



DEPARTMENT OF APPLIED PHYSICS
C o l u m b i a U n i v e r s i t y

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Introduction

The Department of Applied Physics was established at Columbia in 1978, as part of the Graduate School of Arts and Sciences (GSAS) and the School of Engineering and Applied Science (SEAS), to bring together applied physics and applied mathematics in an environment that would foster growth and cooperation. In 1989, a Division of Applied Mathematics was formed within the department to recognize the growing role played by applied mathematics.

The department offers undergraduate majors in applied physics and applied mathematics and graduate programs in applied physics, applied mathematics, and nuclear engineering. There is extensive interaction and cooperation with other Columbia science and engineering departments and research laboratories. Research is focused in the areas of Plasma Physics and Controlled Fusion, Space Plasma Physics, Quantum Electronics, Solid State Physics, Nuclear Engineering, and Applied Mathematics.

Columbia's Department of Applied Physics is a leading university center for magnetic fusion energy development and free-electron laser research. The first university-based experiments on collective regime free-electron lasers were carried out in our Plasma Physics Laboratory. The department's active research in laser science and solid state physics spans a wide range including Raman and femtosecond laser spectroscopy, semiconductor physics, and *in situ* processing for microelectronics. With the recent addition of M.K. Wu (co-discoverer with Paul Chu of high temperature superconductivity) to our faculty, a new laboratory has been set up for research on high temperature superconductivity. Our applied mathematics research centers on the theory and application of dynamical systems and on large-scale scientific computation, including collaborative research on global climate modeling at



NASA's Goddard Institute for Space Studies. Recent books by faculty members include *Fusion Energy* by R.A. Gross, *Free Electron Lasers* by T.C. Marshall, and *Chaos and Integrability in Nonlinear Dynamics* by M. Tabor.

Presently, 19 full-time faculty members, 6 research scientists, and 100 graduate students contribute to the departmental research effort. A regular series of seminars and colloquia encourage communication and discussion of current research at Columbia as well as at other universities and research laboratories.

Undergraduate Programs

The department's undergraduate majors in applied physics and applied mathematics prepare students primarily for graduate study but also for beginning professional careers. These intensive programs are for the well-prepared student who knows that he/she wants to apply modern science and mathematics to the solution of technical problems. The student should want to be engaged in the challenge of developing new technologies and to work at the forefront of applied science. There is a wide choice of technical and nontechnical electives at Columbia to suit most students' special interests. All SEAS undergraduates share the renowned Core Curriculum with Columbia College undergraduates during their freshman and sophomore years. The Undergraduate Research Involvement Program provides opportunities for undergraduates to work on projects with individual faculty members.

The BACHELOR OF SCIENCE PROGRAM IN APPLIED PHYSICS stresses the basic physics that underlies most developments in engineering and the mathematical tools that are important to both physicists and engineers. Since advances in most branches of technology lead to rapid changes in state-of-the-art techniques, the Applied Physics Program provides the student with a broad base of fundamental science and mathematics while retaining the opportunity for specialization through technical elective choices in the areas of applied mechanics, basic physics, plasma physics, quantum electronics and laser systems, solid state physics, and nuclear science.

The BACHELOR OF SCIENCE PROGRAM IN APPLIED MATHEMATICS prepares the student to use mathematical concepts and techniques

for solving problems in various fields of science and engineering. By its very nature, applied mathematics occupies a central position in the interplay between pure mathematics, the physical sciences, and engineering. Compared with pure mathematics, applied mathematics is more interested in problems coming from other fields. Compared with engineering and the physical sciences, it is more concerned with the formulation of problems and the nature of solutions. Compared with computer science, it is more concerned with the accuracy of approximations and the interpretation of results. Studies include sharply focused training in mathematics as well as courses in fields of application.

Questions about undergraduate admissions procedures, financial aid, and housing should be addressed to the Office of Admissions, School of Engineering and Applied Science, 530 Seeley W. Mudd Building, Columbia University, 500 West 120th Street, New York, New York 10027 (212-854-2931).



Graduate Programs

DOCTORAL DEGREE

The department offers doctoral degree programs in applied physics and in nuclear engineering and an interdepartmental graduate research program in applied mathematics. Within the applied physics program, students specialize in plasma physics, solid state physics, quantum electronics, or applied mathematics. Because of the diversity of the Columbia environment, students in all programs have a wide range of research options.

Course requirements for each graduate student are determined individually. Previous training and specialized research interests are weighed. First-year students work with an assigned advisor until they choose a research sponsor, who also serves as permanent advisor. Sponsors are selected from among the department faculty, joint faculty members, and other engineering and science faculty.

All students take a written qualifying examination at the end of the first year. In addition, an oral examination is required, usually before the end of the second year. As part of the oral examination, applied physics and applied mathematics candidates formally present their thesis proposals.

Course work for the doctorate is generally completed during the first two years. Research work is begun during or at the end of the first year. Doctoral candidates are expected to complete degree requirements and defend their theses within five years of residence at Columbia.

Research seminars are an intrinsic part of graduate training, and students are expected to attend department seminars and colloquia, beginning in their first year. Department-wide research conferences are held Friday mornings when advanced graduate students and faculty members present work-in-progress. Weekly outside speakers present talks at the Plasma Physics Colloquia, the Applied

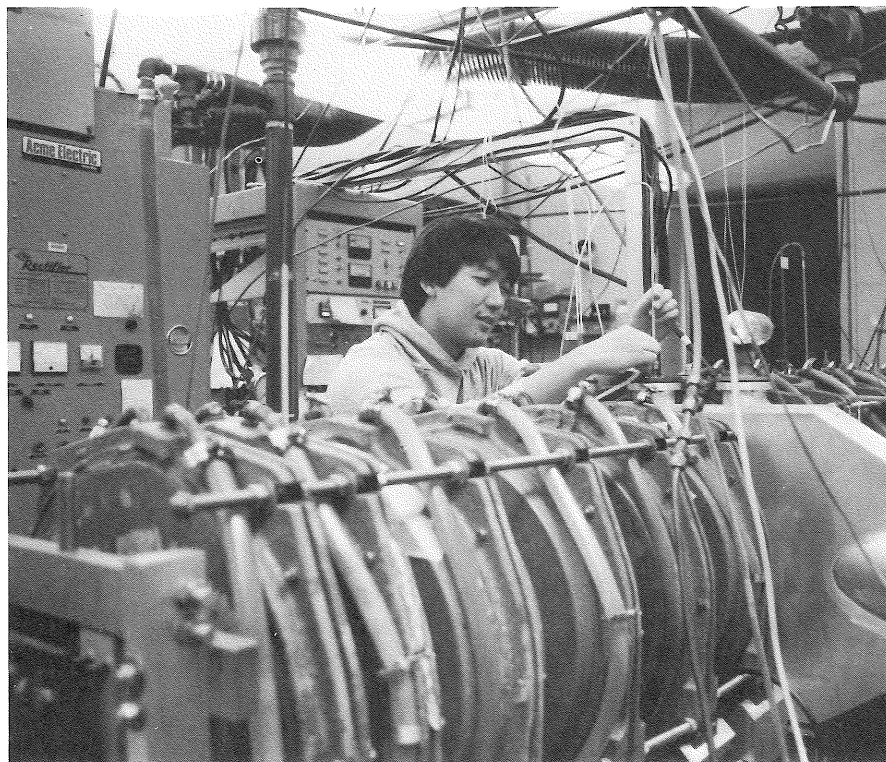
Mathematics Colloquia, and the seminar series of the Microelectronics Sciences Laboratories and the Columbia Radiation Laboratory. Both outside speakers and Columbia faculty and students participate in the Nuclear Engineering Seminars.

The department has been highly successful in placing all its graduates in leading research and academic institutions.

MASTER'S DEGREE

The department offers master's degree programs in applied physics and in nuclear engineering. Students can pursue a master's degree before continuing on to a doctorate or as a final degree. Primary areas of specialization at the master's level include plasma physics, quantum electronics, solid state physics, applied mathematics, and nuclear engineering.

Thirty points of course work are required for the degree. The specific direction of the program is determined for each student individually, and can be heavily weighted toward a specific area. Although no thesis is required for a master's degree, many master's students choose to perform research for which they are granted degree credit. Lists of approved courses for the master's degree in applied physics and the master's degree in nuclear engineering are available from the department office. All required nuclear engineering courses are available in the late afternoon and evening, making it possible to complete the master's program in nuclear engineering as a part-time student.



Research Programs / Laboratories

Plasma Physics Laboratory

The Plasma Physics Laboratory was founded in 1961 and is an integral part of the department. It is an experimental research facility devoted to the study of basic and applied plasma physics in a broad range of applications. Several experimental projects are underway. The Columbia High-Beta Tokamak (HBT) supports the national program to develop controlled fusion energy. The Free-Electron Laser facility, which is powered by a pulsed relativistic electron beam accelerator, studies collisionless plasma

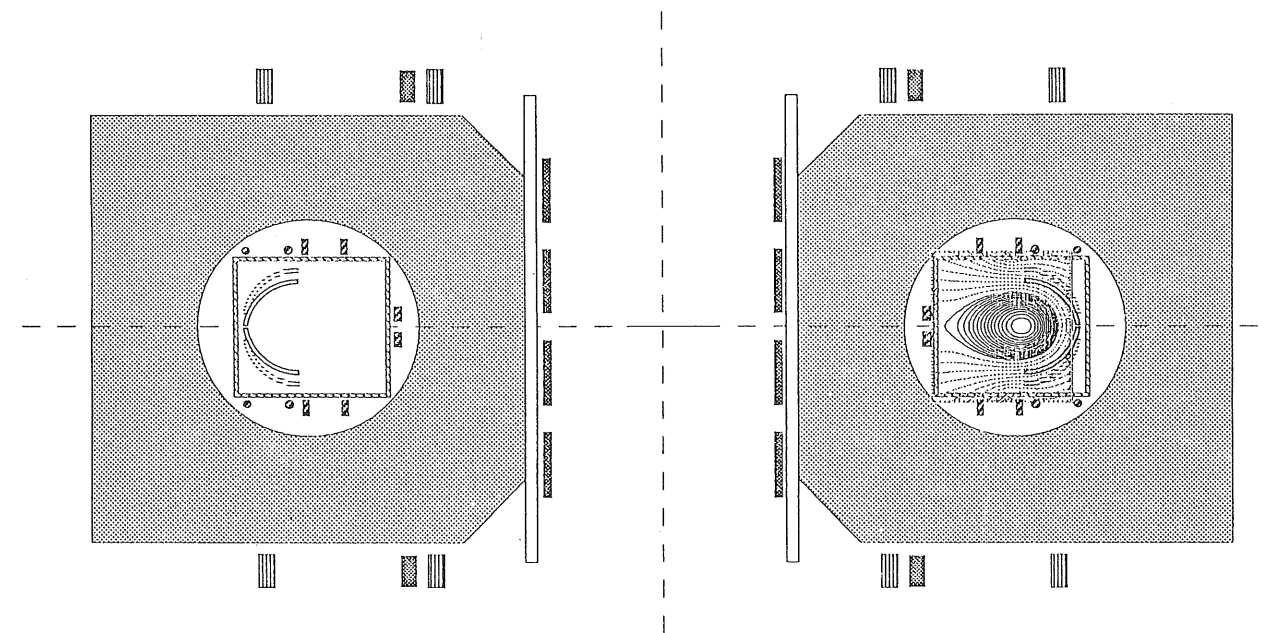
instabilities, plasma transport, and active feedback stabilization of plasma instabilities.

As a major university research center in controlled fusion research, Columbia's laboratory is very well-equipped with laser and magnetic plasma diagnostics as well as two VAX 11/750s. The VAX systems are networked to several PDP-11 computers for data acquisition which are part of the departmental computer network.

In addition to the experimental effort, there is a broad program in theoretical and computational plasma physics, with applications to fusion, space plasmas, and free-electron lasers. Recent research interests of the theory

group include magnetohydrodynamic (MHD) equilibrium and stability, transport and the dynamo effect in turbulent plasmas, and optical guiding and sideband instabilities in free-electron lasers.

Support for these research programs comes from the U.S. Department of Energy, the National Science Foundation, the National Aeronautics and Space Administration, and the Office of Naval Research.



Schematic of the new tokamak, HBT-EP, under construction in the Plasma Physics Laboratory.

Research Programs / Laboratories

Applied Mathematics

Research in applied mathematics is centered around two foci: nonlinear dynamics and large-scale scientific computing.

In nonlinear dynamics, there is intensive study of integrable and nonintegrable nonlinear differential equations, including chaos and its relationship to turbulence, soliton mathematics, and polymer physics. Professor Michael Tabor as well as Professors Edward Spiegel (Astronomy), Christopher Durning (Chemical Eng.), Ben O'Shaughnessy (Chemical Eng.), Philip Pechukas (Chemistry), Rene Chevreay (Mechanical Eng.), and Drs. Gregory and David Chudnovsky (Mathematics) are among those collaborating on many problems in these exciting research areas. Research has been supported by

the Office of Naval Research, the Department of Energy, and the National Science Foundation.

In large-scale scientific computation, work is active in plasma physics, fluid dynamics, and oceanography. In plasma physics, Professors C. K. Chu and Amitava Bhattacharjee have been involved recently with the problems of equilibrium and stability of rotating plasmas. The work is in conjunction with the experimental group in the Plasma Physics Laboratory, and is supported by the Department of Energy. In fluid dynamics, our department is particularly known for its work in grid generation used in aerodynamic computations, through the work of Dr. Peter Eiseman, which has been supported by NASA and the

Air Force Office of Scientific Research. In oceanography, Professor Chu, Dr. Mark Cane (Lamont-Doherty), and Dr. Inez Fung (NASA Goddard Institute for Space Studies) work together on global ocean circulation, which is needed for accurate climate predictions. The work is supported by NASA and the Environmental Protection Agency.



Phase plane of particle orbits in a two-dimensional fluid.

Nuclear Engineering Research

Graduate research in nuclear science and engineering at Columbia is concerned primarily with the transport of ionizing radiation in matter. Radiation, as it moves through matter, both affects and, in turn, is affected by that matter. Particular emphasis is placed on the transport perturbations that result from any inhomogeneities in materials and possible fluctuations in the energy dependence of radiation-associated material properties.

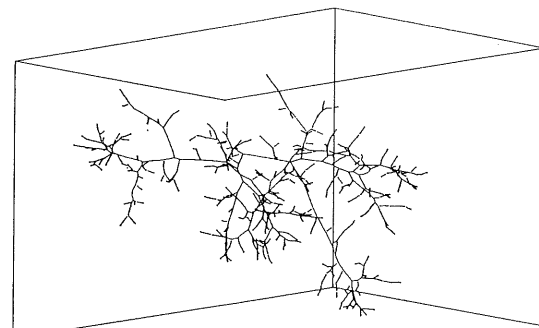
The perturbing effects of the rapidly varying energy dependence of neutron cross-sections are treated to relate uncertainties in calculations on neutron flux and core reactivity to uncertainties in those data. Some of the techniques developed may be applicable to the design of next-generation reactor cores. Neutron transport in fission reactor structures is studied to gain knowledge and understanding of radiation damage to those structures. The current focus is

on pressure vessel studies applied to specific pressurized water reactors.

Medical topics are treated ranging from radiotherapy to *in vivo* element analysis and the modifications to tomographic measurements that result from inhomogeneities in the subject under investigation. Spectral emission and transmission tomography techniques have similarly been applied to non-destructive analysis on other than biological systems. Research in these areas is carried out with associated medical centers as well as

with Brookhaven National Laboratory.

Nuclear waste disposal and reactor safety are issues of continuing interest at Columbia, as they are nationally. Research in multi-phase heat transfer and its impact on reactor safety have been studied, often in conjunction with the Heat Transfer Facility of the Department of Chemical Engineering and Applied Chemistry. Cooperative research in these areas can also be carried out with members of the Department of Mechanical Engineering.



Simulation of radiation-induced damage cascade in steel.

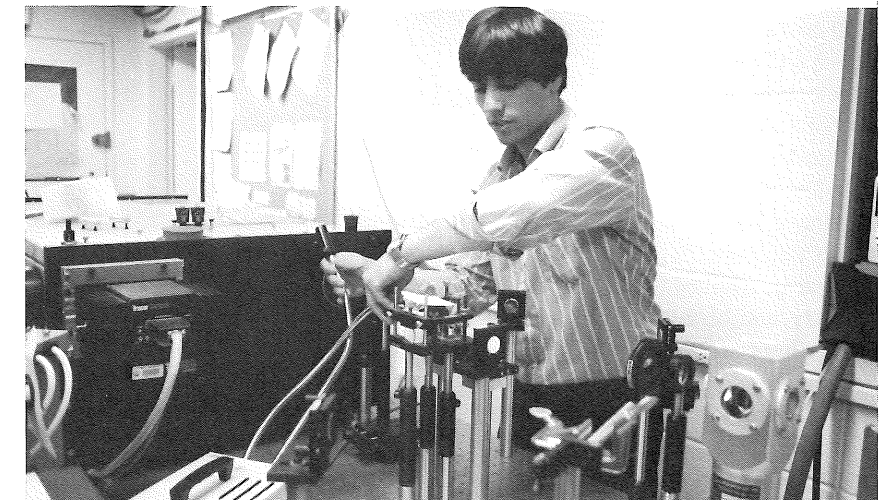
Laser Diagnostics and Solid State Physics Laboratory

The Laser Diagnostics and Solid State Physics Laboratory conducts studies in laser spectroscopy of semiconductor thin films and superlattices, and laser diagnostics of thin film processing, in association with the Microelectronics Sciences Laboratories and the Columbia Radiation Laboratory. The Laser Lab focuses primarily on the study of materials under high pressure, laser surface chemical processing, and new semiconductor structures.

