FUSION SCIENCE CENTER
FOR EXTREME STATES OF MATTER

University of Rochester
Ohio State University
Massachusetts Institute of Technology
Lawrence Livermore National Laboratory
University of Nevada at Reno
General Atomics
University of California at San Diego
University of California at Los Angeles
Institute for Laser Science Applications

ANNUAL REPORT
April 2011 – April 2012
EXECUTIVE SUMMARY

The Fusion Science Center (FSC) for Extreme States of Matter began operation in August 2004 under the sponsorship of the Department of Energy (DOE), the Laboratory for Laser Energetics (LLE), the University of Rochester (UR) and the Institute for Laser Science Applications (ILSA) at Lawrence Livermore National Laboratory. In 2011, $150K in matching funds were provided by the New York State Energy Research and Development Authority (NYSERDA) through LLE, UR contributed with $81K of indirect-cost waivers, and the DOE provided $1.5M for FY11 under cooperative agreement DE-FC02-ER54789. Ten institutions and ten principal investigators participate in the FSC. A major goal of the Center is to bring together researchers from around the country and the international community to build a comprehensive understanding of the physics underlying the creation of extreme states of matter and the exploration of advanced inertial-fusion concepts. Another function of the Center is to stimulate academic involvement and student interest in the area of High Energy-Density Physics (HEDP). As part of its outreach and academic mission, the FSC organized the 2011 Summer School in High Energy Density Physics.

FSC Outreach and Education Mission

The FSC held its fourth summer school in High Energy Density Physics the week of July 10-16, 2011, in San Diego (CA). The summer school was held on the Campus of the University of California San Diego. The FSC provided forty-three scholarships to graduate and undergraduate students. Twelve scientists from the field of High Energy Density Physics lectured on a broad range of subjects including: laser-plasma interactions, laboratory astrophysics, equations of state, plasma-based particle accelerators, inertial confinement fusion, high-energy lasers, Z-pinches, material science under extreme conditions, and HEDP diagnostics. Student and participant posters accompanied each day’s thematic focus. Daily poster sessions offered the students a unique opportunity to discuss their work in detail, not only with the lecturers but with the many other students who were in attendance. More detailed information concerning the 2011 HEDP Summer School can be found in Section 4 and are available on the FSC web site at http://fsc.lle.rochester.edu/.

Highlights of the FSC HEDP research

The FSC has promoted close collaboration among several HEDP researchers (some supported by the Center and some by other sources) in the area of laser-plasma interactions, electron transport, hydrodynamics and magnetohydrodynamics, and target fabrication. The FSC identified the following critical areas of HEDP:

[1] Strong Shocks in Plasmas and applications to shock ignition
[2] Relativistic Laser-Plasma Interactions and applications to fast ignition
[3] Magnetized HEDP and other fundamental science
Highlights on Strong Shocks in Plasmas

**Strong Shock Generation in Planar Foil Experiments.** Experiments to study the generation of strong shocks (shock pressure >> 10 Mbar) with shock-ignition-type laser pulses and the associated laser-plasma interactions (LPI) have been conducted at the OMEGA laser facility using planar targets. A schematic of the experimental setup is shown in Fig. 1(a). Planar targets were irradiated with an on-target intensity profile such as shown in Fig. 1(b). A low-intensity pedestal (0-1.6ns) generated the pre-plasma, followed by a high-intensity spike to drive the shock. The peak intensity at ~1.9 ns was varied by adjusting the energy contained in the spike. The target consisted of multiple layers, a CH ablator onto which the laser was focused, a Mo layer, used to study the hot-electron component, and a SiO₂ layer, in which shock propagation could be observed. Backscatter diagnostics were used to infer the energy coupled into the target. Results for the hot electron temperature and population as a function of the nominal laser-spike intensity are displayed in Fig. 2. The electron temperature [Fig. 2(a)] increases strongly with intensity, indicating an increase in LPI, and reaches a peak of ~70 keV for the highest intensity case. Results for the percentage of SRS and SBS backscattered laser light are displayed in Fig. 2(b). This increases strongly with incident intensity, reaching ~7% for the highest intensity case. The spike-driven shock strength was inferred by matching numerical simulations using the 2-D radiative hydrocode *DRACO* to the experimental data. To extract the ablative-driven shock pressure in these simulations, the impedance mismatch between the plastic and Mo layers needs to be taken into account. The heavier Mo causes a partial shock reflection which overlaps with the laser-driven one, leading to an increase of the observed simulated shock strength in the ablator layer. The purely ablative-driven shock strength is inferred through simulations using the same laser conditions, incident onto a pure CH target. This results in a reduction of ~30% in the observed peak pressure. The numerical results for shock propagation time and CH-only ablation pressure were used to provide a scale for the experimental data to infer an ablation pressure from the experimental shock propagation time. The results for peak ablation pressure versus the nominal on-target intensity are shown in Fig. 2(c). The simulated plasma scale length in these experiments is ~350 μm at the time of the high-intensity spike. Based on these results, a peak pressure of ~70 Mbar was achieved with a
drive intensity of \( \sim 1.2 \times 10^{15} \) W/cm\(^2\), in the presence of a long-scale length preplasma. The results from these experiments have been submitted for publication to Physical Review Letters.

**Highlights on Relativistic Laser-Plasma Interactions**

**First Measurements of Hot Electron Temperature in Relativistic LPI.** Ultrafast measurements of the hot-electron relaxation time in high-intensity laser-solid interactions have been carried at LLE. Thin-foil targets were irradiated with 0.5- to 1-ps pulses focused to intensities from \( \sim 10^{18} \) to \( 10^{19} \) W/cm\(^2\) and the hot-electron equilibration dynamics studied with time-resolved K\(\alpha\) spectroscopy. In these interactions, the full width at half maximum (FWHM) of the K\(\alpha\) signal increases with laser intensity from \( \sim 3 \) to \( 6 \) ps. These are the first experiments at relativistic laser intensities to show rapid hot-electron relaxation times with K\(\alpha\)-emission pulse widths up to a factor of \( 4 \times \) shorter than in previously reported experiments. To provide insight into the mean energy of the hot electrons contained inside the target, the duration of the measured K\(\alpha\) signals are compared to predictions from a collisional energy-transfer model. Assuming collisional energy transfer dominates, the data suggest that hot electrons with mean energies from \( \sim 0.8 \) to \( 2 \) MeV are contained inside the target. The inferred mean hot-electron energies are broadly consistent with ponderomotive scaling over the relevant intensity range.

The experiments were carried out with the Multi-Terawatt (MTW) laser. Figure 1 shows a schematic of the experimental setup. The MTW laser delivered 1- to 10-J, 0.5- to 1-ps pulses at a wavelength of 1.053 \( \mu \text{m} \) that were focused by an \( f/3 \) off-axis parabolic mirror to a spot with a FWHM of \( \sim 5 \) \( \mu \text{m} \), providing peak vacuum-focused intensities from \( \sim 10^{18} \) to \( 10^{19} \) W/cm\(^2\). The laser-intensity contrast was \( \sim 10^8 \) at 100 ps before the peak of the main laser pulse. The laser was focused at normal incidence on \( 500 \times 500 \times 20-\mu \text{m}^3 \) Cu-foil targets mounted on 17-\( \mu \text{m}-\text{diam} \) silicon carbide stalks.

Time resolving the K\(\alpha\) radiation generated in these experiments is a direct technique for inferring the hot-electron relaxation time. K\(\alpha\) radiation emitted from the target was measured with a 2-ps time-resolution x-ray streak camera coupled to a HAPG (highly annealed pyrolytic graphite) crystal spectrometer. The HAPG crystal was 50 \( \times \) 14 mm\(^2\) in area and had a three dimensional, elliptically curved surface with radii \( R_1 = -22.000 \) mm and \( R_2 = -10.620 \) mm, and conic constants \( k_1 = -0.825 \) mm and \( k_2 = -0.955 \)
mm, collecting radiation from 7.8 to 8.5 keV. This spectral range covers the $2p\rightarrow1s$ transition in Cu, allowing for time-resolved Cu Kα measurements at 8.05 keV. Assuming collisional energy transfer dominates, the experimental data suggest that hot electrons with mean energies from $\sim0.8$ to 2 MeV are contained inside the target. The inferred mean hot-electron energy scaling with laser intensity is broadly consistent with ponderomotive scaling (Fig. 2). These findings are important for the understanding of a wide range of high-energy-density physics applications that require a large and fast energy input into matter. These results have been published in Phys. Rev. Letts in 2012.

**First Integrated Experiments of Fast Electron Transport in Imploded Capsules.** Through the National Laser Users Facility (NLUF) program, we have obtained 2-day joint OMEGA and EP e-transport shots to investigate the coupling efficiency and spatial distribution of fast electrons' energy deposition in imploded CD shells attached to Au cone targets. This experiment was modeled after previous integrated fast ignition heating experiment led by W. Theobald et al., at LLE but with Cu dopant (at $\sim1\%$ atomic density) added to the CD shell, which allows characterization of fast electron transport via fast electron induced 8.048 keV Cu Kα fluorescence radiation. The first day experiment (July 27th, 2011) consisted of two parts: i) characterization of background 8 keV x-ray emission generated from the compression (by 20 kJ of OMEGA beams) of the CD shell with and without Cu-dopant and ii) characterization of fast electron produced Cu fluorescence emission from the compressed Cu-doped CD with an additional kJ, 10 ps high intensity OMEGA EP beam timed and injected into the compressed core through the...
FIG. 4. Comparison of “measured” (diamonds) and simulated (solid line) path-integrated B fields. The simulated fields were generated by post-processing DRACO output, while the “measured” data were calculated from actual image RMS amplitudes after Au cone tip. The primary diagnostics were a narrow band Spherical Crystal Imager (SCI) to image 8.048 keV x-ray emission and a Zinc Von Hamos (ZVH) x-ray spectrometer tuned for Cu K-shell and ionic line emission yield measurement. Several other diagnostics including broadband x-ray imaging diagnostics such as pinhole cameras and KB microscopes, neutron time-of-flight detectors and magnetic electron spectrometers (one multichannel spectrometer along the EP beam axis and one single channel spectrometer at the side) were employed. In this experiment, fifty-four (54) of the sixty (60) OMEGA beams with low-adiabat pulse shape (LA24170P with SSD off) were used (18 - 20 kJ) to compress the shell while the remaining 6 beams were used to destroy the target cone 5 ns after the short pulse laser was fired in the cone. The 10 ps OMEGA EP backlight beam BL2 was used with ~3.65 ns delay at 10 ps, tight focus at the inner cone tip, and a minimum pre-pulse. The target consisted of a plastic (CD) shell with an outer diameter of 870 µm and a cone with a full angle of 34 degrees with 40 µm offset distance between the outer cone tip and the shell center. The CD shell consists of a 10 µm pure CD outer layer as the ablator and a 27 µm inner layer doped with Cu at ~1% atomic number density of CD. Such shell target was designed to have same mass and outer diameter as the 40 µm thick pure CD shell used in previous integrated FI heating experiments, therefore to maintain similar implosion and fuel assembly as discussed below. The thickness of the cone tip was 15 µm while the cone wall thickness was 10 µm. Figure 3 shows the recorded images with and without Cu doping from the first set of experiments. Those are the first experiments of this kind. This platform will be improved in upcoming experiments to optimize the signal from the short pulse.

Highlights on Magnetized HEDP and other Fundamental Science

First Measurements of Magnetic Fields Produced by Rayleigh-Taylor (RT) Instabilities. Charged-particle radiography has been used to quantitatively study magnetic fields generated by Rayleigh-Taylor (RT) instabilities in laser-driven CH foils at OMEGA, making possible the first direct comparison of measurements with simulations for RT-induced B-field formation. The foils were 20 µm thick, had pre-imposed parallel grooves 0.5 µm deep at a wavelength of ~120 µm, and were driven by a 2-ns, square laser pulse with intensity ~4×10^{14} W/cm². Radiographs made with 15-MeV protons were
recorded at different times after the onset of the laser drive, and for each image the modulation amplitude of structures related to the parallel grooves was measured. These modulations were shown to be dominantly caused by self-generated magnetic fields due to the RT instability in the plasma. The measured modulations were converted to path-integrated “measured” B-field strengths and compared to ideal MHD predictions of the benchmarked 2D hydrodynamic code DRACO, as seen in Fig. 4. Simulations indicated an upper estimate of field strength due to non-dissipative assumptions and were found to agree reasonably well with data. These results have been accepted for publication in Physical Review Letters.

**Plasma Nuclear Science.** Thermonuclear reaction rates and nuclear processes have been explored traditionally by means of conventional accelerator experiments, which are difficult, and at times even impossible, to execute at energies and conditions relevant to stellar nucleosynthesis. Even when measurements are possible using accelerators, thermonuclear reaction rates in burning plasmas of stars are inherently different from those in accelerator experiments. The fusing nuclei are surrounded by bound electrons in accelerator experiments, whereas electrons occupy mainly continuum states in a stellar environment. To begin exploring these issues, a proof-of-principle study of the $^3$He-$^3$He reaction, which plays an important role in the pp chain in first-generation hydrogen-burning Population III stars and in stars like our Sun, was recently conducted using ICF laboratory plasmas produced by the OMEGA laser. A preliminary example of the resulting $^3$He-$^3$He proton spectrum is shown in Fig. 5.

![Image](image.png)

**FIG. 5.** (a) The MIT-developed charged-particle spectrometer CPS2 during installation on the OMEGA chamber. The cone-shaped end contains the entry aperture, while the cylindrical section contains a 7.6-kG magnet and CR-39 detectors. CPS2 was used to simultaneously measure energy spectra of deuterons and tritons elastically scattered by 14.1-MeV neutrons. (b) Measured differential cross section for elastic n-D scattering, normalized to a Faddeev calculation. (c) Measured and calculated differential cross section for elastic n-T scattering. The blue solid curve represents an *ab-initio* NCSM/RGM calculation, and the red dashed curve represents an R-matrix calculated n-T cross section.

