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FY17 LLNL Omega Experimental Programs

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FY17 LLNL OMEGA Experimental Programs

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In Fiscal Year 2017 (FY17), Lawrence Livermore National Laboratory's (LLNL's) High-Energy-Density Physics (HED) and Indirect Drive Inertial Confinement Fusion (ICF-ID) programs conducted numerous campaigns on the OMEGA and OMEGA-EP (EP) laser systems. Overall these LLNL programs led 413 target shots in FY17, with 282 shots using just the OMEGA laser system and 131 shots using just the EP laser system. Approximately 27% of the total number of shots (78 OMEGA shots and 35 EP shots) supported the Indirect Drive Inertial Confinement Fusion Campaign. The remaining 73% (204 OMEGA shots and 96 EP shots) were dedicated to experiments for High-Energy-Density Physics. Highlights of the various HED and ICF-ID campaigns are summarized in the following reports.

In addition to these experiments, LLNL Principal Investigators (PIs) led a variety of Laboratory Basic Science campaigns using OMEGA and EP, including 85 target shots using just OMEGA and 70 shots using just EP. The highlights of these are also summarized, following the ICF and HED campaigns.

Overall, LLNL PIs led a total of 568 shots at LLE in FY 2017. In addition, LLNL PIs also supported 30 NLUF shots on Omega and 46 NLUF shots on EP, in collaboration with the academic community.

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Table of Contents

Indirect Drive Inertial Confinement Fusion (ICF-ID) Campaigns	4
1. Hydrodynamic Response from Ablator Non-Uniformities (PI: S.J. Ali)	4
2. Diamond Sound Speed Measurements Between 8-14 MBar (PI: A. Fernandez Panella)	6
3. Thomson Scattering Measurements from Foam and Gas-Covered Gold Spheres (PI: G. Swadling)	7
4. Study of Interpenetrating Plasmas on Omega (PI: S. LePape)	8
5. Measurements of Anisotropy in Non-LTE Low Density Iron-Vanadium Plasmas (PI: L.C. Jarrott)	10
6. Imaging Electric Field Structure in Strong Plasma Shocks (PI: H. Rinderknecht)	12
7. Measuring Thermal Conductivity of D2 (PIs: S. Jiang and Y. Ping)	13
8. Characterization of Laser-Driven Magnetic Fields (PI: B.B. Pollock)	14
9. Study of Shock Fronts in Low-Density Single- and Multi-Species Systems (PI: R. Hua, LLNL/UCSD/MIT collaboration)	15
High-Energy-Density (HED) Campaigns	16
A. Material Equation-of-State and Strength Measured Using X-Ray Diffraction	16
1. Measurement of Pb Melt Curve Along Hugoniot Using In-Situ Diffraction (PI: C.E. Wehrenberg)	16
2. Development of New Platform for Measuring Re-Crystallization of Lead (PI: F. Coppari)	17
3. High Pressure Crystal Structure of Ramp-Compressed Pb and Ta, to Resolve Known or Potential High-Pressure Phase Transformations (PI: A.E. Lazicki)	18
4. Development of an In-Situ Pressure Standard for Diffraction Experiments (PI: F. Coppari)	19
5. Development of Simultaneous Diffraction and Fine-Structure Measurements (PI: F. Coppari)	20
6. Texture Diffraction and Recovery of Shock Compressed Samples for Ex-Situ Study (PI: A. Krygier)	21
B. Material Equation-of-State Using Other Techniques	22
1. Development of Flyer-Plate Impact Platform for Equation of State Measurements (PI: F. Coppari)	22
2. Development of Simultaneous Absorption Fine-Structure and VISAR Measurements (PI: Y. Ping)	23
3. Development of Platform for L-Edge Absorption Fine-Structure Measurements (PI: F. Coppari)	24
4. Development of Spherically-Convergent Equation of State Measurements (PI: A.E. Lazicki)	25
5. Development of Conically-Convergent Equation of State Measurements (PI: A.E. Lazicki)	26
C. Material Dynamics and Strength	27
1. Copper Rayleigh-Taylor Growth Measurements (PI: J.M. McNaney)	27
2. Evaluation of Additive-Manufactured Foams for Ramp Compression Experiments (PI: R.F. Smith)	29
D. National Security Applications	30
1. Solar Cell Electrostatic Discharge Experiments (PI: K. Widmann)	30
2. Plasma Instability Control to Generate High Energy Bremsstrahlung X-ray Source (PI: P.L. Poole)	32
E. Plasma Properties	33
1. Investigation of Orthogonal Plasma Flows with Background Magnetic Fields (PI: B.B. Pollock)	33
2. Measurement of Gold Thermal Transport and M-Shell Emission (PI: E.V. Marley)	34
F. Hydrodynamics	35
1. Experiments on the Rayleigh-Taylor Instability in the Highly Nonlinear Regime (PIs: C.C. Kuranz, Univ. of Michigan, and C.M. Huntington, LLNL)	35
2. Proton Heating of Copper Foam on Omega-EP (PI: J. Benstead, LLNL/AWE Collaboration)	36
3. Development of Radiography-and-VISAR Platform for Hydrodynamics Measurements (PIs: D.A. Martinez and M. Rubery, LLNL/AWE collaboration)	38
4. Development of Gamma-Ray Sources for MeV Radiography (PI: F. Albert)	40
5. Measurements of Instability Growth and Shell Trajectory Relevant to NIF Double-Shell Designs (PI: Y. Ping)	41

Laboratory Basic Science (LBS) Campaigns	42
1. Experimentally Constraining the High-Pressure Thermal Conductivity of Iron (PI: R.F. Smith)	42
2. Recovery of Dynamically Compressed Samples (PI: C.E. Wehrenberg)	43
3. Absolute EOS Measurements from Spherically Converging Shock Waves (PI: A. M. Saunders)	44
4. Time Resolved Measurement of the Radiative Properties of Open L-Shell Zinc (PI: E.V. Marley)	45
5. Measuring Plasma Shock-Front Structure Using Thomson Scattering (PI: H.G. Rinderknecht)	46
6. Pressure Ionization in Ramp Compressed Materials (PI: S. Jiang)	47
7. Backlighters for Imaging Low Density Plasmas for Eagle Pillar Studies	48
8. EOS, Structure and Optical Properties of Silicates at Multi-Mbar Pressure (PI: M. Millot)	49
9. High-Pressure Properties of Silicon Carbide Using Decaying Shocks (PI: R.F. Smith)	50
10. Exploring Pair Plasmas and Their Applications (PI: H. Chen)	51
11. Astrophysical Collisionless Shock Experiments with Lasers (ACSEL)	
(LBS PI: H.-S. Park; Shot PI: G.F. Swadling)	52
12. Laser Driven Collisionless Shock Acceleration of Ions (PI: A. Pak)	53

Indirect Drive Inertial Confinement Fusion Experiments

1. Hydrodynamic Response from Non-Uniformities in Plastic, High-Density Carbon, and Beryllium (PI: S.J. Ali)

With P.M. Celliers, S.W. Haan, S. Baxamusa, M. Johnson, H. Xu, N. Alexander, H. Huang, V. Smalyuk and H. Robey

The Capseed campaign goal is to measure shock front velocity non-uniformities in Inertial Confinement Fusion (ICF) ablator materials and quantify the level of non-uniformity caused by intrinsic effects. This is done using the Omega High Resolution Velocimeter (OHRV) to obtain velocity maps of the optically reflecting shock front following release of the ablator material into either PMMA for the warm experiments or cryogenic deuterium for the cryo experiments. For the three half-days in FY17 the focus was twofold: complete measurements on the impact of oxygen heterogeneity and oxygen mitigation layers for glow discharge polymer (GDP), and begin measuring velocity non-uniformities on deep release from Be, GDP, and high-density carbon (HDC) into D₂ with improved velocity sensitivity.

Performance and yield from fusion capsules at the National Ignition Facility (NIF) are highly dependent on the uniformity of the capsule implosion and hydrodynamic instabilities are a significant source of performance degradation during the implosion. A possible explanation for the observation of unexpectedly large in-flight modulations during NIF capsule implosions was a hypothesis involving surface oxygenation of GDP; laboratory tests of GDP samples under controlled conditions confirmed the heterogeneous surface oxygenation effect. In FY16 the OHRV was used to test this idea further by obtaining two-dimensional velocity maps for both oxygen-modulated and unmodulated samples. Modulated samples showed clear evidence of the propagation of a rippled shock wave as a result of the photo-induced oxygen heterogeneity. To mitigate the effect the target fabrication team proposed depositing a 20 nm oxygen barrier layer of alumina. Tests of the mitigation in the 17A and B campaigns determined, via OHRV measurements on warm GDP samples, that this barrier layer did not introduce additional perturbations in the shock velocity. In 17C the velocity roughness on deep release from GDP into D₂ with and without this barrier layer was also measured and no significant difference was determined. The velocity non-uniformities in both samples were close to the detection limit of the diagnostic, as described in Figure 1.

The remaining shots in 17A were used to measure velocity non-uniformities slightly below the first shock level in HDC and at the first shock level in sputtered Be, both releasing into D₂. The velocity non-uniformity for the Be shots varied significantly (35 ± 6 m/s and 24 ± 6 m/s), but in both cases, was approximately 3-5 times larger than would be expected from the surface roughness. Non-uniformity in HDC was measured at 7 and 10 Mbar and was found to decrease with increasing pressure (from 124 ± 17 m/s for 7 Mbar to 85 ± 17 m/s for 10 Mbar) but was again a few times larger than is predicted from surface roughness alone. These experiments are continuing into FY18, with further cryogenic measurements planned.

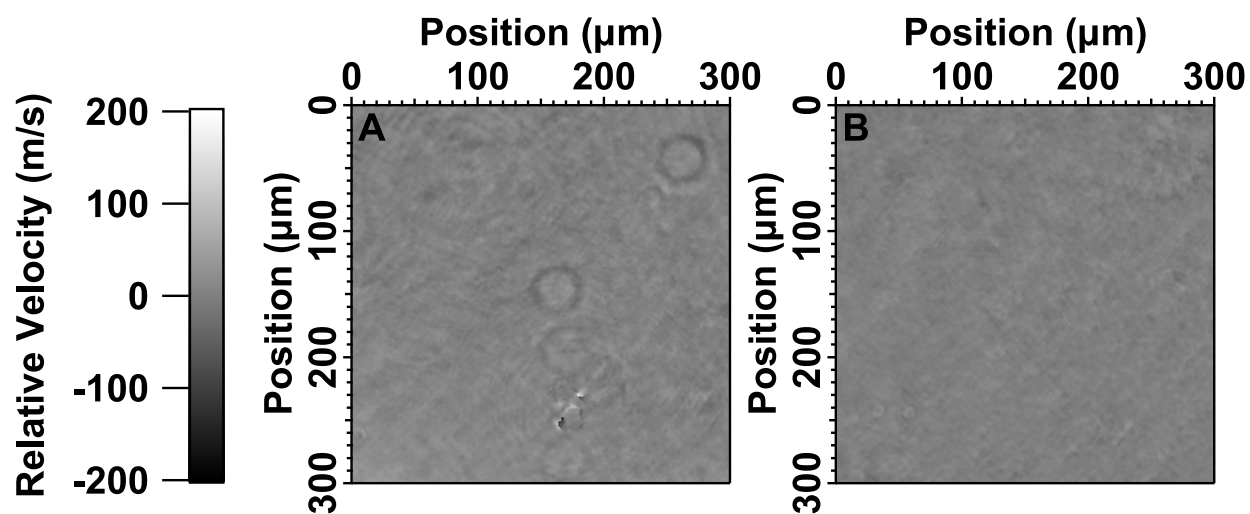


Figure 1. Velocity maps from alumina-protected (A) and unprotected (B) GDP releasing into D2. RMS velocity roughness was 8.6 m/s for A and 6 m/s for B, with a diagnostic detection limit of 6 m/s.

2. Diamond Sound Speed Measurements Between 8-14 Mbar

(PI: A. Fernandez-Panella)

with D. Fratanduono and P. Celliers

This half day at OMEGA was designed to collect high quality data on the sound speed of diamond in the multi Mbar range, where currently little data exists, for the purpose of constraining equation of state models. It was the continuation of the DiamondSS-15B campaign where two data points were obtained at 10 Mbar.

The campaign DiamondSS-17A used planar targets and a direct-drive configuration with a CH ablator, a quartz pusher and two targets side by side, quartz (standard) and diamond. The velocity profiles at the free surface were recorded using VISAR as the primary diagnostic (Figure 1). Throughout the day, the laser drive energy was changed in order to probe different shocked pressure states in diamond. The laser pulse was designed to produce a small pressure perturbation that propagated through both the standard and the sample. The wave propagation analysis described in [1] was applied to extract the sound speed of both materials, quartz and diamond, from their velocity profiles (Figure 2).

The results indicate that sound speed measurements are sensitive enough to constrain EOS models. The Livermore LEOS table 9061 shows good agreement with the data. Further measurements in an extended pressure range are desirable in order to better constrain the models. The results of this campaign are being used to optimize the design for the next DiamondSS-18A campaign, where Be ablators will be used instead of CH, to reach higher pressure states, and a different pair of etalons will be chosen in order to increase the accuracy of the velocity measurements, to enable extraction of not only the sound speed but also the Grüneisen coefficient.

[1] D. Fratanduono et al., Journal of Applied Physics 116, 033517 (2014)

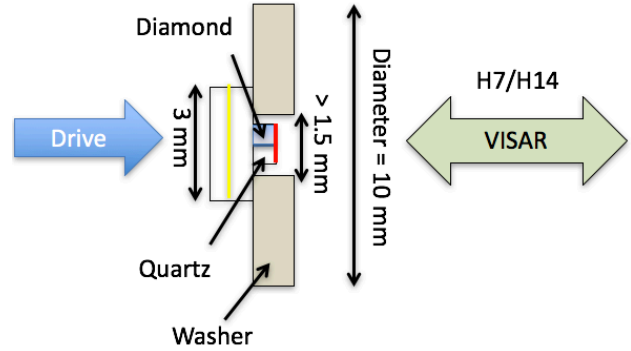


Figure 2. Experimental setup and target design for DiamondSS-17A campaign.

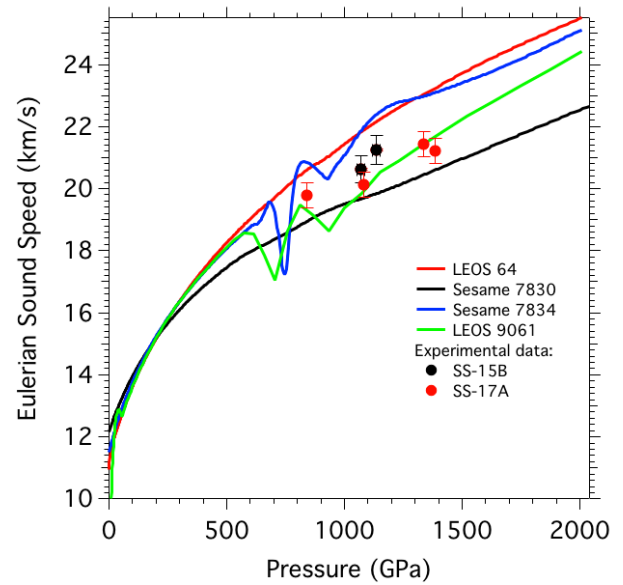


Figure 3. Diamond sound speed versus pressure plot.

3. Thomson Scattering Measurements from Foam and Gas Covered Gold Spheres (PI: George Swadling)

with J. S. Ross, M. Rosen, K. Widmann and J. Moody

The FoamCoSphere-17A campaign performed foam and gas-covered high-Z sphere experiments illuminated in direct drive geometry to investigate atomic physics models, radiative properties of the laser spot plasma, and the interpenetration of multi-ion species plasmas relevant to ICF indirect drive ignition hohlraums. These experiments use laser irradiation at 10^{14} to 10^{15} W/cm², similar to the intensities found in hohlraums fielded at the National Ignition Facility.

For the foam experiments the Au sphere was embedded in a low-density (3.8 mg/cc) CH foam. For the gas covered experiments the spheres were located inside a gas-bag filled to 1 atm of propane, or 1 atm of a 70/30 mix of propane and methane, to achieve initial electron densities of 4.0% of the critical density of the 3ω drive beams and mimic the interaction of the hohlraum Au wall with the low density hohlraum fill gas. Significant target development work was required to prepare the open-geometry foam covered targets and we look forward to leveraging this target development work in future shot days.

The plasma temperature and density at various radial positions in the blow-off plasma are characterized using Thomson scattering, while x-ray flux from the gold sphere was recorded using the DANTE and DMX soft x-ray spectrometer diagnostics. The laser beams use a shaped laser pulse (1 ns square foot, 1 ns square peak) designed to pre-ionize the gas/foam before the main drive pulse.

The electron temperature and density, the plasma flow velocity, and the average ionization state are measured by fitting the theoretical Thomson scattering form factor to the observed data. An example of the Thomson scattering data from ion acoustic fluctuations is shown in Figure 1. Continued data analysis and simulations are in progress to better understand the plasma evolution and heat transport.

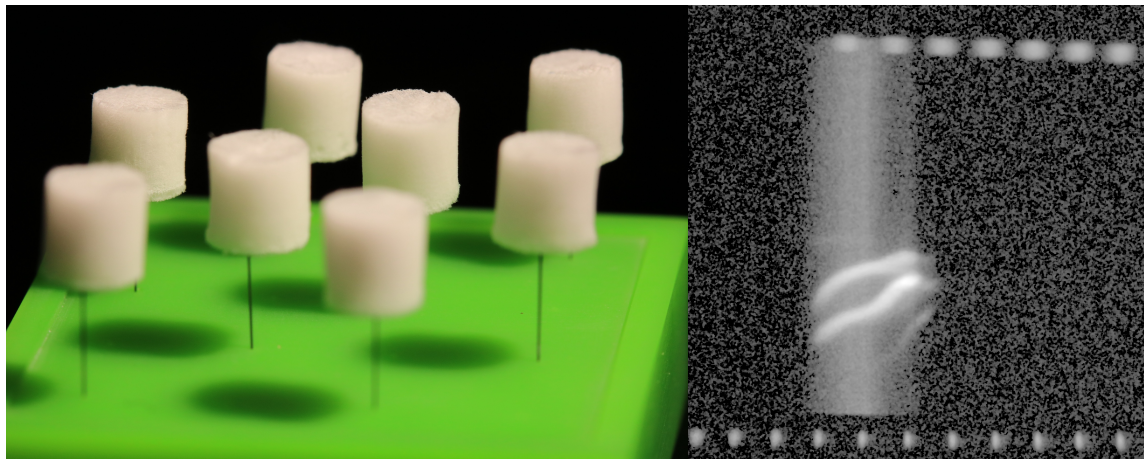


Figure 4: A 1 mm diameter Au sphere's centered in a 5mm diameter foam. An example of the Thomson scattering ion feature is shown where the Thomson scattering k-vector is directed radially, giving sensitivity to the ablation velocity of the Au plasma.

4. Study of Interpenetrating Plasmas on Omega (PI: S. Le Pape)

This campaign is designed to study the dynamics of plasma interpenetration in an environment relevant to hohlraums used on the National Ignition Facility to drive High Density Carbon capsules. The question this campaign is trying to answer is whether a fluid description of plasma flows in a low gas fill hohlraum (<0.3 mg/cc of helium gas in the hohlraum) is accurate, or if a kinetic description of the flows has to be used. Following the first series of shots in 2016 that looked at the time evolution in one point in space in the gap between the two flows, this series of shots focused on 1D spatially resolved Thomson scattering data as well as looking at the effect of helium gas density on the flows interaction. During this series of shots the helium gas density was changed, as well as the ring material (carbon, aluminum and gold) and the laser energy used to drive the target.

Two main diagnostics are fielded on these experiments: first a soft x-ray time resolved imager looking at the self-emission of the plasmas along the ring axis (figure 1-b,c,d), secondly a spatially resolved Thomson scattering diagnostics (figure 2-a,b) to diagnose electron and ion temperature, flow velocities and densities.

Time resolved x-ray images (Figure 1 c,d) indicate that the helium gas is holding the plasma expansion and that as time goes when helium is present a bright layer is appearing presumably being the helium compressed between the low Z and high Z plasma.

Figure 2 shows a 1D spatially resolved spectrum acquired on a Carbon/Carbon shot without helium, providing information on plasma temperature, densities and plasma stagnation length. High quality data were obtained. Results of this campaign are being analyzed.