Semiconductors under current scrutiny include germanium-silicon alloys and II-VI semiconductors, such as zinc selenide. Further understanding of these materials is expected to advance microelectronics and optoelectronics.

The development of new optical spectroscopic methods for materials diagnostics is also being pursued in the laboratory. The Raman microprobe,

laser-induced fluorescence, and photoluminescence are among the optical methods under investigation.



High Temperature Superconductivity Laboratory

Research in the High Temperature Superconductivity Laboratory aims at better understanding the science and technology of high temperature superconducting materials. Current investigations emphasize two areas: 1) investigating the feasibility of raising the critical current density in bulk oxide superconducting composite material through a dispersion of fine metal oxides, and 2) understanding the basic mechanism responsible for high transition temperature through detailed characterization of electrical, magnetic, and optical properties of superconducting oxides.

In working to optimize bulk superconducting properties, the composites and composite material interactions and compatibility are examined. Studies are carried out to determine the optimum heat treatment conditions such as temperature, oxygen pressure, and cooling rate. A sputtering system has been constructed to

study the process of fabricating high quality superconducting thin films using ion-assisted sputtering.

Various high T_c oxides are doped with oxygen and cations to examine the correlation of magnetic and optical properties and structure with doping. The information obtained is used to establish the correlation between magnetism and superconductivity, and to understand superconductivity from its normal state electrical and optical properties. A wide range of experimental methods are used, including X-ray crystallography, electron microscopy, infra-red spectroscopy, Raman scattering, and electrical and magnetic properties characterization.

The laboratory is equipped with various types of high temperature furnaces, AC and DC electrical resistivity measurement apparatus, an AC magnetic susceptometer, a X-ray diffraction unit, a scanning electron

microscope, and a transmission electron microscope. In association with the Laser Diagnostics and Solid State Physics Laboratory and the Microelectronics Sciences Laboratories, various optical spectroscopy and surface characterization facilities are also available.

Research Programs / Laboratories

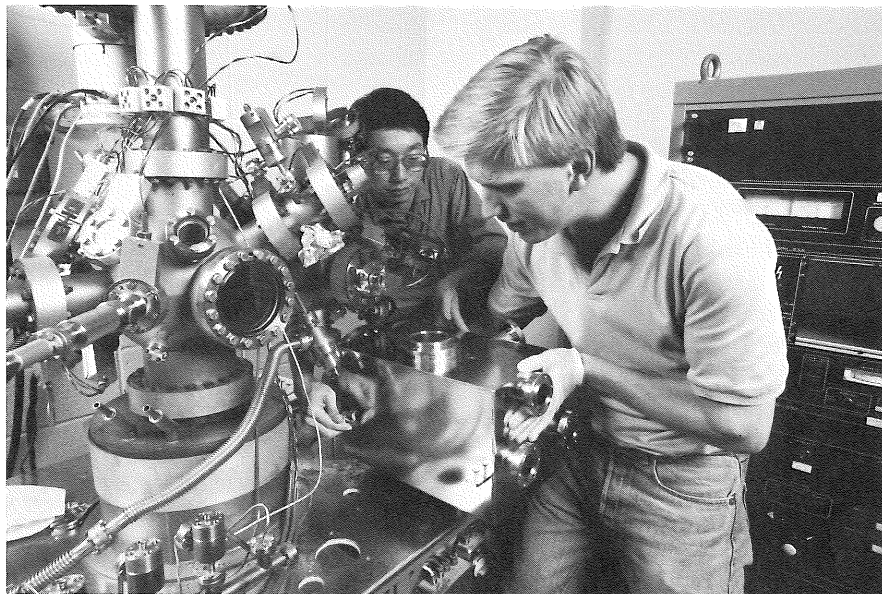
Microelectronics Sciences Laboratories

In 1982, Columbia University, in cooperation with the School of Engineering and Applied Science and the Columbia Radiation Laboratory, established a center for fundamental research and education in the microelectronics sciences: the Columbia Microelectronics Sciences Laboratories (MSL).

MSL is by its nature interdisciplinary, with affiliated faculty from the departments of Electrical Engineering, Applied Physics, Chemistry, and Metallurgy and Material Science.

Annual funding for the Columbia Microelectronics Sciences Laboratories is at present approximately \$3 million. Primary funding is provided by the Office of Naval Research and the IBM Corporation. Additional government funding comes from the National Science Foundation (in part through Columbia's National Center for Telecommunications Research) and the Department of Defense (through the Joint Services Electronics Program, Air Force Office of Scientific Research, Army Research Office, and DARPA). Substantial funding also comes from industry, including AT&T and the Semiconductor Research Corporation. Such funding helps to support thirteen faculty, five research associates, and numerous graduate students and support staff.

Primary research includes work in ultra-high-speed electronics, advanced maskless processing, advanced optoelectric and imaging devices, and surface science. In each of these areas, precise understanding of the phenomena through basic studies is emphasized. MSL's philosophy is to anticipate the future needs of industry and government in developing basic and applied research programs. This approach has brought MSL to the forefront in laser direct writing, charge-coupled devices, and optoelectronic high-speed sampling techniques.



Wide-ranging facilities are available to support diversified research programs. Research in the area of metal-semiconductor and semiconductor-semiconductor contacts utilize specially designed high vacuum chambers which are also used to study laser oxidation of surfaces. Analytical equipment, which includes XPS, ISS, AES, SIMS, and STM take an active role in interface studies. A fully equipped clean room and molecular beam epitaxy system allow the development of quantum well optoelectronic devices. The laser diagnostics and laser processing

laboratories are leaders in maskless processing and thin film analysis. Many MSL facilities will move to the adjoining Center for Engineering and Physical Science Research building, presently under construction.

The broad spectrum of knowledge at the MSL enables the university to maintain a leading position in silicon, GaAs, and other compound semiconductor research.

The Columbia Radiation Laboratory

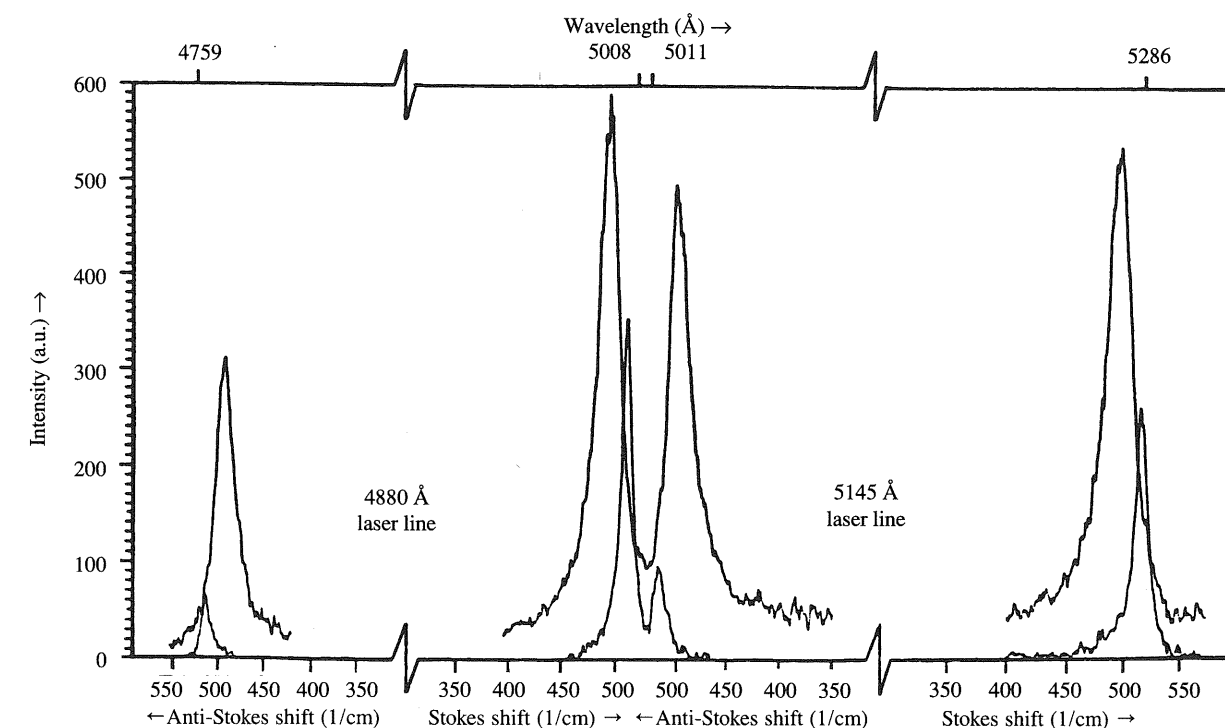
The Columbia Radiation Laboratory (CRL) was organized in 1942 by the late, Nobel Prize winning Professor I. I. Rabi, and has since been a leader in many fields of research on electromagnetic radiation. CRL's research has ranged from microwave tube work during World War II, to microwave spectroscopy, the discovery of the Lamb shift, and the invention of the maser in the 1950's, to laser development, spectroscopy and astrophysics in the 1960's and 1970's. CRL's current direction involves coupling optical physics and electronics.

Current Columbia Radiation Laboratory activities involve modern optical and electronics research through three broad areas of activity: (1) solid-state electronics and

optoelectronics; (2) quantum detection and generation, control of optical radiation, and nonlinear optics; and (3) energy transfer and chemical dynamics as related to quantum electronics and microelectronics. The program integrates research in solid-state and quantum electronics with fundamental investigations of physical and chemical phenomena in both physics and chemistry. Quantum electronic devices are being used to develop better microelectronic etching techniques, to study solid-state electronic materials, to investigate collisional energy transfer processes, and to study fundamental

photochemical events which impact on laser photoetching techniques. Developing better methods for control and generation of short and long wavelength radiation is a prime concern.

Primary support of the Columbia Radiation Laboratory comes from the Joint Service Electronics Program through the Army Research Office. Faculty from the departments of Applied Physics, Electrical Engineering, Chemistry, and Physics are associated with CRL.



Raman microprobe analysis of silicon.

Research Programs / Laboratories

NASA Goddard Institute for Space Studies

The Institute for Space Studies, part of the Goddard Space Flight Center of the National Aeronautics and Space Administration, is located at Broadway and 112th street (Armstrong Hall), adjacent to the Morningside campus. The Institute conducts theoretical and experimental research in astrophysics, planetary atmospheres, and climate.

The planetary atmospheres program includes theoretical studies of structure, radiative transfer, and dynamics of the atmospheres of Mars, Venus, and the giant planets, and participation in experimental studies conducted from space probes. The climate program involves basic research on the nature of climate change and climatic processes,

including the development of numerical climate models. The work is aimed at using space-acquired data in climate analysis and prediction, and understanding the paleoclimatic data collected by Columbia University's Lamont-Doherty Geological Observatory in Palisades, New York.

Research at the Institute is carried out in collaboration with Columbia and other universities in the metropolitan area. Institute members hold faculty appointments, give courses, and supervise graduate research in fields related to the Institute program.

The Institute holds colloquia, scientific conferences, and summer training programs in which members of the University community

participate. Opportunities for visiting scientists to conduct research are provided by a post-doctoral research associate program, administered by the National Academy of Sciences-National Research Council and supported by the National Aeronautics and Space Administration.

Computer Facilities

The departmental computer facilities include two VAX 11/750s, two multi-user VAX 2000 workstations, and several smaller computers, all connected to a high-speed network. The VAX workstations and several other networked terminals are located in the recently dedicated Richard J. Meehan Computer Room. A Macintosh local area network is available for word processing and graphics. A PDP 11/55, a PDP 11/73, and a PDP 11/23 act as dedicated data acquisition / data analysis systems for the Plasma Laboratory. A PDP 11/20 is used with suitable instrumentation for nuclear radiation measurement experiments. These and several IBM PS-2's have graphics capabilities and are available to students and staff of the department. The department's local area VAX

network is also linked to the CRAY 1 and CRAY 2 supercomputers at the National Magnetic Fusion Energy Computer Center in Livermore, California.

Several University computer systems are also available including

the IBM 4381 and VAX 8700 which are useful in moderate- to large-scale computations in time-sharing mode. Three Sun 4/280 systems are used primarily for instruction.



Faculty Research Profiles

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David H. Auston

Professor (Quantum Electronics and Solid State Physics)
Joint Member of EE and AP Departments
B.A.Sc., Toronto, 1962
M.A.Sc., 1963
Ph.D., California (Berkeley), 1969

My work focuses primarily on the area of high-speed optics and electronics, and its applications to the measurement of the properties of materials and devices. While at AT&T Bell Laboratories, I developed a new approach to the measurement of the high-speed properties of materials and devices which uses picosecond and femtosecond lasers to probe the electronic response of semiconductor materials, devices, and circuits. This measurement technique, known as ultrafast optoelectronics, permits the generation and measurement of electronic signals with a time resolution as fast as 250 femtoseconds. A wide range of applications of this approach have been pursued, including the measurement of the dynamics of hot electrons in semiconductors, the relaxation of phonons and polaritons in crystals, and the electronic response of high-speed optical and electronic devices such as field effect transistors and photodetectors. In a recent experiment, the relaxation of optically injected electrons in a sample of gallium arsenide was studied by measuring the rise time of the photoconductivity with femtosecond electrical pulses. The technique for generating femtosecond electrical pulses is to use nonlinear optical crystals in which optical rectification occurs producing a very fast electrical pulse from an optical pulse by removing the optical carrier frequency. This technique, known as electro-optic Cherenkov radiation, has been shown to be capable of producing the fastest electrical pulses that can be produced by any technique.

A new ultrafast optoelectronics research laboratory has been established at Columbia for work in this area. Two complete high-speed laser systems are being used. One is a

femtosecond dye laser system operating at 600 nanometers which produces optical pulses having a duration of 30 femtoseconds. An optical amplifier system increases the pulse energy by a factor of 10,000 for experiments requiring very high optical intensities. A second laser system uses a different approach to produce tunable sub-picosecond pulses in the near infrared region of the spectrum. It is intended for use in experiments involving resonant excitation of semiconductor multi-quantum wells. An optical amplifier will also be added to this infrared laser to increase its power for measurements of the nonlinear optical properties of semiconductors.

A number of new research activities are currently in progress. These include an experiment in collaboration with Professor Wen Wang to study the electro-optic properties of strained layer superlattices. A related experiment will explore the possible use of these same materials to generate and detect coherent acoustic phonons in the frequency range from 300 to 1000 GHz. Research on new techniques to generate and detect femtosecond electrical pulses will also continue. One of the projects in this



area is to attempt to produce electrical pulses of 50-femtosecond duration by optical rectification in new electro-optic materials. A related research project is the generation and measurement of electric solitons in nonlinear dielectrics. Very high-speed photoconductors will also be studied with the goal of generating coherent bursts of sub-millimeter wave radiation for measurements of the properties of materials. This approach uses very high-speed photoconductors as radiating antenna structures in the frequency range from 100 GHz to 1 THz. Electro-optic measurement techniques are also being developed for the non-invasive optical probing of electrical signals in high-speed integrated circuits. In optical communications, new methods of compressing and decompressing very high-speed digital packets are being studied.

Selected Publications

"Ultrafast Optical Electronics," chapter in *Ultrashort Light Pulses, III*, edited by W. Kaiser (Springer-Verlag, Heidelberg, 1988).

"Picosecond Photoconductivity: High Speed Measurements of Devices and Materials," chapter in *Probing High Speed Electrical Signals*, edited by R. B. Marcus (Academic Press, 1988).

"Electro-Optic Generation and Detection of Femtosecond Electrical Transients," with M. C. Nuss, *IEEE J. Quantum Electron.* **24**, 184-197 (1988).

"Sub-Picosecond Photoconducting Dipole Antennas," with P. R. Smith and M. C. Nuss, *IEEE J. Quantum Electron.* **24**, 255-260 (1988).

"Direct Measurement of Carrier Mobility of Photoexcited Electrons in GaAs," with M. C. Nuss, *Phys. Rev. Lett.* **58**, 2355-8 (1987).

Amitava Bhattacharjee

Associate Professor (Theoretical Plasma Physics)
B.S., Indian Institute of Technology, 1975
M.S., Michigan, 1976
M.S.E., 1978
M.A., Princeton, 1979
Ph.D., 1981

My research interests span theoretical plasma physics (with applications to fusion and space plasmas), free-electron lasers, and Hamiltonian systems.

A focal point of my research is the theoretical study of relaxation phenomena in plasmas. These are phenomena in which magnetic reconnection plays a crucial role. My interest in this problem began with my Ph.D. dissertation. R. L. Dewar and I developed a quasi-thermodynamic method for the study of relaxation processes in which a plasma seeks states of low potential energy while it preserves certain constraints of motion. This method has produced interesting results for reversed-field pinches, tokamaks, and magnetospheric plasmas.

