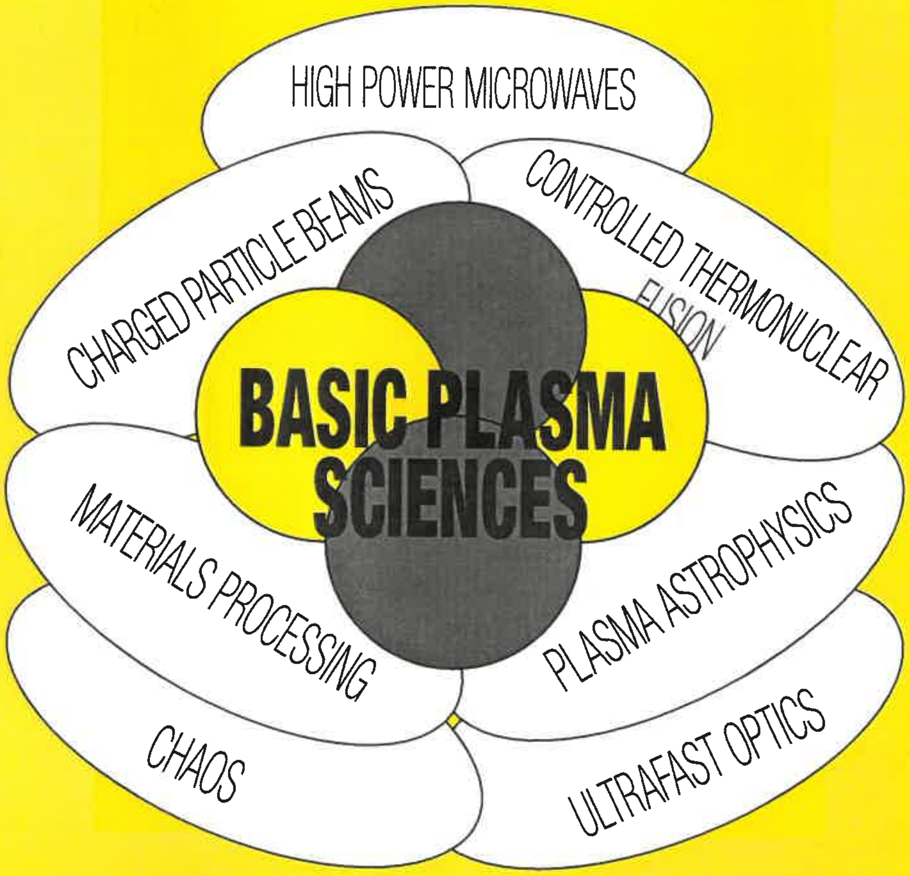
RESEARCH PROGRAMS

INSTITUTE FOR PLASMA RESEARCH



University of Maryland at College Park

RESEARCH PROGRAMS*

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INTRODUCTION

The Institute for Plasma Research (IPR) is housed in the Energy Research Building and in part of the A.V. Williams Building on the College Park campus. IPR conducts basic and applied research on physical phenomena in plasmas (hot, electrically charged gases, the stuff that the sun and stars are made of) in charged particle beams (electron and ion beams) and on high power microwaves generation with relativistic electron beams. One important area of application is Controlled Thermonuclear Fusion (CTF) (both in magnetically confined plasma and in plasma created and compressed by lasers or heavy ion beams); CTF reactors would provide a lasting solution to the world's energy problem. A second area of application is in the development of advanced accelerators for use in high energy physics research. Other areas of impact include millimeter-wave electronics, materials processing technology, and microstructure fabrication.

Experimental and theoretical research and computer simulation is pursued in the Institute by 28 faculty members from five academic departments, primarily the Physics Department and the Electrical Engineering Department. In addition, there are 30 members of the IPR research faculty. Some three dozen graduate students are working on their doctoral research projects under the direction of the Institute faculty.

The research is sponsored by the Department of Energy, the Department of Defense, the National Science Foundation, and the National Aeronautics and Space Administration. The research focuses on a number of critical areas including the following:

- theory of plasma stability and transport;
- theory of chaotic dynamics in general dissipative nonlinear systems;
- measurement of high temperature plasma properties;
- charged particle beam acceleration and transport;
- generation of high power microwaves for application to particle acceleration, plasma heating, and advanced radar and countermeasure systems;
- fabrication of microstructures with ion beams;
- ion beam lithography for producing integrated circuits with dense packing of components;
- ultrahigh power, short pulse lasers for studies of intense field phenomena in atoms, molecules and plasmas;
- multifrequency microwave sintering of ceramics;
- the physics and chemistry of lightning.

CHARGED PARTICLE BEAM RESEARCH

The Charged Particle Beam (CPB) research group is a member of IPR and involves faculty of the Electrical Engineering and Physics Departments at the University of Maryland.

Research in the CPB group covers a wide spectrum of activities ranging from the physics and design of high brightness beams for advanced accelerator applications and ion beam projection lithography (in collaboration with the LIBRA group), research and development on high-power microwave sources for future linear colliders (gyroklystron), radar/communication systems, and other applications to plasma microwave electronics and microwave processing of materials. Most of the group's research is centered around experimental facilities, but there is also a strong theoretical effort involving both analytical theory and numerical simulation in support of the experiments in our laboratory and elsewhere.

CURRENT STUDIES

RESEARCH ON THE PHYSICS OF SPACE-CHARGE DOMINATED BEAMS

Reiser, Wang

Intense charged particle beams play an important role in many advanced particle accelerator applications, such as high-energy physics colliders, heavy ion inertial fusion, nuclear waste transmutation and energy production, spallation neutron sources for materials research, medical therapy, high-power microwave and free electron laser generations. Due to the ever-increasing requirements for high current and low emittance, the dynamics of such beams is dominated, or significantly affected, by the space-charge forces. These forces may lead to significant beam deterioration and losses if the particle distribution is not in thermal equilibrium or if there are instabilities due to interaction with the external environment (e.g., the resistive wall instability).

We study the effects of space-charge forces on intense beams in experiments employing low energy electron beams, in combination with theoretical investigations and computer simulations. Our facilities include two electron beam injectors, a five-meter long periodically focused solenoidal transport facility, a one-meter long resistive-wall transport facility, and advanced equipment, beam diagnostic instruments, and data acquisition and analysis facilities.

Recent experiments involved the study of image and halo formation in the merging of a 5-beamlet configuration (see figure 1)[1], the longitudinal compression of space-charge dominated electron bunches with rectangular or parabolic profiles, the generation and propagation of localized perturbations as slow or fast space-charge waves, the measurement and determination of the geometry factor for space-charge dominated coasting beams, reflection and transmission of space-charge waves at beam bunch ends (see figure 2),[2] longitudinal instabilities in a resistive-wall transport channel, longitudinal energy spread of electron beams from a thermionic source.

Theoretical studies are concerned with the thermal equilibrium state (Maxwell-Bockmann distribution) of beams, equipartitioning effects if a beam is not in thermal equilibrium (as is usually the case), and the effects of image forces due to conducting boundaries.

A new initiative to design and develop an electron recirculator is underway. This project is to study the strong space-charge effects in circulating beams, including fast resonance traversal and current limits, bending of intense beams, injection and extraction, mismatch, longitudinal-transverse coupling and relaxation towards thermal equilibrium.

References:

1. M. Reiser, Theory and Design of Charged Particle Beams, John Wiley & Sons, Inc., New York, 1994, Ch. 6.

2. J. G. Wang, D. X. Wang, H. Suk, and M. Reiser, Phys. Rev. Lett. **74**, (16), 3153 (1995).

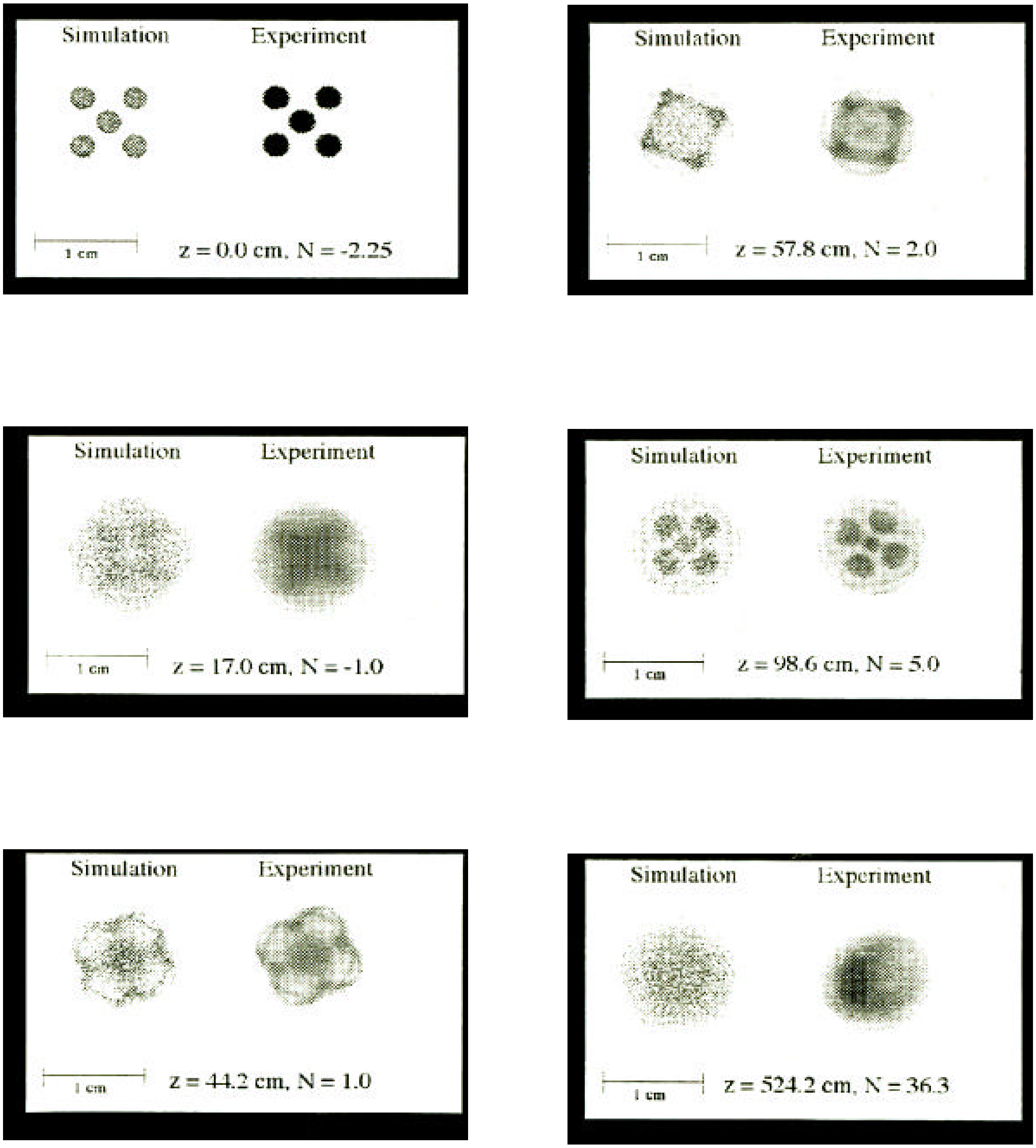


Figure 1. **Simulation plots and fluorescent-screen pictures of the electron beam profiles at six different locations along the transport channel showing the evolution of an initial 5-beamlet configuration into one single beam with increased temperature and emittance.**

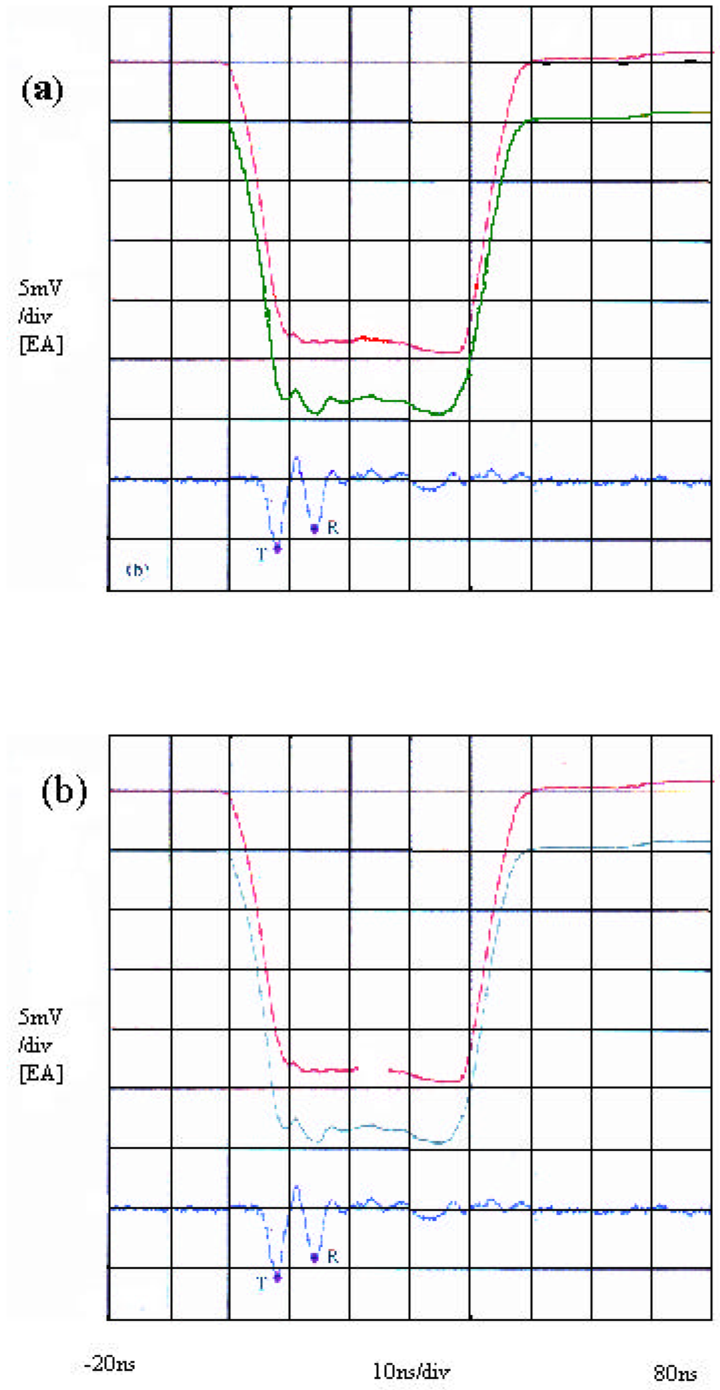


Figure 2. Observation of reflection and transmissions of space-charge waves at bunch end of an eroded rectangular beam: (a) a single fast wave (F) approaching the beam front end; (b) reflected wave (R) and transmitted wave (T) around the beam front end downstream. In each figure the top trace is the beam current pulse without space-charge waves, the middle one is the pulse with localized space-charge waves, and the bottom trace is the difference between those two signals and represents the net space-charge wave modulated on the beam.

