2016 Plasma & Electro-Energetic Physics Annual Program review

Dr. Jason Marshall | November 29-30, 2016 | Arlington, VA

ABSTRACTS

Computational & Theoretical Plasma Physics

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

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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, ion acceleration due to pondermotive forces solved by the MHD equations, and a phase-accurate particle push algorithm. This presentation will focus on recent developments made in the CR modeling of Argon with level grouping, introduce inelastic collisions to non-Maxwellian distributions, and methods to blend solutions of different fidelities together to make a more efficient solver.

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KEEN Waves and their Interactions with Generalizations to Multispecies Plasmas, Relativistic Dynamics, Collisionality and Multidimensionality

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

We will discuss a number of codes and numerical strategies we are pursuing in order to uncover the dynamics of Kinetic Electrostatic Electron Nonlinear (KEEN) waves and their pair plasma cousins, KEEPN waves.

We have been working with PIC and Vlasov codes of different flavors and simulation philosophies. Some of these will be highlighted. Advantages and complimentary attributes of these approaches, be they Semi-Lagrangian, Split Step Methods [1], or mass conserving PIC, adaptive or with fixed grids, utilizing multirsolution analysis tools, explicit or fully implicit, symplectic or geometric integrators of high order, or mere finite difference second order, all come into play.

One outstanding problem is finding the vast reduction in dynamical degrees of freedom that arises from the condensation of a KEEN wave vortical structure in phase space into nested partitions that maintain a multimode coherent wave structure atop a flatter distribution function than a Maxwellian. How to find these partitions in an automated way will be discussed and a number of algorithms given. Spanning the entire gamut of waves with very distinct structures in the omega_Drive, k_Drive plane with different amplitude drives makes for very large number of runs. We are currently testing the codes to decide which algorithm to use for which cases to get at the physics of KEEN waves most efficiently and reliably. The chaotic particle orbits, trapping-untrapping and retrapping oscillations complicate the simple story contained in BGK prescriptions. And certainly lead us very far from linear resonance triggered waves which can be single mode and reach steady state masking the vastness of parameter space where much more complicated yet useful and more robust structures exist such as KEEN waves and KEEPN waves in electron with fixed massive ion, and pair plasmas, respectively. How KEEN waves arise in the context of relativistic Stimulated Raman scattering simulations will also be given, highlighting results from a recent publication [2].

[1] B. Afeyan, F. Casas, N. Crouseilles, A. Dodhy, E. Faou, M. Mehrenberger and E. Sonnendrucker, Simulation of kinetic electrostatic electron nonlinear (KEEN) waves with variable velocity resolution gross and high order time-splitting. European Journal of Physics D68, 295 (2014).
[2] M. Shoucri and B. Afeyan, Vlasov-Maxwell simulations of backward Raman amplification of seed pulses in plasmas, Laser and Particle Beams, 1-25 August 2016 (DOI: 10.1017/S0263034616000495.)

Simulation for Electron Impact Excitation/Deexcitation and Ionization/ Recombination

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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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

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

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

The high intensity of proton beams that can be generated with relativistically intense lasers necessitates careful treatment in simulations of their transport. As we have previously demonstrated with particle-in-cell simulations, beams with sufficient intensity can change the material they transport through into a warm or hot state (>1 or even >100 eV) within their transit time, leading to a change in stopping power and numerous observable consequences for the beam. We have turned our attention to experimental techniques to visualize beams' transport through relatively thick material, 1mm Cu foams. The intense proton beams were created by irradiating a curved C foil with the LFEX petawatt laser (1 kJ on target, 1.5 ps, 1053 nm, I >2×10^19 W/cm^2). Using magnetic spectrometers and a

Thomson parabola, the proton spectra were measured with and without the Cu samples. When included, they were observed using Cu K-shell x-ray imaging and spectroscopy. I will present the observed beam spectral downshift and experimental images and discuss plans to compare them to simulations with various stopping power models.

Studies of Plasma Sheath Physics using Continuum Kinetic Simulations of Plasmas

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Program: Studies of Plasma Sheath Physics Using Continuum Kinetic Simulations of Plasmas (FA9550-15-1-0193)

A novel continuum kinetic model is developed to study plasma sheath physics. For any scenario where 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. The knowledge of the distribution function is important for careful treatment of the surface physics, most notably the secondary emission. We use the discontinuous Galerkin method to directly solve the Boltzmann-Poisson system to obtain a particle distribution function. We have performed benchmarks in 1X/1V (one spatial dimension and one velocity dimension) and 1X/2V (one spatial dimension and two velocity dimensions) for the Vlasov solver. Fully kinetic sheath simulations, with collisions and ionization, are performed with and without magnetic fields and are compared to two-fluid sheaths.

Physics-Based-Adaptive Plasma Model for High-Fidelity Numerical Simulations

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Program: Physics-Based-Adaptive Plasma Model for High-Fidelity Numerical Simulations (FA9550-15-1-0271)

Plasmas are complex systems that interact on disparate temporal and spatial scales. The mathematical models that describe the interactions and resulting dynamics span the range from resolving only the most basic charged fluid physics, e.g. the MHD model, to capturing the detailed evolution of probability density functions for each constituent plasma species, e.g. the kinetic model. This research effort aims to couple continuum plasma models, such as MHD, Hall-MHD, 5N-moment and 13N-moment multi-fluid, and continuum kinetic plasma models. Local plasma properties in a given computational subdomain determine the appropriate physical model, which is selected as the simplest plasma description that is formally valid. Motivation for this physics-based-adaptive plasma model will be provided through a posteriori analysis of a two-fluid plasma simulation. Progress on developing the continuum plasma models will be described. Recent applications using a statically domain-decomposed physics-based plasma model will be presented.

Progress on a Hamiltonian Treatment of Plasmas

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

The standard treatments of plasma theory -- linearized Vlasov equation and multi-wave mixing for theoretical calculations, and particle-in-cell algorithms for numerical work -- typically ignore the underlying Hamiltonian structure of the Maxwell-Vlasov equations. This talk presents recent effort to build a picture of plasmas using Hamiltonian methods such as symplectic maps and Lie algebras. We will discuss first a Hamiltonian perturbation theory for plasma dynamics that can capture the long-time dynamics of self-interacting particles. We will then discuss symplectic approaches to plasma algorithms, including a Lagrangian electrostatic algorithm and a map-based approach to electromagnetic plasmas.