Another important relaxation phenomenon is the "dynamo effect." Historically, the dynamo effect was invoked to explain the sustainment of magnetic fields in astrophysical plasmas. E. Hameiri and I have formulated a self-consistent theory of the dynamo effect for laboratory plasmas. From certain rigorous properties of the dynamo, we have derived a novel Ohm's law for turbulent plasmas, and the new effect is popularly known as "hyper-resistivity." This Ohm's law gives a mechanism for the phenomenon of self-reversal observed in reversed-field pinches.

Recently, our group has been investigating the stability of rotating plasmas. Tokamaks, which are produced in the laboratory and heated by neutral beams, and Jupiter's magnetosphere are representative plasmas of this type. In particular, we have identified certain novel

instabilities which have interesting experimental and theoretical ramifications.

I am also actively involved in the free-electron laser research effort at Columbia. Our group has recently given one of the first experimental demonstrations, supported by theory, of refractive optical guiding in a free-electron laser (see Professor T. C. Marshall's profile for additional details). I have also been involved in the study of quantum effects in the free-electron laser. We have completed a theoretical study of squeezed light, quantum noise, and photon statistics in free-electron lasers.

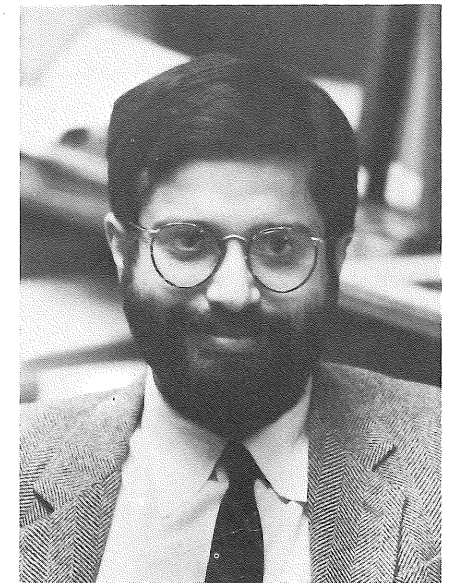
Magnetic fields are an interesting class of Hamiltonian system. I have been involved recently in the study of magnetic field topologies in systems without symmetry. This work has produced a formula for the island size in a toroidal plasma with finite pressure. These conditions have interesting implications for Euler flows in fluid mechanics as well.

The concepts and mathematical techniques of plasma physics are rich and varied. They provide an interesting point of view for many problems in space physics, astrophysics, fluid dynamics, and nonlinear dynamics. Recently, Professor A. Hasegawa and I have formed the Space Plasma Physics Group at Columbia, an area of research we hope will continue to grow. During the next decade, plasma physics is sure to broaden its base and affect the development of other branches of applied physics.

Selected Publications

"Energy Confinement in Turbulent Fluid Plasmas," with E. Hameiri, *Physics of Fluids* **31**, 1153 (1988).

"Observations of Optical Guiding in a Raman Free Electron Laser," with S. Y. Cai, S. P. Chang, J. W. Dodd, and T. C. Marshall, *Physical Review Letters* **60**, 1254 (1988).



"Generation of Squeezed Radiation from a Free-Electron Laser," with I. Gjaja, *Physical Review A* **36**, 5486 (1987).

"Relaxation of Magnetotail Plasmas," *Journal of Geophysical Research* **92**, 4735 (1987).

"MHD Equilibrium and Stability of Axisymmetric Plasmas in the Presence of Rotation," in *Theory of Fusion Plasmas*, edited by A. Bondeson, E. Sindoni, and F. Troyon (Editrice Compositori, Bologna, Italy, 1987).

"Self-Consistent Dynamo-Like Activity in Turbulent Plasmas," with E. Hameiri, *Physical Review Letters* **57**, 206 (1986).

"Energy Principle with Global Invariants for Toroidal Plasmas," with R. L. Dewar and D. A. Monticello, *Physical Review Letters* **45**, 347 (1980).

Philip H. Bucksbaum

Adjunct Associate Professor (Applied Physics)
A.B., Harvard, 1975
M.A., California (Berkeley), 1978
Ph.D., 1980

My present interest is high-intensity atomic physics, which is the study of atoms and electrons in very intense light. Tightly focused beams from modern lasers can achieve intensities of 10^{14} W/cm² or higher. As the electric field of light nears atomic strength, atoms become unstable to decay by photoionization. By studying atomic decays, we are learning about the electromagnetic interaction in this regime, where standard calculation methods such as perturbation theory no longer work well.

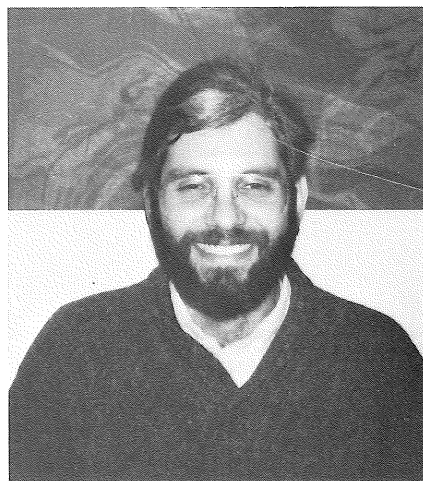
Our experiments are conducted at AT&T Bell Laboratories in Murray Hill, New Jersey, where we are developing some of the world's most intense laser sources. These lasers are so bright that the light itself can damage the lasing medium. To prevent this, we employ new techniques that stretch out short intense laser pulses into longer, less intense pulses before amplification. Then the pulses are recompressed to make ultra-intense light.

Through experiments on photoionization of rare gas atoms and simple molecules, we have seen several new high-intensity phenomena. One of the most dramatic new effects is Above-Threshold Ionization (ATI), which is the photoemission of very high-speed electrons from an atom. We now know more about the conditions necessary to produce ATI, but theory is still unable to calculate most of the features that we observe, even for the simplest atoms. Since many photons are involved in the ionization process, some features of ATI are essentially classical. However, quantum mechanics is important for many ATI phenomena, and a good theory has yet to emerge.

A second phenomenon under study in our laboratory is stimulated Compton scattering, which dominates the interaction between intense light

and free electrons. The stimulated scattering rate in our experiments can exceed the optical frequency. A free electron in this field is violently accelerated by the scattering force, which tends to expel the electron from regions of intense light. This stimulated scattering force is a powerful means to manipulate electrons. It gives rise to electron diffraction effects such as the Bragg scattering of electrons from an optical standing wave (Kapitza-Dirac effect), and also may be used to accelerate particles.

Future activities revolve around a new light source capable of intensities up to 10^{19} W/cm², using titanium-doped sapphire as a lasing material. At these intensities, accelerations become so violent that electrons become relativistic. Examples of relativistic effects are nonlinear Compton scattering and relativistic self-focusing of the light in a low density plasma, due to the mass shift of the electrons. We would also like to extend



photoionization studies into this regime, by observing effects in highly stripped ions.

My research background includes not only work on intense lasers, but also nonlinear optics, rapid melting processes, photoionization spectroscopy of solids, and even extends outside electromagnetism to the study of weak interactions. I have written a textbook on the subject of weak interactions.

Selected Publications

"Asymmetries in Above-Threshold Ionization," with M. Bashkansky and D.W. Shumacher, *Phys. Rev. Lett.* **60**, 2458 (1988).

"High Intensity Kapitza-Dirac Effect," with D.W. Shumacher and M. Bashkansky, *Phys. Rev. Lett.* **61**, 1182 (1988).

"The Ponderomotive Potential of High Intensity Light and its Role in the Multiphoton Ionization of Atoms," with R.R. Freeman and T.J. McIlrath, *IEEE J. Quantum Electron.* **24**, 1461 (1988).

"Scattering of Electrons by Intense Coherent Light," with M. Bashkansky and T.J. McIlrath, *Phys. Rev. Lett.* **58**, 349 (1987).

"Role of Ponderomotive Potential in Above-Threshold Ionization," with R. R. Freeman, M. Bashkansky, and T.J. McIlrath, *J. Opt. Soc. Am. B* **4**, 760 (1987).

Weak Interactions of Leptons and Quarks, with E.D. Commins (Cambridge University Press, New York, 1983).

C. K. Chu

Professor (Applied Mathematics and Plasma Physics)
B.S., Chiao-Tung, 1948
M.M.E., Cornell, 1950
Ph. D., Courant Institute, New York University, 1959

I work primarily in applied mathematics, particularly scientific computing. Applications include fluid dynamics, magnetohydrodynamics, shock waves, and plasma simulation.

One of my current research projects is plasma fusion simulation, in which the behavior of a magnetically confined plasma is simulated by the solution of a set of partial differential equations. Of particular interest are plasma equilibrium, stability, transport, and initial formation. Initial formation dynamics was for many years the specialty of the Columbia plasma physics group, and Columbia was noted for being a major supplier of Ph.D.'s in the field of plasma computation.

I have recently directed much of my attention toward nonlinear waves and nonlinear phenomena in hydrodynamics, and their numerical computation. In collaboration with the NASA Goddard Institute for Space Studies, I am now also active in computational studies of global ocean circulation. In particular, this involves the calculation of behavior of intensified currents, such as the Gulf Stream, using special grids, and a self-consistent study of the thermohaline convection.

What excites me about computational physics is the understanding and discovery of physical phenomena and mathematical facts through the intelligent use of the computer. In a sense, computation parallels theory and experiment as a highly effective method to study physical phenomena.



Selected Publications

"Lagrangian Turbulence in Stokes Flow," with J. Chaiken, M. Tabor, and Q. M. Tan, *Phys. Fluids* **30**, 687 (1987).

"High-Beta Tokamak Research," with R. A. Gross, G. A. Navratil, et al., *Nucl. Fusion* **25**, 1105 (1985).

"Solitary Waves Generated by Boundary Motion," with L. W. Xiang and Y. Baransky, *Commun. Pure Appl. Math.* **36**, 495 (1983).

"Two-Dimensional Simulation of the Formation of the Princeton Spheromak," with H. C. Lui and A. Aydemir, *Phys. Fluids* **24**, 673 (1981).

"Computational Fluid Dynamics," in *Numerical Methods for Partial Differential Equations*, edited by S. Parter (Academic Press, 1979).

"Numerical Methods in Fluid Dynamics," in *Advances in Applied Mechanics*, edited by C.S. Yih (Academic Press, 1977), Vol. 17.

Peter R. Eiseman

Senior Research Scientist (Applied Mathematics)
B.S., California (Berkeley), 1966
M.S., Illinois (Urbana), 1967
Ph.D., 1970

My research focuses on the numerical simulation of physical processes in a realistic setting.

That setting arises when a physical region is of a general shape or when certain physical quantities experience rapid changes. The shape of any region is, of course, determined by its boundaries, and involves geometric and topological properties. The rapid solution changes are either predictable or unpredictable, and correspondingly, adequate resolution is provided in either an *a priori* or automatic fashion. The latter case is referred to as an adaptive method since the numerical scheme must then dynamically adjust to the requirements of the evolving solution. The desire for realistic numerical simulations in physics has provided the impetus for a new subject: numerical grid generation.

Numerical grid generation was established by myself and Joe F. Thompson of Mississippi State University. It has now grown into a multifaceted topic and is a basic bridge between numerical solution algorithms for partial differential equations and the intended realistic application to physical problems.

The main problem we study is what has become known as computational fluid dynamics. In particular, a major driving force behind the development of grid generation has been aerospace applications along with the corresponding interest of industry and government.

We are applying these methods to aerospace engineering problems where internal and external flow simulations have been considered for both inviscid and viscous flows. These have varied from turbomachinery (jet engines) to full aircraft and include some activity for the aerospace plane. Specific examples are the Euler equation solutions for the flow about an

experimental aircraft configuration, being tested in the NASA Langley wind tunnels, and the adaptive simulation of a shock-vortex interaction which is important in aeroacoustics. In plasma physics, an adaptive algorithm was also developed for equilibrium studies.

The topics considered within grid generation include algebraic, elliptic, hyperbolic, and parabolic methods with various degrees of user interaction, automation, and adaptivity. This is being developed in two and three spatial dimensions and involves careful treatment of boundary curves and surfaces. When the configuration is complex, the topology of the region must be addressed in a fashion which also accounts for the anticipated physical properties. Because of the presence of physical properties such as attached boundary layers, the grid topology often assumes a more general connectivity pattern than that dictated by the continuum topology, traditionally measured by the cohomology groups from a co-chain complex.

In the treatment of topology, the most versatile template is provided by a block-structured approach. This follows the earlier continuum approach which leads to the construction of differentiable manifolds. The glue between patches or blocks, however, is different. Instead of overlaps with composed maps defined thereon, there is usually a juncture seam line or surface between the distinct blocks. There are also further variations within the context of structured grids and additional variations in the unstructured and hybridized cases.

Selected Publications

"Adaptive Grid Solution for Shock-Vortex Interaction," with M.J. Bockelie, in *Proceedings of the Eleventh International Conference on Numerical Methods in Fluid Dynamics*, Williamsburg (Springer-Verlag, in press).

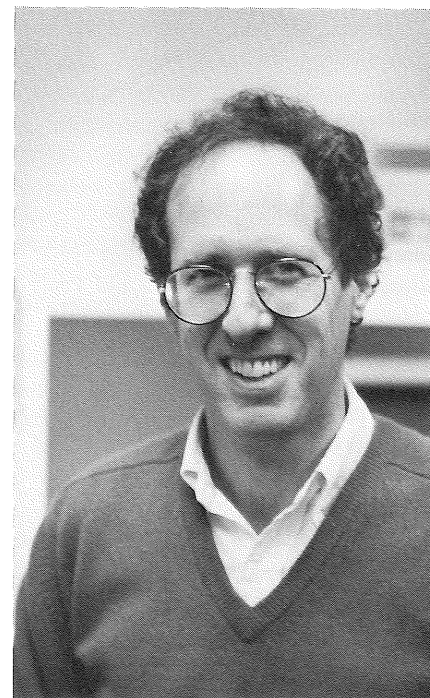
"A Control Point Form of Algebraic Grid Generation," *Intl. Journal for Numerical Methods in Fluids* 8, 1165-1181 (1988).

"Adaptive Grid Generation," *Computer Methods in Applied Mechanics and Engineering* 64, 321-376 (1987).

"Grid Generation for Fluid Mechanics Computations," *Annual Review of Fluid Mechanics* 17, 487-522 (1985).

"Geometric Methods in Computational Fluid Dynamics," Von Karman Institute Lectures, 1980 and ICASE Report No. 80-11 (1980).

"Conservation Laws of Fluid Dynamics – A Survey," *SIAM Review* 22, 12-27 (1980).



Inez Y. Fung

Adjunct Professor (Earth Science)
S. B., Massachusetts Institute of Technology, 1971
Sc.D., 1971

Study of the Earth system presents a unique challenge in fluid dynamics and computational mathematics. My research interests are focused on using numerical models of the atmosphere-ocean-land system to understand global changes in response to natural feedbacks and anthropogenic perturbations.

The oceans control the time response of the climate system. With Prof. C.K. Chu, we are developing a new ocean general circulation model to be coupled to the atmospheric general circulation model at the Goddard Institute for Space Studies. Development of the model is complicated, on the one hand, by the need to resolve adequately energetic boundary currents along the irregular coastlines and steep bathymetry of ocean basins, and, on the other, by the demand for a computationally economical model for centuries-long simulations.

A particular research focus of mine for the past few years has been the modeling of the global carbon cycle. Observations from satellites, ships, and field programs are integrated in a global three-dimensional atmospheric tracer transport model. The model is used to test different hypotheses about the sources and sinks of carbon dioxide. Only 50-60% of the carbon dioxide released from fossil fuel burning remains in the atmosphere. Our modeling of the north-south profile of carbon dioxide in the atmosphere suggests that the sink for fossil fuel carbon dioxide is not the southern oceans, but is probably on land in the northern hemisphere.

Selected Publications

"Observational Constraints on the Global Atmospheric Carbon Dioxide Budget," with P. Tans and T. Takahashi, *Science*, in press.

"Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model," with J. Hansen, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, and G. Russell, *J. Geophys. Res.* 93, 341 (1988).

"Application of Advanced Very High Resolution Radiometer Vegetation Index to Study Atmosphere-Biosphere Exchange of CO₂," with C. Tucker and K. Prentice, *J. Geophys. Res.* 92, 2999 (1987).



"Climate Response Times: Dependence on Climate Sensitivity and Ocean Mixing," with J. Hansen, G. Russell, A. Lacis, D. Rind, and P. Stone, *Science* 229, 857 (1985).

"The Variability of Net Longwave Radiation at the Ocean Surface," with D. E. Harrison and A. Lacis, *Rev. of Geophysics and Space Physics* 22, 177 (1984).

