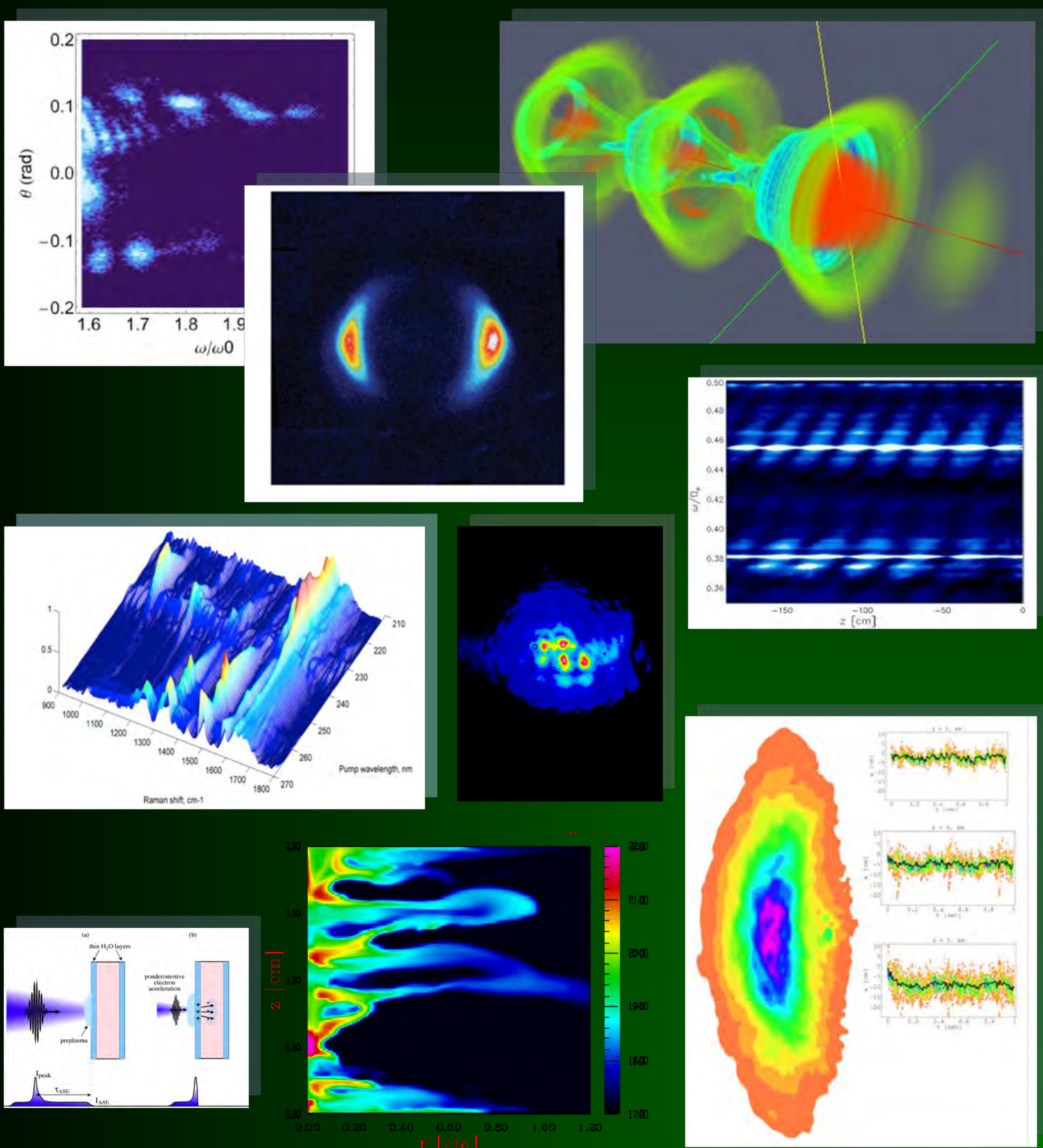
Plasma Physics Division

2013 Annual Report



PLASMA PHYSICS DIVISION

2013 ANNUAL REPORT

Plasma Physics Division personnel in front of Quarters A

Inside this issue:

Foreword

Dr. Thomas A Mehlhorn
Superintendent
Plasma Physics Division

Keeping in mind that “the third time is the charm…,” I am pleased to introduce the third edition of the Plasma Physics Division Annual Report. This edition includes an organizational chart, scientific and technical accomplishments organized by Branch; awards and recognitions; a pictorial roster; and a condensed overview of some of the Division’s major facilities and capabilities. This year we remember the passing of Mabel Gloria who was an NRL employee since 1989 and one of our Administrative Officers – she will be greatly missed.

This report is distributed throughout the Division, to NRL executive management, and to a variety of external collaborators and sponsors. The breadth of the Division research is impressive and spans the topics of lasers and directed energy, electromagnetic railguns, inertial confinement fusion (ICF), high power beams and pulsed power, space plasmas, radiation atomic physics, low temperature plasmas and non-equilibrium plasma reactions, and nonlinear dynamics. The Division capabilities span theory, computation, diagnostics, and experiments. This report includes recent accomplishments in improved understanding of fundamental z-pinch physics with applications to K-shell experiments at Sandia; measuring the hyperspectal response of bacteria using Raman techniques; mitigating corrosion of aluminum using pulsed electron beams; and validating a novel hybrid ICF drive concept. 2013 saw the completion of a new small caliber railgun that will be capable of repetitive operation in 2015; space experiments that combined ionospheric modification and satellite communication; and the chemical functionalization of graphene. Our pulsed power team is developing a novel battery bank for the small railgun; has used hybrid codes to begin to explain magnetic field penetration in plasmas; and has demonstrated the use of ion beams as a surrogate for cold x-ray testing. Progress is reported in laser and directed energy (combined effects, controlling prepulse pedestals, and remote power beaming to UAVs), improved understanding and modeling of the plasmasphere and the impact of gravity waves on the ionosphere; progress on a 550 GHz gyrotron and mitigation of multipactor in dielectric wall accelerators; improved understanding and acoustic pulse generation in laser-water interactions; and many new results in non-linear dynamics.

We congratulate Dr. Phillip Sprangle for receiving the 2013 APS DPP James Clerk Maxwell Prize, Dr. Guru Ganguli for receiving our first ever Edison Award, and Dr. Jack Davis in celebration of his 40th year of service.

I hope that you enjoy reading the articles and find this information both interesting and useful.

Plasma Physics Division has contributed to DOD and DOE missions for almost 50 years

Established in 1966 to create X-ray simulators for testing nuclear weapons effects (NWE) on materials and components of military hardware, study the physics and effects of High Altitude Nuclear Explosions (HANE), & perform Fusion research.

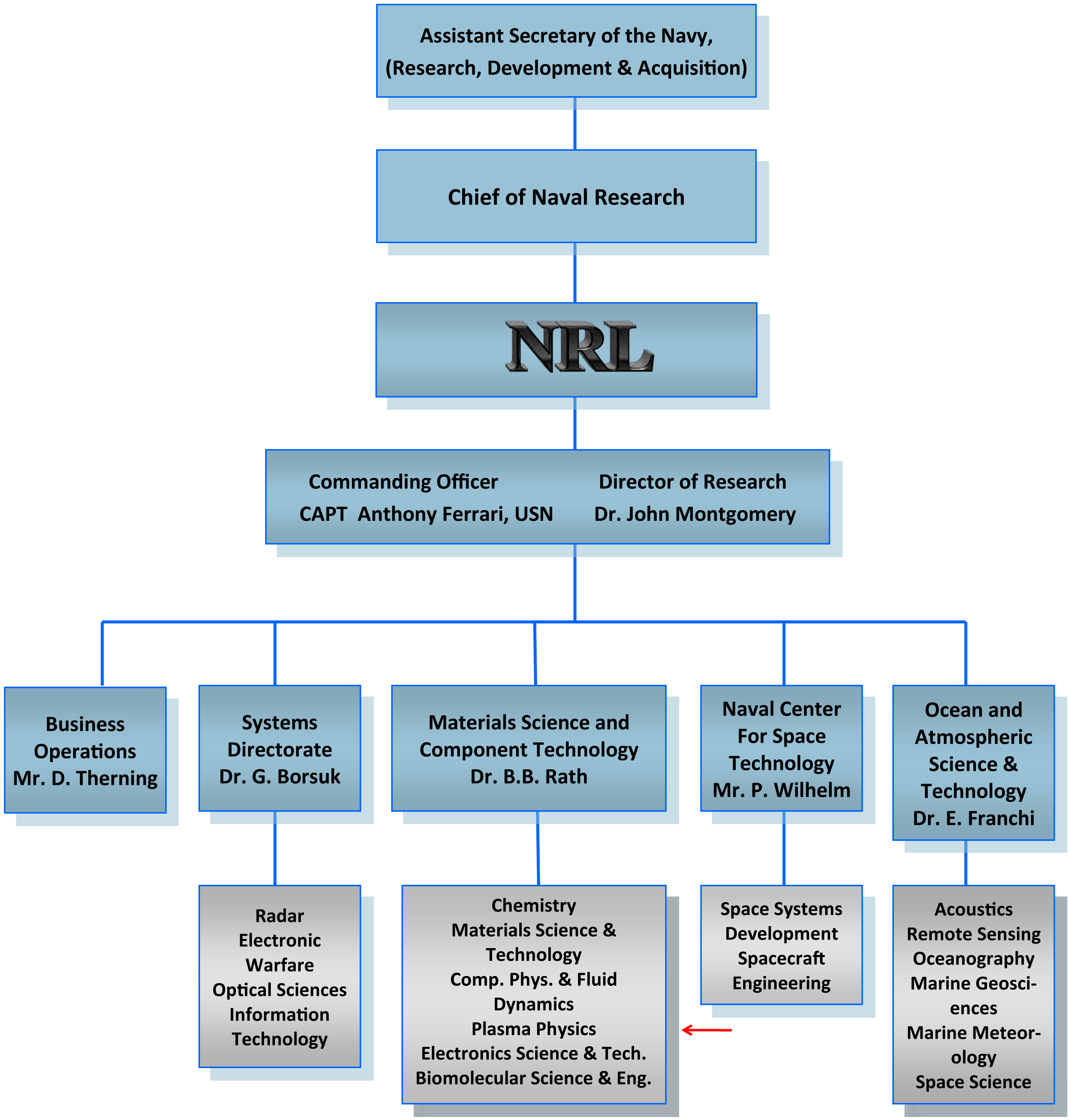
The Plasma Physics Division Mission

Conduct basic & applied research in plasma physics, space plasmas, intense electron & ion beams, radiation-atomic physics and magnetohydrodynamics, pulsed power, laser physics, inertial confinement fusion, EM acceleration, materials processing, spectral diagnostics, & nonlinear systems.

The research combines theoretical & computational modeling with both in-house & external experimental efforts.

The programs focus on providing benefit to the Navy & Marine Corps, as well as the broader S&T community, both nationally & internationally.

Plasma Physics is one of 18 NRL Research Divisions



Code 6700 Senior Management

PLASMA PHYSICS DIVISION

Dr. THOMAS A. MEHLHORN, SUPERINTENDENT

CODE 6700

Associate Superintendent
Dr. Richard F. Hubbard
Code 6701

Senior Scientist for Directed Energy Physics
Dr. Phillip Sprangle
Code 6703

Senior Scientist for Radiation Phys & High Energy Density Mat'ls
Dr. Jack Davis, Code 6705

Senior Scientist for Intense Beams & Plasma Processes
Dr. Gurudas Ganguli

Radiation Hydrodynamics Branch
Dr. John Giuliani
Code 6720

Laser Plasma Branch
Dr. Stephen Obenschain
Code 6730

Charged Particle Physics Branch
Dr. Robert Meger

Pulsed Power Physics Branch
Dr. Joseph Schumer

Beam Physics Branch
Dr. Joseph Peñano
Code 6790

X-ray driven gold targets

Dr. Jack Davis
Senior Scientist, Code 6705

Introduction

An atomic model for gold was constructed by NRL to investigate the femtosecond dynamics by which hole states are created and destroyed when an incident coherent, high intensity (>10^{17} W/cm2), x-ray laser pulse impinges on planar gold targets. There are two aspects to this modeling. One is the construction of a detailed atomic model of platinum-like gold inclusive of the large variety of atomic states that are formed from the inner-shell photoionizations of atomic gold. Second is the computation of the population dynamics that ensues when an x-ray pulse interacts with gold. The photoionization of gold, coupled with Auger and radiative decays in platinum-like gold, define the femtosecond dynamics of this model. A variety of hole states are simultaneously generated that depend on the intensity and wavelength of the driving x-ray pulse. The excited state populations reached during a few femtosecond timescales are high enough to generate population inversions, whose gain coefficients were calculated. They provide important diagnostics of the x-ray dynamics, and their generation suggests a nonlinear way, which is illustrated in this paper, of decreasing the wavelength of the coherent x-ray pulses that are generated during the dynamics relative to the wavelength of the input x-ray pulse.

Background

When gold is irradiated by a high intensity, high frequency x-ray pulse, a large number of inner-shell hole -states are generated in platinum-like gold. These states then decay either by radiative or by Auger processes. The Auger decays take place in femtosecond and sub-femtosecond time scale over which the inner -shell dynamics must be studied.

Accomplishment

A detailed non-equilibrium model was constructed to investigate this dynamics of gold. The atomic data needed in the model was obtained from the FAC code, and it included (1) a complete set of hollow-shell levels in Pt-like Au with energies up to 80 keV, (2) radiative and Auger decay rates of these states, and (3) photoionization cross sections of gold. The photoionization dynamics was driven by a range of incident x-ray pulses, and the excited state populations reached during the interaction were calculated. They produced a variety of population inversions and gain coefficients. Thus, the reemitted x-ray spectrum arising from the incident x-ray pulse, has unique features produced by the amplifications that are possible and by variations in the frequency and intensity of the incident x-ray pulse. Finally, by way of an example, a calculation was carried out for an incident photon energy of 3.973 keV and for a sufficiently high incident intensity, that demonstrated the possibility of a nonlinear, three photon absorption at 11.54 keV taking place that produced an amplified x-ray output pulse of higher frequency than that of the incident pulse. This work is submitted to Physics of Plasmas [1]. If a betatron driver is used instead of a single-frequency XFEL driver, amplification was computed for more than 10 transitions [2]. Amplified emission was observed experimentally in optical range when the light from KrF laser impinges on a gas of xenon clusters. The experiments were performed by a group at the University of Chicago, modeled by the NRL group and published in a series of papers [3-6].

Significance

A non-equilibrium radiation model was developed to study x-ray amplification from x-ray driven gold. We determine that FEL x-ray lasers in turn can produce other x-ray lasers, which add to the tunability of the overall facility. Experimentally, there are no yet capabilities to generate coherent x-rays at such high energies and the goal of our work was to establish the conditions at which such x-ray amplifications will occur.

Application

The study of the interaction of a laser pulse with gold targets is important for numerous application such as: indirect-drive inertial confinement fusion, ion acceleration, high-resolution K-shell and L-shell spectroscopy, non-linear x-ray studies, different range of x-ray drivers, micro machining, x-ray production, synchrotron and K_α radiation for bio- and medical applications, etc.

load material into the K-shell then the observed power will likely correlate with the electron temperature. If the load can be designed to attain a high electron temperature in a small region this would optimize the total K-shell yield of interest.

Key Personnel

Tzvetelina B. Petrova and George M. Petrov
K. Whitney from Berkeley Scholars, Inc.

References

[i] Tz. B. Petrova, K. G. Whitney, and J. Davis, submitted to Phys. Plasmas.
[ii] J. Davis, K. G. Whitney, and Tz. B. Petrova, submitted to Phys. Plasmas.
[iii] Tz. B. Petrova, K. G. Whitney, and J. Davis, J. Phys. B: At. Mol. Opt. Phys. 43, 025601 (2010); J. Phys. B: At. Mol. Opt. Phys. 44, 125601 (2011).
[iv] Tz. B. Petrova, J. Davis, K. G. Whitney, and G. M. Petrov, HEDP 8, 209(2012).
[v] J. Davis, K. G. Whitney, Tz. B. Petrova, and G. M. Petrov, HEDP 8, 238 (2012).
[vi] K. G. Whitney, J. Davis, Tz. B. Petrova, and G. M. Petrov, Phys. Rev. A 85, 063408 (2012).

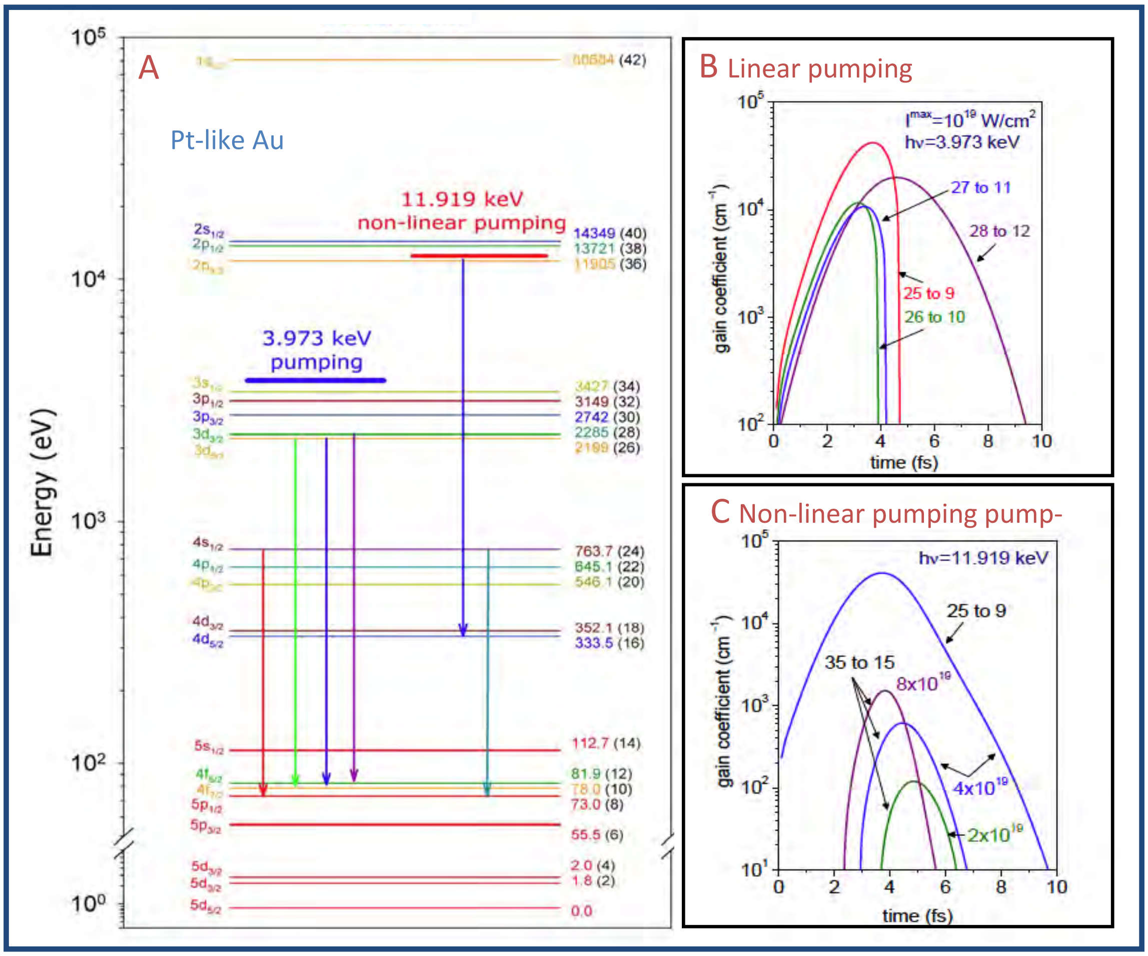


Fig. Energy level diagram of the inner shell (n,l) hole states of Pt-like gold. Gain coefficients as a function of time for x-rays with wavelength ~5 and ~1 Å.

Sponsor: DOE, NNSA, 6.1 Base Program

Intense Beams & Plasma Processes

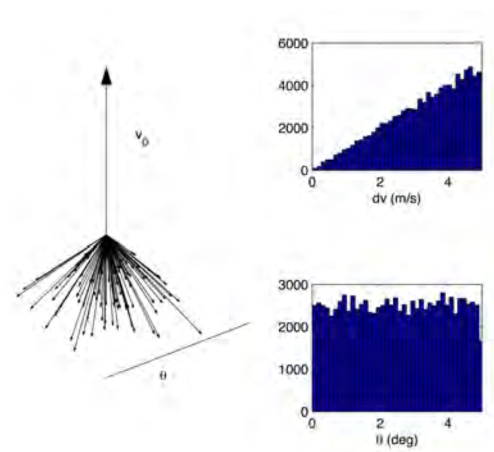
Dr. Gurudas Ganguli
Senior Scientist, Code 6709

Protection of Space Assets

Space Superiority and Securing the Ultimate High Ground

Harnessing plasma physics processes in the space environment to actively mitigate hazardous conditions for critical DoD space assets is a new frontier in science and technology. Satellite enabled capability is now considered indispensable to DoD operations and modern society in general. Extreme space conditions, e.g. formation of deadly radiation belts, can naturally occur due to large solar eruptions or man-made causes such as high altitude nuclear detonation or salvage fusing of incoming warheads. These conditions can damage or destroy critical space assets. With proliferation of weapons of mass destruction and launch capability, the vulnerability to US space assets has increased. Space defense systems are necessary to counter this threat to effective and efficient DoD operations. Practical implementations of space environment remediation technologies are emerging from basic research in Code 6709. Research indicates that enhanced radiation belts can be mitigated by artificially generating and amplifying electromagnetic waves in the right spectrum by exploiting the properties of the space plasma environment and utilizing them to pitch angle scatter the 'killer' trapped electrons out of the radiation belts. The properties of the natural radiation belts are being carefully studied to learn how nature regulates the radiation belts in order to refine and design better active remediation concepts.

In particular, data from the recently launched NASA/Van Allen Probes offer the possibility of validation of the nonlinear radiation belt models that are being developed. The first weak turbulence based radiation belt whistler propagation model has been developed by incorporating the effects of nonlinear scattering into a ray tracing code. This is a significant improvement over the mainline radiation belt ray tracing models based on a linear description of the small amplitude waves and will lead to a more accurate description of the radiation belt properties. The linear theory becomes insufficient when the wave amplitudes become large especially during disturbed times. Among the major new revelations is that with increasing amplitude of waves, the induced nonlinear scattering becomes a major contributor to the plasma dynamics in the radiation belts. It can lead to the formation of a long-lasting energy reservoir within a magnetospheric cavity filled with whistler energy. Repeated scattering within the cavity maintains the waves with low obliqueness making it efficient for pitch angle scattering. The wave-particle interaction time is now the turbulence lifetime inside the cavity, which is much longer than the single pass wave-particle resonance time possible when nonlinear scattering is neglected. This can lead to a shorter lifetime of the trapped energetic electrons that are known to damage on orbit space assets. In addition, a new suite of analysis tools to investigate the distribution of wave energy as a function of the three dimensional wave-vector in turbulent anisotropic plasmas as well as tools for investigating the properties of coherent waves from single-point measurements of the electromagnetic field vector have been developed. These tools are important for diagnosing wave data from space experiments (Van Allen Probes) and for laboratory experiments in the NRL Space Chamber.



Initial Distribution of Delta V for First Release of Dust Particles in Simulation that lead to formation of ring of Tungsten dust particles within a month.

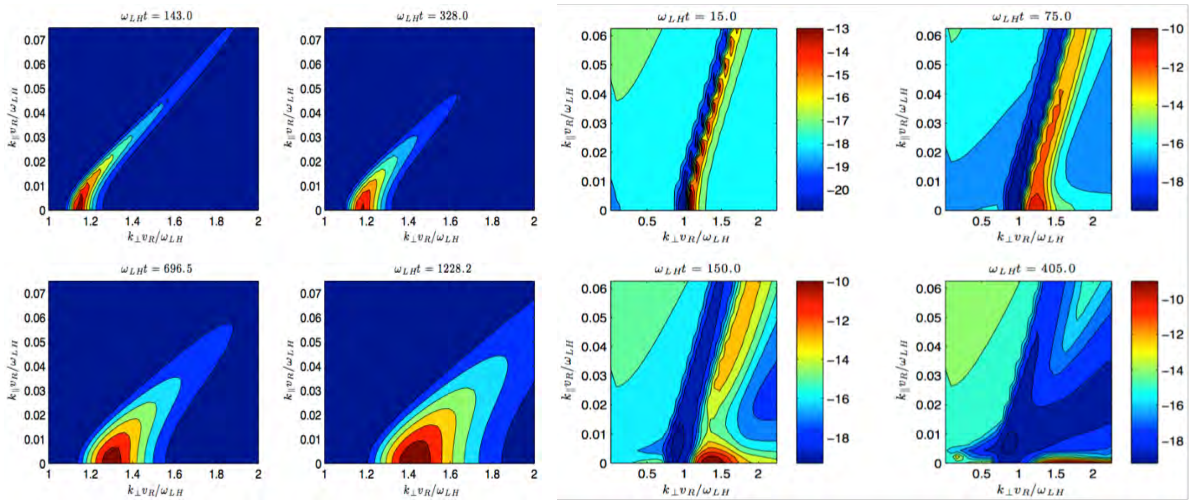
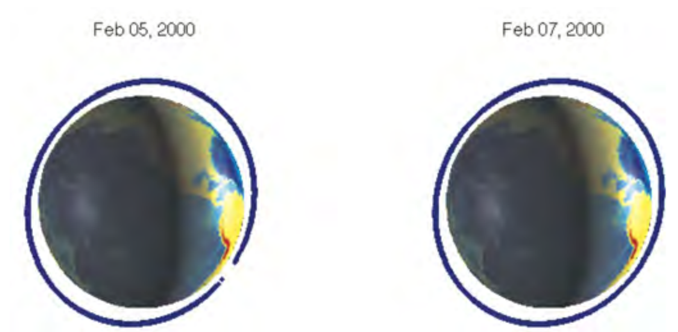


Figure (left) Plasma evolution in the standard quasi-linear radiation belt model shows that wave energy remains in k-space where it was deposited. Fig. (right) The nonlinear model shows dramatic difference due to redistribution of energy in k-space by nonlinear scattering resulting in measurable macroscopic effects: i) increase of propagation angles, ii) waves become more electromagnetic, iii) formation of a radiation belt cavity with amplified whistler waves, iv) enhancement of pitch angle scattering, and v) shorter lifetime of the trapped population.

Threat to satellites also exists from impact with orbital debris. Code 6709 is also developing the science base to remove small orbital debris, which cannot be individually tracked and evaded, by artificially increasing the drag on the debris in a limited region of space. Research indicates that it is possible to deploy dust in a narrow altitude band and use the Earth's natural atmosphere to decay the dust orbits while simultaneously exploit the descending dust layer to induce artificial drag enhancement to the debris situated at altitudes below the dust layer. In effect, this creates a sweeping snow-plow-like effect on the orbital debris and decays their orbits to force premature reentry. The injected dust will also reenter the earth's atmosphere.

