the Department of Physics. He joined the physics faculty in 1934 and was appointed full professor in 1950.

Briefly with MIT's Radiation Laboratory, Professor Allis conducted research on magnetron theory and was then selected to serve as the liaison officer between the Pentagon and Rad Lab for the duration of World War II. He achieved the rank of lieutenant colonel and, in 1945, was awarded the Legion of Merit.

Professor Allis' theoretical research has encompassed all aspects of gaseous electronics. He and Professor Sanborn C. Brown were instrumental in establishing RLE as one of the premier laboratories in this field. Professor Allis was responsible for starting the American Physical Society's Gaseous Electronics Conference and, after serving as its chairman from 1949 to 1962, was named honorary chairman in 1966. He also served as Assistant Secretary General for Scientific Affairs with NATO from 1962 to 1964. Since his retirement from MIT in 1967, he has travelled extensively as a visiting professor and lecturer.

*Bursting with an energy that belies*



Professor Emeritus William P. Allis  
(Photo by John F. Cook)

*his ninety-one years, Professor Allis continues to practice mountain climbing at nearby Mount Monadnock, chop firewood and mark the trails at Yonder Farm, and of course, bicycle wherever he goes.*

### • What attracted you to MIT?

My father, E.P. Allis, Jr., went to MIT and graduated in 1870. Although he finished all the courses with high grades, he never got his degree because the custom then was to write a thesis after leaving MIT, then you got your degree. He went back to his father's company, the E.P. Allis Company (now the Allis-Chalmers Manufacturing Company), but he never wrote his thesis.

I was educated entirely in France, mostly by teachers who came to our house, so I never went to school. I took entrance exams for both MIT and Harvard, but couldn't get into Harvard because they had a Latin requirement, and I didn't know Latin. Of course, I could speak French and Italian fluently, but without Latin, I couldn't get into Harvard. It was the math exam that got me into MIT with advanced standing. MIT was actually the first school I ever attended. I entered as a sophomore, took physics, and finished in three years. I received a Master's of Science degree in 1924 for my thesis "Photoelastic Properties of Celluloid Glass and Fused Quartz."

I was interested in applying my knowledge of mathematics, and I was able to do that the moment I got into a physics course. One of my professors, Professor Moore, once told me that as an undergraduate, "You didn't know much mathematics, but you knew how to use what you did know!" Theoretical physics is not difficult when you know the laws and the necessary mathematics. Experimental physics can be very difficult.

### • Did you have a mentor?

I didn't have anybody special, but John Slater is one of the professors I remember particularly well.

### • What was the nature of your post-graduate work?

The University of Nancy in France was trying to make contacts here at MIT, and, in 1924, I was recommended for entrance there. I was given an experimental problem to work on, building a small, 10-megahertz oscillator and measuring its Q value, and we published an article on it. I received a degree for this work, but French degrees are not the same as American degrees. The only academic degrees that really matter are the ones backed by the French government. Universities, at their pleasure, award similar degrees which are not endorsed by the government. I was awarded a Docteur d'Université from the University of Nancy, which isn't recognized by the French government. In 1925, I returned to MIT to teach a course in electrodynamics.

After I taught at MIT for a few years, I decided that I really didn't know enough physics or the necessary mathematics. First, I went to Princeton for a year in 1929 to study relativity, and then went on to spend a year with Professor Arnold Sommerfeld's group at the University of Munich. Sommerfeld gave me a problem: the experimental scattering cross section of atoms for electrons varies peculiarly with the electron's energy, frequently having a pronounced minimum at a low energy. This is called the *Ramsauer effect*. Sommerfeld guessed correctly that it was a diffraction effect of electron waves, but this had to be

shown, and Sommerfeld invited me to do so. I set up the mathematics and was stuck. Philip Morse came to Munich that same year, and he suggested that we put numbers in my formulae. We did that together, and the computed cross sections showed peculiarities quite similar to those observed. This was in fact the first numerical computation to show the wave-particle duality of electrons. Phil and I had explained this effect as a resonance of the electric field of the atom, and the electronic wave associated with the incident electronic beam.

• *Was there research in gaseous electronics at MIT before World War II?*

No. There was little gaseous electronics research yet. Plasmas were just being introduced by Irving Langmuir, whose interest was stimulated by the importance of mercury rectifiers. His successor in this field was Karl Compton, who was later drafted as president of MIT. I became interested in this work, and the first thing I investigated was what happens when an electric spark is made on a plate of glass and it produces a diagram with peculiar branches. Compton asked me to find out about these peculiar branches. So, I started working on that. I got nowhere, but that was my start in gaseous electronics.

My first successful work in this field was with Phil Morse. Phil got a problem from Karl Compton, who was then at Princeton. The problem involved a hollow cathode, a hollow space in which electrons are emitted. Compton said the hollow cathode didn't have a Maxwell distribution of electron velocity, and he wanted to know why. So, that put both of us on the project. Phil used the Boltzmann equation, which I hadn't used before. In 1935, Phil, Edward Lamar, and I published a paper, "Velocity Distributions for Elastically Colliding Electrons," in *The Physical Review*. At that time, the theoreticians who worked on gas discharges analyzed the phenomena according to Townsend methods. They investigated the behavior of an average electron in a gas. Statistical methods of the kinetic theory of gases had been known since Boltzmann, and our

research introduced the systematic use of distribution functions and the Boltzmann equation as applied to electrons. Our paper on non-Maxwellian distributions is considered by some to be the beginnings of the modern theory of plasmas and gas discharges. It was my first paper in plasma electronics.

• *What was the focus of your work on magnetron oscillators at the Rad Lab?*

The British came over with their magnetron and asked if we could take up its development. I worked at Rad Lab for about a year, but I wasn't part of any particular group. I just took this problem from John Slater, who asked what the electrons were doing as they went round and round in the magnetron. I put down the mathematics and developed the formula for the efficiency of a magnetron. It's quite surprising that one should get a clear and easy formula on such a complicated plasma. That was really my only contribution there. Rad Lab was becoming very effective in magnetron research, but they needed a better liaison with the Army. So, the Army took me from Rad Lab and gave me an office in the Pentagon with the rather high rank of major. I discussed problems directly with colonels, telling them what was reasonable to ask of Rad Lab and reciprocally telling Rad Lab what the Army really needed.

On returning from military service, I found that the theory of magnetrons had been carried far beyond my earlier war work, but that my yet earlier interest in the theory of glow discharges had not been so cataclysmically surpassed. The situation had in fact been simplified by the work on microwave cavity discharges which had been stimulated by the need for an automatic switch, the T-R box, which would protect the receiver from the powerful radar pulse on its way to the antenna, yet leave the circuit open to the reception of the weak echo on the same antenna. This had led to experimental work on microwave breakdown and on the recovery by the gas of its transparency to microwaves.

