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FY16 LLNL Omega Experimental Programs

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FY16 LLNL OMEGA Experimental Programs

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In FY16, LLNL's High-Energy-Density Physics (HED) and Indirect Drive Inertial Confinement Fusion (ICF-ID) programs conducted several campaigns on the OMEGA laser system and on the EP laser system, as well as campaigns that used the OMEGA and EP beams jointly. Overall these LLNL programs led 430 target shots in FY16, with 304 shots using just the OMEGA laser system, and 126 shots using just the EP laser system. Approximately 21% of the total number of shots (77 OMEGA shots and 14 EP shots) supported the Indirect Drive Inertial Confinement Fusion Campaign (ICF-ID). The remaining 79% (227 OMEGA shots and 112 EP shots) were dedicated to experiments for High-Energy-Density Physics (HED). Highlights of the various HED and ICF campaigns are summarized in the following reports.

In addition to these experiments, LLNL Principal Investigators led a variety of Laboratory Basic Science campaigns using OMEGA and EP, including 81 target shots using just OMEGA and 42 shots using just EP. The highlights of these are also summarized, following the ICF and HED campaigns.

Overall, LLNL PIs led a total of 553 shots at LLE in FY 2016. In addition, LLNL PIs also supported 57 NLUF shots on Omega and 31 NLUF shots on EP, in collaboration with the academic community.

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Indirect Drive Inertial Confinement Fusion Experiments

1. Hydrodynamic response from oxygen non-uniformities in GDP plastic (PIs: P.M. Celliers and S.J. Ali)

Simulations and target characterization indicated that inhomogeneity in oxygen content could be a significant seed for Rayleigh-Taylor growth in National Ignition Facility (NIF) implosions using glow-discharge polymer (GDP) plastic shells. This has been indirectly supported by observation of larger than expected in-flight modulations during NIF GDP capsule implosions, and the realization that such inhomogeneities can result from photo-induced oxygen uptake. In order to investigate the magnitude of the effect of these oxygen heterogeneities on the hydrodynamic response of GDP ablators, oxygen modulations were photo-induced in GDP foils by illuminating the foils with blue light through a periodic mask pattern. The foils were then fielded at OMEGA, as ablators driven by a half-ram so as to replicate foot conditions on NIF. The resulting optically reflective shock wave was observed using the OMEGA High Resolution Velocimeter (OHRV), a 2-D single-gate measurement. Two-dimensional velocity maps were obtained for both oxygen-modulated and unmodulated samples, with the modulated samples showing clear evidence of the propagation of a rippled shock wave as a result of the photo-induced oxygen heterogeneity. A time series spanning approximately 2.3-4.2 ns after shock breakout from the GDP ablator into a PMMA witness layer was obtained and clearly showed that the decay in the amplitude of the perturbation was dependent on the perturbation wavelength, as expected.

2. Principal Hugoniot measurements of liquid deuterium above 100 GPa (PI: A. Fernandez Panella)

These two half-day campaigns using cryogenic targets at OMEGA investigated the principal Hugoniot of liquid deuterium at high precision above 100 GPa. This study was motivated by a systematic discrepancy between previous experimental data on different platforms (Omega, Z and NIF keyhole data) and current EOS models above 100 GPa, with the data suggesting higher compression than models, including the current preferred equation of state (EOS) used in ICF simulations (Kerley, 2003). However, experimental uncertainties of the existing data are too large to rule out the models unambiguously. Examining this discrepancy is relevant as the first shock in an ICF implosion lies on the principal Hugoniot of the fuel. Recent diagnostic improvements, and the availability of the recent high accuracy calibration of the quartz EOS standard (Knudson & Desjarlais, SNL) enable new experiments to collect data with much higher accuracy.

The first campaign carried out three measurements of shock-compressed deuterium along the principal Hugoniot at pressures ranging from 350-550 GPa, the highest pressures to date. The ablator material was 90 μm thick beryllium and the targets were driven by a 2 ns flat square laser pulse. VISAR was used as the main diagnostic to measure shock velocities. In the alpha-quartz reference material, shock velocities of 34-40 km/s were measured, and velocities of 50-64 km/s were obtained in the deuterium. A summary of the data is shown in Figure 1. Note the improvement of the data quality with respect to previous campaigns (e.g. D. Hicks '09); the uncertainties in the shock velocities in the present campaign are a factor of 3 smaller.

The impedance matching analysis relies on accurate knowledge of the EOS of the standard material (alpha-quartz) to determine the particle velocity, pressure and density of the sample (shock-compressed deuterium). Because the new data extend beyond the valid range of the quartz calibration, two tabular quartz EOS models have been used to estimate the systematic uncertainty of the new data. The results are shown in Figure 2. All the experimental data show higher compression along the Hugoniot (4.5-4.7) than the current EOS models predict (e.g., 4-4.3 with LEOS 1014 Kerley). This trend is similar to the previous data obtained at different facilities, Omega, Z and NIF, which also showed a similar discrepancy with current models beyond 100 GPa. Further analysis is underway to understand the systematic uncertainties, and to understand the underlying reasons for such discrepancy with the models.

The second half-day in August was very successful as well. The addition of an extra quartz anvil to the target design enabled measurement of a re-shock and a second impedance data point. Four shots were taken that will complete the data set at lower shock pressures ($100 < P < 350$ GPa) where the Knudson-Desjarlais quartz calibration is more accurate.

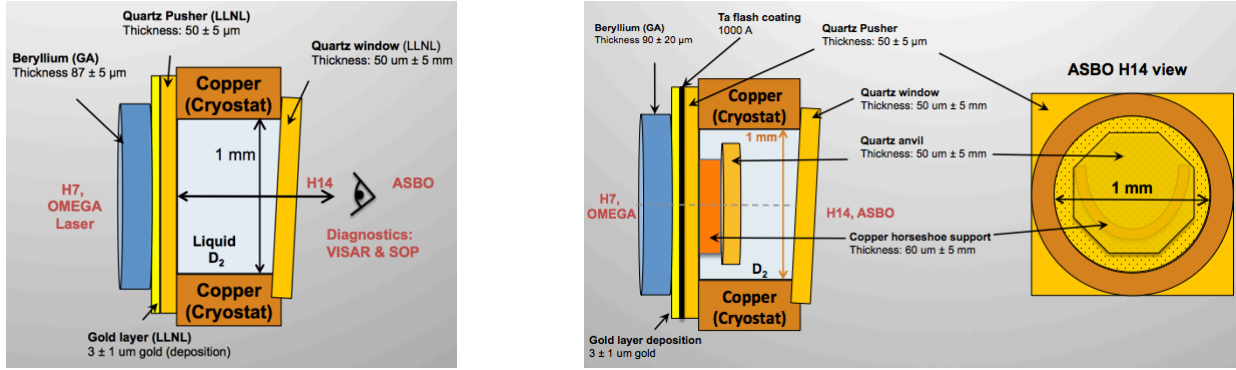


Figure 3. Schematic of the target design and experimental configuration for the PCRYO-16A (Left) and PCRYO-16B (Right) campaigns, respectively.

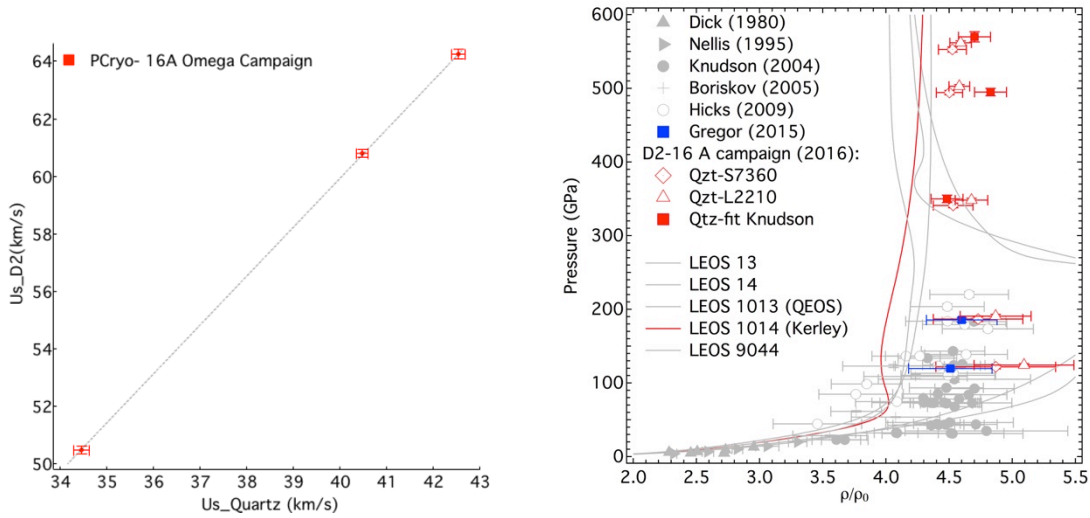


Figure 2. (Left) Summary of the observables: transmitted shock velocity in D_2 versus incident shock velocity in quartz. (Right) Pressure versus compression along the principal Hugoniot of liquid deuterium. Experimental data: vertical triangle by Dick et al., horizontal triangle by Nellis, filled circles by Knudson et al., crosses by Boriskov, open circles by Hicks et al., blue squares recent data (not yet published) by M. Gregor et al. (LLE), red symbols this work (preliminary result) analyzed using the Knudson-Desjarlais quartz calibration and also using two tabular quartz EOS models (SESAME 7360, Kerley and LEOS 2210).

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

The Near Vacuum Campaign on the NIF has shown that radiation-hydrodynamic codes such as HYDRA do not provide an accurate description of the collision of two high velocity flows, e.g. ablated gold from the hohlraum wall and ablated carbon from the capsule, with relative velocity of 8×10^7 cm/s, at an electron density of 10^{21} /cm³. In this parameter space, rad-hydro simulation predicts a stagnation of the two plasmas leading to a density ridge at the materials boundary; however, experimental data do not support this scenario. The main hypothesis to explain the discrepancy is that the flows' interpenetration cannot be described by a fluid code, but requires a full kinetic description at this high relative velocity and low density. To explore this, an Omega campaign was designed to emulate a Near Vacuum Hohlraum environment in a simpler geometry allowing diagnosis of the material boundary using both Optical Thomson Scattering and time resolved X-ray imaging. To reach NIF relevant conditions, laser beams are used to irradiate both an outer ring of material ranging (depending on the shot) from low to high Z (Carbon, Aluminum, Gold) and an inner ring of high-density carbon (Figure 1). The laser energy was also varied during the campaign.

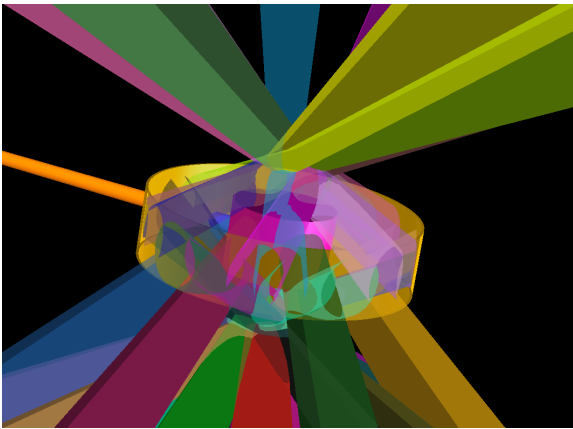


Figure 1: VISRAD view of the target geometry with laser beams.

High quality data was obtained from both main diagnostics. Figure 2 illustrates that as the Z of the outer ring material is increased from carbon to gold, and plasma collisionality is increased, the material boundary becomes more apparent for the same laser drive and time.

Figure 3 shows Ion Acoustic Wave (IAW) and Electron Plasma Wave (EPW) spectra. From these spectra flow velocities, ion temperatures, electron densities and flow compositions are deduced, providing a complete picture of the plasma parameters.

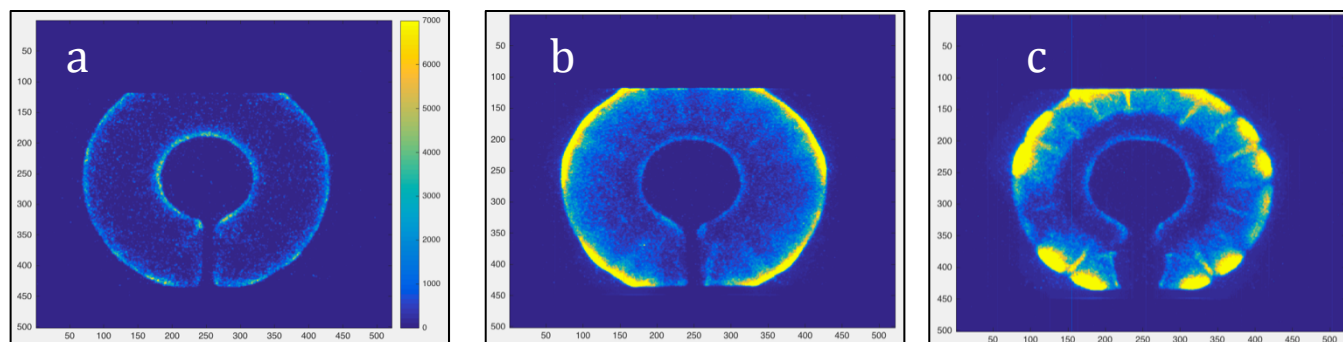


Figure 2: X ray images at 0.9 ns for the three different rings (a- carbon, b- aluminum, c- gold). Center circle is the high-density carbon ring. Outer circle is the low to high Z ring.

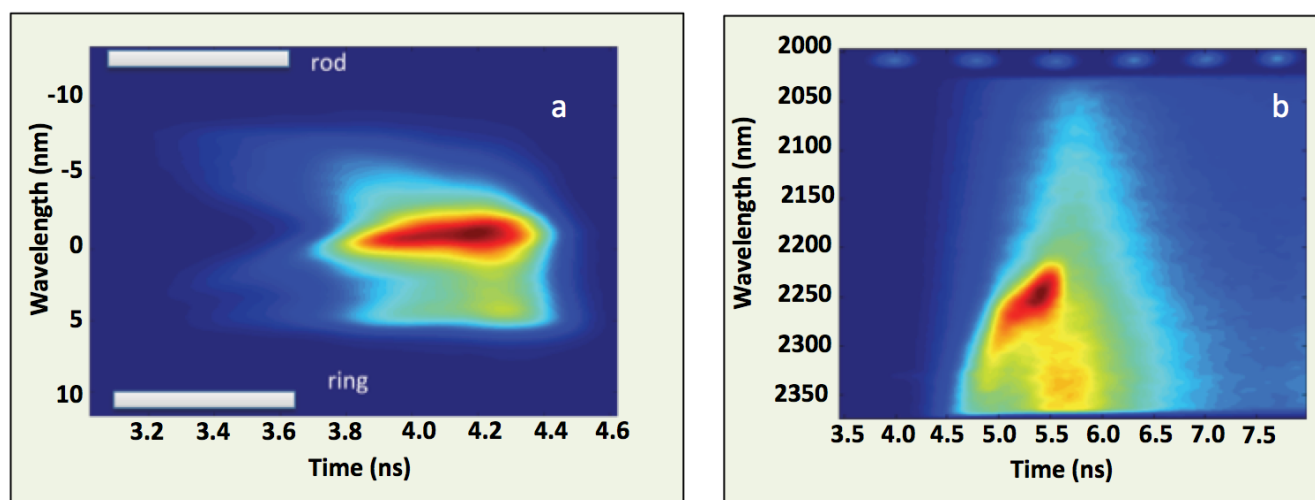
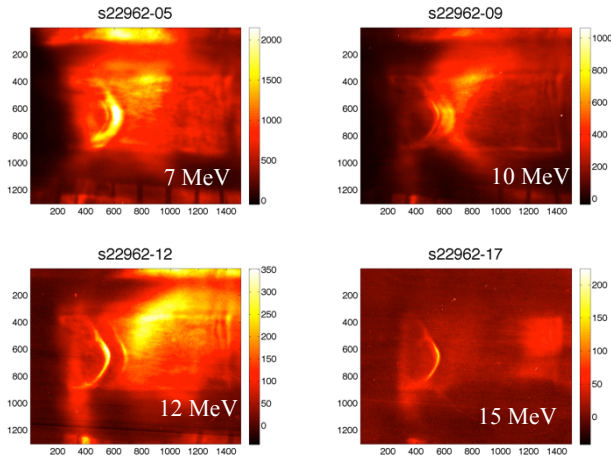


Figure 3: A -Ion Acoustic Wave (IAW) and B- Electron Plasma Wave (EPW) spectra for Carbon into carbon.

4. Broadband proton radiography of shock front in gases (PIs: Y. Ping and R. Hua) with H. Sio (MIT), C. McGuffey (UCSD), F. Beg (UCSD) and G. W. Collins

This campaign is based on an experimental platform developed on EP in FY15 to study shock front structure and field effects in low-density systems. The broadband proton backlighter is generated by high-intensity short-pulse interaction with metal foils through the well-known TNSA (target normal sheath acceleration) process. The shock is driven by 3 UV long-pulse beams in a gas cell with CH ablator. Both shot days provided excellent proton radiographs and soft-x-ray spectra of shock propagation in gases. Figure 1(a) displays proton radiographs with different-energy protons, showing clearly energy-dependent deflection of protons and complex structure at the shock front. VSG was added as a spectroscopic diagnostic for He-Ne mixtures. The spatially resolved spectra, shown in Fig. 1(b), provided shock velocity in a single shot and a constraint on shock temperature by Ne lines. A radiative precursor was also observed as indicated in Fig. 1(b) as the He-like Ne line extended beyond the shock front. A paper on this new platform has been submitted to RSI (H. Sio, et al.) and radiograph analysis paper is in progress.