Efficient methods to release tungsten dust particles in a nearly circular orbit at an altitude directly above the majority of orbital debris has been developed and currently undergoing laboratory tests. The orbital mechanics of the dust was studied in detail to ensure the integrity of the deployed ring for long durations (several years) under expected fluctuations and seasonal variations in the background parameters. Effects of various forces on dust orbit including, nonuniform gravity, solar radiation pressure, solar cycles as well as solar and lunar gravity, and dust charging effects, etc., were individually analyzed. Then a reduced force model was developed to enable the computation of hundreds of thousands of orbits. A candidate release scheme was developed that allows the formation of the ring approximately one month after the release. Tolerances on the manufacture of the dust were also determined, indicating potential trade-offs in efficiency versus manufacturing costs. The calculations reveal that a coherent ring can form around the earth of appropriate dimensions that persists for the duration of the mission. The calculations also reveal that the uniformity of particle dimensions must be maintained for the ring particles not to disperse in altitude.

(left) 34 Days after final release the ring is almost complete. (right) 36 Days after final release the ring is complete.



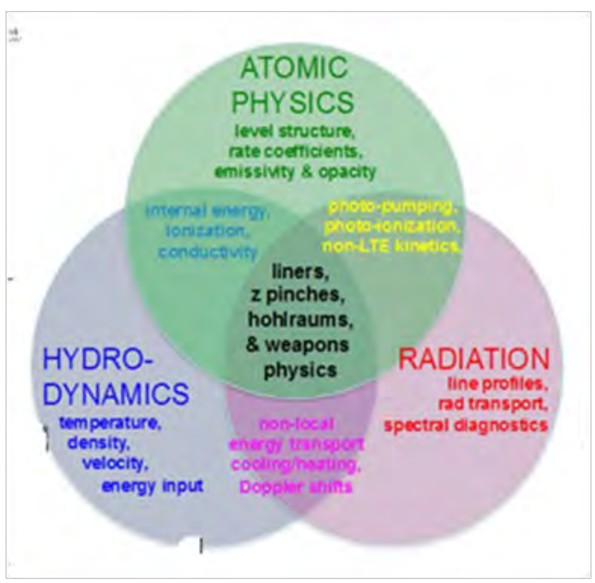
Radiation Hydrodynamics Branch

Dr. John Giuliani
Branch Head, Code 6720

The Radiation Hydrodynamics Branch, Code 6720, is focused on understanding High Energy Density (HED) plasmas produced by pulsed power generators or high intensity, short pulse lasers. Over the years the Branch has made significant contributions to the design, development, prediction, and analysis of intense plasma radiation sources from HED plasmas resulting from a Z-pinch implosion driven by multi-megampere pulsed current generators. In addition there is ongoing work in conjunction with Code 6705 on the interactions of a ultra intense short pulse laser with a thin planar target. This configuration produces high energy beams of protons, ions, or even neutrons from the rear of the target. This research on radiation sources and accelerated ions is primarily implemented through numerical simulations and diagnostic analysis. HED plasmas are far from local thermodynamic equilibrium and can only be properly modeled by accounting for the interplay between atomic physics, hydrodynamics, and radiation transport. Expertise within the Branch exists in each of these subfields, and the simulation capability arises from the combined efforts of the scientific members.

Figure 1. A Venn diagram schematic of the research performed in the Radiation Hydrodynamics Branch. A number of first principles atomic physics codes represented by the top circle is employed to generate a data base for specific elements. This data base contains the atomic level structure, ground and excitation states, in all ionization stages of the element. The atomic physics codes also calculate rate coefficients for collisional and radiative process, such as electron impact excitation, that connect the atomic levels. The insert in the upper left of the figure is a schematic of these connective processes. To compute the populations in each of the levels also requires photonic processes, which are driven by photons from the entire plasma. This non-local interaction requires treatment of radiation as depicted in the right circle. The coupling with atomic physics is through radiation transport leading to photo-pumping and photo-ionization. Furthermore, the coupling manifests itself in the emitted spectrum, an example of which is shown in the upper right. When an element is so ionized that only two or fewer electrons remain bound, the emitted high energy radiation is from the K-shell. The shells in the Bohr atom model displayed below the spectrum is color coded to the photon energy in the various components of the spectrum. Spectral analysis of the emitted spectrum from a plasma allows one to infer properties of the plasma under investigation. The three dimensional nature of radiation transport is indicted by the sample ray in the lower right insert. Continuing around the Venn diagram, the radiative cooling or heating due to absorption impacts the hydrodynamics of the plasma, contained in the left circle. The work in the Branch considers several mechanisms of energy input to the plasma. One mechanism is a wire array z-pinch that implodes due to the JxB force of the axial current into a hot, dense column, as shown in the lower left. Another input mechanism under study is an intense femtosecond laser directed at a thin target. The hydrodynamics, or magneto-hydrodynamics in the case of a Z-pinch, changes the density and temperature of the plasma, which in turn changes the atomic processes, such as collisional ionization.

Thus the three physics components of atomic physics, radiation, and hydrodynamics are coupled in a non-linear manner. The interrelated combination of the three distinct realms of fundamental physics are central to the understanding of liners, pinches, radiation hohlraums, and weapons physics.



Determining the nature of intense x-ray "bright spots" in Z pinches

Dr. Joseph Ward Thornhill, Code 6721

Introduction

To shed light on the nature and physics of "bright spots" in Z pinch plasmas, axially resolved K-shell spectra from 4 Z pinches driven by the Z generator at Sandia National Laboratories were analyzed for their properties. The atomic numbers of the loads varied from 13 to 29. We find that higher spatial K-shell intensity in the Al pinch correlates with density. The K-shell intensity within a copper shot taken on ZR correlates strongly with increased electron temperature, but another, somewhat less well-diagnosed copper shot from Z shows correlation with density. The bright spots in a Ti pinch correlate with neither density nor temperature, but do correlate with the product of density and diameter (proportional to opacity). This opacity correlation is also observed in the other three pinches, along with their temperature or density correlations.

Background

Z pinches are the most powerful and energetic laboratory source of x-rays, and as such are a unique resource for materials studies that include applications such as radiation hardening of electronics and optical coatings. Localized, intensely radiating regions are often observed in Z pinches. High resolution images of such areas have been recorded at least as far back as the 1970s. However, there is as yet no widely accepted consensus on the nature of these "bright spots" or how they are formed. This phenomenon has also been referred to "hot spots" or "micropinches". In some experiments these "bright spots" may be the dominant contributor to the overall K-shell yield.

Accomplishment

K-shell spectra of the four Z pinches were analyzed to obtain electron temperature and electron density of the spots using calculated isocontours of K-shell power and ratios of K-shell line intensities. The experimental data were obtained from axially resolved spectra. Because of the spatial resolution the data could be examined in a number of slices, typically about twenty, along the z-axis. For each of the pinches statistical correlations were examined between the K-shell power and the ion density, the electron temperature, and the opacity. Images of the pinches provided information on the location of the "bright spots" within each slice. For the load material with a low atomic number (Al, 13), the K-shell power was correlated with the mass density. For the load material with the highest atomic number (Cu, 29) the correlation of the K-shell power is with the electron temperature in the best quality data. For an intermediate atomic number material (Ti, 22) the K-shell power is correlated neither with density nor with temperature, but rather with optical depth (opacity) of the K-shell emitting region.

Significance

Since the "bright spots" are the most intense radiating regions within the pinch, it would be desirable to be able to produce more of them and/or control their evolution and conditions. The first step toward doing this is to understand their origin and properties. The present work has shown that the "bright spot" phenomenon in Z pinches does not appear to have a single explanation but arises under different conditions depending on the load material and the current in the pulsed power driver. It is possible that sometimes, large differences in conditions attained by stagnated Z pinches are due to relatively small differences in initial and early time implosion conditions. For wire array loads like the ones analyzed in the present work, the complexity and characterization of early time conditions (including ablation and the formation of on-axis precursor plasma) has made prediction of detailed conditions at stagnation difficult. Lacking such a total capability, semiempirical scaling models (based on self-consistent radiation models) have successfully been employed to predict K-shell yields and design wire array loads for a variety of elements, without needing to predict the precise imploded density and temperature profiles.

Application

Radiation sources with photons in the range of 10 – 20 keV are of interest for several applications in DoD. There is the potential of using a Z pinch to implode high atomic number materials and produce K-shell line emission in this domain. If the current in the generator is just sufficient to ionize a small amount of the load material into the K-shell then the observed power will likely correlate with the electron temperature. If the load can be designed to attain a high electron temperature in a small region this would optimize the total K-shell yield of interest.

Key Personnel

John P. Apruzese and J. Ward Thornhill

Acknowledgements: Sandia National Laboratories.

References

[i] "Analysis of spatially resolved Z-pinch spectra to investigate the nature of "bright spots", J. P. Apruzese, J. L. Giuliani, J. W. Thornhill, C. A. Coverdale, B. Jones, and D. J. Ampleford, Physics of Plasmas, vol.20, p.022707 (2013).

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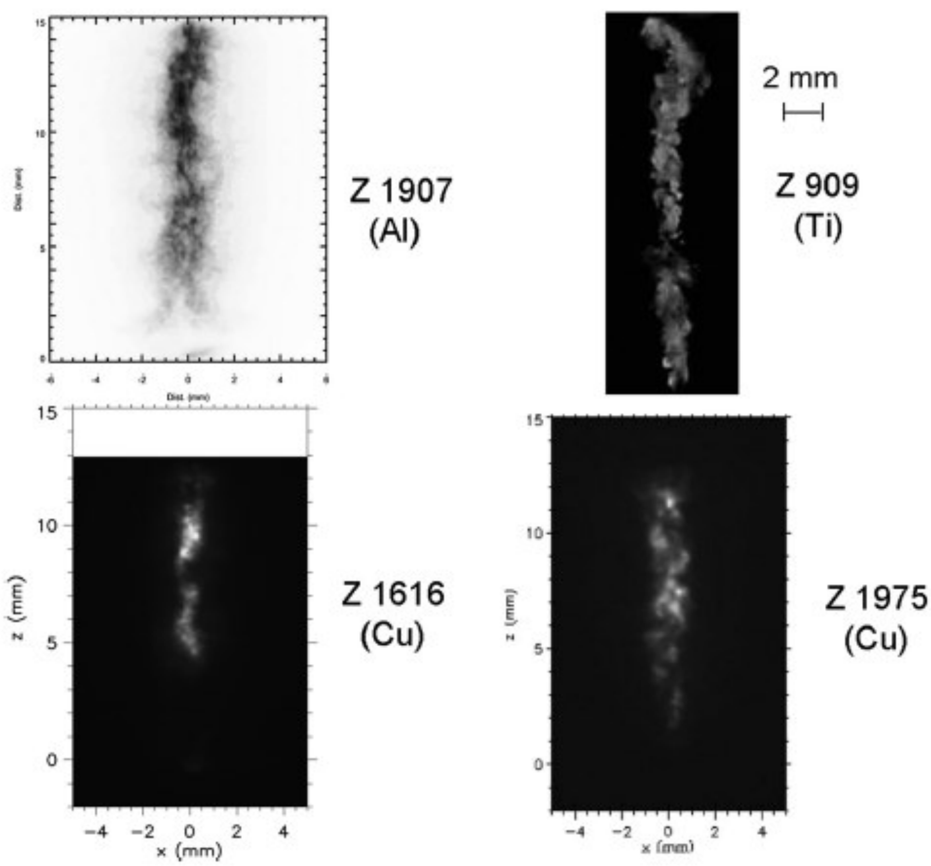

Fig. X-ray pinhole images of 4 different Z pinches filtered to show the "bright spots" of K-shell emission near the time of peak power. Shot Z1907 is a negative, the other three are positives.

Sponsor: DOE, NNSA

K-α spectroscopic analysis from a Cu Z Pinch

Dr. Arati Dasgupta, Code 6720

Introduction

Experiments at the Sandia National Laboratories' (SNL) Z facility can be utilized to test complex theories and models of x-ray production. The 20 MA Z accelerator is the most efficient producer of multi-kilovolt x-rays in the 1-20 keV range. Recent significant improvements in diagnostic techniques on the Z accelerator's wire-array and gas-puff load configurations stimulated investigations of K-α spectroscopy of high Z materials (such as Cu) by the Radiation Hydrodynamics Branch at NRL. These nested wire array Cu K-α spectra provide a wealth of information about the implosion dynamics and ionization history of the pinch. K-α emissions occur when K-shell vacancies are created from inner-shell excitation and ionization by thermal and hot electrons as well as by high-energy photons emitted within the implosions. These vacancies are subsequently filled by Auger decay or resonance fluorescence; the latter gives rise to the K-α lines. A 1-D non-LTE radiation hydrodynamics model of NRL has been employed to analyze the ionization dynamics and K-α spectra using the conditions in the Z accelerator. Detailed excited state atomic modeling with self-consistent coupling of radiation transport provide accurate predictions of spectral energies and emissivities of K-α emission that compares very well with Z spectroscopic data.

Background

X-ray emission spectra from the K- and complex L-shell of high Z ions provide valuable information with which to assess plasma conditions and X-ray performance in a variety of laboratory plasmas such as z-pinch plasmas. The Z machine produces up to 250 TW and 1.8 MJ of radiation by driving 22 MA of current with a 100 ns rise time through a cylindrical array of several hundred fine wires or a gas puff. The self-generated jXB force implodes the materials, creating a high-energy-density (HED), radiating plasma column on the axis of symmetry and the emitted radiation is mostly X-rays. The theoretical approach for the study of energetics and spectroscopic diagnostics of this non-LTE (NLTE) HED plasma has three critical components; atomic physics, radiation transport and magneto-hydrodynamics. The Radiation Hydrodynamics Branch has the unique capability to couple all three components simultaneously and in equitable state-of-the-art treatments. We employ a full NLTE collisional radiative equilibrium (CRE) method for ionization balance; a full time-dependent treatment of the atomic populations is also possible with our model. A simulation of the doubly-nested copper wire-array SNL shot Z1975 was performed with the DZAPP code to investigate the K- and L-shell lines as well as K-α lines of Cu, Ni, Fe, and Cr present in the Z experimental spectra. The DZAPP radiation hydrodynamics code is a 1D coupled MHD, detailed non-LTE atomic physics and radiation transport code, incorporating a transmission line circuit model, developed for the simulation of z-pinch implosions. K-? emission is associated with 2p→1s inner-shell-electron radiative transitions in highly charged ions. Using atomic population data from a full simulation of experimental data of Z1975 on the Z generator, we calculated K-α radiation due to inner-shell vacancies created by energetic electrons (including electron beams) produced by the processes of radiationless electron capture (dielectronic recombination) and inner-shell electron collision processes as well as photoexcitation and photoionization. The resulting spectra show excellent agreement for the K-α radiation in each of the modeled elements (both in energy positions and intensities) when compared to the Z1975 data.

Accomplishment

Recently Dr. Dasgupta and other members of the Radiation Hydrodynamics Branch analyzed K-α emission from a Cu/Ni wire array load from the Z facility by investigating both photoionization (fluorescence) and hot-electron collisional ionization processes using a combination of collisional-radiative and radiation-hydrodynamic models. It was concluded from this research that the spatial distribution of K-α emission can help distinguish between non-thermal and fluorescence effects. K-shell vacancy production from fluorescence and e-beams were large compared to that due to thermal electrons. This study indicates that both electron beams and photo-processes are responsible for creating the K-shell vacancies that are filled by K-α emission. Similar methodology has been used by researchers at SNL to analyze recent experimental data from the Z accelerator that have included high-energy inner-shell K-α emission from molybdenum wire array z-pinches. Our analysis of K-a lines can be used as an additional diagnostic tool for understanding the dynamics of a z-pinch and for uncovering the dominant atomic processes in these plasmas.

Significance

NRL has successfully demonstrated the capability to predict X-ray diagnostics using state-of-the-art atomic and plasma modeling of high energy density plasmas, such as from z pinches at the Z accelerator in SNL.

Acknowledgements: Sandia National Laboratories.

Application

Spectroscopic studies of K-shell radiation with inner-shell K-α emission have uses from basic fundamental plasma research to radiation effects testing. Theoretical analysis of K-α emission built on experimental spectroscopy from z-pinches spotlight the underlying atomic and plasma physics and offer inertial confinement fusion and laboratory astrophysics applications under similar temperature and density conditions.

Key Personnel

Arati. Dasgupta, Nicholas D. Ouart and Robert W. Clark

References

[i] "K-α emission spectroscopic analysis from a Cu Z-pinch", A. Dasgupta, R.W. Clark, J. L. Giuliani, N.D. Ouart, B. Jones, D. J. Ampleford and S.B. Hansen, High Energy Density Physics 9 (2013) 347-353.

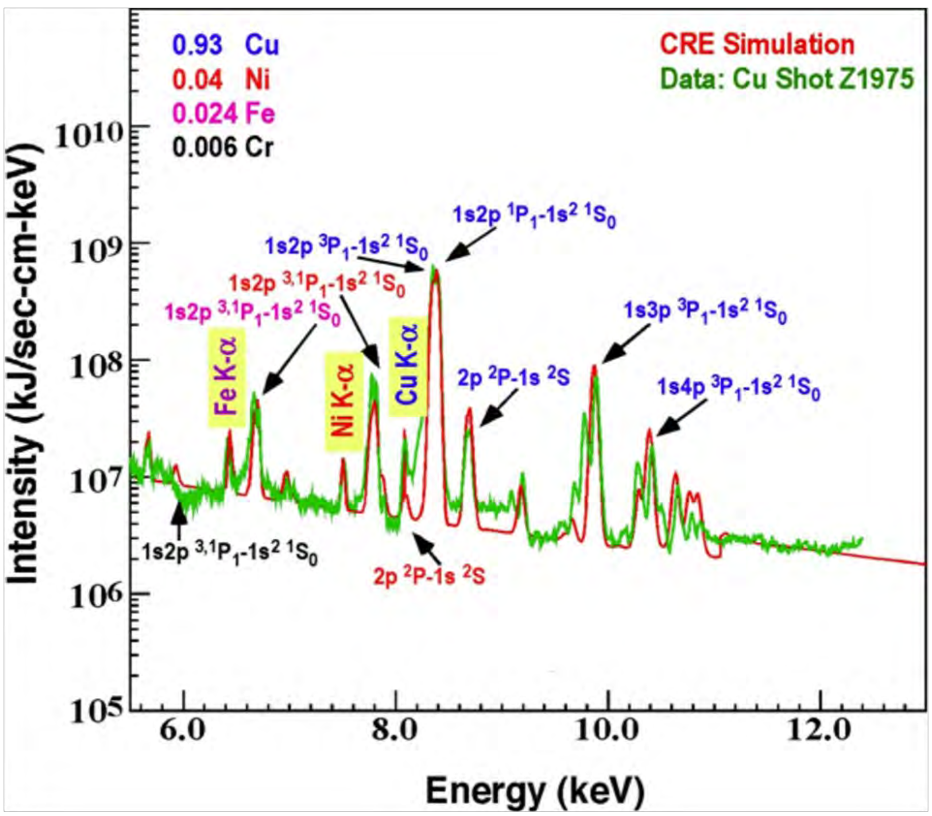

Fig. Time-integrated K-shell spectra of Cu, Ni, Fe, and Cr including L-shell K-α lines from Cu, Ni, and Fe. Most of the K-α lines are generated by assuming 1% e-beam. The fractional abundance of each species in the pinch is listed in the upper left corner.

Sponsor: DOE, NNSA

Effective vs Thermal Ion Temperatures in Z Pinches: Modeling for Stagnation Physics

Dr. John L. Giuliani, Code 6720

Introduction

The difference between the ion thermal and effective temperatures was investigated through simulations of a neon gas puff Z pinch reported by the Weizmann Institute of Science. Calculations are performed using the two-dimensional, non-local thermodynamic equilibrium (non-LTE), radiation-magnetohydrodynamic (MHD) code, Mach2-TCRE. The extensive data set of imaging and K-shell spectroscopy from the experiments provides a challenging validation test for Z-pinch simulations. Synthetic visible images of the implosion phase match the observed large scale structure if the breakdown occurs at the density corresponding to the Paschen minimum. At the beginning of stagnation (-4 ns), computed plasma conditions change rapidly showing a rising electron density and a peak in the ion thermal temperature of ~1.8 keV. This is larger than the ion thermal temperature (< 400 eV) inferred from the experiment. By the time of peak K-shell power (0 ns) the calculated electron density is similar to the data and the electron and ion thermal temperatures are equilibrated, as is observed. Effective ion temperatures are obtained from calculated emission line widths accounting for thermal broadening and Doppler velocity shifts. The observed, large effective ion temperatures (~4 keV) early in the stagnation of this Ne pinch can be explained solely as a combination of compressional ion heating and steep radial velocity gradients near the axis.

Background

In a Z pinch the voltage across a wire array or gas puff initiates a breakdown, whereupon the axial current (J) through the plasma produces an azimuthal magnetic field (B), and the resultant inward radial force (JxB) compresses the material onto the axis. During the implosion the plasma accelerates and acquires kinetic energy that is subsequently converted to internal energy during stagnation. The physics of stagnation and thermalization is of keen interest whether the application is K-shell radiation sources, neutron sources, or pinch driven hohlraums for inertial confinement fusion.

Sponsor: DOE/NNSA

Accomplishment

The neon gas puff Z pinch experiments conducted at the Weizmann Institute of Science provided detailed results from a collection of imaging and spectroscopic diagnostics. Such an extensive data set has never been accomplished before, and was possible because the experiments were at the 1 MA current level and could be repeated many times in a single day. After extensive comparisons and careful measurements of the initial density in the gas puff, the radiation-MHD simulations performed by NRL matched quite well the data from the diagnostics. An example is given in the visible imaging during the implosion in the associated figure. This agreement provided strong validation of the numerical code, including the treatment of non-equilibrium ionization population kinetics and radiation transport. This accomplishment further enhances the reputation of NRL in terms of its knowledge and ability to model complex plasma radiation MHD behavior as well as demonstrated the capability throughout the DOE/NNSA/DOD community.

Significance

The observations of excessive effective ion temperatures in Z pinches dates back over 15 years. Such data is obtained from spectral measurements of emission line widths and was found to be incompatible with numerical simulations. Detailed measurements of the plasma conditions in the neon gas puff indicated that the line widths were not due to thermal Doppler broadening and were attributed to unknown hydrodynamic, possibly turbulent, motion. In the present work, the simulations were analyzed in a similar way to the diagnostic, i.e., synthetic spectra were calculated based on a non-equilibrium calculation of the double excited atomic levels and the radiation transport through the plasma was accounted for. The result of this research showed that the discrepancy between the true thermal temperature and the effective one from line widths is due to an interplay between thermalization of the ion kinetic motion at stagnation into heat and steep velocity gradients in the radial velocity near the axis of symmetry. This result was not expected but demonstrates, based on fundamental MHD physics and atomic physics, remarkable agreement with the data.

Application

Within the DoD there is a need to develop intense radiation sources with high (keV) photon energies to test the reliability of electrical and other components in space systems against attack and blinding by nuclear weapons. Z-pinches on large pulsed power generators with 10 – 20 MA have provide the strongest sources for these tests. Understanding the fundamental physics of pinch stagnation and radiation production reveals optimal source conditions without recourse to an expensive series of exploratory shots.

Acknowledgements

Weizmann Institute of Science, Rehovot, Israel.

Key Personnel

J.Ward Thornhill. Arati Dasgupta, John P. Apruzese, Alexander L. Velikovich, Robert Clark, Young K. Chong, and Thomas A. Mehlhorn.

References:

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Yu. Zarnitsky, V. Bernshtam, A. Fisher, T. A. Mehlhorn, and C. Deeney. Submitted to Physics of Plasmas, August, 2013.

[ii] "Effective vs ion thermal temperatures in the Weizmann Ne Z-pinch: modeling and stagnation physics", J. L. Giuliani, J. W. Thornhill, E. Kroupp, D. Osin, Y. Maron, A. Dasgupta, J. P. Apruzese, A. L. Velikovich, Y. K. Chong, A. Starobinets, V. Fisher,

Yu. Zarnitsky, V. Bernshtam, A. Fisher, T. A. Mehlhorn, and C. Deeney. Invited presentation at Sandia National Laboratories, June 26, 2013.

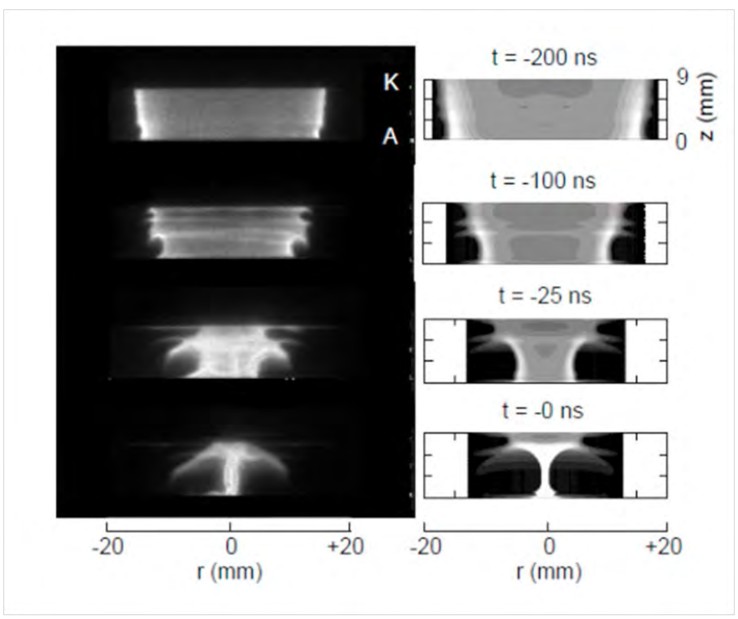


Fig. Experimental images on the left of a neon pinch during implosion and synthetic images calculated from the radiation MHD simulation on the right. The times in nanoseconds prior to stagnation on the right correspond to the same times on the left images.

Laser Plasma Branch

Dr. Steve Obenschain
Branch Head, Code 6730

The Laser Plasma Branch has research efforts in the science and technologies of laser fusion, the development and applications of high-power pulsed electron beams and the development of detection mechanisms for biological, chemical and explosive hazards.

Laser fusion and basic laser target interaction research

The Branch supports the Department of Energy's Inertial Confinement Fusion (ICF) program. This work includes: 1) conducting high-intensity laser-target interaction experiments using the NRL Nike krypton-fluoride (KrF) laser facility and other ICF facilities, 2) developing advanced radiation hydrocodes and the theory of laser target interactions, 3) conducting simulations of laser target interactions in support of experiments and to design robust high -performance targets for inertial fusion and 4) advancing the krypton (KrF) laser technology for inertial fusion and basic high-energy density experiments. Nike is the world's largest KrF laser and can provide up to 3 kJ on target. Experiments include basic studies of hydrodynamic instabilities of laser-accelerated planar targets, high pressure shocks, radiation from laser irradiated targets and laser plasma instabilities. The KrF laser has distinct advantages for ICF experiments including deeper UV wavelength (λ=248 nm) and its capability to provide both extremely uniform illumination of a target and to change the diameter of the focused light during the laser pulse. In addition to ICF work the Nike facility has used to simulate certain aspects of underground nuclear tests in collaborative experiments with scientists from Lawrence Livermore Laboratory.

