A Hybrid Model for Multiscale Laser Plasma Simulations with Detailed Collisional Physics

David Bilyeu

Rocket Propulsion Division, Aerospace Systems Directorate, Air Force Research Laboratory (AFRL/RQR), Edwards Air Force Base, CA 93524

Program: A Hybrid Model for Multiscale Laser Plasma Simulations with Detailed Collisional Physics (14RQ05COR)

This presentation reports on recent developments in the field of Laser Plasma Interaction (LPI) simulations. Prior work from AFRL/RQRS showed the validity of our level grouping technique for collisional-radiative (CR) model, a one-to-one comparison of Vlasov, PIC, and Multi-Fluid solvers of a collisionless shock simulation, and ion acceleration due to pondermotive forces solved by the MHD equations. We demonstrated that the Boltzmann grouping technique was superior to the uniform grouping technique for atomic Hydrogen, and that this method conserved energy to machine precision. The comparison between the three solvers showed good agreement between PIC and Vlasov. The ion acceleration simulation demonstrated that the Multi-fluid equations were adequate to capture electron hydrodynamics. One of the key challenges associated with LPI simulations is the wide range of length and time scales that need to be resolved. A brute force attempt to solve the associated numerical simulation is not currently feasible so new algorithms must be developed and tested. This presentation will focus on recent developments in expanding the level grouping technique to new species, a new integration technique for the BGK integrator, a spectral solver for the Vlasov equations, and a phase-accurate multiscale particle push.

DISTRIBUTION A. Approved for public release: distribution unlimited. PA# 15584
Simulation for Electron Impact Excitation/Deexcitation and Ionization/Recombination

Russel Caflisch†, Bokai Yan‡, Jean-Luc Cambier‡

† Department of Mathematics
University of California, Los Angeles (UCLA), Los Angeles, CA 90095
‡ Computational Mathematics, Information and Networks Division, Air Force Office of Scientific Research, Arlington, VA 22203

Program: Kinetic Simulation of Non-Equilibrium Plasmas (FA9550-14-1-0283)

We developed a kinetic model and a corresponding Monte Carlo simulation method for excitation/deexcitation and ionization/recombination by electron impact in a plasma free of external fields. The atoms and ions in the plasma are represented by continuum densities at a range of excitation levels and the electrons by an energy distribution function. A Boltzmann-type equation is formulated and a corresponding H-theorem is formally derived. A Monte Carlo method is developed for an idealized analytic model of the excitation and ionization collision cross sections. This system suffers from two difficulties: a large number of interaction types with very large variation in the interaction rates; and a singularity in the recombination rate at small energy for (either of) the incoming electrons. To accelerate the simulation, a binary search method is used to overcome the singular rate in the recombination process. Numerical results are presented to demonstrate the efficiency of the method on spatially homogeneous problems. The evolution of the electron distribution function and atomic states is studied, revealing the possibility under certain circumstances of system relaxation towards stationary states that are not equilibrium states (i.e., not Gibbs distributions), due to non-ergodic behavior. If ionization/recombination is also included, then the system goes to equilibrium.

Hybrid VFP Modeling of Electron Transport and Radiation Generation

Alexander Thomas

Nuclear Engineering and Radiological Sciences Department
University of Michigan, Ann Arbor, MI 48109-2104

Program: Hybrid VFP Modeling of Electron Transport and Radiation Generation (FA9550-14-1-0156)

The physics of dense, ultrashort-laser heated plasma is of interest for a number of related applications including ion acceleration, neutron production and inertia fusion energy. In addition, more recently the use of X-ray FELs such as the LCLS are able to volume heat dense material. To model these, we are developing a hybrid Vlasov-Fokker-Planck / fluid code which models the transport of energetic electrons in dense plasma. Here we report on recent developments in the code, including the inclusion of ionization and equation of state
modeling for the background fluid, and a new positivity preserving spectral solver for the Vlasov momentum space distribution that offers a number of benefits over other momentum space advection schemes. We study the effect of the new physics models in X-ray heating experiments relevant to those on the Matter under Extreme Conditions end station of the LCLS laser.

**Studies of Plasma Sheath Physics Using Continuum Kinetic Simulations of Plasmas**

Bhuvana Srinivasan  
*Aerospace and Ocean Engineering*  
*Virginia Polytechnic Institute and State University, Blacksburg, VA 24060*


Continuum kinetic models of plasmas will be developed to study plasma sheath physics. For any scenario where a plasma interacts with a surface, such as plasma-wall interactions, a plasma sheath forms at the interface. For high temperature plasmas, energetic electrons have been known to cause secondary electron emissions from the wall. This can have consequences for devices such as Hall thrusters as electron emissions can increase the rate of erosion of the electrodes affecting the performance of the device. A study and understanding of secondary electron emissions and sheath stability can also have a significant impact on other applications where plasmas contact material surfaces such as plasma-material interaction on satellites and instruments in space, plasma actuators, and other low-temperature plasma applications, to name a few. The development effort will involve high-order numerical methods such as the discontinuous Galerkin method to directly solve the Vlasov-Poisson and Vlasov-Maxwell equations using an energy-conserving algorithm with the code, Gkeyll.

**Variational Algorithms for High-Fidelity Plasma Simulations**

Stephen Webb,  
*RadiaSoft, LLC, Boulder, CO 80304*

Program: Variational Algorithms for High-Fidelity Plasma Simulations (Young Investigator Award, FA9550-15-C-0031)

Simulating plasma physics phenomena has traditionally been limited to a few plasma oscillations because of numerical heating in the plasma. This artificial heating eventually washes out physical effects, making the results unreliable. To mitigate this effect and study beam and plasma systems over many hundreds or thousands of oscillations, new algorithms which prevent this artificial heating are required. We will discuss the concept
behind so-called multisymplectic or variational algorithms, and present results showing their exceptional long-time stability. We will also discuss some details of their implementation, and future work required for plasma wakefield accelerator applications.