Emission, Emittance and Entropy of High Intensity Electron Beams

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Program: Emission, Emittance and Entropy of High Intensity Electron Beams (FA9550-16-1-0037)

Exact solutions of model systems play an important role in elucidating the behavior of real systems. I will describe some results on an exactly solvable simple model of ionization of a bound state, induced by an oscillating field. The aim is to get a fuller understanding of the effect of lasers on the ionization of atoms and electron emission from cathodes. We are particularly interested in the connection between two commonly used descriptions of the emission process: 1) solution of a non-relativistic Schrodinger equation in an oscillating potential of frequency f and 2) instantaneous absorption of discrete photons of that frequency, as in the photo-electric effect. These processes seem a priory very different yet both yield, under appropriate conditions, similar results. Computing the energy distribution of the emitted particles in our model system we show that the Schrodinger equation for this model does indeed yield "photons" when the strength of the oscillating potential is small compared to the ionization energy.It does not do so however when the strength is large. This is surprising and could be checked experimentally. Time permitting I will also mention other work on emittance and entropy as well as on transmission through moving barriers.

Energy Transport in Solids

Innovative Study of Electrical Contact and Electron Transport

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

The following topics, all published in 2016, are featured in this AFOSR program review.

1. Contact resistance and current crowding in nanolasers [1].

2. Nonlinear heat transport in a 1-dimesional conductor, such as a carbon nano-fiber [2].

3. Solved and unsolved problems in ultrafast and nano-scale diodes [3], [4].

4. Novel results in vacuum electronics: Simple scaling law for spherical and cylindrical diodes in the relativistic regime [5], crossed-field [6] and linear beam devices [7].

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[1] P. Zhang, Q. Gu, Y. Y. Lau, and Y. Fainman, "Constriction resistance and current crowding in electrically pumped semiconductor nanolasers with the presence of undercut and sidewall tilt," IEEE J. Quantum Electronics, 52, 2000207 (2016).
[2] F. Antoulinakis, D. Chernin, Peng Zhang, and Y. Y. Lau, "Effects of temperature dependence of electrical and thermal conductivities on the Joule heating of a one dimensional conductor," J. Appl. Phys. 120, 135105 (2016).

[3] P. Zhang and Y. Y. Lau, "Ultrafast and nano-scale diodes," J. Plasma Phys. 82, 595820505 (2016).
[4] P. Zhang and Y. Y. Lau, “Ultrafast strong-field photoelectron emission from biased meetal surfaces: exact solution to time-dependent Schroedinger equation,” (Nature) Scientific Reports 6, 19894 (2016).
[5] A. D. Greenwood, J. F. Hammond, P. Zhang, and Y. Y. Lau, “On relativistic space charge limited current in planar, cylindrical, and spherical diodes,” Phys. Plasmas 23, 072101 (2016).
[6] D. H. Simon, Y. Y. Lau, G. Greening, P. Wong, B. Hoff, and R. M. Gilgenbach, "Stability of Brillouin flow in the presence of slow-wave structure," Phys. Plasmas 23, 092101 (2016).
[7] Brad W. Hoff, David S. Simon, David M. French, Y. Y. Lau, and Patrick Wong, " Study of a high power sine waveguide traveling wave tube amplifier centered at 8 GHz," Phys. Plasmas 23, 103102 (2016).

Thin Film Spreading Resistance Modeling for Improved Micro-Contact Performance

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Program: Thin Film Spreading Resistance Modeling for Improved Micro-Contact Performance (15RT0631)

(Abstract not recieved)

Nonlinear Dielectrics and Magnetics for Compact Pulsed Power & HPM Protection

Susan Heidger[1], Brad Hoff[1], Renee Van GinHoven[1], John Horwath[2], Zafer Turgut[2] and Brandon Howe[3]

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Program: Nonlinear Dielectrics and Magnetics for Compact Pulsed Power & HPM Protection (16RDCOR281)

(Public Release for Abstract Pending)

Fundamentals of Thermal Conductance at Elevated Temperatures

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Program: Fundamentals of Thermal Conductance at Elevated Temperatures (FA9550-14-1-0395)

While traditional predictive models assert thermal boundary resistance is primarily limited by an overlap, or lack-thereof, in the vibrational spectra of two materials, interfacial properties, such as roughness, concentration gradients, and adhesion have been shown, experimentally, to impact the interfacial resistance by as much as an order of magnitude. In a series of metal/In-based III-V semiconductors, the overlap in phonon density of states was investigated. It was determined that the vibrational spectra plays a much smaller role in the interfacial conductance above cryogenic temperature relative to the bond strength between the metal and semiconductor. Molecular dynamics (MD) simulations are also utilized to investigate the effect of anharmonicity on thermal transport at atomically mass mismatched solid/solid interfaces with an added intermediate thin layer. It has been shown that adding an intermediate thin layer can enhance thermal boundary conductance [1]. However, the fundamental processes that cause the enhancement are not well understood. By comparing thermal boundary conductance calculations in the presence of inelastic processes with those of harmonic systems, we show that anharmonicity can play a major role in this enhancement. Inelastic phonon processes are naturally included in our MD simulations due to the anharmonic interatomic potentials. Furthermore, we compare our MD results with those of non-equilibrium Green's function formalism (NEGF), which are solely harmonic, to isolate the contribution from inelastic phonon scattering. We show that our calculations from these two methods are in agreement at very low temperatures where energy transport is dominated by harmonic phonon interactions. We prescribe different levels of anharmonicity by changing the atomic mass, and thickness of the intermediate layer and also varying the temperature. We show that thermal conductance at the mass mismatched interfaces can be expressed as a function of atomic mass ratio. Thus thermal conductance can be maximized by adding an intermediate layer with atomic mass close to the geometric mean of the substrates' atomic masses.

[1] English, T. S.; Duda, J. C.; Smoyer, J. L.; Jordan, D. A.; Norris, P. M. & Zhigilei, L. V.; Enhancing and tuning phonon transport at vibrationally mismatched solid-solid interfaces; Phys. Rev. B, American Physical Society, 2012, 85, 035438

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

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Program: Scattering and Relaxation Mechanisms of Electronic Materials (FA9550-15-1-0079)

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 and phonon transport in metal and non-metal films, in an effort to actively control and monitor the heat transport mechanisms in materials via the application of externally applied stimuli. We will demonstrate the ability to perturb the "intrinsic" thermal interface scattering processes via energetic external stimuli, including multiple short pulse absorption affecting electron-interface scattering rates in thin metal films, and external electric fields changing the thermal and mechanical properties of ferroelectric materials. Our results have guided the advances of short-pulsed-based diagnostic techniques that can be used to interrogate thermal transport during energetic processes via in situ measurements. We show this using thermoreflectance-based techniques without the application of metal film transducers for direct probing of thermal conductivity of active devices, along with demonstrating thermoreflectance as probes of energetic plasma excitations and temeratures. Finally, we will demonstrate recent progress toward creating thermally driven logic devices through manipulation of electrical transport through rapid thermal absorption of a short pulse in vanadium dioxide undergoing a phase change.

