Shock Experiments on Pre-Compressed Fluid Helium

J. H. Eggert, P. M. Celliers, D. G. Hicks, J. R. Rygg, G. W. Collins, S. Brygoo, P. Loubeyre, R. S. McWilliams, D. Spaulding, R. Jeanloz, and T. R. Boehly

Citation: AIP Conference Proceedings **1161**, 26 (2009); doi: 10.1063/1.3241201
View online: http://dx.doi.org/10.1063/1.3241201
View Table of Contents:
http://scitation.aip.org/content/aip/proceeding/aipcp/1161?ver=pdfcov
Published by the AIP Publishing

Shock Experiments on Pre-Compressed Fluid Helium

J.H. Eggert,[a] P.M. Celliers,[a] D.G. Hicks,[a] J.R. Rygg,[a] G.W. Collins,[a] S. Brygoo,[b] P. Loubeyre,[b] R.S. McWilliams,[c] D. Spaulding,[c] R. Jeanloz,[c] and T.R. Boehly[d]

[a]*Lawrence Livermore National Laboratory, Livermore CA.*
[b]*Commissariat à l'Energie Atomique,, Bruyéres-le-Châtel, France*
[c]*University of California, Berkeley, CA.*
[d]*University of Rochester, Rochester, NY*

Abstract. We summarize current methods and results for coupling laser-induced shocks into pre-compressed Helium contained in a diamond anvil cell (DAC). We are able to load helium, hydrogen, deuterium, and helium-hydrogen mixtures into a DAC and propagate a laser-generated shock into the pre-compressed sample. This technique has allowed us to measure the Hugoniot for helium at initial densities ranging from 1 to 3.5 times liquid density. We have developed and used a methodology whereby all of our measurements are referenced to crystalline quartz, which allows us to update our results as the properties of quartz are refined in the future. We also report the identification and elimination of severe electro-magnetic pulses (EMP) associated with plasma stagnation associated with ablation in a DAC

Keywords: Pre-compressed, Shock, Equation of State, Helium.
PACS: 51.30.+i, 62.50.Ef.

PRE-COMPRESSED HUGONIOT EXPERIMENTS

By pre-compressing a compressible fluid such as helium or hydrogen to several GPa (tens of kilobars) the initial density can be increased substantially. The nature of the Rankine-Hugoniot relations ensures that the higher the pre-compression the lower the internal energy (hence the temperature) at a given density. By measuring a variety of Hugoniots at different initial densities we can probe the P-ρ-T equation of state more completely than has previously been possible.[1,2] Figure 1 illustrates this effect for hydrogen at three pre-compressions P_0 = 1, 5 and 60 GPa. The temperature along these Hugoniots is calculated to vary by over an order of magnitude at a given pressure.

We pre-compressed helium up to 1.25 GPa giving initial densities from 1 to 3.5 times liquid density. We measured the pressure-density-temperature equation of state (EOS) along these Hugoniots up to 200 GPa and 6 eV.[3] All of these measurements were made using crystalline quartz as a reference. In this way, our helium measurements can be updated as the EOS of quartz is improved in the future. Here we report on our quartz reference methods and review the pre-compression methodology.

CP1161, *Atomic Processes in Plasmas,* edited by K. B. Fournier
2009 American Institute of Physics 978-0-7354-0698-8/09/$25.00

In particular, using new diamond anvils we have solved severe EMP issues that plagued our earlier measurements and obtain better coupling of DAC samples with a halfraum drive. These improvements are crucial to extending this technique to higher pre-compressions, and to fielding similar experiments at the National Ignition Facility (NIF).

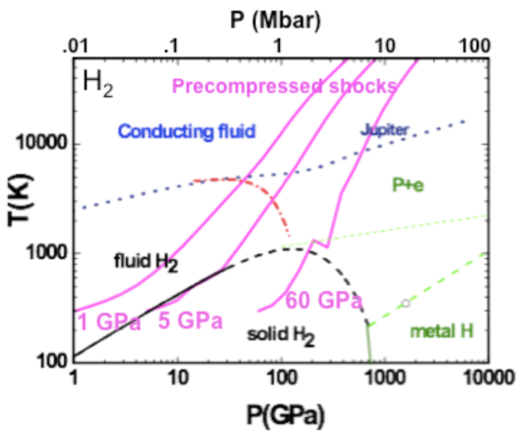

FIGURE 1. Calculated Hugoniots for hydrogen with three different pre-compressions.

We use a modification of the standard DAC for these experiments with one of the anvils replaced by a thin (100-500 μm) diamond plate (figure 2). The other anvil is 6 mm thick sapphire. Sapphire is used instead of diamond for its superior optical transparency. The sample chamber contained by a hard metal gasket is filled with fluid helium and includes a 20-30 μm thick quartz reference plate and a single ruby chip used to measure the initial pressure. The total sample thickness ranges between 80 and 160 μm depending on the initial pressure.