HIGH BRIGHTNESS H$^-$ ION BEAMS, BEAM TRANSPORT AND FOCUSING

Guharay, Reiser, Melngailis, Orloff

Interests in the area of high brightness ion beams have grown due to very stringent requirements of the beam quality in many current research areas in physics and engineering, namely, high luminosity colliders, advanced accelerators for radioactive waste transmutation and for spallation neutron sources, ion projection lithography, ion beams for microscopy and materials science, etc. For some of these applications, negative ion beams have special advantages over positive ions. We have developed a new laboratory for studies of intense, high brightness H$^-$ beams. Our current research interest is directed to: (a) application of H$^-$ beams for ion projection lithography (IPL), and (b) study of ion beam transport and focusing using electrostatic quadrupole (ESQ) lenses.

In view of the IPL program our goal is to achieve high quality H$^-$ beams with their characteristics beyond the present state-of-the-art positive ion beams which are being used in current IPL machines. The desired H$^-$ beams parameters are: emission current density of $\gtrsim 1\,\mathrm{A/cm^2}$, normalized beam brightness of $\gtrsim\ 10^{13}\,\mathrm{A/(m\,rad)^2}$, and energy spread of about 2 eV. We have developed a test stand using two types of H$^-$ sources in the surface plasma source family: (i) a magnetron-type and (ii) a Penning-type source. The hardware of the ion sources was developed through our collaboration with the Superconducting Super Collider Laboratory (for the magnetron source) and with the Budker Institute of Nuclear Physics, Russia (for the Penning source). We are currently operating the ion sources in pulsed mode with a duty cycle of $\lesssim 1\%$. We have achieved an H$^-$ emission current density of $>\ 1\,\mathrm{A/cm^2}$. Preliminary measurements suggest the normalized beam brightness of $\sim\ 10^{13}\,\mathrm{A/(m\,rad)^2}$. Experiments for optimization of the beam parameters are in progress. This study guides us to develop a cw source for IPL. The ion source can also be operated for production of H$^+$ ions, and future studies will be done to investigate the beam characteristics of H$^-$ and H$^+$ beams. Additional details can be found in the article "Ion Projection Lithography" in the LIBRA section of this brochure.

Our studies on high brightness beam transport and focusing stem from our past involvement in developing a low energy beam transport system (LEBT) for the Superconducting Super Collider. Strict emittance budget for high-luminosity colliders offers a challenge to achieve a satisfactory solution for LEBTs. We made detailed simulation studies of the beam dynamics to design an efficient LEBT which can deliver a matched beam (30 mA, 35 kV) to a radio-frequency quadrupole accelerator (RFQ) without any significant emittance dilution. Experimental constraints have been strictly included in this study. The ESQ LEBT system has been constructed in-house. Voltage holding tests without beams show satisfactory results. Further work is in progress in view of a potential collaboration with the Fermi National Accelerator Laboratory and the High Energy Physics Institute in Japan (KEK).

HIGH POWER GYROKLYSTRON AMPLIFIERS FOR DRIVING ELECTRON-POSITRON SUPERCOLLIDERS

Granatstein, Lawson, Reiser, Saraph, Calame, Nusinovich, Hogan

Basic high energy physics research will require electron positron colliders with center of mass energy in the range 0.5 — 5 TeV. To keep the length and cost of the electron and positron accelerators that make up such a collider within reasonable bounds one must develop more capable microwave amplifiers.

A figure of merit for such amplifiers is the ratio $P_p\tau_p/\lambda^2$, where P_p is the peak microwave output power from each amplifier, τ_p is the microwave pulse duration, and λ is the wavelength. The presently operating Stanford Linear Collider is driven by klystron amplifiers operating at a frequency of 2.856 GHz and with a value of $P_p\tau_p/\lambda^2 = 2$ MW μsec/cm^2. Gyroklystron amplifiers have inherent advantages over conventional klystrons in terms of producing higher power at shorter wavelengths. A frequency doubling gyroklystron in the Institute for Plasma Research has already demonstrated microwave output pulses at 19.7 GHz with $P_p\tau_p/\lambda^2 = 11$ MW μsec/cm^2.

Research that is currently underway seeks to increase the value of $P_p\tau_p/\lambda^2$ by as much as an additional factor of 10. Analysis, numerical simulation, and laboratory experiments are all employed in attempting to maximize amplifier efficiency and minimize spurious phase fluctuations. Variations in the amplifier circuit configuration (e.g., gyrotwystrons) are also under consideration.

PREBUNCHED GYROTRONS

Lawson, Destler, Rodgers

For the prebunched gyrotron amplifier program, we are working on the development of novel high efficiency, harmonic gyrotron sources. One such device, called the axially-modulated, cusp-injected, large-orbit gyrotron, is a hybrid microwave amplifier that uses the axial bunching mechanism of the klystron amplifier on an annular, linearly-streaming beam to prebunch a large-orbit gyrotron. The axial bunches are created ballistically after the beam passes through an input cavity which is driven with a TM$_{n10}$ circularly-polarized mode. Axial bunching is converted into azimuthal bunching when the beam encounters a balanced, nonadiabatic magnetic transition (cusp) and begins to rotate at the cyclotron frequency. Efficiencies as high as 65% have been simulated with third-harmonic circuits. A proof-of-principle experiment is under construction.

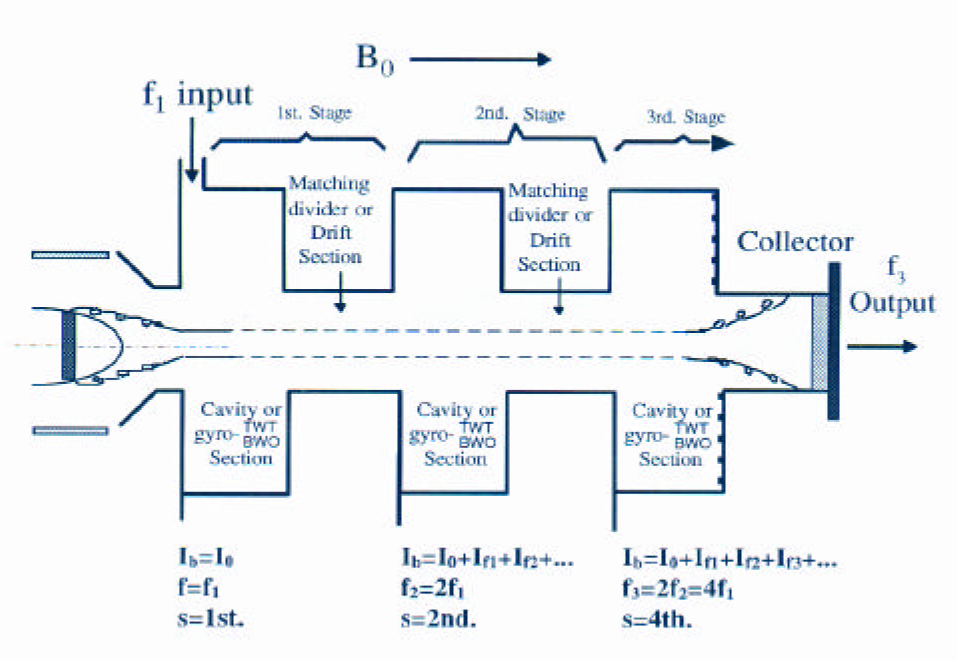
HARMONIC MULTIPLYING GYROTRON PHASE-LOCKED OSCILLATORS AND AMPLIFIERS

Guo, Granatstein, Nusinovich, Rodgers, Walter

For the development of imaging radars, electronic warfare and communication systems, high power sources of millimeter-wave, phase-controlled radiation are of great interest. Some of the best candidates for these applications are low voltage, harmonic gyrotron amplifiers and phase-locked oscillators. Operation at low voltages leads to reduction of the weight and size of both the high voltage supplies and the microwave tubes. Operation at cyclotron harmonics (when operating frequency is S times higher than the electron cyclotron frequency, where S is the harmonic number) allows one to develop millimeter-wave gyrodevices without using cryogenically cooled solenoids. All this is especially important for airborne systems.

The development of low voltage harmonic phase-controlled gyrodevices was started in collaboration with the Jet Propulsion Laboratory and involved an experimental demonstration of phase-locking in a gyrotron oscillator. In this experiment a 35 GHz, 100 kW second harmonic gyrotron oscillator was used. An external, low power, injection signal was sent via a quasi-optical circulator and then through the output window back into the tube, thus providing phase-locking of oscillations.

At present, our program includes both theoretical and experimental studies of various configurations of multistage gyrodevices. Among them are two-stage gyrotraveling wave tubes, gyrotwystrons and inverted gyrotwystrons (these devices combine in their microwave circuits both waveguide and resonator components), and multistage gyroklystrons with successive frequency multiplication. In the latter scheme, as shown in the figure below, the electrons interact with the field of the first cavity at the fundamental cyclotron resonance. Then, these electrons excite the second cavity field being in resonance at the second harmonic. Finally, an electron beam prebunched in such a way excites the output cavity with a fourth harmonic interaction. The frequency multiplication makes it possible to operate in a millimeter-wave region using low frequency drivers and low magnetic fields which can be produced by permanent magnets. Studies also include selective circuits providing stable operation with symmetric TE_{on} modes.



Physical mechanism and configuration of the harmonic multiplying gyrotron

EFFICIENCY ENHANCEMENT OF GYROTRONS BY USING DEPRESSED COLLECTORS

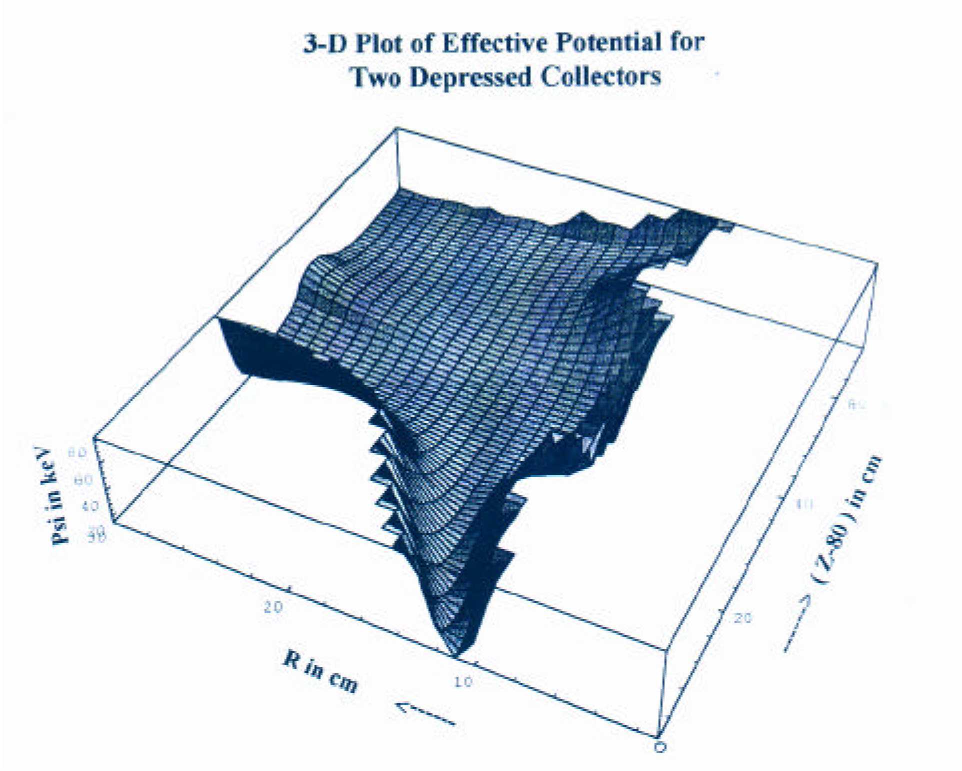
Singh, Granatstein, Rajapatirana, Goldman

High power millimeter wave sources, such as gyrotrons and free electron lasers, do not presently have the efficiency of the most efficient conventional tubes operating at longer wavelengths. Overall efficiency is an important consideration in various applications such as plasma heating, materials processing, high energy electron accelerators, etc. The Institute for Plasma Research has been actively engaged in studies on enhancement of overall efficiency by using depressed collectors.

Techniques have been developed for tailoring the electric and magnetic field configurations in the collector region, such that electrons in the spent beam would be sorted according to energy and would not turn back before getting collected. These techniques have been applied to the cases of large and small orbit gyrotrons. Designs were developed for tubes with axially and radially extracted beams, and for cavity-type as well as quasi-optical-type resonators for rf interaction.

A library of computer codes has been developed to assist in various stages of depressed collector design. They help to define the regions of accessibility for electrons, and provide pre- and post-processors for the code which simulates electron trajectories. They help to reduce the design time and evaluate new designs in terms of collector efficiency and heat dissipation density profile. Among other things they provide insights into the behavior of the electron trajectories through three-dimensional representation of an effective potential. Animated contours can be generated to get an overview of the effect of variations due to different parameters.

A feasibility study was done for a single-stage depressed collector for a gyrotron for the International Thermonuclear Experimental Reactor (ITER). Currently a design is being developed for a two-stage depressed collector for it, in close collaboration with industry. Some additional tubes have been suggested for being taken up for incorporation of depressed collectors in the future.



3-D plot of effective potential for two depressed collectors

THEORY AND MODELING OF ADVANCED HIGH ENERGY MICROWAVE SOURCES

Antonsen, Nusinovich, Saraph

The Institute for Plasma Research houses one of the leading groups of theoreticians involved in the theoretical description, analysis, and modeling of both slow-wave and fast-wave advanced microwave sources. This theory group presently provides strong support for experimental activities at both Maryland and other institutions such as MIT, the Naval Research Laboratory, and Varian Associates. The various members of the group are intimately involved in all source development activities including the gyroklystron, gyrotwystron, harmonic gyrotron amplifier, backward wave oscillator, plasma/microwave electronics, and free electron laser programs. In particular, the group is internationally known for pioneering work on the nonlinear theory of slow-wave devices and mode competition in overmoded fast-wave devices. One of the most important problems in the design of high power, high frequency radiation sources is ensuring operation in the desired mode. This problem is especially difficult in high power devices because, typically, at the optimum operating point, a large number of modes can be excited. One is then led to ask the following question: what steps must be taken to maximize the efficiency of the device while ensuring single mode operation? The central theme of the theoretical research at the University of Maryland is developing analytical and numerical models capable of addressing this question. These models have been used in the analysis of mode competition in fast-wave devices such as gyrotron oscillators, gyroklystrons, gyro-TWTs, free electron lasers, and slow-wave devices such as relativistic backward wave oscillators and amplifiers. The computer codes based on these models have been successfully applied to existing experiments.