(a) Proton radiographs



(b) Spatially resolved VSG spectra

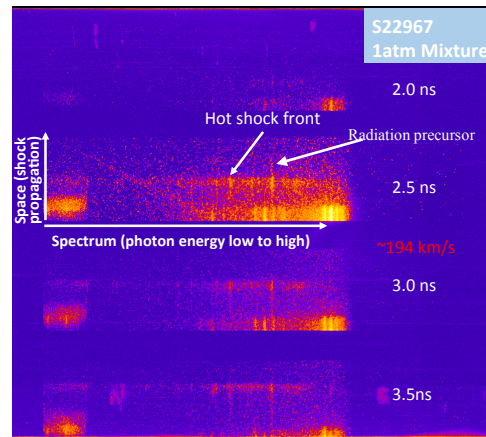


Figure 1: (a) Proton radiographs of a shock front in He gas, showing energy-dependent structure. (b) Spatially resolved spectra by VSG. Both shock front and radiative precursor were clearly observed.

5. Studies of kinetic and multi-ion-fluid effects in ICF implosions using nuclear-reaction and x-ray emission histories (PI: H. Sio, LLNL/MIT Collaboration)

The motivations for the one-day DTh₃-16A campaign on OMEGA were, first, to measure simultaneously the DT and D³He reaction histories on the same instrument, and second, to measure multiple x-ray emission histories in different x-ray energy bands. Measurements of the nuclear reaction histories enable time-resolved comparison of the nuclear rates as implosions transition from a more hydrodynamic (~ 2.3 mg/cc initial gas fill) to a more kinetic (~ 0.3 mg/cc initial gas fill) regime. Comparison with hydrodynamic and kinetic-ion simulations will be used to understand how plasma density and temperature profiles are altered by non-hydrodynamic effects during shock-burn.

At the same time, the ratio of two different nuclear reaction histories will be used to infer a spatially-averaged $T_i(t)$. X-ray emission histories in different x-ray energy bands will be used to infer a spatially-averaged $T_e(t)$ from the slope of the Bremsstrahlung continuum. As both the nuclear reaction histories and the x-ray emission histories are simultaneously measured on the Particle X-ray Temporal Diagnostic (PXTD), their relative cross-timing is very well known (< 10 ps). $T_i(t)$, $T_e(t)$, and their relaxation toward equilibrium, will be used to measure ion-electron (i-e) equilibration rate to experimentally validate the Coulomb logarithm for various plasma conditions.

In addition to the primary PXTD data, other nuclear (WRF, CPS, PCIS), optical (FABS), and x-ray (DANTE, SFC, KB-FRAMED) diagnostics also measured good data to constraint implosion trajectory, laser absorption, nuclear yields, ion temperatures, and x-ray output.

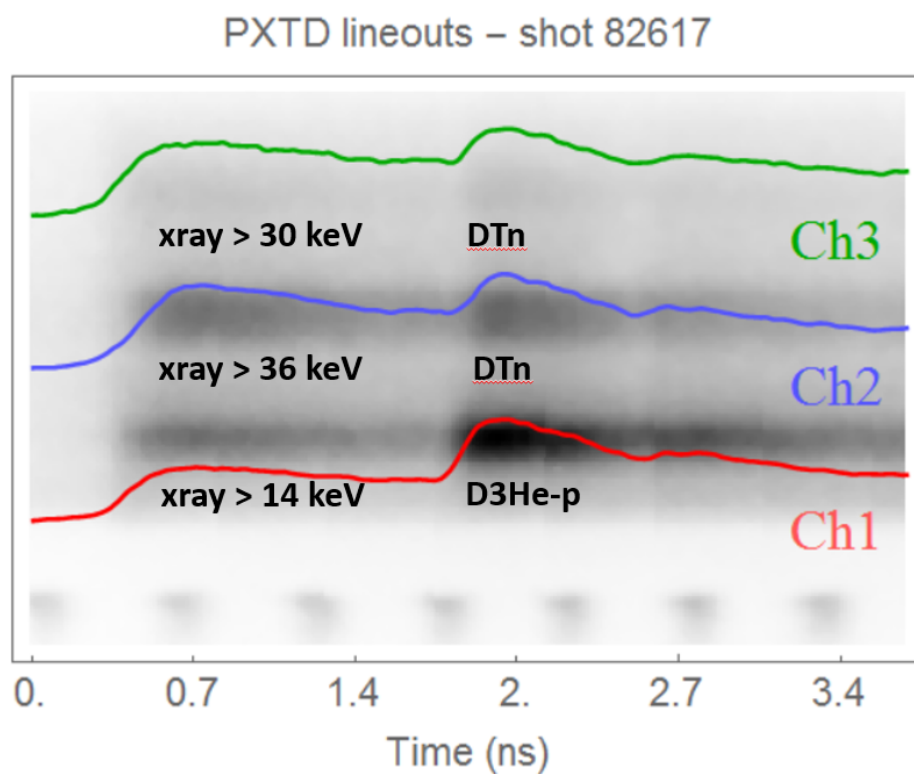


Figure 1: PXTD channel lineouts on shot 82617. X-ray emission histories (in the energy band above 14, 30, and 36 keV) and nuclear reaction histories (DT, D3He) are measured simultaneously on one streak. Each streak channel has its own filtering in front of, and light attenuation filter behind, the scintillator to equalize the signal relative to the other channels.

6. X-ray blanking mitigation experiments for the NIF optical Thomson scattering diagnostic (PIs: G.F. Swadling and J.S. Ross)

The XRayBlanking-16A experiment was carried out to assess the risk posed to the NIF optical Thomson scattering (OTS) diagnostic by x-ray driven “blanking” of the optical debris shield, and to test a Xe gas x-ray shield design concept. A total of eleven target shots allowed the acquisition of high quality data, both addressing the threshold for x-ray blanking effects and demonstrating the feasibility of the Xe gas x-ray shield concept.

The radiation environment presented by NIF hohlraums is extreme; they typically produce radiation temperatures of ~ 300 eV, with soft x-ray (< 3 keV) fluxes of $\sim 10 - 20$ TW sr $^{-1}$, and total time-integrated yields of ~ 60 kJ sr $^{-1}$. An optically transparent debris shield will be installed in front of the OTS collection telescope to protect it from target debris produced during shots. The optical layout constrains this shield to be < 60 cm from the target, but at this distance, during a typical ignition-scale experiment, the window could receive a total time-integrated soft x-ray fluence of up to 16 J cm $^{-2}$. This fluence raises the potential for “blanking” of the debris shield - induced optical opacity due to the effects of soft x-ray irradiation.

In the XRayBlanking-16A experiments, the Omega laser system was used to heat a gold sphere target to produce soft x-rays with a comparable spectrum and power to that produced by NIF hohlraums. The soft x-ray flux and spectrum were diagnosed using the Omega Dante diagnostic. Sample optics were exposed to this soft x-ray flux, and their optical transmissions measured using a 532 nm probe laser beam. Blanking was observed over a fluence range from 0.2 to 2.5 J cm $^{-2}$. This threshold falls significantly below the expected soft x-ray fluence onto the NIF OTS debris shield, indicating that measures are required to mitigate this effect.

An optically transparent, but x-ray opaque Xe gas x-ray shield concept was tested. The x-ray shield successfully mitigated x-ray blanking of glass samples, demonstrating the feasibility of this concept (See Figure 1). The x-ray shield concept will be applied to the NIF OTS.

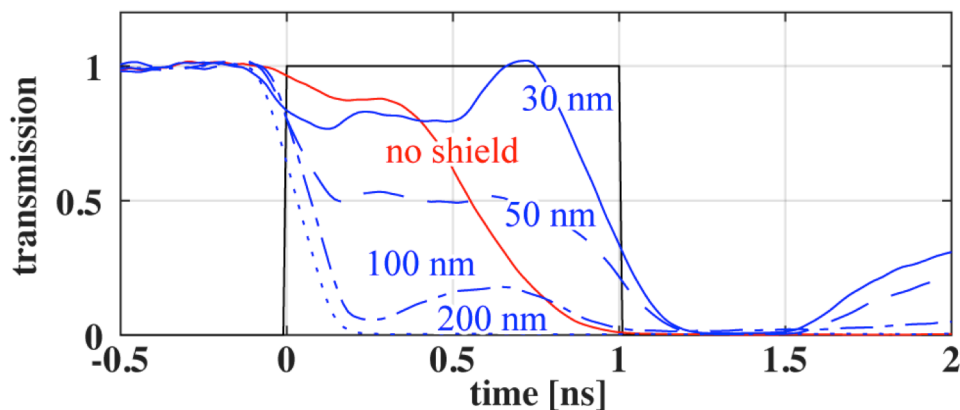


Figure 1) Example of 532 nm sample transmission data from XRayBlanking-16A. The black line shows the nominal square laser pulse shape. The red line shows the transmission of a sample in the absence of an x-ray shield. The sample is exposed to ~ 2.5 J cm $^{-2}$ of soft x-rays over the duration of the experiment. The blue lines show transmission through samples protected by a 10 cm long Xe gas shield at a pressure of 0.04 atm. The gas was contained by thin (30 – 200 nm) SiN membranes, which were themselves ablated by the soft x-rays. For membranes ≤ 50 nm thick, the optical transmission was extended significantly relative to the unshielded sample. The thicker membranes appear not to have expanded sufficiently to allow transmission of the probe without significant absorption.

7. 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 optical depth effects, which create geometrical anisotropies in K-shell line emission from low-density non-LTE plasmas, is very important for improving line-ratio based temperature measurements in hohlraums on NIF, as well as Omega. This campaign built upon the established tamped-foil non-LTE platform at Omega, with specific goals to increase the laser intensity, verify the hydrodynamics of the target expansion, and provide a robust calibration of the x-ray spectrometers. Two target types were used. The primary target was a 10 μ m thick, 1000 μ m diameter beryllium tamper containing a volumetrically equal mixture of iron and vanadium, 200nm thick and 250 μ m in diameter. The second target was a “null” where the beryllium tamper contained no sample material. Three beam-target orientations were used over the course of 13 shots. In the first configuration, an MSPEC spectrometer situated in TIM2 and a gated pinhole imager in TIM3 had an edge-on view of the target, while another MSPEC in TIM6 and another pinhole imager in TIM4 had a face-on view. In the second configuration, the target orientation with respect to TIM2 and TIM6 was reversed. In the third configuration, all primary TIM-based diagnostics had a viewing angle of 45 degrees with respect to target normal. These 3 target-beam orientations provided an *in situ* cross-calibration of the spectrometers and pinhole imagers. The data obtained from 13 shots included simultaneous, time-resolved edge-on and face-on measurements of (1) the iron and vanadium K-shell spectra and (2) the expanding plasma volume. The K-shell spectral data provided time-resolved electron temperature measurements of the expanding plasma, with preliminary analysis indicating $T_e > 2$ keV, higher than previous campaigns.

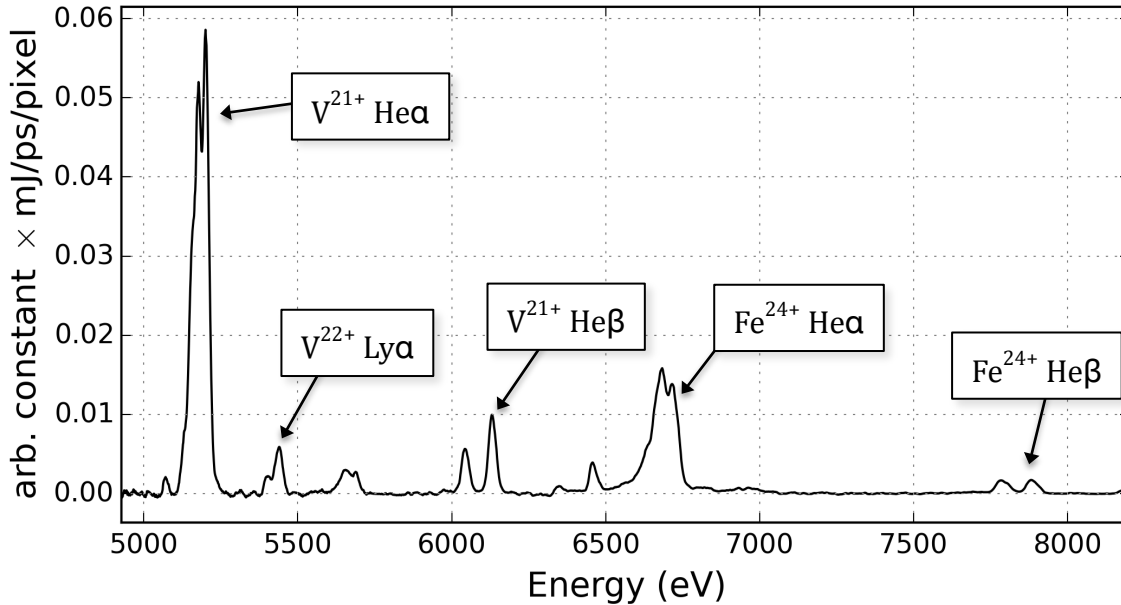


Fig1: Spectrum measured by an MSPEC spectrometer of the X-ray emission from K-shell transitions in highly charged vanadium and iron. An electron temperature > 2000 eV is inferred from the various line ratios.

8. Optical Thomson Scattering measurements from gas-covered Au spheres

(PI: J.S. Ross)

with G. Swadling, R. Heeter, M. Rosen, K. Widmann, J. Moody (LLNL) and D. Froula (LLE)

The GasCoSphere-16A campaign performed “gas-covered” high-Z sphere experiments, with a gold-coated CH sphere placed inside of a gas-bag and illuminated using a 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 a laser irradiation of 10^{14} - 10^{15} W/cm², similar to NIC hohlraums. The gas-bag was filled with 1 atm of either propane or a 70/30 mix of propane and methane, achieving (respectively) initial electron densities of 7.5% and 6.0% of the critical density of the 3ω drive beams. With these conditions the gold-gas interface mimics the interaction of a hohlraum’s gold wall with the low density hohlraum fill gas.

In these experiments, the plasma temperature and density at various radial positions in the blow-off plasma were characterized using optical Thomson scattering. The laser drive used a shaped laser pulse (1 ns square foot, 1 ns square peak) to reduce the shock produced by the gasbag window. The electron temperature and density, the plasma flow velocity, and the average ionization state are inferred 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. The measured data is compared to post-shot simulations with and without a diffusion model in Figure 2. The data and simulations show minimal diffusion of Au into the low-Z CH plasma. Continued data analysis and simulations are in progress to better understand the plasma evolution and heat transport.

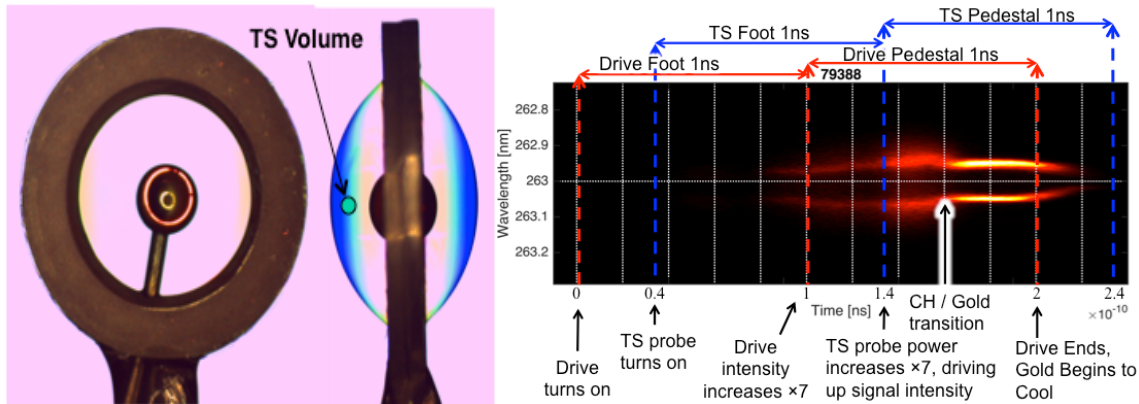


Figure 2: A 1 mm diameter Au sphere centered in a 2.6 mm diameter gasbag. The location of the Thomson scattering volume is shown. An example of the Thomson scattering ion feature is shown where the transition from scattering from Au to scattering from CH plasma is observed at 1.6 ns.

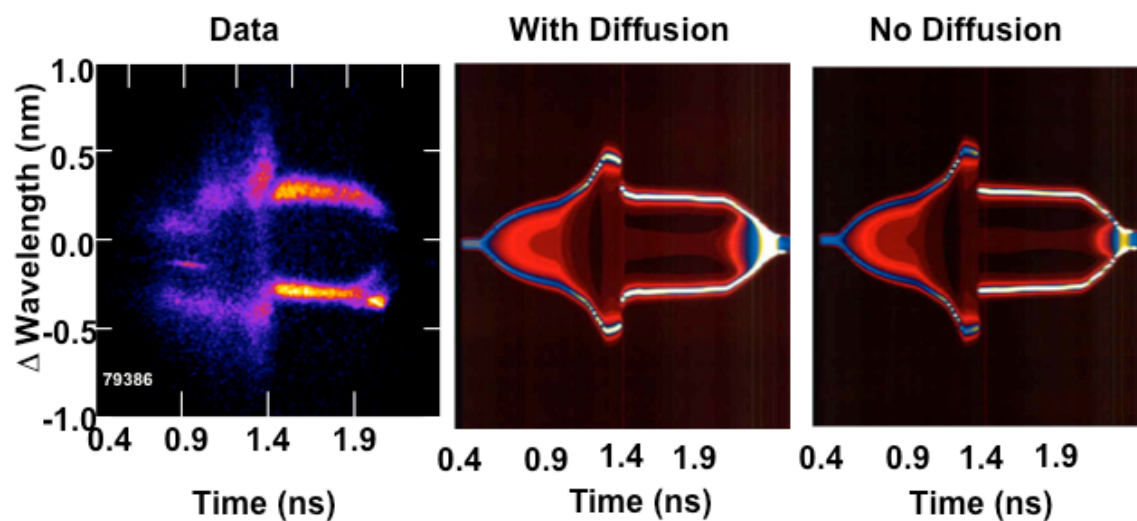


Figure 2: The measured Thomson scattering signal (left) is compared to post-shot simulations using (center), or not using (right) a diffusion model to investigate the interpenetration of Au into the CH plasma.