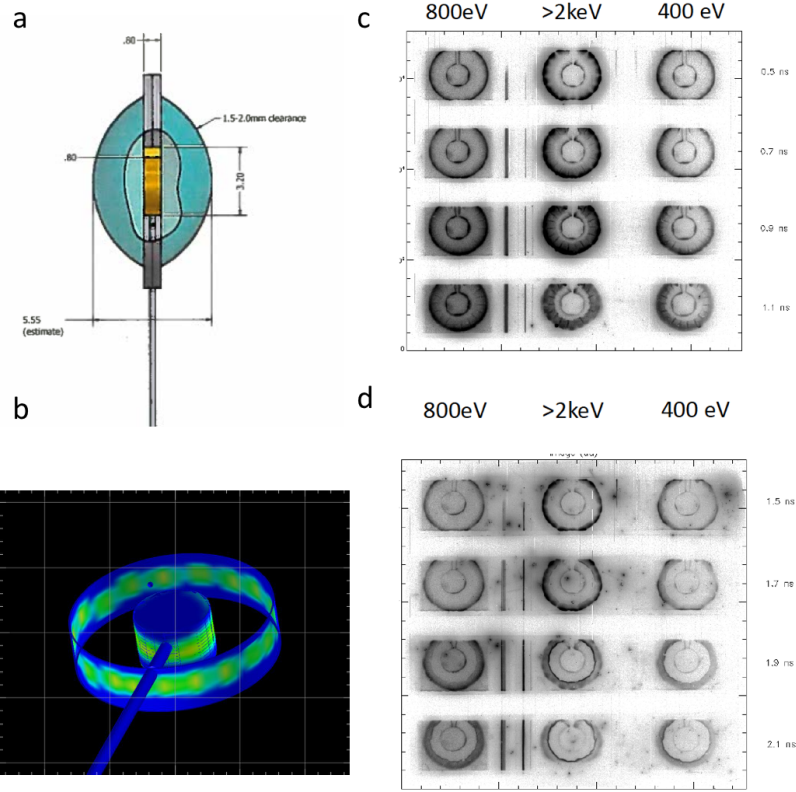


Figure1: (a) Gas bag target drawing. The ring and rod that the laser interacts with are enclosed into a gas bag that holds the helium gas. (b) VISRAD calculation of the laser deposited energy on the ring and HDC rod. (c and d) Time resolved x-ray images of the plasma self-emission. The inner feature is the carbon rod, the outer feature is the low or high Z ring. (c) shows gold ablating into HDC without helium fill, and (d) shows gold ablating into HDC with 0.2 mg/cc helium gas.

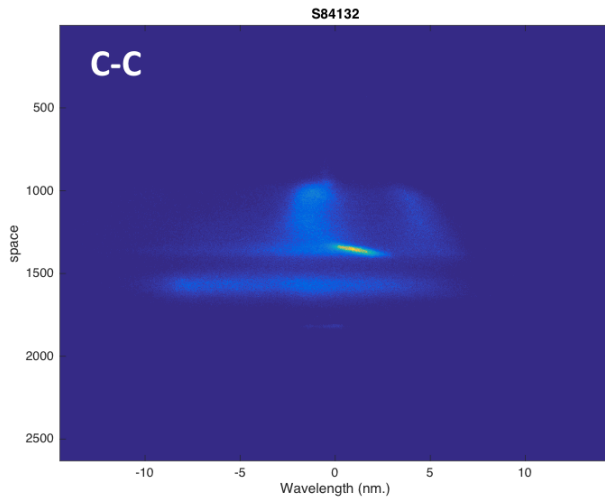


Figure 2: 1D spatially resolved Thomson scattering data of a Carbon plasma flowing into a Carbon plasma.

5. Measurements of Anisotropy in Non-LTE Low Density Iron-Vanadium Plasmas (PI: L.C. Jarrott)

with M.E. Foord, R.F. Heeter, D.A. Liedahl, M.A. Barrios Garcia, G.V. Brown, W. Gray, E.V. Marley, C.W. Mauche, K. Widmann and M.B. Schneider

Accurate characterization of the effects of geometrical anisotropies on K-shell line emission is very important for improving line-ratio based temperature measurements in low-density, non-LTE plasmas. OpticalDepth-17A built on the OpticalDepth-16A campaign, which established a working platform for accurately characterizing low-density mid-Z non-LTE plasmas. Specific goals of this platform included a characterization of heat conduction in the nominal target point design by comparison of a layered sample target material to a mixed sample target material. Additionally, this campaign attempted to improve on-target laser drive efficiency by virtue of a picketed pulse shape to improve the laser-target interaction interface. Both OpticalDepth campaigns used three laser-target configurations, varying target angle to verify the accuracy of data acquired. The primary target was a 10 μ m thick, 1000 μ m diameter beryllium tamper with an embedded volumetrically equal mixture of iron and vanadium, 0.2 μ m thick and 250 μ m in diameter. The second target type was identical to the primary target except that the sample material was layered ([50nm Fe | 100nm V | 50nm Fe]) rather than mixed. The third target type was a null target where the beryllium tamper contained no sample material. Three beam-target orientations were used over the course of 14 experimental shots. In the first configuration (LC-1), the MSPEC gated X-ray spectrometer situated in TIM2 had an edge-on view of the target, while an identical MSPEC in TIM6 had a face-on view. In the second configuration (LC-2), the target orientation with respect to TIM2 and TIM6 was reversed compared with the first configuration. In the third configuration (LC-3), all primary TIM-based diagnostics had a viewing angle of 45 degrees with respect to target normal. Using multiple target-beam orientations resulted in an *in situ* cross-calibration of the spectrometers and pinhole imagers. The data included simultaneous measurements of (1) time-resolved iron and vanadium K-shell spectra viewed from both the target edge and the target face, and (2) time-resolved images of the expanding plasma, viewed from both the target edge and target face, to infer plasma density for both layered and mixed sample target materials. The K-shell spectral data provided time-resolved electron temperature measurements of the expanding plasma, with preliminary analysis implying a plasma temperature above 2 keV.

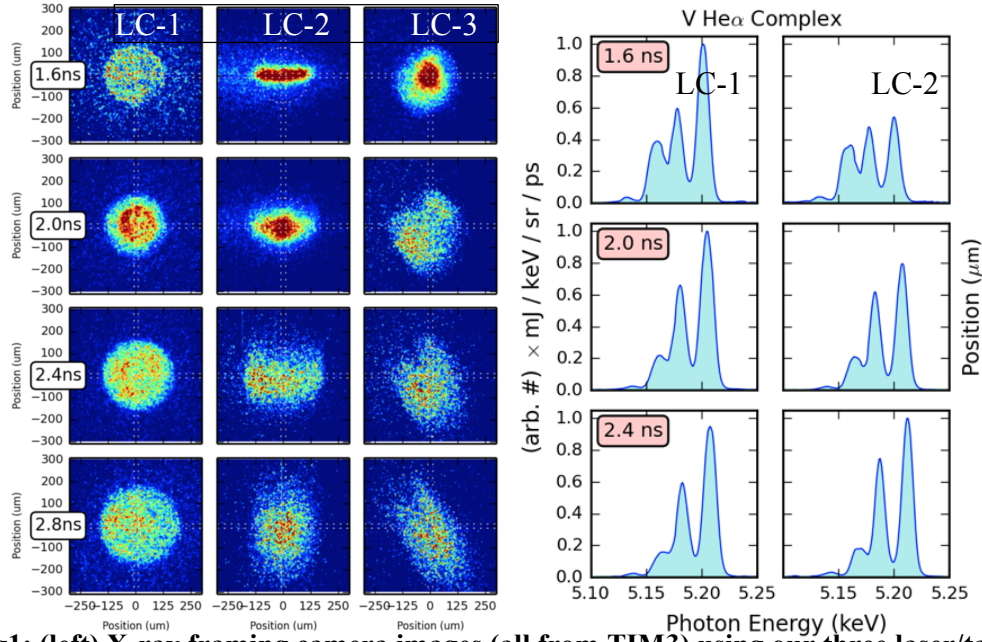


Fig1: (left) X-ray framing camera images (all from TIM3) using our three laser/target orientation configurations, showing a face-on view (LC-1), side-on view (LC-2), and 45° view (LC-3). (right) Spectrum measured by the MSpec spectrometer of the X-ray emission from K-shell transitions in highly charged vanadium and iron using laser/target configuration 1 and 2.

6. Imaging Electric Field Structure in Strong Plasma Shocks

(PI: H.G. Rinderknecht)

with H.-S. Park, J. S. Ross, S. Wilks, and P. Amendt

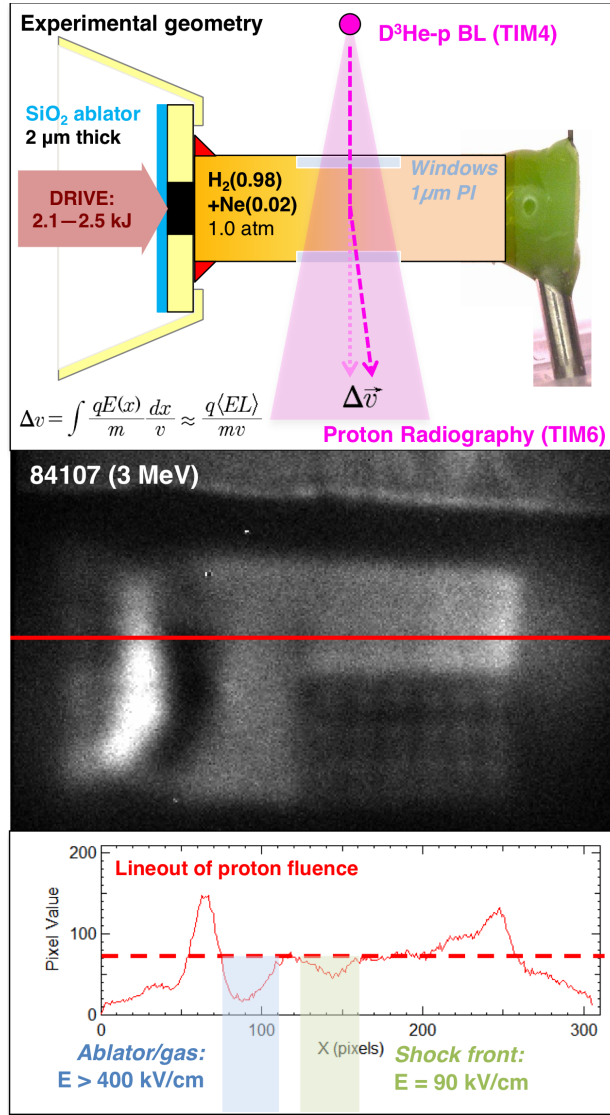


Figure 5. Experimental configuration, 3.0-MeV proton radiograph, and lineout of proton fluence for shot 84107.

This series of shots was designed to measure the electric fields produced by strong shocks in single- and multi-species plasmas. Strong shocks ($M > 1.6$) produce electric fields due to streaming of the electron precursor ahead of the ion shock, which is not accurately reproduced in hydrodynamic models. This experiment is intended to quantify electric field strength and position in a shock platform previously characterized in FY16 [1], for use constraining high-fidelity physics codes.

The KineticDynamics-17A campaign performed proton radiography of a shock-tube target platform developed in the KineticShock-16 series. Ten beams with 2.5-kJ in a 0.6-ns impulse drove a 2-μm thick SiO₂ ablator attached to one end of the tube, launching a strong shock into the 1-atm gas contained in the tube. A D³He-filled backlighter capsule was imploded to produce 3.0- and 14.7-MeV protons, which transited perpendicular to the shock front and were recorded using CR-39. Deflections of the protons due to electric fields were recorded as changes in the proton fluence with position on the detector, as shown in Figure 1. Gas fills of H₂ (2 shots), Ne (3 shots), and H₂ + 2% Ne (6 shots) were probed while varying the backlighter timing relative to the shock.

Radiographs were collected on all shots, demonstrating electric field formation both at the shock front and the ablator/gas interface. X-ray framing camera images recorded perpendicular to the radiography axis confirm the flow velocity is consistent with previous experiments (450 μm/ns) and identify the position of the SiO₂ ablator at the radiography sample time on each shot. Analysis is ongoing and results have been presented at the APS Division of Plasma Physics meeting in October 2017.

[1] H.G. Rinderknecht, et al., BAPS.2016.DPP.GO5.11 (2016)

7. Measuring Thermal Conductivity of D₂ (PIs: S. Jiang and Y. Ping)

with P. Celliers and O.L. Landen

This campaign successfully developed a platform of refraction-enhanced X-ray radiography for planar cryogenic targets, and obtained usable radiographs. The campaign fielded 2 half days on OMEGA during FY17. The series of cryogenic shots was designed to measure the thermal conductivity of liquid D₂ at 1-10eV, which helps to benchmark different transport models used in ICF ignition target design. Figure 1 shows the experimental configuration. The CH and liquid D₂ were heated to different temperatures by the X rays generated from heating lasers incident on a thin Zn foil. This builds up a density gradient due to thermal conduction. The evolution of the CH/D₂ interface was measured using refraction-enhanced X-ray radiography with high spatial resolution. The temperature can be constrained by the wave velocities in CH/D₂. A vanadium foil backlighter was used to generate the probing X rays. The backlit X ray images were collected with a 4-strip framing camera. Useful radiographs at different delays were recorded, shown in Figure 1, including undriven and driven data at 0.5ns, 1.5ns, 2ns and 2.5ns. Analysis of the measured data is in progress.

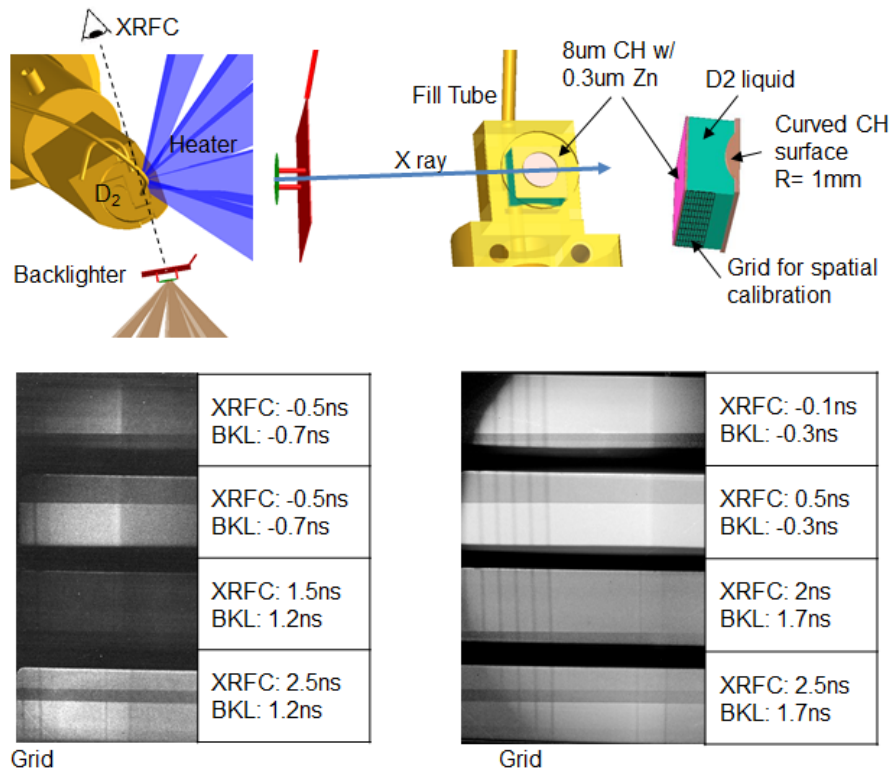


Figure 1: The experimental configuration, target geometry, and raw radiographs from a framing camera. The delays of both the framing camera and the X ray backlighter, with respect to the heating pulses, are shown in the table next each radiograph.

8. Characterization of Laser-Driven Magnetic Fields (PI: B.B. Pollock)

with C. Goyon, J. Williams, D. Mariscal, G. Swadling, J.S. Ross, S. Fujioka, H. Morita, and J.D. Moody

BFieldLoop-17A and B continued the laser-driven magnetic field experimental campaign at Omega EP. The goal for 17A was to study the impact on the magnetic field generation process of modifying the target geometry, while the primary objective for 17B was the extension of the probing time for the field. Figure 1 shows the general experimental geometry. The field is produced by currents flowing in a U-shaped gold foil target. One or two long pulse beams are directed through holes in the front side of the target to produce a plasma on the interior rear side of the target. Plasma produced in this region expands toward the front side, setting up a voltage across the target which drives the current. The fields are measured by proton deflectometry, where the protons are produced through target normal sheath acceleration by the EP backlighter beam incident on a separate, thin Au foil.

Previous experiments showed that for 1 TW long-pulse laser drive, fields of ~ 200 T can be produced in the interior of the loop portion of the target. The 17A experiment modified the front of the target by removing the bottom portion where the laser holes are located. This target modification showed a difference in the resulting proton images recorded by the RCF, and modeling is ongoing to quantify the modification to the field strength and topology.

For 17B, a gold shield was added between the main target and the backlighter target to protect the rear surface of the backlighter and allow for late-time probing of the magnetic fields. Prior to 17B the ability to measure magnetic fields after the long pulse beams turned off had been limited. But using a 750 ps long pulse B-field drive beam, the addition of this shield allowed the probe time to be extended from 750 ps (the end of the drive beam) to 16 ns. Preliminary analysis of these results indicates that the magnetic field persists long after the drive laser turns off, decaying exponentially with a time constant of ~ 2 ns. This is consistent with a circuit theory treatment of the interaction, where the drive laser acts as a voltage source while on; after the voltage is turned off, the current (and consequently the magnetic field) decay with the L/R time constant of the target. For the geometry of the 17B targets, this L/R time is ~ 2.6 ns.

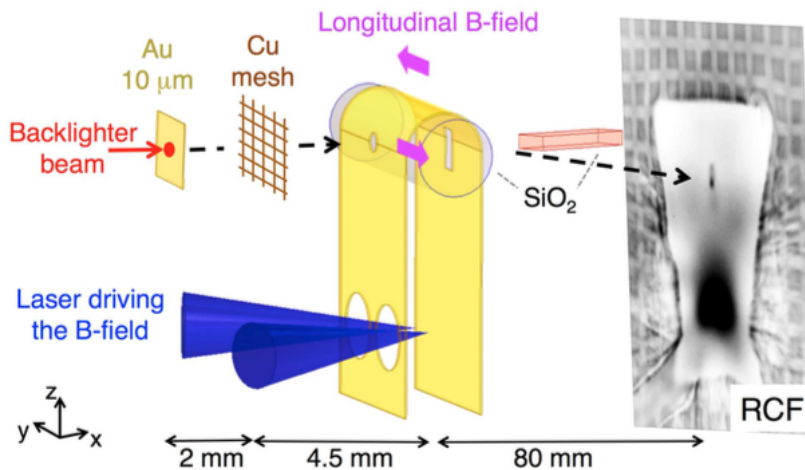
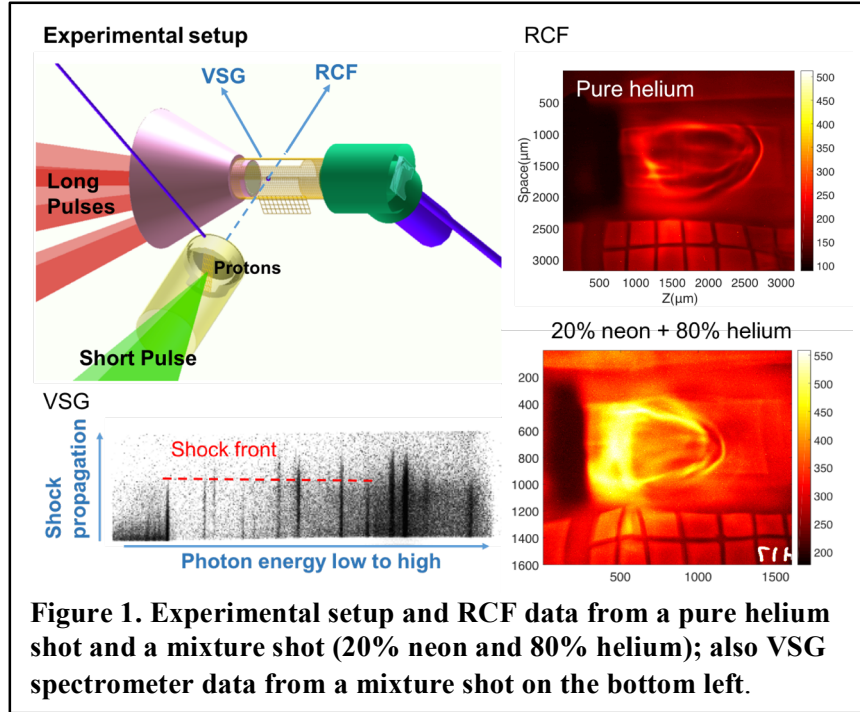


Figure 6. Experimental configuration for BFieldLoop experiments.