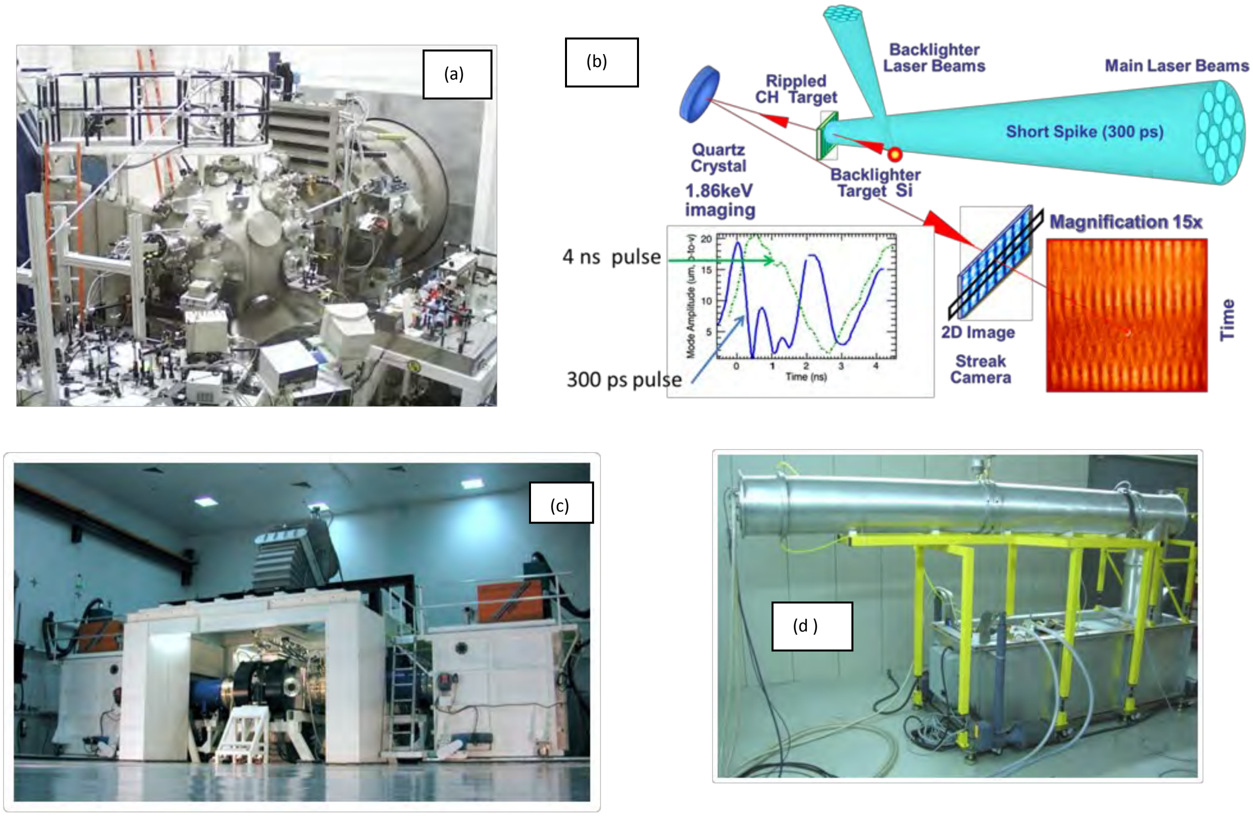
The FASTRAD3D hydrocode supports the experiments and also is the primary tool for designing direct drive ICF targets. FASTRAD3D is a 3D massively parallel Eulerian-based radiation-hydrodynamics code that includes a variety of shock-capturing hydrodynamic algorithms, a real equation of state, LTE and non-LTE multigroup diffusion radiation transport, alpha particle transport, either flux-limited or non-local electron thermal conduction modeling, and laser inverse bremsstrahlung absorption and ray-tracing packages. It has been benchmarked on problems of specific interest in direct-drive ICF, including planar (NIKE and Omega) and spherical (Omega) implosion experiments, and used in high resolution 2D mode to design direct-drive ICF targets for the National Ignition Facility.

High power pulsed electron beams

The Branch has developed high-power pulsed electron beam diodes for a 700 J KrF facility called Electra that can operate for hours at 5 pulses per second. Branch scientists and Engineers are exploring alternate uses for the electron beams including: enhancement of the surface hardness and corrosion resistance of components used by the Navy, and use of electron beams to catalyze chemical reactions. The research includes development of long-lived efficient electron-beam diodes and pulse power systems.

Detection of biological, chemical and explosive hazards

The branch has developed and patented a detection instrument called the Swept Wavelength Optical resonant-Raman Device (SWOrRD). This device interrogates an unknown sample with a sequence of as many as 100 laser wavelengths and measures the spectrum of light scattered from the sample at each laser wavelength. The assembly of scattered light-spectra constitutes a two-dimensional signature of the sample from which the components of the sample can be determined, with an appropriate algorithm. SWOrRD enables rapid detection and identification of bacteria, chemicals, and explosives in complex situations such as the in environment, in hospitals, food production lines, or on the battlefield.



Branch Facilities: (a) Nike target chamber, (b) experimental set up to measure ablative Richtmyer Meshkov instability where a laser accelerated target is backlit by laser produced x-rays to detect growth of areal mass nonuniformity , (c) the Electra high-repetition rate KrF amplifier (d) 250 kV 5 kA 10Hz pulse generator utilizing all solid state switches.

Sponsors: DOE-NNSA, ONR, DTRA

Swept-wave resonance Raman detector characterizes bacteria

Dr. Jacob Grun, Code 6730.2

Introduction

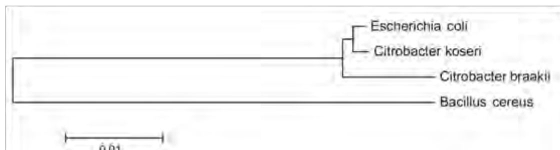
Swept-wave resonance-Raman spectroscopy was used to identify the effects of growth phase and growth medium on bacteria. Gram-positive and Gram -negative bacteria were grown to logarithmic and stationary phases in two different growth media. Spectra of bacteria were obtained at multiple deep-ultraviolet wavelengths between 220 and 260 nm; a range which encompasses the resonance frequencies of cellular constituents. We find that spectra of the same bacterial species exhibit differences due to both growth condition and growth phase, but the largest changes are due to growth phase. Moreover, the differences in the Raman spectra correlate with genetic differences among the species. Using a Pearson correlation based algorithm, we achieve successful identification of unknown bacteria in 83% of the cases.

Ultraviolet resonance Raman spectroscopy is developing into a reliable tool that allows for rapid and reagent-less identification of micro-organisms. Resonance Raman spectra of bacteria, which arise from constituent aromatic amino acids, nucleic acids, and other UV absorbing chromophores, have been used to elicit information about bacterial growth phase, Gram type, genus and species, as well as molar ratios, and antibiotic response.[1-13] Measuring resonance Raman spectra at multiple illumination wavelengths increases the amount of information available for identification because it not only captures Raman features that are resonant at specific wavelengths but also provides information about the variation of scattering cross-sections as a function of wavelength. Multiple-wavelength resonance Raman spectroscopy has been demonstrated to offer significant advantage over conventional Raman spectroscopy in distinguishing between different types of bacteria and chemicals, especially when they are present in complex mixtures. [14, 15]

We studied four bacterial species - *Escherichia coli*, *Bacillus cereus*, *Citrobacter koseri*, and *Citrobacter braakii*- in their log and stationary growth phases cultured in two different media – nutrient broth and Brain heart infusion (BHI) broth to understand differences between them. Resonance Raman spectra were acquired at 9 different deep-UV wavelengths between 220 nm and 260 nm. In this range some illumination wavelengths interact preferentially with nucleic acids, while others interact preferentially with protein bonds, enabling us to identify the biological conditions responsible for the differences.

Multiple two-dimensional signatures were obtained for all bacteria and averaged. Difference maps were calculated from the averaged signatures to understand changes due to growth culture. Representative signatures of *E. coli* are shown in Figure 1. Several differences were observed between log- and stationary-phase cells. The relative ratio of peak intensity at 1485 cm^{-1} compared to 1616 cm^{-1} is higher in log-phase cells and increases as the excitation wavelength is changed from 232 nm to 248 nm. This ratio did not appear to depend on Gram status. The 1485 cm^{-1} peak derives from adenine and guanine bases while the 1616 cm^{-1} peak can be attributed to tyrosine and tryptophan present in protein. This is consistent with the fact that cultures in the log phase have greater ribosomal RNA content and nucleic acid/protein mass ratios.[16] While the principal biochemical peaks were identical for bacteria are grown in different media, minor changes were observed in the intensities at several wavenumbers - 1009, 1180, 1336, 1462, 1485, 1554, 1579, 1614, 1624 and 1658 cm^{-1}.

We examined the correlation of two-dimensional spectroscopic Raman signatures with the genetic relatedness among species calculated using16S rRNA sequences. [17] Root mean squared differences were calculated between every pair of bacteria in the stationary phase in BHI growth. Clustering patterns with this analysis were found to be consistent with genetic differences and are shown in Figure 2. As expected, the two *Citrobacter* species are most closely related to each other while the Gram-negative species are the most different from Gram-positive *B. cereus*.



	EC	CK	CB	BC
EC	0	2.91	2.37	5.87
CK	2.91	0	2.18	7.79
CB	2.37	2.18	0	6.92
BC	5.87	7.79	6.92	0

Figure 2: Root mean squared differences are shown between every set of species. These differences in the 2D signature correlate well with estimates of genetic relatedness among species obtained by comparing 16S rDNA sequences.

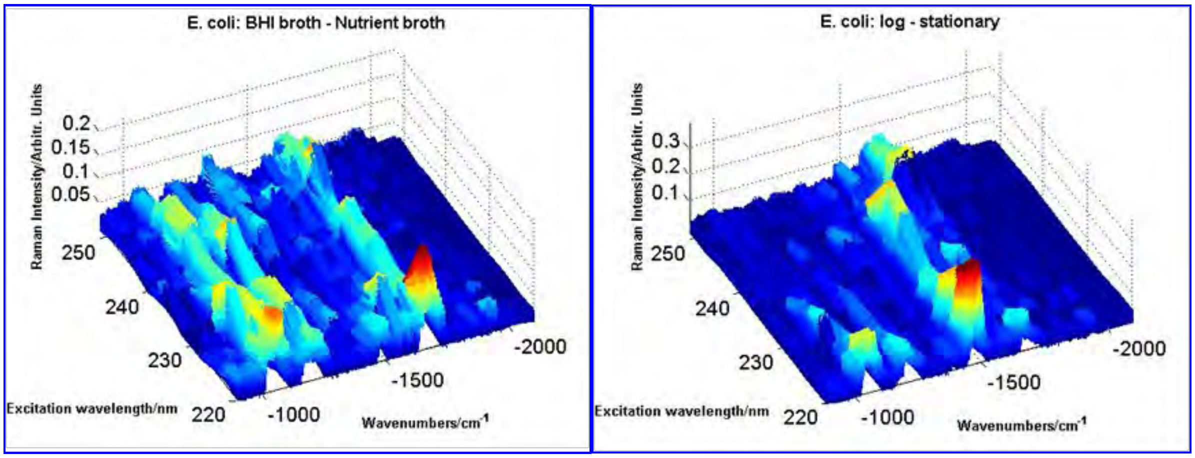


Figure 1: Two-dimensional difference signatures of E. coli reflect changes due to growth medium (left) and growth phase (right). Individual signatures were normalized to the tallest peak and averaged before calculating the difference.

Key Personnel

Robert Lunsford, David Gillis, Jeff Bowles, Zheng Wang

Acknowledgements

Pratima Kunapareddy, Sergei Nikitin , RSI Contractor s to Code 6730.2

Sponsor: Defense Threat Reduction Agency

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Pulsed electron beam remediation of key corrosion mechanism in structural aluminum

Dr. John Sethian, Code 6733

Introduction

A multi divisional NRL Team has demonstrated a pulsed electron beam can reverse environmentally induced "sensitization" of the 5000 series aluminum alloy used in Navy Ships. Sensitization reduces corrosion resistance and leads to stress cracking. Once cracking occurs, the only recourse is costly part replacement. The problem is Navy wide, as 5000 Series aluminum is used extensively in the DDG 963, CG 47, and FFG classes, the Littoral Combat Ship (LCS), the Joint High Speed Vessel (JHSV), and the Joint Maritime Assault Connector.

Background

The 5000 series of aluminum alloy contains magnesium to enhance strength. Under prolonged high temperature in-service exposure, the magnesium migrates to the surface grain boundaries, where it is deposited as Al_3Mg_2. This compound is susceptible to environment. Studies have shown sensitization can be reversed (called desensitization) by heating the aluminum to above 240 °C. The unique advantage of an electron beam is, unlike all other heating methods, it heats just the surface while allowing the bulk material (and hence the inside of the ship) to stay cool. A secondary advantage is that it does not apply any mechanical pressure to the aluminum structure.

Accomplishment

A series of experiments showed the pulsed electron beam completely reverted a sensitized sample. The samples were Navy ship quality 5000 series alumi num that had been aged (sensitized) in the laboratory using industry accepted techniques. In f act, the exposed sample had sensitization than the origin nal. The Code 6733 Electra system was used to produce the electron beam with parameters 500,000 Volts, 230 Amps/cm^2, 140 nsec pulse, 100 pulses at 5 pulses per second. This work was done by a collabor ative team of NRL researchers from Codes 6733, 6355, 6352, and 6176.

Significance

This could allow *insitu* reversal of sensitization before the onset of cracks. As corrosion repair is a significant cost the Navy, this could meaningfully lower Total Ownership Costs

Application

Some R&D remains, primarily for optimization of the e-beam size, for measurements of the treatment depth, and for verification that the desirable material properties are retained. The next step would be to design a deployable prototype system. It is believed that with further development, it may be possible to develop a transportable system that could be deployed to the fleet.

Key Personnel

Dr. John Sethian, Code 6733
Dr. Mathew Wolford, Code 6733
Mr. Mathew Myers, Code 6733
Ron Holtz, Code 6355
Alexis Lewis, Code 6352
Kathryn Wahl, Code 6176

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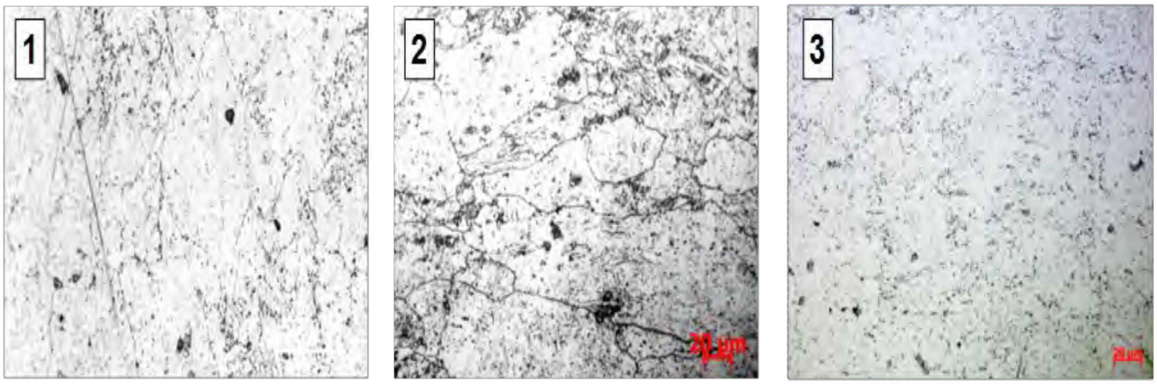
Frank Hegeler, Commonwealth Technology Inc, Contractor to Code 6733
Derek Horton, Contractor to Code 6134

The photos show the sample: (1) as received, (2) after it was aged (sensitized) in the laboratory, and (3) after the aged sample was treated with the pulsed electron beam. Desensitized aluminum is characterized by *thin discontinuous* grain boundaries (appearing as faint, irregular lines), sensitized aluminum is characterized *by wide continuous* boundaries. The treated sample appears better than the original.



Some R&D remains, primarily optimization and to ensure the desirable material properties are retained. After that, the next step would be to design a deployable prototype system.

Sponsor: ONR

An attractive hybrid indirect and direct drive approach to laser fusion tested on the Nike laser

Dr. Max Karasik, Code 6736

Introduction

Inertial confinement fusion requires a highly uniform pressure on a spherical shell of fuel to implode the fuel to densities and temperatures required for fusion burn to start. The main line approach pursued on the National Ignition Facility (NIF) uses a gold cavity to convert laser energy to x-rays that are used to implode the fuel capsule in order to smooth out laser non-uniformity. The laser fusion group at the Plasma Physics Division has found a method of smoothing out the laser drive while applying the laser beams directly to the capsule, thus avoiding the complexities of the conversion cavity and allowing more efficient use of laser energy. The method uses a high atomic number coating to smooth out the laser drive. Originally developed on Nike at NRL over a decade ago, it has now been demonstrated to work with the intensities and laser pulse shapes relevant to the fusion ignition-scale lasers such as the National Ignition Facility.

Background

Inertial confinement fusion requires a highly uniform pressure on a spherical shell of fuel to implode the fuel to densities and temperatures required for fusion burn to start. Modern laser smoothing techniques, such as utilized on the Nike laser at NRL, are thought to give sufficiently uniform laser illumination to accomplish that. The main line approach pursued on the NIF however uses a gold cavity (hohlraum) to convert laser energy to x-rays that are used to implode the fuel capsule in order to smooth out laser non-uniformity. While this can result in a highly uniform drive, the hohlraum introduces additional complexity and loss of efficiency in coupling the laser energy to the fuel.

Accomplishment

The laser fusion group at the Plasma Physics Division has found a method of smoothing out the laser drive while applying the laser beams directly to the capsule, thus avoiding the complexities of the conversion cavity and allowing more efficient use of laser energy. The method utilizes a thin high atomic number (high-Z) overcoat, such as gold or palladium, to absorb the initial part of the laser pulse and generate the x-rays that smoothly drive the capsule and create a deep buffering layer to smooth out laser non-uniformity. As the laser pulse intensity ramps up, the coating expands, becoming transparent to the more energetic part of the pulse and allowing the laser to drive the target directly with high efficiency. The first experiments on this method, performed on Nike at NRL over a decade ago, utilized a low intensity step on the laser pulse to precompress the target. The recent experiments on Nike extend this method to the spike laser pulse used on the current polar direct drive designs for the National Ignition Facility.

Significance

The success of the high-Z coatings in suppressing imprint is expected to enable a range of new experiments on the National Ignition Facility, where laser beam smoothing is insufficient for most direct drive experiments. If successfully 'ported' to the laser conditions there, it would enable higher performance direct drive fusion capsule implosions there.

Application

The high-Z coating method is going to be further tested in planar experiments on the OMEGA EP glass laser at the Laboratory for Laser Engineering at University of Rochester and then applied to the experiments on the National Ignition Facility.

Key Personnel

James L. Weaver, Jaechul Oh, Yefim Aglitskiy, and Stephen P. Obenschain.

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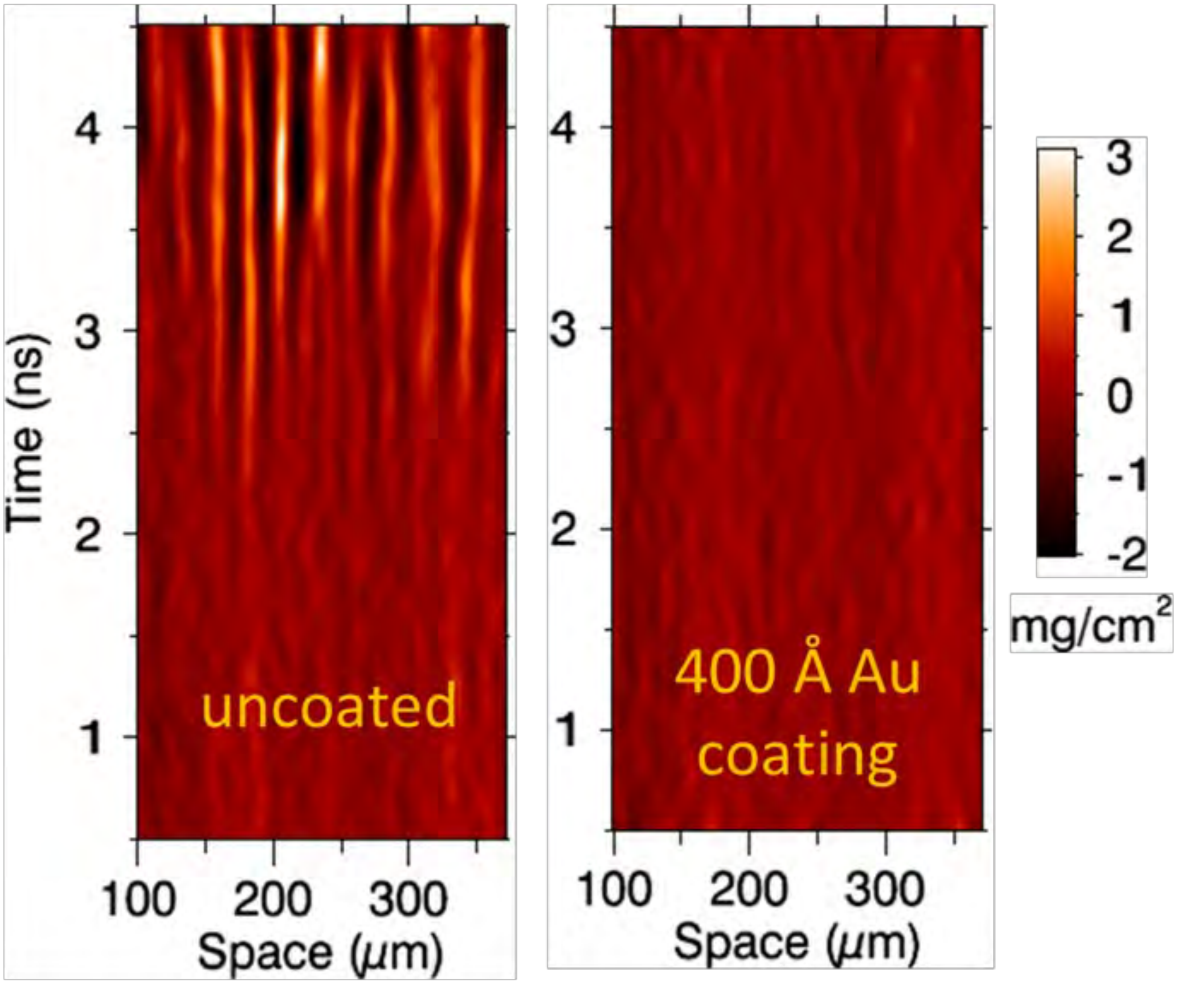


An example of use of a thin gold coating to improve laser drive uniformity. The left image shows the growth in time of areal mass perturbations caused by laser non-uniformity amplified by the Raleigh-Taylor instability for an uncoated plastic target measured by x-ray radiography. Large amplitude perturbations are evident starting at about 3ns. The right image shows the same conditions but with a 400Å gold coating on the target. No perturbations above the measurement noise are present in this case.

Sponsor: DOE, NNSA

X-RAY SPECTROSCOPY OF HIGH-Z ELEMENTS ON NIKE

Dr. Yefim Aglitskiy, Code 6731

NRL Nike laser, when its several kilojoules of the vacuum ultraviolet light are focused on a target, is capable of producing the ions with muli kilovolt ionization potentials. As such it is a unique platform to benchmark HED plasma diagnostics and relevant atomic physics simulations.

In particular**,** a detailed study of the x-ray spectra of gold has been inspired by the necessities of the National Ignition Campaign to learn more about the M-band contribution to the total energy balance inside the NIF's hohlraum. For this purpose a survey x-ray spectrometer covering a spectral range from 0.5 to 19.5 angstroms has been added to the Nike diagnostic suite. This instrument allows simultaneous observation with high spectral resolution of both M- and N - spectra of the ions originated from the elements with Z from 70 to 85. Complexity of these spectra requires the study of several elements along the same isoelectonic sequence to make sure that we have positive identification of specific spectral lines that are of our major interest.

Shots taken with a power density of $2x10^{14}$ W/cm^2 on the foils of Hf, Ta, W as well as Pt and Au confirmed a strong presence of transitions of Ni-like ions of the above mentioned elements along with the multiple satellite lines originated from the lower stages of ionization, (see Pt and Au on fig.1). Simulations based on NOMAD code (Dr. Yu. Ralchenko from NIST) were applied to recorded spectra and multiple transitions were identified (see fig. 2).

This is an important milestone for testing and using similar spectrometers that are to be built by NRL for NIF as a part of the National Ignition Campaign.