**Design of graphene-based interfaces for applications in energy, electronics and photonics**

Ricky (Lay Kee) Ang

*Engineering Product Development*
*Nanyang Technological University (NTU), Singapore 637457*

Program: Modeling of Ultrafast Laser Induced Emission from TI and Graphene (FA2386-14-1-4020)

In this presentation, we will present our recent findings in revising some traditional scaling laws in using monolayer graphene. The first topic is to present a new scaling of electron thermionic emission from graphene and its application as thermionic energy convertor (TIC). It is found that that the traditional thermionic emission law (Richard-Dushman law) is no longer valid for graphene, and a new thermionic emission law for graphene was proposed, which agree with a recent independent experimental finding. This new thermionic emission model also suggests that traditional diode equation of a metal-semiconductor contact may not be valid for a graphene-semiconductor contact. Using the graphene as cathode material, we will show that an efficiency of about 45% at 900K is possible. If the vacuum region between the electrodes is replaced with 2-dimensional materials based van der Waals hetero-structures, the performance can be improved to operate at 400K with an efficient from about 10% to 20%, which is unmatched in comparison to the best TE materials at $ZT = 1$ to 4. The second topic is to show that the plasmonic mode for graphene is different from metals, for which the excitation of the graphene plasmonic model can be realized at a much lower excitation energy at longer wavelength. This finding can be useful for create compact coherent radiation source at longer wavelength.

**KEEN and KEEPN Wave Simulations Using the Vlasov-Poisson Model Equations**

Bedros Afeyan

*Polymath Research Inc. Pleasanton, CA 94566*

Program: KEEN Waves and their Interactions with Generalizations to Multispecies Plasmas, Relativistic Dynamics, Collisionality and Multidimensionality (FA9550-15-1-0271)

We show for well-driven KEEN (Kinetic Electrostatic Electron Nonlinear) waves and their analogs in pair plasmas KEEPN (Positron) waves, how the dynamics is captured in a variety
of complimentary numerical approaches. Symplectic integration and quadrature node based techniques are deployed to achieve satisfactory results in the long time evolution of highly nonlinear, kinetic, non-stationary, self-organized structures in phase space. Fixed and composite velocity grid arbitrary-order interpolation approaches have advantages we highlight. Adaptivity to local phase space density morphological structures will be discussed starting within the framework of the Shape Function Kinetics (SFK) approach. Fine resolution in velocity only in the range affected by KEEN waves makes for more efficient simulations, especially in higher dimensions. We explore the parameter space of unequal electron and positron temperatures as well as the effects of a relative drift velocity in their initial conditions. Ponderomotively driven KEEPN waves have many novelties when compared to KEEN waves, such as double, staggered, vortex structures, which we highlight.

---

High Power Electromagnetic Sources

High Power Recirculating Planar Amplifiers

Ronald M. Gilgenbach†, Y.Y. Lau†, Nicholas Jordan†, David Chernin†, Steven Exelby†, Geoff Greening†, Brad Hoff‡, David Simon†, Patrick Wong†, Peng Zhang†

† Nuclear Engineering and Radiological Sciences Department
University of Michigan, Ann Arbor, MI 48109-2104
‡ High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117

Program: High Power Recirculating Planar Amplifiers (FA9550-15-1-0097)

Experiments and theory at UM are directed towards the goal of extending the successful, Recirculating Planar Magnetron RPM oscillator (up to 150 MW) to the amplifier regime at 10’s to 100 MW [1]. Experiments are driven by the MELBA generator at parameters -300 kV, 1-10 kA with pulselengths up to 0.5 microsecond. The RF driver for amplifier experiments will be a conventional 3-GHz, 2.6 MW magnetron operated at 48 kV and 110 A with a pulselength of 5 microseconds. Initial amplifier designs and simulations will be presented.

UM collaborations with Air Force Research Lab are being conducted on a coaxial all-cavity extractor CACE-RPM. Another AFRL collaboration is UM testing of a recirculating planar magnetron produced by additive manufacturing (3-D printing).

Theory research concerns Brillouin flow, which is the prevalent flow in crossed-field devices. We systematically study its stability in the conventional, planar, and inverted magnetron geometry. We find that the Brillouin flow in the inverted magnetron is more unstable than that in a planar magnetron, which in turn is more unstable than that in the
conventional magnetron [2]. Thus, oscillations in the inverted magnetron and planar magnetron may startup faster than the conventional magnetron. This is consistent with simulation studies, and with the negative mass property in the inverted magnetron configuration. Also examined is the absolute instability at the band edges for a beam that exhibits positive or negative mass behavior [3].


**Physics of GW-class High Power Microwave Amplifiers**

Peter J. Mardahl, Brad W. Hoff

*High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117*

Program: Physics of GW-class High Power Microwave Amplifiers (13RD04COR)

(Public Release for Abstract Pending)

**Overmoded Circuits for High Power Traveling Wave Tubes and Klystrons**

Jason Hummelt, Michael Shapiro, Richard Temkin

*Plasma Science and Fusion Center
Massachusetts Institute of Technology (MIT), Cambridge, MA 02139*

Program: Volume Mode Traveling Wave Tube Amplifier (FA9550-15-1-0058)