It is important to notice the small error bars, and the abundance of data points obtained in these experiments as compared to traditional accelerator experiments. These results show the importance of ICF facilities in high precision nuclear measurements for fundamental nuclear science. These results were published in Physical Review Letters in 2011.
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**Members - Faculty and Research Scientists**

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<thead>
<tr>
<th>Name</th>
<th>Institution</th>
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<tr>
<td>F. Beg</td>
<td>UCSD</td>
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<td>R. Betti</td>
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<td>D. Correll</td>
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<td>R. Freeman</td>
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<td>C. Li</td>
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**Members - Post docs and Researchers**

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<td>K. Anderson</td>
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<td>B. Chrisman</td>
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**Graduate Students**

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<td>F. Aymond</td>
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<td>A. Zylstra</td>
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**Administrators**

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<td>J. Morris</td>
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**Collaborators - Research Scientists (not funded)**

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<td>J. Delettrez</td>
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<td>W. Theobald</td>
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**Member** is a Researcher (post doc or scientist) partially or fully supported by the FSC, or a Principal Investigator. **Graduate students** are fully or partially funded by the FSC, or closely collaborating with the FSC. **Collaborators** are not currently supported by the FSC.
3. FUSION SCIENCE CENTER MEETINGS

10th Fusion Science Center Meeting, October 30-31 (2011), Columbus OH

11th Fusion Science Center Meeting, June 27-29 (2012) at the Anomalous Absorption Conference, Key West FL

(FSC meeting presentations are available on the FSC web site at fsc.lle.rochester.edu)

4. THE FSC EDUCATION MISSION

The 4rd FSC Summer School in High Energy Density Physics
July 10-16, 2011 UCSD Campus, San Diego, CA

Lecturers and subjects

P.B. Radha - LLE Hydro Simulations
F. Beg - UCSD Physics of Z-Pinches
R. Betti – UR, Implosion Hydrodynamics
G. Collins – LLNL, Material Properties at High Pressures
P. Drake - UM Introduction to HEDP
D. Hinkel - LLNL Laser-Plasma Intensity
P. Patel - LLNL Fast Ignition
D. Meyerhofer – UR, HEDP Diagnostics
W. Mori – UCLA, Laser-Plasma Interaction
C. Ren, – UR The Particle-in-Cell Method
M. Rosen - LLNL, Inertial Confinement Fusion
L. Van Woerkom – OSU, Fast-Electron Transport
The UC San Diego hosted the 4th FSC HEDP Summer School
88 attendees
43 financial aid packages from the FSC
56 graduate students
14 post docs
18 research scientists

Sponsors: FSC, ILSA, GA, IMDEC
5. REFEREED PUBLICATIONS
(Published or accepted for publication in April 2011-2012)

1. *Time-Resolved Measurements of Hot-Electron Equilibration Dynamics in High-Intensity Laser Interactions with Thin-Foil Solid Targets*
   Nilson PM, Davies JR, Theobald W, Jaanimagi PA, Mileham C, Jungquist RK, Stoeckl C, Begishev IA, Solodov AA, Myatt JF, Zuegel JD, Sangster TC, Betti R and Meyerhofer D
   PHYSICAL REVIEW LETTERS Volume 108, Article Number: 085002 Published: FEB 2012

2. *Coherent transition radiation in relativistic laser-solid interactions*
   Bellei C, Davies JR, Chauhan PK and Najmudin Z
   PLASMA PHYSICS AND CONTROLLED FUSION Volume 54, Article Number: 0350011 Published: March 2012

3. *Dynamics of intense laser propagation in underdense plasma: polarization dependence*
   Singh DK, Davies JR, Sarri G, Fiuza F and Silva LO
   PHYSICS OF PLASMAS Submitted: APR 2012

4. *One-dimensional planar hydrodynamic theory of shock ignition*
   Nora R., Betti R.
   PHYSICS OF PLASMAS 18, 082710, Published: AUG 2011

5. *Fusion Yield Enhancement in Magnetized Laser-Driven Implosions*
   Chang P. Y.; Fiksel G.; Hohenberger M.; et al.
   PHYSICAL REVIEW LETTERS Volume: 107, Article Number: 035006, Published: JUL 15 2011

6. *Impeding Hohlraum Plasma Stagnation in Inertial-Confinement Fusion*
   Li C. K.; Seguin F. H.; Frenje J. A.; et al.
   PHYSICAL REVIEW LETTERS Volume: 108, Article Number: 025001, Published: JAN 11 2012

7. *Scaling hot-electron generation to long-pulse, high-intensity laser-solid interactions*
   Nilson P. M.; Solodov A. A.; Myatt J. F.; et al.
   PHYSICS OF PLASMAS Volume: 18 Article Number: 056703, Published: MAY 2011

8. *Initial cone-in-shell fast-ignition experiments on OMEGA*
   Theobald W.; Solodov A. A.; Stoeckl C.; et al.
   PHYSICS OF PLASMAS Volume: 18 Issue: 5 Article Number: 056305, Published: MAY 2011

9. *Target-heating effects on the K-alpha 1, K-2-emission spectrum from solid targets heated by laser-generated hot electrons*
   Nilson P. M.; Theobald W.; Mileham C.; et al.
   PHYSICS OF PLASMAS Volume: 18 Issue: 4 Article Number: 042702, Published: APR 2011

10. *Structure and Dynamics of Supersonic Plasma Jets, Jet Collisions, and their Spontaneous Fields*

11. *Measurements of the T(t,2n) 4He neutron spectrum at low reactant energies from inertial confinement implosions*.

12. *Evidence for stratification of deuterium-tritium fuel in inertial confinement fusion implosions*
    D. T. Casey, J. A. Frenje, et al
13. Impeding hohlraum plasma stagnation in inertial-confinement fusion
C. K. Li, F. H. Séguin, J. A. Frenje, et al

14. Measurements of hohlraum-produced fast ions
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20. Shock ignition experiments with planar targets on OMEGA
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22. Monochromatic Imaging of 8.0 keV Cu Kα Emission Induced by Energetic Electrons Generated at OMEGA EP
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23. Proton Radiography of Intense-Laser-Irradiated Wire-Attached Cone Targets
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6. INVITED PRESENTATIONS AT CONFERENCES AND WORKSHOPS

- **D. Casey**
  Measurements of the TT fusion neutron spectrum and anomalous DD and TT yields in ICF implosions
  53rd Annual Meeting of the APS Division of Plasma Physics (14 - 18 November, 2011, Salt Lake City, UT

- **M. Hohenberger**
  Fusion Yield Enhancement in Magnetized Laser-Driven Implosions on OMEG
  53rd Annual Meeting of the APS Division of Plasma Physics (14 - 18 November, 2011, Salt Lake City, UT

- **F. N. Beg**
  Electron/proton generation from solid targets and applications,
  Committee on Optical, Molecular and Laser Sciences, The National Academy of Sciences, Washington DC, April 2011.

- **F. N. Beg**
  Fast electron source and transport in laser driven shock heated warm dense matter
  5th International Conference on Frontiers of Plasma Physics, Singapore, April 2011.

- **H. Sawada**
  Diagnosing Laser-Driven, Shock-Heated Foam Target with Al Absorption Spectroscopy on OMEGA EP,

- **M.S. Wei**
  Investigation of dependence of laser energy coupling on target material and preplasma scale length for

- **R.B. Stephens**

- **T. Yabuuchi**
  Study of fast electron transport in plasmas using a kJ-class laser pulse, 12th Int. Workshop on Fast Ignition of Fusion Targets, Bordeaux-Lac, France, 12-16 September 2011.

- **F. N. Beg**
  Fast electron generation and transport in laser-driven shock heated warm dense matter,

- **F. N. Beg**
  Fast electron generation and transport in hot plasmas

- **D. Higginson**
  Experimental and Simulated Coupling and Spectra of Hot Electrons into Cone-Wire Targets

- **M.S. Wei**
  Study of fast electron generation and transport for fast ignition
  24th IAEA Fusion Energy Conference (FEC), San Diego, CA, October 8 – 13, 2012
• **R. Betti**  
  *Review of the Ablative Rayleigh-Taylor Instability*  
  Turbulent Mixing and Beyond, Trieste, Italy, August 22-26, 2011

• **R. Betti**  
  *Overview of Shock Ignition Ignition*  
  1st International Workshop on Shock Ignition, Laboratory for Laser Energetics, Rochester NY, March 8-10, 2011
7. Shock Ignitions Studies with Planar Targets on OMEGA

The concept of shock ignition (SI) [1] has recently been proposed as an advanced ignition scheme for inertial confinement fusion [2]. It is based on using shaped laser pulses to separate fuel-assembly and ignition stages and benefits from lower implosion velocities and more efficient fusion gain compared to ‘conventional’ hot-spot ignition. A compression laser pulse is followed by a short, high-intensity laser spike launching a strong, spherically converging ignitor shock into the compressing fuel. To take full advantage of the SI scheme, laser-generated shocks of order a few hundred Mbar strength are required, which need to be launched in the presence of a long-scale length preplasma generated by the assembly laser pulse. For such strong shocks on-target intensities exceeding $10^{15}$ W/cm$^2$ are necessary and laser-plasma instabilities (LPI), such as stimulated Raman and Brioullin scattering and two-plasmon decay play an important role in the coupling of laser energy to the target.

Experiments to study the accessible shock parameters with SI-type laser pulses and the associated LPI have been conducted at the OMEGA laser facility [3] using planar targets [4]. A schematic of the experimental setup is shown in Fig. 1(a). Planar targets were irradiated with an on-target intensity profile such as shown in Fig. 1(b). A low-intensity pedestal (0-1.6ns) generated the pre-plasma, followed by a high-intensity spike to drive the shock. The peak intensity at ~1.9 ns was varied by adjusting the energy contained in the spike. The target

![Fig. 1: (a) Experimental setup to study strong-shock generation in planar geometry. (b) Example for the on-target intensity profile. A low-intensity foot up ~1.6 ns drives the preplasma, followed by a high-intensity spike to launch a strong shock into the target.](image)

![Fig. 2: Experimental results plotted as a function of peak laser intensity. (a) Hot-electron temperature (b) Fraction of backscattered laser energy (SRS+SBS) (c) Laser-driven ablation pressure inferred from the simulations.](image)
consisted of multiple layers, a CH ablator onto which the laser was focused, a Mo layer, used to study the hot-electron component, and a SiO2 layer, in which shock propagation could be observed. Backscatter diagnostics were used to infer the energy coupled into the target. Results for the hot electron temperature and population as a function of the nominal laser-spike intensity are displayed in Fig. 2. The electron temperature [Fig. 2(a)] increases strongly with intensity, indicating an increase in LPI, and reaches a peak of ∼70 keV for the highest intensity case. Results for the percentage of SRS and SBS backscattered laser light are displayed in Fig. 2(b). This increases strongly with incident intensity, reaching ∼7% for the highest intensity case. The spike-driven shock strength was inferred by matching numerical simulations using the 2-D radiative hydrocode DRACO [5] to the experimental data. To extract the ablative-driven shock pressure in these simulations, the impedance mismatch between the plastic and Mo layers needs to be taken into account. The heavier Mo causes a partial shock reflection which overlaps with the laser-driven one, leading to an increase of the observed simulated shock strength in the ablator layer. The purely ablative-driven shock strength is inferred through simulations using the same laser conditions, incident onto a pure CH target. This results in a reduction of ∼30% in the observed peak pressure. The numerical results for shock propagation time and CH-only ablation pressure were used to provide a scale for the experimental data to infer an ablation pressure from the experimental shock propagation time. The results for peak ablation pressure versus the nominal on-target intensity are shown in Fig. 2(c). The simulated plasma scale length in these experiments is ∼350 μm at the time of the high-intensity spike. Based on these results, a peak pressure of ∼70 Mbar was achieved with a drive intensity of ∼1.2×1015 W/cm², in the presence of a long-scale length preplasma.

References

8 A. Hot-Electron Equilibration Dynamics in High-Intensity Laser Interactions with Thin-Foil Solid Targets

High-intensity laser interactions with solid targets generate extreme states of matter [1] with unique energy-transport properties [2,3]. At laser intensities above 1018 W/cm², high-current electron beams with ∼MeV energies are generated [4–7], heating matter to high thermal temperatures over picosecond time scales [2,3,8]. Understanding the energy partition and its evolution in these highly non equilibrium plasmas is an important open issue, underpinning applications in high-energy-density science [1], plasma-based particle acceleration [9], warm dense matter [10], high-peak-power γ-ray generation [11], and advanced inertial fusion energy concepts, including fast ignition [12]. In these conditions, the hot-electron equilibration dynamics are not completely understood and accurate time-resolved measurements are required to test energy partition and temperature equilibration models.

The only previous hot-electron equilibration data in this regime are the time-resolved Kα-emission data of Chen et al. [13]. Those experiments irradiated thin-foil targets with ∼0.5-
ps pulses focused to intensities up to $10^{19}$ W/cm² and used the $K_\alpha$-emission pulse width to characterize the time scale for energy thermalization ("relaxation") between hot and cold electrons. The data showed $K_\alpha$-emission pulse widths from ~12 to 16 ps. The data were compared to an electron-energy transfer model that included ion-front expansion and collisional electron-energy transfer based on Landau–Spitzer theory [14]. With increasing laser intensity, the model did not reproduce the rise time (~10 ps) or the duration of the measured $K_\alpha$ signals, revealing an incomplete picture of the hot-electron equilibration dynamics.

In this work, ultrafast measurements of the hot-electron relaxation time in high-intensity laser-solid interactions are reported. Thin-foil targets were irradiated with 0.5- to 1-ps pulses focused to intensities from ~$10^{18}$ to $10^{19}$ W/cm² and the hot-electron equilibration dynamics studied with time-resolved $K_\alpha$ spectroscopy. In these interactions, the full width at half maximum (FWHM) of the $K_\alpha$ signal increases with laser intensity from ~3 to 6 ps. These are the first experiments at relativistic laser intensities to show rapid hot-electron relaxation times with $K_\alpha$-emission pulse widths up to a factor of 4x shorter than in previously reported experiments [13]. To provide insight into the mean energy of the hot electrons contained inside the target, the duration of the measured $K_\alpha$ signals are compared to predictions from a collisional energy-transfer model. Assuming collisional energy transfer dominates, the data suggest that hot electrons with mean energies from ~0.8 to 2 MeV are contained inside the target. The inferred mean hot-electron energies are broadly consistent with ponderomotive scaling [6] over the relevant intensity range.

The experiments were carried out with the Multi-Terawatt (MTW) laser [15] at the University of Rochester's Laboratory for Laser Energetics. Figure 1 shows a schematic of the experimental setup. The MTW laser delivered 1- to 10-J, 0.5- to 1-ps pulses at a wavelength of 1.053 µm that were focused by an f/3 off-axis parabolic mirror to a spot with a FWHM of ~5 µm, providing peak vacuum-focused intensities from ~$10^{18}$ to $10^{19}$ W/cm². The laser-intensity contrast was ~$10^8$ at 100 ps before the peak of the main laser pulse [16]. The laser was focused at normal incidence on 500 $\times$ 500 $\times$ 20-µm³ Cu-foil targets mounted on 17-µm-diam silicon carbide stalks.

Time resolving the $K_\alpha$ radiation generated in these experiments is a direct technique for inferring the hot-electron relaxation time [13]. $K_\alpha$ radiation emitted from the target was measured with a 2-ps time-resolution x-ray streak camera [17] coupled to a HAPG (highly annealed pyrolytic graphite) crystal spectrometer. The HAPG crystal was 50 x 14 mm² in area and had a three dimensional, elliptically curved surface with radii $R_1 = -22.000$ mm and $R_2 = -10.620$ mm, and conic constants $k_1 = -0.825$ mm and $k_2 = -0.955$ mm, collecting radiation from 7.8 to 8.5 keV. This spectral range covers the 2p→1s transition in Cu, allowing for time-resolved Cu $K_\alpha$ measurements at 8.05 keV.

The streak camera was independently characterized by direct illumination of the photocathode with a 10-mJ, 0.5-ps pulse of 263-nm light. Figure 2 shows a schematic of the setup. By passing half of the UV beam through a quartz plate of known thickness, two pulses were generated, providing a sweep-speed calibration. Figure 2(b) shows a typical streak-camera trace for these two pulses. The pulse widths (FWHM) are 1.8±0.1 and 1.9±0.1 ps. Temporal dispersion in the streak camera gives a slightly different impulse response for x-ray
illumination. Monte Carlo modeling of the electron optics inside the streak tube shows that this offset is ~0.2 ps, giving an impulse response for x rays of ~2 ps.

Figure 3 shows an example of time-resolved plasma x-ray emission data for different high-intensity laser irradiation conditions. Figure 3(a) shows the time-resolved Kα emission from a 500 × 500 × 20-µm³ Cu foil irradiated with a 0.9-J, 0.6-ps pulse focused to 3.6 × 10¹⁸ W/cm². The pulse width is 3.0±0.2 ps. Figure 3(b) shows the Kα emission from a similar target irradiated with an 8.5-J, 0.8-ps pulse focused to 2.9 × 10¹⁹ W/cm². The pulse width is 5.5±0.1 ps. The Kα emission from these targets was measured as a peaked signal with a sharp rise and a slower decay. The signal rise time did not vary with laser intensity and was determined by the experimental resolution. The signal decay time increased with laser intensity and was sensitive to the hot-electron equilibration dynamics.

Kα radiation is generated in these experiments by hot electrons that are confined by target charging [7,18,19]. The thin-foil target rapidly charges because of the electrostatic potential that develops after the initial loss of a small fraction of high-energy electrons [18]. The remaining hot electrons (>90% of the total laser-accelerated population) make multiple round-trips of the target as they recirculate (reflux) because their collisional range is several hundred microns at solid density [20].

