IREAP
INSTITUTE FOR RESEARCH IN
ELECTRONICS & APPLIED PHYSICS

The History of
The Institute for Research in Electronics and Applied Physics

September 28, 2018

The Institute for Research in Electronics and Applied Physics

Mission (http://www.ireap.umd.edu)

The Institute for Research in Electronics and Applied Physics (IREAP) is a joint institute of the **College of Computer, Mathematical, and Natural Sciences** and the **A. James Clark School of Engineering**. The mission of IREAP is to advance modern science through research and educational programs that are interdisciplinary between physical science and engineering. The flow of knowledge between basic science and engineering at IREAP is bidirectional: applying basic science skills to problems of practical importance and engineering skills to aid in fundamental scientific investigations, with an emphasis on diversity, quality, and excellence. IREAP is recognized internationally as a leading university research center and conducts experimental and theoretical research in many areas; such as, high-temperature plasma physics, plasma spectroscopy, microwave electronics, high-brightness charged particle beams, laser-plasma interactions, nonlinear dynamics, biophysics, ion beam microfabrication techniques, nonlinear and quantum optics, quantum information, nanoscience, and nanotechnology.

Constituents

Currently 21 faculty members from the Departments of Physics, Electrical and Computer Engineering, Mathematics, Materials Science and Engineering, Geology, the Joint Quantum Institute, UMD Radiation Facilities, and the Institute for Physical Science and Technology participate in IREAP research. Additionally, IREAP supports 19 research scientists, 16 postdoctoral researchers, and is home to six emeritus faculty members. At present, 62 graduate students work on their research dissertation projects with members of the IREAP faculty, and since its founding, IREAP has produced over 340 Ph.D. students. The research activity is reinforced and broadened by visiting scientists and supported by an energetic and competent staff of 17, who provide both administrative and technical support to the research efforts.

Founding

The Institute was first formed in 1979 as the Laboratory for Plasma and Fusion Energy Studies by merging the plasma physics group led by Prof. Hans Griem and the charged particle beam group led by Prof. Martin Reiser. Activities moved to the building IREAP currently occupies in 1981 upon its construction. The Institute subsequently evolved through the years from its initial focus on plasma physics, fusion and charged particle beam research, to an interdisciplinary research unit with the broad range of activities found today. Along the way its name has changed, first to the Laboratory for Plasma Research, then to the Institute for Plasma Research, and in 2001 to the Institute for Research in Electronics and Applied Physics.

Leadership

The Institute is led by a Director who reports to the Deans of the two colleges of which IREAP is a part. The first (acting) director, appointed in 1979, was Professor Chuan Liu of the Department of Physics, who presided over the groundbreaking of the Energy Research Building that currently houses IREAP and who was responsible for building the plasma theory group. Liu subsequently went on to be Dean of the Graduate School at UMD and President of National Central University in Taiwan. He returned to the University of Maryland in 2007 where he is now an emeritus professor. In 1981 Hans Griem, also of the Physics Department and a founding member of the Institute, was appointed as the first permanent director. Griem had joined the University in 1957 and is currently an emeritus professor and member of IREAP. Griem was succeeded in 1987 by Professor Victor Granatstein of the Department of Electrical and Computer Engineering. Granatstein, at that time a recent arrival from the Naval Research Laboratory, expanded the Institute's activities in high power microwave electronics. He is currently an emeritus professor in IREAP. In 1998 Professor Thomas Antonsen, with joint appointments in Physics and Electrical and Computer Engineering, was named acting director. Antonsen joined the University in 1980 and is a current member of IREAP and Distinguished University Professor (IREAP has four). Antonsen was replaced in 2001 by Professor Patrick O'Shea of the Department of Electrical and Computer Engineering. O'Shea arrived in 1998 from Duke University, after receiving his Ph.D. degree in 1985 from the Institute for Plasma Research under the guidance of Professors Martin Reiser and William Destler. Destler, a founding member of the Institute, went on to be Chair of Electrical and Computer Engineering, Dean of the Clark School, and President of the Rochester Institute for Technology. O'Shea stepped down in 2005 to become Chair of the Department of Electrical and Computer Engineering here at Maryland in the Clark School. He subsequently became Dean of the Graduate School and Vice President for Research at Maryland. He is currently the president of his alma mater, University College Cork in Ireland. O'Shea was succeeded by Professor Daniel Lathrop who has appointments in the Physics and Geology departments. Lathrop came to the University in 1997 as part of an initiative to expand the activities in nonlinear dynamics. Lathrop stepped down in 2012 to become Associate Dean in CMNS. He was succeeded by Professor Thomas Murphy of the Department of Electrical and Computer Engineering. Professor Murphy, an expert in nonlinear optical science, is the current Director.


Chuan S. Liu


Hans R. Griem


Martin P. Reiser


Victor L. Granatstein


Thomas M. Antonsen


Patrick G. O'Shea


Daniel P. Lathrop


Thomas E. Murphy

Reputation/honors

The unit is nationally and internationally recognized for its excellence in applied science. Corresponding awards in various areas of the IREAP activity are mentioned below.

Plasma Physics

The University of Maryland has had an internationally recognized program in plasma physics since the 1960s. Initially, efforts were focused in the Physics Department and the predecessor to the Institute for Physical Science and Technology. Research topics included basic plasma theory, plasma spectroscopy, space and experimental plasma physics, and controlled fusion research. Members of the original group produced several classic plasma textbooks: *Principles of Plasma Physics* (Krall and Trivelpiece), *Plasma Kinetic Theory* (Montgomery and Tidman), *Nonlinear Plasma Theory* and *Theory of Nonneutral Plasma*s (Davidson), and *Plasma Spectroscopy* (Griem).

During the 1970s the plasma physics effort expanded with a focus on the physics of magnetically confined plasmas for controlled thermo-nuclear fusion. The objective being to produce electrical energy by the same type of nuclear reaction occurring in the sun. Research at this time was largely supported by the Department of Energy. On the experimental side, Professors Boyd, DeSilva, Ellis, Goldenbaum, Skiff and Griem formed the core group at the time of the Institute's founding. Their efforts included developing diagnostics for the large fusion facilities in Princeton, San Diego and at MIT. However, at that time, the main experimental focus at Maryland was developing the Spheromak: a donut-shaped configuration with a magnetic field that was self-sustained by turbulent relaxation of the plasma. As a result, Maryland was the world-center of Spheromak research.

The theory group grew substantially through the 1970s as well. Under the leadership of Professor C.S. Liu a number of young theorists were brought in: Edward Ott, James Drake, Adil Hassam, Parvez Guzdar, Anders Bondeson, Y. C. Lee, H. H. Chen, Robert Kleva, Thomas Antonsen and John Finn (a Maryland Ph.D.). Thus, by the time the Energy Research Building was occupied Maryland had perhaps the largest theory group at any university. The theory group focused its efforts on issues of plasma stability and turbulence, the transport of energy and mass that results from turbulence, nonlinear plasma wave interactions, transport generated by electromagnetic waves, and the physics that controls the topology of magnetic fields (magnetic reconnection). An important transformation also occurred during this time: the group was initially composed of traditional "paper and pencil" theorists. However, the explosive growth in computing power led to the growth in importance of computational plasma physics. Members of the group adapted by becoming experts in numerical simulation of plasmas. This trend was further enhanced with the hiring of Professor William Dorland, who joined the group in 1999, and the Physics Department faculty in 2001.

The group is known for its contributions to the theory and numerical simulation of magnetized plasmas, including:

- Analysis of the stability of plasma configurations to the growth of low frequency modes; these are the precursors to the appearance of turbulence.

- Development of gyrokinetic models and codes describing the nonlinear and turbulent transport of mass, energy, and momentum. Gyrokinetics is a reduced description of magnetized plasmas, which assumes that fields evolve on a timescale long compared with the gyration period of the charged particles and on a timescale short compared to the evolution of the equilibrium, yet have with spatial structure on the scale of the gyro-orbit.
- Theory of magnetic reconnection, describing changes in magnetic topology in laboratory, and space and astrophysical plasmas. Reconnection is an explosive process in which magnetic energy is converted to particle energy in spatially localized regions.
- Particle acceleration in reconnecting, turbulent plasmas. Here the issue addressed is the mechanism by which particles can gain large amounts of energy in low frequency turbulent fields, especially during reconnection.
- Fundamental plasma instabilities affecting heat transport in the galactic intracluster medium.
- Novel magnetic confinement schemes based on plasma rotation.
- Collisional transport in magnetic confinement configurations with no symmetry. The stellarator is an example of toroidal plasma configuration in which the magnetic fields have no rotational symmetry. Consequently, a subset of particles can escape due to their magnetic drifts alone. Design and optimization of the fields in these devices requires sophisticated tools and deep understanding of the interplay of magnetic drifts and collisions.
- Turbulence in space and astrophysical contexts. The development of turbulence due to the conversion of macroscopic flows into cascades of microscopic flows is ubiquitous in the universe, and a problem even more challenging than Navier-Stokes turbulence.