9. Study of Shock Fronts in Low-Density Single- and Multi-Species Systems

(PI: R. Hua, UCSD)

with Y. Ping (LLNL), H. Sio (MIT), S. C. Wilks (LLNL), C. McGuffey (UCSD), M. Bailly-Grandvaux (UCSD), F. N. Beg (UCSD), G. W. Collins (LLNL, LLE), R.F. Heeter (LLNL) and J.A. Emig (LLNL)



This series of shots are designed for studying the shock front structure of low-density single and multi-species systems in a planar geometry, using proton radiography from a broadband target-normal sheath-acceleration (TNSA) source, and X-ray emission spectroscopy. Unlike most other low-density shock experiments, that are mostly carried out in convergent geometry with near-monoenergetic D^3He proton radiography, these experiments' planar geometry enables one to distinguish the shock front

from its pusher, and the TNSA protons provide broadband energy measurements.

In this platform, the strong shock of interest is initiated by launching three long pulse beams from EP onto a 2 micron SiO_2 foil. By ablation, the foil pushes into a cylindrical kapton tube that is prefilled with either pure helium or a helium-neon mixture. A short pulse beam is fired a few nanoseconds after the shock-driving beams, onto a TNSA proton target normal to the axis of the kapton tube. The protons are driven through two windows on the tube into a stack of radiochromic films (RCF) on the other side. Photons emitted from the shock front through another window are recorded by a 1-D spatially-resolved soft x-ray spectrometer (called VSG). The details of the design and its feasibility have been published [1].

With pure helium fill, a proton accumulation layer at the shock front, due to a self-generated electric field has been recorded on the RCF. A discussion of the field information inferred from the proton behavior has been published recently [2]. Shocks in the mixed gas displayed different features. Not one, but two proton accumulation layers are observed. In addition, line emission from the added neon gas is recorded by the VSG, which provides the potential to constrain the temperature and density of the shock front. Further analysis of these results is in progress. Results of these campaigns are being used to further optimize the platform to make more measurements in FY18.

[1] H. Sio, *et al.* Rev. Sci. Instrum. **88**, 013503 (2017).

[2] R. Hua, *et al.* Appl. Phys. Lett. **111**, 034102 (2017).

High-Energy-Density Experiments

A. Material Equation of State and Strength Measured Using Diffraction

1. Measurement of Pb Melt Curve Along the Hugoniot Using In-Situ Diffraction

(PI: C.E. Wehrenberg)

with R. Kraus, F. Coppari, J. McNaney, J. Eggert.

This series of shots was designed to measure the melt curve of Pb on the Hugoniot using in-situ X-ray diffraction on the PXRDIIP diagnostic on EP. The physics package consists of a 40 μm epoxy ablator, 12.5 μm lead foil, and 100 μm LiF window for VISAR. A single UV beam is used to drive a steady shock through the ablator and into the Pb sample. A separate beam drives a Ge X-ray source target and the diffracted x-rays are collected on image plates mounted on the inside of the PXRDIIP box. The solid or liquid state of the shock-compressed lead is determined by the presence of diffraction signal as either sharp lines (solid) or a single diffuse line (liquid). Figure 1 shows a diffraction pattern containing both the diffuse liquid signal from lead under 47 GPa of shock compression, and sharp diffraction lines generated by the Pt pinhole.

This campaign is performed in conjunction with similar campaigns on NIF and LCLS. The epoxy ablator setup, which eliminates reverberations between the ablator and any glue layers, and the Ge X-ray source target were developed on the NIF campaign before being applied on these shots. This Omega-EP day, alternating beams to increase the shot rate, achieved 11 shots, providing a large data set to map the melt curve on the Hugoniot. This data will be compared with similar experiments performed on LCLS, allowing comparison of shots done with greater x-ray diffraction precision (due to the XFEL) with the greater precision shock drive available on EP. In addition, these melt curve measurements will inform the design of future NIF shots using shock-ramp combination drives to measure melt curves in off-Hugoniot states.

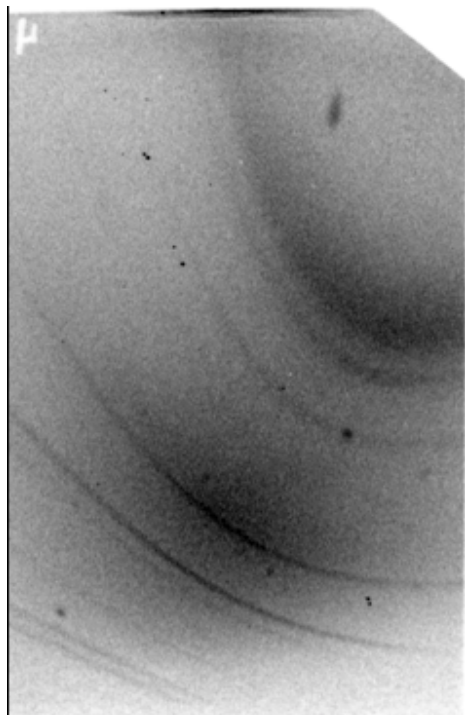


Figure 1. Example diffraction image showing diffuse signal generated by liquid Pb under shock compression at 47 GPa and sharp diffraction lines generated by the Pt pinhole.

2. Development of a New Platform for Measuring Re-Crystallization

(PI: F. Coppari, Designer: R. Kraus)

with C. Wehrenberg, J. Eggert

This campaign seeks to develop a platform for measuring re-crystallization of Pb through shock-ramp compression. By launching a first initial shock to compress the sample along the Hugoniot close to the melting pressure, letting the sample release into the liquid phase, and then recompressing it with a ramp-compression across the solid-liquid phase boundary, one can measure high pressure melting lines of materials. The structure of the Pb upon shock, release and ramp-compression is monitored by x-ray diffraction. The onset of melting is identified by the appearance of a diffuse scattering pattern and the disappearance of the Bragg diffraction lines characteristic of the solid. The pressure is monitored by VISAR looking at the interface between the Pb and a LiF window.

Building upon the successful use of Be ablaters initiated in FY16, the FY17 series used a slightly modified target design that included a Ge preheat shield (Figure 1). Hydrocode simulations allowed design of a suitable laser pulse shape to compress the Pb sample along this complicated shock-release-ramp path.

Diffraction data indicate that Pb completely melts above 50 GPa along the Hugoniot. Resolidification into a structure consistent with the bcc lattice has been observed upon subsequent ramp compression to higher pressure. Data analysis is ongoing and will inform future Omega and NIF campaigns.

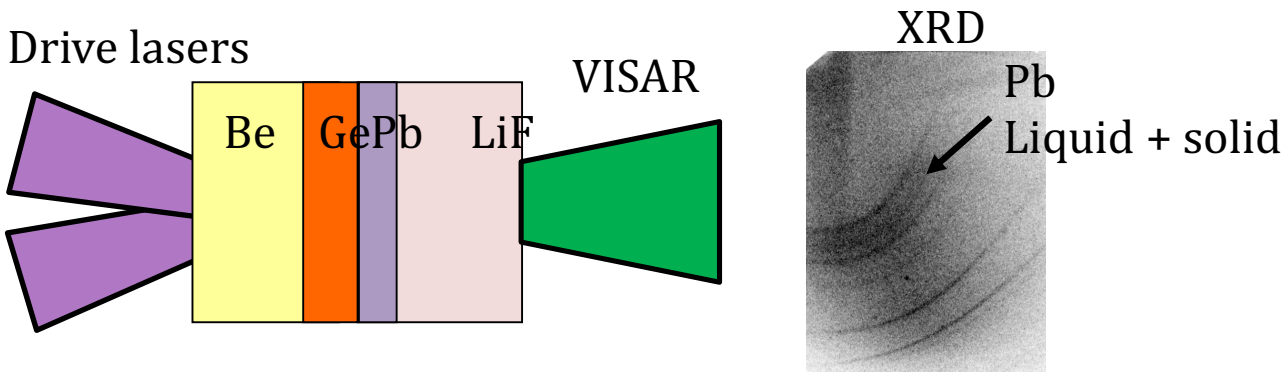


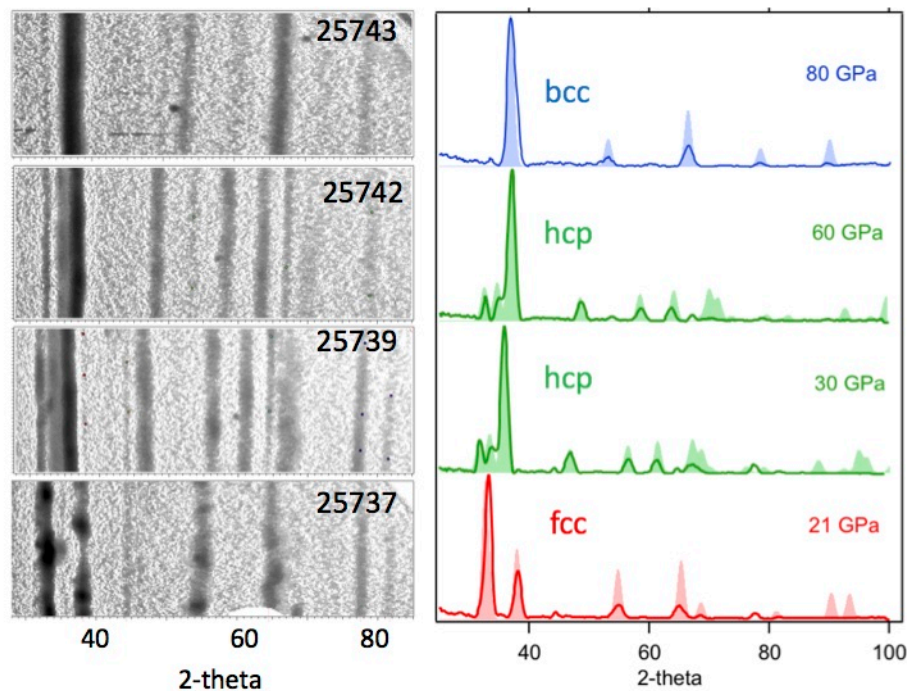
Figure 1. (Left) Target schematic. (Right) Example diffraction image showing diffuse (liquid) and sharp (solid) features from the Pb sample.

3. High Pressure Crystal Structure of Ramp-Compressed Pb and Ta, to Resolve Known or Potential High Pressure Phase Transformations (PI: A.E. Lazicki)

with F. Coppari, R. Kraus, C. Wehrenberg, J. McNaney, D. Swift, D. Braun and J. Eggert (LLNL) and R. Rygg, D. Polsin and G.W. Collins (LLE)

Several previous experiments on Omega, Omega-EP and NIF in the past 5 years have examined crystal structure of Pb and Ta at high pressure. Pb is of specific interest because its high pressure – high temperature phase diagram, including two phase transformations, is well constrained between 0-100 GPa from diamond anvil cell experiments. Thus, it provides an opportunity to test for the effects of rapid compression and heating, inherent from ramped laser drives, on phase boundaries. Although very high-quality data have already been collected in the 100-500 GPa pressure regime, previous measurements have failed to reach sufficiently low pressures to cross the two known phase boundaries. Meanwhile, measurements of Ta structure have suggested a possible new high pressure phase, but contamination of the diffraction pattern by diamond, a material which has previously always been present in the target packages, has made the determination ambiguous. The goals of this Omega-EP campaign were to capture the low-pressure phase transformations in Pb and, in the case of Ta, to eliminate all diamond from the target and examine the pressure regime where previously a new phase was suggested. Both target packages used beryllium ablaters and LiF windows, with thin (3-5 μm) layers of Pb. The shots used a combination of Cu and Ge backlighter sources.

Very high quality diffraction data was collected on all shots and the low pressure phases of Pb clearly observed and followed with pressure, constraining the phase boundaries (Figure 1). The



diagnostic damage incurred from the explosive ablation of beryllium made it impossible to quite reach the desired pressure regime for the Ta measurements, but the measurements provided a least a clear lower bound to the transition. These results were presented at an invited talk at the 55th meeting of the European High Pressure Research Group and are being prepared for publication.

Figure 7. Raw data and integrated diffraction patterns from three phases of Pb. A Cu He- α x-ray source was used.

4. Development of an In-Situ Pressure Standard for Diffraction Experiments

(PI: F. Coppari)

With: J. Eggert, R. Kraus

The goal of this campaign is to develop a new way of determining pressure in diffraction experiments, based on the use of an in-situ pressure gauge. By measuring the diffraction signal of a standard material (whose equation of state is known) compressed together with the sample, one can determine the pressure reached during ramp-compression.

Currently pressure is determined from VISAR measurements of diamond free surface velocity or particle velocity through a transparent window (such as LiF or MgO). This method is in some cases ambiguous (lack of reflectivity or shock formation) or relies on assumptions and equation of state models. Cross-checking the VISAR measurement with in-situ pressure determination using the diffraction signal of a standard material will improve the diffraction platform by providing a complementary way of determining the pressure state within the sample, with great impact to the programmatic effort of determining structures and phase transitions at high pressure and temperature. In addition, combining pressure determination from VISAR and from the in-situ gauge can give information about the temperature of the sample by measuring the calibrant thermal expansion.

Building upon the results obtained in FY16, this FY17 campaign focused on the study of Au, Ta, Pt and W pressure standards ramp-compressed to 2 Mbar on Omega. Data were collected on 8 successful shots in a half-day, including diffraction patterns of the Au/Ta and Pt/W pairs. All shots gave useful data. Comparison of the pressures obtained from VISAR analysis and from the diffraction patterns will yield information on the accuracy of the VISAR method as well as on the existence of pre-heating.

Future directions of this work will look at characterizing the pressure standards at higher pressure, and implementing this technique into other diffraction experiments. This platform still needs some additional development before routine use in diffraction experiments, but the data collected so far are extremely encouraging and suggest that the use of an in-situ pressure gauge can be a viable path forward in future XRD measurements both at Omega and NIF.

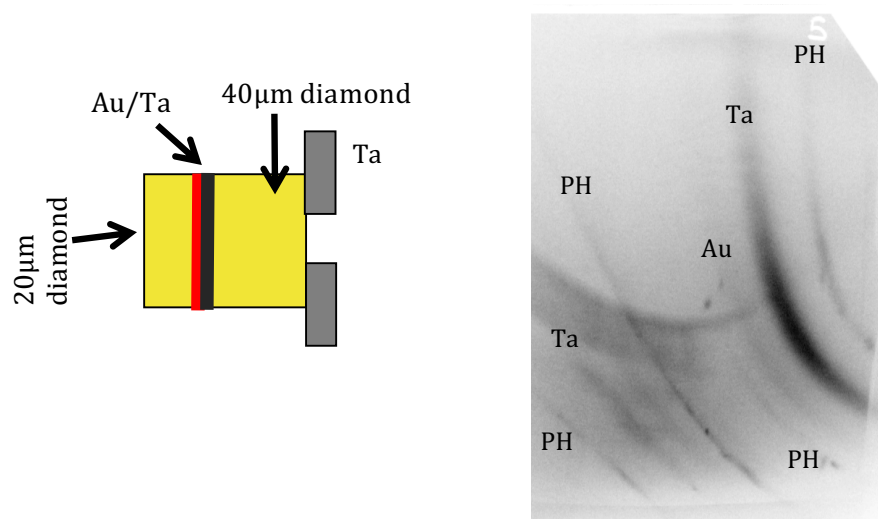


Figure 1. (Left) Target schematic. (Right) Example diffraction image showing features from Au and Ta.

5. Development of Simultaneous Diffraction and EXAFS Measurements

(PI: F. Coppari)

With: Y. Ping, J. Eggert

Being able to measure simultaneous diffraction and EXAFS signal in the same shot will be an enormous advance for laser-based materials experiments, providing a simultaneous probe of both the long- (XRD) and short-range (EXAFS) order of the material, as well as two complementary probes of the Debye-Waller factor to gain information about the temperature state of the material under investigation. The approach successfully developed in FY16 was to use the PXRDIP diagnostic to measure diffraction, and the XRS spectrometer to measure EXAFS. The challenge was to find a single suitable backlighter that would generate both a monochromatic (for diffraction) and broad-band (for EXAFS) x-ray source. Success was achieved in measuring simultaneous XRD and EXAFS of Fe by using a dual-foil Bremsstrahlung backlighter, where one foil is optimized to generate He-alpha radiation for diffraction and the other to generate a continuous and broad band x-ray source for EXAFS (see figure).

The goal for the FY17 campaign was to improve the quality of the EXAFS measurement, by using a higher-Z foil to increase the Bremsstrahlung radiation, thus generating a brighter x-ray source to allow EXAFS measurements at higher energy (Zr K-edge at 18 keV). Both Au and Ta were tested as x-ray sources for EXAFS, and Fe or Cu as X-ray sources for diffraction. The spectrum generated by Au is indeed brighter, but it was not yet possible to see the EXAFS modulation above the Zr K-edge. Poor spectral resolution certainly played a role in the deterioration of the EXAFS data: in this experimental setup, the spectral resolution is limited by the X-ray source size, which is enlarged by the expanding plasma generated by direct laser ablation of the foil. Further improvement could be obtained by using a spectrometer with focusing geometry that would be less sensitive to source size effects.

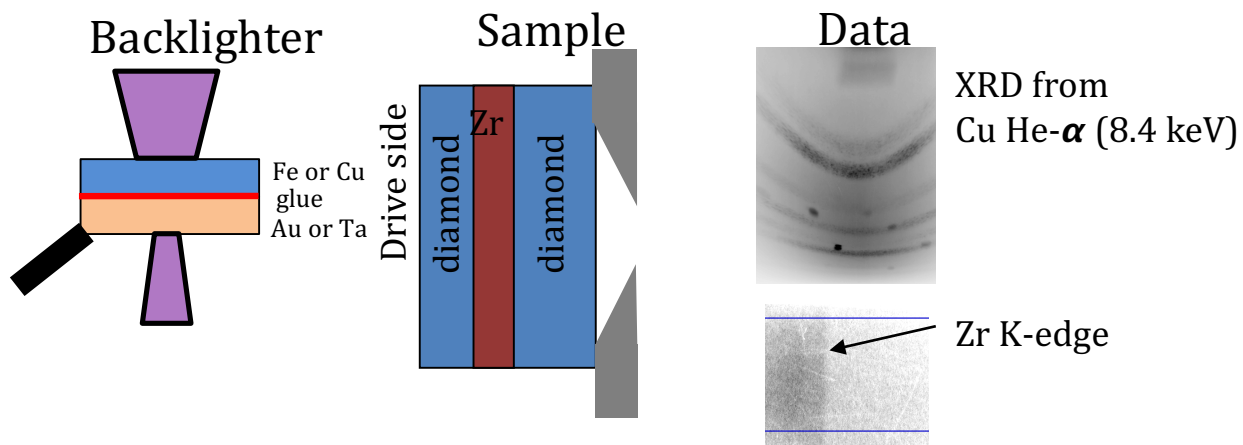


Figure 1. (Left and Middle) Target schematics for backlighter and physics package, respectively. (Right) Example diffraction and EXAFS images.

6. Texture Diffraction and Recovery of Shock Compressed Samples for Ex-Situ Study (PI: A. Krygier)

with CE Wehrenberg, H-S Park, and DC Swift

This shot day continued the previous work of CE Wehrenberg¹ on highly-textured Ta that studied the deformation response of Ta to shock waves. The goal of these shots is to study



whether effects seen on the initial shock are present during a second shock. In particular, twinning, which is not included in the Livermore strength model for Ta, was observed to play a significant role in deformation over a wide range of shock pressures (30-150 GPa). X-ray scattering was measured using the PXRDI platform in combination with VISAR on Omega EP.

These shots included a time series of X-ray diffraction measurements of various pressure histories. In the first configuration, the sample was shocked to the twinning regime, released and then shocked above twinning. Twinning was observed, as shown by the red circle in Figure 1, in the initial shock but not on release or on the second shock. In the second configuration, the sample was shocked to the twinning threshold, released, and then shocked into the twinning regime. Twinning was not observed either on the release or on the second shock, suggesting that dislocations generated by a shock wave moderate the deformation response. In addition, a shock+ramp history was performed, using the initial shock in the twinning regime, that is approximately analogous to strength experiments in Ta performed at NIF. In this regime, a new texture was observed that cannot be explained by twinning – analysis is ongoing.

Figure 1. Diffraction image for shocked tantalum, showing twinning feature (circled).

B. Material Equation of State Using Other Techniques

1. Development of a Platform for Equation of State Measurements Using Flyer Plate Impact (PI: F. Coppari)

With: R. London, P. Celliers, M. Millot, D. Fratanduono, A. Lazicki, and J. Eggert

This ongoing campaign is developing a platform to use Omega to accelerate flyer plates to high velocity for absolute equation of state measurements by symmetric impacts. The concept is to ramp compress a metallic foil through indirect laser ablation across a vacuum gap, and observe the flyer impact on a same-material sample, mounted side-by-side with a transparent LiF window (Figure 1). By measuring the flyer-plate velocity through the transparent window prior to impact, and the resulting shock velocity in the metallic sample using transit time measurements, the principal Hugoniot of the metallic foil can be determined *absolutely* (e.g. without needing a known pressure reference), enabling the development of an EOS standard.