Herbert Goldstein

Professor (Nuclear Science and Engineering)
B.S., College of the City of New York, 1940
Ph.D., Massachusetts Institute of Technology,
1943

For some time now my research interests in the nuclear field have centered on the ways in which the characteristics of the microscopic neutron cross sections affect the macroscopic transport of neutrons through large material bodies. In such theoretical studies one must be sure that the methods of calculating the gross transport of neutrons represent accurate descriptions of what takes place in nature, and that these methods sensitively reflect the properties of the microscopic cross section. Hence, much of my research, and that of my thesis students, has been oriented to developing and refining calculational methods that give "gold-standard" results for neutron calculations. They represent the most advanced, detailed, and accurate transport calculations for the present state-of-the-art of numerical computation, although the methods are usually, but not always, too detailed and complex for routine engineering calculations. Transport methods that have come out of these researches include techniques for including point-energy descriptions of rapidly fluctuating cross sections, and analytic rigorous methods for transport with slowing down when the cross sections are constant in energy. Microscopic cross sections whose effects have been investigated include the so-called anti-resonance dips in the cross sections and the distributions of secondary neutrons from inelastic scattering.

In recent years the knowledge and experience gained from these researches has been applied to more practical nuclear engineering problems, particularly to the long-term neutron irradiation of reactor pressure vessels and the consequent effect on the embrittlement of the metal. We have been in the process of developing software to facilitate more realistic discrete ordinate calculations in

complex studies of the reactor and its surroundings out through the pressure vessel. We are also performing Monte Carlo studies of detailed surveillance capsule geometries to better understand modeling errors associated with discrete ordinate calculations in such complex reactor systems. These projects are being conducted in collaboration with Public Service Electric and Gas Research Corporation and Consolidated Edison of New York.

In addition, I am continuing to pursue my interests in classical mechanics and broader energy and scientific issues. While serving as Columbia's Thomas Alva Edison Professor from 1984 to 1986, I gave a series of lectures on nuclear energy issues. My involvement in developing an undergraduate course, "The Theory

and Practice of Science," with colleagues from other science disciplines has resulted in a textbook, *The Scientific Experience*, to be published shortly.

Selected Publications

The Scientific Experience, with J.K. Gross and R.L. Pollack (Columbia University Press, in press).

Classical Mechanics, revised second edition (Addison-Wesley, 1981).

"Slowing Down and Transport in Monoisotropic Media with Constant Cross Sections, I: Spatial Moments," with D. Cacuci, *J. Math. Phys.* (1977).

Fundamental Aspects of Reactor Shielding (Addison-Wesley, 1958).



Robert A. Gross

Dean and Percy K. and Vida L. W. Hudson
Professor (Plasma Physics)
B.S., Pennsylvania, 1949
M.S., Harvard, 1950
Ph.D., 1952

My professional fields of interest are fusion energy, plasma physics, and high temperature gas dynamics. My research has been focused on high-beta tokamak physics, wall-confined fusion, very strong shock wave physics, chemical and nuclear detonations and supersonic combustion.

The attainment of fusion as a practical new major source of energy is one of mankind's most important and difficult challenges. It involves a complex and interesting combination of science and engineering. My colleagues and I are engaged in both experimental and theoretical programs directed towards developing a high-energy density fusion plasma toroidal confinement concept called a high-beta tokamak.

I am also interested in an alternate approach to achieving fusion, wall-confined fusion. If successful, it can lead to rather small and compact energy sources. In this approach, hot plasma is physically confined by metal walls. The extreme energy transfer rates to these walls are reduced to practical levels by employing modest magnetic fields, parallel to the walls and in the plasma. An understanding of the physics of the thermal boundary layer is crucial to the success of this concept.

The nuclear fuels to be burnt in first generation fusion reactors will be deuterium and tritium. There are significant advantages to be achieved by using advanced fuels such as D-³He, ³He-³He, p-⁶Li, and D-D. To burn such fuels requires very high temperatures (300-900 keV) which are generated by special techniques. I am fascinated by the physics of advanced fuel fusion cycles and their extreme physical states.

I am intrigued by very strong shock wave physics. These waves, that occur

in supernova and stellar phenomena, may be produced by very high-powered, short pulse-length laboratory experiments and by nuclear explosives. I also have a long time interest in chemical and nuclear detonation waves and in supersonic combustion. My research bridges both theory and experiment, encompassing studies of practical applications of these physical phenomena for the production of electrical power and propulsion.

Selected Publications

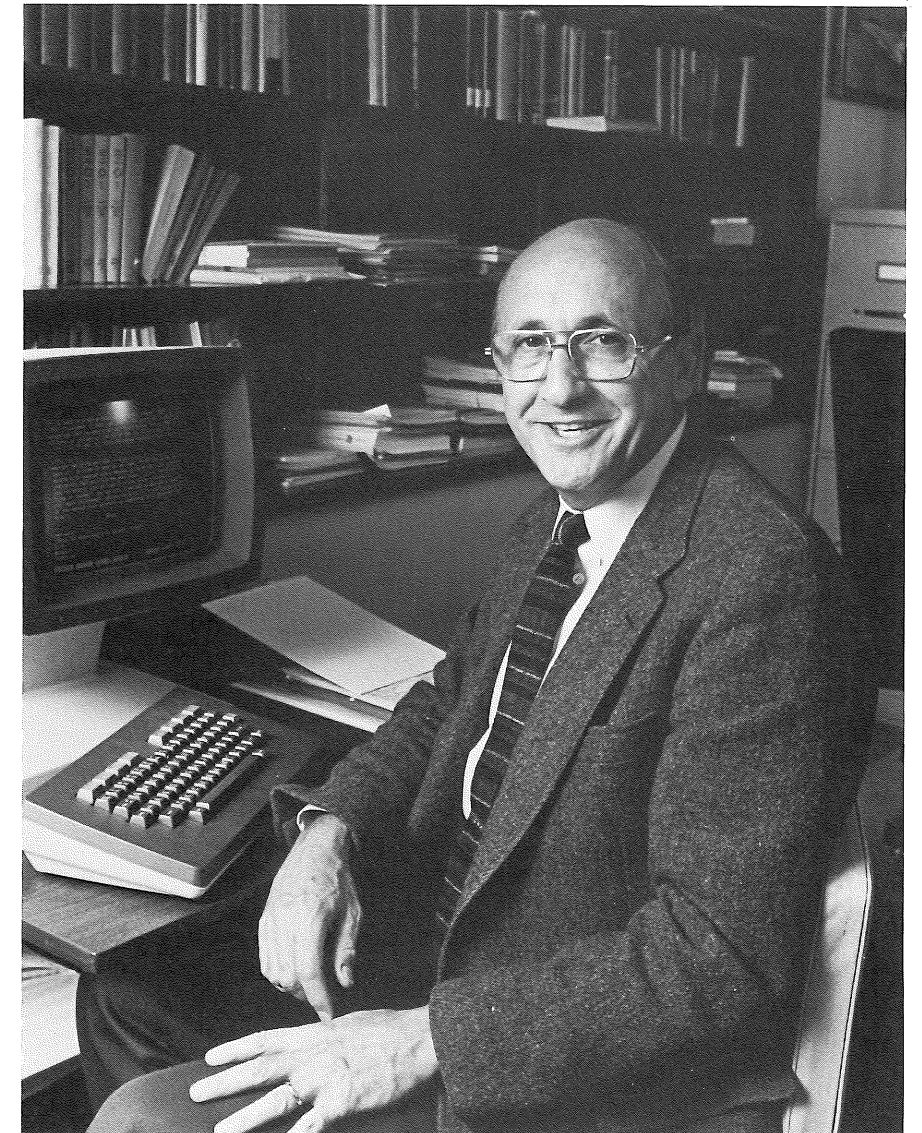
Fusion Energy (John Wiley & Sons, New York, 1984).

"Survey of Reactor Aspects of Compact Fusion Concepts," *Nuclear Techn./Fusion* 4, 305 (1983).

"Physics of a Wall-Confined Fusion System," *Nuclear Fusion* 15, 729 (1975).

"Thermonuclear Detonation Wave Structure," with A. Fuller, *Phys. Fluids* 11, 534 (1968).

"Strong Ionizing Shock Waves," *Reviews of Modern Physics* 37, 724 (1965).



Akira Hasegawa

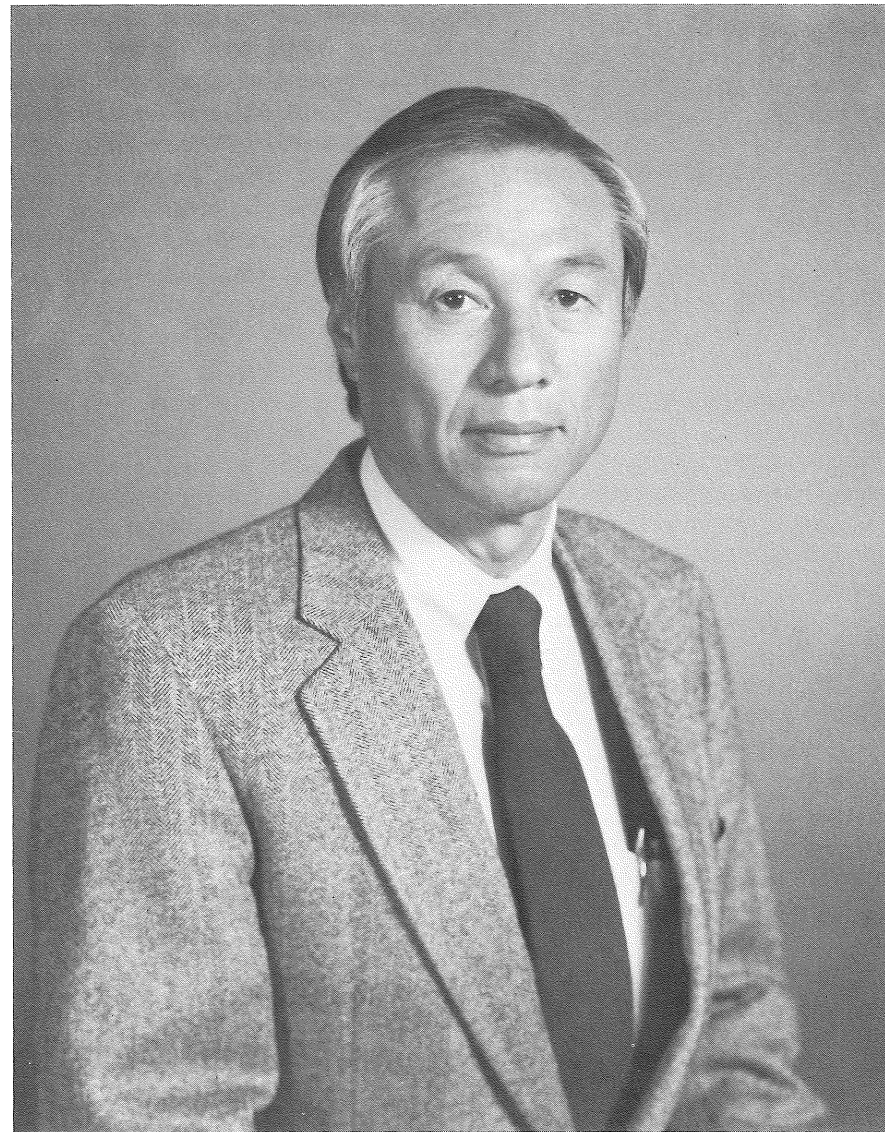
Adjunct Professor (Plasma Physics)
B.S., Osaka, 1957
M.S., 1959
Ph.D., California (Berkeley), 1964
Dr. Sci., Nagoya, 1966

I specialize in plasma physics, optics, and space science. Plasma (ionized gas) is very rich in its behavior and is an ideal material to study in classical physics. The motions of charged particles in an electromagnetic field develop chaos, but their collective motion often form ordered structures, such as solitons.

I have been involved in studying the space environment within the solar system and mechanisms of aurora formation. We have contributed to showing the mechanism of the earth's magnetic field oscillations as observed from the ground as well as from satellites. The space environment is filled with plasmas of both solar origin and earth origin.

Plasma has an important application in controlled thermonuclear fusion. In order to achieve ignition, it must be confined by a magnetic field or by inertia. The confinement scheme, however, often develops instability and produces turbulence. But the turbulence sometimes organizes itself to form a coherent structure. Our group has developed many theories to describe these complicated behaviors of plasmas. Most recently we have discovered that at sufficiently high density and temperature, a dipole magnetic field may be used as a plasma container such that deuterium and helium 3 may be burned.

In optics, we have discovered an optical soliton in glass fiber. The glass fiber is used to guide light waves for high-speed signal transmission. However, the glass material has the property of dispersion in that the light waves propagate at different speeds, depending on their wavelengths. The material also responds nonlinearly and as a consequence the index of refraction changes as a function of the light intensity. We have shown



theoretically that the combinations of dispersion and nonlinearity of the fiber can form an extremely stable optical pulse called an optical soliton, and we have proposed to use it for a high-speed communication system. Recently an optical soliton has been demonstrated to propagate free of distortions over a distance of 6,000 km at AT&T Bell Laboratories.

In addition to a wide range of scientific activity, I am also involved in the social sciences, particularly economics and philosophy. I have published four technical books on plasmas, optics, and space physics. I have also written six non-technical

books in Japanese. The most recent one, "A Dialogue between Taoism and Modern Physics," is being translated into English.

Selected Publications

Space Plasma Physics, with T. Sato, (Springer-Verlag, 1988), Vol. I.

"Optical Solitons in Fibers," in *Frontiers of Physics* (Kyoritu Pub., 1988), Vol. 20.

"The Alfvén Wave," with C. Uberoi, (U.S. Department of Energy, 1982).

"Plasma Instabilities and Nonlinear Effects" (Springer-Verlag, 1975).

John L. Helm

Assistant Professor (Nuclear Engineering)
B.S., Columbia, 1977
M.S., 1978
Ph.D., 1989

The field of radiation damage to structural materials encompasses most of my research activity. Nuclear particle irradiation changes the physical properties of the materials from which fission and fusion systems are built. My research is directed at understanding the relationship between the mechanisms of failure and the composition and structure of materials such as steel, understanding how interactions with radiation alter the material structure, devising methods that predict the extent to which such alteration occurs as a function of radiation exposure, and developing methods to compute the exposure.

To pursue these topics, fairly advanced computer simulation techniques are required, especially in order to represent the complex and dynamically changing geometry that often arises. For example, when an energetic neutron strikes and dislodges an atom in a material, it behaves much like a queue ball on a billiard table, striking other atoms which then strike others still, and so on. I have been developing computer methods to describe the trajectories and interactions that occur to the members of these "cascades." These methods are now being used to simulate the radiation damage to ferritic steel that can be measured experimentally in order to gain insight into how the microstructure changes.

If one is to predict the damage caused by irradiation, in addition to understanding how radiation makes changes to the properties of materials, it is also necessary to compute and/or measure the amount of exposure. In most technologically useful systems, such as nuclear power reactors, the calculation of this exposure is a challenging problem in transport theory. To address this challenge, I have been developing methods to perform the most realistic calculations

possible of the neutron transport in these complex systems and to assess their precision and accuracy.

In addition to my work on irradiation effects, I also study the safety and environmental aspects of energy systems and infrastructure. Understanding the safety and environmental performance of energy systems is important because the production, distribution, and consumption of energy by industrialized society produces humankind's largest loading of the environment. It is becoming increasingly clear that the health and well-being of ourselves and our children is inextricably linked to the health of the environment. As the world population grows and

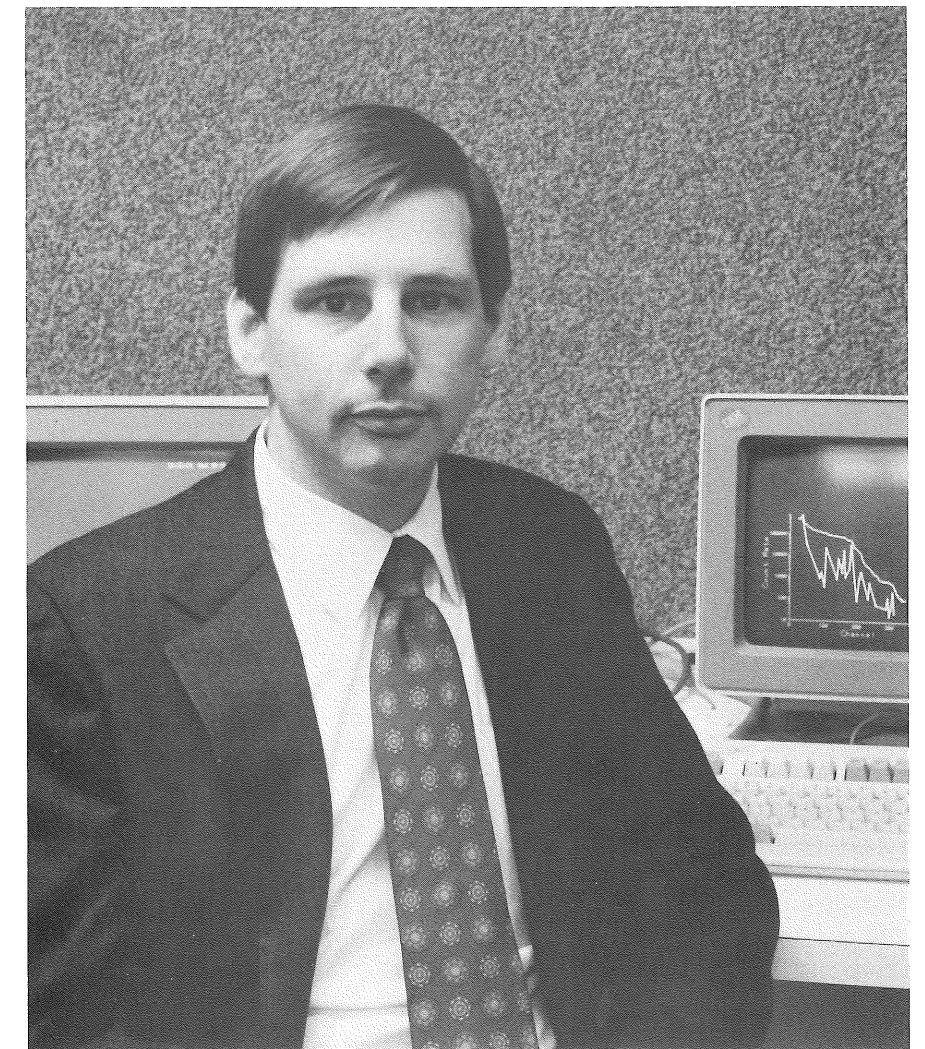
developing countries continue to industrialize, the need to evolve towards safe, clean, and sustainable energy systems is becoming vital.