Nanostructure Techniques to Obtain Enhanced Permittivity Dielectrics

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Program: Nanostructure Techniques to Obtain Enhanced Permittivity Dielectrics (16RQCOR307)

The Gor'kov-Eliashberg (GE) theory predicted that enormously enhanced permittivity could be achieved through the use of metallic nanoparticles. This theory was shown to be invalid due to an oversite involving the depolarization field associated with the spherical geometry of the nanoparticles. A few years later, Rice and Bernasconi predicted that the enormous permittivity predicted by GE could be achieved if the geometry of the nanoparticles was long, thin strands instead of spherical. This effort attempts to confirm and explore applications of this theory. Efforts are currently being made to create nanowires within the pores of anodic aluminum oxide (AAO). Test capacitors will then be fabricated to measure the dielectric properties of the nanowire loaded AAO films. Meanwhile, plans are being made to directly fabricate quasi-2D capacitors with more accurately controlled nanowire dimensions using e-beam lithography. Although the capacitors will be only 2 dimensional, calculations indicate that their capacitance will be sufficient for permeability measurement according to the GE theory. While not likely to find use in the manufacture of fieldable capacitors, these e-beam patterned nanostructures can help illuminate effect of physical dimensions on the dielectric properties of metallic nanowires.

In addition to the direct fabrication of nanowires, previous research by this group has been done in an attempt to produce and characterize a particular nanoparticle of niobium consisting of precisely twelve atoms. The symmetry of Nb12 is expected to result in a very stable and inert nanoparticle with high polarization. These particles are produced using a plasma gas condensation tool. Isolation of Nb12 particles had proved difficult with our current spectrometer. A new, more sensitive spectrometer has been ordered and is expected to help isolate Nb12 particles and thereby facilitate a better understanding of the deposition parameters necessary for optimizing production of this particular particle. The ability to produce small, though significant amounts of Nb12 will then allow for more detailed characterization of the particles and eventually the formation capacitors with Nb12 loaded dielectric layers.

Cathode Emission Study for High Power Microwave Sources

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Program: Cathode Emission Study for High Power Microwave Sources (16RDCOR299)

Space charge limited current greatly influences the performance of modern day vacuum electronics, crossed-field devices and high power microwave sources. It has been shown that the classic 1D Child-Langmuir law is modified when electrons are restricted to emit over a finite strip of width W in a planer gap of gap separation D [1]. To gain an understanding of the high aspect ratio effect on space charge limited emission, we performed a 2-D analysis using the in-house PIC code ICEPIC [2]. We analyzed a planar gap with non-relativistic voltage. The anode-cathode plate is 4cm in width (W), and the third dimension is infinite and uniform. The finite strip has a height H of arbitrary values, the aspect ratio of the cathode is defined as the ratio of H over W/2. The anode-cathode (AK) gap D measured from the tip of the cathode to the anode is fixed at 1cm. ICEPIC simulation shows that when the aspect ratio of the cathode becomes small, namely H << W/2, the cathode appears as a flat strip and the space charge limited current previously obtained by Luginsland et. al. was recovered. As the aspect ratio increases, the space charge limited current also increases as expected. More surprisingly, the space charge limited current is found to reach saturation at a certain value of aspect ratio, beyond which no change of space charge limited current was observed. These results were obtained from both a dual cell emission and beam algorithm within ICEPIC.

[1] J.W. Luginsland, Y.Y. Lau, and R.M. Gilgenbach, "Two-Dimensional Child-Langmuir Law," Phys. Rev. Lett. 77, 4668 (1996).
[2] R.J. Peterkin and J.W. Luginsland, "A Virtual prototyping environment for directed-energy concepts," Comput. Sci. Eng., vol. 4, no. 2, pp.42-49, Mar. 2002.

Phase-Controlled Magnetron Development

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Program: Phase-Controlled Magnetron Development (FA9550-16-1-0083)

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. In our research we are designing, building, and simulating a magnetron using a faceted cathode that contains Gated Field Emission Arrays (GFEAs) to provide the addressable, modulated electron source. The magnetron experiment uses use the circuit, output coupler, and components of the commercially available L3 CWM75KW, 915 MHz, 10 cavity cooker magnetron. L3 has demonstrated that the magnetron can be operated at very low power with P<1 kW VCat=-8.3kV, B=900 G, and I=150 mA. The magnetron cavity has been attached to a vacuum flange and connected to our vacuum test chamber so that a cathode can be inserted into the cavity for experiments. The magnetron has 5 electron spokes, and each spoke must be driven using 4 phase elements of the GFEAs. The cathode has 10 facet plates/sections with each divided into 2 phase elements. Hence, there are 20 controllable elements around the cathode. We have designed and fabricated cathode structure prototypes with RF delay lines using a Low Temperature Co-Fired Ceramic (LTCC). This cylindrical structure allows for the electrical connection of 30 GFEA die using vias and a backside ground. Each facet section has 3 die stacked along the cathode extent (axially). Each die is divided into 2 phase elements. We have also designed and tested a driver system that uses an RF delay line to drive the phase elements. The GFEAs that are being fabricated for this experiment are capable of generating 100 A/cm2 at 70 V; however our experiment will only require 200 mA/cm2 to achieve 150 mA of injection current. The results of the cathode and GFEA design and fabrication will be presented.