A collisional energy-loss model for understanding hot-electron relaxation and the time dependence of Kα emission in these targets has been developed. The model calculates the Kα emission rate for a given hot-electron energy distribution, assuming that all of the electrons are trapped inside the foil. The hot-electron energy loss rate is given by [20]

\[
\frac{dE}{dt} = -\frac{n_e e^4 I_{\text{d}}}{4 e \varepsilon_0^2 m_e v},
\]

where \( n_e \) is the electron density for solid Cu (2.46 × 10²⁴ cm⁻³), \( E \) is the hot-electron energy, \( m_e \) is the electron rest mass, \( v \) is the hot-electron velocity, \( e \) is the electron charge, and \( \varepsilon_0 \) is the permittivity of free space. The stopping number \( L_{\text{d}} \) (or “log Λ”) depends weakly on material and the hot-electron energy, with values for Cu taken from Ref. 21. The time spent by hot electrons outside the target during recirculation is assumed negligible and energy losses to ion acceleration and self-generated electric fields are not considered in this model [7,18,19]. The implications for these assumptions on the inferred mean hot-electron energy will be discussed later.

Kα-emission pulse widths have been calculated for hot electrons with exponential

\[
f_h \propto e^{-\gamma m_e c^2 / k_B T_h}
\]

and three-dimensional relativistic Maxwellian

\[
f_h \propto \gamma \left( \gamma^2 - 1 \right)^{1/2} e^{-\gamma m_e c^2 / k_B T_h}
\]

distributions, where \( f_h \) is the hot-electron energy distribution function, \( k_B \) is Boltzmann’s constant, \( T_h \) is the hot-electron temperature, and \( \gamma \) is the Lorentz factor. Isochoric energy transfer to solid matter in these calculations is assumed. The Kα emission rate is proportional to the Cu-ion density, the time-varying number of hot
electrons, and the parameter $\langle \sigma_K v \rangle$ averaged over the hot-electron energy distribution, where $\sigma_K$ is the K-shell ionization cross section and $v$ is the hot-electron velocity. On the timescale of the detection, the conversion of hot-electron energy to a $K_\alpha$ photon is considered to be instantaneous. The cross section for ionization of K-shell electrons was taken from Ref. 21.

Figure 3 shows synthetic $K_\alpha$ streaks that were calculated from this model. The synthetic pulse widths were fit to the data by adjusting the signal intensity and the mean hot-electron energy in the model. They represent a convolution of the calculated $K_\alpha$-emission rate with the laser pulse duration and the temporal resolution of the x-ray streak camera. In the low-intensity case [Fig. 3(a)], the model predicts well the $K_\alpha$ emission pulse shape, independent of the hot-electron energy distribution that was used. The best fit of the experimental data was obtained with the parameters $\langle E \rangle_{\text{exp}} = 0.47$ MeV for the exponential energy distribution and $\langle E \rangle_{\text{RM}} = 0.58$ MeV for the 3-D relativistic Maxwellian energy distribution. In the high-intensity case [Fig. 3(b)], the best fit was obtained with the parameters $\langle E \rangle_{\text{exp}} = 1.55$ MeV and $\langle E \rangle_{\text{RM}} = 1.73$ MeV. In this case, the $K_\alpha$-emission pulse shape was better reproduced by model calculations with a 3-D relativistic Maxwellian energy distribution.

Figure 4 shows the variation with increasing laser intensity of the measured $K_\alpha$ emission pulse width. An upper estimate of the true $K_\alpha$-emission pulse width was obtained by accounting for instrumental effects, subtracting the FWHM of the impulse response function from the streak-camera trace in quadrature. Gaussian pulse shapes are assumed. For laser intensities between $2.7 \times 10^{18}$ and $3.4 \times 10^{19}$ W/cm$^2$, the duration of the measured $K_\alpha$ signal increases from ~3 to 6 ps. Over this intensity range, a least squares fit shows that the $K_\alpha$-emission pulse width increases with laser intensity and is given by

$$\tau_{K_\alpha} = (4.1 \pm 0.3)I_{19}^{0.35 \pm 0.07},$$

where $I_{19}$ is the laser intensity in units of $10^{19}$ W/cm$^2$.

To obtain a mean hot-electron energy scaling, these data were compared with the collisional energy-loss model. Figure 5(a) shows the relationship between the calculated $K_\alpha$ emission pulse width and the mean hot-electron energy for exponential and 3-D relativistic Maxwellian energy distributions. In these calculations, the $K_\alpha$-emission rate was convolved with a 0.8-ps FWHM Gaussian pulse that approximated the range of laser pulse durations that were used in these experiments. The synthetic pulse was convolved with a 2-ps FWHM Gaussian instrument response that was removed in quadrature for comparison with the experimental data (Fig. 4). Figure 5(a) shows that calculations with a 3-D relativistic Maxwellian energy distribution have slightly higher mean hot-electron energies than with an exponential energy distribution for a given $K_\alpha$ emission pulse width. This offset is ~100 to 200 keV.

Figure 5(b) shows the mean hot-electron energies that are inferred from the experimental data based on this model. Two scaling laws are obtained: For an exponential energy distribution, $\langle E \rangle_{\text{exp}} [\text{MeV}] = (1.12 \pm 0.11)I_{19}^{0.51 \pm 0.11}$. For a 3-D relativistic Maxwellian energy distribution, $\langle E \rangle_{\text{RM}} [\text{MeV}] = (1.19 \pm 0.11)I_{19}^{0.46 \pm 0.10}$. Assuming collisional energy
transfer dominates, these results show that mean hot-electron energies from ~0.8 to 2 MeV are required to generate $K_{\alpha}$-emission pulse widths consistent with the experimental observations.

Figure 5(c) compares these inferred mean hot-electron energies with ponderomotive scaling [6]. Ponderomotive scaling gives $\langle E\rangle = m_e c^2 \left[ 1 + \left( \frac{2U_p}{m_e c^2} \right) \right]^{1/2}$, where $U_p = 9.33 \times 10^{-14} I [\text{W/cm}^2] \lambda [\mu\text{m}]^2$ is the ponderomotive potential. In each case, the inferred mean energies are slightly higher compared with ponderomotive scaling. The best agreement was found for calculations with an exponential energy distribution. A similar scaling predicting ~100 to 200 keV higher mean hot-electron energies was found with calculations using the 3-D relativistic Maxwellian energy distribution. Compared with ponderomotive scaling, the power law fits give a faster increase in mean energy with intensity near $10^{18}$ W/cm$^2$ and provide a better fit to the experimental data.

The collisional energy-loss model presented here is not intended to fully model the experiment but is used to help interpret the data. The model neglects energy loss to self-generated electric fields and to ion acceleration and it neglects the time electrons take to be reflected by the electrostatic field outside the target. All of these effects would be expected to increase with laser intensity and an accurate assessment of them will require numerical modeling. The accuracy with which the collisional model reproduces all of the experimental results and the relative insensitivity of the mean energy to the energy distribution indicates that the values are likely not significantly in error. Measurements of the ion emission at these intensities show that it is not a significant energy sink [22]. The results presented here form a comprehensive test bed for future comparison with numerical modeling that may include these effects.

In summary, the hot-electron equilibration dynamics in thin-foil solid targets irradiated with high-intensity laser pulses have been studied. Time-resolved $K_{\alpha}$ spectroscopy measurements show $K_{\alpha}$-emission pulse widths from ~3 to 6 ps for laser intensities between $\sim 10^{18}$ and $10^{19}$ W/cm$^2$. Assuming collisional energy transfer dominates, the experimental data suggest that hot electrons with mean energies from ~0.8 to 2 MeV are contained inside the target. The inferred mean hot-electron energy scaling with laser intensity is broadly consistent with ponderomotive scaling. These findings are important for the understanding of a wide range of high-energy-density physics applications that require a large and fast energy input into matter.

FIG. 1. Experimental setup. HAPG: highly annealed pyrolytic graphite.
FIG. 2. (a) Streak camera calibration setup. (b) Streak camera response measurement with 0.5-ps, 263-nm pulses showing pulse widths of 1.8±0.1 and 1.9±0.1 ps.

FIG. 3. Experimental time-resolved $K_{\alpha}$ emission data from $500 \times 500 \times 20-\mu m^3$ Cu foils. The targets were irradiated with (a) a 0.9-J, 0.6-ps pulse and (b) an 8.7-J, 0.8-ps pulse. The data are shown with theoretical fits based on a collisional energy-loss model with exponential (long-dashed line) and 3-D relativistic Maxwellian (short-dashed line) hot-electron energy distributions.
FIG. 4. Experimental $K\alpha$-emission pulse width as a function of laser intensity. The pulse widths have been adjusted to account for the impulse response of the streak camera.

FIG. 5. (a) Calculated mean hot-electron energy $\langle E \rangle$ as a function of $K\alpha$-emission pulse width based on a 0.8-ps laser-pulse duration. (b) Inferred $\langle E \rangle$ as a function of laser intensity, assuming exponential (solid line) and 3-D relativistic Maxwellian (dashed line) hot-electron energy distributions. (c) Comparison of the experimentally inferred $\langle E \rangle$ with ponderomotive scaling [6].
High-intensity laser–solid interactions at $>10^{18}$ W/cm$^2$ generate powerful hot-electron sources that are capable of creating high-energy-density plasmas over picosecond time scales. Numerous applications provide significant impetus for understanding the underlying electron-energy–deposition phenomena, including high-energy particle acceleration, isochoric (i.e., constant volume) off-Hugoniot heating, high-
temperature plasma opacity studies, and ultrafast x-ray generation for dense-matter probing.\textsuperscript{21,22}

K-photon spectroscopy is a direct technique for diagnosing energy deposition within plasmas that contain hot electrons.\textsuperscript{23} Previous thin-foil–target experiments have compared K\textsubscript{\alpha}-emission spectra from near-neutral ions to electron-transport calculations to infer the total hot-electron beam energy.\textsuperscript{24–28} For plasmas with high thermal-electron temperatures (several hundred electron volts and greater), the presence of multiple ionized ions shifts the cold K-photon emission spectrum to higher energies.\textsuperscript{29} By comparing the K-photon energy shift to collisional-radiative atomic physics modeling, high-temperature–plasma parameters can be inferred, such as the mean ionization state, which is typically integrated over the target volume and the hot-electron lifetime.\textsuperscript{29,30} Understanding the shifted K\textsubscript{\alpha}-emission spectrum from high-temperature plasmas is important because it provides information on how hot-electron energy is deposited within the target material.

Recent experiments have shown that spatial and temporal heating variations are important for calculating the total K-photon yield from thin-foil targets heated by laser-generated hot electrons.\textsuperscript{24–28} In this manuscript, it is shown that target-heating effects are important for calculating the time-integrated K\textsubscript{\alpha\textsubscript{1,2}}-emission spectrum from high-temperature, small-mass targets. Combining time-dependent target heating with a collisional-radiative atomic physics model, providing insight into the target-heating dynamics, reproduces the main spectral features that are observed experimentally.

The experiments were carried out on the Multi-Terawatt (MTW) Laser Facility at the University of Rochester’s Laboratory for Laser Energetics. The MTW laser provided 5-J, 1-ps pulses at a wavelength of 1.053 \( \mu \)m (Refs. 31 and 32). The laser was focused onto small-mass Cu targets at normal incidence with an f/2 off-axis parabolic mirror [Fig. 1(a)]. The laser-spot radius containing 80\% of the laser energy was \( \approx 5 \mu \)m, providing vacuum-focused intensities of \( 5 \times 10^{18} \) W/cm\(^2\). The target-foil dimensions were 500 \( \times \) 500 \( \times \) 20 \( \mu \)m\(^3\) and 50 \( \times \) 50 \( \times \) 2 \( \mu \)m\(^3\).

K-shell emission from the target was diagnosed with a Bragg crystal x-ray spectrometer coupled to an SI-800 charge-coupled device (CCD). The CCD detector provided good shot-to-shot reproducibility in the spatial location of the measured x-ray emission spectrum. The crystal spectrometer was operated in the mosaic-focusing mode and used a highly oriented pyrolytic graphite (HOPG) crystal to obtain high-integrated reflectivity\textsuperscript{33} and a spectral resolution of \( \lambda/\Delta\lambda = 600 \).

Figure 1 shows K-shell emission spectra for Cu-foil targets with two different target volumes. K\textsubscript{\alpha\textsubscript{1}} \((^2P_{3/2} \rightarrow ^2S_{1/2} - 8.045 \text{ keV})\) and K\textsubscript{\alpha\textsubscript{2}} \((^2P_{1/2} \rightarrow ^2S_{1/2} - 8.025 \text{ keV})\) emission is observed from the 500 \( \times \) 500 \( \times \) 20-\( \mu \)m\(^3\) target (black). When the target volume is reduced by a factor of 1000 to 50 \( \times \) 50 \( \times \) 2 \( \mu \)m\(^3\) (red), the K\textsubscript{\alpha\textsubscript{1,2}} doublet is spectrally broadened and shifted to higher energies. This is consistent with previous experimental observations under similar laser-irradiation conditions\textsuperscript{18,29} and is caused by multiple ionized ions that have an increased K-shell ionization potential.

The experimental spectra were compared to synthetic spectra calculated with the non-LTE (local thermal equilibrium) collisional-radiative atomic physics code PrismSPECT.\textsuperscript{34}
This code is based on single-zone slab geometry and generates K-shell emission spectra based on either steady-state or time-dependent plasma conditions.

Figure 1(b) shows a synthetic $K_{\alpha_{1,2}}$-emission spectrum for a 20-$\mu$m-thick Cu target, assuming steady-state conditions and solid-density material. The calculation assumes a hot-electron temperature of 200 keV and a thermal-electron temperature of 10 eV. Instrumental broadening is included. In the large-target case, good agreement is found between the experimental and the calculated emission spectra. Differences in the spectral fit at higher energies have been observed in previous studies\textsuperscript{33} and are caused by an intrinsic defocusing effect in the HOPG crystal related to volumetric diffraction at high photon energies. This instrumental effect is not included in the spectral modeling.

Thermal-electron temperatures >10 eV are required to explain the $K_{\alpha_{1,2}}$-emission spectrum from the 50 × 50 × 2-$\mu$m\textsuperscript{3} target. Figure 2(a) shows synthetic spectra for solid-density Cu under steady-state, non-LTE conditions with thermal-electron temperatures of 10 eV (green), 150 eV (blue), and 300 eV (red). The hot-electron temperature is 200 keV and the calculation includes instrumental broadening. Figure 2(b) shows the corresponding mean ionization states as a function of increasing bulk thermal-electron temperature. The Cu ionization balance model used in PrismSPECT is shown to be in good agreement with the self-consistent field model muZe (Ref. 35) and the relativistic multiconfiguration atomic model FAC\textsubscript{36,37} as reported in Ref. 29. While modeling shows that the target is heated to several hundred electron volts, the experimental emission spectrum is not reproduced, suggesting that a time-dependent mean ionization state would be more appropriate for calculating the $K_{\alpha_{1,2}}$-emission spectrum from small-mass targets.

A K-shell emission model is developed that includes target heating to aid interpretation of the experimental emission spectrum from the 50 × 50 × 2-$\mu$m\textsuperscript{3} target. The model assumes isochoric target heating and a linear rise in thermal-electron temperature. Spatial gradients are assumed to be small because the collisional range for hot electrons is up to several hundred microns – far greater than the small-mass target dimensions. Hot electrons are assumed to rapidly fill the entire target as they heat it during the refluxing phase. The duration of the heating phase is 10 ps and is consistent with previous time-resolved K\textsubscript{\alpha}-emission measurements\textsuperscript{30}. The heating period is longer than the laser-pulse duration because recirculation allows hot electrons to couple energy to the target until they range out.

Figure 3 shows the effect of target heating on $K_{\alpha_{1,2}}$ emission. The spectra are generated assuming a 2-$\mu$m-thick target and linear heating profiles from 1 eV to 300 eV (Profile A), 350 eV (Profile B), and 400 eV (Profile C). Figure 3(a) shows the time-dependent mean ionization states for each of these heating profiles. Figure 3(b) shows the corresponding synthetic $K_{\alpha_{1,2}}$-emission spectra that include instrumental broadening.