Selected Publications

"Neutron Irradiation Damage to a Reactor Pressure Vessel Wall," Ph.D. dissertation, Columbia University, 1989.

"Energy in Context," with William F. Kieschnick, in *Energy: Production, Consumption, and Consequences*, edited by J. Helm (National Academy Press, 1989).

"What to Do About CO₂," with Stephen H. Schneider, in *Energy: Production, Consumption, and Consequences*, edited by J. Helm (National Academy Press, 1989).



Irving P. Herman

Associate Professor (Quantum Electronics and Solid State Physics)
S.B., Massachusetts Institute of Technology, 1972
Ph.D., 1977

My research concentrates on the fundamental aspects and applications of laser interactions with matter. This includes optical physics of the solid state, molecular physics, and optical spectroscopy. My research has included studies of optically pumped lasers, laser isotope separation, infrared laser multiple-photon dissociation, laser chemical modifications of surfaces, and optical microanalysis of semiconductors.

One active area of research in our group is the study of the physical and chemical changes on surfaces induced by laser radiation, much of which can lead to new fabrication and diagnostic methods in microelectronics. We have employed Raman microprobe spectroscopy to study how lasers can be used to heat surfaces locally within micrometer-sized regions and how tightly focused lasers can be used to probe direct laser writing reactions on the surface in real time. This work also addresses the mechanisms of these reactions, including the nature of nucleation during the early phases of laser-assisted thin film growth and the significance of laser-induced stresses and strains during laser processing and diagnostics. Some of these studies have indicated that novel surface photophysical processes may be quite important in laser interactions with semiconductor surfaces.

I am also interested in optical spectroscopy of semiconductors. One project in this area is the study of phonons in germanium-silicon alloys by Raman spectroscopy. Another is the optical spectroscopy of materials subjected to high pressure in diamond anvil cells. Currently we are investigating II-VI semiconductor thin films and multiple-quantum wells at high pressure using photoluminescence and other optical methods. The goal of these studies is to understand the

electronic structure of these materials better, in order to make more efficient use of them in applications and design of even better structures.

Selected Publications

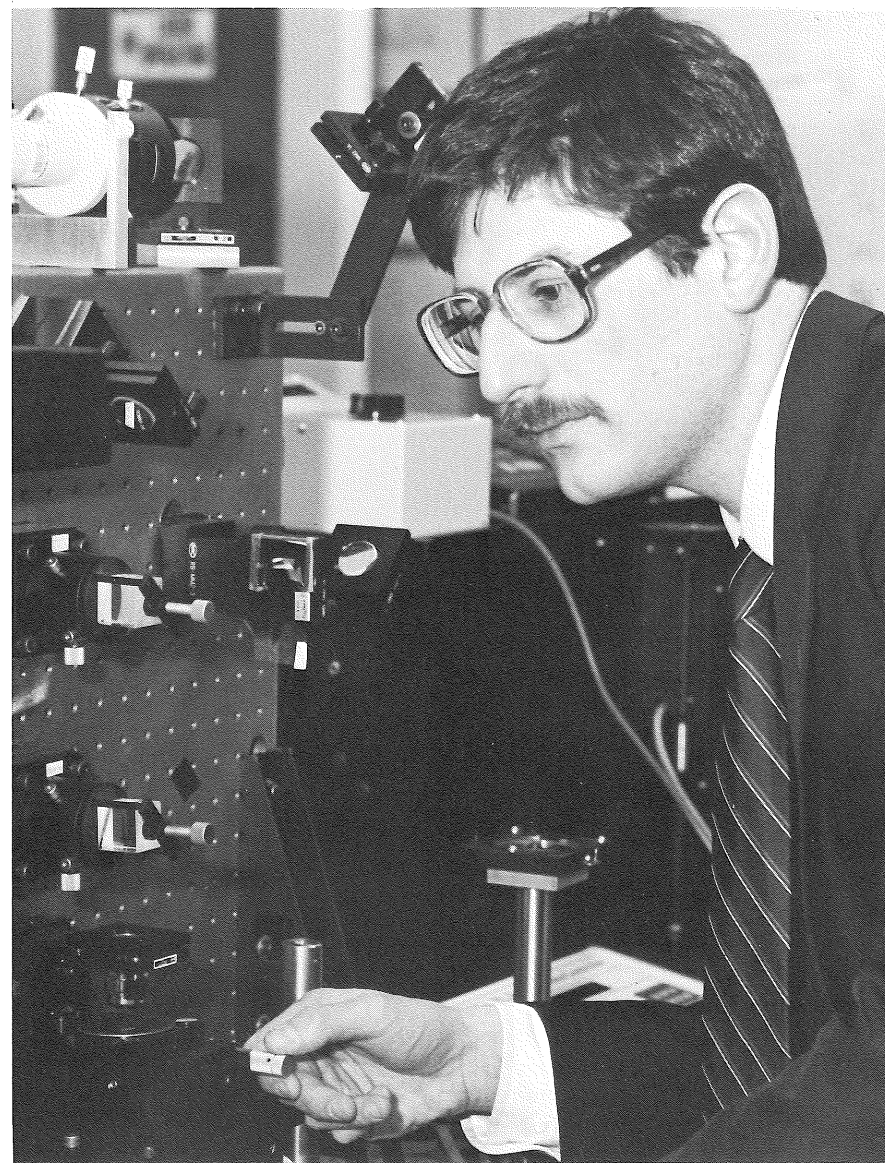
"Stokes/Anti-Stokes Raman Microprobe Analysis of Laser-Heated Silicon Microstructures on Silicon Dioxide," with G. Pazonis, H. Tang, and L. Ge, *Mat. Res. Soc. Sym. Proc.* **101**, 113 (1988).

"Laser Separation of Tritium," with K. Takeuchi and Y. Makide, chapter in *Laser Applications in Physical Chemistry* (Marcel Dekker, New York, 1988).

"A Real-Time Monte Carlo Simulation of Thin Film Nucleation in Localized-Laser Chemical Vapor Deposition," with D. E. Kotecki, *J. Appl. Phys.* **64**, 4920 (1988).

"The Importance of Thermal Stresses and Strains Induced in Laser Processing with Focused Gaussian Beams," with L. P. Welsh and J. A. Tuchman, *J. Appl. Phys.* **64**, 6274 (1988).

"Raman Microprobe Analysis During the Direct-Laser Writing of Silicon Microstructures," with F. Magnotta, *Appl. Phys. Lett.* **48**, 195 (1986).



Leon Lidofsky

Professor (Nuclear Engineering and Medical Physics)
B.S., Tufts, 1945
M.A., Columbia, 1947
Ph.D., 1952

My research interests are associated broadly with the transport of radiation in matter and with environmental and safety aspects of nuclear fission power.

Radiation, in interacting with matter, may cause changes in that matter. Typically, the goal of my research in such instances is the development of methods that, given the radiation and material environments, permit the physical consequences of the interactions to be predicted.

A primary application has been in radio-oncology where my students and I have developed and applied methods to permit the detailed and accurate determination of dose distributions resulting from the irradiation of the highly inhomogeneous human body by high energy photon beams.

The same methods appear to have value in designing radiation shielding under circumstances where inhomogeneous shields must be used. In other instances, the focus is on the modification of the properties of escaping radiation following interactions of the primary radiation with the irradiated matter. The goal is to enable an inference of those properties of the irradiated matter that would have led to the particular distributions of escaping radiations that were observed. For instance, in usual imaging applications, analyses tend to be based on the assumption that the interaction removes the radiation. Yet, the changes that take place due to nonabsorbing interactions may be significant and can serve to provide a further source of information.

Applications cover both medical and non-medical fields. The medical studies range, for instance, from observations of cerebral blood flow for purposes of monitoring brain function to precise *in vivo* determinations of

particular elements in human subjects so that changes associated with medical treatment can be monitored. These latter measurements require the observation of the products of neutron irradiation of humans. Our present focus is on optimizing the information content of the measurements relative to the dose to which the patient must be subjected.

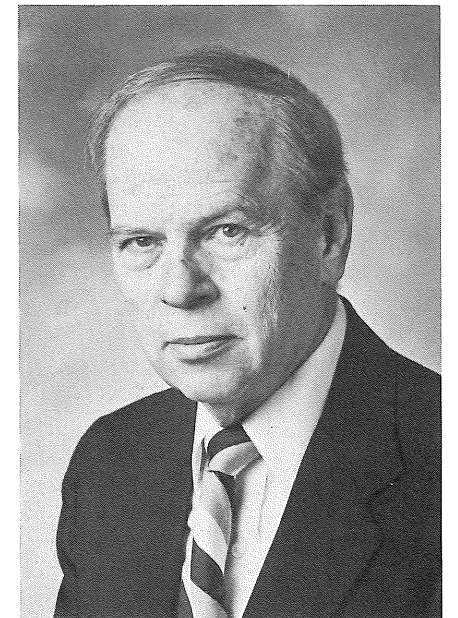
As an example of a non-medical application, my students and I have treated modifications of CAT images caused by local inclusions of materials within the scanned section whose atomic numbers differ from that of the bulk matter. That capability is useful in, but not limited to, evaluation of techniques for the recovery of heavy shale oil.

My research in environmental and safety aspects of nuclear fission power is distinct from these other interests. I focus on both minimization of risks associated with present technology and changes that would minimize that risk by severely limiting consequences of malfunctions.

Selected Publications and Student Theses

"Differential Pencil Beam Dose Computation Model for Photons," with R. Mohan and C. Chui, *Med. Phys.* **13**, 64 (Jan/Feb 1986).

"Report to the American Physical Society by the Study Group on Radionuclide Release from Severe Accidents at Nuclear Power Plants," with R. Wilson, K. J. Araj, A. O. Allen, P. Auer, D. Boulware, F. Finlayson, S. Goren, C. Ice, A. L. Sessoms, M. L. Shoaf, I. Spiewak, and T. Tombrello, *Reviews of Modern Physics* (1985).



Ward, Leonard William, "A Simplified Methodology for the Prediction of the Small Break Loss-of-Coolant Accident," Ph.D. dissertation, Columbia University, 1988.

Sarfaraz, Esfandiar, "Development of Analysis Technique for Single Photon Emission Tomography and Its Application to Determination of Cerebral Blood Flow," Ph.D. dissertation, Columbia University, 1987.

Chui, Chen-Shou, "A Method for Three Dimensional Gamma Ray Dose Calculations in Heterogeneous Media and Its Applications in Radiation Therapy," Ph.D. dissertation, Columbia University, 1985.

Zhang, Xiang, "A Modified Computerized Tomography Reconstruction Method for Heavy Inhomogeneous Media," Ph.D. dissertation, Columbia University, 1984.

Thomas C. Marshall

Professor (Quantum Electronics and Plasma Physics)
B.S., Case Institute of Technology, 1957
M.S., Illinois, 1958
Ph.D., 1960

Our group has pioneered the development of free-electron lasers (FELs) which have been shown to generate prodigious amounts of power from the microwave to the optical regions of the spectrum. High efficiency and tunability characterize these traveling-wave, electron beam devices. Unlike traditional sources (e.g., the traveling-wave tube), these are "fast wave" devices which can generate a wavelength far smaller than the physical dimensions of the apparatus. FEL physics has a close relationship with laser, accelerator, and plasma physics.

FEL research at Columbia, which began in 1975, has focused upon the validation of the physical principles that govern the FEL interaction. In 1978, a group including myself and Professor Perry Schlesinger operated the first FEL in the regime of exponential gain. We have investigated FEL gain, efficiency (including efficiency enhancement techniques), optical guiding, and sideband generation using the laboratory's 800kV pulsedline accelerator. This accelerator makes an electron beam which interacts with a periodic, magnetostatic field ("undulator") to produce several megawatts of pulsed, millimeter-wave power. We have also developed new non-interactive electron beam diagnostics which are useful in determining the "quality" of the beam.

Recently, our group has shown that the electron beam in a FEL has the capacity to guide the radiation it generates in much the same way that a fiber-optic carries light, by refractive guiding. Optical guiding not only improves the gain of a FEL, it also makes possible advanced devices which amplify radiation but require no mirrors, such as ring lasers and vacuum ultraviolet FELs. This

illustrates how the validation of physical principles can open technology for new sources. It turns out that optical guiding can be utilized across the spectrum, even though our experiment studied comparatively long-wavelength phenomena. We are also currently working on techniques to improve the coherence of FEL light as well as techniques to demonstrate that the FEL can produce very short pulses of radiation spontaneously.

Another very active area of research in the department is the program on the High-Beta Tokamak (HBT) device. The antecedent of HBT began operation at Columbia in 1978, and after undergoing a series of improvements over the years, has demonstrated the capacity to generate plasmas which have a larger ratio of particle-to-magnetic pressure than can be obtained in conventional tokamaks. The objective here is to study the equilibrium and stability of such toroidally confined plasmas in the MHD (magnetohydrodynamic) limit. Operation at high "beta" value is necessary to use thermonuclear reactions in electric power reactors which produce no neutrons and which therefore present no radioactive hazard.

Recent studies on HBT have documented and described high-beta equilibria using an array of small magnetic probes. These probes are now being used to detect instabilities in certain of the equilibria. Some of these instabilities are "benign," in that the plasma motion is periodic, while some are disruptive. On the other hand, some equilibria appear to be stable. A comprehensive effort is underway here, involving many individuals, to understand the physics involved and connect it to research which is going on with other tokamaks.

Selected Publications

"Observations of Optical Guiding in a Raman Free Electron Laser," with A. Bhattacharjee, S. Y. Cai, S. P. Chang, and J. W. Dodd, *Physical Review Letters* **60**, 1254 (1988).

"Regenerative Gain in a Raman Free Electron Laser," with J. Masud, S. P. Schlesinger, and F. G. Yee, *IEEE J. Quantum Electron.* **QE-23**, 1594 (1987).

"Sideband Control in a Millimeter Free Electron Laser," with J. Masud, et al., *Physical Review Letters* **58**, 763 (1987).

"Plasma Formation and Equilibrium in a High-Beta Tokamak," with A. V. Deniz and X. L. Li, *Physics of Fluids* **30**, 2527 (1987).

"Transition of a Tokamak Plasma From a State with Low to High-Poloidal Beta," with A. V. Deniz, T. Ivers, X. L. Li, and M. Mauel, *Physics of Fluids* **29**, 4119 (1986).

Free Electron Lasers (Macmillan, New York, 1985).



Michael E. Mauel

Assistant Professor (Plasma Physics)
S.B., Massachusetts Institute of Technology, 1978
M.S., 1979
Sc.D., 1983

My primary research interests are in the experimental identification of plasma instabilities, the measurement of the impact of these instabilities on magnetic confinement, and the analysis of the role of instabilities on the design of thermonuclear power plants. By conducting controlled experimental studies using a variety of magnetic confinement devices, we are attempting to further our fundamental understanding of the linear and nonlinear dynamics of microscopic and macroscopic plasma instabilities. The results of the experiments are applied to both man-made plasma confinement devices, such as future thermonuclear fusion plants, and to

plasmas confined in planetary magnetospheres.

I am involved with both the high-beta tokamak (HBT) and linear machine experiments in Columbia's Plasma Physics Laboratory. In the high-beta tokamak experiment, we combine detailed magnetic measurements, taken at several locations within the tokamak discharge, with sophisticated numeric techniques in order to correlate our observations with the theoretical predictions of ideal magnetohydrodynamical (MHD) equilibrium and linear stability. Direct measurements of the growth and saturation of pressure and current-driven kinks are possible, thereby testing the theories used to design large-scale fusion devices. In the linear machine, my interest lies in developing techniques for local control of the ion temperature profile and using one of these

techniques to produce the ion temperature gradient instability—a drift instability that may be responsible for anomalous thermal transport in tokamaks.

My research is also directed in three other areas. The first involves extending the pulse length of HBT with very high power ion cyclotron heating. With the addition of careful equilibrium control and a close-fitting stabilizing shell, this heating may demonstrate the first sustained operation in the tokamak's second stability regime. The second project seeks to understand the fundamental physics of electron cyclotron plasma sources used for the production of integrated circuits. A fully automated experiment, supported in part by IBM, is being built to produce three-dimensional images of plasma and microwave parameters. The third project involves the design and construction of a large, steady-state magnetic dipole, or terrella, to study collisionless particle motion in planetary magnetospheres. Application of the intense low frequency magnetic fluctuations produced from the terrella will enable us to take controlled measurements of non-linear particle dynamics, precisely identify the onset of particle chaos, and establish basic principles of plasma transport.