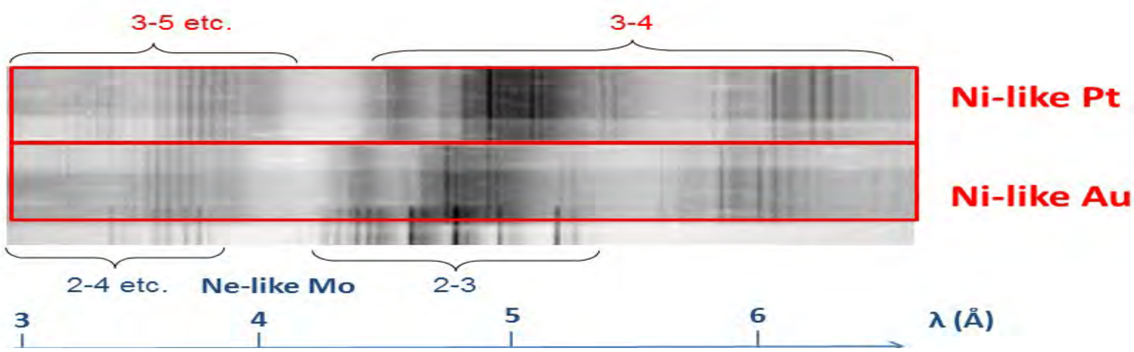


Figure 1

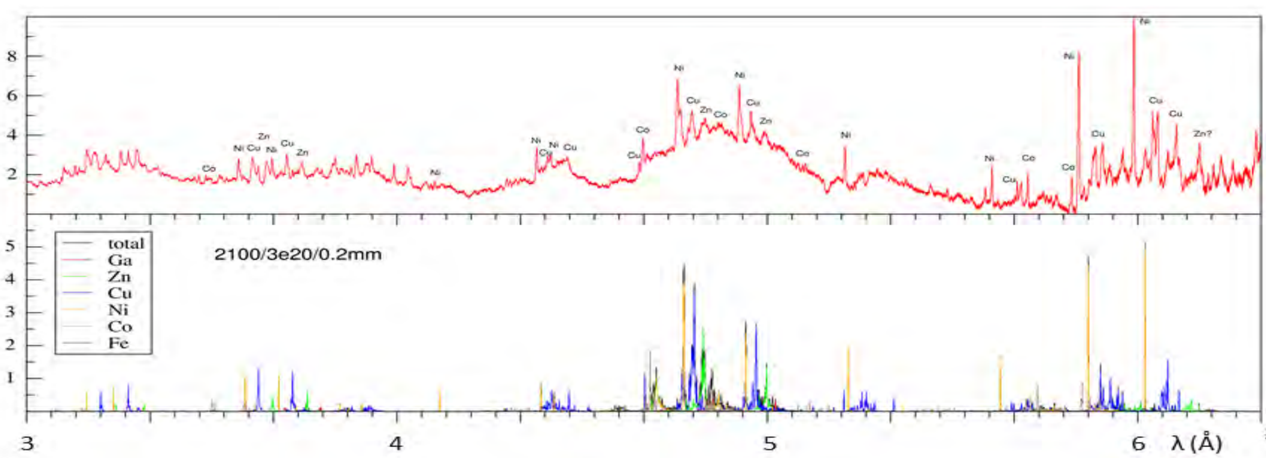


Figure 2

NRL Small Railgun Program

Dr. Robert Meger, Code 6750

The Navy is developing hypersonic electromagnetic railgun launcher technology for ship self defense, long range fire support, surface to surface combat, and anti-missile defense missions. Future systems could provide area defense for land bases and offensive capability for medium to large Navy ships. NRL has been involved in the Navy's Electromagnetic Railgun (EMRG) program for the last decade. NRL has been the lead laboratory on the barrel materials challenges and basic physics associated with high power launch. The primary platform for this research has been the 6-m long; 5-cm diameter bore railgun located in the Materials Testing Facility (MTF) designed and built in 2003. This railgun is capable of launching 500 g projectiles to over 1.5 km/s. Launch dynamics and the effects of high power launch have been investigated using a range of electromagnetic, optical, and metallographic diagnostic tools. Recently NRL designed and built a new small bore railgun to investigate a number of issues associated with high power launch. This new gun line was built using state of the art design principles. It was designed to accept a wide range of rail and insulator core designs as well as provide adequate diagnostic access for experimental research. It is designed to operate in a single shot mode or at several shots per minute. The new Small Railgun (SRG) was brought on line in March 2014 for single shot testing. It will be fully operational in rep-rate mode in FY15 and will be used for materials and thermal analysis.

The new SRG railgun (Fig. 1 and 2) is comprised of a 4-m long, 1-inch diameter barrel fed by a 10 shot per minute autoloader. The smaller bore allows scaled experiments to be performed at relevant power levels. The gun is powered either by a subset of the MTF railgun power supplies or by a battery charged rep-rate power supply which will be capable of launching 10, 100 g projectiles per minute at 1.5 km/s. It will be used for armature and barrel design experiments, rail and power supply cooling tests, materials testing, and other experiments.

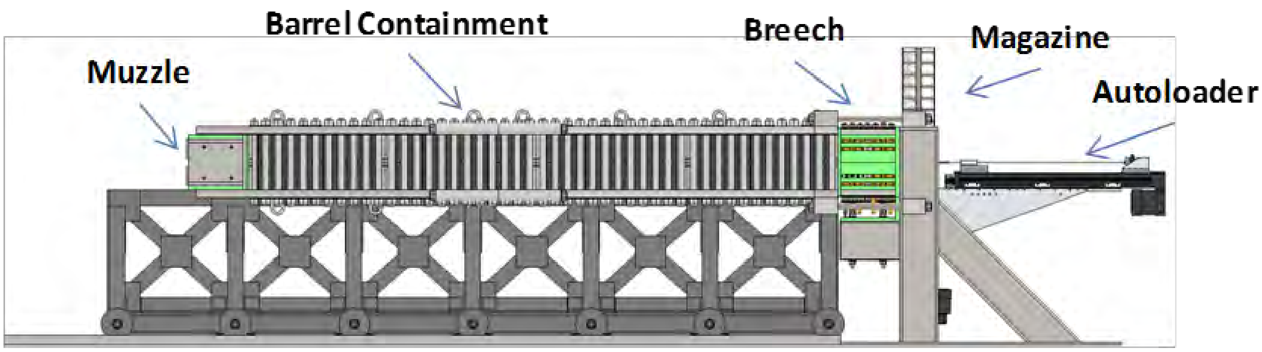


Figure 1. Side view of the NRL Small

Figure 2. Small Railgun experimental system undergoing initial testing.

Sponsor: ONR,

Charged Particle Physics Branch

Dr. Robert Meger
Branch Head, Code 6750

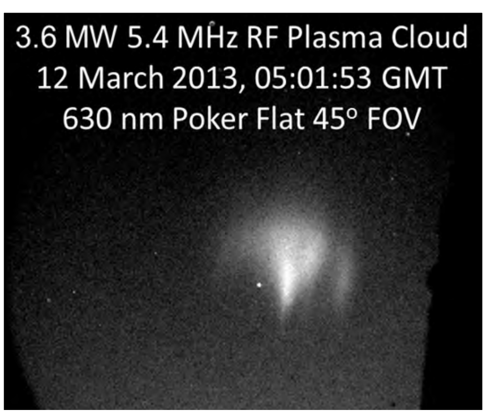
Materials Testing Facility

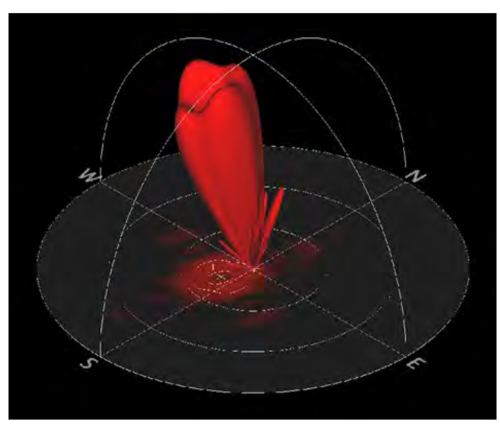
The Charged Particle Physics Branch performs research on electric launchers for DOD applications. Shown in the figure is a shot on the 6-m long, 5-cm diameter bore, 1.5 MJ launch energy Materials Testing Facility (MTF) railgun powered by a 12-MJ capacitor bank. This railgun is utilized primarily for barrel materials studies. The system launched over 1500 projectiles over the last 6 years of operation. Effects of the current drive, barrel materials, and geometry are measured using in situ launch diagnostics coupled with ex situ metallographic materials analysis. A second 4-m long, 2.5 cm diameter bore gun called the Small Railgun (SRG) powered by a battery charged capacitor system was added in 2014 to address barrel scaling issues as well as repetitive launch effects.

SRG Railgun

The space Use and Plasma Environment Section Code 6754

The Space Use and Plasma Environment Section employs high power radio waves to generate plasma clouds in the upper atmosphere. The High Frequency Active Auroral Research Program (HAARP) transmitter in Alaska beams electric fields in the 2.6 to 10 MHz frequency range to generate breakdown of neutral gasses in the upper atmosphere for formation of large regions of enhanced ionization. With appropriate phasing, the HARRP antenna array launches conical radio beams that yield quasi-stationary plasma balls at altitudes usually devoid of electrons and ions. These 50 km wide plasma clouds are maintained as along as the powerful radio waves are transmitter. The plasma balls serve as artificial mirrors for HF radio waves and irregularity screens for satellite transmissions in the VHF and UHF frequency bands. The structures of these plasma clouds are seen in visible images obtained using low-light-level cameras. Numerical models are used to simulate the electron acceleration and resonant ionization processes that are pumped by multi-Gigawatt transmissions. The goal of this research is to control the radio propagation environment in the Earth's upper atmosphere.

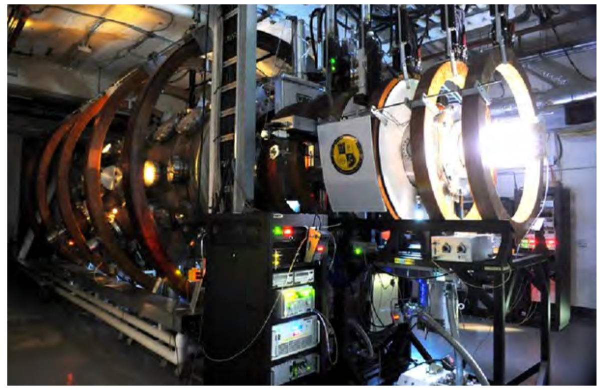




HF Twisted Beam at 5.4 MHz

Sponsor: ONR, 6.1 Base Program

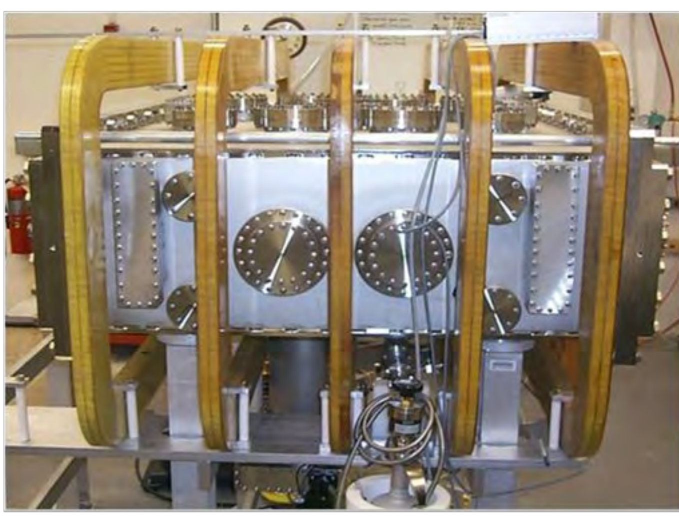
The Space Chamber

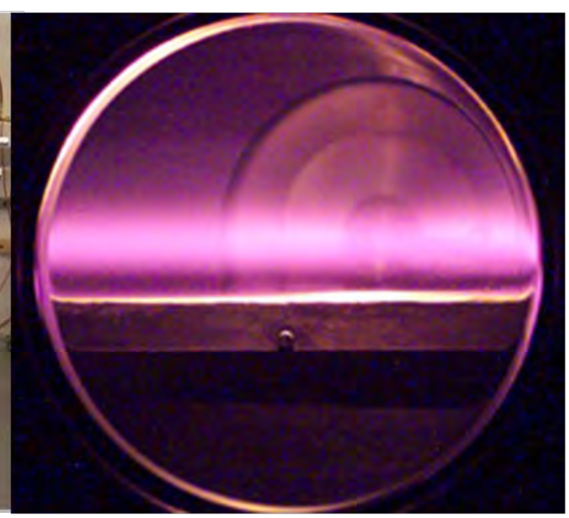


The NRL Space Physics Simulation Chamber (SPSC) is a unique device for basic plasma experimentation and the ground-based investigation of space plasma phenomena. Large volume, steady-state, space-like plasmas are created in the main vacuum chamber (2-m diameter by 5-m length), with an addition 2 m of plasma column length are provided by the source chamber section. Steady-state magnetic fields with controllable axial profiles, combined with a variety of plasma sources, allow Space Chamber plasma conditions to be scaled to a wide range of near-Earth space plasma regions. SPSC experiments have investigated such phenomena as radiation belt dynamics, broadband ionospheric ion-cyclotron wave generation, wave and Joule heating of ionospheric plasma, and magnetotail particle and wave dynamics. Spacecraft diagnostic development and hardware testing/qualification are also performed in the SPSC due to its ability to produce realistic ionospheric plasma conditions.

Plasma Applications

The Plasma Applications Section performs research in the production, characterization, and use of low temperature plasmas and related areas. The research activities employ the use of numerous diagnostics to fully characterize the plasmas and to understand material modifications. The laboratory has several chambers operating under vacuum conditions for low pressure plasma systems as well as atmospheric pressure plasma systems. A variety of plasma and particle collection diagnostics are used, including Langmuir and RF probes to measure plasma density, plasma potential, electron temperature, and the electron energy distribution; a dual energy analyzer/ quadrupole mass analyzer to interrogate the flux of ions and neutrals at surfaces; and, optical diagnostics to measure excited species. In materials processing, the research efforts are aimed at developing a comprehensive understanding of plasma-based processing applications ranging from etching to deposition to surface activation of both organic and inorganic materials. Shown in the figure is the Large Area Plasma Processing System (LAPPS), NRL developed technology, based on the use of mid-energy (few keV) electron beams to drive plasma production. The system has been used to develop plasma processing strategies for materials used in next-generation electronic and sensing applications.





Generation and Detection of Artificial Radio Scintillations Using High Power Radio Waves

Dr. Paul A. Bernhardt, Code 6754

Introduction

The High Frequency Active Auroral Research Program (HAARP) transmitter in Alaska has been used to produce localized regions of artificial ionization at altitudes between 150 and 250 km. Recent research by NRL at HAARP has produced the longest lived and denser artificial ionization clouds using HF transmissions at the harmonics of the electron cyclotron frequency and ring-shaped radio beams tailored to prevent the descent of the clouds. The artificial ionization yields ultra-strong VHF, UHF and L-Band scintillation induced into trans-ionospheric signals from satellite radio beacons. VHF Beacon Transmissions at 253 MHz have provided high latitude scintillation monitoring from Gakona Alaska using the NRL COMMX instrument on TACSat4. This is the first demonstration of significant effects on radio scintillations using high power HF radio waves to disturb the ionosphere. On 29 September 2013, the NRL Tri-Band CERTO beacon was launched into orbit to provide radio signals at VHF (150 MHz), UHF (400 MHz) and L-Band (1066 MHz). This multi-frequency will be used to determine the effectiveness of HAARP generated artificial irregularities for disturbing satellite communication and navigation signals.

Background

Radio Scintillation is the highest priority phenomena in the ionosphere that impacts the Navy (Ref.: CNO 2008). Natural radio scintillations have produced blanketing disruptions of GPS navigation and UHF SATCOM over active theaters of operations during the Gulf Region Wars. The ability to create artificial irregularities that can induce radio scintillations upon demand has been one major objective for the creation of the HAARP facility in Alaska. This work shows to what degree navigation and communications systems can be disrupted by high power radio wave facilities operating in the HF radio frequency band.

Accomplishment

With the new ability to generate radio scintillation upon demand, techniques for improved signal detection and discrimination in a scintillation environment can be tested without having to wait for natural scintillation events.

Significance

The TACSat4/COMMX scintillation monitoring system has been used to detect natural and artificial field aligned irregularity effects on the amplitude and phase of VHF carriers where typical scintillation amplitudes are 2dB or less. Using the HAARP transmitter in Alaska, TACSat4 was used to discover the artificial ionization clouds produce scintillation with as much as 16 dB and scintillation amplitude indices S4 greater than unity. For the first time, high power HF waves have been shown to have a strong effect on satellite signals passing though the modified ionosphere.

Application

HF wave transmissions on operational platforms may be able to intentionally disrupt satellite radio transmissions used for communications, navigations, and space based radar. High power radio waves systems may be transitioned to the operational Navy if portable platforms can be designed. This research can be used to define the requirements of an operational ionospheric modification system.

Key Personnel

Code 6754 Personnel (Paul Bernhardt, Carl Siefring, Stanley Briczinski)
Code 8233 Personnel (Keith Aikens)

References

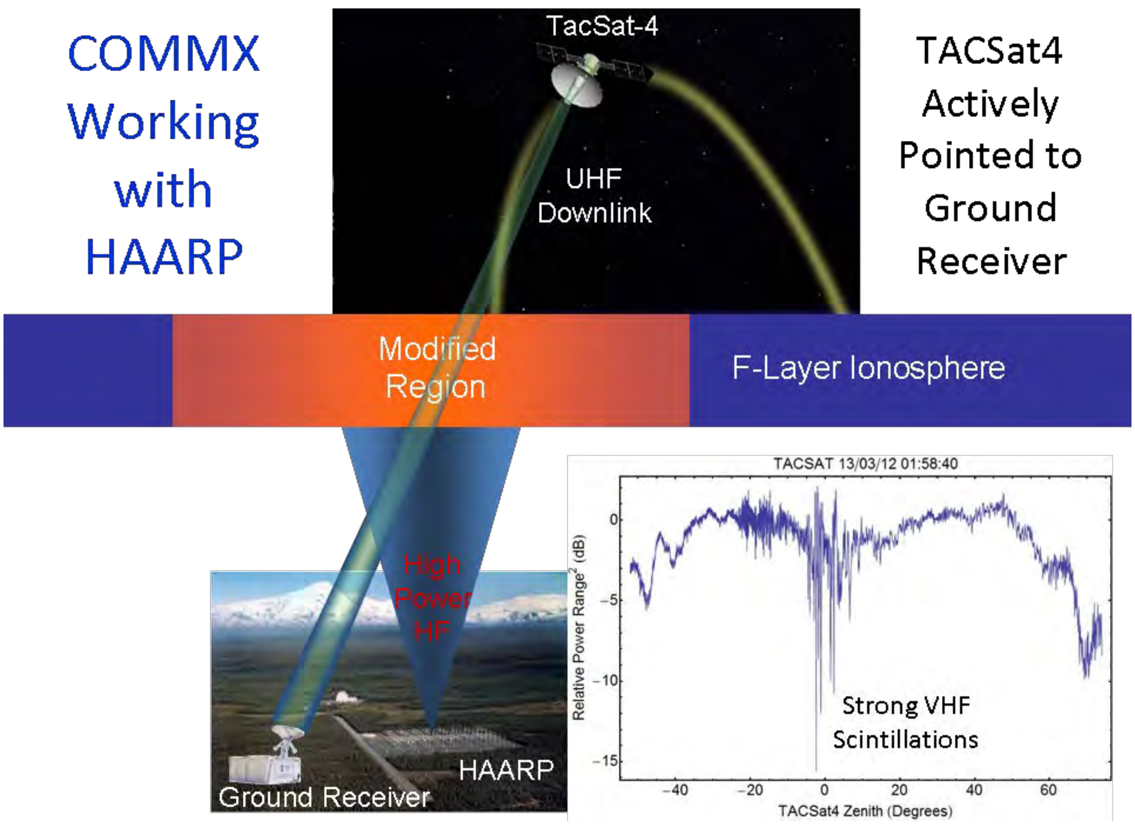
Invited AGU Abstract 2013, Paul A. Bernhardt, Methods for Creation and Detection of Ultra-Strong Artificial Ionization in the Upper Atmosphere, San Francisco, CA December 2013.

Acknowledgements

SWRI Personnel (Robert Michell)

Sponsor:

6.1 Base Program, BRIOCHE DARPA



Impact of satellite radio signals passing through regions of artificial ionization created by high power HF transmissions from the HAARP facility in Alaska.

The Production of Chemical Gradients on Graphene to Drive Droplet Motion

Dr. Scott Walton, Code 6756

Introduction

Graphene has attracted enormous attention due to its unique chemical, mechanical, optical, and physical characteristics, which together, make graphene an ideal candidate material for a broad range of next-generation electronic, energy conversion, and sensing devices. Researchers in NRL's Plasma Physics Division developed, using NRL-patented technology, an approach to creating chemical gradients on graphene, which can be used to push or pull small drops of liquid.

Background

Gradients in the wettability of a material are widely found in nature, such as the famous lotus-leaf effect or in spider webs. Researchers who study these effects have found that to be useful, a chemical gradient must be especially smooth without defects that can snag the water droplet. The effect has been achieved before with large molecules or polymers but not with graphene—a layer of carbon only a single atom thick. Given this atomic thinness, manipulating the surface chemistry of graphene requires a delicate touch since there is a fine line between tuning the chemical properties and eroding the material. In the Plasma Physics Division, we have developed plasma-based approaches to tuning the surface chemistry on both a global and local scale. Using these approaches, we have been able to produce gradients in fluorine and oxygen on the surface of graphene, which can be used to push or pull liquid droplets. Importantly, graphene can be transferred to arbitrary substrates and thus graphene gradients can be produced on many different surfaces. Combined, these advantages provide potential breakthroughs in device design for applications ranging from microfluidics to sensing.

Accomplishment

Our approaches have been used to change the surface chemistry of graphene and these global changes in surface chemistry has been shown to effect the properties of graphene – relevant to this work, is the ability to change surface reactivity (hydrophobic vs. hydrophilic). We have also demonstrated the ability to vary the surface chemistry locally. That is, to "pattern" the distribution of chemical moieties on the surface of graphene. In this work, we were able to produce gradients in surface chemistry by combining plasma processing with masking techniques. This, in turn, provides a gradient in the hydrophobic/hydrophilic characteristics of the surface. When a liquid drop interacts with such a surface it will feel a "push" or "pull" towards the region of higher hydrophilicity. Under the right conditions the liquid drop will move along this gradient. In particular, the ability to move liquid drops of water and DMMP (a nerve agent simulant) was demonstrated.

Significance

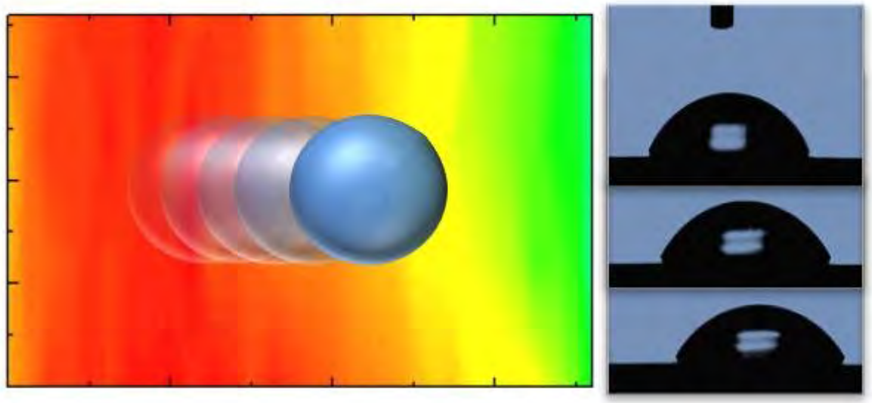
There are many examples where naturally occurring or synthetic gradients can move liquids. Importantly, this motion does not require externally supplied energy beyond that required to assemble the surface. Thus, such surfaces can be exploited for no- or low-applications such as self cleaning surfaces, sensors, and microfluidics devices. In many cases, the production of such gradients and their specific applications are tightly linked. That is, substrates typically require specific surface chemistries, which may or may not be compatible with a desired application. Graphene – a single monolayer of carbon - provides a unique solution. Carbon is rich in possible chemistries and it can transferred to any substrate thus providing greater flexibility in design. It is also important to note that the plasma processing approach is scalable to meet the needs of high-throughput production. The significance of this work has attracted the interest of the scientific news media. Reports on the work can be found at "materials 360 online" and "*Signal* Media".

Key Personnel

Plasma Physics Division: Sandra Hangarter, (NRC) Evgeniya Lock, David Boris, NRL C0-investigators: Paul Sheehan, Thomas Reinecke

Application

The production of chemical gradients can be used in applications such as pump-free micro fluidics, two-dimensional chemical pre-concentrators, and direct analytes to site-specific receptor points in sensing devices.



(Left) Schematic of the surface with a moving droplet. The image shows increasing surface oxygen concentration derived from XPS measurements where red and green represent low and high concentration, respectively. (Right) Still images taken from a video following the movement of water drops along the

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Acknowledgements

Brian Pate (DTRA)

Sponsors

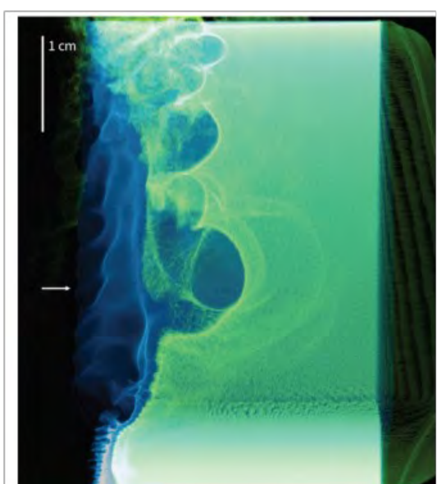
NRL 6.1/6.2 Base Program; ONR, DTRA

Pulsed Power Physics Branch

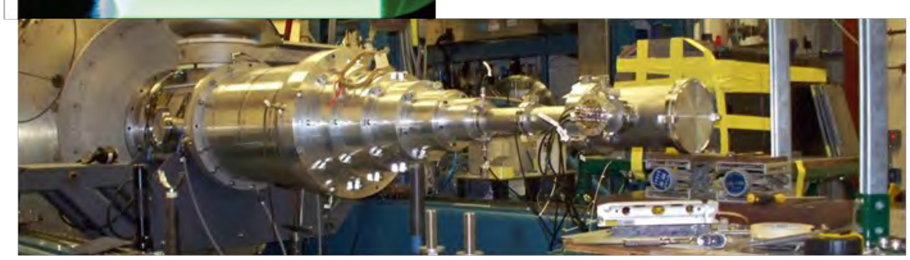
Dr. Joseph Schumer
Branch Head, Code 6770

The overall mission of Pulsed Power Physics Branch is to advance technology in the areas of pulsed power relevant to ONR, DoD, and Department of Energy (DOE) applications. To these ends, the Branch develops high-energy pulsed power systems employing capacitive and inductive energy storage, producing and utilizing pulsed plasmas and intense high-power, charged particle beams. We provide some of the Nation's technological basis for high-energy-density plasma experiments, high-power switching, and advanced radiation sources, advancing applications of this technology for areas such as Nuclear Weapon Effects Simulation, Science-Based Stockpile Stewardship, Detection of Nuclear Materials, Electromagnetic Launchers, and Inertial Confinement Fusion. The Pulsed Power Physics Branch is a 26-member team of PhD physicists, electrical and nuclear engineers, and specialized pulsed power technicians.

To help manage this group and accomplish our sponsored missions, the Branch is divided into three Sections: Theory and Analysis Section (Code 6771) - concerned with providing theoretical and numerical support and guidance for the Branch and for sponsoring agencies; Plasma and Beam Experiments Section (Code 6773) - concerned with performing experiments using the Branch pulsed power generators for applications involving pulsed plasmas and/or intense particle beams; and Electromagnetic Launcher & Advanced Systems Section (Code 6777) - concerned with the development of advanced, compact, high-power pulsed systems that integrate vacuum inductive storage, plasma opening switch techniques, and loads such as launchers, bremsstrahlung x-ray diodes, and plasma radiation sources. Section members work with each other amorphously, bringing to bear expertise needed for the task at hand.



