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FY19 LLNL Experimental Programs at Omega

R. F. Heeter, F. Albert, S. J. Ali, L. R. Benedetti, N. Candeias Lemos, H. Chen, F. Coppari, A. Fernandez Panella, D. E. Fratanduono, M. Ginnane, M. Gorman, M. Hohenberger, S. Jiang, G. E. Kemp, S. F. Khan, P. King, A. Krygier, A. E. Lazicki, T. Ma, M. J. MacDonald, D. Mariscal, E. V. Marley, M. C. Marshall, D. A. Martinez, M. A. Millot, C. A. J. Palmer, H. S. Park, J. Park, G. Perez Callejo, Y. Ping, B. B. Pollock, P. L. Poole, J. Ralph, A. M. Saunders, G. F. Swadling, R. Tommasini, K. Widmann, A. Zylstra, O. L. Landen, W. W. Hsing, A. S. Wan

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In Fiscal Year 2019 (FY19), 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. This was the 21st year of National Lab collaborative experiments at OMEGA since the Nova Laser at LLNL shut down in 1999 [1], building upon prior collaborations. In FY19 overall, these LLNL programs led 488 target shots, with 259 shots using just the OMEGA laser system and 229 shots using just the EP laser system. Approximately 33% of the total number of shots (84 OMEGA shots and 79 EP shots) supported the Indirect Drive Inertial Confinement Fusion Campaign. The remaining 67% (175 OMEGA-only shots and 150 EP-only 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 80 target shots using just OMEGA, 68 shots using just EP, and 7 Joint shots using both lasers together. The highlights of these are also summarized, following the ICF and HED campaigns.

Overall, LLNL PIs led a total of 636 shots at LLE in FY 2019. In addition, LLNL PIs supported 7 NLUF shots on Omega and 32 NLUF shots on EP in collaboration with the academic community.

[1] LLE 1999 Annual Report, DOE/SF/19460-332 (January 2000). This report notes on page 222 that LLNL conducted 173 shots on OMEGA in 1999.

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Indirect Drive Inertial Confinement Fusion Experiments

1. Hydrodynamic Response from Non-Uniformities in High-Density Carbon Ablators (PI: S. Ali)

with P. M. Celliers, A. Fernandez-Panella, C. Weber, S. W. Haan, V. Smalyuk

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. These can arise due to, among other reasons, intrinsic heterogeneity within the capsule material. High density carbon (HDC) is a polycrystalline diamond material that has complex microstructure, as well as being acoustically anisotropic, which can lead to variations in the shock speed in crystallites of different orientations, potentially seeding instabilities. Additional sources of heterogeneous response include behavior of the grain boundary material, which is often of a different bonding character than the crystallites, voids in the deposited material, and static internal stresses in the polycrystalline structure. The current strategy for reducing the impact of internal heterogeneities is to fully melt the ablator material on the first shock, requiring >12 Mbar for HDC.[1-3] This

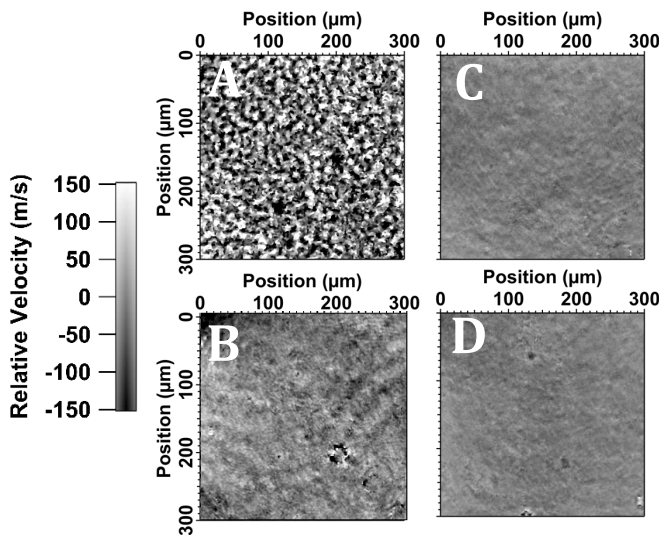


Figure 1 Velocity maps from nanocrystalline HDC releasing into cryogenic D_2 at (A) ~ 7 Mbar with RMS 100 m/s (B) $\sim 8-9$ Mbar with RMS 45 m/s, (C) ~ 10 Mbar with RMS 14 m/s, and (D) ~ 12 Mbar with RMS 12 m/s. The diagnostic detection limit is 10 m/s for B and 5 m/s for A, C, and D.

Capseed campaigns, we have been moving toward using large diameter (4.5-5 mm) capsules for our two half-day campaigns in FY19. Unfortunately, due to the complexity involved in fabricating these large spheres, the 5 mm HDC spheres were not complete in time for 19B, but a secondary goal of measuring the effect of grain size on the nonuniformity was achieved. Relative to the microcrystalline HDC, the onset of velocity uniformity in the 10-20 m/s range occurred at just under 10 Mbar, as shown in Figure 1. This suggests that nanocrystalline capsules can be driven on a lower adiabat than larger grain size capsules, while still remaining relatively free of instabilities. This work is ongoing, and target fabrication has made great strides in fabricating the

strong shock also raises the entropy of the fuel, making it more difficult to reach the high densities required for ignition. As part of the effort to understand both the origin and impact of the velocity non-uniformities in HDC, we have conducted two-dimensional velocimetry experiments on planar foils under conditions near the first shock in HDC.

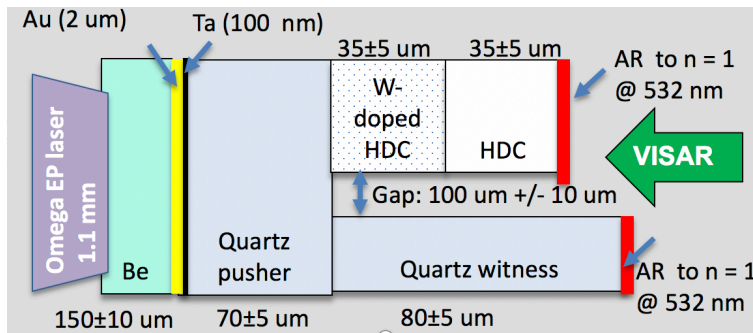
The Capseed campaign goal is to measure shock front velocity non-uniformities in Inertial Confinement Fusion (ICF) ablator materials and quantify the level of non-uniformity caused by intrinsic effects. This is done using the Omega High Resolution Velocimeter (OHRV) to obtain velocity maps of the optically reflecting shock front following release of the ablator material into either PMMA for the warm experiments or cryogenic deuterium for the cryo experiments. As part of our attempt to move toward more capsule-like targets, as opposed to the planar foils that have been used for past

larger diameter spheres, so the plan remains to move toward the capsule-like samples while still investigating other potential sources of perturbation.

- [1] D. K. Bradley, S. T. Prisbrey, R. H. Page, D. G. Braun, M. J. Edwards, R. Hibbard, K. A. Moreno, M. P. Mauldin and A. Nikroo, *Phys. Plasmas* **16** (2009).
- [2] D. K. Bradley, J. H. Eggert, R. F. Smith, S. T. Prisbrey, D. G. Hicks, D. G. Braun, J. Biener, A. V. Hamza, R. E. Rudd and G. W. Collins, *Phys. Rev. Lett.* **102** (2009).
- [3] S. W. Haan, J. D. Lindl, D. A. Callahan, D. S. Clark, J. D. Salmonson, B. A. Hammel, L. J. Atherton, R. C. Cook, M. J. Edwards, S. Glenzer *et al.*, *Phys. Plasmas* **18** (2011).

2. Determination of EOS and Melt Line of W-Doped Diamond Between 6-12 Mbar (PI: Amalia Fernandez Pañella) with M. Millot and P. Celliers

This half day at OMEGA-EP was designed to collect high quality data on the melt line and EOS of W-doped diamond (0.3 at. %) in the multi Mbar range. W-doped HDC is used in ICF capsules at NIF, but scarce EOS data is available, and little is known about what effect the doping has on the diamond melt line. MD simulations by Stanimir Bonev predict that the melt temperature of HDC decreases with increasing Si dopant concentration. Similar effects are expected with W dopant, but experimental verification is required.



The W-doped HDC-19A campaign used planar targets and a direct-drive configuration with Be ablator, a quartz pusher and two samples side by side, one being W-doped HDC and pure HDC glued together and the other being a quartz witness (see Fig.1). The velocity profiles were recorded using VISAR and the

emissivity using SOP. Throughout the day, the laser drive energy was changed in order to probe different shocked pressure states in the diamond.

We obtained 6 good data points from 600-1200 GPa. The experimental design was successful, and shocks were steady as indicated by the quartz witness velocity history. The W-doped HDC target at 0.3 at. % is completely opaque at the VISAR and SOP wavelengths. Transit time

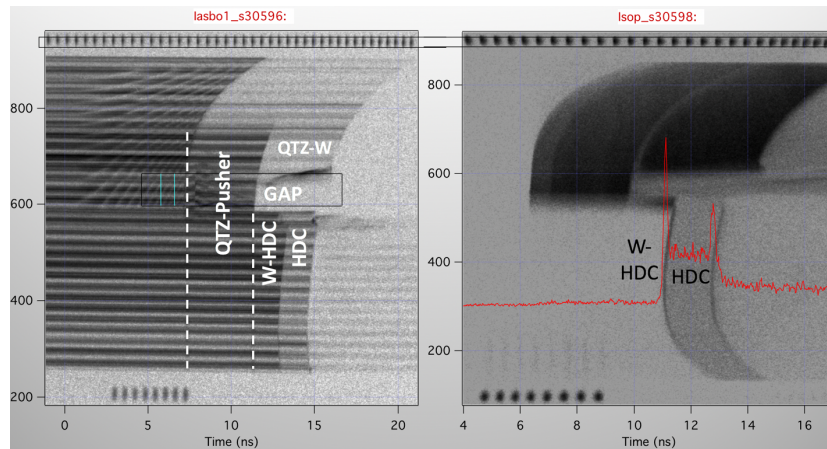


Figure 3 Visar and SOP data from S30596, corresponding to 9.5 Mbar. No fringe movement nor emission is observed in the W-HDC sample.

analysis will be used to infer EOS data. Furthermore, we will also use the SOP data from the pure and transparent HDC to constrain its temperature along the melt line of pure diamond. Once we finish the analysis of the data, we will be able to constrain the EOS of W-doped HDC in a pressure range relevant for ICF experiments.

3. Study of the Melting Temperature of Diamond with Pyrometry

(PI: Marius Millot)

with Peter Celliers (LLNL)

This series of shot aims at measuring the shock temperature of diamond over a broad pressure range from 5 Mbar to 40 Mbar. To do this, the approach builds on the previous work by Eggert *et al.* carried out at Omega in 2005-2006 and reported in [1]. Namely, the idea is to launch a strong, unsupported shock in a thick sample of diamond and track simultaneously the shock velocity and reflectivity with VISAR velocimetry instrument (ASBO) and the spectral radiance with the Streaked Optical Pyrometry (SOP) [2]. A gray-body approximation using the measured reflectivity to determine the emissivity then allows to obtain the variation of the shock temperature as a function of shock velocity which one can relate to pressure using a previously determined U_S - u_p equation of state relationship.

With excellent laser performance and support, we collected 8 system shots in the half-day allocation returning excellent quality data. In particular, the new optical telescope with improved achromaticity and therefore enhanced spatial resolution resulting in noticeably higher quality SOP (see Figure 1).

The on-going data analysis will be used to improve our understanding of the thermodynamic properties of diamond near the pressure-temperature conditions that are relevant for Inertial-Confinement-Fusion experiments using high-density carbon (HDC) ablaters [3].

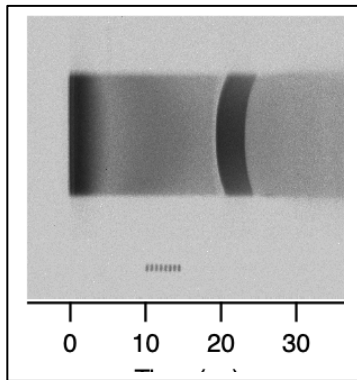


Figure 1. Example SOP data for the DiamondMelt19A campaign.

[1] Eggert, J. H. *et al.* Melting temperature of diamond at ultrahigh pressure. *Nat. Phys.* **6**, 40–43 (2009).

[2] Millot, M. Identifying and discriminating phase transitions along decaying shocks with line imaging Doppler interferometric velocimetry and streaked optical pyrometry. *Phys. Plasmas* **23**, 014503 (2016).

[3] LePape, S. *et al.* Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility. *Phys. Rev. Lett.* **120**, 245003 (2018).

4. Investigation of the Atomic Structure of Dense Carbon with X-Ray Diffraction (PI: Marius Millot)

with Federica Coppari, Amalia Fernandez-Panella, James Emig, Vern Rekow and Peter Celliers (LLNL)

This series of shot aims at measuring the atomic structure of diamond in the multi megabar range and near the pressure-temperature conditions achieved during the initial stage of Inertial Confinement Fusion (ICF) implosions using high-density carbon (HDC) ablaters at the National Ignition Facility [1]. In particular, we aim at unraveling how shock-compressed diamond transforms to a conducting fluid above 11 Mbar as expected from previous experiments, numerical simulations and theoretical modeling. Further, we wish to elucidate if dense fluid carbon formed by shock compression could solidify upon decompression and the link with a possible maximum in the melting curve of carbon near 5 Mbar [2].

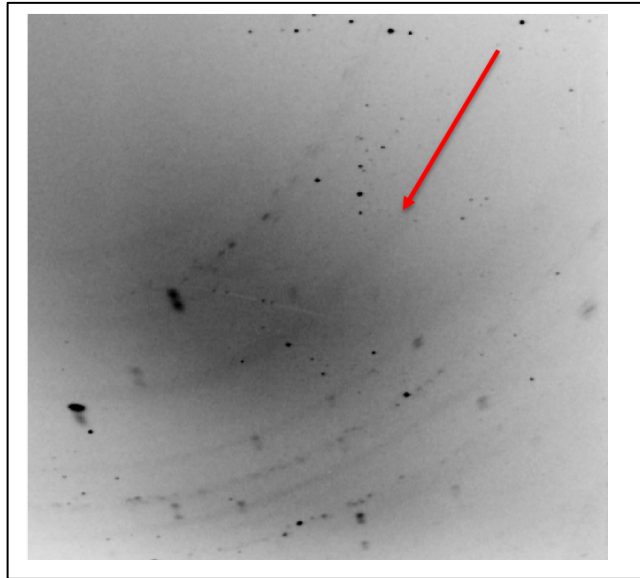


Figure 1. Example raw PXRDIP data showing the x-ray diffraction pattern of diamond shock-compressed near 8 Mbar (red arrow), together with calibration line.

This campaign at OmegaEP used a combination of ultrafast x-ray diffraction and optical diagnostics using new laser dynamic compression techniques. We collected excellent quality data on 8 system shots using 1 UV beams to compress the water sample layer and 3 UV beams to generate an x-ray source flash for the x-ray diffraction measurement. Preliminary analysis suggests that we successfully manage to record high-quality x-ray diffraction data and scan a broad range of pressure from 5 to 12 Mbar.

The on-going data analysis and upcoming experiments at Omega EP in FY20 and at the National Ignition Facility (NIF) will be used to improve our understanding of the microscopic and thermodynamic properties of carbon at extreme conditions, build improved constitutive models and inform future designs for ICF at the NIF. In

particular, we hope to resolve the discrepancy between current equation of state models and experimental data unveiled by the analysis of shock-timing experiments at NIF and described in [3].

[1] LePape, S. *et al.* Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility. *Phys. Rev. Lett.* **120**, 245003 (2018).

[2] Benedict, L. X. *et al.* Multiphase equation of state for carbon addressing high pressures and temperatures. *Phys. Rev. B* **89**, 224109 (2014).

[3] Millot, M. *et al.* Measuring the shock impedance mismatch between high-density carbon and deuterium at the National Ignition Facility. *Phys. Rev. B* **97**, 144108 (2018).

5. Proton Radiography Measurements Using DT^3He -Filled Exploding Pushers as Proton and Deuteron Sources (PI: B.B. Pollock)

with G. Sutcliffe, C. Li, and J.D. Moody

MagHohlMultiPBL-19A is the first experiment in a campaign to probe hohlraum relevant physics with protons and deuterons from a DT^3He -filled exploding pusher source.

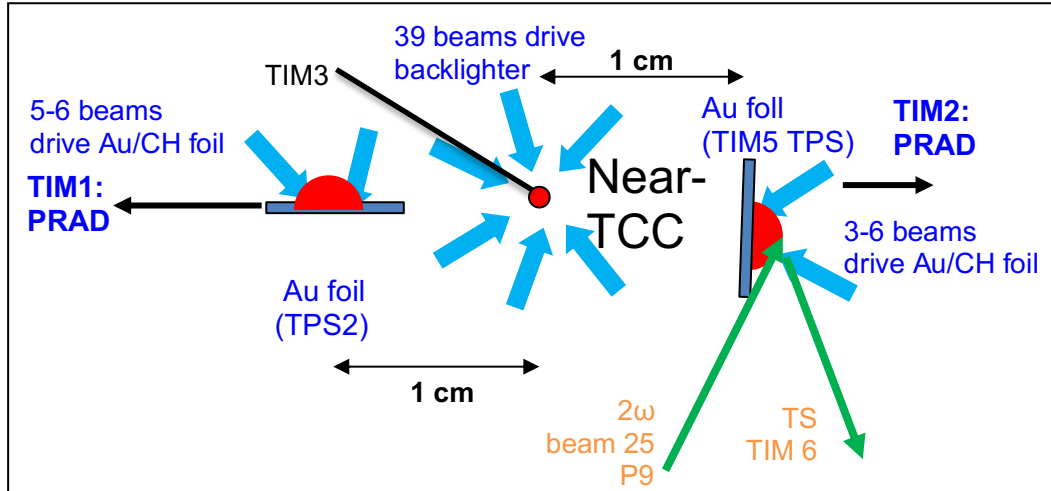


Figure 4. Experimental configuration for MagHohlMultiPBL19A. Two foils are placed ~ 1 cm away from an exploding pusher capsule target positioned near TCC. The capsule is filled with either DT^3He or D^3He . When compressed, both capsule fills produce 3.0 and 14.7 MeV protons; with T present in the fill, 9.5 MeV deuterons are also produced. These particles probe the electric and magnetic field structures either across or through the foil targets depending on the foil orientation. Protons and deuterons are recorded on CR39 detectors.

Figure 1 shows the general experimental geometry. The backlighter capsule location and drive was the same for all shots on the day, but the fill varied between DT^3He and D^3He . The capsules were driven by 39 beams of Omega, while the others were used for driving foil targets and for Thomson scattering. Two foil configurations were studied during the shot day. The first irradiated flat CH foils in both foil locations with six beams each, where protons (and deuterons if the capsule contained T) probed the electric and magnetic field structures at the target surface either through or tangential to the target face. In this configuration, 2w Thomson scattering was performed at various locations relative to the surface of one of the target foils in order to measure electron density and temperature for comparison with simulations of the expanding surface plasma. The second configuration used Au foils in both locations, one flat and one curved; both foils were probed edge on with the protons and deuterons from the pusher. The maximum number of beams was reduced to either three or five depending on the foil geometry, and the on-shot beam orientation was varied by dropping one or more beams from each shot. By changing the effective beam spacing, the resulting field structures are also affected and can be distinguished using the (up to) three charged particles emitted from the pusher. The proton data is still being processed, but initial estimates of the deuteron yield from the capsules containing T are approximately three times less than initial estimates based on scaling from prior experiments. This discrepancy is being investigated further and future experiments will attempt to drive the capsules with more energy to achieve higher yields.

6. Characterization of Compressed MIFEDS Fields in Cylindrical Targets

(PI: B.B. Pollock)

with J. Davies, J. Peebles, and J.D. Moody

BFieldAmp-19A and B were the first experiments in this campaign to attempt to characterize compressed magnetic fields in cylindrical geometries on Omega.

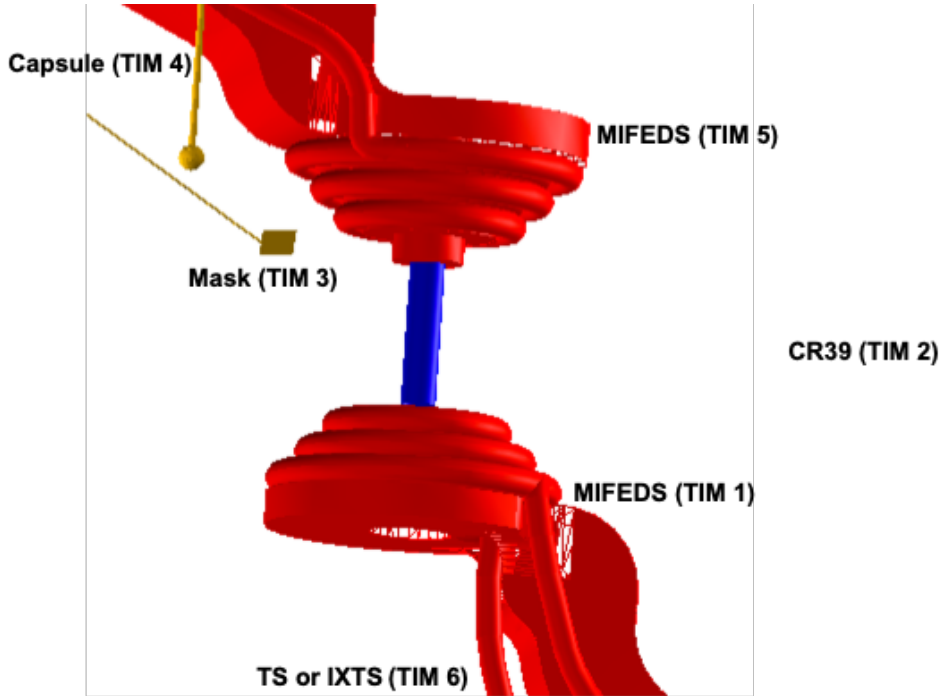


Figure 5. Experimental configuration for BFieldAmp experiments. A plastic tube (blue) is attached to one MIFEDS coil, while a second coil is inserted on the opposing side to allow for up to 30 T magnetic field production at the center of the tube. The tube is irradiated with 40 beams around its waist to drive it radially inward from an initial diameter of ~ 600 μm to a final diameter of ~ 50 μm . Protons are produced from the implosion of a D3He-filled capsule target, some of which are collected on a CR39 detector on the opposite side of the tube from the capsule. The mask was only present in 19B, and partially blocks proton line of sight to the CR39 on one side of the tube only. The optical Thomson scattering collection system was used to measure plasma emission on 19A, while the IXTS system was used to measure x-ray emission on 19B.

Figure 1 shows the general experimental geometry for BFieldAmp-19A and B. The target for both shot days was an empty plastic tube of ~ 600 μm diameter with a 30 μm thick wall. The tube is irradiated around its waist to drive >10 times convergence of the tube diameter. Provided the inner wall of the tube was sufficiently ionized from x-rays produced by the laser-wall interaction on the exterior of the tube, the magnetic field should compress with the tube wall and result in an increased B-field strength proportional to the square of the tube convergence ratio. The strength of the applied MIFEDS magnetic field was varied from 5 to 30 T between the two shot days, and optical and x-ray emission measurements were taken to look for evidence of the magnetic field compression. However, the proton data from these experiments is currently inconclusive about

the compression of the initial magnetic field during the tube implosion, as are the spectroscopic measurements. Further analysis is underway, and future experiments will add a gas fill to the tube similar to that of the mini-MagLIF experiments of J. Davies et. al. With the initial gas fill the tube will have material to push against, potentially reducing the convergence ratio, but in this configuration the gas has been shown to be able to be ionized by the x-rays produced during the implosion and should therefore be more robust for entraining the initial magnetic field and compressing it as the tube implodes. Following a successful characterization of B-field compression, additional future work will use the high-field region at the compressed tube center as a platform for ultra-high magnetic field experiments.

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

with S. Fujioka, H. Morita, K. Law, and J.D. Moody

BFieldLoop-19A is a continuation of the laser-driven magnetic field experimental campaign at Omega EP. The goals for 19A were to study current diffusion in the loop targets, as well as to examine the B-field dependence on target material choice for the loops.

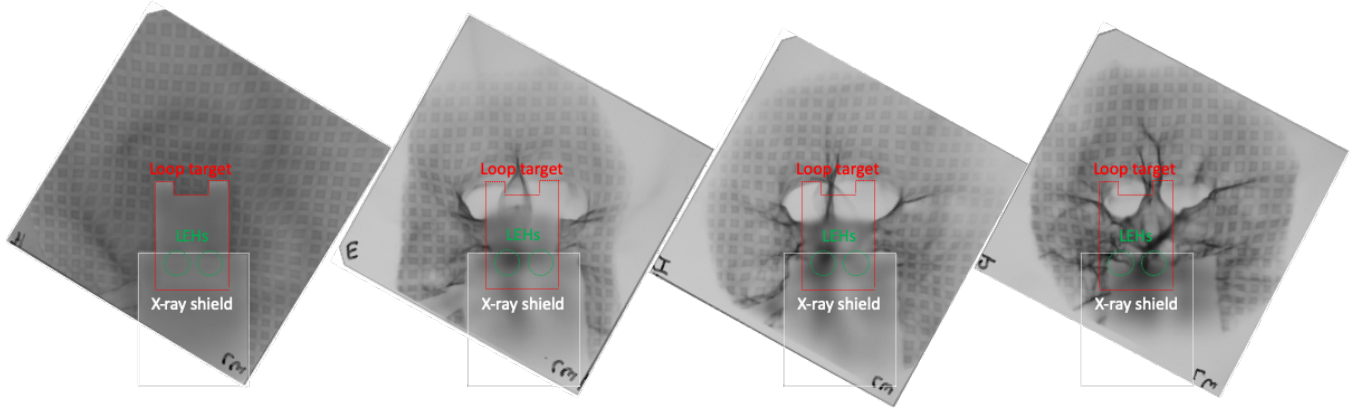


Figure 6. Proton radiography images for undriven Au, driven Au, driven Cu, and driven Al targets (from left to right). The targets are foils folded to produce parallel rectangular plate sections that are 1.1 mm wide and 1.5 mm tall, with 300 μm wide, 250 μm radius straps at the edges connecting the plates (which are separated by 500 μm). The B-field is produced by irradiating the target interior through one of the laser entrance holes (LEHs, typically the left side in these images), which generates a voltage difference between the plates, driving a current through the straps, resulting in a magnetic field around the top portion of the target. The x-ray shield blocks the line of sight from the LEHs back to a 10 μm thick Au foil, which is irradiated by the 1 ps backlighter pulse on EP at 200 J to produce the probing protons via the TNSA mechanism. A Cu mesh between the TNSA foil and the B-field target produces the grid structure in the images.