High-Energy-Density Experiments

A. Material Equation of State Using Diffraction Techniques

1. Measurements of the high-pressure refractive index of magnesium oxide windows (PI: R.F. Smith)

Magnesium oxide, MgO, has the potential to be a good alternative to LiF as a window material in high-pressure equation of state (EOS) experiments. The goal of this half-day Omega campaign was to measure the refractive index of MgO to pressures up to 800 GPa, following the experiments and analytical techniques outlined in Ref. [1]. The target design, shown in Figure 1, consists of 100 μm micro-grained diamond with, on the rear surface, a half layer of 100 μm MgO [100] single crystal. A 0.3 μm Ti layer was coated onto the inner MgO surface to enhance reflectivity for VISAR measurements, and an anti-reflection coating was added to the rear surface. Target normal was oriented along the Omega H7-H14 axis. Six 23 degree beams with the RM38v001 pulse shape were incident onto the diamond ablator, using 220 J/beam, SG8 phase plates and beam delays to achieve a ~ 7 ns ramped laser pulse. With this configuration a ramp compression wave with a peak pressure of 800 GPa was launched into the target assembly. The LLE-ASBO (VISAR) diagnostic then simultaneously measures the diamond free-surface velocity and the diamond-MgO interface velocity. With knowledge of the sample thicknesses and the EOS of both diamond and MgO, one can compare the expected diamond/MgO interface velocity with the measured velocity. The discrepancies between the two can be then used to determine the density correction on the MgO refractive index with that of LiF [1]. Good quality data was obtained on this campaign to support this analysis.

[1] D. E. Fratanduono *et al.* “Refractive index of lithium fluoride ramp compressed to 800 GPa”, J. Appl. Phys. 109, 123521 (2011).

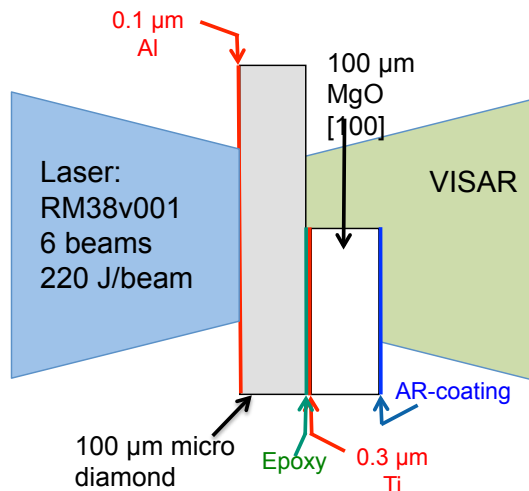


Figure 3: Target design for the MaxOxWindow-16A experiment.

2. Ramp compression of MgO and development of Ge diffraction backlighter on Omega-EP (PI: R.F. Smith)

The target and laser design for the W-MgO-DiffEP-16A experimental campaign is shown in Figure 1(a). This campaign successfully demonstrated the capability of ramp compression of samples to high pressure on Omega-EP (Figure 1(c)). With a slight variation of the target design in Figure 1(a), a 10-ns ramped pulse shape ERM99v006 launched a steady shock into the MgO sample. By increasing the laser power (shock pressure) on a shot to shot basis, it was established that along the Hugoniot single crystal MgO loses its 532 nm transmission at ~ 300 GPa; this is consistent with the onset of the B1-B2 phase transformation.

Simultaneously, this campaign tested the efficacy of a Ge He-alpha 10.2 keV source for x-ray diffraction measurements. The Ge target consisted of a 6 μm layer of Ge, coated onto a graphitic carbon substrate, and then illuminated with a 1 ns flat top pulse which delivered 1250 J into a 200 μm spot. Using this configuration a strong He-alpha peak was measured, and found to be sufficiently strong for use as a source in subsequent x-ray diffraction experiments.

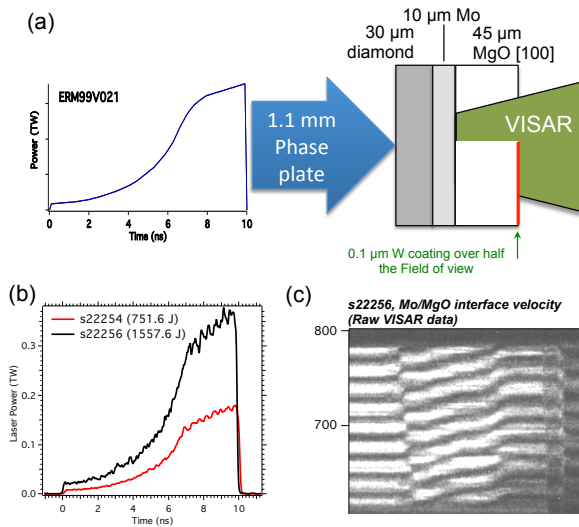


Figure 1. (a) Laser and target request for the W-MgO-DiffEP-16A shots. A 10 ns pulse (ERM99v021) was designed to compress to pressures of 500 GPa+ and then hold at that pressure. The target package consists of a 30 μm Diamond ablator, 10 μm Mo foil and a 45 μm thick MgO [100] window. Half of the MgO free surface was coated with 0.1 μm W, such that the EP-VISAR diagnostic could simultaneously measure both the Mo/MgO interface velocity and the MgO free-surface velocity. (b) As delivered laser power for two shots. (c) VISAR data from a shot successfully ramp compressing the MgO to several hundred GPa.

3. Development of a new Platform for measuring re-crystallization (PI: F. Coppari, Designer: R.G. Kraus)

The goal of this campaign is 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 it 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 phase of the Pb upon shock, release and ramp-compression is monitored by time-resolved 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. This campaign tested for the first time the use of beryllium ablaters in diffraction experiments at Omega. This was possible thanks to excellent support from the Omega staff to implement special procedures to avoid Be contamination of the diffraction diagnostic hardware and of the image plate media used to record the data. The behavior of Be ablaters is relatively easy to capture with hydrocode simulations, improving predictive capabilities for this class of experiments. In this experiment it was possible to accurately tune the laser pulse shape and compress the Pb sample along this complicated shock-release-ramp path. Beryllium is also a highly efficient ablator, especially compared to standard plastic ablaters, so the same pressure can be obtained with lower laser energy, with the added desirable effect of reducing the ablation x-ray background that may interfere with the diffraction measurements. On this recent EP shot day excellent diffraction data were obtained that will help inform future Omega and also NIF campaigns.

4. How much do the backlighter x-rays heat unshocked diffraction samples?

(PI: D. Erskine)

with J. Eggert

Recently many diffraction shots on NIF, using the TARDIS diffraction platform, have successfully returned valuable information about the structure of materials under shock loading. These use an x-ray backlighting source created by intensely illuminating a material such as Fe or Cu to produce K-shell x-ray lines. This illumination occurs while other laser illumination creates a pressure wave that moves through the sample. The x-rays diffract from the compressed sample, and the angular directions of the diffracted rays are recorded by a set of time-integrating imaging plates that surround the sample. Simultaneously, a pair of VISAR interferometers measures the Doppler velocity of the target surface, and the velocity history reveals information about the shock loading of the target.

The question is, does the backlighting illumination itself cause enough heating in the sample to perturb these measurements? To find out, this experiment shot a set of diffraction targets which were NOT illuminated by the pressure drive lasers, only the backlighting x-rays. If the temperature increase due to absorption of x-rays is significant, the thermal expansion creates a velocity (and displacement) signature. The answer is yes, a small signal can be observed, but only at maximum EP laser power to the backlighter and with thicker (50 micron) samples. This was established using one day of Omega EP time to deliver 9 shots using various sample thicknesses and backlighter sources. No heating signature was observed for the first 6 shots using moderate backlighter laser power, on either 5 or 50 micron thick samples. But on 3 shots, a small thermal expansion displacement was observed when delivering the maximum amount of backlighter power onto a relatively thick sample. These data will be used to refine the design of upcoming diffraction measurements.

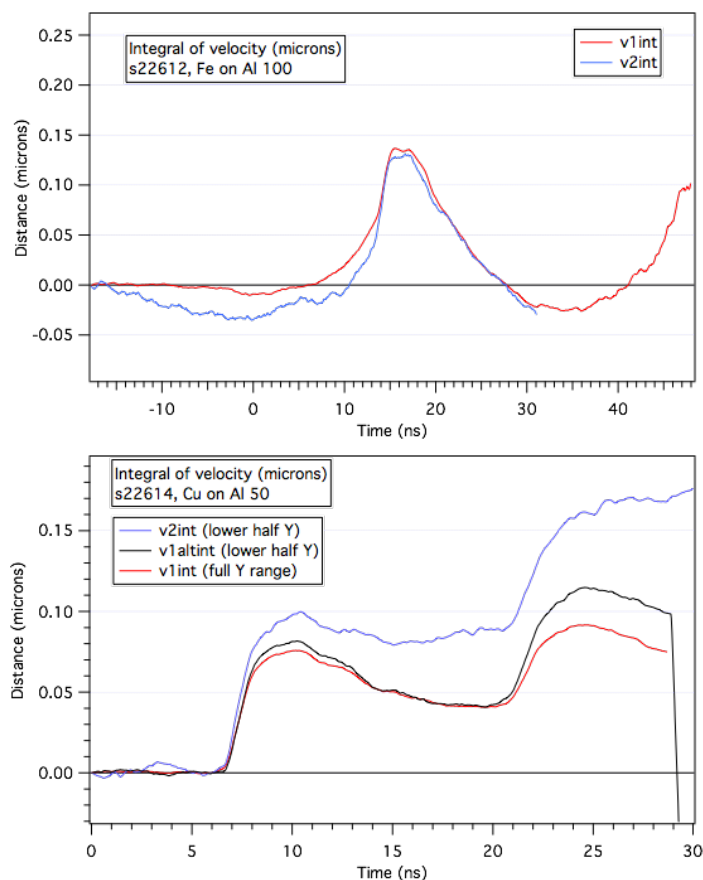


Figure 1: Measured displacement of diffraction sample rear surface vs time, by integrating the VISAR velocity signal. Two VISARs (1=red, 2=blue) monitor the same sample but have different record lengths. Upper panel shows shot s22612 (Fe backlighter on 100 microns of Al). Good agreement between VISARs was obtained. Lower panel shows shot s22614 (Cu backlighter on 50 microns of Al). The discrepancy between the blue trace (VISAR2) and the red and black traces (integrating different regions on VISAR1) requires further investigation.

5. Development of in-situ pressure standard for diffraction experiments (PI: F. Coppari)

with J. Eggert

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 EOS is known) which has been compressed together with the sample, one can determine the pressure reached during ramp-compression.

Currently pressure is determined with VISAR measurements of diamond free surface velocity, and this method is in some cases ambiguous (e.g. due to lack of reflectivity or shock formation). 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. In addition, combining pressure determination from VISAR and from the in-situ gauge can also give information about the temperature of the sample by measuring the calibrant thermal expansion.

In this experiment, different pressure gauge materials (Au, Pt and Mo) were tested in ramp-compression to moderate pressure (2-3Mbar). Excellent quality data were obtained. The Pt standard gave the best results, as the diffraction signal was strong and untextured. Although this platform still needs some development effort before being used routinely in diffraction experiments, 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 x-ray diffraction measurements both at Omega and NIF.

6. Development of simultaneous diffraction and EXAFS measurements

(PI: F. Coppari)

with Y. Ping and J. Eggert

Being able to measure simultaneous diffraction and extended x-ray absorption fine-structure (EXAFS) signals in the same shot will be an enormous advance for laser-based materials experiments, by providing simultaneous probes of both the long-range (diffraction) and short-range (EXAFS) order of the material, as well as two complementary probes of the Debye-Waller factor to probe the temperature of a single material state.

The approach in this campaign used the PXRDIIP diagnostic to measure diffraction, and the XRS spectrometer to measure EXAFS. The challenge was to find a suitable backlighter that would generate both a monochromatic (for diffraction) and broadband (for EXAFS) x-ray source. Different schemes were tested out in the different campaigns, such as Kr-filled capsule implosions or illumination of a high-Z foil to exploit both the line and the continuum emission, but these initial schemes did not work for both diffraction and EXAFS. However, success was achieved in measuring simultaneous XRD and EXAFS by using a dual-material foil backlighter, where one side of the foil is optimized to generate He-alpha radiation for diffraction (i.e. Fe foil driven with 6 beams at 500J and 300 μ m laser spot) and the other side is used to generate a broadband brehmsstrahlung continuum for EXAFS (i.e. Ag foil, driven with 13 beams at 500 J and best focus to maximize the laser intensity), as shown in Figure 1. The sample material in these shots was a “diamond sandwich” with an Fe sample as typically used in ramp-compression experiments. Examples of the EXAFS and diffraction data are shown in the Figure. Further development is needed to improve the data quality, but this result represents a big step forward in the study of dynamically compressed matter.

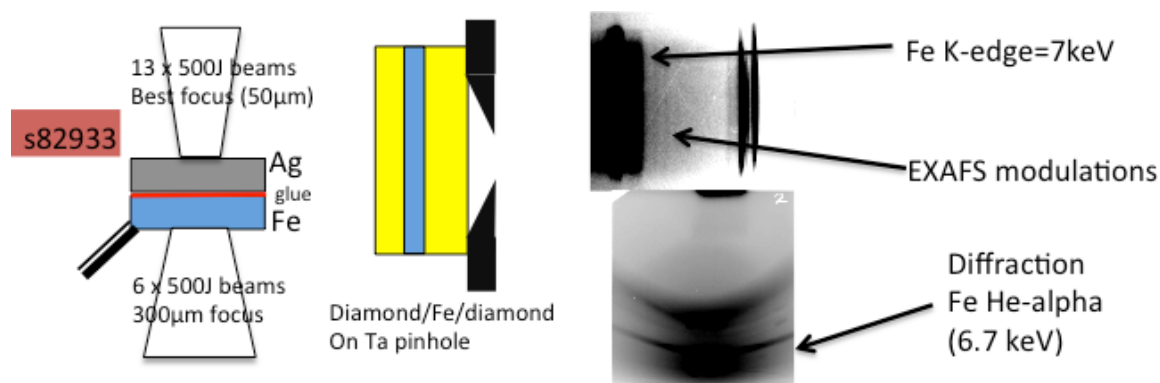


Figure 1: Schematic of the backlighter and target used in the XRD-EXAFS_16C campaign to successfully measure simultaneous EXAFS (top data) and diffraction (bottom) of an Fe foil sandwiched between a diamond ablator and window.

B. Material Equation of State Using Other Techniques

1. Development of spherically-convergent equation of state measurements

(PI: A.E. Lazicki)

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

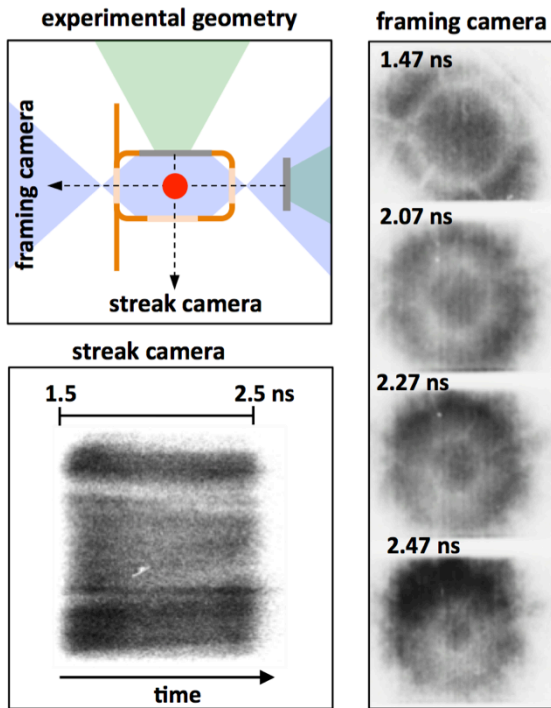


Figure 4. Experimental configuration and raw radiographs from a streak camera and framing camera for shot 79708.

This series of shots was designed to test and qualify 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 first two campaigns, GbarEOS-16A and 16B, used a hohlraum (indirect drive) to launch converging shock waves into solid spheres of CH_2 , similar to an existing platform on NIF but not yet in use on Omega. Along the axis of the hohlraum, backlit 2D x-ray images of the imploding sphere were collected with a framing camera; streaked backlit images of a slice of the sphere, imaged through a slit in the hohlraum, were also recorded with a streak camera (Figure 1). The radiographs yield density and shock velocity, which allow calculation of the shock state using the Rankine-Hugoniot equations. The two campaigns experimented

with variations in camera configuration, hohlraum gas fill, x-ray backlighter energies and hohlraum drive energy. Usable data was collected on all diagnostics for a subset of the shots, indicating pressures between

30-200 Mbar, and analysis is in progress. In a subset of the shots, x-ray Thomson scattering measurements were made using a spectrometer with a view along the hohlraum axis, in an effort to constrain temperature as well. An analysis of these results has been published [1]. The third half-day campaign (GbarEOS-16C) used the Omega beams to directly ablate a sphere of deuterated plastic (CD) to drive the convergent shock wave, with the core material state assessed via radiography, x-ray Thomson scattering, and neutron yield diagnostics. Results of these campaigns are being used to further optimize the platform to make more measurements in FY17.

