# Anomalous Absorption Conference
# 2011 Conference Abstracts

June 19-24, 2011
Paradise Point Resort
San Diego, California

# 41st Annual Anomalous Absorption Conference
June 19-24 2011
San Diego, CA

Organizing Committee

Frank S. Tsung
Warren B. Mori
Ben J. Winjum
Michail Tzoufras
John Tonge
Tanya Sussman
Patrice Tonnis, UCLA
Jamie Marty, LLNL

# Monday, June 20th, 2011

| Sunset Room I, II, III -- Edward Williams, Chair | | | | |
|---|---|---|---|---|
| 8:15-8:30 | Welcome/Introduction | Frank | Tsung | UCLA |
| 8:30-9:10 | Optimal Control of Laser-Plasma Instabilities in HEDP Using STUD Pulses: Spike Trains of Uneven Duration and Delay | Bedros | Afeyan | Polymath Research Inc. |
| 9:10-9:30 | Inferring SRS source characteristics from time-dependent near field backscatter measurements in NIF hohlraums | John | Moody | LLNL |
| 9:30-9:50 | Understanding Raman scattering in NIF Ignition Experiments | David | Strozzi | LLNL |
| 9:50-10:10 | Stimulated Brillouin Scatter of laser light from Ignition-Scale Hohlraums | Richard | Berger | LLNL |
| 10:10-10:30 | pF3D simulations of stimulated Raman and Brillouin scattering from overlapping quads in experiments conducted at the National Ignition Facility | Steven | Langer | LLNL |

10:30-10:50 **Coffee Break**

| Sunset Room I, II, III -- Jason Myatt, Chair | | | | |
|---|---|---|---|---|
| 10:50-11:10 | Anomalously Heated Electrons Due to Stimulated Raman Rescattering for Parameters Relevant to the National Ignition Facility | Ben | Winjum | UCLA |
| 11:10-11:30 | Raman Amplification of Laser Pulses Creating Conditions for Kinetic Inflation | Ian | Ellis | UCLA & LLNL |
| 11:30-11:50 | Saturation Effects on the Time Dependent Stimulated Raman Scattering from Ignition Targets | Robert | Kirkwood | LLNL |
| 11:50-12:10 | Near-field images from pF3D and SLIP | Edward | Williams | LLNL |
| 12:10-12:30 | UV laser beam propagation through the Xe-filled target chamber of an IFE power plant: Inverse Bremsstrahlung, non-linear refraction and Electronic Stimulated Raman Scattering | Laurent | Divol | LLNL |

| Sunset Room I, II, III -- Mordy Rosen, Chair | | | | |
|---|---|---|---|---|
| 7:30-8:30 | Inertial Confinement Fusion Experiments on the National Ignition Facility | Siegfried | Glenzer | LLNL |
| 8:30-10:30 | **Poster Session** | | | |

## Monday, June 20th 8:30-10:30PM Bayview Room

| | | | | |
|---|---|---|---|---|
| 1 | Recent experimental and theoretical results on laser-plasma interaction in the long pulse regime at CEA-DAM | Michel | Casanova | CEA |
| 2 | Particle-in-Cell Simulations of Laser Plasma Instabilities near the Quarter Critical Layer | Frank | Tsung | UCLA |
| 3 | Strong Langmuir Turbulence in the Nonlinear Saturation of Parametric Instabilities Driven by Coherent Electromagnetic Waves | Don | DuBois | Lodestar Research Corp. |
| 4 | Scaling and mitigating stimulated scattering and two plasmon decay instability in NIF hohlraums | William | Kruer | UC Davis |
| 5 | Using High Intensity Lasers to Accelerate Electrons at Solid Density Matter-Vacuum Interfaces | Joshua | May | UCLA |
| 6 | Studies of Particle Wake Potentials in Plasmas | Ian | Ellis | UCLA and LLNL |
| 7 | Ultrafast Electron Beam Radiography of Self-Generated Magnetic Fields from High Intensity Laser-Solid Interactions | Will | Schumaker | University of Michigan |
| 8 | Optimal Control of Laser-Plasma Instabilities in HEDP Using STUD pulses: Spike trains of Uneven Duration and Delay | Bedros | Afeyan | Polymath Research Inc. |
| 9 | Numerical Study of Self and Controlled Injection in 3-D Laser Driven Wakefields | Asher | Davidson | UCLA |
| 10 | PIC Simulations of Stimulated Raman Scattering for NIF Scale Lengths and Density Profiles | Ben | Winjum | UCLA |

## Tuesday, June 21st, 2011

| Sunset Room I, II, III -- Bill Kruer, Chair | | | | |
|---|---|---|---|---|
| 8:30-9:10 | Positron Creation Using Ultra-Intense Lasers | Scott | Wilks | LLNL |
| 9:10-9:30 | Narrow Energy-Spread Proton Beams Generated in a Gas Jet by High-Power CO2 Laser Pulses | Dan | Haberberger | UCLA |
| 9:30-9:50 | Fast Ignition with Laser-Driven Ion Beams: Progress on Ignitor Beam Development* | Juan | Fernandez | LANL |
| 9:50-10:10 | PEAK PROTON AND CARBON ION ENERGY SCALING WITH ULTRA-HIGH ENERGY LASERS | Dustin | Offermann | LANL |
| 10:10-10:30 | TRIDENT 200TW "DIAL-A-CONTRAST" LASER SYTSTEM EXPERIMENTS PRODUCING PROTONS UP TO 75 MEV | Kirk | Flippo | LANL |

10:30-10:50 **Coffee Break**

| Sunset Room I, II, III -- Juan Fernandez, Chair | | | | |
|---|---|---|---|---|
| 10:50-11:10 | Conversion efficiency scaling of carbon ions accelerated in the Break-Out Afterburner regime | Daniel | Jung | LANL |
| 11:10-11:30 | Recent Results of Full-Spatial Scale hybrid-PIC Modeling of Fast Ignition | John | Tonge | UCLA |
| 11:30-11:50 | Controlling the divergence of laser-generated fast electrons through resistivity gradients in fast-ignition targets | Andrey | Solodov | U. Rochester |
| 11:50-12:10 | Mechanism of pre-formed plasma electrons heating in relativistic laser-solid interactions | Bhooshan | Paradkar | UCSD |
| 12:10-12:30 | PIC MODELING OF MATERIAL DEPENDENCE ON FAST ELECTRON GENERATION AND TRANSPORT | ROHINI | MISHRA | UCSD |

| Sunset Room I, II, III -- Warren Mori, Chair | | | | |
|---|---|---|---|---|
| 7:30-8:30 | Relativistic Shocks in Astrophysics and Driven by Lasers | Luis | Silva | IST |
| 8:30-10:30 | **Poster Session** | | | |

## Tuesday, June 21st 8:30-10:30PM  Bayview Room

| | | | | |
|---|---|---|---|---|
| 1 | Asymmetric effects of cone-guided targets on three-dimensional implosion for fast ignition | Takumi | Yanagawa | Nagoya University |
| 2 | Modeling Electron Divergence in Fast Ignition Modeling | John | Tonge | UCLA |
| 3 | Two-dimensional Vlasov simulations of electron plasma wave trapping, self-focusing, and sideloss | Richard | Berger | LLNL |
| 4 | Imaging X-Ray Thomson Scattering Spectroscopy for Characterizing Extreme Matter States | Eliseo | Gamboa | University of Michigan |
| 5 | Mix in Defect Imaging Experiments on Omega | Paul | Bradley | LANL |
| 6 | A VLASOV-FOKKER-PLANCK CODE FOR HIGH ENERGY DENSITY PHYSICS | Michail | Tzoufras | UCLA |
| 7 | Performance of ignition capsules with aerogel supported fuel for the National Ignition Facility and for reactor application | Darwin | Ho | LLNL |
| 8 | Short-pulse laser amplification and saturation using stimulated Raman scattering | Jun | Ren | LANL |
| 9 | Magnetic Field Generation in Rayleigh-Taylor Unstable Plasmas | Bhuvana | Srinivasan | LANL |

# Wednesday, June 22nd, 2011

| Sunset Room I, II, III -- Denise Hinkel, Chair | | | | |
|---|---|---|---|---|
| 8:30-8:50 | Thomson Scattering from Direct-Drive Targets | Dustin | Froula | LLE |
| 8:50-9:10 | Simulations and Analyses of Long-Scale-Length Plasma Experiments on the Omega EP Laser Facility | Suxing | Hu | LLE |
| 9:10-9:30 | Impeding hohlraum plasma stagnation in inertial-confinement fusion | Chikang | Li | MIT |
| 9:30-9:50 | The high flux hohlraum model, one year later | Mordecai | Rosen | LLNL |
| 9:50-10:10 | Progress on Drive and Symmetry for Ignition on NIF | Debra | Callahan | LLNL |
| 10:10-10:30 | Ignition Hohlraum Radiation Temperature | Nathan | Meezan | LLNL |

10:30-10:50 **Coffee Break**

| Sunset Room I, II, III -- Dustin Froula, Chair | | | | |
|---|---|---|---|---|
| 10:50-11:10 | Simulations of the NIF ignition capsule design in 3-D | Daniel | Clark | LLNL |
| 11:10-11:30 | Modeling cross-beam energy transfer on NIF experiments | Pierre | Michel | LLNL |
| 11:30-11:50 | Reducing the Cross-Beam Energy Transfer in Direct-Drive Implosion Targets Through Laser-Irradiation Control | Wolf | Seka | LLE |
| 11:50-12:10 | Crossed-Beam Energy Transfer in Polar Direct-Drive Implosions | Dana | Edgell | LLE |
| 12:10-12:30 | Modeling of Energy Transfer Between Spatially Incoherent Crossing Laser Beams | Andrei | Maximov | UR/LLE |
| 12:30 | **Business Meeting** | | | |

| Sunset Room I, II, III -- Bedros Afeyan, Chair | | | | |
|---|---|---|---|---|
| 7:30-8:30 | Thomson Scattering in High Energy Density Plasmas | David | Montgomery | LANL |
| 8:30-10:30 | **Poster Session** | | | |

## Wednesday, June 22nd 8:30-10:30PM  Bayview Room

| | | | | |
|---|---|---|---|---|
| 1 | Studies of Spectral Modification and Limitations of the Modified Paraxial Equation in Laser Wakefield Simulations | Wenxi | Zhu | UMD |
| 2 | 2.5D Plasma Evolution and Evolving Beam Diver in WAKE for Plasma Wakefield Acceleration | Neeraj | Jain | UMD |
| 3 | ePLAS Modeling of laser-plasma interactions | Rodney | Mason | Research Applications Corp. |
| 4 | Forward Directed Ion Emission in a LWFA with Ionization Injection | Ken | Marsh | UCLA |
| 5 | Status of Directly-Driven Shock Ignition Target Designs | Andrew | Schmitt | NRL |
| 6 | Hot Electron Generation from Laser-Cone Target Interactions in Fast Ignition | Chuang | Ren | U Rochester |
| 7 | Modeling NIF Polar Direct Drive Capsule Implosions in 2D and 3D using HYDRA | Natalia | Krasheninnikova | LANL |
| 8 | Laser Hohlraums for Warm Dense Matter Studies | Thomas | Kwan | LANL |
| 9 | The effects of laser absorption on direct-drive capsule experiments at OMEGA | Evan | Dodd | LANL |

# Thursday, June 23rd, 2011

## Sunset Room I, II, III -- Raoul Trines, Chair

| | | | | |
|---|---|---|---|---|
| 8:30-9:10 | Efficient Raman Amplification into the Multi-PetaWatt Regime | Raoul | Trines | RAL |
| 9:10-9:30 | Raman Scattering of Intense, Short Laser Pulses in Modulated Plasmas | John | Palastro | UMD |
| 9:30-9:50 | Characterization of plasma wake excitation and particle trapping in the nonlinear bubble regime | Carlo | Benedetti | LBL |
| 9:50-10:10 | Electron acceleration by circular polarized laser pulse with phase modulation | Zheng-Mao | Sheng | Zhejiang University |
| 10:10-10:30 | Trapping of Low Energy Electrons in Quasi-Phase Matched Direct Laser Acceleration | Sung Jun | Yoon | UMD |

10:30-10:50 **Coffee Break**

## Sunset Room I, II, III -- Frank Tsung, Chair

| | | | | |
|---|---|---|---|---|
| 10:50-11:10 | Energetic Electron Generation in Two-Plasmon Decay Instabilities in Direct-Drive Inertial Confinement Fusion | Rui | Yan | U. Rochester |
| 11:10-11:30 | Langmuir Turbulence and Suprathermal Electron Production from the Two-Plasmon Decay Instability Driven by Crossed Laser Beams in an Inhomogeneous Plasma | Hoanh | Vu | UCSD |
| 11:30-11:50 | Convective Multibeam Two-Plasmon Decay for Beam Configurations Relevant to Polar Direct-Drive | Robert | Short | LLE |
| 11:50-12:10 | Evaluation of a quasilinear model for the two-plasmon decay instability in inhomogeneous plasmas | Jason | Myatt | UR/LLE |
| 12:10-12:30 | Laser-Plasma Instabilities in the Quarter Critical Density Region Driven by the Nike KrF Laser | James | Weaver | NRL |

7:30 **Banquet**

## Friday, June 24th, 2011

### Sunset Room I, II, III -- David Strozzi, Chair

| | | | | |
|---|---|---|---|---|
| 8:30-8:50 | GENERATION OF STRONG TERAHERZ RADIATION AND SIMULATION OF LOOP-TOP X-RAY EMISSION IN SOLAR FLARES | Yutong | Li | IOP, Chinese Academy of Sciences |
| 8:50-9:10 | Increasing dwell time in a plasma liner driven magneto-inertial fusion device with a special liner shaping | Grigory | Kagan | LANL |
| 9:10-9:30 | Influence of radiation on non-LTE Xenon | Marcel | Klapisch | ARTEP |
| 9:30-9:50 | Cone-guided fast ignition with imposed magnetic fields | David | Strozzi | LLNL |
| 9:50-10:10 | Plasma Adiabatic Lapse Rate | Peter | Amendt | LLNL |
| 10:10-10:30 | The interplay of spatially non-uniform cross-beam transfer and overlapping quads of beams on stimulated Raman scatter in experiments conducted at the National Ignition Facility | Denise | Hinkel | LLNL |
| 10:30-10:50 | **Coffee Break** | | | |
| 10:50-11:10 | CHARACTERIZING PLASMA MIRRORS NEAR BREAKDOWN | Matthias | Geissel | Sandia Laboratories |
| 11:10-11:30 | Using High Intensity Lasers to Accelerate Electrons at Solid Density Matter-Vacuum Interfaces | Joshua | May | UCLA |
| 11:30-11:50 | Numerical Study of Self and Controlled Injection in 3-D Laser Driven Wakefields | Asher | Davidson | UCLA |

**See you in 2012!!**

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# Optimal Control of Laser-Plasma Instabilities in HEDP Using STUD Pulses: Spike Trains of Uneven Duration and Delay

B. Afeyan
S. Huller[2]

*[1]Polymath Research Inc., Pleasanton, CA*
*[2]Ecole Polytechnique, Palaiseau, France*

A number of long standing problems that have plagued the control of laser-plasma instabilities (LPI) may find a favorable solution by the use of rapidly and strongly modulated laser pulses with a few orders of magnitude contrast between 'on' and 'off' states, and when the speckle patterns of each 'on' spike is sufficiently uncorrelated with the speckle patterns of its neighboring spikes. Scrambling speckle patterns in space and breaking up laser pulses into a variable length on-off set of spikes allows adaptive control to any plasma conditions without any prior knowledge of what those conditions may be, especially, as those conditions are modified by the action of many high intensity laser beams. This scheme is called STUD pulses for Spike Trains of Uneven Duration and Delay.