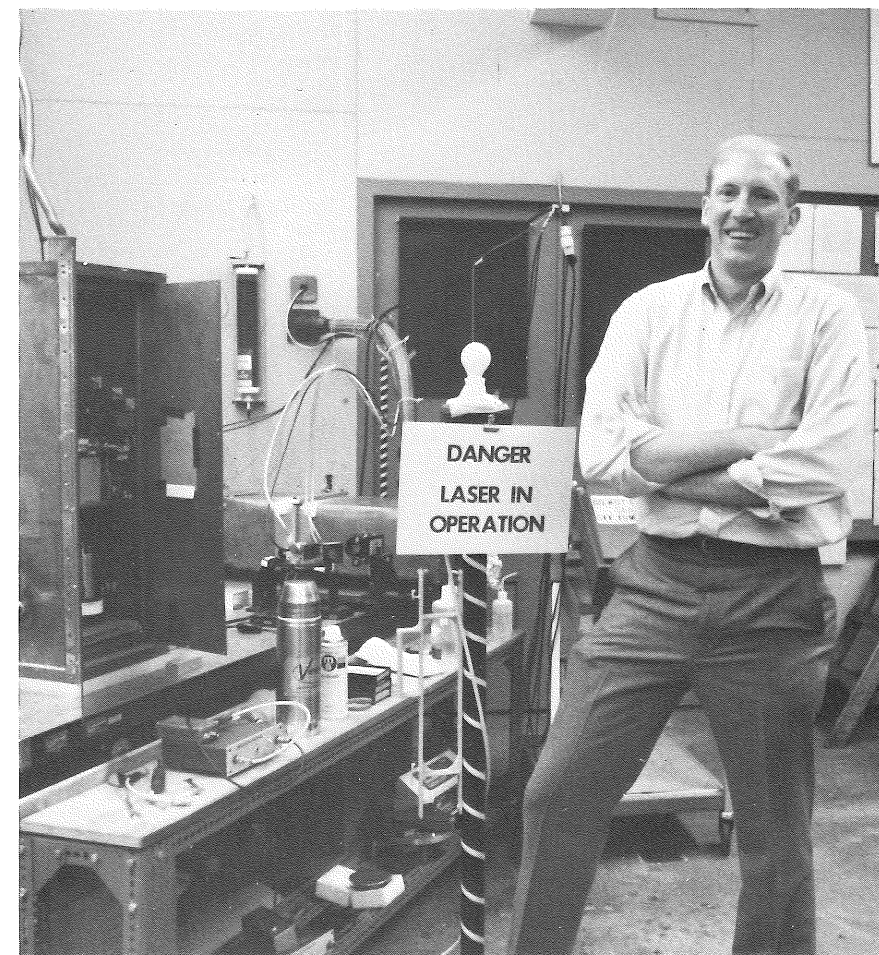
Selected Publications

"The Use of Scaling Laws for the Design of High-Beta Tokamaks," *Nuclear Fusion* **27**, 313 (1987).

"Ballooning Mode Stability of Elongated High-Beta Tokamaks," *Physics of Fluids* **30**, 3843 (1987).

"Warm Electron-Driven Whistler Instability in an Electron-Cyclotron-Resonance Heated Mirror-Confined Plasma," with R. C. Garner, S. A. Hokin, R. S. Post, and D. L. Smatlak, *Physical Review Letters* **59**, 1821 (1987).

"Electron Cyclotron Heating in a Pulsed Mirror Experiment," *Physics of Fluids* **27**, 12 (1984).



Gerald A. Navratil

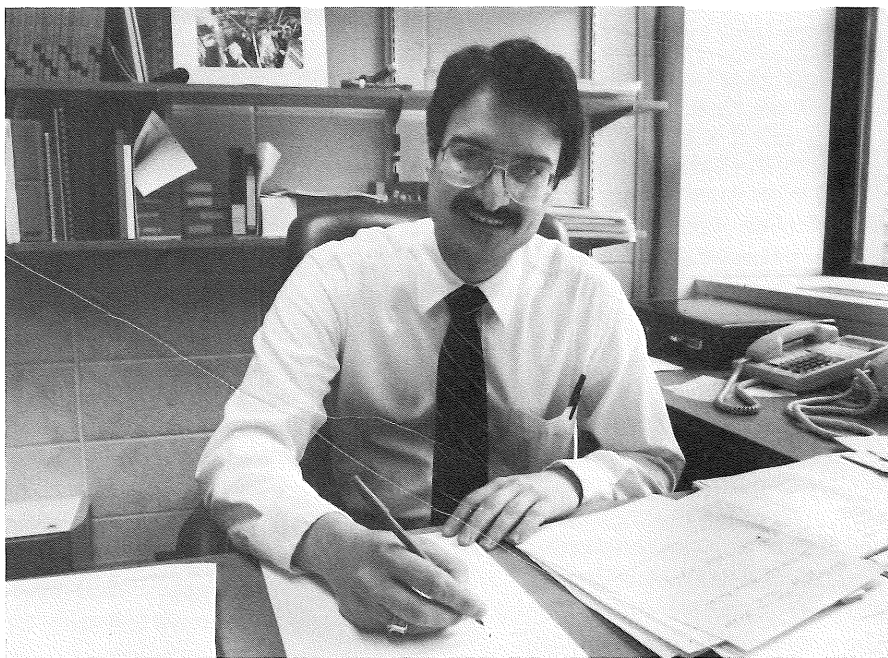
Chairman of the Department and Professor
(Plasma Physics)
B.S., California Institute of Technology, 1973
M.S., Wisconsin, 1974
Ph.D., 1976

My research concentrates on applying experimental plasma physics to the problem of developing controlled thermonuclear fusion as a source of energy. The national research program to develop fusion energy is now more than thirty-five years old and has been receiving substantial amounts of federal funding since the period of energy shortage in the mid-1970's. Fusion energy has the potential to provide a virtually unlimited source of power with a very plentiful fuel supply (deuterium and lithium) and a greatly reduced environmental hazard.

The U.S. Department of Energy funds the High-Beta Tokamak Research Program carried out on the HBT tokamak in the Columbia Plasma Physics Laboratory. The objective of this research is to discover what processes limit the stability of a magnetically confined plasma in a tokamak device when the pressure of the plasma becomes comparable with the magnetic field pressure. These "high-beta plasmas" are needed to make fusion a practical source of electric power since the fusion power density scales as the square of the plasma pressure.

The investigations of high-beta plasma physics have led us to develop innovative measurement techniques to determine the spatial distribution of the density and temperature in the hot (100,000 °K to 1,000,000 °K) plasma. These include the first multi-point Thomson scattering system by a university research group and the development of 2D emission tomography using a maximum entropy reconstruction technique for determination of density and temperature distributions in a cross-section of the plasma.

Along with Professor Sen, we have carried out a series of experiments in



basic plasma physics on a steady-state linear mirror machine. This work allowed us to make the first observations of two important instabilities, predicted by theory, to occur in magnetized plasmas: the dissipative trapped ion instability and the collisionless trapped ion instability. Presently we are concentrating our work on the use of active feedback control for instability suppression and measurement.

Another concern of our work involves improved approaches to fusion power plant design. Professors Mauel, Marshall, Bhattacharjee, and I have been working with Grumman Aerospace Corporation researchers to develop an improved tokamak configuration. This device would operate in the theoretically predicted "second regime of stability" at high-beta values. This has led to the conceptual design of a Second Regime Experiment or SRX which is one of several options for new experimental initiatives being considered by the U.S. Department of Energy.

Selected Publications

"Tomographic Analysis of the Evolution of Plasma Cross Sections," with A. Holland, *Rev. Sci. Instrum.* **57**, 1557-66 (1986).

"Production and Identification of a Collisionless, Curvature-Driven, Trapped-Particle Instability," with R. Scarmozzino and A. K. Sen, *Physical Review Letters* **57**, 1729 (1986).

"High-Beta Tokamak Operation in the Second Stability Regime," with T.C. Marshall, *Comments on Plasma Physics and Controlled Fusion* **10**, 185 (1986).

"Multi-Point Thomson Scattering," with F.M. Levinton, *Rev. Sci. Instrum.* **54**, 35 (1983).

"Experimental Study of the Dissipative Trapped Ion Instability," with A.K. Sen and J. Slough, *Physics of Fluids* **26**, 1044 (1983).

"Experimental Study of High-Beta Tokamak Stability," with M. Machida, *Physical Review Letters* **51**, 992 (1983).

Arthur S. Nowick

Professor (Solid State Physics)
Joint Member of Henry Krumb School of Mines
and AP Department
B.A., Brooklyn, 1943
M.A., Columbia, 1948
Ph.D., 1950

The work in our laboratory is centered in the study of atomic scale defects, called "point defects," in ionic-type crystal, particularly oxides. Such defects control the transport of matter in these crystals as well as many other properties that are interesting from a fundamental viewpoint as well as technologically. For example, many of the materials that we study conduct electricity by the flow of ions rather than the flow of electrons. Such materials, called "solid electrolytes," are of interest in the development of

new solid-state type battery systems and high-temperature fuel cells. Of special interest in the program are materials that are protonic conductors, since the proton is a very unusual ion whose role affecting the behavior of materials has only recently begun to be appreciated. Some of the best high-temperature protonic conductors are crystals having the "perovskite" structure. Among these are KTaO_3 and SrCeO_3 . We have obtained considerable insight into the way in which protons go into these crystals and the nature of the "hopping" process that they undergo inside the crystal. Interestingly enough, the newly discovered high- T_c superconducting oxides also have structures related to the perovskite, and part of our work

has been to study the effects of introducing protons on the superconducting properties of these materials.

A quite different series of studies has centered on defects in quartz crystals, since these crystals are widely used for frequency control and the demands for frequency stability are always increasing. We have learned much about the way that impurities such as Al and Fe, as well as gamma irradiation, affect the defect structure and therefore the frequency stability of such crystals.

In another program, sponsored by IBM, we are investigating the way that moisture (i.e., H_2O molecules) enters and affects the properties of polymer materials used in electronic packaging.

In all of these investigations, a wide variety of techniques have played a role, including the following: electrical conductivity measurements, dielectric relaxation, infrared absorption, electron paramagnetic resonance, nuclear magnetic resonance, and internal friction.

Selected Publications

"Bulk Protonic Conduction in Yb-Doped SrCeO_3 and BaCeO_3 ," with T. Scherban and W. K. Lee, *Solid State Ionics* **28-30**, 585 (1988).

"Dielectric Relaxation of the Aluminum-Hole Center in α -Quartz: An Example of Photon-Assisted Tunneling," with J. Toulouse and S. Ling, *Physical Review B* **37**, 7070 (1988).

"Anelastic and Dielectric Relaxation of Scandia-Doped Ceria," with R. Gerhardt and W.K. Lee, *Journal de Physique* **48**, C8-251 (1987).

"Protonic Conduction in Acceptor Doped KTaO_3 Crystals," with W.K. Lee and L.A. Boatner, *Solid State Ionics* **18/19**, 989 (1986).

"The Grain-Boundary Effect in Ceria Doped with Trivalent Cations," with R. Gerhardt, *Journal of the American Ceramic Society* **69**, 641 (1986).



Richard M. Osgood, Jr.

Higgins Professor(Quantum Electronics and Solid State Physics)
Joint Member of EE and AP Departments
B.S., U.S. Military Academy, 1965
M.S., Ohio State, 1968
Ph.D., Massachusetts Institute of Technology, 1971

One of my areas of interest is basic and applied surface science, including operations such as etching, deposition, and doping, which were pioneered by our group. These techniques are particularly important in advanced microelectronics circuits because they permit processing at low temperatures and without the use of photomasks. The experimental work uses continuous-wave and pulsed ultraviolet lasers to do such operations as custom interconnection of application specific integrated circuits (ASICs), ultrashallow doping of GaAs, and direct fabrication of optical waveguides and devices.

My work in surface science emphasizes the use of lasers to study and alter the fundamental properties of surfaces in ultrahigh vacuum and in a relatively high pressure ambient. My present studies include photoelectron emission from surfaces undergoing high intensity irradiation, ultraviolet and infrared studies of the spectroscopy of adsorbed molecules on semiconductor surfaces, and the fundamental mechanisms of carrier-assisted surface chemistry.

I have an ongoing interest in the development of new laser sources and the observation of novel optical effects. Recently, for example, in collaboration with the M.I.T. Lincoln Laboratory, we investigated large-area electron beam excitation of CdS and ZnS lasers.

Selected Publications

"Laser Fabricated GaAs Waveguiding Structures," with A.E. Wilner, D. J. Blumenthal, M. N. Ruberto, and D. V. Podlesnik, *Appl. Phys. Lett.* (in press).

"Total Internal Infrared Spectroscopy Study of U. V. Reactions on Silicon Surfaces," with E. Sanchez, P. Shaw, and J. O'Neill, *Chem. Phys. Lett.* **147**, 153 (1988).

"The Effect of UV-Grown Oxide on Metal-GaAs Contacts," *J. Vac. Sci. Technol.* **A6**, 1446 (1988).

"Electron-Pumped High-Efficiency Semiconductor Laser," with V. Daneu, D. P. DeGloria, A. Sanchez, and F. Tong, *Appl. Phys. Lett.* **49**, 546 (1988).

"Rapid Direct-Writing of High-Aspect-Ratio Trenches in Silicon: Process Physics," with G.V. Treyz and R. Beach, *J. Vac. Sci. Technol.* **B6**, 1 (1988).

"Interaction of Deep Ultraviolet Laser Light with GaAs Surfaces in Aqueous Solutions," *JOSA B3*, 775 (1986).

"Laser-Induced Chemistry for Microelectronics," with T. F. Deutsch, *Science* **227**, 4688 (1985).



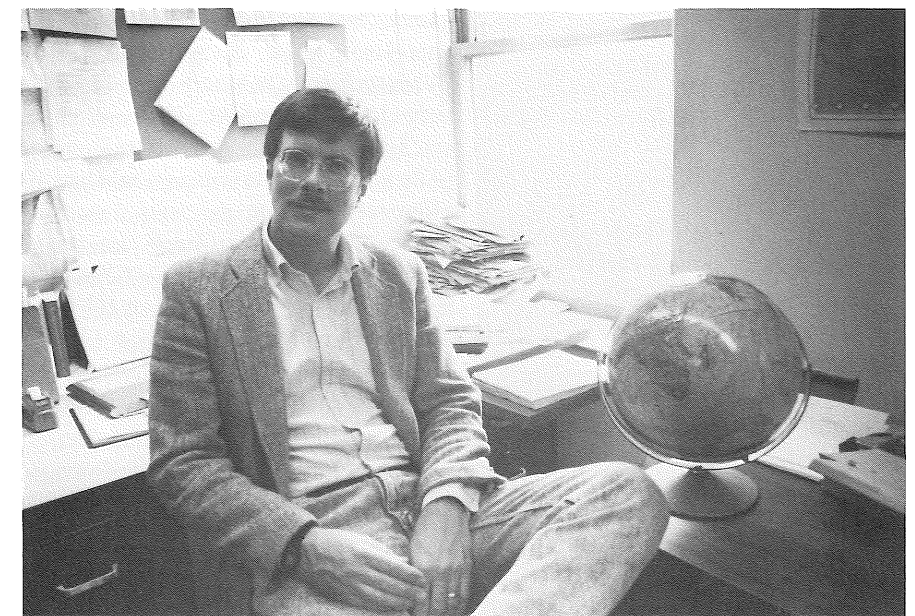
Michael J. Prather

Adjunct Professor (Geochemistry and Atmospheric Science)
B.S., Yale, 1969
B.A., Merton College, Oxford, 1971
Ph.D., Yale, 1976

My scientific studies over the past decade have been directed towards theoretical modeling of the atmospheres of Earth and other planets in our solar system. My research involves colleagues in the Department of Applied Physics and takes advantage of the major resource in atmospheric modeling at NASA/GISS in Columbia's Armstrong Hall.

The development of atmospheric models in my research area focuses on the chemistry, composition, and evolution of atmospheres. This area of research has received considerable public attention recently because of the global changes induced by human activity: specifically, the antarctic "ozone hole" and the "greenhouse" effect. Both of these global-scale perturbations are associated with the growing concentration of trace gases in the atmosphere.

Three-dimensional chemical transport models are the basic tools being developed to understand the current cycles controlling the concentration of trace species, whose sources range from industrial release of chlorofluorocarbons to biospheric emissions of methane. These models bring together the general circulation of the atmosphere, industrial and natural sources, and atmospheric chemistry. Some recent applications of these trace-gas transport models include (1) simulation of the European pollution episodes at an observing site in western Ireland, (2) studies of the global variability of methane induced by a combination of surface sources and atmospheric chemistry, and (3) predicting the global impact of the "hole" in stratospheric ozone that now appears every spring over Antarctica



(e.g., what happens subsequently to the ozone abundances over Australia during summer?). The long-term goal of the 3-D chemical transport models is to provide realistic, predictive capability that can be used to assess the impact of societal actions (i.e., atmospheric emissions) on our future air quality and climate.