There is great interest in extending the operating frequency of traveling wave tubes (TWTs) and klystrons into the 100 to 1000 GHz frequency range at power levels in the tens of watts to kilowatts. We are exploring the use of overmoded interaction structures to provide the desired performance in devices that can be built using present-day technology. In a first set of experiments, we have demonstrated an overmoded TWT at W-Band. Operating at a voltage of 30.6 kV with 250 mA of collector current, the TWT was zero-drive stable and achieved $21 \pm 2$ dB linear device gain with 27 W peak output power. For the next phase of this research, we are considering the use of a Photonic Bandgap (PBG) structure to create a slow wave structure with an oversized beam tunnel. The increase in beam tunnel diameter will allow either a dramatic increase in device power or an increase in device frequency at constant beam power. The PBG structure has the advantage of confining only the selected mode while allowing unwanted modes to diffract out of the structure.
High Power Microwave/Terahertz Generation from Superconductor Antennas for Military Applications

Timothy J. Haugan†, Wilkin W. Tang‡

† Power and Control Division, Aerospace Systems Directorate, Air Force Research Laboratory (AFRL/RQQ), Wright Patterson Air Force Base, OH 45433
‡ High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117

Program: High Power Microwave/Terahertz Generation from Superconductor Antennas for Military Applications (15RQCOR215)

(Public Release for Abstract Pending)

Field Emission Cathode Research

Don Shiffler1, Wilkin Tang1, Jennifer Elle2, Kevin Jensen3, John Harris4

1 High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117
2 High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), National Research Council Fellow, Kirtland AFB, NM 87117
3 Naval Research Laboratory, Washington, DC 20375
4 Naval Research Laboratory, Naval Reserve Office, Washington, DC 20375

Program: Cathode Materials Research for High Power Microwave Sources (14RD04COR)

(Public Release for Abstract Pending)

Carbon Nanotube Fiber Field Emission Cathodes

Steven Fairchild1, Nathaniel Lockwood2, Matteo Pasquali3

1 Functional Materials Division, Materials & Manufacturing Directorate, Air Force Research Laboratory (AFRL/RXA), Wright Patterson AFB, OH 45433
2 High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), National Research Council Fellow, Kirtland AFB, NM 87117
3 Department of Chemical and Biomolecular Engineering and Department of Chemistry, Rice University, Houston, TX 77005

Program: Investigation of Novel Nanomaterials (12RX17COR)

Field emission (FE) cathodes made from carbon nanotube (CNT) fibers have demonstrated high emission currents, low turn-on voltages, long lifetimes and offer considerable potential for use as electron sources for vacuum electronic devices. CNT fibers
were fabricated by wet-spinning of pre-made CNTs\(^1\) and consist of CNT fibrils held together by van der Waals forces. The fibers were 10-100 \(\mu\)m in diameter and their morphology was controlled by fabrication method, processing conditions, as well as purity, size, and type of the CNT starting material. Thermal and electrical conductivity was measured with the 3-omega method, and fiber density was determined with transmission electron microscopy. Wide angle x-ray diffraction was used to measure fiber alignment. Fibers with the highest density, alignment, thermal and electrical conductivity had the best field emission performance. Recent results have demonstrated a single 5 mm long fiber with a 20 \(\mu\)m diameter emitting 5.2 mA before failure, and 6.1 mA when treated with Boron Nitride\(^2\).

Residual gas analysis (RGA) was used to identify the species desorbed during field emission and model was developed for the transition from adsorbate-enhanced FE at low bias to FE from pure CNTs at high bias\(^3\). Infrared images of CNT fibers during FE have been captured with an InGaAs array camera, showing temperatures of \(\sim600^\circ\)C while emitting currents of \(\sim4\)mA. Mechanisms of fiber heating during FE, to include Joule and Nottingham effects, were investigated. Calculated thermal performance based on measured thermal conductivity is presented, and comparisons between observed and calculated thermal performance are discussed.


* Work supported by a Government Agency

Case Number: 88ABW-2014-1386; Material was assigned a clearance of CLEARED on 03 Apr 2014

**Phase-Controlled Magnetron Development**

Jim Browning

**Department of Electrical and Computer Engineering**

**Boise State University, Boise, ID 83725**

Program: Phase-Controlled Magnetron Development (Award Pending)

Simulations (2D) of a Rising Sun magnetron using the code VSIM have shown that it is possible to actively control the RF phase of a magnetron by modulating the electron source at the oscillating frequency (f) or an odd sub-harmonic (f/3). The concept uses a spatially addressable cathode that allows electron injection at locations and timing to control the startup and location of the electron spokes and, hence, the RF phase. Simulation has also
shown that only 10% of the total injected current must be modulated to dynamically control the phase. In our new research we plan to build a magnetron using a faceted cathode that contains Gated Field Emission Arrays (GFEAs) to provide the addressable, modulated electron source. The facet plates use electron hop funnels that allow the GFEAs to be placed on the back side of the plate out of the magnetron interaction space. Electrons are injected into the interaction space through slits in the plates, so the GFEAs are protected. The magnetron experiment will use the circuit of a commercially available 915 MHz magnetron which will be placed inside a vacuum test chamber. We also plan to simulate this new magnetron experiment in 3D. Simulation results demonstrating the phase control concept along with design plans for the magnetron experiment will be presented.

---

**Fundamental Processes and Interactions in Plasmas**

**Understanding Intense Laser Interactions with Solid Density Plasma**

* Alexander Thomas  

*Nuclear Engineering and Radiological Sciences Department*  
*University of Michigan, Ann Arbor, MI 48109-2104*

Program: Understanding Intense Laser Interactions with Solid Density Plasma (FA9550-12-1-0310)

* reassigned from Energy Transport in Solids session due to logistical considerations.