We will show theoretical arguments for why this approach is optimal and present estimates for stimulated Raman (SRS) and Brillouin scattering (SBS) as well as two plasmon decay cases of interest to direct drive, indirect drive, shock ignition and fast ignition. In particular, enabling the use of 527 nm drivers as opposed to 351 nm ones as used today on the NIF will be highlighted. Furthermore, the advantages of STUD pulses to allowing true LPI control of crossing laser beams will be explained in terms of the ability to interlace, interleave or superpose the STUD pulses of overlapping laser beams. Theoretical models that treat SBS in nonuniform, flowing plasmas in the weak and strong coupling regimes and in the weak and strong damping limits will be highlighted. Simulation results including the effects of pump depletion, diffraction, self-focusing in two dimensional speckle patterns will also be shown which were obtained using a substantially modified and STUD-pulse adapted version of the code Harmony. Here, RPP, SSD, Pseudo-STUD pulse and STUD pulse cases will be compared at various "gain at the average intensity in a single hot spot" levels. We will show how the orders of magnitude reduction in reflectivity or plasma mode (IAW or EPW) cumulative and repetitive amplitude growth suppression can be achieved with STUD pulses and to a far lesser degree by pseudo-STUD pulses and practically not at all with SSD, when compared to plain RPP f/8 beams. With STUD pulses, the laser is strongly modulated in time and the speckle patterns are scrambled between laser spikes. In pseudo-STUD pulses the temporal modulation is the same as in STUD pulses but the speckle patterns are held fixed in time. In SSD, a one directional slow sweep of the hot spots is affected which could even destabilize instabilities. RPP beams have fixed speckle patterns. How to implement the STUD pulse program on the Trident laser at LANL including novel time-lens systems for measuring the resulting SRS and SBS signatures with psec resolution and lasting for nsecs will also be explained.

**This work was funded in part by the DOE NNSA-OFES Joint HEDLP Program, by a DOE OFES Phase I SBIR award.

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# Inferring SRS source characteristics from time-dependent near field backscatter measurements in NIF hohlraums

J. D. Moody, E. A. Williams, R. L. Berger, D. Callahan, S. Dixit, L. Divol, S. H. Glenzer,
D. Hinkel, O. Jones, R. K. Kirkwood, O. Landen, B. J. MacGowan, N. Meezan, P.
Michel, D. J. Strozzi, and R. Town
Lawrence Livermore National Laboratory
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Livermore, CA 94550

The time-dependent near-field distribution of SRS backscatter light from NIF hohlraum experiments is measured using a new time-dependent near backscatter instrument. This instrument utilizes 40 optical fibers to detect the SRS signal from a spatially distributed set of near-field locations and the fiber signals are streaked in time. We use interpolation to determine the time-dependent 2-D near-field light distribution for the SRS with 0.1 ns time resolution and construct a movie of the SRS evolution. We compare these measurements to SRS ray-trace calculations that use hydrodynamic maps of the hohlraum plasma from radiation-hydrodyamic simulations of the experiments. This allows us to infer SRS source location characteristics consistent with the measurements. These results are compared with separate simulations that directly compute the SRS source location characteristics. We will describe the time-dependent backscatter measurements and show how we infer SRS source characteristics from ray-trace modeling.

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

# Understanding Raman scattering in NIF Ignition Experiments

D. J. Strozzi, D. E. Hinkel, E. A. Williams, R. P. J. Town, P. A. Michel,
L. Divol, R. L. Berger, J. D. Moody
*Lawrence Livermore National Laboratory*
*7000 East Ave., Livermore, CA 94550*

Stimulated Raman scattering (SRS), especially from the two inner cones of laser beams, has played an important role in ignition hohlraum experiments on NIF. The goal of this work is to determine if, and how, linear analysis correlates with observed scattered-light spectra and reflectivities, and can be used to extrapolate to new target designs. These include higher laser energies, different wavelength difference schemes, and new hohlraum geometries.

We analyze SRS using linear gains on plasma conditions from post-shot radiation-hydrodynamics calculations performed with the Lasnex code. The as-shot laser pulse is used, and modified to account for cross-beam energy transfer (as calculated using plasma conditions from Lasnex) as well as measured backscatter losses. The simulations employ what is known as the “high-flux” model, involving a higher-emissivity opacity model that includes di-electronic recombination, and electron heat transport with a large flux limiter. The gains are computed with the NEWLIP post-processor.

We explore various effects on linear gain, such as the role of overlapping laser beams. Of particular interest is the development of SRS early in the main part of the laser pulse. Experiments with varying laser energy, pulse length, and wavelength differences are investigated.

### Stimulated Brillouin Scatter of laser light from Ignition-Scale Hohlraums

Richard Berger[1], John Moody[1], Pierre Michel[1], Richard Town[1], Cliff Thomas[1], Laurent Divol[1], Debra Callahan[1], Nathan Meezan[1], Siegfried Glenzer[1], John Kline[2], Edward Williams[1], David Strozzi[1], Laurance Suter[1] [1]*Lawrence Livermore National Laboratory, Livermore, CA, US*
[2]*Los Alamos National Laboratory, Los Alamos, NM, US*

Stimulated Brillouin backcatter (SBS) measurements in NIF hohlraum targets are shown to scale with the calculated SBS gain with a threshold for significant SBS from the 30° beam for a gain of about 20 or a laser intensity of $\sim 6-7 \times 10^{14}\mathrm{W/cm^2}$ for the simulated plasma conditions. This SBS gain threshold is consistent with previous measurements of SBS from laser beams that had polarization smoothing and SSD. The SBS measurements are interpreted as scatter from the slow ion-acoustic mode in the CH-capsule-ablator plasma. Previous experiments with similar laser intensity and plasma parameters but lower ion temperature generated SBS from the fast ion-acoustic mode.

SBS is measured on two quads (2 by 2 array of beams) located on two NIF cones. One quad is at 30° (inner cone) and the other is at 50° (outer cone) with respect to the hohlraum axis. The 50° cone backscatter is typically negligible (few percent). The frequency shift of the inner-cone backscattered light is consistent with scatter from the slow ion-acoustic mode in the CH ablator plasma. This mode has a phase velocity between the thermal velocity of hydrogen and carbon ions. It is the least damped IAW in the path of the inner beams because ion temperature $T_i \sim T_e/2$, where $T_e$ is the electron temperature. Previous experiments with hydrocarbon plasmas (Froula PRL **101**, 115002 (2008), Neumayer PRL **100**, 105001 (2008)) with similar intensity, electron density and electron temperature but lower ion temperature measured SBS from the fast ion acoustic wave because the laser pulse duration was less than the temperature equilibration time. Our conclusion of SBS scattering from the slow ion acoustic mode is also consistent with other experimental observations. For example, when the initial helium gas-fill density is lowered from 6% to about 3% of $n_{\mathrm{cr}}$ density for 351nm light (when fully ionized), the 30° beam path length through CH is longer and the SBS is greater than at higher fill density. In several cases where there was air condensation on the laser entrance hole window the $\sim 1\,\mu$m of nitrogen and oxygen ice delays the arrival of the incident laser light to the hohlraum wall causing the capsule ablation to be delayed and reducing the SBS relative to the case with no air condensation. Simulations of SBS with F3D will be presented with models of cross beam power transfer and competition with stimulated Raman scatter.

# pF3D simulations of stimulated Raman and Brillouin scattering from overlapping quads in experiments conducted at the National Ignition Facility

S. H. Langer, C. H. Still, D. E. Hinkel, A. B. Langdon, E. A. Williams, P. A. Michel, and R. P. J. Town

Experiments [1] conducted at the National Ignition Facility (NIF) have shown that interactions between beams in different quads are very important in laser-plasma interactions inside NIF hohlraums. Cross-beam energy transfer plays a major role in the symmetry of the x-rays generated in the hohlraum. The SRS frequency indicates that SRS is generated in regions where the beams from the 23 degree and 30 degree cones overlap.

In this talk we use pF3D [2] to simulate the interaction between a 23 degree quad and a 30 degree quad in the SRS generation region of a NIF hohlraum during the main drive pulse. These simulations have been carried out on the Cielo computer at LANL using 32 thousand (or more) processors. The simulations include both SRS and SBS backscattered waves.

The simulations produce estimates of the SBS and SRS backscatter level, the SRS spectrum, and the distribution of scattered light at the target chamber wall. We compare these results to the values measured during NIF experiments. The SRS is emitted in bursts strong enough to lead to pump depletion. We present visualizations showing the temporal and spatial variations of the SRS.

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

[1] N. B. Meezan *et al.,* Phys. Plasmas **17**, 056304 (2010); R. P. J. Town *et al.,* Phys. Plasmas **18**, May, 2011.
[2] R. L. Berger, C. H. Still, E. A. Williams, and A. B. Langdon, *Phys. Plasmas* **5**, 4337 (1998); C. H. Still, R. L. Berger, A. B. Langdon, D. E. Hinkel, L. J. Suter, and E. A. Williams, Phys. Plasmas **7**, 2023 (2000); D. E. Hinkel, D. A. Callahan, A. B. Langdon, S. H. Langer, C. H. Still, and E. A. Williams, *Phys. Plasmas* **15**, 056314 (2008).

# Anomalously Heated Electrons Due to Stimulated Raman Rescattering for Parameters Relevant to the National Ignition Facility*

B. J. Winjum, J. E. Fahlen, F. S. Tsung, and W. B. Mori
*University of California, Los Angeles*

Hot electrons are a potential threat to the National Ignition Facility (NIF) and future Inertial Fusion Energy (IFE) devices because they can preheat the fuel target. In this regime, stimulated Raman backscattering (SRBS) and forward scattering (SRFS) can generate such hot electrons through wave-particle interactions. The plasma wave in SRBS interacts more strongly with the electron distribution than SRFS, due to its lower phase velocity, but it cannot generate electrons with kinetic energies above 100 keV.

Through one- and two-dimensional particle-in-cell simulations using the code OSIRIS, we show that rescattering of SRS scattered light can heat electrons up to and above 100 keV for parameters relevant to NIF. SRS rescattering of both SRBS and SRFS scattered light produces plasma waves with phase velocities intermediate between SRBS and SRFS plasma waves. The rescattered plasma waves interact more strongly with the electron distribution than SRFS, and they accelerate electrons to energies higher than SRBS.

Furthermore, rescattering can accelerate electrons to velocities at which they are more readily trapped by SRFS plasma waves. This progressive acceleration mechanism can generate 0.4-1.0 MeV electrons. We will discuss the effects of mobile ions and density gradients on these various processes, including the suppression of SRFS by the Langmuir decay instability.

*Supported under Grants DE-FG52-09NA29552 and NSF-Phy-0904039; simulations were performed on the UCLA Hoffman2 Cluster and NERSC's Franklin and Hopper II systems.

LLNL-ABS-479949

# Raman Amplification of Laser Pulses Creating Conditions for Kinetic Inflation*

Ian N. Ellis[a,b], David J. Strozzi[a], Benjamin J. Winjum[b], Frank S. Tsung[b],
Thomas Grismayer[b], Jay E. Fahlen[b], and Warren B. Mori[b]
[a]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[b]*University of California, Los Angeles, California, USA*

Under certain NIF-relevant conditions, a low-amplitude seed pulse undergoing modest backward Raman amplification can modify a plasma in a way that causes kinetic inflation at later times. Thorough studies have been performed of stimulated Raman scattering (SRS) under inflationary conditions, focusing on effects such as saturation mechanisms, nonlinear frequency shifts, and sidebands. However, no research has focused on the fact that a seed pulse undergoing Raman amplification with a relatively low-intensity pump can create conditions that lead to large reflectivity at later times.

We present 1D simulation results from the particle-in-cell (PIC) code OSIRIS with a pump intensity of $\sim 10^{14}$ W/cm$^2$ and seed pulses of various durations, intensities, and wavelengths. Relativistic effects, finite particle sizes, and current smoothing in the simulation modify the dispersion relation, and, in turn, modify the linear gain curve. Using a dispersion relation that takes these effects into account, we calculate the linear gain curve and compare it with the measured gain. However, different parts of the seed pulse see different gains, so we use the coupled mode solver pF3D to perform a more thorough comparison with the simulations.

Kinetic inflation occurs in many simulations after the seed pulse leaves the simulation box. The magnitude of this kinetically inflated burst of SRS and the time for it to reach maximum reflectivity depend strongly on the duration and intensity of the seed pulse. We quantify the effect of inflation by launching a second seed pulse after the first and measuring and comparing its gain with that of the first seed pulse. The gain decreases significantly when the second seed pulse coincides with the reflectivity saturation of the kinetically inflated SRS. We present a detailed analysis of events from the first seed pulse through a second seed pulse interacting with kinetically inflated SRS.

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and by the University of California, Los Angeles under Grant DE-FG52-09NA29552.

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# Saturation Effects on the Time Dependent Stimulated Raman Scattering from Ignition Targets

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Stimulated Raman scatter (SRS) is observed to saturate at a level that allows energy coupling to targets in the National Ignition Campaign (NIC) to be > 85% efficient for incident energies up to 1.3 MJ. In experiments where the incident laser energy is increased in otherwise similar hohlraum targets it is observed that the SRS energy reflectivity does not increase significantly [1]. Particle in cell simulations [2] are being used to study the role of electron kinetic saturation mechanisms in limiting the SRS in these targets. The simulations include the effects of trapped electrons in the driven plasma waves, and have previously shown that these effects and the associated wavefront bowing has been effective in saturating the scatter from a single pump beam in small scale experiments with normalized plasma conditions similar to NIC [3]. We consider the time and spectrally dependent SRS in the NIC cases and identify two distinct regions of SRS scatter, early time, short wavelength and late time, long wavelength [4] for which the plasma conditions are significantly different and the scaling of the SRS power is also observed to be different. VPIC simulations, coupled with Hydra simulations of the plasma conditions and models of the time dependent rate of power transfer between the beams and its effect on incident power [1] are used to study the scaling of the scatter with incident laser power and find a weak scaling of the reflectivity with the incident power in a homogeneous plasma with conditions relevant to the late time NIC case. Simulations including the inhomogeneous plasma profile of the NIC target will also be described as well as implications for experiments with higher incident energy.

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[3] R. K. Kirkwood et al, Journal of Plasma Physics (2010) doi:10.1017/S0022377810000681
[4] R. K. Kirkwood et al, to appear in Physics of Plasmas.

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# Near-field images from pF3D and SLIP.

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Modeling the SRS backscatter from NIF hohlraums provides a path to a better understanding the under-dense plasma conditions created within, which have yet to be measured directly. The wavelength of the backscatter is determined by the existence of plateaus of high spatial gain rate satisfying the wavelength matching condition. The spatial location of these regions influences the amount of refraction that the scattered light undergoes and thus its angular distribution exiting the laser entrance hole of the hohlraum.

We have a variety of tools to address these questions with increasing fidelity and computational cost.

Here we describe how we use pF3d and SLIP in combination to calculate the near field distribution of the SRS backscatter. pF3d is a time-dependent code that models the interaction of the incident laser and the backscattered light, described in a time-enveloped paraxial model via plasma waves induced in the background plasma. SLIP is a stripped down version of pF3d that calculates the steady-state amplification of backscatter from noise. It has considerably lower computational cost in terms of time and memory requirements, even though it is still a parallel code.

We compare these results to the measurements made by the improved time-dependent NBI (Nearbackscatter Imager) and the FABS (Full-aperture Backscatter) diagnostic.