Specifically, this campaign tested three flyer plate materials to check performance and hydrodynamic prediction capabilities. Plates of Mo, Cu and W were chosen because they can be “easily” ramp-compressed to high pressure, and don’t exhibit structural solid-phase transitions. Building upon the previous FY16 campaign, a successful half-day of 8 shots was fielded in FY17, accelerating flyer samples to different velocities. While Cu and W showed anomalous behavior, such as flyer breakup resulting in the loss of VISAR reflectivity before impact, Mo was successfully accelerated to 14 km/s, corresponding to a shock pressure into the Mo sample of about 1 TPa. As Figure 1 shows for the lower pressure shot, the velocity ramps up smoothly and VISAR data is obtained up to impact. The impact actually shocked the LiF window into a pressure range where it is no longer transparent, impairing the VISAR signal. Future experiments will look at accelerating Mo flyer plates to different pressures to characterize its Hugoniot EOS in a wide pressure range, using Quartz as transparent window.

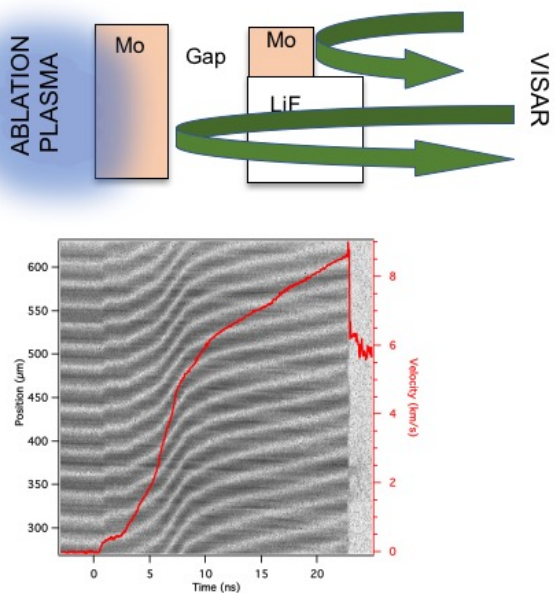


Figure 1. (Top) Experimental Concept. (Bottom) Sample VISAR data.

2. Development of Simultaneous EXAFS and VISAR Measurements (PI: Y. Ping) with F. Coppari and J. Eggert

This campaign aims to test mirror shielding for simultaneous VISAR measurements in the presence of the implosion backlighter needed for Extended X-ray Absorption Fine Structure (EXAFS) measurements. Both the VISAR and EXAFS measurements must pass through the sample, so an X-ray transparent optical mirror is used to redirect the VISAR probe beam onto the sample. This mirror is however vulnerable to blanking. For these FY17 shots a tilted mirror design was implemented to move the mirror out of the line of sight of the X-ray transmission path, so that more shielding of the mirror could be applied. This design extended the mirror life time by about 1ns, but after that the mirror was still blanked and the VISAR signal lost. On the other hand, good EXAFS data were collected for the Co K-edge for the first time, as shown in Figure 1. Separate shots for VISAR without the implosion also produced good VISAR data to characterize the pressure. The similar experimental design on NIF has the mirror positioned behind the target, which survived and produced VISAR signal in presence of the implosion in a recent NIF shot.

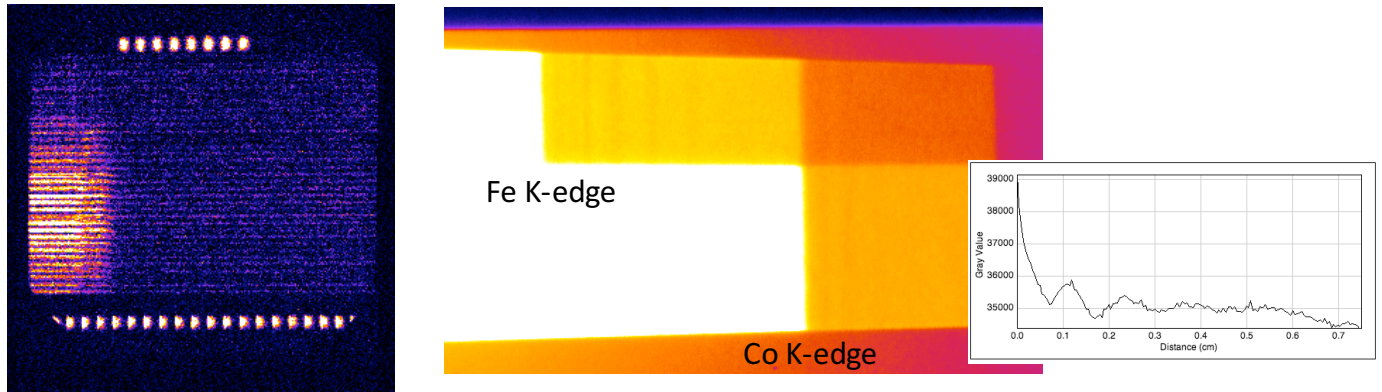


Figure 8. (Left) Raw image of VISAR, showing blanking of the mirror delayed by ~1ns. (Right) EXAFS spectra at the Fe and Co K-edges. The lineout shows the EXAFS modulations at the Co K-edge.

3. Development of a Platform for EXAFS Measurements at the L Absorption Edge of High-Z Materials (PI: F. Coppari)

With Y. Ping and J. Eggert

EXAFS measurements in the 7 keV X-ray region are routinely performed at the Omega laser during shock and ramp compression. However, because the brightness of the capsule implosion used as an X-ray source decreases at high energy, measuring EXAFS of materials with absorption edge higher than 7 keV is very difficult in a single shot. In addition, as one seeks to study higher-Z materials and observing the L absorption edge, the amplitude of the EXAFS signal decreases as well, because the cross section for the absorption at the L edge is lower than at the K edge. These issues make these measurements extremely challenging.

In prior years the TaXAFS campaigns looked at the Ta L3-edge (~ 10 keV) and were able to obtain a good signal-to-noise by averaging 15 shots or by using a multi-crystal spectrometer [Ping, RSI 2013]. The goal of the FY17 campaign is to look at materials whose L-edge is closer to 7 keV, where the number of photons generated by the capsule implosion is higher, to see if good signal could be obtained in a single shot. The shots studied the Ce L3-edge (5.7 keV), but although a nice contrast at the Ce L-edge has been measured, no clear EXAFS modulations could be observed in a single shot (figure), probably also due to limited spectral resolution. This suggests that in order to successfully measure L-edge EXAFS, a spectrometer with focusing geometry is needed, to increase the signal because of the higher collection efficiency, reduce the sensitivity to x-ray source size broadening, therefore improving the quality of the data.

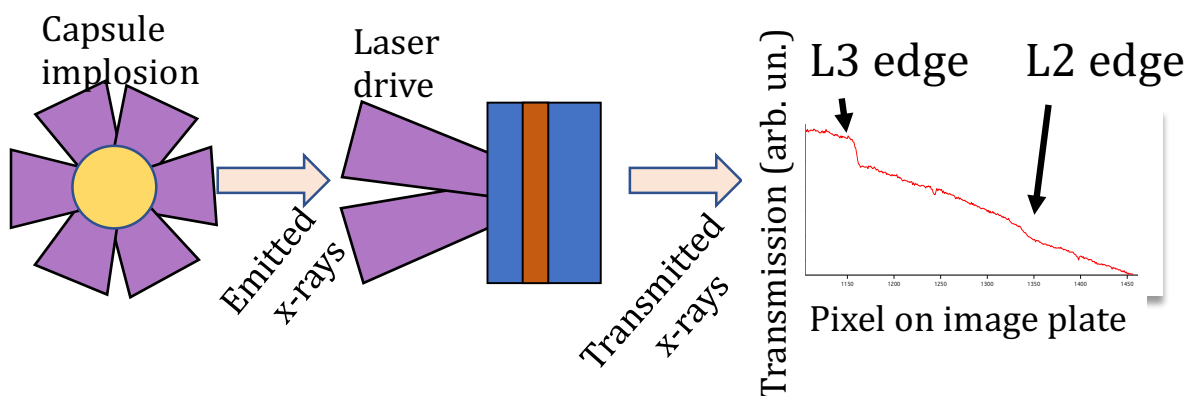


Figure 1. (Left) Experimental Concept. (Right) Sample EXAFS data.

4. Development of Spherically-Convergent Equation of State Measurements (PI: A.E. Lazicki)

with D. Swift, A. Saunders, T. Doeppner, R. Nora, F. Coppari, R. London, P. Celliers, J. Eggert, G. Collins, H. Whitley, J. Castor, and J. Nilsen

This campaign is developing a platform for measuring Hugoniot equation of state at pressures much higher than can be achieved using a standard planar drive. This platform is intended to collect data in the 100+ Mbar pressure regime, where currently very little data exists for any material, for the purpose of constraining equation of state models.

The FY17 campaigns first used a hohlraum (indirect drive) to launch converging shock waves into solid spheres of CD (deuterated) and CH (normal) plastic. Along the axis of the hohlraum, Vanadium He- α -backlit 2D X-ray images of the imploding sphere were collected with a framing camera. On some shots, X-ray Thomson scattering measurements were also made using a Zn backlighter and a spectrometer at the hohlraum equator (Figure 1a & 1b). The radiographs yield density and shock velocity, which allow calculation of the shock state using the Rankine-Hugoniot equations, and the scattering data yield information about temperature and ionization state.

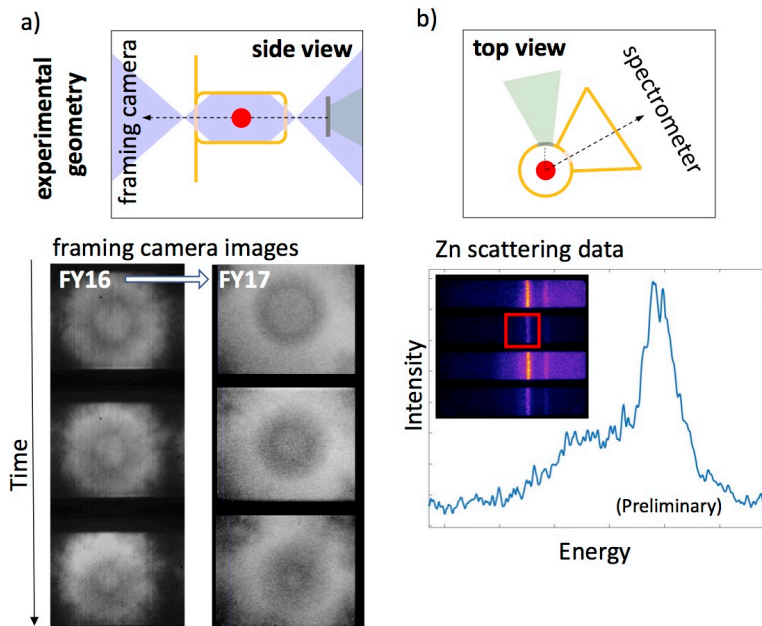


Figure 9. a) experimental geometry and representative 2-D framing camera images of the imploding sphere, comparing results from FY16 and FY17 (83557). b) geometry and representative Zn X-ray Thomson scattering data (85304)

The FY17 shots improved on prior measurements by increasing hohlraum gas fill, to eliminate suspected hohlraum blow-off features, and using faster-gating cameras to improve spatial resolution. Neutron diagnostics were also fielded to detect neutrons from the hot spot. The new design for the X-ray scattering measurement yielded a high-quality Compton feature and an elastic feature potentially artificially elevated due to Zn plasma leakage. These results, together with the FY16 measurements on CH₂, are being summarized for a publication describing the principal Hugoniot of plastic from the initial densities of CH, CH₂ and CD.

In addition, a separate half-day of shots continued development of a platform to achieve 100's of Mbar pressures in a spherically-converging shockwave, launched using direct laser ablation of the sphere. This measurement probed deuterated plastic (CD) using radiography, X-ray Thomson scattering, and neutron yield. Data improved in quality compared to FY16, but indicated some drive asymmetry and preheating effects, requiring further design optimization.

5. Development of Conically-Convergent Platform for Hugoniot Equation of State Measurements in the 100 Mbar-Gbar Pressure Regime (PI: A.E. Lazicki)

with D. Swift, F. Coppari, R. London, D. Erskine, D. Fratanduono, P. Celliers, J. Eggert, G. Collins, H. Whitley, J. Castor and J. Nilsen

This campaign was designed to develop a platform for measuring Hugoniot equation of state of arbitrary (including high-Z) materials at pressures much higher than can be achieved using a standard planar drive. This platform is intended to collect data in the 100+ Mbar pressure regime, where currently very little data exists for any material, for the purpose of constraining equation of state models.

To achieve the desired pressure amplification, converging shock waves are launched into a cone inset in a halfraum. For appropriate cone angles, nonlinear reflections of the shock wave result in formation of a Mach stem: a planar high-pressure shock that propagates along the axis of the cone. This approach was tested in FY16 and produced promising results, but suggested the need for preheat shielding. The FY17 half day campaign attempted overcome this with Au preheat shield layers, and experimented with a porous cone material, from which simulations suggested that increased pressure amplification would be possible. Additionally, these shots tested multiple cone angles and fielded targets with quartz windows and Al steps, to attempt to quantify the Mach wave strength and steadiness. Some results are shown in Figure 1. Transit

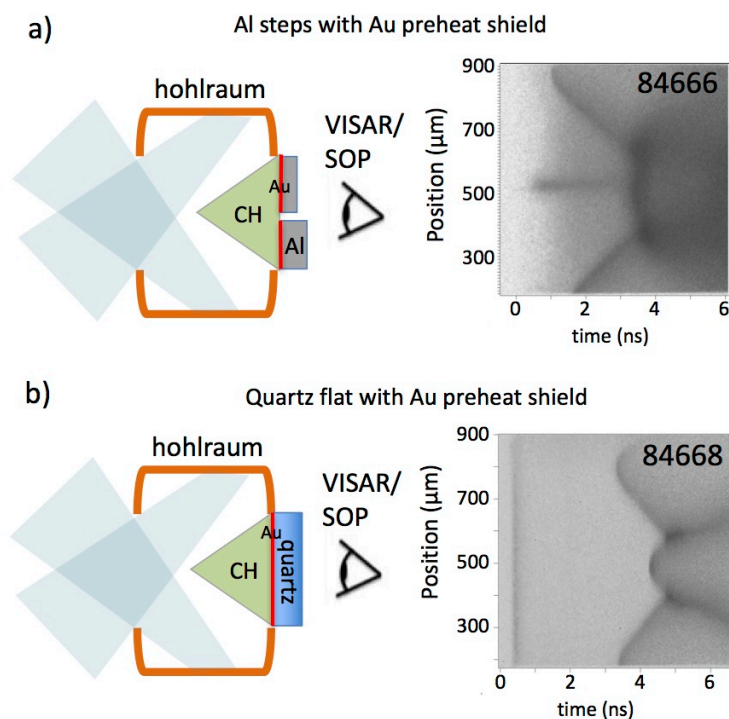


Figure 10. Experimental configuration and raw SOP data showing the breakout time from a) a stepped Al sample with Au preheat shield layers and b) a thick quartz sample with Au preheat shield layer.

time calculations indicate that 100+ Mbar shock waves were generated in the CH cones. At peak laser intensities the quartz windows blanked, indicating that the Au preheat shield thicknesses were not sufficient, and the profile of the shock breakout suggested the Mach wave was decaying (unsupported) through the full target thickness. A subset of the shots also attempted to use area-backlit radiography to image the Mach wave formation in the cones themselves, through slits in the halfraums. Geometric issues made interpretation of the framing camera images very difficult. However, the lessons

learned on this shot day were very important in designing a successful test shot on the NIF, completed on 8/31/17.

C. Material Dynamics and Strength

1. Copper Rayleigh-Taylor (CuRT) Growth Measurements (PI: J.M. McNaney)

with S. Prisbrey, H.-S. Park, C.M. Huntington and C.E. Wehrenberg

The CuRT campaign is part of the Material Strength effort, which is aimed at assessing the strength of various metals at high pressure and high strain rate. The goal of the CuRT platform is to measure Rayleigh-Taylor (RT) growth of samples that behave “classically,” i.e. can be fully modeled using a fluid description. In this series of experiments the intent is to measure RT growth in liquid copper at high pressure. A second goal is to demonstrate the dynamic range of the technique by measuring RT growth in solid copper.

Without the stabilization of strength, classical RT growth is characterized by a growth rate $\gamma = \sqrt{kgA_n}$, where k is the wavelength of the unstable mode, g is the acceleration, and the Atwood A_n number quantifies the magnitude of the density jump at the interface. Acceleration of the sample in the experiment is provided by the stagnation of a releasing shocked plastic “reservoir,” which is directly driven by approximately 2-8 kJ of laser energy, depending on the desired material condition. The growth of pre-imposed ripples is recorded using transmission X-ray radiography of a copper He- α slit source, where the opacity of the sample is calibrated to the ripple amplitude. The pre-shot metrology and measured ρ of the driven sample together yield the growth factor, which is compared to models of RT growth. Diagnostic features such as a gold knife-edge on the sample allow one to measure the modulation transfer function and create an opacity look-up table on each shot, resulting in error bars of approximately $\pm 10\%$.

The March 2017 campaign produced the first results for liquid copper RT. Analysis of velocimetry (Figure 1) indicated that the copper RT samples were subjected to a shock of ≈ 5 Mbar leading to complete melt of the sample and subsequent RT growth in the liquid phase. The liquid Cu RT growth curve is presented in Figure 2. A second day of liquid copper shots took place on September 13, 2017. The results of those experiments (also in Figure 2) were consistent with the values obtained in the March data. Simulations of the liquid Cu growth are in progress.

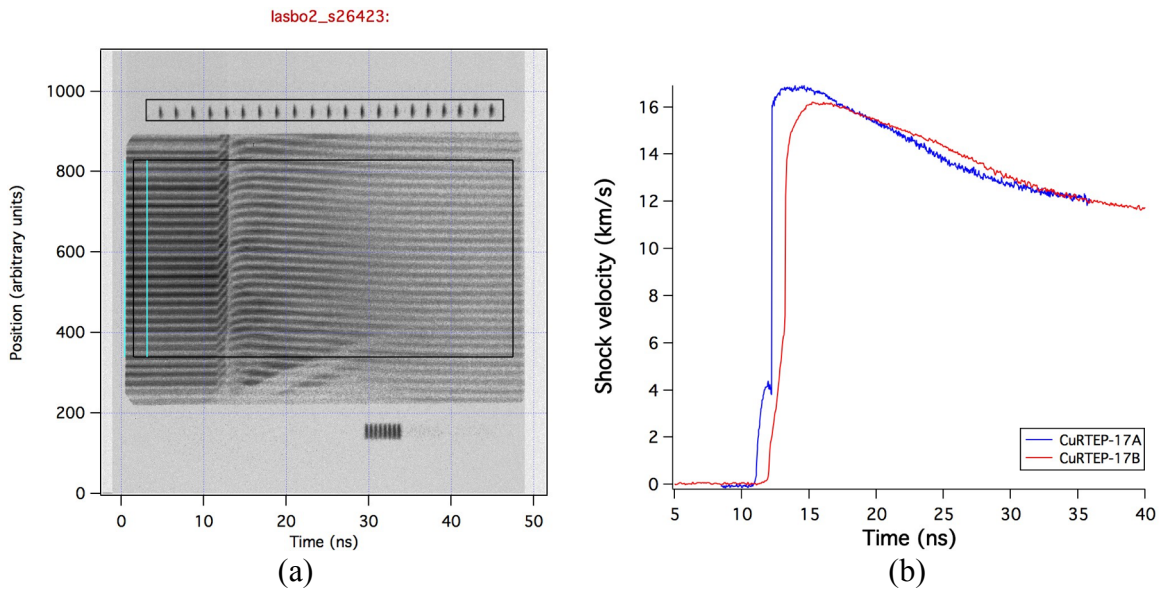


Figure 1. The ASBO data from shot 26423 (September 2017) are shown in (a), with analyzed results and comparison to March 2017 result in (b).

