ANOMALOUS ABSORPTION 2019

Abstracts

LPI

Monday Session1

Broadband mitigation of laser–plasma instabilities for hydrodynamically equivalent implosions on OMEGA*

R. K. Follett,[1] J. G. Shaw,[1] D. H. Froula,[1] C. Dorrer,[1] E. M. Hill,[1] J. F. Myatt,[2] and J. P. Palastro[1]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
rfollett@lle.rochester.edu
[2]University of Alberta
Edmonton, AB T6G 2R3, Canada

Laser–plasma instabilities such as cross-beam energy transfer (CBET), stimulated Raman scattering (SRS), and two-plasmon decay (TPD) present a major challenge for laser-driven inertial confinement fusion (ICF). The plasma waves driven in these instabilities inhibit the compression of the fusion capsule, and ultimately the gain, by scattering light and accelerating hot electrons that preheat the fuel. A promising path toward mitigation of these instabilities is through the use of broadband drive lasers. Simulations performed using the laser-plasma simulation environment (*LPSE*) code suggest that ~1% of relative bandwidth would be sufficient to suppress these instabilities on OMEGA. A broadband laser based on optical parametric amplification, with sufficient energy and bandwidth to validate these predictions, is currently being developed at LLE. A next-generation ICF driver capable of suppressing CBET, TPD, and SRS will allow for higher laser intensities and ablation pressures, greatly expanding the ICF design space.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

Planar laser–plasma interaction experiments at direct-drive ignition-relevant scale lengths at the National Ignition Facility*

M. J. Rosenberg,[1] A. A. Solodov,[1] W. Seka,[1] R. K. Follett,[1] J. F. Myatt,[2] P. Michel,[3] S. P. Regan,[1] M. Hohenberger,[3] R. Epstein,[1] A. V. Maximov,[1] T. J. B. Collins,[1] V. N. Goncharov,[1] R. W. Short,[1] D. H. Froula,[1] P. B. Radha,[1] T. Chapman,[3] J. D. Moody,[3] L. Masse,[3] J. W. Bates,[4] and A. J. Schmitt[4]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
mros@lle.rochester.edu
[2]University of Alberta
Edmonton, AB T6G 2R3, Canada
[3]Lawrence Livermore National Laboratory
Livermore, CA 94550, USA
[4]U.S. Naval Research Laboratory
Washington, DC 20375 USA

Experiments at the National Ignition Facility have studied laser–plasma interaction (LPI) and hot-electron production at scale lengths relevant to direct-drive ignition.[1] The irradiation of planar slabs generated a plasma at the quarter-critical surface with predicted ignition-relevant density scale lengths of $L_n \sim 500$ to 700 μm, electron temperatures of $T_e \sim 4$ to 5 keV, and overlapped laser intensities of $I \sim 4$ to 15×10^{14} W/cm^2. At these conditions, between 0% and ~5% of laser energy is converted to hot electrons, increasing linearly with intensity above the threshold around 5×10^{14} W/cm^2. Optical data show a singlet $\omega/2$ feature indicative of absolute stimulated Raman scattering (SRS) near the quarter-critical density, along with significant SRS at lower densities, which is attributed in part to sidescattering.[2] Measurements of $3\omega/2$ emission using Thomson scattering have revealed evidence of two-plasmon decay (TPD) as well as SRS, although the contribution of TPD to hot-electron generation is still under study. Correlation of SRS and hard x-ray data suggest that underdense SRS is most strongly connected to hot-electron generation. These results guide hot-electron preheat mitigation strategies for direct-drive–ignition designs.

*This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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[1] M. J. Rosenberg *et al.*, "*Origins and scaling of hot-electron preheat in ignition-scale direct-drive inertial confinement fusion experiments*," Phys. Rev. Lett. **120**, 055001 (2018)
[2] P. Michel *et al.*, "*Theory and measurements of convective Raman side scatter in inertial confinement fusion experiments*," Phys. Rev. E **99**, 033203 (2019)

Controlling Laser Plasma Interactions with Temporal Bandwidth*

Presenter F. S Tsung[1], J. Weaver[2], and R. Lehmberg[2]
(1) University of California, Los Angeles
405 Hilgard Ave
Los Angeles, CA 90095
(2) Naval Research Laboratory
Washington, DC 20375-5320
contact-email@eserver
[†]Second institution if needed
Second City, State zipcode

Using the particle-in-cell code OSIRIS, we have performed a large number of 1D and 2D simulations under laser and plasma conditions relevant to the NIKE laser with induced spatial incoherence and several THz of bandwidth, which could be achieved experimentally through rotational Raman scattering. In our 1D and 2D simulations, we have observed that, given sufficiently large bandwidth (where the inverse bandwidth is comparable to the linear growth time), time-averaged laser-plasma interaction can be reduced by a factor of 2 under shock ignition relevant conditions. We will discuss these results and present future plans to include the effects of laser speckles and binary Coulomb collisions.

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Hot-electron preheat and energy deposition in direct-drive implosion experiments at the National Ignition Facility*

A. A. Solodov,[1] M. J. Rosenberg,[1] A. R. Christopherson,[1] R. Betti,[1] M. Stoeckl,[1] W. Seka,[1] R. Epstein,[1] R. K. Follett,[1] P. B. Radha,[1] S. P. Regan,[1] D. H. Froula,[1] V. N. Goncharov,[1] J. F. Myatt,[2] M. Hohenberger,[3] and P. Michel[3]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
asol@lle.rochester.edu
[2]University of Alberta
Edmonton, AB T6G 2R3, Canada
[3]Lawrence Livermore National Laboratory
Livermore, CA 94550, USA

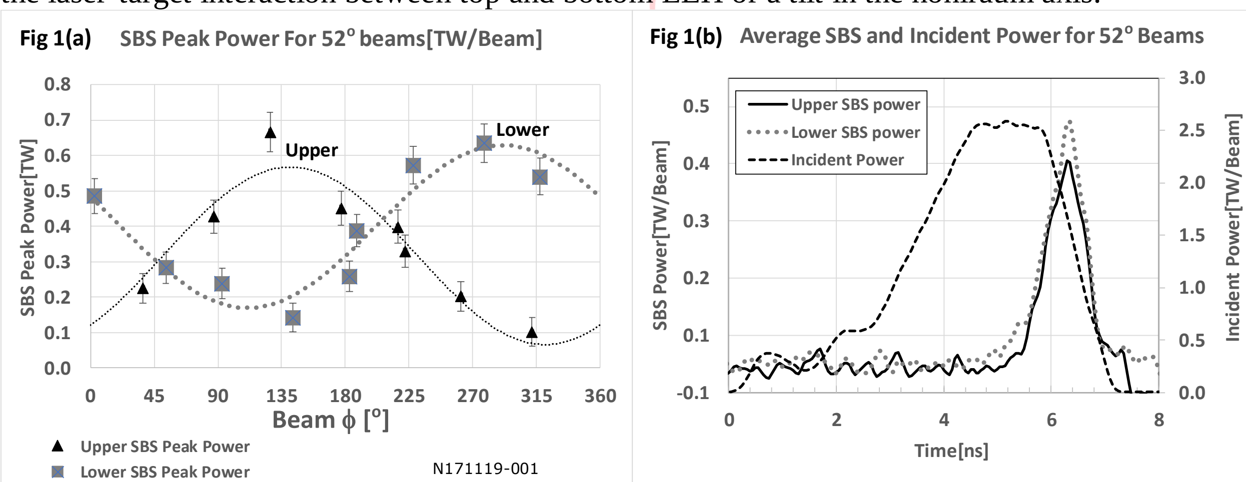
Laser–plasma instabilities, such as stimulated Raman scattering and two-plasmon decay, can degrade the performance of direct-drive inertial confinement fusion implosions by generating hot electrons that preheat the target. Planar-target laser–plasma interaction experiments at direct-drive ignition-relevant plasma conditions at the National Ignition Facility (NIF) demonstrated hot-electron production close to the levels that can be tolerable in direct-drive–ignition designs but can still significantly constrain the design space. To assess the extent of hot-electron preheat in polar-direct-drive implosions, an experimental platform on the NIF has been developed and fielded to study the hot-electron energy deposition in an unablated shell. The target consists of an outer plastic ablator and an inner Ge-doped plastic layer (payload). Hot-electron transport and energy deposition in the imploded shell is studied by comparing hard x-ray production between the mass-equivalent plastic and multilayer implosions and by measuring the Ge K_α emission. The experiments demonstrate how the divergence of hot electrons and the extent to which they slow down in the ablator reduce the preheat. The goal is to diagnose the hot-electron–deposition profile in the imploding shell. Measurements indicate that 0.27±0.06% of laser energy is deposited in the unablated shell, with 0.13±0.03% deposited in the outer 20% portion and 0.14±0.03% deposited in the inner 80% of the imploding shell. About a quarter of total hot-electron energy is coupled to the unablated shell, indicating a wide angular divergence of hot electrons.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

Variability of Stimulated Brillouin Scattering from NIF Hohlraums*

B.J. MacGowan, P. Michel, M. Biener, D. A. Callahan, J-M Di Nicola, A. Kemp, T. Chapman, R. L. Berger, N. Lemos, L. Divol, O. S. Jones, R. Kirkwood, O. L. Landen, R Lowe-Webb, , N. B. Meezan, J. D. Moody, A. Nikroo, A Peer, S. Schiaffino, J. Ralph, D. J. Strozzi, D. Van Blarcom, P. Whitman and C. Widmayer
Lawrence Livermore National Laboratory, Livermore, CA 94551
macgowan1@llnl.gov

Indirect drive experiments at the National Ignition Facility (NIF) often produce Stimulated Brillouin Scattering (SBS) of the 3ω drive laser beams that propagates back into the incident beam optics. Variability in the level of SBS can present a risk for damaging the laser 1ω transport mirrors, but also may provide insight into mitigation techniques being considered. SBS power measurements are made on 30% of NIF beams enabling mapping of the SBS generated at 58 separate points around the target. Within a single experiment or for different realizations of a particular experiment, a variability of a factor of 2 or more in SBS measurements is seen. As an example, Fig 1a shows the angular distribution of peak SBS power measured from an Indirect Drive implosion experiment. Data are plotted for 17 beams at 52^o to the hohlraum axis in the upper and lower hemispheres. The dashed lines are fits to cosϕ with phase 140^o and 290^o for upper and lower respectively. The associated time history of the average SBS measurement for the upper and lower beams is shown in Fig1(b), these data illustrate a factor 3 difference in SBS on a single shot with a potential correlation in azimuthal angle that is different for each laser entrance hole (LEH). This may indicate a difference in the symmetry of the laser-target interaction between top and bottom LEH or a tilt in the hohlraum axis.



We will describe trends in SBS variability and attempts to correlate the observed variability with asymmetries in the target LEH, beam alignment, synchronization and drive performance.

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LPI

Monday Session 2

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Non-linear polarization mixing in non-linear optical media*

P. Michel, T. Chapman, L. Divol, C. Goyon, E. Kur[†], M. Lazarow[†], B. Saltzman[†], D. Turnbull[††], M. R. Edwards[†††], G. Marcus[††††], L. Friedland[††††] and J. S. Wurtele[†]

Lawrence Livermore National Laboratory, Livermore, CA 94551
[†]Physics Department, University of California, Berkeley, CA 94720
[††]University of Rochester, Laboratory for Laser Energetics, Rochester, NY 14623
[†††]Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544
[††††]Hebrew University of Jerusalem, Jerusalem 91904, Israel
michel7@llnl.gov

Manipulating the polarization of intense laser beams in plasmas was recently proposed[1] and later demonstrated in proof-of-principle laboratory experiments, revealing new concepts of plasma-based photonics devices such as plasma-Pockels cells[2] or polarizers[3]. However, both the theory and experiments were carried out in the "linear regime" of polarization mixing, whereby the "pump" beam that was used to introduce birefringence in the plasma was much more intense than the "probe" beam whose polarization was being manipulated. While this concept and other ideas in the realm of "plasma photonics", like plasma-based pulse compression, offer the promise of light manipulation at extreme fluences, the "energy budget" has been a major obstacle to practical developments so far.
Here, we investigate the theory of the "non-linear" polarization mixing problem, where the pump and probe are both intense enough to affect each other's polarization states. We unveil new phenomena such as the swapping of polarization states between two light waves, and propose a new configuration where a probe beam's polarization can be fully controlled by a pump beam

[1] P. Michel et al., Phys. Rev. Lett. **113**, 205001 (2014).
[2] D. Turnbull et al., Phys. Rev. Lett. **116**, 205001 (2016).
[3] D. Turnbull et al., Phys. Rev. Lett. **118**, 015001 (2017).

whose intensity is much smaller. This could potentially solve the energy budget issue of plasma-based polarizers and Pockels cells.
We will finally show that these concepts can be generalized to non-linear media other than plasmas, such as Kerr media and photorefractive crystals. This could enable new ways to control the polarization of light waves in gas or solids at ultra-fast time scales.

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Cherenkov radiation from a plasma*

J. P. Palastro,[1] T. M. Antonsen Jr.,[2] R. K. Follett,[1] A. Colaïtis,[3] D. Turnbull,[1] J. Vieira,[4] and D. H. Froula[1]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
jpal@lle.rochester.edu
[2]University of Maryland
College Park, MD 20742, USA
[3]Université de Bordeaux, Centre Lasers Intenses et Applications
Talence, France
[4]Instituto de Plasmas e Fusão Nuclear-Laboratório Associado, IST
Lisboa, Portugal

The dispersion of electromagnetic waves in plasma has traditionally precluded the emission of Cherenkov radiation into the far field: the phase velocity of the radiation exceeds the speed of light in vacuum and therefore the speed of a conventional driver. The flying focus—a moving focal point resulting from a chirped laser pulse focused by a chromatic lens—provides an intensity peak that can travel at superluminal velocities. Theory and simulations show that a plasma ponderomotively excited by a flying focus pulse can emit far-field Cherenkov radiation at terahertz frequencies.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

Reduction of hot electron generation from laser plasma instabilities using circularly-polarized lasers*

S. H. Cao[1], C. Ren[1], R. Yan[2], H. Wen[3] and J. Li[4]
[1] University of Rochester
Rochester, NY, 14627
scao5@ur.rochester.edu
[2] University of Science and Technology of China
Hefei, Anhui, 230026, China
[3] University of California, Los Angeles
Los Angeles, CA, 90095
[4] Los Alamos National Laboratory
MS F699, Los Alamos, NM 87545

Understanding laser-plasma instabilities (LPI) is critical to the success of inertial confinement fusion (ICF). The interaction of two plasmon decay (TPD) and side stimulated Raman scattering (SSRS) was studied using 3-D particle-in-cell simulations under ICF-relevant conditions for linearly and circularly polarized lasers. In the linear stage, theoretical growth rates agreed well with the simulation results. SSRS took place under $n_e = 0.235n_c$ and TPD dominated near the quarter-critical density surface. In the nonlinear stage, SSRS reduced TPD through pump depletion. Hot electrons were found to be first accelerated by the SSRS plasma waves and then by TPD plasma waves, different from the TPD-only staged-acceleration in the 2-D simulations[1]. This reduced the hot-electron flux. Compared to the linearly-polarized case with the same laser intensity, both SSRS and TPD were reduced due to the lower laser amplitude in the circularly-polarized case. As a result, a 30 percent decrease in hot electron flux was observed.

* This work is supported by DOE under Grant No. DE-SC0012316, and DOE/NNSA under Grant Nos. DE-NA0003600 and DE-NA0001944.

[1] Yan, R., Ren, C., Li, J., Maximov, A. V., Mori, W. B., Sheng, Z. M., & Tsung, F. S. (2012). Generating energetic electrons through staged acceleration in the two-plasmon-decay instability in inertial confinement fusion. *Physical review letters*, *108*(17), 175002.

Modeling stimulated Raman scattering and cross-beam energy transfer in direct-drive National Ignition Facility plasmas*

A. V. Maximov, J. G. Shaw, and J. P. Palastro
Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
amax@lle.rochester.edu

The direct-drive approach to inertial confinement fusion (ICF) relies on multiple laser beams depositing their energy in the inhomogeneous plasmas of ICF targets. Laser–plasma interactions determine the balance between absorption and scattering of the laser light in the target corona, and the production of fast electrons that can preheat the target. The interaction region of key importance is located near the quarter-critical plasma density, where the incident laser light can drive three main instabilities: stimulated Raman scattering (SRS), two-plasmon decay (TPD), and stimulated Brillouin scattering (SBS), leading to cross-beam energy transfer (CBET).

Modeling of the interplay between SRS, TPD, and CBET near the quarter-critical density for plasma parameters relevant to direct-drive ICF at the National Ignition Facility (NIF) has been performed using the laser-plasma simulation environment (*LPSE*).[1] Due to the large scale lengths (~500 μm) in NIF experiments,[2] and the proximity of the Mach 1 region to the quarter-critical density, the instabilities can more easily reach a nonlinear state with mutual interactions. For instance, the low-frequency density perturbations driven by CBET can modify the growth of SRS and TPD.

The transmission and scattering of laser light through this complex region of overlapping and nonlinear instabilities are calculated for multibeam laser irradiation.

* This work was supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

[1] J. F. Myatt *et al.*, *"A wave-based model for cross-beam energy transfer in direct-drive inertial confinement fusion,"* Phys. Plasmas **24**, 056308 (2017).
[2] M. J. Rosenberg *et al.*, *"Origins and scaling of hot-electron preheat in ignition-scale direct-drive inertial confinement fusion experiments,"* Phys. Rev. Lett. **120**, 055001 (2018).

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Nonlinear electron and ion dynamics in the saturation of crossed-beam energy transfer*

Lin Yin, Brian Albright, David Stark, Robert Bird, and William Nystrom
Los Alamos National Laboratory
Los Alamos, NM 87545
lyin@lanl.gov

Crossed-beam energy transfer (CBET) exchanges energy between laser beams through stimulated Brillouin scattering. Understanding the nonlinear saturation of CBET, including effects of wave-particle interaction, excitation of secondary instabilities, and speckle geometry is important for controlling low-mode symmetry in ICF implosions. Nonlinear CBET dynamics for multi-speckled lasers has been examined using VPIC simulations under NIF-like conditions[1]. CBET saturates rapidly (~10s of ps) through ion trapping and excitation of forward stimulated Raman scattering (FSRS) in the seed beam. Ion trapping reduces wave damping and speckle interaction increases wave coherence length to ~10 μm, together enhancing energy transfer. Ion acoustic wave (IAW) breakup de-traps ions and increases damping, contributing to CBET saturation. The seed beam can become unstable to oblique FSRS, which deflects the beam and downshifts the frequency. FSRS saturates by electron plasma wave self-focusing, leading to hot electrons with energy exceeding 300 keV, which may cause preheat. CBET increases with beam average intensity, diameter, and crossing area, but is limited by excitation of FSRS, IAW breakup, and pump depletion. FSRS deflects seed beam energy by greater than 40% of the incident beam energy and puts few-% levels of beam energy into hot electrons. This limits the use of CBET for symmetry tuning at late times in implosions and could account for "missing energy" inferred in implosions.

* This work was performed under the auspices of the U.S. Dept. of Energy by the Triad National Security, LLC Los Alamos National Laboratory and was supported by the LANL Directed Research and Development (LDRD) Program, and the LANL Office of Experimental Sciences Inertial Confinement Fusion program.

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[1] L. Yin, B. J. Albright, D. J. Stark, R. F. Bird, D. Nystrom, K. J. Bowers, "Nonlinear electron and ion dynamics in the saturation of crossed-beam energy transfer," submitted to Phys. Rev. Lett.

Plenary
Monday

Recent adventures in crossed-beam energy transfer*

D. Turnbull,[1] T. Chapman,[2] A. Colaïtis,[3] L. Divol,[2] R. K. Follett,[1] D. H. Froula,[1] C. Goyon,[2] A. M. Hansen,[1] P. Michel,[2] A. L. Milder,[1] J. D. Moody,[2] J. P. Palastro,[1] and D. J. Strozzi[2]
[1]Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623, USA
turnbull@lle.rochester.edu
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[3]Centre national de la recherche scientifique, Talence, France

Crossed-beam energy transfer (CBET) strongly impacts both the direct- and indirect-drive approaches to inertial confinement fusion (ICF), and accounting for it is essential in integrated implosion modeling. The persistence of ad hoc clamps and multipliers undermines confidence in our understanding of the process and potentially obscures other physics that is missing from simulations. Recently, CBET platforms were developed at the Jupiter Laser Facility as well as the Laboratory for Laser Energetics, combining uniform quasi-stationary gas jet plasmas with robust plasma characterization in order to provide direct CBET model validation. Experiments have highlighted the subtle but potentially important influence of laser polarization[1], yielding the first demonstrations of laser-plasma wave plates[2] and polarizers.[3] In at least one instance, ion acoustic waves appeared to saturate at the $\delta n/n \approx 1.5\%$ level—higher than the clamps that are sometimes imposed on plasma wave amplitudes in order to reproduce integrated observables.[4] Our most recent experiments used simultaneous electron- and ion-feature Thomson scattering to show that laser heating drives non-Maxwellian electron distribution functions[5] of the type predicted decades ago by Langdon[6] and Matte[7], which significantly modifies CBET, as predicted by Afeyan.[8] The non-Maxwellian CBET model is currently being implemented in integrated indirect-drive ICF simulations and is expected to reduce, and possibly eliminate, the need for a saturation clamp.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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[1]P. Michel *et al.*, "*Dynamic control of the polarization of intense laser beams via optical wave mixing in plasmas*," Phys. Rev. Lett. **113**, 205001 (2014).
[2]D. Turnbull *et al.*, "*High power dynamic polarization control using plasma photonics*," Phys. Rev. Lett. **116**, 205001 (2016).
[3]D. Turnbull *et al.*, "*Refractive index seen by a probe beam interacting with a laser-plasma system*," Phys. Rev. Lett. **118**, 015001 (2017).
[4]D. Turnbull *et al.*, "*Crossed-beam energy transfer: polarization effects and evidence of saturation*," Plasma Phys. & Cont. Fusion **60**, 054017 (2018).
[5]D. Turnbull *et al.*, "*Impact of the Langdon effect on crossed-beam energy transfer*," submitted to Nat. Phys. (2019).
[6]A. B. Langdon, "*Nonlinear inverse bremsstrahlung and heated-electron distributions*," Phys. Rev. Lett. **44**, 575 (1980).
[7]J. P. Matte *et al.*, "*Non-Maxwellian electron distributions and continuum x-ray emission in inverse bremsstrahlung heated plasmas*," Plasma Phys. and Cont. Fusion **30**, 1665 (1988).
[8]B. B. Afeyan *et al.*, "*Kinetic theory of electron-plasma and ion-acoustic waves in nonuniformly heated laser plasmas*," Phys. Rev. Lett. **80**, 2322 (1998).

Poster Sessions

Monday

Long Scale-length Plasmas to Support Studies of LPI Mitigation Via Laser Bandwidth at the Nike Laser *

J. Weaver, J. Oh, D. Kehne, A. J. Schmitt, J. Bates, R. Lehmberg[a], R. Follet[b],
J. Williams[c], F. Tsung[d], and S.P. Obenschain
Plasma Physics Division, U.S. Naval Research Laboratory, Washington, DC 20375
james.weaver@nrl.navy.mil
[a]*Research Support Instruments Inc.,*
[b]*LLE/University of Rochester,*
[c]*General Atomics,*
[d]*UCLA*

Experiments at the Nike laser are characterizing growth of laser plasma instabilities (LPI) in large underdense plasmas with long scale lengths. The long term objective is to demonstrate mitigation techniques for LPI via increased laser bandwidth. The output spectrum for the Nike laser can be broadened by etalons in the front end or by stimulated rotational Raman scattering after the final amplifier. [1] A previous LPI campaign used a single type of low density foam target to produce large volume plasmas with estimated 5-10x longer density and velocity scale-lengths versus solid CH targets. The current study explores a wider range of initial foam densities and utilizes exploding foil targets for comparison to LPI experiments from longer wavelength laser systems. The current campaign also uses a 5th harmonic probe laser (213 nm) to determine the electron density profile around the time of peak pump intensity via a grid image refractometry (GIR) diagnostic.[2] This poster will present the results from this campaign and simulations (FASTrad3D[3] and LPSE[4]) performed to evaluate the growth of TPD, SRS, and SBS in these plasmas.