Although World War II interrupted our work, it supplied a vital element: the new RLE fell heir to the microwave

equipment and techniques of the Rad Lab, and this directed our efforts into microwave discharges. Money for research assistants was supplied to RLE by the armed services. Twelve people on a budget of \$60,000 constituted what was practically the only "plasma school" in the country then; the other school at the University of California, under Leonard Loeb, was quite small.

• *What was the nature of your work with Professor Sanborn Brown?*

Sanborn Brown and I were essentially one inseparable pair. Sandy was a very good experimentalist, but he sometimes had trouble interpreting the results. Although I couldn't do the experiments, I could often interpret the results. So, Sandy and I formed a good combination. When RLE was established, an experimental group was set up under Sandy Brown to study microwave discharges experimentally, with me as its theoretical mentor.

I was very interested in the experimental side of research since I used it all the time, but I'd never done experimental work. Well, yes, my work at the University of Nancy was experimental, but overall, I was not clever experimentally. I took the experiments and tried to find out why things came out the way they did. My work with Sandy depicted the measurements that his group had made and tried to explain why things happened. That involved working atomic structure into the Boltzmann equation and coming up with the answers. I was merely there to interpret their measurements. When Sandy left the lab to devote himself to administrative tasks at MIT, I was left rather high and dry.

Following my work with Sandy, I received much of my stimulus from the gaseous electronics conferences, where I took part in discussions that often gave me problems to work on.

• *Could you describe your work in the field of plasma fusion?*

From about 1955 onward, plasma physics became closely tied to controlled fusion research. My interest was mainly in the theory of waves in plasmas. A magnetized plasma is an anisotropic medium, and since it con-

sists of charged particles, coupling occurs between electromagnetic and electroacoustic waves. To simplify this situation, the CMA (Clemmow-Mullaly-Allis) diagram was developed to help consider the different shapes that an index surface can have.

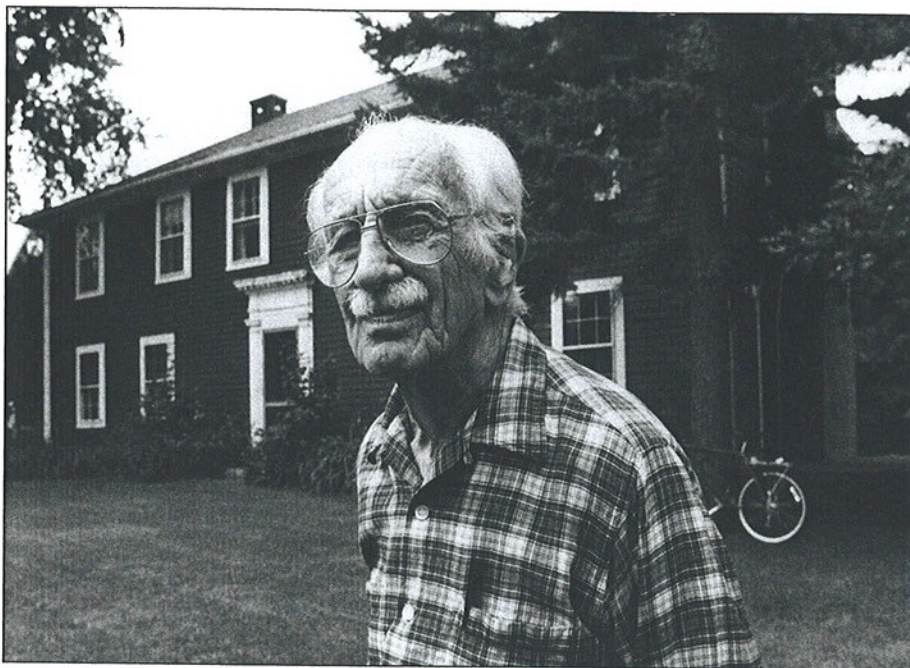
• *What was the significance of the Second Conference on the Peaceful Uses of Atomic Energy in Geneva in 1958?*

I remember almost nothing about the conference itself. But, the summer going there I remember very well because that's when I took my family and friends on a bicycle trip through Europe. The boat from the U.S. landed in Venice, and from there we bicycled to Vienna through Austria, through southern Germany, and up to Basel, Switzerland. Then, the group went off to a port by Brussels while I bicycled down to the conference. I remember arriving at the conference on my bicycle. I got off my bicycle and asked the doorkeeper if I could go inside. The doorkeeper called to his assistant, pointed at my bicycle, and yelled, "Take this!" Most of the people had arrived at the conference in big, black limousines!

For me, it wasn't so important because it wasn't a research conference, although I did edit a book that contained a collection of American contributions. But, it was important in the sense that it worked plasmas into nuclear physics. Most of the controlled thermonuclear projects both here and in Russia were declassified at this conference, and a great forward impulse was obtained from this interaction.

• *What was your role with the Los Alamos National Laboratory?*

I was useful while I was there, but not much more. They were too focused on nuclear things, and I'm not nuclear. So, I was of little use after the year that I spent there, which is when they started to produce helical discharges for high-energy plasmas. They were working for a definite objective and I've never been interested in objectives. I'm more interested in understanding what's going on, rather than creating something new.



*With his bicycle at the ready, Professor Allis enjoys a warm summer day at Yonder Farm in Dublin, New Hampshire. (Photo by John F. Cook)*

• *What are your views on classified research?*

In 1952, the possibility of controlling a thermonuclear reaction in a magnetic bottle was glimpsed, and the Atomic Energy Commission (AEC) embarked on a gigantic effort to beat the Russians in doing so. Both sides lost in this contest. My work on ionized gases in magnetic fields led naturally to my becoming involved in the AEC's Sherwood program. In fact, the AEC wished RLE to undertake a large classified research program in this area; RLE refused, and rightly so, on account of its classified nature. Once security was relaxed, we had an AEC contract of \$250,000 which supported about 30 people.