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

# UV laser beam propagation through the Xe-filled target chamber of an IFE power plant: Inverse Bremsstrahlung, (non-)linear refraction and Electronic Stimulated Raman Scattering

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G. Loosmore and J. Latkowski

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Inertial fusion energy (IFE) power plant designs have shown that filling the target chamber with a low-pressure inert gas (~ 1 Torr) can alleviate the material requirements for the first wall, by stopping heavy ions and absorbing X-rays. The current LIFE design uses 0.351 μm lasers to heat a hohlraum to ignition drive temperatures. We will present an assessment of the impact of the low density chamber gas fill (Xenon at a few μg/cc) and residues from targets (mostly Pb at 1/10th of the Xe density) on the propagation of the UV driver beams over meters.
Key physical mechanisms are:

- Inverse Bremsstrahlung absorption over the last 30 cm, in the low temperature/high frequency regime;
- Linear and nonlinear refraction over 6 meters;
- Electronic Stimulated Raman Scattering (ESRS) in the Pb vapor.

We will show that the current design should lead to minimal perturbation and energy loss and will briefly discuss possible forthcoming experimental validations.

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

# Inertial Confinement Fusion experiments on the National Ignition Facility

S. H. Glenzer, M. J. Edwards, J. Atherton, P. E. Bell, R. Bionta, D. K. Bradley, S. Brandon, M. Bower, D. A. Callahan, J. Caggiano, P. Cellier, D. T. Casey, M. Gatu Johnson, D. Clark, C. Cerjan, E. L. Dewald, L. Divol, S. Dixit, T. Doeppner, R. Dylla-Spears, E. Dzenitis, M. J. Eckart, J. Fair, D. Farley, D. Fittinghoff, J. Frenje, V. Glebov, S. Glenn, G. Grim, S. Haan, A. V. Hamza, E. Hartouni, C. Haynam, R. Heeter, D. Hicks, D. Hinkel, N. Izumi, D. H. Kalantar, J. D. Kilkenny, J. Knauer, O. Landen, D. Larson, S. LePape, J. D. Lindl, O. Jones, T. Ma, B. MacGowan, A. Mackinnon, J. McNaney, E. Mapoles, A. McPhee, F. Merrill, N. Meezan, P. Michel, J. Moody, M. Moran, D. Munro, A. Nikroo, A. Pak, T. Parham, J. Ralph, S. Regan, H, Robey, C. J. Sangster, M. B. Schneider, B. Spears, P. Springer, C. Stoefll, L. J. Suter, R. P. J. Town, B. K. F. Young, B. VanWonterghem, S. V. Weber, P. Wegner, K. Widmann, P. Whitman, R. Zacharias, H. Herrman, D. Wilson, J. Kline, G. Kyrala, and E. Moses

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The first inertial confinement fusion implosion experiments with cryogenic fuel layers have been fielded in preparation for ignition experiments on the National Ignition Facility. These experiments use mega joule laser energies that compress fusion capsules in indirect dive hohlraums to test initial hot spot formation and thermonuclear fuel assembly. Hydrogen-rich fuel (THD) provides a relatively low yield and diagnostics rich environment allowing us to measure the implosion core, the neutron yield, temperatures and fuel areal density from a suite of x-ray and neutron diagnostics. These experiments have successfully demonstrated the control of the implosion shape using ignition grade cryogenic fuel layers, laser pulse shaping, and nonlinear plasma optics. The implosions show scaling of the DT fusion yield with ion temperature over more than one order of magnitude to a yield in excess of $10^{14}$ neutrons. With improved tuning we assess the implosion performance with yield and areal density measurements with the goal to switch to pure DT fuel for observations of alpha particle heating.

Prepared by LLNL under Contract DE-AC52-07NA27344.

# Recent experimental and theoretical results on laser-plasma interaction in the long pulse regime at CEA-DAM

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In order to be prepared for the first campaigns of physics on the LMJ facility in 2015, we have been carrying on with experimental, analytical and numerical studies in the field of laser-plasma interaction (LPI) in the long pulse regime.

For experimental studies, we used the two laser facilities, ALISE and LIL, from the CEA-CESTA in Bordeaux. The ALISE facility delivers an energy of 100 J in 1 ns. We used this facility to carry out about 60 shots intended to study the effect of smoothing on LPI at 1.053 µm in helium jets. These experiments were well instrumented. Our results will be discussed and, more specifically, we will show Brillouin reflectivities and spectra, and the amount of transmitted radiation. Regarding the LIL facility, we have continued the LPI campaign we started in 2007. Twelve shots were carried out in February and March of this year. The laser energy was about 14 kJ with a 4+2 ns pulse at 0.35 µm. Three kinds of cylindrical targets filled with neopentane were studied: 3 mm long targets with one window, 4 mm long targets with two windows, and 1.5 mm long targets with two windows. This campaign gave many results, of which the analysis is still going on. We will give a first report of this campaign.

Concerning analytical and numerical results, we are trying to improve our modeling of LPI. More specifically, we have developed new tools for a quick study of ionic species mixtures. Based on a rigorous mathematical approach, we have determined a very accurate Padé approximant for the derivative Z' of the plasma dispersion function. The different acoustic modes and the Landau damping rates can then be computed very quickly and efficiently as a function of the laser and plasma parameters. We will explain this method.

# Particle-in-Cell Simulations of the High Frequency Hybrid Instability in Inertial Confinement Fusion Plasmas*

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We present results on the laser-plasma interaction near the quarter critical surface under conditions relevant to inertial fusion. Under these conditions, the high frequency hybrid instability (HFHI) where one of the daughter waves have mixed polarization, is likely to be dominant. In fully nonlinear kinetic simulations with the code OSIRIS we show that the spectrum at early time is consistent with theory. We also investgiate the saturated electrostatic (and electromagnetic) spectrum for long timescales for both fixed and mobile ions. For high temperatures where the HFHI is dominant the absorption is dominated by the absolutely unstable modes and absorption levels near 40% can occur even when C_mult is less than 1. We also investigate in detail the evolution of unstable modes. Nonlinear effects, such as the generation of hot electrons, half harmonics generations and the excitation of low frequency ion fluctuations, will also be discussed.

*This work is supported by DOE DE-FG52-09NA29552.

## Strong Langmuir Turbulence in the Nonlinear Saturation of Parametric Instabilities Driven by Coherent Electromagnetic Waves.

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A nonlinear state of strong Langmuir turbulence (SLT) is predicted [1] and observed [2] in experiments involving the excitation of parametric instabilities by HF waves near their reflection altitude in the ionosphere. The predictive modeling includes the fully kinetic reduced particle-in-cell (RPIC) model and the extended Zakharov model (including the quasilinear evolution of the electron velocity distribution), which agree in detail [3] in weakly driven regimes. The state of SLT is characterized by short correlation lengths, in some regimes it may be dominated by the secondary Langmuir decay instability (LDI), and in other regimes may exhibit very spiky fields consisting of Langmuir "cavitons" which collapse to small dissipation scales. Supra thermal electrons are generated by this turbulence. SLT phenomena, including LDI, are predicted [4] for stimulated Raman scattering (SRS) when the SRS Langmuir waves are in the weak Landau damping regime and are observed by Thomson scattering in single hot spot experiments [5]. Simulations of the nonlinear stage of the two plasmon decay (TPD) instability have also revealed SLT behavior [6, 7, 8]. Here we will review the elements of SLT, with emphasis on recent predictions for the TPD instability [8].

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# Scaling and mitigating stimulated scattering and two plasmon decay instabilty in NIF hohlraums

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Experiments[1] have now well established that stimulated Raman and Brillouin scattering can occur at very significant levels in ignition-scale hohlraums. Calculations[2] further show that the two plasmon decay instability (and related high frequency instabilities near the quarter-critical density) can be a significant source of hot electron preheat. Overlapped beam effects such as cross beam energy transfer[3] play an important role in enhancing these laser plasma instability levels. Some models for the scaling with laser energy are presented for the stimulated scattering and the laser energy at risk to the two plasmon decay instability. Simple models are also used to illustrate the plasma conditions as well as explain the relatively benign behavior of the outer beams. Key uncertainties in the characterization of the laser plasma coupling in ignition-scale hohlraums are identified, and some additional diagnostics recommended. The importance of re-designing the hohlraum in order to minimize the cross beam energy transfer is again emphasized. Some other ways to potentially reduce stimulated scattering are further discussed, including changing the spot size and overlap of the laser beams and intentionally enhancing the plasma temperature.

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3. P. Michel *et. al*., Phys. Plasmas **17**, 056305 (2010) and references therein.

# Using High Intensity Lasers to Accelerate Electrons at Solid Density Matter-Vacuum Interfaces*

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The acceleration and heating of electrons by an intense laser normally incident on a steep over-dense plasma interface is investigated using the particle-in-cell code OSIRIS. We show that the energetic electrons are generated by the laser's electric field in the vacuum region within a quarter wavelength of the surface and that only those electrons which originate within the plasma with a sufficiently large transverse momentum can escape the plasma into the vacuum region; even in 1D this leads to an inherent beam divergence at the source. No acceleration occurs for initially cold plasmas until the plasma is heated by other mechanisms. The maximum energy generated by this mechanism is 2eA where e is the charge of an electron and A is the peak vector potential of the laser. Absorption is much different for circularly polarized light, which has applications for Radiation Pressure Acceleration.

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LLNL-ABS-479950

# Studies of Particle Wake Potentials in Plasmas*

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A detailed understanding of electron stopping and scattering in plasmas with variable values for the number of particles within a Debye sphere is still not at hand. Presently, there is some disagreement in the literature[1,2,3] concerning the proper description of these processes. Theoretical models assume electrostatic (Coulomb force) interactions between particles and neglect magnetic effects. Developing and validating proper descriptions requires studying the processes using first-principle plasma simulations. We are using the particle-particle particle-mesh (PPPM) code ddcMD and the particle-in-cell (PIC) code BEPS to perform these simulations. As a starting point in our study, we examine the wake of a particle passing through a plasma in 3D electrostatic simulations performed with ddcMD and with BEPS using various cell sizes. In this poster, we compare the wakes we observe in these simulations with each other and predictions from Vlasov theory. The relevance of the work to Fast Ignition is discussed.

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and by the University of California, Los Angeles under Grant DE-FG52-09NA29552.

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**Title:**

Ultrafast Electron Beam Radiography of Self-Generated Magnetic Fields from High Intensity Laser-Solid Interactions

**Authors:**

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**Abstract:**

Using ~10 fs electron bunches generated with laser wakefield acceleration as a probe, the femtosecond temporal evolution of a ~$4\text{x}10^{19}$ W/cm$^2$ short laser pulse with a metallic foil has been studied experimentally. Magnetic fields of ~100 megagauss were observed travelling outward from the interaction point of the laser with the metallic foil at nearly the speed of light. These results are supported by OSIRIS particle-in-cell simulations.

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June 19-24, 2011

# Optimal Control of Laser-Plasma Instabilities in HEDP Using STUD Pulses: Spike Trains of Uneven Duration and Delay

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A number of long standing problems that have plagued the control of laser-plasma instabilities (LPI) may find a favorable solution by the use of rapidly and strongly modulated laser pulses with a few orders of magnitude contrast between 'on' and 'off' states, and when the speckle patterns of each 'on' spike is sufficiently uncorrelated with the speckle patterns of its neighboring spikes. Scrambling speckle patterns in space and breaking up laser pulses into a variable length on-off set of spikes allows adaptive control to any plasma conditions without any prior knowledge of what those conditions may be, especially, as those conditions are modified by the action of many high intensity laser beams. This scheme is called STUD pulses for Spike Trains of Uneven Duration and Delay.

We will show theoretical arguments for why this approach is optimal and present estimates for stimulated Raman (SRS) and Brillouin scattering (SBS) as well as two plasmon decay cases of interest to direct drive, indirect drive, shock ignition and fast ignition. In particular, enabling the use of 527 nm drivers as opposed to 351 nm ones as used today on the NIF will be highlighted. Furthermore, the advantages of STUD pulses to allowing true LPI control of crossing laser beams will be explained in terms of the ability to interlace, interleave or superpose the STUD pulses of overlapping laser beams. Theoretical models that treat SBS in nonuniform, flowing plasmas in the weak and strong coupling regimes and in the weak and strong damping limits will be highlighted. Simulation results including the effects of pump depletion, diffraction, self-focusing in two dimensional speckle patterns will also be shown which were obtained using a substantially modified and STUD-pulse adapted version of the code Harmony. Here, RPP, SSD, Pseudo-STUD pulse and STUD pulse cases will be compared at various "gain at the average intensity in a single hot spot" levels. We will show how the orders of magnitude reduction in reflectivity or plasma mode (IAW or EPW) cumulative and repetitive amplitude growth suppression can be achieved with STUD pulses and to a far lesser degree by pseudo-STUD pulses and practically not at all with SSD, when compared to plain RPP f/8 beams. With STUD pulses, the laser is strongly modulated in time and the speckle patterns are scrambled between laser spikes. In pseudo-STUD pulses the temporal modulation is the same as in STUD pulses but the speckle patterns are held fixed in time. In SSD, a one directional slow sweep of the hot spots is affected which could even destabilize instabilities. RPP beams have fixed speckle patterns. How to implement the STUD pulse program on the Trident laser at LANL including novel time-lens systems for measuring the resulting SRS and SBS signatures with psec resolution and lasting for nsecs will also be explained.

**This work was funded in part by the DOE NNSA-OFES Joint HEDLP Program, by a DOE OFES Phase I SBIR award.

# Numerical Study of Self and Controlled Injection in 3-Dimensional Laser-Driven Wakefields

A. W. Davidson, W. Lu, C. Joshi, L. O. Silvia, J. Martins, R. A. Fonseca, W. B. Mori,
UCLA

In plasma based accelerators (LWFA and PWFA), the methods of injecting high quality electron bunches into the accelerating wakefield is of utmost importance for various applications. Understanding how injection occurs in both self and controlled scenarios is therefore important. To simplify this understanding, we start from single particle motion in an arbitrary traveling wave wakefields, an electromagnetic structure with a fixed phase velocity (e.g., wakefields driven by non-evolving drivers), and obtain the general conditions for trapping to occur. We then compare this condition with high fidelity 3D PIC simulations through advanced particle and field tracking diagnostics. Numerous numerical convergence tests were performed to ensure the correctness of the simulations. The agreement between theory and simulations helps to clarify the role played by driver evolution on injection, and a physical picture of injection first proposed[1] is confirmed through simulations. Several ideas, including ionization assisted injection, for achieving high quality controlled injection were also explored and some simulation results relevant to current and future experiments will be presented.

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# PIC Simulations of Stimulated Raman Scattering for NIF Scale Lengths and Density Profiles*

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Stimulated Raman scattering (SRS) poses a threat to the successful operation of the National Ignition Facility (NIF). Particle-in-cell (PIC) simulations, both with our code OSIRIS and with other codes, have shown SRS to be bursty in space and time, with localized plasma wave packets for sub-speckle-length scales and bursts of light on the sub-picosecond time scale, but most PIC simulations of SRS for NIF-relevant parameters have only simulated speckle-size plasmas. Here we present one-dimensional PIC simulation results for plasmas 1.5 mm in length, $T_e$ = 2.5-3.0 keV, laser intensities 4-8 x $10^{14}$ W/cm$^2$, and with NIF-relevant density profiles covering $n_e/n_{cr}$ = 0.09-0.15.

Most of the SRS bursts are again spatially localized within 200 microns and generate sub-picosecond bursts of light whose periodicity is related to the nonlinear plasma wave frequency shift as shown in our previous work. For linearly increasing density profiles with scale length ~3 mm, SRS is shown to initially grow at densities of $n_e/n_{cr} \sim 0.13$-0.14, corresponding to $k\lambda_D < \sim 0.30$. For other density profiles with changing slopes or regions of uniform density, SRS is shown to grow at densities below $n_e/n_{cr}$ = 0.11 provided the slope in density is sufficiently shallow. The location of SRS growth changes very little as laser intensity increases, although additional bursts start occurring at lower densities. We discuss the range of scattered light wavelengths and reflectivity levels that result.