Figure 1 shows data from four different shots on the day. The first is a radiograph of the loop target without driving the magnetic field. The loop target and the x-ray shield blocking line of sight to the proton generation foil can be seen clearly in the image. The top of the target shows shadowed regions at the edges, corresponding to the location of the thin strap pieces that connect the front and back rectangular plate portions of the target, which are intended to restrict the ability of current to diffuse away from the target edges. This configuration also produces a magnetic reconnection geometry between the straps, which may be investigated further in future experiments.

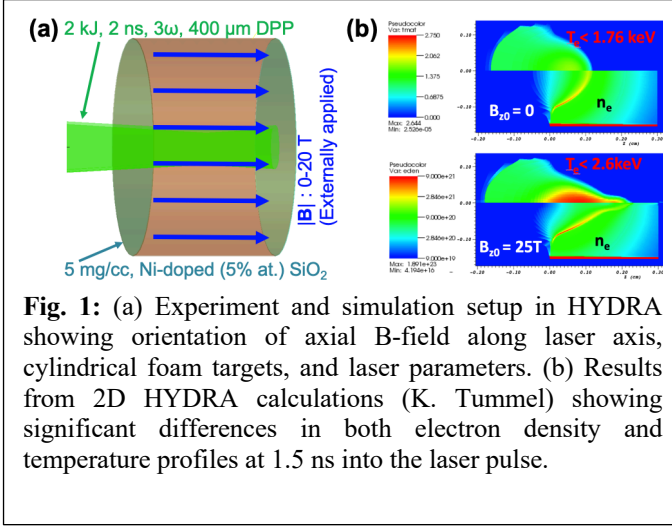
The second panel shows the result of driving a Au target with 0.5 TW of laser power for 3 ns, consistent with previous experimental configurations with complete loop sections at the target top. The lateral width of the shadowed region outside the outline corresponding to the undriven target location is correlated with the strength of the magnetic field being produced around the straps, but there is also significant additional structure developing on the interior part of the target between the straps. Changing the target material to Cu shows an enhancement in this structure, as well as enhanced caustic features at the edges of the proton shadows around the

straps. Reducing the target Z even further by using an Al target shows more structure still compared to the Cu and Au targets. These additional materials were initially chosen to study the effect of different conductivities and specific heats on current diffusion processes; the enhanced structures around the target location need further analysis to determine the full impact of target material choice on the current and B-field generation processes. These data are still being analyzed, but future experiments will measure the B-field structure in the non-Au targets at earlier evolution times as well as after the end of the pulse (as has been done previously with Au).

8. Experiments to Address Laser Transport in Magnetized Plasmas (PI: D. Mariscal)

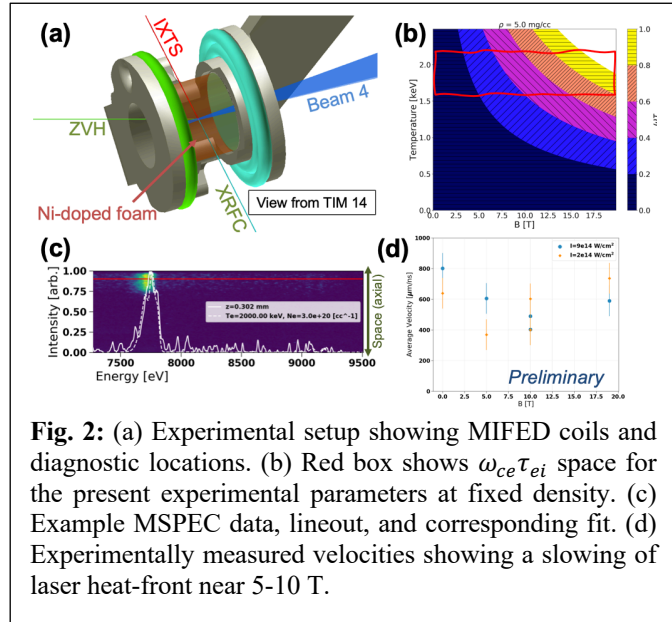
Co-Investigators: G. E. Kemp (LLNL), E. Marley (LLNL), K. Tummel (LLNL)

Simulations using HYDRA with MHD packages predict enhanced laser propagation and plasma temperatures when magnetic fields are imposed along the laser axis, as seen in Figure 1. These experiments explore parameters that produce magnetized plasmas (electrons) where these effects can be examined and used to determine which MHD terms are important for reproducing results in HYDRA.



$\sim 2 \times 10^{14}$ or $\sim 1 \times 10^{15}$ W/cm² laser intensity. With these parameters, the plasma density is $\sim 0.2 n_e/n_c$ with temperatures of ~ 2 keV and as seen in Figure 2 (b), allows exploring plasma Hall parameters up to ~ 1 . The multipurpose spectrometer (MSPEC) was used to acquire spatially and temporally resolved x-ray data along the laser axis as seen in Fig. 2 (c) while a x-ray framing camera (XRFC) was used to image the heat front propagation (Fig. 2 (d)).

Over two shot days, 17 target shots were completed, resulting in both a successful platform demonstration and a dataset scanning two intensities and four B-field values (0, 5, 10, and 19 T). Preliminary analysis seems to indicate a dip in propagation velocity in the neighborhood of 5-10 T. HYDRA simulations are underway to compare against this dataset that should provide important insight regarding the importance of B-fields in hydrodynamic calculations of laser-driven experiments at ICF-relevant conditions.



9. Experimental Study of Laser-Entrance-Hole Dynamics (PI: J. Ralph)

With M. Tabak, W. Farmer, O. Landen, P. Amendt

These experiments test several designs of the hohlraum laser entrance hole (LEH) for use in advanced next generation hohlraums. In total, 14 shots were performed comparing the LEH closure, hohlraum drive, and backscatter when using a variety of LEH types. The 1 mm diameter hohlraums were aligned to the H4-H17 axis; the surrounding 6 beams at 21.5 degrees were focused at the 400 or 500 μm diameter LEH and incident on a 25 mm thick Au plate located at about the middle of the hohlraum. The laser pulse used on all experiments is the 2 kJ pulse shown in Figure 1 (right). The x-ray framing camera timing (blue arrows) are shown relative to the laser pulse. We tested 4 types of LEHs: a simple opening; a 0.5 μm polyimide window; a CH lined Au plate with polyimide window; and finally 100 μm thick Au foam with polyimide window.

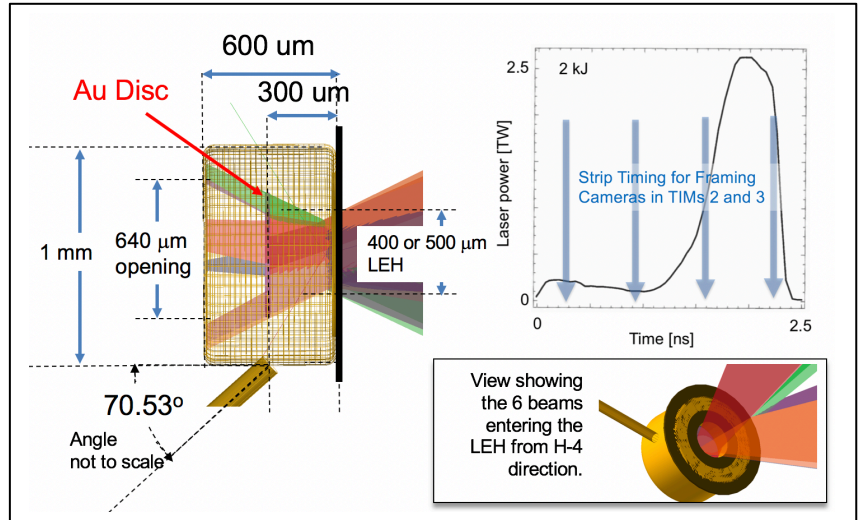


Figure 1. Target and Experimental configuration.

All experiments used the same laser pulse. The main results are summarized in Figure 2. Here we see the 400 μm x-ray framing camera data from TIM3 looking in through the LEH, and TIM2 looking at the hohlraum emission. The LEH side framing camera measures the LEH closure as a function of time as shown in Figure 2. We find the CH liner maintains the complete opening of 400 μm throughout the pulse. The TIM2 framing camera data shown in Figure 2 provides a measure of the peak hohlraum emission using a 2° Ge mirror combined with a 1 μm Zn filter. From this data, the Au foam seems erratic, low at early time and high later in the pulse. The remaining LEH designs show an overall decline with time. Neglecting the Au foam data, it appears that during the middle of the pulse, the CH lined LEH results in about 25% more emission. These results will inform future experiments and designs at NIF.

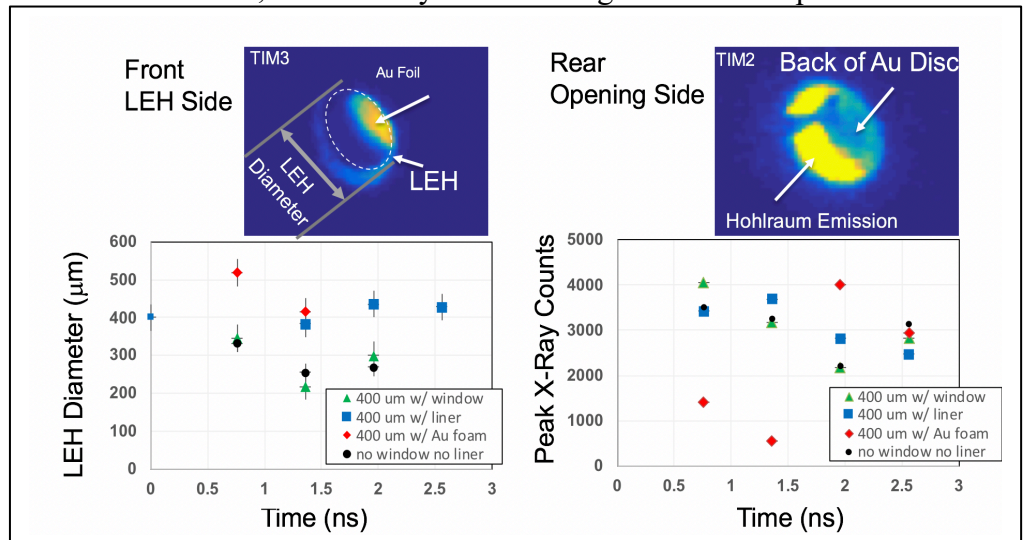


Figure 2. X-Ray Framing Camera Data.

10. Assessing Heat Transport in the Transition Between Local and Non-local Regimes (PI: G. F. Swadling)

with W. Farmer (LLNL), M. Sherlock (LLNL), M. Rosen (LLNL), B. Pollock (LLNL), D. Edgell (LLE), C. Bruulsema (UA), W. Rozmus (UA)

In the BeSphere-19A campaign we performed experiments heating Beryllium coated spheres in a direct drive geometry. The experiments were diagnosed using the OMEGA Thomson scattering system (TSS), scatter calorimeters and the DANTE x-ray spectrometer. The aim of these experiments was to make quantitative measurements of the parameters of the blow-off plasma produced from these spherical targets. Seven target shots were completed in the half-day.

The data from these experiments is currently being used to benchmark heat transport models. Using Beryllium as the target material removes complications introduced by the high radiative losses and complex atomic physics of gold. To further simplify comparisons between experiment and simulation the targets were heated at a comparatively low intensities of $1 - 2.5 \times 10^{14} \text{ W cm}^{-2}$; at these intensities coupling of the laser to the target was shown to be better than 90%.

The Thomson scattering diagnostic measured the time resolved spectrum of light scattered by fluctuations in n_e with wavevectors $\vec{k}$ tangential to the surface of the sphere. The size of the scattering volume, defined by the overlap of the probe beam and collection cone, was $\sim [50 \mu\text{m}]^3$. Measurements were made at locations 200, 300 and 400 μm from the sphere surface. The diagnostic recorded scattering from both high frequency electron plasma wave fluctuations (EPW, T_e , n_e) and low frequency ion-acoustic wave fluctuations (IAW, T_e , T_i , v_{flow}). Examples of the data recorded are shown in Figure 1. Fitting these measured spectra results in quantitative measurements of the plasma parameters which may be compared with the results of numerical modeling. As an example, a comparison of the T_e and T_i profiles measured in the experiment with those calculated in a LASNEX run are presented in Figure 1, illustrating the good agreement achieved.

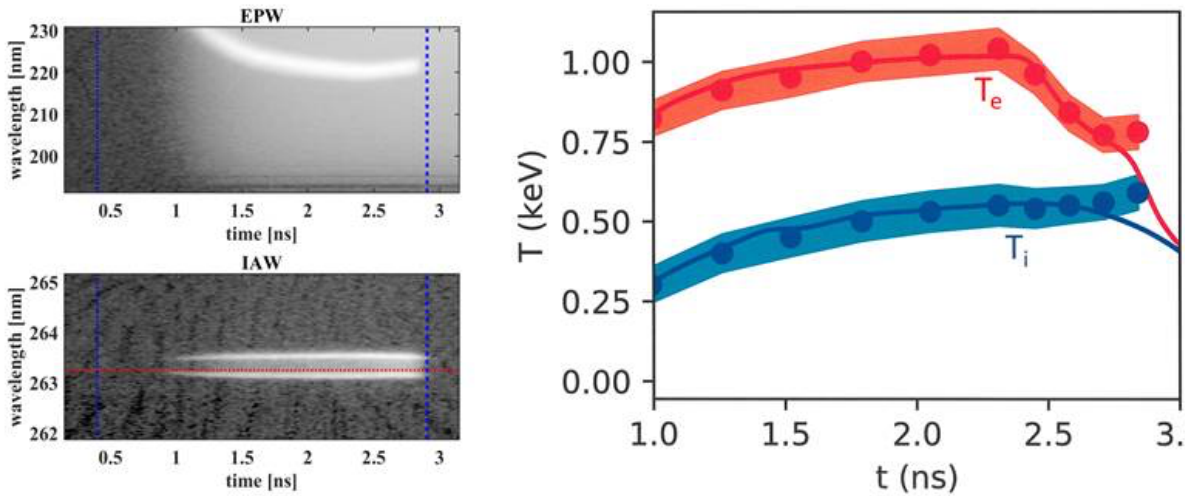


Figure 1. Left, Raw IAW and EPW Thomson scattering spectra. Right, example of a comparison between plasmas parameters measured by fitting the Thomson data and those calculated in a LASNEX simulation of the experiment. Dots are measurements, the shaded band indicates experimental uncertainty and the solid lines show the LASNEX values.

11. Generation of TNSA Short-Pulse Laser-Accelerated Deuterons with up to 30 ps Pulse-Length (PI: J. Park, UCSD)

with T. Ma, D. Mariscal, G. Cochran (postdoc), and A. Zylstra (LLNL); R. Simpson (MIT, student); J. Kim (UCSD) and F. Beg (UCSD)

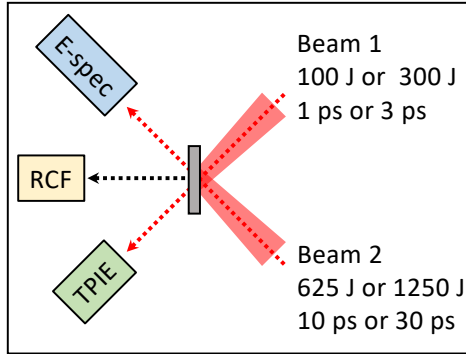


Fig. 1 Top down view of the experimental setup.

This series of shots investigated the generation of proton and deuteron beams via short-pulse laser-acceleration using the target normal sheath acceleration (TNSA) mechanism in the multi-ps regime. 35 μm thick CD foils were illuminated with EP short pulse beams with varying pulse length (1 to 30 ps) and intensity ($10^{17}\sim 10^{18}$ W/cm²), relevant to NIF ARC conditions. Over the course of the day, the two EP short pulse beams were alternated in single-beam shots: beam 1 delivered between 100 J and 300 J energy on targets over 1 or 3 ps pulse length while beam 2 delivered between 625 J and 1250 J energy over 10 ps or 30 ps. Both beams were defocused, $\sim$

45 μm R/80, to achieve the desired laser intensity. Several target shots utilized a novel configuration of combining both beams to provide a temporally shaped pulse to test proton and deuteron generation [1]. On this shot, the two beams were spatially overlapped on the target, but beam 1 (3 ps) arrived prior to beam 2 (30 ps) by $\sim$ 45 ps. Three diagnostics were used to measure proton, deuteron and electron spectra with varying laser conditions; Radiochromic Film (RCF) along the target rear normal, Thomson parabola ion energy (TPIE) analyzer and electron spectrometer (E-spec) at 45° from the target rear normal, Figure 1.

It was observed that there is a strong scaling of the ion flux and maximum ion energy with laser energy when a single beam is used; a 3 ps long pulse with 100 J generated protons up to 3.6 MeV but no observable deuterons while a 30 ps long pulse with 625 J generated protons up to 5.1 MeV and deuterons up to 1.8 MeV. When both beams

were simultaneously used, the maximum energy increased to 6.8 MeV and 4.9 MeV for protons and deuterons, respectively. The electron flux also significantly increased up to 7x when comparing single beam to dual beam configurations. The increase in the maximum ion energy due to this increased electron flux or the electron temperature is still under investigation.

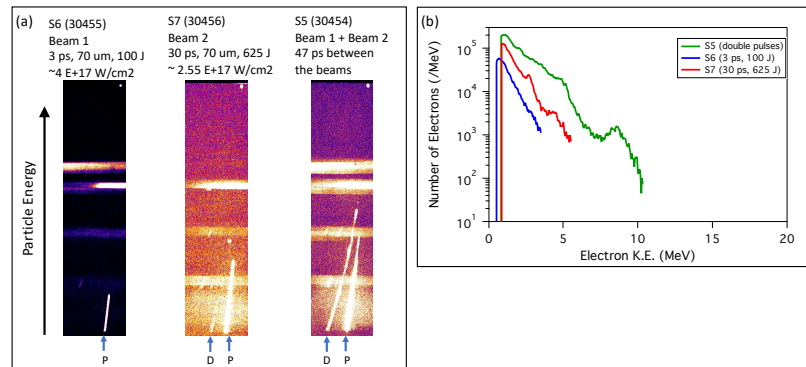


Fig. 2 Raw data from TPIE and electron spectra from CD targets with three different laser configurations

[1] J. Kim, *et al.* Physics of Plasmas **25**, 083109 (2018).

12. Increasing Laser-Accelerated Particle Energies with “Shaped” Short-Pulses (PI: D. Mariscal)

Co-Investigators: T. Ma and G. Cochran (postdoc, LLNL); J. Park and J. Kim (postdocs, UCSD)

Newer kJ-class short-pulse (ps) lasers such as the National Ignition Facility’s Advanced Radiographic Capability (ARC) laser have recently been shown to be able to accelerate protons to energies that far exceed conventional scalings. While these results are encouraging, the proton energies necessary for probing indirectly-driven ICF experiments are 2X higher than currently achievable with ARC. A new concept inspired by a unique ARC capability, the ability to deliver multiple short-pulse beams to the same location with specified delays, was tested at Omega EP by delivering both short-pulse beams to a single target in order to create pseudo-shaped short laser pulses.

The experimental geometry is shown in Figure 1. Both short pulse beams were defocused to $R_{80} \sim 45 \mu\text{m}$ in order to simulate ARC-like laser conditions. One beam delivered at 550 J @ 4 ps while the trailing beam delivered 1.6 kJ @ 30 ps. Simple flat Cu foils (1 mm diam X 35 μm thick) were used as targets. The choice of Cu enabled the use of the SCI instrument for monitoring spatial overlap of the two beams on target while the ultra-fast x-ray streak (UFXRS) camera and time-resolved channel of the high resolution spectrometer (HRS) to monitor the relative timing of the beams on target. Particle diagnostics including radiochromic film (RCF) and the electron positron proton spectrometer (EPPS) were used to monitor the particle characteristics for each shot. Particle spectra were recorded from single beam shots before combining the beams and varying the relative timing between the two throughout the day.

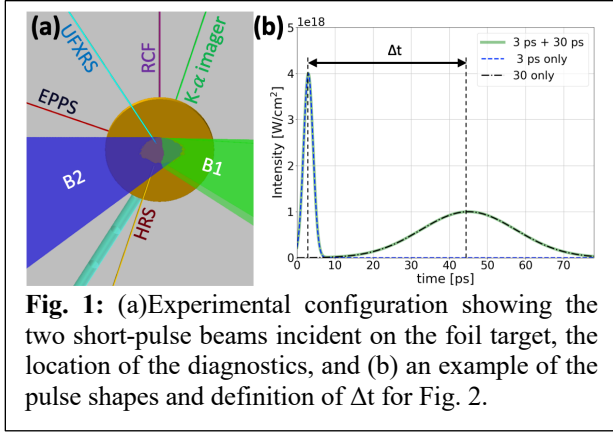


Fig. 1: (a) Experimental configuration showing the two short-pulse beams incident on the foil target, the location of the diagnostics, and (b) an example of the pulse shapes and definition of Δt for Fig. 2.

A successful day with 9 data shots was completed (4 single beam + 5 combined beam). A preliminary look at the data (Fig. 2) indicates that electron temperatures and yields were significantly increased when pulse combinations were used, with a factor of 2+ increase in total conversion efficiency into hot (>1 MeV) electrons, 50% increase in e^- temperature, and a corresponding 50% increase in maximum proton energy. This data suggests that the use of shaped short-pulses could increase the energy and efficiency of MeV particle sources driven by NIF’s ARC through manipulation of time-dependent particle acceleration physics at the ps level. These novel results stimulated follow-up experiments now scheduled in FY20.

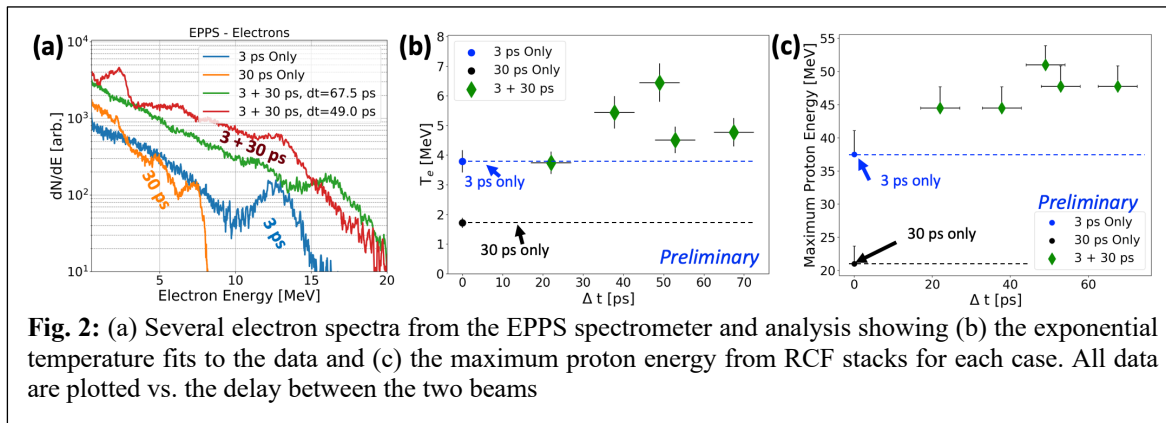


Fig. 2: (a) Several electron spectra from the EPPS spectrometer and analysis showing (b) the exponential temperature fits to the data and (c) the maximum proton energy from RCF stacks for each case. All data are plotted vs. the delay between the two beams

13. Development of Improved Backlighters Using In-Situ Plasma Reflectors

(PI: R. Tommasini)

with J. Park, L. Divol, A. Kemp

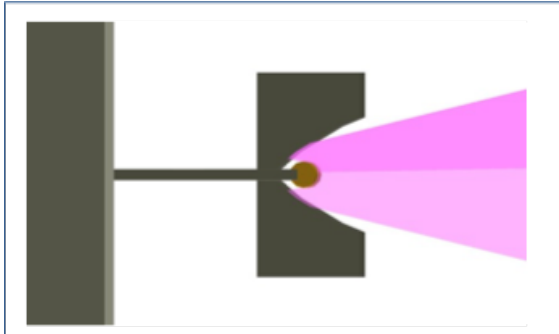


Figure 7. End on view of 25- μm diameter Au wire in a U-shaped plasma mirror, illuminated by the Omega EP side-lighter beam.

The SmallSpotBL-EP-19 campaign continued the development and test of novel small source x-ray backlighters that started with the prior campaign, SmallSpotBL-EP-17. The concept is to use in-situ plasma mirrors to enhance the laser energy coupling on micro wire backlighters that can be used as point sources in high-energy x-ray radiography and at the same time increase the tolerance to laser pointing jitter.