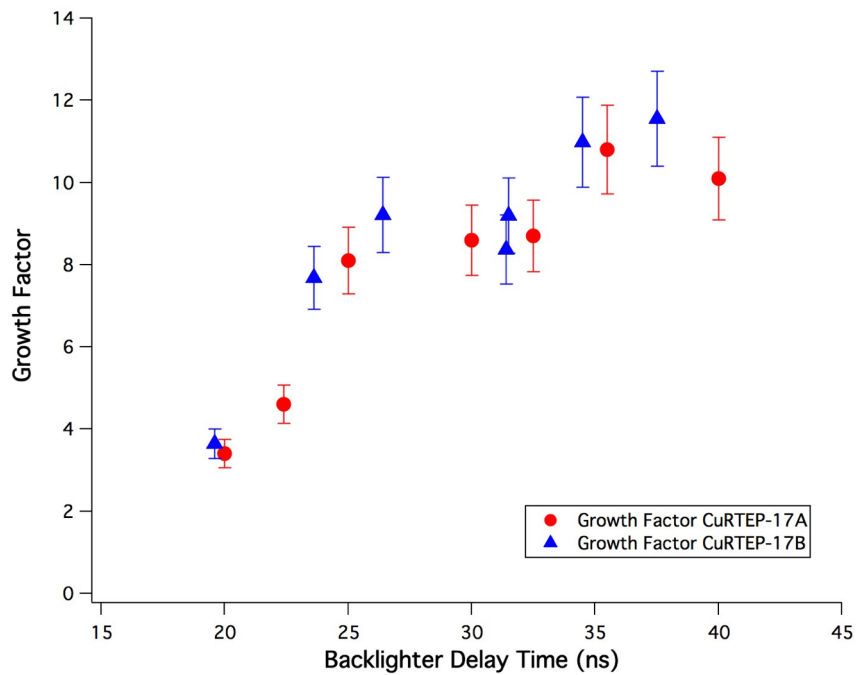


Figure 2. Growth factor data for liquid copper from the March and September shot days.

2. Evaluation of Additively-Manufactured Foams for Ramp Compression Experiments (PI: R. Smith)

The FY17 “AMFoam” campaigns continued to evaluate the use of 3D-printed or Additively Manufactured Foams as surrogates to carbonized resorcinol foams (CRF) in ramp compression target designs. The 3D printed foams may be characterized as follows. The $100 \times 100 \times 16 \mu\text{m}^3$ log pile blocks composed of individually printed lines, are stitched together to form layers that are 1.7 mm in diameter. Seven $16 \mu\text{m}^3$ layers are then stacked on top of one another to arrive at cylindrical “AM foams” that are $112 \mu\text{m}$ tall [1]. These foams are glued onto a $25 \mu\text{m}$ Br + $120 \mu\text{m}$ 12% Br/CH assembly (Figure 1a). Following the ramp compression design described in Ref. [2], fifteen beams of the Omega laser with 300 J in 2 ns results in a ramp compression wave being launched into a stepped-Al/LiF sample (Figure 1a). At a controlled time after this compression begins, the OHRV (2D VISAR probe) takes a two dimensional snapshot of the reflectivity and velocity field with a spatial resolution of $\sim 3 \mu\text{m}$ [3]. An example of the intensity field recorded on the 2D VISAR is shown in Figure 1c.

These campaigns have varied the structure of the 3D printed foam with the goal of optimizing the temporal ramp profile. These experiments have been conducted in support of Material Strength experiments on the National Ignition Facility.

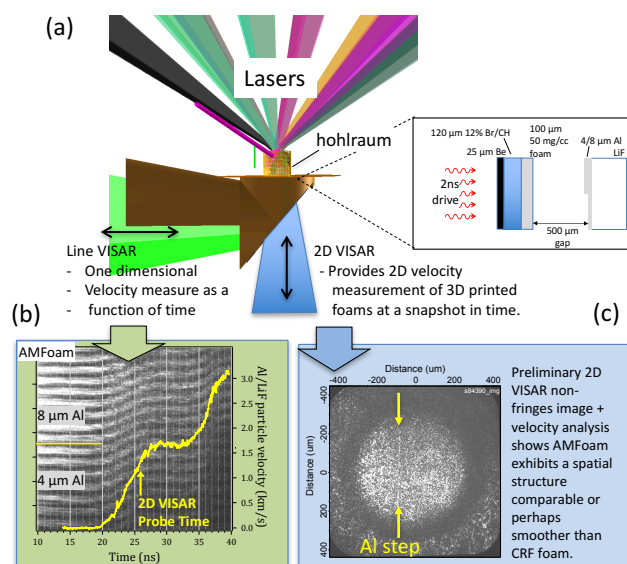


Figure 11(a) Schematic diagram describing the experimental setup for the AMFoam-17A campaign, which combined the OHRV (2D VISAR) and ASBO diagnostics on a single shot. The goal of these shots was to characterize the temporal and spatial drive associated with additively-manufactured (3D printed) foam targets. **(b)** ASBO record shows a characteristic ramp/pressure-hold/ramp compression profile. **(c)** Sample reflectivity at OHRV probe time. For the AMFoam-17B campaigns only the ASBO (VISAR) diagnostic was used.

[1] James S. Oakdale, Raymond F. Smith, et al., “Direct Laser Writing of Low-Density Interdigitated Foams for Plasma Drive Shaping”, *Adv. Funct. Mater.* 1702425, (2017); DOI: 10.1002/adfm.201702425

[2] R.F. Smith et al., “High planarity X-ray drive for ultrafast shockless-compression experiments” *Phys. Plas.* **14**, 057105 (2007).

[3] R.F. Smith et al., “Heterogeneous flow and brittle failure in shock-compressed silicon”, *J. Appl. Phys.* **114**, 133504 (2013).

D. National Security Applications

1. SolarCellESD: Solar Cell Electrostatic Discharge Experiments (PI: K. Widmann) with Phil Jenkins (NRL), Steve Seiler (DTRA), Patrick Poole (LLNL) and Brent Blue (LLNL)

The overall goal of the SolarCellESD campaign is the experimental determination whether prompt X-rays can induce failure modes in solar arrays that are not accounted for by simply testing the individual solar cells alone. The solar-cell array is fielded as part of the X-ray Langmuir Probe Detector (XLPD) cassettes and exposed to X-rays from a laser driven source. The FY17 campaigns added a partial EMI enclosure of the XLPD front end – “partial”, because the enclosure has a large rectangular opening providing an unobstructed view of the x-ray source for the solar-cell array. The bias and diagnostic electronics for the solar cells were also improved such that the bias circuit is fully isolated from any of the target chamber components and the bias voltage can be changed manually between shots. This bias voltage allows one to mimic the voltage difference between two adjacent solar cells from different strings in large arrays, which can range from tens to a few hundred Volts. Figure 1 shows a sketch and a picture of the new and improved XLPD front end.

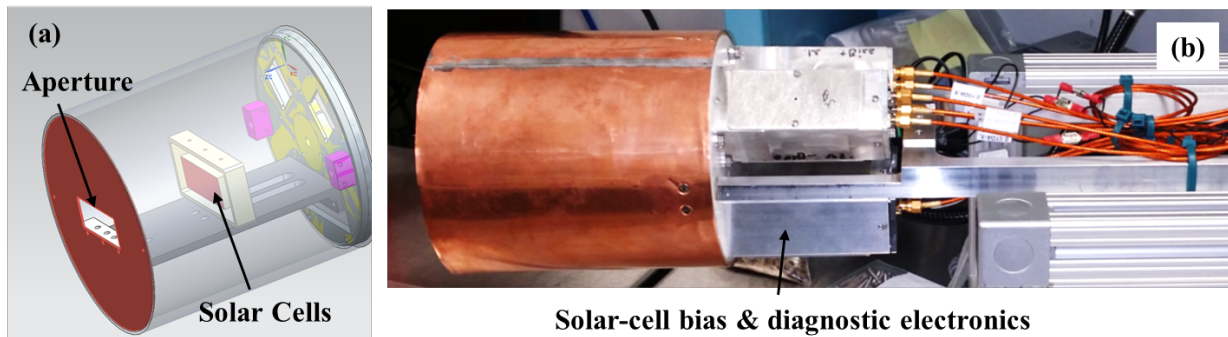


Figure 1: (a) Front end of the XLPD with the solar cell (mini) array, i.e., 2 x 1 cells; (b) Picture of the XLPD (side-on view) with the new EMI enclosure and the various bias and diagnostic electronics.

The FY17 campaign continued using the X-ray source developed in FY15, a small gold halfraum (600- μm diameter, 600- μm long) with a small pinhole (60 μm or 100 μm diameter) at the “closed” side of the halfraum. The targets were driven with three sets of 1ns laser pulses to generate X-ray pulses of 3-ns duration. These targets provide two significantly different x-ray flux (and fluence) levels depending on the target orientation with respect to the solar cell array (“open side” versus “pinhole side”). Despite the large difference in the measured radiant X-ray power, from 300 GW/sr peak flux for the open side down to a few tens of GW/sr for the pinhole side, the spectral intensity distribution should be very similar. Unfortunately, the low signal level on the Dante X-ray diodes for the low-flux case did not allow a good quantitative comparison of the unfolded spectral intensities. Figure 2 shows the x-ray flux measured with Dante for a couple of “open-side” shots.

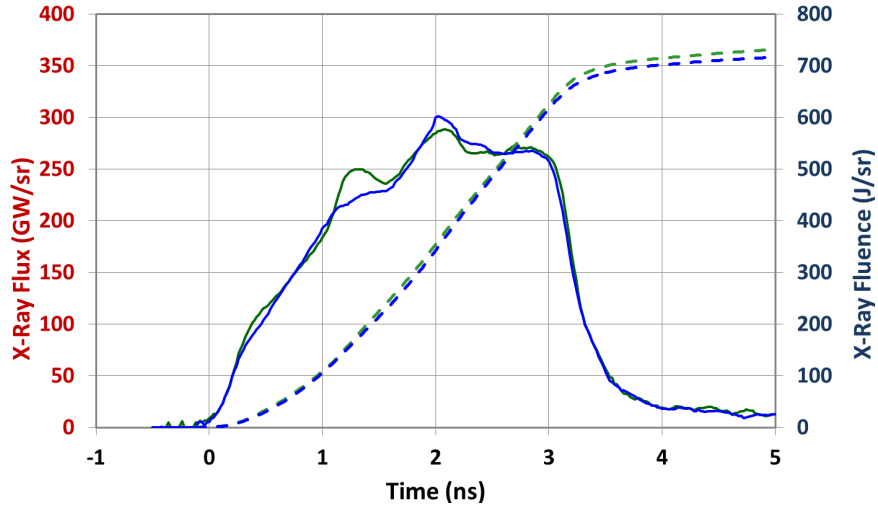


Figure 2: Dante measurements of the output (radiant power & x-ray fluence) of the laser-driven x-ray sources for two shots in the “open side” configurations (see text for details) showing a shot-to-shot variation of only 2% in the total x-ray fluence, within the uncertainty of the Dante X-ray flux measurement.

With the improved hardware, it was possible to generate and observe, for the first time, X-ray induced arcing just between the solar cells, without creating discharge between the solar cells and any of the other components in the target chamber. These shots also demonstrated the feasibility of mitigating the X-ray induced arcing by altering the bias voltage for the solar-cell array. The next goal for this campaign is a detailed parameter scan to determine the threshold values for the X-ray fluence, and associated bias voltage levels, respectively, for X-ray induced arcing in solar cell arrays.

2. Plasma Instability Control to Generate High Energy Bremsstrahlung X-ray Source (PI: P. L. Poole)

with R. Kirkwood, S. C. Wilks, M. May, K. Widmann, and B. E. Blue

In FY17 a campaign began to develop a high fluence x-ray source in the 30 – 100 keV range by deliberately stimulating and optimizing plasma instabilities. High fluence sources at lower energies are currently used for materials effects studies in extreme environments, but stronger sources are needed for 30+ keV X-rays. This project aims to enhance laser conversion to plasma instabilities such as Stimulated Raman Scattering (SRS), which accelerate electrons in plasma waves that will convert to high energy X-rays via bremsstrahlung in the high-Z hohlraum wall.

The SRS-Xray-17A half day centered on optimizing plasma conditions within a hohlraum for high SRS gain by reversing ideas on how to mitigate these effects for fusion conditions (SSD bandwidth off, phase plate changes, etc.). Two types of targets were fielded to test SRS generation: one with 6 mg/cc (0.2 n_{crit}) SiO₂ foam fill, the other with 10 μ m of parylene-N (CH) inner lining. The CH-lined hohlraums were illuminated with an 80 ps picket prepulse arriving a variable time before the main 1 ns 450J/beam laser drive.

Primary results were promising: the best targets exhibited *10x more x-ray yield in the 50+ keV regime than typically seen on direct drive shots*. The SRS streak data is being compared to the various x-ray diagnostics fielded to obtain a detailed picture of instability gain and directionality and its impact on x-ray fluence. While the CH prepulsed targets exhibited factors of 6 more direct SRS backscatter than the no-prepulse CH and foam targets, these latter configurations had the best X-ray yield (Fig. 1). The increased indirect backscatter on the no-prepulse CH target provides an avenue of further simulation and future experimental study investigating the directionality of SRS backscatter within the hohlraum and its impact on the ultimate x-ray yield. Target design simulations are underway, using these valuable experimental results to plan the FY18 Omega and NIF campaigns. These promising initial results are a valuable stepping stone toward a new x-ray source which will represent a large capability increase for National Security Applications and related materials under extreme conditions studies, with the additional benefit of broadening the understanding of plasma instability control for fusion and other applications.

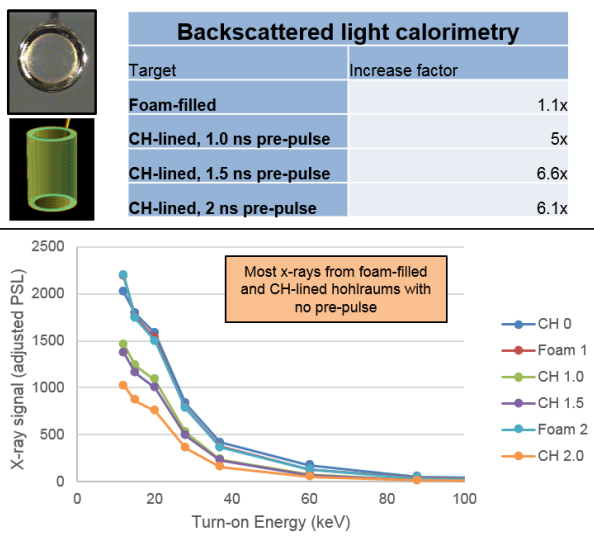


Figure 12: Data summary for SRS-Xray-17: highest SRS backscatter from CH-lined hohlraums irradiated with pre-pulse; highest x-ray yield from no pre-pulse CH and foam-filled targets.

E. Plasma Properties

1. Investigation of Orthogonal Plasma Flows in the Presence of Background Magnetic Fields (PI: B.B. Pollock)

with T. Johnson, G. Swadling, J.S. Ross, and H.-S. Park

The DebrisPlasma-17A shots continued the Magnetized Collisionless Shock – Weapons Effect campaign from previous years. The goal for this series of experiments is to quantify the interaction of orthogonal plasma flows, with and without a background magnetic field. The field is supplied by the LLE MIFEDS, which delivers 4-8 T at the interaction region of the experiments, depending upon the specific geometry of the MIFEDS coils. The orthogonal plasma flows originate from two separate foil targets, one of which is mounted to the MIFEDS structure. The foil material composition, laser drive, spacing, and time of flight to the interaction region can be varied on each shot.

The interaction region of the two flows is simultaneously probed with 2w Thomson scattering and protons from the implosion of a D^3He -filled capsule. Initial measurements of the electron density and temperature from the Thomson scattering do not indicate a strong dependence on the strength or direction of the background magnetic field. The proton deflectometry data do show structural differences in the measured proton distribution with and without the field, but further modeling and simulations are needed in order to quantify these differences.

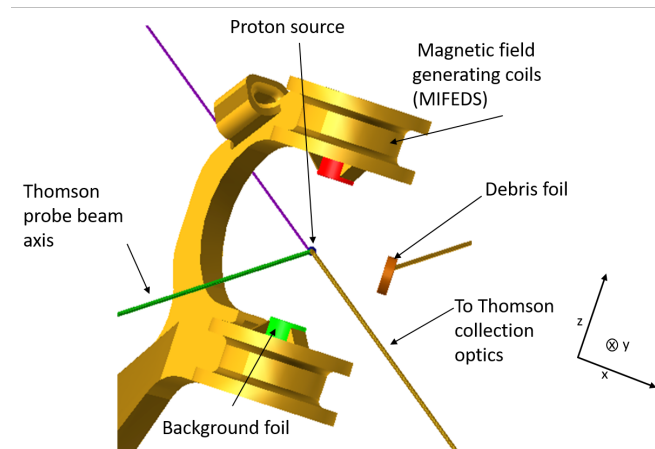


Figure 13. Experimental configuration viewed from the proton detector in TIM1. One or two foils can be mounted to the MIFEDS structure, which is centered at TCC. The Thomson Scattering geometry is k-matched to the z-axis of the experiment. The capsule is 1 cm into the page from TCC, and the debris foil is 2 mm from TCC.

2. Measurement of Gold Thermal Transport and M-shell Emission Using a Buried Layer Platform (PI: E.V. Marley)

with L.C. Jarrott, M.B. Schneider, G.E. Kemp, M.E. Foord, R.F. Heeter, D.A. Liedahl, K. Widmann, C.W. Mauche, G.V. Brown, J. Emig

This campaign was designed to measure the thermal transport through gold layers as well the emitted M-shell gold spectra from a well characterized and uniform plasma for comparison to atomic kinetic models. The buried layer target geometry used for this experiment is capable of generating plasmas with an electron temperature of ~ 2 keV at electron densities of 10^{21} electrons per cubic centimeter. These are within the range of conditions found inside gold hohlraums used on experiments at the National Ignition Facility (NIF), providing a stable laboratory setting for radiation transport and atomic kinetic studies of hohlraum plasmas.

Planar, buried layer targets were illuminated evenly on both sides (Figure 1) to heat the sample, composed of Ti, Mn, and Au. The sample was buried between two 5 μm thick layers of Be serving as an inertial tamp to slow the expansion of the sample. Time resolved 2-D images of the target's x-ray emission, viewed both face on and side on, were recorded using time-gated pinhole cameras. The K-shell spectra from the Ti and Mn were used to determine the electron temperature of the plasma. The time resolved spectra were recorded using a crystal spectrometer coupled to a framing camera, as well as a crystal spectrometer coupled to an x-ray streak camera. Two additional time-resolved crystal spectrometers were used to record the full range of the Au M-shell emission. All of the framing cameras used, for imaging as well as spectroscopy, were co-timed so the plasma conditions at the time of the measured Au M-shell emission could be established from synchronous K-shell and imaging data.

Two different sample thicknesses were used during the campaign, to measure the thermal transport through Au. There were also two different pulse shapes used, to assess which was most efficient for coupling laser energy into the buried layer target. A complete set of data from all 6 precisely co-timed diagnostics was recorded for both target types, using both pulse shapes during this August campaign, at temperatures ~ 2 keV. Data analysis is underway.

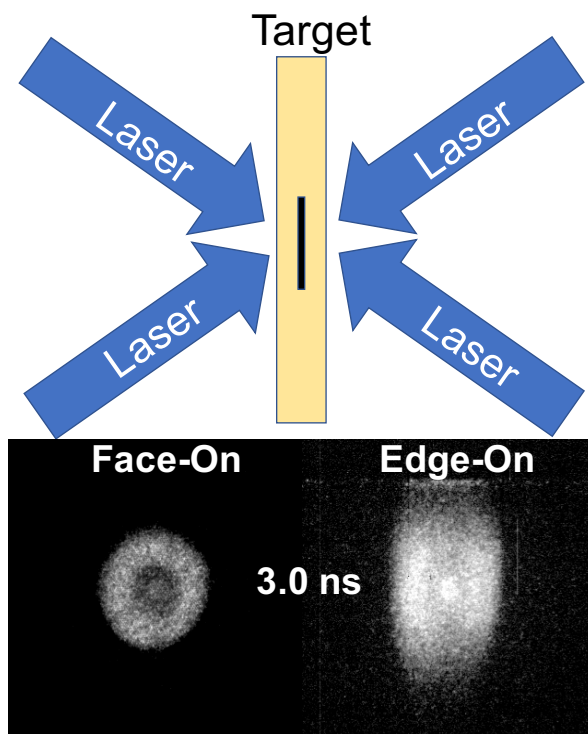


Figure 14. Experimental configuration and pinhole images of the emission area at 3.0 ns of shot 86860.

F. Hydrodynamics

1. Experiments on the Rayleigh-Taylor Instability in the Highly Nonlinear Regime* (PIs: C.C. Kuranz at Univ. of Michigan, C.M. Huntington at LLNL)

with L. Elgin, T. Handy, G. Malamud, M.R. Trantham, S.R. Klein, R.P. Drake, and D. Shvarts

These experiments observe the evolution of the single-mode Rayleigh Taylor instability (RTI) in low- and high-Atwood number regimes at late scaled times. Models predict two growth phases of the RTI: exponential growth, followed by a nonlinear stage reaching a terminal velocity [1]. For low-Atwood number systems, numerical simulations show an additional growth phase in the late nonlinear stage, characterized by reacceleration [2]. But there are claims that this reacceleration may be an artifact of the simulations and may not reflect the evolution of classical RTI. Prior experimental studies of RTI growth have not created the conditions necessary to observe the late nonlinear stage, which requires large aspect ratios of the spike and bubble amplitudes to the perturbation wavelength ($1 \leq h_{s,b}/\lambda \leq 3$) [2].