In a classified project the students must be cleared before they can even find out what is going on. Then, once they are in, they can only discuss their work with the small clique who are similarly cleared. While a student learns much from his own failures and his faculty advisor, he learns even more from discussions and the interchange of ideas with his fellow students, and this is severely limited by classification. It is probably true that the individual genius contributed most

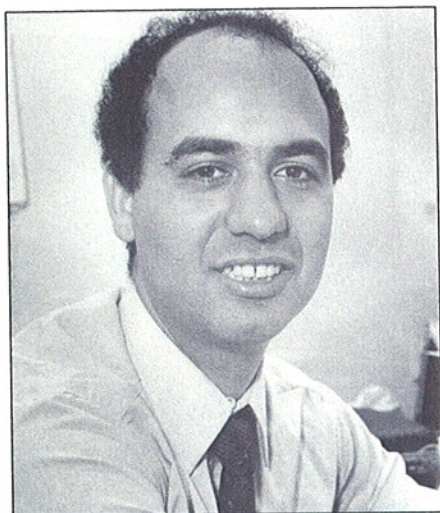
to the advancement of scientific knowledge through the nineteenth century, but the rapid advance in this century has been due to the collective efforts of individually free scientists, and one has to learn to work "collectively" just as one learns anything else. I am distinguishing here the collective work of individuals working in the same area but free to follow their own intuitions from the team work of individuals who follow a leader. The latter resembles much more the earlier work of isolated scientists.

I was not interested in classified things. Classified research made putting its use ahead of principles, and I was more interested in the principles of research.

• *What is your most significant achievement?*

It's the students I've educated! Whenever I am travelling in some distant, crowded airport, someone inevitably comes up to me and says, "Professor Allis, I worked with you!" That is my principal contribution, and it's something that's remembered rather than written. That has been the most rewarding aspect of being a teacher.





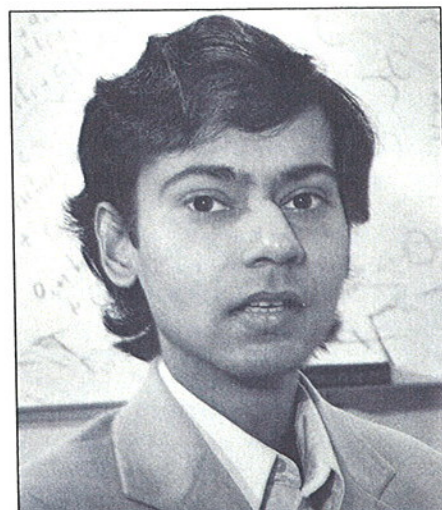
**Dr. Raymond C. Ashoori** will join RLE's Quantum-Effect Devices Group as Assistant Professor of Physics on January 1, 1993. Since 1990, Dr. Ashoori has been a member of the postdoctoral technical staff at AT&T Bell Laboratories in Murray Hill, New Jersey. His work involves experiments in low-dimensional systems in III-V semiconductors, and he has successfully developed a technique to investigate the electronic charging behavior of a single quantum dot. In future research, he plans to investigate mesoscopic systems in semiconductors and to develop probe techniques that can reveal single defects in epitaxially grown crystals. Dr. Ashoori is a graduate of the University of California at San Diego (BA '84) and Cornell University (PhD '90).  
(Photo by John F. Cook)



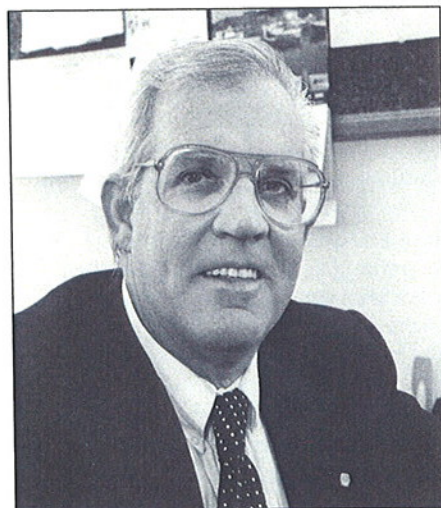
**Dr. Sylvia T. Ceyer**

interactions. Professor Ceyer joins nine other MIT faculty members as new AAAS fellows this year. (Photo by John F. Cook)

operational, administrative, and fiscal functions of the laboratory. (Photo by John F. Cook)



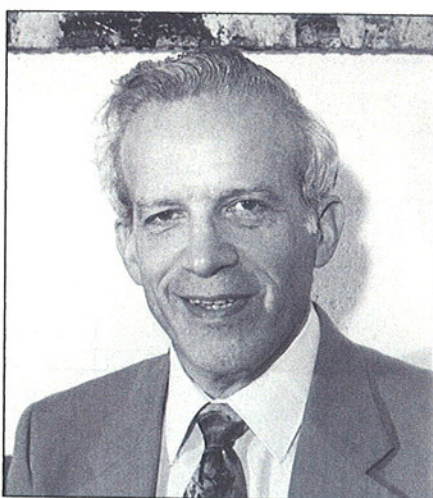
**Dr. Srinivas Devadas**, Assistant Professor of Electrical Engineering and Computer Science, received a 1992 Young Investigator Award from the National Science Foundation. The award, formerly known as the Presidential Young Investigator Award, is intended to encourage the development of future academic leaders, both in teaching and research. Professor Devadas conducts research in the Circuits and Systems Group on the computer-aided design of very large-scale integrated circuits and systems. His interests focus on the synthesis for testability and the formal verification of VLSI circuits. Professor Devadas has introduced a new computer-aided design course in the Department of Electrical Engineering and Computer Science, and plans to develop another course in formal verification in VLSI design. (Photo by John F. Cook)



**Mr. Joseph F. Connolly** was appointed RLE Administrative Officer, effective October 5, 1992. Since 1986, Mr. Connolly has served as the Assistant to the Director at MIT's Haystack Observatory in Westford, Massachusetts. He has worked in various capacities at MIT since 1965, including the Center for Space Research, the Office of Institutional Studies, the Joint Center for Urban Studies, and the Office of Sponsored Programs. A graduate of Boston College (BS '70), he will oversee all

**Dr. Sylvia T. Ceyer**, William M. Keck Professor of Chemistry, was elected fellow of the American Academy of Arts and Sciences at its annual meeting on April 8, 1992. Professor Ceyer joined the MIT faculty in 1981 and, as an investigator in RLE's Surfaces and Interfaces Group, she has researched the dynamics of molecule-surface interactions that has resulted in the discovery of new mechanisms for dissociative chemisorption, desorption and absorption of adsorbates, and surface

**Dr. Daniel Kleppner**, Associate Director of RLE and Lester Wolfe Professor of Physics, was elected fellow of the Optical Society of America on May 8, 1992. Professor Kleppner was cited for his distinguished service in the