Here we show that in ultrafast laser interactions with a free flowing heavy water target, significant fusion neutron production can occur. Neutrons have numerous applications in diverse areas, such as medicine, security, and material science. For example, sources of MeV neutrons may be used for active interrogation for nuclear security applications. Ultrashort laser pulse interactions with dense plasma have attracted significant attention as compact, pulsed sources of neutrons. To generate neutrons using a laser through fusion reactions, thin solid density targets have been used in a pitcher-catcher arrangement, using deuterated plastic for example. However, the use of solid targets is limited for high-repetition rate operation due to the need to refresh the target for every laser shot. Using a free flowing 10 micron scale diameter deuterated water target and the high repetition rate (500 Hz) Lambda-cubed laser system at the Univ. of Michigan (12mJ, 800nm, 35fs), D-D fusion reactions occur generating 2.45 MeV neutrons. Under best conditions, a time average of \(\sim10^5\) neutrons / s are generated. We also find the scaling of the neutron generation with laser power.
Characterizing Hypervelocity Impact Plasmas and Effects on Spacecraft with Particle-In-Cell (PIC)

Sigrid Close†, Alex Fletcher‡,

† Department of Aeronautics and Astronautics
Stanford University, Stanford, CA 94305
‡ Massachusetts Institute of Technology (MIT, Cambridge, MA 02139) & Center for Space Physics, Boston University (Boston, MA 02215)

Program: Characterizing Hypervelocity Impact Plasmas and Effects on Spacecraft with Particle-in-Cell (FA9550-14-1-0290)

When a hypervelocity particle, such as a meteoroid or piece of orbital debris, impacts a spacecraft, a fraction of its incoming energy is converted into ionization. This results in a warm, dense plasma that expands into the vacuum. In order to understand the plasma generated by a hypervelocity particle, we have developed smoothed particle hydrodynamics (SPD) and discontinuous Galerkin (DG) particle-in-cell (PIC) techniques to model the shock and resulting plasma. The impact-produced plasma is in a regime called warm dense matter (or equivalently, non-ideal plasma or strongly coupled plasma). It is difficult to treat theoretically, since the non-ideality alters the equation of state, reduces the energy transfer rate between ions and electrons, and most critically, increases the charge state by depressing ionization potentials. Both SPD and DG can treat this unique regime and can be combined to give the first parameters of hypervelocity impact plasma.

Recently we have computed both plasma density and temperature as a function of time and distance from the impact point and shown that the temperature is on the order of a few eV, which is an order of magnitude smaller than predicted. This result agrees with recent data from our experimental campaign. The results also show a minimum velocity threshold of 18 km/s for fully ionized plasma production, which matches the velocity threshold for radio frequency (RF) measurements from impact experiments detected using patch antennas. Furthermore, the fully ionized plasma produces electrostatic oscillations that can couple to an electromagnetic wave that propagates away from the plasma. These results are highly dependent upon the mass and velocity of the impactor, as well as the angle of incidence and target type. High velocity particles impacting on tungsten produce plasmas with the highest density and potential for RF emission.
Energy Flow in Dense Off-Equilibrium Plasma

Seth Putterman

Department of Physics and Astronomy
University of California, Los Angeles (UCLA), Los Angeles, CA 90095
http://acoustics-research.physics.ucla.edu/

Program: Energy Flow in Dense Off-Equilibrium Plasmas (FA9550-12-1-0062)

Nature likes to form dense plasmas! When energy is injected into a dense gas, a plasma with an unexpectedly high free charge density is created. The charge density is thousands of times greater than would follow from application of Saha's equation of ionization. This phenomenon has been observed in laser breakdown, spark discharges and inside of a collapsing bubble. The charge densities of these plasmas is so large that they are opaque. For instance a spark discharge in a dense gas can block light from a powerful laser over a range of wavelengths greater than 500nm. On the nanosecond time scale we have observed a limiting of the energy density which is similar to luminosity saturation in nuclear explosions. For the spark and collapsing bubble ns energy transport is dominated by screened binary collisions. On the picosecond time scale we observe for hydrogen a stationary contact discontinuity which is interpreted in terms of a 25000K electron gas serving as the charge compensating background for cold charged ions with a plasma parameter of 70. According to Teller such a warm dense plasma has formed a condensed phase. The presence of the condensate, enhances and stabilizes the off-equilibrium state so that energy transfer is no longer characterized by screened binary collisions, but instead is dominated by electron-phonon [i.e. particle wave] interactions. We propose that this new regime for plasma physics will enjoy applications and that an elucidation of the new transport processes will be key to realizing new devices.

Spectroscopic Analysis of Energy Distribution in Low Temperature Plasmas for AF Applications

Steven F. Adams

Power and Control Division, Aerospace Systems Directorate, Air Force Research Laboratory (AFRL/RQQ), Wright Patterson Air Force Base, OH 45433

Program: Electron Energy Distribution and Transfer Phenomena in Non-Equilibrium Gases (13RQ13COR)

This presentation reviews the FY15 results of the AFOSR in-house laboratory task, LRIR#13RQ13COR. The task consists of research to apply advanced spectroscopic techniques to measure, monitor and ultimately control the distribution of electronic and kinetic energies within low temperature plasmas and enhance the understanding of
phenomena associated with non-equilibrium energy distributions. This effort supports developments in areas of interest to the Air Force such as plasma switching, ignition enhancement, laser medium excitation and plasma surface treatments. Since standard kinetic modeling is typically not applicable to an ionized gas, accurate computations must represent the energy dependent behavior of all charged and neutral species in the non-equilibrium environment. The primary objective of this task has been to analyze the kinetics and resulting chemistry of radicals, ions and electrons within laboratory scale plasma systems. Achievements during FY15 include measurement of temperatures and energy distributions within micro-discharges, the study of the secondary ionization coefficient in dc breakdown via Paschen curve analysis, the investigation of ion chemistry leading to ignition of advanced fuel molecules and the investigation of multi-photon absorption and ionization techniques for both diagnostics and pre-ionization seeding for gas breakdown. Experimental approaches were to apply advanced spectroscopic techniques, including methods in subtractive triple-grating spectroscopy, laser scattering techniques, optical emission spectroscopy and multi-photon laser techniques to laboratory gas systems. Advanced spectroscopic analyses have determined fundamental rate constants, process kinetics and energy distributions of non-equilibrium gases. During FY15, four journal papers have been published from this task along with four more journal manuscripts submitted.