The first two experiments in this new campaign were conducted in FY17. A laser-driven blast-wave accelerates an RT-unstable interface in a shock tube. X-ray radiographs along dual orthogonal axes, capture the evolution of RTI. Late scaled times are achieved with small-wavelength ($\lambda=40 \mu\text{m}$) seed perturbations at the interface. PAI plastic (1.4 g/cc) is used as the heavy fluid. The lighter fluid consists of CRF foam, with pre-shock densities of 0.05 g/cc (high-Atwood) or 0.4 g/cc (low-Atwood). The first shot day demonstrated X-ray backlit imaging capable of resolving the small-wavelength RT spikes and bubbles. But the plastic shock tube could not support the higher internal pressure of the dense, low-Atwood targets. A new target design was developed and fielded for the second shot day. Improvements included Be walls, which can be thicker due to the high X-ray transmission of Be, and a larger tube diameter, which delays the effects of transverse waves. The new design extended the time scale for observations of RTI growth in low-Atwood targets from 30 ns to >40 ns. However, the ablators did not meet specifications, compromising the physics of the experiment. The data are being analyzed to extract as much information as possible, and the team is working with the ablator manufacturer to ensure that the parts for the FY18 experiments meet all specifications.

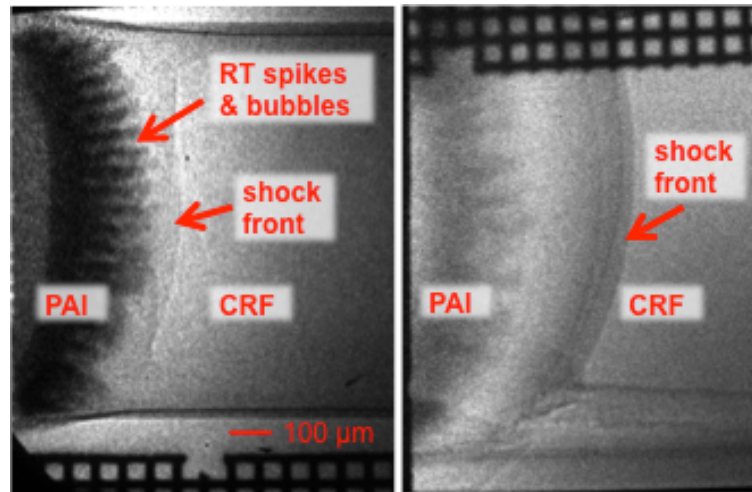


Figure 15. (Left) RID 83095 (10/06/16) with high-A, $\lambda=40 \mu\text{m}$ target at 15 ns. (Right) RID 85111 (4/06/2017) with low-A, “flat” interface target at 26 ns.

[1] Layzer, *Astrophys. J.* **122**, 1 (1955).

[2] P. Ramaprabhu et al., *Phys. Fluids* **24**, 074107 (2012).

* This work is funded by the Lawrence Livermore National Laboratory under subcontract B614207.

2. Proton Heating of Copper Foam on Omega-EP (PI: J. Benstead)

with E. Gumbrell, S. McAlpin, M. Crook-Rubery, R. Merritt, and W. Garbett (AWE)

This LLNL-AWE campaign studies the heating of a cylindrical puck of copper foam irradiated by a short pulse generated proton beam. This shot day was an extension of previous shot days in 2014 and 2016, and featured a refined target and diagnostic design. The two major aims of the experiment were to measure the temperature distribution through the target and to quantify the extent of expansion of the rear surface.

The experimental setup is depicted in Figure 1. A gold foil was irradiated with the Omega EP sidelighter (SL) beam delivering 200 J over 3 ps. The SL produced a beam of protons and ions which were used to heat a copper foam puck positioned 0.5 mm away. An aluminum foil was placed between the gold foil and the copper puck to improve heating by filtering out heavier ions and low energy protons which non-uniformly heat the target. The subsequent sample expansion was imaged with an x-ray radiography system. This used a nickel area backlighter, irradiated with 3 long pulse beams, coupled to an x-ray framing camera (XRFC) which imaged the back-lit target. The backlighter (BL) beams were delayed with respect to the SL beam in order to observe the heated and expanded target at different times. The Streaked Optical Pyrometry (SOP) diagnostic was fielded orthogonal to the heating axis, with its imaging slit oriented such that the temperature through the central section of the disc could be measured front to rear over the first 5 ns of heating (see Figure 2). And a Radio-Chromic Film (RCF) stack measured the proton/ion beam spectrum on each shot (see Figure 3).

In total, 7 shots were fired with data acquired on the XRFC, RCF and SOP diagnostics. Full data analysis is still in progress, but preliminary results indicate that the degree of heating achieved was as desired. Slightly unusual features present on the SOP data have been attributed to the reduced target size relative to previous shot days, causing unexpected interactions with the SL pulse.

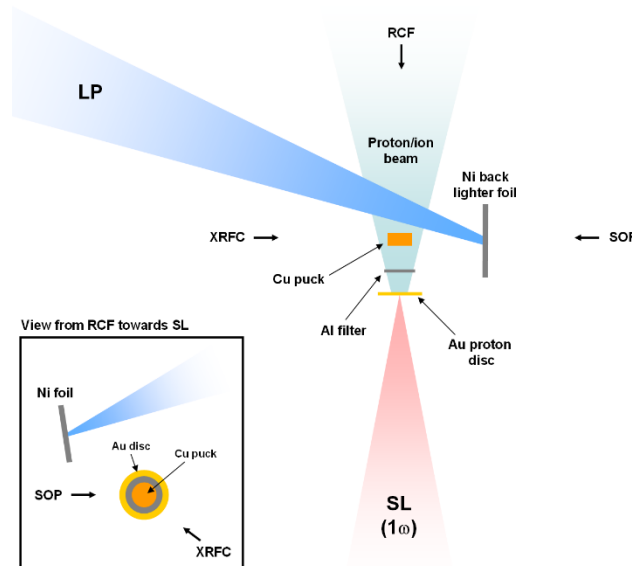


Figure 1. Experimental layout for proton heating shots with combined x-ray radiography, SOP and RCF. Only 1 Long Pulse beam (of the 3 used) is shown for simplicity.

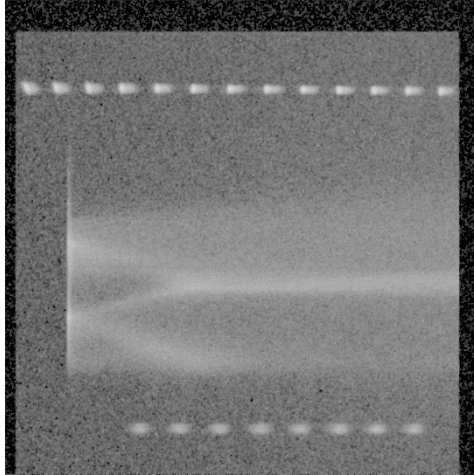


Figure 2. SOP data from a proton heating shot. The proton field is directed from the top downwards and the 1D spatial image is taken through the centre of the puck. The anomalous features observed appear to be due to the reduced target dimensions causing more complicated interactions with the beam and proton field relative to previous shot days in this campaign.

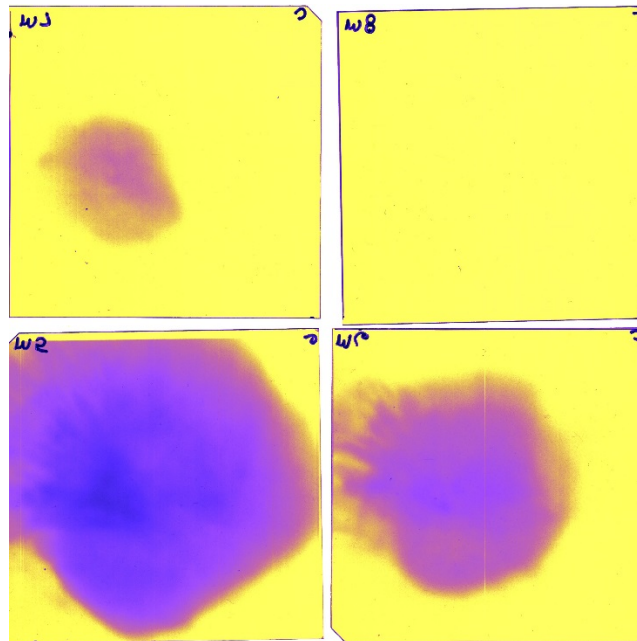


Figure 3. RCF data showing the attenuation of the proton and ion fields on one shot in the final 4 pieces of the film stack. The film pieces move progressively further away from the target beginning at the bottom left image, then bottom right, then top left, and finally top right.

3. Development of Radiography-and-VISAR Platform for Hydrodynamics Measurements (PIs: M. Rubery, AWE and D. Martinez, LLNL) with G. Glendinning (LLNL), S. McAlpin, J. Benstead and W. Garbett (AWE)

One and a half shot days were performed on the Omega laser system during FY17 as part of the LLNL/AWE Carisbrook campaign. The platform consists of a halfraum and shock tube package driven using 15 x 500J beams from the Omega H7 axis (Figure 1a). The objectives for the two shot days were to diagnose the evolution of a hohlraum-driven interface using simultaneous point projection x-ray radiography and VISAR, a configuration that was successfully demonstrated during FY16. A secondary objective for FY17 was to demonstrate the use of a reduced-mass backlighter (3 mm Ta disc vs. 4 mm Ta square, Figure 1b). If successful, the new configuration should sufficiently reduce the amount of vaporized metal generated during the experiment to allow future campaigns to use the EP short pulse beam with debris shields removed (higher energy).

To generate the 7.8 keV He-alpha point projection X-ray source, a 600 um square nickel microdot was driven to 2×10^{15} W/cm² using 4 x 400J 1ns backlighter beams (Figure 1b). The X-ray emission is projected through a 20 um Ta pinhole plate aligned along the shock tube and towards the TIM 6 cranked snout axis of $\theta = 123.1$ and $\phi = 172.76$. Images are recorded on film using a gated x-ray camera (XRFC).

A quartz window, aluminium flash coating and light shield cone are added to the rear of the target, allowing VISAR measurements to be made along the TIM-5 H14 axis.

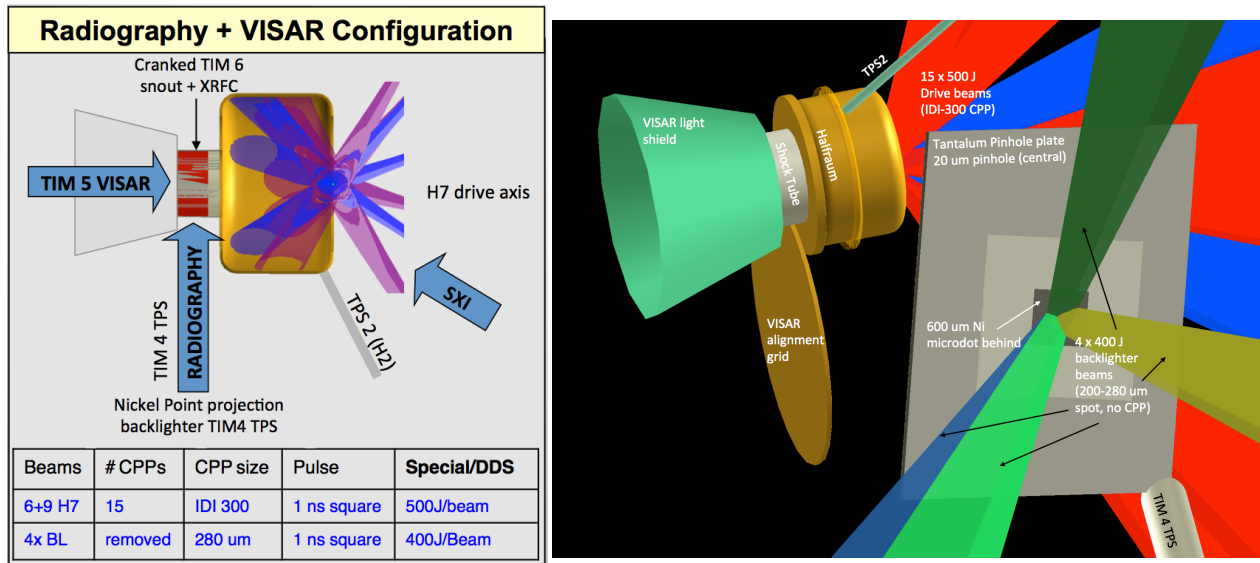


Figure 1a and 1b – Radiography + VISAR configuration overview (1a). VISRAD isometric view of the experiment (1b)

The VISAR diagnostic performed well during all shots from Ca-17A and 17B. Figures 2a and 2b show good quality streak camera images from both legs of the VISAR diagnostic on shot 86473. The Shock Optical Pyrometer (SOP) diagnostic, which uses the same optical relay as the VISAR, also produced good quality data on both shot days.

Unfortunately, during the first shot day, no radiography images were recorded. The source of this failure was found to be in the assembly of the backlighter. The mounting location

of the nickel microdot was measured > 100 μm away from the design position; this deviation is sufficiently large to move the nickel X-ray emission out of the XRFC field of view. In response to this the backlighter design was modified to reduce sensitivity to build and target alignment. The microdot was increased from 400 μm square to 600 μm square, and the backlighter beam-spots increased from 200 μm to 280 μm diameter. The backlighter energy was also increased from 200J/beam to 400J/beam to maintain intensity. On the second shot half-day these modifications were found to be 100 % successful.

In addition, the new reduced-mass backlighter was successfully fielded on the second day, and produced a radiograph with no observable drop in image quality, opening up the possibility of a future Joint shot day, without the limitations on pulse energy introduced by parabola debris shields.

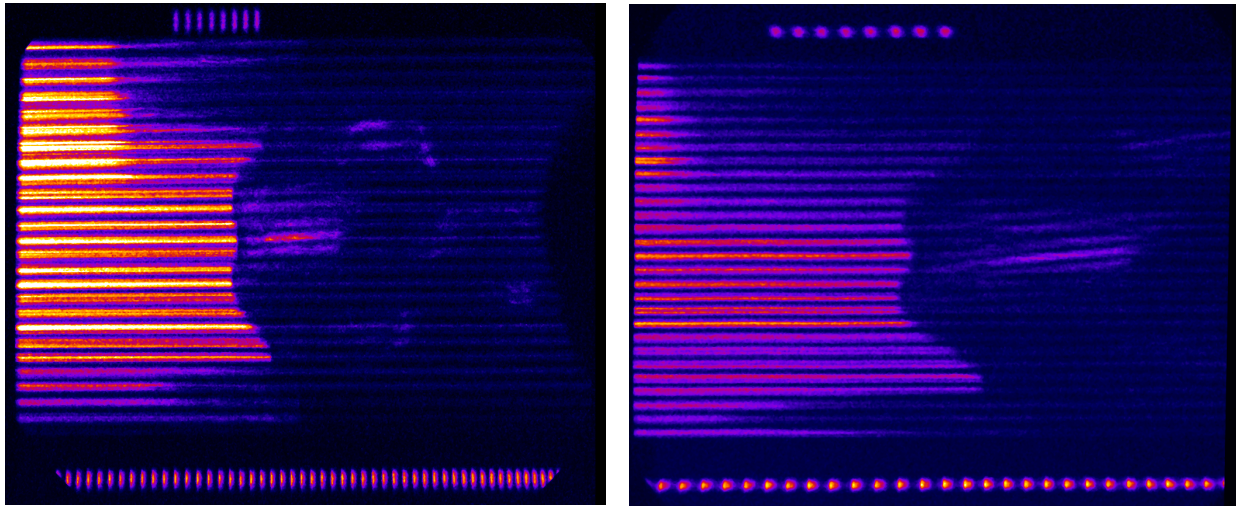


Figure 2a (left) and 2b (right). VISAR streaked images from Omega shot 86473, Ca-17B.

4. Development of Gamma-Ray Sources for MeV Radiography (PI: F. Albert)

with N. Lemos, J. Shaw (LLE), D. Martinez, V. Smalyuk

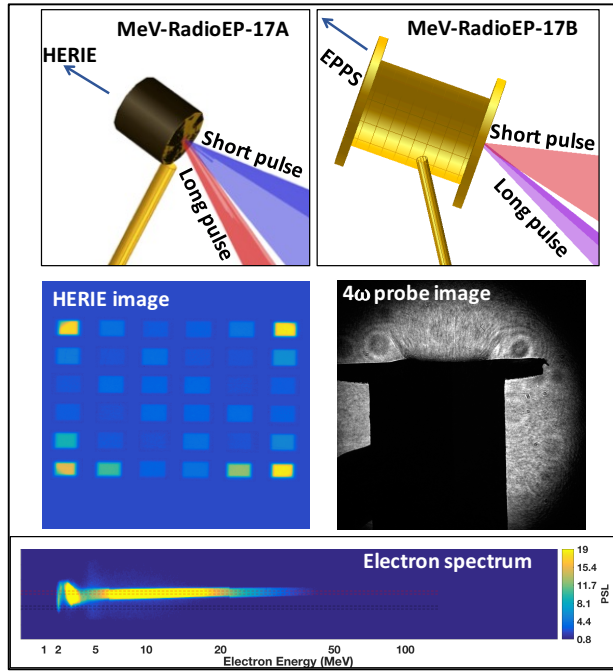


Figure 1. (Top) Experimental configurations for the two shot days. (Middle) HERIE diagnostic image for MeV-RadioEP-17A, and 4ω probe image. (Bottom) Measured electron spectrum for MeV-RadioEP-17B.

This series of shots was designed to develop gamma-ray sources intended for a future MeV radiography capability on NIF's Advanced Radiography Capability (ARC) short pulse laser. MeV radiography on NIF will serve a number of applications, such as double shell implosions and imaging of dense objects.

The first FY17 campaign alternatively focused the backlighter and sidelighter short pulses (10 ps, 900 J) onto tantalum targets coated with 10 μm of plastic to produce hot electrons and subsequent gamma-ray emission from bremsstrahlung radiation. The electron spectrum was measured with EPPS (both along the short pulse laser axis and at 90 degrees), and the gamma-ray spectrum with HERIE using a tantalum step-wedge filter pack. This diagnostic was used to retrieve an emitted photon spectrum of the form $f(E) = A \exp(E/E_T)$, where E_T is the spectrum temperature, comprised between 0.5 and 1 MeV for this experiment. About 10^{12} - 10^{13} photons/eV/steradian were detected with this process. Targets included both 1 mm thick, 1 mm diameter, as well as 500 μm thick, 25 μm

diameter tantalum pucks. The source size was measured by imaging an 800 μm diameter tungsten sphere onto HERIE, and was found to be around a few 100 μm for the thick targets. Further shots are required to determine the effect of the target geometry on the source size.

The second campaign (MeV-Radio-EP-17B) aimed to look at an alternative electron production scheme (laser-wakefield acceleration in underdense plasmas) for future development of MeV photon sources on ARC. During this shot day, the 3-10 ps OMEGA-EP short pulse beams (alternately sidelight and backlighter) were focused at intensities around 10^{18} W/cm^2 onto a 3 mm plastic gas tube filled with helium at atmospheric pressure. The gas tube was closed with 1 μm thick mylar windows, which were blown down using an OMEGA-EP long pulse beam timed 5-10 ns before the short pulse. Plasma density at the entrance of the gas tube was monitored with the 4ω probe diagnostic. The main diagnostic, EPPS, measured accelerated electron energies up to 50 MeV.

Analysis of these campaigns is ongoing, and the results of the two shot days will be used to design efficient gamma-ray sources for LLNL programs.

5. Measurements of Instability Growth and Shell Trajectory Relevant to NIF Double-Shell Designs (PI: Y. Ping)

With V. Smalyuk, P. Amendt, R. Tipton, J. Pino, O. Landen, F. Graziani

The goal of this campaign is to measure instability growth rate and shell trajectory in planar geometry under conditions relevant to the double shell design on NIF. The target is halfraum with an attached physics package consisting of an ablator, CRF foam and a Cu inner shell. For the instability growth measurements, ripples with 30um and 60um periods and 0.5um amplitude were imprinted on the Cu inner surface, and face-on gated x-ray radiography was employed to measure the ripple growth over time. For the shell trajectory measurements, side-on x-ray radiography with a streak camera was employed. The shot day was very successful with excellent data in both configurations, as shown in Figure 1 (left) and (right). Data analysis shows reasonable agreement with simulations on the ripple growth, yet the observed preheat of the Cu shell was under-predicted in the modeling. These results are being organized for publications and also used for target design in FY18.