Particle-in-cell simulation of a plasma opening switch – A. Richardson, IEEE Trans. Plasma Science 2014.



Front-end of "Mercury", an 8-MV, 200-kA, 50-ns pulsed power generator

Kinetic Simulation of Magnetic Vortices in a Plasma Opening Switch

Dr. Stuart Jackson, Code 6773 and
Dr. Andrew (Steve) Richardson, Code 6771

Introduction

Vortex formation and propagation were observed in kinetic particle-in-cell (PIC) simulations of a plasma opening switch plasma. Propagation of the vortices due to plasma density gradients was studied using implicit PIC algorithms, and the propagation speed was found to be proportional to the Hall speed. Strong forces in the vortices gave rise to significant charge separation that accelerated plasma ions and led to separation of ion species in the plasma and dissipation of the vortex. This species separation and the faster-than-expected magnetic field penetration associated with it have been observed experimentally, but in the past, limitations in computational capability had prevented modeling of the underlying physics at relevant timescales and densities. It is hoped that better understanding of the plasma opening switch will lead to its application to compact pulsed power desired for Navy, Department of Defense, DOE, and foreign government applications (active detection of special nuclear materials, radiography, etc.).

Background

The Plasma Physics Division's Pulsed Power Physics Branch (Code 6770) has been involved in plasma opening switch research since the early 1980s, sponsored by the Department of Energy (DOE) and the Defense Threat Reduction Agency (DTRA). Despite this extensive work, and the work of other plasma physics groups at DOE laboratories, DTRA laboratories, and internationally, the basic physics of phenomena experimentally observed in these switches remains poorly understood. This lack of understanding has resulted in perceived shortcomings that have limited the plasma opening switch's application in advanced pulsed power systems. (For example, building a modular pulsed-power system with multiple plasma opening switches in parallel is not practical if the jitter in the switch timing is large enough to affect the power flow.) This lack of understanding is due, in large part, to past limitations in computational capability that prevented fully kinetic, particle-in-cell (PIC) simulations of plasma opening switch plasmas at relevant timescales and densities. More computationally-efficient magnetohydrodynamic simulations were used instead, but these models neglected much of the relevant physics. Modern computing power and algorithms have now been applied for the first time to this problem.

Accomplishment

Vortex formation and propagation were observed in kinetic particle-in-cell (PIC) simulations of a plasma opening switch. Vortex propagation speed was found to be proportional to the Hall speed. Strong forces in the vortices gave rise to significant charge separation. PIC simulations show that the electric field in the vortex can accelerate plasma ions, which leads to separation of ion species and dissipation of the vortex.

Significance

Faster-than-expected magnetic field penetration in plasma opening switch plasmas has been observed experimentally and linked to separation of ion species (*e.g.*, hydrogen ions and carbon ions). These new PIC simulations of magnetic vortices have begun to capture the relevant physics of this observed fast field penetration and species separation. These results also apply to a broader collection of weakly-magnetized laboratory and astrophysical plasmas.

Application

The plasma opening switch is an enabling technology for compact pulsed power desired for Navy, Department of Defense, DOE, and foreign government applications (active detection of special nuclear materials, radiography, etc.). By first conducting and then abruptly interrupting the flow of current, the plasma opening switch allows multi-megavolt voltages normally associated with large pulsed power generators to be produced by significantly smaller systems.

Key Personnel

Drs. A. S. Richardson, J. R. Angus, S. B. Swanekamp, P. F. Ottinger, and J. W. Schumer

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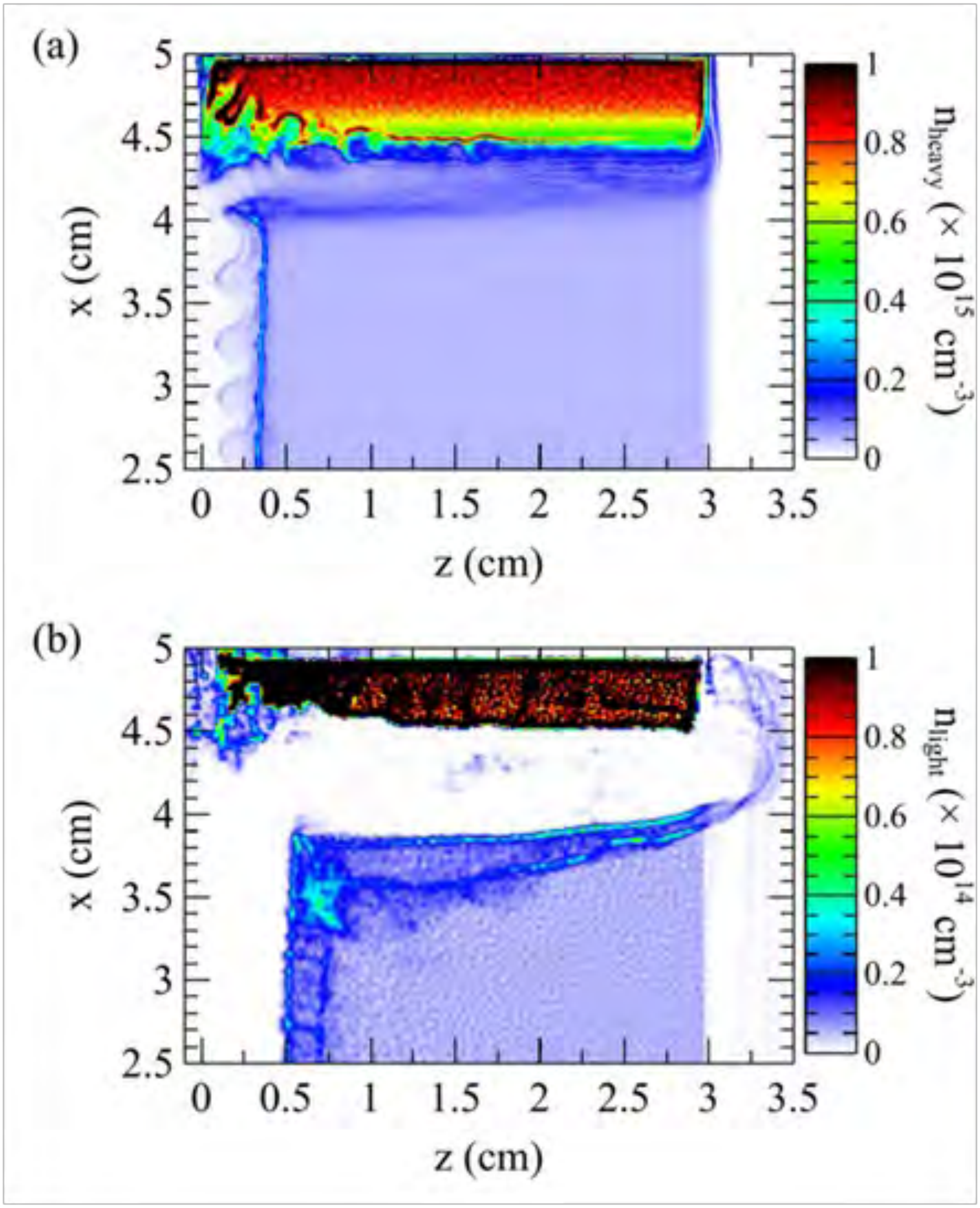
"Theory and simulations of electron vortices generated by magnetic pushing," A.S. Richardson, J.R. Angus, S. B. Swanekamp, P.F. Ottinger, and J.W. Schumer, Physics of Plasmas, vol. 20, p. 082115, 2013



Ion density contours from a PIC simulation of a plasma opening switch showing separation of light and heavy ion species in the plasma that may lead to gap formation and the opening of the switch. (a) The density of the heavy ions has been slightly perturbed by vortices accompanying penetration of the plasma (from left to right) by the magnetic field. (b) A gap has formed by vortices in the density distribution of the light ion species, and some light ions have been pushed downstream of the original plasma-filled region.

Sponsor: 6.1 Base Pro-

Evaluation of the Application of Electrochemical Energy Storage Devices to Compact Pulsed Power Systems

Mr. Brett Huhman, Code 6777

Introduction

The emergence of high power density battery cells in combination with the decrease in capacitor size and enhanced capability of silicon switches in the last few years has the potential to enable the development of portable repetitive pulsed power systems such as lasers, microwave generators, and electromagnetic launchers. Thermal management of these systems is critical, as the heat generated by multiple shots will start to degrade the components and cause lifetime issues. NRL has developed a novel battery cooling system that has been demonstrated to keep all of the battery temperatures 20°C below the maximum recommended operating temperature during the entire 50 shot test series. Damage in battery cells is accelerated greatly by heat, thus keeping the cells cool ensures the maximum lifetime possible and will prevent premature field replacement of a system.

Background

Pulsed power devices such as an electromagnetic launcher are only useful when they can be quickly charged and fired. In the field, source power of a level necessary to directly charge the capacitor bank system is not available. To resolve this issue, high power battery cells can be used instead to directly charge the capacitors. However, the cells will heat during discharge and cause a variety of internal failures to develop. If the cells are kept cool during the test series, these failure mechanisms will develop much more slowly and the expected lifetime of the battery cells will be kept as high as possible.

Accomplishment

NRL demonstrated the viability of the use of high power density battery cells to deliver sufficient current and voltage to rapidly charge and recharge a capacitor bank for 49 shots. Traditional battery cells would be sealed lead acid, which are quite large and heavy. The new $LiFePO_4$ cells are a small fraction of the volume and weigh much less. Lithium-based cells generate a substantial amount of heat, but NRL has developed an integrated cooling system that has been shown to keep all of the battery temperatures 20°C below the maximum recommended operating temperature during the entire 50 shot test series.

Significance

The successful demonstration of a stable battery pack that can deliver the power necessary to rapidly and repetitively charge a capacitor bank and remain under the thermal limits will enable the future deployment of directed energy systems such as railguns, lasers, and microwave devices to mobile platforms such as ships and land vehicles.

Application

This technology will enable the safe use of high power density battery modules to directly drive directed energy systems on mobile platforms such as ships and land vehicles. The small footprint of the batteries in combination with the magazine depth available will allow for sustained engagements with advanced systems not currently available in the field.

Dr. Carl Carney removes a battery pack from a 12-pack array for maintenance. Each capacitor (blue) requires 12, 50-V battery packs connected in series to rapidly charge the capacitor to 5-kV in approximately five seconds.

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Key Personnel

Dr. Jess Neri, Code 6777

Acknowledgements

NSWC-Dahlgren Division, NSWC-Carderock Division, the University of Missouri, and the University of Texas-Arlington

Simulation of cold-x-ray effects on materials relevant to re-entry nose cones using intense ion beams

Dr. David Hinshelwood, Code 6773

Introduction

A series of materials-response experiments validated the use of intense pulsed ion beams to simulate cold x-ray fluence on materials relevant to re-entry nose cones. The Gamble II generator produces 1.3-to-1.9 MV, 400-to-500-kA, 50-ns ion-beams, at fluences from 3-80 calories/cm^2. Ion beams are attractive for this application because their deposition profile in typical materials is similar to that for cold x-rays. The ion beams were characterized using calorimetry, dosimetry, carbon activation, and Rutherford scattering. Target response was diagnosed using multichannel photonic interferometry as well as velocity and strain measurement. Strategic systems materials of interest along with generic benchmark materials were tested. The materials-response results will be used by our sponsors both to validate codes and to evaluate new materials of interest.

Background

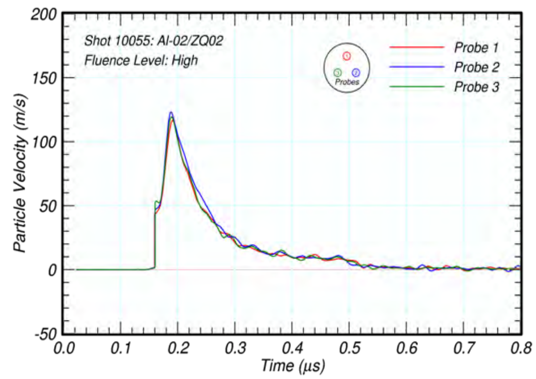
Code 6770 had a very successful, ~10-year effort in this area in the 1990's. These experiments represent a re-start of this research effort. The recent experiments began in 2011 and will continue in 2014.

Accomplishment

We were able to obtain sufficient ion-beam fluence, uniformity, and deposition-profile-fidelity to provide a relevant surrogate for cold x rays. We have shown the ability to vary both the deposition depth (by varying the endpoint beam energy) and the deposition profile (by selectively filtering the beam). The deposition profile has been characterized experimentally. As part of this work, we have been sponsored to construct our own photonic-interferometric system that will be employed in a variety of future experiments.

Significance

The viability of the US and UK strategic deterrent depends in part on aeroshell materials that can withstand a high fluence of cold x rays, greater than that obtainable from present cold-x-ray sources. Using ion beams as a surrogate for cold x-rays provides fluences well above those required. The high fluence, relatively low cost, and high shot rate of Gamble II, compared with those of the large facilities used to generate cold x-rays, make ion beams a very attractive approach for materials-response experiments.



Typical high fidelity rear surface particle velocity measurement in Al6061 using a multi-probe photonic displacement interferometer (PDI) at high fluence (~42 cal.cm^2) indicating excellent beam uniformity across the face of the 32-mm-diameter exposure.

Application

Both sponsors have planned successor experiments in FY2014. A separate round of experiments sponsored by the UK AWE (this time via the Navy) are planned in FY2014. These will necessarily involve the Navy SSP through the Joint Reentry Systems Working Group Agreement. Having established contacts with two distinct Navy groups, we should be well positioned to respond to future Navy needs for reentry-vehicle hardness and vulnerability assessment.

Key Personnel

D.G. Phipps and G. Cooperstein, Contractor

Acknowledgements

Exelis Inc. (Colorado Springs, CO)
U.K. Atomic Weapons Establishment

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Beam Physics Branch

Dr. Joseph Penano
Branch Head, Code 6790

The Beam Physics Branch, Code 6790, explores a broad, fundamental and applied research agenda involving theoretical and experimental investigation of advanced radiation and particle beam sources, directed energy, laser-matter interaction, nonlinear systems dynamics, space sciences, and materials processing. The production and interactions of photon and particle beams with matter involve a broad range of physical processes including ionization, plasma heating, material phase transitions, hydrodynamics, lattice interactions, relativistic effects, and nonlinear optics. With the advent of ultra-short, ultra-intense lasers, and compact, high-average power lasers, a broad range of spatial scales (sub-micron to kilometer) and temporal dynamics (femtoseconds to minutes) must be resolved often within the same problem, which makes modeling these interactions extremely challenging. Experimental facilities within the Branch include four kW-class single-mode fiber lasers, a kHz Ti:Sapphire femtosecond laser, a high-average current (~1A) rf-gated (~100 psec) electron source, an 83-GHz, 15 kW gyrotron source, a 75 kW 915 MHz source, and two 6 kW 2.45 GHz sources for materials processing research, a magnicon facility for advanced accelerator development, a unique intense underwater laser propagation and interaction laboratory, and state of the art ultrafast diagnostics. Over the years the Branch has made pioneering contributions in the areas of laser-driven accelerators, ionospheric modeling, solar physics, microwave materials processing, ultra-short pulse laser interactions, advanced radiation sources, nonlinear optics modeling, and laser weapon systems.

Recent scientific achievements include:

Theoretical and numerical investigation of filamentation in atmospheric turbulence (J. Penano, B. Hafizi, A. Ting, M. Helle) The propagation of laser beams with powers larger than the nonlinear self-focusing power through atmospheric turbulence was theoretically investigated. Excellent agreement was found between our simulations and a previously published laboratory-scale experiment. Simulations were performed to calculate probability distributions for filament onset and wander over kilometer distances and are compared with theory. The use of focusing optics to control filamentation range was also investigated. (NRL 6.1 and HEL-JTO)

Development of fully explicit nonlinear optics modeling (D. Gordon, M. Helle, J. Penano) which incorporates the nonlinear optics of anisotropic crystals into a particle-in-cell framework. This first-principles modeling of optical nonlinearity is unprecedented and allows for simulating interactions between crystals, ultra-short laser pulses, intense relativistic electron bunches, plasmas, or any combination thereof. (NRL 6.1)

Combined Ultrashort Pulse and CW Laser Material Interactions (M. Helle, A. Ting, J. Penano) Experiments to examine the combined effects of Ultrashort Pulse (USP) and Continuous Wave (CW) lasers on various materials. It was observed that for materials such at copper, graphite, carbon fiber, and painted composites that, with the addition of just a few watts of average power in the form of a USP, laser burn through times were reduced by upwards of 2.5 relative to cw beam illumination. The underlying mechanisms for enhancement are currently being investigated using new experimental techniques and computer simulations. (NRL 6.1 and HEL-JTO)

Origin and control of the subpicosecond pedestal in femtosecond laser systems (D. Kaganovich, J. Peñano, M.H. Helle, D.F. Gordon, B. Hafizi, and A. Ting) We investigated experimentally and analytically the picosecond time scale pedestal of a multi-terawatt femtosecond laser pulse. We discovered that the origin of the pedestal is related to the finite bandwidth of the laser system. By deliberately introducing a modulated spectrum with minimums that match this limited bandwidth, we managed to reduce the pedestal, with no deleterious effect on the main pulse. Using this technique we experimentally demonstrate a sub-picosecond scale, order of magnitude enhancement of contrast ratio that led to a significant increase of electron energy in a laser wakefield accelerator. (DOE)

High Resolution Time-resolved Studies of Intense Underwater Laser Interactions (T. Jones, D. Kaganovich, M. Helle) We have taken the first comprehensive high-resolution time-resolved images and spectra of underwater laser-induced breakdown (LIB) generated by nanosecond, picosecond, and femtosecond duration laser pulses. Underwater LIB dynamics, including photoionization, heating, photodissociation, and shock generation, were imaged with fs-time-resolution and 1-µm-spatial-resolution shadowgraphy. In addition we performed the first time-resolved spectroscopy measurements of underwater laser-generated plasma, revealing plasma temperatures near 10,000 K, and plasma lifetimes more than 100,000x longer than expected from average liquid-density collision times. (NRL 6.1)

Design of a Quasi-Optical Output Coupler for a 550 GHz Gyrotron (A. Fliflet, B. Rock) Modern gyrotrons rely on a quasi-optical mode converter to transform the high order cavity mode into a near-Gaussian beam at the output window. For many terahertz applications a Vlasov-type helical launcher and single focusing reflector based on geometrical optics provides moderate bandwidth and acceptable beam quality. We have derived a more general set of analytic equations for the focusing reflector and demonstrated that a quasi-analytical solution to the Kirchhoff diffraction integral can accurately model the diffraction spreading of the launched radiation. This approach produces a more focused beam than previous work and avoids the need for expensive, computationally intensive Electric Field Integral Equation simulation software. (NRL 6.1)

Active Microwave Pulse Compressor Using an Electron-Beam Triggered Switch (S.H. Gold) A high-power two-channel dual-mode active microwave pulse compressor was developed that operates by modulating the quality factor of the energy storage cavities by means of mode conversion controlled by a triggered electron-beam discharge through the switch cavities. The pulse compressor operates at 11.43 GHz and has produced 190 MW, 20 ns output pulses at a record power gain of 26:1 with ~50% efficiency. **(DOE)**

Multipactor Suppression in a Dielectric-Loaded Accelerating Structure Using an Axial Magnetic Field (S. Gold) Efforts have been under way over the past decade to develop Dielectric-Loaded Accelerating (DLA) structures capable of supporting high gradient acceleration when driven by an external rf source. Single-surface resonant multipactor has been identified as one of the major limitations on the practical application of DLA structures in electron linear accelerators. We have demonstrated partial suppression of multipactor in an X-band DLA structure through the use of an applied solenoidal magnetic field. This represents an advance toward the practical use of DLA structures in accelerator applications. (DOE)

Impact of gravity waves on the development of equatorial plasma bubbles (J.D. Huba) NRL's three-dimensional simulation code SAMI3/ESF is used to study the response of the post-sunset ionosphere to plane gravity waves. The effect of the vertical wind component of the wave is included and shown to play a significant role in the seeding of equatorial spread F (ESF) by gravity waves. It is also shown that the strength of the coupling of the gravity wave to ESF increases with the vertical wavelength of the gravity wave. Long vertical wavelength modes (> 100 km) aremore effective for seeding ESF. Finally, it is demonstrated that an upward vertical background wind can suppress ESF. (NASA)

Ionospheric modeling using the SAMI3 code (J. Huba, J. Krall) The SAMI3 code was developed at NRL and has been modified to capture the onset and evolution of small-scale equatorial bubbles(L~10km) within the framework of a self-consistent global model (L~1000s km) which is unprecedented. Recently, the code has been upgraded to use a 4th order flux-corrected-transport scheme (partial donor cell method). The model now reproduces observations of complex structuring and bifurcation of equatorial plasma bubbles.

Solar Physics modeling (J. Chen). A new ideal MHD model has been developed that provides a physical mechanism to unify the three most energetic manifestations of solar eruptions: coronal mass ejections (CMEs), flares, and eruptive prominences (EPs). This is the first theoretical model that can replicate the observed CME trajectories from the Sun to 1 AU, the observed X-ray emission profiles associated with CME eruptions, and the evolved CME magnetic field measured in situ at 1 AU. (NRL 6.1)

Advancements in tracking and control of swarm patterns in fluids (I. Schwartz) Tracking Lagrangian coherent structures (LCS) in dynamical systems is important for many applications such as oceanography and weather prediction. We presented a collaborative robotic control strategy designed to track stable and unstable manifolds. The technique does not require global information about the fluid dynamics, and is based on local sensing, prediction, and correction. The collaborative control strategy is implemented on a team of robots to track coherent structures and manifolds on static flows as well as a noisy time-dependent model of a wind-driven double-gyre often seen in the ocean. (NRL 6.1, ONR)

Predicting rare events in stochastic systems-from theory to practice (I. Schwartz) Randomness in dynamical systems is ubiquitous, and as such as plays an important role in stochastic prediction theory. Applications range from all areas of physics, biology, and the social sciences. Of particular interest is the prediction of rare events, such as switching between patterns in spatio-temporal systems, or extinction in population dynamics. In this effort we have developed new mathematical methods and associated algorithms to determine the most likely paths which lead to rare events. (NRL 6.1, ONR)

Selected Recent Publications:

"Theoretical and numerical investigation of filament onset distance in atmospheric turbulence," J.R. Peñano, B. Hafizi, A. Ting, M. Helle, JOSA B **31**, 963 (2014)

"Origin and control of the subpicosecond pedestal in femtosecond laser systems," D. Kaganovich, J.R. Peñano, M.H. Helle, D.F. Gordon, B. Hafizi, and A. Ting, Optics Letters **38**, 3635 (2013)

"Underwater Nanosecond Laser Induced Filaments," M.H. Helle, T.G. Jones, J.R. Peñano, D. Kaganovich, and A. Ting, "Applied Physics Letters **103**, 121101 (2013)

"Fully Explicit Nonlinear Optics Model in a Particle-in-Cell Framework," D.F. Gordon, M.H. Helle, J.R. Peñano, J. Comp. Phys. 250, 388 (2013)

"Generation of mid-IR and visible radiation from 4-wave amplification of ultrashort laser pulses in transparent dielectrics," J. Peñano, D.F. Gordon, B. Hafizi, Journal of Optical Society of America B **30**, 708 (2013)

"Analysis and Design of a Quasi-Optical Mode Converter for a 1-kW, 550 GHz, $TE_{15,2}$-Mode Gyrotron," B.Y. Rock and A.W. Fliflet, *IEEE Transactions on Terahertz Science and Technology*, **3**, 641 (2013).

"Active Microwave Pulse Compressor Using an Electron-Beam Triggered Switch," O.A. Ivanov, M.A. Lobaev, A.L. Vikharev, A.M. Gorbachev, V.A. Isaev, J.L. Hirshfield, S.H. Gold and A.K. Kinkead, *Phys. Rev. Lett.,* vol. 110, 115002 (2013).

"Modeling the plasmasphere with SAMI3," J. Huba, J. Krall, Geophysical Research Letters **40**, 6 (2013)

"Simulation of the seeding of equatorial spread F by circular gravity waves," J. Krall, J.D. Huba, G. Joyce, and M. Hei, Geophys. Res. Lett. 40, (2013)

"Intervention-Based Stochastic Disease Eradication", L Billings, L Mier-y-Teran-Romero, B Lindley, IB Schwartz, PLOS ONE 8 (2013) e70211. *(Highlighted in Scientific American)*

Relativistic Quantum Optics on Graphical Processors

Dr. Daniel F. Gordon, Code 6791

Introduction

A numerical model for relativistic quantum optics was developed. The model solves the Klein-Gordon equation for a charged particle in an arbitrary applied electromagnetic field. The model is useful for describing photo-ionization of tightly bound electrons in the relativistic limit. Advanced computer architectures are employed to accelerate the computation.

Background

The physics of photo-ionization is ubiquitous in laser-plasma interactions. This process is both relativistic and quantum mechanical when tightly bound inner shell electrons are considered. In order to describe such a process from first principles, a solution of the Dirac or Klein-Gordon equation is required. The difficulty in developing such a solution lies partly in the need for computational speed, which in turn follows from the disparity between the Compton wavelength and the wavelength of a typical high power laser system. We have solved this problem by combining OpenCL programming for general purpose graphical processing units (GPGPU) with Message Passing Interface (MPI) programming for distributed memory parallelism. As a result, it is now possible to carry out relativistic photo-ionization simulations on GPGPU clusters. The dynamics of atomic electrons in extreme magnetic fields can also be described.

Accomplishment

An ab initio model for relativistic quantum optics was developed which makes use of GPGPU clusters. The model was used to visualize, for the first time, the quantum mechanical analog of the ponderomotive force.

Significance

Relativistic quantum optics is an inevitable outcome of the interaction of extreme laser fields with moderate to high atomic number atoms. The model allows for the accurate description of high energy electrons and photons produced during the interaction.

Application

Optimization of high energy particle sources based on ultra-intense laser-matter interactions.