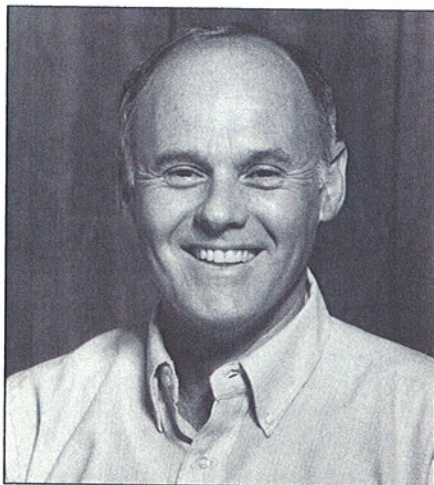
**Dr. Daniel Kleppner**

advancement of optics, particularly for contributions to spectroscopy. A principal investigator in RLE's Atomic, Molecular, and Optical Physics Group, Professor Kleppner's research interests include quantum chaos, the study of hydrogen at extremely low temperatures, and ultraprecise laser spectroscopy. He recently received the American Physical Society's 1991 Julius Edgar Lillienfeld Prize and the Optical Society's 1991 William F. Meggers Award. (Photo by John F. Cook)



**Dr. Melanie L. Matthies**, Technical Assistant in RLE's Speech Communication Group, was promoted to Research Scientist in May 1992. Dr. Matthies carries out research design, and data analysis and collection for several of the group's experiments. These include the use of alternating magnetic fields to transduce articulatory movements and the analysis of speech production in patients with cochlear implants. She is a graduate of the State University of New York at Buffalo (BA '76), Purdue

University (MS '78), and the University of Illinois at Urbana/Champaign (PhD '84). Before joining RLE in 1989, Dr. Matthies was a visiting assistant research professor at the University of Illinois and an editorial consultant to the *Journal of Speech and Hearing Research*. Dr. Matthies is a member of the American Speech, Hearing and Language Association; the American Auditory Society; and an associate member of the Acoustical Society of America. (Photo by John F. Cook)



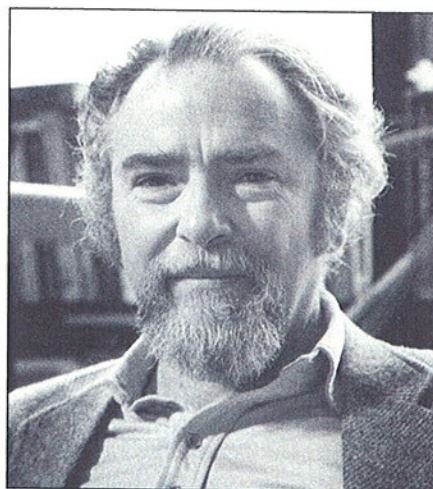
**Dr. Joseph S. Perkell** (SB '62, PhD '74), Senior Research Scientist in the Speech Communication Group, was elected fellow of the Acoustical Society of America in May 1992. Dr. Perkell was cited by the society for his contributions to the measurement and modelling of speech production. His current research involves a series of experiments to explore the control and coordination of speech articulatory movements. Dr. Perkell also studies the influence of hearing on the speech production of cochlear implant patients and the underlying mechanisms in certain types of voice disorders. (Photo by John F. Cook)

**Dr. William F. Schreiber**, Professor Emeritus of Electrical Engineering and Computer Science, was awarded the 1992 Journal Award of the Society of Motion Picture and Television Engineers (SMPTE) for the fourth time in his career. Dr. Schreiber, a fellow of the society, was cited for his article, "Considerations in the Design of HDTV Systems for Terrestrial Broadcasting,"



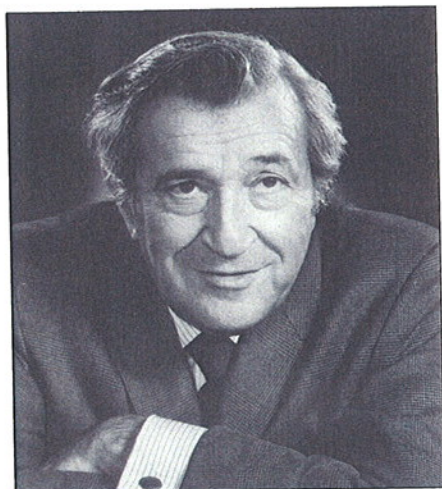
**Dr. William F. Schreiber**

which was selected as the year's most outstanding paper. The article appeared in the September 1991 *SMPTE Journal*. The Journal Award was presented to Dr. Schreiber on November 10, 1992, at the 134th SMPTE Technical Conference in Toronto. (Photo by John F. Cook)



**Dr. Thomas F. Weiss** (SM '59, PhD '63) was appointed Thomas and Gerd Perkins Professor of Electrical Engineering in May 1992. The goal of the newly established professorship in the Department of Electrical Engineering and Computer Science is to advance the fields of electrical engineering with an emphasis on areas of potential importance to human health. Professor Weiss is an investigator in RLE's Auditory Physiology Group and explores the ear's cochlear mechanism by which sound stimuli are encoded into auditory nerve signals. He recently developed *Quantitative Physiology: Cells and Tissues*, the first in a series of bio-

engineering subjects as part of the department's bioelectrical engineering option. (Photo by John F. Cook)

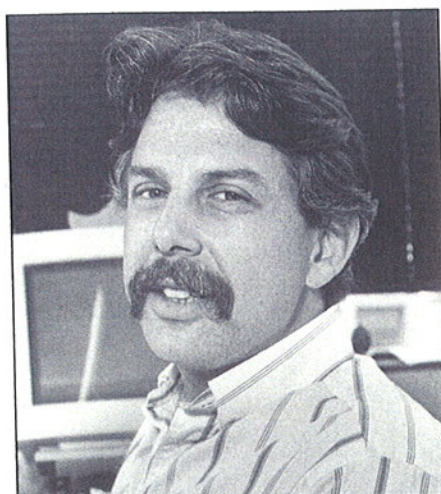


**Dr. Jerome B. Wiesner**, President Emeritus of MIT and Director Emeritus of RLE, received the National Science Board's Vannevar Bush Award at a ceremony in Washington, DC, on April 29, 1992. The Bush Award recognizes senior statesmen of science whose out-

standing public service activities contribute significantly to the national welfare. Dr. Wiesner was honored for his role to further public understanding of the risks of nuclear testing while he served as presidential science advisor to Presidents Kennedy and Johnson. Dr. Wiesner's efforts led to the signing of the 1963 Limited Nuclear Test Ban Treaty by the U.S., the Soviet Union, and Great Britain. This landmark treaty barred all nuclear tests, except those underground. (Photo by Karsh)



**Dr. David L. Zeltzer** will join RLE's Sensory Communications Group on January 1, 1993 as Principal Research Scientist. A graduate of Southern Oregon State College (BS '78) and Ohio State University (MS '79, PhD '84), Dr. Zeltzer has served as Director of the Computer Graphics and Animation Group at MIT's Media Laboratory and as a faculty member of the Media Arts and Sciences Section since 1984. His



**Dr. David L. Zeltzer**

research at the Media Lab includes a study of techniques to animate realistic computer simulations of human movement and the development of an animation system to perform simple problem solving tasks. Dr. Zeltzer will work with the Sensory Communication Group to develop multisense interfaces for teleoperator and virtual environment systems. (Photo by John F. Cook)

## alumni notes



**Dr. George N. Hatsopoulos**

**George N. Hatsopoulos** (SB '49, SM '50, ME '54, ScD '56) and **William B. Lenoir** (SB '61, SM '62, PhD '65) were elected to five-year terms as team members of the MIT Corporation on June 1, 1992. Dr. Hatsopoulos, founder and chairman of the board of the Thermo Electron Corporation of Waltham, Massachusetts, was affiliated with RLE from 1960 to 1964, and conducted research in thermionic energy conver-



**Dr. William B. Lenoir**

sion. He served on the faculty of MIT's Department of Mechanical Engineering from 1956 to 1962, and continued his association with MIT as a senior lecturer until 1990.