* Work supported by DoE/NNSA.

[1] Weaver, J, et al., Applied Optics, **56** (31), 8618 (2017).
[2] Oh, J., et al., Rev. Sci. Instruments, **86** (8), 083501 (2015).
[3] Gardner, J. H., et al., Phys. Plasmas, **5**, 1935 (1998).
[4] Myatt, J., et al., Phys. Plasmas, **24**, 056308 (2017).

Non-standard wave activity in plasmas following stimulated Raman scattering of picosecond laser pulses

C. Rousseaux[1], S. D. Baton[2], K. Glize[3], L. Lancia[2]
D. Bénisti[1], L. Gremillet[1]

[1]CEA, DAM, DIF, F-91297 Arpajon, France
E-mail: christophe.rousseaux@cea.fr
[2]LULI - CNRS, Ecole Polytechnique, CEA: Université Paris-Saclay; UPMC Univ. Paris 06: Sorbonne Universités, F-91128 Palaiseau cedex, France
[3]Rutherford Appleton Laboratory, Appleton, UK

In previous experiments performed at LULI (ELFIE facility), backward stimulated Raman scattering (B-SRS) of short laser pulses was investigated using time- and space-resolved Thomson diagnostics suited to the typical sub-picosecond timescales of B-SRS. In particular, by means of two spatially separated laser beams, it was demonstrated that both the threshold and saturation level of B-SRS in a weak-intensity laser speckle can be affected by a neighboring stronger-intensity speckle up to distances of several tens of microns [1] [2]. Such a coupling was attributed to enhanced electrostatic fluctuations excited by suprathermal electrons, produced as a result of the damping of the nonlinear electron plasma waves (EPWs) driven through B-SRS in the strong speckle.
This poster presents Thomson scattering measurements carried out in recent, single-beam experiments that aimed at characterizing those enhanced fluctuations. First, we report on the observation of non-standard high-amplitude ion acoustic waves (IAWs), distinct from those expected from backward stimulated Brillouin scattering (B-SBS) or from the usual secondary plasma parametric instabilities. This observation is found to be correlated with the detection of B-SRS at earlier times. The lifetime (or damping time) of such IAWs is measured as a function of the plasma density and laser intensity. Second, by means of two imaging systems, space-resolved along the laser pump direction, it is shown that the B-SRS-driven EPWs develop on transverse scales of several tens of microns, i.e., much larger than the laser focal width. Possible scenarios accounting for those results will be discussed.

[1] C. Rousseaux, K. Glize, S.D. Baton, L. Lancia, D. Bénisti, L. Gremillet, Phys. Rev. Lett. **117**, 015002 (2016).
[2] K. Glize, C. Rousseaux, D. Bénisti, V. Dervieux, L. Gremillet, S.D. Baton, and L. Lancia, Phys. Plasmas **24**, 032708 (2017).

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Density Dependence of Stimulated Raman Scattering in CBET-amplified Multi-speckled Beams *

David J. Stark, Lin Yin, Brian J. Albright, William Nystrom, and Robert Bird
Los Alamos National Laboratory
Los Alamos, NM 87545
djstark@lanl.gov

Cross-beam energy transfer (CBET) is the process by which two crossing laser beams transfer energy between one another through stimulated Brillouin scattering (SBS). Understanding the nonlinear saturation of CBET, including the effects of wave-particle interaction, the excitation of secondary instabilities such as stimulated Raman scattering (SRS) and forward SRS (FSRS), and speckle geometry, is important to controlling low-mode asymmetry in ICF implosions. In this work, particle-in-cell simulations using VPIC are performed to characterize the SRS and FSRS in a CBET-amplified multi-speckled beam across a range of plasma densities that commonly occur in ICF experiments. In particular, we discuss the changes in the scattering angle across different densities, the dependencies of growth rates, and the cascade of energy to lower frequency modes. A large fraction of the beam energy is deposited into a hot electron population created during the scattering processes.

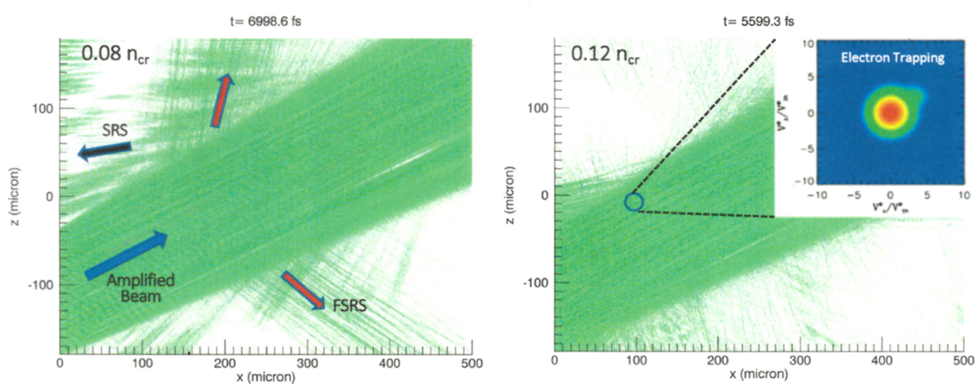

Figure: Laser electric field E_y snapshots of an amplified multi-speckled beam at 2 x 10^{14} W/cm^2 propagating through a plasma of 0.08 n_{cr} (left) and 0.12 n_{cr} (right). An electron velocity distribution (inset) is sampled at the region circled in black.

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Nearly Isotropic Vlasov Multi-Directional Model

Presenter: Harvey A. Rose
harvey5249@yahoo.com

A generalization of the Vlasov Multi Dimensional Model[1] is presented. In lieu of the unique kinetic direction of the original VMD, there are an arbitrary number of such directions, N_θ, distributed equally in angle, θ. It is found that the generalized VMD model with $N_\theta = 8$ qualitatively reproduces Landau's dispersion relation *for all* propagation directions. If the initial state is thermal with even N_θ, then the initial distribution function symmetry, $f_\theta = f_{\theta+\pi}$, is maintained if driven out of equilibrium by an external electric field, effectively reducing the number of kinetic directions by a factor of two.

1. H. A. Rose and W. Daughton, Physics of Plasmas **18**, 10 (2011).

Mitigating cross-beam energy transfer with optical vortices*

Jason F. Myatt† and Blaine Armstrong
Department of Electrical and Computer Engineering
University of Alberta
Edmonton, Alberta, T6G 1H9 Canada
†myatt@ualberta.ca

A reasonably complete understanding of laser-plasma instabilities in the context of directly-driven inertial confinement fusion has been gained over the past few years. This has come about by a combination of advances in theory, model development, and experiment. On the basis of these models, the application of laser bandwidth at the 1% level is expected to greatly improve the prospects of ignition on a MJ-scale facility.[1] Schemes to implement such bandwidth are currently being pursued with vigor. Unfortunately, such modification of present laser systems will be both intrusive and expensive. As an alternative approach, recent simulation work will be presented that explores the use of complex spatial (rather than temporal) laser beam conditioning on direct-drive laser-plasma instabilities [cross-beam energy transfer (CBET)] with the hope of achieving similar mitigating effects. The beam conditioning suggested could potentially be generated by phase plates alone (perhaps using meta-materials) and therefore could be implemented on existing laser facilities that lack a broad bandwidth capability.

We have started this investigation by quantifying the stimulated Brillouin scattering (SBS) that occurs between laser beams containing optical vortices ("twisted light") and having an associated orbital angular momentum (OAM). These simulations have been performed with the Laser Plasma Simulation Environment (*LPSE*) code.[2] The *LPSE* code is well suited to the task as the problem is inherently three dimensional. The behavior of such beams in nonlinear media (e.g., Kerr media) is known to give rise to many interesting physical effects, such as the spiraling of vortex solitons.[3] We quantify here the degree to which a difference in OAM between crossing beams can frustrate the SBS process responsible for CBET.

*the authors acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) [funding reference numbers RGPIN-2018-05787, RGPAS-2018-522497]

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[1] R. K. Follett, J. G. Shaw, J. F. Myatt, J. P. Palastro, R. W. Short, and D. H. Froula, "Suppressing two-plasmon decay with laser frequency detuning", Phys. Rev. Lett. **120**, 135005 (2018); J. W. Bates, J. F. Myatt, J. G. Shaw, R. K. Follett, J. L. Weaver, R. H. Lehmberg, and S. P. Obenschain, "Mitigation of cross-beam energy transfer in inertial confinement-fusion plasmas with enhanced laser bandwidth", Phys. Rev. E **97**, 061202(R) (2018).
[2] The authors are grateful to the LLE at the University of Rochester for making the *LPSE* code available.
[3] A. S. Desyatnikov in "The Angular Momentum of Light", D. L. Andrews and M. Babiker (Cambridge University Press, 2013).

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Rayleigh-Taylor instability with kinetic plasma transport in a kinetic test regime and in ICF deceleration plasma*

E.L. Vold, L.Yin, and B. Albright
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545
elv@lanl.gov

Rayleigh-Taylor (R-T) instability between plasma species is examined with a plasma transport approximation to the ion species kinetics, including viscosity and species mass flux as implemented within a hydrodynamic fluid code (xRage), and results are compared to a fully kinetic particle-in-cell approach (VPIC). An analytic model for the dispersion relation governing R-T instability growth rate is modified from the literature to include plasma kinetic effects in viscosity and species transport. We compare growth rates calculated from code outputs and from the analytic model over a range of initial wavelengths, first in a kinetic regime and then in a regime approximating ICF deceleration. We find reasonable agreement between simulations in the kinetic regime, including the wave number of maximum growth rate. However, the simulations show significantly smaller instability growth rates than expected for the classical fluid instability, with the fully kinetic VPIC growth rates less than the plasma fluid transport results. Several reasons for the difference are examined and found to be dominated by the kinetic heat flux which is not considered in the classical analytic R-T growth rate. The fluid code with plasma transport is then applied to R-T instability under conditions for the deceleration phase during typical ICF implosions, estimated from 1D simulations of Omega-like or NIF-like implosions. The R-T deceleration is expected to last for 0.5 nanosecond or less, and has a maximum growth rate limited by the temperature dependent viscosity, with a maximum wave number in the range of (0.2 – 0.5) um^{-1}, or wavelengths of maximum instability, ~ 10 – 30 um , for ion temperatures of 1 - 2keV. The perturbation wavelengths attenuated by the kinetics increase with increasing temperature. Simulation details show the R-T instability with a cascade to smaller scale structures for varying inviscid hydrodynamic solver options, and smoothed solutions when including plasma transport. Simulations compare a range in initial wavelengths and initial perturbation amplitudes. For the ICF deceleration conditions over the 0.5 nanosecond duration, the inviscid unstable solutions give rise to small scale structures down to the grid cell dimension, while including the plasma transport smooths fluid structures smaller than several microns, independent of grid resolution. Initial perturbation wavelengths of 10 um at the time of deceleration onset show no cascade to smaller scale structures beyond a primary vortex roll up, due to the smoothing by ion transport. This leads to a grid-converged solution for the R-T instability growth when kinetic effects are included in the simulations. This also leads to a fortuitous similarity between a transport converged solution and a solution with only numerical diffusion on a sufficiently course grid.

*This work was conducted at Los Alamos National Laboratory, managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA under Contract No. 89233218CNA000001.

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Scaling of thermomagnetic processes in coronal plasmas*

M. Sherlock and J.J. Bissell†
Lawrence Livermore National Laboratory
7000 East Avenue
California 94550
sherlock3@llnl.gov
†University of Warwick, United Kingdom

The generation of magnetic field in plasmas by the Biermann battery is thought to be responsible for the inhibition of heat flow in laser-plasma interactions. We have performed two-dimensional Vlasov-Fokker-Planck simulations of magnetic field growth under a range of conditions relevant to laser fusion and find magnetic field growth is strongly suppressed, leading to a lack of magnetization of the coronal plasma and stabilization of field generating instabilities. Three primary mechanisms account for this: a strong reduction in the strength of the Biermann battery in non-local conditions, the rapid convection of magnetic field by heat flow, and the finite scale-length of the magnetic field. Scaling laws are given which describe these effects.

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Autoresonant excitation of large amplitude standing ion acoustic waves*

L. Friedland[1], G. Marcus[1], J.S. Wurtele[2], and P.A. Michel[3]
[1]The Hebrew University
Jerusalem, Israel
[2] Department of Physics
University of California, Berkeley
Berkeley, CA 94720
wurtele@berkeley.edu
[3] Lawrence Livermore National Laboratory
Livermore, CA 94550

Large amplitude standing ion acoustic waves (SIAW) can be created in a plasma by nonlinear phase locking (autoresonance) a low amplitude, chirped frequency standing-wave ponderomotive drive. Simulations based on a water bag model indicate that the local ion and electron densities in the autoresonant SIAW may significantly exceed the initial unperturbed plasma density and are only limited by the kinetic wave-breaking. The underlying theory and the simulation results will be presented along with rough parameters for a proof-of-principle experiment.

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The Evolution of NIF Capsule Fill Tube Assembly Diameters from 10 µm to 2 µm*

J.W. Crippen, N.G. Rice, E.L. Alfonso, C. Kong, J. Reynolds

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
Wendi.Sweet@ga.com

Capsule Fill Tube Assemblies (CFTA's) are comprised of an ablator capsule and fill tube. The requirement to better understand and minimize the fill tube effect during a capsule implosion has motivated the reduction of the fill tube diameters at the point of attachment to the ablator capsule. Engineering efforts have been conducted to reduce the dimensions of the laser drilled fill tube hole in the capsule ablator and the resultant mass deficit in the ablator capsule in support of 5 µm and subsequently 2 µm CFTA designs. The most recent fill tube design consists of a 2 µm fill tube with a taper of length of 3.9 mm and a cleaved back O.D. end of 26 µm. The cleaved back end is inserted and hermetically sealed into flexible 150 mm O.D. by 30 µm I.D. polyimide fused silica tube. Assembly of the 2 µm fill tubes to the ablator capsule (aka CFTA) have a) passed both ambient and cryogenic testing at General Atomics, b) survived handling and transport to Lawrence Livermore National Laboratory, c) been assembled into National Ignition Facility cryogenic targets and d) shot.

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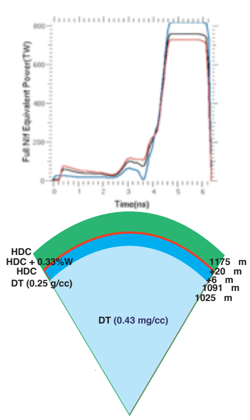
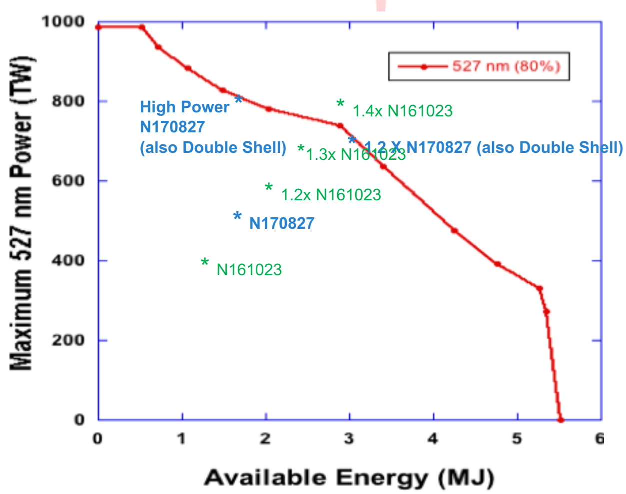
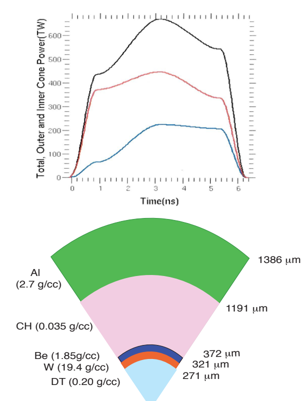
Ignition Targets for NIF at 527nm*

D. C. Wilson, J. P. Sauppe, E. N. Loomis, L. Yin, R. F. Sacks, B. J. Albright, L. B. Hopkins†, M. L. Spaeth†, D. Strozzi†, D. Munro†, C. Widmayer†, B. Raymond, †and K. Manes†
Los Alamos National Laboratory
P.O.Box 1663
Los Alamos, NM, 87545
dcw@lanl.gov
†Lawrence Livermore National Laboratory
Livermore, CA 94550

Suter *et al.* (2004)[1] described the capabilities of NIF using 527nm light and explored beryllium ablator single shell capsule designs. We have expanded this set to include single shell HDC capsules based on the high yield (1.8e16 neutrons) NIF shot N170827, and double shell capsules based on the current aluminum ablator design. HYDRA calculations included gold hohlraums with scaled capsules, laser pulses, and beam pointings. The figure shows the NIF peak power and laser energy design space available at 527 nm based on Suter *et al.*[1]'s 1054 nm NIF capabilities and an assumption of 80% conversion to 527 nm light. Also plotted are the peak laser power and energy of 527 nm NIF capsules. Changing from 351 to 527nm light led to very slight changes in the hohlraum radiation temperature history and to shock timing. Drive symmetry changes were accounted for by using a 0.3mg/cc hohlraum gas fill. 2D integrated calculations of the 1.2X N170827 and double shell designs shown below used peak powers of 800TW and 3.1 MJ energy to produce yields of 1.6 and 1.0e+18 neutrons. A variety of designs are available to exploit NIF's capability at 527nm.







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First Experiments on Revolver Shell Collisions*

Brett Scheiner^, M. J. Schmitt, S. C. Hsu, D. W. Schmidt, J. Mance[†], D. N. Polsin[#], T. R. Boehly[#], F. J. Marshall[#], N. Krasheninnikova, K. Molvig[@], and H. Huang[%]
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
bss@lanl.gov
^Also at the University of Iowa
[†]Mission Support and Test Services
[#]Laboratory for Laser Energetics, University of Rochester
[@] Also at the Massachusetts Institute of Technology
[%]General Atomics

Results of recent experiments on the OMEGA Laser are presented, demonstrating the ablator-driver shell collision relevant to the outer two shells of the Revolver triple-shell inertial-confinement-fusion concept. These nested two-shell experiments measured the pre- and post-collision outer-surface trajectory of the chromium inner shell. Measurements of the shell trajectory are in excellent agreement with simulations; the measured outer-surface velocity was 7.52 ± 0.59 cm/μs compared to the simulated value of 7.27 cm/μs. Agreement between the measurements and simulations provides confidence in our ability to model collisions with features which have not been validated previously. Notable features include the absence of ~40 mg/cc foam between shells commonly used in double shell experiments, a dense (7.19 g/cc) inner shell representative of the densities to be used at full scale, approximately mass matched ablator payload and inner shells, and the inclusion of a tamping-layer-like cushion layer for the express purpose of reducing the transfer of high mode growth to the driver shell and mediation of the shell collision. Agreement of experimental measurements with models improves our confidence in the models used to design the Revolver ignition target.

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Experimental and Radiation-Hydrodynamics Modeling Studies of Isochoric Heating at the Texas Petawatt Laser*

R. Roycroft[†, *], B. Bowers[†], H. Smith[†], E. McCary[†], F. Aymond[†], G.M. Dyer[††], H.J. Quevedo[†], E.L. Vold[*], P.A. Bradley[*], B.J. Albright[*], L. Yin[*], and B.M. Hegelich[†,**]
[†]University of Texas, Austin
Austin, TX 78712
rroycroft@utexas.edu
[††]SLAC National Accelerator Laboratory
Menlo Park, CA 94025
[*]Los Alamos National Laboratory
Los Alamos, NM 87545
[**]Center of Relativistic Laser Science - Institute of Basic Science
Gwangju, Republic of Korea

We present experimental and simulation studies of warm dense matter produced by isochoric heating at the Texas Petawatt Laser Facility. Experimental studies of warm dense matter are important for measuring equation of state, thermal conductivity, and other physical quantities that in turn provide for more accurate modeling. This work presents results of experiments in which aluminum foils (7-10μm) and carbon foams (100μm, 60mg/cc) are heated by means of a laser accelerated TNSA proton beam, as well as radiation-hydrodynamics simulations of the heated targets.

We shoot the petawatt laser pulse at a 5μm gold foil target, and subsequently the ion beam heats a secondary target. The brightness temperature and heating over time of the secondary target is measured by a streaked optical pyrometer, which images the rear surface of the secondary target. We have observed peak brightness temperatures from 1-20eV.

We model the cooling and expansion of the heated target in xRAGE, an Eulerian radiation-hydrodynamics code developed at Los Alamos National Laboratory. We find good agreement between experiment and simulation results when we include time dependence to the energy source at the rear surface of the aluminum foil.

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LA-UR-19-23494

Electron beam properties from combined direct laser acceleration and plasma acceleration in regimes relevant to fast ignition*

F.-Y. Li, C.-K. Huang, P. K. Singh, and S. Palaniyappan
Los Alamos National Laboratory, Los Alamos, NM 87544

Direct laser acceleration (DLA) of electrons can play an important role in different configurations involving the interaction between a laser pulse and a particle beam, particularly for plasma-based acceleration where either blow-out plasma wakes in underdense plasmas or laser channels in dense plasmas are formed. The latter can be critical to collimated electron beam generation for the fast ignition of laser fusion pellets. However, DLA is often conceived to be sensitive to the laser and particle beam phase space dynamics, as well as vulnerable to any mismatch in laser and beam conditions. Moreover, in many cases the transverse laser fields can significant alter the beam divergence of resulting electrons. We numerically study the problem and develop a general understanding towards the beam properties from DLA assisted by plasma acceleration. We consider the effects of different acceleration components for various laser-plasma conditions and initial beam properties. We also examine the beam phase space dynamics and discuss potential ways to stabilize the acceleration leading to collimated electron beams. These understandings will be discussed in the context of full-scale plasma simulations and near-term experiments under design.

* Work supported by the LDRD program at Los Alamos National Laboratory.

Angular momentum conversion of light by laser plasma interaction*

C. K. Huang, C. J. Zhang, K. A. Marsh, C. E. Clayton, and C. Joshi
University of California Los Angeles
405 Hilgard Avenue
Los Angeles, CA 90095
ckhuang@ucla.edu

The angular momentum properties of nonlinear harmonic generation by an intense laser in plasmas have been studied. Even harmonics are excited when plasmas have transverse density gradients produced either by ponderomotive force of the laser or in the boundary region of an optical-field ionized (OFI) plasma.[1] We experimentally observe the conversion of spin to orbital angular momentum by measuring the twisted wavefront of the second harmonic light generated from an OFI helium plasma produced by an intense circularly polarized pulse.

*This work conducted under the auspices of DOE and NSF.

[1] E. Esarey, A. Ting, P. Sprangle, D. Umstadter, and X. Liu, "Nonlinear Analysis of Relativistic Harmonic Generation by Intense Lasers in Plasmas" IEEE Transactions on Plasma Science **21**, 95 (1993).