Key Personnel

Dr. Daniel Gordon (6791), Dr. Bahman Hafizi (6791)
Dr. Michael Helle (6795)

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D.F. Gordon, B. Hafizi, M.H. Helle, “Numerical Relativistic Quantum Optics,” NRL Memorandum Report NRL/MR/6790--13-9496 (2013)

Sponsor: NRL 6.1 Base Program

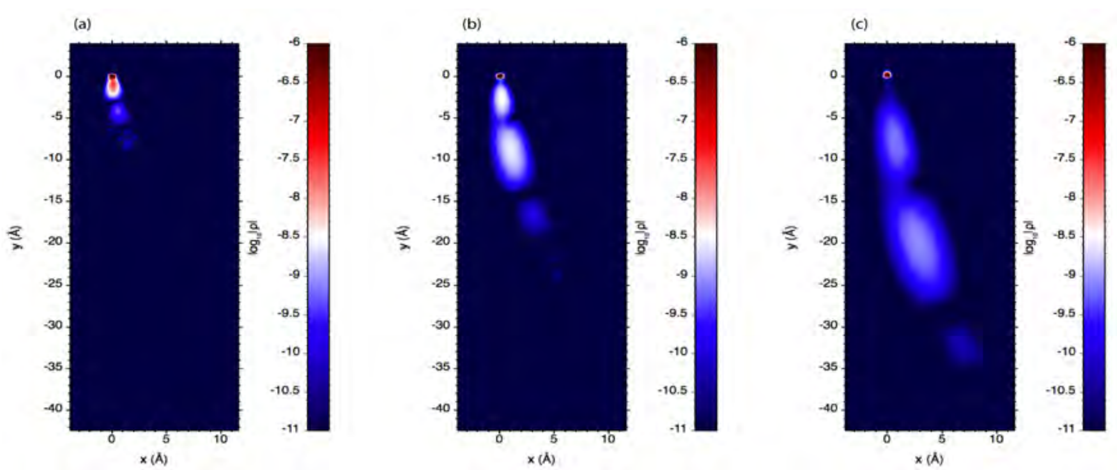


Figure caption: Tunneling ionization of hydrogen-like argon after (a) 26 attoseconds, (b) 39 attoseconds, (c) 52 attoseconds. In a relativistic theory, the wavefunction is associated with a charge density rather than a probability density. The images show negative charge being released in the direction opposite the polarization of the applied electric field (-y). Unlike the non-relativistic case, the charge is also accelerated in the direction of photon momentum (+x). The simulation was carried out on a cluster of 12 GPGPU nodes.

Combined Ultrashort Pulse and CW Laser Material Interactions

Dr. Joseph Penano, Code 6790

Introduction

Drs. Michael Helle and Antonio Ting preformed experiments to examine the combined effects of Ultrashort Pulse (USP) and Continuous Wave (CW) lasers on various materials. This was done using the kTFL laser system (15 mJ 35 fs) and a 200 W fiber laser. Both lasers were separately focused and combined on target to produce an average fluence of ~500 W/cm^2. Burn through times were measured for a large number of targets. It was observed that for materials such at copper, graphite, carbon fiber, and painted composites that burn through times were reduced by upwards of 2.5. Additional experiments were completed that examined the effect on both high reflectivity coated and uncoated transparent dielectrics. It was observed that the combined interaction of the USP and a 1.6 kW CW fiber laser could lead to enhanced heating of the dielectric and eventual mechanical failure, e.g. cracking. The underlying mechanisms for enhancement are currently being investigated using new experimental techniques and computer simulations.

Background

A CW beam, because of its relatively low intensity compared to a USP, heats the material surface but maintains thermal equilibrium between electrons and the atoms of the material. At sufficiently high average power, this heating can lead to a phase change in the material (e.g. melting of a solid). However, materials with low absorption or high reflectivity do not couple well with the CW beam and are difficult to modify.

Compared to a CW beam, an USP laser carries significantly less average power, however its peak intensity can be sufficient to ionize a material regardless of its optical properties. Furthermore, thermal equilibrium is not maintained as electrons are heated to significantly higher temperatures (a few eV) compared with the ions. As the resulting plasma thermalizes due to electron collisions, the material lattice heats and can eventually break apart. This damage tends to be contained within a limited volume due to the small amount of energy (~mJ's) carried by the USP. Nevertheless, with the recent development of high repetition rate intense USP lasers, the time necessary to significantly modify a material has been drastically reduced.

Accomplishment

It has been observed during experiments, that the material modification produced by the USP laser leads to enhanced coupling of the CW beam into various materials. These materials included both opaque and transparent dielectric materials as well as metals. It was observed that he USP laser created scattering centers within transparent dielectrics that act to increase absorption of the CW beam. This increased absorption produced heating within the transparent dielectric and in some cause led to mechanical failure. Meanwhile for opaque targets, the USP produce surface structures that also enhance absorption. The enhanced absorption causes an overall reduction in the time it took to burn through the targets. For targets materials such as copper, graphite, carbon fiber, and painted composites, a reduction in burn through times by factors of ~2.5 was observed.

Significance

The enhanced material interactions observed under the coillumination of USP and CW lasers has significant DOD applicants in that it could lead to reduced power requirements and increased effectiveness for DOD HEL laser weapon systems. Also, USP lasers have great potential to fulfill other role within such a system, e.g. chem/bio detection, adaptive optics, etc.

Application

Possible applications of this effect include advanced industrial cutting as well as next generation DOD HEL laser weapon systems.

Key Personnel

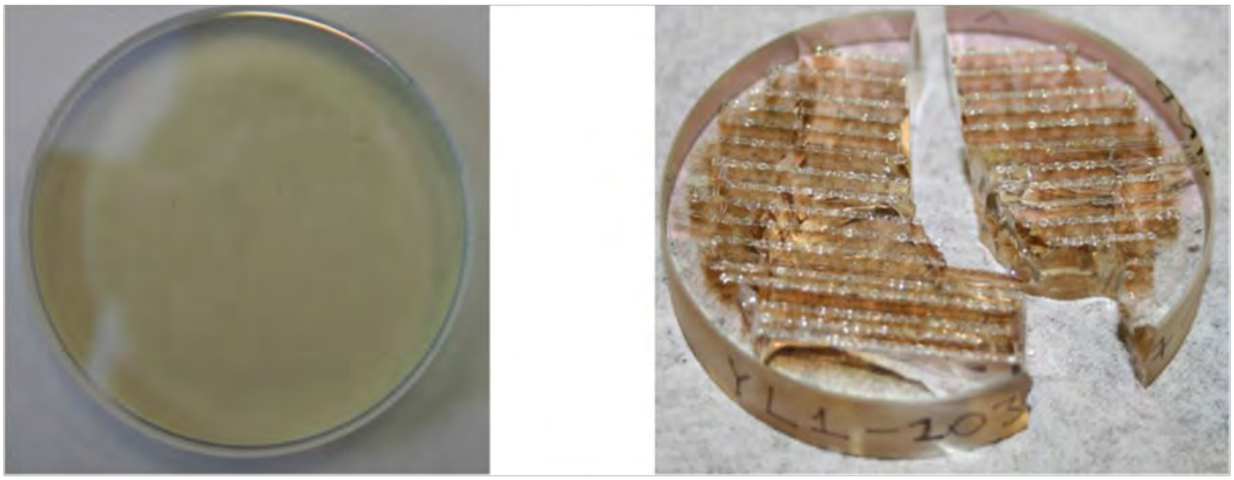
Dr. Michael Helle, Dr. Antonio Ting (6795)

References

Results recently presented at the Directed Energy Professional Societies Annual Meeting March 10-14, Huntsville, AL; JTO-HEL Annual Review April 29-May 2, Albuquerque, NM

Sponsor: High Energy Laser Joint Technology Office

Figure: Images showing high reflectivity coated dielectric mirrors after being exposed to a 1.6 kW fiber laser. The image on the right was exposed to a focused beam from the kTFL laser prior to the kW fiber laser. There was no noticeable temperature rise in the mirror on the left, while the mirror on the right exceeded 200^0C and eventually cracked.



Advancements in stochastic model reduction and prediction of slow-fast systems

Dr. Ira B. Schwartz, Code 6792

Introduction

Inroads have been made into a particularly challenging problem in physics and biology: how to analyze high-dimensional systems perturbed by noise in terms of lower dimensional models. Typically these systems might be addressed via computational methods, but such approaches are not guaranteed to be useful unless significant computing power is brought to bear. Using modern results from dynamical systems theory, we have developed a method that can accurately predict the frequency of extremely rare events that occur in stochastic systems. The method is general and works on a great variety of problems ranging from chemical kinetics to population dynamics.

Background

Many stochastic systems of physical interest possess dynamics which occur over multiple time scales. Stochastic systems are frequently used to model both micro-scale and macro-scale behaviors that are inherently noisy or simpler to visualize as driven by randomness. Examples of these systems range from nonlinear vibration in structures to networks of sensors in noisy environments, and to the control of epidemics, with scales ranging from nanometers to kilometers. Such systems present unique difficulties since multiple time scales interact with noise to affect the dynamics, leading to phenomena such as rare event occurrences resulting from large fluctuations. Such rare events are the cause of several obstructions to predictability: e.g., the collapse of structural network, the explosion of an epidemic, or the loss of information in sensor network. The new techniques reported here allow one to use large fluctuation theory to predict the probability of such rare events. It is tractable due to the fusion of new stochastic theories with global dynamical system analysis on low dimensional models. The analysis provides a new efficient way to harness the multi-scale behavior of the systems so that costly large simulations of rare events are avoided. Moreover, the new techniques allow for the the analysis of controls to either enhance to prevent the occurrence of rare events.

Accomplishment

We have written a paper, and submitted the analysis for publication to *Physica D*. In addition, an invited talk was presented at the Dynamical Systems meeting in Madrid in June, 2013. In addition, the Bulletin of Math Bio. Paper describes how to use the theory with data to predict unobserved dynamics from stochastic observations.

Significance

In developing this method, we have simplified and streamlined a method of analysis that is relevant to a generic stochastic dynamical system. Furthermore, the approach we take is both scalable, physically relevant, and has applications in a diverse number of fields.

Application

The method has already been used to properly reduce the model dimension of a stochastic system, and then calculate the likelihood of rare events in a set of generic systems that embody a simplified energy landscape: the double-well potential. It has been used to explicitly compute switching rates in nonlinear oscillators in the presence of weak noise. In addition, the method has been applied to multi-scale epidemic models and data. The theory allows one to extract unobserved exposed individuals from case history directly in a complete stochastic setting.

Key Personnel

Christoffer R. Heckman, Ira B. Schwartz

Acknowledgement

Eric Forgoston, Montclair State University

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NRL 6.2 Base Funding

Advances in random delay coupled swarms

Dr. Ira B. Schwartz, Code 6792

Introduction

We study the effects of discrete, randomly distributed time delays on the dynamics of a coupled system of self-propelling particles. Bifurcation analysis on a mean field approximation of the system reveals that the system possesses patterns with certain universal characteristics that depend on distinguished moments of the time delay distribution. Specifically, we show both theoretically and numerically that although bifurcations of simple patterns, such as translations, change stability only as a function of the first moment of the time delay distribution, more complex patterns arising from Hopf bifurcations depend on all of the moments.

Background

Currently, an area of intense research is that of interacting multi-agent, particle or swarming systems in various natural and engineering fields. Interestingly, these multi-agent swarms can self-organize and form complex spatio-temporal patterns even when the coupling between agents is weak. Many of these investigations have been motivated by a multitude of biological systems such as schooling fish, swarming locusts, flocking birds, bacterial colonies, ant movement, etc., and have also been applied to the design of systems of autonomous, communicating robots or agents and mobile sensor networks.

Accomplishment

We considered a randomly delay distributed coupled swarm model, and analyzed the mean-field bifurcations of various patterns as a function of delay characteristics and coupling strength. In particular, we found an infinite series of Hopf bifurcations whose location and shape is strongly-dependent on all the moments of the time delay distribution. In the single delay case, where the time delays are distributed according to a Dirac delta function, all of the succeeding Hopf bifurcations are all subcritical and continuous. In contrast, when all moments are present, the bifurcations may not even be continuous, presenting their structure as isolated closed curves bounded by fold bifurcations. Numerical simulations show that the pattern transitions of the full swarm equations do occur at approximately the parameter values predicted by the mean-field. Our analysis implies that as the time-delay distribution widens, some spatio-temporal patterns become inaccessible as he parameter regions where they are stable diminish greatly in size. In contrast, other patterns take over and become dominant at realistic parameter values. This research has been published in Physical Review E.

Significance

As with the system we investigated in this work, we expect that once distributed delays are accounted for, other coupled oscillator systems such as lasers, neurons, ecological populations, etc., with multiple synchronous states and other complex global behavior will generically display behaviors involving bifurcations that include all moments of the coupling delay distribution.

Application

Our results will be of use in the design of agent-interaction protocols to carry out robotic motion planning, consensus and cooperative control, and spatio-temporal formation. Some important applications making use of scalable numbers of agents are: obstacle avoidance, boundary tracking, environmental sensing, decentralized target tracking, environmental consensus estimation and task allocation.

Key Personnel

Luis Mier-y-Teran-Romero, Brandon Lindley and Ira B. Schwartz

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"Coherent Pattern Prediction in Swarms of Delay-Coupled Agents", Mier-y-Teran-Romero, L.; Forgoston, E.; Schwartz, I. B. ,IEEE Trans. Ro-

NRL 6.1 Base funds and ONR

Predicting rare events in stochastic systems-from theory to practice

Dr. Ira B. Schwartz, Code 6792

Introduction

Randomness in dynamical systems is ubiquitous, and as such as plays an important role in stochastic prediction theory. Applications range from all areas of physics, biology, and the social sciences. Of particular interest is the prediction of rare events, such as switching between patterns in spatio-temporal systems, or extinction in population dynamics. In this effort we have developed new mathematical methods and associated algorithms to determine the most likely paths which lead to rare events.

Background

One important aspect of the study of dynamical systems is the study of noise on the underlying deterministic dynamics. Although one might expect the deterministic dynamics to be only slightly perturbed in the presence of small noise, there are now many examples where noise causes a dramatic measurable change in behavior, such as noise induced switching between attractors in continuous systems, and noise induced extinction in finite size systems. In systems transitioning between coexisting stable states, much research has been done primarily because switching can be now investigated for a large variety of well-controlled micro- and mesoscopic systems, such as trapped electrons and atoms, Josephson junctions, and nano- and micro-mechanical oscillators. In these systems, observed fluctuations are usually due to thermal or externally applied noise. However, as systems become smaller, an increasingly important role may be played also by non-Gaussian noise. It may come, for example, from one or a few two-state fluctuators hopping at random between the states, in which case the noise may be often described as a telegraph noise. It may also be induced by Poisson noise.

Accomplishment

We have developed new mathematical theory s for the prediction of rare events in various stochastic systems. Using the theory, we have developed a new code, called the IAMM code, which predicts the most likely way a rare event will occur.

Key Personnel

Luis Mier-y-Teran-Romero, Brandon Lindley, Lora Billings, Mark Dykman and Ira B. Schwartz

Significance

The prediction of rare events is important in many aspects of science and engineering, and is observed across many spatial scales and times. One of the drawbacks in finding the most likely path of a rare event is that of computation. Monte Carlo runs are expensive. Using the new IAMM code developed at NRL allows one to find the optimal path of the rare event efficiently, even for infinite dimensional dynamical systems.

Application

We have applied the theory and software to predict rare events in switching systems and extinction events. Included in the application are delayed dissipation effects, which induce back-action effects in nano-scale opto-mechanical devices. The effects of random controls on disease extinction are also revealed.

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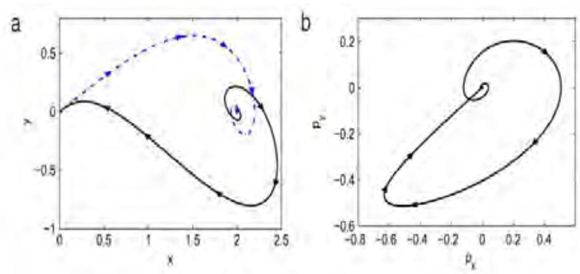


Plotted is the optimal path, as computed by the IAMM code of a general unforced Duffing nonlinear oscillator. The two equilibria points are at (0,0) and (2,0), and noise serves to drive the system to oscillate between the two equilibria (as indicated by the arrows). The p-variable represents the conjugate momenta associated with the optimal path from (2,0) to (0,0), a stable attractor and a saddle point, respectively.

Advancements in tracking and control of swarm patterns in fluids

Dr. Ira B. Schwartz, Code 6792

Introduction

Tracking Lagrangian coherent structures (LCS) in dynamical systems is important for many applications such as oceanography and weather prediction. We presented a collaborative robotic control strategy designed to track stable and unstable manifolds. The technique does not require global information about the fluid dynamics, and is based on local sensing, prediction, and correction. The collaborative control strategy is implemented on a team of robots to track coherent structures and manifolds on static flows as well as a noisy time-dependent model of a wind-driven double-gyre often seen in the ocean.

Background

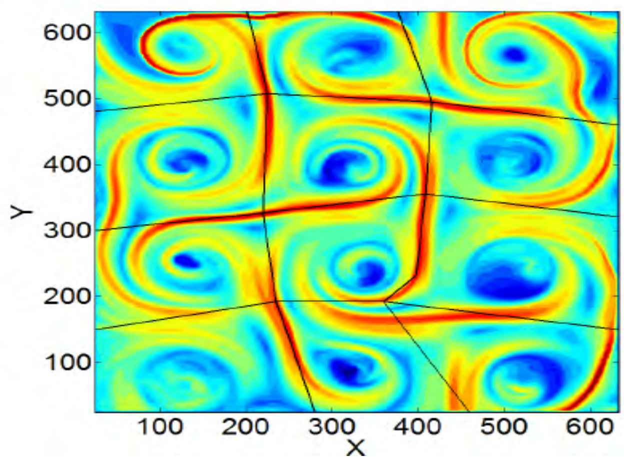
LCS have been shown to coincide with optimal trajectories in the ocean which minimize the energy and the time needed to traverse from one point to another. Furthermore, to improve weather and climate forecasting, and to better understand various physical, chemical, and geophysical processes in the ocean, there has been significant interest in the deployment of autonomous sensors to measure a variety of quantities of interest. One drawback to operating sensors in time-dependent and stochastic environments like the ocean is that the sensors will tend to escape from their monitoring region of interest. Since the LCS are inherently unstable and denote regions of the flow where more escape events may occur, knowledge of the LCS are of paramount importance in maintaining a sensor in a particular monitoring region.

Significance

The novelty of this work lies in the use of nonlinear dynamical and chaotic system analysis techniques to derive a tracking strategy for a team of robots. The cooperative control strategy leverages the spatio-temporal sensing capabilities of a team of networked robots to track the boundaries separating the regions in phase space that support distinct dynamical behavior. Additionally, our boundary tracking relies solely on local measurements of the velocity field. Our technique is quite general, and may be applied to any conservative flow.

Application

We have applied the tracking and control to locating the coherent structures in ocean flows. In addition, we have used this information to control swarm patterns in large scale flows.



Finite time Lyapunov exponent field for the temporal mean of experimental velocity data in a fluid tank of gyres. The field is discretized into a grid of 4×3 cells whose boundaries are shown in black. LCS ridges are in red. (From Nonlinear Processes in Geophysics, 2013.)

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NRL 6.1 Base funds and ONR

Active Microwave Pulse Compressor Using an Electron-Beam Triggered Switch

Dr. Steven Gold, Code 6793

Introduction

A high-power two-channel dual-mode active microwave pulse compressor has been developed that operates by modulating the quality factor of the energy storage cavities by means of mode conversion controlled by a triggered electron-beam discharge through the switch cavities. The pulse compressor operates at 11.43 GHz and has produced 190 MW, 20 ns output pulses at a record power gain of 26:1 with ~50% efficiency.

Background

NRL has had a long-term collaboration with Omega-P, Inc., and through them, with the Institute of Applied Physics (IAP) of the Russian Academy of Sciences, to develop active microwave pulse compressors at 11.4 GHz. The pulse compressors have been developed by Omega-P and the IAP, and the testing program has been carried out in collaboration with Code 6793 using the facilities of the X-band magnicon laboratory in NRL Bldg. 256. DoE's interest in pulse compressors is for application to high-gradient lepton linear accelerators, including the development of TeV linear colliders. A proposed future TeV electron-positron linear collider operating at X band (11.4 or 12.0 GHz) would require high-peak microwave powers of hundreds of megawatts in pulses lasting hundreds of nanoseconds. One method to provide such pulses is through the use of a microwave pulse compressor to multiply the power produced by high-power klystrons producing multi-microsecond output pulse widths. Such a compressor can be passive, employing phase switching to discharge microwave energy storage cavities such as in SLED II compressor at SLAC, or active, in which a triggered increase in the output coupling coefficient of the energy storage cavities is used to extract the high-power microwave pulse. Active microwave pulse compressors are of interest because they are more capable of both substantially higher compression ratios and higher efficiencies than passive compressors.

Sponsor: Department of Energy

Accomplishment

A test of an 11.43 GHz, two-channel, dual-mode active microwave pulse compressor using electron-beam triggered switch cavities has produced 190 MW, 20 ns output pulses at a record power gain of 26:1 with ~50% efficiency.

Significance

The successful demonstration of an efficient, high power, high gain active microwave pulse compressor that appears to be capable of long lifetime and high repetition rate demonstrates the potential of this technology for application to future rf accelerators and colliders requiring up to GW power levels and pulse durations of several hundred nanoseconds. This could be accomplished by driving the pulse compressor with multi-microsecond high-power klystrons and combining the type of switch employed in this device with longer resonant energy storage delay lines, such as those used in the passive SLAC SLED-II pulse compression system.

Application

After further testing and development, including enlargement to more than one single detector, use with some other thermal neutron detector concept (^{6}Li or ^{10}B), or integrated with specialized electronics, this concept could be actualized in a stand-off detection system. The detection of prompt neutrons using this technique is uniquely suited to the NRL IPAD concept and offers a more sensitive means of detecting SNM at a distance.

Acknowledgements

This work is carried out in collaboration with Omega-P, Inc. and the Institute of Applied Physics of the Russian Academy of Science in Nizhny Novgorod, Russia.

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"Active Microwave Pulse Compressor Using an Electron-Beam Triggered Switch," by O.A. Ivanov, M.A. Lobaev, A.L. Vikharev, A.M. Gorbachev, V.A. Isaev, J.L. Hirshfield, S.H. Gold and A.K. Kinkead, *Phys. Rev. Lett.,* vol. 110, 115002 (2013).

Multipactor Suppression in a Dielectric-Loaded Accelerating Structure Using an Axial Magnetic Field

Dr. Steven H. Gold, Code 6793

Introduction

Efforts have been under way over the past decade to develop Dielectric-Loaded Accelerating (DLA) structures capable of supporting high gradient acceleration when driven by an external rf source. Single-surface resonant multipactor has been identified as one of the major limitations on the practical application of DLA structures in electron linear accelerators. We have demonstrated partial suppression of multipactor in an X-band DLA structure through the use of an applied solenoidal magnetic field. This represents an advance toward the practical use of DLA structures in accelerator applications.

Background

Dielectric-loaded accelerating (DLA) structures are a potential alternative to metal disk-loaded structures for high-gradient rf linear accelerators driven either by wakefields or by external rf sources. The key difficulty to the practical application of DLA structures is the occurrence of strong multipactor loading on the dielectric surfaces. Our program is investigating multipactor physics and exploring means to suppress multipactor growth.

Accomplishment

We have carried out an experiment on an X-band dielectric-loaded accelerating structure that demonstrated partial suppression of multipactor growth through the use of an applied axial magnetic field. The suppression was partial because the DLA structure in this first test was longer than the uniform portion of the solenoidal magnetic field, so that the suppression was effective only in the central portion of the structure. This represents an advance toward the practical use of DLA structures in many accelerator applications.

Significance

This is the first reported test of the use of an axial magnetic field to suppress multipactor growth in dielectric-loaded accelerating structures, and may make possible the practical application of dielectric structures to improve the performance of high-gradient rf linear accelerators. .

Application

The application is to the development of dielectric-loaded accelerating structures as an alternative to periodic copper accelerating structures in high-gradient rf linear accelerators.

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Sponsor: Department of Energy

Atmospheric Winds Affect the Shape of the Plasmasphere

Dr. Jonathan Krall, Code 6794

Introduction

The plasmasphere is a cold, tenuous plasma that is the extension of the topside ionosphere into space. The Earth's geomagnetic field in the inner magnetosphere contains this plasma. Geomagnetic storms, driven by the solar wind, can effectively "open" these field lines, allowing plasma to escape very rapidly, over a time of a few hours. During subsequent quiet times, the ionosphere slowly refills the plasmasphere. The tenuous plasmasphere is like a tail being wagged by two dogs: the magnetosphere and the ionosphere. Using the NRL SAMI3 ionosphere/plasmasphere model, we have shown that the plasmasphere oscillates as it spins with the Earth, that these oscillations compare well to measured densities, and that the oscillations are strongly influenced by winds in Earth's upper atmosphere (the thermosphere). This new result shows that the plasmasphere can now be thought of as a tail being wagged by *three* dogs: the magnetosphere, the ionosphere and the thermosphere.

Background

The SAMI3 ionosphere model has been developed in order to better understand space weather and the effect of space weather on communication and navigation systems. SAMI3 computes the motion of 7 ion species (H+, He+, O+, N+, O2+, N2+, NO+), each treated as a separate fluid, with temperature equations being solved for H+, He+, O+ and the electrons. We have coupled the SAMI3 model to the Weimer empirical magnetosphere model, creating the only ionosphere/plasmasphere model that can accurately transport plasma along and across the geomagnetic field throughout the inner magnetosphere (other models do not extend as far into space or do not allow full motion of plasma across the magnetic field). SAMI3 also computes the self-consistent dynamo electric fields at mid-to-low latitudes, driven by specified winds.

Accomplishment

Using SAMI3, we have simulated a quiet-time period, February 1-5, 2001, that was also measured by the RPI (Radio Plasma Imager) instrument on the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft. We compared the IMAGE/RPI measurements to SAMI3 plasma densities

The image (top panel) shows SAMI3 curves (dashed, solid) and corresponding IMAGE/RPI measurements (triangles, squares). As the storm on Day 32 (February 1) ends and the magnetosphere settles down, the dashed SAMI3 curve threads its way through the triangles and the solid SAMI3 curve, corresponding to a position further out in space, threads its way through the squares. Oscillations at the rate of one per day appear in the SAMI3 curves. However, the spacecraft orbit is a lengthy 14 hours and the measurements do not occur often enough to resolve the oscillations. We can only say that the degree of variation in the model and the data is quite similar. The second panel is just like the first except that the model thermospheric winds come from the HWM07 model instead of the older HWM93 model. Again the SAMI3 curves thread the data points nicely, but the oscillations are out of phase with those in the top panel. In the third panel, the winds are set to zero and the oscillations disappear. This result shows that thermospheric winds, previously thought to be unimportant, instead strongly affect the shape of the plasmasphere.

Significance

This result shows that atmospheric winds, previously thought to be unimportant to space weather at these high altitudes, instead strongly affects the inner magnetosphere. This result will change the way that space weather data is interpreted.

Application

The NRL SAMI3 code is used by numerous space weather researchers. As such it is a leading candidate to be added to a future space weather prediction system. Whether or not the SAMI3 code is used in this way, SAMI3 results continue to affect the development of such systems. This specific result shows that atmospheric wind measurements will be more important to space weather prediction than previously realized.

Acknowledgements

This work involved two NASA LWS "Teams", one including Richard E. Denton of Dartmouth College, who provided the IMAGE/RPI data, and one including Geoff Crowley of ASTRA Inc., who assisted with thermospheric modeling.