Pushing the Frontiers of the Relativistic Magnetron

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Program: Pushing the Frontiers of the Relativistic Magnetron (FA9550-15-1-0094)

The relativistic magnetron was introduced by Bekefi at MIT 40 years ago in 1976.[1] That device is referred to as the A6 magnetron and operated with 35% efficiency. No significant advance in the efficiency of the A6 magnetron was achieved until we introduced the transparent cathode in 2005[2] and then used it in an A6 magnetron with axial extraction (the magnetron with diffraction output – MDO)[3]. In this device we achieved 70% efficiency in particle-in-cell (PIC) simulation and 63% efficiency in experiment when the cathode endcap electrically broke down. Experiments are planned to demonstrate 70% using new cathode endcaps. Most recently our thinking about the A6 MDO has evolved from using a solid cathode to a transparent cathode, and now to no physical cathode in the device![4] Instead, we demonstrate high efficiency operation of the MDO that uses a virtual cathode (VC) as opposed to a physical cathode as the electron source in the interaction space. The cathode generating the electron beam is external to the MDO interaction space and, therefore, is immune from electron bombardment, pulse shortening, decreasing electron efficiency, and frequency shift attributed to expanding cathode plasma. Electronic efficiency exceeding that achieved with the MDO with a transparent cathode has been achieved in simulations. This presentation will review the results of analytical theory and PIC simulations, and will present experimental plans at UNM and in collaboration with NSWC Dahlgren Division (under separate support from ONR).

[1] G. Bekefi and T.J. Orzechowski, "Giant Microwave Bursts Emitted from a Field-Emission, Relativistic-Electron-Beam Magnetron," *Phys. Rev. Lett.*, vol. 37, 379 (1976).
[2] M. Fuks and E. Schamiloglu, "Rapid Start of Oscillations in a Magnetron with a "Transparent" Cathode," *Phys. Rev. Lett.*, vol. 95, 205101 (2005).
[3] M.I. Fuks and E. Schamiloglu, "70% Efficient Relativistic Magnetron with Axial Extraction of Radiation Through a Horn Antenna," *IEEE Trans. Plasma Sci.*, vol. 38, 1302 (2010).
[4] M.I. Fuks, S. Prasad, and E. Schamiloglu, "Efficient Magnetron with a Virtual Cathode," *IEEE Trans. Plasma Sci. Special Issue on High Power Microwave Generation*, vol. 44, 1298 (2016).

Volume Mode Traveling Wave Tube Amplifier

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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 that provide a larger interaction dimension and are thus consistent with more available and rugged fabrication technologies such as precision CNC machining and EDM machining. In a first set of experiments, we 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 ± 2 dB linear device gain with 27 W peak output power. For the next phase of this research, we have designed 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 Recirculating Planar Amplifiers

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

The goal of this research program is to develop a crossed-field amplifier capable of operation at extremely high power levels of 10's to 100's of MW. The Recirculating Planar Crossed Field Amplifier (RPCFA) is a high power microwave device adapted from the Recirculating Planar Magnetron (RPM),1 developed at the University of Michigan. A travelling-wave, rectangular, meander line design has been developed in simulation that amplifies a 1.3 MW signal at 3 GHz to approximately 29 MW, a gain of approximately 13.5 dB, with nearly 53% electronic efficiency. The amplifier is designed to be driven by the Michigan Electron Long Beam Accelerator (MELBA), which is currently configured to deliver a -300 kV, 1-10 kA, 0.3-1.0 us pulse. The RF signal will be provided by an MG5193 magnetron, which can deliver microwave pulses with a peak power output of 2.6 MW at 3 GHz for up to 5 us.

The slow wave structure (SWS) of the RPCFA was developed using the finite element frequency domain code Ansys HFSS. Driven modal simulations were performed to optimize this structure, which transmitted the 3 GHz signal with minimal reflection. Additionally, this structure was required to slow the phase velocity of the RF signal to speeds at which an electron hub could be synchronized. These conditions would ensure RF power would flow into the RPCFA, amplify through interaction with the hub, then flow out without reflecting RF power back into the device. When no RF signal was present, no significant oscillating or amplifying modes were observed and minimal (< 1-MW) power was measured at the terminals of the amplifier. Even after amplifying an RF signal, once RF power was removed the output power levels and spectrum returned to the zero-drive-stable state. Parameter sweeps were performed on this optimized RPCFA to gather further information on the design. It was found to be relatively robust to changes in DC voltage and magnetic field. Gain tended to decrease slowly with increased applied RF power. A gain of 12 dB was predicted at 2.5 MW of input RF, the rated peak power for the MG5193 magnetron. Gain of >10 dB was found for an approximately 300 MHz range centered below (but including) the design point 3 GHz frequency, giving a bandwidth of around 10%. The gain, efficiency and bandwidth found in simulation are comparable to existing crossed field amplifiers. A 3-D printed, metal version of the slow wave structure is being fabricated for cold-tests and installation in the MELBA facility.

[1] R.M. Gilgenbach, Y.Y. Lau, D.M. French, B.W. Hoff, J. Luginsland, and M. Franzi, "Crossed Field Device," U.S. Patent US 8,841,867 B2, Sept. 23, 2014.

Study of High Power Microwave Amplification Driven by Energetic Electron Beams

Brad W. Hoff

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Program: Study of High Power Microwave Amplification Driven by Energetic Electron Beams (16RDCOR310)

Results from work pertaining to a 20-stage X-band sine waveguide amplifier, driven by a 40 A, 100 kV, cylindrical electron beam will be presented. This amplifier is studied using numerical simulation and results are interpreted using Pierce's classical traveling wave tube theory. For an input signal power level of 1.8 kW, particle-in-cell simulations predict gain and bandwidth values exceeding 14 dB and 13%, respectively. For an input signal power level of 7.2 kW, particle-in-cell simulations predict gain and bandwidth values exceeding 12 dB and 15%, respectively, with output power levels exceeding 110kW at peak gain. Also given are: an assessment of the space charge factor (Pierce's QC parameter) for the complex circuit using simulation data, and an evaluation of the harmonic contents in the beam current. Status of the design and fabrication of the experimental hardware for the X-band sine waveguide amplifier experiment will also be presented.

Tunable Broadband GHz/THz Radiation Generated Via Ultrafast Laser Pulsing of Inductively Charged Superconducting Antennas

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Program: Microwave/Terahertz Generation from Superconductor Antennas (15RQCOR215)

An electromagnetic transmitter typically consists of individual components such as a waveguide, antenna, power supply, and an oscillator. In this communication we circumvent complications associated with connecting these individual components and instead combine them into a non-traditional, photonic enabled, compact transmitter device for tunable, ultrawide band (UWB) radiation. This device is a centimeter scale, continuous, thin film superconducting ring supporting a persistent super-current. An ultrafast laser pulse (required) illuminates the ring (either at a point or uniformly around the ring) and perturbs the super-current by the de-pairing and recombination of Copper pairs. This generates a microwave pulse where both ring and laser pulse geometry dictates the radiated spectrum's shape. The transmitting device is self-contained and completely isolated from conductive components that are observed to interfere with the generated signal. A rich spectrum is observed that extends beyond 30 GHz (equipment limited) and illustrates the complex super-current dynamics bridging optical, THz, and microwave wavelengths.