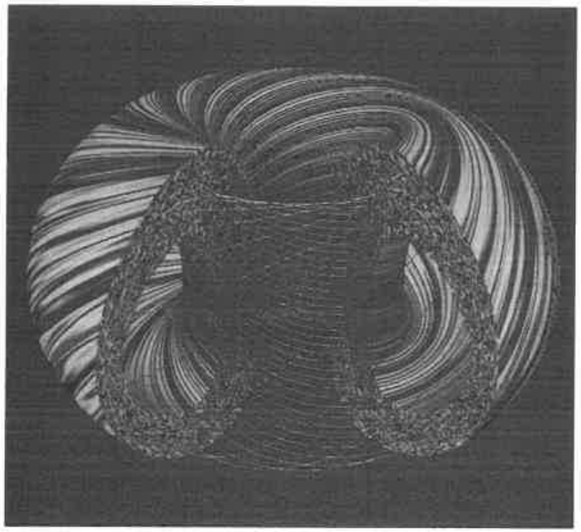


Figure 1. Numerical simulation of plasma turbulence in a toroidal magnetic field plasma confinement configuration for controlled fusion energy production, a tokamak. Courtesy W. Dorland

Nonlinear Dynamics/Chaos

The first IREAP member doing research in nonlinear dynamics/chaos was Edward Ott, who was recruited to UMD from Cornell in 1979 to do work in plasma and charged particle beam theory. Partly as a result of their shared interests, as well as the proximity of their offices in the Atlantic Building, Ott and James Yorke, a professor of mathematics, started a research collaboration on chaotic dynamics. They also secured a government grant, which enabled the hiring of a postdoc, Celso Grebogi, who later became a UMD faculty member based in IREAP. Success of this group's theoretical and computational research subsequently resulted in UMD being ranked as number one by U.S. News and World Report in the sub-field of nonlinear dynamics/chaos. This led to UMD's administrative decision to expand IREAP's efforts in this field by broadening the group's range of activities to include experimental research. As a result, three outstanding experimentalists were recruited: Prof. Daniel Lathrop in 1997, Prof. Rajarshi Roy in 1999, and Prof. Wolfgang Losert in 2000. These faculty members have subsequently led a broad interdisciplinary experimental program focused on nonlinear dynamics/chaos from a wide range of physical perspectives including photonics (Roy), fluids (Lathrop), granular matter (Losert), neuroscience (Roy), geodynamos (Lathrop), and biophysics (Losert). More recently, in 2008 Prof. Michelle Girvan, a statistical physicist specializing in networks, was recruited to the group. In addition to the above group members, the group has attracted extensive collaborations with other faculty whose primary past associations have been with other IREAP groups (particularly, Antonsen and Murphy), and even more broadly with faculty in other units of the University, such as mathematics (particularly Profs. Yorke and Hunt), engineering, physics, meteorology, etc.

All this has resulted in a vast amount of significant notable research successes. As an example of but one of these, we note the revolutionary research program (directed by Lathrop) whose goal is to create a laboratory model for studying the natural processes by which magnetic fields are generated in planets (like the Earth), stars and galaxies; see Fig. 2.

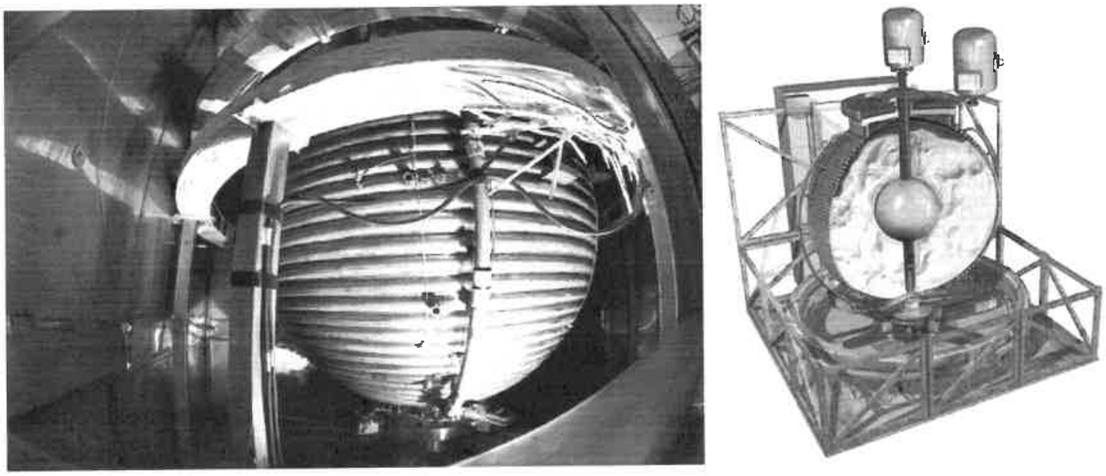


Figure 2. The University of Maryland Three-Meter Model of the Earth's Core. Photograph (left) and computer rendering (right) of Lathrop's laboratory model of the Earth's core, a 3-meter diameter hollow stainless steel sphere containing a 1-meter diameter solid sphere. The space between the two spheres is filled with sodium metal, which is liquid at stove-top temperatures and serves to mimic the molten iron in our Earth's core.

The future of this group appears to be bright as new applications and implications of dynamics and chaos continue to arise unexpectedly across a wide array of interdisciplinary fields. For example, a recent new research program of the group is the application of machine learning for the study of dynamical processes and the complementary study of dynamical principles underlying machine learning.

High Power Microwaves, Millimeter Waves and Terahertz Waves

The thrust of research on this topic was to extend the power and frequency of vacuum electronics oscillators and amplifiers in the frequency range from 7 GHz to 700 GHz by exploiting new physical principles and configurations. The effort was of interest in a number of applications including driving linear accelerators for high energy physics research, millimeter wave radars, heating plasma in controlled thermonuclear fusion reactors, nonlethal weapons, and detection of concealed radioactive materials.

The power limitation in scaling microwave tubes to higher frequency, while operating in the same waveguide or resonator mode, is imposed by cross-sectional dimensions which shrink with decreasing wavelength. Such a limitation can be overcome by operating in higher-order modes in overmoded cavities and wave-guiding structures whose transverse dimensions are much larger than the wavelength. Operation in such modes is possible in fast-wave devices where electromagnetic fields are not localized near the circuit walls. One of the simplest fast-wave devices are gyro-devices operating in uniform magnetic fields. Electrons propagating in these fields gyrate with the electron cyclotron frequency, and the transfer of energy from the electrons to the electromagnetic wave arises from the dependence of the mass of *relativistic* electrons $m = m_0\gamma$ and, hence, the electron cyclotron frequency on electron energy. Electrons entering the interaction space at different instants of time acquire different changes in the electron energy that causes their gyration with slightly different frequencies and results in electron bunching that may be followed by coherent electromagnetic radiation from bunches. The IREAP group studied amplifiers and oscillators which exploit this phenomenon and operate near the electron cyclotron frequency; specifically, gyroklystron amplifiers and gyromonotron oscillators (known as gyrotrons) were studied intensively.

Gyroklystron Amplifiers for Driving TeV–Class Linear Colliders

Linear electron accelerators for high energy physics research in the 50 GeV energy range typically employ large numbers of state-of-the-art conventional klystrons (e.g., the klystrons used at Stanford Linear Accelerator Center, SLAC, each produce output power of 65 megawatts (MW) at a frequency of 2.865 GHz in microsecond pulses). For future research the TeV energy range is of interest and more capable microwave amplifiers are required to keep the length and cost of the accelerator within reasonable bounds. It was proposed that gyroklystron amplifiers might be developed to surpass the conventional klystron capabilities; a multi-year, multi-million dollar research program in IREAP was funded by the U.S. Department of Energy to fully evaluate this proposal. The principal investigators were Victor Granatstein, the late Martin Reiser and Charles Striffler. Subsequently, Wesley Lawson played a leading role in the experimental studies; Peter E. Latham, Gregory S. Nusinovich and Thomas M. Antonsen Jr. played a leading role in numerical simulations and theoretical studies.

Results of gyroklystron studies were reported in a series of Physical Review Letters. In 1991, efficient operation of a 10 GHz, 2-cavity gyroklystron was reported with an output power of 24 MW. In 1993, operation of a frequency doubling, second harmonic gyroklystron was reported with output power of 30 MW at 20 GHz. In 1998, 80 MW of output power at 8.6 GHz was achieved by using a co-axial geometry. A review of the gyroklystron research appeared in1996; a recent and more complete review paper appeared in 2017 describing the gyroklystron research at the University of Maryland in detail and evaluating its worldwide impact on other projects.

A collaboration of industry (Communications & Power Industries), government (Naval Research Laboratory) and the gyroklystron research group at the University of Maryland developed a 94 GHz gyroklystron as the driver for the most capable millimeter wave radar ever deployed; the gyroklystron average power was 10 kilowatts (peak power 100 kW) which surpassed other millimeter wave sources at this frequency by an order of magnitude.