DISTRIBUTION A. Approved for public release: distribution unlimited. Case # 88ABW-2015-4704

**Non-equilibrium kinetics in high pressure gas mixture plasmas**

James Scofield

*Power and Control Division, Aerospace Systems Directorate, Air Force Research Laboratory (AFRL/RQQ), Wright Patterson Air Force Base, OH 45433*

Program: Non-equilibrium kinetics in high pressure gas mixture plasmas (13RQ09COR)

(Public Release for Abstract Pending)

**Fundamental Studies of Atmospheric Pressure, Nanosecond Pulsed Microplasma Jets**

Chunqi Jiang\(^1,2\), Jamie L. Lane\(^1\), Shutong Song\(^1,2\), Johanna Neuber\(^1,2\), Martin A. Gundersen\(^3\), Andras Kuthi\(^3\)

\(^1\) Frank Reidy Research Center for Bioelectrics  
*Old Dominion University, Norfolk, VA 23508 USA*

\(^2\) Department of Electrical and Computer Engineering  
*Old Dominion University, Norfolk, VA 23529 USA*

\(^3\) Department of Electrical Engineering – Electrophysics  
*University of Southern California, Los Angeles, CA 90089, USA*
Nanosecond pulsed microplasma jets are highly non-equilibrium plasmas propagating in ambient air and with at least one dimensions less than 1 mm. They promise a broad range of applications including surface decontamination, air purification, infectious disease control and plasma ignition for combustion. Dynamics of the microplasma jets powered by nanosecond voltage pulses was studied with high-speed imaging as well as spatially and temporally resolved optical emission spectroscopy. Shorter pulses with shorter rise times allowed higher energy deposition into the plasma and promote rapid acceleration of the ionization wavefronts; 4 times higher of the wavefront velocity was observed for a 5 ns pulsed plasma streamer compared with that by the 164 ns pulsed excitation. Microplasma jets powered by shorter (e.g. 5 ns) voltage pulses enhanced the production of excited atomic oxygen at the same rotational and vibrational temperatures (300 K and 3000 K, respectively) compared with the microplasma driven by >140 ns pulses at the same voltage. In addition, two-photon absorption laser induced fluorescence spectroscopy resolved a 1-mm He/(1%)O2 plasma jet producing atomic oxygen density on the order of 1013 cm-3. Absolute measurements of OH density for the plasma jet are in progress using the cavity ring-down technique.

* Work also supported by the Air Force Office of Scientific Research (AFOSR Award No. FA9550-11-1-0190, FA2386-14-1-3006 (DURIP)).

**Ponderomotively Driven Quasi-Free-Space Electron Series Resonance Plasmas**

Brad W. Hoff, Remington R. Reid

*High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117*

Program: Ponderomotively Driven Quasi-Free-Space Electron Series Resonance Plasmas (13RD02COR)

(Public Release for Abstract Pending).

**Threat Detection Using a Modular Cosmic Ray Muon Tomography System**

James L. Popp, Kevin R. Lynch

*Earth and Physical Sciences Department
York College, The City University of New York, Jamaica, NY 11451*

Program: Threat Detection Using a Modular Cosmic Ray Muon Tomography System (FA9550-15-1-0048)
We will leverage recent developments in computing and electronics to develop a simple, effective, robust, modular threat assessment system to detect contraband using naturally occurring cosmic ray muons. We will build this system using the core technologies of single board computers, scintillating plastic sheet, and gaseous electron multipliers. We will use this “LEGO”–like system to demonstrate simple tomography of brick-size mock threats within 55 gallon-drum scale targets. By using commercial, off-the-shelf techniques and components, we simplify construction and reduce costs compared to designing significant custom equipment. We aim to build a system where deployment should be possible by trained, but not expert, personnel. We will demonstrate the robustness of the system by collecting data in a variety of outdoor conditions for an extended period.

During the course of this research, we will: 1) Build a suite of detectors. 2) Construct modular, weather tight modules for these detectors. 3) Demonstrate simple tomography of small dense threats in 55 gallon drum-scale containers. 4) Use the design and construction process to drive student development and education. 5) Perform detailed studies of the real-world backgrounds important for this screening method and their dependence on factors including terrestrial and solar sources.

Plasma and Laser Kinetics within a Discharge Assisted Noble Gas Laser

Greg Pitz†, Nathaniel Lockwood‡

† Laser Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDL), Kirtland AFB, NM 87117
‡ High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117

Program: Plasma and Laser Kinetics within a Discharge Assisted Noble Gas Laser (14RD03COR)

The Advanced Noble Gas Laser (ANGL) uses a mild RF discharge to excite argon (Ar) atoms from the ground state (s0) to the metastable s5 state, allowing Ar to be optically pumped (s5 – p9) as a quasi-three level laser similar to the Diode Pumped Alkali Laser (DPAL). Helium (He) collisional mixing from the p9 to the p10 state allows lasing from p10 to s5 at 912 nm. Previously, 2 mW of average output power has been achieved at the Air Force Research Laboratory (AFRL) using a 811 nm pulsed Titanium:Sapphire (Ti:Sapph) laser to pump a plasma discharge tube with a 1-10% Ar:He mixture. Recently, number density and gain diagnostics have been conducted in a parallel-plate discharge configuration. This architecture will also be used in demonstrating the world’s first continuous wave (cw) diode-pumped ANGL.
Dr. Pitz is a research physicist at Air Force Research Lab in Albuquerque, New Mexico where he leads a team developing the world’s first open-cycle flowing diode pumped alkali laser. Dr. Pitz has made numerous contributions to atomic spectroscopy of alkali atoms, the development of hybrid lasers, and modeling of innovative new designs. He has produced numerous publications on DPALs and their applications, including broadening and high pressure line shape of the D1 and D2 lines. In 2013, he was awarded the Presidential Early Career Award for Scientists and Engineers by President Obama for his contributions to DPAL research along with his leadership in the field and active participation in STEM outreach programs. He has most recently served in Washington, D.C., developing policy to better integrate Air Force operators into the development planning process.