Selected Publications

"European Sources of Halocarbons and Nitrous Oxide: Update 1986," *J. Atmos. Chem.* **6**, 375 (1988).

"Cloud Chemistry on Jupiter," with B.E. Carlson and W.B. Rossow, *Astrophys. J.* **322**, 559 (1987).

"Chemistry of the Global Troposphere: Fluorocarbons as Tracers of Air Motion," with M. McElroy, S. Wofsy, G. Russell, and D. Rind, *J. Geophys. Res.* **92**, 6579 (1987).

"Numerical Advection by Conservation of Second-Order Moments," *J. Geophys. Res.* **91**, 6671 (1986).

"Reductions in Ozone at High Concentrations of Stratospheric Halogens," with M.B. McElroy and S.C. Wofsy, *Nature* **312**, 227 (1984).

Malvin A. Ruderman

Professor (Theoretical Physics and Astrophysics)
Joint Member of Physics and AP Departments
B.A., Columbia, 1945
M.S., California Institute of Technology, 1947
Ph.D., 1951

I work on various astrophysical phenomena involving particle acceleration to very high energies. Most involve neutron stars in various systems with emphasis upon the following: 1) Solitary radiopulsars which radiate gamma rays. Such

gamma rays have been detected at energies up to 10^{12} electron volts. 2) Neutron stars in binary systems with very close companions. The neutron star's strong gravitational attraction pulls mass from the companion which ultimately falls onto the neutron star's surface. In the process some particles are accelerated to energies sufficiently high that they are the source of 10^{12} - 10^{15} electron volt gamma rays. 3) Neutron stars which are transient sources of bursts of gamma rays lasting

between 10^{-1} and 10^2 seconds. While they burst, these are the brightest gamma-ray sources in the sky. Usually the interval between bursts from any given neutron star is very many years. 4) Neutron stars in binaries with very low mass companions. An energetic flux from near the neutron star can be intercepted by and may even significantly evaporate the companion. Such systems may also be the source of strong fluxes of electron-positron pairs whose annihilation in the central region of our galaxy has been observed. 5) Finally, neutron star cores which contain an extraordinarily high temperature superconductor (transition temperature about 10^9 °K) expel quantized magnetic flux tubes. The dynamics of this process is of crucial importance in understanding the survivability of the stellar magnetic fields and the particle accelerators which depend upon them.

Selected Publications

"Late Evolution of Very Low Mass X-ray Binaries Sustained by Radiation From Their Primaries," with J. Shaham, M. Tavani, and D. Eichler, *Astrophys. J.*, in press.

"Period Differences Between X-rays and Very High Energy γ -ray Observations of Accreting X-ray Pulsars," with K.S. Cheng, *Astrophys. J.*, in press.

"Low Energy Galactic Center Region γ -rays from Low Mass X-ray Binaries," with W. Kluzniak, J. Shaham, and M. Tavani, *Nature*, in press.

"Nature and Evolution of the Eclipsing Millisecond Pulsar PSR 1957+20," with W. Kluzniak, J. Shaham, and M. Tavani, *Nature* **334**, 225 (1988).

"Evolution of a Short-Period Gamma-ray Pulsar Family: Crab, Vela, Cos B Source, Gamma Ray Burst Source," with K.S. Cheng, *Astrophys. J.* **335** (1988).



Amiya K. Sen

Professor (Plasma Physics)
Joint Member of EE and AP Departments
Dipl., Indian Institute of Science, 1952
M.S., Massachusetts Institute of Technology, 1958
Ph.D., Columbia, 1963

I am interested in magnetohydrodynamics, magnetospheric physics, plasma physics, and controlled nuclear fusion. In particular, I am deeply involved in experimental and theoretical research in ion temperature gradient instability, anomalous transport, and remote feedback via halo and modulated beams.

A critical roadblock for the success of controlled thermonuclear fusion is the residual instability of confined fusion plasma. We are attempting to understand and control these instabilities. The feedback control and suppression of the worst of these instabilities may greatly enhance the confinement quality of a fusion machine. Some of the elementary theoretical results have been successfully implemented by our group. More sophisticated multi-mode feedback control systems are being devised to suppress several modes of plasma instability simultaneously. Concepts and designs for remote sensors and suppressors appropriate for fusion systems are also being developed in our laboratory.

Trapped particle instabilities are the most dangerous instabilities in both types of mainline magnetic fusion machines, tokamaks, and tandem mirrors. The first observation and identification of these plasma microinstabilities occurred in a unique linear plasma machine in our Plasma Physics Laboratory. At present we are pursuing the production and study of ion temperature gradient instability, which is expected to be a serious problem for reactor-type tokamaks.

Anomalous transport due to a plasma instability is a strong function of the nonlinearly saturated amplitude of the instability. We study the problem of saturated spectra and the consequent anomalous diffusion as a problem in nonlinear statistical mechanics. Anomalous diffusion is theoretically and experimentally determined and compared.

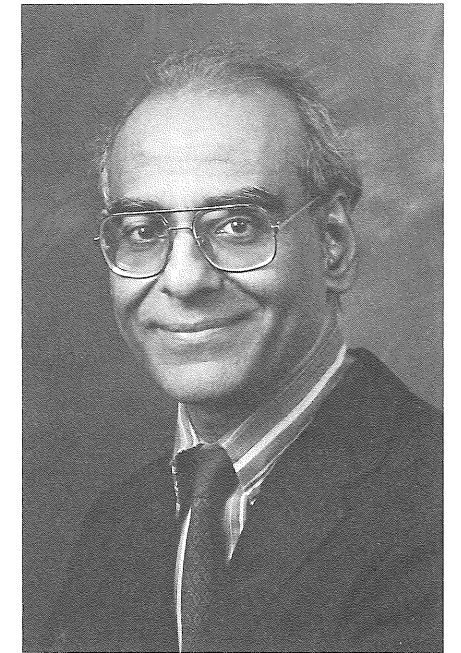
I am also pursuing alternative fusion concepts because the immense complexity of mainline magnetic fusion machines may make them economically unattractive and technologically difficult to maintain and operate. Therefore, our group is studying machines that are much simpler in geometry, coil configurations, plasma heating and access. In particular we are examining machines based on linear theta pinches, which easily satisfy all criteria for fusion feasibility except for end losses. A unique scheme for end configurations to stopper the end losses is currently under investigation in our laboratory.

Selected Publications

"Effects of Collision on the Trapped Particle Modes in the Columbia Linear Machine," with O. Mathey, *Physics of Fluids* **31**, 2310-2319 (1988).

"Study of a Collisionless Curvature Driven Trapped Particle Instability," with R. Scarmozzino and G.A. Navratil, *Physics of Fluids* **31**, 1773-1786 (1988).

"Nonlinear Saturation of Collisionless Trapped Particle Instability in Tandem Mirrors," with S.Y. Kim, *Physics of Fluids* **31**, 1690-1694 (1988).



"Drift Wave Turbulence Spectrum in a Sheared Magnetic Field," with S.Y. Kim, *Plasma Physics and Controlled Fusion* **28**, 1009-1019 (1986).

"A Phenomenological Theory of Nonlinear Saturation of Drift Wave Type Instability," *Plasma Physics and Controlled Fusion* **28**, 1067-1082 (1986).

Michael Tabor

Professor (Applied Mathematics)
B.Sc., Bristol, 1972
Ph.D., 1976

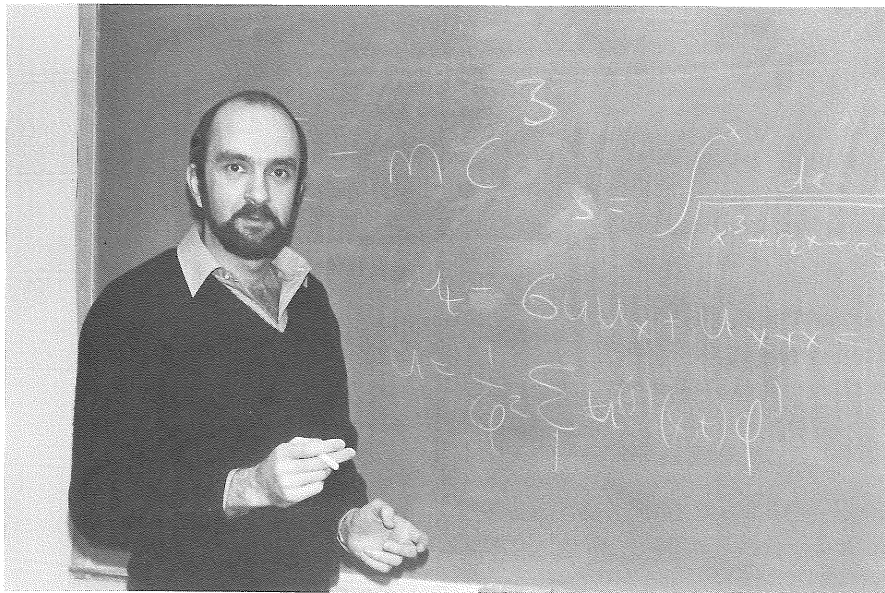
My interests cover a variety of topics in applied mathematics. Nonlinear effects in ordinary and partial differential equations can result in a wide variety of phenomena ranging from chaos and strange attractors exhibited by small systems of ordinary differential equations (ODEs), to the very stable soliton solutions exhibited by certain nonlinear partial differential equations (PDEs). Despite their great diversity, many nonlinear equations have certain fundamental properties in common which are revealed by studying the types of singularities that their solutions can exhibit in the complex domain. This research involves the mathematical techniques of nonlinear dynamics, complex variable theory, and algebraic geometry as well as the development of certain new mathematical methods.

These methods have, for example, helped solve the age-old problem of how to determine whether or not a given system of ODEs is integrable. Furthermore these techniques have been extended to PDEs and are able to predict and construct soliton solutions. The most recent research has shown how to apply these ideas to nonintegrable systems and has been successful in supplying analytical insights and special solutions to systems of equations that were hitherto considered to be intractable. Apart from their general value as a mathematical tool for studying nonlinear systems, these methods may be particularly useful for solving problems in field theory and statistical mechanics.

We are also working on the mathematical description of turbulence. The approach to this fundamental problem is through the Lagrangian picture of fluid dynamics, that is, the description of the fluid in terms of fluid particle trajectories. This approach provides a direct link to ideas in nonlinear dynamics and is

particularly well-suited for such real world problems as mixing technologies, sedimentation, and drag reduction. These studies include some simple experimental work and the development of dynamical models of the Lagrangian picture at high Reynolds number in an attempt to study the connection between "Lagrangian" and "Eulerian" turbulence.

A closely related research problem is that of the dynamics of polymer molecules in simple and complex flows. The latter problem, namely that of "complex objects in complex flows," is mathematically very difficult. It is, however, of immense practical significance since the addition of just a few parts per million of polymer solution to turbulent pipe flow can result in dramatic reduction in drag. There is, to date, no wholly convincing explanation of this phenomena. Our research on this topic draws together many ideas in nonlinear dynamics, polymer physics, and fluid mechanics.



Selected Publications

Chaos and Integrability in Nonlinear Dynamics: An Introduction (John Wiley & Sons, New York, 1989).

"Integrating the Nonintegrable: Analytic Structure of the Lorenz Equations Revisited," with G. Levine, *Physica* **33D**, 189-210 (1988).

"Singularity Clustering in the Duffing Oscillator," with J. D. Fournier and G. Levine, *J. Phys. A* **21**, 33-54 (1988).

"A Unified Approach to Painlevé Expansions," with A. C. Newell and Y. B. Zeng, *Physica* **29D**, 1-68 (1987).

"Experimental Study of Lagrangian Turbulence in a Stokes Flow," with J. Chaiken, R. Chevray, and Q.M. Tan, *Proc. R. Soc. Lond. A* **408**, 165-174 (1986).

"A Cascade Theory of Drag Reduction," with P.G. de Gennes, *Europhys. Lett.* **2**, 519-522 (1986).

Malvin C. Teich

Professor (Quantum Electronics)
Joint Member of EE and AP Departments
S.B., Massachusetts Institute of Technology, 1961
M.S., Stanford, 1962
Ph.D., Cornell, 1966

My interests lie in the areas of photonics, lightwave communications, quantum optics, and sensory perception.

Information can be transmitted in many ways. I am particularly interested in the transmission of *optical information* (e.g., lightwave or fiber-optic communication systems) and *neural information* (e.g., the transformation of sound and light into neural digital signals transmitted from the ear and the eye to the brain in living organisms). These areas are closely related in that they both involve the coding, transmission, and detection of random digital signals. The photonics research conducted by our group involves two aspects of lightwave communications: the design of new light-generation and light-detection devices for use in fiber-optic communications systems.

We are studying a solid-state light source that uses the Franck-Hertz Effect. Such light has an added randomness in its phase but a more stable photon number than the laser (there is a trade-off between photon number and phase uncertainty arising from the Uncertainty Principle). It produces light whose photon number is "squeezed."

We are also investigating the properties of new kinds of superlattice avalanche photodetectors. These are enhanced-ionization devices, in which electrons multiply but holes do not. They are made by molecular beam epitaxy, and make use of quantum wells and graded energy gaps. These devices are expected to introduce very little noise into the detection process, and therefore to allow weak optical signals to be transmitted over long optical fibers with few repeaters and high reliability.

Our study of neural information systems (cybernetics) centers on the



nature of signal processing performed by living systems and their modeling by neural networks. Discovering the methods that living systems use promises better design of man-made communication systems and methods of information transmission. Microelectrode neural recording experiments are conducted in our laboratory at Columbia's College of Physicians and Surgeons, where we carry out research jointly with Professor of Auditory Biophysics Shyam M. Khanna. We are interested in the neural mechanisms that mediate the encoding and recognition of speech. These studies are conducted using engineering principles, mathematical modeling, digital signal processing, information theory, nonlinear dynamics, and bioengineering.

Selected Publications

"Quantum - Mechanical Lossless Beam Splitter: SU(2) Symmetry and Photon Statistics," with R.A. Campos and B.E.A. Saleh, *Phys. Rev. A* **40**, 1371-1384 (1989).

"Fractal Character of the Auditory Neural Spike Train," *IEEE Trans. Biomed. Eng.* **36**, 150-160 (1989).

"Theory of the Temporal Response of a Simple Multiquantum-Well Avalanche Photodiode," with K. F. Brennan, Y. Wang, B. E. A. Saleh, and T. Khorsandi, *IEEE Trans. Electron Devices* **35**, 1456-1467 (1988).

"Photon Bunching and Antibunching," in *Progress in Optics*, with B. E. A. Saleh, edited by E. Wolf (North-Holland, Amsterdam, 1988), Vol. 26, pp. 1-104.

"Can the Channel Capacity of a Lightwave Communication System Be Increased by the Use of Photon-Number-Squeezed Light?" with B. E. A. Saleh, *Phys. Rev. Lett.* **58**, 2656-2659 (1987).

"Photon-Number-Squeezed Recombination Radiation in Semiconductors," with F. Capasso and B.E.A. Saleh, *J. Opt. Soc. Am. B* **4**, 1663-1666 (1987).

"Statistical Properties of Cosmic-Ray Showers at Ground Level Determined from Photomultiplier-Tube Background Registrations," with R. A. Campos and B. E. A. Saleh, *Phys. Rev. D* **36**, 2649-2665 (1987).

Wen I. Wang

Professor (Solid State Physics)
Joint Member of EE and AP Departments
B.S., National Taiwan, 1975
M.E.E., Cornell, 1979
Ph.D., 1981

My interests lie in the areas of molecular beam epitaxy, heterostructure transistors, semiconductor lasers, excitonic properties of quantum wells, and surface science. Much of my work centers on the device physics of novel III-V semiconductor heterostructures and the materials characterization and physics of these semiconductors. Our research group uses photoresponse, photoluminescence, absorption, and excitation spectroscopy to study shallow and deep impurities, and excitonic properties of bulk materials and superlattices.

I am also interested in producing high-speed electronic devices using band-structure-engineered materials, including high electron mobility transistors and tunneling transistors. Here, compound semiconductor heterostructures provide an ideal laboratory for do-it-yourself quantum mechanics of solids.

Quantum-well optoelectronic devices, including transmitters and receivers for optical communication links are another interest. The integration of optical and electronic components based on modulation-doped structures can offer significant speed advantage over conventional devices. Due to the large binding energies of excitons in quantum wells, many novel modulators and switches can be built. We are also investigating the anisotropic properties of the heavy-hole and light-hole excitons.

Selected Publications

"Resonant Tunneling in AlSb/InAs/AlSb Double Barrier Heterostructures," with L.F. Luo and R. Beresford, *Appl. Phys. Lett.* **53**, 2320 (1988).

"Inelastic Tunneling in AlAs/GaAs/AlAs Heterostructures," with E.E. Mendez and E. Calleja, *Appl. Phys. Lett.* **53**, 977 (1988).

"Dynamical Conductivity of GaAs/AlGaAs Two-Dimensional Electron Gas at Low Temperature and Carrier Density," with Z. Schlesinger and A. H. MacDonald, *Phys. Rev. Lett.* **58**, 73 (1987).

"Electronic Properties of Quantum Wells in Perturbing Fields," with R.T. Collins, L. Vina, C. Mailhot, and D.L. Smith, *Proc. SPIE* **792**, 2 (1987).