In general, good agreement to the experimental data is found for the 50 × 50 × 2-$\mu$m\textsuperscript{3} target (black) with peak thermal-electron temperatures ~300 to 350 eV. Higher peak thermal-electron temperatures generate broader synthetic spectra with wavelength shifts in the short- and long-wavelength limits that are not observed experimentally. This demonstrates the importance of time-dependent (isochoric) heating for interpreting time-integrated $K_{\alpha_{1,2}}$-emission spectra from small-mass targets.
While no single linear heating rate is able to fully recover the emission spectrum from the smallest-mass target, the theoretical fit reproduces to a good approximation the main spectral features that are observed experimentally. The model does not include laser-electron coupling or spatial variations in hot-electron–energy deposition and assumes target heating to several hundred electron volts, which is consistent with previous studies.25,27,29 Time-dependent K-photon spectroscopy measurements will be required in future work to confirm the validity of the isochoric heating assumption and the suggested linear heating rate that is used here.

In conclusion, K\(\alpha_{1,2}\) emission from high-temperature, small-mass targets irradiated by high-intensity laser light has been studied. K-shell emission induced by hot electrons that deposit energy within material heated over the hot-electron lifetime is shown to make an important contribution to the time-integrated \(K\alpha_{1,2}\)-emission spectrum from the smallest-mass targets. A collisional-radiative atomic physics model that includes time-dependent isochoric heating reproduces the main spectral features that are observed experimentally.

FIG. 1. (a) Experimental setup. (b) Experimental \(K\alpha_{1,2}\)-emission spectra from 500 × 500 × 20-\(\mu\)m\(^3\) (black) and 50 × 50 × 2-\(\mu\)m\(^3\) (red) Cu foils irradiated with 5-J, 1-ps pulses. Synthetic spectrum (blue) calculated with PrismSPECT\(^{34}\) assumes solid-density Cu and a single, time-independent thermal electron temperature of 10 eV. Instrumental broadening is included.
FIG. 2. (a) Experimental spectrum from a \(50 \times 50 \times 2\)\(\mu\)m\(^3\) Cu foil compared to synthetic spectra calculated with PrismSPECT,\(^{34}\) assuming solid-density Cu and thermal-electron temperatures of 10 eV, 150 eV, and 300 eV. Instrumental broadening is included. (b) Calculated mean ionization state for solid-density Cu as a function of bulk thermal-electron temperature for three different ionization-balance models.

FIG. 3. (a) Time-dependent mean ionization states for solid-density Cu heated from 1 to 300 eV (Profile A), 350 eV (Profile B), and 400 eV (Profile C) over a 10-ps period calculated with PrismSPECT.\(^{34}\) (b) Experimental spectrum from a \(50 \times 50 \times 2\)\(\mu\)m\(^3\) Cu foil compared to synthetic spectra calculated based on the heating profiles shown in Fig. 3(a). Instrumental broadening is included.
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8 C. Characterization of fast electron transport and energy coupling into imploded high-density plasmas using Cu-doped CD shell targets with the OMEGA and EP lasers

Understanding the generation of fast electrons in a cone and their subsequent transport into hot dense plasma is crucial to the success of the cone guided fast ignition scheme. Through the National Laser Users Facility (NLUF) program, we have obtained 2-day joint OMEGA and EP eTransport shots to investigate the coupling efficiency and spatial distribution of fast electrons' energy deposition in imploded CD shells attached to Au cone targets. This experiment was modeled after previous integrated fast ignition heating experiment led by W. Theobald et al., at LLE [Theobald11], but with Cu dopant (at ~1% atomic density) added to the CD shell, which allows characterization of fast electron transport via fast electron induced 8.048 keV Cu Kα fluorescence radiation. The first day experiment (July 27th, 2011) consisted of two parts: i) characterization of background 8 keV x-ray emission generated from the compression (by 20 kJ of OMEGA beams) of the CD shell with and without Cu-dopant and ii) characterization of fast electron produced Cu fluorescence emission from the compressed Cu-doped CD with an additional kJ, 10 ps high intensity OMEGA EP beam timed and injected into the compressed core through the Au cone tip. The primary diagnostics were a narrow band Spherical Crystal Imager (SCI) to image 8.048 keV x-ray emission and a Zinc Von Hamos (ZVH) x-ray spectrometer tuned for Cu K-shell and ionic line emission yield measurement. Several other diagnostics including broadband x-ray imaging diagnostics such as pinhole cameras and KB microscopes, neutron time-of-flight detectors and magnetic electron spectrometers (one multichannel spectrometer along the EP beam axis and one single channel spectrometer at the side) were employed.

Figure 1 shows pictures of the cone-in-shell target and experimental layout including TIM and port locations for various diagnostics. In this experiment, fifty-four (54) of the sixty (60) OMEGA beams with low-adiabat pulse shape (LA24170P with SSD off) were used (18 - 20 kJ) to compress the shell while the remaining 6 beams were used to destroy the target cone 5 ns after the short pulse laser was fired in the cone. The

FIG. 1: a) Picture of the Au cone-in-(Cu-doped) CD shell target; b) contact x-ray radiograph image of the target; c) experiment and diagnostics layout.

FIG. 2: SCI recorded 8 keV x-ray images from an OMEGA only compression shot with cone-in-CD shell without (a) and with (b) Cu doping. Also shown is a joint shot with EP beam energy of 260 J at 9 ps with equivalent contrast to previous images (c) and enhanced contrast (d).
10 ps OMEGA EP backlight beam BL2 was used with ~3.65 ns delay at 10 ps, tight focus at the inner cone tip, and a minimum pre-pulse. The target consisted of a plastic (CD) shell with an outer diameter of 870 µm and a cone with a full angle of 34 degrees with 40 µm offset distance between the outer cone tip and the shell center. The CD shell consists of a 10 µm pure CD outer layer as the ablator and a 27 µm inner layer doped with Cu at ~1% atomic number density of CD. Such shell target was designed to have same mass and outer diameter as the 40 µm thick pure CD shell used in previous integrated FI heating experiments, therefore to maintain similar implosion and fuel assembly as discussed below. The thickness of the cone tip was 15 µm while the cone wall thickness was 10 µm.

In this experiment, the SCI was fielded for the first time on OMEGA. Figure 2 is a comparison of 8 keV x-ray emission recorded with the SCI in three different shots; a) background x-ray emission from an OMEGA only imploded cone-in-CD-shell target (without Cu dopant), b) bremsstrahlung and fluorescence emission from an imploded cone-in-CD-shell target with Cu dopant, and c) bremsstrahlung and fluorescence emission from a joint shot of both OMEGA and OMEGA-EP with EP being fired with 300 J energy and d) enhanced contrast view of the image in c). The Cu fluorescence emission in the OMEGA only implosion shots with Cu-doped CD shell is due to the driver-beam-produced super-thermal (10’s keV) electrons and photon pumping by hot corona plasmas.

The 8 keV x-ray image from the joint shot (as seen in Fig. 2 c) and d)) shows emission from the imploded plasma just outside of the cone tip area with features that were not observed in the OMEGA only shots, which can be attributed to short pulse OMEGA EP beam produced fast electrons. In joint shots with EP beam energy > kJ, the SCI diagnostic was blinded by extremely high background. We have proposed several improvements which are discussed in section B and are currently being implemented for the planned eTransport shots on June 13th, 2012.

Cu K-shell and ionic line emission (Fig. 3) measured by the ZVH spectrometer showed a roughly 30%±20% increase in Cu Kα yield was observed in this joint shot due to EP beam produced fast electrons.

FIG. 3: Comparison of Cu K-shell yield for an OMEGA only shot and a joint shot with a kJ, 10 ps OMEGA EP pulse. 30% increase in Cu Kα yield was observed in this joint shot due to EP beam produced fast electrons.

FIG. 4: 2D hydrodynamic simulations using DRACO. Plots (a) and (b) showing mass density of CD and Cu-doped CD targets respectively at the time of OMEGA EP injection into the Au cone. Plots (c) and (d) showing mass density at 3.82 ns
enhancement in Cu K-shell yield signifying a contribution of Cu K-shell radiation from the fast electrons produced by OMEGA EP. The ZVH spectrometer also showed an extremely strong Cu He-α line emission. 1D and 2D radiation hydrodynamic modeling of the implosion suggested that this is due to the direct interaction and heating of the implosion driver beam with the Cu-doped CD layer after completely ablating off the first 10 µm non-doped CD layer. A slightly thicker ablator of 15 µm will be used in the improved targets for the future experiments to avoid such strong Cu He-α line emission to improve the Cu Kα line emission measurement.

2D radiation hydrodynamic simulations using the DRACO code were performed by A. Solodov at LLE to determine the effects of a Cu dopant on the implosion dynamics for a CD shell. Results of the simulations (Fig. 4) show that, for a Cu-doped CD shell of equivalent mass, the cone-tip breakout time, bang time, and peak ρR time are the same as a pure CD shell to within 50 ps. The results show that the tip of the cone is broken roughly 100 ps before the bang time with the bang time occurring 100 ps before peak ρR.

In summary, the NLUF fast electron transport experiment with cone-in-shell (with Cu doping) target has been successfully performed on the OMEGA facility with a comprehensive suite of x-ray, particle diagnostics including the newly implemented monochromatic x-ray imager (SCI) and multi-channel electron spectrometer. The platform for complex electron transport physics experiments has been established and will be pursued for > kJ short pulse laser energies with improved diagnostics and target design for the planned 2nd day shots on June 13th, 2012 and future joint-shot experiments on OMEGA with the improved ultra-high contrast EP beam described in the planned work section.

8 D. Study of fast electron generation and transport dependence on target material and laser pulse length

Efficient conversion of laser energy to hot electrons and their subsequent energy transport to the compressed fuel are extremely important for the success of fast ignition to reduce the cost of the ignition pulse. Energy coupling is controlled by the nature of the plasma (i.e., density profile, ionization etc.) at the laser-plasma interface and the dynamic response of the transport material, which evolve with time, therefore dependent on laser pulse length. Previous experiments [Wei11a, Chawla12] performed on the Titan laser (0.7 ps pulse length, 150 J) at Lawrence Livermore National Laboratory (LLNL) showed that 10 µm high-Z material in the multilayer planar solid target can suppresses fast electron angular spread. Through the National Laser Users Facility program, we obtained 4-shot days on the kJ, 10ps OMEGA EP laser to extend such study from sub-ps to 10 ps. This work consists of two steps:

1) With same electron source, study fast electron transport dependence on different transport
material with sub-ps (0.7 ps) EP laser pulse at 300 J and 10 ps pulse at 1.5 kJ to compare with the Titan (0.7 ps, 150 J) results.

2) With identical multilayered targets, investigate fast electron generation and transport dynamics with three different pulse length, i.e., 0.7 ps, 3 ps and 10 ps at similar laser intensity. Our first two OMEGA EP shot days in FY11 (Ecoupling-11A and -11B on 8 June, and 17 August, respectively) were used to examine the dependence of fast electron transport on target material and pulse length for the planar geometry using multilayer planar foil targets. The targets and setup were the same for the two experiments (Fig. 1). The high intensity short pulse EP backlight beam (300 J at 0.8-1 ps for the first day, 1500 J at 10 ps for the second day) was tightly focused (80% of laser energy in a 50–60 μm focal spot). The 1×1 mm² multilayer target consisted of a front surface Al layer (4 μm) over a thin transport layer (~10 μm) of various Z materials (Au, Mo and Al), an Al spacer (75 μm), a Cu tracer layer (12 μm) followed with a 20 μm thick Al layer. It was backed with a 1 mm thick 5×5 mm² wide conductive plastic layer to minimize electron refluxing. Fast electrons were characterized by two primary diagnostics, i.e., a spherical crystal imager (SCI) to measure the spatial distribution of fast electron induced 8.048 keV Cu Kα radiation from the Cu trace layer and a Zinc Von Hamos (ZVH) x-ray spectrometer (cross calibrated) tuned for measurement of the absolute Cu-Kα yield, which is proportional to the fast electron flux in such non-refluxing target.

FIG. 2: SCI recorded Cu Kα emission spots in 1 ps interaction experiment. a) from a Z=Al transport target; b) from a Z=Au transport target; c) plot of Cu Kα spot size (R50) for three different transport layer targets; d) SCI view of the target. Images are with same color and spatial scales.
In the 1 ps EP laser interaction experiment, we observed a clear trend of reduction of Cu Kα spot size with the high Z transport layer targets with good reproducibility. As shown in Fig. 2, the measured Cu-Kα spot in Z=Au case is about 60 μm in radius (R50 is the radius of the spot counting all the pixels with signal ≥ half the peak value) and ~90 μm for the Z=Al target case, which is consistent with the previous Titan results [Chawla12]. 2D collisional PIC modeling [Mishra11] including dynamic ionization and radiation cooling using the PICLS code [Sentoku08] suggest strong resistive magnetic fields inside the high-Z transport target collimate fast electrons and reduce forward-going fast electron angular spread (Fig. 3).

FIG. 3: 2D PIC simulations show electron transport partially collimated due to strong B-fields generated inside Z=Au transport target. The magnetic fields (a) and electron energy density (c) for Z=Au case compared to the fields and electron energy density for the pure Al case (c) and (d) at the end of the laser pulse (Gaussian in time and space, fwhm 730 fs long, fwhm10 μm diameter, Imax=9×10^19 W/cm^2).

In the 1 ps EP laser interaction experiment, we observed a clear trend of reduction of Cu Kα spot size with the high Z transport layer targets with good reproducibility. As shown in Fig. 2, the measured Cu-Kα spot in Z=Au case is about 60 μm in radius (R50 is the radius of the spot counting all the pixels with signal ≥ half the peak value) and ~90 μm for the Z=Al target case, which is consistent with the previous Titan results [Chawla12]. 2D collisional PIC modeling [Mishra11] including dynamic ionization and radiation cooling using the PICLS code [Sentoku08] suggest strong resistive magnetic fields inside the high-Z transport target collimate fast electrons and reduce forward-going fast electron angular spread (Fig. 3).

FIG. 4: Schematic of the multilayer foil target a) and laser and diagnostics layout b) in FY12 ECoupling experiment.
Experiments with 10 ps, 1500 J EP pulse in FY11 however showed a large shot-to-shot variation with indication of significantly different behavior of laser produced fast electrons and their transport shown in the observed $K\alpha$ spots compared to the experiments with 1 ps. No clear trend of the transport material dependence can be measured. Instead, we observed filamentary structures and irregular shapes (not shown here) in the fluorescence spot, which suggest the growth of widely separated, stable filaments on 10 ps time scale, either in the laser plasma interaction region or inside the solid target.

To further verify this and also to identify the transition phase of fast electron generation and transport from sub-ps to 10 ps, ECoupling-12 experiment (2-day shots on May 9-10, 2012) was dedicated to the laser pulse length scan using the identical multilayer targets with an improved front surface quality (roughness < 200 nm rms).

In addition to the primary $K\alpha$ diagnostics (imaging and x-ray spectroscopy measurements), we have developed and implemented two fixed port Bremsstrahlung MeV x-ray Spectrometers (BMXS) [Chen08] for the OMEGA EP experiments. BMXS measures fast electron induced high-energy bremsstrahlung x-ray emission from the target, from which we can infer essential information about the laser produced fast electron temperature, divergence, and laser-to-electron conversion efficiency [Chen09, Westover11].

Fig. 4 shows the schematics of the multilayered target and laser beam and diagnostics layout for the ECoupling-12 experiment. Cu tracer layer (22 µm thick) was buried 125 µm beneath the Al target and 1mm thick conductive plastics was used to minimize fast electron refluxing. Fast electrons were characterized by measuring their

![Fig. 4](image1.png)

**FIG. 4** The raw image plate dosimeter signal (normalized to the laser energy) is shown for the BMXS at EP-25 port shots taken with various laser pulse lengths. The high-energy IP dosimeter layers registered an increased signal in 10 ps shots compared to that in sub-ps shots.
induced K-shell emission from Cu tracer layer and bremsstrahlung emission from the target at two angles, i.e., BMXS-EP25 being 25 degree above the EP Backlighter beam axis from the equatorial plane and BMXS-55 about 65 degree off-side from the EP backlight axis on the equatorial plane. The high intensity EP Backlighter beam was normally incident onto the center of the target front surface with three different pulse lengths at similar laser intensity, i.e., 0.7 ps, 100-150 J; 3 ps, 400 J; 10 ps, 1500 J. With the measured R_{80} laser focal spot size of ~20 µm, the average intensity in this experiment was about 1×10^{19} W/cm^2.