DISTRIBUTION A. Approved for public release: distribution unlimited. Case # 377ABW-2015-0642

---

**Energy Transport in Solids**

**Electron Dynamics During High-Power, Short-Pulsed Laser Interactions with Solids and Interfaces**

*Patrick E. Hopkins*

*Mechanical and Aerospace Engineering Department*

*University of Virginia, Charlottesville, VA 22904-4746*

Program: Electron Dynamics During High-Power, Short-Pulsed Laser Interactions (FA9550-13-1-0067)

This objective of this Young Investigator Program is to explore the effects of spatially-confined ultrafast optical excitations of materials to a state of strong electron-phonon nonequilibrium on the evolution of deposited energy, electronic scattering processes and structural transformations driving material processing and manipulation with high-power pulsed lasers and/or applied electric fields. Through various measurements of thermal properties of thin film metals and non-metals using pump-probe thermoreflectance spectroscopy with sub-picosecond temporal resolution, we demonstrate the role of excited electrons and/or externally applied fields on heat transfer mechanisms and resulting nanoscale structural properties of the materials. Notably, we demonstrate the strong role of nanoscale interfaces on hot electron relaxation through measurements of the electron-phonon coupling factor in thin gold with and without adhesion layers on various substrates. We observe that the coupling between the electronic and the vibrational states is increased by more than five-fold with the inclusion of a ~3 nm Ti adhesion layer that strengthens the interfacial bonding. Furthermore, we show that the electron-phonon coupling in composite metal films on thermally insulating substrates do not play a role in steady state laser damage, and that this damage mechanisms is driven by heating the metal
film to above the melting threshold from the accumulation of laser pulse energy. In addition, we demonstrate the ability to control the thermal conductivity in thin films with applied electric field by manipulating internal interfaces. We experimentally show active and reversible tuning of thermal conductivity by manipulating the nanoscale ferroelastic domain structure of a lead-zirconate titanate film with applied electric fields.

**Dynamics of High-Intensity Laser-Driven Proton Beam Transport in Solid Density Materials**

Christopher Mcguffey

*Mechanical and Aerospace Engineering Department*  
*University of California, San Diego, CA 92093-0411*

Program: Dynamics of High-Intensity Laser-Driven Proton Beam Transport in Solid Density Materials (FA9550-14-1-0346)

When extraordinarily intense particle beams, made possible with short-pulse lasers, enter matter, complex dynamics apply including the matter's response to the intense beam (heating, ionization, strong return currents, current-driven fields) and in turn the beam's response to the matter (temperature- and ionization state-dependent stopping, field effects). To investigate the fundamental dynamics at hand, we have used a hybrid particle-in-cell code and experimental data from world-class short-pulse lasers. In the first year of the project we have explored options to improve the stopping power model used in the simulations, conducted series of simulations to quantify proton range as a function of beam flux in different materials, and modeled beam transport through solids for comparison to experimental data. Our simulations have demonstrated that intense proton beams can exhibit departure from cold stopping power behavior (J. Kim, PRL, 2015). For extremely intense and focused beams, the deposition profile can be completely different in both the longitudinal and transverse target dimensions due to target heating effects and self-generated fields, respectively. Among the interesting results beyond the PRL, we find that for extremely high current density beams, the heating due to Ohmic drag of the return currents can become comparable to the energy rate deposited by the beam itself, and a multi-picosecond intense beam will deposit much deeper into a target than a shorter beam of the same energy or intensity.

**Nonlinear Dielectrics for Compact Pulsed Power & HPM Protection**

Susan Heidger, Brad Hoff, Renee Van GinHoven, Andrew Greenwood, David French

*High Power Electromagnetics Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/RDH), Kirtland AFB, NM 87117*
RF Generation Based on Nonlinear Transmission Lines

Jose Rossi

Associated Plasma Laboratory
National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais, INPE)
São Paulo, Brazil

Program: Study of HV Dielectrics for High Frequency Operation in Transmission Lines (FA9550-14-1-0133)

Nonlinear transmission lines (NLTLs) provides an ingenious way of generating RF without using vacuum tubes. Their main envisaged applications are in RF sources in battlefield communication disruption, carrier waves in telemetry systems of space vehicles, transmitters of pulsed radars for remote sensing, etc. In the RF frequency range up to 400 MHz, a dispersive lumped NLTL based on nonlinear elements (ferrite inductors or ceramic capacitors) is used. Above 400 MHz, a configuration using a loaded coaxial line with external magnetic bias (known as gyromagnetic NLTL) has shown better performance. The goal of this presentation is to describe the research on lumped capacitive NLTLs and gyromagnetic lines developed so far at Plasma Laboratory from INPE. In this work, as lumped capacitive NLTLs employ nonlinear dielectric mediums, ceramic dielectrics based on lead zirconate titanate (PZT) and barium titanate (BT) were characterized. To assess the performance of these dielectrics, HV PZT and BT NLTLs were built and tested, achieving RF generation at 100 MHz in both cases. The NLTL principle of operation was also studied using a low voltage line built with varying capacitance diodes (varactors) in the frequency range of 200-400 MHz as these components show higher nonlinearity than commercial ceramic capacitors. For the gyromagnetic lines, the focus was on computer simulations using a circuit simulator called LT-Spice to ease the design of such lines for high frequency operation above 1 GHz rather than using complex numerical codes. Finally, the implications of these research results on design of NLTLs will be discussed.