In this campaign we introduced an improvement of the plasma mirror geometry by using 25 μm -diameter Au micro wires at the vertex of parabolic-like CH profiles, for brevity U-shaped PM (Fig.1).

The 30-ps-long, 1kJ-energy, pulses from the Omega-EP side-lighter beam were pointed at the vertex of the plasma mirror profile. The x-ray yield and source size were measured, along the line of sight aligned parallel with the gold wire, by radiographing a tantalum step-wedge and a calibrated tungsten sphere, 200 μm in diameter.

We also performed shots with the original V-shaped CH profiles (V-shaped PM) and with bare Au wires. The results have confirmed 2X-3X increase in conversion efficiency when using the V-shaped plasma mirror configuration as compared to bare wires, and a 4X-5X increase when using the U-shaped plasma mirror configuration. We also reported reduced statistical variation in x-ray yield between shots. The backlighter source size, when using plasma mirrors, has measured similar or smaller in size with respect to bare micro wires and always very close to the wire diameter.

These novel backlighters are ideal for hard-x-ray radiography of ICF implosions and allow the reduction of the backlighter size in order to record radiographs with higher spatial resolution while maintaining sufficient signal to noise. They have been used to record Compton radiographs of the imploding fuel on two layered THD shots on the NIF.

High-Energy-Density Experiments

A. Material Equation of State and Strength Measured Using Diffraction

1. X-ray diffraction of shock-ramped platinum

(PI: A.E. Lazicki; co-PI: M. Ginnane (LLE))

with R. Kraus, J. Eggert, M. Marshall, and D. Fratanduono (LLNL); D. Polsin, X. Gong, T. Boehly, R. Rygg, and G. Collins (LLE); J.-P. Davis, C. McCoy, C. Seagle, and S. Root (SNL)

This campaign seeks to determine the structure of platinum (Pt) at high temperatures and pressures. Platinum is of interest because it is often used as a pressure calibration standard in diamond anvil cell experiments due to its low reactivity and wide pressure-temperature stability. Shock-ramp experiments on Sandia's Z machine have suggested evidence of a phase transition occurring at ~ 150 GPa. The inverse Z method applied to Pt by L. Burakovsky (2014) suggests a solid-solid phase transition in a similar pressure region. The goal of this experiment was to use x-ray diffraction (XRD) to study the crystal structure at the pressure regime where a new phase is suggested. A series measurements were carried out using the PXRDI platform on OMEGA EP. The target package consisted of a Be ablator, a 25- μm Al foil, a 7- μm Pt foil sample, and a 130- μm LiF window. The thickness of the Be ablator was varied between shots in order to reach different shock pressures (50-200 GPa). Two 10-ns UV beams were combined to create a 20-ns drive that shocked the sample and then ramp-compressed to various pressures, up to ~ 500 GPa. A Ge backlighter foil was driven to create a 1-ns flux of 10.25 keV x-rays that were diffracted by the target package and collected on the image plates shown in Figure 1. The ASBO telescope was focused at the sample/LiF interface and used to infer a pressure history in the Pt.

Six of the seven shots had either 3 or 4 solid diffraction lines, consistent with the face centered cubic (fcc) phase. In the remaining shot, liquid diffraction is believed to have been observed, but blanking in ASBO means the exact pressure is unable to be determined using the usual method. Initial hydrodynamic simulations suggest the Pt was shocked to >800 GPa. This last shot will inform an upcoming shot day to determine where Pt melts on the Hugoniot.

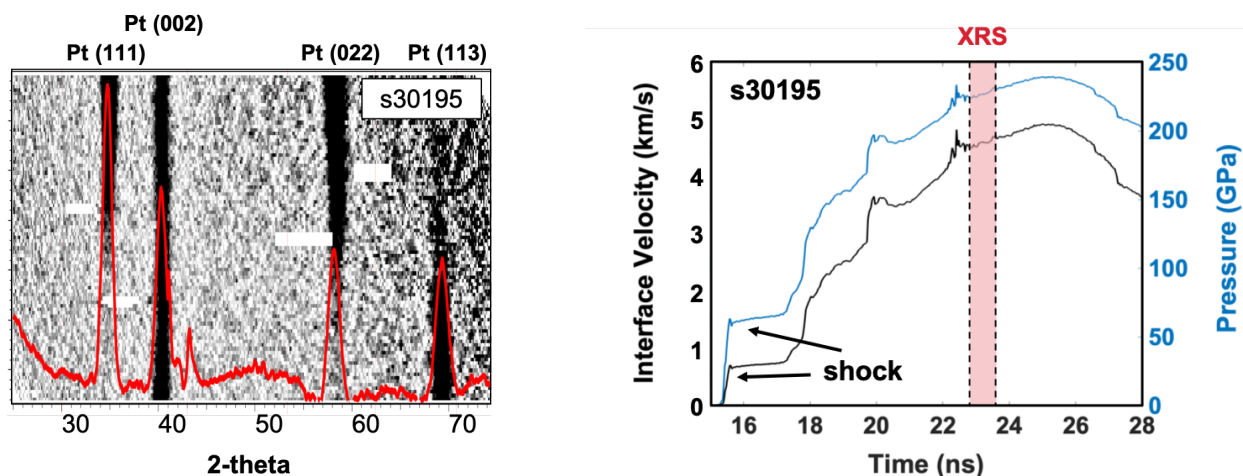


Figure 1. (Left) Example diffraction data showing four lines generated by solid Pt in the fcc phase. (Right) The sample particle velocity, inferred pressure profile and timing of the x-ray source (XRS) obtained from VISAR.

2. Laue diffraction from Ta using Cu foil backlighter

PI: A. Krygier (LLNL), with CE Wehrenberg and H-S Park (LLNL)

The TextureDiff-19A experiment investigated deformation in [100] and [110] single crystal tantalum at high pressure. Twinning has been found to play an important role in deformation under some conditions in tantalum and this experiment was motivated to investigate this effect in single crystal samples. Additionally, previous measurements of diffraction from single crystal samples have not been able to constrain the in-situ density due to the nature of the technique. This experiment developed a new technique to simultaneously measure density and strain anisotropy in single crystal samples.

A shock wave was driven into the samples using direct laser ablation. The strength of the material produces strain anisotropy, where the sample is more compressed in the loading direction than the transverse directions. We probe this with white-light X-ray diffraction. Previous measurements of this sort used a capsule implosion to produce the smooth, high-flux, short duration X-ray pulse. We additionally probe the sample velocity using the ASBO diagnostic. We tested using a foil backlighter for this purpose, based on observation of X-ray flux enhancement made by the extended X-ray absorption fine structure (EXAFS) campaign. By using a copper foil backlighter, the X-ray spectrum has both a broad white-light feature useful for measuring strain anisotropy with Laue diffraction, as well as quasi-monochromatic $\text{He}\alpha$ emission that is used for measuring density with powder diffraction from polycrystalline samples and geometrically allowed single crystal reflections. We also tested Au-Cu foils to compare bremsstrahlung emission but found this dramatically increased unwanted probe-heating to the sample. This capability has the added bonus of enabling use of PXRDIIP instead of BBXRD, which improves the quality of the diffraction due to the geometry.

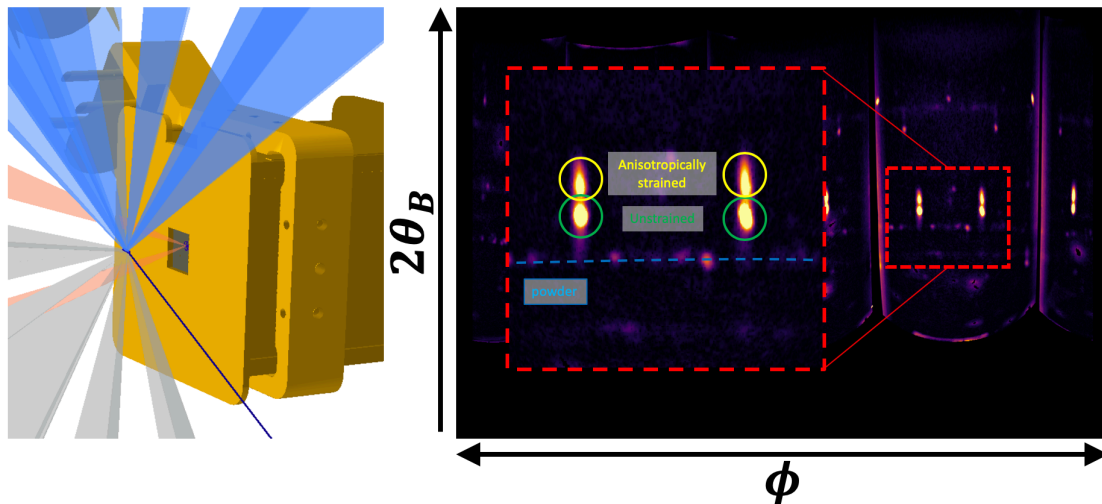


Figure 1: (Left) 1-2 beams drive a shock wave into the Ta sample package. 19 beams heat a Cu or Au-Cu foil to produce white-light + $\text{He}\alpha$ X-ray pulse. (Right) Example data from [100] Ta. In the inset, green circles show the undriven Laue reflections; yellow circles show the anisotropically strained reflection that arises due to strength at high pressure. The blue dashed line shows powder diffraction from the monochromatic Cu $\text{He}\alpha$.

3. Probing the High-Pressure Crystal Structure of Lithium Fluoride

(PI: M. Gorman, LLNL)

with Raymond Smith and Chris Wehrenberg (LLNL)

These experiments explored the high-pressure phase diagram of Lithium Fluoride. A structural transformation from the B1 phase to the B2 phase has been predicted [1]. Observing this transition may explain why nonlinear corrections to the refractive index of LiF are required in ramp compression experiments at NIF [2]. The target design is shown in Fig. 1 left. A 50 μm polycrystalline LiF sample was sandwiched between a 40 μm diamond ablator and a 100 μm MgO window. The Omega VISAR (ASBO) measures the LiF/MgO particle velocity from which the sample pressure as a function of time can be determined [3] as shown in Fig. 1 center. In these experiments we combine nanosecond x-ray diffraction [3] and ramp compression to dynamically compress and determine the crystal structure of LiF to peak pressures up to 600 GPa. Using the Omega PXRDI diagnostic [3] the compressed LiF sample is probed with a 2-ns He-alpha x-ray source to determine crystal structure at a well-defined sample pressure (VISAR). An example of the quality of the data obtained is shown in Fig. 1 right. Here we obtain information on the high-pressure B1 phase of LiF. Also observed are peaks from the ambient pressure Ta pinhole which serve to calibrate diffraction angle. We find that LiF remains in the B-1 phase up to at least 600 GPa along a quasi isentrope.

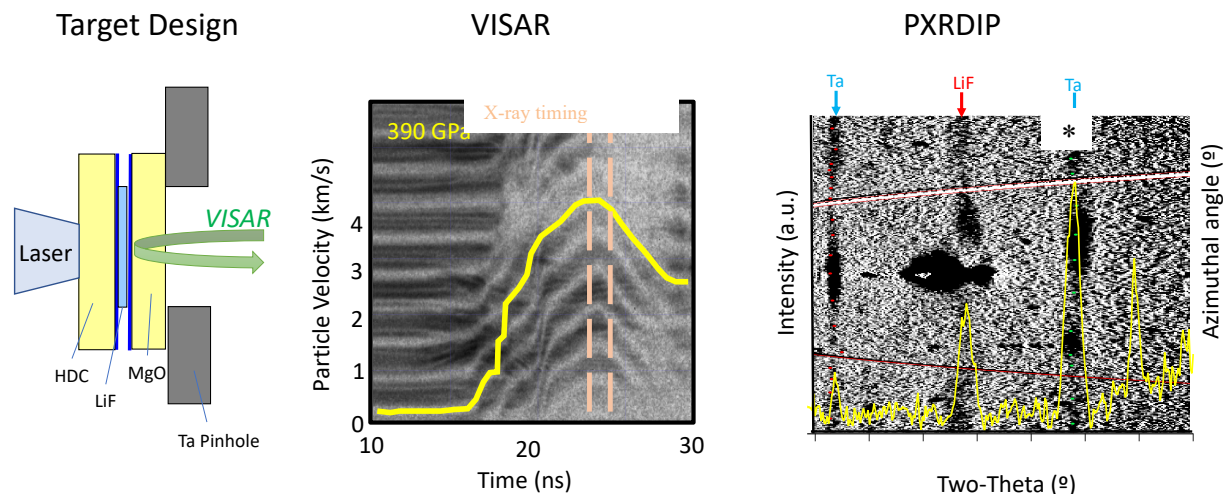


Figure 8. (Left) Typical target design with 40 μm diamond ablator, 50 μm polycrystalline LiF sample and 100 μm single crystal MgO window. (Center) Raw VISAR fringe data with analyzed velocity profile overlaid. (Right) De-warped PXRDI diffraction data with 1D lineout overlaid. Profile shows diffraction from the B1 phase of LiF at 390 GPa.

[1] P. C. Myint et al. “Two-phase equation of state for lithium fluoride” *J. Chem. Phys.* **150**, 074506 (2019).

[2] L.E. Kirsch et al. “Refractive index of lithium fluoride to 900 gigapascal and implications for dynamic equation of state measurements” *Journal of Applied Physics* **125**, 175901 (2019)

[3] J.K. Wicks, R.F. Smith, D.E. Fratanduono, F. Coppari, R.G. Kraus, M.G. Newman, J. R. Rygg, J.H. Eggert, T.S. Duffy, “Crystal structure and equation of state of Fe-Si alloys at super-Earth core conditions” *Sci. Adv.* 2018;4:eao5864

4. Development of a time-resolved x-ray diffraction platform at Omega-EP (PI: L. R. Benedetti)

with F. Coppari (LLNL); D. Polsin, J. R. Rygg and C. Sorce (LLE)

Based on the work we did in 2018, in which we learned that there was substantial EMP upset caused by the proximity of the large PXRDIIP box to the x-ray streak camera, we completely redesigned the Omega-EP time-resolved-diffraction test platform. In the new platform (Figure 1, Left) we have removed the PXRDIIP box (and associated image plates) and replaced it with a baffle/shield that prevents light from the back lighter from directly hitting any diagnostic. We are now also testing an x-ray framing camera for imaged diffraction (in addition to the x-ray streak camera) because the x-ray framing camera may be better shielded than the x-ray streak camera. As with the x-ray streak camera, dedicated hardware is required to maneuver the x-ray framing camera to an appropriate location to collect diffraction.

We used this experimental setup on two shot days in FY2019, during which we collected two diffraction patterns of undriven iron onto the x-ray framing camera (Fig. 1, right). Ongoing challenges are alignment accuracy, photometrics, and still-unexplained background signals along the streak camera line of sight.

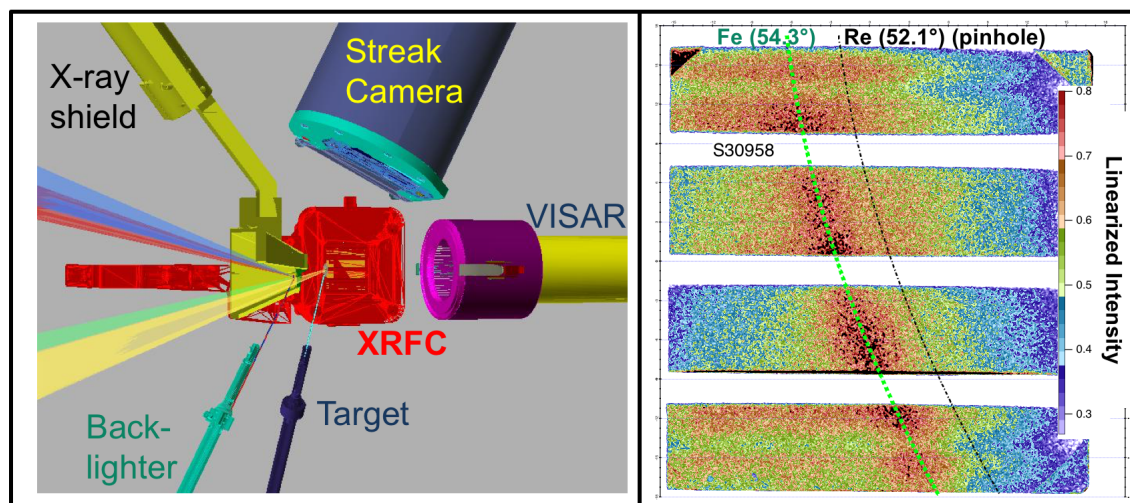


Figure 1: Imaged x-ray diffraction at Omega-EP. Left: Updated experimental setup that maximizes distance between shielding elements and SSCA. Right: X-ray diffraction to the x-ray framing camera (XRFC) of undriven Fe. Calculated diffraction is shown as an overlay.

5. New approach to pressure determination in diffraction experiments using an in-situ pressure standard (PI: F. Coppari)

With: J. Eggert, R. Kraus (LLNL), M. Vasquez (CalPoly, summer student at LLNL)

The goal of the *InSitu-Pressure* campaign is to develop a new way of determining pressure in diffraction experiments based on the use of an in-situ pressure gage. By measuring the diffraction signal of a standard material (whose Pressure-Volume equation of state is known) compressed together with the sample, one can determine the pressure upon ramp-compression from the volume determined from the measured diffraction pattern.

Currently the pressure is determined from the measurements of the diamond free surface velocity or particle velocity through a transparent window (such as LiF) using VISAR. This method is in some cases ambiguous (lack of reflectivity or shock formation) or relies on assumptions and equation of state models for the window materials. 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 gage can give us information about the temperature of the sample by measuring the calibrant thermal expansion.

We collected 12 successful shots in two half-days at the Omega laser, where we continued the work started in the previous FY looking and pushing it to higher pressure. The targets consisted of diamond ablaters, Au/Ta or Pt/W coatings as in-situ pressure standards and diamond or LiF window (Fig.1a). We reached pressures as high as ~600 GPa and collected very good quality diffraction data (12 shots) in two half-days (Fig.1b). Simultaneous VISAR data were also collected. Data analysis is being finalized and comparison of the pressures obtained from VISAR and from diffraction will inform us on the accuracy of the VISAR method as well as on the existence of pre-heating. If successful, this platform will be implemented into a real diffraction experiment to be used as either a complementary or an alternative way of determining pressure and will also be developed on other experimental facilities such as NIF, XFEL and synchrotrons.

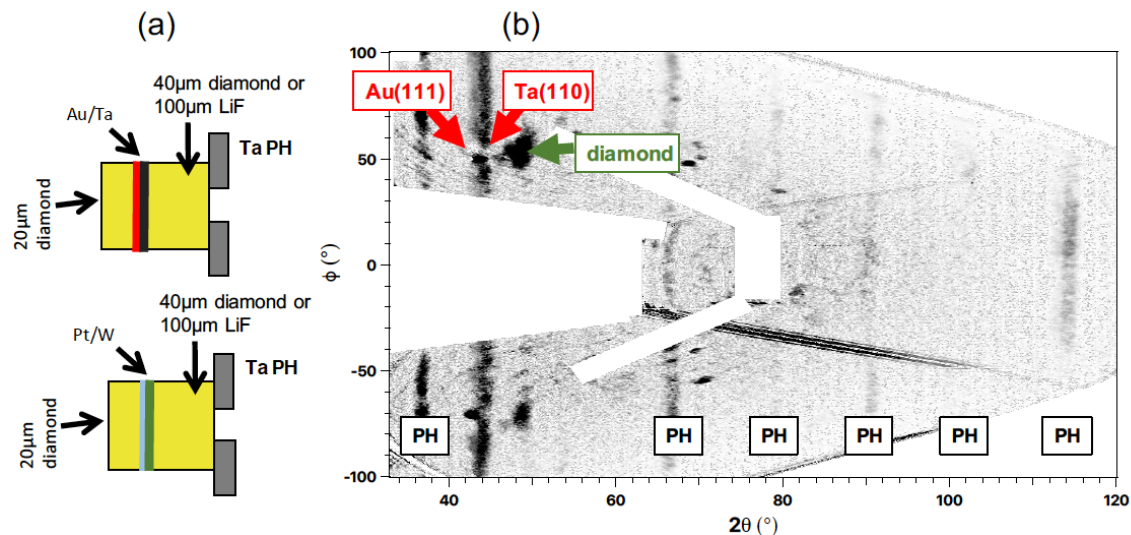


Figure 1:

(a) Schematic of the target assembly. Diamond or LiF windows were coated with 1 μm thick Au/Ta or Pt/W pairs used as pressure standards in the diffraction experiment. All targets had 20 μm diamond ablator and were mounted on Ta pinholes.

(b) Diffraction data collected in one of the experiments using Au/Ta as standards. At least one peak from compressed Au and Ta are visible, as well as lines from the Ta pinhole (PH) used to calibrate the diffraction geometry and single crystal Laue spots due to the diamond. Cu He- α radiation (~ 8.4 keV) was used to obtain the diffraction data.

4. Development of the New Forward-Backward X-Ray Diffraction Diagnostic. (PI: A Krygier)

with CE Wehrenberg, H-S Park, and JH Eggert (LLNL)

This experiment was the first effort at development of the new Forward-Backward X-Ray Diffraction diagnostic. By using two monochromatic X-ray sources, we will be able to constrain the in-situ strain anisotropy induced by material strength in a polycrystalline sample. In this experiment we tested several design features. First, we measured the first reflection diffraction at Omega-60 using a floating Fe micro-foil with no pinhole. Second, we optimized the reflection X-ray cone shield, finding that a larger cone performed significantly better, with low background. Third, we tested a U-6wt%Nb sample pinhole used in transmission diffraction at NIF, finding that it produces unwanted X-ray diffraction in the reflection geometry. Finally, we confirmed high quality diffraction in the transmission configuration with the extra features required for reflection diffraction (shield cone, etc.).

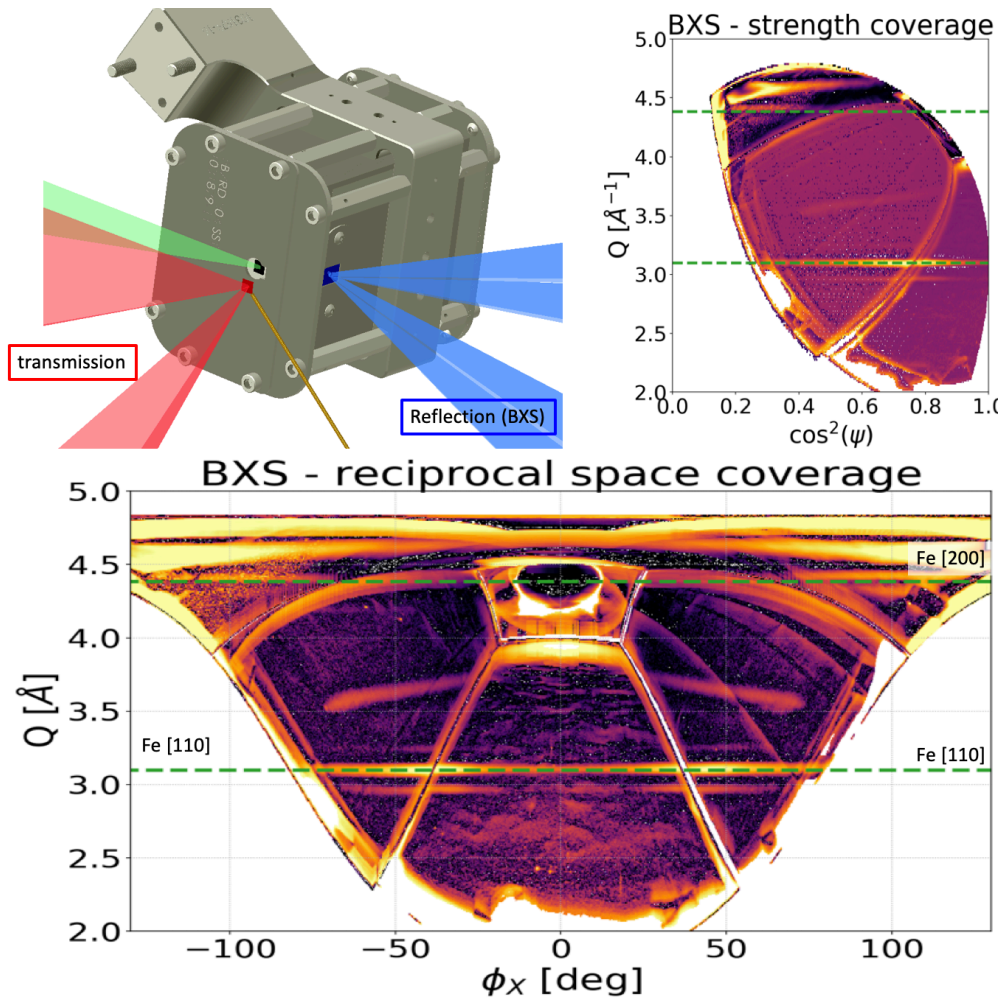


Figure 9 – (Top Left) Experimental setup. (Top Right) Reflection diffraction from undriven Fe, displayed vs $\cos^2 \psi$, the important parameter for strength; ψ is the angle between the diffracting plane and the applied stress. (Bottom) The same data projected in reciprocal lattice-azimuthal coordinates. Extra reflections are from multiple emission lines from the Ti backlighter. Extraneous signal is also seen between the [110] and [200] Fe reflections.

B. Material Equation of State Using Other Techniques

1. Equation of State Measurements Using Laser-Driven Mo Flyer Plate Impacts (PI: F. Coppari)

With: R. London, P. Celliers, M. Millot, A. Lazicki, and J. Eggert (LLNL)

The goal of the campaign is to develop a platform for absolute equation of state measurements by laser-accelerated symmetric flyer-plates impacts.