PLASMA MICROWAVE ELECTRONICS

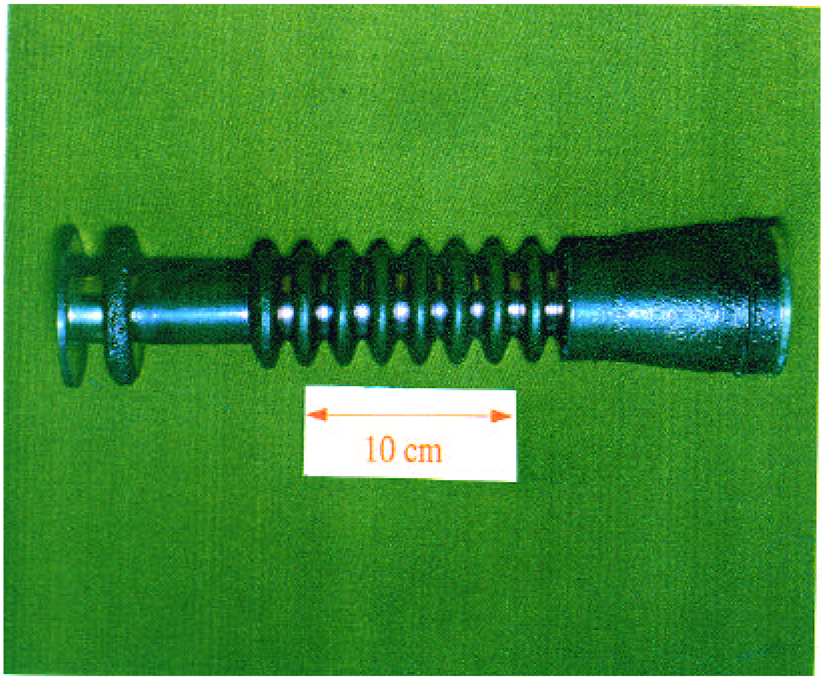
Carmel, Destler, Antonsen, Granatstein, Rodgers, Shkvarunets, Nusinovich

Coherent sources of microwave and millimeter waves are commmonly used for communications, radars, and for the heating of materials. In many microwave sources a streaming electron beam is slowed down and its excess kinetic energy is transferred to an electromagnetic wave which is growing in amplitude. This process usually takes place inside an evacuated cavity or some other electrodynamic structure, and then the radiation is transmitted out.

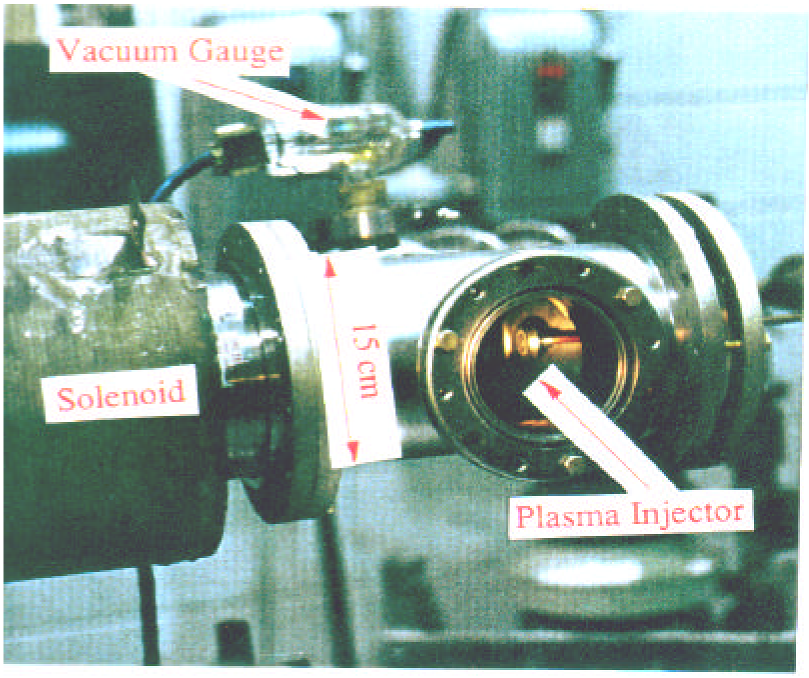
A controlled amount of a low density background plasma inside microwave devices was shown to have beneficial effects on their operation. For example, the conversion efficiency of electron beam kinetic energy to radiation may be enhanced by the plasma. Also, the plasma can be used to electronically control the operating frequency of the device and to increase its power handling capabilities.

At the Institute for Plasma Research we are involved in experimental and theoretical research aimed at improving our understanding of the nature of the interaction between the electron beam, the electromagnetic waves, and the background plasma. Specifically, we accelerate high current ($>$ 100's of Amperes) electron beams to relativistic velocities ($> 90\%$ the speed of light) and investigate their interaction with plasma-loaded spatially periodic electromagnetic structures. Also investigated are techniques for efficient generation and characterization of plasmas, as well as effects of the plasma on the electromagnetic properties of electrodynamic structures. The goal of our work is to improve the basic understanding of plasma-loaded microwave oscillators and amplifiers in order to design advanced microwave sources of higher peak powers ($> 10^9$ Watt), higher efficiency, and improved bandwidth.

We conduct an interdisciplinary research activity in such areas as electrical engineering and physics. Also, we emphasize collaboration with industry and with scientists in other countries.



Key Component of a Plasma-Loaded Backward Wave Oscillator:
The Microwave Cavity



The Plasma Injector
(mounted inside the vacuum chamber)

PSEUDOSPARK
Rhee

Dr. Rhee's research interests cover the broad area of charged particle beams, beam qualities, pulsed power systems, plasma focus, and pseudospark discharge.

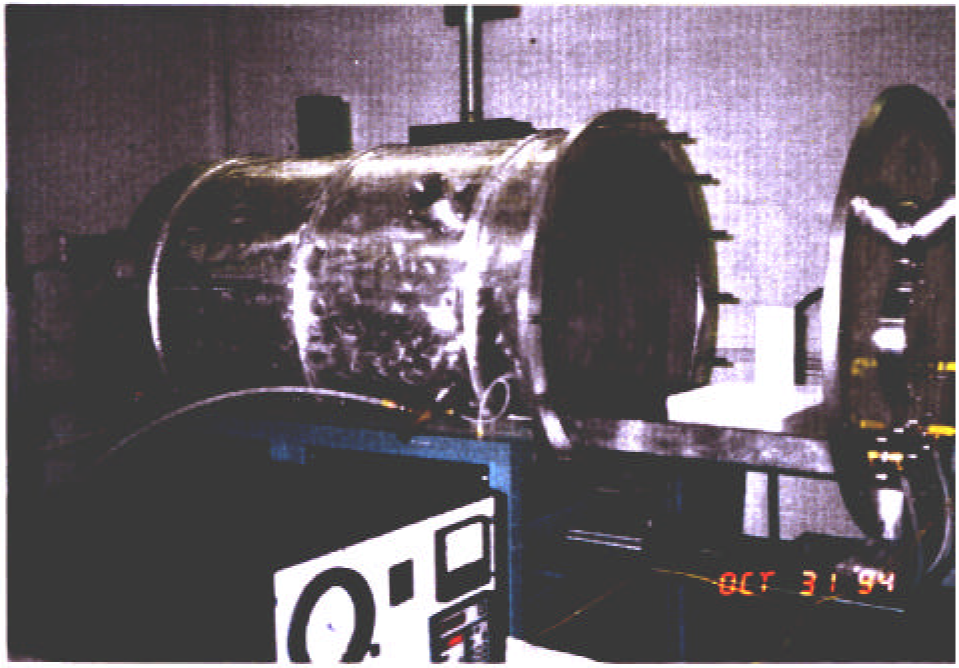
His current research activities are centered around studies on pseudospark discharge. The pseudospark is a fast low-pressure gas discharge between a hollow cathode and a planar anode. Interesting phenomena associated with the discharge include fast spark-like discharge and charged particle emission during the discharge. Such phenomena would find immediate applications in fast switches, high-quality charged particle beam sources, and beam sources for material processing. Systematic experimental studies have been carried out for the breakdown voltage characteristic, the electron beam current scaling, and the post acceleration of the electron beam. Interesting experimental results obtained are expressed in empirical formula that would be useful in understanding further the pseudospark phenomena. Currently, the study of modeling the pseudospark breakdown is underway based on the measured breakdown voltage characteristic that distinctively differ from Paschen's law.

MICROWAVE PROCESSING OF MATERIALS
Carmel, Lloyd, Calame, Antonsen, Granatstein

The hope of achieving superior material properties unattainable by other methods of processing led to increased interest in microwave processing.

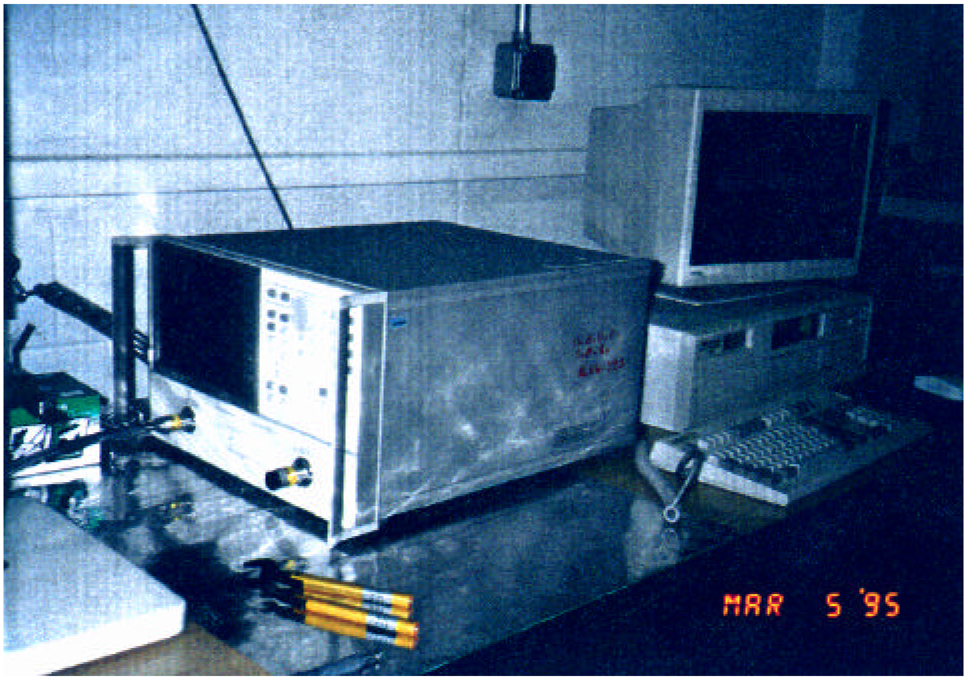
This program involves research and development of new ways of processing materials, such as ceramics and polymers, using microwave radiation. There are several advantages to be gained from using microwave processing instead of conventional heating, including significant reductions in processing time, control over thermal gradients, novel microstructures and properties, selective heating in composites, and the synthesis of new materials. These advantages are based on the fact that the heat is generated within the material instead of diffusing in from external heat applied to the surfaces. We are currently investigating a wide range of experimental topics, including studies of microstructure, acoustic properties, and dielectric properties of ceramics such as zinc oxide during the sintering process; the development of improved, economical microwave applicator systems and thermal diagnostics; and basic research on possible nonthermal enhancements of the sintering process induced by microwaves. Theoretical issues under study include modeling the sintering process in space and time using the combined numerical solution of the heat equation, densification equation, and Maxwell's electromagnetic equations. Additional research topics include the development of improved dielectric and thermal mixing laws, electromagnetic and thermal modeling of ceramic microstructures, and fundamental studies of dielectric absorption in ceramic grain boundaries.

We conduct an interdisciplinary research activity in such areas as electrical engineering, material science and physics. Also, we emphasize collaboration with industry and with scientists in other countries (Canada, Russia).



The University of Maryland Microwave Processing Laboratory:
500 Liter Processing Applicator
Computerized Process Control

3000 W @ 2.45 GHz
1250 W @ 28 GHz



The University of Maryland Microwave Processing Laboratory:
Dielectric Measurement Set-Up

Measurements of real and imaginary dielectric constants of solids and liquids over the frequency range of 0.1 to 20 GHz

FACULTY

THOMAS M. ANTONSEN, JR.
Professor

Thomas M. Antonsen, Jr. was born in Hackensack, New Jersey, in 1950. He received his B.S. degree in electrical engineering in 1973, and his M.S. and Ph.D. degrees in 1976 and 1977, all from Cornell University. He was a National Research Council postdoctoral fellow at the Naval Research Laboratory in 1976-1977, and a research scientist in the Research Laboratory of Electronics at MIT from 1977 to 1980. In 1980 he moved to the University of Maryland where he joined the faculty of the Departments of Electrical Engineering and Physics in 1984. He is currently professor of physics and electrical engineering. Prof. Antonsen has held visiting appointments at the Institute for Theoretical Physics (UCSB), the Ecole Polytechnique Federale de Lausanne, Switzerland, and the Institute de Physique Theorique, Ecole Polytechnique, Palaiseau, France. He was selected as a fellow of the Division of Plasma Physics of the American Physical Society in 1986.

Prof. Antonsen's research interests include the theory of magnetically confined plasmas, the theory and design of high power sources of coherent radiation, nonlinear dynamics in fluids, and the theory of the interaction of intense laser pulses and plasmas. He is the author or co-author of over 140 journal articles and co-author of the book "Principles of Free-electron Lasers." Prof. Antonsen has served on the editorial board of Physical Review Letters, The Physics of Fluids, and Comments on Plasma Physics.

JEFFREY P. CALAME
Assistant Research Scientist

Jeffrey Calame received his doctorate in electrical engineering from the University of Maryland in 1991.

Dr. Calame's research involves the development of improved microwave ceramic sintering processes and apparatus, fundamental investigations of loss mechanisms in microwave absorbing ceramics, polymers, and composites, the development of improved microwave absorbers for use in power tubes and accelerators, theoretical and experimental studies of electromagnetic wave propagation in waveguide and cavity structures loaded with very lossy dielectrics, and the investigation of materials-science issues related to high vacuum system construction and processing.

YUVAL CARMEL
Senior Research Scientist

Yuval Carmel was born in Israel in 1942. He received the B.S. (EE) and M.S. (EE) degrees from the Technion, Israel Institute of Technology, in 1966 and 1971, respectively, and the Ph.D. (EE) degree from Cornell University, Ithaca, NY, in 1974. He was with the government of Israel, the Naval Research Laboratory, and is currently with the University of Maryland at College Park.

His research interests include electromagnetic radiation from intense electron beams, plasma microwave devices, and materials processing with electromagnetic waves. He has been a reviewer for the NSF, AFOSR, and DOE. He has co-authored more than 60 research papers in regular journals and holds three patents. He served as a consultant to the Jet Propulsion Laboratory, Physical Sciences, Inc., Science Applications International Corporation, and Jaycor. He is a senior member of IEEE and a member of the American Physical Society and the American Ceramics Society.

WILLIAM W. DESTLER
Professor

William W. Destler received the B.S. degree from the Stevens Institute of Technology in 1968 and the Ph.D. degree from Cornell University in 1972.

Prof. Destler's research interests have been primarily in the areas of high power microwave sources and advanced accelerator technology, and he is the author or co-author of over 100 research papers on these and related topics. He is also the recipient of numerous awards for teaching excellence, including the 1989 AT&T/ASEE Award for Excellence in Engineering Education for the Mid-Atlantic States. Prof. Destler is a fellow of both the IEEE and the American Physical Society.

VICTOR GRANATSTEIN
Professor

Victor Granatstein received his doctorate in electrical engineering and plasma physics from Columbia University in 1963. He was a research scientist at Bell Telephone Laboratories from 1964 to 1972. From 1972 to 1983, he was with the U.S. Naval Research Laboratory where he was Head of the High Power Electromagnetic Radiation Branch. He joined the Maryland faculty in 1983 and was appointed Director of the Institute for Plasma Research in 1988.

Prof. Granatstein's research interests are in the area of relativistic microwave electronics, especially gyrotrons and free electron masers with application to plasma heating in magnetic fusion energy (MFE) research, advanced particle accelerators for high energy physics (HEP) research, microwave processing of materials, millimeter-wave radar systems, and unconventional electronics warfare (EW).