*Supported under Grants DE-FG52-09NA29552 and NSF-Phy-0904039; simulations were performed on the UCLA Hoffman2 Cluster.

## Tuesday

# Positron Creation Using Ultra-intense Lasers

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Recent experiments (Chen, *et. al.* PRL 2010) have confirmed theories which have long predicted that copious positrons can be created from ultra-intense laser-solid interactions. Due to the shortness of the laser pulses used (~ picoseconds), the brightness of this new source of positrons (~ $10^{20}$ e+/sec) is orders-of-magnitude brighter than current sources. The density of positrons created for this brief time (~ 100 picoseconds) approaches $10^{14}$ $cm^{-3}$inside the target. A review of the basic theories and experiments behind laser-based positron generation will be given, and results of recent experiments and simulations will be presented. It is found that sheath fields on the rear of the target play a key role in understanding the observed positron spectra. An immediate consequence of this research lies in the potential to use these positrons to more accurately diagnose the hot electron energy distribution obtained from laser-matter interactions. This would benefit not only fast ignition, but virtually all High Energy Density Science experiments that require a better understanding of hot electron generation.

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# Narrow Energy-Spread Proton Beams Generated in a Gas Jet by High-Power $CO_2$ Laser Pulses

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Over the past decade, Laser driven ion acceleration (LDIA) has been extensively studied using high power lasers around the 1$\mu$m wavelength incident upon solid density targets. LDIA schemes typically produce a thermal distribution of ions in the 10's of MeV/nucleon range at a laser $a_o$ of 5-10, though some narrow energy-spread features have been obtained at lower ion energies. At the UCLA Neptune Laboratory, we have investigated LDIA using a high-power $CO_2$ laser pulse in a $H_2$ gas jet. The gas jet can be easily tuned to neutral gas densities around the critical plasma density of $10^{19}$cm$^{-3}$ for 10$\mu$m light. The $CO_2$ laser pulses consist of a train of 3ps pulses separated by 18ps with a peak power of up to 4TW and total energy of 50J [D. Haberberger *et. al.*, Opt. Exp. 18, 17865 (2010)]. Protons have been accelerated from this interaction to energies of up to 22MeV, which far exceeds that predicted by ponderomotive force scaling for our vacuum $a_o \sim 2$. Comparable proton energies have only been achieved with 100TW 1$\mu$m systems. Furthermore, these high energy protons are contained within an energy spread of $\Delta E/E_{FWHM} \sim 1\%$, and have an estimated transverse emittance of down to $\sim$3mm·mrad. The temporal dynamics of the laser-plasma interaction was probed using a picosecond 532nm pulse and studied via 2D OSIRIS simulations. This analysis has uncovered a multistage process for the production of monoenergetic protons based on the shock acceleration mechanism which will be discussed.

This work is supported by DOE Contract No. DE-FG03-92ER40727.

# FAST IGNITION WITH LASER-DRIVEN ION BEAMS: PROGRESS ON IGNITOR BEAM DEVELOPMENT*

J. C. Fernández[1], B. J. Albright[1], K. J. Bowers[1], D. C. Gautier[1], J. J. Honrubia[2], C.-K. Huang[1], R. P. Johnson[1], D. Jung[1], S. A. Letzring[1], S. Palaniyappan[1], R. C. Shah[1], T. Shimada[1], L. Yin[1], H.-C. Wu and B. M. Hegelich[1]
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We report on the encouraging progress from research on fusion fast ignition (FI) initiated by carbon ions [1,2], a technologically convenient ion species from a target-fabrication perspective with advantageous characteristics for FI [2]. Specifically, we concentrate on the progress towards a quasi-monoenergetic C-ion beam with an ion energy of ~ 0.5 GeV, which is necessary to penetrate to the core of the compressed DT fuel. Although all the required ion-beam parameters have not been achieved simultaneously in the present generation of high-energy, high intensity lasers, ignition-relevant performance on key parameters has been achieved in isolation on experiments at our Trident laser facility at LANL. These encouraging results include a laser conversion efficiency into ions ~ 10%, control of the energy spectrum, and ~ 0.5 GeV maximum ion energies. In order to achieve such energies, we work in a new regime of relativistic laser-plasma interactions, the *relativistic transparency regime*, where the laser interacts volumetrically with a target plasma that is classically overdense, and where new ion-acceleration mechanisms become accessible. In addition to the Break Out Afterburner mechanism previously considered [3], we have recently discovered a new acceleration mechanism based on solitary waves [4,5], which is summarized here. The relativistic-transparency regime can be used not only to access novel acceleration mechanisms, but also to improve their performance using compound targets [6]. In order to get a full picture of the physics and to control the interaction in this regime, we have added an unprecedented level of laser and plasma diagnostics in these Trident experiments. The experimental setup, and what we have learned about the underlying physics from these new diagnostics is also presented in this paper.

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# PEAK PROTON AND CARBON ION ENERGY SCALING WITH ULTRA-HIGH ENERGY LASERS

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Experiments have been conduted at Los Alamos National Laboratory's Trident and the Laboratory for Laser Energetics's Omega EP Laser Facilities. Tens of microns thick, foil targets were irradiated using the two facilities' shortpulse beam lines in order to generate Multi-MeV ion beams via the Target Normal Sheath Acceleration Mechanism. In this work, we consider the peak energy for both the carbon ions and protons in the beam and its scaling with different laser conditions. The parameter space includes laser energy (tens of J to 1 kJ), pulse duration (0.5 ps to 10 ps), and target thickness (100 nm to 25 μm). The corresponding intensities range from $2 \times 10^{20}$ W/cm$^2$ down to $5 \times 10^{18}$ W/cm$^2$. Two types of target conditions were used. The first was a heated CVD diamond, which removed all contaminants and produced a pure carbon ion beam. The second was an unheated CVD diamond, which produced mostly carbon ion and proton beams originating from contaminants on the target surface. Deviations of the peak carbon ion energy in the two cases as the laser energy was increased has provided new insight in the temporal evolution of the sheath field responsible for the acceleration.

# TRIDENT 200TW "DIAL-A-CONTRAST" LASER SYTSTEM EXPERIMENTS PRODUCING PROTONS UP TO 75 MEV

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We report on recent experiments using the high-contrast (< $10^{-9}$) high-intensity ($2\times10^{20}$ W/cm$^2$) LANL Trident short-pulse laser system, in which a novel "dial-a-contrast" ability has been implemented on the system. Starting from a high contrast beam, < $10^{-9}$ at 50 ps before the main pulse, we now have the ability to change the short-pulse temporal contrast shoulder's rise around the main pulse in the range from $10^{-3}$ to $10^{-8}$ in intensity on a 100 ps time scale before the main pulse. In addition, short-pulse pre-pulses between $10^{-3}$ and $10^{-8}$ in intensity can be added up to 500ps before the main pulse to adjust the amount of pre-plasma in front of the target. This allows us to now "dial-a-contrast" to explore the preplasma effects from nearly none to hundreds of microns of scale-length produced by a short-pulse or "long" shoulder ASE-like effects. Large targets (1 x 1 mm$^2$), spanning 3 decades in thickness, between 100 μm and 100 nm were tested on this system to understand the optimization of ion beams, energetic electrons, neutrons and backscattered light on contrast conditions. Cones and limited mass foils (< 500 x 500 μm$^2$) were also tested and compared, showing improvements in proton energies from 50 MeV up to 75 MeV.

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# Conversion efficiency scaling of carbon ions accelerated in the Break-Out Afterburner regime *

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In the past ten years target normal sheath acceleration (TNSA[1]) has been studied intensively, experimentally as well as theoretically. TNSA, however, predominantly accelerates protons by virtue of its acceleration mechanism. Recently, improved laser contrast and steadily increasing laser intensities made novel acceleration mechanisms such as the radiation pressure acceleration (RPA[2]) or the Break-Out Afterburner (BOA[3,4]) accessible experimentally. These mechanisms predominantly couple energy in the dominant target ion species, not in the hydrocarbon surface contaminants, making these mechanisms a competitive alternative to conventional accelerators on a much wider basis. However, little experimental research or simulations have up to know investigated conversion efficiency and beam distributions, which is essential for any application, such as ion based fast ignition (IFI[5,6]).

We here present for the first time experimental data addressing conversion efficiency and ion distribution scaling for carbon $C^{6+}$ ions within the Break-Out Afterburner regime and the transit into the TNSA regime. Unique high resolution (in energy and angle) measurements of the angular carbon $C^{6+}$ ion distribution for targets ranging from 30nm to 20μm - recorded with a novel ion wide angle spectrometer (iWASP[7]) - are used to derive scaling estimates. The measured conversion efficiency is ~5% at the optimum target thickness of 150nm for carbon $C^{6+}$ ions above 33.5MeV into a cone of 16°, where the ion distribution undergoes a dramatic change for the BOA dominated acceleration as compared with TNSA.

*This work conducted under the auspices of the LANL Laboratory Directed Research & Development (LDRD), the DOE Office of Fusion Energy Sciences (OFES), and by the Deutsche Forschungsgemeinschaft (DFG) through Transregio SFB TR18, the DFG Cluster of Excellence Munich-Centre for Advanced Photonics (MAP) and DFG LMU-Excellence (M. Hegelich).

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# Recent results of full-spatial scale hybrid-PIC modeling of fast ignition

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We show recent results of full-spatial scale modeling of fast ignition, from both full-PIC and the recently developed hybrid-PIC capability of OSIRIS 2.0. Our results show full-scale modeling of fast ignition over full density and time scales, where laser absorption, electron beam divergence, and energy deposition in the compressed core will be addressed in a self-consistent manner. Full-PIC and hybrid-PIC simulations of isolated targets will be presented, illustrating the importance of this type of modeling in order to accurately infer the beam divergence and transport properties.

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# Controlling the Divergence of Laser-Generated Fast Electrons Through Resistivity Gradients in Fast-Ignition Targets

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The divergence of laser-generated fast electrons is a crucial parameter that determines the incident petawatt laser energy in fast-ignition targets. Experiments and particle-in-cell (PIC) simulations predict a large divergence of laser-generated fast electrons, underlining the importance of finding regimes in which electron divergence can be controlled. This paper investigates the recently suggested scheme of controlling the fast-electron divergence using a resistivity mismatch in structured targets in the regime of realistic ignition-relevant laser energies and intensities. Different from most studies and proof-of-principle experiments performed so far for low-energy laser pulses and room-temperature targets, this analysis applies to ignition-relevant energies of the fast-electron beam. Hybrid-PIC simulations using the code *LSP* are performed for cone-in-shell fast-ignition targets with cones comprised of different material layers. The effects of wires attached to the cone tip to guide hot electrons to the dense core are also investigated. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement Nos. DE-FC52-08NA28302 and DE-FC02-04ER54789, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

# MECHANISM OF PRE-FORMED PLASMA ELECTRONS HEATING IN RELATIVISTIC LASER-SOLID INTERACTIONS

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Understanding the influence of pre-formed plasma in front of the solid target on fast electrons generation is crucial for various relativistic laser-solid interactions experiments. Recent experiments with flat [1] as well as cone shaped [2] targets have shown that the fast electrons generation is significantly modified by the presence of long scale-length pre-formed plasma. In particular, high-energy electrons with energies significantly greater than laser ponderomotive energy are observed with the long pre-formed plasma present in front of target.

In our recent work [3], we have demonstrated the influence of large electrostatic potential well present inside pre-formed plasma on acceleration and heating of these pre-formed plasma electrons. This potential well is self consistently formed in order to maintain quasi-neutrality in response to heating of pre-formed plasma electrons by the laser. The synergetic effects of potential well and laser radiation are found to be responsible for the generation of high-energy tail of the electron energy distribution.

In present work, we have studied in detail this heating mechanism by analyzing, both analytically and numerically, the stochastic motion of an electron in presence of electrostatic field and laser radiation. Results of electron dynamics in presence of such fields and its influence on stochastic heating will be presented in this paper.

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# PIC MODELING OF MATERIAL DEPENDENCE ON FAST ELECTRON GENERATION AND TRANSPORT*

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The energy coupling from laser to the compressed core in cone guided fast ignition strongly depends on laser produced fast-electron-beam-divergence and their transport. 2D Particle-in-Cell (PIC) simulations have been performed to investigate fast electron source divergence and their transport in a resistive medium using the PICLS code[1] which incorporates relativistic binary collisions, dynamic ionization, radiative losses and can efficiently model the underlying physics present in FI relevant experiments, i.e., collisionless LPI and highly collisional interactions in high density region.

Simulations were performed for fast electron transport in the low-Z warm dense matter (WDM) experiments[2] where fast electrons are produced at planar Au source foil by intense laser ($10^{20}$ W/cm$^2$) and propagate into and through WDM. They show that the laser pressure deformed absorption surface can potentially lead to wide electron source divergence. We also observed that the resistive magnetic channels are extended from source Au layer to the WDM transport medium, and that these channels guide the electrons without much deflection, allowing fast electrons to carry the source angular divergence information with minimal perturbation. Simulations reproduce a wide fast electron beam divergence (> 100°) inferred in the experiment. Simulations results are also compared where WDM transport layer is replaced by CH insulator and Al metal foil. In addition, effects of the surface material on the LPI produced fast electron source characteristics are examined in both planar and buried cone geometry.

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# Relativistic shocks in astrophysics and driven by lasers

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Extreme astrophysical events such as gamma ray bursters have led to a renewed interest in collisionless shocks as the central mechanism and site to magnetic field generation and amplification, particle acceleration, and generation of non-thermal radiation. In these scenarios the plasma is initially unmagnetized, the flows are relativistic and the dissipation processes required for the formation of the shock are dominated by plasma instabilities, in particular by self-generated magnetic fields via the current filamentation instability. I will review recent progresses on relativistic collisionless shocks with an emphasis on the collective plasma mechanisms (current filamentation and Kelvin-Helmolhtz) that can contribute for the formation of the shocks and for the particle acceleration mechanisms, and on recent experiments on collisionless shocks in the laboratory. The possibility to drive relativistic-like shocks with ultra-intense lasers and mediated by self-generated magnetic fields, reproducing the key physical mechanisms observed in relativistic astrophysical shocks, is also discussed and the conditions to drive these shocks in the laboratory are identified.

Work in collaboration with R. A. Fonseca, F. Fiúza, S. F. Martins, J. L. Martins, E. P. Alves, T. Grismayer, A. Stockem (IST), and J. Tonge, W. B. Mori (UCLA). Work partially supported by the European Research Council (ERC-2010-AdG Grant 267841), and FCT (Portugal) grants PTDC/FIS/111720/2009.

# Asymmetric effects of cone-guided targets on three-dimensional implosion for fast ignition*

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Fast ignition is one of the ignition schemes for laser fusion. In this scheme, a fusion target is attached with a gold (Au) cone and irradiated with implosion lasers except the cone region, and the core is compressed to high density enough for fusion. At the maximum compression, an ultra high intense heating laser is fired into the cone. A large number of energetic electrons are produced by interactions between the cone and the heating laser. These energetic electrons, then, raise the core temperature enough to initiate fusion reaction. For achieving the high density, it is important to uniformly implode the target. However, an asynmetric implosion is essencially occurred due to the existence of the cone. It is required to investigate the effect of the cone on the uniform implosion of the target by fully three-dimensional fluid simulations.