Field Emission Cathode Research

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

Although Fowler and Nordheim developed the basics of field emission nearly one century ago with their introduction of the Fowler-Nordheim equation (FNE), the topic continues to attract research interest particularly with the development of new materials that have been proposed as field emitters. The first order analysis of experiments typically relies upon the

FNE for at minimum a basic understanding of the physical emission process and its parameters of emission. The three key parameters in the FNE are the work function, emission area, and field enhancement factor, all of which can be difficult to determine under experimental conditions. Current work at AFRL focuses on understanding the field enhancement factor ⍰. It is generally understood that ⍰ provides an indication of the surface roughness or sharpness of a field emitter cathode. However, we experimentally and computationally demonstrate that cathodes with highly similar surface morphologies can manifest quite different field enhancements solely through having different emission regions. This fact can cause one to re-interpret results in which a single sharp emitter is proposed to dominate the emission from a field emitting cathode . Additionally, we explore the variation of ⍰ with respect to both small (<9) and large (<100) arrays of field emitters. Ultimately, however, the field enhancement stems from the distribution of charge on the surface of an emitter. We have begun to study the time behavior of this charge and the resultant field enhancement factor through a series of experiments utilizing a femtosecond class laser. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

Cleared for Public Release (AFRL/RD OPSEC review number 9127)

Nanostructured Anode and Cathode Materials for Vacuum Electronic Devices

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Program: Investigation of Novel Nanomaterials (12RX17COR) & Anode and Cathode Materials for Next Generation Directed Energy Devices (17RXCOR428)

Improved vacuum electronic source materials are needed for applications such as traveling wavetube amplifiers, particle accelerators, and microwave generators. Stable, long term device operation is hampered by plasma formation in the anode-cathode gap region which results in pulse shortening and cathode damage caused by ion back bombardment. Plasma originates from gas molecules that are desorbed from both the cathode and anode surfaces when heated. Secondary electron emission (SEE) from the anode surface leads to ionization of the molecules near the surface. Improved materials for electron beam emission and collection are needed to mitigate these effects, and novel nanostructured materials have shown considerable promise towards this realization.

Field emission (FE) cathodes made from carbon nanotube (CNT) fibers have demonstrated high emission currents, low turn-on voltages and long lifetimes. The CNT fibers were ~50um in diameter and showed increasing electrical and thermal conductivity with increasing fiber alignment. Fiber alignment was characterized with wide angle x-ray diffraction and fiber morphology was investigated with SEM and scanning 3D X-ray microscopy with 50 nm resolution. Stable field emission currents exceeding 1 mA for 10 hours and at an operating field strength of $< 1V/\mu m$ were achieved [1]. Residual gas analysis (RGA) was used to identify the species desorbed during field emission which showed a sharp threshold for H_2 desorption at an external field strength that coincides with a breakpoint in the FE data [2]. Graphene was used to improve anode material performance during electron beam collection experiments. Hydrogen outgassing was induced by repeated pulses (60 s duration) of 60 keV electrons onto anode material samples and recording the H_2 signal with a line of sight RGA. A nickel – graphene surface reduced the H_2 outgassing and SEE by factors of three and two respectively over a bare nickel surface. Additionally, metallic anode samples were treated with the laser surface melting (LSM) technique to further reduce hydrogen outgassing. The samples were irradiated with a continuous high energy laser beam which resulted in melting, flow and re-solidification of the surface which decreased the number of grain boundaries through which hydrogen can diffuse. The data show at least a five-fold reduction in hydrogen outgassing from the LSM treated sample, compared to those that were untreated. Graphene applied to an LSM treated metallic surface offers the ideal combination of reduced SEE and H_2 outgassing for anodes. Experimental results for these layered structures will be discussed.

[1] S B Fairchild et al 2015 Nanotechnology 26 105706
[2] P T Murray et al 2013 Appl. Phys. Lett. 103 053113

Case Number: 88ABW-2016-3585. The material was assigned a clearance of CLEARED on 22 Jul 2016

Integrated Photonics for Electron Emitters

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Program: Optical Cavity Enhanced Electron Emitters (FA9550-16-1-0306)

Here, we explore microscale optical cavities coupled to electron emitters to enable a class of efficient and potentially ultrafast optically-modulated, on-chip, electron emitters. The devices consist of a microfabricated optical cavity, such as Fabry-Perot or ring resonator, and a thermionic or field emitter. First, we discuss the basic principles of cavity coupled emitters, focusing on the design rules for coupling efficiency and time response. Next, we look at cavity coupled heterostructured thermionic emitters and carry out coupled optical and thermal simulations to determine the steady-state and transient performance of these devices. The heterostructure is designed with a small bandgap or metallic thermionic emitter (e.g. LaB6) deposited on a wider bandgap electrical and thermal conductor (e.g. doped Si). We show that by tuning the response of the optical cavity and we can ensure photons are efficiently and selectively absorbed by the small bandgap/metallic emitter, potentially enabling design of GHz-THz on-chip electron emission sources. We will also discuss some initial experimental results in this direction.

Fundamental Processes and Interactions in Plasmas

Fundamental studies of atmospheric pressure, nanosecond pulsed microplasma jets[i]

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Program: Fundamental Studies of Transient, Atmospheric-Pressure, Small-Scale Plasmas (FA9550-11-1-0190)

Nanosecond pulsed microplasma jets are highly non-equilibrium plasmas propagating in ambient air and with at least one dimensions less than 1 mm. Understanding of these plasmas, particularly in forms of transient streamers generated in mixed flow fields and with nanosecond pulsed electric fields, is essential to adoption of these plasmas for a variety of applications including energy-efficient engine ignition and combustion, noise reduction, pollution control, and effective and efficient biomedical disinfection and decontamination. Effects of impulse parameters on the dynamics and associated chemistry of the plasma jets were studied using spatiotemporally resolved high-speed imaging and emission spectroscopy. Shorter pulses with shorter rising times allowed higher energy deposition into the plasma and promoted rapid acceleration of the ionization wavefronts; 4 times higher wavefront velocity was observed for a 5 ns pulsed plasma streamer compared with that by the 140 ns pulsed excitation. Microplasma jets powered by shorter (e.g. 5 ns) voltage pulses enhanced the production of excited atomic oxygen compared with the microplasma driven by 140 ns pulses at the same rotational and vibrational temperatures (300 K and 3000 K, respectively)[ii]. However, the use of voltage pulses with higher pulse duration, e.g. 164 ns, and fast falling time, could initiate a negative streamer, which would contribute significantly to the production of the reactive plasma species and resulted in higher production of the total excited species than the 5 ns pulsed plasma jet[iii]. In addition, efforts were invested to understand the plasma dynamics and chemistry when the plasma is exposed to wateri[v] as well as the antimicrobial effects of the plasma against common nosocomial pathogens on wet or dry surfaces[v].

