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Citation: AIP Conference Proceedings **1793**, 090006 (2017); doi: 10.1063/1.4971625
View online: http://dx.doi.org/10.1063/1.4971625
View Table of Contents: http://aip.scitation.org/toc/apc/1793/1
Published by the American Institute of Physics

Using Phase Contrast Imaging to Measure the Properties of Shock Compressed Aerogel

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Abstract. The Hugoniot states of low density materials, such as silica aerogel, are used in high energy density physics research because they can achieve a range of high temperature and pressure states through shock compression. The shock properties of 100mg/cc silica aerogel were studied at the Materials in Extreme Conditions end station using x-ray phase contrast imaging of spherically expanding shock waves. The shockwaves were generated by focusing a high power 532nm laser to a 50μm focal spot on a thin aluminum ablator. The shock speed was measured in separate experiments using line-VISAR measurements from the reflecting shock front. The relative timing between the x-ray probe and the optical laser pump was varied so x-ray PCI images were taken at pressures between 10GPa and 30GPa. Modeling the compression of the foam in the strong shock limit uses a Gruneisen parameter of 0.49 to fit the data rather than a value of 0.66 that would correspond to a plasma state.

INTRODUCTION

Most of the observable matter in the galaxy is much hotter and denser than solids, liquids and gases on the surface of the earth. Shock compressed low-density foams can achieve densities and temperatures in a regime known as warm dense matter (WDM). WDM is an extreme material state that lies between condensed matter and high temperature plasma. The properties of WDM are relevant to the interiors of gas and ice giant planets, as well as on the pathway to inertially confined fusion[1]. The extreme heating that occurs in shock compression of aerogels like 100mg/cc silica (<5% solid density) is due to the volume collapse. For low-pressure shocks the sample compresses to full density. At high pressures the thermal component of pressure dominates and the shock density decreases with increasing shock pressure generating an anomalous Hugoniot. Understanding these unique properties of low density materials are of current scientific interest due to the use of low density foams in a range of different high energy density (HED) experiments[2]. We present results where phase contrast imaging was used to investigate the Hugoniot state of shock compressed 100mg/cc silica aerogel.

EXPERIMENTAL SETUP

These experiments used a 10ns, 532nm optical laser pulse at the Matter in Extreme Conditions (MEC) end station of the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory. The optical laser was focused to a 50μm spot on a 50μm thick aluminum ablator at an intensity of ~7×10^{13}W/cm^2. Due to the tight focal spot the lateral release quickly creates a spherically expanding wave. Figure 1a) shows a schematic diagram of the

Shock Compression of Condensed Matter - 2015
AIP Conf. Proc. 1793, 090006-1–090006-4; doi: 10.1063/1.4971625
Published by AIP Publishing. 978-0-7354-1457-0/$30.00

experiment. At these pressures the shock front reflects 532nm light so the velocity of the spherically expanding shockwave was measured on surrogate experiments without the x-ray probe using the line-VISAR system (velocity interferometer system for any reflector) at MEC. The shock velocity as a function of time from these experiments was used in calculating the pressure.

The x-ray free electron laser at LCLS was tuned to 0.155nm (8keV) to perform magnified phase contrast imaging (PCI) measurements of the expanding shockwave in the aerogel sample. An array of beryllium lenses focused the x-ray beam 270mm upstream of the sample[3]. The expanding x-rays passed through the sample before being recorded on the detector, 1890 mm down stream from the target. Figure 1 b) shows a schematic diagram of the x-ray setup. Figure 1c) shows an example phase contrast image of a shock wave in aerogel foam. A single x-ray snap shot is taken for each experiment.