[1] A. M. Saunders et al., Rev. Sci. Instrum. 87, 11E724 (2016).

2. Development of Conically-Convergent Equation of State Measurements

(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

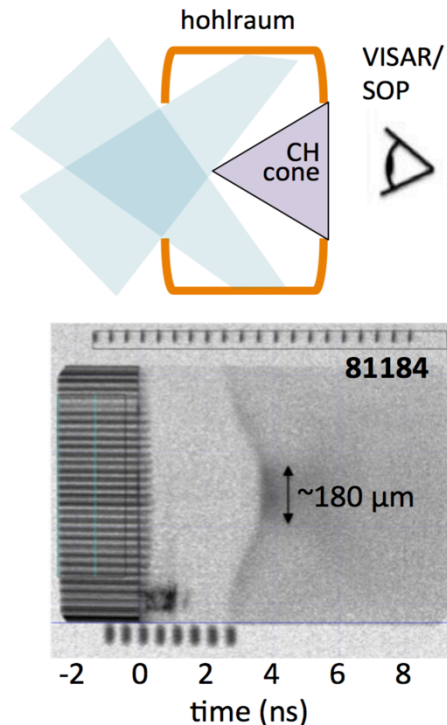


Figure 5. Experimental configuration and raw VISAR data showing the breakout time from a CH cone.

(rexolite polystyrene) cone. Results indicate formation of a Mach stem at pressures exceeding 200 Mbar. The data will be used to develop an equation of state measurement on Omega in FY17, with extension to more extreme conditions using NIF as well.

This campaign was designed to test a conically convergent platform for measuring Hugoniot equation of state of arbitrary materials, 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, this campaign experimented with convergent shock waves launched into a cone inset within 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 halfraum. This concept has previously been demonstrated on high-explosives platforms [1] and proposed for a laser drive [2], but never previously tested. One advantage of this geometry over a spherically convergent geometry is that, since the Mach reflection is planar, it can be launched into a planar target package to make a traditional transit-time impedance-matching measurement using a velocimetry diagnostic.

One half-day of Omega shots was used to test 3 different cone angles, using the VISAR and SOP diagnostics to register shock breakout times and profiles from the free surface of a CH

[1] Bushman, A. V., Kanel', G. I., Ni, A. L., and Fortov, V. E., Intense Dynamic Loading of Condensed Matter, Taylor and Francis, London, 1993.

[2] Swift, D.C. and Ruiz, C.R. (2006), Am Inst. Phys. Conference Proceedings 845 pp.1297-1300.

3. Ramp Equation of State Measurements on Gas-Encapsulated Samples (PI: R.F. Smith) with D.E. Fratanduono

The goal of this campaign was to test a new target design in which the sample is encapsulated in a gaseous environment of Nitrogen or Argon. The target was designed to determine if the velocity at a diamond/gas interface was different from the velocity off a diamond/vacuum free-surface.

The target was oriented along the H7-H14 axis. Six omega beams, incident 23 degrees off axis with a 3.8 ns ramp laser pulse shape, were combined to generate a ~ 7 ns overall ramp compression drive in a diamond sample. Peak sample pressures of 800 GPa were generated. The ABSO (VISAR) diagnostic simultaneously measured the diamond/gas interface velocity and the diamond/MgO interface velocity. Using the diamond/MgO interface velocity, the known diamond thickness and the previously measured equation of state of diamond, one can infer the diamond free-surface velocity. Discrepancies between the diamond/gas and calculated diamond free-surface velocities provide an indication as to the effect of gas encapsulation. During the half day of shots, the gas pressure was varied to obtain a range of data to establish operating boundaries for future experiments with different sample materials.

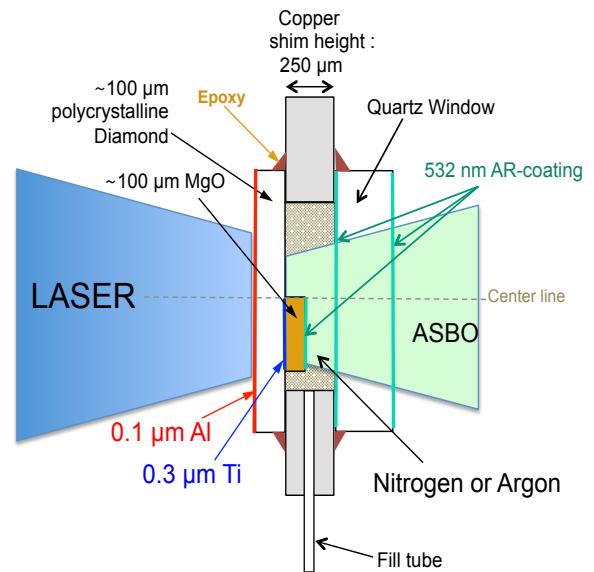


Figure 6: Target design for RampReverb-16B.

4. Optical Blanking Test for Gas-Encapsulated Equation of State Measurements

(PI: D.E. Fratanduono)

with R. Smith

Following up on the gas encapsulation ramp campaign, this campaign was to continued to explore a new target design in which the sample is encapsulated in a gaseous environment. The target was designed to determine if a diamond/gas interface velocity differs from the velocity off a diamond/vacuum free-surface. The new gas-fill capability on Omega-EP was employed.

Eight experiments were performed as shown in Figure 1, to examine if a low density gas would blank (become opaque to the VISAR probe beam) when ramp compressed using the UV lasers on EP. Neon, Xenon, Argon and Nitrogen were examined at 1.0 atm and 1.5 atm. No issues were observed with Neon, Argon and Nitrogen. Blanking was observed in the Xenon data. This data will be useful for designing future NIF experiments with encapsulated samples.

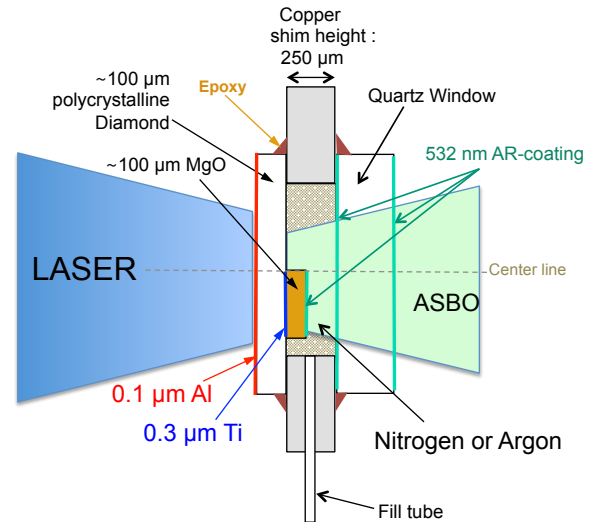


Figure 7: Target design for EncapRampEP-16A.

5. 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

The goal of this campaign is to develop a platform to accelerate diamond flyer plates to hyper-velocity for equation of state (EOS) measurements. The conceptual design was to ramp compress a diamond plate on the end of a halfraum, using x-ray ablation to accelerate the diamond into vacuum. After propagating a known distance, the diamond flyer impacts a transparent diamond window. By measuring the diamond flyer-plate velocity prior to impact, together with the resulting shock velocity in the diamond witness, the principal Hugoniot of diamond can be determined *absolutely* (e.g. without requiring a known pressure reference), enabling the development of diamond as a high-pressure EOS standard.

These FY16 shots pioneered the indirect drive approach, which greatly improved planarity and resulted in more homogeneous, smooth flyer acceleration compared to direct-drive flyer experiments in FY15. However, the maximum pressure achievable at Omega remains below the onset of diamond reflectivity, so instead quartz was used as a window and reference. Issues with the diamond flyer breaking up before impact, because of spalling, arise when attempting to reach higher pressure. This currently prevents obtaining high quality VISAR data (and high precision EOS measurements) from a full-density diamond flyer. But since the technique appears promising, future campaigns will explore different flyer materials which could also become useful absolute EOS standards (i.e. Mo, Cu).

6. Backlighter Development for Extended X-Ray Absorption Fine Structure Measurements (PI: F. Coppari)

With Y. Ping, R. Rygg and J. Eggert

Extended X-ray Absorption Fine Structure (EXAFS) measurements require a bright, smooth and broad-band x-ray source for absorption spectroscopy near x-ray edges of the sample material. The X-ray radiation emitted by a capsule implosion meets these requirements and is currently used in laser-based EXAFS experiments. However, this x-ray emission decays rapidly at higher photon energies, making EXAFS measurements above 10 keV very challenging. To extend the x-ray energy range of laser-based EXAFS measurements, this campaign explored the possibility of using brehmsstrahlung sources from foil backlighters driven at relatively high intensity. The specific goal of this campaign was to determine the optimum material and laser power configuration for this technique at Omega. Both Mo and Ag foils were tested, with laser intensity varying from $8 \times 10^{16} \text{ W/cm}^2$ to $3 \times 10^{17} \text{ W/cm}^2$. The source spectrum and size were measured for each shot. The Ag foil driven with full intensity and tight laser focus is in fact somewhat brighter than the capsule backlighter above 10 keV (see Figure 1). The brehmsstrahlung backlighter's simplicity and potential for further improvement make this approach a valuable alternate x-ray source for high energy EXAFS measurements.

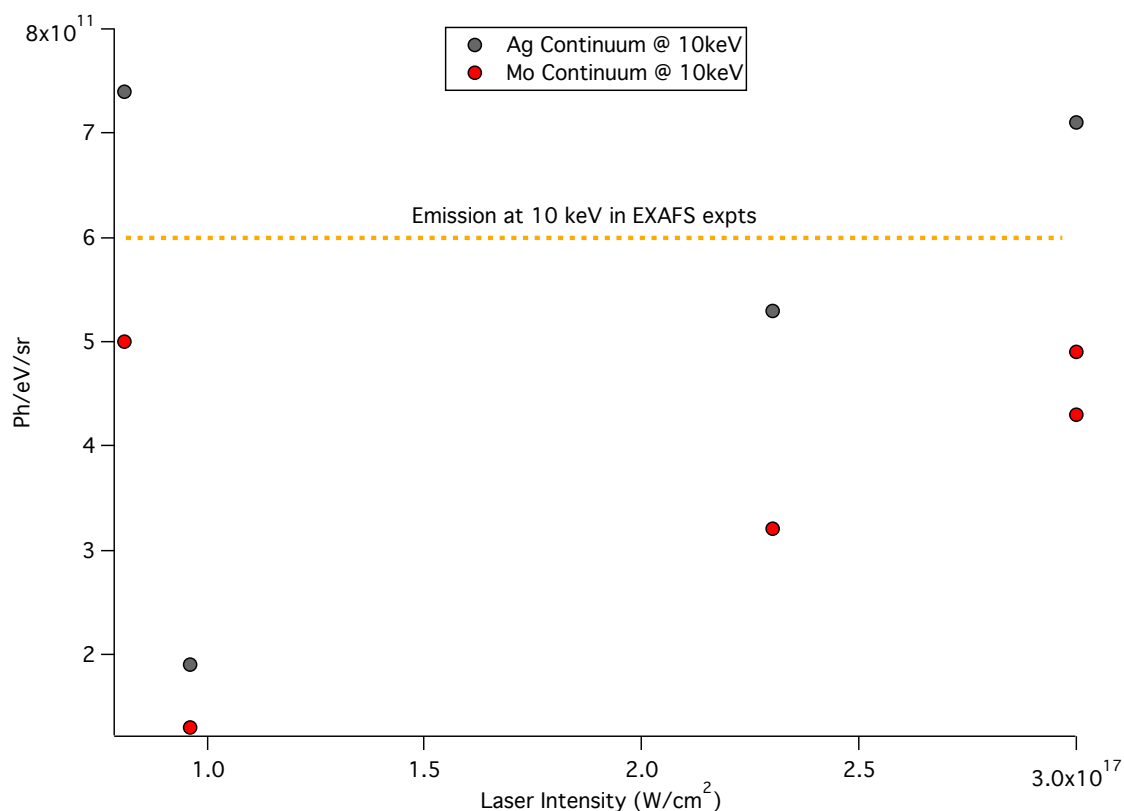
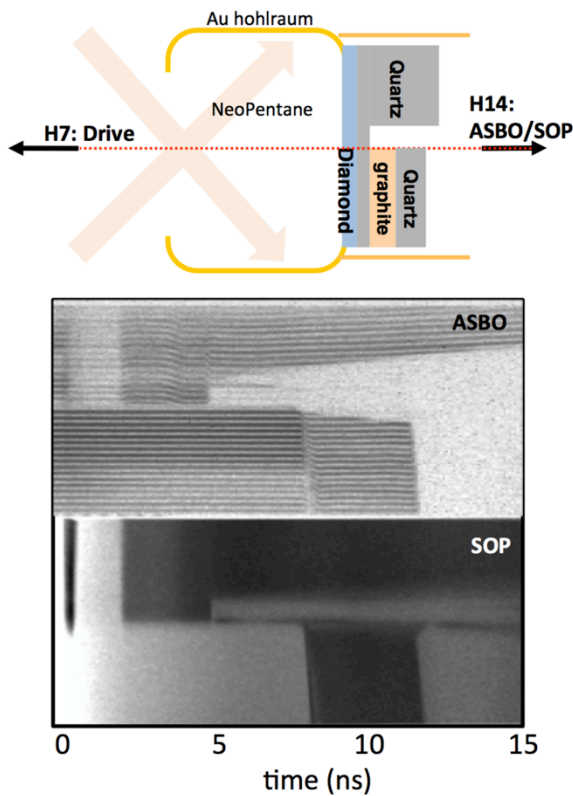


Figure 1: Brightness of Ag and Mo foils at 10 keV as a function of laser intensity. The dashed line represents the brightness of the capsule backlighter at 10 keV, currently used as an x-ray source for EXAFS measurements at Omega.

7. Hugoniot equation of state of low-density porous graphite (PI: A.E. Lazicki)

with F. Coppari, R. London, D. Swift, M. Millot, D. Fratanduono, H. Whitley, J. Castor and J. Nilsen



This campaign was designed to probe a preheated Hugoniot equation of state, using pore-collapse of a porous material to generate preheating. Pressure and density of shocked states were determined by impedance-matching with a quartz standard. As shown in Figure 1, the samples were driven using the gas-filled hohlraum indirect drive platform, and the VISAR and SOP diagnostics measured shock transit times in samples of porous graphite. Shock steadiness during transit through the graphite samples (which are opaque to the VISAR) was determined from a quartz witness sample placed next to the porous graphite, from which a continuous record of the shock speed was simultaneously recorded. High quality data was collected for 12 shots during 2 half-days in FY16, and detailed analysis is underway.

Figure 8. Experimental configuration and raw graphite EOS data for shot 80846

C. *Hydrodynamics*

1. Mix Width Measurements of Rayleigh-Taylor Bubbles in Opaque Foams (PI: C.M. Huntington)

Foam Bubbles is an OMEGA campaign that addresses challenges in deeply non-linear, multimode hydrodynamic instability measurements. The interface between two materials of different densities may be susceptible to either Richtmyer-Meshkov (RM) or Rayleigh-Taylor (RT) instabilities if it is shocked or accelerated, respectively. These instabilities in turn drive mixing, where perturbations on the interface determine how the low- and high-density materials interpenetrate. This campaign aims to measure the extent of the interpenetration (“mix width”) in cases where the perturbation is complex and the materials mix on small scales. This is achieved through careful manipulation of the properties of the materials in the system. Particular emphasis is placed on the densities, which set the instability growth rates, and on the x-ray opacity characteristics, which determine the contrast in the x-ray image used to diagnose the mix width.

A technique that has been developed over many previous planar RT experiments is the use of a high-opacity material, often iodinated plastic, embedded in the plastic portion of the target that comprises the “high-density” part of the unstable interface. When driven using indirect drive from a halfraum, and then imaged with transmission x-ray radiography, the location of the high-opacity tracer material is clear, and reveals the position of the high-density material in the system. However, this technique can obscure the shape and extent of the low-density “bubbles” when the foam mixes with the doped plastic. In contrast to this, Foam Bubbles uses an opaque *foam*, which when set next to the more transparent plastic, highlights the extent of the *foam penetration into the plastic*. This system has identical hydrodynamic behavior as the traditional doped plastic / foam interface, but with inverse x-ray characteristics. The target for the Foam Bubbles campaign includes both interfaces, ensuring that the entire system experiences the same acceleration. An example of the data collected is shown in Figure 1. This image was generated using tilted, tapered, point-projection x-ray imaging, and clearly shows the layers on each side of the split target. The extent of bubble penetration in an RT unstable system is a fundamental quantity, and this measurement furthers the understanding of hydrodynamic systems, from ICF implosions to supernovae.