There is a numerical method called "Immersed Boundary Method (IBM)" that appropriately deals with a boundary oblique to grids even in Cartesian coordinates. In the IBM calculation, computational cells are categorized to three types (fluid, body and ghost cells). A boundary is crossing the ghost cell and the center point of the ghost cell must be inside the body. The value of the ghost point is determined by an interpolation and the boundary condition as follows: (1) an image point corresponding to the ghost point is defined so that the line connecting the image and ghost points is normal to the boundary, (2) the value of the image point is calculated by the interpolation from neighboring fluid points, and (3) the ghost point value is set by using the image point value to satisfy the boundary condition. The IBM makes it possible to treat a boundary like the cone even in Cartesian coordinates.

In this paper, an open angle of the cone, a distance from the cone tip to the origin and an off-axis distance are used as survey parameters. The initial values are determined by self-similar analysis assuming the stagnation phase. The dependence of these survey parameters on the density and temperature at the maximum compression is investigated by three-dimensional fluid simulations. It is found that the degradation of the implosion performance is no more than 3% compared with the coneless case, therefore, the existence of the cone have little effect on the uniform implosion. Additionally, time evolutions of Rayleigh-Taylor instability with imposed perturbations are also investigated. We will discuss in detail.

# Modeling Electron Divergence in Fast Ignition Modeling

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Understanding and Controlling Electron Divergence is Critical for the success of Fast Ignition. We show recent results of 2D PIC with OSIRIS modeling of electron divergence relevant to fast ignition. We study the impact of physical and numerical effects on electron divergence. We also look at a variety of schemes to reduce electrons divergence in fast ignition targets.

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**Two-dimensional Vlasov simulations of electron plasma wave trapping, self-focusing, and sideloss** R. L. Berger[1], J. W. Banks[1], S. Brunner[2], B. I. Cohen[1], and J. A. F. Hittinger[1] [1]*Lawrence Livermore National Laboratory, Livermore, CA, US* [2]*École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*

Two-dimensional Vlasov simulations of nonlinear electron plasma waves are presented. The plasma wave is created with an external traveling wave potential with a transverse envelope of width Δy such that thermal electrons transit the wave in a “sideloss” time, $t_{sl} \sim \Delta y/v_e$. Here, $v_e$ is the electron thermal velocity. The quasi-steady distribution of trapped electrons and its self-consistent plasma wave are studied after the external field is turned off. In cases of particular interest, the bounce frequency, $\omega_{be} = k\sqrt{e\phi/m_e}$, satisfies the trapping condition $\omega_{be}t_{sl} > 2\pi$ such that the wave frequency is nonlinearly downshifted by an amount proportional to the number of trapped electrons. Here, $k$ is the plasma wave wavenumber and $\phi$ is its electric potential. For sufficiently short times, the magnitude of the negative frequency shift is a local function of $\phi$. Because the trapping frequency shift is negative, the phase of the wave on axis lags the off axis phase if the trapping nonlinearity dominates linear wave diffraction. In this case, the phasefronts are curved in a focusing sense. In the opposite limit, the phasefronts are curved in a defocusing sense. Analysis and simulations in which the wave amplitude and transverse width are varied establish criteria for the development of each type of wavefront. The damping and trapped-electron-induced focusing of the finite-amplitude electron plasma wave are also simulated. The damping rate of the field energy of the wave is found to be about the sideloss rate, $\nu_e \sim t_{sl}^{-1}$. For large wave amplitudes or widths Δy, a trapping-induced self-focusing of the wave is demonstrated.

poster preferred

# Imaging X-Ray Thomson Scattering Spectroscopy for Characterizing Extreme Matter States

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In many laboratory astrophysics experiments, intense laser irradiation creates novel material conditions with large, one-dimensional gradients in the temperature, density, and ionization state. X-ray Thomson scattering (XRTS) is a powerful technique for measuring these plasma parameters. However, the scattered signal is typically measured with little or no spatial resolution, which limits the ability to diagnose these inhomogeneous plasmas.

We report on the development of a one-dimensional imaging spectrometer for use on the Omega laser at the Laboratory for Laser Energetics. Diffraction of scattered x-rays from a toroidally curved crystal creates high-resolution images that are spatially resolved along a one-dimensional profile in the target while simultaneously spectrally resolving the scattered radiation. We will discuss anticipated uses of this instrument in upcoming Omega experiments.

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# MIX IN DEFECT IMAGING EXPERIMENTS ON OMEGA

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Los Alamos is engaged in project to design high neutron fluence experiments at the NIF that can be applied to feature-driven mix, such as from a fill tube or the joint in a beryllium capsule. The results will also be important for inertial fusion energy, where we will need to predict how much imperfection a capsule can have and still produce useful energy. To prepare for the NIF experiments, we have been fielding experiments at the Omega laser. These shots were part of the Defect Imaging Experiment (DIME-I) series[1], with shots fired in April 2009, September 2010, and January 2011. We use an Eulerian code to simulate the results of these Omega experiments. In what follows, we break our comparisons into thin (~8.5 μm) and thick (~15 μm) shell capsules. All the capsules have 5 atm of DT gas in the center and an outer diameter of about 870 μm. Within each capsule type, we cover four cases; no equatorial groove, a 2 to 2.5 μm deep groove, a 4 to 5 μm deep groove, and an 8 to 9 μm deep groove. The grooves are 20 to 30 μm wide. We start our comparisons of simulations to data with the "perfect" capsules. We find that the Eulerian no-mix calculations considerably over-predict the burn averaged ion temperature, along with the yields by a factor of 5 to 7 (thin) or nearly 20 (thick). The calculations also under-predict the full-width half-maximum burn width by a factor of two. With this code, we have the BHR-2 mix model[2] that we use to mix capsule material into the DT gas. For our nominal case, we use an average surface roughness of 50 nm (about mode number 10) and a specific kinetic energy of $10^{13}$ $cm^2/s^2$ (~1% of the total specific kinetic energy). With this "nominal" amount of mix, the agreement is improved. The burn averaged ion temperatures are within 1 keV of the data (the error bar is 0.5 keV). The neutron yields are within a factor of four of the data for both types of capsules. However, the simulation burn widths are still only about 60% of the data. In addition, we will compare simulated radius versus time plots and x-ray emission images to those derived from data.

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# A VLASOV-FOKKER-PLANCK CODE FOR HIGH ENERGY DENSITY PHYSICS

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A parallel relativistic 2D3P Vlasov-Fokker-Planck code has been developed primarily to study laser-solid interactions. It incorporates a spherical harmonic expansion of the electron distribution function, where the number of terms is an input parameter that determines the angular resolution in momentum-space. The algorithm employs the full 3D electromagnetic fields and a rigorous linearized Fokker-Planck collision operator. The numerical scheme conserves energy and number density. This enables simulations for plasmas with temperatures from *MeV* down to a few *eV* and densities from less than critical to more than solid.

The main advantage of this approach is realized for collisional plasmas, in which angular scattering tends to isotropize the distribution function by rapidly damping the high-order harmonics. In collisional plasmas the code recovers transport coefficients with excellent accuracy. Furthermore, we demonstrate that it can model highly anisotropic collisionless plasmas by using two examples: the relativistic two-stream and the relativistic current-filamentation instabilities. As a first application of this code we present a preliminary study of electron transport for the interaction of intense ($I = 10^{15} – 10^{17}$ W/cm$^2$) short-pulse ($\tau = 1$ - 100ps) lasers with overdense plasmas.

# PERFORMANCE OF IGNITION CAPSULES WITH AEROGEL-SUPPORTED DT FUEL FOR THE NATIONAL IGNITION FACILITY (NIF) AND FOR REACTOR APPLICATIONS

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There is growing interest in fielding ignition capsules with aerogel-supported DT fuel (“foam-filled” capsules). For high rep-rate reactor applications, foam-filled capsules would have substantial benefits: much reduced fill time compared to β-layering and increased strength for ensuring target survival during injection into the chambers. For pure liquid DT fuel, the high vapor pressure results in a higher-than-desired DT gas density. But the vapor pressure is lowered once liquid DT is imbedded in a foam matrix, and the gas density is consequently closer to the desired density. We describe the performance of NIF-scale foam-filled capsules in both 1-D and 2-D simulations. The present limit for the lowest density foam is 0.02 g/cm$^3$ (yield decreases rapidly with increasing foam density). At this foam density, for liquid DT in foam, there is a 9% degradation in the clean 1-D yield if we include 2-D roughness up to a Legendre mode number of 60. This degradation in yield can be partially recovered if the radiation flux near peak laser power is increased by only a few percent or if the capsule aspect ratio is increased. However, higher drive causes more ablator burn off which can result in more growth in high modes, e.g., mode numbers up to 1000. 2-D high mode simulations show that a CH capsule with Si dopant is robust to RT-instability at the ablator-fuel interface and consequently most of the fuel region remains clean at the time of peak velocity. In comparison with capsules with clean DT fuel, the yield for foam-filled capsules falls off more rapidly with an increase in surface roughness. We will also present a statistical assessment of the capsule reliability to all expected manufacturing and physics uncertainties between capsules with clean DT fuel and with liquid DT in a foam. The performance of larger foam-filled capsules with yield between 150 to 200 MJ will also be presented.

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# Short-pulse laser amplification and saturation using stimulated Raman scattering*

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Recent theoretical and experimental work has focused on using stimulated Raman scattering (SRS) in plasmas as a means of laser pulse amplification and compression[1][2][3]. Importantly, the amplifying material is not susceptible to damage since the plasma electrons have been stripped from the ions, facilitating direct short pulse amplification without the need for stretching and compression stages used in chirped-pulse amplification (CPA). We present initial computational and experimental work on SRS amplification in a capillary-discharge-generated Xe plasma. The experimental set-up uses a ~100 ps pump pulse with an 800 nm wavelength seeded by a 100 fs pulse from a broadband source and counter-propagates the pulses through a plasma of length ~1 cm and diameter 0.1 cm. Results from initial experiments characterizing the plasma and on short-pulse amplification will be presented.

The SRS and capillary-discharge processes are both very complex, and we will use a number of simulation techniques to model this complexity. Particle-in-cell (PIC) simulations are typically used to study the SRS instability, however even large-scale PIC simulation domains cannot include the entire length of the capillary discharge. We are using the LSP PIC code for our modeling work in two important ways. First, LSP can be used as an explicit PIC simulation to study SRS in small sub-domains, ~100 μm. Second, it can model the capillary discharge used to create our preformed plasma for the SRS-amplification experiments. Modeling the capillary discharge itself will provide confidence in our understanding of the plasma conditions present in the experiments. We also wish to study the experiments using pF3D[4], which can model SRS over the length-scales of a capillary discharge. Ultimately, we would like to initialize LSP or pF3D with the output from LSP models of the capillary discharge. Additionally, we will discuss the role of SRS saturation and determine the possible significance of electron trapping, and the possible use of an electron-trapping model implemented in pF3D[5].

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# Magnetic Field Generation in Rayleigh-Taylor Unstable Plasmas

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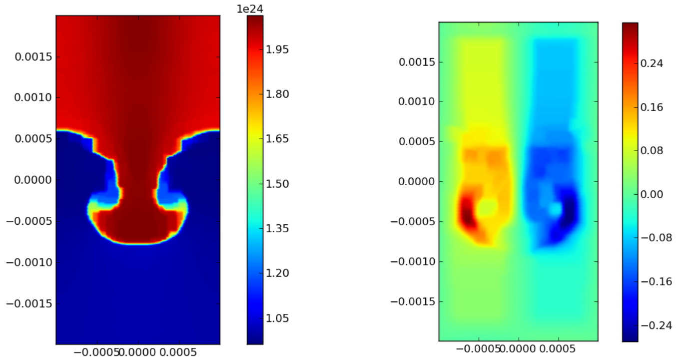
It has long been expected that Rayleigh-Taylor instabilities in ICF implosions can generate magnetic fields. This motivates the inclusion of a plasma model, more specifically one that includes ion and electron physics, for ICF simulations in order to accurately capture the magnetic fields. The two-fluid plasma model consists of the $5$-moment equations to describe the ions and electrons. It provides a continuity, momentum, and energy equation for each of the ion and electron species. Maxwell's equations are used to evolve the electric and magnetic fields. Washington Approximate Riemann Plasma (WARPX) code is a finite element code based on the full two-fluid plasma model which uses the Runge-Kutta discontinuous Galerkin method.

Single-mode studies of a Rayleigh-Taylor instability are performed in a stratified two-fluid plasma. The simulations are initialized such that a force balance exists in the system for both ions and electrons. This involves initializing the densities of both species, pressures of both species, and an electric field. The species velocities and magnetic fields are zero initially. The density of both species is then perturbed and the solution is allowed to evolve. Self-consistent magnetic fields are observed and these fields grow as the Rayleigh-Taylor instability progresses. Figure 1 presents preliminary results of the ion density (a) and the resulting out-of-plane magnetic field (b) in a $2$-dimensional simulation after $3.5\tau_{RT}$ (where $\tau_{RT}$ is the classical Rayleigh-Taylor growth time).



(a) (b)

Figure 1: Ion density in m$^{-3}$ (a) and out-of-plane magnetic field in T (b) after $3.5\tau_{RT}$

The severe time-step restrictions that result from solving an explicit full two-fluid plasma model require that the simulations are performed at lower densities as compared to ICF conditions. Scaling studies are included to determine how variations in density, temperature, gravitational acceleration, and instability wavelength affect the resulting magnetic fields. Explicit diagnostics of individual terms in the generalized Ohm's law are compared to determine their relative contributions to the electric fields, and consequently, the magnetic field. The studies performed will allow us to estimate the magnitude of the magnetic fields that can be expected in ICF and to understand the mechanism that causes the formation of such fields.

# Wednesday

# Thomson Scattering from Direct-Drive Targets

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In recent experiments on the Omega Laser Facility, a frequency-quadrupled (0.263-$\mu$m) laser beam was used for Thomson-scattering measurements of the coronal plasma conditions around a directly driven capsule. Nearly 0.7 ns after the initial picket illuminated the target, the plasma expanded to a distance 400 $\mu$m from the initial target surface and two characteristic ion-acoustic wave features were observed. The multiple ion-acoustic modes present in the CH plasma provide an accurate measure of the ion temperature while the features separation is a measure of the electron temperature. The light scattered from the ion-acoustic waves is heavily blue shifted as a result of the outward plasma flow velocity which, through conservation of momentum, drives shocks into the capsule. Furthermore, the ion-acoustic features provide a measure of the relative drift between the ions and electrons near the phase velocity of the ion-acoustic waves. This drift velocity is a reaction of the plasma to maintain quasi-neutrality as “fast” heat carrying electrons move outward and is related to the heat flux calculated in fluid simulations. The combination of these measurements provides a powerful set of criteria to assess hydrodynamic models and the results will be compared to both flux-limited and nonlocal models. This work was supported by the U.S. Department of Energy (DOE) Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority.

# Simulations and Analyses of Long-Scale-Length Plasma Experiments on the Omega EP Laser Facility

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This work reports on simulations and analyses of long-scale-length plasma experiments performed on the Omega EP Laser Facility using the two-dimensional radiation hydrodynamics code *DRACO*. Understanding laser–plasma interaction (LPI) in long-scale-length plasmas is essential for direct-drive-ignition designs on the National Ignition Facility (NIF). For direct-drive-ignition targets on NIF using plastic ablators, the typical density scale length is about $L_n$ ~ 500 $\mu$m at the quarter-critical regime. At a drive laser intensity of ~8 × $10^{14}$ W/cm$^2$, LPI processes such as stimulated Brillouin scattering, stimulated Raman scattering, and two-plasmon decay (TPD) may grow above their gain thresholds in such long-scale-length plasmas. To study these LPI processes in plasmas of scale-length similar to NIF conditions, we have performed planar-target experiments using large distributed phase plates on the Omega EP Laser Facility. We have created long-scale-length plasmas of $L_n$ ~ 300 to 400 $\mu$m with beam energies currently available on OMEGA EP. The total amount and temperature of TPD-produced fast electrons are experimentally inferred using both continuous hard x-ray signal and $K_\alpha$ emission measurements. The trend of fast-electrons production depending on the plasma conditions at different laser intensities and target materials has been analyzed using radiation–hydrodynamic simulations. The ultimate goal is to gain a full understanding of these LPI processes to find ways to suppress/mitigate them in such long-scale-length plasmas. This work was supported by the U.S. Department of Energy (DOE) Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority.