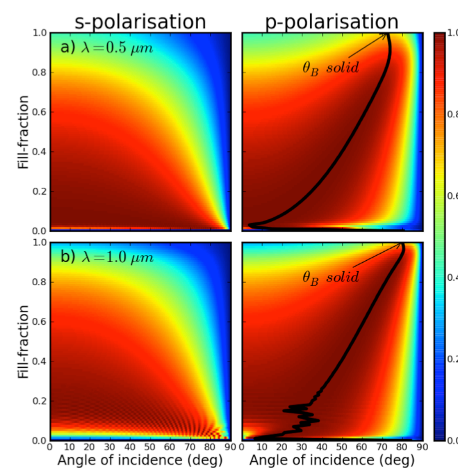
Absorption of intense ultrafast laser pulses in Nickel nanowire targets*

R.S. Marjoribanks, A. Miscampbell†, G. Thomas, R. Royle†, O. Humphries†,
R. Ko, L. Lecherbourg, A. Tan, J. Li, Q. van den Berg†, M. Kasim†,
B. Nagler††, E.C. Galtier††, J.S. Wark†, and S. Vinko†
University of Toronto
60 St George St.
Toronto, ON, Canada M5S-1A7
marj@physics.utoronto.ca
† University of Oxford
Oxford, UK OX1-3PU
†† SLAC National Accelerator Laboratory
Menlo Park, USA 94025
§ *current address: Commissariat à l'Energie Atomique et aux Energies Alternatives, France*

Conventional solid-density laser-plasma targets quickly ionize to make a plasma mirror, which largely reflects ultra-intense laser pulses. This Fresnel reflection at the plane boundary largely wastes our efforts at ultra-intense laser/solid interaction, and limits target heating to nonlinear generation of high-energy electrons which penetrate inward.

One way around this dual problem is to create a material with an anisotropic dielectric function, for instance by nanostructuring a material in such a way that it cannot support the material responses which generate a specularly reflected beam. We reported the first use of nanowires as laser-plasma targets in 2000[1].

Here, we present linear-absorption theory for metallic and plasma nanowires, and particle-in-cell simulations of the interaction of ultra-intense femtosecond pulses with nickel nanowires, showing penetration of laser light through material far denser than critical on average, for depths far deeper than a nickel skin-depth, helping to uniformly heat near-solid-density material to conditions of high energy-densities.



Modelled absorption of very large (~20μm) thickness layers *s*- and *p*-polarization, as a function of fill-fraction and angle of incidence, and for two different wavelengths.

*This work conducted with support from the Natural Sciences and Engineering Research Council of Canada.

[1] G. Kulcsar, D. AlMawlawi, F. W. Budnik, P. R. Herman, M. Moskovits, L. Zhao, and R. S. Marjoribanks, "*Intense Picosecond X-Ray Pulses from Laser Plasmas by Use of Nanostructured "Velvet" Targets*", Physical Review Letters 84, 5149 (2000).

Collimation of low-divergence high-current electron beams in a high density plasma*

C.-K. Huang†, F.-Y. Li, P. K. Singh, S. Palaniyappan
Los Alamos National Laboratory
Los Alamos, NM 87544
†huangck@lanl.gov

Collimation of laser-driven electron beams through the resistive magnetic field in a background collisional plasma is highly desirable for the transport of such beams. Previous fast-ignition concept employs a divergent electron beam which will traverse an anomalous resistivity region due to electromagnetic instabilities at the edge of compressed fuel. The instabilities also complicate the condition for optimal collimation of the beam by the resistive magnetic field. Control of the laser-plasma interaction may open up opportunity for the generation of a beam with lower divergence. We conduct numerical study of the latter scenario with both hybrid and kinetic simulations. We will discuss the condition for collimated beam transport which will help the design of the planned experiment.

* Work supported by the LDRD program at Los Alamos National Laboratory.

Formal Developments for Studying Laser Beams Intersecting in a Plasma*

Eugene Kur[‡], Malcolm Lazarow[‡], Jonathan S. Wurtele[‡], and Pierre Michel[†]

[‡]Department of Physics
UC Berkeley, Berkeley CA 94720
wurtele@berkeley.edu
[†] Lawrence Livermore National Laboratory
Livermore, CA 94550

Understanding the interaction of overlapping laser beams in a plasma is important for precise control of laser energy flow at the National Ignition Facility (NIF) and for creating plasma-based high-power optical components. We describe the relevant geometry and consider the dynamics of s-polarized and p-polarized incident laser pulses.[1,2] We highlight the consequences of gauge invariance on polarization exchange between two beams. We further discuss ongoing development of theoretical tools to address the complex many-beam systems used at NIF. These include improved numerical schemes and variational formulations for laser beam interactions.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 the NSF-DOE Partnership in Plasma Science under Grant 1803874, and the LLNL-LDRD Program under Project tracking No. 18-ERD-046.

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[1] Michel, P., et al. "*Dynamic control of the polarization of intense laser beams via optical wave mixing in plasmas*." Phys. Rev. Lett. **113,** 205001 (2014).

[2] McKinstrie, C. J., et al. "*Two-dimensional analysis of the power transfer between crossed laser beams*." Phys. Plasmas **3,** 2686 (1996).

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Improved imaging using Mn He-α x-rays at OMEGA EP

C. F. Kawaguchi, K. A. Flippo, C.A. Di Stefano, A. M. Rasmus, E. C. Meritt, N. N. Vazirani, E. Doss and K. Kelso
Los Alamos National Lab
Street address
Los Alamos, State zipcode
codie_y@lanl.gov

We report on an updated x-ray imaging system fielded at the OMEGA EP laser facility. This system is an upgrade to the existing 10x Spherical Crystal Imager (SCI) that now has increased pointing accuracy, improved spatial resolution as well as higher magnification and comparable temporal resolution. The system is designed to use crystals cut for various x-ray energies bent into spherical geometry to image the x-rays onto a detector. Previous crystals employed have been quartz crystals cut for Si He-α and Cu K-α line radiation. We report on the new LANL supplied Mn He-α spherical quartz crystal to image the 6.8 keV line emission. We show a ~15 um spatial resolution and 500-ps temporal resolution with a 50 % increase in magnification, all of which returns a clearer image. Further, the longer, 500 - 1000ps pulse compared to the previous 10 ps pulse used for the Cu K-α lines provides more photons.

Work supported by the National Nuclear Security Administration, performed by Los Alamos National Laboratory, operated by Triad National Security, LLC, under contract 89233218CNA000001

*This work conducted under the auspices…., if you have any. If not, then delete this line, and the asterisk at end of title.

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Computational study of strong electric field measurement in intense laser-driven plasmas via K-alpha spectroscopy

T. R. Joshi, P. Hakel, and S. Palaniyappan
Los Alamos National Laboratory
Los Alamos, NM 87545
Contact: tjoshi@lanl.gov

We present results from a theoretical work modeling the x-ray fluorescence (XRF) technique as a diagnostic to measure the strength of the collisionless shock electric field in intense laser (intensity ~10^{20} W/cm^2) driven near-critical plasmas. XRF is a technique where inner shell electrons of an atom are removed by exposing material to radiation with an energy greater than their binding energy followed by electrons from higher orbitals filling the resulting hole, which is accompanied by the release of a photon with the energy equal to the energy difference between the two orbitals involved. Due to the varying degrees of screening, the photon energy thus emitted is also a function of the different ionization stages of the diagnostic element. In this work, a carbon foam with embedded titanium (Ti) layer is used as the target. K-shell vacancies in Ti are created using a vanadium He-α x-ray source at 5.2 keV, above the Ti K-shell binding energy of 4.966 keV. The laser irradiation of the foam drives a collisionless shock in the foam (shock electric field ~TV/m). The shock field ionizes Ti atoms further and produces K-α emission from the various ionization stages of Ti. XRF has been used to study collisional shocks in similar work [M. J. MacDonald *et* al., JAP (2016)]. In this work, the shifts in the K-alpha emission are used to infer the strength of the electric field of the collisionless shock. In support of this investigation we performed atomic structure calculation and collisional-radiative modeling for computing Ti level populations, emissivities and opacities via the Flexible Atomic Code (FAC) [M. F. Gu, Can. J. Phys. 86, 675 (2008)] and the LANL suite of atomic codes [C. J. Fontes et al., JPB 48, 144014 (2015)].

LPI

Tuesday Session 1

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Cross-beam energy transfer in flowing ICF plasmas with laser speckles and ponderomotive self-focusing *

W. Rozmus[1,2], S. Hüller[3], G. Raj[3], and D. Pesme[3]

[1] Department of Physics, University of Alberta, Edmonton, AB, Canada.
[2] SLAC National Accelerator Laboratory, Menlo Park, CA, USA.
[3] Centre de Physique Théorique, CNRS, Ecole Polytechnique, Palaiseau, France

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Cross-Beam Energy Transfer (CBET) between laser beams remains an active area of research in Inertial Confinement Fusion (ICF) experiments that are related to both, indirect and direct fusion schemes. We have modelled CBET by means of numerical simulations with a wave coupling code [1], taking into account the speckle (hot spot) substructure of "smoothed" laser beams. We have shown that transfer of energy from laser hot spots of one beam to the another beam, via forward stimulated Brillouin scattering, self-focusing in the presence of a plasma flow and beam bending proves to affect considerably the angular distribution and spectra of the laser light behind the region of beam overlap for laser intensities $I\lambda^2 > 10^{14}$ W cm^{-2} μm^2. For these reasons the angular distribution and spectra of transmitted light from smoothed laser beams (with speckles) is very different from the angular distribution of beam when the beam speckle structure is disregarded. We have also examined the importance of nonlinear, shock-like structures in ion waves and of plasma-induced smoothing on CBET.

[1] G. Raj and S. Hüller, Phys. Rev. Lett. **118**, 055002 (2017).

*This work was partially supported by the DOE Fusion Energy Sciences user Contract No.FWP10018

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Design of a high-bandwidth probe laser for LPI and plasma photonics experiments*

Joshua Ludwig[1†], Pierre Michel[1], T. Chapman[1], M. Belyaev[1], and Wojciech Rozmus[†]
Lawrence Livermore National Laboratory Street address
7000 East Ave Livermore, CA 94550
jludwig@ualberta.ca
[†] Theoretical Physics Institute, University of Alberta
Edmonton, Alberta T6G2G7, Canada

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Pump-probe laser-plasma experiments have recently demonstrated that the refractive index of a laser-plasma system could be arbitrarily modified, enabling the design of plasma-based optical elements such as polarizers and Pockels cells [1 2]. In this presentation, we will present a new design for a probe laser with high, tunable bandwidth. The goal is to achieve single-shot probing of plasma photonics structures. Our design is a variation on smoothing by spectral dispersion (SSD). In this study we are varying several key parameters (e.g. modulation frequency, modulation depth, color-cycling and angular dispersion) while keeping the bandwidth fixed, and look at the impact on laser-plasma interactions for single-shot probing of plasma photonics structures, and mitigation of LPI in ICF experiments.

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* This work was supported by the LLNL-LDRD Program under Project No. 45020/81435.
Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

49th Annual Anomalous Absorption Conference
Telluride, CO
June 9-14, 2019

Experimental Evidence for Reduced Stimulated Brillouin Backscatter in hohlraums when using a Ta2O5 liner

Presenter: J. E. Ralph, P. Michel, A. Kemp, B. MacGowan, N. Meezan, T. Chapman, R. Berger, D. Strozzi, N. Lemos, L. Divol

Lawrence Livermore National Laboratory, USA
7000 East Ave.
Livermore, CA 94550
ralph5@llnl.gov

High levels of Stimulated Brillouin Backscatter (SBS) from experiments on the National Ignition Facility (NIF) remain a significant damage risk for optics. Light from SBS near the 3ω (351 nm) laser wavelength can propagate backward through the final optics assembly and result in significant damage. As a result, each new experiment on the NIF must ramp up in power and energy over several shots slowing the development and testing of new designs. Mitigation of SBS may be achieved by designing targets with materials that damp the growth of ion acoustic waves. Theory and simulations show that trapping and acceleration of the relatively light oxygen species, in Ta2O5, by the heavy Ta and/or Au ion acoustic waves effectively damps these waves and therefore results in decreased backscatter [A, Kemp, this conference]. We conducted a series of four integrated experiments in which the interior of a gold hohlraum was lined with 1.1 μm Ta2O5 liner or left unlined. We measured the effect on outer beam SBS, implosion symmetry, hohlraum hydrodynamics and hohlraum performance. Detailed measurements show that the presence of the Ta2O5 liner reduces the SBS by 5x in the outer 50 deg. beamlines compared to unlined gold. Measurements of the wall bubble show that the Ta2O5 liner expands roughly 10% faster than the pure gold wall. As a result, the self-emission hot spot shape measurements show a more oblate implosion with capsule implosion Legendre mode P2/P0 decreasing from -29% with pure gold to -49% with the Ta2O5 liner. Experimental results will be presented and compared with hydrodynamic simulations.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Is helium a good surrogate to study LPI in deuterium?*

Matthias Geissel, A.J. Harvey-Thomson, D.E. Bliss, J.R. Fein, B.R. Galloway, M.E. Glinsky, C. Jennings, M.W. Kimmel, K.J. Peterson, P. Rambo, J.E. Shores, S.A. Slutz, I.C. Smith, C.S. Speas, M.R. Weis, D. Woodbury, J.L. Porter

Sandia National Laboratories
Albuquerque,
New Mexico, USA
mgeisse@sandia.gov

Using helium as a surrogate fill gas can be convenient to avoid flammability hazards in an experiment. To test the degree of equivalency between deuterium and helium, experiments were conducted in the Pecos target chamber at Sandia National Laboratories.

Observables such as laser propagation, energy deposition, and signatures of laser-plasma-instabilities (LPI) were recorded for multiple laser- and target-configurations. It was found, that some observables can differ significantly despite the apparent similarity of the gases with respect to molecular charge and weight. A qualitative behavior of the interaction may very well be studied by finding a suitable compromise of laser absorption, electron density, and LPI cross-sections, but a quantitative investigation of expected values for deuterium fills may not succeed with surrogate gases.

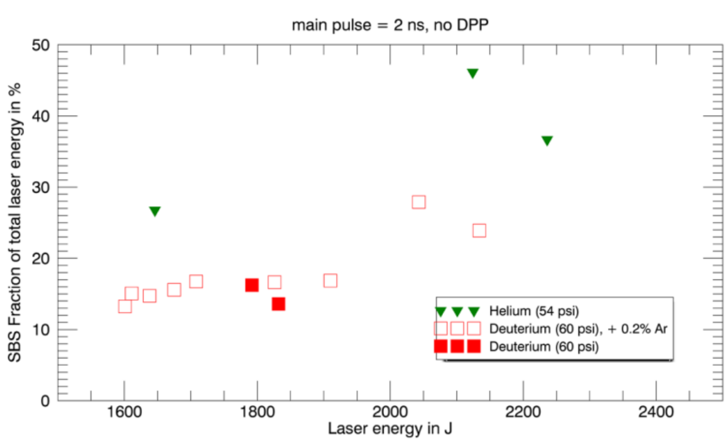

Fig. 1. The backscattered fraction of laser light from SBS is significantly stronger for helium (green triangles) than for deuterium (red squares). Shown here are measurements without the use of a Distributed Phase Plate (DPP).

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Signatures of preheat performance in Magnetized Liner Inertial Fusion experiments from time-resolved stimulated Raman and Brillouin backscatter spectra*

J. R. Fein, D. Bliss, M. Geissel, A. Harvey-Thompson, D. Ampleford, M. E. Glinsky, M. Gomez, E. Harding, K. MacRunnels, S. Patel, D. E. Ruiz, D. Scoglietti, M. R. Weis, K. Peterson

Sandia National Laboratories
1515 Eubank Blvd SE
Albuquerque, NM 87123
jrfein@sandia.gov

The Magnetized Liner Inertial Fusion (MagLIF) platform on the Z Machine requires efficient coupling of laser energy (preheat) to the underdense D_2 fuel to produce significant fusion yield. Diagnosing laser preheat on fully-integrated MagLIF experiments separate from the later stages of implosion and stagnation has proven difficult as a result of limited diagnostic access and signal contamination by intense background produced during the late-time stagnation. Time-resolved backscattered light from laser-plasma instabilities, collected at the laser's final optic assembly, shows promise for monitoring laser preheat. We present time-resolved spectral measurements of stimulated Raman and Brillouin backscatter from preheat experiments conducted on both the Z Machine and the PECOS target chamber at Sandia National Laboratories. The measurements exhibit time-dependent signatures of the density and temperature of the laser entrance window and heated plasma channel produced in the gas by the Z Beamlet laser. The measurements demonstrate significant differences in the laser-plasma interactions when changing the laser pulse shape and beam profile. In addition, these measurements may provide signatures of detrimental events during preheat, such as the laser hitting the bottom of the MagLIF target or clipping the laser-entrance-hole washer.

* Sandia National Laboratories is a multimission laboratory managed and operated by NTESS, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's NNSA under contract DE-NA-0003525.

Modeling
Tuesday Session 2

Measurement and control of ionization waves of arbitrary velocity*

P. Franke, D. Turnbull, J. P. Palastro, J. Katz, I. A. Begishev, R. Boni, J. Bromage, J. L. Shaw, A. L. Milder, A. Davies, S. Bucht, D. Haberberger, A. M. Hansen, and D. H. Froula
Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
pfra@lle.rochester.edu

Ionization fronts with precisely controlled characteristics could dramatically extend the efficacy of several laser-plasma–based technologies such as photon acceleration, Raman amplification, and terahertz generation. Such an ionization front is produced when the intensity of a flying focus, a moving focal point that results from the chromatic focusing of a chirped laser pulse, exceeds the ionization threshold of a background gas.[1] These ionization waves of arbitrary velocity (IWAV's) were previously observed to generate ~10-μm-diam plasma channels over several millimeters in the far field of the laser. The IWAV's were found to have theoretically predictable velocities that can be tuned to any value by adjusting the chirp of the flying focus drive pulse, but their small diameters provide limited applicability.[2]

To control and expand the diameter of the plasma channels, IWAV's were produced in a defocused beam, i.e., the quasi-far field. The temporal evolution of the IWAV position and density were measured using a novel, spectrally resolved interferometry diagnostic. Along with conventional interferometry measurements, these data were used to infer the instantaneous velocity, density scale length, and diameter of the IWAV's. Theory predicted and experiments demonstrated IWAV's with diameters ~100 μm. IWAV velocity, density scale length, and diameter were found to depend on the details of the power spectrum of the flying focus drive pulse, which suggests that intentional power-spectrum shaping can be used to customize IWAV characteristics.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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Thermal conduction modeling for direct and indirect drive inertial confinement fusion*

Mehul V. Patel and Kevin H. Ma†
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550
patel15@llnl.gov
†University of Michigan
Ann Arbor, MI 48105

Radiation hydrodynamics simulations of laser produced plasmas commonly use a Spitzer-Harm thermal diffusion model that relies on an ad-hoc flux-limiter which cannot include pre-heat that would be driven by steep temperature gradients present in these systems. In the LLNL ICF 2D/3D code HYDRA, a non-local SNB[1] model is also available to provide a better model of the thermal conduction. Recently, this model has been improved[2] and calibrated against VFP codes (IMPACT[3] and K2[4]). We present results from simulations of directly driven spheres (Be, Al, Cu) and ICF hohlraums to assess the impact of the improvements. The spheres provide a good platform for studying thermal transport since there are fewer active physical processes and less uncertainty in the plasma modeling compared to a hohlraum. For the spheres, the SNB models generally agree well with VFP calculations and comparisons with flux limited diffusion highlight the shortcomings of a local diffusion model. For hohlraums, these calculations are much more challenging. We find that differences in modeled temperatures due to the recent SNB improvements may be significant enough to cause variations in predicted radiation drive symmetry. The overall radiation drive, however, is less sensitive to thermal conduction modeling than other physics models (e.g. non-LTE kinetics in Au wall).

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA2734

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Subgrid model of laser-foam interaction with experimental comparison to SiO_2 aerogels*

M. A. Belyaev†, R. L. Berger, S. H. Langer, and O. S. Jones
Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA 94550
belyaev1@llnl.gov

Foams are materials composed of microscopic solid density elements but with average density substantially less than solid density. For instance, SiO_2 aerogels can have densities as low as 2 mg/cc and feature sizes as small as 10-100 nm. Foams open up a design space between that of a solid and a gas, and they can be used as liners or fill gas replacement in ICF hohlraums.

Global ICF hohlraum simulations with micron resolution or greater cannot resolve the foam microstructure. As a result, foams are often modeled as a uniform density medium. However, experiments show that a laser beam with intensity 10^{13}-10^{15} W/cm^2 propagates more slowly in a foam than in a homogeneous medium of equivalent average density[1,2,3]. Semi-analytical models attribute this difference to the energy deposited in burning down the foam microstructure[1,4].

We have modified the energy-conserving foam model of Belyaev et al. and implemented it in pF3D. We treat the foam as a medium with an anomalous opacity due to the geometric cross-sections of individual foam elements above critical density. We model the expansion of heated foam elements within a computational cell using a subgrid model. When neighboring foam elements overlap on a subgrid scale, the foam microstructure is destroyed and the kinetic energy of expansion is deposited into ion thermal energy.

Using our energy-conserving subgrid model of foam element expansion in pF3D with hydrodynamics and heat conduction turned on, we explain the reduced speed of laser propagation in a foam compared to a gas of equivalent homogeneous density. We also explain the reduced SBS for 2 mg/cc SiO_2 aerogels (<10% of expected) measured by Mariscal et al. compared to pF3D simulations on plasma conditions taken from HYDRA simulations that modeled the aerogel as a uniform density medium[3]. The reduced SBS is due to an increased ion temperature in a foam vs. a gas that results from burning down the foam microstructure.

* This work conducted under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under LDRD-17-ERD-118.

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HYDRA Simulations of Laser-heated Foams*

Presenter S. H. Langer, M. A. Belyaev, and O. S. Jones
LLNL
7000 East Ave.
Livermore, CA 94550
Langer1@llnl.gov

The use of foams in ICF hohlraums opens up a number of design options. For example, metal foams may be used as liners to reduce wall motion and thereby improve the symmetry of the radiation drive. Wall liners may also reduce the level of backscattered light. Very low density (~1 mg/cc) foams might replace the fill gas and would provide more options for the plasma filling the interior of the hohlraum (helium and neon are the only gases that do not freeze out). Experiments have shown that thermal waves propagate more slowly in subcritical foams than through a gas with the same average density as the foam[1,2].

This talk describes 2D HYDRA simulations of foams made using additive manufacturing (AM). The simulations have zones small enough (50 nm) to resolve the ablation of individual filaments in the foam. The JLF experiments had laser intensities of 10^{13}-10^{15} W/cm^2 of 2ω light. The simulations model patches of foam that are smaller than the JLF laser spot to reduce computational cost. Using 50 nm zones to simulate an entire hohlraum is not possible. Our goal is to develop a sub-grid model that captures the key effects of the internal structure in foams.

HYDRA simulations have been performed for subcritical and supercritical electron densities. The speed of the thermal wave as a function of time is extracted from each run. The propagation speed for a gas with the same average density as each foam is provided as a reference. The simulations are compared to JLF experiments.

The partitioning of the laser energy between electron internal energy, ion internal energy, and ion kinetic energy provides insight into the differences between foams and gases. In particular, simulations with individual filaments have expansion kinetic energy during the homogenization process whereas gas targets only have bulk kinetic energy in the laser direction. We also examine differences between foams with many small filaments and a few large filaments where both have the same average density.

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*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under LDRD-17-ERD-118. Lawrence Livermore National Security, LLC. LLNL-ABS-772618.