Dr. Lenoir conducted graduate research in RLE's Radio Astronomy Group. He was a Ford Foundation postdoctoral fellow and served two years on the faculty of MIT's Department of Electrical Engineering. A for-

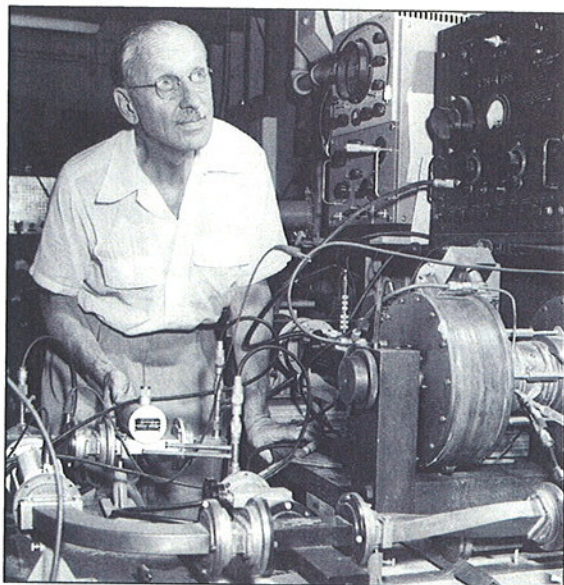
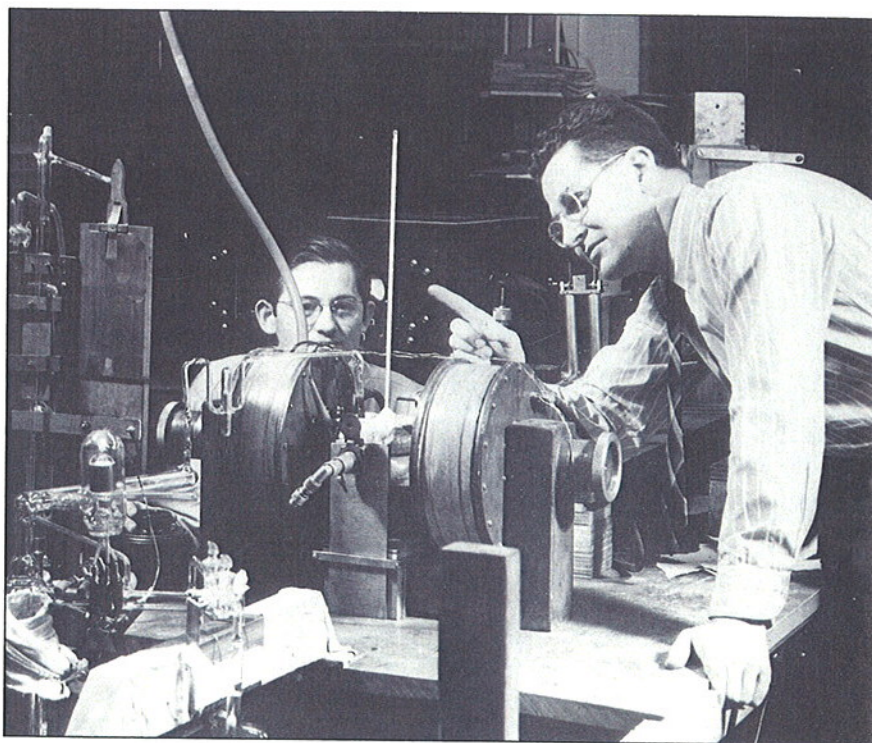
mer astronaut and administrator at NASA, Dr. Lenoir is currently vice president of Booz, Allen & Hamilton, Inc. of Bethesda, Maryland, and manages the company's Space Systems Division. The MIT Corporation is comprised of 75 leaders in education, science, engineering, and industry. It meets four times a year to discuss policy issues at MIT. Professor Hatsopoulos and Dr. Lenoir joined two life members and seven other team members in their election to the corporation. (Photos courtesy George N. Hatsopoulos and William B. Lenoir)

**Steven C. Chamberlain** (SB '68) was appointed Dean of the College of Engineering and Computer Science at Syracuse University on July 1, 1992. Dr. Chamberlain completed his PhD in sensory sciences at Syracuse and was then appointed to the university's faculty. In 1986, he became the first chairman of the new Department of Bioengineering. He recalls his undergraduate thesis work in auditory physiology at the Eaton-Peabody Laboratory under the supervision of Professor Michael Wiederhold.

# History of Plasma Physics at RLE

1949

*Gas discharges are observed in a magnetic field between the circular magnets by graduate student Benjamin Lax and Professor Sanborn C. Brown. Dr. Lax later joined the faculty in MIT's Department of Physics and became the first Director of MIT's Francis Bitter National Magnet Laboratory in 1960. Professor Brown, an experimentalist and an authority on gaseous discharges in plasmas, collaborated with Professor William P. Allis, a theorist in the field. Their combined research led to a better understanding of the behavior of microwave gas discharges and high-density plasmas. (Photo courtesy MIT Museum)*



1957

*Although highly regarded for his theoretical research, Professor William P. Allis ventures into the laboratory to inspect a magnetic cusp, one of the early magnetic bottles used in RLE to contain hydrogen plasmas. (Photo courtesy MIT Museum)*



1958

*Professors George N. Hatsopoulos and Joseph Kaye of the Mechanical Engineering Department examine a model of a new thermionic energy conversion device which they invented to convert heat directly into electricity. The thermo-electron engine operated without any mechanical parts and was built with assistance from RLE's technicians and staff members. Professor Hatsopoulos joined the RLE faculty in 1960 to investigate thermionic energy conversion. (Photo courtesy MIT Museum)*



## 1961

At the blackboard, Professor David J. Rose details the operation of the Wingerson magnetic corkscrew bottle to graduate students Richard C. Wingerson and James S. Tulenko. The corkscrew wire generated a magnetic field in the magnetic pipe which accelerated an entering gas particle. In combination with a magnetic bottle, it was anticipated that high-energy particles could be trapped to form a thermonuclear plasma.