His current research interests are focused on developing gyrotron amplifiers and oscillators which operate efficiently at harmonics of the electron cyclotron frequency and are of particular interest in the HEP, radar, and EW applications. The approach being investigated is harmonic multiplication at each successive stage of a multistage gyrotron circuit; harmonic multiplication reduces the magnetic field in the gyrotron and thus avoids the requirement of using superconducting magnets. Employing depressed collectors to enhance gyrotron efficiency is also being investigated. In free electron maser research directed at the MFE application, the possibility of using micro-wigglers in high average power configurations is being investigated with the aim of reducing voltage requirements. Studies of plasma-filled backward-wave oscillators are also being pursued on a path to developing more compact high-power-microwave (HPM) generators. Finally, the basic phenomenology of microwave sintering of ceramics is being studied with the aim not only of improving sintering technology but also of producing ceramics with superior mechanical and electrical properties.

SAMAR K. GUHARAY
Associate Research Scientist

Samar K. Guharay received his Ph.D. in physics from the University of Calcutta in 1980. He joined the Maryland faculty in 1984. Prior to this, he had been at the Centre d'Etudes Nucleaires de Grenoble, France, and the Institute of Plasma Physics, Nagoya University, Japan.

Dr. Guharay's current research interests include: (a) development of intense, high brightness negative ion sources, (b) study of negative ion beams for ion projection lithography, and (c) beam transport studies for high energy accelerators.

Dr. Guharay collaborates with the Fermi National Accelerator Laboratory and the Budker Institute of Nuclear Physics, Novosibirsk, Russia. During May 10 – August 11, 1995, Dr. Guharay was awarded a guest professorship by the Ministry of Education and Culture, Japan, and he worked on neutral beams for magnetic fusion at the National Institute for Fusion Science, Nagoya.

HEZHONG GUO
Associate Research Scientist

Hezhong Guo was born January 27, 1937 in Jiangsu, China. He received the B.S. and Ph.D. equivalent degrees in electrical engineering from the Nanjing Institute of Technology, Nanjing, China, in 1961 and 1965, respectively. He became a research member at the Institute of Electronics, Academia Sinica, in 1965, and was promoted to associate professor and full professor of microwave electronics in 1978 and 1986, respectively. From 1981 to 1983, he joined the Department of Engineering and Applied Science at Yale University, New Haven, CT. Since 1989, he has been a research scientist at the Institute for Plasma Research, University of Maryland.

Dr. Guo has taught and done research on traditional millimeter-wave vacuum devices and relativistic electronic devices. His current fields of research interests are high harmonic gyrotron amplifiers, phase-locked oscillators, and other types of high power microwave devices. Dr. Guo has co-authored 61 papers in regular scientific journals and a design handbook of millimeter-wave tubes. He was a member of the Council of Fusion and Plasma Physics Society of China and a fellow of the Chinese Institute of Electronics before he was given a permanent position working in the United States in 1991.

GREGORY NUSINOVICH
Senior Research Scientist

Gregory Nusinovich was born in 1946 in Berdichev, former Soviet Union. He received the B.S. and Ph.D. degrees from Gorky State University in 1968 and 1975, respectively.

After graduating from Gorky University he joined the Gorky Radiophysical Research Institute. From 1977 to 1990 he was a research scientist and head of the research group at the Institute of Applied Physics of the Academy of Sciences of the USSR. From 1968 to 1990 his scientific interests were aimed at developing high power millimeter- and submillimeter-wave gyrotrons. He was also a member of the Scientific Council on Physical Electronics of the Academy of Sciences of the USSR.

In 1991 he emigrated to the USA, where he joined the research staff at the Institute for Plasma Research, University of Maryland. His current research interests include the study of high power electromagnetic radiation from various types of microwave sources. Since 1991 he has also served as a consultant to the Science Applications

International Corporation and the Physical Sciences Corporation.

WESLEY LAWSON
Associate Professor

Wesley Lawson received his doctorate in electrical engineering from the University of Maryland in 1985. He worked for three years as a research scientist before joining the faculty of the Electrical Engineering Department.

Prof. Lawson is leading experimental and theoretical studies in fast-wave devices, thermionic electron guns, and high power microwave components. Major efforts at the present time include the gyroklystron and the prebunched gyrotron programs.

MARTIN REISER
Professor

Martin Reiser received his doctorate in physics in 1960 from the Johannes Gutenberg Universität Mainz in Germany, while working as a research physicist at the AEG-Forschungsinstitut Frankfurt (from 1958 to 1961) on the design of the sector-focusing cyclotron for the Karlsruhe Nuclear Research Center. From 1961 to 1964 he was assistant professor in the Physics Department of Michigan State University, and from 1964 to 1965 he worked as a supervisory research physicist at the Naval Radiological Defense Laboratory, San Francisco, California. In September 1965, he joined the University of Maryland as an associate professor with a joint appointment in the Electrical Engineering Department and the Department of Physics and Astronomy. He was promoted to full professor in 1970. He was co-founder of the University of Maryland's Institute for Plasma Research, established in 1981.

Prof. Reiser's experimental and theoretical research is in the area of charged particle beam physics and accelerator design. His research work and interests range from cyclotron and collective accelerators (in the sixties and seventies) to advanced accelerator applications (during recent years) in high energy physics, in the energy field (e.g., heavy ion inertial fusion), in material science, and in other areas. A major topic of his current research in advanced accelerator applications is the physics of space-charge dominated beams and sources of beam quality deterioration due to conversion of free energy (experiments, theory, and particle simulation).

Prof. Reiser is author or co-author of more than 180 research papers, co-editor of two books, and in 1994 published his book "Theory and Design of Charged Particle Beams" (Wiley and Sons). He is a fellow of the American Physical Society and a fellow of the IEEE.

MOON-JHONG RHEE
Professor

Moon-Jhong Rhee received his doctorate in space science and applied physics from the Catholic University of America in 1970.

Prof. Rhee's broad research interests include pulsed power systems, opening switches, charged particle beam physics, beam emittance, development of beam diagnostics, plasma focus, and pseudospark discharge.

Prof. Rhee is currently working on problems in beam emittance increase in a nonlinear system, inductive-energy pulsed power systems, high brightness electron beam in pseudospark discharge, and pseudospark produced soft x-ray.

GIRISH SARAPH
Faculty Research Assistant

Girish Saraph received his doctorate in electrical engineering from the University of Maryland in 1995 and joined the research faculty at Maryland.

Dr. Saraph is currently working on the design studies of relativistic gyroklystrons in support of the experimental program at Maryland.

AMARJIT SINGH
Senior Research Scientist

Amarjit Singh received his doctorate in electron physics from Harvard University in 1949. He has been with the Institute for Plasma Research since 1987. His current areas of interest are microwave and millimeter-wave tubes, and enhancement of their overall efficiency by using depressed collector techniques. Before joining the University of Maryland, he was the Director of the Central Electronics Engineering Research Institute, Pilani, India, from 1963 to 1984, and National Chief Project Coordinator for the United Nations Development Program in 1985 and 1986.

MARK WALTER
Assistant Research Scientist

Mark Walter received a B.S. in physics from the United States Military Academy in 1985, and a MSE and Ph.D. from the University of Michigan in 1995. He joined the University of Maryland in 1995.

Dr. Walter's current research interests include design, modeling, and experimental optimization of microwave oscillators and amplifiers.

JIAN-GUANG WANG
Associate Research Scientist

Jian-Guang Wang joined the University of Maryland faculty in 1989 after he received his doctorate in nuclear engineering from the University of Michigan.

Dr. Wang is participating in electron beam transport experiments that concern the dynamics of space-charge dominated beams which have significant application for advanced accelerators, e.g., the next generation high energy physics accelerators and induction linacs as the driver for heavy ion inertial fusion, high power microwave tubes, and free electron lasers, etc.

His ongoing research projects are studies of the beam dynamics in the longitudinal phase space, investigations of perturbations and space-charge waves in intense beams, the study of the longitudinal instability of an intense electron beam transported in a resistive channel, and the design of a space-charge dominated electron recirculator for beam physics research.

LABORATORY FOR ION BEAM RESEARCH AND APPLICATIONS

In the past two decades high resolution (submicrometer) focused ion beams based on field emission ion sources have gone from laboratory instruments studied in two or three universities to essential tools for the fabrication of semiconductor devices and important research tools for mass spectrometry, lithography, beam induced chemistry patterned implantation, and micromachining.

The Laboratory for Ion Beam Research and Applications was formed in 1993 for the purpose of furthering research in high brightness ion sources, high resolution focused ion beams and their applications. Staffing began in 1993 with the appointments of Prof. John Melngailis and Prof. Jon Orloff. The laboratory was equipped during 1994 and 1995 with a variety of ion beam systems including two liquid metal ion source-based high performance focusing columns, one for beam induced chemistry and the other a combined focused ion beam scanning electron microscope for high resolution micromachining work. A high voltage (150 kV) focused ion beam system for implantation is due to be delivered in December 1996. Research on high brightness ion sources began in 1994. In 1995 work began in the area of ion optics and ion beam lithography, as well as collaborative work with other groups in the Institute for Plasma Research, the Department of Electrical Engineering, the Department of Material Sciences and the Department of Physics. At the end of 1995 the laboratory had 7 full-time graduate students and one research associate, two full-time engineers and a secretary.

CURRENT STUDIES

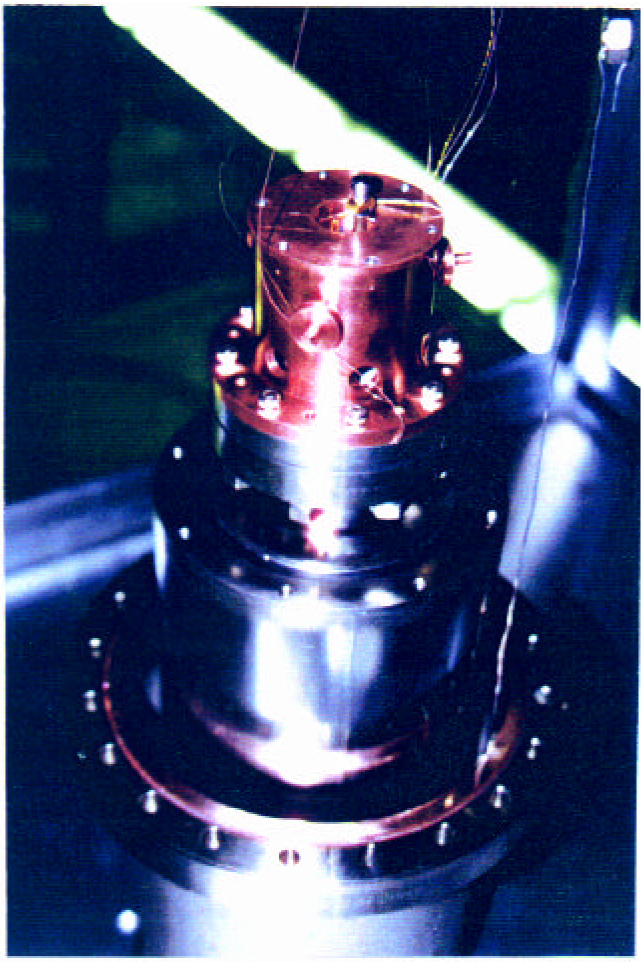
HIGH BRIGHTNESS ION SOURCES

Orloff, Edinger, Melngailis

High brightness ion sources are the key to high resolution focused ion beams. The highest brightness sources currently known are based on the principle of field ionization, which is related to the field electron emission process that has enabled spectacular advances in high resolution scanning electron microscopy in the past two decades. Field emission ion sources exist that produce ions from the gas phase (gas field ionization sources or GFISs) and from the liquid phase (primarily liquid metal ion sources or LMISs). The properties of these sources are most conveniently understood in terms of their angular intensities and exceedingly small physical emitting areas. Ions are emitted from surfaces by the action of electric fields with strength $\sim 10^{10}$V/M. To obtain such a field with a reasonable voltage (10^3-10^4 volts) requires an emitting area with a radius $\sim$100 nm, which can be achieved by electrochemical etching of W wire to form a field emitter in the case of a GFIS or by the balance between electrostatic stress and surface tension forces in the case of a liquid metal supported on a blunt field emitter (end radius $\approx 10\mu$m).

Field emission ion sources have very small virtual source sizes — the size as seen looking back to the source through an ion optical focusing system — of about 1 nm in the case of a GFIS and of about 50 nm in the case of a LMIS. Therefore a finely focused spot can be created with a rather simple optical system. For example, the current state of the art with LMISs is a focused beam of $\approx$ 1 pA of GA$^+$ ions producing 5-10 nm imaging resolution at an energy of 30 keV. The current density in such a focused spot is about 10 A cm^{-2}, and the source brightness is about 10^6 cm^{-2}sr-1. By contrast, the state of the art of GFISs appears to be about $10^{10}-10^{11}$A cm^{-2}sr^1. By contrast, the state of the art of GFISs appears to be about $10^{10}-10^{11}$ A cm^{-2}sr^1 with a source cooled to near liquid He temperature. It is not yet known what sort of focused beam performance might be achieved with such a source. Because in most focusing systems the source size of a GFIS is much smaller than the beam on the target, the angular intensity dI/d- (measured in A sr^{-1}) is a more useful parameter than the brightness. For both LMISs and the most intense GFISs, dI/d- $\sim 10-100\mu$A sr^{-1}.

Work at IPR is concentrating on cryogenic GFISs that can produce H$^+$ beams for use in fast ion beam lithography. It has been known for some years that, because of the higher stopping power of ions in matter and the lack of large distance scattering of ions in resist ("proximity effect"), ion beam lithography with field emission ion sources is intrinsically faster than electron beam lithography. Because of the lack of proximity effects, ions should be ideally suited for lithography where extremely small features ($\lesssim 0.1\ \mu$m) need to be written. Research is concentrating on producing field emitters that tend to concentrate the ions near the axis of emission so as to produce the highest possible angular intensity and brightness.



Cross section of the LH_e dewar used for gas phase field ionization experiments

MICROMACHINING
Orloff

Micromachining is the programmed removal of material from or addition of material to a surface in order to create a desired structure using a focused ion beam (FIB). A focused ion beam acts like a tiny milling machine with a tool bit size $< 1\mu$m. A beam of 30 keV Ga^+ ions can remove (by sputtering) about 1 μm^3 of Si per second per nA of beam current, for example. Material can be added to a surface by introducing an appropriate gas into the vacuum system to create a local ambient of molecules with a flux rate onto the specimen comparable to the current density of the ion beam. Since the ion beam can be focused to 0.01 μm or better and its position controlled to within 1 nm, there are interesting possibilities for micromachining indeed.

The primary applications of micromachining to date have been for semiconductor device manufacturing, where FIBs are routinely used to repair lithographic masks, to dissect integrated circuits for failure analysis, and to rewire ("edit") integrated circuits in the design phase. Research on micromachining at IPR is just beginning and is concentrating on developing methods to produce three-dimensional structures and ways to manipulate objects built on a scale $\sim$ 10-100 μm.