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[i] All Materials were cleared for public release, and supported by the Air Force Office of Scientific Research (AFOSR Award No. FA9550-11-1-0190).

[ii] C. Jiang, J. Lane, S.T. Song, S.J. Pendelton, Y. Wu, E. Sozer, A. Kuthi, M.A. Gundersen, Single-electrode He microplasma jets driven by nanosecond voltage pulses, J Appl Phys, 119 (2016).

[iii] S. Song, J. Lane, C. Jiang, Comparison study of spatiotemporally resolved emissions of nanosecond pulsed microplasma jets, IEEE Tran Plasma Sci, in review (2016).

[iv] C. Jiang and S. Song, Nanosecond pulsed helium plasma jet over a water electrode, Plasma Process Polym, in submission.

[v] J. U. Neuber, S. Song, M. A. Malik, and C. Jiang, Nanosecond pulsed plasma brush for bacterial inactivation on Laminate, IEEE Tran Plasma Sci, in submission.

Characterizing Hypervelocity Impact Plasmas and Effects on Spacecraft with PIC

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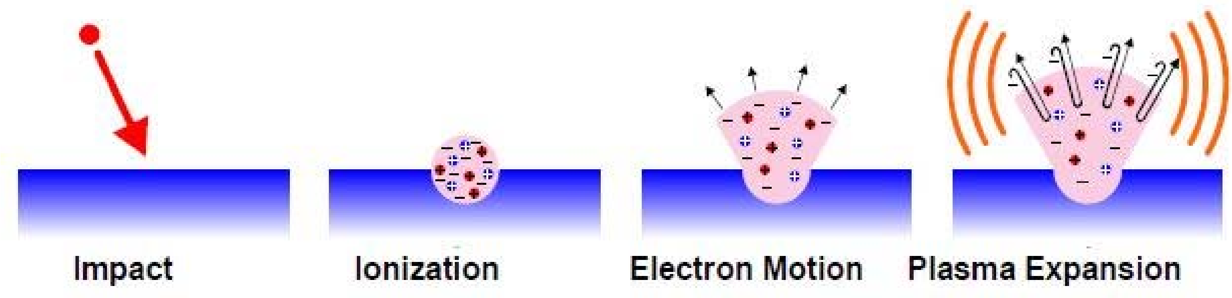
Program: Characterizing Hypervelocity Impact Plasmas and Effects on Spacecraft with Particle-in-Cell (FA9550-14-1-0290)

Hypervelocity micro particles, including meteoroids and space debris with masses < 1 ng, routinely impact spacecraft and create dense plasma that expands at the isothermal sound speed. This plasma, with a charge separation commensurate with different species mobilities, can produce a strong electromagnetic pulse (EMP) with a broad frequency spectrum. Subsequent plasma oscillations resulting from instabilities can also emit significant power and may be responsible for many reported satellite anomalies. We present theory and recent results from ground-based impact tests aimed at characterizing hypervelocity impact plasma. We also show results from particle-in-cell (PIC) and computational fluid dynamics (CFD) simulations that allow us to extend to regimes not currently possible with ground-based technology. We show that significant impact-produced radio frequency (RF) emissions occurred in frequencies ranging from VHF through L-band and that these emissions were highly correlated with fast (> 20 km/s) impacts that produced a fully ionized plasma.



Measurements and Applications of Strongly-Correlated Plasmas Generated in Dense Noble Gases

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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, one creates a plasma with a free charge density that is so unexpectedly large that the system is opaque. This phenomenon has been observed in laser breakdown, spark discharges and inside of a collapsing bubble. A micron-sized spark discharge in 10bar xenon establishes a blackbody on a nanosecond time scale in a plasma with a shell structure wherein the energy per nucleus is ~15eV independent of size and density. Such spark discharges can block light from a powerful laser operating in the range 200nm to 800nm. We are constructing such a sub-nanosecond switch for UV light. 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 25,000K 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. In this situation plasma transport is controlled by the liquid/solid-like structure factor. For instance, off-equilibrium energy transfer is in this case dominated by electron-phonon [i.e. particle wave] interactions. According to our model the plasma parameter, and therefore the process of femtosecond laser breakdown depends on the ambient temperature of the gas! We report on preliminary measurements on, this issue, and the tensile strength of the strongly correlated plasmas.

Intriguing Transport Properties of Magnetized Ultracold Neutral Plasmas

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Using molecular dynamics simulations and analytic theory, we show that plasmas that are both strongly magnetized and strongly coupled can exhibit unusual and intriguing properties, including the strong suppression of both momentum and energy transport rates. Strongly coupled plasmas are those in which the Coulomb potential energy at the average interparticle spacing exceeds the average kinetic energy of particles. A strongly magnetized plasma is one in which the gyrofrequency exceeds the plasma frequency. Both of these conditions may be satisfied in future ultracold plasma experiments. Here, we describe two transport processes that may be experimentally accessible: Ion diffusion and the rate of temperature anisotropy relaxation. Using simulations of the one-component plasma, we show that in the strongly coupled regime the rate of diffusion both perpendicular and parallel to the magnetic field are strongly suppressed. This is in contrast to conventional weakly coupled plasmas, where only the perpendicular diffusion rate is suppressed by a magnetic field. We also show that the temperature anisotropy relaxation rate is sharply reduced, in contrast to weakly coupled plasmas in which energy relaxation processes are not influenced by a magnetic field. These results describe a qualitatively new plasma state that has never been observed before, providing an impetus for future experiments.

Novel Features in Complex Plasmas

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Chubu University, Kasugai, Japan

Program: Study of Complex Plasmas with Magnetic Dipoles (FA2386-14-1-4021)

Novel features of a complex plasma are reviewed. A complex plasma, or a dusty plasma, is characterized by a plasma with micron-size dust particles. The unique features we have revealed include formation of a wake potential formed behind a dust particle placed in a sheath, bow shock formation in the supersonic dust flow, a vortex formation of dust particles in the presence of applied magnetic field, dust chain and helical structure formation, and the presence of electromagnetic band-gap in a complex plasma.