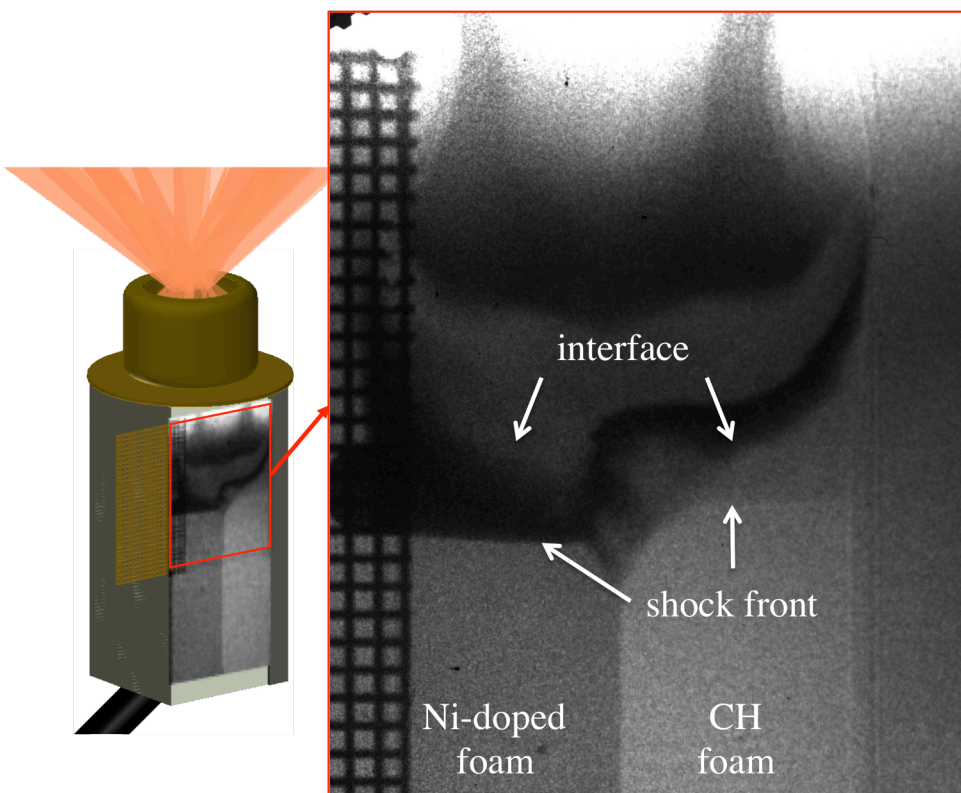


Figure 1: The indirectly driven target is shown, with an example of the data collected. The shock appears as a flat line across the foams, with the mixing evident at the foam-plastic interface downstream of the shock.

2. 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)

Continuing prior work on detailed radiography of hydrodynamic systems, a half-day of hohlraum-driven experiments were performed by an LLNL-AWE collaboration using the OMEGA laser system in FY16. The objectives for this campaign were to investigate the evolution of a driven interface using point projection X-ray radiography, qualify a new simultaneous Radiography-and-VISAR configuration, and obtain drive characterization data using the Dante diagnostic.

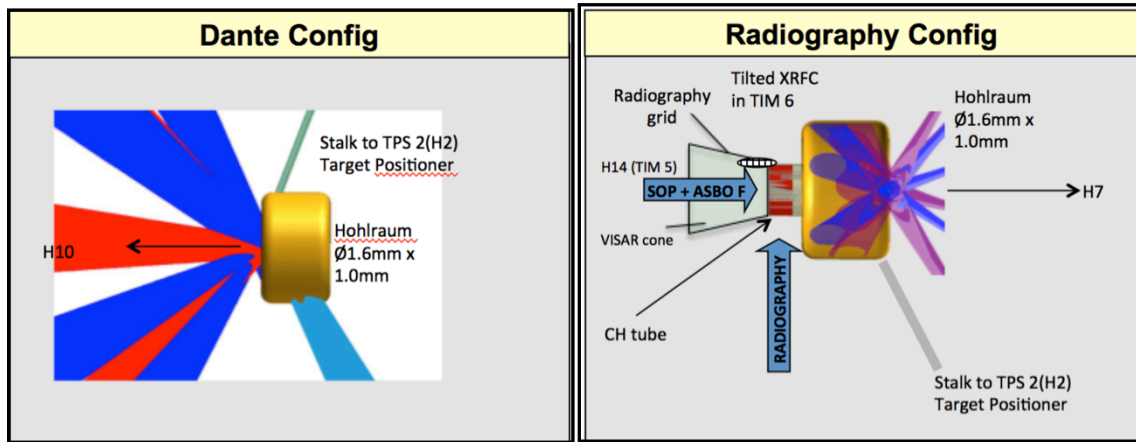


Figure 1: Dante-optimized (left) and Radiography-and-VISAR (right) target configurations.

For the radiography measurements, a point-projection backlighter was generated through a 20 μm pinhole along the “cranked” TIM 6 axis, and recorded with a single strip gated imager. A quartz window with aluminum flash coating and light shield cone were applied to the rear of one radiography target, allowing a VISAR measurement to be made along the TIM5 (port H14) axis. Separate hohlraum drive measurements were performed with hohlraums oriented towards Dante along the H10 axis, using a simplified target with physics package removed. A 75 J timing laser was incorporated into the Dante configuration to improve cross-timing of each Dante channel.

This half-day of experiments was successful, firing 2 radiography shots, 4 Dante shots and 1 combined Radiography-and-VISAR shot. Figure 2 shows the VISAR data from the combined radiography-and-VISAR design. Excellent data was recorded on all diagnostics and the experiments met the goals of the HED program.

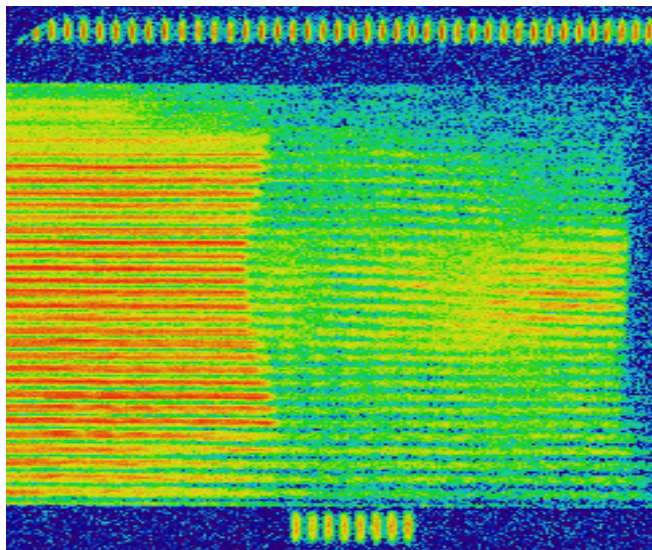


Figure 2: VISAR data confirming the success of the new dual-Radiography and VISAR target configuration.

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

with E. Gumbrell, P. Allan, S. McAlpin, M. Crook-Rubery, L. Hobbs, and W. Garbett (AWE)

This LLNL-AWE collaborative campaign studied the heating of a cylindrical puck of Copper foam irradiated by a short pulse generated proton beam. 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.

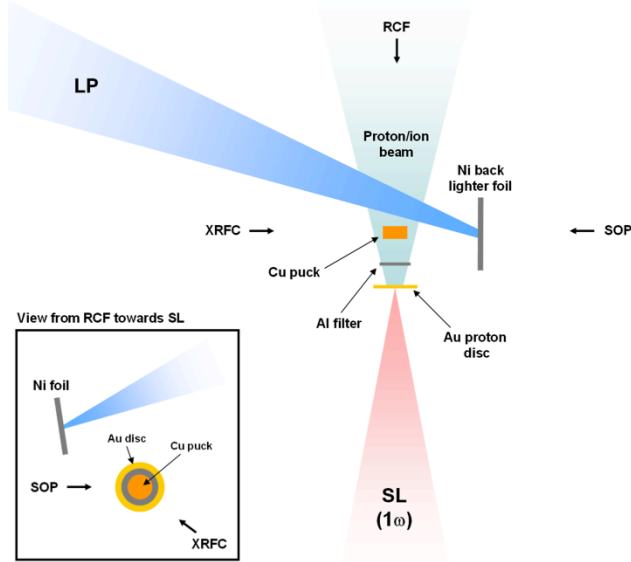


Figure 2: Experimental layout for proton heating shots with combined x-ray radiography, SOP and RCF. For simplicity, only 1 backlighter beam (of the 3 used) is shown.

The experimental setup is depicted in Figure 1. A gold foil was irradiated with the Omega EP sidelighter (SL) short-pulse beam delivering 300 J over 0.7 ps. The SL produced a beam of protons and ions which were used to heat a copper foam puck positioned ~ 1.8 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 would 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 backlit 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 (see Figure 2).

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 3). In addition, a Radio-Chromic Film (RCF) stack measured the proton/ion beam spectrum on the shot.

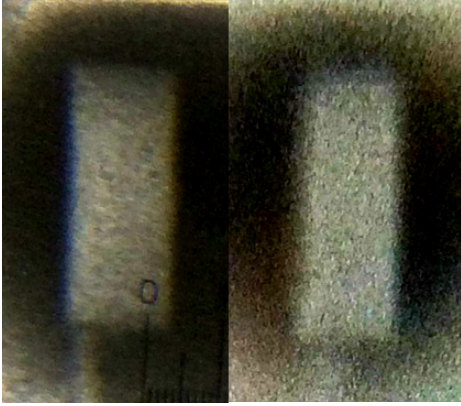


Figure 2: Gated x-ray imaging data from an unheated (left) and heated (right) copper foam puck. For the heated shot the backlighter was delayed by 20 ns. From this perspective, the protons propagate from left to right through the target. There is clear expansion of the front (left) surface.

In total, 6 shots were fired, with data acquired on the XRFC, RCF and SOP diagnostics. The SOP indicated the front surface was significantly hotter, and expanding faster, than the rear surface over the first 5 ns. This agreed well with the XRFC data, which showed the front surface had expanded while there was minimal rear surface expansion on most shots.

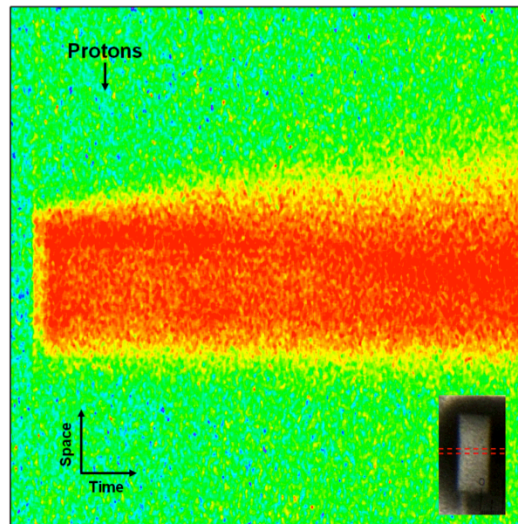


Figure 3: SOP data from a proton heating shot. The insert shows the position and orientation of the SOP slit relative to the target. There is a clear difference between the expansion of the front (proton-facing) and rear surfaces.

D. Plasma Properties

1. Shock Front Structure in Multi-species Plasmas (PI: H. Rinderknecht)

with H.-S. Park, S. Ross, S. Wilks, P. Amendt, and B. Remington (LLNL)

Two Omega shot days were dedicated to developing a new experimental platform for the study of shock front structure in low-density plasmas composed of single and multiple ion species. In these experiments, 10 or 12 beams deliver 2.1–2.7 kJ in 0.6 ns to a thin ablator (2 μm SiO₂ or 5 μm CH) mounted to one end of a CH tube, launching a strong shock into a low-density gas (1 atm) contained within. After thin windows on two sides of the tube are destroyed by $\sim 150\text{J}$ of laser light, Omega's 4 ω beam probes the shocked plasma and scatters light which is detected by the Thomson scattering diagnostic. Figure 1(a) shows the experimental design used on the first day.

High quality Thomson scattering data was achieved on several shots, after tuning the destroyer beam energy and the delay between the destroyer and probe beams. Figure 1(b) shows Ion Acoustic Wave (IAW) features from a shocked plasma composed of H+2%Ne, which shows the shock beginning to pass through the TS volume as blue-shifting of the scattered light. Lineouts shown in Figure 1(c) uniquely demonstrate the evolution of a multi-species shock front structure: the scattered light feature associated with the hydrogen is blue-shifted (beginning to “shock up”) while the peaked Neon feature remains static. Analysis of these features shows the hydrogen is heated ($T \sim 0.8$ keV) and flowing ($V \sim 250$ $\mu\text{m}/\text{ns}$), while the Ne is cold ($T \sim 0.1$ keV) and still ($V \sim 0$): a multi-fluid or kinetic phenomenon that cannot be captured in standard single-fluid models.

On the second shot day, single-species (H) and multi-species shocks (H+2%C) were compared, using predominantly CH ablators. The CH ablators launch weaker shocks than the SiO₂. Further analysis of the TS data is in progress. These results will be used to constrain models of shock front formation, which are sensitive to kinetic physics and relevant to the shock phase of capsule implosions. The shock-tube TS platform also enables more detailed shock physics studies for laboratory astrophysics.

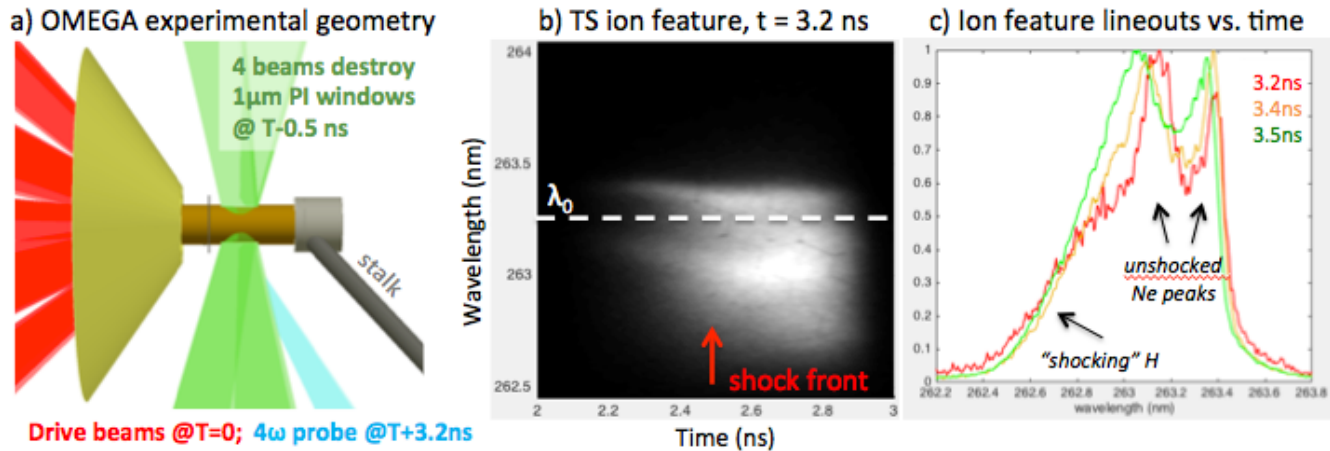


Fig. 1. Experimental design and results for Thomson scattering in a shock tube on OMEGA. a) A 2.1mm diameter CH tube filled with 1 atm H(0.98)+Ne(0.02) was shocked by 12 OMEGA beams driving an SiO₂ ablator. 1- μm thick CH windows were destroyed using 75 J each in 0.6 ns, allowing a 4 ω probe beam and scattered light to pass. b) Thomson scattering ion feature recorded on this experiment, showing the evolution of the shock front. c) Lineouts of the TS ion feature showing kinetic features in the shock evolution: differential velocity and temperature between the H and Ne ion species is observed.

2. Magnetized Collisionless Shocks for Weapons Effects (PI: B.B. Pollock)

with H.-S. Park, J.S. Ross, C. Huntington, and G. Swadling

In FY16 the MCLSWEffEffect campaign on Omega continued an investigation of interpenetrating plasma flows in the presence of background magnetic fields. The campaign employed the MIFEDS pulsed-power magnetic field system to provide a background field. As illustrated in Figure 1, the field was directed along the direction of a low density plasma plume which was produced inside the MIFEDS structure, into which a high density plume was then expanded after a variable delay. The interaction region was probed with Thomson scattering and proton deflectometry to measure the plasma density, temperature, flow velocity, and field structure. This campaign increased the field of view for the proton diagnostic roughly three-fold by inserting the proton detector much closer to the interaction than in previous experiments. The analysis of this recent experiment is ongoing and will inform the FY17 continuation of this effort.

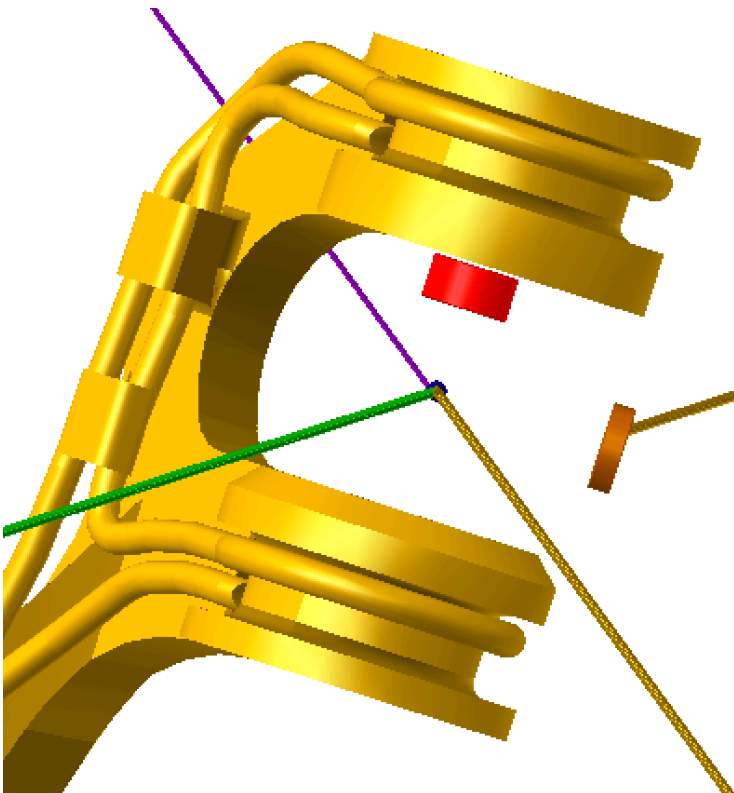


Figure 1: The MIFEDS used in this campaign. The red disk on the upper surface is illuminated by 4 beams, producing a low-density plasma along the MIFEDS magnetic field axis. The gold-colored disk on the right then provides the orthogonal plasma plume which interacts with the low-density plasma. The Thomson scattering volume is at the intersection of the surface normal for these disks, while the proton radiography field of view slightly overfills the MIFEDS interior region.