PIC Simulations of Laser-Irradiated Foam Filaments: Plasma Heating, Interpenetration, and Stagnation*

B. J. Winjum[1], S. Wilks[2], O. Jones[2], S. Langer[2], M. Belyaev[2], J. Milovich[2]
[1]University of California Los Angeles, Los Angeles, CA 90095
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550
bwinjum@ucla.edu

We have been studying the early interpenetration and stagnation processes of laser-irradiated additive-manufactured foam materials with particle-in-cell simulations. Here we present 1D and 2D simulations of solid-density, pre-ionized foam filaments (slabs in 1D and cylinders in 2D) with and without an incident laser. The foam filaments consist of single or multiple ion species at temperatures up to approximately 100 eV and separated from each other by vacuum regions ranging from 0.1 to 10 microns in width. We discuss the impact of an incident laser on heated filaments as they expand and fill space, as well as the range of effects that occur as plasma particles stream between filaments, spanning the range from relatively collisionless interpenetration to very collisional interpenetration giving rise to small shocks where the counter-streaming plasmas meet. We comment on the heating that occurs during stagnation, as well as on our diagnosis of quantities that can be compared with rad-hydro calculations in an attempt to bring together PIC and hydro modeling of realistic foams.

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Plenary

Tuesday

Low fuel convergence path to ignition using multi-shell implosions*

David S. Montgomery
Los Alamos National Laboratory
P.O. Box 1663, MS E526
Los Alamos, NM 87545
montgomery@lanl.gov

An imploding dense metal shell, such as gold or tungsten at about 20 g/cm^3, surrounding D-T fuel needs to spherically converge only a factor of ~10 to achieve stagnation pressures of 100's Gbar, sufficient to create conditions that could ignite the fusion fuel and produce significant burn. This dense high-Z shell can be accelerated inward via collision with one or more outer shells, where the outermost shell serves as an ablator driven indirectly by x-ray radiation or directly using lasers.

In this talk, we will discuss the issues, challenges and opportunities unique to multi-shell implosions compared to traditional single shell capsules, discuss some of the underlying physics of multi-shell implosions, and describe a simple model for the minimum conditions required to achieve robust burn. We will present double shell and triple shell (so-called Revolver) target designs intended to be fielded at the NIF laser. Experimental results from NIF and Omega that explore multi-shell implosion physics will be presented and discussed, as well as future plans.

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Poster Sessions

Tuesday

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Tailoring Landau damping to control Stimulated Brillouin Scatter in Ignition hohlraums*

A. Kemp, B. MacGowan, J. Ralph, N. Meezan, T. Chapman, R. Berger, D. Strozzi, N. Lemos, O. Landen, O.Jones, L. Divol and P. Michel
Lawrence Livermore National Laboratory
7000 East Ave
Livermore CA94550
Kemp7@llnl.gov

Stimulated Brillouin scattering (SBS) in low-fill hohlraum experiments on the NIF has the potential to cause optics damage, and thus limits the current design space. As part of an effort to mitigate SBS through innovative hohlraum designs, we have investigated the effect of using solid tantalum oxide (Ta2O5) liners. Based on a sequence of hydrodynamic simulations with gold vs. Ta2O5-lined hohlraum walls, we are able to differentiate the effects of hydrodynamics, i.e., using various models of flux-limited electron heat transport, on the one hand, and Landau damping of ion acoustic waves in the presence of low-Z ions, on the other. We use three-dimensional modeling with the code pf3d to calculate the reflectivity of the outer (50 degree) beams. Our modeling predicts that, almost independently of the flux limiter model used, Landau damping due to the presence of oxygen ions in the expanding Ta2O5 bubble dominates the suppression of SBS over differences in hydro flow patterns. This prediction is confirmed by experimental observations of SBS spectra [J.Ralph, this conference] which show significantly reduced SBS reflectivity in Ta2O5-lined gold, as compared to pure gold hohlraums.

* Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

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Particle-in-cell simulations of Stimulated Brillouin Scattering Relevant to Advanced Target Designs*

F. S. Tsung[1], P. Amendt[2], M. Belyae[v]2, R. Berger[2], T. Chapman[2], and D. Hinkel[2]
(1) Department of Physics, University of California, Los Angeles
405 Hilgard Ave
Los Angeles, CA 90095
tsung@physics.ucla.edu
[†]Lawrence Livermore National Laboratory
Livermore, CA 94550

We will present particle-in-cell simulations using OSIRIS and pf3D to assess the risk of SBS under conditions relevant to advanced target designs including foam-lined hohlraums and high-efficiency Frustraums whose (double-cone) shape minimizes the wall surface area and provides a greater volume above the capsule waist. Another advantage of the Frustraum shape is that the outer beams have relatively shorter beam paths compared to traditional (cylindrical) hohlraums and are therefore less susceptible to laser plasma instabilities. However, the threat of SBS remains in the inner beams. In this presentation, we will discuss both our current workflow - which extracts plasma conditions from hydro simulations or experiments to assess SBS threats in advanced target designs - and our long term goals, which includes the validation and verification of the various tools available to assess LPI, improving the capabilities of the OSIRIS code and post-processing capabilities to match those currently being used on the SRS and TPD problems, and understanding the various kinetic effects that can control or suppress SBS, including multi-species effects, binary collisions, and temporal bandwidth.

*This work is supported by DOE, NSF and LLNL and supported by LDRD-17-ERD-119.

Inferring Mix from Spectroscopic Measurements with Deep Learning*

B.A.Hammel, B.D.Hammel†, E. Marley, H.A.Scott, L. Peterson, C. Weber
Lawrence Livermore National Laboratory
Livermore, CA 94550
hammel1l@llnl.gov
†Mythic Inc.
Redwood City, CA 94062

The growth of perturbations in ICF capsules can lead to significant mix of dense material into the hot-spot (H-S), degrading performance. H-S mix that includes high-Z doped (e.g. Ge, W, Cu) ablator material (e.g. CH, HDC, Be) results in characteristic x-ray emission from the dopant materials when they enter the H-S. Experiments on the National Ignition Facility (NIF) have provided clear evidence of ablator mix, consistent with simulation predictions,[1,2,3] however a detailed understanding of the amount of H-S mix remains a challenge.

Using a 2D Cretin[4] model reported previously,[5] which treats the compressed core as a series of concentric shells with different densities, temperatures, and material concentrations (including mixed mass in H-S), we calculate the x-ray emission, including radiative transfer through the shell, as measured by a detector. By performing many simulations (30,000) over a plausible range of the shell model input parameters, we create a data set of possible spectral observations. A deep neural network, trained on this data set, learns the correspondence between spectral details and 11 shell parameters. The trained network is then used to predict mixed mass, and other imploded capsule parameters, from spectroscopic measurements in NIF experiments. Estimating uncertainty in the inferred parameters is an important area of research.[6,7] We are developing a Bayesian deep neural network and will also report on progress in this area.

* Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-730120

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Performance Porting VPIC to Modern Architectures*

W. D. Nystrom, R. F. Bird, and G. Chen
Los Alamos National Laboratory
Mail Stop B272, Group HPC-ENV
Los Alamos, NM 87545
wdn@lanl.gov

VPIC[1] is a 3D relativistic, electromagnetic Particle-In-Cell plasma simulation code. The 3D grid or mesh is a structured Cartesian mesh with uniform grid spacing. Most of the computational work in a time step is done in a series of loops over either particles or grid cells. The average number of particles per cell can range from a few tens to a few thousands depending on the problem being solved. This work has been focusing on the case of a few hundred particles per cell. VPIC was designed to use single precision floating point arithmetic to optimize the use of the available memory bandwidth. Both the particle data and the grid data are organized in an Array of Structures (AoS) storage format that is aligned along the appropriate word boundaries. Data is read and stored using SIMD vector loads and stores and is then transposed on the fly so it can be used in vector operations. VPIC uses asynchronous MPI as the top level of parallelism, Pthreads or OpenMP as the middle level of parallelism and vectorization at the lowest level. The granularity of work assigned to a thread is large. To achieve vectorization, VPIC uses a light weight C++ vector wrapper class that wraps vendor specific intrinsic function implementations of basic math operations.

VPIC is being ported and optimized on several modern architectures. These include KNL processors available on Trinity, Cori and Stampede2, Skylake processors available on Mare Nostrum and Stampede2, IBM Power 9 processors and Volta GPUs available on Summit and Sierra and ARM ThunderX2 processors, available on Astra at Sandia and ARM clusters at Los Alamos National Laboratory. VPIC is in production on several of these systems. These architectures vary in many ways including available memory bandwidth, vector length, threads per core, clock frequency and overall node architecture. This work is focused on single node performance. Current efforts to optimize single node performance are exploring use of Array of Structure of Arrays (AoSoA) for key data structures, performance portable algorithm changes, use of performance portability frameworks such as Kokkos and performance profiling with a variety of performance analysis tools. Results will be presented which compare the performance of VPIC on these different architectures.

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Tiling: A Dynamic Load Balancing Algorithm in OSIRIS

Roman P. Lee, Kyle G. Miller, Ricardo A. Fonseca†, Anton Helm†, Viktor K. Decyk, Adam Tableman, Warren B. Mori

University of California, Los Angeles
475 Portola Plaza,
Los Angeles, CA 90095
romanlee@physics.ucla.edu

† GoLP/Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico (IST), Universidade Tecnica de Lisboa (UTL)
Lisbon, Portugal

For many problems in high energy density plasma (HEDP) physics particle-in-cell (PIC) simulations are effective and widely utilized. PIC codes can effectively utilize leadership class computing facilities through parallelization strategies using domain decomposition. The plasma is broken up into small physical domains that fit onto a compute node which may have many CPUs or cores. However, as a problem is simulated in practice the simulation particles can be unevenly distributed across the nodes and the time to solution will be limited by the node with the most particles (particle operations dominate the PIC algorithm). This is referred to as load imbalance. We have implemented a dynamic load balancing algorithm in the PIC code OSIRS to improve its parallel scalability. The algorithm divides the simulation box into a number of tiles of fixed size in space. Each tile is responsible for the grid points in its domain, as well as any particles that happen to be there at any given time step. Then, load balancing across nodes is achieved by shuffling tiles between node depending on the computational load per tile so that the computational load is constant across each node. In two or three dimensions, the load can either be balanced along a space filling curve which strings the tiles together, or by using a rectilinear partitioning scheme. In one dimension determining the optimal distribution of tiles across nodes for best load balancing is trivial. For cases where each node has multiple threads loads are also balanced within each node using Open MP parallelism. Depending on the computational weight of a tile, the Open MP loop is done either inside tiles or across tiles in order to minimize the overhead associated with Open MP. We show preliminary results that demonstrate that the new algorithm can provide a 10x speedup for some for some HEDP problems. Timings within 10 % of a perfectly load balanced problem are found.

*Work supported by DOE, NSF

The Particle-in-Cell and Kinetic Simulation Software Center*

Presenter B. J. Winjum[1], W. B. Mori[1],
W. An[1], S. Chase[1], T. N. Dalichaouch[1], V. K. Decyk[1], R. A. Fonseca[2],
L. Hildebrand[1], Q. Hu[1], R. Lee[1], F. Li[1], J. May[1], K. Miller[1], Q. Su[1],
A. Tableman[1], F. S. Tsung[1], X. L. Xu[1], Y. Zhao[1]
[1]University of California Los Angeles
Los Angeles, CA 90095
[2]ISCTE - Lisbon University Institute
Lisbon, Portugal
picksc.org@gmail.com

The UCLA Particle-in-Cell and Kinetic Simulation Software Center (PICKSC) aims to support an international community of PIC and plasma kinetic software developers, users, and educators; to increase the use of this software for accelerating the rate of scientific discovery; and to be a repository of knowledge and history for PIC. We present the latest algorithmic developments of our software, including novel developments for particle pushers, field solvers, and parallelization strategies. We will also discuss progress towards making available and documenting illustrative open-source software programs and distinct production programs; developing and comparing different PIC algorithms; and coordinating the development of resources for the educational use of kinetic software. We welcome input and discussion from anyone interested in using or developing kinetic software, in obtaining access to our codes, in collaborating, in sharing their own software, or in commenting on how PICKSC can better serve the community.

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An implicit, conservative, adaptive multi-scale algorithm for the arbitrary-species 1D-2V Vlasov-Fokker-Planck-Ampère system*

Steven E. Anderson, W. T. Taitano, L. Chacon, and A. N. Simakov
Los Alamos National Laboratory
Los Alamos, NM, 87545, USA
andeste@lanl.gov

We discuss the continued development of a fully kinetic electron capability for the 1D-2V iFP Vlasov-Fokker-Planck (VFP) code. The purpose of this work is to enable efficient, high fidelity fully kinetic arbitrary-species simulations of HED plasmas, particularly in ICF-relevant regimes. Efforts to date have achieved success with a fully kinetic algorithm for the Vlasov-Ampère (VA) system on a static Cartesian mesh with an adaptive velocity-space. We discuss further development towards a fully kinetic capability for the Vlasov-Fokker-Planck-Ampère (VFPA) system in spherical geometry, with an adaptive moving mesh capability in configuration-space. We address the numerical stiffness inherently arising from the presence of kinetic electrons (e.g., electrostatic timescales, such as the inverse electron plasma frequency) through use of a suitably preconditioned High-Order–Low-Order (HOLO) scheme to avoid resolving timescales irrelevant to the system dynamics.[1] To efficiently resolve species with disparate temperatures and flow velocities, each species' VFP equation is analytically transformed by a time- and space-dependent normalization (to the species' thermal speed) and shift (to the species bulk velocity) in velocity-space, while transformation to a moving mesh coordinate frame allows tracking of sharp features, such as shocks. Conservation of mass, momentum, and energy is achieved through the addition of nonlinear constraint functions and pseudo-operators similar to the approaches of Taitano & Chacón and Taitano *et. al.*[2,3] To demonstrate the effectiveness of the scheme, we present results from several benchmark problems of varying complexity.

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High-Order Accurate Minimally-Dissipative Conservative Finite Difference Methods for 2D+2V Vlasov Simulation

A. Gianesini Odu, and J.W. Banks
Rensselaer Polytechnic Institute
110 8th Street
Troy, NY 12180
gianea@rpi.edu

The kinetic code LOKI [1, 2] simulates solutions to single- and multi-species Vlasov-Maxwell and Vlasov-Poisson systems in 2+2-dimensional phase space; at its core are a discretely conservative finite difference formulation of the governing equations, a minimally dissipative nonlinear scheme based on the well-known WENO approach, and MPI parallelism. In this talk, we discuss details of the algorithms and their fourth- and sixth-order accurate formulations, and advocate the use of high-order finite difference schemes to confront the elevated cost of direct kinetic simulation in high-dimensional phase space.
Results of code verification studies, through the method of manufactured solutions and comparison to classical Landau damping, and physically motivated applications, such as the growth of longitudinal and transverse instabilities in single- and multi-species plasmas [3], are presented.

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Photon acceleration in a flying focus*

A. Howard, D. Turnbull, A. Davies, P. Franke, D. H. Froula, and J. P. Palastro
Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
ahowa17@u.rochester.edu

A high-intensity laser pulse propagating through a medium triggers an ionization front that can frequency upshift and accelerate the photons of a secondary pulse. Dramatic frequency shifts, for instance from the optical to extreme ultraviolet, require that the photons remain in the ionization front over an extended distance. Traditionally, several effects have limited the interaction distance: the accelerated photons quickly outpace the ionization front or the ionizing pulse refracts from the plasma. The “flying focus”—a moving focal point resulting from a chirped laser pulse focused by a chromatic lens—overcomes these limitations. A flying focus pulse can drive a counter-propagating ionization front that travels at the speed of light in vacuum over a distance much greater than the Rayleigh range. Photon kinetics simulations are presented to demonstrate photon acceleration in such a front. Here, an 87-fs pulse with a central wavelength of 400 nm is frequency upshifted to a minimum wavelength of 91 nm over 1 cm of propagation. Further improvements to this scheme are proposed that may enable future iterations as a novel tabletop source of spatially coherent x rays.

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Polarization Exchange of Laser Beams Intersecting in a Plasma*

Malcolm Lazarow[‡], Eugene Kur[‡], Jonathan S. Wurtele[‡], and Pierre Michel[†]

[‡]Department of Physics
UC Berkeley, Berkeley CA 94720
wurtele@berkeley.edu
[†] Lawrence Livermore National Laboratory
Livermore, CA 94550

Experiments at the National Ignition Facility (NIF) require precise understanding of the electromagnetic fields of 96 laser beams that overlap and propagate through a hot plasma at the entrance of "hohlraum" targets. These overlapping beams modify each other's energy and polarization through a ponderomotive interaction with the plasma.[1] In addition, the finite transverse size of the beams introduces important geometric effects on beam propagation.[2] Continuing previous work,[3] we present simulations of polarization and energy transfer between two laser beams that incorporate the additional geometric aspects and discuss the experimental implications for developing plasma-based optical elements.

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Probing of wake structure in nonlinear laser wakefields via optical phase-space excitation

Colton B. Fruhling, G. Golovin, S. Banerjee and D. Umstader
University of Nebraska-Lincoln
500 Behlen Laboratory
Lincoln, NE 68588
colton.fruhling@huskers.unl.edu

High-intensity laser-plasma interactions and laser wakefield acceleration has been shown to be a useful laboratory setting for studying particle acceleration in plasmas and energy transport. Of particular interest, is nonlinear laser-driven wakes used to accelerate particles where current techniques for diagnostics in this regime include shadowgraphy[1], holography[2], and electron scattering[3]. We present a novel method to study the phase-space of the electrons in comparison to the density and electric field of the wake from the methods previously mentioned. The precise injection and acceleration conditions in a wakefield, the evolution of the wakefield, and the transfer of energy from laser to plasma is probed by using a secondary probe laser pulse to controllably inject electrons in wakefield. One can then map from the accelerated electron parameters the structure of the wakefield as it evolves on the femtosecond time scale. This research could have implications in astro-[4], planetary[5], and high-energy physics[6].

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Solutions for the Nernst Wave within an Ablating Thermal Front*

Presenter John Giuliani, Alexander Velikovich, and Steve Zalesak†
Plasma Physics Division, Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375
john.giuliani@nrl.navy.mil
†Syntek Technologies
Arlington, VA 22203

In magnetized laser or magnetically driven liner inertial fusion the Nernst effect is known to play an important role in the transport of magnetic flux through fusion plasmas wherein the temperature diffusivity is much greater than the magnetic diffusivity. This situation is characteristic of cylindrical targets as in MagLIF[1] and magnetized spherical targets as on OMEGA[2]. Under the assumption of constant pressure, we present self-similar solutions with the Braginskii set of plasma transport equations in a planar geometry initially containing a hot, magnetized plasma in contact with cold material that is subject to thermal ablation. The latter emulates the liner or the DT layer in the "ice-burner" regime. As the heated, cold plasma expands, the heat diffusion proceeds through the material interface that separates cold and hot layers. But the Nernst-transported magnetic flux leaves the material interface behind, propagating into the expanding cold plasma as a narrow front that we denote as the Nernst wave. We report analytic and MHD numerical solutions for the Nernst waves and describe their effect upon magnetic flux and heat losses from the hot plasma. We find that to reproduce the correct magnetic field profile by a MHD code requires careful treatment of the advection term involving the Nernst velocity in the magnetic diffusion equation. In our code this was accomplished with the piecewise parabolic method[3]. We will also show that full MHD numerical solutions without the constraint of constant pressure asymptotically approach the self-similar solutions, as found earlier for the case of a fixed cold wall[4]. These solutions provide challenging verification tests for the proper treatment of the Nernst effect in advanced, multi-physics codes.

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Three wave performance analysis of plasma-based amplification of a NIF laser beam*

B.D. Saltzman[‡], T. Chapman[†], L. Divol[†], P. Michel[†], and J. S. Wurtele[‡]
[‡]Department of Physics
University of California, Berkeley
Berkeley CA 94720
wurtele@berkeley.edu
[†] Lawrence Livermore National Laboratory
Livermore, CA 94550

Plasma amplifiers can potentially handle power levels greatly in excess of the damage threshold of conventional optics. The goal is to demonstrate the plasma-based compression and amplification of an 88 ps NIF beam to a pulse length of roughly 7 ps with energy roughly 300 J using a single NIF beam as the pump laser with 0.5 ns pulse length and 1 kJ energy. We present a three-wave analysis of the performance of the proposed experiment. The three-wave model is used for sensitivity studies and parameter optimization. Comparisons with more realistic codes such as Pf3D is discussed.

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2D simulations of diffusing jets in ICF capsule implosions*

Nelson M. Hoffman, Erik L. Vold, and Paul A. Bradley
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545
nmh@lanl.gov

Strongly directional jet flows can be induced in ICF capsule implosions by asymmetric structures (e.g., capsule mounts and fill tubes) or non-uniform drive[1,2,3]. At high enough temperatures (> a few keV) and low enough densities (< ~0.1 g/cm^3) in the imploding shell and gaseous fuel, ion mean free paths may be long enough that ion species, especially hydrogen isotopes, can drift with respect to each other, giving diffusive separation of initially mixed species, and diffusive mixing of initially separate species. Such diffusive transport can modify the motion of a jet, and enhance its ability to mix shell material into the fuel. To investigate this phenomenon, we are performing 2D simulations of direct-drive OMEGA[4] plastic-shell capsule implosions, using the xRAGE code[5] and an implementation of a new multi-species ion transport model[6]. The simulations show that the plasma transport enhances momentum transport (i.e., viscosity) as well as mass transport, smearing out the jet induced by the capsule mount. If the shell contains deuterium, as in a separated-reactants experiment, the jet increases the amount of deuterium mixed into the fuel.

*This work conducted under the auspices of the National Nuclear Security Administration of the US Department of Energy, under contract 89233218CNA000001.

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Multiresolution Advection in HYDRA*

Presenter C. R. Schroeder
Lawrence Livermore National Laboratory
7000 East Avenue L-472
Livermore, CA 94550
schroeder10@llnl.gov

HYDRA simulations play an important role in designing, analyzing, and understanding inertial confinement fusion and high energy density physics experiments at the National Ignition Facility and elsewhere. Many such calculations have been enabled or made dramatically less expensive by the multiresolution Lagrangian evolution capability added to HYDRA in the 1990's. Certain classes of simulations, particularly higher resolution ones, have required users to remap the calculation to a different mesh topology mid-run, which can be problematic for a variety of reasons. This presentation will cover the recent implementation and verification of a new multiresolution advection capability designed to eliminate the need for this remapping along with results from the first calculations to utilize it.

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X-ray scattering and plasma conductivity*

S. Hansen, T. Nagayama, T. Gomez, A. Baczewski, and A. Cangi
Sandia National Laboratories
Albuquerque, NM 87185
sbhanse@sandia.gov

X-ray scattering measurements reveal details of the dynamic structure factor $S(k,\omega)$, which is related to other dynamic properties such as the dielectric function and frequency-dependent conductivities. Scattering measurements can thus help constrain transport properties such as electrical and thermal conductivities[1] and are especially useful for materials at extreme conditions where direct conductivity measurements are extraordinarily challenging. Here, we review the connections between ionic and electronic material structure, $S(k,\omega)$, and conductivities and compare predictions of scattering signatures from average-atom[2], time-dependent density functional theory[3], and more heuristic models.