Figure 5 shows SCI recorded Cu Kα images observed in the experiment with three different pulse lengths cases. In shots with sub-ps laser pulse, we consistently observed a single Kα spot with FWHM size of ~100 µm as seen in Fig 5(a). Such single spot behavior doesn't depend on interaction laser energy in the range of 40 J to 300 J. With 10 ps pulse, laser produced electrons beam break out into multiple filaments as shown in Fig. 5(c). Each filament has a spatial size of about 35 µm and is quite well separated at ~100 µm distance. Electron beam behavior with 3 ps interaction pulse is somewhere in between. As shown in Fig. 5(b), one can see one intense spot (~70 µm) with an additional shoulder feature, less separated than the main spot in the 10 ps case. Detailed analysis of the spatial intensity distribution in the measured Kα emission spots and 2D PIC modeling are under way.

Fig. 6 is the measured bremsstrahlung signal (normalized to the laser energy) on the 15 layers of image plate (IP) detector with various K-edge and differential filters to discriminate the x-ray spectrum (up to 700 keV with the current filter configuration). The larger the IP number, the higher x-ray energy it is measuring. The measured spectrum in the 10 ps case seems to suggest increase in electron temperature presumably due to preplasma formed at the front of the target with 10 ps pulses. The spectrum in the 3 ps interaction case is more consistent with the 0.7 ps case. Detailed bremsstrahlung data analysis with ITS modeling and hybrid ZUMA calculation is planned to obtain important information on fast electron temperature, divergence and laser-to-electron conversion efficiency in this experiment.

8 E. Study of fast electron transport in warm dense matter

Experiments conducted with the OMEGA EP laser indicated that fast electrons from a short pulse interaction experience substantially different transport when propagating through warm dense matter as compared to cold solid matter [Yabuuchi11]. The three cases studied included transport materials of cold solid CH, cold CH foam, and shock-heated CH foam. In the shock-heated foam case, a 1.2 kJ, 3.5 ns driver pulse heated the foam to ~40 eV. In this case, fast electrons experienced transverse spreading and impeded forward transport, resulting in reduced energy fluence delivered to the rear of the target as diagnosed by K-α x-ray signal from a Cu foil (shown in Fig. 1). The

![Image of Cu foil Kα signal](image.png)
signal from the K-α imaging diagnostic and ZVH spectrometer both decreased by a factor of ~20 in the case of the shock heated foam.

Ongoing Particle-In-Cell simulations performed by J. May in Prof. W. Mori’s group at UCLA using the OSIRIS code [Fonseca02] investigate the cause of the inhibited transport in warm dense matter. In a simulation intended to model the heated foam case, a laser with $a_0=3$ is incident on a 300 µm width target composed of a 10 µm thick Au layer followed by a 100 µm thick CH plasma at 40 eV and $7n_e$. Magnetic filaments form where the hot electrons enter the foam region and the return current is significantly filamented as shown in Fig. 2.

As discussed later in this report, previous and ongoing simulation work by our group indicates that when these filaments are formed, electron beam divergence can be increased due to scattering by the intense Weibel B-fields. New post-processing diagnostics are being developed to determine the energy flux at the rear of the target for comparison to the experimental Cu K-α signal. Additional simulations are being run to compare the transport through a solid density transport material and also to evaluate the relative importance of the Au/CH interface.
Transport of superthermal electrons currents driven by relativistically intense laser pulse (intensity $I > 10^{18} \text{ W/cm}^2$) is crucial for various potential applications, including fast ignition, and the generation of secondary sources of particle (ions, X-rays, positrons, neutrons). However, the stability and uniformity of those currents transported through targets are an important parameter in order these processes efficient. One method to get information about the hot electron beam is using proton imaging. Protons used for the imaging are produced by irradiating a thin foil with a short-pulse, ultra-high intensity laser and are predominantly accelerated from the rear-surface of the target [Fuchs05]. The fast electrons propagated through the foil excite a $\sim$TV/m electrostatic sheath field on its rear surface that ionizes the surface atoms and accelerates the resulting ions. The accelerated ion beam is composed mostly of protons originating primarily from contaminant layers of water vapor and hydrocarbons on the target surface.

Recently it has been shown that hot electron beam are more uniform in conducting metals than in insulators [Fuchs03], since in insulators there is lack of background electron to provide the return current that neutralizes the forward electrons. In this work, we show that conducting metal target could have stable or unstable transport owing to the resistivity evolution inside the ultra-fast heating target, see Fig.1. This will be an important aspect to control the hot electron transport to realize the applications.

![Experimental setup: a short-pulse, high energy laser beam hits a solid target. Protons stemming out from the rear target surface are imaged on RCFs. (a) Proton image at 6MeV, 3cm away from 40μm aluminum target, (b) same image from 15μm copper, (c) 40μm copper, and (d) 10μm gold.](image)

The main purpose of this project is to understand the different transport features in a several metal targets observed in the experiments by particle-in-cell (PIC) simulations using the same laser and targets conditions with the experiments. Typically, the electron currents generated near the vacuum plasma interface by 100TW laser light exceeds mega-ampere (MA), which is higher than the Alfven critical current. In vacuum, these currents induce self-consistent B fields bending the electron trajectories backwards and preventing their penetration.
into the overdense plasma. While in a dense plasma important shielding effects arise and the high energy electron current is neutralized by a cold electron return current. This allows the high energy electrons to propagate unimpeded into the overdense plasma. However, the system is unstable to a relativistic electromagnetic two-stream instability so-called Weibel instability [Weibel59]. In a solid plasma, the kinetic instabilities are collisionally damped as discussed in Ref. [Sentoku08], and the resistive magnetic fields driven by the Ohmic fields $E_R=\eta J$, which evolve by the following source terms,

$$\frac{\partial B_i}{\partial t} = -(\eta \nabla \times J + \nabla \eta \times J)$$

plays an important role on the hot electron transport. We found that in low-Z targets, such as aluminum, the first term of RHS is a dominant source term of the resistive magnetic fields. While in high-Z targets due to a large heat capacity, and dynamic ionization, the second term becomes an important source. The magnetic field is able to be amplified in order of ~ 100MG, and changes its pattern following the resistivity evolution.

The experiments were performed using the 100 TW short pulse laser at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI). Laser pulses of ~ 20-30 J of 1μm light (350 fs) were focused at $I_{\text{max}} \sim 6 \times 10^{19}$ W/cm$^2$ onto the front surface of various conductor targets. We used as diagnostics proton imaging, i.e. the accelerated protons that are detected in multiple layers of radiochromic film (RCF) densitometry media. The spatial distribution of the protons in a given RCF layer gives the angular emission pattern at a specific interval of proton energy. As targets, we used Al, Cu, and Au targets. The targets had on their rear surface a grooved pattern. Those targets, that have a periodic shallow modulation of the target rear-surface, allow to imprint regular modulations in the proton beam that thus allow to image the accelerating sheath surface.

Figure 1 shows the experimental setup and selected images of 6 MeV protons from various targets. We see strong modulation in the image from 40 μm Al target, Fig.1(a), while 10 μm gold produces more smooth distribution with tightly focused peak at center(d). The 6MeV protons from a thin (15 μm) copper have a doughnut distribution (weak at center) (b), while a thicker (40 μm) copper has a smooth distribution and less doses (c). Note here that the maximum proton energy does not vary sensibly with the target materials, but target thickness. Also an experiment with lower (1/3) laser energy with the same spot size and pulse length showed a smooth profile from 40 μm Al target. Based on these results we infer that the fast proton images are sensitive to the target resistivity, which evolves in time due to dynamic ionization.

We analyze the experiments using the two-dimensional Particle-in-Cell (PIC) code PICLS2d [Sentoku08], which features binary collisions among charged particles and ionization processes in gas and solid density plasmas. The target is modeled as a uniform slab with a small preplasma with a few micron scale in front of the target. We prepare the same material targets with the images in Fig.1, 40 μm Al, 15 and 40 μm Cu, and 10 μm Au with its surface normal oriented along a Cartesian Y axis. The target is attached to the transverse boundaries, and we use absorbing boundary condition for particles to represent the large transverse volume of target. The ion density is set to $50n_c$, here $n_c=10^{21}$ cm$^{-3}$ is the critical density for laser wavelength 1 μm. The mass (fully ionized charge) of Al, Cu, and Au ions are 27$M_p$ (13), 64$M_p$ (29), and 197$M_p$ (79), respectively, here $M_p$ is the proton mass. Then the mass density of each target becomes $\rho_{Al}=2.2$, $\rho_{Cu}=5.3$, and $\rho_{Au}=16.9$ g/cm$^3$. These are close to the mass density of each metal at solid density. Initially we set the ion charge state $Z=3$ for all targets, and electron
density is set to neutralize ion charges. Our ionization model is the Thomas-Fermi model in dense plasmas. The electron density increases dynamically during laser irradiation via ionization processes. Initially particles are at rest, with initially zero temperature. Our spatial (temporal) resolution is $1/50$ of the wavelength ($\tau$: laser oscillation period) for Al and Cu targets, and $1/100$ of the wavelength ($\tau$) for Au target.

Since the laser is focused on the target surface with a gaussian profile, the hot electron current has a peak at the center, namely, the first term of Eq. (1) naturally becomes positive at lower side of focal area and negative at upper side. The second term depends the resistivity evolution during heating and ionization by ultra-fast laser irradiation.

![Fig. 2](image)

**FIG. 2.** (a) Electron energy density, and (b) quasi-static magnetic fields at 330 fs of 40 $\mu$m Al target. (c) Resistivity profile obtained 1 $\mu$m inside Al target at 80 fs. (d) Electron energy density, and (e) quasi-static magnetic fields at 200 fs of 15 $\mu$m Cu target. (c) Resistivity profile obtained 1 $\mu$m inside Cu target at 80 fs. (g) Electron energy density, and (h) quasi-static magnetic fields at 200 fs of 10 $\mu$m Au target. (c) Resistivity profile obtained 1 $\mu$m inside Au target at 80 fs.

Figure 2 summarizes the simulation results of 40 $\mu$m Al, 15 $\mu$m Cu, and 10 $\mu$m Au targets. In the Al target, the hot electron flows (a) split to twin jets (hollow beam), like observed in Ref. [Storm09]. The resistive magnetic fields (b) are in an order of $\pm$ 5MG, and they form twin channels with many small filaments, consistent with the hot electron pattern,
due to the resistive instability driven by the hot electron current. We plot the resistivity inside 1 μm from the target surface at the early time (t=80fs) before the resistive fields start to grow in order to determine the dominant source term of the resistive fields. In Fig.2 (c) η has the minimum at the center. This is because the aluminum has less heat capacity and easily ionized almost to full charge state. Therefore the temperature increase is predominant over the increase of average charges, namely, η simply drops during the heating since $\eta \propto Z/T^{3/2}$. Then the transverse gradient of resistivity $\partial \eta / \partial y$ has the opposite sign to the current gradient $\partial J_x / \partial y$. Because the magnetic fields at 80 fs before breaking into twin jets (before starting the resistive instability) has the same sign with $\partial J_x / \partial y$, we conclude that the current gradient (1st term of Eq.1) is the dominant source term in the Al target. The propagation speed of magnetic fields is relatively fast, which is about 60% of the speed of light and consistent with the speed of ionization waves (or heat waves) observed in the simulation.

In the Au target, however, η drops slower than the Al target due to large heat capacity, owing higher electron density as a result of ionization and more energy taken to ionize the Au ions from the thermal energy. As a result, η inside the gold could have a peak at the center because the electron density has a peak at the center, and the bulk temperature stays relatively low during ionization. Fig.2 (i) shows η profile inside the Au target observed at the same time of (c). We see the η had a peak at the center. With this η profile the second source term in Eq. (1) has a positive feedback to the first term, then the resistive magnetic fields are excited more effectively. Also the observed propagation speed of the ionization waves in Au target are about 15% of the speed of light, which is ~ 4 times slower than that in the Al target. The slower propagation could grow the magnetic fields temporally longer, then together with the feedback effect of the resistivity gradient, the resistive magnetic fields is amplified to an order of magnitude stronger than those in the Al target. The resistive magnetic fields in Fig.2 (h) forms a single channel with amplitude ± ~100MG, which pinches hot electron current as seen in (g).

In the copper, the resistivity profile Fig.2(f) is an intermediate between Al and Au targets. The η had a twin peaks profile due to the balance of competition between heating (T increases) and ionization processes (Z increases). As a result, the resistive magnetic fields, of which amplitude is close to in the Au target, have a hollow channel (e). So that the hot electrons inside the Cu target have the hollow beam structure (d), which is similar with the Al target, however the mechanism of the formation of the hollow beams is quite different.

We had studied the MA current transport in conductive metal targets by two-dimensional collisional/ionization PICCLS simulations. We found that the current term ($\mathbb{J} \times \mathbb{J}$) is dominant source term in low Z (Al) target of resistive magnetic fields. While the resistivity gradient $\eta$ plays an important role in high Z targets, such as Cu and Au targets. In high Z target, the resistive magnetic fields become extremely strong 100MG, and structure depends on the evolution of resistivity inside the ultra-fast heated target. In the current experimental conditions, the Cu target has hot electrons in a hollow beam structure, and the Au target has one single channel beam pinched by the magnetic fields. Hot electron currents affected by the strong resistive fields modulate the sheath potential patterns at target rear surface, which are imprinted in MeV protons accelerated from the target rear surface, are recorded in the RCF images. These simulations are consistent with the experimental observations.

References

8 G. Anomalous inhibition in front of ionization wave driven by relativistic laser pulse in dielectric solid

The formation of ionization wave inside glass target as result of interaction with short laser pulse (pulse duration $\tau<100$ fs, wavelength $\lambda=616$ nm) at low intensity $I\sim 5\times 10^{14}$W/cm$^2$, was observed by Vu et al. [Vu94] by using Doppler shift of the reflected probing beam. Reconstructed expansion velocity $\sim 1.8\times 10^7$cm/s has been explained by standard electron thermal conduction model. The first observation of laser-driven ionization wave inside glass target at high laser intensity, $I\sim 10^{17}$ W/cm$^2$ ($\tau<2$ ps, $\lambda=1054$ nm) with single frame shadowgraphy has been reported by Ditmire et al. [Ditmire96]. It has been shown hemispherical expansion of ionization wave up to $\sim 0.1$ mm inside glass target with velocity $\sim 8\times 10^8$cm/s that is consistent with radiation driven thermal transport. A shadowgram measurement of fast electrons driven by ultraintense laser pulse with $I\sim 10^{19}$ W/cm$^2$ ($\tau<0.35$ ps, $\lambda=530$ nm) was done inside glass target by Gremillet et al. [Gremillet99]. It was shown a presence of narrow axial jets moving with almost speed of the light as well as hemisphere ionization expanding with the velocity $\sim c/2$. Coherent transition radiation diagnostics [Storm09] was used for investigation of interaction of high-intensity laser, $I\sim 10^{19}$ W/cm$^2$, with metal films. There was studied the divergence of the electron beam with distance.

Theoretical studies of the ionization wave driven by the relativistic electron current in initially insulator targets including the breakdown effect are limited. There had been a work with a three-dimensional hybrid code [Gremillet99], which models the ionization expansion as a quasi-neutralized diffusive plasma neglecting the breakdown field in the dynamic ionization process. A one-dimensional collisional particle-in-cell (PIC) simulations, which include a model of collisional ionization, and field ionization, had been used to study the ionization wave in an insulator target for sub-relativistic regime, where the diffusive effect is dominant and the sheath field is lower than the breakdown field [Kemp04].

In this work we first demonstrate the two-dimensional PIC simulation, which includes binary collision, collisional ionization, and field ionization in order to show the dynamics of ionization wave in the breakdown regime. The simulation show the strong electrostatic inhibition of the fast electron current at the insulator/plasma transition, and quasi-static magnetic fields excitation at the ionization front. On top of that, very energetic electrons proceed beyond the ionization front, and go deeply in the insulator region, where the fast electron charges are not neutralized. The self-induced fields by the fast electron charges are not strong enough to make breakdown locally, but they can diverge the fast electrons radially, like a “fountain” of electrons. Based on a simple model of ionization wave, we derive a scaling of the ionization speed for the relativistic laser intensities.