Fundamentals of Thermal Conductance at Elevated Temperatures

Pamela Norris

Mechanical and Aerospace Engineering Department
University of Virginia, Charlottesville, VA 22904-4746
Solid-solid interfaces serve as the primary scattering point to energy carriers at the micro- and smaller-length scales, therefore understanding, predicting, and tuning the thermal conduction across these interfaces is of paramount importance to designing energy efficient devices. Thermal boundary conductance is particularly important at high temperatures, above room temperatures, which are typical operating temperatures of high power, high frequency devices. Current predictive models do not accurately capture the magnitude or trends of thermal boundary conductance at temperatures above room temperature, thus in the work presented here, we aim to elucidate the parameters which influence thermal boundary conductance at high temperatures using coupled experimental and computational investigations. Molecular dynamics (MD) results show that for an ideal interface anharmonicity results in enhancement of thermal boundary conductance. Occurrence of anharmonic phonon events within the bulk however, can play a more important role in thermal interfacial transport rather than those happening at the interface. Time domain thermoreflectance was then used to measure the temperature dependent thermal boundary conductance at a series of interfaces, chosen so that varying levels of anharmonicity would be expected. TDTR results indicate that the effects of anharmonicity on thermal boundary conductance, at these interfaces, can be overshadowed by the effects of interfacial features, such as roughness, diffusion, and disorder.

**Scattering and Relaxation Mechanisms During High Energy Photo-Excitation of Electronic Materials**

Patrick E. Hopkins

*Mechanical and Aerospace Engineering Department*
*University of Virginia, Charlottesville, VA 22904-4746*

In applications involving high energy and power densities, the scattering, relaxation and transport mechanisms will be strongly coupled to the degree of carrier nonequilibrium induced from the delivered fields. This has tremendous impact on materials and systems used in directed energy, nonequilibrium plasma, and pulsed power applications. In this program, we are studying the role of strongly perturbed electronic distributions on the heat transfer mechanisms in solid and at material interfaces. We use pump-probe spectroscopy with sub-picosecond pulses to measure the electronic relaxation mechanisms, resulting scattering rates, and subsequent diffusive thermal transport while
varying the pump pulse characteristics to strongly influence the excited number density in the metal or non-metal of interest. In this talk, I will discuss our studies on the role of non-equilibrium distributions on electron relaxation in both gold films and GaAs wafers. In Au films, we show that electron-electron scattering along with electron-phonon scattering have to be considered simultaneously to correctly predict the transient nature of electron relaxation during and after short-pulsed heating of metals at elevated electron temperatures. However, the role of electrons in a non-equilibrium do not significantly couple energy directly to the phonons, indicating that the primary mechanism of electron-phonon heat transfer is mainly from the thermalized electronic distribution. In GaAs, we demonstrate the ability to measure the excited carrier scattering rates decay separately from the accumulated charged density – that is, we show that the relaxation rates of excited electrons can be separated into two regimes based on the single-carrier/transient response and the accumulated-carrier/frequency response.

Innovative Study of Electrical Contact and Electron Transport

Y. Y. Lau, Peng Zhang

Nuclear Engineering and Radiological Sciences Department
University of Michigan, Ann Arbor, MI 48109-2104

Program: Innovative Study of Electrical Contact and Electron Transport (FA9550-14-1-0309)

We systematically evaluate the current crowding and spreading resistance in thin film contacts with very large contrasts in dimensions and resistivity [1], based on our exact field solution. The current transfer length is compared with the classical transmission line model. We develop a self-consistent model for the tunneling current in a quantum diode, including the effects of anode emission, space charge, and exchange-correlation potential. This yields the general current-voltage characteristics in a nanoscale junction which govern all four regimes [2]: direct tunneling, field emission, and both quantum and classical space-charge-limited regime. Also presented is our recent theory on laser induced electron emission from a metal surface under dc bias.

We study various mechanisms to enhance the coherent Smith-Purcell radiation, including optimized grating, prebunched beams, and open cavity [3]. We examine the absolute instability at the bandedges of traveling-wave amplifiers [4], and quantify the surprisingly high harmonic contents in the small signal regime [5].


**Additional Abstracts***

* (programs not presented at this review, but which are part of the Plasma and Electroenergetic Physics Portfolio; all categories; programmatic affiliations or sub-thrusts listed with program information )

**Measurements of Output from an Overmoded BWO Based on a Surface Periodic Lattice**

Alan Phelps

*Department of Physics*  
*University of Strathclyde, Glasgow, Scotland, UK*

Program: High Power Microwave Low-Contrast Surface Artificial Materials (FA8655-13-1-2132) - *Core funded program, associations: HPEM Sources & 2012 MURI on Transformational Electromagnetics*

Numerical finite-difference-time-domain and particle-in-cell simulations carried out during the first years of the project have demonstrated a successful electron-beam/wave interaction in an overmoded, mode selective cavity formed by a cylindrical two-dimensional periodic surface lattice. Optimization of this structure’s physical properties resulting in the design of a suitable cavity was reported in the Plasma and Electroenergetics program review in December 2014. During 2015 following the construction and cold testing of the cavity, electron beam and magnetic field systems have been designed and assembled. The electron beam properties have been measured and the electron beam has been used to excite the cavity. Initial measurements have been made of the microwave output from the overmoded BWO, created using the two dimensional surface periodic lattice cavity. These initial measurements are compared with the theoretical and numerical modelling predictions. The positive indications are that the principle of using two dimensional periodic surface lattices allows effective mode selection in overmoded cavities, providing a route to higher output powers at higher frequencies.