"On the Band Offset of AlGaAs/GaAs and Beyond," *Solid-State Electron.* **29**, 133 (1986).

"Resonant Magnetotunneling in Heterostructures," with E. E. Mendez and L. Esaki, *Phys. Rev. B* **33**, 5854 (1986).

"Valence Band Offset of AlAs/GaAs and the Empirical Relations for Band Alignments," with F. Stern, *J. Vac. Sci. Tech. B* **2**, 1280 (1985).

"Molecular Beam Epitaxial Growth and Material Properties of GaAs and AlGaAs and Si(100)," *Appl. Phys. Lett.* **44**, 1149 (1984).

"P-Channel MODFETs Using AlGaAs/GaAs Two-Dimensional Hole Gas," *IEEE Electron Device Lett.* **5**, 333 (1984).



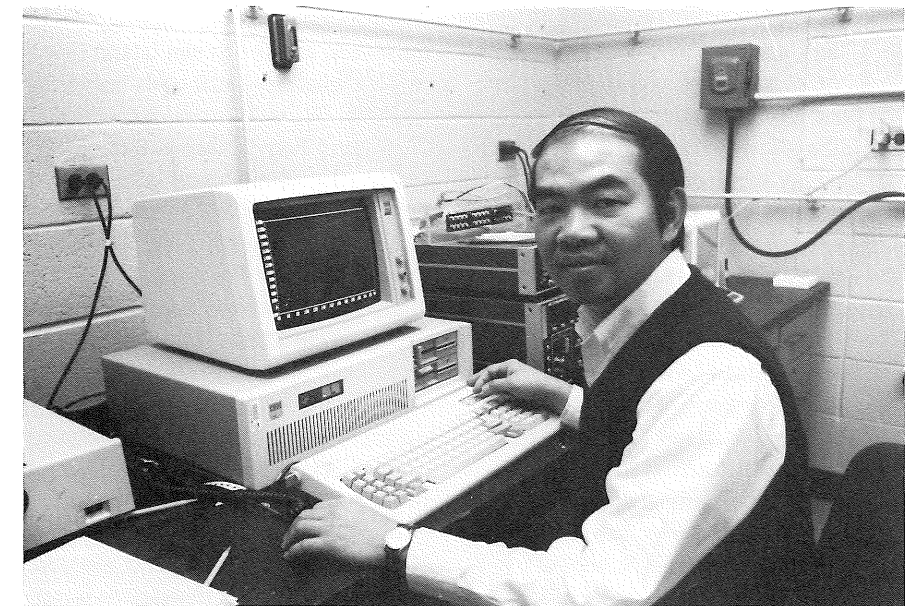
Maw-Kuen Wu

Professor (High Temperature Superconductivity, Materials Science)
B.A., Tamkang College of Arts and Sciences, 1973
M.S., 1975
Ph.D., Houston, 1982

My research interests are primarily in the area of high temperature superconductivity. I recently joined Columbia after pioneering work on developing superconductors with a transition temperature of 95°K. This recent breakthrough in critical temperature of oxide superconductors has spurred a renewed interest in both the understanding and application of superconductors at institutions and research laboratories around the world.

During our early search for oxide compounds with possible high temperature superconducting properties, my students and I observed an interesting correlation between the superconducting temperature and the interatomic distance of the K_2NiF_4 -type compounds. Heat treatment details including temperature, heating time, and cooling rate were also found to be critical to the formation of oxide compounds with proper crystal structure. Based on these factors, the first superconducting compound with a 90°K transition temperature (Y-Ba-Cu-O) was synthesized. Similarly, two new high T_c superconductors, Y-Sr-Cu-O and Bi-Sr-Cu-O, have recently been developed. I am currently continuing to pursue additional high temperature superconducting phases following similar empirical guidelines.

I have also investigated the possibility of raising the critical current density in the bulk oxide superconducting material through a dispersion of fine metal oxides. As a result of these studies, an unusually large magnetic flux pinning effect was discovered in a composite of Y-Ba-Cu-O and AgO. A large current density enhancement, about two orders of magnitude compared with the sintered bulk Y-Ba-Cu-O, resulted in this composite. In order to



optimize the bulk superconducting properties, we have continued to examine the composites and composite material interactions and compatibility.

In addition to the above research activities, I am interested in the studies of magnetic and optical properties of materials, particularly in studying the possible correlation between magnetism and superconductivity, and using the optical spectra of the materials to probe the excitations which may lead to better understanding of the properties of the observed material.

A wide range of experimental methods are used to carry out the research, including x-ray crystallography, electron microscopy, infra-red spectroscopy, Raman scattering, and electrical and magnetic property characterizations.

Selected Publications

"High Temperature Processing of Cuprate Oxide Superconductors," with J. R. Ashburn, C. A. Higgins, C. Fellows, B. H. Loo, D. H. Burns, A. Ibrahim, T. Rolin, P. N. Peters, R. C. Sisk, and C. Y. Huang, *Appl. Phys. Lett.* **52**, 1915 (1988).

"Superconductivity in Y-Sr-Cu-O Systems," with J. R. Ashburn, C. A. Higgins, B. H. Loo, D. H. Burns, A. Ibrahim, T. Rolin, and C. Y. Huang, *Phys. Rev. B* **37**, 9765 (1988).

"Superconductivity at 93°K in a New Mixed Phase Y-Ba-Cu-O Compound System at Ambient Pressure," with J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, *Phys. Rev. Lett.* **58**, 908 (1987).

Life In New York City

The University's official name is "Columbia University in the City of New York," and the University's location allows it to be an integral part of the City while maintaining the character of a unique neighborhood. The 32-acre campus is situated in Morningside Heights on the upper west side of Manhattan Island, between Riverside Park and the Hudson River to the west, and Morningside Park to the east. Broadway, a main north-south artery, separates Columbia from Barnard College across the street. Many other educational and religious institutions are nearby: Teachers College, the Manhattan School of Music, Union and Jewish Theological Seminaries, and the Cathedral of St. John the Divine. The campus was originally designed in the 1890s by the architectural firm of McKim, Mead, and White. Today, over 12,000 graduate and professional students and 2,600 faculty come here to work.

When you're not studying, New York offers a host of diversions. It has some of the world's best museums: the Metropolitan Museum of Art, the Museum of Modern Art, the Guggenheim, and the Whitney, to name a few. New York has five major ballet companies and two principal opera companies, the Metropolitan Opera and the New York City Opera. The New York Philharmonic plays at Avery Fisher Hall and almost every rock concert tour makes a stop at Madison Square Garden. Broadway plays, shopping on Fifth Avenue (especially around Christmas time), Chinatown, Little Italy, Greenwich Village, South Street Seaport, Wall Street, and the Bronx Zoo are all within easy reach. *The New Yorker* magazine or the *Village Voice* list hundreds of things to do in any given week.

If your budget reflects the cost of higher education, there is still plenty to do. Discount tickets are available for most major Broadway shows, there are student admission rates for the

museums, and the Staten Island Ferry (a great boat ride) still costs only a quarter.

Central Park is always free. Only a few blocks from Columbia, it is one of the most spectacular municipal parks in the nation. Covering 843 acres, it was designed by Frederick Law Olmsted and Calvert Vaux and was completed in 1873. Here you can get away from the hustle and bustle of the city, row a boat, hire a horse-drawn carriage, or bicycle to your heart's content. During the summer, there are street performers, outdoor concerts, opera, and "Shakespeare in the Park." The "Great Lawn" is the best place in the park to lie out in the sun, or watch other people lying out in the sun. In winter, there is ice-skating, available at two outdoor rinks, or cross-country skiing, snow conditions permitting. Stop by the "Dairy," the park headquarters at 65th Street near 5th

Avenue, to get a schedule of park events.

Getting around in New York is easy. The subway and buses run 24 hours a day, and taxis are ubiquitous. The majority of the subway cars are brand-new stainless steel, much quieter than the old ones. Graffiti is now the exception, not the rule. Most people find the subways safe and convenient to use, if they take a few simple precautions.

There is something special about New York. The people, the places, the history, and the happenings give it a unique character unlike anywhere else in the world. If you come with an open mind, you may just end up calling yourself a New Yorker.



Columbia in New York City

1. Baker Field

2. The Cloisters

3. Columbia-Presbyterian Medical Center

4. American Geographical Society, The Museum of the American Indian, The Hispanic Society of America, The American Numismatic Society, The Academy of Arts and Letters

5. City College of New York

6. Grant's Tomb and Riverside Park

7. Riverside Church

8. The Cathedral of St. John the Divine

9. Equity Library Theatre

10. Yankee Stadium

11. The Museum of the City of New York

12. The Guggenheim Museum

13. The Metropolitan Museum

14. The American Museum of Natural History/Hayden Planetarium

15. The Whitney Museum

16. Gracie Mansion

17. Hunter College

18. The Frick Collection

19. Temple Emanu-El

20. Central Park Zoo

21. Lincoln Center for the Performing Arts/The Metropolitan Opera House, Avery Fisher Hall, Alice Tully Hall, New York State Theatre, Vivian Beaumont Theatre, The Juilliard School, The Library and Museum of Performing Arts

22. Carnegie Hall

23. Broadway Theatre District

24. Times Square

25. Port Authority Bus Terminal

26. Rockefeller Center/Radio City Music Hall

27. The Museum of Modern Art
28. St. Patrick's Cathedral

29. Grand Central Terminal

30. Chrysler Building

31. United Nations Headquarters

32. The New York Public Library

33. Jacob Javits Convention Center

34. Madison Square Garden/Pennsylvania Station

35. Pierpont Morgan Library

36. Empire State Building

37. St. Mark's Church

38. Washington Square Park/Greenwich Village

39. New York University

40. Lower East Side

41. Chinatown

42. Little Italy

43. Centre Street/Courthouse District

44. City Hall

45. Trinity Church

46. Wall Street/Stock Exchange

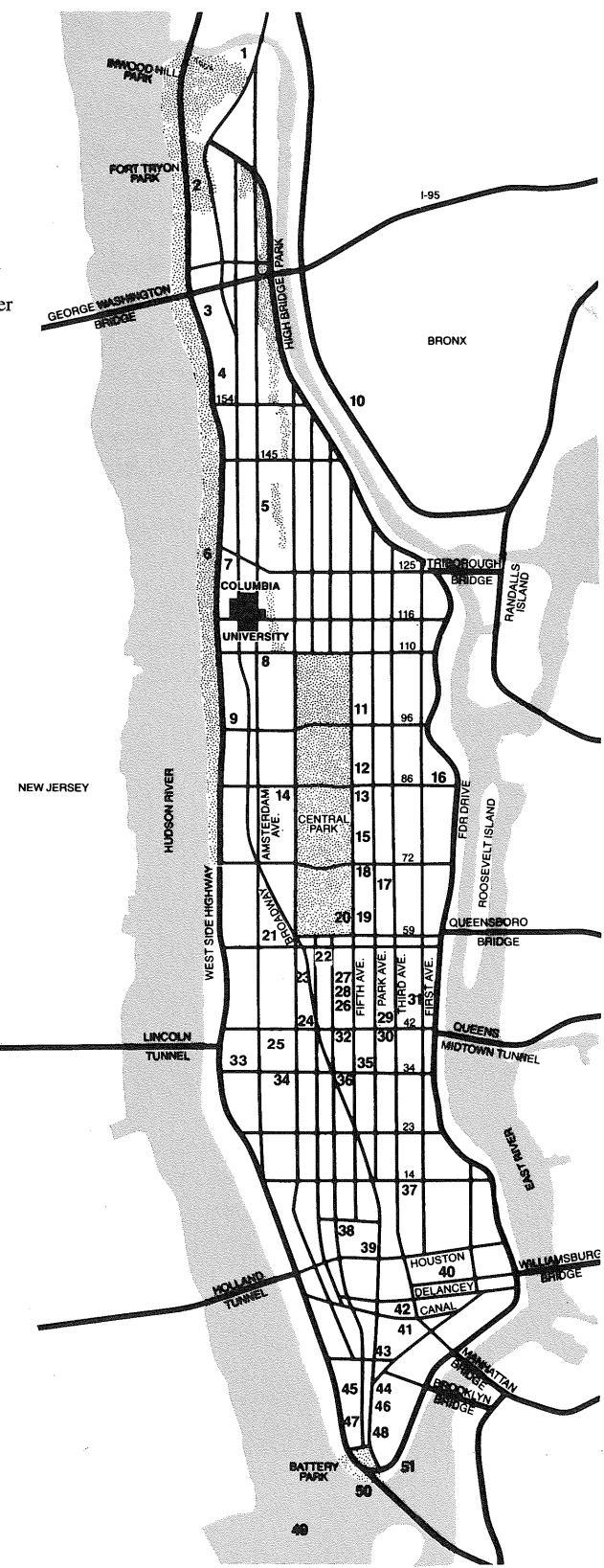
47. World Trade Center

48. Fraunces Tavern

49. Statue of Liberty

50. Staten Island Ferry

51. South Street Seaport



How to Get to Columbia

The Department of Applied Physics is located in the Seeley W. Mudd Building, 500 West 120th Street at Amsterdam Avenue. You may enter Mudd from 120th Street or from the fourth floor entrance at the northeast corner of campus.

By Car:

Columbia is best reached by taking the 95th/96th Street exit of the Henry Hudson Parkway (West Side Highway). Use the 95th Street off ramp and turn left onto Riverside Drive. Proceed north to 116th Street. A right turn at 116th Street leads you to the campus gate. The main campus runs from West 114th Street to West 120th Street between Broadway and Amsterdam Avenue.

To reach the Henry Hudson Parkway:

From the North - (1) New York Thruway (Route 87) to Cross Bronx Expressway in the direction of the George Washington Bridge. Bear right as you approach the bridge and take the exit for the Henry Hudson Parkway south. (2) New England Thruway (I-95) becomes the Cross Bronx Expressway. Proceed as above. (3) Saw Mill River Parkway south or Cross County Parkway west to Henry Hudson Parkway south.

From the West - New Jersey Turnpike (I-95) north or I-80 east to George Washington Bridge. Follow signs as you cross bridge to exit for Henry Hudson Parkway south.

By Train or Bus:

Train and bus service arrive at New York's Grand Central Station, Pennsylvania Station, or Port Authority Bus Terminal where a visitor can take either public transportation or a taxi north to the campus.

By Air:

La Guardia is the closest airport to the city and is about a \$15 taxi fare to the campus. For those coming into John F. Kennedy or Newark airports, bus service is available to either the East Side Terminal or Port Authority Bus Terminal. Taxi Service is available from these two airports, but it is expensive.

Public Transportation:

Four bus lines (M4, M11, M5, M104) and two subways (the Broadway IRT #1 and #9 locals) serve the Columbia/Morningside Heights area. If you find yourself on the Broadway IRT #2 express or #3 express, be certain to change to a #1 or #9 local train at 96th Street. The Columbia stop is 116th street.



Graduate Admission Procedures

The departmental graduate programs are primarily full-time doctoral programs. The department offers both the Ph.D. (Graduate School of Arts and Sciences) and Eng.Sc.D. (School of Engineering and Applied Science) degrees. First-year students are expected to obtain a M.S. degree while pursuing the doctorate and, because of University regulations, are enrolled in the Engineering School during their master's candidacy regardless of their eventual degree status.

For admission to the graduate programs, a bachelor's degree in science or engineering is required. The department considers any outstanding applicant. Deficiencies in background may be remedied while in graduate school. The GRE general test is required and essential for financial aid consideration. The TOEFL examination must be taken by applicants from abroad whose native language is not English.

Additional information on specific programs may be obtained by writing to the Department of Applied Physics, 202 Seeley W. Mudd Building, Columbia University, 500 West 120th Street, New York, New York 10027 (212-854-4457).

Applicants with specific interests are invited to contact individual faculty members. Visits to the department by prospective applicants are encouraged. The most useful time to visit is after submission of a completed application form.

Applications are due at the beginning of January for admission in the following autumn. Forms for application and financial aid are available from the Office of Admissions, School of Engineering and Applied Science, 530 Seeley W. Mudd Building, Columbia University, 500 West 120th Street, New York, New York 10027 (212-854-2931). Applicants planning to apply for National Science Foundation or Fannie and John Hertz Foundation fellowships should consult the department office.

Graduate Financial Support

Financial support is awarded on a competitive basis in the form of fellowships / graduate research assistantships or teaching assistantships. Fellowships and research assistantships are awarded initially on a nine-month or twelve-month basis. Teaching assistantships are for nine months. All support consists of a stipend plus tuition exemption for a full-time course program. Funding is awarded in March for the following academic year. There is little opportunity for funding at mid-year. The stipend rate is adjusted periodically for inflation. The twelve-month research assistant stipend for 1989-90 is \$11,500. Tuition exemption for 1989-90 represents approximately \$14,000.

Graduate Housing

Columbia housing is varied. Dormitory-style rooms and suites, for which a yearly contract is signed, are available in University residence halls for single and married students. Many apartments are also available for lease in Columbia-owned buildings in the immediate neighborhood. Application may also be made to International House, an independent residence that provides rooms and dining and recreational facilities for both international and U.S. students. Most housing is located within a ten-minute walk from Applied Physics laboratories and offices.

The department has been able to secure University housing in a timely manner for all supported graduate students who have requested it to date. However, since housing in New York City is limited, it is important that new students return their housing applications promptly.