3. X-ray spectroscopy of fully characterized non-LTE gold plasmas (PI: R. F. Heeter)

with J.A. Emig, M.E. Foord, L.C. Jarrott, D. Liedahl, E. Marley, C.A. Mauche, M.B. Schneider, and K. Widmann

In pursuit of a more precise understanding of the radiative properties of non-LTE gold, to improve the fidelity of hohlraum X-ray drive simulations for National Ignition Facility experiments, the AuNLTE-16A campaign continued to study laser-heated beryllium-tamped gold-iron-vanadium foils. Prior measurements in FY13-FY15 suggest a need for refinements to an earlier benchmark¹, involving a higher gold ionization vs. temperature, but the plasma conditions and uniformity needed to be more fully understood. The FY16 campaign acquired both hydrodynamic expansion imaging data and detailed x-ray spectra for various laser drive arrangements. Data obtained on 11 shots included simultaneous measurements of (1) time-resolved gold M-band spectra from 2 to 5.5 keV, (2) measurements of the plasma electron temperature via K-shell emission from helium-like and hydrogenic V and Fe ions, and (3) measurements of the plasma density from time-resolved face-on and edge-on imaging of the sample's expansion from its initial size. Preliminary analysis indicates electron temperatures at or above 1.5 keV were obtained, based on the presence of the Lyman alpha lines for V and Fe. Figure 1 provides a sample of the imaging data, which shows highly uniform M-band emission at 1.6 ns into the 3.2 ns laser drive, followed over the next 1 ns by an evolving bright spot suggestive of a radial compression-rarefaction wave. The radial feature is undergoing further investigation. Detailed analysis is expected to deliver improved M-band benchmark spectra for non-LTE models.

1. R.F. Heeter *et al.*, *Phys. Rev. Lett.* **99**, 195001 (2007).

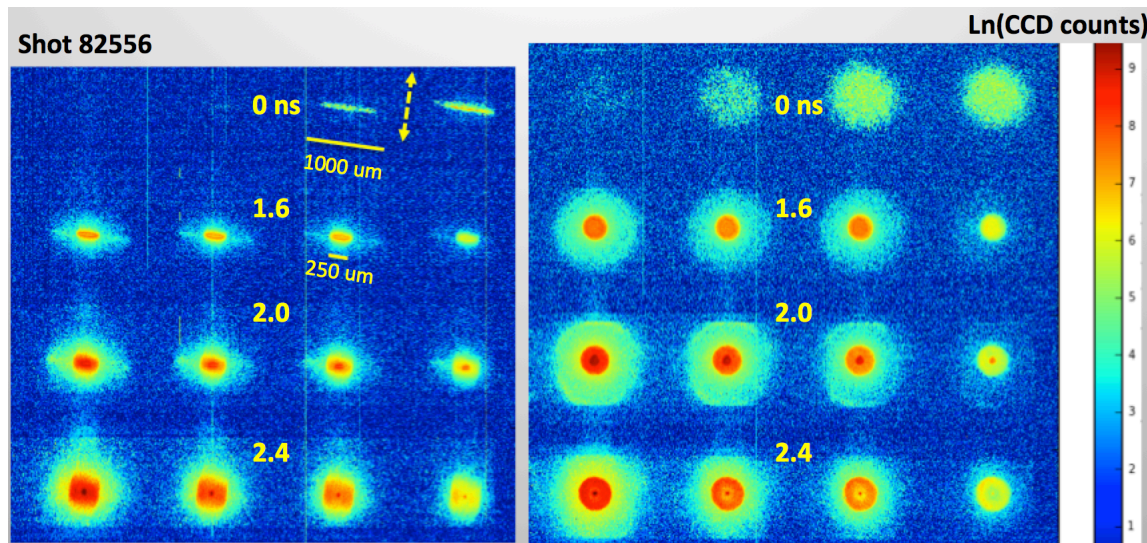


Figure 1: Log-scale rendering of gated x-ray images of the circular AuNLTE target. Images at left were obtained by viewing the target edge-on; images at right are face-on. The cameras were synchronized by observing laser turn-on (first row of images). Timing for each strip is labeled in the center, with the gate pulse propagating from left to right along each strip. Target dimensions are provided for the images on the left. The x-ray emission from the 250 micron diameter high-Z sample (orange-red) is visible inside the relatively weak signal from the 1000 micron diameter beryllium tamper (cyan halo).

E. 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,” meaning they 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, with a second goal of demonstrating the dynamic range of the technique by measuring RT growth in solid copper. The FY16 shots made significant progress towards these goals.

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 number, A_n , quantifies the magnitude of the density jump at the interface. Acceleration of the sample in this Omega-EP experiment is provided by the stagnation of a releasing shocked plastic “reservoir,” which is directly driven by approximately 1-2 kJ of laser energy, depending on the desired material condition. The growth of pre-imposed ripples is recorded using transmission x-ray radiography from a copper He- α slit backlighter source, where the opacity of the sample is calibrated to the ripple amplitude. The pre-shot metrology and measured profile of the driven sample together yield the growth factor, which is compared to models of RT growth. A gold knife-edge on the sample provides a measure of the modulation transfer function, and a step-wedge creates an opacity look-up table on each shot, resulting in error bars of approximately $\pm 10\%$.

In December 2015 a new set of large-spot phase plates were commissioned, and the drive was recalibrated to produce pressure conditions similar to those present during the shots earlier in 2015 with smaller laser spots. Excellent planarity was achieved (Figure 1) and it was established that the laser energy was sufficient to reach the highest pressure condition necessary for the campaign.

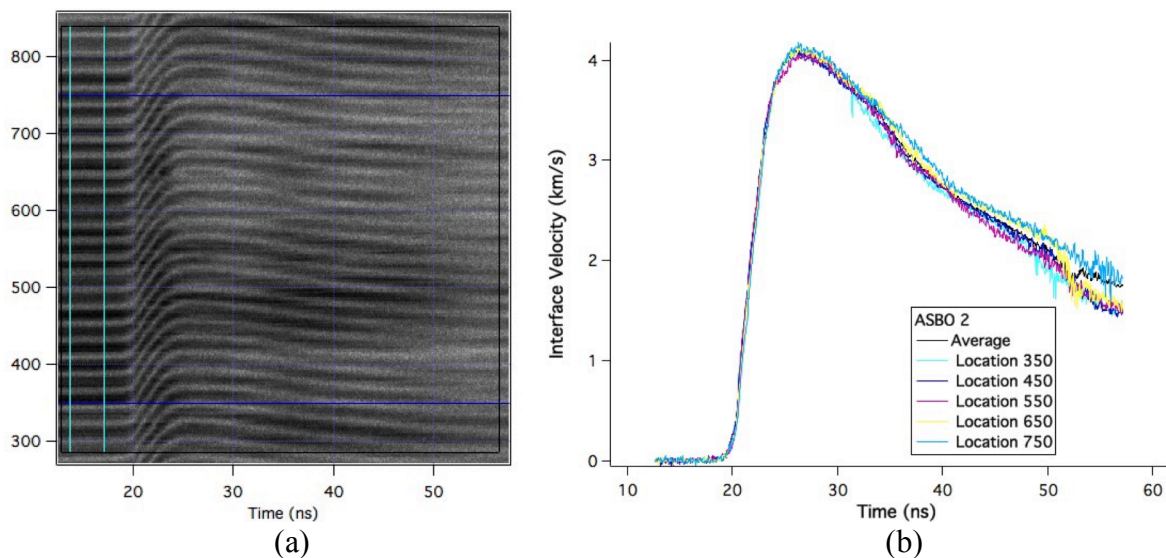


Figure 1. The ASBO (VISAR) data from shot 24063 is shown in (a) and a series of lineouts taken across the image is plotted in (b) showing excellent planarity.

Later
in

FY16, Due to a target build that was out of specification, measurements of liquid phase RT growth were delayed, but the targets as built were sufficient to investigate solid state copper behavior. RT growth data (Fig. 2) collected under very similar peak pressures in solid state copper indicates that the smaller phase plate data diverges from the large phase plate data at late times, likely due to the loss of planarity and more rapid drop off in ripple driving force. The analysis of this data is ongoing and modeling of the ripple growth is underway. Additional experiments are planned for FY17.

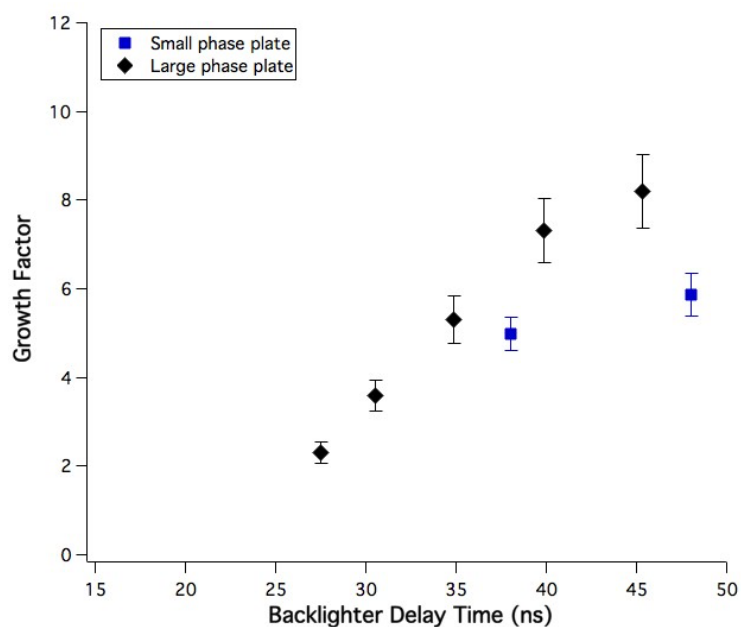


Fig. 2. Growth factor data for solid copper using small and large phase plates.

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

The four half-day AMFoam campaigns evaluated the use of 3D printed or Additive Manufactured Foams as surrogates to carbonized resorcinol foams (CRF) in ramp compression target designs, in support of ongoing Material Strength experiment on the National Ignition Facility. The 3D printed foams were structured as follows: individually printed lines were grouped into $100 \times 100 \times 16 \text{ } \mu\text{m}^3$ “log pile” blocks, which in turn were stitched together to form $16 \text{ } \mu\text{m}$ thick layers 1.7 mm in diameter. Seven of the $16 \text{ } \mu\text{m}$ layers are then stacked to arrive at cylindrical “AM foams” that are 1.7 mm in diameter and $112 \text{ } \mu\text{m}$ tall. These foams are then glued onto a $25 \text{ } \mu\text{m}$ Be + $180 \text{ } \mu\text{m}$ 12% Br-doped CH ablator assembly. Following the ramp compression platform described in Ref. [1], fifteen beams of the Omega laser with 300 J in 2 ns drive through the ablator and launch the foam across a gap to send a ramp compression wave into an Al/LiF sample (see Figure 1, lower left), which is diagnosed using 1-D line VISAR viewing the sample off a semireflective mirror. In addition, 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 $\sim 3 \text{ } \mu\text{m}$ [2]. An example of the intensity field recorded on the 2D VISAR is shown in Figure 1, lower right. Over the course of the four campaigns the structure of the 3D printed foam was varied, with the goal of optimizing the temporal ramp profile.

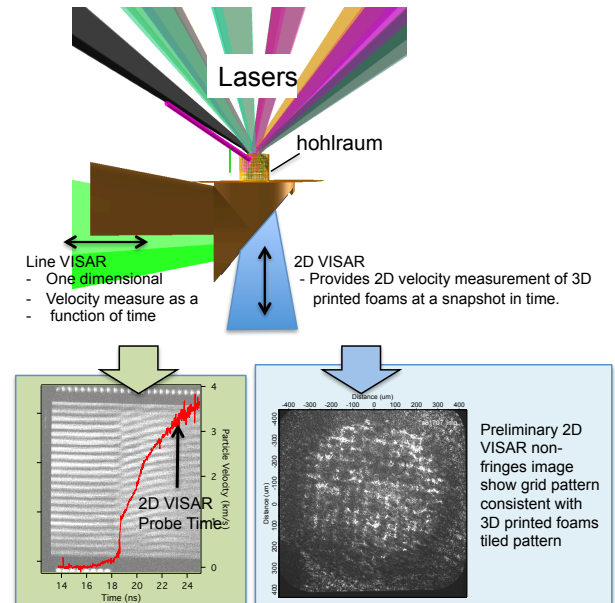


Figure 9 Schematic diagram describing the experimental setup for the AMFoam-17C/D campaigns, which combine the OHRV and ASBO diagnostics on a single shot. The goal of these shots was to characterize the temporal and spatial drive associated with additive manufactured (3D printed) foam targets. For the AMFoam-17A/B campaigns only the ASBO (VISAR) diagnostic was used.

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

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

3. Development of Experimental Platform for Reflection Diffraction Measurements During Shock or Ramp Compression (PI: C.E. Wehrenberg)

This campaign seeks to develop a platform for x-ray diffraction in-situ during shock or ramp compression in a reflection geometry. To measure the strain state of a material in detail, it is necessary to probe the strain in several directions, yet diffraction experiments to date on Omega and NIF have been limited to transmission diffraction in a narrow range of angles of incidence. A capability to measure diffraction in reflection geometry would greatly increase a diffraction experiment's sensitivity to shear strain.

In this campaign, 1 or 2 UV beams drove an Fe backlighter, while 1 or 2 UV beams drove a shock into an ablator and a sample (Ta or Fe). A 3D-printed mount held both the sample and a pinhole to collimate the incoming x-rays. A separate positioner held an image plate detector, and a shield attached to the backlighter prevented x-rays from going straight-through to the detector. The campaign tested several configurations for the backlighter shielding, pinhole, and detector filtering, and also measured the background created by the sample drive. The campaign was successful in recording the first reflection diffraction signal, albeit a weak signal, as shown in Figure 1. Future work will need to improve shielding and collimation to improve the diffraction resolution and signal-to-noise.

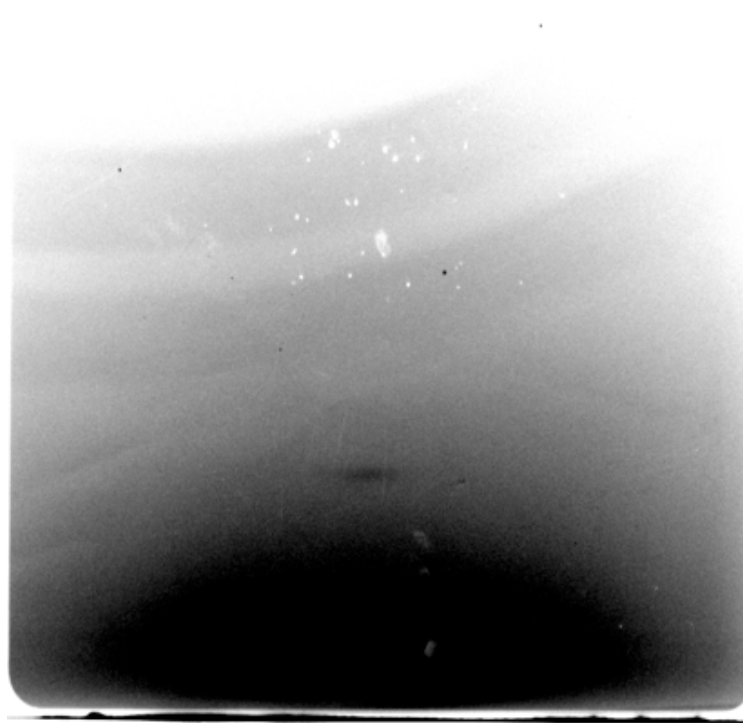


Figure 1: Diffraction pattern from Ta sample in reflection geometry. The two “Saturn ring” broad diffraction lines near the top are an indication that improvements in the x-ray collimation are needed.

4. Understanding Plasticity Mechanisms in Ramp-Compressed Tantalum (PI: C.E. Wehrenberg)

This campaign seeks to understand the mechanism for plasticity in ramp compressed Ta, using x-ray diffraction (XRD) to track the texture change. The Ta samples initially had a sharp (011) fiber texture, which allows subsequent texture changes that develop during compression to be easily detected. Since previous XRD campaigns studying Ta have encountered issues with diffraction signal from the diamond pusher overlapping the expected Ta signal, this campaign developed a ramp drive using a kapton ablator/pusher. This Omega-EP campaign used two UV beams to drive a zinc backlighter and two more UV beams to drive a ramp wave through the kapton ablator and into the Ta sample. Eight shots were performed, with the first four shots successfully demonstrating a ramp drive to 1.6 Mbar. Figure 1 shows a comparison between the data from an ambient (static, undriven) sample (bottom row) and data from a 1.6 Mbar shot (top row). The change in position of the azimuthal texture spots in the ramp-compressed pattern, when compared to the ambient one, will be used to determine the operative deformation mechanisms.