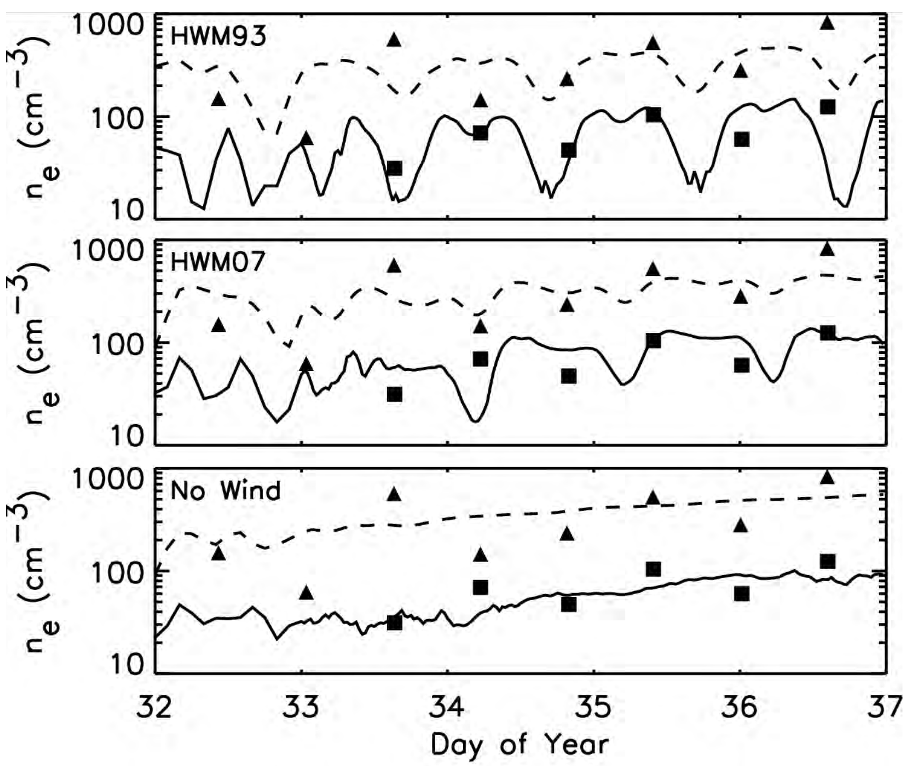
Key Personnel

Joseph D. Huba (6790, P.I. on the Ion-Neutral Coupling grant), Tsai-Wei Wu (6790)

References:

[1] Huba, J. and J. Krall, 2013, "Modeling the plasmasphere with SAMI3", Geophys. Res. Lett. 40, 6-10, doi:10.1029/2012GL054300

[2] Krall, J., and J. D. Huba, 2013, "SAMI3 simulation of plasmasphere refilling", Geophys. Res. Lett., 40, 2484-2488, doi:10.1002/GRL.50458
This latest work was presented at NASA LWS site visits in February and September 2013 (LWS Plasmasphere



The image shows SAMI3 curves (dashed, solid) and corresponding IMAGE/RPI plasma density measurements (triangles, squares). As the storm on Day 32 ends, the dashed SAMI3 curve compares well with the triangles and the solid SAMI3 curve, corresponding to a position further out in space, compares well with the squares. In the second panel, model thermospheric winds come from the HWM07 model instead of the older HWM93 model. In the third panel, the winds are set to zero and the oscillations disappear.

Sponsor: NASA Living With a Star Program

Design of a Quasi-Optical Output Coupler for a 550 GHz Gyrotron

Dr. Arne Fliflet, Code 6793

Introduction

Modern gyrotrons rely on a quasi-optical mode converter to transform the high order cavity mode into a near-Gaussian beam at the output window. For many terahertz applications a Vlasov-type helical launcher and single focusing reflector based on geometrical optics provides moderate bandwidth and acceptable beam quality. We have derived a more general set of analytic equations for the focusing reflector and demonstrated that a quasi-analytical solution to the Kirchhoff diffraction integral can accurately model the diffraction spreading of the launched radiation. This approach produces a more focused beam than previous work and avoids the need for expensive, computationally intensive Electric Field Integral Equation simulation software.

Background

Modern gyrotrons rely on a quasi-optical mode converter to transform the high order cavity mode into a near-Gaussian beam at the output window. High power millimeter-wave gyrotrons for continuous wave applications, such as electron cyclotron heating of confined plasmas, require highly efficient narrow-bandwidth output couplers. On the other hand, for moderate average-power terahertz applications a Vlasov-type helical launcher and single focusing reflector based on geometrical optics provide more bandwidth and acceptable beam quality. Previous analyses have presented design equations for a reflector which generates approximately parallel output rays, but reflector designs which focus the rays to a point have heretofore been only numerically determined. Launcher simulation codes based on Electric Field Integral Equation such as Surf3d have been developed for guiding output design, but these are expensive and computationally intensive.

Accomplishment

We have derived a more general set of analytical equations for the focusing reflector of a Vlasov-type output coupler for a gyrotron and demonstrated that a quasi-analytical solution to the Kirchhoff diffraction integral can accurately model the diffraction spreading of the launched radiation. This approach produces a better, more focused beam than previous analytic formulations. We have used the new equations and methods to design an output coupler for a 1-kW, 550 GHz gyrotron.

Significance

This approach produces a better, more focused beam than previous geometrical optics formulations and avoids the need for expensive, computationally intensive software. The more tightly focused beam reduces losses as the beam propagates from the interaction cavity located at the center of a large superconducting magnet to the output window located outside the magnet dewar. The main lobe of the beam is also separated from the side lobes, making it more suitable for end-use.

Application

Kilowatt power level terahertz gyrotrons are of interest for coherent-on-receive radars and remote sensing applications.

Key Personnel

Benjamin Rock and Arne Fliflet

References

B.Y. Rock and A.W. Fliflet, "Analysis and Design of a Quasi-Optical Mode Converter for a 1-kW, 550 GHz, $TE_{15,2}$-Mode Gyrotron," *IEEE Transactions on Terahertz Science and Technology*, **3**, 641 (2013).

Acknowledgements

Joint proposals for terahertz gyrotron development with other organizations such as U. Md. are being pursued.

NRL 6.2 Base Program

Impact of gravity waves on the development of equatorial plasma bubbles

Dr. Joseph D. Huba, Code 6794

Introduction

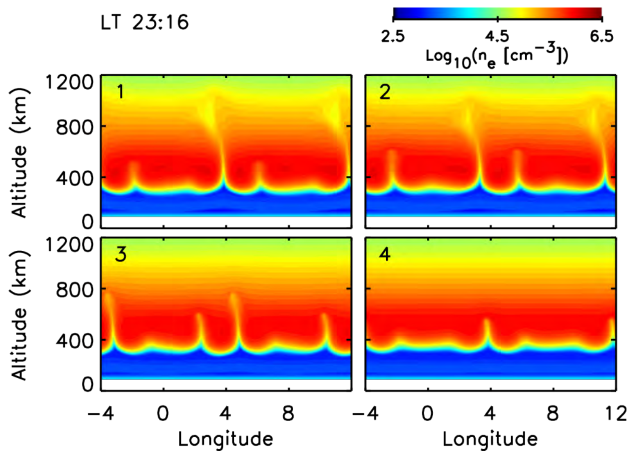
The Naval Research Laboratory three-dimensional simulation code SAMI3/ESF is used to study the response of the post-sunset ionosphere to plane gravity waves. The effect of the vertical wind component of the wave is included and shown to play a significant role in the seeding of equatorial spread F (ESF) by gravity waves. It is also shown that the strength of the coupling of the gravity wave to ESF increases with the vertical wavelength of the gravity wave. Long vertical wavelength modes (> 100 km) are more effective for seeding ESF. Finally, it is demonstrated that an upward vertical background wind can suppress ESF.

Background

The earth's ionosphere is a partially ionized gas that surrounds the earth in the altitude range 90 – 1000's km. Electromagnetic waves propagating through the ionosphere can suffer a number of adverse effects such as phase and amplitude fluctuations, absorption, scattering, frequency shifts, etc. The degradation of electromagnetic radiation can adversely impact communication and navigation systems. The equatorial ionosphere can become extremely disturbed after sunset because of a phenomenon known as equatorial spread F (ESF). During ESF the equatorial ionosphere becomes unstable and large-scale (10's km) electron density depletions (or `bubbles') develop and rise to high altitudes (> 1000 km at times) which disrupt communication and navigation signals. Thus, it is important to understand and characterize ESF to improve operational systems

Accomplishment

SAMI3/ESF simulations of the post-sunset ionosphere in the presence of plane gravity waves show that the strength of the coupling of the gravity wave and the generalized Rayleigh-Taylor instability increases with the vertical wavelength of the gravity wave (shown in Figure 1). Short wavelengths (< 100 km) are generally ineffective for seeding ESF. We also find that vertical winds can play a crucial role in the seeding and growth of ESF, both in terms of the gravity wave seed and the ambient wind conditions. Specifically we show that a background vertical wind of magnitude 20 m/s can significantly amplify the instability or suppress it entirely, depending on the direction of the wind. Although nominal vertical neutral wind speeds are relatively small (about 1 m/s) in the low- to mid-latitude ionosphere, there is evidence that they can be much higher (10 - 40 m/s) in the nighttime equatorial ionosphere.



Impact of different gravity wave vertical wavelengths on the development of equatorial spread F bubbles. The vertical wavelength is decreasing from panels 1 to 4. Shown are color-coded contours of the electron density. Plasma bubbles are well-developed for long wavelength gravity waves (panel 1) but not for short wavelength gravity waves (panel 4).

Significance

The development of a self-consistent 3D model of ESF is a major step forward in our ability to both characterize and eventually predict the onset and evolution of equatorial spread F.

Key Personnel

J.D. Huba T.-W. Wu, J. Krall, D. Fritts (GATS, Inc.)

Application

The long term application of this effort is develop models for the national Space Weather Program.

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NRL 6.1 Base Program

High Resolution Time-resolved Studies of Intense Underwater Laser Interactions

Dr. Ted G. Jones, Code 6795

Introduction

Our group has taken the first comprehensive high-resolution time-resolved images and spectra of underwater laser-induced breakdown (LIB) generated by nanosecond (ns), picosecond (ps), and femtosecond (fs) duration laser pulses. Underwater LIB dynamics, including photoionization, heating, photodissociation, and shock generation, were imaged with fs-time-resolution and 1-µm-spatial-resolution shadowgraphy. In addition we performed the first time-resolved spectroscopy measurements of underwater laser-generated plasma, revealing plasma temperatures near 10,000 Kelvin (K), and plasma lifetimes more than 100,000x longer than expected from average liquid-density collision times.

Background

NRL's Remote Underwater Laser Acoustic Source (RULAS) patented technology enables intense optical pulses to propagate through air and into the water, where they generate underwater acoustic pulses through laser-induced breakdown, heating, and shock generation. Details of these processes determine optical to acoustic energy conversion efficiency, and ultimately the acoustic source level (peak pressure), a key parameter for any Navy acoustic source. NRL's Underwater Laser-Guided Discharge program aims to research and develop techniques for advanced micromachining, pulsed power, potential undersea weapon applications.

Accomplishment

Our group has imaged and characterized underwater laser ionization with 1 micron spatial resolution and 50 fs time resolution (5 orders of magnitude faster than is possible with optoelectronic instruments). These new high resolution images revealed microbubble generation during ns and ps laser ionization, as well as optical filament formation for all laser pulse durations. Analysis of the resulting gas confirmed water dissociation. Time-resolved spectroscopy revealed underwater plasma with initial temperature of up to 9500 K, lasting over 100 ns after laser generation, as well as excited molecular water emission lines lasting over 130 ns.

Significance

These new measurements reveal interesting structures and dynamics during intense underwater laser interactions, using a broad range of different laser pulses. mechanisms Intense underwater laser interactions, including laser scattering and absorption, laser-induced breakdown, laser heating, and shock generation processes, all combine to determine optical to plasma energy and optical to acoustic energy conversion efficiencies.

Application

Optical to plasma energy and optical to acoustic energy conversion efficiencies are key parameters for laser acoustic generation and for laser-guided underwater discharge schemes. Thorough understanding of these processes can lead to a predictive model for acoustic waveforms as a function of laser pulse parameters, as well as techniques for mitigating laser energy losses during underwater propagation and plasma heating. The NRL RULAS source has a wide range of potential Navy applications, including communication with undersea vessels and equipment, rapid airborne sonar searches and terrain mapping, navigation, and platform protection. High source levels can increase the range and robustness of the RULAS source, and together with acoustic pulse shaping, can also improve its directivity and stealth. Potential Navy applications of laser-guided underwater discharges include advanced micromachining, pulsed power generator switches, and low frequency laser acoustic generation as envisioned in a recent NRL patent application.

Key Personnel:

Dr. Dmitri Kaganovich, Code 6795

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T.G. Jones, A. Ting, D. Gordon, M. Helle, and J. Peñano, "Two Laser Generation of Extended Underwater Plasma," U.S. Patent Application 13/711,752 (filed Dec. 2012).

T.G. Jones, A. Ting, and D. Gordon, "Underwater Laser-Guided Discharge," U.S. Patent Application 13/293,338 (filed Nov. 2011).

T.G. Jones, D. Kaganovich, M. Helle, J. Peñano, A. Ting, and D. Gordon, "High-Resolution Femtosecond Measurements of Underwater Laser Ionization and Filamentation for Electrical Discharge Guiding," IEEE Pulsed Power and Plasma Physics Meeting, San Francisco, CA (June 2013).

T.G. Jones, M. Helle, D. Kaganovich, D. Gordon, A. Ting, and J. Peñano, "Extended Underwater Plasma Generation Using Laser Filamentation," APS Div. of Plasma Physics Meeting, Providence, RI (Dec. 2012).

Figure caption: A high-resolution shadowgraphy image, taken with a 50 fs laser backlight, freezes creation and growth of microbubbles along the ionizing laser beam axis during underwater laser-induced breakdown. The ionizing pulse had a 6 ns duration and 13 mJ of energy, at 532 nm wavelength.

Record Underwater Acoustic Source Level Using a Compact Laser

Dr. Ted G. Jones, Code 6795

Introduction

Our group has demonstrated record underwater acoustic source levels (SLs) of 218 dB, generated by a compact portable laser. This represents an order of magnitude increase over peak acoustic pressures previously generated by compact lasers. Compact lasers can be flown on aircraft or based on surface ships for remote generation of underwater acoustic signals for a variety of applications, including communications, sonar, navigation, and platform and harbor protection. .

Background

NRL's Remote Underwater Laser Acoustic Source (RULAS) patented technology enables intense optical pulses to propagate through air and into the water, where they generate underwater acoustic pulses through laser-induced breakdown, heating, and shock generation. An important recent RULAS development is the ability to control the acoustic waveform and directivity by varying key laser pulse parameters. The closest comparable technologies, active sonobuoys or low-frequency AUV-based sonar (under development), require complex hardware in the water, are stationary or slow-moving once deployed, or have limited operating lifetimes due to high power requirements and limited energy storage.

Accomplishment

Our group has demonstrated underwater laser acoustic generation with record acoustic source level of 218 dB (re: 1 micro-Pascal at 1 meter from the source), using a compact portable laser. This particular laser system was recently purchased using NRL Capital Procurement Program funds. It produces 10 nanosecond (ns) duration laser pulses with up to 2 Joules (J) of energy.

Significance

The new record SL of 218 dB represents an order of magnitude increase in peak pressure over previously demonstrated RULAS SLs using compact lasers.

Application

The NRL RULAS source has a wide range of potential Navy applications, including communication with undersea vessels and equipment, rapid airborne sonar searches and terrain mapping, navigation, and platform protection. High source levels can increase the range and robustness of the RULAS source, and together with acoustic pulse shaping, can also improve its directivity and stealth.

Key Personnel:

Dr. Dmitri Kaganovich and Dr. Michael Helle ,
Code 6795

References

"Tailoring Underwater Laser Acoustic Pulses," 2012 NRL Review article, published Sept.2013.

NRL 6.2 ONR direct funding

Flight Testing of UAV Powered by High-Power Laser

Dr. Richard Fischer, Code 6795

Introduction

A series of flight tests was successfully conducted during the last year over a 40-m path in the prototyping high bay in the Laboratory for Autonomous Systems Research at NRL, where a high-power fiber laser was used to beam power to a UAV. A 2 kW, single-mode fiber laser (1.07 micron wavelength) transmits power to a photovoltaic (pv) array fabricated using InGaAs laser power converter chips from Spectrolab (Sylmar, CA). The individual chips are 40-50% efficient at the fiber laser wavelength, and the array provides more than 160 W of electricity to power the vehicle. Off-the-shelf components were used to develop the optical tracking system, which automatically positions the laser beam on the center of the pv array during flight. Researchers in the Tactical Electronic Warfare Division designed and fabricated a custom 3.8-lb, dual-rotor UAV that provides air cooling of the pv array using the rotor wash.

Background

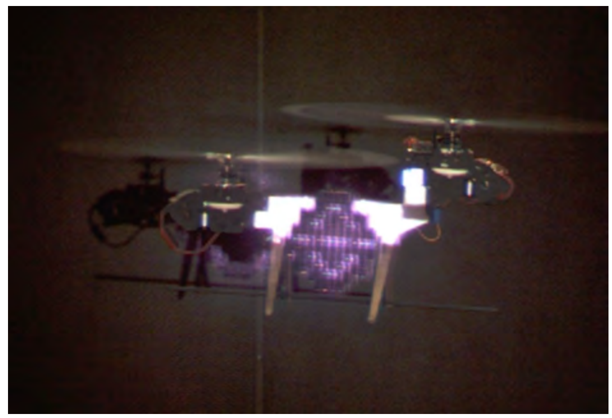
We have recently demonstrated high-power cw (> 4 kW), single-mode, fiber laser beam propagation in the atmosphere over extended distances (> 3 km). An optimized photovoltaic converter on a remote platform, such as an unmanned aerial vehicle (UAV), can efficiently (~60%) convert laser energy to electrical power. A power beaming architecture using fiber lasers can provide a significant weight reduction by removal of batteries, extended flight duration day and night, and possible extended range. Code 6790 has four high-power, single-mode fiber lasers with a total cw power of 6.2 kW and wall-plug efficiency > 25%. These fiber lasers are used to develop an efficient long-range laser power beaming architecture to stationary and dynamic platforms. The NRL approach to long-range laser power beaming uses the same wavelength and technology as Navy designs for 100 kW-class solid-state lasers for ship self-defense.

Significance

The demonstration of power beaming to a UAV using fiber lasers at significant power levels is an important step towards longer range and higher power.

Application

Long-range laser power beaming to UAVs can allow for long-duration flights with reduced manpower requirements for many Navy and DoD missions, including off-board decoys, persistent surveillance, and communication relays.



NRL dual-rotor UAV with PV array, illuminated with fiber laser during power beaming flight tests in LASR facility (2013).

Key Personnel

Dr. Richard Fischer 6795, Dr. Tony Ting 6795, Greg DiComo 6795, Dr. Phil Sprangle 6703, Steve Tayman 5712

Acknowledgements:

Spectrolab Inc. (Sylmar, CA) developed the InGaAs laser power converter cells and assembled the pv array.

References:

U.S. patent #7,970,040, "Incoherent combining of high power lasers for long-range directed-energy applications," June 2011. R. Fischer, G. DiComo, A. Ting, S. Tayman, and P. Sprangle, "Power beaming experiments using high-power fiber lasers at 1.07 microns," in preparation.

NRL 6.2 Base Funding

Origin and control of the subpicosecond pedestal in femtosecond laser systems

Dr. Antonio C. Ting, Code 6795

Introduction

We investigated experimentally and analytically the picosecond time scale pedestal of a multi-terawatt femtosecond laser pulse. We discovered that the origin of the pedestal is related to the finite bandwidth of the laser system. By deliberately introducing a modulated spectrum with minimums that match this limited bandwidth, we managed to reduce the pedestal, with no deleterious effect on the main pulse. Using this technique we experimentally demonstrate a sub-picosecond scale, order of magnitude enhancement of contrast ratio that led to a significant increase of electron energy in a laser wakefield accelerator.

Background

Pulse contrast and shape of the laser pulse are a crucial part of sub-picosecond, multi-terawatt chirped-pulse amplification (CPA) laser systems [1, 2]. A high contrast ratio is critical in experiments on laser-matter interaction, where pedestals and prepulses can generate unwanted plasmas in front of the main pulse [2]. Several earlier experiments demonstrated that pulse shape and prepulse contrast greatly affect quality and usability of laser wakefield accelerated (LWFA) electron beams [3, 4]. Latest efforts in contrast enhancement are concentrated on prepulses and pedestals in the 100 picosecond to a few nanosecond range. At the same time most of today's LWFA accelerators operate in so called bubble regime [5-7] where even short scale (picosecond or less) pedestals or prepulses could suppress beneficial effects of ionization in the main pulse. If these pedestals are intense enough to ionize the plasma in front of the main pulse, the back of the main pulse might experience slower and less predictable self-focusing, leading to a shorter propagation distance of the accelerating bubble structure. We investigated the origin of pedestal-like contrast degradation in the immediate proximity (±1 ps) of the main pulse. We showed that this pedestal is caused by the limited bandwidth of the laser CPA system. We provided a simple solution that allows significant enhancement of this pedestal and showed that this reduction enhances electron acceleration in the laser wakefield.

Accomplishment

Using a simple pulse splitter and delay line, we have produced significant (order of magnitude) improvement of sub-picosecond-scale laser contrast. We interpret this contrast enhancement as a result of linear interference among two chirped input pulses producing a modulated laser spectrum that is matched to the bandwidth of the optical system. Because we can work near points of constructive interference and the amplifier is run to saturation, the energy in the amplified pulse is preserved. This contrast enhancement is shown to increase the energy of laser wakefield accelerated electrons by creating favorable conditions for the accelerating plasma bubble.

We demonstrated the effect of a picosecond pedestal on accelerated electrons generated in the bubble regime of LWFA. We compared the energy and charge of the accelerated electrons for reduced pedestal and for the unmodified laser pulse. The laser pulse with enhanced contrast generated a significantly higher (at least a factor of 2, from 30 to 60 MeV) electron beam energy, while the charge of the accelerated electrons remained almost unchanged (250 pC).

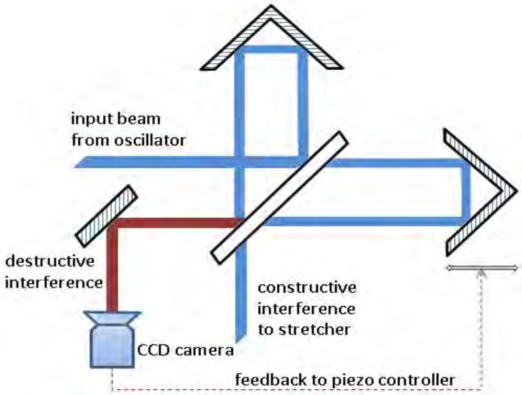
The major results of this work were published:

D. Kaganovich, J.R. Penano, M. H. Helle, D. F. Gordon, B. Hafizi, and A. Ting, "Origin and control of the subpicosecond pedestal in femtosecond laser systems," Optics Letters, 38, 3635 (2013).

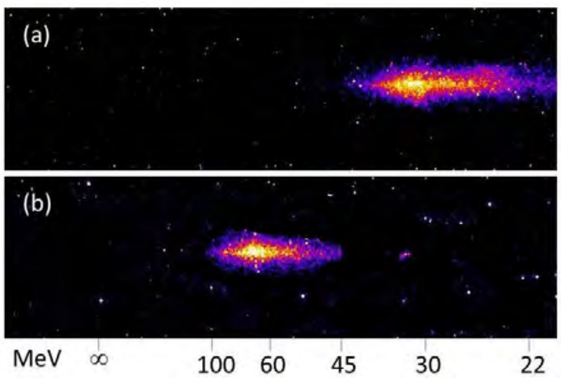
Navy invention disclosure #102638, "Enhancement of laser contrast in chirped-pulse amplification systems," was submitted in August 2013.

Significance

The proposed scheme of subpicosecond pedestal contrast enhancement can be implemented in high power (100 TW – PW and higher) lasers. Our scheme is compatible with other, already standard techniques like double chirped pulse amplification [8] and cross-polarized wave filtering [9]. Combination of the proposed spectral modulation scheme with these techniques might produce temporally clean laser pulses at both short (subpicosecond) and long (tens of picoseconds) time scales.



Interferometer is producing a modulated laser spectrum that is matched to the bandwidth of the optical system. Destructive interference beam is used for a stabilization feedback of nanometer precision delay line.



Effect of the laser contrast enhancement on the Accelerator 022 output energy. Image (a) from the output of the electron spectrometer shows the electron energy for unmodified laser beam (30±10 MeV). Image (b) shows the electron energy spectrum for the reduced contrast laser beam (70 MeV ± 20). The wider energy spread in (b) is due to the limited resolution of the spectrometer at higher electron energy.

Application

The laser contrast enhancement scheme will be used in the NRL laser-plasma Accelerator 022 (room 142 building 101). Modification of the contrast enhancement scheme will be used to shape the laser beam pulse for generation of Raman backscattering (RBS) radiation inside the plasma acceleration cavity. Extended scattering of RBS off the laser accelerated electrons is a potential way to create compact synchrotron source of polarized, monochromatic and coherent X-rays. This idea is submitted as a 6.1 new start proposal (P.I. Dmitri Kaganovich).

Key Personnel

Dmitri Kaganovich 6795, Joe Penano 6790, Mike Helle 6795, Daniel Gordon 6791, Bahman Hafizi 6791.

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AWARDS and RECOGNITIONS

Dr. Phillip Sprangle is the 2013 recipient of the James Clerk Maxwell Prize

Dr. Phillip Sprangle, Senior Scientist for Directed Energy Physics, Plasma Physics Division at the U.S. Naval Research Laboratory, is awarded the American Physical Society James Clerk Maxwell Prize, the most prestigious award in the field of plasma physics.

Dr. Phillip Sprangle was the 2013 recipient of the James Clerk Maxwell Prize. Presentation of this award is the highest honor bestowed upon plasma physics researchers and is the first in the laboratory's 90-year history. Presented by the American Physical Society (APS), the Plasma Physics Division's Dr. Sprangle is recognized for 'pioneering contributions to the physics of high intensity laser interactions with plasmas and to the development of plasma accelerators, free-electron lasers, gyrotrons, and high current electron accelerators.' Dr. Sprangle's research at NRL spans several decades and a multitude of research disciplines that include the atmospheric propagation of high-energy lasers, ultra-short pulse laser-matter interaction and propagation, nonlinear optics, free electron lasers and laser driven accelerators.

Chief scientist (ST) for Directed Energy Physics in the Plasma Physics Division. He is a Fellow of the American Physical Society (APS), the Directed Energy Professional Society (DEPS), the Institute of Electrical and Electronics Engineers (IEEE) and the Optical Society of America (OSA).