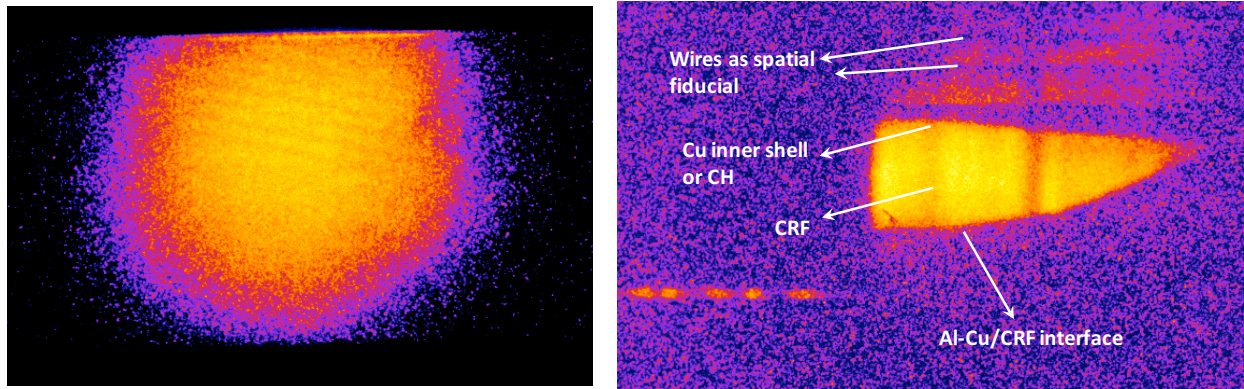


Figure 16. (left) A typical x-ray radiograph of ripple growth. (right) Streaked x-ray radiograph of the shell trajectory.

Laboratory Basic Science Experiments

1. Experimentally Constraining the High-Pressure Thermal Conductivity of Iron (PI: R.F. Smith) with J. Wicks (Johns Hopkins Univ.)

High-pressure thermal conductivity is one of the most important and yet most difficult to measure physical property of materials. Within the Earth's interior the thermal conductivity, k , of Fe and Fe-rich alloys at core pressure-temperature conditions (135-360 GPa, 2500-5000 K) is a key parameter for heat transport models and plays an important role in determining the temperature profile and energy balance of our planet. The thermal conductivity of the Earth's core remains poorly constrained because of the extreme difficulty in making thermal transport measurements under the relevant pressure and temperature conditions. Two experimental studies published in Nature in 2016 report values of k for Fe which vary by a factor of seven at ~ 130 GPa ($34 \rightarrow 225 \text{ W m}^{-1} \text{ K}^{-1}$) [1][2]. The goal of the Omega experiments was to constrain the thermal conductivity at high pressures, using a ramp compression platform previously developed on Omega [3] (Fig. 1). The raw ASBO/SOP data provides velocity and thermal transport information through stepped Fe samples (Fig. 2). Analysis is underway to translate this data into a measurement of thermal conductivity.

[1] Z. Konôpková, R.S. McWilliams, N. Gómez-Pérez and A.F. Goncharov, Direct measurement of thermal conductivity in solid iron at planetary core conditions, *Nature* **534**, 99 (2016).

[2] K. Ohta, Y. Kuwayama, K. Hirose, K. Shimizu, Yasuo Ohishi, Experimental determination of the electrical resistivity of iron at Earth's core conditions, *Nature* **534**, 95 (2016).

[3] R.F. Smith et al., "High planarity x-ray drive for ultrafast shockless-compression experiments" *Phys. Plas.* **14**, 057105 (2007).

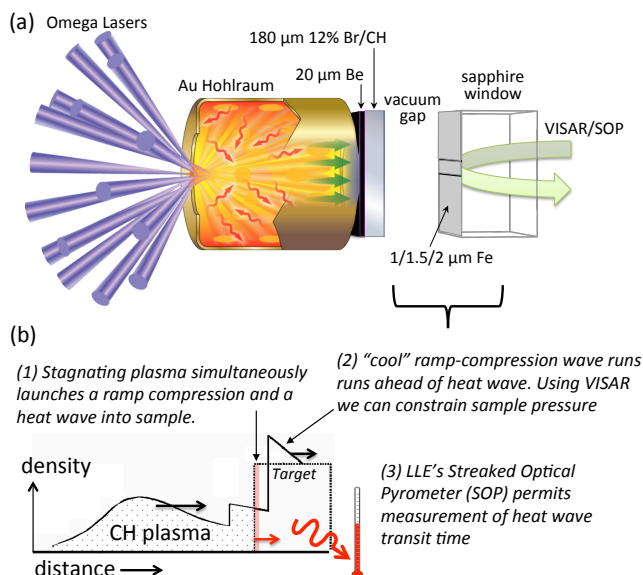


Figure 17. Target design to measure heat flow in ramp compression stepped-Fe sample.

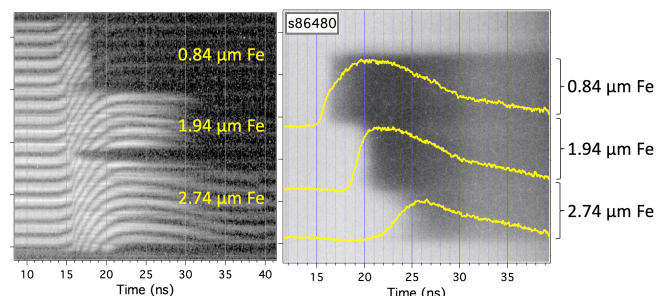


Figure 18. ASBO (left) and SOP (right) for 0.84/1.94/2.74 μm Fe step sample provides sufficient information to constrain the high pressure thermal conductivity of Fe.

2. Recovery of Dynamically Compressed Samples (PI: C.E. Wehrenberg)

with S. Zhao and M. Meyers (UCSD), B. Remington and A. Krygier (LLNL).

This LBS campaign studied the deformation response of a variety of materials to shock compression. Sample materials were mounted onto the front of steel recovery tubes that are in turn mounted on a TIM. A single Omega-60 beam is used to drive a shock into the sample material, and the sample remains in the recovery tube after the shot so that it can be recovered for further ex-situ study. Two recovery tubes and a VISAR target were fielded for each shot. Thus a large data set of 12 recovered samples and 6 visar traces was produced using just a half day of shots.

A wide variety of samples were recovered during this campaign. Previous iterations of this campaign have been very successful in studying the deformation response of semi-conductors (Si & Ge) to shock compression, producing a series of high-profile papers on pressure-shear induced amorphization [1,2]. The FY17 campaign studied GaAs, graphite, and olivine, and generated the first dynamic compression data on a new class of materials, high-entropy alloys. These samples will be taken to Oak Ridge National Laboratory for TEM study.

[1] S. Zhao, B. Kad, C. E. Wehrenberg, B. A. Remington, E. N. Hahn, K. L. More, M. A. Meyers. "Generating gradient germanium nanostructures by shock-induced amorphization and crystallization." *Proc. Natl. Acad. Sci. U.S.A.* **114**, 9791-9796 (2017).

[2] S. Zhao, E. N. Hahn, B. Kad, B. A. Remington, C. E. Wehrenberg, E. M. Bringa, M. A. Meyers. "Amorphization and nanocrystallization of silicon under shock compression" *Acta Mat.* **103**, 519-533 (2016).

3. Absolute Equation of State Measurements from Spherically Converging Shock Waves on the OMEGA Laser (PI: A. M. Saunders)

with T. Doeppner, R. Nora, W. Theobald (LLE), A. Jenei, D. Swift, J. Nilsen, and R. W. Falcone (LBNL, UC Berkeley)

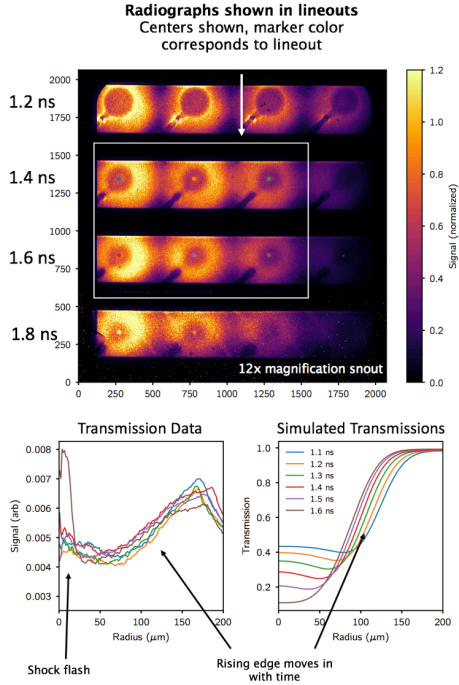


Figure 1. X-ray radiography measurements of shock-compressed CH spheres (shot number 85691).

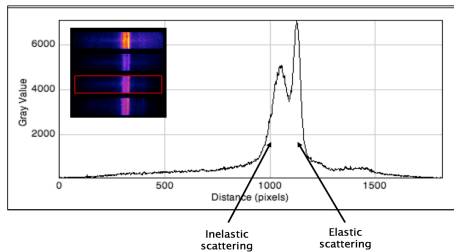


Figure 2. XRTS measurements from HDC spheres (shot number 85696).

X-ray Thomson scattering (XRTS) is an experimental technique that directly probes the physics of warm dense matter by measuring electron density, electron temperature, and ionization state. XRTS in combination with x-ray radiography offers a unique ability to measure the absolute equation of state (EOS) of material in extreme conditions.

The OMEGA campaign GbarIPD-17A took XRTS and x-ray radiography measurements from directly-driven carbon-containing spheres compressed to electron densities of order of $1 \times 10^{24} \text{ cm}^{-3}$ and temperatures of $\sim 30 \text{ eV}$. X-ray radiography measurements were obtained for both plastic (CH) and high-density carbon (HDC) spheres. 52 beams compressed the spheres, and 6 beams drove a foil backlighter. The x-rays from the foil backlighter were observed in transmission through the sphere using a gated x-ray framing camera. The top portion of Figure 1 shows an example of the raw data obtained from the imploding CH spheres. The bottom portion of Figure 1 shows the radial lineouts from several of the radiography images, each at a different point in the implosion time. They show that the shock front travels inwards as predicted by simulations. The radial lineouts allow for the shock velocity to be obtained. A more complicated analysis of post-shock density at each time step will also be performed; the combination of density and shock velocity will allow for an absolute measurement of the EOS.

In conjunction with the radiography measurements, XRTS spectra were obtained from HDC spheres. A zinc helium-alpha x-ray source was used to scatter from the imploding spheres at a scattering angle of 135° , and then collected by a crystal spectrometer (ZSPEC) in conjunction with a gated x-ray framing camera. Figure 2 shows an example of the raw data collected and a lineout of one of the

strips. The XRTS data will provide an independent measurement of the mass-averaged electron temperature of the imploding sphere. The temperature measurement will further constrain the EOS measurement obtained from the radiography analysis. In summary, the data obtained in this campaign shed light on the equations of state of matter under compression, and support EOS measurements previously taken on the NIF.

4. Time Resolved Measurement of the Radiative Properties of Open L-Shell Zinc (PI: E.V. Marley)

with L.C. Jarrott, M.B. Schneider, G.E. Kemp, M.E. Foord, R.F. Heeter, D.A. Liedahl, K. Widmann, C.W. Mauche, G.V. Brown, J. Emig

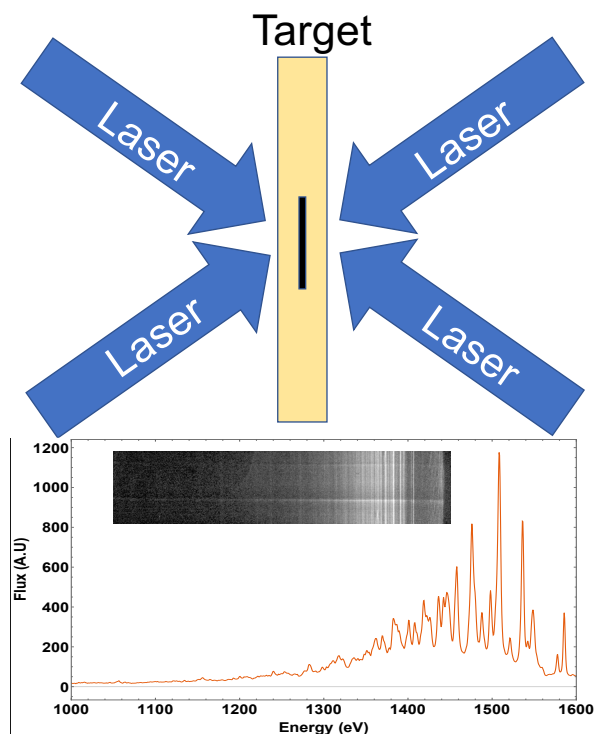


Figure 19. (Top) Experimental configuration. (Bottom) Time Resolved Zn L-shell spectra with data inset at 2.8 ns of shot 85317.

This campaign was designed to measure the emitted L-shell zinc spectra from a well characterized and uniform plasma for comparison to atomic kinetic models. Recent studies have shown a discrepancy between atomic kinetic models and high Z M-shell spectral data. This study was done to test the accuracy of models for L-shell emission.

Planar, buried layer targets were illuminated evenly on both sides (Fig. 1) to heat the sample, composed of Ti and Zn. The sample was buried between two 6.7 μm thick layers of Be which inertially tamps the sample, slowing its expansion. Time resolved 2-D images of the target's x-ray emission, viewed both face on and side on, were recorded using pinhole cameras coupled to framing cameras. The K-shell spectra from the Ti was used to determine the electron temperature of the plasma. The time resolved spectra were recorded using a crystal spectrometer coupled to a framing camera. A second crystal spectrometer/framing camera system was used to record time-resolved zinc L-shell emission. More L-shell spectra were recorded with a spectrometer coupled to a streak camera, to give a continuous

record of the ion population shifts over time. A third spectrometer, which utilized a variably spaced grating and a slit, was coupled to a framing camera to give a temporally and spatially resolved spectral measurement of the zinc L-shell. This measurement will help to verify the uniformity of the plasma at different times during the experiment. All of the framing cameras used, those for imaging as well as those used for spectroscopy, were co-timed on the shot day so that plasma conditions could be determined for the measured zinc L-shell spectra.

Two different pulse shapes were used. The first was a 3.2 ns square pulse and the second was a 3.0 ns square pulse with a 100 ps picket preceding it by 1 ns. The second pulse tested whether creating a pre-plasma before the main pulse would create a smoother interface, allowing for a more efficient coupling of energy into the target. The results look promising. A complete set of data from all 6 co-timed diagnostics was recorded for both pulse shapes during the campaign at sample temperatures ~ 1 keV.

5. Measuring Strong Plasma Shock-Front Structure Using Thomson Scattering Imaging (PI: H.G. Rinderknecht)

with H.-S. Park, J. S. Ross, D. Froula (LLE)

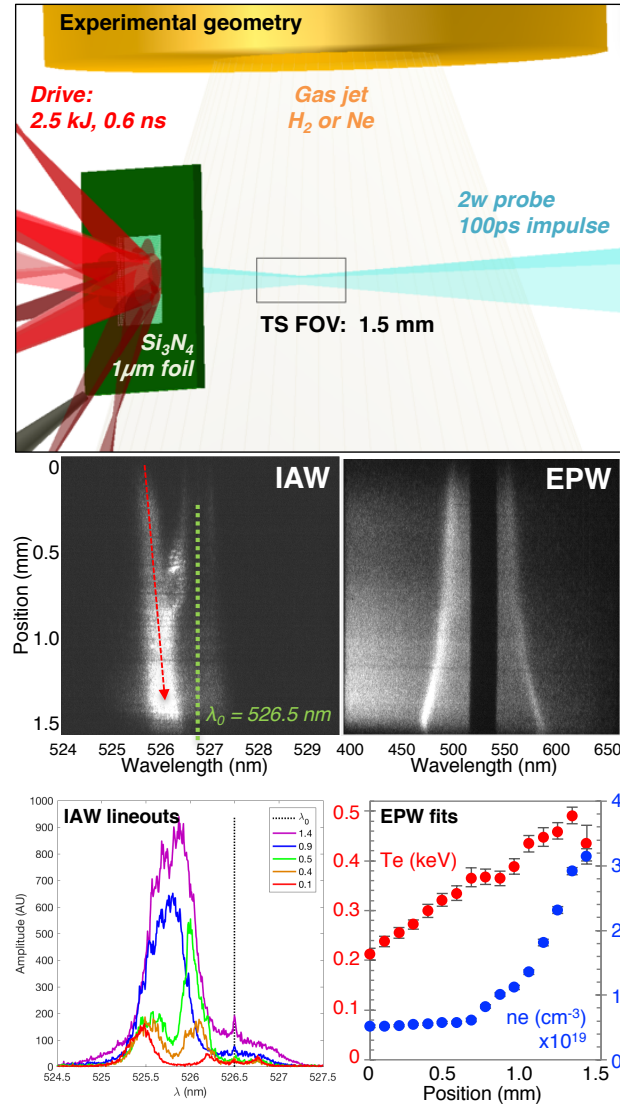


Figure 20. Experimental layout; raw Thomson scattering images; lineouts from IAW data showing merging of ion populations in shock; and fits to EPW spectrum showing heating and density jump due to shock in shot 86801.

strong shock formation: heating of electrons in the pre-shock region, followed by increase in density as the ion shock forms. IAW data appears to show streaming protons in advance of the shock front, heating and slowing down on the pre-shocked plasma; analysis of these results is underway. These exciting results will be presented in an invited talk at the APS Division of Plasma Physics meeting in October, 2017, and demonstrate the high value of this platform for future kinetic plasma studies on OMEGA.

This series of shots was designed to directly measure for the first time the spatial structure of a strong shock front in a plasma. The experiments were intended to develop a platform for kinetic plasma studies using the new Gas Jet System (GJS) on OMEGA to quantify collisional phenomena in high-energy-density plasmas, and to benchmark high-fidelity physics codes. These experiments were also the first use of the gas jet system on OMEGA-60.

The KineticShockLBS-17A campaign on August 24th used the new gas-jet system to inject a column of hydrogen or neon gas into the OMEGA target chamber. A 1- μm Si_3N_4 foil positioned near the gas jet nozzle was driven by 10 beams with 2.5-kJ in 0.6-ns, exploding the foil to drive a strong shock into the low-density ($\sim 5 \times 10^{18} \text{ cm}^{-3}$) gas. A 526.5-nm probe beam with 40-J in a 100-ps impulse was injected normal to the ablator foil at a 4–6 ns delay from the drive beams, and Thomson-scattered light from the probe was imaged along the probe axis. The imaged region was 3.25–4.75 mm from the ablator, with a resolution of 20 μm . Despite operational difficulties with GJS on its first shot day, six shots were completed, and excellent data was collected on all shots for which the gas-jet successfully operated.

Figure 1 shows Ion Acoustic Wave (IAW) and Electron Plasma Wave (EPW) Thomson scattering images from shot 86801. Fits to the EPW data demonstrate the characteristics of

6. Characterizing Pressure Ionization in Ramp Compressed Materials with Electron Induced Fluorescence (PI: S. Jiang)

with Y. Ping, R. Smith, A. Jenei and J. Eggert

This campaign used 1 day on OMEGA EP to measure ionization in compressed materials as a function of density, using K shell fluorescence spectroscopy. The K shell line emissions were induced by hot electrons generated through short-pulse laser-solid interactions. The high pressure was achieved by ramp compression using the long pulse drivers, while keeping the temperature low. A large, thick target was used to avoid heating from the short pulse, as shown in Figure 1(a). The configuration is intended to compress the material up to 1.5x–2x its original density without raising the thermal ionization effect. There is still little consensus on pressure ionization under these conditions despite extensive theoretical and experimental efforts.

A schematic of the experimental setup is displayed in Figure 1(a). The main diagnostic used in this campaign was the high-resolution X ray spectrometer IXTS. The Cu K_α and Co K_β fluorescence lines were successfully observed with high signal to noise ratio, as can be seen in Figure 1(b). Under the designed experimental conditions, pressure ionization has a negligible effect on the innermost electron shells (K, L), but it can affect the M shell. Therefore, the Cu K_α line is not subject to an energy change and can be used as a reference. On the other hand, the Co K_β line is more prone to a shift. Figure 1(b) shows the measured Co K_β peaks under different driver energies and time delays. While some differences can be observed between the undriven and driven conditions, the energy shifts are small enough so that they are close to the resolution of the spectrometer ($\sim 4\text{eV}$). In the future experiment, we will increase the driver energy to reach a higher pressure, and also probe other materials.