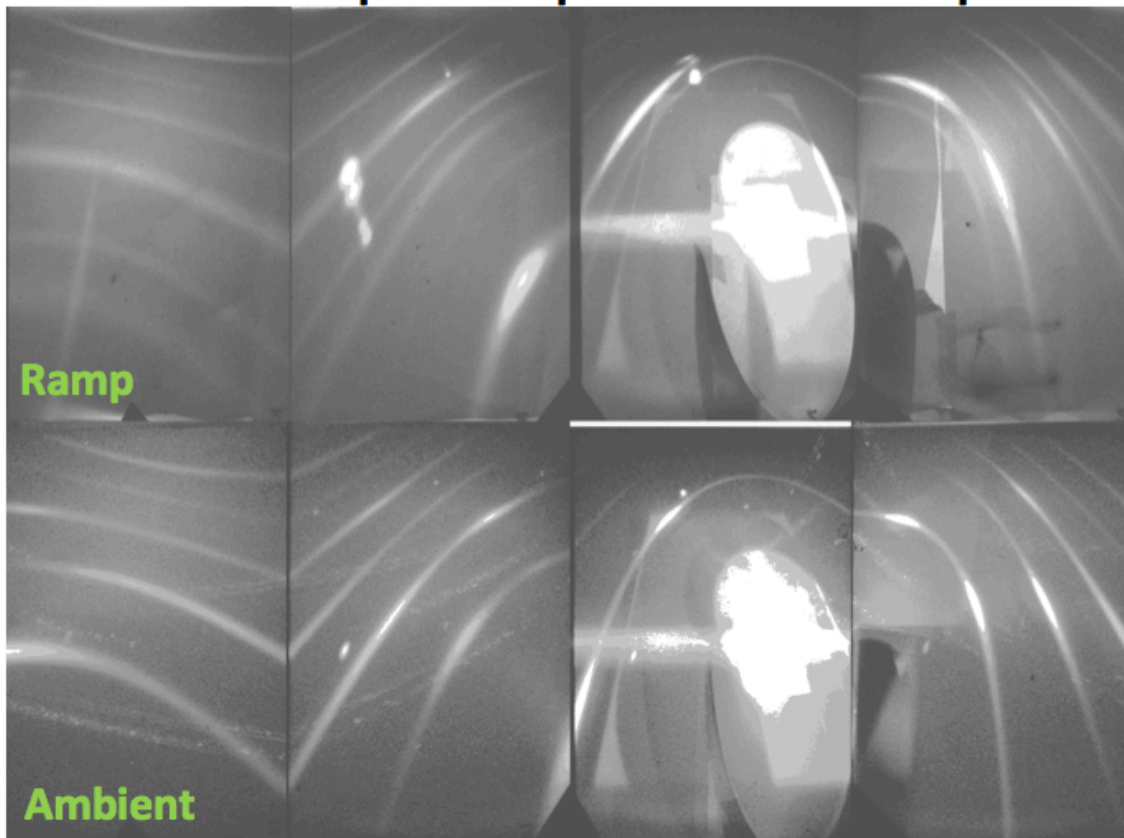


Figure 1: (Top) Diffraction from (011) fiber-textured, ramp-compressed to 1.6 Mbar. (Bottom) Diffraction from the same (011) fiber-textured sample under ambient conditions.

5. Understanding Plasticity Mechanisms in Shock-Compressed Tantalum (PI: C.E. Wehrenberg)

This campaign seeks to understand the mechanism for plasticity in shock compressed Ta, using x-ray diffraction (XRD) to track the texture change. Similar to the TaStrDiff-16A campaign on EP, which used ramp compression, in this campaign on Omega the Ta samples initially had a sharp (011) fiber texture, which allows subsequent texture changes that develop during compression to be easily detected. This campaign used 16 beams to drive a zinc backlighter, and two beams to drive a steady shock through the kapton ablator and into the Ta sample. A total of 13 shots were performed, scanning a pressure range from 30-160 GPa. The figure below shows example data for a ~ 80 GPa shock. A new texture component is observed in the data that corresponds to twinning across the (112) plane, which produces a reorientation of the atomic lattice and thus a change in the diffraction pattern. This type of driven data can now be used to determine the mechanism for plasticity during shock compression.

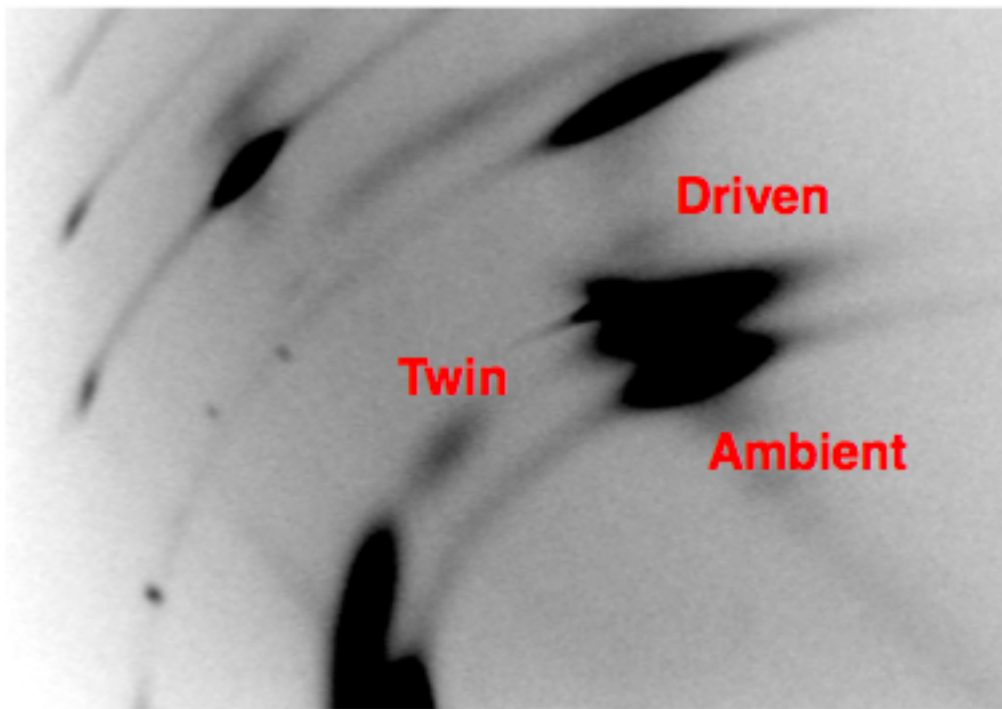


Figure 1: Diffraction data for (011) fiber-texture Ta which has been shock-compressed to ~ 80 GPa. The data is taken as the shock is in-transit through the sample, so diffraction patterns from both ambient and compressed (driven) material are observed. A new texture component can be seen in the data from the compressed material, that corresponds to the twinning across the (112) plane.

Laboratory Basic Science Experiments

1. Structural Studies of Electride Phases of High-Density Matter: Structures of Mg to above 10 Mbars (PI: A.E. Lazicki)

with Federica Coppari, Ray Smith, Richard Kraus, Ryan Rygg, Dayne Fratanduono, Jon Eggert and Gilbert Collins (LLNL), Malcolm McMahon, Martin Gorman and Amy Coleman (U. of Edinburgh), David McGonegle and Justin Wark (Oxford), Lisa Peacock and Steve Rothman (AWE)

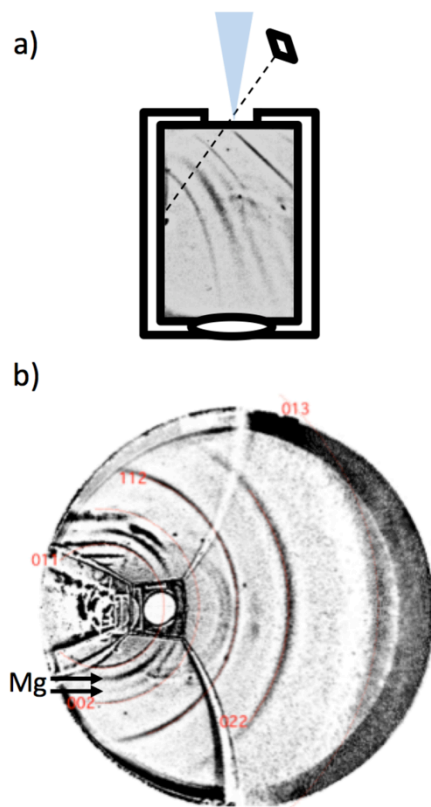


Figure 10. a) Cross section of the PXRDIIP diagnostic showing the laser drive in blue and the x-ray source incident at ~ 45 degrees into the image plate chamber, where diffraction peaks are registered. b) Image plates digitally warped into a stereographic projection to show the x-ray diffraction peaks from Mg near 400 GPa (indicated with arrows) and from an ambient Ta calibrant (marked with red lines).

This campaign sought to realize new theoretically predicted high pressure phases of Mg, which have the interesting feature of density-driven electron localization in interstitial regions in the crystal lattice, occurring as a direct consequence of strong quantum mechanical constraints on the electronic wave functions of core and valence electrons at high compression. Three of these ‘electride’ phases are predicted between 4 and 12 Mbar for Mg [1-3].

The experiment compressed solid Mg to the 10 Mbar pressure regime using ramped laser pulses, and probed crystal structure using the PXRDIIP diagnostic via transmission diffraction of He- α x-rays from a metal foil backlighter. Pressure in the sample was probed by measuring the target free surface velocity using VISAR and correlating it with a pressure state. Four half-days on Omega were used to optimize the target design, pulse shapes, diagnostic filtering and timing, and then to collect data between 2 and 15 Mbar. In spite of the very weak x-ray scattering strength of low-Z Mg, diffraction peaks were registered at up to 6-7 Mbar, above which pulse length limitations hampered the ramp compression of the Mg, despite a high background due to ablation plasma x-rays. Above 4 Mbar, the data shows indications of a new phase, albeit inconsistent with the theoretical predictions. These results are being used to design further measurements on the National Ignition Facility.

- [1] Neaton & Ashcroft, *Nature* **400**, 141 (1999)
- [2] Liu *et al*, *J. Appl. Phys.* **105**, 123505 (2009).
- [3] Pickard & Needs, *Nat. Mat.* **9**, 624 (2010).

2. Pressure Ionization in Ramp Compressed Materials

(LBS P.I. Y. Ping; Shot P.I. S. Jiang)

with R. Shepherd and R.F. Heeter

The pressure ionization campaign comprised 2 half-days on OMEGA during FY16. This campaign used ramp compression to compress an iron foil up to twice its original density, while keeping the temperature below 1 eV. The driver consisted of five laser pulses stacked in time. Separately, a spherical implosion provided a broadband X-ray backlighter. Both the absorption and fluorescence spectra were measured, to study the energy shift of the Fe inner shells due to pressure ionization. Figure 1(a) shows the measured absorption spectrum. The top is a raw image from a 2x compression shot. X-ray filters of Fe, Mn and Cr at the entrance slit of the spectrometer provided K-edge wavelength fiducials. The Fe K-edge was measured for 4 different cases: undriven Fe, Fe with 2x and 1.5x compression, and liquid Fe. No obvious shift of the Fe K edge was observed in any of these cases. Figure 1(b) shows the fluorescence spectra measured using MSPEC, in which $K\alpha$ fluorescence was observed for the first time in ramp-compressed iron, despite noise and high background levels. The top two images on Figure 1(b) show raw spectra processed using a despeckling technique. The two lines from right to left correspond to Fe $K\alpha$ and Cu $K\alpha$ (from an undriven Cu washer used to mount the iron sample). The Cu $K\alpha$ line provides a reference to compare different shots. The bottom plot of Figure 1(b) compares the $K\alpha$ peaks from liquid Fe (blue) and from solid Fe with 2x compression (red). There appears to be a slight shift in the $K\alpha$ energy. Future experiments will improve the signal-to-noise ratio, use of a higher resolution spectrometer to confirm the energy change, and seek to measure the weaker $K\beta$ signal which is more prone to a shift due to pressure ionization.

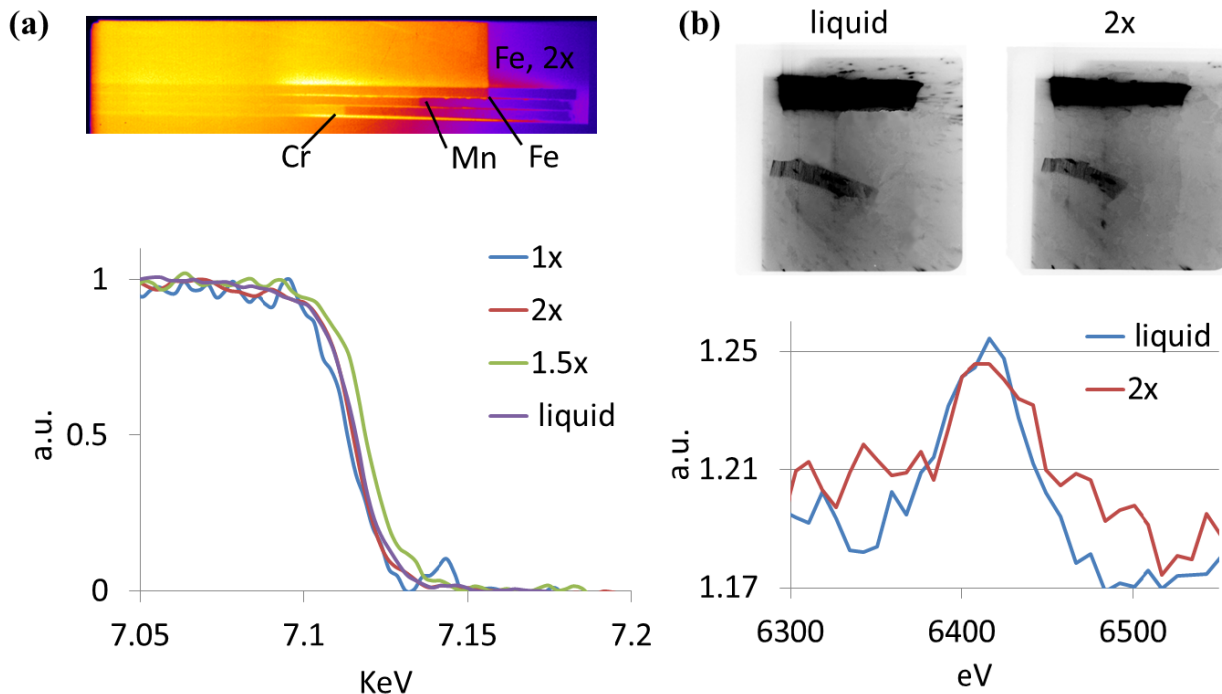


Figure 1: (a) Top: a raw image of the measured absorption spectrum for 2x compressed Fe. Bottom: measured Fe K edge under four different conditions. (b) Top: measured MSPEC spectra, despeckled to reduce noise. Bottom: lineouts of the Fe $K\alpha$ feature for liquid and 2x compressed Fe.

3. Hohlraum Magnetization Using Laser Driven Currents

(LBS PI: J. Moody; Shot PI: B.B. Pollock)

with J.S. Ross, D. Turnbull, C. Goyon, A. Hazi, G.F. Swadling and W. Farmer

In FY16 the 2-day LDMag campaign on Omega EP continued a basic science investigation of the feasibility of using laser-generated currents to self-magnetize targets, such as future ICF hohlraums. These experiments substantially improved the proton deflectometry capability of previous campaigns to probe the fringing magnetic field structure around the outside of the half-loop target shown in Figure 1. On the open side of the loop are parallel plates, into one of which holes were placed so that the EP long pulse beams may shine through to produce a plasma at the surface of the second plate. Hot electrons from this plasma collect around the holes in the first plate, driving a current through the half-loop which connects the plates, and producing a magnetic field on the loop axis and in the surrounding volume.

To probe these fields, protons are produced through the target-normal sheath acceleration (TNSA) mechanism from the interaction of the two orthogonal EP short pulse beams with two, separate, thin Au foil targets as shown in Figure 2. Cu meshes impose fiducials in the proton images recorded on radio-chromic film, providing detailed measurements of the field profile millimeters from the target. The loop structure was probed both along and across its axis by protons produced using the orthogonal short pulse beams. Fields up to 200 T were inferred at the end of the 0.75-1 ns, 1 TW B-field drive laser pulses. The analysis of this recent experiment is ongoing and will inform the FY17 continuation of this effort.

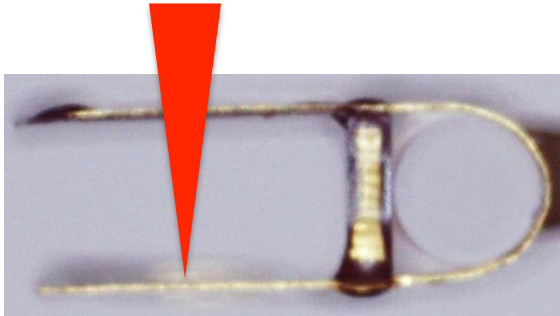


Figure 1: (Left) End-on view of geometry for hohlraum self-magnetization on Omega-EP, with beampath shown schematically in red.