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Comparison of STA simulation to measured spectra from hot and dense germanium plasmas

T.-G. Lee[†,1], M. Busquet[2], M. Klapisch[3], J.W. Bates[1], A.J. Schmitt[1], and J.L. Giuliani[1]
U.S. Naval Research Laboratory, Washington, DC, 20375
[†]teckghee.lee@nrl.navy.mil
[2]RSI, Lanham, MD, 20706
[3]Syntek Technologies, Arlington, VA, 22203

The germanium emission spectra have been measured in short-pulse laser experiments [1]. This report compares the synthetic spectra, obtained using the Super Transition Array (STA) simulations, to the experimental data. The aim of the comparison is to assess our radiative opacity and emissivity calculations of highly stripped, mid-Z elements (e.g., germanium), which has received little consideration due to the difficulty in achieving conditions near local-thermodynamic-equilibrium (LTE) at high temperatures. The experimental spectrum shows the contribution from the 2p–3d and 2p–3p and 2p–4d transitions from a layer of germanium buried in plastic and heated by the laser beam. Taking the temperature and density gradients into account, the calculated emission spectrum reflects these features clearly and indicates the plasma temperature T_e = 600 eV and density ρ = 2.25 g/cc. These results are close to those obtained from other LTE opacity models (e.g., GRASP2K, CASSANDRA, DAVROS). Results from a non-LTE collisional-radiative equilibrium FLYCHK, however, shows a best match to the experimental spectra at T_e = 800 eV and ρ = 1.0 g/cc.

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Recent Advancements in Opacity Target Fabrication and Metrology*

H. Huang, B. Stahl, J. Walker, K.L. Sequoia, K.J. Boehm, K.C. Engelhorn, F.H. Elsner, and M.P. Farrell

General Atomics, P.O. Box 85608, San Diego, California 92186-5608
Haung@fusion.gat.com

Precision targets are central to all ICF/HED programs. Many targets are in planar form, requiring accurate knowledge of areal density, which requires innovations in both target fabrication and metrology. With this in mind, we developed a unique photolithography-based approach to produce opacity targets integrated onto silicon rings designed for ease of measurement and fielding. Such samples have been shot on Sandia's Z machine and have produced very clean spectra for solar opacity studies. More complex samples with line patterns have been produced for upcoming studies of inter-diffusion of metallic species under warm dense plasma conditions. We have also constructed an automated "AutoEdge" system in-house to push the limits of x-ray absorption measurements: (1) We have compiled five x-ray databases, namely NIST X-COM, NIST XFFAST, LBNL Henkie, LLNL, and SNL, into a single program for direct comparison and sample data analysis on the fly, (2) We have benchmarked gravimetric areal density on single-element foils to validate and differentiate x-ray databases at the 1% level which provides the accuracy needed for x-ray absorption-based quantification, (3) We have verified and improved measurement precision via empirical photon-counting statistics studies.

With such efforts, the areal densities of our currently produced samples are known with an unprecedented precision and accuracy. These targets are currently being shot in support of ICF/HED experimental campaigns. The improved knowledge of the x-ray databases is also broadly applicable to other programs. GA has recently joined the Initiative on X-ray Fundamental Parameters, an international collaboration led by several NIST-equivalent institutions to refine the existing x-ray databases for the worldwide scientific community.

*Work supported by General Atomics IR&D

Innovative Laser Micromachining Process Improvements*

J.C. Calleja-Aguirre,[1] L.C. Carlson,[1] A.C. Forsman,[1] B. Bachmann,[2] T. Sarginson,[2] H. Abu-Shawareb,[1] E.L. Alfonso[1]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
Wendi.Sweet@ga.com
[2]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

Improvements in the fabrication of custom pinhole plates are presented, which are used in a variety of National Ignition Facility X-ray diagnostics instruments. With state-of-the-art femtosecond laser machining and innovative post-machining processes, high precision components are fabricated, characterized and delivered in a timely manner. Implementation of a femtosecond laser has expanded the feature sizes in a range of material thicknesses that are routinely fabricated. Femtosecond laser machining, in conjunction with processes improvements that a) compensate for laser kerf, b) deburr parts, and c) provide advanced part metrology, have impacted throughput and product quality. The ability to both fabricate and comprehensively characterize high precision components enables experimental uncertainties in X-ray experiment results to be well understood. This poster will describe a) the implementation of a micro-blasting system, b) laser machining of <10 micron features, c) inspection improvements to rapidly examine and generate data reports, and d) the advanced fabrication of precise 'penumbral' apertures.

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Millimeter-Scale Seamless 2-Photon Polymerization Additive Manufacturing*

A. Haid,[1] L.C. Carlson,[1] N.B. Alexander,[1] B.E. Russ,[1] A.C. Forsman,[1]
J. Oakdale,[2] and S. Chen[3]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
Wendi.Sweet@ga.com
[2]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550
[3] University of California San Diego, 9500 Gilman Dr, La Jolla, CA 92093

Two-photon polymerization (2PP) techniques have been developed at General Atomics for additively-manufacturing novel target designs including polymer templates for metal foams, spherical gradient density foams, and micro-structured surfaces. A custom-made 2PP system was developed for the explicit purpose of target fabrication and has eliminated stitching defects present in commercial 2PP systems. A next generation 2PP system is being developed that incorporates expanded build volume, synchronized scanning mirror galvanometer and stage motion, holographic beam shaping, long working distances, dual beam super resolution techniques, conformal printing on target surfaces, and advanced 3D model generation (e.g. random foams, triply periodic minimal surfaces) will also be presented.

*Work supported by General Atomics IR&D

Plasma Kinetics
Wednesday Session 1

Electron Transport Effects in Burning Plasmas

Brian Appelbe, Mark Sherlock [†], Aidan Crilly, Chris Walsh, and Jeremy Chittenden
Centre for Inertial Fusion Studies
Imperial College London
United Kingdom
bappelbe@ic.ac.uk
[†]Lawrence Livermore National Laboratory
California, USA

Burning plasmas in Inertial Confinement Fusion and Magneto-Inertial Fusion produce large fluxes of alpha particles which are responsible for self-heating of the plasma as they undergo Coulomb collisions with electrons and ions. This work focuses on the electron kinetics occurring in burning plasmas. It is shown that the flux of alpha particles accompanying burn can perturb the electron distribution function from Maxwellian. A Vlasov-Fokker-Planck model is used to quantify this perturbation and to derive a set of electron transport equations (a heat flow equation & Ohm's law) incorporating this effect.

These electron transport equations are included in highly resolved hydrodynamic and magneto-hydrodynamic simulations of burn fronts, which also include alpha heating effects. It is found that the heat flow equation has a significant effect in the region behind the burn front, transporting energy from regions in which rapid self-heating is occurring to those regions with a lower alpha particle density. For magnetized plasmas, the suppression of the electron heat flow can significantly reduce burn propagation into the cold fuel. It is also found that magnetic field transport at a burn front is sensitive to the fuel magnetization. For low values of the electron Hall parameter, the magnetic field can be compressed by a propagating burn front, but for high values rarefaction of the field occurs due to expansion of the heated plasma. These field transport effects can result in further suppression of heat flows in a burn front region.

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Multi-dimensional Simulations of Interpenetrating Plasmas *

R. L. Berger, D. Ghosh, J. W. Banks, W. J. Arrighi, M. A. Belyaev, S. Brunner, T. Chapman,

D. M. Copeland, A. Dimits, J. A. F. Hittinger, O. Jones, and W. Rozmus[†]

Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA 94550
berger5@llnl.gov

Interpenetrating plasmas naturally occur in ICF hohlraums, in the sun's corona and wind, in laboratory experiments that model astrophysical shocks, and in the laser propagation through foams. The development of large-amplitude electrostatic and magnetic waves through streaming instabilities have motivated theoretical and computational studies with collisionless kinetic codes for 50+ years. Here, we describe the use hydrodynamic and kinetic approaches.

Hydrodynamic: A three-dimensional multi-species, multi-flow set of hydrodynamic equations is proposed and solved with EUCLID on an Eulerian mesh at the experimental scale. Plasmas moving at high relative velocity evolve on a shared Cartesian mesh nearly independently, coupled by the shared electron pressure, ion-ion and electron-ion friction, and temperature equilibration. Examples with several ion species with their own flows and ion temperatures are simulated.

Kinetic: Simulations of simultaneous electrostatic and magnetic instabilities over the much smaller spatial scales of Debye (v_e/ω_{pe}) and skin depths (c/ω_{pe}) are also presented with the 2D and 2V Vlasov code, LOKI.

* *This work conducted under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344 and funded by the Laboratory Research and Development Program at LLNL under project tracking code 17-ERD-081. Computing support for this work came from the Lawrence Livermore National Laboratory (LLNL) Institutional Computing Grand Challenge program.*

Mass and charge dependence of ion shock coupling and thermal equilibration in ICF shock phase*

Neel V. Kabadi, H. Sio, R. Simpson, C. Parker, P.J. Adrian, A. Bose, J.A. Frenje, M. Gatu Johnson, C.K. Li, F.H. Séguin, R.D. Petrasso, C. Forrest*, V. Yu Glebov*, C. Stoeckl*, D. Edgell*, S. Atzeni†, W. Taitano#, A. Simakov#, L. Chacon#, and O. Larroche^

Massachusetts Institute of Technology
77 Massachusetts Ave
Cambridge, MA 02141
kabadi@mit.edu

*Laboratory for Laser Energetics
Rochester, NY 14623

†University of Rome Sapienza
Rome, Italy

#Los Alamos National Lab
New Mexico 87545

^CEA France
Gif-sur-Yvette, France

During the shock-convergence phase of ICF implosions there are steep spatial gradients and the ion mean free path becomes long compared to the system size, indicating that multi-ion and kinetic effects may be important. It has been shown that there is substantial thermal decoupling and possibly other kinetic effects in D^3He plasmas with conditions relevant to the NIF shock-phase. In this presentation, I will show recent work conducted on the Omega laser facility recreating these conditions in DT plasmas. Results indicate a system that is better captured by average-ion hydrodynamic simulations than the D^3He case. We are working to understand this behavior. Combined DT and D3He burn averaged observables are consistent with an equilibrating two-temperature model. This has major implications for our understanding of kinetic and multi-ion plasma physics and our modeling of ICF implosions.

*This work conducted under the auspices of the DOE and NNSA

Shock-Enhanced Plasma Diffusion at a Gas-Metal Interface*

Brett D. Keenan, William T. Taitano, Andrei N. Simakov, Luis Chacón, and Brian J. Albright
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
keenan@lanl.gov

Multi-shell ICF designs, such as the Revolver[1] and Double Shells,[2] are predicted to ignite at lower temperatures/convergences than conventional single shell capsules. This is facilitated by the use of a high-Z (metal) inner pusher to reduce radiation losses of fuel energy; which, unfortunately, entails some tradeoffs. For example, any significant mix of the pusher material into the fuel (gas) may have a sizable impact on burn performance. The hydrodynamic stability of the gas-metal interface is an obvious concern,[2,3,4] but 1D effects may also be detrimental. Such effects include plasma diffusion at material interfaces; which has been the subject of numerous investigations[5,6,7] (mostly in the hydrodynamic limit). However, other 1D mix mechanisms may exist, which have yet to be thoroughly explored. In particular, plasma kinetic effects may drive mix when a shock breaks out of a gas-metal interface.[8,9] Using the state-of-the-art, hybrid (kinetic-ion/fluid electron), multi-ion Vlasov-Fokker-Planck code, iFP,[10] we show that plasma diffusion at a gas-metal interface is kinetically enhanced following the shock breakout. In particular, shock-driven kinetic effects reconfigure the interface, and the interfacial width subsequently grows $\propto M^{5/2}$ with time (where M is the initial shock Mach number in the metal). Additionally, we show that the intermediate evolution of the interface is governed by one principal parameter: the ratio of the shock transit time to a characteristic energy relaxation time. Finally, we consider any implications for high-Z pusher designs.

*Work performed under the auspices of the U.S. Department of Energy National Nuclear Security Administration under Contract No. 89233218CNA000001.

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LA-UR-19-23534

A semi-implicit, energy- and charge-conserving particle-in-cell algorithm for the relativistic Vlasov-Maxwell equations*

Presenter G. Chen, L. Chacon, L. Yin, B. J. Albright, D. J. Stark, and R. F. Bird
Los Alamos National Laboratory
Los Alamos, NM 87544
gchen@lanl.gov

Conventional explicit electromagnetic particle-in-cell (PIC) algorithms do not conserve discrete energy exactly. Time-centered fully implicit PIC algorithms can conserve discrete energy exactly, but may introduce large dispersion errors in the light-wave modes. This can lead to intolerable simulation errors where accurate light propagation is needed (e.g. in laser-plasma interactions). In this study, we selectively combine the leap-frog and Crank-Nicolson methods to produce an exactly energy- and charge-conserving relativistic electromagnetic PIC algorithm. Specifically, we employ the leap-frog method for Maxwell's equations, and the Crank-Nicolson method for the particle equations. The semi-implicit algorithm admits exact global energy conservation, exact local charge conservation, and preserves the dispersion properties of the leap-frog method for the light wave. The algorithm employs a new particle pusher designed to maximize efficiency and minimize wall-clock-time impact vs. the explicit alternative. It has been implemented in a code named iVPIC, based on the Los Alamos National Laboratory VPIC code. We present numerical results that demonstrate the properties of the scheme with sample test problems: relativistic two-stream instability, Weibel instability, and laser-plasma instabilities. [1]

*This work conducted under the auspices of the U.S. Department of Energy by the Triad National Security, LLC, Los Alamos National Laboratory and was supported by the U.S. Department of Energy Office of Science, Fusion Energy Sciences. Simulations were run on the LANL Institutional Computing Clusters.

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Kinetic Effects and Mix

Wednesday Session 2

Ion-velocity structure in strong collisional plasma shocks*

H. G. Rinderknecht,[1] R. K. Follett,[1] D. Haberberger,[1] J. Katz,[1] D. H. Froula,[1] H. S. Park,[2] J. S. Ross,[2] P. A. Amendt,[2] D. P. Higginson,[2] S. C. Wilks,[2] B. Keenan,[3] A. Simakov,[3] and L. Chacon[3]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
hrin@lle.rochester.edu
[2]Lawrence Livermore National Laboratory
Livermore, CA 94550
[3]Los Alamos National Laboratory
Los Alamos, NM 87545

Strong shocks are important in inertial confinement fusion and high-energy-density plasmas, but little experimental data exist measuring their structure and evolution. Initial experiments measuring the ion-velocity structure in strong (M = 6 to 11) collisional shocks in low-density (ρ = 0.01 to 0.1 mg/cm^3) plasmas using optical Thomson scattering on OMEGA observed nonthermal ion distributions within the shock front.[1] However, shock-front widths were observed to be narrower than the theoretical values, and more rapid flow stagnation was observed than predicted by particle-in-cell calculations. These effects were hypothesized to be caused by the nonsteady-state nature of a shock front not yet decoupled from its driving mechanism, and the growth of a two-stream instability observed in the data. Shocks in multiple species (H, Ne) showed a colder forward-streaming population than predicted by Vlasov–Fokker–Planck (VFP) simulations, which could be explained by the ionization dynamics of neon.[2]

This work presents the results of new experiments probing the long-term behavior of shock propagation in a multispecies collisional plasma. Experiments irradiated a thin (1-μm) Si_3N_4 foil with 2.5 kJ in a 0.6-ns square pulse to drive a strong shock into a background gas of either pure hydrogen or a hydrogen:helium (4:1) mixture. The density of the background gas was approximately 10× larger than in the previous experiments, reducing the mean free path and thereby the predicted final shock width and the shock formation time by an order of magnitude, allowing the shocks to approach steady state. Thomson-scattering images record the electron density and ion-velocity structure from the unmoving, preheated plasma through the shock formation region into the fully shocked plasma, showing a detailed record of shock formation, structure, and evolution in an unmagnetized, multispecies laboratory plasma.

* This work conducted under the auspices of the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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49th Annual Anomalous Absorption Conference
Telluride, CO
June 9-14, 2019

Predicting QED Photon Jets from Plasma Experiments with Present-Day Lasers*

S. V. Luedtke[†‡], L. Yin[†], L. A. Labun[‡§], O. Z. Labun[‡§], B. J. Albright[†], D. J. Stark[†], R. F. Bird[†], W. D. Nystrom[†], and B. M. Hegelich[‡§]
[†]Los Alamos National Laboratory
Los Alamos, New Mexico 87545
sluedtke@lanl.gov
[‡]Center for High Energy Density Science, University of Texas
Austin, Texas 78712
[§]Department of Physics and Photon Science, Gwangju Institute of Science and Technolog
Gwangju 61005, South Korea

Discovery of quantum radiation dynamics in high-intensity laser-plasma interactions and engineering new laser-driven high-energy particle sources require accurate and robust predictions. Using QED-particle-in-cell simulations, we investigate a characteristic dipole pattern of high-energy photon emission that results when the laser pulse bores through the target, forming a channel that enhances the laser field. Motivated by similar observables in high-energy physics, we introduce a new “jet” observable to describe the high-energy photon emission. We observe significant stochasticity in macroscopically identical simulations, and we expect the stochasticity to be present in experiments. The non-deterministic nature of the channeling phenomenon has important implications for designing an experimental campaign to detect QED photons and validate quantum radiation theory in strong fields, namely, experiments must produce a distribution of results to compare with predictions. We provide sample predictions for a petawatt-class laser.

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49th Annual Anomalous Absorption Conference
Telluride, CO
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Nonlinear evolution of the ion-ion streaming instability in single- and multi-ion species plasmas*

T. Chapman, B. J. Winjum†, R. L. Berger, A. M. Dimits, S. Brunner††, and D. Ghosh
Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551, USA
†Department of Electrical Engineering, University of California Los Angeles
Los Angeles, California 90095, USA
††Swiss Plasma Centre, École Polytechnique Fédérale de Lausanne
Station 13, CH-1015 Lausanne, Switzerland

When two streams of ions flow through one another, the relative flows may drive the growth of large-amplitude ion acoustic waves. From the resultant waves, particle trapping combined with collisionless scattering can efficiently heat the ions to many times above their initial temperatures both parallel and perpendicular to the flow direction.

We present high-fidelity and high-order Vlasov simulations of interpenetrating ion flows in two spatial and velocity dimensions (2D+2V), with a fully kinetic treatment of the electron and ion species and physically correct mass ratios. Due to the inherently low numerical noise of the Vlasov method, we observe growth of electrostatic modes from a thermal noise level through to saturation and into the strongly nonlinear stage of evolution. We simulate neutral plasmas with a range of relative flow speeds and ion species mixtures, with initial ion temperatures that are cool relative to the electrons. While we find that equal and opposite ion streams typically do not exhibit a strong slowing down even far into the nonlinear stage, we find that when flows of mixed ion species interact, the lighter species can be slowed down dramatically. Additionally, both heavy and light species undergo similar strong heating in all directions. Here, our treatment of the plasma is deliberately electrostatic in order to clarify the role of the fast electrostatic instability in the absence of the much slower electromagnetic (Weibel) instability. Our Vlasov simulation results are supported by particle-in-cell simulations that confirm the eventual nonlinear state of the plasma. Our numerical methods and physical results are of interest to simulating collisionless shock breakup, space plasmas, and basic laboratory experiments of interacting ion flows.

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Initializing anisotropic and unstable electron velocity distributions needed for investigating plasma kinetic instabilities*

C. K. Huang, C. J. Zhang, K. A. Marsh, C. E. Clayton, and C. Joshi
University of California Los Angeles
405 Hilgard Avenue
Los Angeles, CA 90095
ckhuang@ucla.edu

In this work, we demonstrated anisotropic and unstable electron distribution functions can be initialized via optical-field ionization (OFI) using ultrashort laser pulses. These distribution functions can be manipulated by the choice of laser wavelength(s), intensity, polarization, and ionization state of the gas. We experimentally show this control by using Thomson scattering of a frequency doubled, 90 fs laser pulse to probe the characteristic electron velocity distributions in helium plasmas produced on a 10-fs timescale by linearly and circularly polarized 800 nm laser pulses. In both cases, Thomson scattered spectra consistent with non-thermal and highly anisotropic initial electron distributions from OFI of both He electrons are observed. Until they are isotropized and thermalized such plasmas cannot be described by the fluid theory and thus present a new platform for studying kinetic effects and instabilities in laboratory plasmas.

*This work conducted under the auspices of DOE and NSF.

Optical field ionized gases as a new laboratory platform for studying kinetic plasma instabilities*

C. J. Zhang, C.-K. Huang, K. A. Marsh, C. E. Clayton, W. B. Mori and C. Joshi
University of California Los Angeles
405 Hilgard Avenue
Los Angeles, CA 90095
chaojiez@ucla.edu

Kinetic instabilities such as two-stream[1], filamentation[2] and Weibel[3] instabilities arising from anisotropic electron velocity distributions (EVD) are ubiquitous in ionospheric, cosmic and terrestrial plasmas, and therefore have been extensively investigated in theory and simulations. However, there have been relatively few direct laboratory verifications of these instabilities because of the lack of a suitable platform that would allow initialization of known anisotropic EVD. Here we show that ultrafast optical field ionized plasmas[4] have a large velocity anisotropy, and therefore undergo a variety of kinetic instabilities such as the streaming, filamentation and Weibel-like filamentation instabilities that act to isotropize the plasma. The polarization dependent frequency and growth rates of these kinetic instabilities, measured using Thomson scattering of a probe laser, agree well with the kinetic theory and simulations. Therefore, we have demonstrated a novel laboratory platform for studying kinetic instabilities in plasmas.

*This work conducted under the auspices of DOE and NSF.

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HED Physics
Thursday Session 1

MARBLE – A Separated Reactants Mix & Burn Campaign*

Brian J. Albright, T. J. Murphy, M. Douglas, T. Cardenas, J. H. Cooley, T. H. Day, C. Di Stefano, R. A. Gore, M. Gunderson, J. Haack, B. M. Haines, C. E. Hamilton, Y. Kim, P. M. Kozlowski, M. N. Lee, J. A. Oertel, R. E. Olson, R. B. Randolph, R. C. Shah†, J. M. Smidt, D. Woods, L. Yin
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
balbright@lanl.gov
†University of Rochester – Laboratory for Laser Energetics
250 E. River Rd.
Rochester, NY 14623

MARBLE[1] is a separated reactants campaign on the NIF designed to investigate the effects of heterogeneous mix on thermonuclear burn. The goal of MARBLE is to obtain quantitative data that can be used to validate models of thermonuclear burn in heterogeneous, mixing plasmas. Marble uses Si-doped plastic capsules filled with deuterated plastic (divivylbenzene) foam and cryogenic hydrogen-tritium or argon-tritium gas fills. Embedded in the foam are "macro-pores," engineered voids in the foam of known sizes and locations, which allow for control of the level of plasma heterogeneity. In MARBLE implosions, the ratio of deuterium-tritium (DT) to deuterium-deuterium (DD) yield is measured, from which the morphology of the mix at bang time can be inferred. The higher the DT to DD neutron yield ratio, the more homogeneous the morphology. Early MARBLE 1-shock and 2-shock experiments that used a hydrogen/tritium gas fill did not show the expected variation of yield with macro-pore diameter; rather, they showed an increase in DT to DD yield ratio with macro-pore dimension, consistent with results seen in high-resolution 3D xRage simulations[2] as well as VPIC kinetic plasma simulations[3] under MARBLE conditions. In contrast, recent MARBLE experiments on the National Ignition Facility using a 33.6 mg/cm^3 gas fill of 91% argon 9% tritium do show a pronounced decrease in yield ratio with pore size. In this presentation, results from recent MARBLE experiments will be presented and implications for the validation of mix and burn models will be discussed.

*Work performed under the auspices of the US DOE by the Triad National Security, LLC, Los Alamos National Laboratory and was supported by the Office of Experimental Sciences.