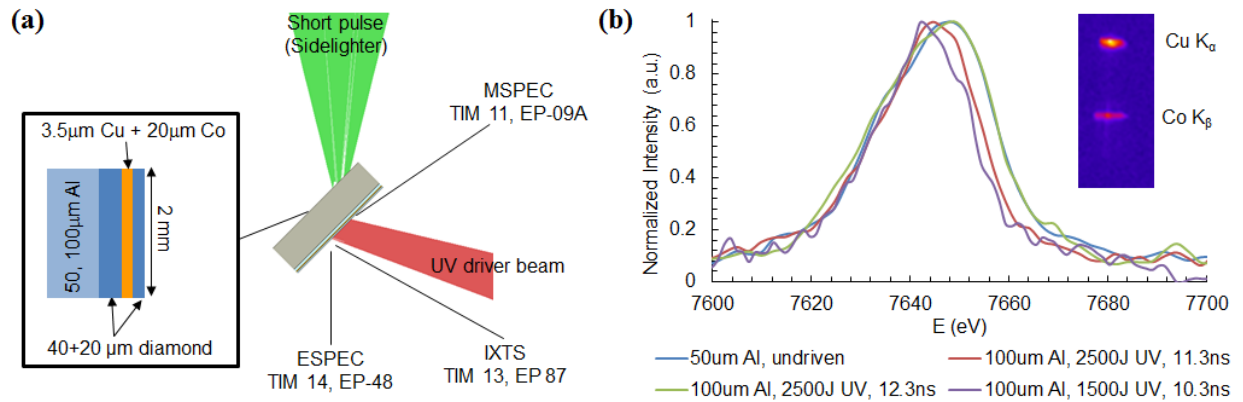


Figure 1. (a) A schematic of the experimental configuration. The inset shows the target geometry. (b) Measured IXTS spectra of Co K_β (normalized with the peak intensity). The lineouts are from different driver conditions. An example of the raw image is shown in the inset.

7. Optimizing Backlighters for Imaging Low Density Plasmas for Eagle Pillar Studies (PI: D. A. Martinez)

with Jave Kane and Bob Heeter (LLNL), Bruno Villette and Alexis Casner (CEA, France).

The LBS Eagle Pillar experiments were designed to optimize the backlighter for imaging the plasma plume created by an ablated CH solid density cone target in conditions similar to counterpart NIF Discovery science experiment. The CH target was driven for 30ns using three Cu hohlraums (figure 1) heated in succession, which will eventually create a comet like flow behind the solid target (away from the drive). This flow is expected to coalesce behind the solid target and the hohlraum x-ray drive will confine the plasma to generate a plasma pillar. To observe this requires a backlighter with sufficiently low photon energy to image the warm low-density plasma. This campaign used Ti (4.7 keV) and U (1.2keV) area backlighters to try to image the ablating CH target. Seven shots were taken, with a backlighter delay between 20-35ns with respect to the start of the drive, using both U and Ti backlighters. Due to debris risk, the experiment used image plates with a 200 μm Be blast shield, increasing the average photon energy for the U backlighter to 3-4 keV range. Images obtained from the U backlighter were comparable to the Ti backlighter, both suggesting this photon energy was too high. The U backlighter also showed significant structure in the backlighter profile as shown in figure 2. More work is needed to reduce the photon energy sufficiently to image the ablated plasma.

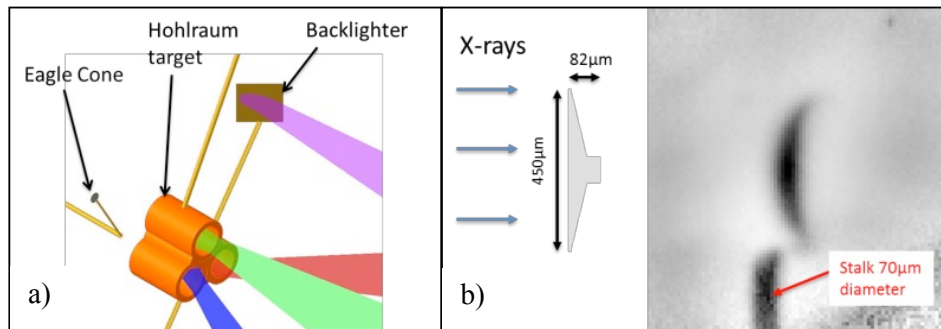


Figure 1: a) Layout of the experiment showing all beams on target. b) Hohlraum drives a cone target for 30ns and imaged with a Ti (shown) or U backlighter.

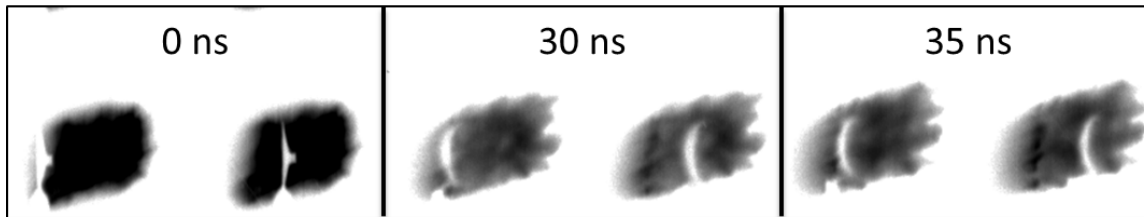


Figure 2: Time Sequence of the target imaged through a pinhole array backlit with a U backlighter. Multiple images are obtained to remove the backlighter structure. 0ns had lower filtering but 30 and 35ns had 200 μm Be.

8. Equation of State, Structure and Optical Properties of Silicates at Multi-Mbar Pressure for Super-Earth Mantle and Accretion Modeling (PI: M. Millot)

with F. Coppari, D. Fratanduono, S. Hamel (LLNL), N. Dubrovinskaia, L. Dubrovinsky (Bayreuth Univ., Germany), R. Jeanloz (UC Berkeley)

During FY 17, an international research team conducted two campaigns at the Omega Laser Facility to investigate the equation of state, structure and optical properties of silicates at multi Mbar pressure using shock compression. Following a previous study on the melting line of SiO_2 using stishovite crystals [1], the FY17 campaign conducted a shock compression study of MgSiO_3 Bridgmanite (perovskite) samples synthesized at Bayreuth University in Germany to investigate the pressure-density-temperature equation of state and the melting temperature of MgSiO_3 , a representative of the material making up the interiors of rocky planets and the cores of gas giants. Preliminary analysis of the velocity interferometry (VISAR) and pyrometry (SOP) data indicates that these experiments successfully observed reflecting shocks up to 15 Mbar.

Another set of experiments used Omega EP's pulse-shaping capabilities to launch carefully timed series of two steady shocks into stishovite samples, to enable determining the atomic structure of SiO_2 at Neptune core conditions using x-ray diffraction. Composite three-beam pulse shapes allowed generating the complex drive conditions, while the other beam was focused onto a Ge foil to generate a 1 ns pulsed x-ray source. Preliminary analysis indicates that XRD patterns for single- and double-shock compressed silica were obtained up to 9 Mbar.

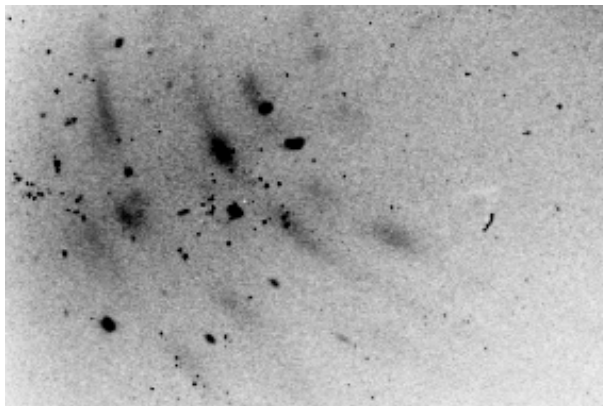


Figure 21: Example XRD pattern of silica shock compressed to ~3 Mbar along the stishovite Hugoniot.

[1] Millot, M. *et al.* Shock compression of stishovite and melting of silica at planetary interior conditions. *Science* **347**, 418–420 (2015).

9. Determining the High-Pressure Properties of Silicon Carbide Using Decaying Shocks and In-Situ X-Ray Diffraction (PI: R.F. Smith)

with June Wicks (Johns Hopkins Univ.)

The goal of this campaign was to determine the high-pressure properties of single crystal SiC along the Hugoniot, using a combination of shock decay [1] and nanosecond x-ray diffraction techniques [2]. Silicon carbide is an important material in geology and planetary science. It may be a host of reduced carbon in the Earth's interior as it is found in rocks from the mantle and in inclusions in deep diamonds [3]. It also occurs in

meteorites and impact sites. The target design in Figure 1 is modeled off previous campaigns on Omega [1]. The raw ASBO (shock velocity) and SOP (shock front thermal emission) data allows determination of the pressure-temperature onset of melt. During this shot day the PXRDIP diagnostic was also used, to determine the high pressure crystal structure (pre-melt).

[1] M. Millot, et al., "Shock compression of stishovite and melting of silica at planetary interior conditions" *Science* **347**, 418 (2015).

[2] J.R. Rygg et al., "Powder diffraction from solids in the terapascal regime" *Rev. Sci. Instr.* **83**, 113904 (2012).

[3] E. Mathez, R. Fogel, I. Hutcheon, and V. Marshintsev, "Carbon isotopic composition and origin of SiC from kimberlites of Yakutia [Sakha]", *Russia, Geochim. Cosmochim. Acta*, **59**(4), 781–791 (1995).

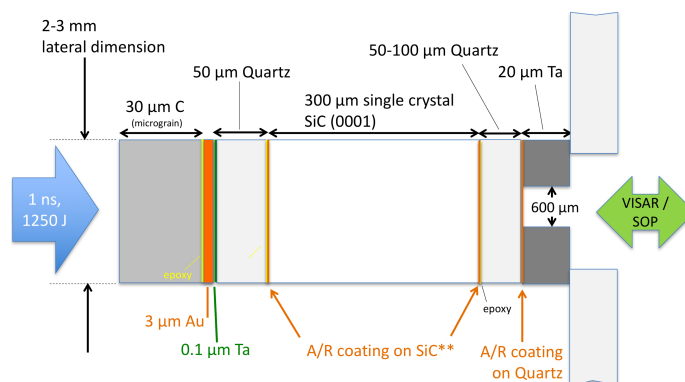


Figure 22. Target design for shock decay experiments in SiC using 1250 J drive in 1 ns (1100-μm phase plate). The Quartz layers serve as calibrants for EP SOP [1].

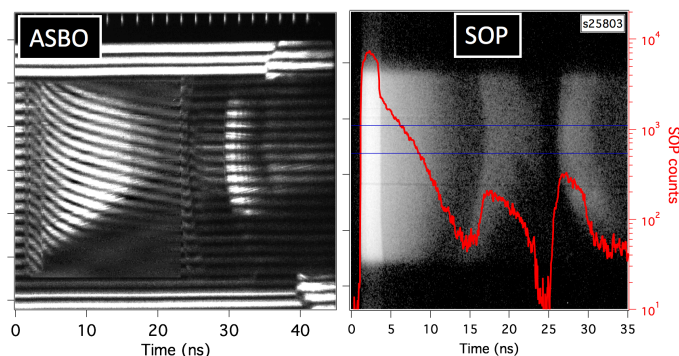


Figure 2. ASBO data provided SiC shock velocity vs time (left) while the EP Streaked Optical Pyrometer (right) provided temperature of the shock front as a function of time.

10. Exploring Pair Plasmas and Their Applications (PI: H. Chen)

In FY17, an LLNL/SLAC/Michigan University team continued the project “Exploring pair plasmas and their applications” with 1 LBS shot day on OMEGA EP. These experiments use the short pulse beams to produce jets of electron-positron antimatter pairs. The FY17 campaign focused on measuring the pair yield enhancement with nano-structured targets. The experiments successfully demonstrated that the laser-positron energy conversion can be improved by using novel structured targets. A total of 12 shots were performed.

The EP short pulse beams (~ 1 kJ in 10 ps) irradiated targets of 1 mm thick Au targets, with and without the nano-structure on the laser interaction surface. It was found that for the same laser energy, positron yields and acceleration both were increased dramatically by using nano-structure. This finding is important to future experiments and applications using laser pair jets. Previous experiments used primarily gold targets and showed that quasi-monoenergetic relativistic positron jets are formed during high-intensity irradiation of thick gold targets [1, 2], and also that these jets can be strongly collimated [3] using the magnetized-inertial fusion electrical delivery system (MIFEDS) [4]. The external field produces a 40-fold increase in the peak positron and electron signal [3]. The positron yield was found to scale as the square of the laser energy [5, 6] in this regime. The yield also increases with the Z of the target material. Together with the nanostructured target yield enhancement, these favorable scalings are expected to enable the laboratory study of relativistic pair plasmas to aid the understanding of some of the most exotic and energetic systems in the universe [6, 7].

- [1] H. Chen et al., Phys. Rev. Lett. **102**, 105001 (2009).
- [2] H. Chen et al., Phys. Rev. Lett. **105**, 015003 (2010).
- [3] H. Chen et al., Phys. Plasmas **21**, 040703 (2014).
- [4] O. Gotchev et al., Rev. Sci. Instrum. **80**, 043504 (2009).
- [5] H. Chen et al., Phys. Rev. Lett. **114**, 215001 (2015).
- [6] H. Chen et al., Phys. Plasmas **22**, 056705 (2015).
- [7] H. Chen et al., High Energy Density Physics, **7**, 225 (2011).

11. Astrophysical Collisionless Shock Experiments with Lasers (ACSEL) (LBS PI: H.-S. Park; Shot PI: G.F. Swadling)

Experiments ACSEL-17A and 17B investigated the physical processes which lead to formation of astrophysical collisionless shocks. These shots continued a broad, long-running, cross-institutional collaboration. A total of twenty-six target shots were completed in two shot days, primarily investigating interactions between beryllium ablation outflows; this material was selected in order to provide a low Z , single species plasma, which greatly simplifies Thomson scattering interpretation and analysis, whilst maintaining the large collisional scale lengths required to observe the development of interpenetrating flow instabilities. In these experiments, the Omega beams heat the surfaces of a pair of opposed planar disk targets (see figure 1), ablating counter-propagating plumes of high velocity (up to $1.5 \times 10^6 \text{ ms}^{-1}$), high temperature ($\sim \text{keV}$) plasma. The outflow parameters are such that the coulomb mean-free path for inter-flow collisions is long, but the interaction of the flows is still susceptible to the growth of the inter-stream instabilities which are believed to mediate the formation of collisionless shocks.

Experiments this year focused on making spatially resolved Thomson scattering measurements across the interaction region, to quantitatively investigate the development of the ion-Weibel instability. Thomson scattering was combined with proton radiography measurements; a D3He exploding-pusher capsule provides a dichromatic (3.3 and 14.4 MeV) proton source for radiography, probing the plasma at two separate times during each experiment. Images are recorded on CR39, with processing and analysis of the CR39 plates carried out by collaborators at MIT.

The OMEGA Thomson scattering diagnostic records both ion acoustic wave and electron plasma wave features of the Thomson scattering spectrum. Analysis of the detailed shape of these spectra enables extraction of information about the spatial variation in electron temperature, electron density, ion temperature and flow velocity across the interaction of the two flows. The primary goal in FY17 was to make direct measurement of spatial density modulations of the ion flows and the underlying electron density of the plasma. High quality data was recorded and is expected to provide a wealth of data on the development of the ion Weibel instability in these experiments; examples of the spectrograms are shown in figure 1). Striations in the intensity of the ion acoustic feature along the probe beam are characteristic of the development of the ion-Weibel instability, while the presence of modulations in the electron plasma wave data suggest that the ion Weibel instability is in the non-linear growth phase.

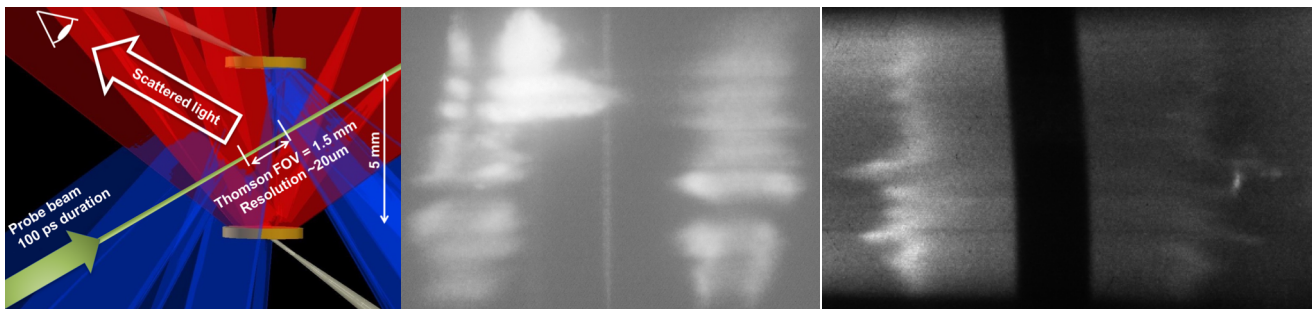


Figure 1. (Left) Diagram of experimental setup for spatially resolved Thomson scattering measurements. (Center) Ion acoustic wave (IAW) data. (Right) Electron plasma wave (EPW) data. The vertical direction in the spectrograms is the direction of spatial displacement along the probe beam, as shown in the diagram. The horizontal direction is the direction of spectral dispersion. Striations in the vertical direction in the IAW image are characteristic of Weibel filamentation. Modulations in the EPW image indicate strong transverse modulations in the electron density across the interaction region.

12. Laser Driven Collisionless Shock Acceleration of Ions (PI: A. Pak)

with T. Link, D. Haberberger, D. Froula, S. Tochitsky, C. Joshi, F. Fiuza

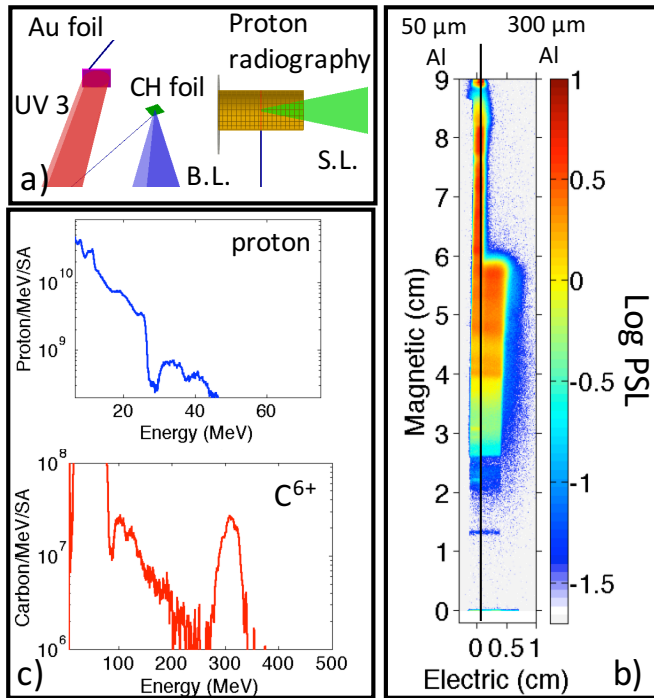


Figure 23. (a) Experimental configuration. (b) Data from the modified TPIE setup with differential filtering and no electrical bias. Vertical black line denotes filter change. (c) The proton and carbon spectra.

This laboratory basic science day explored the acceleration of ions into narrow energy distributions that is caused by the reflection from the strong electrostatic field of a collisionless shock wave. As Fig. 1 a) indicates, a near critical density CH target is first produced by the x-ray drive generated from the ablation of a gold foil by a 1 ns long laser pulse (UV 3). After waiting for the CH target to expand to peak density of $\sim 10 \times 10^{21} \text{ cm}^{-3}$, the ultra-intense backlighter beam is used to irradiate the target and drive the collisionless shockwave. Nearly simultaneously, the sidelight beam produces a beam of protons through target normal sheath acceleration, to radiograph the shock formation process. In these experiments, the pinhole of the Thomson Parabola Ion Energy (TPIE) diagnostic was replaced with a new $\sim 5 \text{ mm}$ wide by 0.25 mm tall slit to extend the angular acceptance of the diagnostic. The electric bias of the TPIE was turned off and differential filtering of $50 \mu\text{m}$ and $300 \mu\text{m}$ Al was used at the image plate detector to differentiate between ion species. TPIE data from this configuration is shown in Fig. 1 b).

On this experiment, narrow energy distributions of both protons and carbon ions were observed to be accelerated to similar velocities of $\sim 0.25 c$. The acceleration of disparate charge to mass ratio ion species to similar velocities is consistent with acceleration from the moving near-relativistic electric field associated with a collisionless shock wave. A distribution of protons centered at 36 MeV (velocity = $0.28 c$), and with energy range $\Delta E/E$ of $\sim 30\%$ was observed, as well as a distribution of C^{6+} ions centered at 308 MeV (velocity = $0.23 c$) and $\Delta E/E$ of $\sim 12\%$. The difference in velocity between the two ion species is thought to arise from the remaining sheath field of the expanded target, which preferentially accelerates the lighter species. Analysis of the radiography and accelerated beam profile data is in progress.