Studies in Raman Compression

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Program: Studies in Raman Compression (FA9550-15-1-0391)

Light waves in plasma can be compressed in time through nonlinear interactions with other light waves, with the important application in achieving the next generation of laser intensities. A variety of techniques have been proposed to achieve the amplification of the desired signal, while tuning out unwanted amplifications. This talk highlights certain achievements over the last year in furthering this goal -- and in framing where the key opportunities lie

Threat Detection Using a Modular Cosmic Ray Muon Tomography System

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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.

Our research efforts have paid off in large part due to finding an enthusiastic graduate student, Luis Maduro, to assist us. We have built a suite of 12”x12” scintillator detectors into weatherproof gun cases and demonstrated that we can use coincidence counting as a tool to probe the density of objects hidden inside a drum-size container. We use the same smart-phone computer technology to record environmental and cosmic-ray coincidence events. We plan to continue refining this technique to reduce the size of some components and begin the task of simplifying the system so that a person with minimal training can operate it.

Plasma and Laser Kinetics within a Discharge Assisted Noble Gas Laser

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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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

Pulse power implosion experiments and simulation study of the impact of Lower Hybrid Drift (LHD) plasma turbulence on the propagation properties of high frequency electromagnetic waves

Vladimir Sotnikov

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Program: Pulse power implosion experiments and simulation study of the impact of Lower Hybrid Drift (LHD) plasma turbulence on the propagation properties of high frequency electromagnetic waves (16RYCOR289)

One of the simplest configurations leading to colliding plasma flows is created by driving strong unidirectional currents through a pair of parallel wires. The azimuthal magnetic fields generated around each wire, and the Ohmic current dissipation and heating occurring upon wire evaporation, launches strong radial outflows of magnetized plasmas. Upon colliding with each other, they form a flow pattern highly suggestive of magnetic field reconnection, and the development of various plasma instabilities. Indeed, a part of the symmetry plane between the wires forms a region of zero magnetic field, where the magnetic lines from the opposing flows reconnect. The potential of this flow to support strong instabilities is worth a separate discussion.

Dynamic Plasma Coupling in Laboratory, Computer, Space

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Program: Dynamic Plasma Coupling in Laboratory, Computer, Space (16RVCOR264)

Momentum-coupling in cross-drifting magnetized plasma spans a broad range of phenomenon including: the coupling between the ionosphere, magnetosphere, and solar wind; ionizing chemical release in space; charged or large extended spacecraft including electro-dynamic tether systems (EDT); High Altitude Nuclear Detonation (HAND), and penetration of reconnection-created plasma jets into plasmasphere and impulsive penetration of solar wind into magnetosphere. Our central thesis is that space charge or displacement current effects that are understood to dominate the small scales of plasma physics, carry over to the large scale and are ignored by most treatments of large scale plasma problems. The motivation for this effort stems from unresolved physical issues that remain from the TSS-1R Tethered Satellite experiment, and the general failure of sophisticated EM wave theory to produce observable predictions of the experiment. Because of these beginnings, this effort first concentrates on the practical study of current collection by a positive probe in a drifting plasma, using 3D EM simulation and the development of a steady state ExB drifting plasma experiment. The simulations so far have found that electron energization in the flux tube wings of the interaction dominate the collection and obscure any electromagnetic contribution to the current. The laboratory experiment is still in development.

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)*

RF Generation Based on Nonlinear Transmission Lines

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Program: Study of HV Dielectrics for High Frequency Operation in Transmission Lines (FA9550-14-1-0133), *associations: HPEM Sources, international program (SOARD)*

High power RF generation using alternative methods based on a non-conventional technique is always of great interest for USAF. In general, conventional based-tube RF generation requires vacuum and heating filament, which consumes space and power. On the other hand, we envisage that NLTLs of compact size could replace the RF tubes in several applications as these NLTL devices are all solid state. For instance, lumped NLTLs could be used in disruption of battlefield communications, UWB and SAR radars for remote sensing and urban applications, mainly in P-band operation because of their limitation up to 300 MHz so far. On the other hand, as gyromagnetic lines have had a better performance in the frequency range starting from 400 MHz up to 2 GHz (S-Band), they offer a good prospect for applications in communications and telecommand systems of satellites as well as in defense platform systems. In our laboratory at INPE, our research has focused on these two approaches for NLTLs. With lumped NLTLs, a new approach is proposed by using SiC Schottky diodes in their construction to extend the upper limit operation frequency above 300 MHz as they have a high reverse breakdown voltage (>1 kV) and great nonlinear C behavior in pF range. With gyro lines, in short, the goal is to validate the SPICE simulation model developed by means of experimental results obtained with a small line prototype of 20 cm in length. Finally, due to scientific challenges faced with the research on NLTLs, several spin-offs can be obtained especially such as high-frequency characterization of magnetic and dielectric materials, development of fast HV ns pump pulse generators using solid-state switches, etc.

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

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

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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

Near Zero Epsilon/Mu Artificial Materials for High-Power Vacuum Electronic Applications

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Cherenkov Interactions at High-Power in Microwave Metamaterials (FA8655-13-1-2111) - *Core funded program, associations: HPEM Sources & 2012 MURI on Transformational Electromagnetics, international program (EOARD)*

In recent years there has been a growing interest in the development of novel electromagnetic media, such as metamaterials, for microwave applications. Unlike conventional media artificial materials derive their properties from their structure rather than their composition. Where these properties can be specifically engineered to give a desired response to an electromagnetic wave and particle beam.

In this work we investigate the response of Artificial Electromagnetic Materials (AEMs) to electromagnetic source excitations. The AEMs we consider here are constructed from off-resonant sub-wavelength structures, to create an artificial media with a near zero effective permittivity and permeability. This results in a relatively low-loss material that can mediate novel particle-wave interactions, and should enable the material to operate in a high-power microwave environment. In this presentation we focus primarily on our numerical results produced using the commercial available FEM packages HFSS and Comsol to simulate low-loss AEMs. Focussing on their electromagnetic and thermal characteristics, and the impact design has on the materials response to an excitation. We discuss the advantages and disadvantages these materials can offer, and compare their characteristics with the more familiar subset of AEMs “metamaterials”. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

Quantum Many-Body Localization in a Strongly Coupled Ultracold Plasma

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Program: Quantum and Classical Measures of Molecular Ultracold Plasma Dynamics (FA9550-12-1-0239) - *Core funded/BRI program, associations: Ultracold Plasma Basic Research Initiative (BRI), Fundamental Processes and Interactions in Plasmas*

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 [1{5]. 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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

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

[1] Basko, D. M., Aleiner, I. L. & Altshuler, B. L. Metal{insulator transition in a weakly interacting many-electron system with localized single-particle states. *Annals of Physics* 321, 1126{1205 (2006).