Gyrotron Oscillators for Plasma Heating in Controlled Thermonuclear Fusion

One of the leading methods for realizing the plasma heating to fusion temperatures in controlled thermonuclear reactors is Electron Cyclotron Resonance Heating (ECRH) using gyrotrons. The first gyrotron oscillator for such heating in the U.S. was developed at the Naval Research Laboratory (NRL); it was subsequently deployed at the Oak Ridge National Laboratory (ORNL) to demonstrate the first significant ECRH in a large Tokamak plasma confinement system. The NRL gyrotron produced 150 kW of output power in 20 millisecond pulses at a frequency of 35 GHz with 30% efficiency by utilizing the TE_{01} mode in the gyrotron cavity.

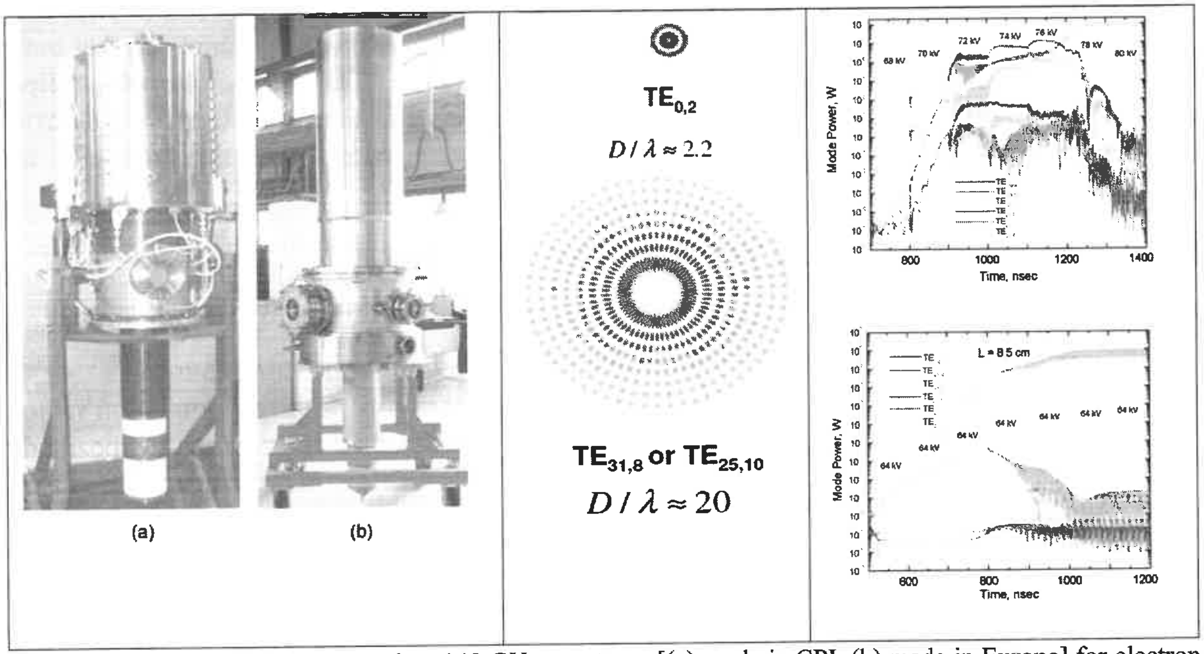


Figure 3. Left: Megawatt-class 140 GHz gyrotrons [(a) made in CPI, (b) made in Europe] for electron cyclotron plasma heating in the German stellarator Wendelstein-7X; Center: cross-sectional structure of transverse electric (TE) modes used in the first gyrotrons (top) and present-day MW-class gyrotrons (bottom); Right: temporal evolution of competing modes in MW-class gyrotrons (simulations done by using the self-consistent code MAGY developed at IREAP.

The megawatt class of gyrotrons developed for thermonuclear fusion reactors have found other novel applications; for example in non-lethal weapons that have an extended range and can be used for riot control without inflicting permanent injury; such systems have been acquired by the U.S. military and by police and prison administrators.

Terahertz Gyrotrons and the Remote Detection of Concealed Radioactive Materials

A scheme to prevent proliferation of bombs laced with radioactive material ("dirty bombs") involves focusing electromagnetic radiation at a frequency near 1 terahertz (THz) into a small spot in space near suspect containers which may contain hidden radioactive material. The probability of having ambient electrons in this spot is low unless radioactive material is present in the container. Electrons injected by the radioactive material can seed an avalanche breakdown in air driven by the THz pulse and the breakdown spark would be detectable. Investigation of this concept at the University of Maryland was funded by the Office of Naval Research.

First, it was found that a suitable THz source could consist of a gyrotron operating at approximately 700 GHz (i.e., 0.7 THz) with pulsed power > 25 kilowatts. The 170 GHz gyrotrons described above for ECRH use superconducting magnets to achieve an electron cyclotron frequency equal to the operating frequency. However, superconducting magnets are not capable of providing the fields required for gyrotron operation at ~700 GHz. Thus the proposal was to develop the required gyrotron using a pulsed magnet. System design was considered and a suitable gyrotron was demonstrated.

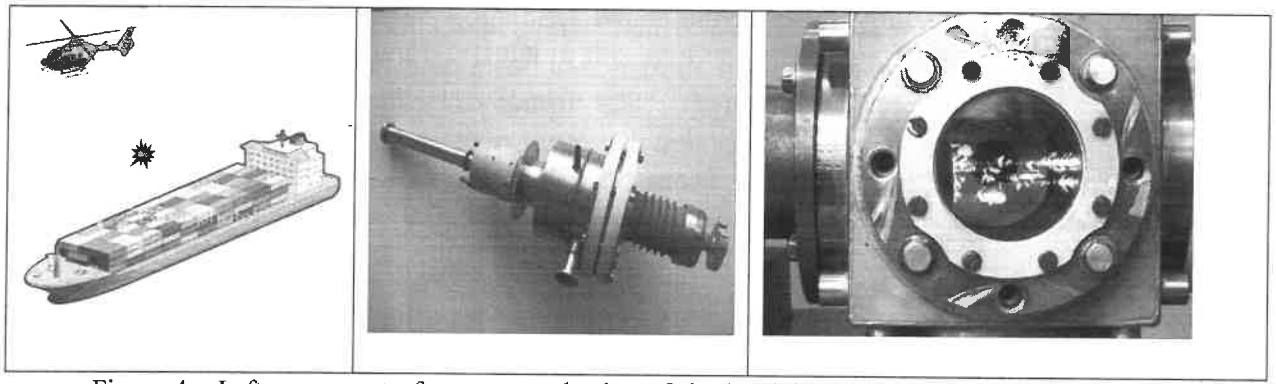


Figure 4. Left: a concept of remote production of the breakdown in air over a ship with hidden radioactive material by using focused THz radiation from a gyrotron installed on a helicopter; middle – photo of a 200 kW, sub-THz gyrotron with a pulsed solenoid; right – gyrotron radiation initiates breakdown in a chamber filled with a mixture of air with Argon.

The pulsed magnet produced a field as large as 28 Tesla with duration of several milliseconds. The gyrotron operated at a frequency of 670 GHz and produced 40 microsecond pulses with the record peak power of 200 kilowatts with 20% efficiency. These power and efficiency levels far exceed the power and efficiency of any competing source at this frequency. The gyrotron development was a joint project of the University of Maryland and the Institute of Applied Physics of the Russian Academy of Science. This research program is described in detail in a recent review paper.

Other Studies of Coherent Generation of Powerful Microwaves and Millimeter Waves

The sections above describe the research projects with the most sustained multi-year support. However, a number of other topics were studied and important results were obtained. Among these topics are: high power microwave radiation from intense relativistic electron beams, free electron lasers, plasma-filled microwave generators, and gyro-amplifiers at high cyclotron harmonics to reduce magnetic field requirements.

Students and Awards

Forty-two doctoral students at the University of Maryland performed their dissertation research on the topics described above. In 1991, one of them, Jeffrey Calame, won the American Physical Society Award for the outstanding doctoral thesis in beam physics and engineering. In 1998, The DOD Advisory Group on Electron Devices presented the Robert L. Woods award to Victor Granatstein for leadership in the vacuum electronics community. The following year, the Robert L. Woods award was presented to the group that developed the gyroklystron for the WARLOC radar including Wesley Lawson and Thomas Antonsen, Jr. In 2011, Gregory Nusinovich was awarded the Kenneth J. Button Prize for outstanding contributions to the science of the electromagnetic spectrum.

Charged Particle Beam and Accelerator Physics

The charged particle beam group formed by Prof. Martin Reiser has a long history of successful modeling of hadron linacs and storage rings, at low cost, using low-energy, high-current electron beams. Ring resonances, beam halo, instabilities, and emittance growth are modified or exacerbated by space charge at low energies, ultimately affecting the intensity and quality of the final beam. Space-charge dominated beams, in which the strength of space-charge induced expansion exceeds that from beam emittance (a beam quality factor), differ from beams where space charge is merely a perturbation. The former can support a variety of collective modes and longitudinal space charge waves that can result in exotic structures on the beam, such as high-density rings, solitary waves, or beam halo, and a host of resonance and instability phenomena. While some of this physics has had a long history of theoretical study, experimental verification over sufficiently long beam transport distances has not been feasible, until the commissioning of the University of Maryland Electron Ring (UMER) shown in Fig. 5.