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# Impeding hohlraum plasma stagnation in inertial-confinement fusion

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This talk [1] reports the first time-gated proton radiography of the spatial structure and temporal evolution of how the fill gas compresses the wall blow-off, inhibits plasma jet formation, and impedes plasma stagnation in the hohlraum interior. Interpenetration of the two materials occurs due to the classical Rayleigh-Taylor instability as the lighter, decelerating ionized fill gas pushes against the heavier, expanding gold wall blow-off. The important roles of spontaneously generated electric and magnetic fields [2, 3] in the hohlraum dynamics and capsule implosion are demonstrated. The heat flux is shown to rapidly convect the magnetic field due to the Nernst effect. This experiment provides novel physics insight into the effects of fill gas on x-ray-driven implosions, and will have important impact on the ongoing ignition experiments at the National Ignition Facility.

This work was supported in part by US DOE and LLE National Laser User's Facility (DE-FG52-07NA28059 and DE-FG03-03SF22691), LLNL (B543881 and LDRD-08-ER-062), LLE (414090-G), FSC (412761-G), and General Atomics (DE-AC52- 06NA 27279). A. B. Zylstra is supported by the Stewardship Science Graduate Fellowship (DE-FC52-08NA28752).

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Abstract for the Anomalous Absorption Conference in San Diego, CA June 19-24, 2011:

# The high flux hohlraum model, one year later*

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Last year at this time, we were first proposing the use of the "high flux model" (HFM) in the ICF design code Lasnex, in order to clarify the performance of the 2009 National Ignition Campaign (NIC) gas filled/capsule imploding hohlraum-energetics campaign. In particular HFM helped explain the level and spectrum of the Stimulated Raman Scattered (SRS) light, the tendency towards pancaked implosions, and drive that exceeded (standard model) predictions early in the campaign, and lagged those predictions late in the campaign. That HFM used a detailed configuration accounting (DCA) atomic physics and a generous flux limiter (f=0.15) both of which contributed to predicting a hohlraum plasma that was cooler than the standard, XSN average atom, f=0.05 model. Here we review developments since then which include: Confirmation of the SRS losses in the $23^0$ beams that were only postulated then (by the need for energy balance using the HFM); Hotter plasmas as we exceed 1 MJ laser drive; An improved DCA model; A non-local electron transport package that is well behaved from a numerical point of view and can replace the use of a flux limiter; Exercising an improved laser deposition package that allows for back propagation of the SRS light within the hohlraum plasma, and the creation of hot electrons via SRS..

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## Progress on Drive and Symmetry for Ignition on NIF*

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In indirect drive targets, the hohlraum needs to provide the drive and symmetry needed for ignition. While there is no requirement on laser plasma interactions (LPI), LPI needs to be low enough that we can meet the drive and symmetry requirements. In addition, there are requirements on the preheat of the capsule by hot electrons and high energy xrays. Over the past two years, we have carried out experiments on NIF to understand drive, symmetry, and LPI in ignition-scale hohlraums. We have shown that we can use crossbeam energy transfer to tune symmetry. We have demonstrated P2/P0 tuning to within the ignition specification at 1 MJ and 1.3 MJ with symcaps and demonstrated symmetry very close to the ignition specification with 1.3 MJ in a layered (THD) implosion. We have shown drives that reach 300 +/- 5 eV radiation temperature inside the hohlraum with 1.3 MJ of laser energy. At 1 MJ, we have seen that the drive is reproducible to the +/- 3% specification. This paper will discuss the results of experiments on drive and symmetry as well as methods for further optimizing the targets for ignition including optimizing the hohlraum geometry, and using uranium as the hohlraum material.

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# Ignition Hohlraum Radiation Temperature*

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This talk describes how to use x-ray diagnostic data from National Ignition Campaign (NIC) experiments to infer the hohlraum radiation temperature $T_{RAD}$ that drives the capsule implosion. Post-processed simulations from the radiation-hydrodynamics code HYDRA guide the techniques used to infer the capsule $T_{RAD}$. Determining the radiation temperature requires knowledge of the radiant intensity (power/solid angle) emitted by the hohlraum laser entrance hole (LEH) and the size of the x-ray source. On the National Ignition Facility (NIF), the specific radiant intensity of the hohlraum is measured by the multi-diode array DANTE. The LEH size is determined using the Static X-ray Imagers (SXI). The SXI has two channels: a channel with beryllium and titanium filters measures the LEH at $h\nu > 2$ keV, while a multi-layer mirror channel takes images at $h\nu = 870$ eV, near the peak of a Planckian at $T_{RAD} = 300$ eV. The two SXI channels together are used to define the characteristic size of the LEH and to correct for x-rays measured by DANTE that do not originate from this region. The x-ray intensity seen by the capsule is determined by solving the irradiation integral using ray-tracing techniques and is compared to the x-ray intensity inferred by DANTE. This technique is then applied to 1 MJ and 1.3 MJ hohlraum experiments from 2011.

*Prepared by LLNL under Contract DE-AC52-07NA27344

# SIMULATIONS OF THE NIF IGNITION CAPSULE DESIGN IN 3-D*

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For sufficiently large initial amplitudes or sufficiently rapid growth rates, interface instabilities in inertial confinement fusion capsule implosions can develop into the nonlinear phase. It is well known that the nonlinear evolution of these instabilities differs between 2-D rotationally or translationally symmetric geometry and the genuine 3-D geometry that prevails in experiment. Accurate modeling of these types of instabilities hence requires a legitimately 3-D treatment. Of course, inherently 3-D initial perturbations, such as crossed grooves in the cryogenic fuel layer or clusters of ablator surface bumps, can also only be modeled in fully 3-D simulations. Several HYDRA simulations of the current ignition capsule design for the National Ignition Facility have recently been run focusing on two types of 3-D nonlinearity: short wavelength instabilities that develop at the interface between the deuterium-tritium fuel and the plastic ablator, and the growth of perturbations seeded by large crossed grooves in the fuel layer along with clusters of ablator surface bumps. While the detailed 3-D evolution of these instabilities is found to be different in 3-D, the ultimate capsule performance is found to be well represented by 2-D analogues. A comparison of 2-D and 3-D simulations of the jet seeded by the capsule fill tube similarly shows the predominantly 2-D nature of this flow with only minor modifications emerging in 3-D.

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## Modeling cross-beam energy transfer on NIF experiments

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Cross-beam energy transfer between laser beams on the NIF has been routinely used since the beginning of the experiments on NIF in 2009 to redirect the laser energy inside the hohlraum and optimize implosion symmetry and laser-target coupling. Large amounts of energy transfer (up to x2 on some beams) are typically required to compensate for absorption and backscatter (predominantly stimulated Raman scattering) energy losses of some of the beams on their way to the hohlraum wall. Our cross-beam energy transfer model typically has to be empirically calibrated against experiments in order to reproduce the measured implosion symmetry. This is usually done by setting an arbitrary saturation level to the plasma waves associated with energy transfer.

In this talk, we will review our modeling of cross-beam energy transfer in NIF hohlraums. Our working model, which consists of gain calculations along straight rays coupled to hydrodynamics calculations, will be compared to a massively parallel 3D steady-state wave model ("SLIP"). We will revisit the effects of refraction, speckles, and intensity profiles modification using these two models. We will also investigate the possible saturation mechanisms of the plasma waves during the cross-beam energy transfer process. In particular, we will revisit the effect of smoothing by spectral dispersion for new target designs where some of the energy transfer occurs in the gold blowoff plasma.

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# Reducing the Cross-Beam Energy Transfer in Direct-Drive Implosion Targets Through Laser-Irradiation Control

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Cross-beam energy transfer via stimulated Brillouin sidescattering affects most direct-drive implosions and reduces the hydrodynamic efficiency of the laser drive. This was identified via scattered-light spectroscopy[1] and post-processing of the hydrodynamic simulations. More recently, this process has been incorporated into the simulations[2] and detailed identification of the losses has been possible. We have identified that the outer parts (rays) of each beam interacts via stimulated Brillouin sidescattering with the central rays of other beams to extract energy from the latter that would otherwise be absorbed most effectively. Based on this concept we have found an irradiation configuration that avoids most, if not all, of the coupling losses at the expense of drive uniformity. For this purpose the beam sizes have been reduced relative to the target diameter. This leads to reduced irradiation uniformity which is presently being assessed. We present data demonstrating the enhanced absorption using changing beam-size-to-target-diameter ratios (the standard ratio is ~1). The target size was kept constant in these experiments. The corresponding scattered-light spectra and their interpretation will also be presented. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

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2. I. V. Igumenshchev *et al*., Phys. Plasmas **17**, 122708 (2010).

# Crossed-Beam Energy Transfer in Polar Direct-Drive Implosions

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Stimulated Brillion scattering can transfer energy between laser beams that cross in a plasma. The beams cross each other at many locations as they refract through the coronal plasma in 60-beam symmetric OMEGA direct-drive implosions. Crossed-beam energy transfer (CBET) in this geometry results in energy being passed from the incident beams to the unabsorbed laser light exiting the plasma. As a result, laser energy "bypasses" the high-absorption region of the plasma near the critical surface. The total laser absorption in the implosion can be reduced by 10% to 20% by CBET. The laser beam profile is effectively changed as CBET preferentially removes energy from the inner portion of the beam profile. Polar drive is a concept to perform direct-drive implosions on the NIF using its existing nonsymmetric beam geometry. The power and pointing of the NIF beam cones are optimized to provide the most symmetric illumination possible for a spherical target. The effect of CBET in the 3-D polar-drive beam geometry is calculated for each of the beam cones and the parts of their profiles most affected are identified. This work was supported by the U.S. Department of Energy (DOE) Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority.

# Modeling of Energy Transfer Between Spatially Incoherent Crossing Laser Beams

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In direct-drive inertial confinement fusion experiments on the OMEGA Laser System, targets are irradiated by multiple laser beams crossing at different angles in the plasma corona. Incident laser beams are usually randomized in space (using distributed phase plates) and in time (using smoothing by spectral dispersion). The nonlinear interaction of crossing laser beams through ion-acoustic density perturbations may lead to energy transfer between the beams that influences laser absorption and scattering.[1]

The nonlinear propagation of crossing randomized laser beams in the plasma corona has been studied using the nonparaxial model of light propagation.[2] This model allows us to characterize the angular spreading and the frequency broadening of the laser beams caused by nonlinear interaction. The results of the nonparaxial model[2] for the beam-to-beam energy transfer are compared to the results of the three-wave model used in large-scale simulations of experiments on OMEGA Laser System.[1]

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1. I. V. Igumenshchev *et al.*, Phys. Plasmas **17**, 122708 (2010).
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# Thomson Scattering in High Energy Density Plasmas

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Thomson scattering is a powerful technique used to accurately measure conditions in dense plasmas such as temperature, density, ionization state, and flow. In the collective regime, Thomson scattering is used to measure density fluctuations associated with plasma waves, and is often used to detect waves driven by various instabilities. In recent years, Thomson scattering has been successfully extended to the x-ray regime to probe near-solid-density plasmas. We review the use of Thomson scattering in various high-energy-density plasma experiments, and discuss potential future directions for this technique.

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# Studies of Spectral Modification and Limitations of the Modified Paraxial Equation in Laser Wakefield Simulations

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## Abstract

Laser pulses propagating through plasma undergo spectra broadening through local energy exchange with driven plasma waves. For propagation distances on the order of a depletion length frequency shifts can be comparable to the laser central frequency, a result of approximate action conservation. Over these distances, the electromagnetic dispersion predicted by the modified paraxial equation is not longer valid, due to its reliance on slow temporal variation. However, propagation simulations using the modified paraxial equation can be more efficient than those solving the full second order electromagnetic wave equation. Here we examine the local frequency shift, energy depletion, and action conservation of nonlinear (a0~1) laser pulses using the modified paraxial simulation WAKE. Although action is theoretically conserved, we observe that for large red shifts due to pulse depletion, the numerical dispersion results in decay of the action. Numerical analysis of the propagation algorithm was conducted and verified the observed behavior. While increased resolution improved action conservation, the simulation times required eliminated the strength of the modified paraxial solver--efficiency. We show that algorithms for the full second order wave equation are more conservative with the potential to be more efficient in situations where propagation over several depletion lengths is important.

## Acknowledgement

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# 2.5D Plasma Evolution and Evolving Beam Diver in WAKE for Plasma Wakefield Acceleration

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WAKE (previously 2D, now 2.5D) provides an efficient simulation platform for plasma wakefield acceleration (PWFA). It utilizes the quasi-static approximation (QSA), in which the beam driver remains unchanged during the transit time of plasma electrons. The 3D code QUICKPIC also uses QSA and has shown speed ups of 100-1000 over the full particle code OSIRIS. For axisymmetric beams a 3D code is not necessary and the 2D axisymmetric code WAKE can further reduce the computation time. However, for cold, under dense plasma, the 2D nonlinear wakefield features a logarithmic divergence corresponding to the spatial convergence of particles at a single point on the propagation axis one plasma period behind the driver. Experimentally the divergence is regularized by the driver asymmetry, beam loading and finite plasma temperature. Here we implement 2.5D evolution of the background plasma with finite temperature in WAKE. This extension of WAKE provides angular momentum dynamics, preventing axis crossing, and ensures convergence of the electric field for sufficient resolution. Thermal modifications to plasma wakefields are examined for range of temperatures relevant to the experiments. In addition, we modify WAKE to treat the kinetic evolution of the beam driver.

# ePLAS modeling of laser-plasma interactions*

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e-PLAS[1] is an implicit/hybrid simulation code that has modeled pulse power switches, short pulse laser foil interactions, ICF cone targets[2], laser-driven hot electron transport in wires[3], fast ion emission from shell targets, shock ignition, laser induced lightning, and B-field-driven production and merger of plasma jets. For laser target interactions the code tracks laser light to critical, hot electron creation from light absorption, and incident hot electron and cold return flow with electron drag and scatter. ePLAS uses either PIC or fluid modeling of multiple electron and ion components. It calculates *E*- and *B*-fields by the implicit moment method[1]. It is 2D in either Cartesian or cylindrical geometry. It has a new implicit electron current mode for long time scale problems. The code can determine degrees of ionization from either fixed, Saha or Sesame equations of state. Problem setup and meshing with the executable is simplified via FORTRAN allocatable memory. Code output can generate $K_\alpha$ imagery. Graphics can be viewed via the IDL Virtual Machine. ePLAS runs efficiently on PCs under the XP, W7, Mac Snow Leopard, and Linux OpenSuse operating systems. See: http://www.researchapplicationscorp.com. We will discuss recent applications of ePLAS to short pulse laser-driven electron transport and the generation of fast ions.

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# Forward directed ion emission in a LWFA with ionization Injection

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With the short-pulse high-intensity lasers available today it is now possible to generate energetic particles such as MeV ions and GeV energy. Recent experiments have also shown that using ionization induced trapping [1, 2] it is also possible to increase the accelerated charge to nC with lower laser intensities.