BEAM INDUCED CHEMISTRY
Edinger, Melngailis

Focused ion beam micromanipulation of material can be greatly expanded by the introduction of a gas to the surface bombarded by the ions. When an organometallic gas, for example, is introduced, the molecules absorbed on the surface are dissociated and a metal is deposited wherever the ion beam is scanned. When a reactive gas, such as Cl_2 or XeF_2 is introduced, material removal rates can be selectively enhanced by factors of 10 to 200. Thus material addition and removal can be carried out at dimensions near the beam diameter (i.e., below 0.1 μm). We plan to study in detail the deposition process and to develop new compounds to improve the quality of metal films. All "metal" films deposited to date contain large (20-50%) concentrations of carbon. Better precursor gases will be sought to reduce the carbon content. The atomic details of the deposition process are not understood and will be studied. We will use scanning tunneling microscopy to observe the deposition produced by a single ion impact event. This will determine the minimum feature size that can be written by this technique.

ION PROJECTION LITHOGRAPHY
Melngailis, Guharay, Reiser, Levush, Birman

Ion projection lithography is a promising candidate for future integrated circuit production when minimum dimensions shrink below 0.15 μm and optical lithography can no longer be used. Our laboratory is participating in the Advanced Lithography Group which is a U.S. led consortium organized to develop ion projection lithography. The first prototype of this machine is planned to be installed at the University of Maryland in early 1997. Our efforts so far have concentrated on the exploration of a $H^{(-)}$ ion source for ion projection. The $H^{(-)}$ source is expected to have some advantages over the H^+ source currently in use. We have exposed resist with $H^{(-)}$ ions and shown that the sensitivity and range are the same as for H^+ ions. We are now installing a new $H^{(-)}$ source obtained from the Budker Institute in Novosibirsk. It is designed to have a very low energy spread of the emitted ions.

Another project in support of ion projection lithography is the study of mask heating. In this lithography technique the mask is a Si stencil (thin membrane with holes in it). The ion flux deposits an energy of 3.3 $\mathrm{mW/cm^2}$ on the mask. Distortion of the mask due to thermal expansion will lead to unacceptable shift in feature positions. We have calculated the expected temperature profiles in the mask and the resulting expansion, which, it turns out, can be unacceptably large. Simulations show that introducing a cold cylinder near the mask to enhance radiative cooling can be used to reduce the temperature rise to an acceptable level. We are also preparing a mask with a set of thin film temperature sensors to measure the temperature profiles under different irradiation and cooling conditions. (See also article "High Brightness H^- Ion Beams, Beam Transport and Focusing" in the Charged Particle Beam section of this brochure.

ION OPTICS
Orloff

A limitation of ion beam focusing systems vis a vis electron beam systems is the necessity for using electrostatic optics. Because electrostatic components operate independently of the charge-to-mass (q/m) of a charged particle beam while magnetic lenses do not, most practical systems use only electrostatic focusing and deflection. An advantage of such systems is that they can be made extremely compact — a high resolution 30 keV FIB optical column is about the size of a loaf of bread — a price is paid in the significantly larger spherical and chromatic aberrations that electrostatic lenses suffer from in comparison with magnetic lenses.

A small program has been undertaken to determine if there are some practical ways in which aberrations can be reduced. Since Scherzer's Theorem states that the spherical aberration of a round lens free of space charge must be nonnegative, there are few possibilities. One is by using mirror optics in which beam direction is reversed. Another is the use of a controlled space charge. The latter ideas, originally formulated by Gabor in the 1940's, has been tried with varying degrees of success in electron microscopy. The work at IPR is aimed at building a purely electrostatic lens with an electron gun contained within it. It may be possible to produce sufficient space charge with sufficient symmetry in this way to partially compensate for the positive spherical aberration in a focusing system. If the spherical aberration can be compensated, it would be possible to build a FIB system that could produce a large ion current with minimal skirts, or tails on the current density distribution. Such a beam profile would be quite valuable for micromachining and especially for the deposition of material from the gas phase, since in the latter process the deposition is sensitive even to very small current densities.

FACULTY

KLAUS EDINGER
Research Associate

Klaus Edinger received his doctorate in physical chemistry from the University of Heidelberg in 1994. He joined the University of Maryland in 1994.

Dr. Edinger's research interests are focused on ion beam related surface phenomena. He is currently investigating high brightness gas field ion sources operating at liquid helium temperature and ion beam induced surface chemistry.

SAMAR K. GUHARAY
Associate Research Scientist

Samar K. Guharay received his Ph.D. in physics from the University of Calcutta in 1980. He joined the Maryland faculty in 1984. Prior to this, he had been at the Centre d'Etudes Nucleaires de Grenoble, France, and the Institute of Plasma Physics, Nagoya University, Japan.

Dr. Guharay's current research interests include: (a) development of intense, high brightness negative ion sources, (b) study of negative ion beams for ion projection lithography, and (c) beam transport studies for high energy accelerators.

Dr. Guharay collaborates with the Fermi National Accelerator Laboratory and the Budker Institute of Nuclear Physics, Novosibirsk, Russia. During May 10 – August 11, 1995, Dr. Guharay was awarded a guest professorship by the Ministry of Education and Culture, Japan, and he worked on neutral beams for magnetic fusion at the National Institute for Fusion Science, Nagoya.

JOHN MELNGAILIS
Professor

John Melngailis has had more than 16 years of experience in the field of microfabrication with the past 8 years devoted almost entirely to focused ion beams and ion lithography. As of October, 1993, he is professor of electrical engineering at the University of Maryland. His previous research position was at MIT, where he initiated and developed an internationally recognized program in applications of ion beams to lithography, to ion induced deposition of conductors, and to unique devices based on direct, maskless implantation. He has authored or co-authored about 100 papers. Prof. Melngailis received his Ph.D. in physics from Carnegie Mellon University in 1965.

JON ORLOFF
Professor

Jon Orloff worked on high brightness sources and focused beams at the Oregon Graduate Institute from 1974 until 1993, when he joined the University of Maryland. His work in the 1980's on focused ion beams was important for the adoption of that technology by the U.S. semiconductor industry. His interests are primarily in field emission sources and optics, and ways of applying finely focused ion beams. His current interests are in improving gas field ion sources for ion probe work and micromachining with focused ion beams. Prof. Orloff was an early recipient of a Presidential Young Investigator Award from NSF and has co-authored several patents for ion beam related work. He has authored or co-authored 60 papers, is on the advisory committee of the International Symposium on Electron, Ion and Photon Beams, and has helped with the organization of several international conferences having to do with focused ion beams.

MARTIN REISER
Professor

Martin Reiser received his doctorate in physics in 1960 from the Johannes Gutenberg Universität Mainz in Germany, while working as a research physicist at the AEG-Forschungsinstitut Frankfurt (from 1958 to 1961) on the design of the sector-focusing cyclotron for the Karlsruhe Nuclear Research Center. From 1961 to 1964 he was an assistant professor in the Physics Department of Michigan State University and from 1964 to 1965, he worked as a supervisory research physicist at the Naval Radiological Defense Laboratory, San Francisco, California. In September 1965, he joined the University of Maryland as an associate professor with a joint appointment in the Electrical Engineering Department and the Department of Physics and Astronomy. He was promoted to full professor in 1970. He was co-founder of the University of Maryland's Institute for Plasma Research, established in 1981.

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Prof. Reiser is author or co-author of more than 180 research papers, co-editor of two books, and in 1994 published his book "Theory and Design of Charged Particle Beams" (Wiley and Sons). He is a fellow of the American Physical Society and a fellow of the IEEE.

LABORATORY FOR ATOMIC, MOLECULAR AND OPTICAL SCIENCE AND ENGINEERING (LAMOSE)

Atomic, molecular, and optical (AMO) science is a fertile area of research activity covering a broad domain of light-matter interactions. In March of 1996 several faculty members at the University of Maryland, whose traditional disciplinary homes and academic units range over physics, chemistry, engineering (EE), the Institute of Physical Science and Technology (IPST), and the Institute for Plasma Research (IPR) have organized themselves into a Laboratory for Atomic, Molecular, and Optical Science and Engineering (LAMOSE) in order to provide a focal point for research and education in these multidisciplinary endeavors. LAMOSE will be the natural home for faculty and students at all levels whose formal training may be in the traditional science or engineering disciplines but whose research pursuits lead them into basic and applied AMO science. The present members of LAMOSE and their affiliations are J. Goldhar (EE), W.T. Hill (IPST), P.T. Ho (EE), C.H. Lee (EE), T.J. McIlrath (IPST), H.M. Milchberg (IPST and EE), F. Skiff (Physics and IPR), and J. Weiner (Chemistry and IPR). The Laboratory is located in a common area in the basement of the Space Sciences Building on the College Park campus. The University has contributed more than a half-million dollars to renovation of this space. The Laboratory has three principal objectives:

1. **Graduate research in AMO science and engineering.** Graduate students trained in LAMOSE will have a principal academic advisor, but many will carry out thesis projects with at least one other co-advisor. The goal is to bring a more integrated experience to graduate research so that students do not train narrowly within the confines of a rigid research tradition and perspective.
2. **Graduate and advanced undergraduate education.** Several LAMOSE members (Hill, Ho, Lee, Weiner) are working on a new course in AMO science and engineering at a level suitable for first-year graduate students. The objective is to bring together unifying ideas in classical optics, quantum mechanics, quantum electronics, and spectroscopy which are often taught in separate departments in a disconnected way.
3. **Partnerships with industry, national laboratories, and other university centers.** We have established a memorandum of understanding (MOU) between LAMOSE and the Instituto de Física de Sao Carlos (IFSC) in Sao Paulo, Brazil, for the frequent exchange of students, faculty, research materials and equipment. Much fruitful collaboration between members of the two groups has already taken place. The MOU will broaden and formalize this activity. We are also working on projects with neighboring federal and private institutions in which graduate students would have the experience of working on scientifically and technically challenging problems with important 'real-world' dimensions. We are developing cooperative agreements with several other centers both in the United States and abroad.

LAMOSE is not only a useful vehicle for pooling technical resources and teaming research groups to work on problems of common interest, but also an experiment in integrating a broader educational experience for graduate students into the traditional research apprenticeship training of the Ph.D.

FACULTY

JULIUS GOLDHAR
Associate Professor

Julius Goldhar received his Ph.D. from MIT in 1976. He joined the Electrical Engineering Department at Maryland in August 1985.

Research interests of Prof. Goldhar include excimer laser technology, interaction intense laser pulses with matter, and application of nonlinear optics to signal processing.

WENDELL HILL
Associate Professor

Wendell T. Hill, III received his doctorate in physics from Stanford University in 1980. He joined the University of Maryland faculty in 1982.

Professor Hill studies multiphoton ionization of atoms and molecules in the presence of intense and superintense radiation fields where perturbation breaks down.

P. T. HO
Professor, Electrical Engineering

Ping-Tong Ho received all his degrees from the Massachusetts Institute of Technology. He joined the University of Maryland in 1982.

His current research interests are in optical microwave interaction, discharge in semiconductors, and laser instrumentation.

CHI H. LEE
Professor, Electrical Engineering

Chi H. Lee received his doctorate in applied physics from Harvard University in 1968. He came to Maryland in 1968.

Prof. Lee's research is in the area of ultrashort pulse lasers and ultrafast optoelectronics. The objective of Prof. Lee's research is to use femtosecond optics to generate, control, manipulate, and characterize high speed/high frequency electronics signals, devices, circuits, and systems. To reduce the size and cost of lasers, a research effort has been concentrated in developing compact, ultrafast laser sources which include semiconductor MQW lasers and diode-pumped solid-state lasers. Prof. Lee collaborates with the Army Research Laboratory and the Laboratory for Physical Sciences.

FREDERICK N. SKIFF
Associate Professor

Frederick N. Skiff received his doctorate in physics from Princeton University in 1985. He joined the University of Maryland faculty in 1989.

Prof. Skiff is currently involved in basic research on plasma wave-particle interactions and on laser induced fluorescence plasma diagnostics.

JOHN WEINER
Professor

John Weiner attended the Pennsylvania State University from 1961 to 1964, majoring in chemistry. From Penn State he went to the University of Chicago for graduate study and obtained his Ph.D. in chemical physics in 1970. The subject of his thesis was an experimental investigation of radiative charge transfer between oppositely charged, slowly moving ions in a "merged beam" apparatus. From Chicago he went to Yale as a postdoctoral fellow to work with Richard Wolfgang, R. James Cross, and Martin Saunders on crossed-beam ion-molecule reactions in simple hydrocarbon systems. In 1973 he was appointed an assistant professor at Dartmouth College in Hanover, New Hampshire. After spending a year at the University of Paris in 1977, Weiner was appointed associate professor in the Department of Chemistry at the University of Maryland in 1978. In 1983 he was promoted to the rank of professor. Thoughout his research career Dr. Weiner has maintained an interest in controlling reactive and inelastic collisions with light fields. Collisions between atoms optically cooled to submillikelvin temperatures and focused into atomic beams or confined in various kinds of neutral-atom traps have provided a fertile area of study since 1988.

NONLINEAR DYNAMICS RESEARCH GROUP

Nonlinear dynamics is a highly active area of scientific research that came into existence as a result of the remarkable revival in the theory of dynamics systems in the last 15 years. The driving forces behind recent developments in the understanding of nonlinear dynamical systems are the availability of computers and the formulation of questions posed by practical and theoretical problems in various fields of science and technology.

Our research in the physical and mathematical aspects of nonlinear dynamics attempts to establish basic principles so that scientists and engineers can then apply these principles to understand and analyze the systems they are investigating in their respective fields. To help us accomplish this, we have access to various supercomputers and a powerful set of chaos dedicated computers in the Keck computational chaos laboratory.