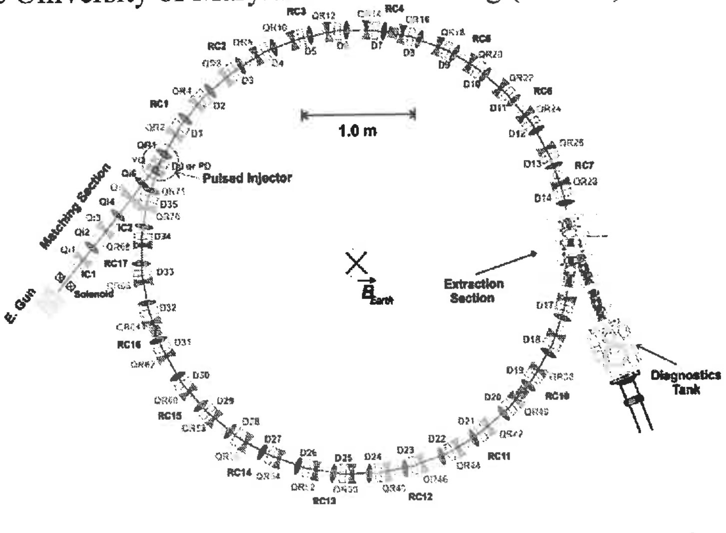


Figure 5. Schematic layout of UMER, including the planned extraction line. The ring has 72 magnetic quadrupole lenses and 36 bending dipoles arranged on an 11.52-m circumference. A 10 keV electron beam is produced from a gridded thermionic gun with the typical 100-ns UMER bunch filling approximately half of the ring circumference. The beam current (0.06–100 mA) and normalized rms emittance (0.1–3.0 μm) are varied by means of an aperture wheel downstream of the electron gun anode. The different beam currents enable varying the strength of space charge from the emittance-dominated to the extreme space-charge-dominated regimes.

UMER is a flexible machine dedicated to beam physics research over a wide range of space-charge intensities, including regimes that directly model low- and medium-energy hadron storage rings. It is unique among facilities in the U.S. in terms of the physics that can be explored, and as a training facility for the next generation of accelerator physicists and engineers. (The University of Maryland has graduated more PhDs in accelerator science than any other U.S. institution.)

Various diagnostics were developed for transverse phase-space beam mapping and halo studies. First, the beam tomography based on imaging the beam over a broad range of quadrupole or solenoid strengths was demonstrated. Then, the investigation of beam halos using a digital micro-mirror device was carried out.

In another milestone, it was found that with a large density perturbation applied at the tail of a long bunch a fast wave develops into a soliton wave train after 2-3 turns. The formation and evolution of the soliton wave train is illustrated in Fig. 6a.

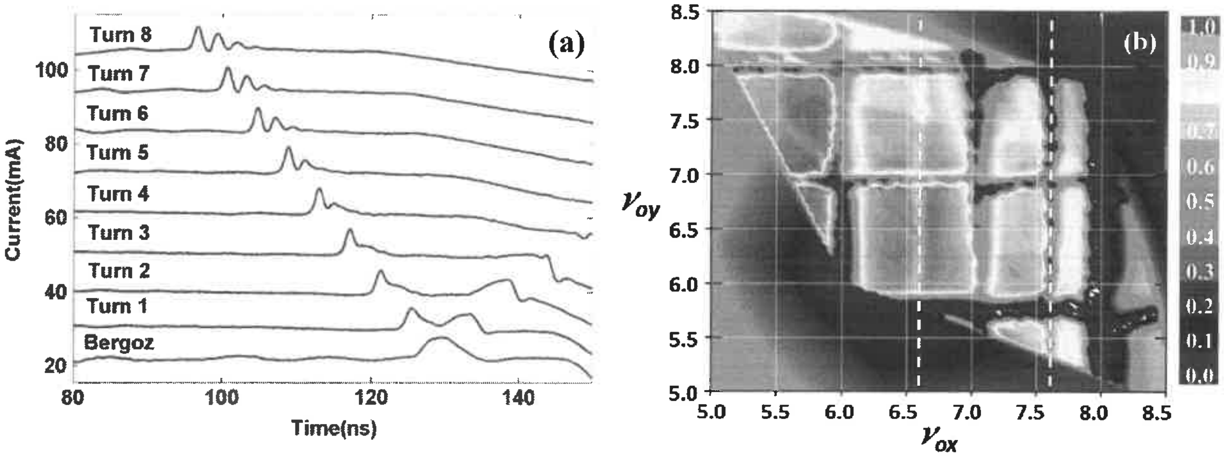


Figure 6. (a) Turn-by-turn evolution of soliton wave train in UMER. (b) Fraction of transmitted beam current at the 10th turn for the 6 mA beam as a function of horizontal and vertical tunes. (The tunes are measures of the strengths of focusing and defocusing quadrupole lenses.) The vertical dashed lines near $\nu_{ox} = 6.5, 7.5$ display the shifts from incoherent space charge.

The recently reassembled and realigned ring has resulted in significantly improved beam transmission as shown in Figure 5b for the 6 mA beam. An incoherent space-charge tune shift of 1.2 – 2.2 was deduced using existing theory. It represents a new technique in UMER that we plan to use to probe the theory over a range of space-charge intensities far broader than what is possible in other rings.

UMER personnel are currently pursuing studies of: nonlinear integrable beam optics with a distributed octupole lattice; production and characterization of ultra-low current beams for the nonlinear optics studies. While more conventional linear focusing is susceptible to many families of resonances that drive particle losses, the use of nonlinear gradients is predicted to create strong damping of resonances by imprinting a tune (frequency) spread in the particle distribution. The proposed method incorporates strong nonlinear focusing while maintaining integrability, or conserved invariants in the equations of motion. The effort at UMER to demonstrate this nonlinear lattice, in parallel with the Integrable Optics Test Accelerator at FNAL, has the potential to be transformative in how ring lattices are designed for future high-intensity machines.

Another area of fundamental interest in many accelerators is the resistive-wall instability. This effect arises from the interaction of bunch particles and fields from currents induced on the walls of the vacuum pipe. At UMER a new approach to the resistive wall instability based on non-relativistic wakefields is being pursued in collaboration with Fermilab.

Optics & Photonics

Optics and photonics represents a significant portion of the research effort at IREAP, and involves nine faculty members from three academic departments (Hafezi, Kim, Murphy, Milchberg, Munday, Rabin, Roy, Leite, Sprangle and Waks) and one research faculty (Ting). Because optics research in IREAP overlaps strongly with related work in materials, plasmas, particle acceleration, and dynamical systems, some of the optics-related research is addressed in those sections. Optics faculty receive funding from a diverse range of federal funding agencies, including DOE, NSF, AFOSR, ARO, ARL, CIA, DHS, DOE, DTRA, and ONR, as well as private foundations (Sloan), corporations (Google, MicroPET), and external Universities (typically as sub-awardees on federally-funded research.) In the last seven years, the optics faculty in IREAP have received several significant awards and recognitions, including three NSF CAREER awards, two ONR Young Investigator Awards, PECASE Award, Sloan Fellowship, the IEEE Photonics Society Young Investigator Award, the OSA Adolph Lomb Medal, NASA Early Career Faculty Space Technology Research Award, DARPA Young Faculty Award, SPIE Early Career Achievement Award, DOE Early Career Award, and the A. James Clark School Junior and Senior Faculty Outstanding Research Awards.

Photonics researchers in IREAP study a diverse range of topics ranging including quantum optics, photovoltaics, nonlinear optics, terahertz optics, plasmonics, and plasma physics, outlined below.

Quantum Photonics

The field of quantum information and quantum computing has experienced extremely rapid progress over the past 10 years. The Waks group focuses on solid-state implementations of quantum information technology with the potential for chip-scale devices. This work could ultimately enable scalable and compact quantum devices needed for secure communication, exponentially faster computation, and ultra-sensitive quantum sensors.

The primary effort of the Waks group had been to develop methods to interact single quantum dots, which act as atomic quantum memories, with single photons. They have made a number of significant contributions to the field that include an all-optical switch with the lowest switching energies reported, nonlinear optical devices operating with less than 10 photons of energy, and ultra-fast coherent control of photons and atoms on a semiconductor chip. One of the most significant outcomes is the first experimental demonstration of a quantum transistor, utilizing excitons in a neutral quantum dot. This was more recently followed by a quantum phase switch based on the spin of a single quantum dot.

Strong Terahertz Physics

Sandwiched between the optical and microwave regimes, the far infrared or terahertz (THz) frequency range has recently drawn special attention due to its ubiquitous nature and broad applications. The physics of THz generation is also compelling, raising fundamental questions about the interaction of strong electromagnetic fields with atoms and molecules.

The Ultrafast Optical Science group, led by Prof. Kiyong Kim, has pioneered intense coherent THz generation in plasmas, especially explaining the generation mechanism of THz pulses in two-color laser mixing. His plasma current model is now widely accepted in the THz community as the fundamental microscopic explanation. Recently, Prof. Kim's group reported macroscopic phase-matching in THz generation, which is crucial for efficient frequency conversion. His group has also demonstrated scalable high-power THz generation via elliptical focusing with a multi-terawatt laser system in collaboration with Prof. Milchberg's group. Such a strong source can create THz fields exceeding 100 MV/cm on a tabletop setting, potentially opening up new opportunities to study extremely-nonlinear terahertz phenomena such as THz-driven harmonic generation. His group also recently developed and used a kHz cryogenically-cooled laser amplifier to generate high-power THz radiation at a high-repetition rate with applications in nonlinear THz optics and spectroscopy.