[2] Oganesyan, V. & Huse, D. A. Localization of interacting fermions at high temperature. *Phys Rev B* 75, 155111 (2007).

[3] Huse, D. A., Nandkishore, R. & Oganesyan, V. Phenomenology of fully many-body-localized systems. *Phys Rev B* 90, 174202 (2014).

[4] Laumann, C. R., Pal, A. & Scardicchio, A. Many-body mobility edge in a mean-field quantum spin glass. *Phys Rev Lett* 113, 200405 (2014).

[5] Nandkishore, R. & Huse, D. A. Many-Body Localization and Thermalization in Quantum Statistical Mechanics. *Annu Rev Condens Matter Phys* 6, 15{38 (2015).

[6] Kondov, S. S., McGehee, W. R., Xu, W. & DeMarco, B. Disorder-Induced Localization in a Strongly Correlated Atomic Hubbard Gas. *Phys Rev Lett* 114, 083002 (2015).

[7] Schreiber, M. et al. Observation of many-body localization of interacting fermions in a quasi-random optical lattice. *Science* 349, 842{845 (2015).

[8] Schauβ, P. et al. Observation of spatially ordered structures in a two-dimensional Rydberg gas. *Nature* 491, 87{91 (2012).

[9] Lesanovsky, I. & Garrahan, J. P. Out-of-equilibrium structures in strongly interacting Rydberg gases with dissipation. *Phys Rev A* 90, 011603 (2014).

Understanding Intense Laser Interactions with Solid Density Plasma

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Program: Understanding Intense Laser Interactions with Solid Density Plasma (FA9550-12-1-0310) - *Young Investigator Program, associations: Energy Transport in Solids,*

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 ~10^5 neutrons / s are generated. We also find the scaling of the neutron generation with laser power. (Abstract from 2015 Plasma and Electroenergetic Physics Review – program concluded)

Hybrid VFP Modeling of Electron Transport and Radiation Generation

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Program: Hybrid VFP Modeling of Electron Transport and Radiation Generation (FA9550-14-1-0156) - *Core funded, associations: Computational & Theoretical Plasma Physics*

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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

Understanding the Psychological/Behavioral Effects of Advanced Weaponry

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Program: Understanding the Psychological/Behavioral Effects of Advanced Weaponry – *Basic Research Initiative (BRI), associations: HPEM sources, Trust and Influence portfolio (Ben Knott), Laser and Optical Physics portfolio (John Luginsland)*

Our goal in this effort is to use wargames to quantify the presumed benefits of advanced weaponry, associated with reduced lethality or collateral damage. To do this we must identify metrics that would differentiate between the social consequences of tactics that use different classes of weapons. This has been done qualitatively to justify research into weapons that are non-lethal and weapons that greatly minimize collateral damage, but there has been no effort to quantify this. The ultimate goal is metrics that would be updated during the course of executing some mission that would somehow "score" the sociological and psychological impact of weapons and tactics while their physical effects are simultaneously simulated. An obvious measure, which has been studied in depth in recent years is level of insurgent violence and how our actions affect that level. Unfortunately, that information, though important, is too short-term to be complete. Any effort to construct such metrics must be informed by a larger scale, longer term model that captures the political, military, economic, sociological, information and infrastructure (PMESII) constraints and dependencies. We are exploring a number of approaches for this in tandem with a separate effort to collect empirical data on the psychological response to the use of different weapons and tactics. The intent is that the all models we develop will evolve as they are progressively constrained by new data. We have completed a review of existing physical models and are testing a PMESII level model to explore mission constraints and metrics. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

Plasmas from deuterated nanostructure arrays irradiated with laser pulses of relativistic intensity

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Program: Ultra-relativistic laser interaction with ordered nanoarrays Beams - *Co-funded; Core funded program, associations: Fundamental Processes and Interactions in Plasmas, Ultrashort Pulse Laser Matter Interaction portfolio.*

We are investigating plasma generated by the interaction of laser pulses of relativisitic intensity with arrays of aligned deuterated nanowires. A new phenomena of relativistic nanopinching is predicted to lead to efficient fast deuterium ion generation and potentially to the production of a large number of neutrons at high repetition rate. The research is based on a recently demonstrated new approach to volumetric plasma heating by the irradiation of arrays of aligned nanostructures with ultrafast laser pulses of relativistic intensity, in which the vertically aligned nanowires trap the femtosecond laser pulses deep into the material. This novel approach to plasma heating overcomes the barrier the critical electron density imposes to the penetration of light into supra-dense plasmas, allowing for the volumetric heating of plasmas with electron density nearly 100 times the critical density to multi-keV temperatures. This made it possible to use only modest laser intensities ($a_0 \sim 1$) to volumetrically heat near solid density plasmas to keV temperatures. At higher intensities 3-D particle-in-cell (PIC) simulations of laser interaction with ordered nanostructured targets reveal a new relativistic nano-scale phenomena in which pinching of the nanowires occurs driven by large electron currents along each nanorods. This current is computed to generate magnetic fields up to 5× higher than those of the laser wave, resulting in an energy density at the surface of the nanorod 10-50 times higher than that corresponding to the laser intensity. This self-generated magnetic field pinches the nanorods leading to the acceleration of ions. This acceleration regime is predicted to result in large numbers of fast deuterium ions in a near-solid density medium with highly favorable conditions for neutron production. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

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

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Program: Modeling of Ultrafast Laser Induced Emission from TI and Graphene (FA2386-14-1-4020), *associations: Fundamental Processes and Interactions in Plasmas, international program (AOARD)*

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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – updated abstract not received)

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

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Program: Electron Dynamics During High-Power, Short-Pulsed Laser Interactions (FA9550-13-1-0067) - *Young Investigator Program, associations: Energy Transport in Solids,*

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. (Abstract from 2015 Plasma and Electroenergetic Physics Review – program concluded