CURRENT STUDIES

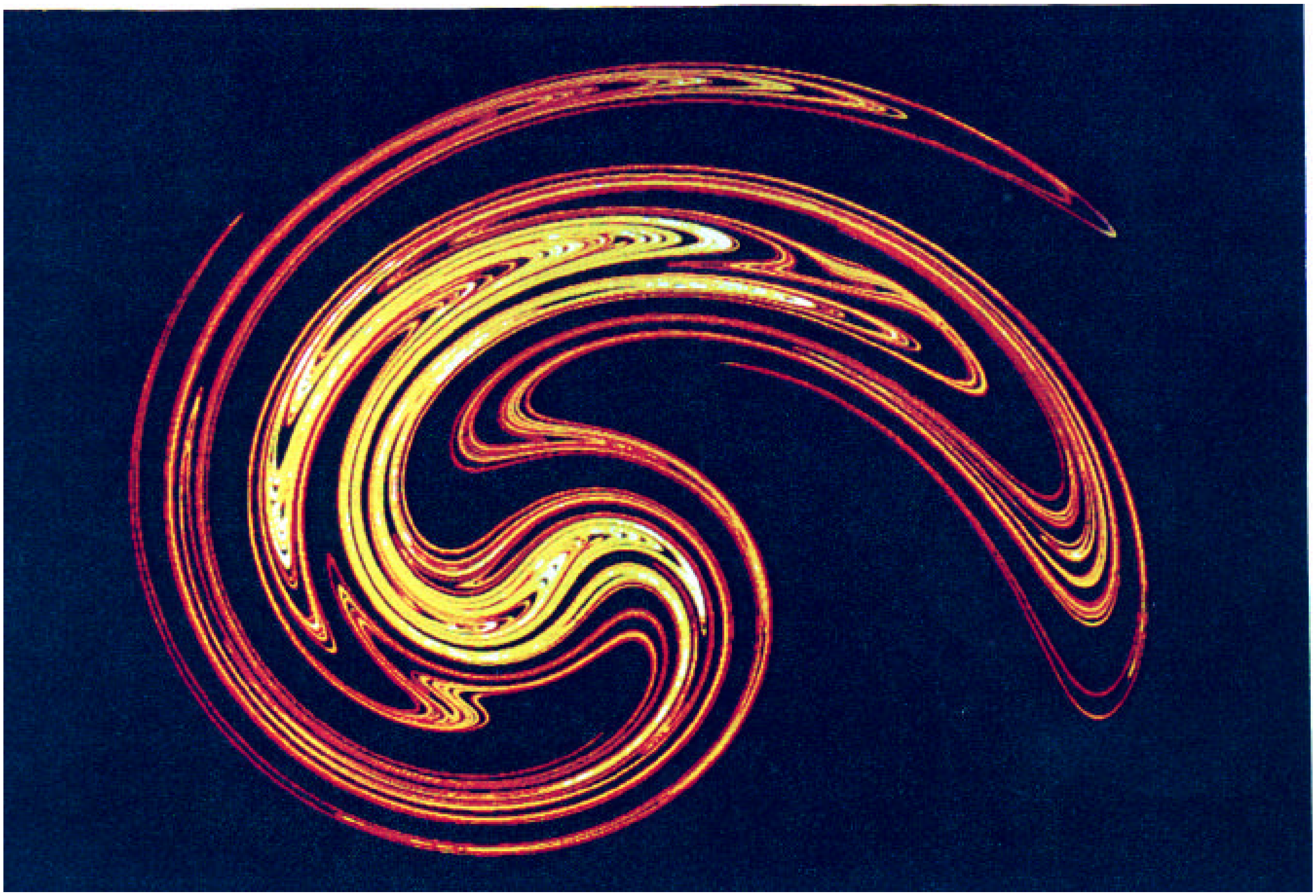
INTELLIGENT COMPLEX NONLINEAR SYSTEMS
Chen

In a neural network, a large number of artificial neurons are connected together by weights. Each neuron is but a simple thresholding unit while the connection weights store the memory or programs that enable the neural network to perform intelligent functions. Interesting topics studied concern mainly the nonlinear dynamical behaviors of such systems and their applications. These include the memory capacity and the complexity of the network, the efficiency of the learning algorithms that allow the network to acquire the ability to perform desired tasks through training over examples. The different architectures endow the network to perform nontrivial calculation of recursive functions or the inference of languages recognized by finite state automata, pushdown automata, or even Turing machines. Applications of neural networks include forecasting, pattern recognition, stability control, system identifications, signal processing, and language acquisition, etc.

In an integrable nonlinear system, solitons could emerge from collisions with each other totally unscathed. This robustness is exploited to implement, for example, a long distance communication system. Optical soliton pulses were used to represent bit informations and propagated down optical fibers with little dissipation and dispersions. All optical amplification systems can be built to boost the bit rate of the communication channels. Solitons are also observed in long stable ocean internal waves from satellite pictures. Its ubiquitous presence in a variety of theoretical and practical systems makes its study very interesting.

CHAOTIC DYNAMICS
Grebogi, Ott

Work in chaotic dynamics includes studies of long-term behavior of the solutions of systems of differential equations, chaotic and strange attractors and their basins of attraction, structure of fractal basin boundaries, bifurcations of chaotic motions, and chaotic transients. In recent years, many nonlinear systems have been discovered whose solutions are chaotic; that is, the solutions oscillate irregularly, never settling down to a regular pattern. Even so, their behavior exhibits some order within its seemingly disordered time variation. The solutions approach spectacularly complex sets, called “chaotic attractors,” that have remarkable structures. Examples of chaotic systems of equations have been found in disciplines as diverse as solid state physics, neurophysiology, meteorology, and plasma fusion. The chaotic attractor shown in the figure below corresponds to the long-term behavior of a solution of a nonlinear system used to model a laser ring cavity. It now appears that chaos is a fundamental property of nature.

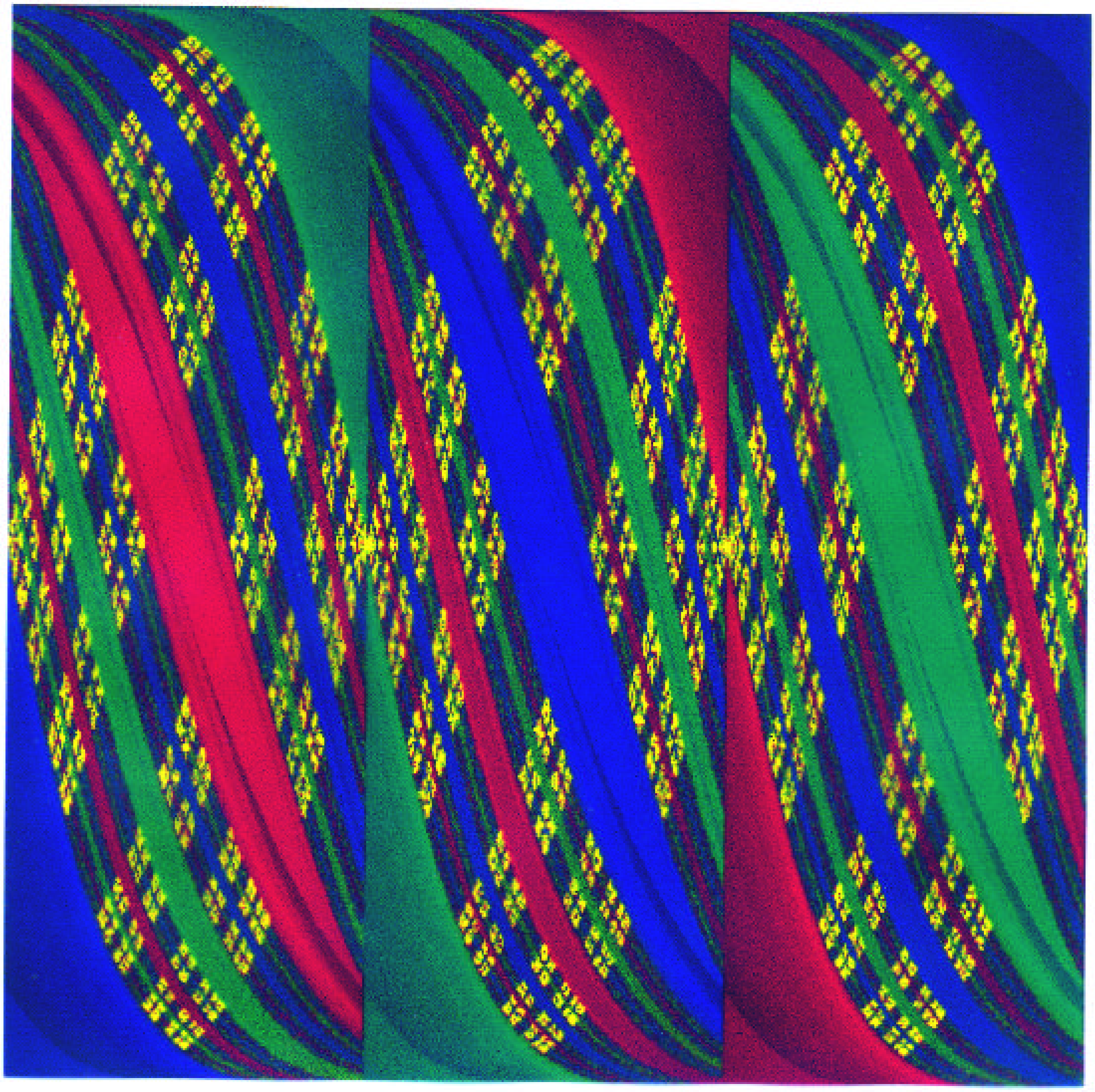


The Ikeda map is $z_{n+1} = p + Bz_n \exp \{i\gamma - i\alpha/(1 + |z_n|^2)\}$, where z is complex $(z = x + iy)$, p is related to the laser input amplitude, B is the coefficient of reflectivity of the partially reflecting mirrors of the cavity, γ is the laser empty cavity detuning, and α measures the detuning due to the presence of a nonlinear medium in the cavity. The parameters are $p = 1.0025$, $B = 0.9$, $\gamma = 0.4$, and $\alpha = 6.0$.

NEW TOPOLOGICAL STRUCTURE OF CHAOTIC SCATTERING

Poon, Campos, Grebogi, Ott

One of the simplest kind of dynamics is that of a particle bouncing between three disks. Each color corresponds to a particular exit a particle took to leave the system. There are three possible exits and they correspond to the colors red, green, and blue in the picture. The interesting feature is the infinitely fine-scale interweaving of the red, blue, and green regions in the vicinity of the boundaries. In fact, this is an example of a new type of topological structure in dynamics first discovered in our group. Namely, each boundary point is a boundary point for all three regions. The example below thus has a fundamentally different topology than is usually associated with boundaries. (The set shown in yellow corresponds to points that stay in the three-disk system region forever.)



FACULTY

THOMAS M. ANTONSEN, JR.
Professor

Thomas M. Antonsen, Jr. was born in Hackensack, New Jersey, in 1950. He received his B.S. degree in electrical engineering in 1973, and his M.S. and Ph.D. degrees in 1976 and 1977, all from Cornell University. He was a National Research Council postdoctoral fellow at the Naval Research Laboratory in 1976-1977, and a research scientist in the Research Laboratory of Electronics at MIT from 1977 to 1980. In 1980 he moved to the University of Maryland where he joined the faculty of the Departments of Electrical Engineering and Physics in 1984. He is currently professor of physics and electrical engineering.

Prof. Antonsen has held visiting appointments at the Institute for Theoretical Physics (UCSB), the Ecole Polytechnique Federale de Lausanne, Switzerland, and the Institute de Physique Theorique, Ecole Polytechnique, Palaiseau, France. He was selected as a fellow of the Division of Plasma Physics of the American Physical Society in 1986.

Prof. Antonsen's research interests include the theory of magnetically confined plasmas, the theory and design of high power sources of coherent radiation, nonlinear dynamics in fluids, and the theory of the interaction of intense laser pulses and plasmas. He is the author or co-author of over 140 journal articles and co-author of the book "Principles of Free-electron Lasers." Prof. Antonsen has served on the editorial board of Physical Review Letters, The Physics of Fluids, and Comments on Plasma Physics.

H. H. CHEN
Professor

H. H. Chen received his doctorate in physics from Columbia University in 1973. He was a member of the Institute for Advanced Studies at Princeton from 1973 to 1975. He came to the University of Maryland in 1975.

Prof. Chen's research is centered on behaviors of complex nonlinear systems. One interesting behavior of such systems is their ability to perform intelligent computations. Examples are cellular automata and neural networks. Another interesting behavior is the existence of solitons in integrable nonlinear systems.

CELSO GREBOGI
Professor

Celso Grebogi received his doctorate from the University of Maryland in 1978. He was a postdoc at the University of California, Berkeley from 1978 to 1981. He returned to the University of Maryland in 1981.

Prof. Grebogi's main research interest is in the dynamics of dissipative and conservative systems. In particular, he has done extensive work on computational methods to investigate chaotic processes.

EDWARD OTT
Professor

Edward Ott received his doctorate from the Polytechnical Institute, Brooklyn, in 1967. He joined the Maryland faculty in 1979.

Prof. Ott's research interests include basic theory of chaotic dynamical systems and applications of chaos theory to problems in science and engineering.

PLASMA EXPERIMENTAL GROUP

Experimental studies in plasma physics are primarily concerned with measurements aimed at broadening our understanding of basic properties of plasmas and of ions in the plasma environment: wave particle interactions, particle distributions in the presence of waves, transport properties, fluctuations, and influences of plasma fields on the radiative properties of atoms and ions. Out of these studies comes, in addition to basic data for comparison with plasma theory, new diagnostic techniques that may be applied for measurement of properties of plasmas in, e.g., the fusion power program and in industrial plasma applications.

CURRENT STUDIES

LIGHTNING
DeSilva, Goldenbaum, Dickerson

We create artificial lightning in the laboratory to study several aspects of natural lightning, including nitrogen fixation, the distribution of energy going into light, sound and heat in a lightning stroke, the influence of trace gases and particulates, etc. For this purpose, we initiate a weak ionization path in air (the analog of the 'leader' in natural lightning), about 10 cm in length, by means of a high voltage generator. This is followed by a capacitor discharge that generates the very large current burst that simulates the main stroke of natural lightning. Discharges are made in a chamber that allows analysis of the resultant gases, as well as measurements of current distribution, light, pressure, and other physical parameters.

STRONGLY COUPLED PLASMAS
DeSilva

A plasma is said to be 'strongly coupled' when the mean Coulomb energy of the ions is comparable to or less than the mean kinetic energy. This occurs in very cool dense plasmas, such as those found in the gaseous planetary interiors, dwarf stars, and in laser-produced plasmas. Transport properties of these plasmas are important in understanding of the structure of stars and gaseous planets, and in laser fusion. We study the electron density fluctuations in plasmas having only moderate coupling by means of light scattering. The fluctuation spectrum can then be related in a straightforward manner to the transport properties, particularly to the thermal conductivity. In other experiments, we create very strongly coupled metal plasmas by vaporizing metal wires in glass capillaries and measure the electrical conductivity of the resultant plasma for comparison with theory.

MAGNETIC FUSION EXPERIMENTS
Griem, Weaver, Welch

A thorough understanding of the edge regions of current and future magnetic fusion devices is essential for preventing both the hot central plasma from reaching the wall and the cold wall material from entering the plasma. Experiments are being performed on the Alcator C-Mod tokamak at MIT in an effort to understand these regions, and scientists from Maryland (IPR) are involved with these experiments. Line widths and shifts of visible and ultraviolet radiation from impurity species are being used to study the temperature, density, and electric/magnetic fields in the plasma, as well as the plasma flows.

INERTIAL CONFINEMENT FUSION
Elton, Griem, Welch

In inertial confinement fusion, small pellets of hydrogen isotopes are inertially compressed following rapid surface heating by a high power laser and subsequent ablation to form extremely high density and temperature plasmas. Internal dynamic conditions are studied using penetrating x-rays. Self-emission is measured spectroscopically to determine plasma densities and temperatures in the compressed region, as well as the localized electric field associated with the intense laser field. Instrumentation and techniques are developed at the University using small-scale laser-produced plasmas and ultimately taken to large national laboratories such as the University of Rochester Laboratory for Laser Energetics (LLE), Lawrence Livermore National Laboratory (LLNL), and Los Alamos National Laboratory (LANL) for actual experiments. Previous successes have included spectral line broadening and merging measurement from which plasma densities have been deduced.

PICOSECOND LASER-PRODUCED PLASMAS
Griem, Goldhar, Iglesias, Welch, Yuan

We are mainly interested in the atomic physics of dense plasmas produced by focusing the light from a homemade, low maintenance, high power 10 ps KrF discharge laser system onto targets of various materials. With laser powers up to $\simeq 10^{15}$ Watt/cm^2 we achieved extremely dense, 10^{22} electrons/cm^3, high temperature $\simeq$ 200 eV, plasmas that we used as the object of our studies to develop spectroscopic methods for analysis of plasma properties under such extreme conditions. So far we have made measurements of the emitted light that range from the soft x-ray to the near ultraviolet range of the electromagnetic spectrum, and successfully observed such elusive effects as the plasma polarization shift on members of the Lyman series of C VI. At this moment we are preparing for the study of the generation of magnetic fields in these plasmas, and we are looking for evidence of an anomalous signature in the recombination spectrum, the "transparency window" effect.