Research in intense THz physics also has strong applications and overlap with related efforts on plasma-based acceleration – another area for which the Institute is widely regarded as a world leader.

Intense laser-matter interactions

The experimental and theory/simulation projects in Prof. Milchberg's group span the range of perturbative nonlinear optics through highly nonperturbative interactions. A main goal has been to study the propagation of high intensity femtosecond pulses through matter. This has necessitated the development of new ultrafast methods for measuring the microscopic non-perturbative nonlinear response of an optical medium's underlying atoms, molecules, and plasmas. Results have included the first ultrafast measurement of n_2 (the nonlinear index) of atomic and molecular gases in the mid-IR, discovery of quantum effects that can steer laser beams in room temperature air, the development of long-lived, femtosecond-pulse-written air waveguides, and the realization that a new type of vortex – the spatio-temporal vortex-- governs the propagation of intense laser pulses after optical collapse. This is a condition occurring in an extremely wide range of propagation scenarios, including relativistic self-focusing and charged particle acceleration in plasmas.

Nonlinear optics

Professor Murphy directs a broad experimental research group with a common underlying theme of nonlinear optics, optical materials, and electro-optics. Research in his lab spans the fundamental physics of nanoscale and two-dimensional materials all the way to system-level demonstrations of radio-over fiber communication systems.

The past decade has seen a renaissance in the physics of atomically thin, 2D materials that began with the discovery of graphene and has now grown to encompass a variety of new designer materials and atomically thin hetero structures. Research in IREAP has focused on measuring and exploiting the unique optical properties of these materials, especially in the mid-IR and far-IR (THz) spectral regime. Notable recent accomplishments include the demonstration of broadband photothermal detection in graphene and black phosphorus 2D layers and the first demonstration of plasmon-enhanced nonlinearity in graphene.

Topological Photonics

Topological features — global properties that are not discernible locally — emerge in variety of physical systems. Deeper understanding of the role of topology in physics has led to a new class of matter: topological states. In the past several years, the Hafezi group has pioneered the science of topological photonics – the study of coupled optical resonators that exhibit topological properties. With this system, they imaged the topological states of light for the first time, using silicon photonics, analyzed their transport properties, and demonstrated that topological robustness indeed protects the system against certain kind of disorders. More recently, they measured topological invariants that are responsible for such kind of robustness in two-dimensional photonic systems. Currently, they are investigating the propagation of non-classical light in such photonic systems to analyze the robustness of the encoded quantum information against disorder.

In collaboration with Prof. Waks, they are also designing and fabricating a new type of topological photonic crystal, which will allow us to integrate strong optical nonlinearity at the single photon level by using solid-state emitters. Such a platform would enable the investigation of chiral quantum optics and fractional quantum Hall states of light.

Photovoltaics

In order to make solar photovoltaics cost-competitive with fossil fuel based technologies, it is essential to reduce inefficiencies that currently limit solar power conversion to about 30%. Research in the Munday group has proved that many of the efficiency losses can be recovered through careful photonic design.

To improve absorption in photovoltaic devices, researchers in the Munday group have borrowed concepts from photonics and have applied them in new ways to photovoltaic technologies. One example includes the use of quantum dot emission to scatter light into a solar cell, enabling thin-film solar cells to generate more power by increasing the optical path length of light. Similarly, they have shown that high-index dielectric nanophotonic resonators dramatically reduce light reflection at the surface of an InP solar cell to nearly 1.3% when averaged over the entire solar spectrum. With collaborators in the Materials Science & Engineering Department, Munday's group has demonstrated a novel, environmentally friendly anti-reflection coating based on wood fibers that has enabled a 20% increase in solar cell efficiency.

Additionally, they have developed fundamentally new methods to increase the photovoltage in solar cells by manipulation of light. In a paper highlighted on the cover of the Journal of Applied Physics, they showed that photonic structures that trap light can increase in the output voltage of the device through a buildup of the carrier density, thereby increasing the efficiency.

Ongoing research seeks to devise new photonic and plasmonic structures that extract an electrical current from hot photo-excited carriers before they equilibrate to the lattice. Initial experiments suggest that 10% power conversion efficiency can be achieved in metallic structures without using semiconductors, and theoretical estimates have predicted efficiencies exceeding 41% in hybrid metal-semiconductor solar cells. Similar hot-carrier effects are also under study in the Murphy group in 2D materials (graphene and black phosphorus), but for a very different purpose: to build a fast and sensitive room-temperature terahertz detector. Future collaborative activities could leverage the complementary expertise of both groups to devise new photonic devices that operate over a broad spectral range.

Future opportunities

The study of optics and in 2D materials has become a competitive field of research, however there are several reasons why IREAP is poised to play a leadership role in this burgeoning field. When dissimilar atomic layers are vertically stacked, the resulting van der Waals heterostructure exhibits optical properties that that are advantageous in photovoltaics, nonlinear optics and quantum optics – separate areas where our Institute is already well-recognized. Our proximity to nearby national laboratories (ARL and NRL) provides unique access to new 2D materials, and existing IREAP faculty (Waks, Rabin) have already developed some of the required deposition capabilities. Taken together, the experimental laboratories in IREAP provide unparalleled capabilities needed to advance this field, including near-field linear and nonlinear microscopy, ultrafast spectroscopy, and cryogenic measurements.

IREAP is in an ideal position to establish strong interactions with nearby government research labs and leverage their extensive facilities and expertise. IREAP is already the lead institute for the Center for Distributed Quantum Computing (CDQI). This center constitutes a joint collaboration between leading institutes in quantum research (including Maryland, MIT, Harvard, Stanford, Duke, and Yale) and the Army Research Laboratories. We are also actively engaged with the Laboratory for Telecommunication Sciences to develop a quantum network between ARL, LTS, and IREAP. Historically, IREAP has been the home of large-scale experiments that require major infra-structure and space. The field of quantum science is now entering the phase where progress requires massive multi-investigator projects with a center like focus. IREAP's infrastructure and abundance of large space present an ideal opportunity to fill this need.

Plasma-based Accelerators

The Plasma-Based Accelerator includes four academic faculty members (Thomas Antonsen, Ki-Yong Kim, Howard Milchberg, and Phillip Sprangle), and a number of research scientists/professors and graduate students. The group performs theory, computation, and experiments in the general areas of laser matter interaction and plasma based acceleration. Funding for the group comes from the DOE Office of High-Energy Physics, NSF, AFOSR, NRL, DTRA, and ONR, DHS (DNDO), DARPA, and ARO.

There are two main thrusts in the experimental work on plasma-based acceleration. One is on the development of novel acceleration schemes using plasma structures. This includes the pioneering work in creating plasma channels that exhibit optical guiding, to extend the acceleration distance for Laser Wake Field Acceleration, and structured (corrugated) plasma channels, to allow for direct laser acceleration of particles. The other is the development of thin and extremely dense gas jets operating in the critical density regime. These allow relativistic self-focusing and laser acceleration with kHz rep rate lasers with only millijoules of laser energy. Recent efforts have turned to investigating the use of novel methods to accelerate protons. The group is also well known for its groundbreaking work in THz generation based on photo-ionization of gas by a two color (fundamental and harmonic) laser pulse. New efforts in the group are directed to the study of CO2 laser driven broad-band IR generation in a nonlinear medium for sensing and remote detection, and the development of a scheme to remotely detect radioactive materials using laser triggered breakdown of the surrounding air. There are multiple lasers dedicated to experiments in advanced accelerator science: a 30 TW peak power laser, and several 10 mJ-scale, 1 kHz lasers, and a new high power femtosecond TW mid-IR laser, of which there are only two others in the world.

Laboratory for Ion Beam Research and Applications

The bombardment of the surfaces of solids by energetic ions has long been an important topic in science and technology in diverse areas such as degradation of nuclear reactor parts by ion bombardment or the construction of ion propulsion rockets for space travel. In the 1970s, techniques for surface patterning using ion beams began to emerge. These techniques were important, and continue to be important, in the fabrication of electronic devices, in particular the ubiquitous integrated circuits. In general, the ion beams are large covering the entire surface of a sample. Patterning is achieved with the use of a stencil fabricated in the sacrificial film on the surface by other techniques.

In the late 1970s and 1980s, a new field of ion beam patterning of materials emerged as a result of the invention of the gallium liquid metal ion source. This was an intense point source of ions, which by the use of charged particle optics could be focused to a point on the surface of a solid. During the 80s and continuing into the 90s a great deal of research was devoted to reducing dimensions of the "point" on the sample into the single nanometer regime and to the complex interactions of such a point beam with various samples. In addition, ion sources were developed for ions other than gallium such as the dopants of silicon and gallium arsenide . Much of this work is summarized in the book by Orloff, Swanson and Utlaut (*High-Resolution Focused Ion Beams: FIB and It's Applications,* 2003, (Kluwer, New York).