Following is the parameters used in the simulation of ionization dynamics in an insulator target. Our simulation tool is the 2D PIC code, PICLS [Sentoku08] featuring binary collision and dynamic ionization. For the ionization, we have the field ionization, and the Thomas-Fermi ionization model for collisionally heated plasmas.
The target consists of solid silica arranged in a slab geometry. A 5μm length of low density gas is placed in front of the target as a pre-plasma. The glass, silicon dioxide, is composed of Oxygen (Z=8) and Silicon (Z=14) in a ratio of 2:1 with a corresponding ion density \( n_{\text{Ox}} = 46n_e \) and \( n_{\text{Si}} = 23n_e \), respectively. The mass density of silica is set to 2.6 g/cm\(^3\). Initially, the target was neutral with no electrons. When it is fully ionized, the electron density could become \( n_e = 690n_e \). The simulation box is 75μm×100μm with 3000×4000 grids with each grid cell containing 6 ions and up to 60 electrons for total of 686 million particles. The electron plasma density was resolved in this simulation up to \( n_e = 91n_e \) with a spatial resolution of 25nm/grid.

The laser used in the simulation is characterized according to the NTF Leopard Laser capabilities. Wavelength is set to 1μm with a focus spot size of 10μm. The pulse length is set to 500 fs with a 100 fs rise/drop time. The peak intensity is \( 5.5 \times 10^{18} \text{W/cm}^2 \) corresponding to a normalized amplitude \( a = \frac{eE}{m_ec\omega} = 2.35 \), where \( m_e \) is the electron mass, \( c \) is the speed of light, and \( \omega \) is the laser frequency. We have used absorbing boundaries for both electromagnetic waves and particles, which encounter the boundaries, completely lose their energy.

A snapshot of the 2D simulation at 300fs is shown in Fig. 3. We find there are two different electric fields involved for relativistic laser driven ionization in an insulator. The first is an electric sheath field which borders the ionization front (≈ 55μm) and is caused by the strong inhibition of fast electrons, see Fig. 3(a). Note here that Fig. 3(a) shows only transverse component of electric fields, but we see strong Ex at the center of the sheath region, so that the sheath surrounding the ionization wave front. The peak of the sheath is \( E_x \sim 10^{11} \text{V/m} \), which exceeds an order of magnitude of the breakdown threshold of silica \( (E_b \approx 10^{10} \text{V/m} \) [Linde96]), and electrostatic potential energy \( e\Phi_s \) in the hot electron Debye length \( (\lambda_{Dh} \sim 5\mu m) \) is approximately 500 keV, which is close to the hot electron temperature \( T_h \sim 460 \text{ keV} \) from the ponderomotive scaling, like the sheath field at the plasma vacuum interface, \( eE_s \sim T_h/\lambda_{Dh} \). This sheath field initiates breakdown process. Note here that there are filamentations of ionization path as seen in Fig. 3 (d) behind the ionization front as the results of the breakdown processes, like electric thunders, and these filamentary cause magnetic filamentations shown in Fig. 3(b).
The second electric field is driven by the fast electrons with energies above $e\Phi_s$, which travel through the potential gap and form a fast electron cloud layer on top of the ionization front, as in Fig.3(c). The absence of free electrons in insulators precludes the possibility of a neutralizing return current. As a consequence, these electrons carries net charges and currents, and they excite the lateral electrostatic field located beyond the ionization front, marked as “fountain field” in Fig.3(a). Since this electric field is weaker than $E_b$, no breakdown occurs, but fast electrons diverge laterally and turning around by this self induced field, like a “fountain” of electrons. The corresponding azimuthal magnetic field, Fig.3(b), ($\approx 500kG$) is also excited by electrons motion. We call this motion pattern as the “fountain effect”. The electric field component of the electron fountain is purely radial ($E_y$) because the observed longitudinal component is of negligible magnitude.

Here we estimate the propagation speed of breakdown ionization using a simple model of current neutralization for the relativistic laser intensities. At the ionization front the local breakdown produces new electrons, and these new born electrons accelerated backward by the sheath field supply the return current. The acceleration time scale is about $\tau \approx l/u$, here $u$ is the ionization wave speed, and the breakdown region is $l=(\lambda_D e)\cdot(1-E_b/E_s)$ where $E_s$ exceed $E_b$. Since behind the ionization front no strong sheath is seen, the fast electron current is mostly neutralized by the return current of new born electrons, $en_n c \approx en_n v_n$, here $e$ is electron charge, $n_n$ ($n_n$) is the hot electron (new born electron) density, $v_n$ is the speed of return current, respectively. Here we neglect the ionization energy since it is much smaller than the hot electron energy flowing into the sheath region. The speed of return current is calculated by, $v_n \approx (eE_{av}/m_e) \tau$, here $E_{av}$ is the average electric field the electron would see, $E_{av} \approx (E_s/2)(1+E_b/E_s)$. By solving current conservation equation for $u$, we get

$$\frac{u}{c} = \frac{1}{2} \frac{n_n}{n_h} \frac{T_h}{m_e c^2} \left(1 - \frac{E_b^2}{E_s^2}\right)$$

This equation shows the ionization wave could proceed ($u > 0$) only when $E_s > E_b$ for breakdown. In the relativistic laser plasma interaction, the hot electron temperature $T_h$ is in ponderomotive scaling, which is proportional to the square root of the laser intensity, $\sim (I\lambda_0^2/1.83\times10^{18})^{1/2}$, so that the ionization wave speed is proportional to $I^{1/2}$. We had performed 1D simulation to check this scaling and make a plot with the previous and our experimental observations in Fig. 4. We see the clear transition of the ionization speed at around $10^{18}W/cm^2$, and the experimental data are also consistent with the $I^{1/2}$ scaling.

![Graph showing ionization speed vs. laser intensity](image)

**FIG. 4:** Ionization speed in non-relativistic to relativistic regimes.
References


8 H. Radiative Damping in Extreme Intense Laser-Matter Interaction

With the advent of high-powered, short pulse lasers, it becomes possible to extend laser intensities to $10^{21}$ W/cm$^2$. By applying a micro-focusing device such as the recently developed elliptical plasma mirror, it is possible to focus the beam to a micron-scale spot, thus enhancing the intensity more than an order of magnitude [Nakatsutsumi10]. In a few years, the intensity will exceed $10^{22}$ W/cm$^2$, and electrons accelerated by such an intense laser field will reach energies beyond 100 MeV and start to strongly emit radiation. Then the radiation loss from an accelerated electron will no longer be negligible and will affect its motion, so-called radiative damping.

In order to study the effects of the radiative damping, a code was developed to solve a set of equations describing the evolution of a strong electromagnetic wave interacting with a single electron. Usually the equation of motion of an electron including radiative damping under the influence of electromagnetic fields is derived from the Lorentz-Abraham-Dirac (LAD) equation treating the damping as a perturbation [Landau94]. Until now, only the first order damping equation of the LAD equation has been used [Zhidkov02, Koga04, Bell08, Sokolov09, Sokolov09, Ford93, Bulanov11, Capdessus11]. This is because the second order terms are thought to be small in comparison with the first order terms, and also deriving the second-order terms is challenging. We have derived up to the fourth order terms, which are the largest terms in each order, and implemented them up to the 2nd order terms in a laser-plasma simulation code.

We have implemented the 1st-order terms and the 2nd-order damping terms in the Particle-in-Cell (PIC) code in order to study radiation effects in the super intense laser-matter interaction for extreme intensity, $I > 10^{22}$ W/cm$^2$. The numerical code used is the one- & two-dimensional (PIC) code PICLS [Sentoku08], which features binary collisions between charged particles and ionization processes in gaseous and solid density plasmas [Sentoku2011].

The target is modeled as a 5µm thick copper slab with uniform density. A few micron thick preplasma is placed in front of the target. The ion density is set to $50n_c$, here $n_c=10^{21}$ cm$^{-3}$ is the critical density for a laser wavelength 1µm. The mass (fully ionized charge) of Cu is $64M_p (29)$, where $M_p$ is the proton mass. Then the mass density of the target becomes $\rho=5.3$ g/cm$^3$, close to the mass density of solid copper. Initially we set the ion charge state $Z=3$, and electron density is set to neutralize ion charges. We placed a 5µm preplasma in front of the target with an exponential profile of a 2µm scale length and a 50n$_c$ peak density for electrons when the preplasma gets fully ionized.

The ionization models include field driven ionization in low density plasmas under strong fields and impact ionization which solves for the collisional cross section in dense plasmas.
The electron density increases dynamically during laser irradiation via ionization processes. The ionization energies are subtracted from the hot electrons when they ionize atoms via collisions with bound electrons. Initially particles are at rest, with initial plasma temperature set to zero. Our spatial (temporal) resolution is 1/140 of the wavelength (laser oscillation period \( \tau \)). The simulation also accounts for the energy loss by emission of soft x-ray radiation from free-bound transition, though it is only a minor effect (less than 0.3% of the laser energy) under the current simulation condition.

One-dimensional simulations were performed to see the effect of radiative damping by only 1st order terms and by 1st + 2nd order terms specially in electron and ion phase space, energy spectrum, energy density. Figure 5 shows the phase plot and energy spectrum of electrons with and without radiative damping at 181.5 fs when the pulse peak with intensity \( I = 10^{23} \text{W/cm}^2 \) hit the target. Strong damping of high energy electrons \( (p_x/m_ec > 1000) \) in the phase plots are observed at this time. The 2nd order damping term has also small contribution in this damping which can be seen in the electron energy spectrum plot (blue-line).

![Figure 5: 1D-PIC result with \( I = 10^{23} \text{W/cm}^2 \): (a) Distribution of electrons in phase space with no radiative damping (Red) and with 1st + 2nd order radiative damping (blue) at \( t = 181.5 \text{fs} \) when the pulse peak hit the target (b) Comparison of electron energy spectrum among three cases at the same time.](image)

Figure 6 shows the phase plot and energy spectrum of electron with and without radiative damping at 214.5 fs when the pulse starts to be reflected. Strong damping of high energy electrons, especially accelerated backward by the reflected pulse \( (p_x/m_ec > 1000) \), in the phase plots are observed at this time. The 2nd order damping term has a significant impact in the radiative damping as seen in the electron energy spectrum plot. This is because the electrons can interact more with the intense laser pulse as co-propagating with it.
FIG. 6: 1D-PIC result with $SI = 10^{23}$ W/cm²: (a) Distribution of electrons in phase space with no radiative damping (Red) and with 1st + 2nd order radiative damping (blue) at $t = 214.5$ fs when the pulse starts to be reflected (b) Comparison of electron energy spectrum among three cases at the same time.

References


8 I. Hosing in relativistically hot plasmas

Recently available kJ-class short pulse lasers not only have the intensity to make electrons oscillate at relativistic speeds but also have the energy to heat these electrons to relativistic temperatures. In our recent Particle-in-Cell (PIC) simulations of laser channeling in mm-scale underdense plasmas for fast ignition the residual electron temperature $T_e$ in the channel were
found to be multi-MeV. We have found that relativistic $T_e$ can significantly affect laser hosing, an instability important to both laser wake field accelerators (LWFA) and fast ignition. The hosing instability affects laser propagation and plasma wake field generation in LWFA. LWFA-relevant Hosing is in the short-pulse regime, which is mediated by the plasma waves and does not involve ion motion. In the channeling/hole-boring scheme of fast ignition, the channeling pulse can also suffer the hosing instability, which causes channel bending and bifurcation, in the underdense plasma of a target. Hosing in this long-pulse regime involves ion motion and is mediated by the ion acoustic waves. However, there is a long-standing discrepancy on the wavelengths of the dominant hosing modes between the existing theory and PIC simulations/experiments. In the short-pulse regime, the hosing modes observed in the PIC simulations had much larger wavelengths than predicted by the cold plasma theory. Although an improved theory predicted a long wavelength regime that encompasses the observed modes, it also predicted that the maximum growth rate should occur at a much shorter wavelength where no mode was observed in the simulations. It was argued that the lack of such modes was due to the interference of Raman instabilities. In the only reported experiment observation of laser hosing, the observed hosing wavelengths were also much longer than predicted by the short-pulse theory. Similar discrepancy also exists for the hosing instability observed in the channeling simulations.

We have shown that this discrepancy can be resolved by properly treating the electron temperature effects in the relativistic regime. Starting from the full relativistic fluid theory, we re-derive the coupled equations of laser envelope and plasma density, in both the short-pulse and long-pulse regimes, extending the equations into the relativistic $T_e$ regime. An analysis of the hosing instability using these equations and a variational method show that as $T_e$ becomes relativistic the dominant hosing modes shifts to longer wavelengths for both short- and long-pulse modes, agreeing with the experiment and PIC simulations. The derived equations will also be useful to study a wide range of nonlinear plasma optical phenomena in the relativistic $T_e$ regime.

This research is part of a PhD thesis on laser channeling and hosing in fast ignition (Gang Li, successfully defended in 4/2012). Papers based on these results are being prepared.

8 J. Hydrodynamic Simulations of Cone-in-Shell Targets for Integrated Fast-Ignition Experiments on OMEGA

Integrated cone-in-shell fast-ignition experiments [1] on OMEGA will benefit from improved performance of the OMEGA EP laser, including higher contrast, higher energy, and a smaller focus. A new target design will be used with a thick low-Z aluminum cone tip, which is expected to improve the target hydrodynamics and reduce the scattering losses of fast electrons.

Simulations of cone-in-shell targets using the radiation–hydrodynamic code DRACO [2] have been performed. Our simulation capabilities were significantly improved over the last year. Radiation transport has been included, the Eulerian scheme was improved by using
proper Coriolis force terms, 3-D laser ray-trace has been included, and cross-beam energy transfer was accounted for. DRACO simulations of the previous target design show that a 15-µm-thick tip of the gold cone is breached by the strong shock from the implosion about 100 ps before the bang time and 280 ps before the time of peak compression. A new target design uses a 60-µm-thick aluminum block mounted in front of a gold cone. A very thin (~2-µm) gold layer inside the cone tip serves as a mounting layer for the block and also helps to shield the radiation. The gold layer has no significant effect on the transport of the fast electrons. DRACO simulations predict that this design is more resilient against the shock than the previous gold-only design and the cone tip breakout is delayed by about 100 ps. Figure 1 shows the results of the simulation for the new design.

FIG. 1: 2-D hydrodynamic simulation of a cone-in-shell target with the code DRACO. (a) Detail of the tip of a cone-in-shell target showing the gold cone with an aluminum tip. (b) Imploding shell before peak compression at 3.25 ns. Simulations predict thermal expansion of the cone material due to radiation preheat. The aluminum tip expands faster than the gold material. (c) Density map at 3.87 ns (~0.19 ns before peak compression) showing better shock resilience of this design than the previous Au cone tip target.

The simulations identify the need of an experimental validation of the hydrodynamic compression of the new target. The fuel assembly will be measured with a back-lighter experimental setup [3] using a Cu foil irradiated by the OMEGA EP pulse. The advantage of this method is a high temporal resolution (~10 ps), high spatial resolution (~10 µm), high signal to background ratio, and monochromatic imaging. Figure 2 shows simulated 8 keV back-lighter images for various times during the implosion. These images were obtained by postprocessing a DRACO simulation with the atomic-spectroscopy code Spect3D [4]. The details of the fuel assembly at different times of the implosion are shown. The last frame is at peak compression. The upper blue triangle shows the absorption of the x-ray radiation by the cone and the decreasing green circle with the blue core is the imploping plastic shell. The calculated peak areal density of the shell exceeds 400 mg/cm². The radiographs also show how the implosion destroys and pushes back the cone tip.
FIG. 2: Simulated 8 keV back-lighter images using the DRACO simulation results from Fig. 1 and post-process them with Spect3D for different times of the implosion (a) 3.55 ns, (b) 3.73 ns, (c) 3.89 ns, and (d) 4.05 ns, which is at peak compression.