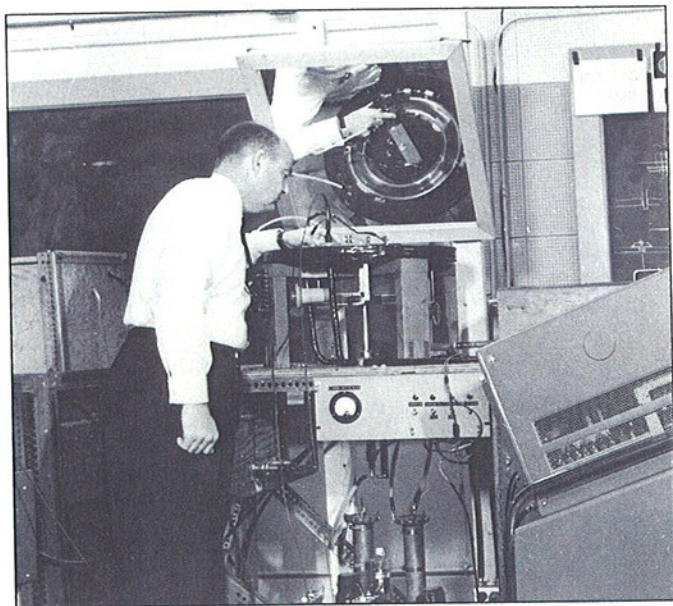
(Photo courtesy MIT Museum)



## 1962

Professor Abraham Bers (left) and graduate student Richard J. Briggs discuss beam-plasma theory related to one of their experiments. Currently, Dr. Briggs is Deputy Director of the Superconducting Super Collider Project in Dallas, Texas.

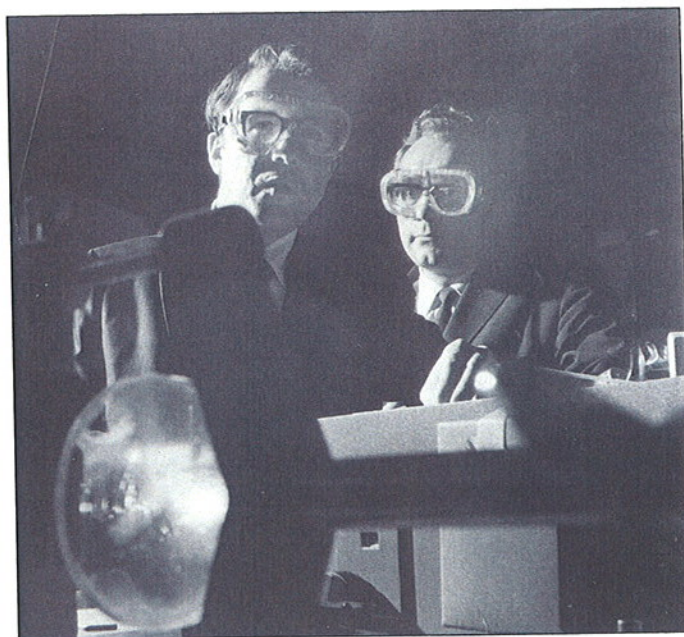
(Photo by Ivan Massar/Black Star)



## 1963

Professor Herbert H. Woodson studies turbulence and wave motion phenomena related to magneto-hydrodynamic energy conversion.

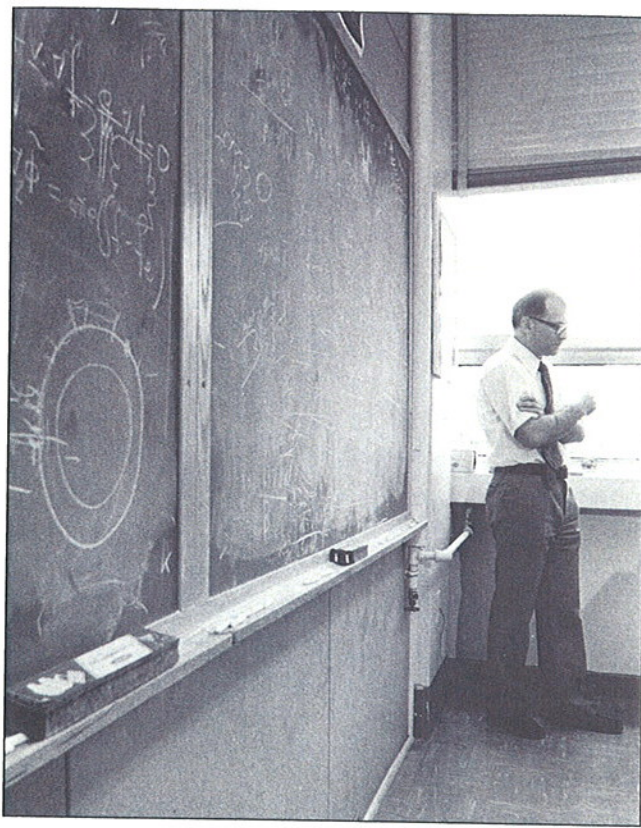
(Photo by Phokion Karas)



## 1970

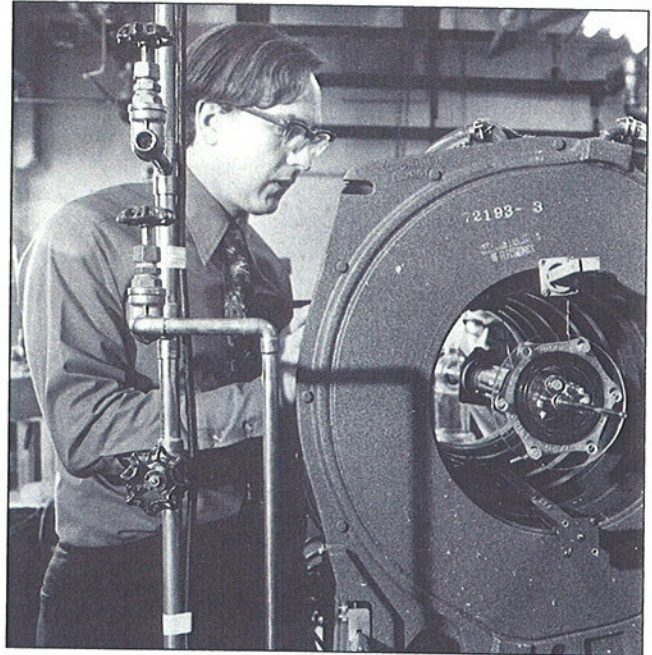
Professors E. Victor George (left) and Hermann A. Haus use a high-pressure carbon dioxide laser to observe laser-plasma interactions and the characteristics of self-pulsing, a form of self-modelocking in a laser.