An unrelated development was the demonstration of ion projection lithography 1982. In this technique a stencil mask is back-illuminated with a broad beam of ions and the image of the stencil mask is demagnified through ion optics and projected onto the surface of a sample. This opened new possibilities in that a single point beam could not fabricate a large area in any practical timeframe but the projection of the entire pattern could potentially overcome that limitation.

In 1993 the Department of Defense recognizing these possibilities granted the University of Maryland a large contract, ($7.5M) to set up a laboratory to investigate these areas. This laboratory was named the Laboratory for Ion Beam Research and Applications (LIBRA) and two new faculty members were hired as full professors. John Melngailis from MIT started work in October 1993 and Jon Orloff from the Oregon Graduate Center started in December 1993. Orloff was one of the early developers of the point ion sources and the cofounder of a company, FEI that manufactures focused ion beam instruments. Melngailis' work at MIT was in the development of focused ion beam applications to semiconductor devices as well as in the understanding of the details of the ion-solid interaction. The focused on beam field as well as the work of the new laboratory can be divided in three categories:

1. Ion projection lithography as a potential technique for replacing optical lithography in integrated circuit fabrication.
2. Low-energy ion beams, principally gallium for use in direct material patterning by milling or beam induced deposition.
3. High-energy ion beams with the dopants of silicon and gallium arsenide(B,As, Si &Be).

Ion Projection Lithography (IPL)

Our information revolution is enabled by the shrinking of dimensions on semiconductor chips. In the 1980s these dimensions were below 1 μm and further shrinking was thought to be limited by the fact that the wavelength of light used in optical lithography was in the 200 to 300 nm range. Alternate technologies were explored by extensive worldwide efforts including x-ray, electron beam, extreme ultraviolet (EUV at 13 nm) and ion projection lithography (IPL). The Department of Defense through DARPA funded the research program to explore IPL. The technology was pioneered by IMS, a small company in Vienna Austria. A new machine was built in Vienna and dimensions down to 70 nm were demonstrated in the late 1990s. LIBRA participated in this effort in the stencil mask fabrication, analysis of thermal expansion and other supporting efforts. Because of expense and technical limitations all alternate technologies, with the possible exception of EUV, have been abandoned. The worldwide semiconductor industry decided to stay with optics with various enhancements. The IMS company (now called IMS Nanofabrication AG) in Vienna has continued to work and has built an electron multi-beam system that is now being developed for mask fabrication.

Low energy ion beams

Gallium ion beams in the 10 to 50 keV energy range can be used for material removal or addition at nanometer dimensions. This technology has matured and is now widely used and all major semiconductor manufacturing facilities. Usually the focused ion beam (FIB) system is coupled with a scanning electron microscope (SEM). In this way the material alteration produced by the ion beam can be observed with an electron microscope. Both Orloff and Melngailis participated in the development of this technology and its applications since its inception in the 1970s and 1980s. They continued to contribute in this area after the formation of LIBRA in 1993.

The laboratory had two systems: one of them operating up to 50 keV volts and the other one up to 30keV which was also coupled to an scanning electron microscope (SEM). Both systems had the possibility of locally feeding in reactive gas, which could be used to chemically enhance the removal of material or to deposit material at nanometer dimensions. These unique capabilities led to countless collaborative projects with colleagues in the Departments of Physics, Materials Science, and Electrical and Computer Engineering as well as NASA and NIST. For example, using gallium ion milling we produced 70 x 70 nm ferroelectric capacitors which still at those dimensions showed ferroelectric operation (Fig. 7)

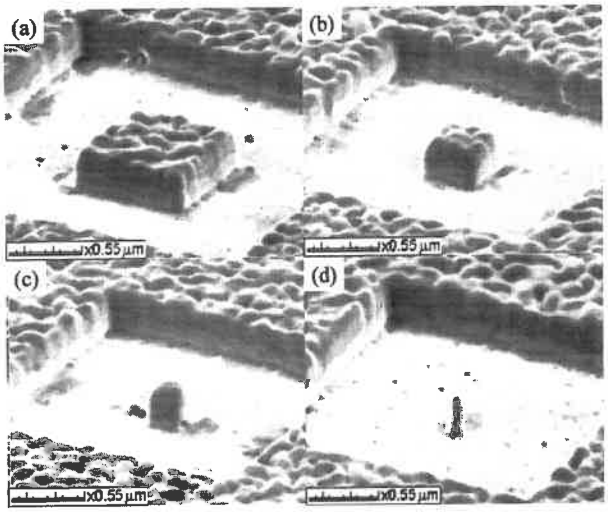


Figure 7. A ferroelectric film of Pt/SrBi2Ta2O9/Pt patterned with a Ga Focused ion beam. Material was sputtered off to leave islands of 1µmx1µm (Upper left) down to 70nmX70nm (lower right). This material could not be patterned by any conventional technique.

Using beam-induced platinum deposition a nano thermometer was built which could measure the temperature on the area of a semiconductor chip at submicrometer dimensions (Fig. 8). With NASA Goddard we participated in the development of a micro-shutter array for use in the James Webb space telescope flown on a satellite. We fabricated specially shaped atomic force microscopy (AFM) tips coated with high permeability material for high resolution Magnetic Force Microscopy. We were also the first to demonstrate the beam-induced deposition of platinum and the deposition of silicon dioxide from numerous precursor gases. These are examples of some of the varied projects of LIBRA. Focused ion beam systems of this type are widely used worldwide in the semiconductor industry for diagnosing failures and/or locally modifying circuits for failure analysis.

High-energy Focused Ion Beams

These systems permit locally controlled implantation of the dopants of silicon and gallium arsenide at nanometer dimensions and at energies up to 300keV. The microelectronics laboratory operated by the Defense Department had two of these machines in the proximity of the University of Maryland and was therefore interested in our work in this area. The high-energy focused ion beam implantation systems open the possibility of making unique transistors locally on a chip as well in making transistors with unique operating capabilities with the implantation of doping gradients. A superior performance MOS semiconductor device was fabricated using our focused ion beam to produce a buried channel implant. Using boron implantation of stripes we demonstrated that a virtual grating could be fabricated in an optical fiber by the implantation of B stripes to alter the index of refraction. The gratings could be used to couple light out of the fiber at selected wavelengths. In spite of the fact that more than 20 machines of this type were in operation worldwide and dozens of unique devices were demonstrated, none found their way into large-scale manufacturing. Therefore, interest in this area diminished.

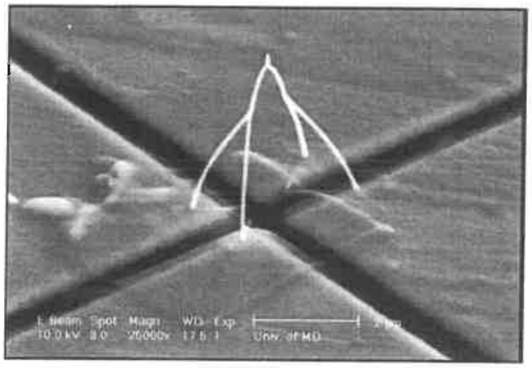


Figure 8. SEM Micrograph of an nanothermal probe consisting of Pt alloy filaments about 50nm diameter. The resistance of the filament is measured by a 4 point method and depends on temperature. The temperature can be measured to ~0.5K with a spatial resolution of 20nm.

Nano Fabrication Laboratory

The work in LIBRA often required conventional fabrication such as chemical etching, lithography, metal deposition, oxide deposition, and plasma etching. We therefore built a laboratory with these capabilities, which served other researchers on campus and led to the formation of a new course in the ECE Department called "Integrated Circuit Fabrication" which is still being taught. Our fabrication facility was later expanded adjacent to our laboratories and served as the main fabrication facility on campus until the Nano Fab was opened in the Kim building.

The Laboratory for Ion Beam Research and Applications ceased operating with the retirement of Jon Orloff in 2006 and the transition of John Melngailis to teaching and off-campus research and other activities, and eventual retirement in 2014.

Recollections from Nolan Ballew

I began working at IREAP in 1994 when it was still IPR, The Institute for Plasma Research. I answered an ad in the Diamondback for a part time person to work in the machine shop. I was hired by Ken Diller, who ran the shop, and Victor Yun, who was an engineer for the Ion Beam group headed by Dr.'s Orloff and Melngailis. I was to work part time in the shop and part time in the lab. I started the same week as Ed Condon, who was working part time doing IT support under the another IPR alum, Matt Naiman.

After a few years I was hired by Wes Lawson to work under Bart Hogan for Wes's Gyroklystron experiment where I was taught to weld, use a helium leak detector and use cnc mills and lathes. Most importantly I learned how to find out what a student/researcher actually needs in contrast to what they are asking for. I also learned, from Bart Hogan, a most valuable lesson, "never build what you can buy".

Victor Yun left the Ion Beam group to pursue interests in the private sector. Before he left he encouraged Dr. Orloff and Dr. Melngailis to hire me full time. Victor also taught me to use an Electron Beam Evaporator and to do non-contact photo lithography. He encouraged me to learn to use the other equipment that was arriving to fill the new IREAP clean room. From Klaus and Dr. Melngailis I was taught to use the chemical vapor deposit machine, the rapid thermal annealer, the reactive ion etcher the deep reactive ion etcher, the thermal evaporative coater, and how to dope wafers.