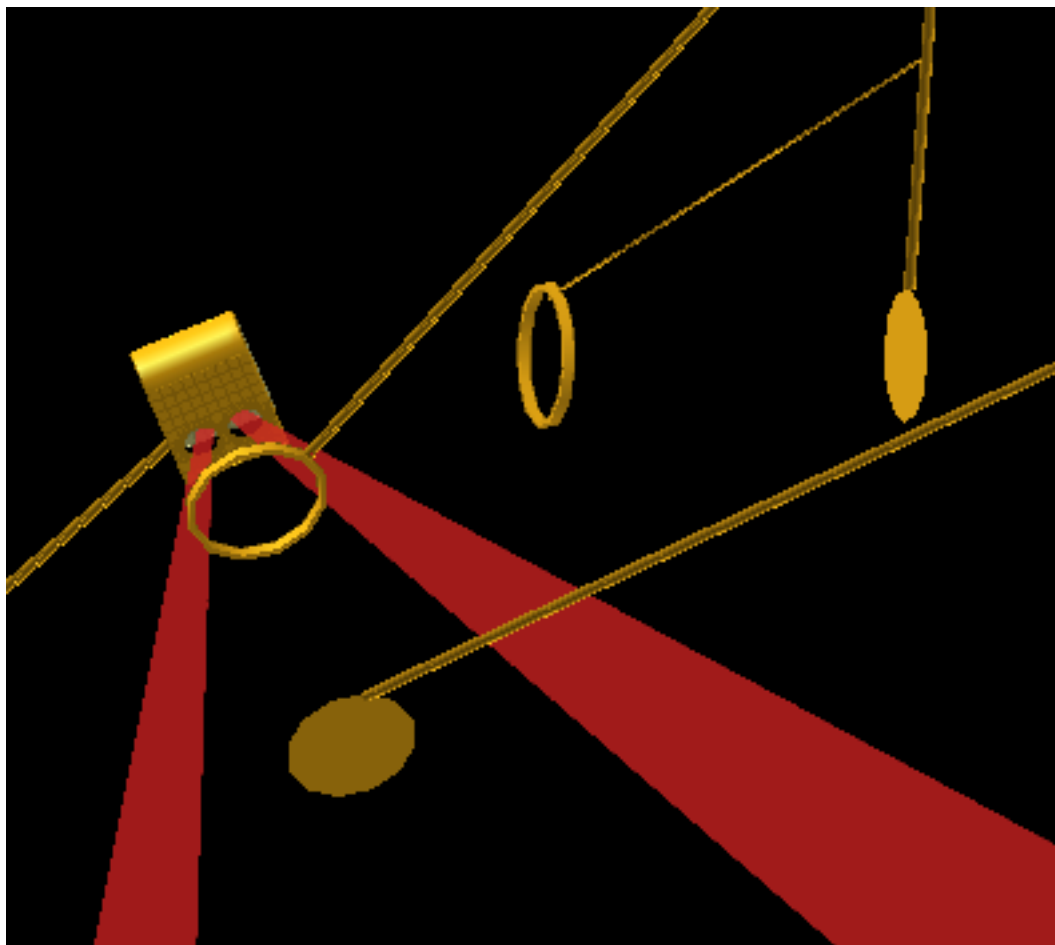


Figure Y: Geometry for proton deflectometry on Omega-EP, with proton detectors (not shown) placed 8 cm behind and to the left of the the B-field target.

4. Shear stress and mechanism of phase transition in shock compressed iron (PI: C.E. Wehrenberg)

The IronLaue-16 campaign was the first campaign to use Laue diffraction to study the response of single crystal iron to shock compression, using in-situ Laue diffraction. As shock compression drives iron through a BCC-Hexagonal phase transition, Laue diffraction can be used to determine the orientation of the transformed phase, and thus the mechanism of transformation. Additionally, Laue can measure the shear strain in the compressed state. In these shots, 32 Omega beams were used to drive an implosion of an empty CH capsule, creating a burst of broadband x-rays during stagnation that are used for Laue diffraction. Separately, 2 beams were used to drive a shock into an ablator and the single-crystal sample. Excellent diffraction data was observed in several shots for a range of shock pressures. Figure 1 below shows an example in which multiple diffraction spots from the shock-compressed iron are visible.

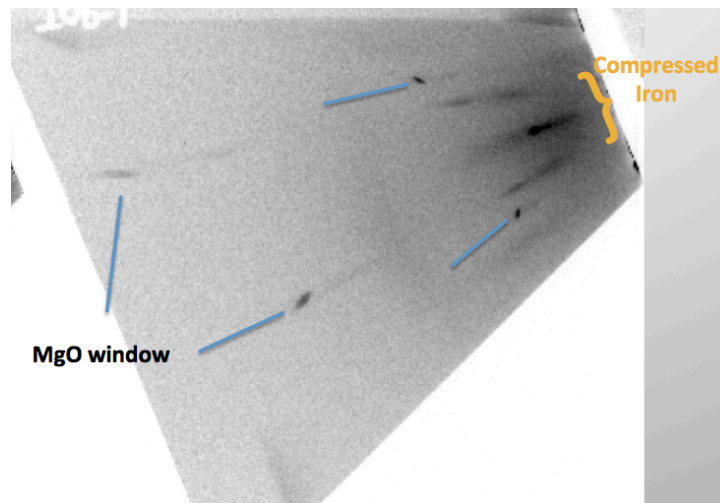


Figure 1: Example Laue diffraction data showing multiple diffraction spots from shock-compressed iron.

5. Laser Driven Electrostatic Shockwave Acceleration (PI: A. Pak)

with D. Haberberger (LLE) and T. Link

This shot day on Omega EP sought to create and image a relativistic collisionless electrostatic shock wave using a high-power short-pulse laser. The astrophysical community is interested in understanding the plasma conditions under which these collisionless shocks form, the structure of their associated electric fields, and the resulting particle acceleration. It's also desirable to assess the viability of this new ion acceleration mechanism to produce an ion beam with the following properties: ~ 100 MeV per a.m.u., narrow energy spread $\Delta E/E \sim 10\%$, and high beam density $\sim 10^{10}$ particles per bunch.

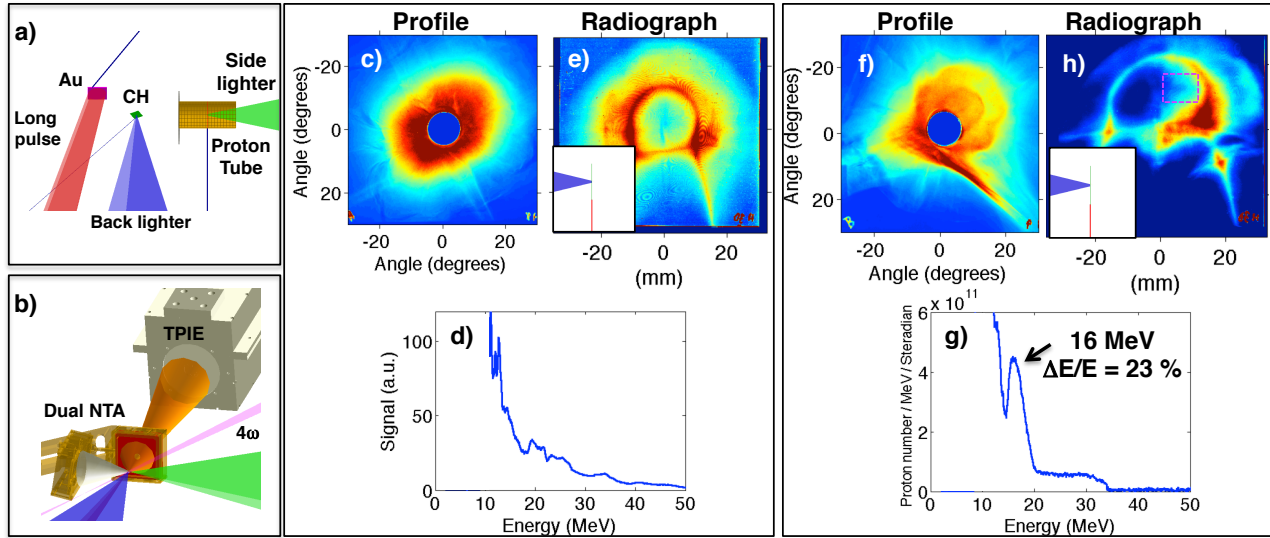


Figure 1: a) Experimental configuration and b) diagnostic suite. A long pulse beam creates x-rays to ablate an initially 1.4 μm thick CH foil, to tailor the plasma density profile. The short pulse “backlighter” beam then drives the target, producing a proton beam via target-normal sheath acceleration (TNSA). Orthogonal to this, the “sidelighter” beam creates a 2nd proton beam as a radiographic probe. c-d) TNSA proton beam profile and spectrum from direct drive of the CH foil, without x-ray preheat. The hole in the profile measurement transmits part of the beam to the Thomson parabola diagnostic. e) Side-on proton radiograph of the TNSA field. f-g) TNSA beam profile and spectrum from an experiment with x-ray tailored plasma density profile. h) The resulting proton radiograph; inset shows backlighter laser incident from the left, while the x-ray preheat comes from the right.

A summary of the experimental and diagnostic setup is shown in Figure 1a & 1b. An x-ray drive is first produced (or not) using a 1 ns laser pulse to irradiate a 25 μm thick gold foil. The x-ray drive ablates and expands an initially 1.4 μm thick CH target. After waiting ~ 500 ps for the peak plasma electron density to fall to $\sim 5 \times 10^{21} \text{ cm}^{-3}$, the backlighter beam drives the electrostatic shock wave to accelerate particles. The sidelighter beam then irradiates a second, orthogonal proton source to probe the CH plasma. Figures (c-e) and (f-h) compare the accelerated proton beam profile, spectrum, and side on proton radiography from, respectively, a unperturbed foil and an expanded target. When the plasma density profile is first tailored with the x-ray drive, the proton spectrum exhibits a narrowband feature at ~ 16 MeV (Fig. 1g), and the side on radiography shows a localized deficit in the probe beam. Both features are consistent with the generation of an electrostatic shock wave, and are absent on the control experiment where an unperturbed target was used. Future work will focus on correlating the accelerated spectrum to the velocity of the electrostatic shock wave as inferred from the proton radiography data.

6. Development of a Compressed Ultrafast Photography diagnostic for time-resolved imaging of dynamically compressed samples (LBS PI: J. Eggert; Shot PI: S.J. Ali) with D.E. Fratanduono

Late in FY16, one day on Omega EP was used to assess the feasibility of ultrafast optical imaging using coded images recorded by a Hamamatsu C7700 streak camera. The target design consisted of a plastic ablator and aluminum pusher driving a shock wave into a 2x2 grid of quartz samples of varying thicknesses, resulting in large scale spatially varying reflectivity changes as a function of time. A subset of the targets had an additional feature etched into the aluminum pusher layer, to assess the resolution of the reconstructed series of images. Over the course of the day, data were collected with four different coded mask resolutions, three different streak camera slit widths, and three different intensity levels on the camera. The full data set will enable assessment of the viability of the diagnostic, and better determination of the ideal experimental parameters for the diagnostic setup. Further analysis is required, as the reconstruction of the images is nontrivial; however, the initial results are promising and suggest that this Compressed Ultrafast Photography (CUP) diagnostic can provide images of the target with roughly 100 ps resolution.

8. Astrophysical Collisionless Shock Experiments with Lasers (ACSEL) (LBS PI: H.-S. Park; Shot PIs: C.M. Huntington and G.F. Swadling)

The ACSEL-16A and 16B experiments continued to investigate the formation of astrophysically relevant collisionless shocks in a diagnosable, laboratory environment. These shots were carried out in support of the ongoing ACSEL effort at LLNL, and with support of the broad, cross-institutional ACSEL collaboration. A total of thirteen target shots were completed during ACSEL-16A, and fourteen during ACSEL-16B. The experiments primarily investigated interactions between beryllium targets, which were selected to provide a low Z , single species blow-off plasma, in order to simplify Thomson scattering analysis. Experiments also investigated end-on proton probing using thin foil targets, and a new dish-shaped plastic target.

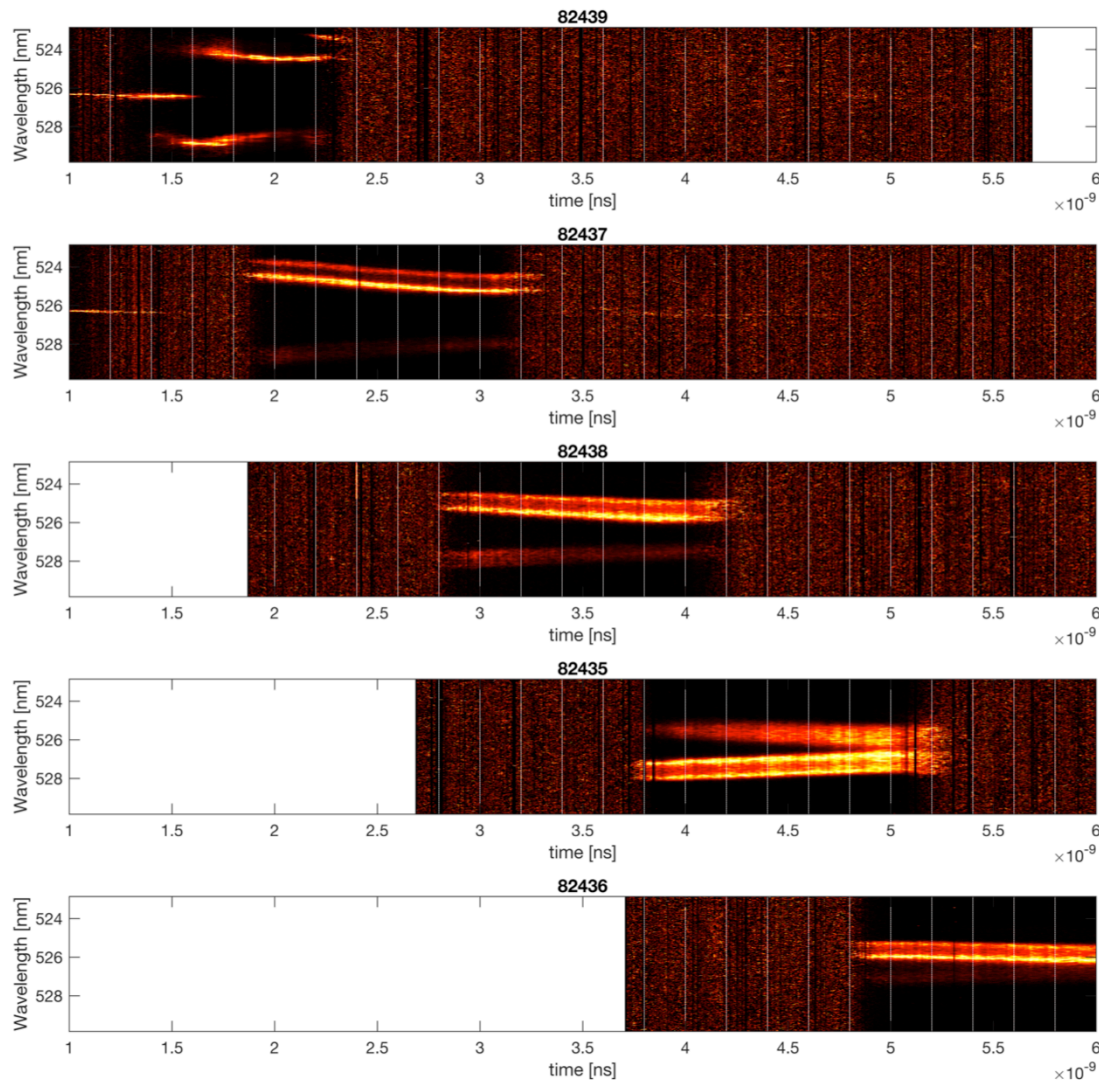


Figure 1) Thomson scattering ion acoustic wave time-series, showing interpenetration of a pair of beryllium plasma flows.

The experiments used the Omega-60 beams to heat the surfaces of a pair of opposed targets, launching counter-propagating plumes of high velocity ($\sim 10^6 \text{ ms}^{-1}$), high temperature ($\sim \text{keV}$) plasma. The parameters of the outflows are such that they are largely collisionless, but with parameters amenable to the growth of instabilities, which can mediate the formation of a collisionless shock.

The interaction of the flows is diagnosed using a combination of a) temporally resolved, single point, optical Thomson scattering and b) proton radiography imaging. A D^3He exploding-pusher capsule provides a dichromatic (3.3 and 14.4 MeV) proton source for radiography, allowing probing at two separate times during each experiment. Images are recorded on CR39 nuclear track detectors whose processing and analysis is carried out by collaborators at MIT. Previous proton imaging data has detected the presence of complex magnetic field structures. The field structures are observed to grow in strength as the experiment progresses; the observed filamentary structures are interpreted as being the result of the growth of the Weibel instability in the region where the flows collide and interpenetrate.

The primary goal of ACSEL-16A&B was to collect improved optical Thomson scattering data by using the beryllium targets to provide single species plasmas; this significantly simplifies the interpretation of the detailed structure of the scattered spectra. The Thomson scattering diagnostic records both ion acoustic wave and electron plasma wave features; data from this diagnostic has been previously used to diagnose the interpenetration of the flows, and to measure heating associated with the development of the two-stream instability. Figure 1 shows sample Thomson scattering data from this campaign. High quality data was captured of the flow interactions at target separations of 4 and 5 mm. Analysis of these data will reveal trends in the evolution of the plasma parameters of the interacting flows.

New experiments carried out in ACSEL-16B investigated a new target configuration. These targets were modified to a “dish” shape, allowing a significantly larger number of beams to impinge on the target within the facility’s incident-angle constraints. This modification to the target geometry increased the density of the outflows by a factor of ten, as measured via Thomson scattering. This density scaling has the potential to allow greater control in the pursuit of the formation of a mature collisionless shock.