(Photo by John F. Cook)



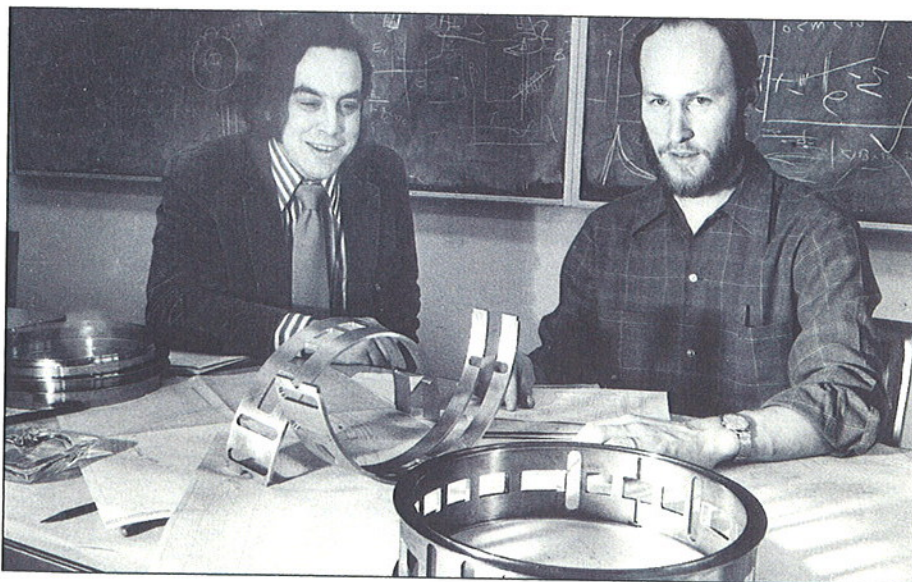
1971

*Professor Bruno Coppi is absorbed in thought as he works on a design for Alcator, a new toroidal magnetic confinement machine. Alcator (from the Latin alto campu toris, or high-field torus) had the same basic design elements of the Russian tokamaks, but its stronger magnetic field of 130,000 gauss enabled very high induced heating currents, a more rapid heating rate, and much higher electron temperatures. (Photo by John F. Cook)*



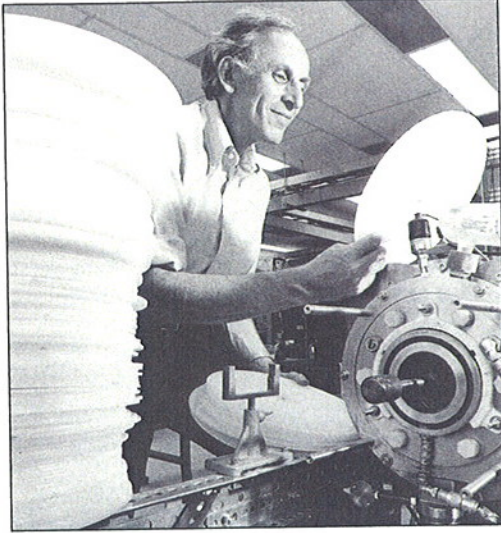
1971

*Plans for the new Alcator tokamak are the topic of discussion between Professor Lawrence M. Lidsky (left) and Dr. D. Bruce Montgomery, group leader and high-field magnet designer from MIT's National Magnet Laboratory. (Photo by John F. Cook)*



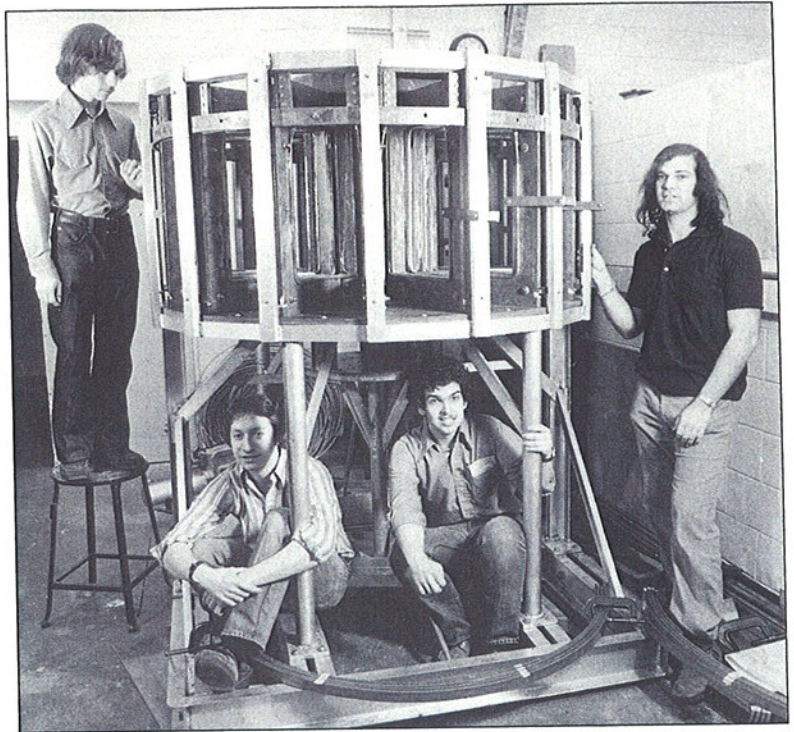
1971

*Professor Ronald R. Parker, Project Manager for the Alcator experiment and now Director of MIT's Plasma Fusion Center, examines equipment for microwave scattering in a plasma. (Photo by John F. Cook)*



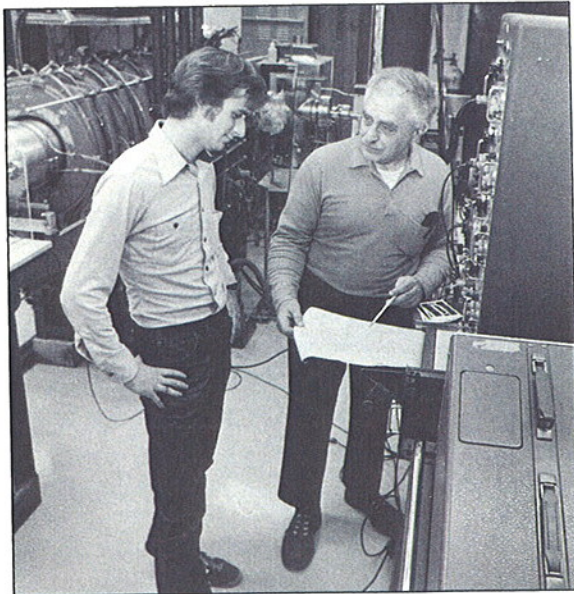
1971

Professor George Bekefi checks the operation of an accelerator switch on a relativistic magnetron device which he designed. (Photo by John F. Cook)