At the wake–vacuum interface the highest energy electrons leave the plasma and set up a DC potential or a sheath. The lower energy electrons however are recirculated in a vortex kind of motion [3, 4] producing an azimuthal magnetic field at the interface. This time dependent B field in turn produces an additional electric field. Both of these effect can then accelerate a thin layer of ions that is located at the plasma vacuum interface, to several MeV in energy.

While this forward directed ion emission has been seen in underdense plasmas using a PW class laser [5], we show here that it also occurs in very dilute plasmas where the electrons are accelerated by the wakefield induced by the short laser pulse.

In this work we show that energetic ions were produced in an underdense 2x10^19 cm^-3 plasma created by a 50 fs Ti:Sapphire laser with 5 TW's of power.The physics of the interaction is studied with 2D and 3D particle-in-cell simulations.

Work supported by DOE grants DE-FG02-92ER40727, NSF grants PHY-0936266 and FCT grant SFRH/BD/37838/2007.

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# Status of Directly-Driven Shock Ignition Target Designs*

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## Abstract

We report on the status of directly driven shock ignition targets designed for inertial fusion energy applications. We have examined the impacts of laser-plasma-instability (LPI) induced intensity limitations and hydrodynamic instability on the gain and robustness of high gain targets. The target aspect ratio can be used to control the drive intensity (during the compression and acceleration of the fuel shell), but with some impact on symmetry and hydrodynamic stability. The biggest lever in these designs is the strength of the ignitor pulse, which will depend upon the inevitable and as yet unpredictable LPI generated during the high intensities ($I > 10^{16}\ W/cm^2$) envisioned for the ignitor pulse.

* Supported by US DoE/NNSA and US DoN

## Hot Electron Generation from Laser-Cone Target Interactions in Fast Ignition

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We present recent two-dimensional particle-in-cell (PIC) simulations for the cone-in-shell integrated fast ignition experiments on the Omega laser facility [W. Theobald et al., Phys. Plasmas, May 2011]. The initial plasma density profile in the PIC simulations is taken from hydrodynamic simulations, including the pre-plasma inside the gold cone generated by the prepulse. The main pulse of Omega-EP has a peak intensity of $10^{19}$W/cm$^2$, duration of 10 ps and total energy of 1 kJ. Hot electron generation from laser-pre-plasma interactions and electron transport in under-100n$_c$ plasmas are studied. We will characterize the hot electron source, including its energy and angular distribution. This work is supported by Fusion Science Center for Extreme States of Matter under the DOE Grants No. DE-FC02-04ER54789 and by Laboratory for Laser Energetics under the DOE Cooperative Agreement No. DE-FC52-08NA28302.

# Modeling NIF Polar Direct Drive Capsule Implosions in 2D and 3D using HYDRA

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## Abstract

Simulations have been performed to determine the effects of asymmetries on direct drive NIF implosions. A 2.2 mm diameter, 30 micron thick CH capsule filled with 5 atmospheres DT was assumed. The HYDRA radiation-hydrodynamic code[1] was used to model the 96 NIF beams in the upper hemisphere impinging in a polar direct drive (PDD) configuration[2] on the capsule. Asymmetries in both polar and equatorial directions around the capsule were observed. In the equatorial direction, the finite number of NIF beams produce 1% ripples in the radial implosion velocity (when the current NIF phase plates are used). Asymmetries in the polar direction are dependent on both the offset (from target chamber center) and defocus of the NIF beams, but was in the range of a few percent or more. Additional simulations to include the effects of missing beams and high-mode number equatorial capsule defects have been performed to assess their effects on symmetry and yield. The results of these simulations and their relation to similar PDD experiments recently performed at Omega will be shown.

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# Laser Hohlraums for Warm Dense Matter Studies

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We have studied WDM generation by thermal x-rays using vacuum hot hohlraums using parameters of the lasers at the National Ignition Facility (NIF). The generation of x-rays from hot hohlraums and its use to radiatively heat samples were studied by Kauffman et al. (*1994*), Lindl et al. (*2004*), and Schneider (*2005, 2007*). The focus of our study is to evaluate the feasibility of creating WDM with minimal transient behaviors and spatial gradients suitable for investigation of equations of state of many materials and densities. In our conceptual design calculations, x-rays are generated in two vacuum hohlraums irradiated by laser beams with a target sample between them. Thermal x-rays are generated in the hohlraums through the interactions of the laser beams with the gold walls and energetic electrons with the gold plasma. The various absorption and emission processes lead to a thermalized x-ray source. The intense x-rays subsequently burn through the end foil and heat the target sample. The target sample is radially confined by a tamper so that the target sample will undergo isochoric heating to become a WDM of a chosen density. A preliminary LASNEX calculation was carried out to model a half-hohlraum, which was 1 mm in length and 1.6 mm in diameter. The walls were 40 $\mu$m thick gold, except for a region thinned to 5 $\mu$m in the back wall. The targets are the vacuum hohlraums, however a low-density background gas with low-density $\rho=1\times10^{-5}$ g/cm$^3$ was included. Most inputs (e.g. EOS, opacities, *etc.*) were taken from NIC ignition calculations, except for the mesh, rezoning and laser pointing. A laser energy of 50 kJ was incident on the target in a 2-ns long flattop pulse with an intensity of ~$4\times10^{15}$ W/cm$^2$. The interactions between laser photons, energetic electrons, gold walls, and plasma resulted in intense high-temperature x-rays. Under these conditions in our simulation, a radiation temperature of ~300 eV was obtained by a synthetic Dante diagnostic aimed at the laser entrance hole (LEH). An additional synthetic Dante diagnostic aimed at the thin back wall measured a temperature of ~100 eV after the radiation burned through the hohlraum back wall. In our presentation, we will show calculations of physical characters of WDM created by thermal x-rays with different temperatures and a conceptual design to field such an experiment.

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# The effects of laser absorption on direct-drive capsule experiments at OMEGA*

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Accurate prediction of capsule implosions at OMEGA for the High-Z project is a challenge to our modeling capability. The High-Z capsule implosions are part of a strategy to experimentally validate burn models in the presence of high-Z dopants. In this presentation, we will critically examine the calculational assumptions used in our modeling of the experiments, and examine one possible source of modeling difficulty in the implosion hydrodynamics. A novel treatment of laser-capsule interaction improves the match to the measured scattered light, which significantly improves the calculated compression ($\varrho$R). However, there continues to exist a discrepancy between the calculated and measured yields for large amounts of dopant. For the remaining discrepancy, we have not distinguished between residual hydrodynamic issues or burn issues, but a path forward has been developed.

The implosion dynamics and yield of an ICF capsule can be greatly affected by the inclusion of high-Z material in the fuel. If the material is either intentionally mixed into the fuel as a diagnostic[1], or if mixing of the shell occurs due to hydrodynamic instabilities, then calculations must be verified. To better understand the effects of high-Z materials on burn, a series of experiments have been fielded at the OMEGA laser[2]. The targets are glass shells with an outer diameter of ~920 μm and a thickness of ~4 μm, and are filled with a mixture of $D_2$ and $^3$He. They may also be filled with controlled amounts a dopant, Ar, Kr, and/or Xe. These targets are then directly driven with a 1.0 ns (0.6 ns) square laser pulse having a total energy of 23 kJ (13.8 kJ), and the data compared with yield and burn-temperature predictions from 1-d radiation-hydrodynamics calculations. To better model the laser absorption we compare the calculated absorbed laser energy to measurements using the method of Seka *et al.*[3], which determines an electron thermal flux-limiter and a multiplier on the incident laser energy.

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# Efficient Raman Amplification into the Multi-Petawatt Regime

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Contemporary high-power laser systems make use of solid-state laser technology to reach petawatt pulse powers. The breakdown threshold for optical components in these systems, however, demands meter-scale beams. Raman amplification of laser beams promises a breakthrough by the use of much smaller amplifying media, i.e. millimetre diameter wide plasmas, but to date, only 60 GW peak powers have been obtained in the laboratory, far short of the desired multi-petawatt regime. Here we show, through the first large scale multi-dimensional particle-in-cell simulations of this process, that femtosecond pulses having multi-petawatt peak powers can be obtained, but only in a narrow parameter window dictated by the growth of plasma instabilities. Furthermore, we show that this process scales to short wavelengths allowing compression of X-ray free electron laser pulses to attosecond duration.

In addition, we show that the duration of the amplified probe pulse can be controlled by adjusting the properties of the pump beam, allowing the generation of picosecond probes at petawatt peak powers. This has important consequences for the demonstration of fast-ignition inertial confinement fusion.

# Raman Scattering of Intense, Short Laser Pulses in Modulated Plasmas

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We examine the exponentiation of the Raman forward scattering instability in modulated plasma channels computationally and analytically. An evolution equation for the complex phases of the Raman scattered waves treating the spatial localization and discrete nature of the channel modes is derived. Simulations with WAKE [P. Mora and T.M. Antonsen Jr., Phys. Plasmas **4**, 217 (1997)] verify the theory in the linear growth regime and provide insight into the nonlinear stage of the instability when cascading and pump depletion play a role. We find that the exponentiation in modulated channels depends on two factors: the increase in coupling due to the increased plasma wave number in the high density regions of the channel and a decreased coupling due to the reduced longitudinal spatial coherence. For the parameters considered, simulations show that the finite extent of the pump pulse is more significant in determining the exponentiation than phase mixing due to the transverse variation of the channel. Both the theory and simulations confirm that modulated channels allow for the stable guiding of longer pulses than non-modulated channels.

# Characterization of plasma wake excitation and particle trapping in the nonlinear bubble regime

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Present laser-plasma accelerator experiments typically operate in a highly-nonlinear regime characterized by expulsion of the plasma electrons by the laser ponderomotive force and formation of a co-moving ion cavity (bubble). In these laser-plasma accelerator experiments, energetic electron beams are generated by self-trapping background plasma electrons. We investigate the process of nonlinear wake formation by an ultra-short and intense ($eA_{\mathrm{laser}}/m_ec^2 > 2$) laser pulse interacting with an underdense plasma. A detailed analysis of particle orbits in the wakefield is performed by using reduced analytical models and numerical simulations using the 2D-cylindrical, envelope, ponderomotive, hybrid PIC/fluid code INF&RNO recently developed at LBNL. In particular we investigate the laser-plasma conditions required for injection/trapping of background plasma electrons in the nonlinear wake. The role of plasma temperature will be investigated. Characterization of the phase-space properties of the injected particle bunch will also be discussed.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

# Electron acceleration by circular polarized laser pulse with phase modulation

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Acceleration of electrons by intense laser pulse is important in applications such as fast ignition in inertial confinement fusion and table-top particle acceleration. Most schemes are based on nonlinear interaction between the laser and the plasma. On the other hand, under suitable conditions electrons in vacuum can also be directly accelerated by electromagnetic waves. Recently, it is found that electrons can be efficiently accelerated to high energies by a radially echelon phased (EP) laser pulse [**?** ]. In this talk, we show that a circularly polarized (CP) laser pulse with phase modulation in the transverse direction can also efficiently accelerate electrons. The mechanism of electron acceleration is physically similar to that in a radially EP laser pulse [**?** ]. An electron in vacuum accelerated by a laser field will in general phase slip with respect to the latter since it is slower than the light speed. Thus, even if the electron is initially optimally placed in the laser field, it will become out of phase quickly and decelerated until it is trapped again in the next suitable wave phase. On average the accelerations and decelerations cancel each other, resulting in very little or no net energy gain by the electron. The staircase-like phase structure of the EP laser field encourages electron trapping in the favorable wave phase, thus greatly increasing the effective acceleration distance. For a CP laser pulse, the acceleration takes place not only in the axial, but also in the transverse direction. It is also shown that with an EPCP laser, the net acceleration of the electron is not too sensitive to its initial phase with respect to the laser field as that with a linearly polarized EP laser, and that a bunch of initially Maxwellian distributed electrons can also be accelerated to high energies by an EPCP laser pulse. The results are confirmed by particle-in-cell simulation using the VORPAL code.

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# Trapping of Low Energy Electrons in Quasi-Phase Matched Direct Laser Acceleration

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Copropagation of a laser pulse and a relativistic electron beam in a corrugated plasma channel has been proposed for the direct laser acceleration of electrons [Palastro *et al*, Phys. Rev. E 77, 036405 (2008)]. In an axially uniform channel, the phase velocity of the laser pulse is strictly superluminal, precluding net energy transfer from the electromagnetic wave to electrons. A laser pulse propagating through a corrugated plasma channel consists of spatial harmonics whose phase velocities can be subluminal. The subluminal spatial harmonics can be phase matched to relativistic electrons resulting in trapping in the electromagnetic wave and linear energy gain over the interaction length. Scaling laws, supported by simulation results, predict linear accelerating gradients of ~100 MeV/cm for ~2 TW of laser power and ~0.6 J of laser energy. However, because the phase velocity of the spatial harmonic is constant, phase matching over extended acceleration lengths requires large initial electron energies. Here we examine several modifications to the density profile, and as a result the phase velocity, which lowers the initial electron energy required for trapping. In particular we examine ramped density profiles, tapered channel radii, and tapered modulation periods. Each modification will be examined using the 2D cylindrical PIC simulation TurboWAVE, which at the same time will provide the first fully self-consistent PIC simulations of quasi-phase matched direct acceleration. Preliminary examinations into optical injection will also be presented.

# Energetic Electron Generation in Two-Plasmon Decay Instabilities in Direct-Drive Inertial Confinement Fusion

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We present a series of 2-D particle-in-cell (PIC) simulations using the full PIC code *OSIRIS* on the long-term (~10-ps) nonlinear behaviors of the two-plasmon-decay (TPD) instability for parameters relevant to inertial confinement fusion. When the TPD threshold is exceeded, the simulation results show that significant laser absorption and energetic electron (>50-keV) generation occur in the nonlinear stage. The energetic electrons are mostly forward oriented, which poses a preheating risk for targets. The hot electrons are stage-accelerated from the low-density region to the high-density region. New modes with small phase velocities develop in the low-density region after saturation. These modes can couple to background thermal electrons and form the first stage for electron acceleration. A fluid code has been developed to show that similar new TPD modes can develop under static ion-density fluctuations. In the PIC simulations the ion-density fluctuations are observed to be driven by plasma waves through the ponderomotive forces. The laser absorption and hot-electron production from these 2-D plane-wave–driven PIC simulations are higher than experimental observations, which could indicate the uncertainty in the simulation parameters or the importance of non-ideal factors such as speckle structure in the actual laser profile. This work was supported by U.S. Department of Energy Grants No. DE-FG02- 06ER54879, No. DE-FC02-04ER54789, No. DE-FG52- 06NA26195, No. DE-FG52-09NA29552, and Cooperate Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

Langmuir Turbulence and Suprathermal Electron Production from the Two-Plasmon Decay Instability Driven by Crossed Laser Beams in an Inhomogeneous Plasma - **H.X. Vu[1], D.F. DuBois[1,2], J.A. Myatt [3], and D.A. Russell[4]**

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The fully kinetic reduced particle-in-cell (RPIC) method, utilizing novel diagnostics, has been applied to simulations of the two-plasmon decay (TPD) instability in an inhomogeneous plasma for parameters consistent with recent direct drive experiments related to laser-driven inertial fusion. Crossed beam geometries are considered for integration times exceeding 20 ps. The nonlinear saturated state of TPD is one of Langmuir turbulence involving the coexistence of the Langmuir cavitation and collapse, the Langmuir decay instability (LDI), and, for times exceeding about 10ps, ponderomotive density profile modification. The saturated state is characterized by very spiky electric fields and Langmuir cavitation occurs most strongly inside density channels produced by the ponderomotive beating of the crossed laser beams, at the density which produces a degenerate *common* Langmuir wave. Statistical analyses show that cavitons follow Gaussian statistics. At times exceeding 20ps, the excited Langmuir turbulence moves away from the quarter critical surface to lower densities. Hot electron temperatures in the range of 30keV to 60keV are calculated with transverse recycling of the heated electrons with significantly smaller values without recycling. The heated electron distribution function is, in all cases, bi-Maxwellian. In all cases considered here, Langmuir cavitation and collapse provides the dissipation, by producing suprathermal electrons, which stabilizes the system in saturation and drives the Langmuir wave (LW) spectrum to the small dissipation scales at the “Landau cutoff.” The net hot electron energy flux out of the system is a small fraction (~0.5% - 2%) of the input laser power in these simulations.