The conceptual design is to use ramp compression to accelerate a Molybdenum flyer across a vacuum gap through indirect laser ablation and observe the flyer impact on a same-material sample, mounted side-by-side to a Quartz window (Figure 1, bottom). Velocity interferometry measurements with VISAR (Velocity Interferometry System for Any Reflector) allow us to measure the flyer acceleration (U_{fs}) through the transparent quartz window providing a measure of U_{p_impact} (for a symmetric impact: $U_{p_impact}=0.5*U_{fs_impact}$). The resulting shock state in the Mo sample is determined via transit time, by measuring the time difference between the impact (t_{Mo_impact}) and the shock breakout (t_{Mo_BO}). The shock velocity U_s is then determined from $U_s = T_{Mo} / (t_{Mo_BO} - t_{Mo_impact})$, where T_{Mo} is the accurately-measured thickness of the Mo sample. Using the Rankine-Hugoniot equations one can then determine pressure and density of Molybdenum *absolutely* (e.g. without needing a known pressure reference), enabling the development of an EOS standard.

This platform will be extremely useful to all programmatic activities interested in equation of state and Hugoniot measurements at pressures of tens of Mbar, where currently there are no materials whose EOS has been experimentally determined.

This campaign built upon the results obtained in the past fiscal years. Very good quality data (Figure 1, bottom) were obtained in all the 14 shots, also thanks to improvements in the target fabrication procedure, that allowed us to obtain much more planar targets and therefore more accurate measurements of the shock velocity.

The Mo EOS was explored up to $U_s=16$ km/s corresponding to about 12 Mbar. In-depth data analysis will allow us to determine if this platform represents a viable path towards absolute EOS measurements.

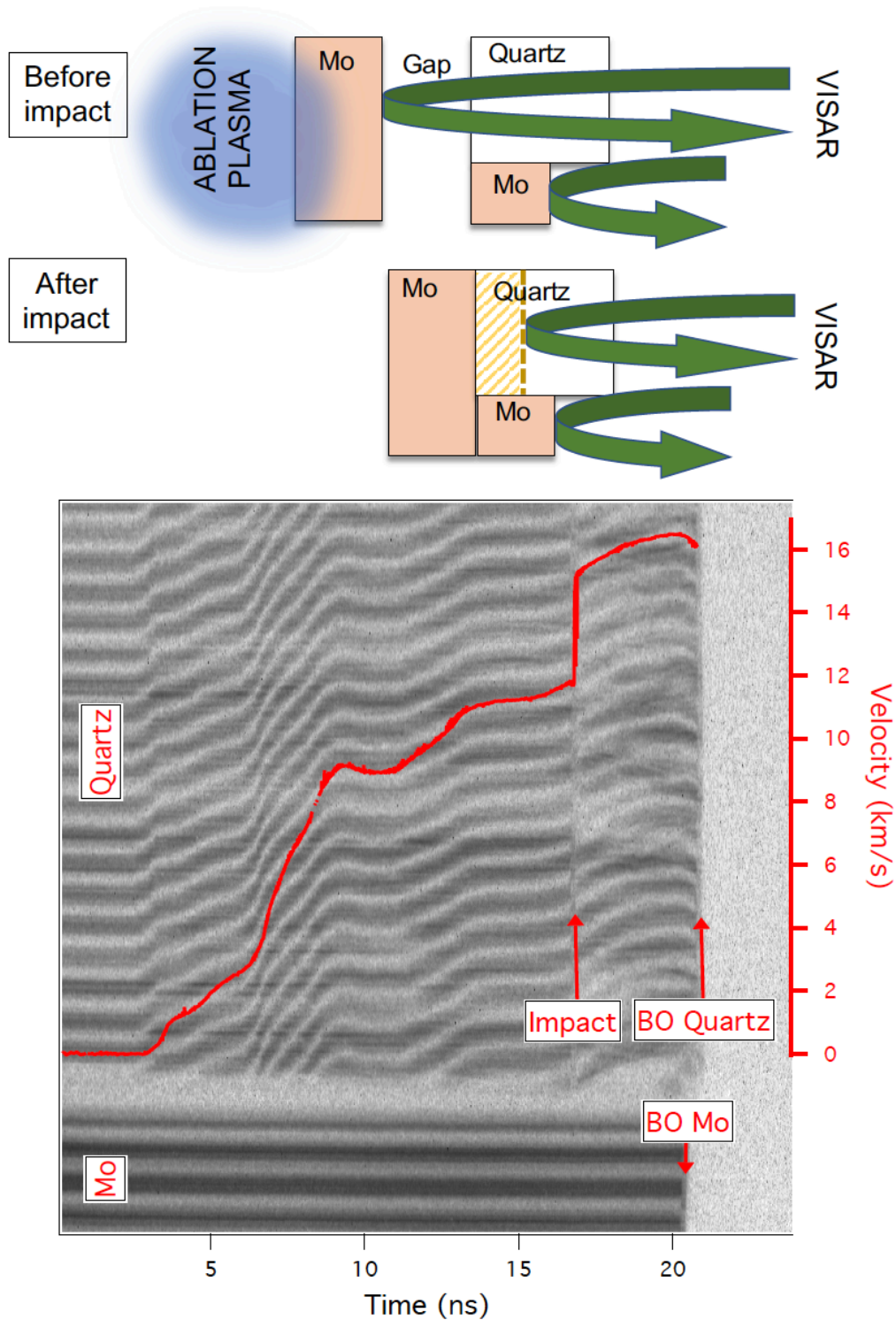


Fig. 1: (Top) Schematic representation of the experimental setup. A Mo foil is accelerated across a vacuum gap and impacted on a transparent Quartz window, mounted side-by-side to a Mo foil. The simultaneous measurement of the flyer velocity and shock velocity upon impact with VISAR gives a measurement of the Mo EOS, without the need to rely on the EOS of a reference material. (Bottom) Representative VISAR record. The main events are indicated by arrows.

2. Developing a Conically-Convergent Platform for Measuring Hugoniot Equation of State in the 100 Mbar-Gbar Pressure Regime (PI: A.E. Lazicki)

with F. Coppari, D. Swift, R. London, D. Erskine, H. Whitley, and J. Nilsen (LLNL)

This campaign was designed to develop a platform for measuring Hugoniot equation of state (EOS) 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, we launched converging shock waves into a plastic 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.

Previous Omega shot days from FY16-19 tested design concepts in preparation for shots on the NIF. At Omega we have not previously been able to generate a Mach wave with sufficient steadiness, planarity and surface area to perform an EOS measurement of sufficient accuracy, because of limitations in pulse energy and length, but we have successfully tested the effects of a wide range of optimization concepts, including cone material, height and angle, hohlraum size and gas fill, laser pulse length and energy and various schemes for heat shielding.

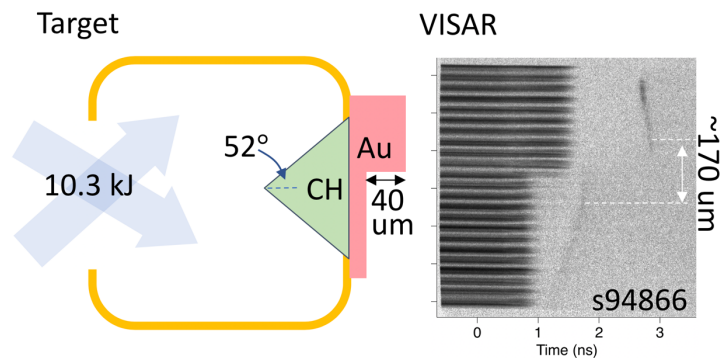


Figure 10 Mach wave generated in a CH cone and propagated through an Au stepped target. Average shock speeds of ~36.4 km/s were achieved in the Au. The visar reflectivity is lost about 1 ns before the shock wave breaks out, indicating that the free surface of Au melted. Shock wave breakout is indicated by a flash of light from thermal emission.

The shots in FY19 (3 half-days for a total of 20 shots) were specifically aimed toward testing a new scale of hohlraum (0.85 mm length, 1.15 mm diameter) midway between the standard, larger-scale EOS hohlraum (1x1.3 mm) which produced insufficiently supported Mach waves, and a smaller scale (0.7x1mm) tested in FY18, which resulted in supported Mach waves but with insufficient surface area, and very high levels of hard x-ray preheat, presumably from hohlraum LPI. We also tested a new concept for constraining target preheat levels by measuring time-resolved x-ray fluorescence, pumped by the

hohlraum radiation, from a thin layer of Cu placed in contact with the physics package.

The mid-scale hohlraum produced Mach waves with slightly reduced area compared to the large scale, but they were better supported, steadier and more planar. We generated pressures up to ~180 Mbar in an Au stepped target, over a ~170 μm planar area (Figure 1). We also tested the effects of changing Mach cone angle in the mid-scale hohlraum, and clearly confirm a predicted trend towards higher Mach wave pressure and smaller area with decreasing cone angle. Because of the large columnar volume of very high pressure material generated in a Mach cone, on shot days 19A and 19B we tested the Mach cone as a neutron generator by making the cones out of deuterated plastic. We generated up to $\sim 2 \times 10^8$ DD yield with a pure CD cone, and an order of magnitude lower when a CH ablator was deposited on the CD cone.

3. Liquid – Ice VII Phase Transition Kinetics in Ramp Compressed Water (PI: M. C. Marshall)

with M. Millot, D. E. Fratanduono and R. F. Smith (LLNL)

RampWaterEP-19A studied the liquid-ice VII phase transition in ramp compressed water at ultrahigh strain rates ($>10^6 \text{ s}^{-1}$). The principal isentrope of water crosses the liquid-ice VII equilibrium phase boundary at $\sim 2.5 \text{ GPa}$, however, ramp-compression experiments at the Sandia Z machine observed the phase transition at 7 GPa (Ref. 1). We are testing the metastability limit of liquid water by ramp compressing over $\sim 10\times$ higher compression rates than the Z experiments.

We completed one day on EP with a total of 13 target shots. A shocked CH reservoir released across a vacuum gap and isentropically loaded the water cell shown in Figure 1(a). A thin water layer ($\sim 15 \text{ }\mu\text{m}$), created using a sapphire diving board inside the water cell, was ramp compressed to $\sim 15 \text{ GPa}$. The experiments were designed to observe two signatures of the phase transition using VISAR. The first was a stress release on the rear sapphire window of the thin water layer caused by volume collapse during the transition (ice VII is 60% more dense than liquid water). The second was a coincident dip in transmission through the water layer from optical scattering of the coexisting liquid and ice phases with different refractive indices.

Preliminary analysis suggests that freezing occurred in several shots at pressures ranging 7-9 GPa. An example of the stress-release signature of freezing is shown in Figure 1(b). No clear evidence for transient opacity has been identified. Analysis is ongoing and a follow-up campaign that uses a variety of windows (sapphire, quartz, and PMMA) on the thin water layer is scheduled at Omega EP in FY20. Data will be compared to predictions using SAMSA, an LLNL kinetics code.

[1] D. H. Dolan, M. D. Knudson, C. A. Hall, and C. Deeny, Nat. Phys. 3, 339-342 (2007).

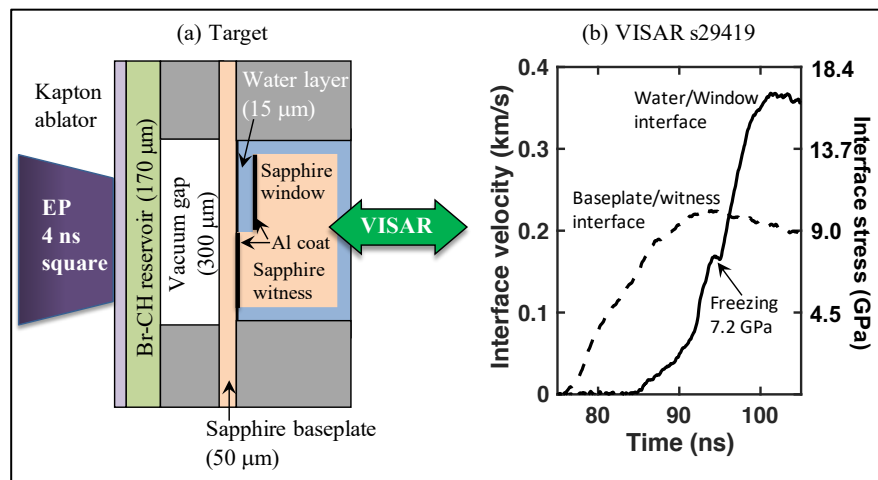


Figure 1. (a) Target design for a stress release measurement and (b) interface velocity and stress as determined from VISAR. The velocity of the baseplate/Al/witness interface (dashed curve) provided a drive measurement for each target shot. The stress release on the water/Al/window is indicative of freezing (solid curve).

4. EXAFS measurements using foil backlighters and a focusing spectrometer (PI: Y. Ping)

with F. Coppari, A. Krygier, J. McNaney, J. Eggert (LLNL)

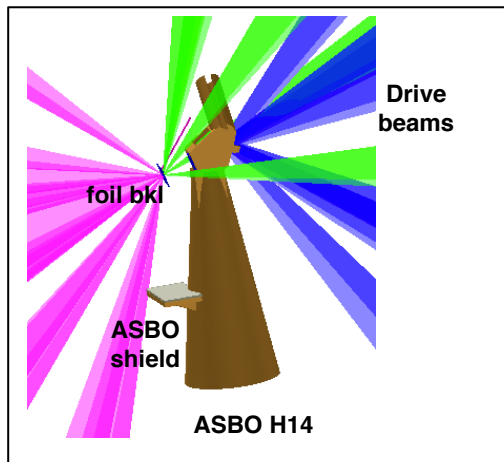


Figure 1. Experimental configuration.

In previous OMEGA shots we discovered that foil backlighters are brighter than the implosion backlighter at X-ray energies $> 10\text{keV}$. This series of shots demonstrated the feasibility of EXAFS measurements using foil backlighters and a focusing spectrometer, and the results supported the associated NIF design.

The experimental setup is shown in Fig. 1. The foil backscatterer (Ti, Ag, or Au) was irradiated by ~ 20 beams marked as green and pink in Fig. 1. The main target is a Fe foil sandwiched between diamond plates which was mounted in a 3D-printed plastic enclosure with VISAR mirror and shield. For high-pressure shots, the Fe package was driven by 5 beams (blue) stacked in time to simulate a ramp drive. The focusing spectrometer was IXTS with a toroidal crystal for 1D

spatially resolved x-ray spectra in Johann geometry where the resolution is insensitive to the x-ray source size.

The Fe EXAFS spectrum was observed as shown in Fig. 2 (left). The resolution was lower than expected due to an unexpected error in the radius of curvature of the toroidal crystal. In FY20 the position of the detector inside IXTS will be adjusted to match the actual radius of the crystal to improve the resolution. VISAR measurements were also demonstrated for the first time simultaneously with EXAFS measurements at OMEGA, by adding a shield to block the direct line of sight from the backscatterer to the ASBO lens as shown in Fig. 1. A typical VISAR raw image is displayed in Fig. 2 (right). In comparison to prior implosion backlighters, foil backlighters require fewer laser beams and produce more photons above 10keV . The new focusing geometry provides much higher signals on the image plate detector, providing a promising platform for x-ray absorption spectroscopy measurements.

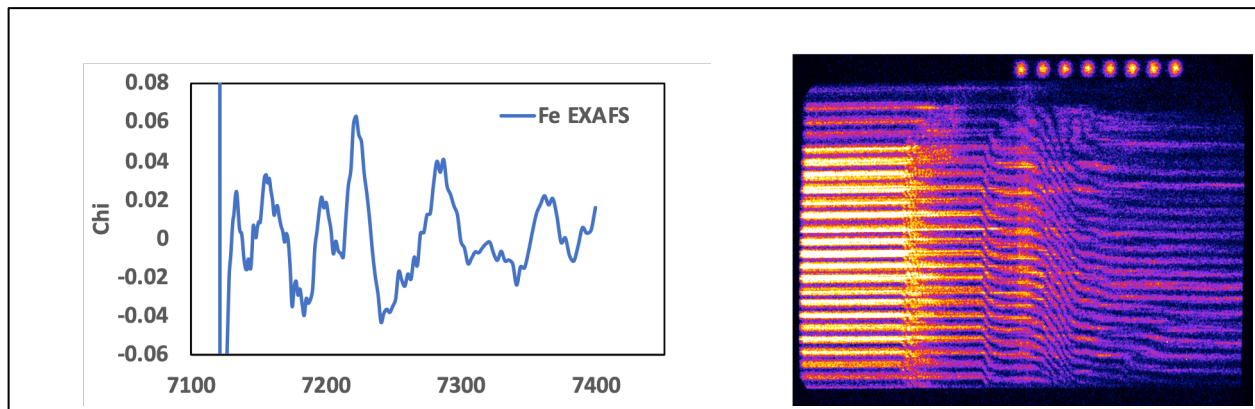


Figure 2. (Left) Fe EXAFS spectrum from IXTS with Ti foil backscatterer; (Right) VISAR data for $\sim 5\text{Mbar}$ drive.

5. Backlighter development for EXAFS measurements at high energy at the Omega Laser (PI: F. Coppari)

With: A. Do, Y. Ping, A. Krygier, and J. McNaney

EXAFS measurements require a bright, smooth and broad-band x-ray source. X-ray radiation emitted by a capsule implosion meets these requirements and is currently used in laser-based EXAFS experiments. The x-ray emission, however, decays quickly at higher energies, making EXAFS measurements above 10 keV very challenging. For high-quality, higher-energy EXAFS measurements there is a need for different x-ray sources. The bremsstrahlung radiation emitted by laser-irradiated higher-Z materials has the potential to be successfully used as such an x-ray source, provided the loss of spectral resolution in the measured EXAFS spectra due to source size effects can be mitigated. This can be accomplished either by collimating the x-rays using a slit (although this will also reduce the total flux) or by using a focusing spectrometer to measure the EXAFS signal.

In these 2-half-day campaigns we collected a total of 14 shots where we looked at different backlighter materials (Ti, Ag -including Ag foams-, Au, Ge), varied the laser drive conditions and characterized the spectra in a wide energy range using combinations of different spectrometers (flat X-Ray Rowland spectrometer[1] and the Dual Crystal Spectrometer[2]).

We found that the brightest spectra were measured for laser irradiance of the order of 10^{17} W/cm², and that Ti emits the brightest spectrum in the energy range below 25 keV, after which Au becomes brighter.

Ti represents therefore a promising choice as backlighter for EXAFS measurements at energies higher than 10 keV, where its spectrum is smooth and free from line emissions. A combination of a Ti foil backlighter and focusing spectrometer is expected to significantly improve the EXAFS platform at the Omega Laser and represents the point design for the development of the EXAFS diagnostic on the NIF. This configuration will be tested further next fiscal year at Omega.

[1] D. Thorn *et al*, RSI 89, 10F119 (2018)

[2] J. Seely *et al*, High Energy Density Physics 3, 263 (2007)

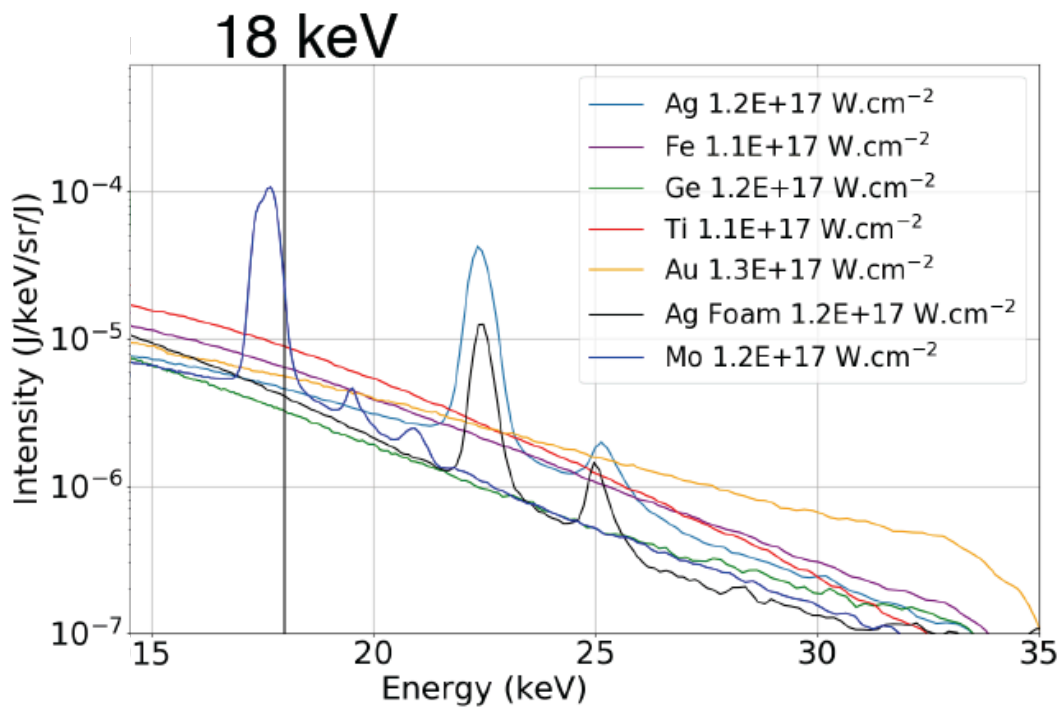


Figure: Spectra measured with the DCS spectrometer for the backlighter materials studied in this campaign (also including data obtained on Ag and Mo in 2016) for laser irradiation of the order of 10^{17} W/cm^2 . Our data clearly show that Ti is brighter than any other material looked at in this study for energies below 25 keV.

6. Isentrope measurements of isochorically heated materials

(PI: A. Saunders)

with Y. Ping, A. Jenei, H. Whitley, J. Nilsen, J. Eggert (LLNL); and M. Hill (AWE)

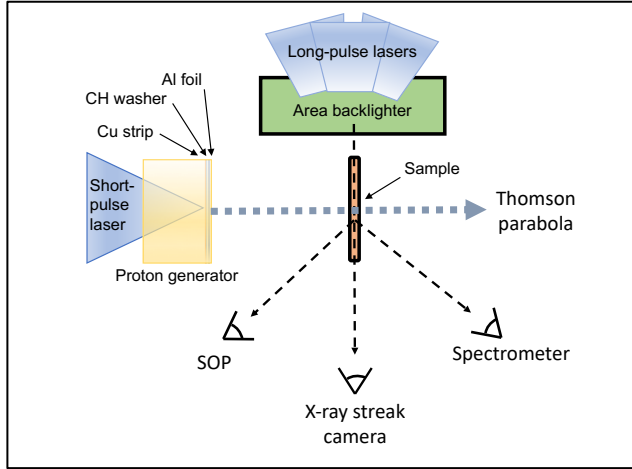


Figure 1. Experimental configuration.

This new series of shots aims to measure the release isentrope of heated materials. The isochoric heating was achieved by fast proton beams generated by high-intensity short laser pulses as illustrated by Fig. 1. The primary diagnostics are streaked x-ray radiography for time-resolved density profiles and streaked optical pyrometry (SOP) for initial temperature after the fast heating. The pressure is obtained from the density measurements using an analytical method developed by Foord et al. (PRE 2004). The target was a 50um square ribbon of diamond, CH or Al to allow radiography and SOP along two orthogonal axes. Other diagnostics, such as Thomson parabola and soft x-ray

spectrometer VSG, were also fielded to provide the energy spectra of the proton beam and x-ray fluorescence spectra of the heated sample.

High-quality data have been obtained from both primary diagnostics as shown in Fig. 2. The x-ray radiograph clearly shows the expansion of the target. The SOP shows that there is some preheat by the x-ray backlighter, which has been reduced in the second shot day by increasing the distance between the backlighter and the sample. The detailed data analysis is under way and a paper on this new platform has been written for submission to Rev. Sci. Instru. The plot at the right side of Fig. 1 shows two isentropes from two different EOSs L130 and Sesame 3718 for Al at 2eV. The large discrepancy between the two models, especially at lower densities, indicates a strong need of experimental data in this warm dense matter regime.

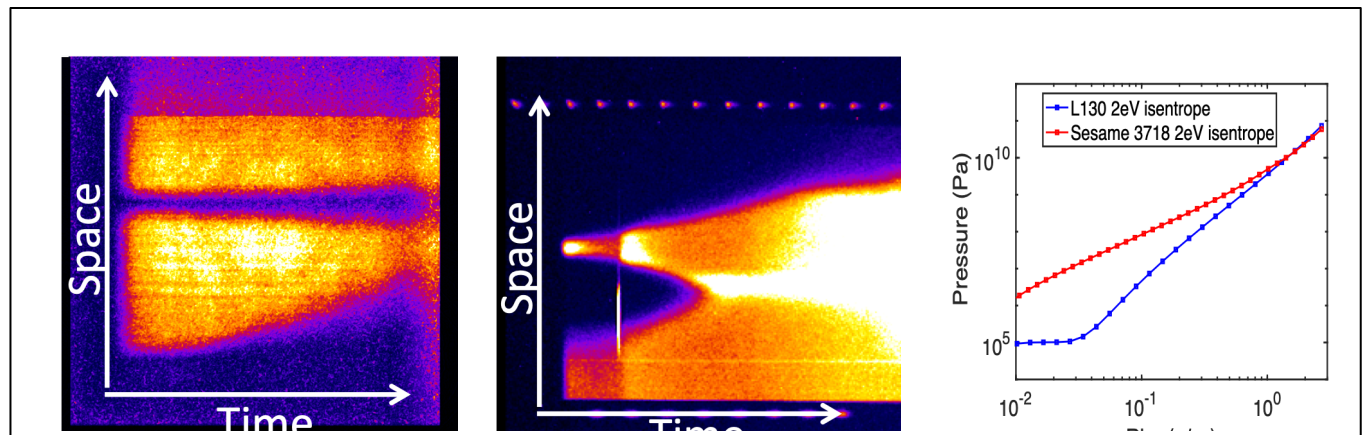


Figure 2. Streaked x-ray radiograph for Al (left), SOP image (middle), and two isentropes from two EOS models L130 and Sesame 3718 for Al heated to 2eV.