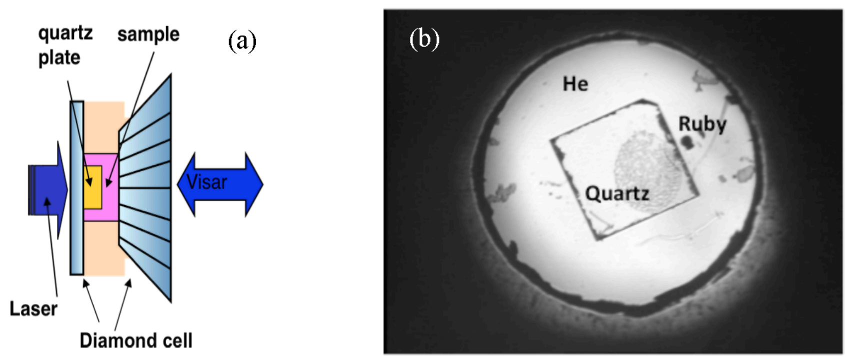

FIGURE 2. (a) Side view of DAC sample. The drive laser directly ablates the thin diamond plate. (b) DAC sample viewed through the sapphire anvil.

Before the shock enters the helium sample it travels through the quartz reference plate. We measure the velocity of the reflecting shock front in the quartz and helium using a VISAR.[4] Shock speed (*Us*) and post-shock particle speed (*Up*) in helium are determined by standard impedance matching methods. The reflectivity of helium is referenced to the reflectivity measured by Hicks et al.,[5,6] in order to account for absorption within the sapphire anvil. Likewise, the temperature in the helium is referenced to the temperature in quartz. Referencing the reflectivity and temperature to quartz is necessary because the DAC contains several potentially limiting apertures, and the transmittance of the sapphire anvil is uncertain during the shot (figure 3).

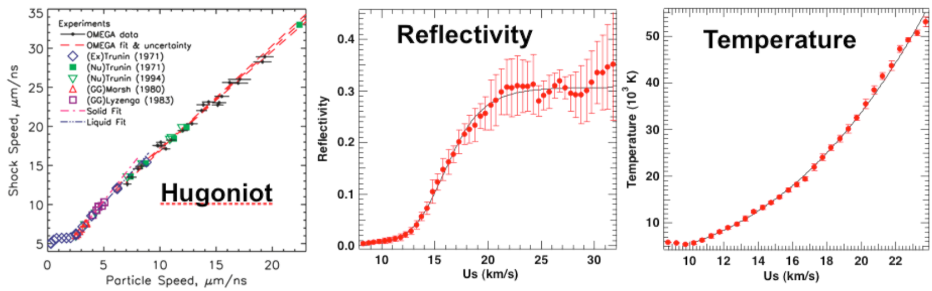

FIGURE 3. Our current knowledge of the shock Hugoniot the reflectivity and the temperature of quartz.

The phase of the VISAR fringes in figure 4a are proportional to the shock velocity because the shock front is reflecting in both the quartz and the helium. The proportionality constant for quartz and helium is simply given by the refractive index of each medium prior to shock compression. The thermal emission (figure 4b) is used to determine temperature,[7] assuming a wavelength-independent emissivity (grey-body model) obtained from reflectivity derived from the VISAR analysis.

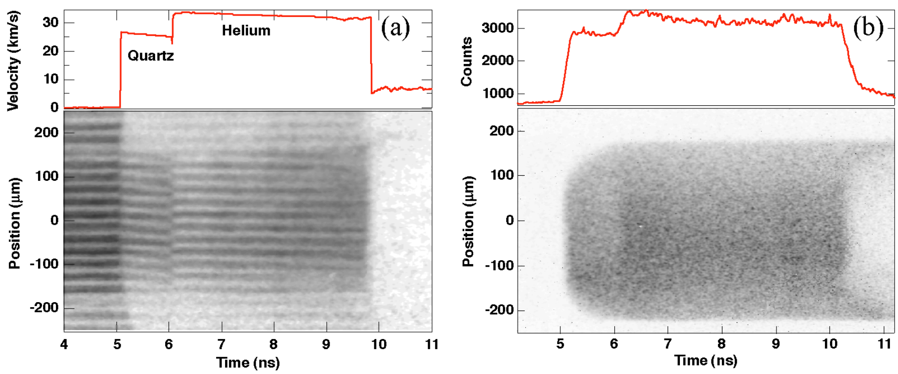

FIGURE 4. Raw data from the VISAR and the streaked optical pyrometer (SOP). (a) The shock propagates through the quartz, speeds up in the helium and then breaks out into the sapphire anvil causing the window to loose its transparency. (b) The intensity of the thermal emission of the shock within the quartz is lower than within the helium. The data are used to determine the helium temperature.[7]

Figure 5 shows time-integrated optical photographs of two different shots conducted at the Omega Laser Facility at the University of Rochester. The bright plasma plume (left side of figure 5a, upper left of figure 5b) is emitted from the diamond ablator driven by the Omega laser beams. The visar imaging telescope is shown in the lower right of figure 5b. These shots were often accompanied by large amounts of high-energy x-rays (>100 keV), and electro-magnetic pulses (EMP) causing electrical interference with streak cameras, computers, and electronic motors.