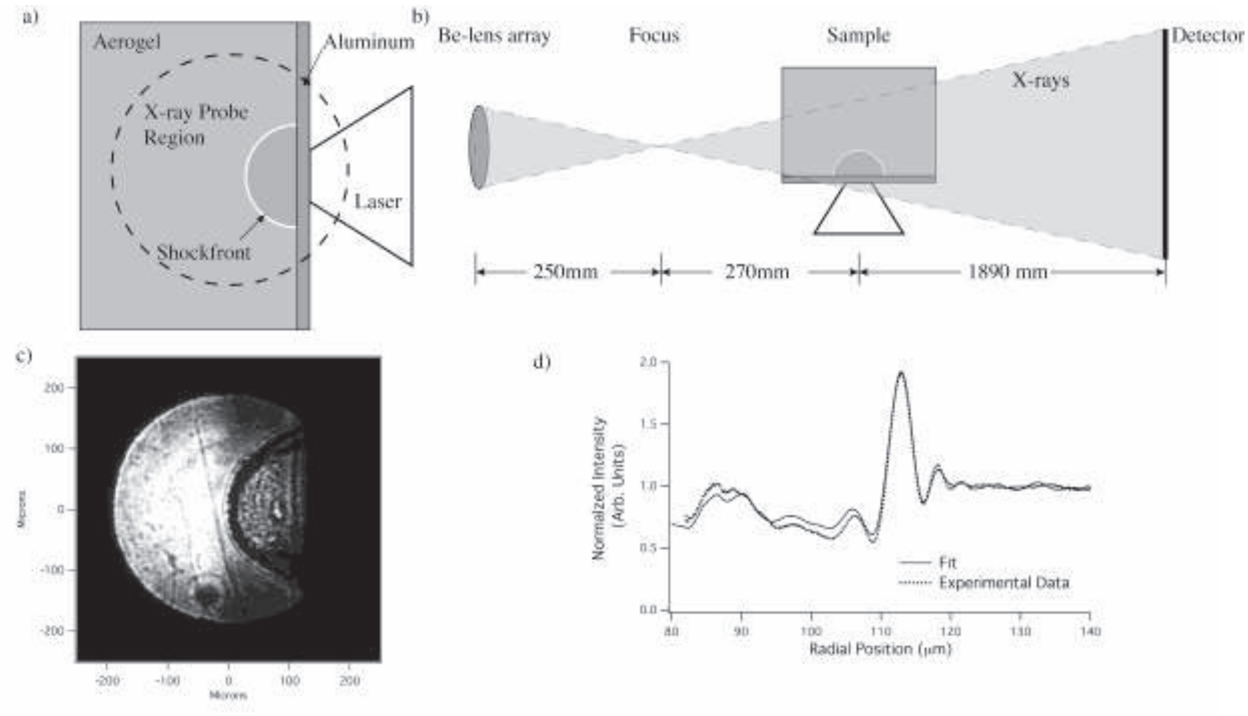

FIGURE 1. a) Schematic diagram of the target sample. The x-rays image a volume at the interface of the aluminum ablator and aerogel sample b) A schematic diagram of the magnified PCI setup. c) A representative x-ray PCI of the spherical shockwave propagating into 100mg/cc silica aerogel, where the dimensions are in the target plain. d) integrated line out and fit normalized to the beam transmitted through the ambient sample.

ANALYSIS

The expanding shock has propagated a sufficient distance from the ablation surface so that the experiment can be analyzed as the horizon of a sphere with a radius given by the curvature of the shock front. To improve signal to noise the image is azimuthally integrated along the shock front. Figure 1d) shows an integrated signal normalized to the beam transmitted through the unshocked sample. Small deviations from a perfect spherical front are corrected for.

An iterative analysis was used to find the best radial density fit to the PCI data. Due to the magnification the effective detector distance was corrected to $z_{eff} = {}^{z}/_{M} = 235$mm where $z = 1890$ mm is the actual detector distance and $M = 8$ is the magnification [4]. The iterative procedure is based on the Hybrid-Input-Output[5] algorithm using the constraint that both the imaginary and real component of the phase in the sample plane must match a single density for the known complex index of refraction for SiO_2 at 8keV where $n = 1 - \delta + i\beta$, for $\delta = 3.28\text{x}10^{-6}$ (ρ[g/cc]) β =4.3x10^{-8}(ρ[g/cc]), where ρ[g/cc] is the density of the aerogel in g/cc.

Figure 2 is a schematic diagram of the iteration process, where white boxes with black text denote real quantities and black boxes with white text denote complex quantities. The sample phase is calculated using the index of refraction of silica and the areal mass from the density profile. The Fresnel integral is used to propagate the complex signal to the detector. The magnitude of the signal at the detector is scaled to match the experimental data. The new signal is back propagated to the sample plain, from which the areal mass can be calculated from both the real and imaginary part of the phase, giving two density profiles which are combined to calculate the correction to the radial density profile for the next iteration. Typically 200 iterations were required to achieve convergence with the data.