# Convective Multibeam Two-Plasmon Decay for Beam Configurations Relevant to Polar Direct-Drive

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To optimize drive uniformity for direct-drive experiments on the NIF, much of the beam intensity will be non-normally incident on the target. Two-plasmon decay (TPD) is the instability currently of most concern for direct-drive irradiation since it has been found to produce significant amounts of hot electrons in OMEGA direct-drive experiments. Furthermore, it has been observed to depend on the collective rather than the single-beam irradiation intensity. Therefore it is of interest to examine how TDP depends on the angular distribution of the beams incident on the target. This dependence will also affect the anisotropy of the hot-electron propagation and thus their propensity to preheat the imploding target core and reduce implosion efficiency. This talk will examine the effects of three angular beam parameters (the angle between two beams and the *s*- and *p*-polarized angles of incidence of the beam centroid) on the growth and anisotropy of the instability. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

# Evaluation of a Quasilinear Model for the Two-Plasmon-Decay Instability in Inhomogeneous Plasmas

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The two-plasmon-decay instability is a potential source of target preheat in direct-drive ICF. A quasilinear-Zakharov model of two-plasmon decay[1] is described and its validity tested, first by the use of a test particle model, and then by comparisons with reduced particle-in-cell calculations.[2] The test particle model is used to compare the diffusion of particle orbits against quasilinear predictions for a few sample cases of experimental importance. Finally, the self-consistent quasilinear-Zakharov model is compared against reduced particle-in-cell calculations for a range of parameters and the respective predictions for hot-electron temperature and hot-electron flux are compared.

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# Laser-Plasma Instabilities in the Quarter Critical Density Region Driven by the Nike KrF Laser*

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The Krypton-Fluoride (KrF) laser is a premiere candidate for inertial confinement fusion due to its short wavelength (248 nm), large bandwidth (1-3 THz), and beam smoothing by induced spatial incoherence. These qualities improve the overall hydrodynamics of directly driven pellet implosions and should permit higher laser intensities due to increased thresholds for laser plasma instabilities (LPI) relative to those for longer wavelength lasers. Intensity thresholds for LPI in the quarter critical region for targets irradiated by the Nike KrF laser have been determined using solid planar plastic targets, a range of pulse lengths ($0.35\text{ns} < \tau < 1.25$ ns), and intensities up to $2\text{x}10^{15}$ W/cm$^2$. Variation of the laser pulse allowed observations with varied electron temperatures and electron density scale lengths. This talk will review the 1/2 $\omega_o$, $\omega_o$, 3/2 $\omega_o$, and x-ray data collected during these experiments. Hard x-ray measurements have shown evidence for hot electron generation and a preliminary determination of $T_{hot}$ of ~ 20-40 keV.

*Work supported by DoE/NNSA and ONR

# GENERATION OF STRONG TERAHERZ RADIATION AND SIMULATION OF LOOP-TOP X-RAY EMISSION IN SOLAR FLARES

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Though THz radiation can be generated with various ways, it is still a big challenge to obtain strong tabletop sources. One of the ways to obtain high power THz sources is based on relativistic intense laser-plasma interactions, in which high laser intensity (up to $10^{19\text{-}20}$W/cm$^2$) can be applied. We have generated strong plasma-based THz radiation with pulse energies larger than ~ 50 μJ/sr using only ~100 mJ laser pulses to irradiate solid targets. The energy of a single THz pulse increases with the pump laser energy. We find that the THz radiation closely depends on the scale length of preplasmas.

Magnetic reconnection (MR) is believed to play an important role in many different plasma phenomena including solar flares, star formation, and other astrophysical events. The loop-top x-ray source in solar flares is one of the most famous observation evidences for MR model. Mega-gauss (MG) magnetic fields could be generated in hot, high-density plasmas by irradiating a solid target with high-power laser beams. During the laser pulse the magnetic field is quasi-steady and approximately "frozen" in the plasma expanding laterally. Based on this quasi-steady state of the magnetic field, we reconstruct the topology of magnetic reconnection in laboratory by using Shenguang II laser facility. The similar results of loop-top x-ray source in solar flares are observed. By applying the scaling law of magnetohydrodynamics they found the physical parameters of both systems have highly similarity.

# Increasing dwell time in a plasma liner driven magneto-inertial fusion device with a special liner shaping

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In contrast to conventional ICF schemes, magneto-inertial fusion (MIF) relies on maintaining the compressed hot spot within the thermonuclear burning condition for as long as possible, rather than on initiating the burn wave. Consequently, in the best case scenario the MIF target persists in the state of maximum compression after the liner-target interface reaches the stagnation radius. Also, the plasma liner driven version of MIF provides substantial freedom in shaping the profiles of the liner pressure, density and fluid velocity.

We explicitly find a regime of liner evolution such that after the liner-target interface is stagnated and the shock wave starts propagating outward into the incoming liner flow, the shocked liner pressure stays constant. The solution describing this regime exactly satisfies both the fluid equations and the jump conditions at the shock front. Thus, as long as the liner flow with prescribed pressure, density, and fluid velocity profiles is maintained, the target is kept still in the state of maximum compression, thereby optimizing the device performance. By comparing the fuel disassembly time against that of a stationary liner flow case, we find that shaping the liner appropriately is likely to increase the dwell time and fusion gain by a factor of four or more.

Moreover, in this newly found regime the shocked region of the liner is at rest. That is, the kinetic energy of the original liner is entirely converted into internal energy. Hence, our result supports the idea of using the deuterium-tritium in the inner parts of the liner or the so-called “after-burner”, which upon becoming shocked will also burn, thus further increasing the gain.

# Influence of radiation field on Non-LTE Xe plasmas

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There has been recently a number of experiments[1, 2] and simulations [3] of Xe due to the possibility of scaling and simulating radiative shocks [4]. It was shown recently that incoming blackbody radiation field on Xe at Te=100 eV, and Ne=1.e20 $cm^{-3}$ can dramatically change the average charge even when strongly diluted [5]. For that work, we used the latest developments of the HULLAC suite of code, which is a detailed fine structure model with configuration interaction, and is now able to compute radiative spectra of high-Z material[6]. Now, extensive and systematic detailed computations were performed for several electron temperatures and densities, with initial conditions far or near Local Thermodynamical Equilibrium. The radiation is described as a Planckian at Trad multiplied by a dilution factor D. In each case, D is varied between 0 and 3 for Trad=Te, and Trad is varied from 0 to Te*1.5 with D=1. We show that in some cases, the dilution factor has more influence on the average charge Z* than the ratio Trad/Te, as can be seen on figure 1. It appears that taking into account radiation field is very important for evaluating Z* and non-LTE opacities.

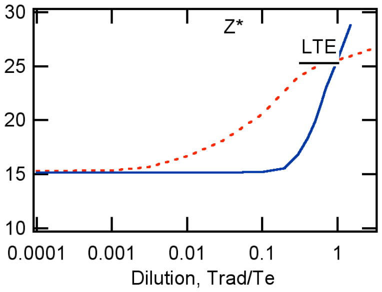

Figure 1. Average charge of Xe at Te=100eV and Ne=1.e20 /cc as a function of dilution factor and Trad/Te

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# Cone-guided fast ignition with imposed magnetic fields

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Recent explicit particle-in-cell (PIC) simulations of short-pulse laser-plasma interactions show the resulting distribution of fast electrons has a wide angular divergence (average polar half-angle ~45 degrees). This poses a severe challenge to fast ignition, where we hope to heat an ignition hot-spot of ~20 μm radius located > 50 μm away from the critical surface where the short-pulse laser is absorbed. We have developed the hybrid particle-in-cell code ZUMA for fast-electron transport studies, and coupled it to the radiation-hydrodynamics code HYDRA[1]. This allows integrated modeling of electron-driven ignition designs, including hydro motion and thermonuclear burn. We find in such studies that using the PIC-based beam distribution gives unacceptable ignitor laser energies (> 1 MJ), while energies only a few times larger than ideal limits (~150 kJ) are obtainable with an artificially collimated beam.

To overcome the divergence, we have explored the use of initial axial magnetic fields of strengths in the 10's of megagauss. Such fields have been obtained in cylindrical and spherical compression experiments at the Omega laser[2], where seed fields of ~50 kG were compressed to 20-40 MG. The basic mechanism is magnetic-flux conservation, via the MHD frozen-in law, in the implosion of a good conductor (such as a plasma). An initial, uniform axial field of 30 MG is sufficient to recover the ignitor energy of an artificially-collimated beam.

However, the imploded magnetic field will not be uniform. In particular, the short-pulse laser will likely be absorbed by relatively uncompressed cone material, so that the electrons will be born in roughly the uncompressed seed magnetic field. As they propagate toward the fuel, if they encounter an increasing axial field they may be reflected by the magnetic mirror effect. ZUMA-HYDRA simulations show this is a serious limitation. To avoid mirroring, we have considered the use of an axial field that peaks at a finite radius, or a magnetic pipe. Fast electrons are then reflected radially inward when they reach the pipe, and do not mirror. Such a tapered pipe (radius decreasing with forward distance) may focus a large, low-intensity laser spot to a smaller ignition hot-spot, substantially reducing the short-pulse ignitor energy. Preliminary work on rad-hydro assembly of such magnetic fields will be discussed.

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# Plasma Adiabatic Lapse Rate*

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The adiabatic lapse rate (or degree of decreasing temperature with increasing altitude) is a well-known phenomenon in atmospheric physics. An analogous effect in plasma physics or inertial confinement fusion (ICF) exists for an accelerating capsule and leads to self-consistent temperature gradients. An analysis is performed for an adiabatic, binary mixture of fuel ions in an ICF capsule to obtain the plasma analogue of an adiabatic lapse rate. A novel source term for generating a plasma temperature gradient that is proportional to a difference in ionization states ($\Delta Z=Z_2-Z_1$) is identified. The motivation for understanding the generation of temperature gradients in ICF targets is based on estimating the strength of self-generated electric fields ("thermoelectric effect") and thermodiffusion. Large, GV/m-scale electric fields have been inferred in imploding capsules using proton radiography [1]. A candidate explanation for the origin of these fields based on charge separation across a plasma shock front was recently proposed [2]. The influence of such fields on pressure gradient-driven diffusion ("barodiffusion") in ICF capsule implosions has been previously described [3]. However, the accompanying role of plasma thermodiffusion on ICF has been largely dismissed or ignored to date. In this work the inclusion of temperature gradients on diffusive phenomena in ICF implosions is described. The theory is applied to studying the degree of potential fractionation of THD fuel mixtures for the ongoing ignition tuning campaign on the National Ignition Facility.

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[Prefer Oral]

# The interplay of spatially non-uniform cross-beam transfer and overlapping quads of beams on stimulated Raman scatter in experiments conducted at the National Ignition Facility

D. E. Hinkel, E. A. Williams, A. B. Langdon, P. A. Michel, R. P. J. Town, S. H. Langer, and C. H. Still

Experiments[1] conducted at the National Ignition Facility have established a hohlraum platform suitable for subsequent ignition experiments. This platform provides the radiation drive and necessary low-mode symmetry required for ignition. Of the many fielded diagnostics, one provides a time-resolved wavelength spectrum of light reflected from the target by stimulated Raman scatter (SRS). SRS occurs when incident light reflects off self-generated electron plasma waves.

Analyses indicate that synthetic SRS diagnostics better match those of experiments when an atomic physics model with greater emissivity is utilized, along with less inhibited electron transport (higher flux, and, ideally, nonlocal electron transport). With these models[2], SRS primarily occurs in a region of the target where nearest-neighbor 23° quads significantly overlap the diagnosed 30°quad. This increases the gain at lower density (lower wavelength), a feature consistent with experimental results. Other predicted features, such as the direction and spreading of the SRS as well as its intensity, are also in better agreement with experiment.

pF3D simulations demonstrate that both the spatial non-uniformity of the cross-beam energy transfer, as well as the fact that overlapping quads of beams can provide additional resonant amplification, impact SRS levels. Results from these simulations will be presented. Incorporating these effects into SRS gains will also be presented.

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

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# CHARACTERIZING PLASMA MIRRORS NEAR BREAKDOWN

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Many high energy density experiments such as the generation of higher harmonics[1] or laser particle acceleration[2,3] use ultra-high contrast lasers for improved gain or for compatibility with ultra-thin targets. An often used tool to increase the contrast of short pulse lasers is the insertion of one or multiple plasma mirrors[4,5], which are windows with a sacrificial antireflection coating (AR) that turns into a highly reflective plasma sheath when irradiated by a certain level of laser fluence. Another important function of plasma mirrors can be to serve as a sacrificial last optical surface in hostile environments, which protects the expensive final focusing optic[6]. Plasma mirrors have been used successfully in many experiments since the early 1990s[7], but the characterization of such devices is demanding.

Experiments dedicated to the characterization of plasma mirrors with a high energy, single shot short-pulse laser were performed at the 100TW target area of the Z-Backlighter Facility at Sandia National Laboratories. A suite of beam diagnostics was used to characterize a high energy laser pulse with a large aperture through focus imaging setup. By varying the fluence on the plasma mirror around the plasma ignition threshold, critical performance parameters were determined and a more detailed understanding of the way in which a plasma mirror works could be deduced. It was found, that very subtle variations in the laser near field profile will have strong effects on the reflected pulse if the maximum fluence on the plasma mirror approaches the plasma ignition threshold.

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# Using High Intensity Lasers to Accelerate Electrons at Solid Density Matter-Vacuum Interfaces*

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The acceleration and heating of electrons by an intense laser normally incident on a steep over-dense plasma interface is investigated using the particle-in-cell code OSIRIS. We show that the energetic electrons are generated by the laser's electric field in the vacuum region within a quarter wavelength of the surface and that only those electrons which originate within the plasma with a sufficiently large transverse momentum can escape the plasma into the vacuum region; even in 1D this leads to an inherent beam divergence at the source. No acceleration occurs for initially cold plasmas until the plasma is heated by other mechanisms. The maximum energy generated by this mechanism is 2eA where e is the charge of an electron and A is the peak vector potential of the laser. Absorption is much different for circularly polarized light, which has applications for Radiation Pressure Acceleration.

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# Numerical Study of Self and Controlled Injection in 3-Dimensional Laser-Driven Wakefields

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In plasma based accelerators (LWFA and PWFA), the methods of injecting high quality electron bunches into the accelerating wakefield is of utmost importance for various applications. Understanding how injection occurs in both self and controlled scenarios is therefore important. To simplify this understanding, we start from single particle motion in an arbitrary traveling wave wakefields, an electromagnetic structure with a fixed phase velocity (e.g., wakefields driven by non-evolving drivers), and obtain the general conditions for trapping to occur. We then compare this condition with high fidelity 3D PIC simulations through advanced particle and field tracking diagnostics. Numerous numerical convergence tests were performed to ensure the correctness of the simulations. The agreement between theory and simulations helps to clarify the role played by driver evolution on injection, and a physical picture of injection first proposed[1] is confirmed through simulations. Several ideas, including ionization assisted injection, for achieving high quality controlled injection were also explored and some simulation results relevant to current and future experiments will be presented.

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