Future work will include more detailed measurements of the microwave output to prove the concept works as predicted. To achieve the greatest benefit from this concept and to achieve the greatest increase in microwave power at higher frequencies the diameter to wavelength ratio should be increased.
A new future project is proposed in which two dimensional, periodic surface lattices with larger diameter to wavelength ratios will be investigated using theoretical analysis, numerical modelling and laboratory experiment to explore whether this principle can be extended to higher diameter to wavelength ratios. This would significantly increase the high power capability of high frequency microwave sources.

Study of the Propagation of Electromagnetic Waves in a Complex Plasma
Osamu Ishihara

*Yokohama National University, Yokohama/Chubu University, Kasugai, Japan*

Program: Study of Complex Plasmas with Magnetic Dipoles (FA2386-14-1-4021) - Core funded program, associations: International (AOARD), Fundamental Processes and Interactions in Plasmas

Complex plasma is characterized by a system of a plasma in which conductive or dielectric dust particles are present (O. Ishihara, Complex Plasma: Dusts in Plasma, J. of Physics D: Appl. Phys. 40, R121 (2007)). The complex plasma is rich in novel features manifested itself through the interaction of collection of charged dust particles and the collective behavior of the background plasma. We have studied electromagnetic wave propagation in a complex plasma with gaseous plasma including metallic particles. When a metallic particle is placed in an oscillating electric field, the polarization induced in the sphere starts oscillation. On the other hand, the background plasma supports various kinds of oscillations, while on the surface of metallic particles electrons oscillate with frequency much higher than the background plasma frequency. The surface plasma oscillations are known as surface plasmons. The effective permittivity of the complex plasma is approximated by the Maxwell Garnett formulation. Our preliminary theoretical study reveals the presence of resonances near the surface plasmon frequency in the dielectric response function of the complex plasma, which necessarily affects the refraction nature of electromagnetic waves propagating in the background plasma. A simulation of electromagnetic wave propagation in a complex plasma with metallic particles is also under way. The study is carried out in collaboration with Sergey Vladimirov of University of Sydney of Australia and Tetsuo Kamimura of Meijo University of Japan.

Quantum Many-Body Localization in a Strongly Coupled Ultracold Plasma
Markus Schluz-Weiling¹, Hossein Sadeghi², Edward Grant¹,²

¹ Department of Physics & Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, CANADA
A many-body system of quantum particles quenched on a disordered potential can undergo a transition to a localized, non-ergodic phase with the properties of a quantum glass [1⁵]. Well-isolated ensembles of ultracold atoms have provided an important proving ground for such phenomena [6, 7]. Rydberg atoms in particular offer the advantage of highly tuneable, very long range interactions [8, 9]. Here we present experimental evidence suggesting a novel route to a state of many-body localization beginning from a quantum-selected initial state in a Rydberg gas of nitric oxide. Laser-crossed molecular-beam excitation forms an ellipsoidal excitation volume. Prompt Penning ionization releases electrons in the dense core of this Rydberg gas. The resulting electron-impact avalanche forms a plasma that spontaneously bifurcates and cools by disposing electron thermal energy to the momentum of separating, strongly coupled ultracold plasma volumes. This disposal of energy to mass transport quenches the plasma, relaxing the electrons on a disordered ion potential that remains stationary on the timescale of electron motion. These cooling dynamics give rise to an extremely robust ensemble of Rydberg and quasi-Rydberg molecules, which seems spatially and energetically immobilized in a band of states very near the ionization continuum. Under natural, delocalized conditions, classical simulations call for this highly excited ensemble of molecular ions and electrons to decay by well-defined, readily accessible channels of recombination, relaxation and fragmentation to form neutral dissociation products and a hot, expanding electron gas. Instead, we observe free-flying, localized ultracold plasma volumes with projected lifetimes of milliseconds, perhaps tens of milliseconds.

This work was supported by the US Air Force Office of Scientific Research (Grant No. FA9550-12-1-0239).


**Emission, Emittance and Entropy of High Intensity Electron Beams**

Joel L. Lebowitz

*Department of Mathematics*
*Rutgers, The State University of New Jersey, Piscataway, NJ 08854-8019*

Program: Emission, Emittance and Entropy of High Intensity Electron Beams (Pending Award) - *Core funded program, associations: HPEM Sources*

We are investigating how the emitted current from various types of cathodes is affected by an alternating electric field, e.g. $E(t) = E[1 + b \sin wt]$. When $w$ is small the process can be considered quasi-stationary. It is then easy to compute its effect on the tunneling current in the FN regime: for $b=1/2$ there is an enhancement by a factor of 5 for a rectangular barrier and by $5/2$ for a triangular one.

When the period of the oscillating field is close to the transit time of the electrons from the cathode to the anode there may be sharp jumps in the current reaching the anode.

For large $w$ the situation is more complicated. The effect now depends on the interaction of the laser field with the electrons in the emitter. There are various approximate theories in the literature on this and we are trying to sort out which, if any, are applicable to the type of experiments done by Don Shiffler's group.

We plan to study the connection between the entropy of a beam and its emittance from the point of view of kinetic theory and non-equilibrium statistical mechanics. Our current state of understanding of such a connection, if any, is very partial. A better microscopic theory will hopefully lead to better control of beam spreading.

The Fowler-Nordheim theory needs drastic modification when the fields are very strong. As shown by Rokhlenko some time ago emission actually decreases when the field becomes very strong. While it may not be possible to use such steady state strong fields, the effect may already show up even at realizable fields, especially in pulses.