I was tricked into teaching the lab section of the then new ENEE 419j. Originally the lecture was done by Dr. Melngailis and the lab was taught by Dr. Klaus Edinger who asked me to assist him in the lab. Just after the beginning of one class he excused himself claiming he would return in a few minutes, when he did not, I slowly went through the rest of the fabrication steps with the students and we had just finished the last step when he returned. Upon seeing that no wafers had broken and no student had dissolved themselves in acid, he proclaimed that as he would now be doing the lecture, I would be teaching the lab. I taught the lab a few times with Klaus, and then with Professors Ghodssi, Illiadis, and Smela.

When the Cleanroom moved into the Kim building I left the university to work at a private company in Silver Spring. I was pretty good at customer service, but not well suited to bug testing software. I was offered a position, again by Victor Yun, at LPS. LPS is a well-equipped, clean, modern and extremely well funded facility. However, it did not offer the opportunity to interact with students and researchers on a daily basis like IREAP. Dan Lathrop, who was then the director, kept claiming that he was going to make me an offer I could not refuse. He did and I returned to IREAP in 2010, just in time to begin filling the three meter sodium experiment (shown in Fig.2).

Advanced Materials

Innovation in synthesis, processing, and implementation of advanced materials is crucial to many modern industries and addressing future challenges in electronics and data processing, clean energy, national security, food and healthcare. The efforts of Materials Science and Engineering faculty Marina Leite, Gottlieb Oehrlein, Oded Rabin and Gary Rubloff within IREAP address various aspects of these challenges. Research is currently supported by a variety of agencies and companies, including NSF, APS, ARL, DOE Basic Energy Sciences and DOE Fusion Energy Sciences, UM Ventures, NIST and SRC. Companies include Saft Batteries, Zeiss and others. Rubloff is Director of Nanostructures for Electrical Energy Storage (NEES), a DOE Energy Frontier Research Center involving eight university and two national lab sites as partners currently funded at $25.2M over 2009-2018.

Prof. M. Leite. Leite's group is engaged in fundamental and applied research of materials for energy harvesting and storage, encompassing photovoltaics, plasmonics and solid-state batteries. The group is focused on developing and implementing scanning probe microscopy with unprecedented spatial resolution to resolve device performance at the nanoscale, with the particular goal of determining where carrier recombination occurs in non-epitaxial materials. Recently, the group realized novel functional imaging methods to map local V_{oc} with nanoscale resolution, including the dynamics of perovskite solar cells.

To overcome the limitation imposed by the pre-defined dielectric function of metals the Leite group is investigating how alloying can be used as an additional knob to tune the optical response of metallic thin films and nanostructures for plasmonics applications by combining experiments with full-field simulations.

In today's society, new rechargeable battery technologies are urgently being developed for a variety of applications. The Leite group is working to understand and control the undesired chemical reactions that leads to solid-electrolyte interphases (SEIs) in all-solid-state batteries by imaging lithation/delithiation through electron microscopy methods combined with chemical analysis tools. This work can potentially transform the future design of all-solid-state batteries, with controlled SEIs.

Leite is the recipient of the 2016 APS Ovshinsky Sustainable Energy Fellowship and the 2014 Maryland Academy of Science Young Outstanding Scientist Award.

Prof. G. S. Oehrlein. G. Oehrlein joined the Department of Materials Science and Engineering and IREAP in January 2000. Oehrlein's group uses the special opportunities that a low temperature plasma environment provides for processing of materials that range from classical electronic materials to biological materials, foods and catalysts.

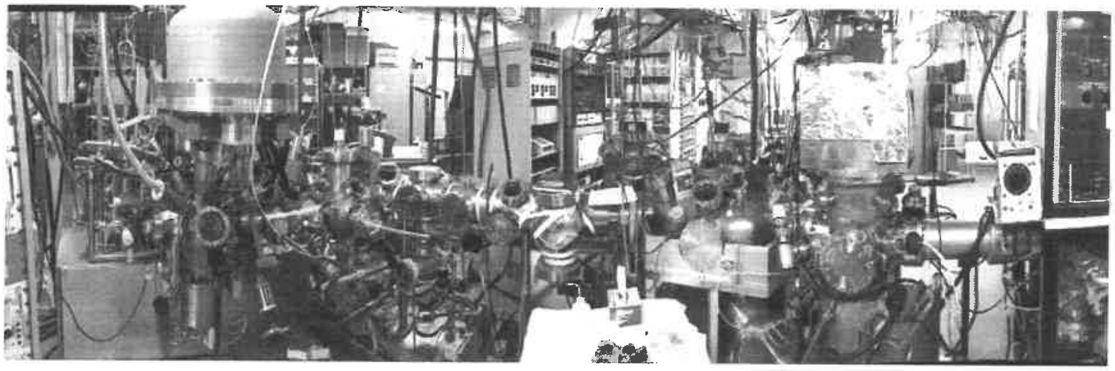


Figure 9. Photograph of Laboratory for Low Temperature Plasma processing of materials showing various plasma processing devices and surface analysis equipment. Plasma-materials interactions are studied by real-time measurements on various LTP devices that are also interconnected by ultra-high vacuum tracks to additional in-situ materials characterization.

Plasma is known as the fourth state of matter, beside the solid, liquid and gaseous phase states, and IREAP has played a prominent role in the science and technology of the plasma state itself. The interaction of the plasma state with materials, e.g., solids or liquids, results in a large range of new phenomena that have important technological applications, in particular if a "non-equilibrium" or low temperature plasma (LTP) is used. In LTP, "heavy" particles, e.g., molecules and ions, remain near ambient temperature ("cold"), while the electrons become hot by electrical heating, and can induce chemical reactivity by breaking covalent chemical bonds of molecules and ionization by collision-induced energy transfer. By careful choice of plasma device and method of energy input, chemistry, and other aspects, non-equilibrium materials processing is made possible and enables synthesis and modification of materials that is not possible by the methods of traditional materials science and engineering.

The group is known for its particular expertise in the area of plasma-surface interactions, the control of which has been essential for the development of plasma-based etching technologies in the semiconductor industry. Achieving atomistic control in plasma–material interactions is a key theme of the group's efforts in this application space. A recent example is the group's first demonstration of atomic layer etching of dielectric materials. Additionally, nanofabrication has become significantly more complex for nm scale dimensions and requires advances in plasma-polymer interactions and development of novel resist materials which is currently being pursued with colleagues in the Chemistry Department.

Another recent development is the realization of LTP devices that work at ambient pressure. This in turn has expanded the range of materials that can be processed, including biological materials, tissue, and foods. The scientific issues connected with plasma-surface interactions at atmospheric pressure are significant and the group recently played an important role by elucidating the key controlling processes in the interaction of LTP with polymers and biological materials, including sterilization of foods.

As our society transitions to sustainable technologies, a number of important opportunities exist for LTP-based materials science and engineering. One of these is the synergy of LTP in conjunction with catalytic materials for accelerating chemical conversion processes of hydrocarbons and greenhouse gases with high conversion efficiency and product selectivity. In particular, the surface-mechanistic origins of these processes, their optimization and use, are not understood and are being pursued by Oehrlein's group to overcome this significant roadblock for industrial implementation.

Oehrlein received the 2010 Faculty Award of IBM Corporation, and the 2005 Plasma Prize, Plasma Science and Technology Division, AVS.

Prof. O. Rabin. Rabin's group performs experimental and modeling research in the areas of thermoelectrics, plasmonics, and carbon-metal composites. The materials capabilities include solution-phase synthesis of nanoparticles with controlled size and shape, thin film fabrication via pulsed laser deposition and/or thermal evaporation, and electrical, thermal and optical characterization.

The group's impact has been through the dissemination of an improved model for the calculation of the thermoelectric properties of nanostructures (quantum wells and quantum wires) and the discovery of the universality of quantum-size effects across a wide range of semiconductor thermoelectric materials. Advances were achieved using pulsed laser deposition (PLD) for the fabrication of complex films, an approach that is promising for thin-film thermoelectrics fabrication. For example, PLD of carbon-metal composites produced films that are as conductive as pure metals but more transparent and less prone to oxidation. As an active member of the Maryland Nanocenter, the group has capitalized on the state-of-the-art FIB and EBL systems to fabricate 3-dimensional plasmonic nanostructures for the control of the near-field and far-field polarization of light. Applications include sensitive chemical detection and miniaturization of non-linear optical components.

Rabin has received an NSF CAREER Award, and one of his PhD students was recognized with the University Distinguished Dissertation Award.

Prof. G. Rubloff. The Rubloff group is seeking solutions and understanding for a next-generation energy storage technology, which exploits nanostructures that combine power and energy benefits as well as robustness with charge/discharge cycling. The group has established a world-class facility (ANSLab) for atomic layer deposition (ALD) combined with other processes, real-time ALD process sensing, in-situ surface analysis (e.g., XPS), and battery fabrication and testing. A striking example has been the nanopore battery array, composed of millions of nanobatteries (~1fL each) formed within alumina nanopores. This approach achieves energy and power density as well as cycle life well beyond other nanostructured battery structures and demonstrates design principles for nanostructured energy storage.