ELECTRON CYCLOTRON EMISSION FROM FUSION PLASMAS
Ellis

In a magnetic field B, electrons spiralling about field lines emit radiation at the electron cyclotron frequency $\omega_{ce} = eB/m_e$ and its harmonics. This radiation has proven to be an excellent diagnostic on tokamak devices for measuring the electron temperature and its radial variation. More recently, efforts have been made to measure the parameters of non-Maxwellian electron distribution functions by using the same electron cyclotron emission. In this case, the radiation is from high energy electrons (100 keV to a few MeV) which, because of their low collision frequency, can maintain a non-Maxwellian distribution.

We are currently operating a large Michelson interferometer on the DIII-D tokamak to measure the emission spectra from thermal and nonthermal electrons, using both a horizontal and vertical view. This instrument has become a baseline diagnostic for measuring electron temperature profiles.

CHAOS IN WAVE PARTICLE INTERACTIONS
Skiff

One area of fundamental interest in plasma physics is the study of plasma dynamics under conditions where particle orbits are chaotic. An example of this is found in the dynamics of ions in a static magnetic field and an electric wave. Experiments on the linear and nonlinear interaction of waves and particles in weakly collisional plasma have to do with understanding the role of chaotic particle dynamics on the transfer of energy between waves, and between waves and the individual particle motions. These experiments also involve the development and application of advanced laser spectroscopic techniques which measure both local and global properties of plasma behavior. Many applications exist for this work in laboratory plasma physics, space physics, microwave generation devices, and industrial plasma physics.

HIGH TEMPERATURE PLASMA DIAGNOSTICS
Boyd, Skiff

High temperature, magnetically confined plasmas frequently require externally driven currents to maintain the plasma equilibrium. Studies of electrical currents in plasmas which are composed of highly energetic particles require a way of measuring the velocity distribution of plasma particles with simultaneous resolution in space, time, and energy. Experiments on measuring high energy particle distributions through the effect of such particles on microwave propagation show how the effects of refraction and absorption can be separated and used to evaluate the state of a plasma. These advanced diagnostics are essential for progress in understanding interactions between waves and particles at high energies and also have potential applications to microwave generation devices.

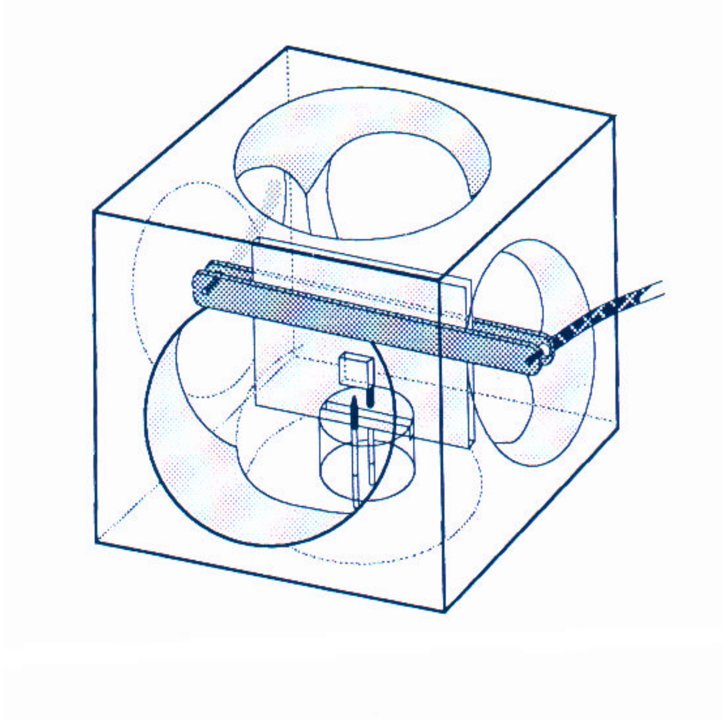
LABORATORY FOR ATOMIC, MOLECULAR, AND OPTICAL SCIENCE AND ENGINEERING (LAMOSE)
Goldhar, Hill, Ho, Lee, Milchberg, McIlrath, Skiff, Weiner

A new interdisciplinary laboratory for atomic, molecular, and optical science and engineering exists for the study of laser matter interactions over a wide range of interaction energies. The physics involved ranges from the study of ultralow energy collision processes to relativistic plasma physics. The goals of this collaboration involve broad-based scientific exchanges both between existing units on campus and between the campus and external laboratories.

FAST PLASMA ELECTRODE POCKELS CELL

Goldhar, Leng, Yun

Laser fusion experiments require precise control of laser pulse shapes and high contrast ratios. The NIKE laser system at NRL, which utilizes Induced Spatial Incoherence for uniform target illumination, needs an electro-optical modulator with unique requirements not met by conventional Pockels cells. In collaboration with the NRL group we are developing a novel Pockels cell shown in the figure below. Discharges in neon gas between the pins and the bar electrodes, on both sides of a thin $KD^{*}P$ crystal, form highly conducting plasmas which act as transparent electrodes. The fast switching electrical pulse travels via the 50- transmission line formed by the two bars above the crystal. Subnanosecond risetimes and efficient switching have been demonstrated.



Schematic of fast plasma electrode Pockels cell

FACULTY

DEREK BOYD
Professor

Derek Boyd received his doctorate from the Stevens Institute of Technology in 1973. He joined the University of Maryland in 1973.

Prof. Boyd's research program involves developing diagnostics for the electrons in high temperature plasmas, particularly those plasmas generated in large tokamaks at major sites around the country. These diagnostics have been based on the electron cyclotron emission from absorption on the magnetically confined electrons. The instrumentation has been adapted from the field of far infrared spectroscopy and conventional microwave circuitry. Pushing the frontiers of this research has led to studies as wide-ranging as the properties of materials at far infrared wavelengths, the search for new detectors, and the subtleties of the generation and propagation of the electron cyclotron waves in inhomogeneous magnetoplasmas.

ALAN W. DeSILVA
Professor

Alan W. DeSilva received his doctorate in physics from the University of California at Berkeley in 1961. He came to the University of Maryland in 1964.

Prof. DeSilva's research interests are in the study of the basic properties of plasmas, particularly dense, cool plasmas such as are found in arcs, laser-produced plasmas, and in nature in certain stars and the giant planets. Plasmas under study in the laboratory are produced in arcs and also by rapid vaporization of metal wires. They are studied mostly by optical techniques, particularly by means of interferometry to measure their time and space development, and light scattering, from which it is possible to measure the density, temperature, and electron density fluctuations and to connect these fluctuations to transport properties. He has developed a technique for measurement of the electrical conductivity of "strongly coupled" plasmas having densities near the density of solids, at temperatures high enough to be in the plasma state. Transport properties of such plasmas are of great interest in the study of stellar interiors. A recent interest is in studies of the physical and chemical processes occurring in lightning, carried out in collaboration with the Department of Meteorology.

RICHARD F. ELLIS
Professor

Richard Ellis received his doctorate in physics from Princeton University in 1970. He has been on Maryland's faculty since 1979.

For the past few years, Prof. Ellis' research has involved the understanding of basic plasma phenomena and their application to experimental situations in magnetic fusion energy.

Prof. Ellis and his colleagues are currently attempting to measure electron parameters on the DIII-D tokamak at GA Technologies using electron cyclotron emission diagnostics.

RAYMOND ELTON
Senior Research Scientist

Raymond Elton received his doctorate in physics from the University of Maryland in 1963 and rejoined the University in 1993 and also in 1988 on a one-year sabbatical from the Naval Research Laboratory.

Dr. Elton's expertise lies in the areas of optical and spectroscopic diagnostics of high temperature plasmas and in particular the development and understanding of lasers for the x-ray spectral region. He is presently involved in fielding diagnostics for large inertial confinement fusion experiments at facilities including the University of Rochester and the Lawrence Livermore and Los Alamos National Laboratories. He also continues to consult on a regular basis at the Naval Research Laboratory on x-ray diagnostics and optical damage problems.

GEORGE C. GOLDENBAUM
Professor

George C. Goldenbaum received his doctorate in physics from the University of Maryland in 1966 and was with the Naval Research Laboratory until 1973 when he joined the faculty at Maryland.

Prof. Goldenbaum, along with Prof. DeSilva, is working on an experiment to understand the production of nitric oxide (NO) in the atmosphere due to lightning discharges. Nitric oxide plays an important role in climate and in the life of plants and animals. The experiment produces discharges that have the same energy per unit length as natural lightning. Prof. Goldenbaum is creating a computer model of the atmospheric dynamics and chemistry of a lightning discharge.

JULIUS GOLDHAR
Associate Professor

Julius Goldhar received his Ph.D. from MIT in 1976. He joined the Electrical Engineering Department at Maryland in August 1985.

Research interests of Prof. Goldhar include excimer laser technology, interaction intense laser pulses with matter, and application of nonlinear optics to signal processing.

HANS R. GRIEM
Professor Emeritus and Senior Research Scientist

Hans R. Griem received his Ph.D. from the Universität of Kiel, Germany, in 1954. He has been at the University of Maryland since 1957.

Prof. Griem's experimental and theoretical research focuses on radiation from highly ionized atoms in high temperature plasmas. Applications include radiation losses from magnetically confined plasmas, radiative energy transport in inertially confined plasmas, and the search for short wavelength lasers. He is also conducting research on electron-ion inelastic collision processes and spectral line broadening (and shifts) in dense plasmas.

Prof. Griem collaborates with the University of Rochester Laboratory for Laser Energetics, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory.

FREDERICK N. SKIFF
Associate Professor

Frederick N. Skiff received his doctorate in physics from Princeton University in 1985. He joined the University of Maryland faculty in 1989.

Prof. Skiff is currently involved in basic research on plasma wave-particle interactions and on laser induced fluorescence plasma diagnostics.

BENJAMIN LAWRENCE WELCH
Assistant Research Scientist

Benjamin Welch received his doctorate in 1991 from the University of Maryland. He joined the research faculty in 1992.

Dr. Welch's experimental research involves spectroscopic diagnostics of magnetically confined fusion plasmas and inertial confinement fusion plasmas.

Dr. Welch collaborates with the MIT Plasma Fusion Center and the University of Rochester Laboratory for Laser Energetics.

PLASMA THEORY GROUP

The field of plasma physics is barely 35 years old, yet the diversity and richness of the phenomena which are exhibited by the "forgotten" fourth state of matter are unsurpassed. The study of plasma physics spans a multitude of subfields from fundamental studies of chaos and strange attractors to applied research in fusion energy and high power sources of electromagnetic radiation, and from small laboratory experiments to magnetospheric, solar, and astrophysics experiments.

The Plasma Theory Group at the University of Maryland is most active in magnetic fusion, charged particle beam, space physics, laser fusion, and nonlinear dynamics research.

CURRENT STUDIES

NUMERICAL SIMULATION OF TOKAMAK PLASMAS

Lau

The Plasma Theory Group performs high resolution 3D turbulence simulations for plasma fluids in tokamaks, which are major plasma confinement systems around the world. The focus has been on the transport processes and the various physical mechanisms driving the transport. The simulations help international fusion scientists better understand experimental results.

Other related topics include destruction of ion orbits near a tokamak edge, bursting phenomenon found in tokamak edges, and more recently, the effects of magnetic shear.

MAGNETIC FUSION THEORY

Antonsen, Drake, Guzdar, Hassam, Kleva, Lau, Liu, Novakovski, Rogers

The tokamak is the primary device which has the potential for achieving thermonuclear fusion in a controlled environment. Over the last decade, very significant advances have been made on this device. New, improved modes of confinement have been found which have profound implications in the design of fusion reactors. A first principles understanding of the cause of these improved modes of confinement has been one of the major areas of research being pursued by the Plasma Theory Group at the University of Maryland.

The first mode of improvement in confinement, observed on devices all over the world, is the so-called L-H transition. In a tokamak heated by a neutral beam to achieve high plasma temperatures, the preliminary results were discouraging. It was observed that as the neutral beam power was increased, the particle and energy confinement times decreased. This mode of operation of the tokamak was referred to as the low (L) mode. This did not bode well for achieving the goals of thermonuclear fusion. However, with the further increase in input power, the discharge made a dramatic transition to a good confined mode, the high (H) mode. The improvement in confinement has been attributed to the generation of shear flow in the edge region of tokamaks, which creates a transport barrier.

The Maryland Plasma Theory Group has made significant contributions in two areas relevant to the understanding of the L-H transition. By doing detailed 3D simulations of the edge region of the plasma, which have progressively been refined over the last few years, the cause of the anomalous transport, which lead to the poor confinement in the L mode phase, has been identified. The edge is prone to short scalelength convection due to the effective gravity (see first figure below) arising from the toroidal curvature of the field lines. The pressure gradient and the gravity on the outside are unfavorable for stability. On the other hand, the pressure gradient on the inside is reversed and the plasma is stable. Thus this "ballooning" instability leads to enhanced particle and energy transport. The strong asymmetry in the transport is an important consequence of the theory, directly verified on some tokamaks which have the necessary diagnostics to measure the transport and fluctuations around the poloidal periphery.

Another area related to the L-H transition problem is to develop an understanding of the generation of shear flow. Here again the Plasma Theory Group at Maryland has advanced a very plausible scenario to explain why the edge spins up when the temperature exceeds a critical temperature. The second figure shows that, due to asymmetric transport, the density varies on the magnetic flux surface. The local enhancement of the density on the inside (depicted by a blob) has a tendency to "fall" under the influence of the effective gravity. However, there are dissipative effects which dampen the fall. As the temperature increases, the damping weakens and the fall causes the blob to spin around in the poloidal direction. This spin-up confined to the edge strongly suppresses the ballooning, thereby giving rise to a transport barrier which improves the confinement. This research has led to a proposed scenario in which the spin-up is induced by neutral beams, thereby facilitating the onset of improved confinement.

Another area of research in which the group plays a significant role is addressing the issues of magnetohydrodynamic (MHD) stability of high density and high temperature reactor-relevant plasmas. Achieving high density in the tokamak is important for making fusion power a commercially viable alternative. Such plasmas tend to develop equilibrium pressure and current profiles very different from present-day devices. The members of the Plasma Theory Group here have developed efficient numerical codes which can readily address these important issues. Results from the group indicate that some of the proposed high density equilibria may be violently unstable to a class of MHD modes which are not present in present-day low density devices.