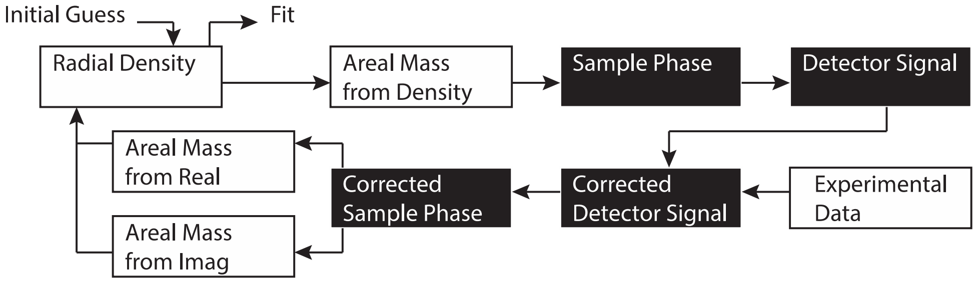

FIGURE 2. Diagram of the iterations used to fit the density profile

RESULTS

Table 1 gives the EOS measurements and calculated values for the imaging experiments and impedance matching experiments performed on the Omega laser for 100mg/cc silica aerogel. Figure 3 is a plot of the pressure versus compression for 100mg/cc aerogel from these experiments and 110mg/cc aerogel from published experiments on the Sandia-Z machine[6]. The little variation in density with shock pressure suggests we are in the strong shock limit where the compression is dominated by thermal component of pressure. We fit the data with a fluid model of the porous Hugoniot which in the high pressure limit ignores any initial strength of the material[7]. In the strong shock limit the compression is given by

$$\frac{\rho}{\rho_0} = 1 + \frac{2}{\Gamma}$$

where Γ is the Gruneisen parameter, and ρ, ρ_0 are the shock and initial density respectively. The dashed line in figure 3 shows the model fit with a Gruneisen parameter $\Gamma = 0.49$, not, $\Gamma = 0.66$, which is expected in the limit of forming a high temperature monotonic gas, suggesting that the silica has not completely dissociated into a plasma or gas.

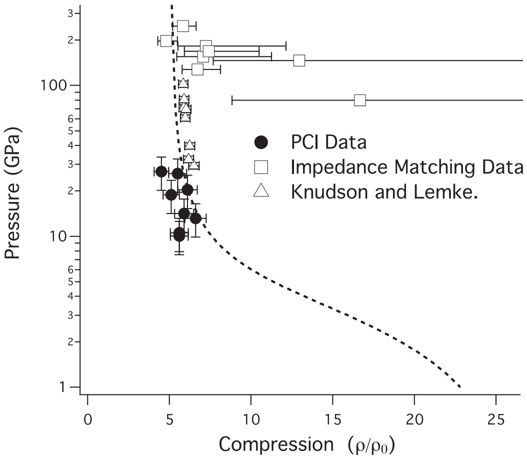

FIGURE 3. The pressure density Hugoniot for 100mg/cc silica aerogel. The filled circles are PCI, the open squares are impedance matching data from Omega and open triangles from Z-machine. The dashed line is a model for the poroue Hugoniot with Γ=0.49.

Foam- U_s (km/sec)	Quartz- U_s (km/sec)	Density- ρ (g/cc)	Pressure - P (GPa)
12.5 +/- 1.9		0.65 +/- .07	13 +/- 4
18.7 +/- 2.8		0.44 +/- .04	27 +/- 8
15.4 +/- 3.2		0.50 +/- .05	19 +/- 6
13.1 +/- 2.0		0.58 +/- .06	14 +/- 4
11.4 +/- 1.7		0.55 +/- .06	11 +/- 3
11.1 +/- 1.7		0.55 +/- .06	10 +/- 3
15.6 +/- 2.3		0.60 +/- .06	20 +/- 6
17.9 +/- 2.7		0.54 +/- .05	26 +/- 8
29.5 +/- 1.0	23.5 +/- 1.0	1.6 +/- 1.2 *	80 +/- 6 *
38.8 +/- 0.5	27.6 +/- 0.4	0.7 +/- 0.1 *	128 +/- 6 *
42.9 +/- 0.5	30.0 +/- 1.0	0.7 +/- 0.3 *	156 +/- 10 *
46.5 +/- 1.0	32.2 +/- 1.0	0.7 +/- 0.3 *	183 +/- 11 *
44.4 +/- 0.5	31.2 +/- 0.8	0.7 +/- 0.2 *	169 +/- 9 *
40.5 +/- 0.5	29.9 +/- 1.2	1.3 +/- 0.7 *	147 +/- 10 *
50.0 +/- 0.8	32.5 +/- 0.5	0.48 +/- .06 *	197 +/- 10 *
54.8 +/- 0.2	36.5 +/- 0.5	0.58 +/- .07 *	248 +/- 12 *

* Error bars are calculated using a Monte Carlo method. For cases with asymmetric error bars the average is quoted.

TABLE 1. EOS values for both the PCI and impedance matching experiments. The impedance matching experiments used Quartz as an impeaence standard have values for the shock speed in the Quartz given.

ACKNOWLEDGMENTS

The authors would like to the work of Tim Uphaus and Stuart Gammon for developing unique ways to make a large quantity of low density aerogel targets to support this experiment. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences

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