The group's research is highly integrated into the DOE-sponsored NEES Energy Frontier Research Center (EFRC), with ALD material layers now incorporated into many battery configurations and dozens of publications. The work is widely recognized in the energy storage research community and the ALD process community.

For our group, two particular opportunities are in 3D solid state nanobatteries and in thin protection layers for electrodes in more conventional batteries. Both directly benefit from ALD processes and address critical safety issues of today's Li ion batteries. The ANSLab is ideally poised to remain at the forefront.

Rubloff became Distinguished University Professor, University of Maryland, College Park in 2016, and received the Faculty Outstanding Research Award 2015, A. James Clark School of Engineering.

UMD NanoCenter

The Maryland NanoCenter (http://www.nanocenter.umd.edu/) was established in 2004 to enhance the coherence and effectiveness of the university's research community in the domains of nanotechnology and microsystems. The NanoCenter is led by the founding director, Prof. Gary Rubloff, and is supported by a combination of user-fees together with support from two colleges, the Vice President of Research, and the Provost. The NanoCenter is funded independently from IREAP. However, the Nanocenter is administratively organized under IREAP, and the Institute manages and oversees all appointments, human resources, accounting, reporting, purchasing, networking and telecommunications support.

A campus-level partnership, the NanoCenter brings together facilities and people from across campus under a single umbrella to support and promote research activities on the campus and in the region. Its mission includes both internal and external goals: (1) coordinate and exploit shared experimental facilities; (2) provide administrative infrastructure support; (3) promote coherent, broad visibility; (4) encourage and facilitate nano program growth and fund-raising; and (5) encourage coordinated educational programs.

The NanoCenter collaborates with other campus research entities in this effort, including the Institute for Research in Electronics and Applied Physics, the Institute for Systems Research, the Institute for Physical Sciences and Technology, the Joint Quantum Institute, the Center for Nanophysics and Advanced Materials, the University of Maryland Energy Research Center, the DOE EFRC Nanostructures for Electrical Energy Storage, the UMD-NCI Partnership for Cancer Technology, the Fischell Institute for Biomedical Devices, and the Center of Excellence in Regulatory Science and Innovation.

Shared Research Facilities

The NanoCenter functions primarily through two major shared user facilities: the FabLab clean room and the AIMLab microscopy lab in the Jeong H. Kim Engineering Building. These laboratories are operated as user facilities open to external users from industry, government, and other universities, as well as UMD research groups. The NanoCenter also maintains a substantial IT infrastructure, which provides database-driven web access, full qualification, web-based scheduling and chargeback for equipment use, and flexible environments to support long-distance collaboration.

The AIMLab (Advanced Imaging and Microscopy Laboratory, https://www.nanocenter.umd.edu/aimlab/) offers high resolution structural and analytical microscopy, supported by four technical staff. Instruments include two 200kV JEOL TEM's (one field emission, one LaB6) with analytical (EDS), as well as EELS capability on the field emission TEM. This is complemented by two SEM's (one high resolution, one offering wavelength dispersive analysis). Recently AIMLab added two TESCAN dual-beam focused ion beam (FIB) systems with EBSD and time-of-flight SIMS capabilities, enabling a host of new advances exploiting milling, TEM sample preparation, and 3D analytical and structural analysis. The FabLab (https://www.nanocenter.umd.edu/fablab/) is a 10,000 sf class 1000 cleanroom facility supported by 5 technical staff, providing deposition, etch, lithography, SEM, metrology, and other microfabrication capability along with key nanosynthesis and patterning capabilities (e-beam lithography, ALD, nanowire growth). The FabLab supports work in conventional semiconductor materials, a wide variety of inorganic materials, polymers, and biomaterials.

In addition to these shared facilities, the NanoCenter works with a number of faculty research labs and departmental labs as partner labs, so that they can make selected equipment in their labs available to the NanoCenter user community. Access policies and user fees are agreed upon between the faculty and the NanoCenter, which makes available its online scheduler, bills user research accounts, and allocates revenues to maintenance of the associated equipment.

NanoCenter research spans a broad portfolio – designer nanomaterials, nanoelectronics and quantum computing, energy at the nanoscale, nanobio technology, microsystems and robotics. Since the user facilities provide the enablement for faculty group research, these facilities and their operation are considered the core strength of the NanoCenter, and indeed they have played a major – even decisive - role in faculty recruiting. Besides its campus impact, the NanoCenter serves roughly 30 companies from the Mid-Atlantic region and a number of surrounding universities.

Education and Training

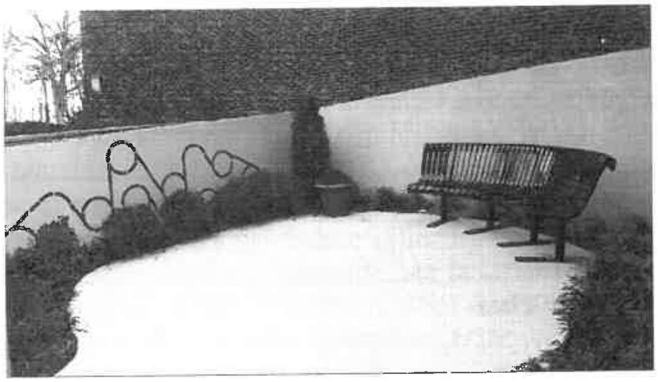
The NanoCenter supports multiple educational pathways. Experienced technical staff train and qualify users on overall safety and use of specific equipment. They also teach lab sections of several courses in different departments and provide short courses on specific instruments. In addition, the Department of Materials Science and Engineering coordinates an Interdisciplinary Minor in Nanoscale Science and Technology.

Research program development and support

Like IREAP, the NanoCenter serves a broad constituency that spans multiple departments and colleges. The NanoCenter also serves as a facilitator to develop multi-investigator research themes and to pursue major research and funding opportunities, such as NSF MRSEC and DOE EFRC programs. The NanoCenter administrative staff includes talent in IT systems (websites, databases), public relations, finance, and programmatic activities ranging from convening workshops and meetings to discussing new research ideas, to supporting the development and preparation of major center-level proposals, to implementing, tracking, and reporting for large funded programs. Together this support lowers the administrative barriers for NanoCenter faculty and allows them to focus on new research ideas.

Development

Like many units on campus, IREAP does not have a dedicated staff member responsible for alumni relations, fundraising and development. However, because of our combined relationship with two academic colleges (Engineering and CMNS), we can potentially benefit from the advice and resources from professional development staff in both colleges.



Martin Reiser Memorial, constructed and opened in 2015.

In recent years, we have had two gifts that have contributed to our mission and visibility. The Reiser Memorial, which was commissioned by Prof. Patrick O'Shea and funded in part by a gift from the Reiser family, was established to honor the legacy of Dr. Martin Reiser, one of the founders of our Institute. The Memorial, located directly in front of our building, includes a small plaque honoring

Dr. Reiser, a bench, a small garden space, and a copper inlay inspired by the accelerator research program founded by Dr. Reiser.

In 2014, IREAP received a generous gift to establish a new endowed lecture series, the Paint Branch Distinguished Lecture in Applied Physics. The goal of this new program is to bring international luminaries in applied physics to our campus to deliver a lecture. Our inaugural Paint Branch Lecturer in 2015 was Prof. Marlan Scully (Texas A&M, Princeton), and our second Paint Branch Lecturer in 2016 was Prof. Eli Yablonovitch (Berkeley.) In 2017, we hosted our first Nobel Laureate speaker, Dr. David Wineland (NIST).

Paint Branch Distinguished Lecturers in Applied Physics (left-to-right): Marlan Scully (2015), Eli Yablonovitch (2016), and David Wineland (2017).

Anecdotal evidence and occasional interviews with exiting students suggests that the students who conduct their doctoral research in IREAP feel a strong connection and loyalty to our Institute – often stronger than the affiliation that they have with their degree-granting department. Our Institute is their intellectual community, and our established tradition of graduate seminars and cross-disciplinary research activities often binds together groups of students from disparate departments and disciplines.

Apart from alumni, there is potential for philanthropic engagement with local companies and corporated sponsors, many of whom benefit from the training, research, and reputation of our Institute. For example, even modest corporate or industrial sponsorship for some of our popular and well-attended seminars would allow us to fund a greater number of visiting speakers and could provide visibility to the sponsoring organization through a named seminar series. Common and recognized facilities such as conference rooms could also be named in honor of influential IREAP leaders or founders, with a modest one-time donation from alumni to help fund significant upgrades to these facilities.

However, the greatest impact on our Institute and University would be the establishment of a chaired professorship in Applied Physics, specifically connected to a partial faculty line in IREAP. Chaired professorships are unfortunately rare on our campus, but IREAP has no scarcity of distinguished faculty who are deserving of this recognition. Having a Chaired appointment would be a significant recruiting and retention tool for our top faculty and would elevate the visibility of our program internationally.

At present, IREAP is working on forming a long-term strategy to broaden our development and engage our alumni and potential corporate sponsors.