7. Measurements of the Single-Crystal TATB Hugoniot to 80 GPa (P.I.: A. Fernandez Pañella)

with M. Marshall (postdoc), T. Myers, J. H. Eggert, T. Bunt, L. Lauderbach, L. D. Leininger

The purpose of the HEEOSEP-19A campaign was to complete the Hugoniot measurements of TATB (triamino-trinitrobenzene) shocked to high pressure that were initiated in FY18. TATB is a high explosive known for its insensitivity to high temperatures and impacts. Experiments were done at the Omega EP laser facility, where TATB was shocked to a range of pressures (15 – 80 GPa) over 8 shots, filling up the gaps from the previous campaign. Hugoniot data were obtained by impedance matching relative to an aluminum standard. Planar targets had a Kapton ablator, aluminum base plate (standard), single-crystal TATB sample, and LIF witness used to correct for shock unsteadiness. Two laser beams with total energies of 580-2300 J were stacked in time, producing a 20-ns drive to support a nearly steady shock in the TATB. VISAR was used to measure interface velocities and shock transit times needed for the impedance-match analysis. These results have been used to complete the single-crystal Hugoniot measurements of TATB (shown in Fig.1). A manuscript has been written after these 2 campaigns.

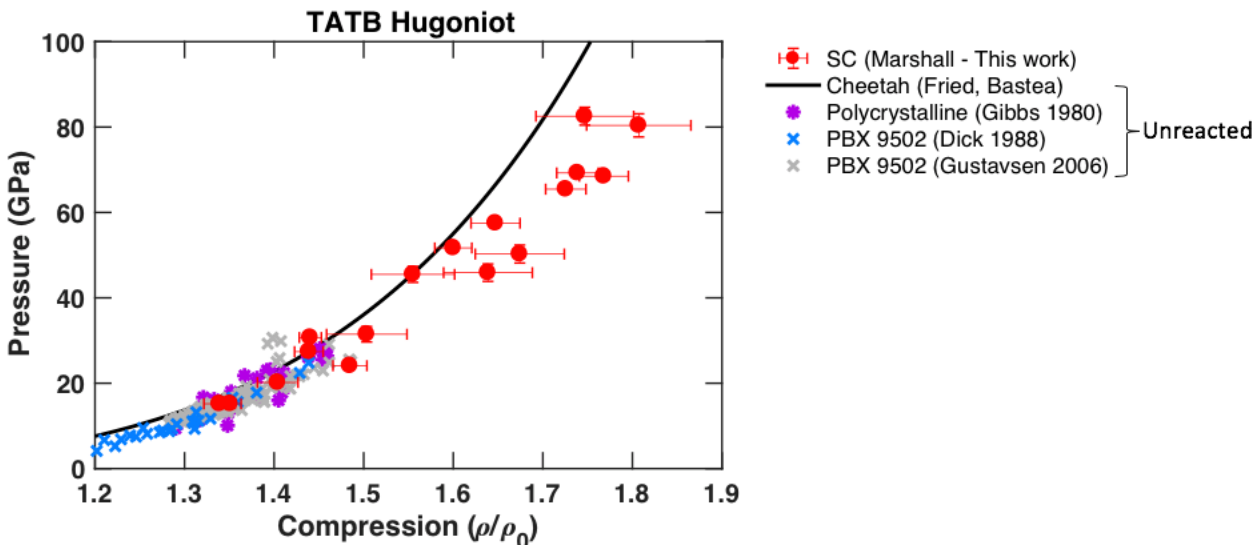


Figure 1. Single-crystal TATB Hugoniot. Pressure vs compression in a pressure range from 15 to 80 GPa covering unreacted and overdriven states.

8. Phase Transformations and Chemical Reaction in Shock-compressed TATB (P.I.: M. C. Marshall)

with A. Fernandez Pañella, M.G. Gorman (postdoc), T. Myers, B. Yancey, J. H. Eggert, and L. D. Leininger (LLNL); and D. N. Polsin (LLE).

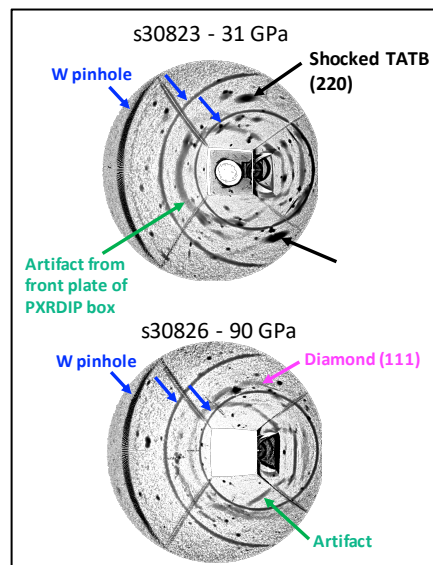


Figure 1. Stereographic projections of PXRDIP data for two shots.

The purpose of the HEXRDEP-19A campaign was to measure phase transformations and chemical reaction products in shocked TATB (triamino-trinitrobenzene) using x-ray diffraction. TATB ($C_6H_6N_6O_6$) is an insensitive high explosive that chemically reacts into inert gases and solid carbon species.

Experiments were done at the Omega EP laser facility, where TATB was shocked to pressures ranging 10 to 90 GPa over 8 shots. The planar targets had an epoxy ablator, single-crystal TATB sample, and a Ti-coated LiF window mounted on a tungsten pinhole. Two laser beams with total energies of 190 to 1090 J were stacked in time, producing a 20-ns drive to support a nearly steady shock in the TATB. The two remaining beams were incident on a Fe backlighter foil, producing He- α emission to probe the crystal structure of the shocked TATB. X-ray diffraction data were obtained using the PXRDIP diagnostic and VISAR was used to measure the TATB/LiF interface velocities needed to determine the shocked TATB pressure.

Initial results indicate that the TATB single crystals remain highly textured solids to ~40-50 GPa. A change in the x-ray diffraction pattern is observed when TATB is shocked over ~55 GPa. A new powder line, consistent with diffraction from the (111) plane of diamond, is observed at 90 GPa (Figure 1). Analysis is ongoing and a follow-up shot day using higher energy Cu backlighters is scheduled for FY20. Data will be used to improve predictive modeling of chemical reactions in TATB-based explosives.

C. Material Dynamics, Strength and Ejecta Physics

1. Strength experiments using direct-drive Rayleigh-Taylor growth rates

(PI: A. Zylstra)

with H.-S. Park, C. Stan (postdoc), D. Swift, T. Lockard and J. McNaney (LLNL); M. Hill and P. Graham (AWE),

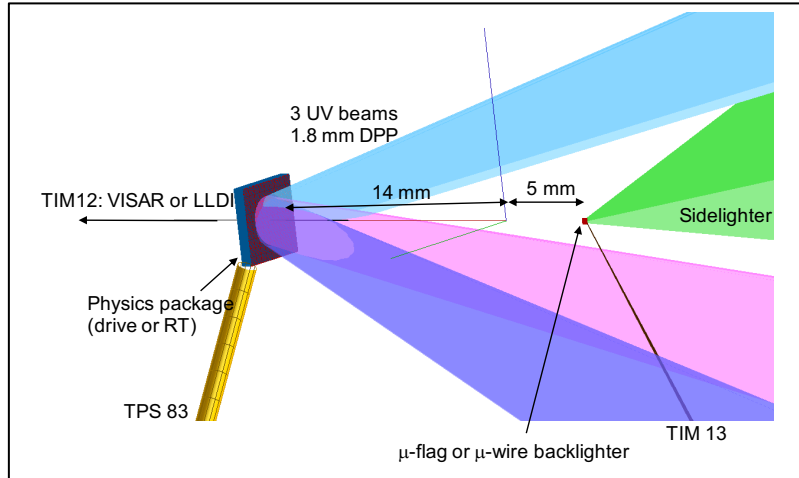


Figure 1. Experimental configuration.

This campaign consisted of two Omega-EP shot days with a total of 11 shots. The goal of this campaign is to measure the growth of pre-imposed ripples at a Rayleigh-Taylor unstable interface on a material sample of interest. Since the material strength will suppress the Rayleigh-Taylor growth rate, strength in the HED regime can be inferred from the measured growth rate.

New in FY19 is the use of a direct-drive configuration on OMEGA EP, unlike previous indirect-drive strength experiments performed on OMEGA [1] or NIF. The major advantages of a direct-drive platform are twofold: first, the pressure history on the sample can be changed by modifying the pulse shape, unlike the indirect-drive technique which requires modifications to the target (through the ‘reservoir’), and second, a direct inference of the growth rate can be performed by comparing the rippled sample in both driven and undriven regions.

The experimental configuration is shown in Fig. 1. Three long-pulse UV beams (2, 3, and 4) with 1.8mm phase plates are used to drive the physics package. The beams are staggered in time to create a 30 ns duration drive using individualized and stitched pulse shapes to compress the sample to ~ 1 Mbar. The physics package is placed 14mm towards TIM 12, which holds the primary diagnostics. For the RT growth measurements the sidelighter beam shoots a micro-flag or micro-wire target placed 5mm away from TCC to create a high-energy x-ray point-projection backlighter. The sidelighter uses 1000J of energy in a 100ps pulse. This campaign starts out using VISAR as the primary diagnostic to measure the shock propagation through a surrogate physics package which characterizes the drive and sample conditions. Then the diagnostic is switched to LLDI for radiography.

The first shot day, DDRT, used tantalum as the material to enable comparison to Ref. 1 and develop the platform. Excellent radiography data were obtained, the results are being interpreted and prepared for publication. Sample radiographs are shown in Fig. 2. Initial indications are that the new analysis method enabled by the direct-drive platform can substantially reduce the uncertainties associated with the strength growth factor measurements. In the second day, the material was switched to tin. An example radiograph is also shown in Fig. 2. Measuring the strength of tin at HED conditions is data needed for a tri-lab project on material strength. Good data were obtained early in time, at the latest sample times the data appear compromised by instability growth at a Au/Re preheat shield layer between the ablator and the

tin sample. Data analysis are still in progress, and the platform will be adapted for improved measurements in FY20 towards meeting the tri-lab goals.

[1] H.-S. Park *et al.* PRL 114, 065502 (2015).

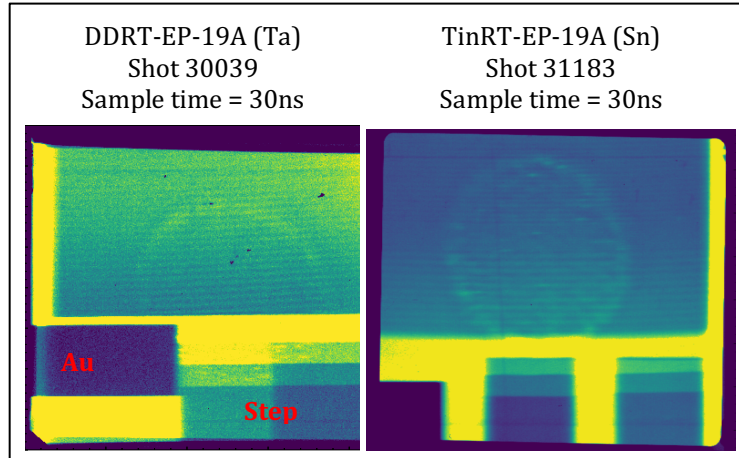


Figure 2. Raw radiographs from each shot day, the growth factor analysis and interpretation is in progress.

2. Spall and Recollection in Ramp-Compressed Tin (PI: S. J. Ali)

with Alison Saunders, H-S. Park, J. H. Eggert, A. Fernandez-Panella, F. Najjar, T. Haxhimali, B. Morgan, Y. Ping and C. Huntington (LLNL); and H. Rinderknecht (LLE).

In dynamically compressed materials undergoing ductile failure, the formation and coalescence of voids due to high-rate tensile stress induces spallation, the formation of one or more 2D sheets that detach from the bulk material. Eventually, the material behind the sheets may catch up and recollection can occur, potentially resulting in closure of the voids or fractures and, depending on

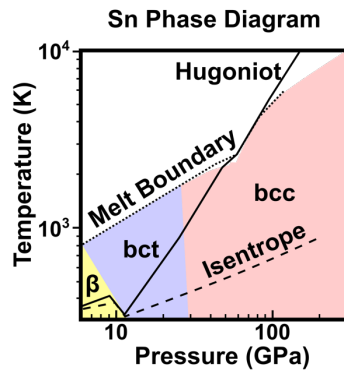


Figure 11 Tin phase diagram (Fernandez-Panella)

the mechanical response of the material, healing of the surface. The formation and recollection of spall layers is a leading hypothesis to explain the origin of spatially-heterogenous reflectivity loss and recovery observed in line-VISAR results for free-surface dynamic compression experiments. In ramp-compression experiments on polycrystalline tin at NIF with small initial shock, this reflectivity loss and late-time recovery is observed in free-surface experiments where the initial shock is below the bct to bcc phase transition, as shown in Figure 1, but no longer observed when the initial shock is higher. This suggests

that the reflectivity loss is due to damage and breakup of the surface during spallation, and that the subsequent impact of either additional spall layers or the bulk, as indicated by the observed acceleration of the material, contributes to the healing or repair of the observed surface. To determine the microphysical nature of the damage, it is necessary to resolve both the spatial distribution of the ejected material fragments, as well as their velocities.

We used the Omega High Resolution Velocimeter (OHRV), a two-dimensional velocimetry diagnostic, to simultaneously image and measure the velocity of ramp-compressed tin. Over the course of two half-day campaigns, we successfully smoothly ramp-compressed tin to a peak pressure of 50-100 GPa, through the bct-bcc phase transition, and while we observed spall-like behavior, shown in Figure 2, and fracture along grain boundaries, we did not observe the reflectivity recovery and acceleration seen in the NIF experiments. Ramp compression was accomplished using a plasma-piston drive, which allows for less flexibility in pulse shaping, and our current hypothesis is that the the behavior observed in the NIF experiments is more sensitive to drive than initially suspected, and further work will be required to understand this sensitivity.

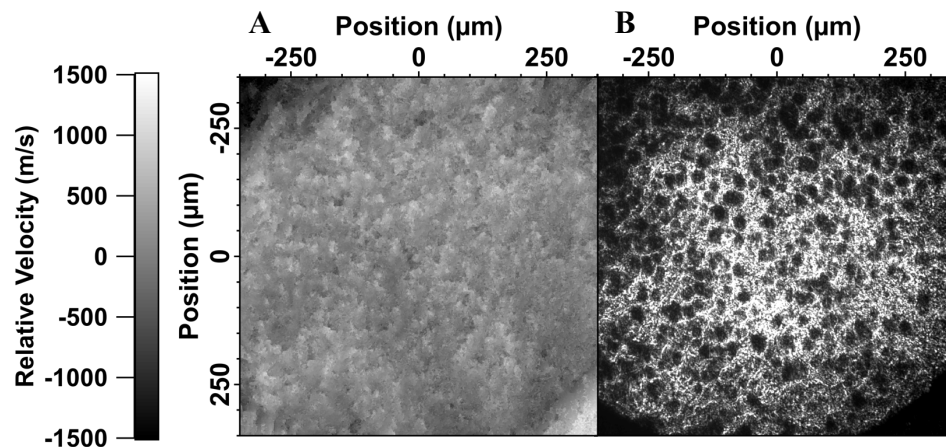


Figure 12 OHRV results from a shot ramping tin to ~70 GPa. OHRV probe was on compression, at ~50 GPa. (A) Velocity map and (B) image both show round features indicative of solid material spall.

3. Development of High Power Laser Platforms to Study Metal Ejecta Interactions (PI: A. Saunders)

with S. J. Ali, H-S. Park, J. H. Eggert, F. Najjar, T. Haxhimali, B. Morgan, Y. Ping, C. Huntington (LLNL); and H. Rinderknecht (LLE).

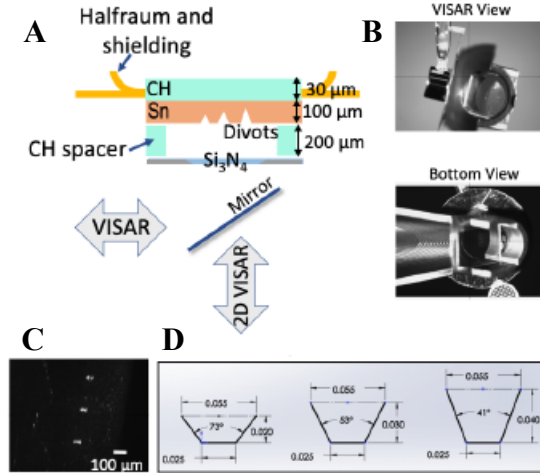


Figure 13. (A) Target schematic, (B) photos of the actual target from the 1-D VISAR view and from the bottom view, (C) image of the divots on the tin surface, and (D) divot schematics

We developed a platform for the OMEGA laser to measure the areal mass density emerging from surface perturbations on tin foils. The platform uses the previously developed target fixture designed to make concurrent 1-D and 2-D VISAR measurements, allowing us to quantify the conditions in the tin upon shock release and provide data about the areal mass density of the ejecta jets. The target package is shown in Figure 1(A) and consists of an ablator, a tin sample with multiple divots, and a silicon nitride collection plate. The silicon nitride is 100 nm thick and reflects a fraction of visible light such that it provides a reflective surface for the VISAR measurements. Jets emerging from the tin divots impact on the silicon nitride window, causing it to accelerate. 1-D VISAR measures the motion of the silicon nitride and tracks the velocity as a function of time. Through the equations for momentum conservation, the areal mass density of the ejecta jets can be solved for in terms of the velocity of the SiN window [1]. The

High velocity ejecta and dust grain interactions are of great interest to the stockpile stewardship program as well as interstellar and interplanetary science. Ejecta particles are generated by the Richtmyer-Meshkov (RM) instability when a strong shock wave interacts with surface defects while breaking out at a metal interface into vacuum or gas. Ejecta formation has been studied extensively, but ejecta particle transport, interaction, and recollection are still poorly understood. This project has been working to apply novel experimental techniques and diagnostics that have been developed for high-energy laser studies to this topic. Specifically, we have used x-ray radiography, as well as line- and 2D-VISAR to explore the details of ejecta transport, interaction, and recollection.

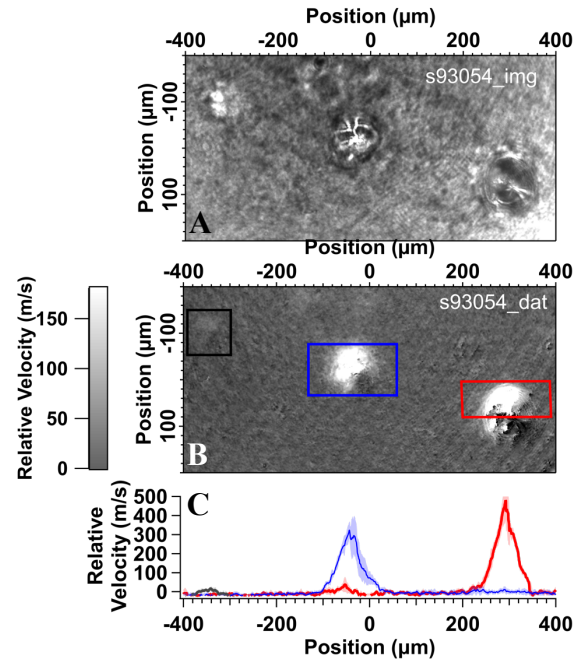


Figure 14. 2D VISAR results from one ejecta shot with three divots with varying depth showing (A) an image of the ejecta interacting with eh SiN, (B) velocity of the ejecta/SiN interaction, and (C) lineouts of the velocity for each divot.

2D VISAR provides an image of the jets impacting the SiN, as well as the velocity as a function of position, as shown in Figure 2.

[1] Saunders, A. M. et al. "Development of High Power Laser Platforms to Study Metal." In review for APS SCCM 2019 Conference Proceedings (2019)

4. Study of Metal Ejecta Recollection, Interactions, and Transport on OMEGA EP (PI: A. Saunders)

with H.-S. Park, S. Ali, J. Eggert, T. Haxhimali, K. MacKay (postdoc), B. Morgan, F. Najjar, Y. Ping, and C. Stan (postdoc) (LLNL); H. Rinderknecht (LLE); and P. Tzeferacos (U. Chicago)

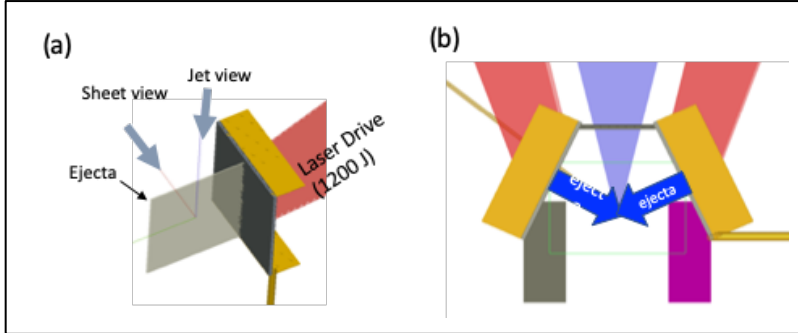


Figure 1. Experimental configuration: (a) single jet platform; (b) interacting jet platform.

This campaign consisted of three shot days with a total of 27 shots to develop a laser-driven experimental platform to understand ejecta properties especially during their recollection, interactions and transport processes. Ejecta are sub- to micron particles that can travel at hyper velocities (1-10 km/s). Understanding ejecta interactions has broad relevance to many fields of science

including impact material physics and debris shielding.

In FY19, the Omega-EP Ejecta-Interact campaigns focused on creating ejecta in both solid and liquid stages, measuring their jet velocities, and developing a radiography platform to understand their morphology and evolution. Figure 1 shows the experimental configuration. The target was a 30 μm thick ablator with a 100 μm thick Sn metal foil. The Sn had a long, 45 μm deep groove with a 60 degree opening in the middle of the surface. The laser drive shocks the Sn target. Release of the shock onto the free surface generates Richtmyer-Meshkov instabilities from the surface perturbation and ejecta jets are created. Figure 1 (a) is the platform for single jet and (b) is the interacting jet configuration.

The drive used 1.8 mm diameter large phase plates and an 8 ns square pulse with varying laser energies. We tried 3 different laser energies to control the ejecta phase (i.e. liquid and solid.) The drive was measured by the VISAR diagnostic on separate shots. From the free-surface velocity measurements, the particle velocities were calculated. From these particle velocities, using the well-known Hugoniot EOS table for Sn, the shock velocities and the shock pressure were derived. The ~1120J laser energy resulted in a

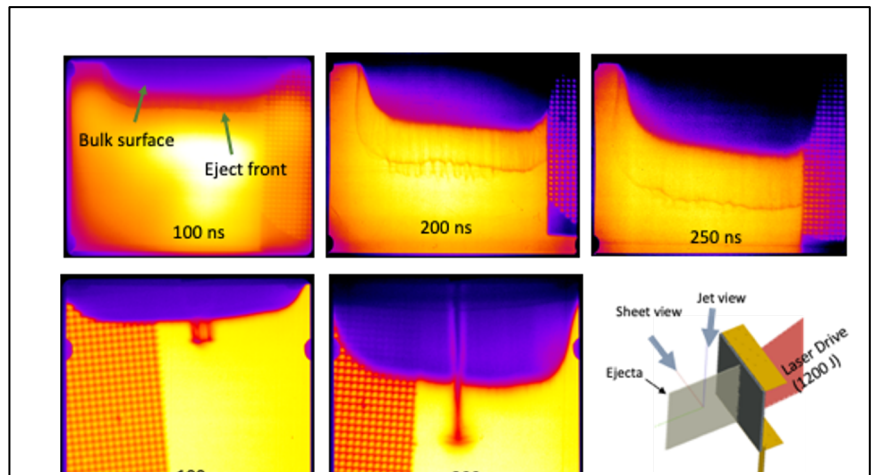


Figure 2. Raw radiographs of expanding liquid Sn ejecta jets taken at different delay times. Top row is the “sheet” view and the bottom row is the “jet” view.

~100 GPa shock pressure that is well above the Hugoniot melt line; thus the ejecta was in the liquid state. At ~300J, we measured ~42 GPa which is still in the liquid state. At ~70J, we measured a shock pressure of ~16 GPa which is well below the melt line. These drive calibration shots were crucial to understanding the ejecta state.

For radiography, we used the short-pulse driven Ti micro-wire backlighter that generates predominantly 4.5 keV K_{α} x-ray photons with ~10 μm spatial resolution. The target geometry was varied such that the radiography was viewing two different orthogonal angles, the “jet” view and “sheet” views of the ejecta jet. Figure 2 shows the resulting single ejecta jet evolution from both jet and sheet view radiography. For these shots, we used a 1200J drive that created melted Sn ejecta at ~100 GPa shock pressure. The initial analysis indicate that the ejecta jet velocity was ~5.3 km/s; the bulk surface was ~2.5 km/s. The radiometric data show that the areal mass density was ~0.3 mg/cm² [1]. The ejecta front travels at a faster velocity than the bulk surface of the tin that can be seen preceding the bulk surface in the radiography.