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Modeling of Hydrodynamically Equivalent Cylindrical Implosions at OMEGA and the National Ignition Facility*

J. P. Sauppe, S. Palaniyappan, K. A. Flippo, J. L. Kline, O. L. Landen[†], D. Shvarts[††], P. A. Bradley, E. N. Loomis, S. H. Batha, B. J. Tobias, N. N. Vazirani, C. F. Kawaguchi, D. W. Schmidt, T. H. Day, L. Kot, and A. B. Zylstra[†]
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
jpsauppe@lanl.gov
[†]Lawrence Livermore National Laboratory
Livermore, CA 94550
[††]Ben-Gurion University of the Negev
Beer-Sheva, Israel

Directly-driven cylindrical implosions studying deceleration phase Rayleigh-Taylor instability (RTI) growth have been successfully fielded at both the OMEGA laser facility and the National Ignition Facility (NIF). Deceleration RTI is particularly detrimental for inertial confinement fusion (ICF) implosions, as it mixes cold ablator material into the fuel, reducing performance. Measurements of instability growth on the inner surface of a spherical shell are limited and are often only inferred indirectly and at limited convergence. In contrast, cylindrical implosions allow for direct measurements of the inner surface while retaining the effects of convergence, which are known to modify RTI growth rates through Bell-Plesset effects.[1]

Recent experiments demonstrate that RTI growth is scale-invariant between cylindrical targets at OMEGA and similar targets at the NIF that are scaled up in size by a factor of three in the radial dimension. The experiments were designed using Los Alamos National Laboratory's radiation-hydrodynamics code, xRAGE,[2] including a new laser ray trace package. The simulations use an *ad hoc* laser drive multiplier to account for cross-beam energy transfer and laser-plasma interaction (LPI) physics that are not currently modeled. The same laser drive multiplier matches the shock and inner surface trajectories of both the OMEGA and NIF-scale targets quite well, despite the disparate plasma length scales, with strong implications for scaling of direct-drive ICF implosions. However, there is greater disagreement between the simulations and the data for the outer surface trajectory. Additional simulations suggest that this could be explained by preheat of the aluminum marker layer, which is not currently modeled directly, or by invoking a turbulent mix model with appropriately chosen initial conditions. Preheat is postulated to result from hot electrons generated by LPI, and the turbulent mix might arise from native surface roughness on the interfaces that is beyond the ability to capture in these direct numerical simulations. The plausibility of both effects is investigated here.

*This work was supported by the US Department of Energy National Nuclear Security Administration through the Los Alamos National Laboratory, operated by Triad National Security, LLC. (Contract No. 89233218CNA000001).

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Hydro Scaling of Direct-Drive Cylindrical Implosions at the OMEGA and the National Ignition Facility*

S. Palaniyappan, J. P. Sauppe, K. A. Flippo, A. B. Zylstra†, O. L. Landen†, D. Shvarts††, S. H. Batha, P. A. Bradley, E. N. Loomis, B. J. Tobias, N. N. Vazirani, C. F. Kawaguchi, L. Kot†, D.W. Schmidt, T. H. Day, R. Gonzales, and J. L. Kline.
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
sasi@lanl.gov
†Lawrence Livermore National Laboratory
Livermore, CA 94550
††Ben-Gurion University of the Negev
Beer-Sheva, Israel

Deceleration-phase Rayleigh-Taylor instability (RTI) growth during inertial confinement fusion (ICF) implosions could lead to ablator-fuel mix, adversely affecting the implosion performance. Precise measurements of such instability growth are essential for both validating the existing simulation codes and improving our predictive capability. Existing RTI measurements in spherical implosions are limited, and inferring the RTI growth in spherical geometry is not straightforward. In contrast, cylindrical implosions allow precise measurements of the inner surface RTI growth while retaining the effects of convergence. We have performed directly-driven cylindrical implosions experiments at both the Omega and the NIF laser facilities using scaled targets. RTI growth is demonstrated to be scale-invariant between the cylindrical targets at OMEGA and the 3X scaled up cylindrical target at the NIF. Single-mode (m=20) instability growth factors of ~17 are measured at a convergence ratio CR~2.5 with nearly identical mode growth at both scales. In addition, we have also developed a method using the Bayesian-Inference-Engine (BIE) to subtract the parallax effects in the measurements, allowing a more precise comparison between the experimental data and the simulations. Designs for higher convergence cylindrical implosions, CR~10-15, are currently underway.

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Forward modeling of backlighter radiography for Bayesian inference of Rayleigh-Taylor growth rates*

B. Tobias, C.F. Kawaguchi, S. Palaniyappan, J.P. Sauppe, R. Gonzales, A.B. Zylstra[†], L. Kot, K.A. Flippo, S.H. Batha, E.N. Loomis, and J.L. Kline
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
tobias@lanl.gov
[†]Lawrence Livermore National Laboratory
Livermore, CA 94550

Cylindrical deceleration-phase Rayleigh-Taylor instability (RTI) experiments have been performed at Omega and the NIF in development of a platform that will soon test hydrodynamic modeling at convergence ratios (CRs) of ~10-15, where hot electrons generated by laser-plasma interaction (LPI), turbulent mixing, and Bell-Plesset effects will have a significant influence on the choice of physics model. The cylindrical platform is advantageous from a radiographic perspective, as it allows for an end-on view of the growing mode without obstruction by other 3D structures. However, accurate diagnosis of RTI growth remains complicated by parallax effects in the image that are inherent to pinhole imaging at large magnification and sensitive to target alignment. The perspective of the gated x-ray framing camera produces effects that are analogous to a non-stationary blur and difficult to remove from the image. We have overcome this challenge by forward modeling the 3D geometry of the pinhole experiment using the Bayes' Inference Engine (BIE).[1] This computational platform allows the geometry of the implosion to be reduced to a parameterized model whose features are optimized by conjugant gradient methods to obtain a maximum a posteriori (MAP) solution. Constrained quantitative inference of this kind allows us to infer the alignment with precision greater than the alignment tolerances of the Ten-Inch Manipulator (TIM) used for inserting the pinhole camera. When this alignment is used to generate image parallax, we find that ellipticity of the implosion (m=2 asymmetry) is typically of 1-2%. Furthermore, we arrive at time-dependent positions of the RTI spike and bubble features consistent enough to resolve linear growth rates with one-sigma confidence intervals in a range of 1.5 to 2 μm/ns (~10%). The process of analyzing Omega experiments at CR ~2.5 informs us that the largest source of uncertainty remains pre-shot characterization of the laser target. As there will be further refinements in quality assurance techniques and some relaxation of tolerances at larger physical dimensions, these results bode well for future high-CR experiments planned for the NIF.

* This work was supported by the US Department of Energy National Nuclear Security Administration through the Los Alamos National Laboratory, operated by Triad National Security, LLC. (Contract No. 89233218CNA000001).

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Generalized Boltzmann plots for temperature measurements of radiation flow on OMEGA*

Pawel M. Kozlowski, H. M. Johns, S. R. Wood, A. Liao, J. W. Morton[†], C. R. D. Brown[†], N. E. Lanier, C. Fryer, C. J. Fontes, J. P. Colgan, T. S. Perry, and T. Urbatsch
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545
pkozlowski@lanl.gov
[†]Atomic Weapons Establishment
Aldermaston, Reading, Berkshire RG7 4PR, United Kingdom

The COAX experiments are designed to provide constraining data for supersonic radiation waves in radiation-hydrodynamic models. We utilize absorption spectroscopy measurements developed on the COAX platform to infer spatially resolved temperature during discrete times. The temperature measurement involves backlighting the physics target with a Kr-filled CH capsule and collecting the resulting absorption spectrum with a 1D spatially resolving spectrometer. Standard forward modeling and fitting of spectra to infer temperature have proven difficult, with discrepancies arising from different models. Boltzmann plots are an inverse method for obtaining temperature from spectroscopic measurements commonly applied to low temperature and density plasmas where multiple lines can be measured from a single element in a single charge state. We explore a generalization of the Boltzmann plot theory to higher temperature and density plasmas where lines from many different charge states must be considered. This generalized Boltzmann plot analysis technique is applied to spectra measured in experiments as a complementary technique for obtaining temperature and resolving discrepancies between atomic/spectroscopic models.

*Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy under contract 89233218CNA000001. LA-UR-19-23486.

Impact of self-generated B-fields on HED experiments*

Presenter D.H. Barnak, K. A. Flippo, C. F. Kawaguchi,
K. V. Kelso, H. Li, S. Li, E. Loomis, Y. Lu, N. Vazirani
Los Alamos National Laboratory
Bikini Atoll Rd., SM 30
Los Alamos, NM 87545
dbarn@lanl.gov

Mixing has been a topic of discussion among the ICF (inertial confinement fusion) community as an explanation for decreased neutron yield and colder ion temperatures. Understanding where mix comes from, how it occurs, and accurately modeling and predicting what causes mix is quintessential to developing future mix mitigation strategies and designing better performing ICF implosions. Strong magnetic fields can be generated when plasma flows shear and go Kelvin-Helmholtz unstable. The presence of strong magnetic fields, although not important to the hydrodynamics in terms of pressure, can affect electron thermal transport and ion transport, and can have energy densities on the order of the turbulent energy, which could affect the mixing behavior. An experiment was conducted to study strong magnetic fields as a result of shear flow from counter propagating shocks similar to the Shock-Shear platform. Magnetic field location and strength was determined using proton radiography through the central sheared region. Whereas, the location and morphology of the shocks and the mixing region were measured using point projection backlighting x-ray radiography on the axis perpendicular to the protons. The presence of these strong magnetic fields in a shock-shear platform may lead to a paradigm shift in the need for including extended MHD (magnetohydrodynamics) effects to accurately model aspects of the mixing in high energy density plasmas.

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Ignition Concepts

Thursday Session 2

Tripling the energy coupling efficiency from hohlraum to capsule on NIF*

Y. Ping, V. A. Smalyuk, P. Amendt, R. Tommasini, J. E. Field, S. Khan, D. Bennett, E. Dewald, F. Graziani, S. Johnson, O. L. Landen, A. G. Macphee[1], A. Nikroo, J. Pino, S. Prisbrey, J. Ralph, R. Seugling, D. Strozzi, R. E. Tipton, Y. M. Wang, E. Loomis[†], E. Merritt[†], and D. Montgomery[†]
Lawrence Livermore National laboratory
7000 East Avenue
Livermore, CA 94550
ping2@llnl.gov
[†]Los Alamos National Laboratory
Los Alamos, NM zipcode

In the current cylindrical-hohlraum indirect drive schemes for ICF, a strong limitation is the inefficient (~10%) absorption of the laser-produced hohlraum x-rays by the capsule as set by relative capsule-to-hohlraum surface areas. The typical energy coupled to the capsule is less than 200 kJ with laser drive energies up to 1.8 MJ. We report a NIF experiment demonstrating ~30% energy coupling to an aluminum capsule in a rugby-shaped gold hohlraum[1]. Based on x-ray radiography measurements, the shell kinetic energy reaches 34 kJ with 1MJ drive at 0.7x subscale, consistent with ~300 kJ capsule energy coupling. More experiments were performed recently at larger, 0.9x scale with 1.5 MJ laser drive. The nuclear bang time and the shell velocity from simulations agree well with experimental data, indicating ~500 kJ coupling with 1.5MJ drive. The laser backscatter inside the low-gas-fill rugby hohlraum is shown to be very low (~1%) at both 0.7x and 0.9x scale. This high coupling efficiency can substantially increase the tolerance to residual imperfections and improve the prospects for ignition, both in mainline single-shell hot-spot designs and potential double-shell targets.

* This work was performed under the auspices of the US DOE by LLNL under contract number DEAC52- 07NA27344, with partial support from the DOE OFES ECRP program.

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[1] Y. Ping, V. Smalyuk, P. Amendt et al. Nature Physics 15, 138 (2019).

Double Shell Target Design for Robust Yield on the National Ignition Facility*

R. F. Sacks, E. N. Loomis, E. C. Merritt, J. P. Sauppe, W. S. Daughton, B. Haines, T. Cardenas, D. S. Montgomery, D. C. Wilson, J. L. Kline, S. F. Khan[†], M. Schoff[‡], M. Hoppe[‡], F. Fierro, R. B. Randolph, B. Patterson, L. Kuettner, E. S. Dodd, W. C. Wan, S. Palaniyappan, S. H. Batha, P. A. Keiter, J. R. Rygg[†], V. Smalyuk[†], Y. Ping[†], and P. Amendt[†]
Los Alamos National Laboratory
Los Alamos NM, 87545
rsacks@lanl.gov
[†]Lawrence Livermore National Laboratory
Livermore CA, 94550
[‡]General Atomics
San Diego CA, 92121

Advances in target fabrication have made double shell capsule implosions a viable platform to study burning fusion plasmas. Utilizing an x-ray driven outer ablator, energy is transferred to an inner high-Z shell via a hydrodynamic collision. The high-Z inner shell compresses DT fuel quasi-adiabatically, which triggers volumetric ignition. The process is aided through the reduction in radiative losses from the presence of the high-Z inner shell[1]. Experiments conducted by Los Alamos have demonstrated the hydrodynamic energy transfer, shape control of the outer ablator, and techniques to mitigate assembly artifacts in the target[2]. Computational studies utilizing the xRAGE and HYDRA codes examine the deleterious impacts of interface surface roughness and the fill tube. This presentation will cover these impacts in addition to mitigation strategies, and benchmarking of the codes against experimental results. Future plans for investigating the impact of mix on burn will be discussed.

1 D. Montgomery *et al.,* "Design considerations for indirectly driven double shell capsules", POP **25**, 092706 (2018)
2 E. Merritt *et al.,* "Experimental study of energy transfer in double shell implosions", accepted to POP, publication May 2019.

*This work conducted under the auspices of the U.S. Department of Energy, contract number 89233218CNA0000001, release number LA-UR-19-23638.

49th Annual Anomalous Absorption Conference
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Large-scale implosions using HDC ablators for the Frustraum*

Darwin D. Ho and P. A. Amendt
Lawrence Livermore National Laboratory
Livermore, CA 94550
ho1@llnl.gov

A diamond-shaped hohlraum ("Frustraum") proposed by Amendt *et al.*[1] may provide adequate radiation symmetry for large capsules (1500 μm radius) while requiring < 1.8 MJ of laser energy using 3ω light and is capable of providing peak radiation temperature in the 290 – 300 eV range. The capsule size can be increased to 1900 μm or larger if 2ω light is used at 2.8 MJ of driver energy and 600 TW of power. The implosion physics and designs for these large capsules are presented here and compared to nominal scale (1100 μm radius) HDC implosions. The fuel adiabat α for the large-scale capsules ranges from 2.5 to 6 multiples of the Fermi degenerate limit. Large scale has high 1D margin or Generalized Lawson Criterion e.g., the α = 4 design gives a 2D yield of 20 MJ while the nominal-scale α = 4 design has a 2D yield of only about 0.5 MJ. Lower hard x-ray fraction (14%) from the Frustraum with DU wall results in a neutral Atwood number on the fuel-ablator interface at peak velocity. This reduces mix and gives a high clean fuel fraction of 95%. Large-scale capsules are also robust to fuel pre-heat, hotspot contamination, and tent and fill -tube perturbations. The improved robustness allows the use of liquid-DT foam as a viable fielding option for a 2*ω* driver. The disadvantage of large-scale is that the ablation-front growth factor increases with capsule size. Therefore, it is advantageous to use a lower-Z ablator, e.g., boron, to reduce the growth factor. The modeling method used for the large-scale designs is the same for recent large Al capsules in a rugby-shaped hohlraum,[2] which gives close agreement with the data.

* This work is supported by LLNL LDRD-17-ERD-119

1. Amendt et al., APS-DPP 2018 and Amendt et al., submitted to Phys. Plasmas 2019.
2. Ping, Smalyuk, Amendt et al., Nature Phys. (https://doi.org/10.1038/s41567-018-0331-5)

Physics-driven design and experimental efforts for the Revolver direct-drive triple-shell ignition concept

Mark J. Schmitt[*], Kim Molvig[*], Natalia Krasheninnikova[*], Brett Scheiner[*], Derek Schmidt[*], Scott Hsu[*], Carl Wilde[*], Lynn Kot[*], Dana Edgell[†], Fred Marshall[†], Patrick McKenty[†], Michael Rosenberg[†], David Turnbull[†], Matthias Hohenberger (LLNL)[‡] and Haibo Huang[⸙]

[*]Los Alamos National Laboratory, MS F699, Los Alamos, NM 87545 mjs@lanl.gov
[†]U. Rochester Laboratory for Laser Energetics, 250 East River Rd, Rochester, NY 14623
[‡]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550
[⸙]General Atomics, 3550 General Atomics Court, San Diego, CA 92121

The Revolver concept[1] employs several unique design and fabrication features to attempt to obtain ignition using the current National Ignition Facility (NIF) laser system. Direct laser drive of a large, thin 6 mm diameter x 50 μm thick outer beryllium shell maximizes laser drive energy conversion to target inward kinetic energy at low intensity (3×10^{14} W/cm^2) while simultaneously minimizing any nonlinear drive non-uniformities and target coupling inefficiencies caused by laser-plasma instabilities. The relatively short laser drive time of 6.5 ns allows the energy to couple to the target before the plasma critical density radius shrinks significantly, thereby eliminating the need for laser zooming of the imploding target. The use of a small laser beam to capsule ratio of ~1/3 allows excellent coupling of the laser energy to the ablator shell while necessitating the optimum placement of NIF's 192 beams to regain ablative drive uniformity.

Shell asymmetry growth from the outer shell into the intermediate copper shell and finally into the inner tungsten shell is examined. Drive uniformity metrics are proposed for achieving multi-megajoule yields on the current NIF. Target design enhancements to mitigate drive non-uniformities are examined for their efficacy against both laser pointing errors and shot-to-shot laser beam power variations. A low density support material under the beryllium ablator shell is crucial for efficient acceleration and laser energy coupling to inward kinetic energy (i.e. hydro-efficiency). Moreover, 2D HYDRA simulations of solid density Be or CH cushions on the exterior surfaces of the inner two concentric shells are shown to be crucial for suppressing the growth of asymmetries in the simulated convergence of the inner shells and liquid DT fuel. Unique fabrication requirements for the complete ignition target include the fabrication of thin hemispherical shells, a low-density (5 mg/cm^3) additively-manufactured support lattice between the outer two shells and a novel fabrication concept for fielding the liquid-DT-density-filled inner tungsten shell at room temperature sans fill tube. An overview of recent Omega experiments using single shell and novel two-shell-on-cone targets will be given. Experimental data inferring excellent laser hydro-coupling efficiencies (>90%) to the outer shell and as-predicted kinetic energy transfer from the outer shell to the second shell will be presented.

Research supported by the Laboratory Directed Research and Development Program of Los Alamos National Laboratory under project number 20180051DR.

[1]Kim Molvig, Mark J. Schmitt, B.J. Albright, E.S. Dodd, N.M. Hoffman, G.H. McCall, and S.D. Ramsey, *Low fuel convergence path to direct-drive fusion ignition*, Phys. Rev. Lett. **116**, 255003 (2016).

Pointing scheme for the NIF laser with "perfect" low mode uniformity*

LA-UR-19-23939

Kim Molvig*† and Mark J. Schmitt*
*Los Alamos National Laboratory, MS F699, Los Alamos, NM 87544 molvig@lanl.gov
†Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139

A pointing scheme for the NIF laser is derived that eliminates all of the 143 spherical harmonic modes of the illumination non uniformity with principle mode numbers less than 12. Beams are assumed to have normally incident axes with identical circular cross sections and equal energy. Zeroing out of these modes is a consequence of the axis pointing angles only, independent of beam width (and therefor of target radius). Beam profile half widths can be a fraction of the capsule diameter to facilitate absorption of the laser energy (greater than 95%) and maximum ablation pressure. Modes with, $l \geq 12$, are not zeroed out but can be reduced in amplitude to less than a percent by beam widths, $R_{beam}/R_{target} \approx 0.3$. The calculation of the complete spherical harmonic spectrum, and the cone angles that zero out the low mode numbers, is an extension of the work of Skupsky and Lee[1]. It considers the early times, when the laser energy is absorbed in a thin surface layer nearly at the critical surface and close to the ablation front, making thermal smoothing ineffective. This is laser imprint phase that is so critical to the net uniformity of the direct drive process. The main predictions of the analytic calculations are validated with two dimensional HYDRA simulations of the Revolver[2,3] ablator shell.

Research supported by the Laboratory Directed Research and Development Program of Los Alamos National Laboratory under project number 20180051DR.

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[2] Kim Molvig, Mark J. Schmitt, B.J. Albright, E. S. Dodd, N. M. Hoffman, G. H. McCall, and S. D. Ramsey, *Low fuel convergence path to direct-drive fusion ignition*, Phys. Rev. Lett., **116**, 255003 (2016)
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Plenary
Thursday

49th Annual Anomalous Absorption Conference
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Expanding the frontiers of physics in radiation hydrodynamics simulation*

Michael M. Marinak, Mehul V. Patel, Scott M. Sepke, Joseph M. Koning,
Christopher R. Schroeder, Robert J. Kingham[†], Chris P. Ridgers[2], Mark W. Sherlock,
John A. Marozas[3], Howard A. Scott, Hai P. Le and Daniel S. Clark
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA, 94550
marinak1@llnl.gov
[†]Imperial College London, UK
[2]University of York, UK
[3]Laboratory for Laser Energetics, University of Rochester

Simulation of inertial confinement fusion experiments requires complex codes which treat a broad spectrum of physical processes. Expanding the set of physical models based more directly upon fundamental principles reduces sources of uncertainty. We consider several new high fidelity physics models implemented in HYDRA for this purpose.

Our most complete production model for X-ray drive generation in hohlraum simulations employs a model of non-local electron transport based on a delocalization kernel. To compare this model with results obtained using electron transport we have enabled HYDRA to operate in conjunction with electron Vlasov-Fokker-Planck (VFP) codes. The K2 electron VFP code solves the time-dependent VFP equations by expanding the distribution function in spherical harmonics and retaining only the first two expansion coefficients (f_0 and f_1). The IMPACT code[1] employs a similar approach to solve time-dependent VFP equations. We will describe the coupling approach and show results from calculations of a 1D surrogate hohlraum, including the impact on the radiation drive spectrum.

We will discuss a newly developed capability to run inline DCA NLTE kinetics using GPUs. This enables use of much more complete and accurate NLTE opacity models in hohlraum simulations, which treat up to 100 times as many configurations as the current standard. In a hohlraum LPI has fundamentally important effects on laser energy flow and hot electron production. We describe a set of semi-empirical models for cross beam energy transfer, SBS and SRS, now available in the 3D laser raytrace. These solve the coupled mode equations to enable a self-consistent treatment of these processes. We discuss how a more complete treatment of the physics influencing hydrodynamic instability growth and hot spot formation benefits simulations of indirect drive capsules. The presentation will also cover a new capability implemented in the laser ray trace which facilitates efficient, high fidelity 3D simulations of direct drive implosions.

*This work was performed under the auspices of the Lawrence Livermore National Security, LLC, (LLNS) under Contract No. DE-AC52-07NA27344

[1] R. J. Kingham and A. R. Bell, J. Comput. Phys. **194**, 1 (2004)

Poster Sessions

Thursday

Simulations of the direct laser acceleration of electrons including the use of a customized field solver and quasi-3D geometry*

Presenter K. G. Miller, F. Li, X. Xu, N. Lemos,† F. Albert,† C. Joshi and W. B. Mori
University of California – Los Angeles
430 Portola Plaza
Los Angeles, California 90095
kylemiller@physics.ucla.edu
†Lawrence Livermore National Laboratory
Livermore, California 94550

There is interest in generating moderately relativistic electrons (10–100 MeV) to produce X-rays for the probing of hot, dense material. One way to produce such hot electrons involves using a high-intensity picosecond laser, which generates relativistic plasma waves and goes unstable due to self-modulational and Raman scattering instabilities.[1] In this configuration, energetic electrons are generated due to a combination of plasma wakefield acceleration and direct laser acceleration (DLA) as a 100fs to 1ps long laser propagates in a tenuous plasma. The electrons then radiate X-rays due to their betatron motion. Recent work has shown that much—and even the majority—of the energy contribution to hot electrons can be from the DLA mechanism.[2] However, properly determining the DLA contribution to the electron energy is challenging due to numerical issues including dispersion errors and the staggering of the velocity and magnetic field with respect to the electric field in most particle-in-cell codes. We present a customized finite-difference field solver designed to minimize errors in the dispersion relation of light waves in vacuum and to take into account the time-staggered electric and magnetic fields. Single-particle tests show that the new solver is much more accurate when compared to theory. We present preliminary results on the acceleration mechanisms of electrons for a variety of laser pulse durations, using both three-dimensional and quasi-3D simulation geometries, with and without the new solver.