Simulations of fast electron propagation and energy deposition in the compressed core have been performed using the hybrid-PIC code LSP [5] integrated with DRACO [6]. Simulations predict improved coupling of fast electron energy into the compressed plasma for anticipated improved laser parameters (higher short-pulse contrast, energy, and intensity). For the integrated experiments using the new target with the thick low Z tip there is the additional advantage that the tip has an electrical resistivity that is higher than the surrounding CD plasma. The resistivity mis-match collimates fast electrons into the assembled fuel [7], which will increase the coupling efficiency. In the Spitzer regime, the resistivity varies according to $\sim Z/T^{3/2}$, where $Z$ is the nuclear charge and $T$ is the electron temperature. Figure 3 shows the results of LSP simulations for a target with an aluminum cone tip, OMEGA EP pulse energy of 1.5 kJ, and negligible amount of preplasma (high contrast). Despite of high initial divergence (~45° half-angle), about 50% of hot electrons are collimated in the aluminum plasma from the inner tip surface to the core. The ion temperature increases by up to 300 eV in the core. The neutron-yield increase by $1-8\times10^7$ is predicted based on DRACO+LSP simulations, taking into account uncertainties for the angular divergence, mean energy, and total energy of fast electrons generated by the OMEGA EP pulse.

FIG. 3: DRACO + LSP simulation for a 10-ps, 1.5-kJ OMEGA EP pulse, showing contours of (a) fast electron density, (b) azimuthal magnetic field, and (c) plasma ion temperature increase with respect to a target without electron beam heating.
8 K. Fokker Planck and PIC Hybrid simulations of shock formation in shock ignition

In 2011 we initiated a research effort to understand the kinetic physics associated with shock ignition; from the absorption of the laser pulse, to the transport of hot electrons and the formation of the shock in the high-density plasma. Our goal is to provide a detailed description of the underlying physical mechanisms and their interdependence, to assist the interpretation of experiments and the design of more efficient shock ignition targets. Performing such an integrated study has recently become possible because of the progress in our unique simulation capabilities, including the Particle-In-Cell code OSIRIS, the hybrid-PIC code OSIRIS-H [2] and the 2D3P Vlasov-Fokker-Planck code OSHUN [1]. The latter two codes have been developed over the past three years, and during 2011 we optimized them to address the challenges of the kinetic physics of shock ignition. Our plan is:

(A) To investigate the absorption of the laser energy in the under-dense corona due to Laser-Plasma Interactions. This study will yield the detailed structure of the hot electron distribution and its dependence on the laser profile.

(B) To characterize the transport of hot electrons from the under-dense to the high-density region. This will connect the hot electron distribution to the heating profile deeper in the target.

(C) To understand the formation of the shock in the high-density region and its dependence on the heat source.

Below we discuss the steps we have taken to address the aforementioned challenges.

As of the summer of 2011 we have started using OSIRIS to study LPI for conditions relevant to shock ignition. The first step is to carefully document the differences between 1D and 2D physics, for it has long been known that in multiple dimensions there are additional phenomena that must be considered for realistic modeling, such as the Two-Plasmon-Decay (TPD) instability and the High-Frequency Hybrid Instability (HFHI). However, 2D simulations require considerable computational resources to accurately capture the physics, even with a highly optimized code such as OSIRIS. For example the 2D simulation shown in Figure 1 requires about 1 million processor hours. Sophisticated post-processing tools are also necessary, and we avail ourselves of the suite of diagnostic tools that has been developed over the years at UCLA to study LPI. In Figure 1 we present a 1D and a 2D simulation of a laser with intensity $10^{16}$ W/cm² shining on an exponential density profile with density ranging from $0.05n_e$ to $0.35n_e$. 2D mechanisms—first and foremost the TPD—lead to considerable differences in the hot electron spectrum between these two cases. Hence, in order to

References:
understand the dependence of the hot electron source on the laser and plasma profiles we are currently performing a series of 2D simulations.

In Figure 2 we present the integrated electron heat flux from two 2D OSIRIS simulations with different laser intensities as a function of time and position. In the higher intensity case the scattered light strongly re-scatters at the n_c/16 surface, thereby generating hot electrons that are going down the density gradient. In this simulation the hot electron flux retains the intermittent features seen in the plasma response in Figure 1, whereas for the lower intensity simulation steady electron flux is observed. Our preliminary results will be presented in a talk at the Anomalous Absorption Conference 2012.

**FIG 1:** Comparison between 1D and 2D OSIRIS simulations. An exponentially rising density profile is irradiated by a plane-wave 10^{16} W/cm^2 laser. The plasma wave history plots, in the first column on the left, show the LPI near the n_c/4 surface and the re-scattering of the scattered light near the n_c/16 surface. Both the evolution of the plasma waves and the spectrum of the accelerated electrons are very different in 1D and 2D. In particular, because 2D simulations allow for plasma waves to have finite perpendicular wavevectors it allows for the TPD instability to grow. The TPD manifests itself in recurring bursts and the hot electron distribution is broader in momentum space.
OSIRIS-H (Hybrid-PIC) is being employed to study the transport of hot electrons, the deposition of the hot-electron energy in the dense plasma and the formation of the shock. To simplify the problem, and relax the computational constraints, we study the transport of cathode-injected—as opposed to self-consistently LPI-generated—hot electrons in plasmas with density ranging from a few times $n_c$ to 1000$n_c$ in 1D. In contrast to conventional PIC codes, for which modeling such ultra-high densities is impossible, OSIRIS-H enables parameter scans, and the use of a cathode facilitates control of the composition of the hot electron source, so as to study its effect on the shock structure.

![FIG 2: Integrated electron heat flux from two 2D OSIRIS simulations with different laser intensities.](image)

![FIG 3: 1D simulation of a plasma with density $10^{24}$ cm$^{-3}$ heated by cathode-injected 70keV electrons at a rate $2\times10^{15}$W/cm$^2$. (a) The ($p_x$,x) plot showing the cathode-injected electrons interacting with the dense target, (b) the strong resistive electric field on the surface of the target shown after 5ps, (c) the electron pressure as a function of time and position, (d) the ion pressure as a function of time and position.](image)
In Figure 3 we present results from the interaction of a $2 \times 10^{16}$ W/cm$^2$ cathode-injected electron beam with a target for which the density rises rapidly from about $10n_c$ to $1000n_c$ and stays constant after that. The 70keV electrons deposit their energy at the surface of the ultra-high-density target and a shock starts forming. A series of simulations with different density profiles and cathode parameters will be discussed in a talk at the Anomalous Absorption Conference 2012. Non-local electron transport in high-density plasmas is usually incorporated in fluid codes using either a flux-limited Fourier’s law for heat conduction, or a multi-group method. In the beginning of 2012 we established a collaboration with the group headed by S. Atzeni to assess the validity of the most common models for non-local transport in fluid codes by benchmarking them against fully kinetic VFP simulations for a series of test problems. In Figure 4(a) we show the comparison of the Schurtz-Nikolaï-Busquet model against VFP simulations for the standard 1D initial value problem of the decay of a temperature perturbation. Each point corresponds to a simulation with either the fluid code DUED (circles) or OSHUN (non-circular shapes). The measurements with OSHUN were taken at steady-state and show good agreement between the two codes. However the transient behavior (not shown) is very different. We are currently performing tests for the boundary value problem. Preliminary results of this benchmark will be presented in a poster at the Anomalous Absorption Conference 2012.

Simulations of high-density targets with explicit VFP codes are limited by the need to resolve plasma oscillations. Therefore, to model non-local transport for shock ignition targets, with density in excess of solid and time-scales on the order of 100ps we have developed a new implicit method for the electric field in OSHUN. This method relies on a conductivity tensor, which is calculated by measuring the effect of electric-field perturbations on the plasma.
current. Therefore, it assumes no a priori form for Ohm’s law and its implementation introduces virtually no additional computational cost. This method has been benchmarked extensively, it was presented in a talk at the Institute of Pure and Applied Mathematics in UCLA (May 2012) and we are preparing it for publication [5].

The main advantage of OSHUN compared to other VFP codes [4] is that it can model an arbitrary degree of anisotropy in momentum space. Moreover, because the grid-size is determined by the need to describe the simulation geometry, rather than by the plasma skin-depth, mm-scale systems can easily be modeled. Thus, OSHUN can be used to model electron transport for problems directly related to shock ignition targets, that include rapid heating by intense laser pulses, and scale-lengths on the order of a mm. In Figure 4(b) we present the temperature profile of target heated for 25ps by a non-planar source with peak intensity $4 \times 10^{15}$ W/cm$^2$. The 4 different profiles correspond to different approximations, the 1D electrostatic, 2D electromagnetic with the diffusive approximation in momentum-space, 2D electrostatic, and 2D electromagnetic. We see that the poorest approximation in this case is the diffusive approximation, while the electrostatic cases fail due to the rise of magnetic fields at the surface of the target. Implicit electromagnetic simulations using the full expansion of the electron distribution function are therefore required to capture the 2D physics of the non-local transport, and we are currently performing such a study.

OSHUN cannot model hot electron beams or laser-plasma instabilities and it utilizes an ad hoc heat source instead. The properties of this heat source are being derived using PIC and hybrid-PIC simulations as discussed above. Finally, because of the lack of ion motion OSHUN cannot be used to study shock formation, OSIRIS-H is being used for this problem. In other words our VFP simulations complement and do not duplicate our work with OSIRIS and OSIRIS-H.

References
In the fast ignition for inertial confinement fusion the two main parameters limiting the energy coupling from the laser to the core are: the high electron beam divergence and the excessive electron temperature/energy associated with ultra-intense laser pulses. For the typically large electron divergence observed in first-principle particle-in-cell (PIC) simulations of fast ignition (> 30° half angle), high ignition laser energies (> 100 kJ) will be required. Taking into account the limitations on the laser duration (~ core heating time < 20 ps) and spot size (~ core radius ~ 25 mm), the use of a single ignition laser will require intensities > 2.5x10^{20} Wcm^{-2}. This implies the generation of very hot electrons (T_{hot} > 6 MeV assuming a form of ponderomotive scaling), with a low stopping efficiency, making fast ignition impracticable.

We have proposed and explored the possibility of controlling the electron spectrum by using multiple low-intensity laser pulses. By having each pulse impinging radially on the target (i.e., with wave-vector align with the target radius) at different positions, lasers will act independently of each other, generating separated heat fluxes that will be merged right at the target core. The use of multiple low-intensity lasers allows for the generation of a larger number of electrons with lower temperature, for the same total laser energy.

We have demonstrated the advantages of this new scheme with fully self-consistent hybrid-PIC OSIRIS simulations for a realistic density profile and ignition target size. In these simulations, we have compared the use of a single ignition laser with \( a_0 = 12 \) (where \( a_0 \) is the normalized laser vector potential), with the use of three ignition lasers, both for \( a_0 = 6 \) and \( a_0 = 3 \). Our results, illustrated in Figure 5, show the merging of the independent heat fluxes at the core region and a considerable increase of the percentage of electrons in the desirable energy range for efficient stopping (1-3 MeV), > 30% (with \( a_0 = 6 \)) and > 60% (with \( a_0 = 3 \)). Furthermore, we observe that the overall electron divergence is maintained (it is relatively insensitive to the laser intensity), meaning that the overall efficiency of the fast ignition scheme.

**FIG 5:** (a) Electron heat flux from an ignition scale hybrid-PIC OSIRIS simulation using three low-intensity radially incident lasers. The fluxes generated by each laser merge at the core of the target. (b) Comparison of the integrated fast electron energy, measured at the entrance of the core, for the case of a single high-intensity ignition laser (red) and multiple low-intensity lasers (green and blue).
can be considerably improved by having the majority of the fast electrons with the correct energy range. In practice, the use of multiple ignition lasers can be envisioned by using either multiple channeling pulses or an inserted cone with a 45° angle and a spherical tip positioned 80 mm from the core. Such cone would allow for instance to deliver 100 kJ in 10 ignition lasers with a spot size of 25 mm and an intensity of 2.5x10^{19} \text{ Wcm}^{-2}.

Simulations have been also been performed to understand the origin of the electron divergence and to compare with recent experimental results by Beg et al. on the Omega laser system. In the experiment, the flux of electrons reaching a copper witness layer separated from a gold foil target is greatly reduced when the distance between the layer and the foil is filled with a pre-formed plasma, as compared to room temperature plastic or foam. In addition, the

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\centering
\includegraphics[width=\textwidth]{fig6}
\caption{PIC simulations for an experiment by Beg et al. Figures at time = 8000/\omega_0. (a) Electron spectrum as a function position (y). (b) Magnetic filamentation due to the interaction of an intense laser with a 10\mu m-thick layer of plasma.}
\end{figure}
electron spectrum was much broader spatially. The goal of our simulation is to provide insight and possible explanations for these results. Our simulation reveals growing magnetic filaments immediately behind the Au-CH boundary (Figure 6(b)), with angle of the filament-spread approximately 90 degrees. The spectrum in what corresponds to the copper region in the experiment is also broad, with only slight dependence on transverse position within the width of the witness copper. Further work will be performed to see if varying the plasma density and geometry will modify the resulting field structure and electron divergence. Results will be presented at the Anomalous Absorption 2012 conference.

To further understand and characterize the features of the hot electron source in fast ignition regimes we used OSIRIS to compare 2D and 3D geometries. The simulations show that early in time, the inherent divergence of the beam in the direction of the electric field—which is theoretically predicted by our model in both 2D and 3D—dominates the 3D divergence. However, later in time (t >~100fs), the divergence grows in both directions exceeding the inherent divergence of the source. This divergence growth was also seen in 2D and is believed to be due to surface deformation, which breaks the conservation property of the transverse

FIG 7: Particle tracks for electrons gaining high energy due to their interaction with an intense laser. The tracks are plotted in a phase-space slice of forward position, forward momentum, and transverse momentum. Particles can be seen gaining forward momentum at the plasma surface, then rotating as they enter the plasma.
canonical momentum. In 3D a new mechanism, that is the growth of magnetic field in the direction of the laser polarization, allows the divergence to also occur in the direction of the laser B field. The effects are comparable in strength, leading to a more or less isotropic divergence in the transverse directions, exceeding the inherent divergence, even for times short compared to those pertinent to a fast ignition drive beam.

9 A. Plasma Nuclear Science Experiments

As described in Physical Review Letters [J.A. Frenje et al., PRL 107, 122502 (2011)], and illustrated in Fig. 1, MIT has worked with collaborators to perform the first basic nuclear physics experiment in a plasma environment. In this experiment, which was carried out at the OMEGA laser facility, the differential cross section for elastic neutron-triton (n-T) and neutron-deuteron (n-D) scattering was measured at a neutron energy of 14.1 MeV utilizing the MIT-developed charged-particle spectrometer CPS2. From these experiments, which were conducted by simultaneously measuring elastically scattered T and D ions from a deuterium-tritium gas-filled ICF capsule implosion, the differential cross section for the elastic n-T scattering was obtained with significantly higher accuracy than achieved in previous accelerator experiments. The results compare well with calculations that combine a resonating-group method with an ab-initio no-core shell model, which demonstrate that recent advances in ab-initio theory can provide an accurate description of light-ion reactions. This work ushers in a new and exciting field of research, Plasma Nuclear Science, blending the separate disciplines of plasma and nuclear physics, described by a MIT-LLNL-LLE joint press release.