1976

The building of a new tokamak, Versator II. Members of Professor George F. Bekefi's construction team include (from left): graduate students Alan S. Fisher, Jonathan B. Green, Manuel T. Gonzalez, and Burton Richards. Versator II was the first American tokamak to demonstrate noninductive, radio-frequency power-driven plasma currents. These studies have been extended to novel wave-launching plasma regimes where self-generated "bootstrap currents" are expected to contribute significantly to plasma current. (Photo by John F. Cook)



1978

Graduate student Robert E. Klinkowstein (left) and Professor Louis D. Smullin use Constance I to study electron cyclotron resonance heating and the plasma instabilities that limit the lifetime of highly ionized plasmas in mirror confinement machines. (Photo by John F. Cook)



1986

Professor Thomas H. Dupree developed the first complete theoretical analysis of cyclotron emission and bremsstrahlung. His pioneering research into the statistical mechanics of nonlinear wave-plasma interactions and the properties of plasma turbulence contributed to the fundamental understanding of nonlinear theory and the prediction of "clumps," fluctuations of local phase density in turbulent plasmas. (Photo by John F. Cook)

## Lights Out for Last LINC

"LINC is now operational!" This handwritten log entry on May 5, 1964, by Robert M. Brown, Chief Engineer at the Eaton-Peabody Laboratory of Auditory Physiology (EPL) of the Massachusetts Eye and Ear Infirmary, heralded twenty-eight years of service for EPL's Laboratory Instrument Computer (LINC). On June 9, 1992, the beeps, gongs, and flashing lights were switched off for the final time on what is believed to have been the last LINC in regular use.

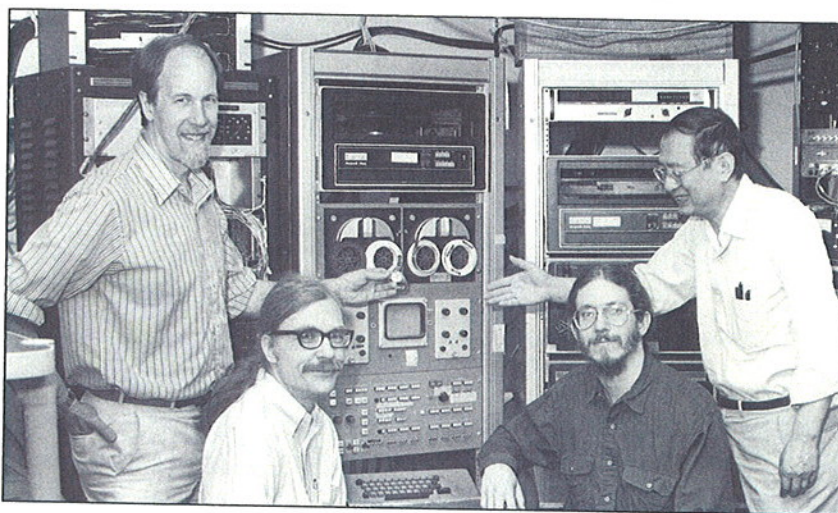
The original LINC was designed in 1962 by MIT's Lincoln Laboratory Group 51, led by William N. Papian (SB/EE '48). Lincoln's Wesley A. Clark (EE '55) designed the logic and colleague Charles E. Molnar (ScD '66) performed the engineering. At a prototype demonstration later that year, the system's digital logic and stored program won acclaim as the first interactive personal computer.

Earlier, in 1958, several members of RLE's Communications Biophysics Group, headed by Professor Walter A. Rosenblith, had collaborated with Wesley Clark to produce the Average Response Computer (ARC-1). ARC was used in the late '50s and early '60s to average evoked responses of the brain to sensory stimuli. The ARC experience led Wesley Clark to propose to the National Science Foundation and the National Institutes of Health an MIT effort that would bring innovative computer technology to bear on basic research in biology and medicine.

In 1963, parts, space, and personnel were assembled at 292 Main Street in Kendall Square, Cambridge. Applicants from across the country gathered to learn LINC's new technology. RLE technician Daniel W. Calileo had wired the first LINC while on assignment to Lincoln Laboratory and joined the Cambridge team in the summer of 1963. He recalls that ten LINC's were built in June and ten in July. Before the program and its spin-offs finally ended, about sixty LINC's had been assembled. In the late '60s, the Digital Equipment Corporation marketed the LINC-8, which evolved into the PDP-12.

The recently retired LINC at Eaton-Peabody Laboratory was built in 1963. Using software produced by

Mary Allen Wilkes, LINC was wed to a clock designed at EPL to measure the responses of single fibers in the auditory nerve to acoustic stimuli. Clicks, tones, noise, and bursts of tone and noise were presented to the subject, then spike discharges of the nerve fibers were measured. Statistical properties of the spikes were computed by LINC on-line, and gave investigators immediate feedback on single-fiber responses. Built by Bob Brown, the clock's two channels and five-microsecond operating resolution made the combined system difficult to improve upon, even with rapid



*After twenty-eight years of continuous service, LINC is presented the traditional retirement honors, a gold watch and a handshake, by Dr. John J. Guinan, Jr. (SB '63, SM '64, PhD '68), EPL Assistant Director/RLE Research Scientist (left), and Professor Nelson Y.S. Kiang, EPL Director/RLE faculty member (right). Both David A. Steffens (SB/EE '69), EPL Chief Engineer/RLE Research Affiliate (seated left), and Ishmael J. Stefanov-Wagner (SB/EE '74), EPL Research Support Engineer/RLE Research Affiliate, have worked with LINC for the last nineteen years. LINC's new home will be the MIT Museum, where it will serve as a reminder of early collaborations between engineers and health scientists to provide flexible, on-site computational resources for research laboratories. (Photo by John F. Cook)*

advances in computer hardware occurring almost daily. The LINC system proved so reliable that there was little need to modernize its functions.

This year, however, EPL Research Support Engineers/RLE Research Affiliates Frank S. Cardarelli and Ishmael J. Stefanov-Wagner (SB/EE '74) finally designed and built an event timer that was compatible with other more modern computers. Teamed with a Macintosh II-fx computer, the timer's three channels and one-microsecond resolution gave reason, LINC computed, for it to retire at last.

*by John F. Cook*