*This work is supported by the DOE, NSF, and LLNL.

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High-yield implosions via high ρR + radiation trapping using Mo doped Be ablators (PSS)*

Darwin Ho and Steve MacLaren
Lawrence Livermore National Laboratory
Livermore, CA 94550
ho1@llnl.gov

A thin layer of mid- or high-Z material (Mo or W) at the inner surface of the ablator can be used to reduce the implosion velocity and hotspot temperature thresholds for ignition. This is because this thin layer can increase the ρR and reduce Bremsstrahlung radiation lost from the hotspot. The problem with the thin layer is that it forms an unstable interface, and this is the paramount concern for this type of implosion configuration. However, recent advances in target fabrication enable the blending of the inner region of Be ablators with mid- or high-Z material with a graded concentration that decreases gradually toward the outer region of the ablator. This substantially reduces the Rayleigh-Taylor (RT) growth during the acceleration phase. High shell kinetic energy reduces the distance travelled during the deceleration phase, resulting in a very low RT growth at the hotspot surface as well as reducing that at the fuel-ablator interface. These desirable features give high yield based on 2D simulations. Two types of capsule configurations, with DT gas only and with a DT ice layer, will be presented. The yield of the gas only capsules, designed for near-term experiments, can be considerably higher than those using conventional low-Z, e.g. CH or HDC ablators. The desirable features of the Mo-doped Be ablators also allow the use of an aerogel supported liquid-DT layer as a viable option for high-yield implosions.

* This work is performed under auspices of U.S. DOE by LLNL under 15-ERD-058 and contract DE-AC52-07NA27344

The Particle-in-Cell and Kinetic Simulation Software Center*

Presenter B. J. Winjum[1], W. B. Mori[1],
W. An[1], S. Chase[1], T. N. Dalichaouch[1], V. K. Decyk[1], R. A. Fonseca[2],
L. Hildebrand[1], Q. Hu[1], R. Lee[1], F. Li[1], J. May[1], K. Miller[1], Q. Su[1],
A. Tableman[1], F. S. Tsung[1], X. L. Xu[1], Y. Zhao[1]
[1]University of California Los Angeles
Los Angeles, CA 90095
[2]ISCTE - Lisbon University Institute
Lisbon, Portugal
picksc.org@gmail.com

The UCLA Particle-in-Cell and Kinetic Simulation Software Center (PICKSC) aims to support an international community of PIC and plasma kinetic software developers, users, and educators; to increase the use of this software for accelerating the rate of scientific discovery; and to be a repository of knowledge and history for PIC. We present the latest algorithmic developments of our software, including novel developments for particle pushers, field solvers, and parallelization strategies. We will also discuss progress towards making available and documenting illustrative open-source software programs and distinct production programs; developing and comparing different PIC algorithms; and coordinating the development of resources for the educational use of kinetic software. We welcome input and discussion from anyone interested in using or developing kinetic software, in obtaining access to our codes, in collaborating, in sharing their own software, or in commenting on how PICKSC can better serve the community.

* Supported by NSF under Grant ACI-1339893 and by the UCLA Institute for Digital Research and Education.

Influence of magnetic fields on nonlinear electron plasma waves and kinetic stimulated Raman scattering*

B. J. Winjum and W. B. Mori
University of California Los Angeles, Los Angeles, CA 90095
bwinjum@ucla.edu

Nonlinear electron plasma waves propagating perpendicular to magnetic fields can be damped due to the fact that trapped electrons (those moving near the phase velocity of the wave) in an average sense all get accelerated perpendicularly across the wave front, continually extracting energy from it[1,2]. We present particle-in-cell simulations of externally driven electron plasma waves showing how the initial damping of the wave, the evolution of the wave after several bounces, and its long time evolution after many bounce times are all effected by even weak magnetic fields ($\omega_c/\omega_p << 1$). This behavior can have significant consequences for laser-plasma instabilities that are sensitive to the nonlinear evolution of electron plasma waves. We use these results to inform our simulations of backward stimulated Raman scattering (SRS) in which small normalized magnetic fields applied perpendicularly to a light wave increase the instability's kinetic threshold and decrease the total reflectivity[3].

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Modeling of laser-plasma interaction in the shock-ignition regime with *LPSE*: Comparison with particle-in-cell simulations and experiments*

A. Ruocco,[1] A. V. Maximov,[2] J. P. Palastro,[2] R. K. Follett,[2] W. Theobald,[2] A. Casner,[1] D. Batani,[1] J. Trela,[1] G. Duchateau,[1] A. Colaïtis,[1] and V. T. Tikhonchuk[1]
[1]Université de Bordeaux, Centre Lasers Intenses et Applications
351 Cours de la Libération
Talence, France
alessandro.ruocco@u-bordeaux.fr
[2]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA

The shock ignition (SI) approach to inertial confinement fusion promises ignition at a lower laser energy than conventional hot-spot schemes. The target is initially driven at a low-implosion velocity, which reduces hydrodynamic instabilities, and then ignited by a high-intensity spike that launches a strong shock into the hot spot. The high-intensity spike, however, can trigger laser–plasma instabilities (LPIs) that generate hot electrons—a serious preheat threat to the capsule. Here, we present the first LPSE simulations studying LPI and hot electron generation for parameters relevant to SI. By employing time-enveloping and a fluid plasma response, *LPSE* models scales intermediate to hydrodynamics and kinetics and has a lower numerical noise than particle-in-cell (PIC) codes, making it particularly suited for studying LPI processes in the plasma corona. Comparisons of *LPSE* simulations, including stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and hot electron production, with previous experimental measurements and PIC results[1] are in good agreement. Notably, *LPSE* predicts SRS and SBS time-averaged reflectivities of ~5% to 7% each, which qualitatively agree with experimental measurements from previous experimental campaigns.[2] Simulations of the quarter-critical region show that significant pump depletion shifts the location of Langmuir wave excitation toward lower densities. This phenomenon may explain the weak quarter-critical Raman signature observed in the measurements.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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Effect of magnetic field on hot electron generation by the two-plasmon-decay instability *

C. Ren and W. D. Liu
University of Rochester
Rochester, NY 14627
chuang.ren@rochester.edu

The large amplitude (>10 T) and scale (100-300 μm) magnetic field observed in the coronal plasma of inertial confinement targets can be generated from the Rayleigh-Taylor instability and further amplified by the magneto-thermal instability[1,2,3]. Particle-in-Cell simulations show that B field on the order of 100T would not change the mode structures of the two-plasmon-decay instability but can significantly reduce hot electron generation by interrupting the staged acceleration process. We will report our progress in developing a theory for staged-acceleration.

*This work conducted under the auspices of DOE/NNSA (DE-SC0012316, DE-NA0003600, and DE-NA0001944)

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Interference between plasma kinetics and atomic physics in ICF hot-spots*

G. Kagan[1], P. Hakel[1], C. J. McDevitt[1], O. L. Landen[2], S. P. Regan[4], D. Svyatskiy[1], H. Sio[3], N. V. Kabadi[3], P. Adrian[3], R. A. Simpson[3], M. Gatu-Johnson[3], J. A. Frenje[3], R. D. Petrasso[3], R. C. Mancini[5], R. C. Shah[4], M. J. Rosenberg[4], R. Epstein[4], T. R. Joshi[1], T. E. Weber[1], H. G. Rinderknecht[4], M. J. Macdonald[2], D. Thorn[2], M. Schneider[2]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545
[2]Lawrence Livermore National Laboratory, Livermore, CA 94551
[3]Massachusetts Institute of Technology, Cambridge, MA 02139
[4]Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623
[5]University of Nevada, Reno, NV 89557

Doping inertial confinement fusion (ICF) capsules with a high-Z impurity such as krypton (Kr) is a promising approach to measuring the electron temperature T_e in the hot-spot. The K-β lines of Kr are distinguishable features, so well-established spectroscopic techniques for the T_e diagnostic can be used. Equally importantly, residing above 15 keV of the photon energy spectrum, these lines are rather insensitive to the opacity effects, allowing the least ambiguous data interpretation. However, in the practical hot-spots with 1-5 keV temperatures, the line emission above 15 keV is mostly due to the suprathermal free electrons, which belong to the tail of the distribution. Their mean-free-path is much larger than that of their thermal counterparts, making them deviate from thermodynamic equilibrium[1,2]. Consequently, a peculiar interference takes place between the plasma kinetic and atomic physics effects. We present the first theoretical study of both fundamental aspects of and practical consequences from this interference. In particular, we demonstrate that neglecting the kinetic effects when inferring T_e from the Kr line spectrum results in the inferred temperature being lower than the actual one.

*This work is supported by the Laboratory Directed Research and Development program under the auspices of the U.S. Dept. of Energy by the Triad National Security, LLC, Los Alamos National Laboratory under Contract No. 89233218CNA000001

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Simulations of laser imprint and isolated defects*

Andrew J Schmitt, Calvin Zulick, Jaechul Oh, and A. L. Velikovich
Plasma Physics Division
Naval Research Lab
Washington, DC 20375
andrew.schmitt@nrl.navy.mil

We have performed experiments at NRL to look at the hydrodynamic response of both flat and structured plastic foils to direct irradiation by the Nike laser. The Nike KrF laser overlaps up to 44 beams with state-of-the-art echelon-free ISI optical smoothing and 1 THz bandwidth, providing extremely smooth and flat irradiation of targets. Two experiments are simulated here. In the first series, flat CH foils were irradiated and experimentally probed through the back surface with 2D VISAR[1] to measure the velocity fluctuations of the shock transmitted into the target. The second set of experiments studied the evolution of isolated defects --- long channels manufactured into the surface of flat CH foils --- which were diagnosed by both face-on and side-on curved-crystal monochromatic radiography.[2] These experiments measure two distinct and separate effects of imprint; the VISAR experiment measures the shock front that is initiated by the early-time laser imprint while the target is being compressed but before it is accelerated by the laser drive. This front decouples from the ablation surface and its velocity fluctuations are expected to decay in time. The second experiment measures the growth of both the isolated defect and the laser imprint throughout the target as they evolve during the shock passage and are later amplified by the Rayleigh-Taylor instability during the acceleration of the perturbed foil. This measurement of the development of the known pre-manufactured defect simultaneously with the growth of the imprint serves as another calibration of the imprint. We will present comparisons of both 2D and 3D FASTrad3D simulations with these experimental results and discuss the difficulties encountered in the modeling.

*This work supported by the US DoE/NNSA

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Modeling Shock Wave Speed in MARBLE Foam*

Douglas N. Woods, B. M. Haines, Y. Kim, P. Kozlowski, T. Murphy, B. Albright, C. Di Stefano, T. Day, T. Cardenas, D. Barnak, R. Olson, M. Gunderson, M. Douglas
Los Alamos National Laboratory
MS K784
Los Alamos, NM 87545
dwoods@lanl.gov

Understanding material mixing is of particular importance to achieving inertial confinement fusion (ICF) ignition. The amount of contaminant mixing with fuel reactant impacts the fusion yield as do heterogeneities generated from capsule material plunging into the hot spot. The MARBLE campaign[1] at Los Alamos National Laboratory (LANL) is a series of separated reactant ICF experiments employing plastic foams with engineered macro-pores designed to investigate heterogeneous material mixing during spherical implosions. The initial conditions are varied by controlling the foam pore sizes. Accurately modeling the dynamics of these foams is challenging for radiation-hydrodynamics codes due to the complex geometry that stresses multi-material sub-grid modeling of equation of state (EOS), opacity, thermal conduction, and thermonuclear burn.

We discuss the results of companion MARBLE Void Collapse experiments performed on the OMEGA laser at the Laboratory for Laser Energetics (LLE). These experiments were designed to validate the radiation-hydrodynamics modeling of shock propagation through foams with macropores. In particular, we will discuss experiments that stress mixed-material EOS modeling. Foam-filled shock tubes were directly-driven by lasers on one end and x-ray radiographs were generated at various times, enabling the direct measurement of shock speed, shock front shape, and shock/interface dynamics, which is not possible in a spherically convergent geometry. We employed xRAGE[2,3] a LANL Eulerian radiation-hydrodynamics code, to perform the simulations and study the material effects. The pore sizes were varied to investigate the effects on shock speed. Additionally, the effect of neopentane fill gas on shock speed was investigated. Our simulations are in good agreement with the experimental shock wave speeds. We will present the conditions necessary for accurate simulation of these experiments and discuss modeling implications.

*This work was supported by the US Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001). Document number LA-UR-19-23097.

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[1] T. J. Murphy et al. "Progress in the development of the MARBLE platform for studying thermonuclear burn in the presence of heterogeneous mix on OMEGA and the National Ignition Facility.", J. Phys.: Conf. Ser., 717, 012072, 2016.

[2] M. Gittings et al. "The rage radiation-hydrodynamic code", Computational Science & Discovery, 1(1), 015005, 2008.

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Symmetry in NIF 2-shock MARBLE Implosions*

R. E. Olson, T. J. Murphy, Y. H. Kim, B. J. Albright, B. M. Haines, M. Douglas,
T. Cardenas, J. H. Cooley, T. H. Day, C. Di Stefano, R. A. Gore,
M. Gunderson, C. E. Hamilton, J. A. Oertel, J. M. Smidt
Los Alamos National Laboratory
Los Alamos, New Mexico 87545
reolson@lanl.gov

The MARBLE platform at the National Ignition Facility (NIF) is used to investigate the effects of heterogeneous mix on thermonuclear burn[1,2]. The goal of MARBLE is to obtain quantitative data that can be used to validate models of thermonuclear burn in heterogeneous, mixing plasmas. The platform utilizes a plastic (CH) capsule filled with a deuterated plastic foam (CD) with a density of a few tens of milligrams per cubic centimeter, with tritium gas filling the voids in the foam. The MARBLE capsule employs a 1% Si-doped CH ablator and is driven with X rays generated in a NIF hohlraum. The experimental platform was designed with 2D integrated (laser input + hohlraum + capsule) Hydra simulations. Although implosion symmetry is not first-principles predictable with Hydra (some reasons for this will be discussed), the time-dependent symmetry of the implosion can be successfully controlled via a cone fraction offset technique[3]. This is demonstrated here via a comparison of experimental and simulated GXD images, along with the associated time-resolved P2 and P4 image analysis. For the MARBLE platform, we used a 5% inner cone fraction (CF) offset from the simulations to provide the slope of P2 vs CF that was used to specify the experimental pulse shape for a round implosion. A frequency dependent source was extracted from an integrated Hydra post shot simulation and was converted for use in capsule-only xRAGE simulations of the 2-shock MARBLE experiments, allowing for an evaluation of the LANL mix and burn model. The bang time, burn history, and pre-heat aspects of the Hydra and xRAGE simulations of the MARBLE experiments were compared, with resulting improvements in the platform design, including the successful concept in which Ar was added to the HT fill gas.

*Work performed under the auspices of the US DOE by the Triad National Security, LLC, Los Alamos National Laboratory and was supported by the Office of Experimental Sciences.

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[1] B. J. Albright *et al.*, "*MARBLE – A Separated Reactants Mix & Burn Campaign,*" these proceedings.
[2] T. J. Murphy *et al.*, "*Progress in the development of the MARBLE platform for studying thermonuclear burn in the presence of heterogeneous mix on OMEGA and the National Ignition Facility,*" Journal of Physics Conf. Ser. 717, 012072 (2016).
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Comparing Backlighter Images at NIF to calculations*

George A. Kyrala[†]
Los Alamos National Laboratory
Los Alamos, NM 87547
kyrala@gmail.com

The properties of backlighter emission at NIF will be compared with predictions and laser spot properties. Emission through different filters will be used to predict the electron temperature in the backlighter spots.
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Using the BIE to study Rayleigh-Taylor growth rates in laser-driven implosions

C. F. Kawaguchi[1], B. Tobias[1], S. Palaniyappan[1], J. P. Sauppe[1], K. A. Flippo[1], C. C. Kuranz[2]

[1]Los Alamos National Lab
P.O. Box 1663 MS E526,
Los Alamos, NM, 87545
codie_y@lanl.gov

[2]University of Michigan,
500 S State St, Ann Arbor, MI 48109

The Rayleigh-Taylor (R.-T.) instability develops in high energy density (HED), inertial confinement fusion (ICF) experiments. Using the Bayes Inference Engine (BIE) we create a parameterized model of 2D implosions to study R.-T. as it evolves in time. Parameters are optimized to obtain maximum likelihood estimates for the amplitude of the instability, returned solutions consider weighted statistical likelihood and prior information. This analysis has confirmed that the asymmetries in the data are due to parallax effects and small misalignments of the pinhole camera array. Implosions are actually symmetric with aspect ratios of 1.007-1.029. This technique improves our ability to establish more statistically significant models, better quantify uncertainties, establish sensible error bars and better constrain our ICF models.

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A microphysics model to understand the solid-to-plasma transition of dielectric ablator materials for direct-drive implosions*

A. Kar,[1] S. X. Hu,[1] G. Duchateau,[2] and P. B. Radha[1]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
akar@lle.rochester.edu
[2]Université de Bordeaux-CNRS-CEA, Centre Lasers Intenses et Applications
33405 Talence Cedex, France

A physics-based model to understand the photoionization process in dielectric ablator materials such as plastic (CH) has been formulated. This model is crucial in understanding the initial plasma formation in solids during the early stages of a laser drive, before the critical density is reached. At present, the state-of-the-art hydrodynamic codes assume an initial plasma state through an *ad hoc* mechanism and ignore the detailed plasma formation process. Implementation of this physics-based model into the 1-D hydrodynamic code *LILAC* shows that the plasma profile during the early stage of an implosion is significantly different from the existing *ad hoc* mechanism. For example, it is observed that the critical surface formation in a plastic target happens around 150 ps for a single-picket, 200-ps-wide Gaussian pulse with a peak intensity of 10^{14} W/cm^2. This model will help resolve discrepancies in simulations and experiments for shock-merger time measurements at low adiabats. Ultimately, the implementation of this model into 2-D or 2-D hydrocodes will provide a better understanding of the laser-imprint mechanism through an accurate estimation of the laser-absorption profiles.

The model includes the multiphotonionization, recombination, and impact-ionization schemes that determine the free-electron density in the conduction band of the material. Besides this, a laser-deposition model coupled with the thermal transport determines the electron and ion temperatures. By incorporating this model, the spatial profiles of the physical quantities such as pressure, mass density, electron number density, and electron temperature profiles are observed to be different between the microphysics model and the original *ad hoc* mechanism in *LILAC*.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

Thomson scattering measurement of laser-produced plasma conditions in a gas-filled hohlraum

H. Zhao, Z. Li[†], D. Yang[†], X. Jiang[†], X. Li[‡], and Y. Ding[‡]
Tsinghua University
Beijing, 100084, China
h-zhao15@mails.tsinghua.edu.cn
[†]Research Center of Laser Fusion, China Academy of Engineering Physics
Mianyang, Sichuan, China
[‡]Institute of Applied Physics and Computational Mathematics
Beijing, China

In the research of indirect-drive laser fusion, hohlraum targets are used to convert the incident laser energy into a radiation field, which has better uniformity than laser spots. To gain a better understanding of hohlraum physics, we have conducted an experimental study on the plasma conditions in a gas-filled hohlraum, which are closely related to physical processes as laser energy deposition and X-ray emission. An ultraviolet Thomson scattering diagnostic[1] was used to measure the plasma evolution near the laser spot on the hohlraum wall. The experiment was conducted on Shenguang-III prototype laser facility, and a simplified hohlraum with quasi-2D configuration was used. Time-resolved collective Thomson-scattering spectra (ion-resonant feature) were measured, and a clear transition from early stage to late stage was observed, indicating the movement of the interface between gas plasma (hydrocarbon) and wall plasma (gold). The X-ray images of gold plasma were also measured by X-ray framing camera. The experimental results were compared with 2D radiation hydrodynamic simulation (LARED[2] code). A discrepancy exists in the movement rate of gas-wall interface, and there is an anomalous electron temperature drop in gold plasma during the main pulse. Further simulations by LARED with different configurations and geometries show that the asymmetries and 3D effects in the experiment are the main cause of the discrepancies. Considering plasma gradient and gas-wall mixing, we have also synthesized Thomson-scattering spectra based on simulation, and some of them have produced similar features as experimental results.

[1] T. Gong *et al*., Rev. Sci. Instrum. **86**, 023501 (2015).
[2] W. Pei, Commun. Comput. Phys. **2**, 255 (2007).

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Tailoring laser plasma instabilities for high fluence bremsstrahlung x-ray source*

P. L. Poole, R. K. Kirkwood, S. C. Wilks, M. May, K. Widmann, and B. E. Blue
Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA 94550
poole11@llnl.gov

X-ray source development seeks to produce high radiation fluences for applications including materials testing. Sources on NIF designed to optimize K-alpha emission can produce 10's to 100's of kJ of < 10 keV x-rays[1], but the conversion efficiency falls of sharply for higher photon energy ranges such that no good testing source exists in the warm x-ray regime (30—100 keV). An alternative approach is being studied that promotes the generation of hot electrons via laser plasma wave damping, which then convert into bremsstrahlung x-rays in a high-Z target wall. Experiments and simulations will be described exploring laser parameters (pulse shape, pre-pulse energy) and target fill (foam, gas, liners) to enhance laser-plasma instabilities[2] and thereby x-ray yields above 30 keV, in particular results from a recent Omega-60 campaign with novel layered foam targets.

*Work performed under the auspices of the U.S. DoE by Lawrence Livermore National Lab under Contract DE-AC52-07NA27344.

[1] M. May *et al.* Phys. of Plasmas **25**, 056302 (2018).
[2] P. L. Poole *et al.* in preparation.

Cr-Be Pushered Single Shell (PSS) Capsule Development*

H. Xu,[1] H. Huang,[1] M. Ratledge,[1] C. Kong,[1] K. Sequoia,[1] N.G. Rice,[1] J. Bae,[1] Y. Wang,[2]
S. Maclaren,[2] S. Baxamusa,[2] M. Stadermann,[2] and A. Nikroo[2]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
huang@fusion.gat.com
[2]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

Graded pushered single shell (PSS) designs have emerged as an alternative to the Double Shell platform for achieving metal-gas implosions while maintaining a hydrodynamically stable ablation front. The design consists of a thin inner Be layer, a 50% Cr:Be plateau region, an S-shaped gradient, and a low Cr (1.5%) tamper layer followed by a pure Be outer layer. Using magnetron sputtering, GA has developed methods for fabricating Cr to Be gradients on GDP mandrels with tailored S-shape profiles for optimal implosion stability. Microstructure analysis of the gradient coating indicates a short order or amorphous structure formed at lower Cr concentration. These PSS capsules were subsequently built into capsule fill tube assemblies (CFTAs), verified to be leak tight at both ambient and cryogenic conditions, and delivered to LLNL for experiments. Unaltered Cr profiles before and after pyrolysis confirms the thermal stability of the gradient structure. However, cracking of the inner Cr layer was observed when the shells were pyrolyzed at 380ºC, which has been attributed to thermal and coating stress. Ozone pyrolysis at reduced temperature was attempted to resolve the cracking issues.