Thermonuclear reaction rates and nuclear processes have been explored traditionally by means of conventional accelerator experiments, which are difficult, and at times even impossible, to execute at energies and conditions relevant to stellar nucleosynthesis. Even when measurements are possible using accelerators, thermonuclear reaction rates in burning plasmas of stars are inherently different from those in accelerator experiments. The fusing nuclei are surrounded by bound electrons in accelerator experiments, whereas electrons occupy mainly continuum states in a stellar environment. To begin exploring these issues, a proof-of-principle study of the $^3$He-$^3$He reaction, which plays an important role in the pp chain in first-generation hydrogen-burning Population III stars and in stars like our Sun (Fig. 2), was recently conducted using ICF laboratory plasmas. A preliminary example of the resulting $^3$He-$^3$He proton spectrum is shown in Fig. 3.
FIG. 1. (a) The MIT-developed charged-particle spectrometer CPS2 during installation on the OMEGA chamber. The cone-shaped end contains the entry aperture, while the cylindrical section contains a 7.6-kG magnet and CR-39 detectors. CPS2 was used to simultaneously measure energy spectra of deuterons and tritons elastically scattered by 14.1-MeV neutrons. (b) Measured differential cross section for elastic n-D scattering, normalized to a Faddeev calculation. (c) Measured and calculated differential cross section for elastic n-T scattering. The blue solid curve represents an *ab-initio* NCSM/RGM calculation, and the red dashed curve represents an R-matrix calculated n-T cross section.

FIG. 2. The proton-proton (pp) chain that took place in first-generation hydrogen-burning Population III stars (at conditions very similar to our \(^3\)He-\(^3\)He experiments) and takes place in hydrogen-burning stars like our Sun. This sequence transforms \(^1\)H nuclei into a \(^4\)He nucleus, which is initiated by the fusion of two protons where one of the protons is converted into a neutron by emitting a positron and neutrino, forming a deuteron. This deuteron is subsequently converted into a \(^3\)He nucleus by the addition of another proton. Two \(^3\)He nuclei are then fused together, producing ordinary \(^4\)He and two protons. The pp chain dominated in the initial stages of first-generation hydrogen-burning Population III stars, which have masses of tens to a hundred solar masses. These stars were responsible for the first synthesis of heavy nuclei in the universe. Understanding their evolution will therefore be critical for calculations of later stellar and galactic dynamics. These stars will be studied with the James Webb Space Telescope.
FIG. 3. The first preliminary $^3$He-$^3$He proton spectrum ever obtained using plasmas (OMEGA shot 61252, with a $^3$He-gas-filled exploding pusher). This proton spectrum is a sum of several spectra measured simultaneously with different WRF spectrometers fielded around the implosion. Both the three-body continuum and the p+$^5$Li resonance at 9.3 MeV are observed at an average CM reactant energy, or Gamow energy, of ~95 keV. Due to the high CM energy, this measurement is directly relevant to the conditions in first-generation hydrogen-burning Population III stars. The D-$^3$He protons shown in the data originate from small levels of deuterium contamination in the $^3$He fuel. The alpha spectrum, and the proton spectrum below 4 MeV, could not be measured in this experiment. In future work, we therefore plan to use a new diagnostic to measure the complete spectra of the alphas and protons.

FIG. 4. The first T-T neutron spectrum ever obtained using plasmas. This spectrum was obtained from OMEGA-MRS data summed over a series of DT-gas filled warm-capsule implosions with an average $T_i$ of 5.8 keV. This temperature corresponds to a CM reactant energy of 23 keV, which is practically the same as the Gamow peak energy for the $^3$He($^3$He,2p)$^4$He mirror reaction in the Sun. The Lacina-modeled three-body continuum developed in the 1960s is also shown for comparison. The 10% and 20% dashed line indicates the effect of the n+$^5$He-resonance at 8.7 MeV if it had been present in the T-T neutron spectrum.

Novel studies of the T-T reaction, which is a mirror to the $^3$He-$^3$He reaction, have also been conducted using plasmas at OMEGA (this work was part of former MIT PhD student D.T Casey’s thesis). An example of a T-T neutron spectrum measured with the MRS is shown in Fig. 4. As shown by the spectrum, it is clear that it consists mainly of the three-body...
continuum and that an $n^+\ suppressing^{5}\text{He}$-resonance (a peak at 8.7 MeV) is absent in the data. At higher CM reactant energies, this $n^+\ suppressing^{5}\text{He}$-resonance is clearly observed on a 10-20\% level of the total T-T neutron spectrum. For detailed studies of the underlying physics of the T-T reaction, these measurements will be upgraded significantly.

**FIG. 5.** (a) Measured $Y_{DT}/Y_{DD}$ yield ratios as a function ion temperature (red points). The solid line represents the expected yield ratio for DT fuel mixture of $f_T/f_D = 0.75$. The grey dashed lines indicate the variation in the expected ratio. The results from 1D hydrodynamic simulations using LILAC (blue triangles) are in agreement with the expected ratio. (b) Measured $Y_{TT}/Y_{DT}$ yield ratios as a function of ion temperature (red points). The solid line represents the expected yield ratio for DT fuel mixture of $f_T/f_D = 0.62$. These results suggest a deuterium fraction in the core that is lower than expected, which is likely to be caused by stratification of the D and T fuel.

In addition to the measurement of the T-T neutron spectrum, the T-T and D-D reaction yields were measured and compared to the D-T reaction yield. From these measurements, it was concluded that the D-D yield is anomalously low and the T-T yield is anomalously high relative to the D-T yield (Fig. 5), an observation possibly caused by stratification of the D and T fuel in the implosion. This is an issue we plan to explore. This work was published in Physical Review Letters [D.T. Casey et al., submitted to Phys. Rev. Letters (2012)]. A similar effect in $D^3\text{He}$-gas filled CH-capsule implosions was observed by former MIT student and post-doctoral associate Dr. Ryan Rygg.
High-Mach-number jets are fundamental astrophysical phenomena in the galaxy and in the universe. Understanding the spatial structure and temporal evolution of jets, and the interactions between colliding jets, is important for many basic sciences and for frontier astrophysics. A particularly critical issue is the effect of spontaneously-generated electromagnetic fields on jet structure and dynamics. It has been widely realized that such fields alter jet dynamics, accelerate particles, seed instabilities, and lead to the generation of various nonlinear astrophysical structures. These issues have now been studied using scaled experiments in the laboratory with laser-generated, supersonic plasma jets that are hydrodynamically similar to astrophysical jets.

We have recently used monoenergetic, charged-particle radiography to make the first observations of spontaneously-generated fields, the effects of fields on plasma jet propagation, and the results of two jets colliding head on. In contrast to previous work using x rays or other optical diagnostics, which have no sensitivity to fields, our experiments used monoenergetic proton radiography, which has unique sensitivity to field structure, instabilities, and dynamics. Subsequent to collision of two jets with each other, low-Mach-number plasma shocks (a nonlinear consequence of plasma instabilities and fields) are observed by imaging electric fields associated with shock fronts. The shocked downstream regions lack collisional field dissipation, indicating these shocks are likely collisionless. These experiments provide important insights into the physics of fields and their effects on astrophysical jet evolution and interactions, and they have critical impact on the study of fundamental astrophysical phenomena and high-energy-density plasmas.

The experiments, illustrated schematically in Fig. 6, were performed at the OMEGA Laser Facility. V-shaped targets were constructed with two 50-µm-thick, 3 mm x 3 mm plastic (CH) foils separated by 60º. Each individual foil was driven by two laser beams (0.351 µm in wavelength) at an angle ~ 28º to the foil normal, with total energy ~ 1000 J during a 1-ns square-top laser pulse with full spatial and temporal smoothing. A plasma plume is generated on each foil as a consequence of laser ablation, and when the plumes from the two foils collide they generated a plasma jet that eventually became well collimated and supersonic. In some experiments, two counter-streaming plasma jets from identical targets collided with each other when they met at the midplane, as shown by a sample proton fluence image and illustrated by a cartoon (Fig. 6).

Figure 7 shows proton fluence images of a single jet at different times. The jet tip moving velocity is estimated using these measurements to be $V_j \sim 2500 \text{ km s}^{-1}$, indicating jet propagation is supersonic with internal Mach number $M \sim 10 - 15$ after it has been adiabatically (non radiatively) traveling for several nanoseconds. The high Mach number reduces spreading of the jet front due to Kelvin-Helmholtz (KH) instabilities, and it minimizes the spreading of jet plasma into the surrounding vacuum. Two-dimensional (2-D) DRACO hydrodynamic simulations, together with Thomson scattering measurements from a related experiment, show that the jet plasma is collisional, with typical plasma ion density $> \sim 10^{18} - 10^{19} \text{ cm}^{-3}$, temperature $\sim 200-800 \text{ eV}$ (depending on the expansion times at the place of jet formation), and collisionality $\zeta \sim 10^{-5}$.

The jet physics inferred from these images is discussed in detail in [C. K. Li et al., submitted to Nature Phys. (2012)]. In addition to astrophysics, implications of these experimental results are significant for other frontier basic sciences including the effects of
fields on hydrodynamics, plasma instabilities and magnetic reconnection. In inertial confinement fusion (ICF) research, for example, understanding the dynamics and effects of a fill tube during a cryogenic capsule implosion is critical to ongoing ICF ignition programs at the National Ignition Facility because it will result in a plasma jet propagating into the core of the fuel capsule, leading to the mix of cold shell material with the central hot spot and subsequent degradation of fusion yields and capsule implosion performance. The experimental results discussed here also provide vital information for benchmarking computer codes.

FIG. 6. Schematic diagram of the experimental setup for proton radiography of a head-on collision between two plasma jets. The proton backlighter (imploded D³He-filled thin-glass-shell capsule driven by 30-OMEGA laser beams) is typically 1 cm from the collision region and has the illustrated monoenergetic spectra from the reactions \( D + ^3 He \rightarrow \alpha + p \) (14.7 MeV) and \( D + D \rightarrow T + p \) (3.0 MeV). A sample radiographic image of proton fluence was taken with 15-MeV D³He protons (the particle energies are slightly upshifted from the birth energies due to positive charging of the capsule) at 4.7 ns from the onset of the laser drive on the V-shaped, CH-foil targets. The distance from the sample region to the CR-39 detector is 27 cm.

FIG. 7. Proton radiographs of single jet propagation and a schematic model of observed instabilities. (a) A striking structure of chaotic deflection shown in these proton fluence images indicates that the jet propagation was subjected to plasma instabilities. (b) An image displaying mean proton energy vs. position shows a very uniform distribution, indicating the deflection structures in (a) are a result of fields, not Coulomb scattering. The cartoons show the side view (c) and end view (d) of the schematic jet diagrams and field-line configurations, illustrating how pressure-driven (interchange) and current-driven (sausage), resistive MHD instabilities lead to the formation of the patterns shown in (a). The red arrows indicate the interchange processes. Note that the dashed lines in (c) indicate the structures of bow shock, cocoon and Mach disk which are not clearly seen in our proton images (a).
9 C. Studies of Self-Generated Magnetic Fields by Rayleigh-Taylor instabilities

Charged-particle radiography has been used to quantitatively study magnetic fields generated by Rayleigh-Taylor (RT) instabilities in laser-driven CH foils at OMEGA, making possible the first direct comparison of measurements with simulations for RT-induced B-field formation. The foils were 20 µm thick, had pre-imposed parallel grooves 0.5 µm deep at a wavelength of ~120 µm, and were driven by a 2-ns, square laser pulse with intensity ~4×10^{14} W/cm². Radiographs made with 15-MeV protons were recorded at different times after the onset of the laser drive, and for each image the modulation amplitude of structures related to the parallel grooves was measured. These modulations were shown [M. J.-E. Manuel et al., submitted to PRL] to be dominantly caused by self-generated magnetic fields due to the RT instability in the plasma. The measured modulations were converted to path-integrated “measured” B-field strengths and compared to ideal MHD predictions of the benchmarked 2D hydrodynamic code DRACO, as seen in Fig. 8. Simulations indicated an upper estimate of field strength due to non-dissipative assumptions and were found to agree reasonably well with data.

FIG. 8. Comparison of “measured” (diamonds) and simulated (solid line) path-integrated B fields. The simulated fields were generated by post-processing DRACO output, while the “measured” data were calculated from actual image RMS amplitudes after subtracting a component for mass modulation (measured from x ray radiographs).
9 D. Studies of magnetic reconnection in laser-produced plasmas

The interaction and reconnection of magnetic fields in plasmas are important fundamental processes with implications for a wide range of basic sciences, including astrophysics, space physics and laboratory physics. In the frontier field of HEDLP (pressures >1 megabar), the generation, evolution, and reconnection of B fields due to laser-plasma interactions takes place in an extreme physical regime. High plasma densities (>10^{20} \, \text{cm}^{-3}), high temperatures (~1 \, \text{keV}), intense B fields [~1 \, \text{MegaGauss (MG)}], and high ratios of thermal pressure to magnetic pressure (\beta \gg 1) distinguish this novel regime from tenuous plasmas, of order 10^{14} \, \text{cm}^{-3} or (usually much) lower, that are the more traditional venue of reconnection experiments. MIT’s radiography experiments involved the first direct observation of field reconnection in the HED regime, where plasma flow is dominated by hydrodynamics and is not strongly affected by fields, even though MG fields are present. The setup is shown in part (a) of Fig. 9, with two laser beams incident on a foil. The results have fundamental implications for basic reconnection physics in all regimes. Quantitative field maps derived from the radiographs reveal precisely and directly, for the first time, changes in the magnetic topology due to reconnection in a high-energy-density plasma (n_e \sim 10^{20}–10^{22} \, \text{cm}^{-3}, \, T_e \sim 1 \, \text{keV}). These observations provided the first precise measurements and mapping of the change in field topology associated with reconnection in a high-\beta, HEDLP experiment.

Recent experiments have probed the magnetic reconnection of laser-generated plasma bubbles – each at a different stage in the bubble evolution – by mismatching the relative interaction times of the laser pulses, using the radiography setup of Fig. 9(a). Sample and interaction times were chosen such that in some experiments reconnection would occur between one bubble in the linear growth phase (with the laser still on) and one bubble in the instability phase (after the laser has turned off). Results of one of these recent reconnection experiments, with bubbles at the same stage in their evolution, are shown in parts (b), (c) and (d) of Fig. 9. Additional experiments have generated side-on images of magnetic reconnection by orienting the imaging axis along the plane of the foil. These images hint at the presence of field-carrying hydrodynamic jets propagating out of the reconnection region perpendicularly to the foil. Side-on radiography of magnetic reconnection will continue to be pursued.

![FIG. 9. 15-MeV-proton-radiography setup (a) used in magnetic reconnection experiments. The radiograph (b) was recorded 1.0 ns after the onset of two laser beams incident on a CH foil, when laser-generated plasma bubbles had interacted and reconnection of magnetic fields around the bubbles had begun. Beamlet displacements (c) due to the fields were used to calculate a map of local field strength (d), where color is related to \int B \times d\ell along the proton trajectories. Magnetic reconnection resulted in diminished field energy where the two plasma bubbles collided.](image)
9 E. Preliminary studies of ion stopping in plasmas

Warm dense plasmas with temperatures of a few eV and densities higher than solids, often found in the universe, can now be created in laboratories by laser-driven shocks and magnetically-driven flyer plates. Stopping power of charged particles in such non-ideal plasmas is still unknown. There have been many theoretical predictions in the past decades \([m2,m3]\) that have shown observable reductions of the stopping power due to coupling and quantum-degeneracy effects. However, no experiments have been conducted so far to verify the theoretical calculations. Investigations of charged-particle stopping power will therefore advance our understanding of ion-electron energy coupling, as well as the electron-(background) ion equilibrium in warm dense plasmas. We performed, in collaboration with LLE, an exploratory measurement of the charged-particle stopping power in non-driven CH foils (Fig. 10). Although detailed analyses of the experiments are under way, the primary results (Fig. 11) indicate that the platform shows strong promise for future studies of the charge-particle stopping power in laser-shocked warm dense plasmas.

**Fig. 10.** Configuration for an exploratory stopping power measurement. 24 OMEGA beams drive a pillbox-shaped planar target at TCC, which is probed by D3He protons generated in a thin-glass exploding pusher. The data is recorded on a WRF proton spectrometer (right).

**Fig. 11.** WRF proton spectra measured through the pillbox target (see Fig. 10) for two shots on OMEGA: 64615 (driven) and 64616 (undriven). The red points are the data. The green line is the cold CH reference line, blue is the inferred proton birth energy, and black is the downshift expected through the pillbox due to cold-matter stopping. We can see that the driven shot (left) shows a discrepancy when compared to cold-matter stopping, indicative of plasma effects.