For EjectaInteract-EP-19C campaign, we created solid state Sn ejecta jets using ~70J of drive laser energy that delivered ~16 GPa of shock pressure. Figure 3 shows the resulting radiography in the jet and sheet views. The sheet view shows interesting layered features that could be spalling. From these views, the solid Sn ejecta jet velocity is ~2 km/s. The interacting jets are created by shocking two targets in opposite directions. The interacting jet view is shown in the third panel. The lineout of the interacting region show more obscuration of the signal indicating that the ejecta density was piling up from inelastic scattering.

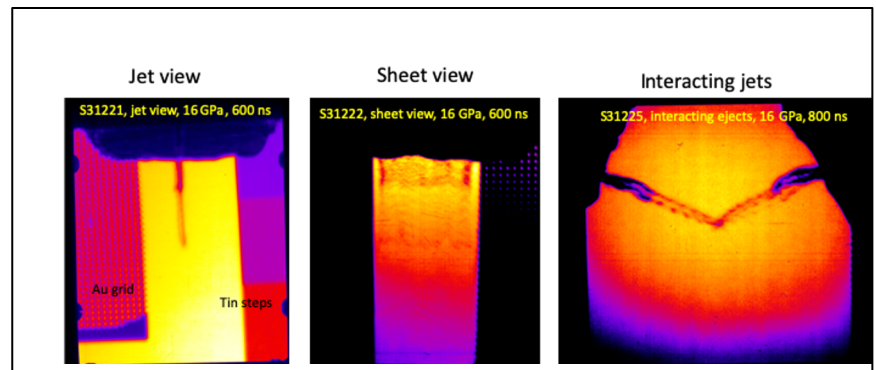


Figure 3. Raw radiographs of expanding solid Sn ejecta jets with “jet” and “sheet” views. The interacting jets are created by two opposing targets. Density pile-up was observed in the interaction region.

Future campaigns will study more details of the interacting ejecta properties and the effect of different materials and different groove shapes. In addition, particle-plate interactions will be studied.

[1] A. M. Saunders *et al.*, “Development of high power laser platforms to study metal ejecta interactions”, submitted to AIP Proceedings of 2019 Shock Compression of Condensed Matter meeting.

D. National Security Applications

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

The experimental determination whether prompt x-rays can induce failure modes in solar arrays remains the key goal of the SolarCellESD campaign. The main difference in vulnerability of an array compared to a single solar cell is the presence of a voltage difference between neighboring cells that can be up to 100s of volts depending on the overall layout of the array. For the experiments at OMEGA, we continue fielding the smallest possible array, i.e., 2x1 cells with electronic controls that allow us to dial in a voltage difference (bias voltage) between the two cells and, thus, to study the failure modes as a function of incident x-ray flux, and bias voltage, respectively.

For the FY19 campaign we deployed a new solar cell coupon design, with a new mechanical support structure that made it easier to exchange the solar cell coupons between shots. We continued using the EMI enclosure but fielded two of the four Langmuir probes in the “shadow” of the EMI enclosure, i.e., away from the line-of-sight of the incident x rays (see Fig.1). The goal of this arrangement was to investigate if the Langmuir probe signal is partly generated by a possible x-ray induced blow-off plasma from the solar cells. Measurements from the probes in the “shadow” didn’t show any significant signal above the noise level and, thus, validated our interpretation of the signal from the Langmuir probes that remained in the line-of-sight of the x-ray source.

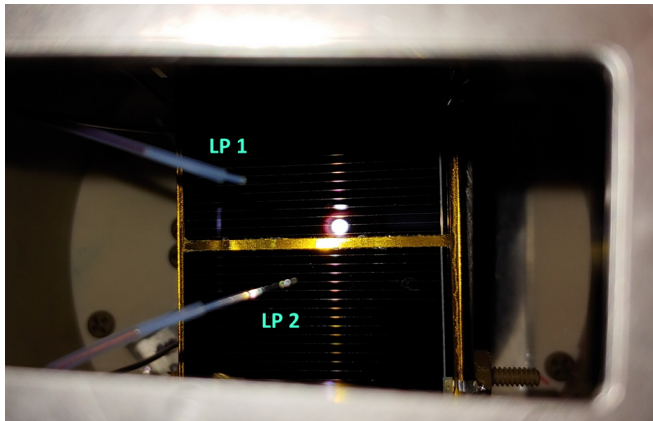


Figure 1. View of the gap between the two solar cells of the 2x1 mini array as seen through the aperture of the EMI enclosure. The two features on the left (LP 1, LP 2) are the Langmuir probes that are in the line-of-sight of the x-ray source. These probes are several centimeters above the surface of the solar cells.

We were able to bracket the threshold conditions for the onset of an electrostatic discharge and for the development of sustained arcing for a fixed bias setting. However, we observed significant variation in the breakdown response based on the view angle for the azimuthally asymmetric laser drive (azimuthal with respect to the hohlraum axis). This important finding will determine the geometry of the experimental setup for upcoming SolarCellESD campaigns. We also tested a high-temperature hohlraum rather than halfraum as the x-ray source. Unfortunately, a failure of the Dante gate valve prevented us from measuring the performance of this new x-ray source, but we plan on repeating the test of the new source in FY20.

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 (LLNL)

FY19 continued a campaign to develop a high fluence x-ray source in the 30 – 100 keV range by optimizing plasma instabilities. High fluence sources at lower energies are currently used for materials effects studies in extreme environments, but no good source exists for 30+ keV x-rays. This project aims to enhance laser conversion to plasma instabilities like Stimulated Raman Scattering (SRS) and Two-Plasmon Decay (TPD) which accelerate electrons in plasma waves that will convert to high energy x-rays via bremsstrahlung in the high-Z hohlraum wall.

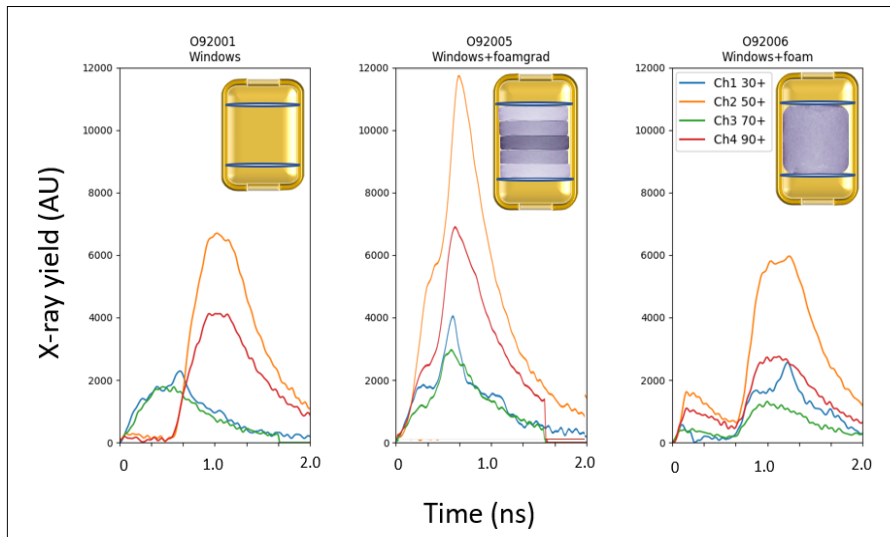


Figure 15: Hard x-ray detector signal from three shots, target type indicated by inset. Enhancement of the desired 50+ keV channel (orange curve) is observed for the windowed hohlraums, with further increases (factor of 4 integrated yield) for the windowed, layered foam hohlraums.

Two half day campaigns during FY19 attempted to optimize and prolong the duration of plasma conditions that have been found favorable for strong plasma wave generation. Experiments from previous years demonstrated x-ray yield enhancement from two hohlraum fills (inner CH liner and low-density CH foams) that also enhanced different plasma instabilities and thus different components of the x-ray spectrum. A natural evolution for FY19 was to study these effects in combination—the insets in Fig. 1 show the usual Au hohlraum with 1 μm thick CH “windows” which could be ablated by the initial prepulse just like the inner liner, but this redesign allowed CH foam to be fielded as well between the windows to maintain sufficient plasma density as the laser ablated away material. This design was also fielded with foam layers increasing in density toward the center of the hohlraum. Hard x-ray detector signals (Fig. 1) showed enhancement of the desired 50+ keV x-rays (orange) with the CH window designs and a further 4x enhancement in total yield for targets that also had the foam layers.

The results from the Omega campaign were used to design a complementary NIF shot day in Q2 FY19, which demonstrated an increase in the hot electron temperature distribution and thereby the 50+ keV hard x-ray signal over FY18 results. These successes have enabled the first shots of materials in high fluence, hard x-ray environments on NIF, and are being fielded on more campaigns in FY20 even as optimizations continue. This new x-ray source represents 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.

3. Enhancing Multi-KeV Line Radiation from Laser Driven Non-Equilibrium Plasmas through Application of External Magnetic Fields (PI: G.E. Kemp¹)

with D.A. Mariscal^{1*}, P.L. Poole^{1*}, J.D. Colvin¹, M.J. May¹, A. Dasgupta², A.L. Velikovich², J. Giuliani², C.K. Li³, A. Birkel³, and B.E. Blue¹.

¹ Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

² Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375-5346, USA

³ Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

* Postdoc

A recent LLNL LDRD effort (17-ERD-027) has been studying the influence of externally applied magnetic fields on laser-driven x-ray sources – like those typically used for high fluence radiography or backlighters – with the ultimate goal of improving multi-keV x-ray conversion efficiency through thermal transport inhibition. This series of shots was to test and qualify a platform for fielding externally generated magnetic fields on previously fielded x-ray sources on the Omega laser facility. This platform is intended to collect data in the 20 T magnetic field regime, where currently very little data exists for such high-Z, non-LTE, magnetized plasma conditions. The collected data will be used to constrain thermal transport inhibition and magneto-hydrodynamics models currently used in the multi-physics rad-hydro code HYDRA.

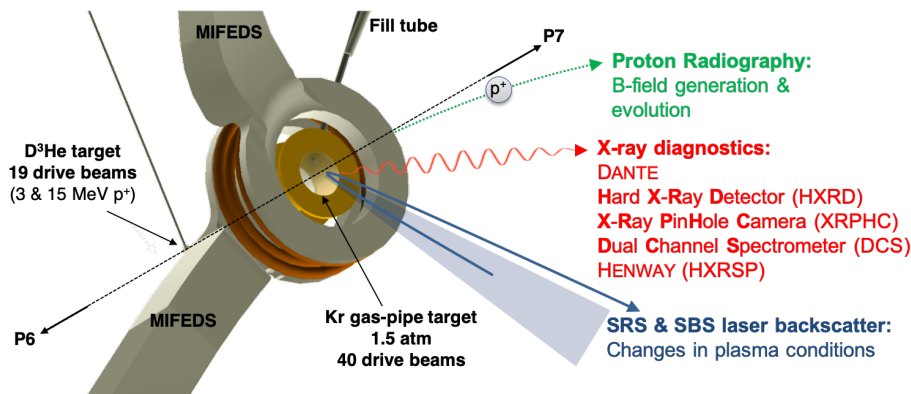


Figure 16. Experimental configuration for MagXRSA-19A. X-ray emission, laser backscatter, and proton radiography data were simultaneously obtained to quantify the evolution and influence of external B-fields in these interactions.

The experimental configuration is illustrated in Fig. 1. Thin walled, cylindrical Kr gas-pipes (1.5 atm), were driven by 20 kJ of laser energy in a 1 ns pulse (40 beams) as typical sources of ~13 keV K-shell line-radiation. A total of 6 shots were taken, half of which had externally imposed B-fields. A dual-MIFEDS (Magneto-Inertial Fusion Energy Discharge System) design was adopted to reach ~20 T field strengths (compared to ~13 T from MagXRSA-18A). Quantifying changes in x-ray emission with increasing external B-field strength was the primary goal of the shots, recorded with Dante (0-20 keV), hard x-ray detectors (20-500 keV), pinhole cameras (>2 keV), and the Dual Channel Spectrometer (11-45 keV). Secondary diagnostics included proton radiography and stimulated Raman/Brillouin laser backscatter. A D³He backlighter capsule provided a source of 3 and 15 MeV protons. Analysis is ongoing, but initial results suggest ~50% enhancements in multi-keV Kr emission (>8 keV) when the 20 T B-field was present, consistent with the pre-shot modeling [1]. Enhancements of 2.6X were also observed in the >80 keV emission, suggesting B-fields could also be used to enhance continuum emission.

Preliminary results from this campaign have led to additional shot time in FY20. With the recent MIFEDS hardware upgrades we anticipate fields in excess of 40 T in the dual-MIFEDS configuration. These promising results have also justified parallel NIF platform development later in FY20 where we will explore magnetized Ag and Xe K-shell x-ray sources.

E. Plasma Properties

1. Development of platform to benchmark atomic models for x-ray spectroscopy of shock-heated materials (PI: M. J. MacDonald)

with A. M. Saunders, T. Döppner, C. M. Huntington, K. B. Fournier, H. A. Scott, T. Baumann (LLNL); S. R. Klein, K. Ma, H. J. Lefevre, C. C. Kuranz and E. Johnsen (Univ. of Michigan); and R. W. Falcone (UC Berkeley).

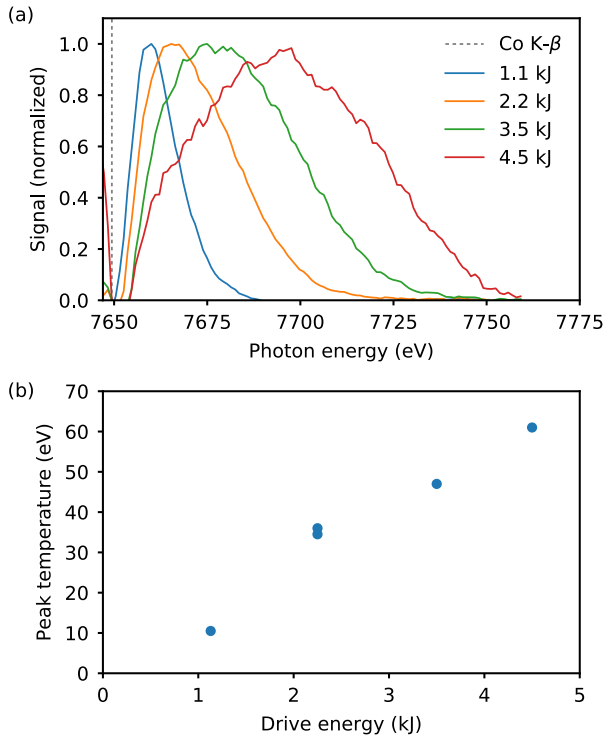


Figure 17: (a) Co K- β spectra taken at different drive energies after removing the contribution from unshocked material. (b) Peak temperatures in the shock-heated foam determined by fitting Co K- β emission to Cretin simulations.

ability to measure Co K- β spectra from the shock-heated layer at a range of drive conditions, as shown in Fig. 1a. Initial estimates of the peak temperature in the shocked layer from the Co K- β spectra as a function of drive energy are shown in Fig. 1b. The temperatures are from simulated emission spectra calculated using Cretin [2], an atomic kinetics and radiation code developed at Lawrence Livermore National Laboratory. Although the XRTS data collected in these experiments will be difficult to interpret due to noise in the data, the results will be helpful in improving the experimental setup for future campaigns.

The FoamXRFTS-19A campaign was the second shot day to develop a platform using simultaneous x-ray fluorescence (XRF) spectroscopy and x-ray Thomson scattering (XRTS) to measure the equation of state of shocked foams. The goal of this platform is to provide XRF spectroscopy data from shock-heated materials at known temperatures, measured independently using XRTS, to benchmark atomic models for future XRF diagnostics.

This platform uses a planar shockwave to heat a cylinder of foam doped with a mid-Z element, similar to previous results published from the Trident laser facility at Los Alamos National Laboratory [1], with the addition of an XRTS diagnostic. A laser-driven Zn He- α backlighter both induced K-shell fluorescence from the Co-doped foam and served as the x-ray source for XRTS. The IXTS spectrometer recorded spatially-resolved Co K- β XRF, measuring the density profile of the shock wave in the foam in addition to resolving XRF spectra from the shocked and unshocked regions of the foam.

This campaign successfully demonstrated the

[1] M. J. MacDonald *et al.*, J. Appl. Phys. **120**, 125901 (2016).

[2] H. A. Scott *et al.*, JQSRT **71**, 689–701 (2001).

2. Measurement of Au M-shell emission using a buried layer platform

(PI: E.V. Marley)

with R.F. Heeter, M.B. Schneider, G.E. Kemp, M.E. Foord, D.A. Liedahl, K. Widmann, and J. Emig (LLNL); D. Bishel (LLE); and G. Perez-Callejo (Univ. of Oxford)

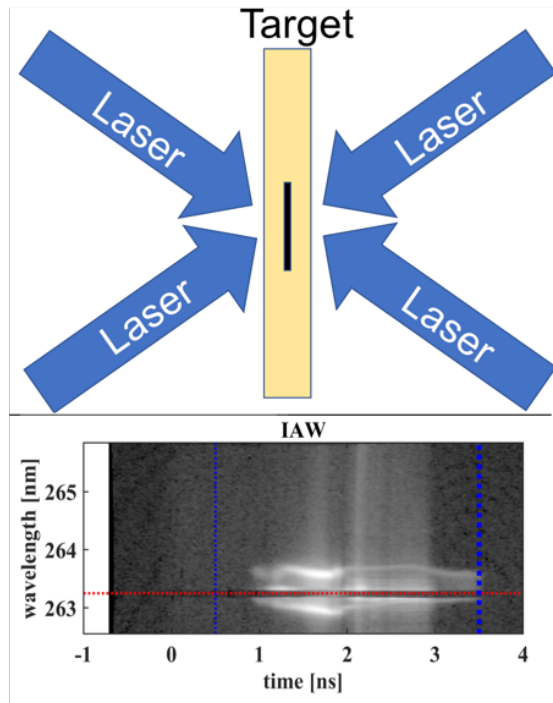


Figure 18. Experimental configuration and Thomson scattering data of shot 93556.

This campaign was designed to measure 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 also the 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.

Planar, buried layer targets were illuminated equally on both sides (Fig. 1) to heat the sample. The sample used in the campaign was a 1300 Å thick Au/V mixture designed to burn through completely before the end of the laser pulse, providing uniform plasma conditions to measure the M-shell emission of the gold. The samples were buried between two 5 μm thick layers of Be which acted as an inertial tamp slowing the expansion of the sample. The targets were designed so that the sample would be

concentric with the Be tamp. However, they were not laser cut to spec and only one of the targets had a sample concentric with its Be tamp.

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 4w probe beam and Thomson spectrometer were also used to measure the scatter of off the electron and ion acoustic features (see figure 1 lower). A new filter package was used during the campaign to filter out the self-emission and unconverted light, which has been an issue in the past with high Z targets, and good quality data was obtained. The K-shell spectra from the V 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. Two crystal spectrometers were used to record the full range of the Au M-shell emission, also time resolved. All of the framing cameras used, those for imaging as well as those used for spectroscopy, were co-timed so the plasma conditions could be determined for the measured Au M-shell emission.

There was a single pulse shape used during the campaign, a 3.0 ns square pulse with a 100 ps picket arriving 1 ns before the main pulse. A complete (All 6 diagnostics, correctly timed) set of data was recorded during the campaign at temperatures ~ 2 keV.

F. Hydrodynamics

1. Performance Verification of Ta₂O₅ Foams for Hydro Experiments

(PI: D. A. Martinez)

with M. Rubery (AWE), S. Prisbrey (LLNL) and S. McAlpin (AWE)

Foam targets are used on a variety of experiments at the National Ignition Facility, and verification of the equation of state of specific foams is necessary for accurate experimental design and analysis. In this experiment on Omega, we tested the Ta₂O₅ foam at a 0.85g/cc density over the course of 5 laser target experiments. The experiment consisted of a gold Hohlraum heated with 15 drive beams with a 1ns pulse at 360 J/beam. The heated hohlraum indirectly drove a polyimide ablator which was used to simultaneously drive a Quartz sample and a Ta₂O₅ sample. Using VISAR and SOP we can verify the drive on the plastic ablator using the Quartz sample and use the information to calibrate our post shot simulations so we can compare the shock breakout time of the Ta₂O₅ foam sample through an SOP measurement. Additionally, the Ta₂O₅ foam produced a reflecting shock while the shock was traversing through the Ta₂O₅ allowing the VISAR diagnostic to provide an additional measurement to verify the accuracy of our Ta₂O₅ equation of state tables. Figure 1 shows the velocity measurements inferred from the VISAR diagnostic. The Ta₂O₅ used the index of refraction reported from Miller [1] The post shot simulation results shown used only the Laser drive to determine the shock velocity in the quartz. The experiments provided useful information for our team to calibrate our models for future NIF experiments.

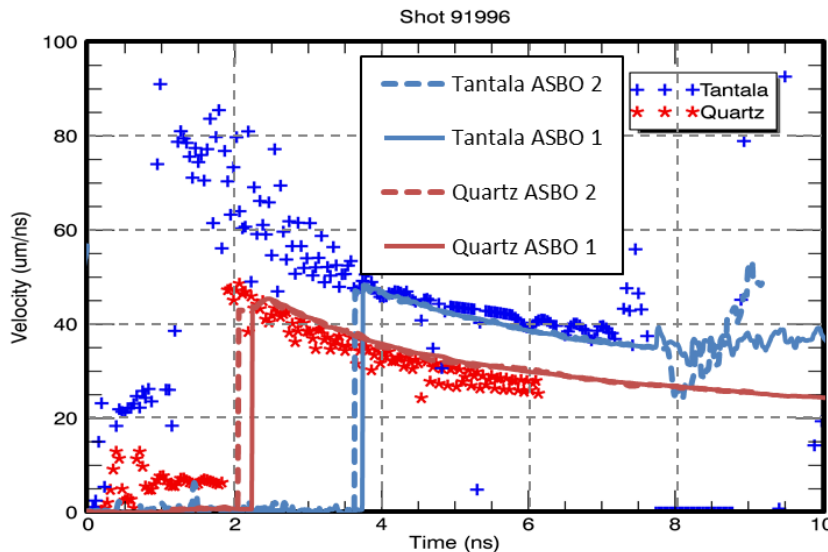


Figure 1: The measured velocity of the reflecting shock from the VISAR diagnostic. Both legs of the diagnostic are reported as Active shock breakout (ASBO) 1 and 2.

1. Miller, "High-Pressure Equation-of-State of Porous Ta₂O₅", PhD. Thesis, University of Rochester, 2007.

2. Mitigating cross talk between high energy backlighters with shielding (PI: S.F. Khan)

with D. A. Martinez, S. C. Wilks, S. Prisbey, D. Kalantar, A. J. Mackinnon (LLNL)

The objective of these Omega EP experiments is to test three shield designs to mitigate the cross interaction of a dual wire back-lighter system with a long delay. Previous Omega EP experiments (Dbl-HEBL-18A) showed that fratricide between the wires significantly degraded the resolution of the 2nd wire for delays above 4ns. The experiments used two 12.5 μ m diameter W wires with a separation of 4mm. Shields in between the wires consisting of gold (375 μ m), plastic (500 μ m) and its combination were tested. Each wire was illuminated by infrared 50ps, 1kJ short pulses with time intervals of 0, 10 and 15ns. Source size of each wire was inferred by a radiograph of a gold test grid. Shadowgraphs of the 2nd wire were recorded using the 4th harmonic probe laser beam and qualitatively illustrates the expansion of the wire.

The tested shields show for a 10ns time separation the source size of the 2nd wire was essentially the same as the first wire within measurement uncertainties. Since the plastic shield is transparent to x-rays above 10keV, this indicates that the primary mechanism for degradation are the electrons or very soft x-rays from the initial wire. The results from this experiment are being used in back-lighter development experiments at NIF.

4 ω probe shadowgraphs

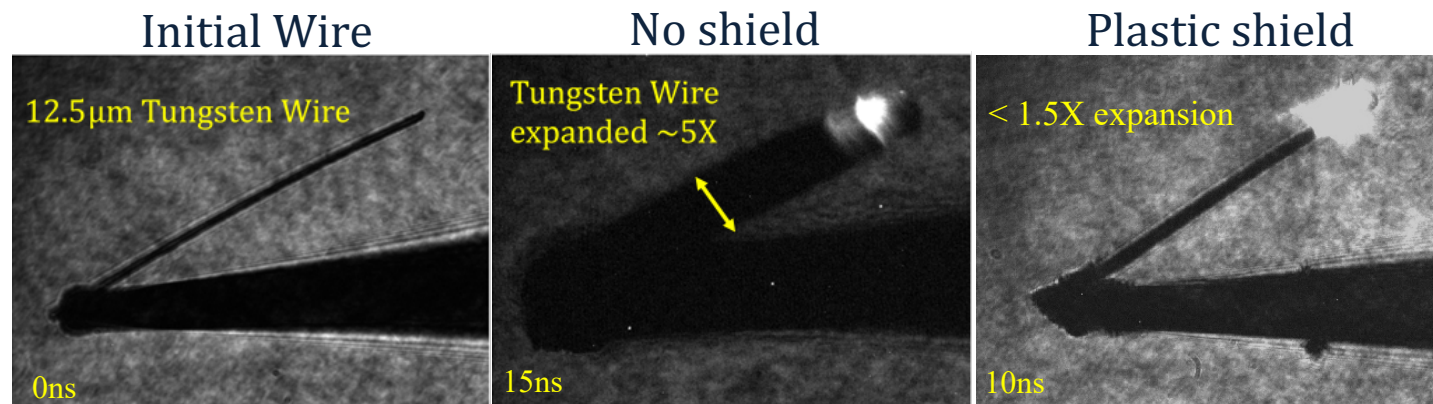


Figure 2: Shadowgraphs of the second wire using the fourth harmonic probe beam. The left image shows the wire before either of the wires are illuminated. The center image shows the 2nd wire 15ns after the 1st wire was illuminated with no shielding in between. The right image shows the 2nd with a 500 μ m polyimide shield in between the wires and 10ns delay. The polyimide shield mitigates the expansion.