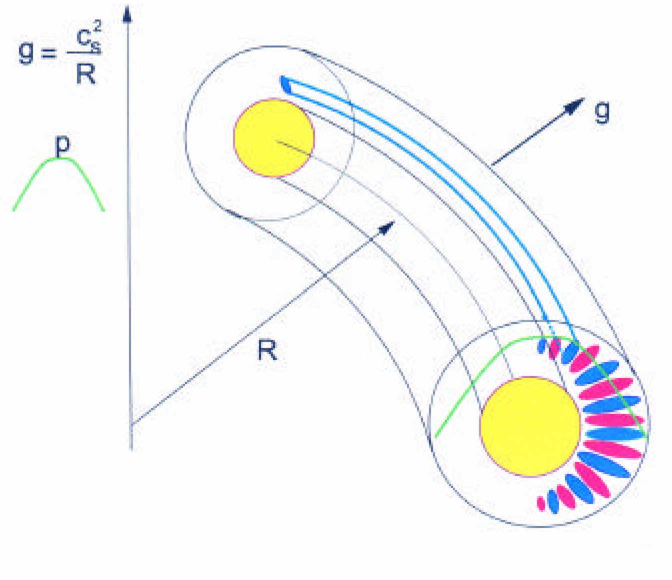


Figure 1

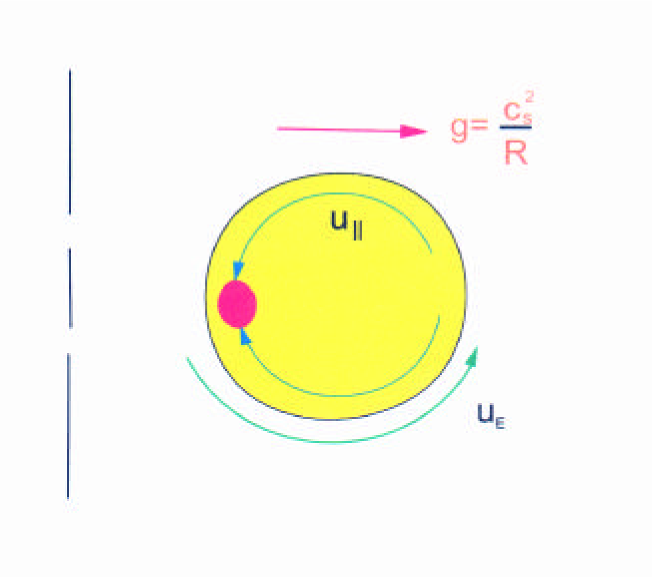


Figure 2

THEORY OF INTENSE LASER PLASMA INTERACTIONS

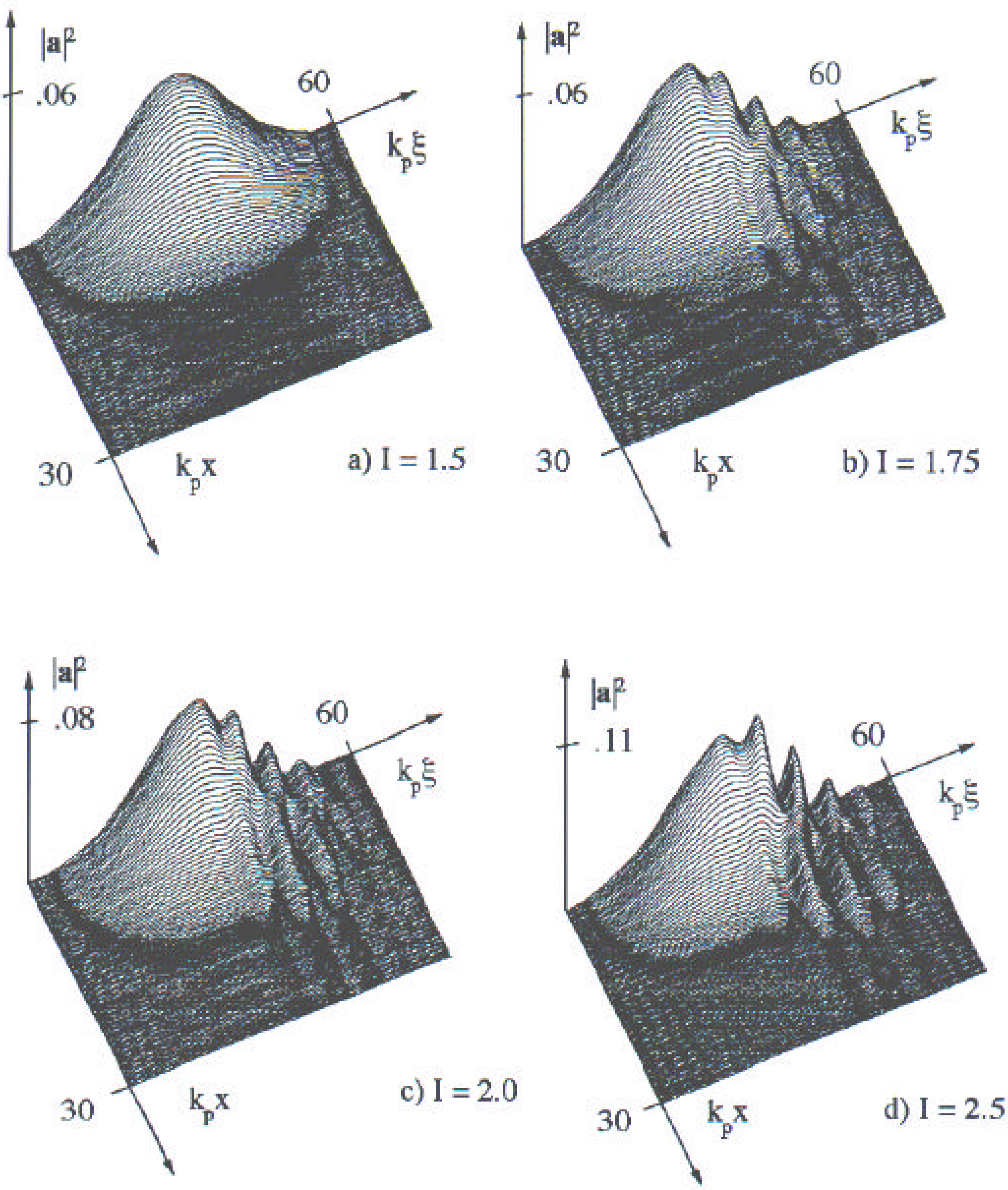
Antonsen

Channeling of intense optical fields in plasmas is a rapidly developing scientific area, with a number of possible applications including x-ray generation, harmonic conversion and electron acceleration. In the context of laser plasma accelerators, intense, ultrashort pulses of laser light are injected into a plasma and create a wake field that can be used to accelerate particles. The major challenge is to produce a wake which is strong enough and coherent over a sufficiently large distance to accelerate particles to high energy.

Many nonlinear physical processes can be expected to affect the propagation of these intense pulses, and their study requires a synthesis of nonlinear optics and basic plasma physics. In particular, intense laser pulses are subject to self-channeling and Raman instabilities. Self-channeling occurs because the oscillating motion of plasma electrons in the presence of the laser field is relativistic for intense pulses. The increase in the effective mass of the electrons which accompanies their relativistic oscillations results in a change in the index of refraction of the plasma and consequently leads to self-guiding of the laser light. In addition, the laser light can also act to expel electrons from regions of high intensity further enhancing the channeling process. Raman instabilities occur when an intense pulse decays by creating a plasma wave and a lower frequency light wave. This usually leads to a breakup of the laser pulse. The interplay of these effects determines the distance over which laser pulses can propagate through plasmas.

Our group has been engaged in developing theory models and numerical simulation tools to study the evolution of intense laser pulses. In addition, there is a strong link to experimental efforts conducted by Prof. H. Milchberg of the Institute for Physical Science and Technology and the Department of Electrical Engineering. The figures below show the results of a numerical simulation of laser light propagation through a preformed plasma channel.

The parameters correspond to those of a proposed experiment to be conducted in Prof. Milchberg's laboratory. Displayed are two dimensional surface plots of the laser intensity after propagation through channels with four different parameters. Visible on the trailing edge of the laser pulses are modulations corresponding to excitation of Raman instabilities. Clearly, the parameters corresponding to channel a provide for the most stable propagation.



Results of a numerical simulation of laser light propagation through a preformed plasma channel

FACULTY

THOMAS M. ANTONSEN, JR.
Professor

Thomas M. Antonsen, Jr. was born in Hackensack, New Jersey, in 1950. He received his B.S. degree in electrical engineering in 1973, and his M.S. and Ph.D. degrees in 1976 and 1977, all from Cornell University. He was a National Research Council postdoctoral fellow at the Naval Research Laboratory in 1976-1977, and a research scientist in the Research Laboratory of Electronics at MIT from 1977 to 1980. In 1980 he moved to the University of Maryland where he joined the faculty of the Departments of Electrical Engineering and Physics in 1984. He is currently professor of physics and electrical engineering. Prof. Antonsen has held visiting appointments at the Institute for Theoretical Physics (UCSB), the Ecole Polytechnique Federale de Lausanne, Switzerland, and the Institute de Physique Theorique, Ecole Polytechnique, Palaiseau, France. He was selected as a fellow of the Division of Plasma Physics of the American Physical Society in 1986.

Prof. Antonsen's research interests include the theory of magnetically confined plasmas, the theory and design of high power sources of coherent radiation, nonlinear dynamics in fluids, and the theory of the interaction of intense laser pulses and plasmas. He is the author or co-author of over 140 journal articles and co-author of the book "Principles of Free-electron Lasers." Prof. Antonsen has served on the editorial board of Physical Review Letters, The Physics of Fluids, and Comments on Plasma Physics.

JAMES F. DRAKE
Professor

James F. Drake received his doctorate in physics from the University of California at Los Angeles in 1975. He has been with the University of Maryland since 1978.

Prof. Drake's research interest is broad, ranging from laboratory magnetic confinement fusion experiments to space plasmas. In magnetospheric physics, his research has focused on the mechanisms by which energy stored in global magnetic fields is transferred to energetic particles.

In recent years, Prof. Drake and his colleagues have made important contributions to the understanding of large-scale magnetohydrodynamic activity and thermal and particle transport in laboratory plasma. He has developed computational and analytical techniques to study the rich variety of nonlinear phenomena which occur in present experiments.

PARVEZ N. GUZDAR
Senior Research Scientist

Parvez N. Guzdar received his doctorate in physics from Gujarat University, India, in 1976. He has been with the University of Maryland since 1983.

Dr. Guzdar's current research interests are: (1) two-dimensional/three-dimensional nonlinear fluid simulation of turbulent transport and self-organization processes in tokamak fusion plasmas, (2) stimulated scattering processes in laser plasma interactions and self-focusing of radio waves in high latitude ionospheric plasmas, (3) three-dimensional nonlinear structuring of ionospheric plasma blobs, (4) the nonlinear dynamical behavior of Rayleigh-Benard convection in fluids caused by the interplay between the convection and shear flow, (5) development of efficient numerical algorithms for the solution of nonlinear equations like the Ginzburg-Landau and the Kuramoto-Shivashinsky equations and the study of spatio-temporal chaos in systems represented by these equations.

ADIL B. HASSAM
Professor

Adil B. Hassam joined the University of Maryland faculty in 1978 after receiving his doctorate in astrophysical sciences from Princeton University.

Prof. Hassam's current research focus is the examination of various processes that can cause the constant bubbling of fusion plasmas. He endeavors to construct turbulence theories that will predict the scaling laws for the anomalous heat loss in fusion devices. In addition, Prof. Hassam has ongoing analytical and computational studies of the MHD mechanisms responsible for the mysterious disruptions in magnetic fusion devices and solar magnetic loops.

ROBERT G. KLEVA
Research Associate

Robert G. Kleva joined the University of Maryland faculty in 1979. He received his doctorate in astrophysical sciences from Princeton University in 1980.

Dr. Kleva's research interests focus on nonlinear phenomena in plasmas and the stability of high pressure equilibria in tokamaks.

YUN-TUN LAU
Research Associate

Yun-Tung Lau joined the University of Maryland faculty in 1988 after receiving his doctorate in physics from the Massachusetts Institute of Technology.

Dr. Lau is currently investigating microinstabilities related to the enhanced confinement regime (the so-called "H-mode") of tokamaks. He is also interested in magnetic reconnection in three dimensions, which is an important process in space plasmas.

CHUAN SHENG LIU
Professor

Chuan S. Liu received his doctorate in physics from the University of California at Berkeley in 1968. He came to Maryland in 1974.

Prof. Liu has been actively studying nonlinear plasma processes both for inertial confinement fusion and magnetic fusion. These include parametric instability of the laser radiation in plasmas, solitons and chaos in laser-collective mode interactions and high frequency plasma turbulence; anomalous transport in magnetically confined plasmas (unstable modes in a magnetized plasma with temperature and density gradients), their nonlinear evolution, saturation, and consequent transport; and plasma heating and driving d.c. current in tokamaks by radiofrequency waves. Recently his research interests include self-organization in plasmas such as spontaneous rotation and self-containment.

SERGUEI NOVAKOVSKI
Research Associate

Serguei Novakovski received his Ph.D. degree from the Institute of Physics-and-Technology, Moscow, Russia, in 1988. He joined the University of Maryland in 1992.

Dr. Novakovski's current research focuses on enhanced confinement of plasmas in tokamaks, computer simulation of plasma instabilities, and plasma turbulence near the wall of toroidal chambers.

BARRETT ROGERS
Research Associate

Barrett Rogers received his doctorate in physics from the Massachusetts Institute of Technology in 1991. He came to Maryland in 1993.

Dr. Rogers' research background spans topics in magnetic fusion, space physics, and cosmology. His recent work has addressed important discrepancies between observed tokamak stability and conventional linear theory. This work has focused largely on the nonlinear behavior of instabilities driven by collisionless magnetic reconnection, and the account of essential non-MHD (magnetohydrodynamic) effects in present-day tokamak experiments.

FELLOWSHIPS

Fellowships have been established for applicants to the graduate school (M.S. or Ph.D. program) with interests in basic research in plasma physics, charged particle beams, laser-matter interaction, and nonlinear dynamics. Also included are applicants with interests in major areas of application of plasma science such as fusion energy, relativistic microwave electronics, ion beam micro-fabrication and plasma astrophysics. These fellowships are open to students in the participating graduate programs in the Departments of Physics, Electrical Engineering, Mathematics, Materials and Nuclear Engineering, and Meteorology. The various IPR research programs in which fellows are encouraged to participate include the following:

- theory of plasma stability and transport;
- theory of chaotic dynamics in general dissipative nonlinear systems;
- measurement of high temperature plasma properties;
- charged particle beam acceleration and transport;
- generation of high power microwaves for application to particle acceleration, plasma heating, and advanced radar and countermeasure systems;
- fabrication of microstructures with ion beams;
- multifrequency microwave sintering of ceramics;
- ion beam lithography for producing integrated circuits with dense packing of components;
- ultrahigh power, short pulse lasers for studies of intense field phenomena in atoms, molecules and plasmas;
- the physics and chemistry of lightning.

Fellows will enjoy the unique opportunity of participating in state-of-the-art research in the Institute in collaboration with leading scientists. Fellows will undertake research in a specialty area of his or her own choosing. Maximum benefit from an interdisciplinary research program is gained through active participation in its research and educational projects. It is in this spirit that fellows are asked to select an IPR research project by the end of their first academic year at Maryland. Fellowship awards for incoming students are initially for one year and are renewable subject to adequate performance.

IPR/NRL fellowships offer generous stipends. In addition, fellows are exempt from tuition fees and are provided with health insurance benefits. Applicants who are selected for an IPR graduate fellowship but have been granted financial awards from other sources still qualify for an IPR supplementary fellowship.

RESEARCH PROGRAMS

from the
Institute for Plasma Research
University of Maryland
College Park, Maryland 20742-3511
Prepared by Dorothea F. Brosius, 1997

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