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Quality Improvements in CH Ablators Fabricated by Microencapsulation*

W. Sweet, R. Jimenez, R.I. Mohammed, F.H. Elsner, K.J. Boehm, J.C. Williams, A. Garcia, R.R. Paguio, M. Ratledge, H. Huang, N.M. Ravelo, N.G. Rice, E. Mathison, H. Xu, and P. Fitzsimmons

General Atomics, P.O. Box 85608, San Diego, California 92186-5608
Wendi.Sweet@ga.com

General Atomics (GA) has been developing polymer shells fabricated via microencapsulation for use both as mandrels as well as directly as capsules for ICF experiments. Microencapsulation enables a low cost, high volume, direct fabrication method for CH ablators.

LLE's 100 GBar initiative requires thin walled CH capsules meeting stringent specifications for composition, sphericity, wall uniformity, buckle strength, and optical quality. As previously reported, GA has fabricated polystyrene capsules meeting these specifications. Here we report on further improvements which dramatically reduce defects in the 0.1-10 μm size range – a critical specification for this program. PS capsules meeting the current specifications for the LLE Point Design have been fabricated, and their quality is comparable to or better than that of recently delivered capsules fabricated by the traditional glow discharge polymer (GDP) coating method.

Capsules fabricated via microencapsulation from other materials, including PVK, PAMS, GA-CH and RF, for use either as mandrels or as foam liners will also be discussed.

*Work supported by General Atomics IR&D

Foams and Aerogels: Unique Solutions to Complicated Challenges*

J.C. Williams

General Atomics, P.O. Box 85608, San Diego, California 92186-5608
Wendi.Sweet@ga.com

Aerogels, due to their low densities, small pore sizes, and tunable compositions continue to draw a great deal of interest in high energy density physics, astrophysics, x-ray and neutron source research, as well as a plethora of other physics topics. Challenges arise in the development of such materials when compositions are requested at ultralow low densities and in precise geometries with specifications that preclude machining as part of the target fabrication process due to the material's low damage thresholds. We present here, recent developments based on our GACH aerogel platform and its fully deuterated analogue, GACD, which have proven to be versatile tools for rapidly obtaining a wide array of materials at low densities with custom compositions in precise geometries free of any machining steps. Furthermore, the material's ease of handling allows for the fabrication of seamless, graded density structures without machining.

*Work supported by General Atomics IR&D

Overview of Laser Machining & Assembly Capabilities at General Atomics*

L.C. Carlson, E.L. Alfonso, J. Calleja, L. Gonzalez, D. Kobs

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

General Atomics has continued to enhance and improve its precision target assembly and laser machining capabilities as necessitated by higher shot rates and increased target complexity. An overview is given of laser machining and drilling capabilities in plastics, foams and capsules, as well as challenging projects in support of fabricating target components. Laser machining improvements for diagnostic pinholes and penumbral imaging is reviewed. Additionally, micro-assembly and metrology capabilities of involved physics packages are reviewed.

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Oral

Lane Carlson, carlson@fusion.gat.com, (858) 455-3905

Temporally- and Spatially-Resolved Thermometry Using Neutron Resonance Spectroscopy: Requirements and Prospects for Laser-Driven Neutron Sources

Juan C. Fernández, Cris W. Barnes, Michael J. Mocko, and Lukas Zavorka
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

The advent of neutron spallation sources enabled the application of Neutron Resonance Spectroscopy (NRS) to make volumetric (bulk) temperature measurements of materials. Specifically, the high penetration power of the neutron probe and the isotopic uniqueness of nuclear resonances enable accurate absolute measurements of material temperature at a localized spot within the sample interior. The temperature of a material is an independent thermodynamic variable in the equations of state. Therefore it is needed for full validation of theoretical models of condensed and warm-dense matter. Yet bulk thermometry in the study of the dynamics of materials subjected to transient extreme conditions of pressure and temperature is a critical unmet scientific need. This is due to the difficulty of dynamic measurements and the need heretofore to co-locate the dynamic experiment at a spallation facility. Thus NRS thermometry of dynamic materials has only been reported once [1]. Alternative techniques, such as pyrometry or embedded sensors, have many drawbacks or are inapplicable. To enable time-dependent and spatially-resolved NRS-based thermometry in dynamic environments, more compact neutron sources that can be used at user facilities in conjunction with other diagnostic probes (such as x-ray light sources) are required. Such sources may be available using ultrafast high-intensity optical lasers. We evaluate such possibilities by determining the sensitivities of the temperature estimate on neutron-beam and diagnostic parameters. Based on that evaluation, requirements are set on a pulsed neutron-source and diagnostics to make a meaningful dynamic temperature measurement. Those requirements have been checked against the work in Ref. [1]. We include a full forward calculation of the fast-neutron generation from a typical laser-produced d+ spectrum using MCNP6 and considering a variety of neutron-converter materials. Given a high-intensity high-quality (excellent contrast) ultrafast laser pulse of sufficient energy (estimated around a few hundred Joules), such a compact source of neutrons could allow a NRS temperature measurement that could transform the dynamic study of materials and warm-dense matter.
Work supported by the National Nuclear Security Administration of the U.S. Dept. of Energy.

[1] V. W. Yuan, et al., Physical Review Letters 94, 125504 (2005).

ICF Diagnosis

Friday Session 1

High-bandwidth fusion reaction history using the new Pulse Dilation – PMT*

Presenter H. Geppert-Kleinrath, Y. Kim, K. D. Meaney,
H. W. Herrmann, N. M. Hoffman, F. E. Lopez, B. J. Pederson, J. A. Carrera[†],
H. Y. Khater[†], A. L. Kritcher[†], M. S. Rubery[††], C. J. Horsfield[††], S. Gales[††], A. Leatherland[††],
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
geppert@lanl.gov
[†]Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550
[††]Atomic Weapons Establishment
Aldermaston,
Reading RG7 4PR, UK

Deuterium-tritium (DT) fusion gamma-rays (16.75 MeV) have been successfully used to provide fusion reaction history at the National Ignition Facility (NIF) for several years. In a Gas Cherenkov Detector (GCD) the gamma-ray to Cherenkov light conversion process is inherently fast with a temporal resolution of < 10 ps, however, state-of-the-art photomultiplier tube (PMT) technology has been limiting the temporal resolution to ~100ps. The new Pulse Dilation – Photomultiplier Tube (PD-PMT) at NIF allows for temporal resolutions comparable to that of the gas cell, or ~ 10 ps. The PD-PMT is well characterized by test measurements performed using the short pulse Orion laser at Atomic Weapons Establishment. PD-PMT is now fielded on the Gas Cherenkov Detector GCD-3 at NIF and takes data on a regular basis. The first data taken at NIF shows high frequency features in the DT reaction history for the first time, such as an asymmetric rise and fall, and some shots having plateaued peaks. The simulations do not capture these high frequency features. The newly obtained high resolution data can point to truncation mechanisms and failure modes in ICF that are currently not well understood and captured. The temporal resolution provided by PD-PMT can additionally help isolate the carbon gamma signal from the ^{12}C ablator material which is temporally separated from a large background. Improvements in measuring the carbon areal density inform performance during the ablation and compression phase in ICF. The lessons learned by fielding PD-PMT on GCD-3 will contribute to the design of the next generation Gas Cherenkov Detector.

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Structure and Dynamics of Plasma Interfaces in Laser-Driven Hohlraums*

C. K. Li[1], J. Pearcy[1], G. Sutcliffe[1], T. Johnson[1], P. E. Masson-Laborde[2], S. Laffite[2], S. C. Wilks[3], P. A. Amendt[3], R. Betti[4], E. M. Campbell[4], J. A. Frenje[1], M. Gatu Johnson[1], R. D. Petrasso[1], T. C. Sangster[4], F. H. Séguin[1], and V. Tassin[2]

[1]Massachusetts Institute of Technology, Cambridge, MA 02139 USA
[2]CEA, DAM, DIF F-91297 Arpajon FRANCE
[3]Lawrence Livermore National Laboratory, Livermore, CA 94550 USA
[4]University of Rochester, Rochester, NY 14627 USA
E-mail: ckli@mit.edu

Understanding the structure and dynamics of plasma interfaces in laser-driven hohlraums is important to inertial confinement fusion. Such interfaces are either kinetically unstable, leading to, for example, forming a diffusion layer and developing an ambipolar electric field, or hydrodynamically unstable, leading to generating Rayleigh-Taylor instabilities. It has been realized that modelling of such phenomena with the conventional single-spices-averaged hydrodynamic codes are largely responsible for some disagreements between the experimental results and numerical simulations. A number of plasma kinetic effects which play critical roles in these processes have been missed in hydrodynamic simulations, including ion interpenetration and diffusion. To that end, a series of experiments was performed at Omega laser facility to explore these important phenomena. Experimental data obtained from several diagnostics, such as proton radiography and x-ray imaging, are compared with modified three-dimension hydrodynamic simulations, providing new insight into hohlraum stagnation and a more completed physical picture about hohlraum dynamics. The work described herein was performed in part at the LLE National Laser User's Facility (NLUF), and was supported in part by US DOE (Grant No. DE-FG03- 03SF22691), LLNL (subcontract Grant No. B504974) and LLE (subcontract Grant No. 412160-001G).

***** The work described herein was performed in part at the LLE National Laser User's Facility (NLUF), and was supported in part by US DOE (Grant No. DE-FG03- 03SF22691), LLNL (subcontract Grant No. B504974) and LLE (subcontract Grant No. 412160-001G).

Three-dimensional neutron imaging of Inertial Confinement Fusion Implosions at the National Ignition Facility

Presenter Verena Geppert-Kleinrath, Steve Batha, Laura Berzak Hopkins†, Christopher Danly, Laurent Divol†, David Fittinghoff†, Valerie Fatherley, Lynne Goodwin, Robin Hibbard†, Justin Jorgenson, John Kline, Sebastien Le Pape†, Tom Murphy, Derek Schmidt, Arthur Pak†, Michael Springstead, Jaquelynne Vaughan, Cory Waltz†, Carl Wilde, and Petr Volegov

Los Alamos National Laboratory
Po Box 1663
Los Alamos, NM 87544
verena@lanl.gov
†Lawrence Livermore National Laboratory
Livermore, CA 94550

The Los Alamos National Laboratory Advanced Imaging team has recently added a third line-of-sight to the neutron imaging diagnostic[1] at the National Ignition Facility (NIF) in December 2018. The team now operates three lines-of-sight, two equatorial views and one polar, allowing for 3D imaging of the fusion burn volume[2] as well as density reconstruction of the remaining cold fuel. Three views of the primary neutron distribution from fusion neutrons, and one view of neutrons that have down-scattered in the surrounding fuel are now available. The powerful 3D diagnostic allows for the limited-view tomography of the fusion neutron emitting burn volume as well as the density reconstruction of the remaining fuel assembly from the four available images under certain symmetry assumptions. The intricate 3D reconstruction algorithms can also be applied to x-ray data as shown recently for the first time – illustrating the mixing of high-Z material into the fuel volume likely from the capsule fill tube. The groundbreaking result illustrates the power of the diagnostic suite neutron imaging has become in recent years –fully characterizing the complete fuel assembly.

[1] Merrill, F. E. et al., "*The neutron imaging diagnostic at NIF*", Review of Scientific Instruments **83.10** (2012).
[2] Volegov, P.L. et al., "*On three-dimensional reconstruction of a neutron/x-ray source from very few two-dimensional projections*". Journal of Applied Physics **118.20** (2015).

Ablator areal density observations and trends on the National Ignition Facility*

Presenter K. D. Meaney, Y. Kim, H. Geppert-Kleinrath, H. W. Herrmann
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
meaney@lanl.gov

In inertial confinement fusion, very few diagnostics are available to look at the final state of the ablator in the integrated, cyro-layered implosions. The Gamma Reaction History diagnostic measures deuterium-tritium fusion gammas (16.8 MeV) as well as the neutron induced 4.4 MeV carbon ablator. Recently, a new analysis routine was developed to isolate this carbon gamma line from other neutron induced background from the surrounding hohlraum and thermal mechanical package, giving the areal density (ρR) of the ablator at bangtime. Now carbon ρR values have been generated for a database of many National Ignition Facility (NIF) shots. The values can be compared and contrasted across the NIF campaigns. They reveal that the ablator compression is sensitive to the dopants, reflecting the increased opacity which prevents preheat and as a result increases the density of the ablator layer. The coast time is also found to be an important metric to the final ablator state, possibly reflecting a combination of the cooling hohlraum after the laser has turned off as well as the rebounding shock transmitting through the ablator and decreasing its density. Finally, specific comparison of shots observed to have a high amount of mixed meteors in the hot spot show that the increased effective carbon ρR can be used in combination with other x-ray diagnostics to estimate the mass and density of all mixed material – cold or hot. Overall, the ρR is another valuable metric that informs capsule performance.

* This work performed under the auspices of the U.S. Department of Energy by LANL under contract 89233218CNA000001.

Anomalous asymmetry of unabsorbed light in OMEGA implosions*

D. H. Edgell, J. Katz, and D. H. Froula
Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
dedg@lle.rochester.edu

Anomalously high asymmetry in the amount of unabsorbed light from symmetric implosions on OMEGA has been measured on three independent scattered-light detectors. This implies that the absorption in an implosion on OMEGA could be more asymmetric than previously believed. Hydrodynamics codes without cross-beam energy transfer (CBET) modeling predict that the laser absorption and unabsorbed light distribution over the spherical surface should be very uniform with an rms deviation of only a few tenths of a percent. When CBET modeling is included, the rms variation over the surface increases by an order of magnitude to a few percent. However, tens of percent variations in the scattered light around the chamber have been measured by multiple scattered-light diagnostics.

The CBET beamlets diagnostic detects unabsorbed light from each OMEGA beam. Beamlets from beams that follow similar pathways through the implosion plasma should have similar intensities in a symmetric implosion, yet much different beamlet intensities are observed. Scattered-light calorimeters at different locations around the target chamber have shown a strong position-dependent asymmetry in the time-integrated scattered light. Charge-coupled–device images of a spectralon plate in one of the OMEGA ports show a variation of 20% in scattered light across the port.

The levels of laser beam imbalance required to produce the observed asymmetry will be examined along with possible polarization effects that might contribute to it.

* This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

Laser Plasma Interactions

Friday Session 2

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Measuring electron distribution functions driven by inverse bremsstrahlung heating with collective Thomson scattering*

A. L. Milder,[1] R. Boni,[1] J. Katz,[1] M. Sherlock,[2] P. Franke,[1] S. T. Ivancic,[1] J. L. Shaw,[1] J. P. Palastro,[1] I. A. Begishev,[1] W. Rozmus,[3] and D. H. Froula[1]
[1]Laboratory for Laser Energetics, University of Rochester
250 East River Rd.
Rochester, NY 14623-1299, USA
amilder@ur.rochester.edu
[2]Lawrence Livermore National Laboratory
Livermore, CA 94550
[3]University of Alberta
Edmonton, AB T6G 2R3, Canada

The basis of many phenomena in laser-produced plasmas is contingent upon the understanding of the underlying electron distribution function. Approximately four decades ago, A. B. Langdon[1] showed that inverse bremsstrahlung heating, the dominant mechanism in most laser-produced plasmas, results in super-Gaussian electron distribution function. This modification to the distribution function in known as the Langdon effect. Thomson-scattering measurements show that during laser heating, the super-Gaussian order of the electron distribution function reaches a steady state consistent with theoretical predictions[2] and Vlasov–Fokker–Plank simulations. An ultrafast, high-throughput spectrometer was used to measure the temporal evolution of the plasma after the heating beams turn off. During this period the plasma was observed to cool and become denser. An atomic physics package was added to the Vlasov–Fokker–Plank simulations in order to reproduce these trends which are consistent with ionization. To measure arbitrary electron distribution functions, an angularly resolved Thomson-scattering system has been designed. This diagnostic spectrally resolved ~100 Thomson-scattering spectra over a 120° collection angle. The relation between scattering angle and the resonant thermal plasma waves probed by Thomson scattering the results will be used to reconstruct arbitrary distribution functions.

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[1] A. B. Langdon, *"Nonlinear inverse bremsstrahlung and heated-electron distributions,"* Phys. Rev. Lett. **44**, 575 (1980).
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Combination of up to 21 frequency shifted beams with a plasma optic*

P. L. Poole, R. K. Kirkwood, T. D. Chapman, S. C. Wilks, W. H. Dunlop, B. J. MacGowan, K. B. Fournier, B. E. Blue and B. M. van Wonterghem
Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA 94550
poole11@llnl.gov

A plasma-based optic is demonstrated that combines the energy and fluence of up to 21, 1.1 kJ, frequency shifted laser beams into a single beam, producing an output of up to 7.7 +- 1.7 kJ in a 1ns pulse[1]. The technique uses Cross Beam Energy Transfer (CBET) and builds on previous work to make beams with energy and fluence beyond that otherwise available at NIF[2,3]. The self-generated plasma diffractive optic used is far more damage resistant, and inherently capable of producing much higher single beam fluence and radiance than solid state optics. Such beams are needed for applications, including potentially pumping a second stage of plasma amplification and compression at multi-ps time scales. The results also aid the validation of models of CBET[3,4] which predict a larger number of non-resonant pump beams will scale up outputs still further. Results from experiments amplifying beams with high focal quality will also be discussed as available.

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Mitigation of self-focusing in Thomson-scattering experiments*

A. M. Hansen, D. Turnbull, J. Katz, and D. H. Froula
Laboratory for Laser Energetics, University of Rochester,
250 East River Rd.
Rochester, NY 14623-1299, USA
ahan@lle.rochester.edu

Thomson-scattering experiments present a substantial challenge because of the small cross section of the interaction. A powerful Thomson-scattering probe laser is required to achieve adequate signal-to-noise in order to make a measurement of plasma conditions. This requirement on probe laser power is balanced by the need to keep power low enough to maintain sufficient beam propagation and avoid self-focusing in the plasma. Self-focusing in a Thomson-scattering probe beam can cause the beam to deflect far enough to miss the scattering volume defined by the collection optics. Using a phase plate in the Thomson-scattering probe beam allows significantly higher amounts of power to be propagated through the plasma, increasing the measured signal-to-noise and enabling measurements that would otherwise be impossible.

By using a Thomson-scattering probe beam with a phase plate, the collective electron plasma and ion-acoustic wave Thomson-scattered features were collected from a gas-jet plasma on the Laser–Plasma Interaction Platform on the OMEGA laser. Two-dimensional Thomson scattering was utilized to analyze Thomson-scattering probe beam propagation and results were found to agree well with the self-focusing theory. Space- and time-resolved Thomson-scattered spectra were analyzed to determine plasma conditions including density, temperature, and flow velocity as a function of space and time. The combinations of these Thomson-scattering measurements enable a complete understanding of the plasma conditions on the Laser–Plasma Interaction Platform.

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Focusing dynamics of femtosecond relativistic intense laser pulse in underdense plasma

Prashant Kumar Singh[1,2*], B. R. Lee[2], S. G. Lee[2], I. W. Choi[2], Y. J. Rhee[2], and C. H. Nam[2]
[1]Los Alamos National Laboratory, Los Alamos, New Mexico, 87545
* pksingh@lanl.gov
[2]Center for Relativistic Laser Science, IBS, Gwangju, 61005, South Korea

With access to peak laser intensity of $10^{21} - 10^{22} Wcm^{-2}$, understanding the coupling mechanism of ultra-relativistic laser pulse with underdense plasma is essential for advancement of various areas such as, laser wake-field acceleration, high-harmonic generation and plasma based x-ray sources. Towards these goal, we present experimental results of relativistic intense laser pulse focusing dynamics in underdense plasma. The focusing of 30 fs laser pulse of intensity $1 \times 10^{20} Wcm^{-2}$ in high-density Ar plasma ($n_e = 4\times10^{20}$ cm^{-3}) lead to localized absorption of laser energy, which is followed by formation of single plasma cavity at the laser focus position and a single ion source. However, on reducing the plasma density by two orders of magnitude, ($n_e \sim 1\times10^{18}$ cm^{-3}), two isolated and symmetric source of plasma is excited before and after the laser focus (Fig. 1(b), 1(d)). On imaging these two-isolated Ar plasma source by a Thomson Parabola spectrometer placed orthogonal to the laser axis, a doublet traces of Ar^+ and Ar^{++} is observed (Fig. 1(a), 1(c)). Each ion trace from the double originates from the two plasma sources located pre and post laser focus. The strength of each individual plasma source is tunable by just adjusting the nozzle central position with respect to the laser focal plane. The results open a possibility of producing two independent ion sources where one could think of ion pump-probe dynamics.

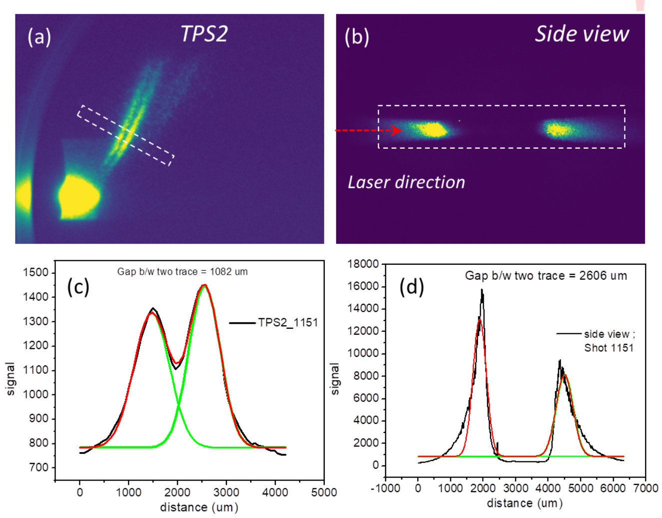

Figure1: Correlation between ion pinhole imaging and plasma scattered image. (a) Transverse TPS raw image showing double of Ar^+ and faint Ar^{++} ion trace. (b) Side view of the scattered plasma emission. The red arrow indicate direction of laser propagation. (c) Ion trace line out taken along white box in (a), showing a clear double ion trace with gap of 1082 μm in the phosphor plane. (d) Line out of plasma scattered light taken along white box in (b), showing two isolated plasma source with gap of 2606 μm.

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Novel criteria for efficient Raman and Brillouin amplification of laser beams in plasma

Raoul Trines[1], E.P. Alves[2], E. Webb[1], J. Vieira[3], F. Fiúza[2], R.A. Fonseca[3], L.O. Silva[3], R.A. Cairns[4], R. Bingham[1]
[1]STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom
[2]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[3]Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal
[4]University of St Andrews, St Andrews, Fife KY16 9SS, United Kingdom
raoul.trines@stfc.ac.uk

Twenty years have passed since the seminal paper on Raman amplification in plasma by Malkin, Shvets and Fisch[1]. While Raman amplification has been explored very successfully in theory and simulations[2], no significant Raman amplification of a laser pulse beyond 0.1 TW or 6% efficiency has been achieved[3], and there exists only one report of Brillouin amplification beyond 1 TW[4]. In this paper, we investigate one aspect of Raman and Brillouin amplification that has been consistently overlooked until now: the parameters and quality of the initial seed pulse. We have developed new criteria for the initial seed pulse in Raman and Brillouin amplification, and show through analytic theory and numerical simulations, that the energy gain and efficiency of the amplification will be significant if and only if these criteria are met. We will analyze the plasma-based Raman and Brillouin amplification experiments carried out to date, and show that the input seed pulses in all but one of these experiments fall short of our criteria, which is the likely explanation for the poor efficiency obtained in them. Finally, we apply our findings to the results of the most promising Raman and Brillouin amplification experiments available[3,4], to test how well those conform to our model.

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