3. Broadband MeV gamma-ray source development (PI: N. Lemos, LLNL)

with A. Pak (LLNL), D. Rusby (LLNL), J. Williams (LLNL), A. Mackinnon (LLNL)

Following prior 2011 Omega EP experiments [1], we have begun to investigate the potential of laser driven MeV radiography. A series of shots was designed to reproduce the past results using one Omega EP short beam and to improve those by coupling the two Omega EP short beams into the same target. We successfully reproduced the past results and showed an improvement when coupling the two beams into the same target.

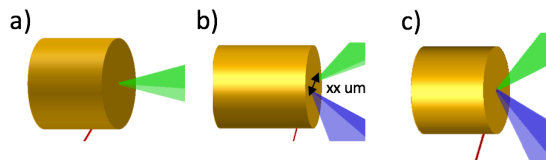
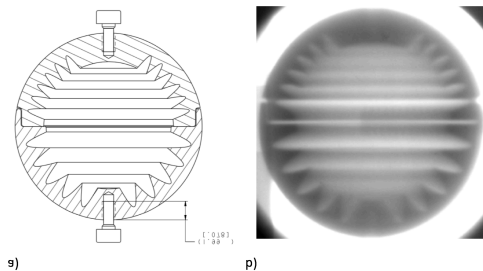


Figure 19: Three experimental setups used in this experiment

and c) was used respectively. For all these configurations the laser beams had an energy of 900J per pulse and a pulse duration of 10 ps, the electron beam temperature was measured and a high-density object (Image Quality Indicator - IQI) was radiographed. The electron beam temperature was used to optimize the x-ray emission since it directly relates to the x-ray spectrum temperature [2] and the IQI is used to characterize the x-ray source imaging capabilities.

Figure 2 shows the measured electron temperature for all 3 experimental setups. The highest electron temperature was achieved when overlapping both beams in time and space (green point), i.e., maximum intensity on target. The second hottest electron spectrum was achieved when both beams are separated by $\sim 100 \mu\text{m}$ (blue point) followed by the single beam shot (red point). To study fratricide we separated both beams by $\sim 100 \mu\text{m}$ and delayed both beams up to $2 \times 5 \text{ ns}$ (blue points). It is clear that when both beams are delayed in time fratricide is occurring since the electrons beam temperature starts to drop.

Figure 3 a) shows a drawing of the section the IQI and b) shows highest quality radiograph of the IQI with an areal density of 13 g/cm^2 obtained when using the experimental setup in fig.1 c). Here we summed the signal recorded in 12 image plates in order to increase the signal to noise ratio. Results of this campaign are being used to optimize a similar platform that is being develop at NIF-ARC.



**Figure 3: a) Cad section of the IQI.
b) x-ray image of the IQI**

This experiment had three objectives, 1 – reproduce the results presented in [1], 2 – Study fratricide by separating both beams in space and time, 3- Maximize x-ray yield by overlapping both beams in space and time. To achieve the three objectives the setup shown in fig. 1 a), b)

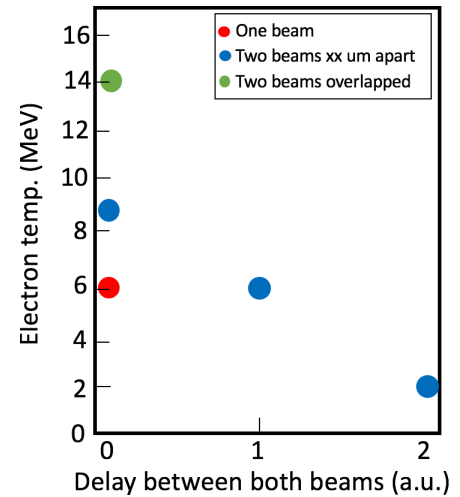


Figure 2: Electron beam temperature for the three experimental setups vs delay between both beams

[1] C. Courtois *et al.*, *Phys. Plasmas* **18**, 023101 (2011)

[2] A. Compant La Fontaine, *et al. Phys. Plasmas*, **19**, 023104 (2012)

Laboratory Basic Science Experiments

1. A journey to the center of Uranus and Neptune: using x-ray diffraction to unravel the atomic structure of new solid and superionic ices at multi-megabar pressures (PIs: M. Millot and F. Coppari, LLNL)

with Dayne Fratanduono and Sebastien Hamel (LLNL), Sabine Stanley (Johns Hopkins University) and Mandy Bethkenhagen (Postdoc, Rostock University, Germany)

We conducted an OmegaEP one-day campaign to investigate the structure and equation of state of solid and superionic water at Uranus' and Neptune's deep interior conditions with a combination of ultrafast x-ray diffraction and optical diagnostics using new laser dynamic compression techniques.

This work expands on our recent discovery of superionic water ice at the Omega Laser facility (LBS Campaign on Extreme Chemistry, FY 13) reported in [1] and the subsequent discovery of a new superionic water ice XVIII (LBS Campaign on SolidWater, FY 14 described in [2]). Superionic ices, a new exotic state of matter are characterized by fluid-like diffusing hydrogen ions (protons) within a solid lattice of oxygen ions, that could dominate the interiors of icy giant planets such as Uranus, Neptune and their extra-solar cousins.

We successfully commissioned the new platform for x-ray diffraction of initially liquid samples at the Omega EP laser and collected excellent quality data on 8 system shots using 2 UV beams to compress the water sample layer and 2 UV beams to generate an x-ray source flash for the x-ray diffraction measurement. Preliminary analysis suggests that the use of longer pulse duration allowed us to explore lower temperature compression paths to search for predicted new phases of solid ices of pure water [3].

We also explored higher temperature compression paths that reproduce the pressure-temperature conditions inside Neptune and Uranus to constrain the melting line near 1 Mbar and document the atomic structure and transport properties of pure water at these conditions.

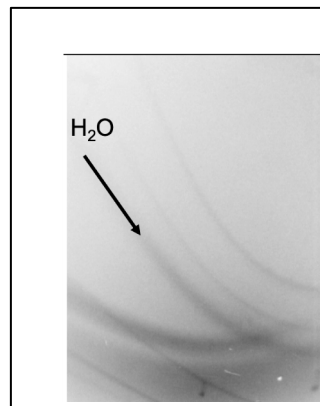


Figure 1. Raw PXRDIP data showing the successful observation of X-ray diffraction from Mbar water ice at Omega EP.

[1] Millot, M. *et al.* Experimental evidence for superionic water ice using shock compression. *Nat. Phys.* **14**, 297–302 (2018).

[2] Millot, M. *et al.* Nanosecond X-ray diffraction of shock-compressed superionic water ice. *Nature* **569**, 251–255 (2019).

[3] Militzer, B. & Wilson, H. New Phases of Water Ice Predicted at Megabar Pressures. *Phys. Rev. Lett.* **105**, 5–8 (2010).

2. Investigating giant impacts between rocky planets with high-pressure melting and shock equation of state measurements on complex silicates

(PIs: Dayne E. Fratanduono and Marius Millot) with Bethany Chidester (postdoc, UC Davis), Erik Davies (student, UC Davis), Kaitlyn Amodeo (student, UC Davis), Dylan Spaulding, and Sarah Stewart (UC Davis), Jie Li (University of Michigan) and Joshua Townsend (Postdoc, Sandia National Laboratories)

We conducted experiments to investigate the melting behavior and pressure-density-temperature (P - ρ - T) shock equation of state (EOS) and document bonding changes in hot liquid states of complex silicates minerals using ultrafast velocimetry and pyrometry measurements up to 2 TPa. Our goal is to address one of the most puzzling questions in planetary sciences: how did energetic collisions in the early solar system result in the physical structures and chemical compositions of the terrestrial planets? We also wish to document the structure and melting processes of multi-component liquids, which is fundamental to both planetary sciences and high energy density (HED) physics.

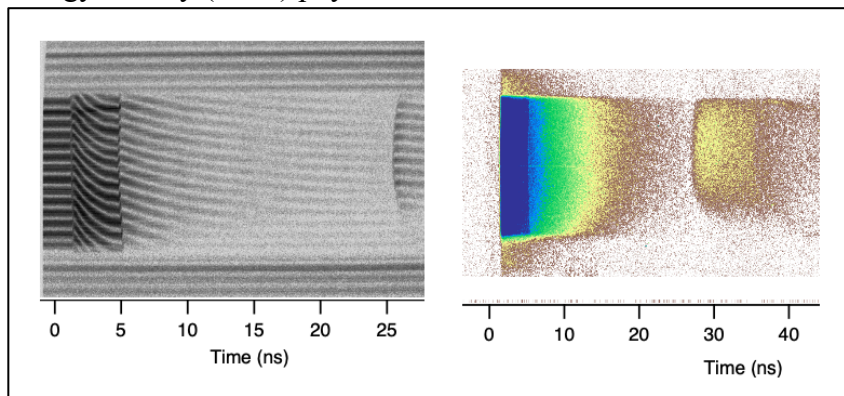


Figure 1. Example ASBO (Left) and SOP (Right) data for the SilicateEOS-EP-19 campaign showing a decaying shock traveling through the multi-layer package to reveal the optical and thermodynamic properties of Bronzite in the Mbar range.

Because it is necessary to constrain the thermodynamic response of the planet-forming materials to understand the dynamics of sub-giant and giant collisions and to examine the potential for chemical equilibration between the target and the impactor, we concentrated our effort on natural samples from the Olivine ((Mg,Fe)₂SiO₄), and orthopyroxene ((Mg,Fe)SiO₃) mineral

families which constitute the majority of the silicate mantles of the terrestrial planets (e.g. Earth, Mars) by volume.

This shot day completed 14 shots on the Omega EP laser, alternating beams to increase the shot rate. Velocity interferometry and optical pyrometry with decaying shocks measured the shock temperature and the intersection of the Hugoniot with the melting curve for two minerals: Olivine: (Mg₉₀,Fe₁₀)₂SiO₄ and Bronzite: (Mg₉₀,Fe₁₀)SiO₃. After detailed analysis and upcoming complementary experiments in FY20, these data will be used to develop improved equation of state models for hydrodynamic simulations of impact events and interior structure models. In particular, the Olivine data will be compared to previous experiments at the Omega Laser Facility on the pure end member mineral forsterite: (Mg₂SiO₄) that were reported in [1]. The Bronzite data will complement the previous work on MgSiO₃ enstatite described in [2].

[1] Fratanduono, D. E. et al. Thermodynamic properties of MgSiO₃ at super-Earth mantle conditions. *Phys. Rev. B* **97**, 214105 (2018).

[2] Root, S. et al. The Principal Hugoniot of Forsterite to 950 GPa. *Geophys. Res. Lett.* **45**, 3865–3872 (2018).

3. Phase transformation kinetics - strain rate tuning of the Peierls distortion in ramp compressed bcc Sn (P.I.s: Martin Gorman and Raymond Smith)

The goals of the SnKinetics-19A/B/C experiments on Omega-60 were to develop a ramp compression platform to determine the crystal structure of Sn up to 70 GPa at several different compression rates. These observations will be compared against shock and static measurements on Sn and are expected to confirm a previously unreported mechanism responsible for altering crystal structure evolution under dynamic compression conditions.

The target design is shown in Fig. 1. Here we use a plasma piston design [1] to ramp compress a $6\mu\text{m}$ thick Sn layer which is directly coated onto a LiF window. To minimize the heat transfer from the plasma to the Sn sample we incorporate a $6\mu\text{m}$ thick preheat shield. A $50\mu\text{m}$ thick, 50g/cm^3 additive manufactured foam (AMFoam) layer is used to temporally shape the ramp and pressure hold profile experienced by the Sn layer [2]. The Omega VISAR (ASBO) measures the Sn/LiF particle velocity from which the sample pressure as a function of time can be determined [3]. These experiments combine nanosecond x-ray diffraction [3] and ramp compression to dynamically compress and determine the crystal structure of Sn/LiF to peak pressures within the 10-70 GPa range. Using the Omega PXRDIIP diagnostic [3] the compressed Sn sample is probed with a 1-ns He-alpha x-ray source to determine crystal structure at a well-defined sample pressure (VISAR). Figure 2 shows an example of the data, with information on the high pressure body centered cubic phase (bcc) of Sn. Also observed are peaks from the ambient pressure W pinhole while serve to calibrate diffraction angle.

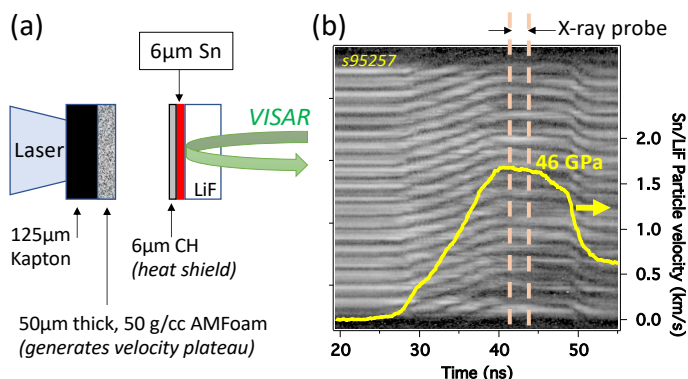


Figure 20(a) Target design for ramp compression experiments of Zr using the Omega laser. (b) Raw VISAR data with extracted Sn/LiF particle velocity profile. As indicated a Cu He-alpha x-ray source is timed to probe the sample at peak compression. For s95257 (as shown) the peak sample pressure for Sn is 46 GPa.

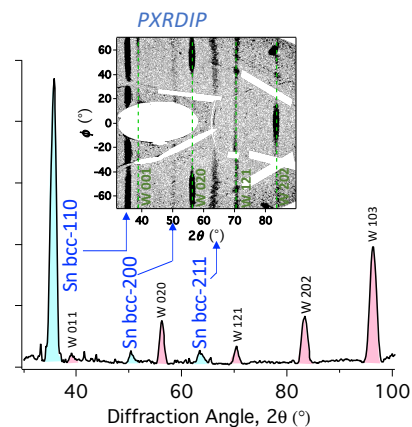


Figure 21. Diffraction pattern for ramp compressed Sn up to peak pressures of 46 GPa. Here the Sn bcc phase is observed along with the ambient pressure W-pinhole

[1] R. F. Smith, J. H. Eggert, M. D. Saculla, A. F. Jankowski, M. Bastea, D. G. Hicks, and G. W. Collins, "Ultrafast Dynamic Compression Technique to Study the Kinetics of Phase Transformations in Bismuth" *Phys. Rev. Letts* **101**, 065701 (2008).

[2] J.S. Oakdale, R.F. Smith, J.-B. Forien, W.L. Smith, S.J. Ali, L.B. Bayu Aji, T.M. Willey, J. Ye, A.W. van Buuren, M.A. Worthington, S.T. Prsbrey, H.-S. Park, P.A. Amendt, T.F. Baumann, J. Biener, "Direct Laser Writing of Low-Density Interdigitated Foams for Plasma Drive Shaping" *Adv. Funct. Mater.* **2017**, 1702425.

[3] J.K. Wicks, R.F. Smith, D.E. Fratanduono, F. Coppari, R.G. Kraus, M.G. Newman, J. R. Rygg, J.H. Eggert, T.S. Duffy, "Crystal structure and equation of state of Fe-Si alloys at super-Earth core conditions" *Sci. Adv.* 2018;4:eaao5864

4. Development of the New Forward-Backward X-ray Diffraction Diagnostic (PI: A Krygier)

with CE Wehrenberg, H-S Park and JH Eggert (LLNL) and A Gleason (SLAC)

This LBS experiment was the first effort to collect simultaneous transmission and reflection diffraction from a sample driven to high pressure with the new Forward-Backward X-ray Diffraction (FBXRD) diagnostic. By using two monochromatic X-ray sources, we simultaneously probe the sample in multiple geometries maximizing coverage of the range of angles between the diffraction plane and applied stress direction. This capability will be able to constrain the in-situ strain anisotropy induced by material strength in a polycrystalline sample.

Many of the shots on this campaign were dedicated to optimizing the backlighter, shielding, and pinhole configuration. We performed a scan of reflection backlighter laser illumination energies and spot sizes using diffraction quality as the ultimate judge of each configuration. We find a range of conditions produces high quality diffraction. We also tested several conical shielding configurations for the backward X-ray scattering (BXS) reflection diffraction setup, including tungsten, stainless steel and plastic; tungsten worked best. We have identified several sources of background signal that confound a full interpretation of the diffraction signal.

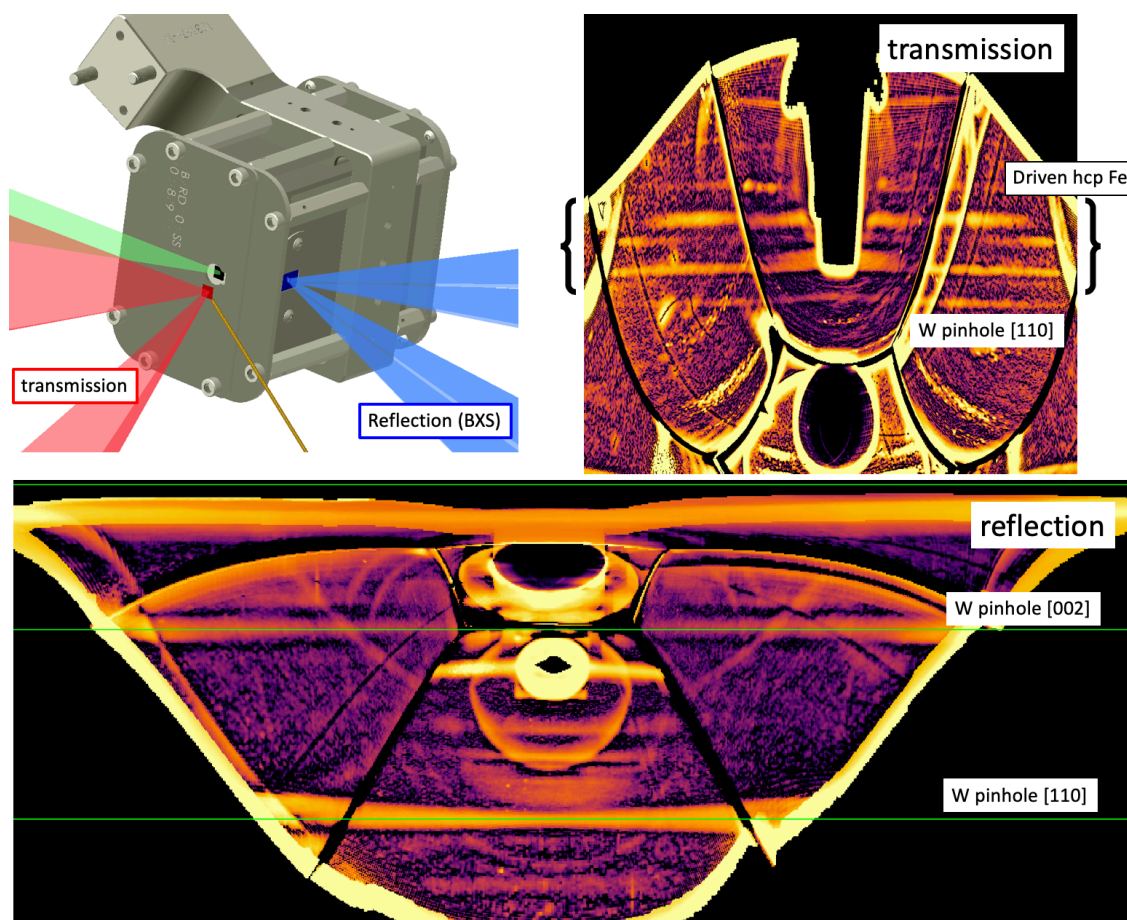


Figure 22 - On top left, the experimental setup. On the top right, driven X-ray diffraction in the transmission geometry showing high pressure Fe hcp phase reflections. On the bottom, reflection geometry X-ray diffraction. The bright lines shown are from the W pinhole.

5. Characterizing pressure ionization in ramp compressed materials with fluorescence and absorption spectroscopy (PI: S. Jiang, Y. Ping)

with A. Lazicki, P. Sterne, P. Grabowski, H. Scott, R. Smith, R. Shepherd, B. Bachmann, J. Eggert (LLNL); and S. B. Hansen (SNL)

This pressure ionization campaign comprised half day on OMEGA and 1 day on OMEGA EP during FY19. Following the previous FY18 campaign, which for the first time provided a direct benchmark between various isolated-atom and average-atom ionization models by measuring K-shell fluorescence emission of Co, the FY19 campaign extended the measurement to study a possible K edge shift, and began investigating L-shell emission lines.

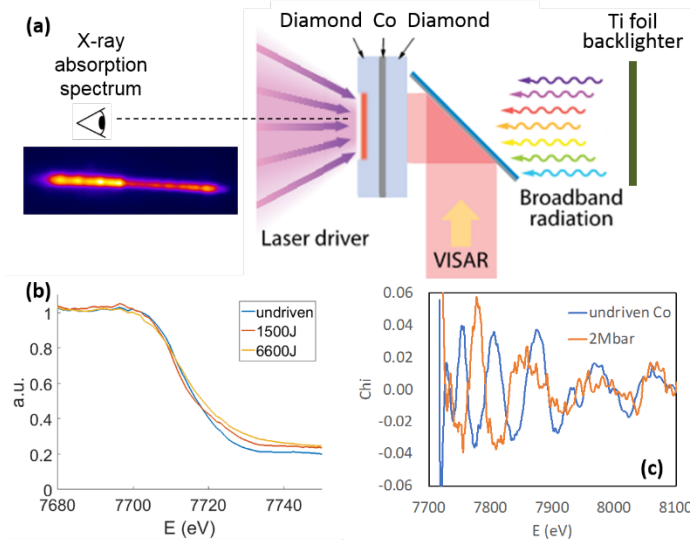


Figure 23. Experimental schematic and results on OMEGA

drive energies, 1500J and 6600J, the sample reached 1.5x and 2.1x compression correspondingly. We used a foil X-ray backlighter and measured the absorption spectra using a high-resolution spectrometer IXTS. No obvious Co K edge shift was observed (Figure 1b), which is consistent with the prediction of average-atom models but disagrees with the commonly used isolated-atom models. We were also able to measure the EXAFS (Figure 1c) to confirm low temperature in compressed Co.

On Omega EP, the L shell fluorescence emission of Sn was observed using the IXTS spectrometer configured with a lower-energy PET crystal. In this experiment a short pulse laser beam irradiated a secondary Be target which is directly attached to a Sn foil. The hot electrons generated due to laser-Be interaction could transport to the Sn layer and induce fluorescence. Sn L_{β} spectra with different Be thicknesses are shown in Figure 2. The L_{β} line shifts to higher energy with increasing temperature (thinner Be). Detection of this L line under compression proved more challenging due to backgrounds generated by the long pulse beams, but is promising for future work.

On OMEGA, we have measured the K edge of compressed Co as a function of density. A schematic of the experimental setup is displayed in Figure 1(a). The high pressure in Co was achieved by ramp compression using the long pulse drivers, so that the temperature was kept low during the compression process. The pulses were designed to mimic the drive used on OMEGA EP during the FY18 campaign. The pressure history was characterized with on-shot VISAR measurements. Under two different

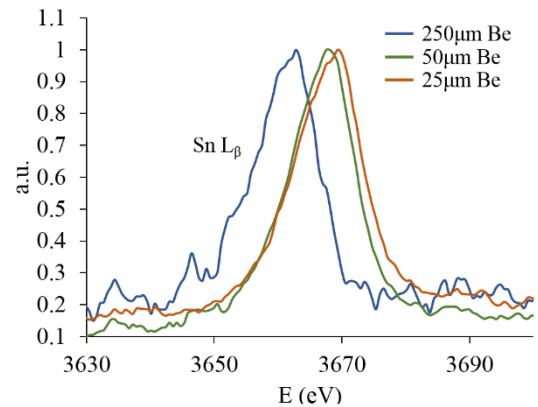


Figure 24. Sn L_{β} fluorescence spectra

6. Time Resolved Measurement of Ge L-shell emission using a buried layer platform (PI: E.V. Marley)

with D. Bishel, M. Frankel, Y. Ehrlich, Z. Shpilman, M.B. Schneider, G.E. Kemp, R.F. Heeter, M.E. Foord, D.A. Liedahl, K. Widmann, J. Emig

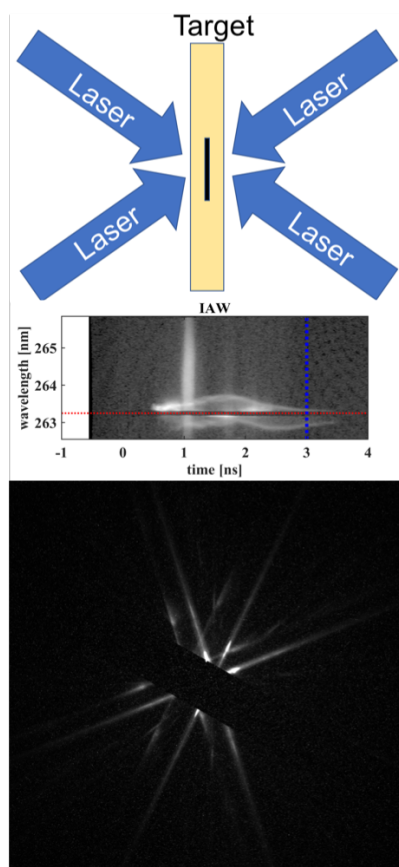


Figure 25.
Top: Experimental configuration
Middle: Thompson scattering data of shot 94085, and Bottom: TGS data of Ge and Sc L-shell spectrum

This campaign was designed to measure the emitted L-shell germanium 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 equally on both sides (Fig. 1) to heat the sample. The sample used in the campaign was a 2000 Å thick Ge/Sc mixture designed to burn through completely before the end of the laser pulse, providing uniform plasma conditions to measure the L-shell emission of the germanium. The samples were buried between two 5 μm thick layers of Be which acted as an inertial tamp slowing 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 pinhole cameras coupled to framing cameras. The 4w probe beam and Thomson spectrometer were also used to measure the scatter of off the electron and ion acoustic features (see figure 1 lower). A new filter package was used during the campaign to filter out the self-emission and unconverted light, providing high quality scattering data. The K-shell spectra from the Sc 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 crystal spectrometer was used to record the Ge L-shell emission, also time resolved. All of the framing cameras used, those for imaging as well as those used for spectroscopy, were co-timed so the plasma conditions could be determined for the measured Ge L-shell emission.