Dr. Sprangle has been the recipient of many notable awards: ONR Dr. Fred E. Saalfeld Award for Outstanding Lifetime Achievement in Science, the Navy Meritorious Civilian Service Award, Top Navy Scientist and Engineer of the Year Award, Sigma Xi Pure Science Award, International Free Electron Laser Prize, and the E.O. Hulburt Science and Engineering Award.

Dr. Andrew Schmitt elected American Physical Society Fellow

Dr. Andrew Schmitt, Is elected Fellow by the (APS) American Physical Society for major contributions to the theory and simulation of laser plasma interactions. Dr. Schmitt is further recognized for his pioneering work on the effects of laser beam smoothing and for advancing high-resolution simulations of laser high-gain direct-drive implosions.

Dr. Jack Davis celebrates Forty Years of service

Dr. Mehlhorn presents the Forty Year plaque to Dr. Davis

Dr. Gurudas Ganguli receives NRL Edison (Patent) Award

The NRL Patent Award recognizes significant NRL Contributions to science and engineering that are perceived to have the greatest potential benefit to the country.

Technique for De-Orbiting Small Debris from the Near-Earth Space Environment

Dr. Gurudas Ganguli, Dr. Christopher Crabtree
Plasma Physics Division

Mr. Scott Chappie, Spacecraft Engineering Department
Dr. Leonid Roudakov, Contractor
Ms. Kathleen Chapman, Office of Associate Counsel

Dr Gurudas Ganguli receives Award from CAPT Ferrari

Left to right: Dr. Christopher Crabtree, Ms Kathleen Chapman, Mr. Scott Chappie, Dr. Gurudas Ganguli, and CAPT Anthony Ferrari

Dr. Joseph Huba receives
Dr. Delores M. Etter Top Scientists and Engineers of the Year Award

Dr. Huba, recipient of the 2012 Dr. Delores M. Etter Top Scientists and Engineers of the Year Award was honored by RADM Klunder, Dr. Montgomery and CAPT Ferrari at an honorary ceremony on Thursday, September 5, 2013.

Left to right: RADM Klunder, Dr. Huba and CAPT Ferrari

Dr. Thomas A. Mehlhorn Named IEEE Fellow

Dr. Thomas Mehlhorn, Superintendent of the Plasma Physics Division at the Naval Research Laboratory, has been named a Fellow of the IEEE. The Grade of Fellow is conferred by the IEEE Board of Directors upon individuals for an outstanding record of accomplishments.

Dr. Joseph Schumer promoted to IEEE Senior Member

Dr. Joseph Schumer elevated to the grade of IEEE Senior Member in recognition for professional standing and service by the Officers and Board of Directors of IEEE.

Dr. Joseph D. Huba Elected as Fellow of the American Geophysical Union

Dr. Joseph Huba, Head of the Space Plasma Physics Section of the Beam Physics Branch at the Naval Research Laboratory, elected as a Fellow of the American Geophysical Union (AGU) for "seminal advances in modeling the dynamics of Earth's ionosphere, magnetic reconnection, and the theory of kinetic/fluid plasma instabilities"

Dr. Sandra Hernandez receives NRC/ASEE Postdoctoral Publication Award

Dr. Hernandez received the Postdoctoral Award for her publication

Chemical Gradients on Graphene To Drive Droplet Motion

Plasma Physics Division's 2013 ARPAD Award Recipients

Dr. David Boris

Controlling the electron energy distribution function of electron beam generated plasmas with molecular gas concentration

D.R. Boris, G.M. Petrov, E.H. Lock, Tz.B. Petrova, R.F. Fernsler and S.G. Walton

Fully Explicit Nonlinear Optics Model in a Particle-in-Cell Framework

D.F. Gordon, M.H. Helle, and J.R. Penano

Dr. Daniel Gordon

Best publications considered for ARPAD by the Plasma Physics Division

Exact self-similar solutions for the magnetized Noh Z pinch problem A Concept for Elimination of Small Orbital Debris
Gurudas Ganguli, Christopher Crabtree, Leonid Rudakov, and Scott Chappie

Generation of energetic (>15 MeV) neutron beams from proton- and deuteron-driven nuclear reactions using short pulse lasers
G M Petrov, DP Higginson, J Davis, Tz B Petrova, C Mcguffey, B Qiao and FN Beg

K-a Emission Spectroscopic analysis from a Cu Z-pinch
A. Dasgupta, R.W. Clark, J.L. Giuliani, N.D. Ouart, B. Jones, D.J. Ampleford, S.B. Hansen

Observation of parametric instabilities in the quarter critical density region driven by the Nike KrF laser
J.L. Weaver, J. Oh, L. Phillips, B. Afeyan, J. Seely, D. Kehne, C.M. Brown, S.P. Obenschain, V. Serlin, A.J. Schmitt, U. Feldman, R.H. Lehmberg, E. Mclean and C. Manka

Theory and simulations of electron vortices generated by magnetic pushing
A. S. Richardson, J. R. Angus, S. B. Swanekamp, P. F. Ottinger, and J. W. Schumer

Investigations into the Design of a Compact, Battery-powered Rep-rate Capacitor Charger
B. M. Huhman and J. M. Neri

Origin and control of the picosecond pedestal in femtosecond laser systems and its effect on laser wakefield acceleration of electron
D. Kaganovich, J.R. Penano, M.H. Helle, D.F. Gordon, B. Hafizi, and A. Ting

Plasma Physics Division

Dr. Thomas A. Mehlhorn, SES
Superintendent

Naval Research Laboratory
4555 Overlook Avenue, S.W.
Washington, DC 20375

Office: (202) 767-2723
Fax: (202) 767-1607
Email: tom.mehlhorn@nrl.navy.mil

The Plasma Physics Division was established at the Naval Research Laboratory in 1966. The Division is a major center for in-house Navy and Department of Defense basic and applied research in plasma physics, laboratory discharge and space plasmas, intense electron and ion beams and photon sources, atomic physics, pulsed power sources, laser physics, advanced spectral diagnostics, and nonlinear systems.

Our research staff includes scientists from many disciplines and diverse backgrounds – working together to respond to requirements and opportunities from the Navy and the Nation.

Our research efforts concentrate on a few closely coordinated theoretical and experimental programs. We emphasize large-scale numerical simulations related to plasma dynamics and other physical phenomena. The Division is organized into five Branches formed along technical subjects.

Dr. Richard F. Hubbard
Associate Superintendent

As the Associate Superintendent, Dr. Hubbard works closely with the Division Superintendent in planning and directing the technical and administrative affairs of the Division. He has primary responsibility for safety, computer security, facility renovations, and maintenance of the Division. He provides guidance to Division personnel on security matters.

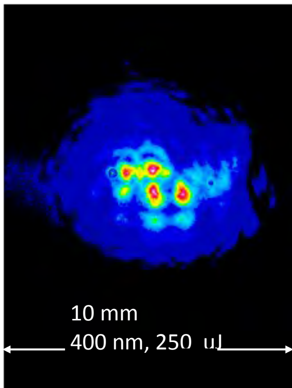
Because of his broad technical background and interests, he plays an active role in planning research activities in the Division. He advises numerous Division personnel on potential sponsor contacts and proposal strategies.

Office (202) 767-2997
Email: richard.hubbard@nrl.navy.mil

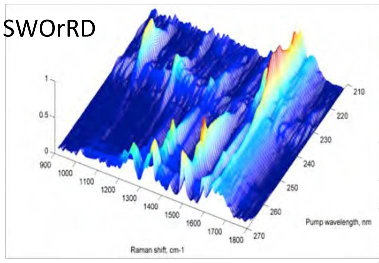
Experimental Facilities

State-of-the-art Plasma Diagnostics

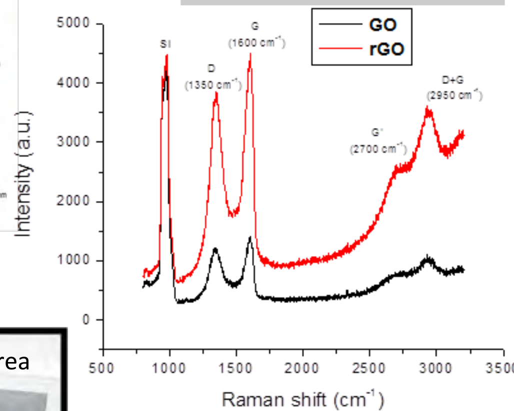
Femtosecond filament



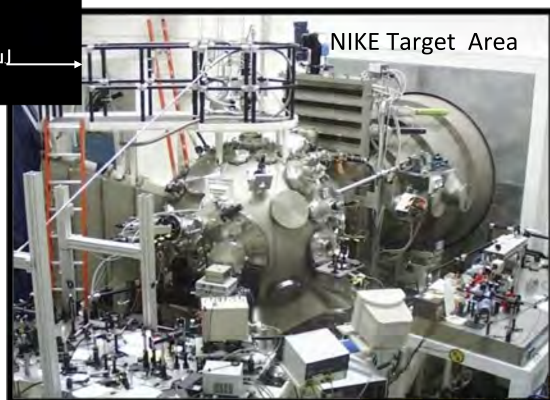
SWOrRD



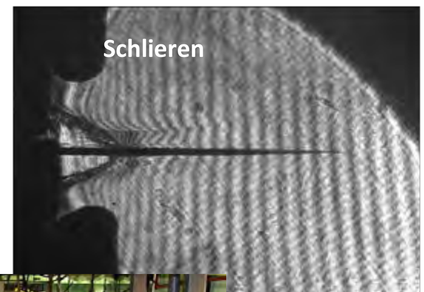
Graphene oxide reduction

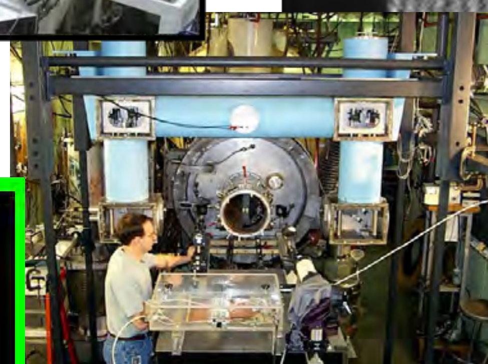


NIKE Target Area



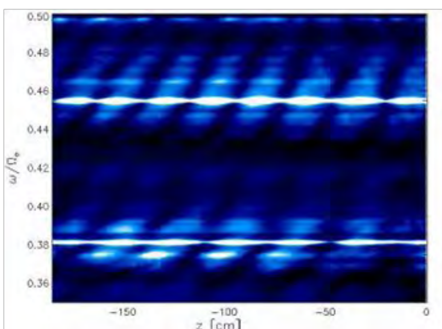
Schlieren



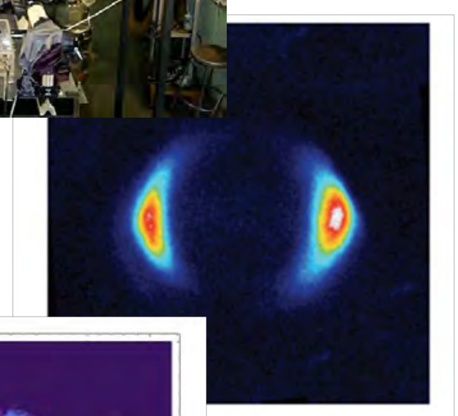


High-sensitivity interferometer

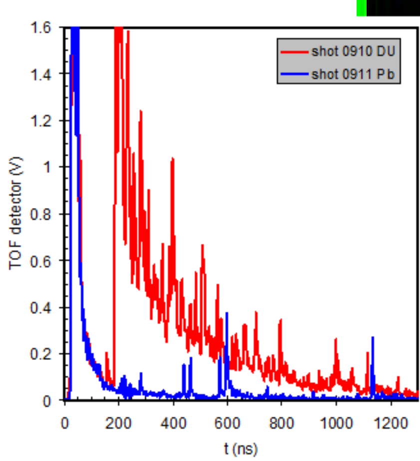
Whistler Wave

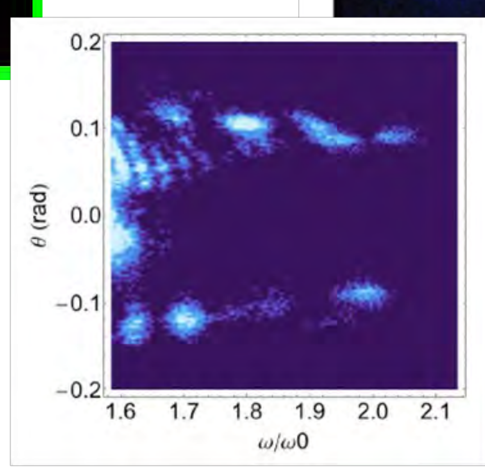


Laser filament In water



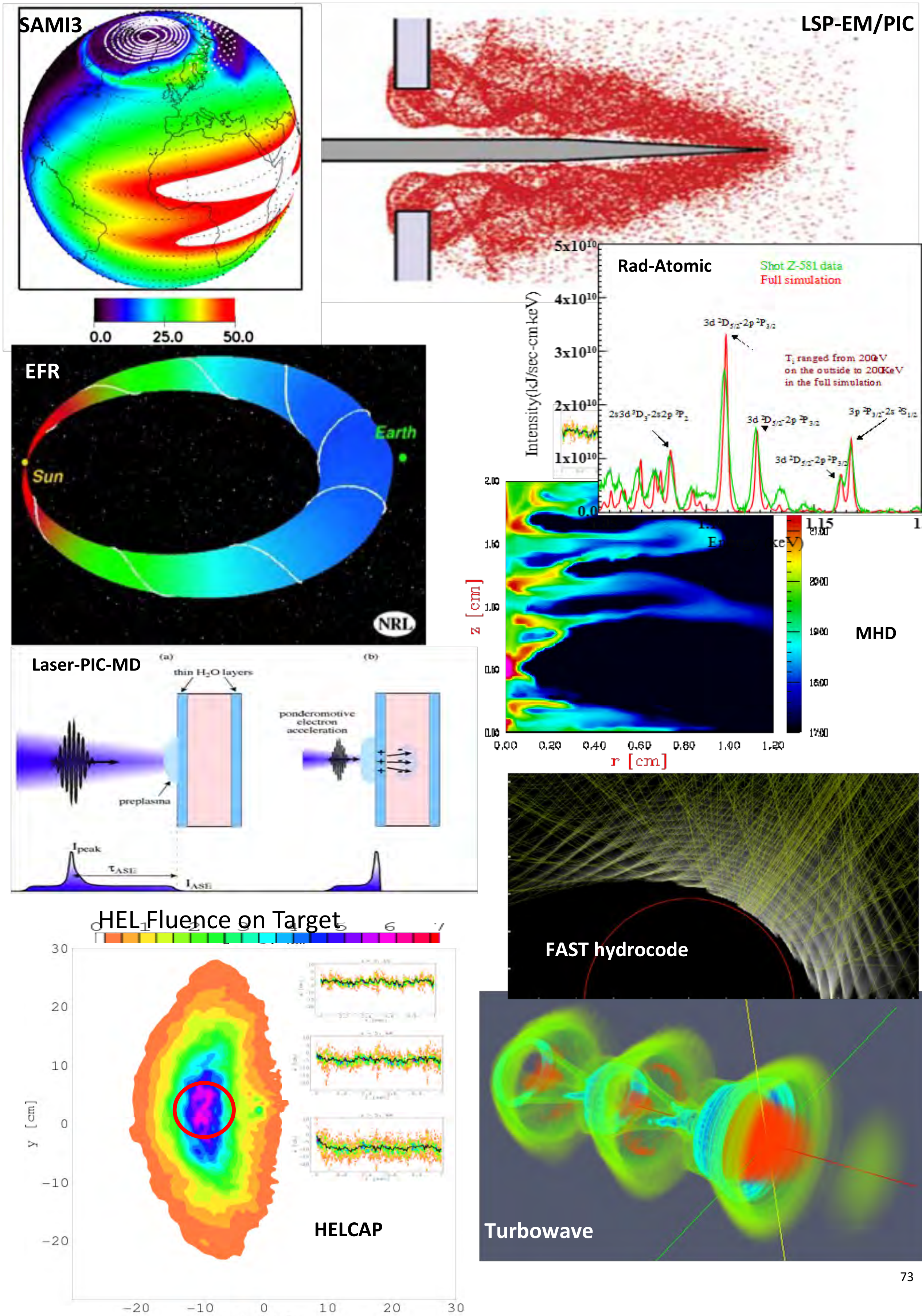
Prompt neutrons





Fwd-scattered 2nd harmonic, EO shock

State-of-the-art Plasma EM & Atomic Physics Codes



FELLOWSHIPS

AAAS FELLOWS

Dr. Mehlhorn	6700

APS FELLOWS

Dr. Mehlhorn	6700
Dr. Sprangle	6703
Dr. Davis	6705
Dr. Ganguli	6709
Dr. Dasgupta	6720
Dr. Velikovich	6720
Dr. Obenschain	6730

REGISTERED PROFESSIONAL ENGINEERS

Mr. B. Huhman	6777

APS FELLOWS (Cont'd)

Dr. Sethian	6730
Dr. Grun	6730
Dr. Schmitt	6730
Dr. Meger	6750
Dr. Bernhardt	6750
Dr. Huba	6790
Dr. Fliflet	6790
Dr. Chen	6790
Dr. Gold	6790
Dr. Ting	6790

DEPS

Dr. Sprangle	6703

OPTICAL SOCIETY OF AMERICA (OSA) FELLOWS

Dr. Sprangle	6703

IEEE FELLOWS

Dr. Mehlhorn	6700
Dr. Sprangle	6703
Dr. Bernhardt	6750
Dr. Commisso	6770
Dr. Gold	6790

AGU

Dr. Huba	6790

EMERITUS FELLOWSHIPS IN THE PLASMA PHYSICS DIVISION

APS Fellows

Dr. Aglitskiy	6730
Dr. Apruzese	6770
Dr. Cooperstein	6770
Dr. Lampe	6709
Dr. Lehmberg	6730
Dr. Manheimer	6707
Dr. Mosher	6770

APS (cont'd)

Dr. Ottinger	6770
Dr. Seely	6730

IEEE Fellows

Dr. Cooperstein	6770
Dr. Ottinger	6770

HELLOS AND GOODBYES 2013

Hello:

Richard Fernsler (Contractor)	6750
Stanley Briczinski	6754
Nickolas Ouart	6720

Goodbye:

Andrew 'Mostovych (Ctr)	6730
Warren Webster (Ctr)	6730
Thomas Albert (Ctr)	6730
Richard Fernsler	6750
David Byers	6750
Carl Enloe (Contractor)	6750
Matthew Hei (Contractor)	6750
Henrique Aveiro	6794

Karles Fellows:

Benjamin Rock (2011)	6793
Erik Tejero (2011)	6755
Justin Angus (2012)	6771
Sandra Hangarter (2014)	6756

NRC Postdoc:

Eric Gillman, NRC	6755
Ian Rittersdorf	6770
Christoffer Heckman, NRC	6792
Klementyna (Klimka) Szwaykowska	6792

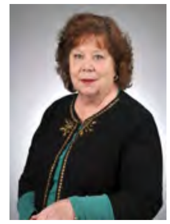
Plasma Physics Division Personnel


Dr. Raymond Allen
Code 6771


Dr. William Amatucci
Code 6755


Dr. Justin Angus
Code 6771


Dr. John Apruzese
Code 6771 (C)


Ms. Mary Austin
Code 6700A


Dr. Jason Bates
Code 6736


Dr. Paul Bernhardt
Code 6754


Mr. Chris Berry
Code 6777 (C)


Dr. David Blackwell
Code 6755


Dr. David Boris
Code 6756


Dr. Craig Boyer
Code 6777


Dr. Stanley Briczinski
Code 6754


Mr. Dennis Brown
Code 6731


Mr. Richard Cairns
Code 6750


Mr. Allan Calica
Code 6702


Dr. Carl Carney
Code 6750


Dr. Yung Chan
Code 6731


Dr. James Chen
Code 6794


Mr. Young Kil Chong
Code 6720


Dr. Robert Clark
Code 6720 (C)


Dr. Robert Commisso
Code 6770.1


Mr. Chris Compton
Code 6756


Dr. Gerald Cooperstein
Code 6770 (C)


Dr. Chris Cothran
Code 6755 ©


Dr. Chris Crabtree
Code 6755


Mr. Anthony Culver
Code 6777 (Ctr)


Dr. Arati Dasgupta
Code 6720


Dr. Jack Davis
Code 6705


Mrs. Susan DeWaters
Code 6790 (CTR)


Mr. Gregory DiComo
Code 6795 (Ctr)


Dr. Scott Douglass
Code 6750


Mrs. Edith Estrella
Code 6750


Mr. Derric Featherstone
Code 6770


Mr. Eric Featherstone
Code 6773


Dr. Joel Fedder
Code 6794


Dr. Richard Fernsler
Code 6752


Dr. Richard Fischer
Code 6795


Mr. Richard Fisher
Code 6777


Dr. Arne Fliflet
Code 6793


Dr. Gurudas Ganguli
Code 6709


Ms. Shanita Gardner
Code 6770 (Ctr)


Mr. George Gatling
Code 6755


Dr. Eric Gillman
Code 6755


Dr. John Giuliani
Code 6720


Dr. Steven Gold
Code 6793


Dr. Daniel Gordon
Code 6791


Dr. Jacob Grun
Code 6730.2


Dr. Bahman Hafizi
Code 6790


Dr. Sandra Hangarter
Code 6756


Dr. Frank Hegeler
Code 6733 (Ctr)


Dr. Mike Helle
Code 6795


Ms. April Higgs
Code 6790


Dr. David Hinshelwood
Code 6773


Mr. Ryan Hoffman
Code 6750


Dr. Joseph Huba
Code 6794


Dr. Richard Hubbard
Code 6701


Mr. Brett Huhman
Code 6777


Dr. Stuart Jackson
Code 6773


Mr. Bruce Jenkins
Code 6731 (Ctr)


Dr. Theodore Jones
Code 6795


Dr. Dmitri Kaganovich
Code 6795


Dr. Max Karasik
Code 6736


Dr. David Kehne
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Mr. J. Travis Kijowski
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Mr. Jude Kessler
Code 6736


Mr. Steven Krafsig
Code 6731


Dr. Jonathan Krall
Code 6794


Mrs. Julita Labson
Code 6702


Mrs. Pilita Ladera
Code 6720


Mrs. Judith Ladringan
Code 6730


Mrs. Loida Lagang
Code 6730


Dr. Robert Lehmberg
Code 6730 (Ctr)

Dr. Brandon Lindley
Code 6792

Dr. Evgeniya Lock
Code 6756

Dr. Robert Lunsford
Code 6730.2

Mr. Areg Mangassarian
Code 6736

Dr. Robert Meger
Code 6750

Dr. Thomas Mehlhorn
Code 6700

Dr. Manish Mithaiwala
Code 6755

Dr. David Mosher
Code 6771 (Ctr)

Dr. Donald Murphy
Code 6777

Mr. Matthew Myers
Code 6733

Dr. Jesse Neri
Code 6777

Mr. Anthony Noll
Code 6756

Dr. Steve Obenschain
Code 6730

Dr. Jaechul Oh
Code 6731 (Ctr)

Dr. Paul Ottinger
Code 6770 (Ctr)

Dr. Nicholas Ouart
Code 6720

Dr. Joseph Penano
Code 6790

Dr. Nino Pereira
Code 6793 (Ctr)

Dr. George Petrov
Code 6720

Dr. Tzvetelina Petrova
Code 6720

Dr. David Phipps
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Dr. Andrew Richardson
Code 6771

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Code 6793

Mrs. Tessie Santos
Code 6702

Dr. Andrew Schmitt
Code 6736

Mr. W. Marc Schmitz
Code 6701 (Ctr)

Dr. Joseph Schumer
Code 6770

Dr. Ira Schwartz
Code 6792

Dr. Victor Serlin
Code 6731

Dr. John Sethian
Code 6733

Dr. Carl Siefring
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Dr. Phillip Sprangle
Code 6703

Dr. Stavros Stephanakis
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Dr. Steve Swanekamp
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Dr. Erik Tejero
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Mr. Stephen Terrell
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Dr. Ward Thornhill
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Dr. Antonio Ting
Code 6795

Dr. Ioana Triandaf
Code 6792

Dr. Alexander Velikovich
Code 6720

Dr. David Walker
Code 6755 (Ctr)

Dr. Scott Walton
Code 6756

Dr. James Weaver
Code 6736

Dr. Bruce Weber
Code 6773

Dr. Kenneth Whitney
Code 6720 (Ctr)

Dr. Matthew Wolford
Code 6733

Dr. Tsai-Wei Wu
Code 6794

Dr. Steven Zalesak
Code 6736 (Ctr)

Dr. Jacob Zier
Code 6773

Dr. Yefim Aglitskiy
Code 6731 (Ctr)

Some of our new members

Plasma Physics Division

KARLES FELLOWS

Dr. Justin Angus
University of California-San Diego, 2012
Karles Fellow

Dr. Benjamin Rock
University of Wisconsin
2011
Karles Fellow

Dr. Erik Tejero
Auburn University
2011
Karles Fellow

Dr. Sandra Hernandez-Hangarter
University of California, 2010
Karles Fellow (2014)

NEW POSTDOCS

Dr. Christoffer Heckman
Cornell University
2012

Dr. Klementyna Szwaykowska (Klimka)
Georgia Institute of Technology, 2013

Dr. Ian Rittersdorf
University of Michigan

In Memoriam

Mabel V. Gloria died December 3, 2013 at her home in Ft. Washington, MD, after a long battle and complications from cancer. She was born in San Nicholas, I locos Norte, Philippines.

Mabel started her career at NRL in February 1989. In 1999 she joined the Plasma Physics Division as a Management Assistant. In 2000 she was promoted to Administrative Officer.

Mabel was the beloved wife of 38 years to Avelino Gloria. She was the loving mother of two sons, Moses and David; and Moses' wife, Andrea. Other survivors include three sisters and three brothers, as well as several nieces and nephews.

Mabel continued working throughout her illness in the Admin Office until shortly before her death. She was a friend and sweetheart to everyone and will be greatly missed.

The Plasma Physics Division

Annual Report

The contents of this report speaks to the outstanding basic and applied research that enables important national security applications of plasmas physics and related technologies to the Navy, the DoD, and the Nation. The Plasma Physics Division is an integral part of the NRL Materials Science and Technology Directorate and has consistently maintained unique capabilities and world class scientists in support of our national security.

DR. B B. RATH

ASSOCIATE DIRECTOR OF RESEARCH
MATERIALS SCIENCE AND TECHNOLOGY DIRECTORATE

THE 2013 PPD ANNUAL REPORT

2013/6700/041

DR. THOMAS A. MEHLHORN, SES

SUPERINTENDENT

LAYOUT, GRAPHIC DESIGN,

and EDITING

Mary Austin

Plasma Physics Division

www.ppd.nrl.navy.mil

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2013 PLASMA PHYSICS ANNUAL REPORT