The Soreq transmission grating spectrometer, as part of the ongoing LLNL/Soreq collaboration, was used to record the

absolutely calibrated time integrated germanium and scandium L-shell emission onto an x-ray ccd.

There was a single pulse shape used during the campaign, a 3.0 ns square pulse with a 100 ps picket arriving 1 ns before the main pulse. A complete (All 6 diagnostics, correctly timed and pointed) set of data was recorded during the campaign at temperatures ~2 keV.

7. The effects of the plasma geometry on the K-shell spectrum of mid-Z (21-26) ions

PI: G. Pérez-Callejo (University of Oxford)

with E.V. Marley (post-doc LLNL), D. Bishel (student LLE), M.B. Schneider, G.E. Kemp, M.E. Foord, R.F. Heeter, D.A. Liedahl, G.V. Brown, J. Emig

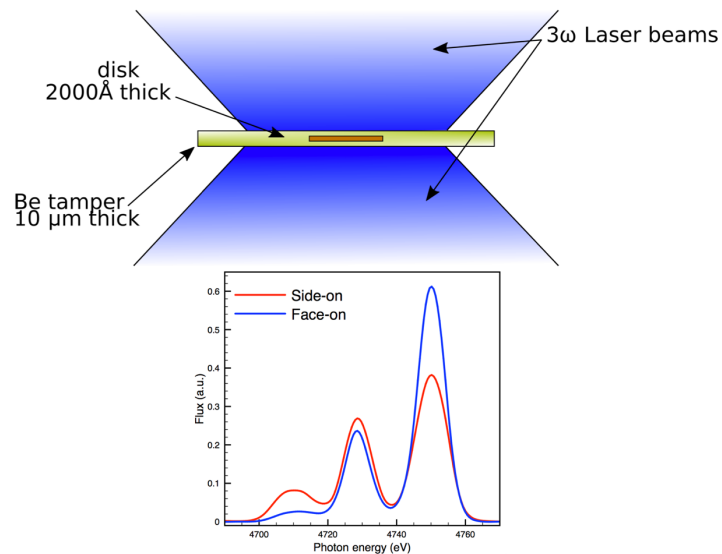


Figure 26. (Upper) Experimental configuration. (Lower) Time resolved Ti H-alpha spectra with data inset at 2.7 ns of shot for both face-on and side-on

This campaign was designed to measure the K-shell spectra of mid-Z atoms in well-defined and uniform plasmas, in order to characterize how the flux from optically thick lines depends on the geometry of the plasma. This idea has been mainly studied in astrophysics, but the aim of this study was to take advantage of said geometric effects for characterizing the plasma conditions in Dot Spectroscopy experiments at NIF. On 2 shot days (A and B), planar buried layer targets were illuminated evenly on both sides to heat the sample (figure 1-top), which consisted of a Ti only disk for the A shot day, and was changed to a 1:1 mixture of Sc and V for the B shot day. This change minimized the presence of Be

impurities in the spectra, as well as the optical depth of the disk. The sample was tamped on both sides by 5 μm thick layers of Be to slow the sample's expansion and provide radial confinement to maintain its cylindrical shape.

In both shot days, the pulse shape was kept the same, a 2.7 ns square pulse to maintain the maximum possible uniformity. A complete (All 6 diagnostics, correctly timed) set of data was recorded during the campaign at temperatures ~1.5 keV. The initial data look promising.

Time resolved 2-D images of the targets' X-ray emission viewed both face-on and side-on were recorded using gated pinhole imagers. The K-shell spectra were measured in 4 time windows using crystal spectrometers, with focus on the He-α complex (figure 1-bottom). The temperature of the plasma was determined from the optically-thin spectra lines using a genetic algorithm approach. For the second day, the ratio of isoelectronic lines provide a more accurate temperature measurement. The plasma density was obtained from the measured size of the plasma at every time by imposing a conservation of particles condition.

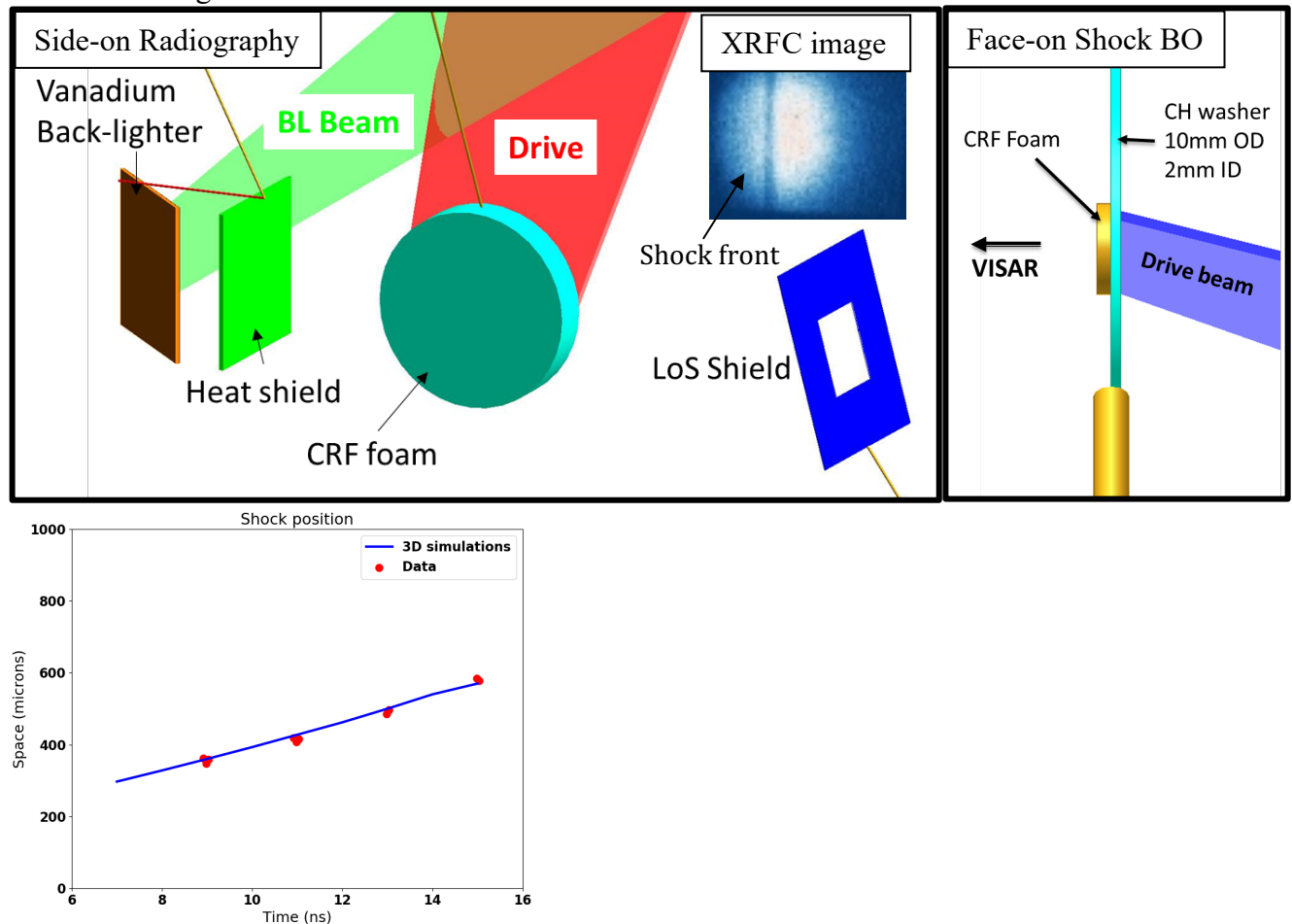
In shot day A, a high-resolution double crystal spectrometer with spatial resolution was fielded at OMEGA, to study possible uniformities in the plasma. In shot day B, this spectrometer was replaced with a streak camera to study the heating processes of the Sc and V in a continuous manner. In both shot days, a Transmission Grating Spectrometer (TGS) from the Soreq Institute in Israel was fielded to check against hydrodynamic simulations, how the plasma was being heated as the laser burnt through the Be tamper.

8. Shock trajectory in low density CRF foams for Landau-Darrieus Instability

(PI: S. F. Khan)

with A. Casner, L. Masse, L. Ceurvorst, T. Goudal, D. Martinez, V. Smalyuk

The objective of these Omega EP experiments is to measure the shock trajectory into driven carbonized resorcinol-formaldehyde (CRF) foams in order to select the optimum material density and drive laser intensity for NIF Discovery Science experiments to study the Landau Darrieus Instability (LDI) in laser ablation. Two CRF densities were tested, nominally 50 mg/cc and 100 mg/cc. The drive laser intensities tested were $5 \times 10^{12} \text{ W cm}^{-2}$, $1 \times 10^{13} \text{ W cm}^{-2}$, and $2 \times 10^{13} \text{ W cm}^{-2}$. The shock trajectory was tracked using side on radiography and the shock breakout was measured using VISAR face-on (see Fig. 1). The side-on radiography was imaged onto a x-ray framing camera using a V backlighter. The shock was clearly visible in most of the frames and the shock breakout was clear. For the 100 mg/cc CRF foam driven at $5 \times 10^{12} \text{ W cm}^{-2}$, side on radiography measured a velocity of 25-30 km/s, the shock breakout measurement gives a velocity of 21 km/s, while initial 2D simulations gave 16 km/s. However, considering these results 3D simulations (see Fig. 2) were performed with actual laser spot size and incidence angle that show a much better agreement. For the NIF Discovery Science experiments, the 100 mg/cc density was chosen to be driven with an intensity of $1.25 \times 10^{12} \text{ W cm}^{-2}$. We used a lower laser intensity in order to observe the LDI before the shock breakout and Rayleigh-Taylor instabilities are generated.



13. Developing Inverted-Corona Fusion Targets as Neutron Sources

(PI: M. Hohenberger, LLNL; S. Glenzer, SLAC)

with N. B. Meezan (LLNL), A. Mackinnon (LLNL), W. Riedel (Graduate Student, Stanford University), M. Cappelli (Stanford University), N. Kabadi (Graduate Student, MIT), and F. Treffert (Graduate Student, SLAC)

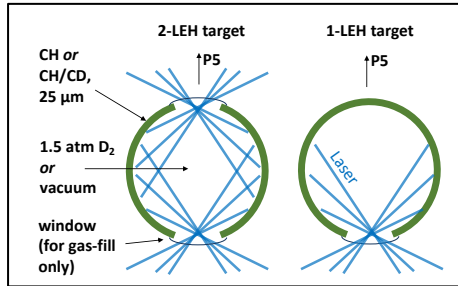


Figure 1. Experimental setup

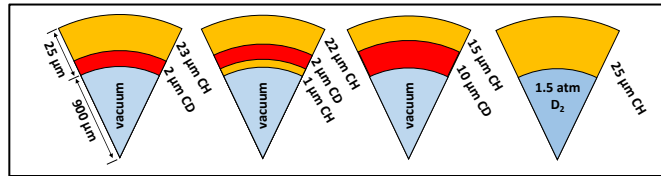


Figure 2. Target types

These experiments were exploring the feasibility of inverted-corona targets as fusion-neutron sources for high-energy-density applications. In inverted-corona targets, laser beams directly ablate a layer of fusion fuel on the inner surface of a target, e.g., a CD-lined capsule [H. Daido et al., APL 51, 2195 (1987); G. Ren, PRL 118, 165001 (2017)]. As the ablative flows converge at the target's center, the plasma particles transition from long-range interactions to collisional stagnation, heating the ions and generating fusion reactions. The fusible material may also be provided as a gas-fill, where, similar to an exploding pusher, the laser-driven ablation launches a centrally converging shock into the gas, thus heating it to fusion conditions.

The experimental setup is shown schematically in Fig. 1. Target capsules with an inner diameter of 1.8 mm and 25- μm thick walls had one (or two) laser-entrance holes (LEH's) and were laser-irradiated by 19 (or 39) beams with 1-ns square pulses at up to 500 J/beam. CH capsules with a 1.5-atm D_2 -gas fill were fielded, as well as vacuum, CD-lined CH capsules with varying liner-thickness or liner-depth, see Fig. 2.

Generally, 2D Hydra calculations predicted a linear scaling of yield with incident laser energy, while the 1- or 2-LEH configuration had little performance impact. With a calculated yield of up to $\sim 10^{11}$ neutrons at 18 kJ incident energy, Hydra 2-D simulations predicted the highest yields for the gas-filled capsules. For the vacuum targets, Hydra predicted most of the DD-fusion to occur in the stagnating ablation plasma from the innermost 1- μm layer of CD liner, with little increase in yield beyond that thickness, and peak neutron yield of $\sim 5 \times 10^{10}$ at 18 kJ incident energy. Recessing the CD liner 1 μm into the wall decreased calculated yield by $>30\times$.

This is in contrast to the experimental neutron yields, which are plotted in Fig. 3 on a logarithmic scale and as a function of laser energy. While these data also follow a linear trend with energy, the experiments generally underperformed compared to the simulations, with Y/Y_{2D} between ~ 5 to $\sim 15\%$. Furthermore, the experimental data exhibit a strong dependence of yield on liner-thickness, with an approximately 15x increase in yield from the 2- μm (circles) to the 10- μm CD liner (triangles), with the latter one giving the highest performance of $\sim 1.5 \times 10^{10}$. This indicates significant mixing in the ablative plasma, confirmed by the minor drop in yield for the recessed 2- μm CD liner (diamonds).

With a detailed data analysis in progress, these experiments support promising applications, e.g., neutron radiography at NIF requiring a total yield of $\sim 10^{14}$ should be possible using a DT-gas-filled, single-LEH target and few-hundred kJ driver energies.

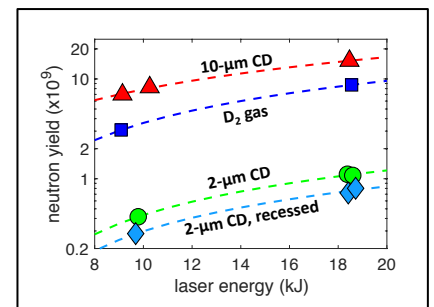


Figure 3. Neutron Yield

14. Laboratory model of particle acceleration in supernova shocks

(PI: H. Chen)

with C. A. J. Palmer (postdoc), A. R. Bell, A. Bott (postdoc), G. Gregori, O. Karnbach (student), J. Matthews (postdoc) (University of Oxford); D. Lamb and P. Tzeferacos (U. Chicago); A. Birkel and C. Li (MIT); and H. -S. Park (LLNL).

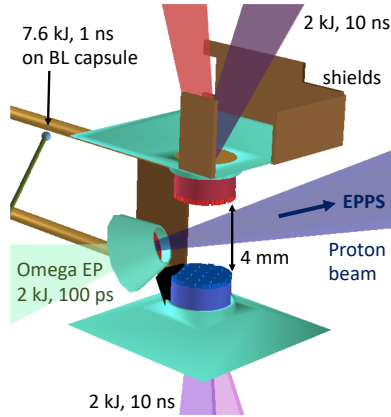
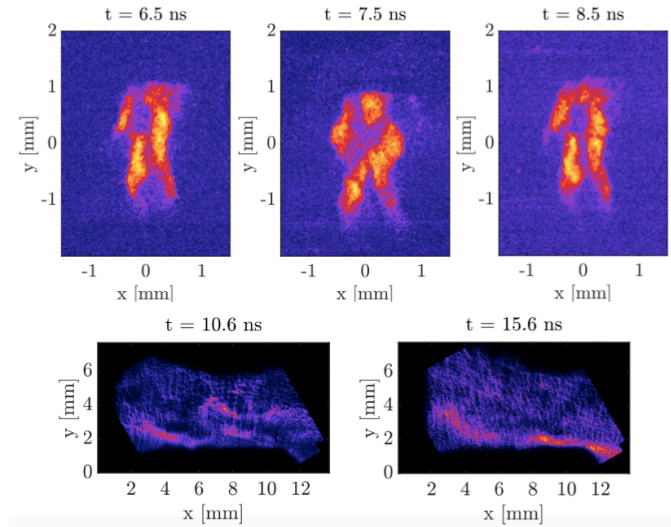


Figure 1. Experimental configuration.

This shot day studied the growth of the non-resonant hybrid instability in a turbulent magnetized plasma driven by a high current proton beam. The TDYNO target platform is used to produce a turbulent magnetized plasma. This is generated by colliding the flow of two plasma jets, each of which has had its flow disrupted by passage through a mesh. The jets are produced by 10 Omega beams with 2kJ energy arranged into a 10 ns long drive. Previous shot days have demonstrated that this can produce plasmas embedded with stochastic magnetic fields with strengths up to 4 kG. One of the EP short pulse beams (2 kJ in 100 ps) was used to produce a proton beam from a thin (50 micron) metal target. This target was positioned 3 mm from the central axis of the turbulent plasma (figure 1). The EP beam was fired 20 ns after the Omega beams, so that the low-energy TNSA proton beam would interact with the turbulent plasma.

The main diagnostics included: x-ray framing camera to measure self-emission from the turbulent plasma, proton radiography using a D3He capsule irradiated with 17 Omega beams (450J/beam, 1 ns) to probe the magnetic field structure of the plasma and the EPPS to measure the energy spectrum of the TNSA proton beam. The EPPS was also equipped with a thin (< 3 mm) RCF/CR39 stack in the front holder to measure the spatial profile of the beam. The streaked Thomson scattering measurements indicate that the colliding plasma conditions are similar to previous experiments with electron temperatures on the order of 300 eV. XRFC indicated fluctuations in plasma density in the collision region (figure 2 top) from which the density spectrum will be extracted. This can be compared with the spectrum of fluctuations in the plasma magnetic field which will be extracted from the PRAD raw data (figure 2 bottom). Qualitative study of the PRAD indicates modulated magnetic fields with small scale structures visible at early times but not at later times. In addition to the displayed data, the EPPS indicates some energy dependent transverse momentum imparted to the EP proton beam as it transits the turbulent plasma.



[1] P. Tzeferacos, *et al.* Nat. Comms. **9**, 591 (2018).

11. Exploring the Applications of Laser Produced Relativistic Electron-Positron Pair Plasma Jets (PI: Hui Chen)

With Joohwan Kim (UCSD), Mario Manuel (GA), Shaun Kerr (Postdoc, LLNL), Andrew Macphee (LLNL), Anthony Link (LLNL)

In FY19, this team completed one LBS shot day on OMEGA EP, alternating the two EP short pulse beams to produce jets of electron-positron antimatter pairs. These 14 FY19 shots used novel targets to explore the laser-target interaction and seeking enhanced pair production. The experiment focused on 1) enhancing the pair yield using nano-structured targets and 2) collimating or focusing positron jets by shaping the rear target surface to modify the sheath potential. The experiments successfully demonstrated both yield enhancement and positron focusing. The data strengthened prospects for future experiments on laboratory astrophysics using the pair jet – plasma interaction to drive beam instabilities.

The EP short pulse beams (~ 1 kJ in 10 ps) irradiated targets of 1 mm thick Au targets, with and without 1) a parabolic cone on the front of the target and 2) convex shaped back surface. It was found that for the same laser energy, positron yields and acceleration both were increased by using the parabolic cones, with similar trend as that found on NIF ARC experiments [1]. This finding is important as well as unexpected due to EP laser has smaller f number ($f \sim 2$) comparing to that of ARC ($f \sim 60$). The underline physics is to be investigated. We also repeated the results obtained in FY18 that using a hemispherical shaped backsurface to focus the positron jets through the sheath field [2] – like that observed in proton focusing. This observation is important as it demonstrated that higher pair density can be achieved by reducing their volume, which may enable the development of instabilities predicted by theory.

The prior experiments showed that quasi-monoenergetic relativistic positron jets are formed during high-intensity irradiation of thick gold targets [3, 4], and that these jets can be strongly collimated [5] using the magnetized-inertial fusion electrical delivery system (MIFEDS) [6]. The external field produces a 40-fold increase in the peak positron and electron signal [4]. The positron yield was found to scale as the square of the laser energy [7, 8]. The FY15 results revealed another dimension of scaling on the target materials. The favorable scaling would enable the laboratory study of relativistic pair plasmas that are important to understanding some of the most exotic and energetic systems in the universe [8, 9].

[1] G. Williams, et al., to be submitted.

[2] J Kim, A Link, D Canning, P Fitzsimmons, J Fooks, S Kerr, T Ma, M Manuel, D Mariscal, R Wallace, G J Williams, L Willingale, F N Beg, and H Chen, “Dynamic focusing of laser driven positron jets by self-generated fields”, submitted to New. J. Physics (2019)

[3] H. Chen et al., Phys. Rev. Lett. **102**, 105001 (2009).

[4] H. Chen et al., Phys. Rev. Lett. **105**, 015003 (2010).

[5] H. Chen et al., Phys. Plasmas **21**, 040703 (2014).

[6] O. Gotchev et al., Rev. Sci. Instrum. **80**, 043504 (2009).

[7] H. Chen et al., Phys. Rev. Lett. **114**, 215001 (2015).

[8] H. Chen et al., Phys. Plasmas **22**, 056705 (2015).

[9] H. Chen et al., High Energy Density Physics, **7**, 225 (2011)

12. Laser Wakefield Acceleration at OMEGA-EP (PI: F. Albert)

with P. King¹ (LLNL/UT Austin), N. Lemos² (LLNL), J. Williams² (LLNL), H. Chen (LLNL), J. Shaw (LLE), D. Haberberger (LLE), D. H. Froula (LLE).

¹Graduate Student, ²Postdoc (now LLNL staff)

This series of shots was designed to accelerate electrons in the self-modulated laser wakefield acceleration (SMLWFA) regime, in collaboration with LLE. The shot day Wakefield-EP-19A was coupled with other LLE-led campaigns (PlasmaLensEP and AdvRadEP), with an overall goal to accelerate high charge, relativistic electrons beyond 100 MeV. This laser wakefield acceleration platform will serve future applications (development and use of novel x-ray sources) at OMEGA-EP and NIF-ARC.

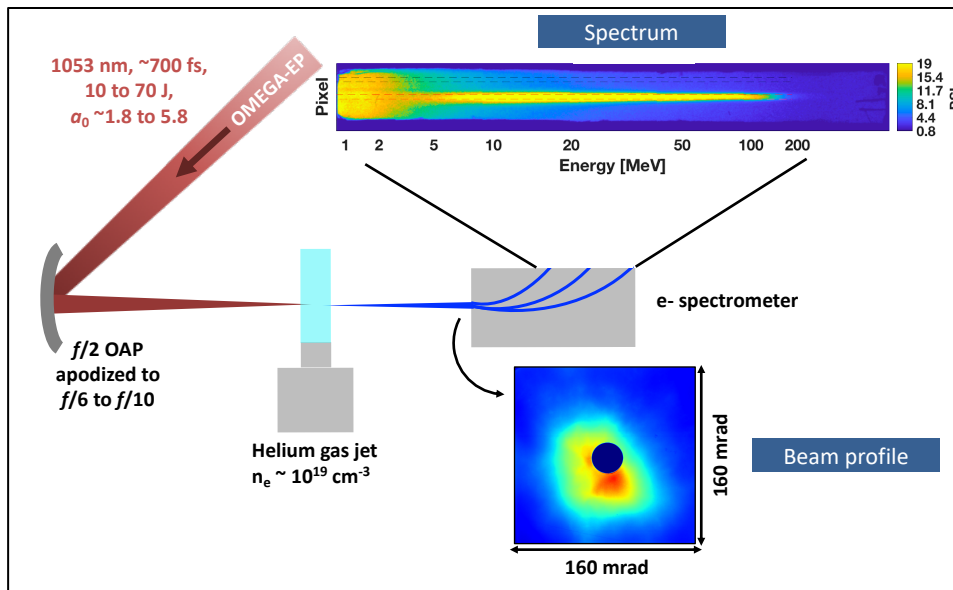


Figure 1. Experimental configuration for Wakefield-EP-19A, with examples of a measured electron spectrum and beam profile.

geometry. This resulted in a maximum energy on target of 95 J (24 J). We used 6 mm and 10 mm-long nozzles and varied the laser intensity between 3×10^{18} and $6 \times 10^{19} \text{ W/cm}^2$.

The campaign successfully measured Maxwellian electron beam spectra up to 200 MeV with the Electron-Proton-Positron Spectrometer (EPPS) as well as the beam profile, using two image plates with a hole placed in front of the diagnostic. Beam profiles with divergences $< 100 \text{ mrad}$ were measured, with a total charge above 100 nC, which is the highest charge recorded in a self-modulated laser wakefield accelerator to date.

Analysis of the campaigns is ongoing, and the results of the shot day, coupled to the LLE-led campaigns, will be presented in an invited talk (and subsequent Phys. Plasmas paper [1]) at the annual 2019 APS-DPP meeting.

[1] J.L. Shaw et al, Phys. Plasmas (in preparation)