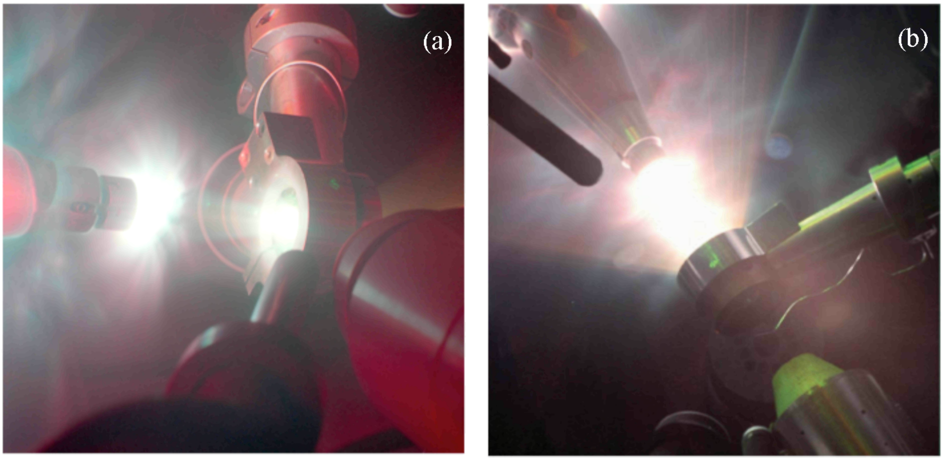

FIGURE 5. Time-integrated optical photographs of two different shots.

In order to support the thin diamond plate used for ablation the tungsten-carbide backing plate for our initial DAC design requires a relatively steep full angle of 80° and a 0.5 mm cylindrical countersink (figure 6a). This cylindrical hole acts as a hohlraum that fills with a plasma that stagnates on the symmetry axis and heats up to high local temperatures within about a nanosecond (figure 6b). We believe that this stagnating plasma, possibly interacting with the drive laser, is the source of the observed EMP. This interpretation is supported by subsequent experiments in which we employed the newly-developed Boehler-Almax diamond-anvil / tungsten-carbide support design shown in figure 6c. These new diamond anvils have three important advantages for us. The more efficient support of the anvil allows shallower full angle of 110° or even 136° so we can field more than twice as many drive lasers as before. The shallow angle also enables better coupling of a halfraum to the diamond ablator. Finally, the design of the anvil eliminates the cylindrical cavity adjacent to the diamond ablator. The shallow angle apparently serves to direct the plasma plume away from the diamond plate so that no stagnating plasma is present in the experiment and no EMP is generated (figure 6d). Using this new anvil design we are able to field more than twice as many drive lasers with no electronic side effects or detectable EMP.

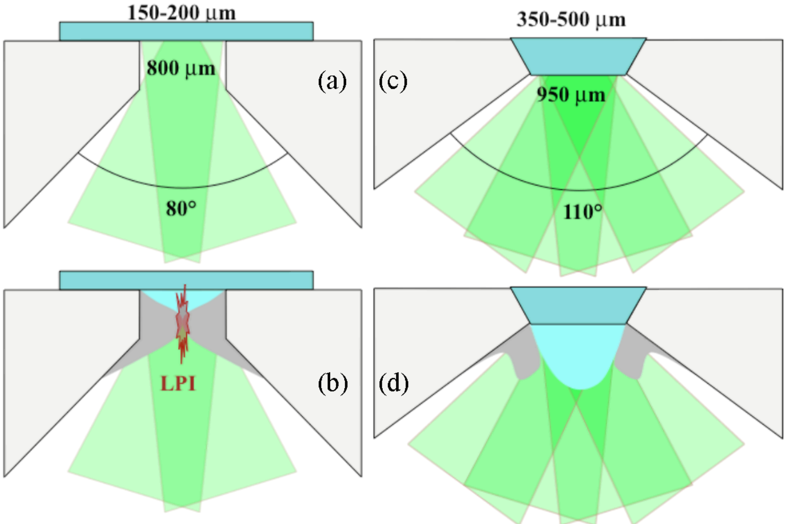

FIGURE 6. Two designs for the diamond plate backing plate in the DACs. The original design (a,b) generated very large EMP due to plasma stagnation. The new design using Boeher-Almax anvils eliminates the plasma stagnation and the associated EMP.

RESULTS

Figure 7 shows the pressure-density results for helium pre-compressed between 1 and 3.5 times liquid density (pressures of 0.11 and 1.25 GPa). For the lowest pre-compression the maximum compression is higher than for the higher pre-compressions.[3] This trend is reflected in both the Saumon-Chabrier-van Horn (SCVH) chemical model[8] as well as *ab-initio* path-integral Monte Carlo (PIMC) simulations.[9] The SCVH model agrees with our data somewhat better than the PIMC simulations. Finally, the temperatures extracted for helium from the SOP, are in good agreement with both the SCVH model and the PIMC simulations.[7]

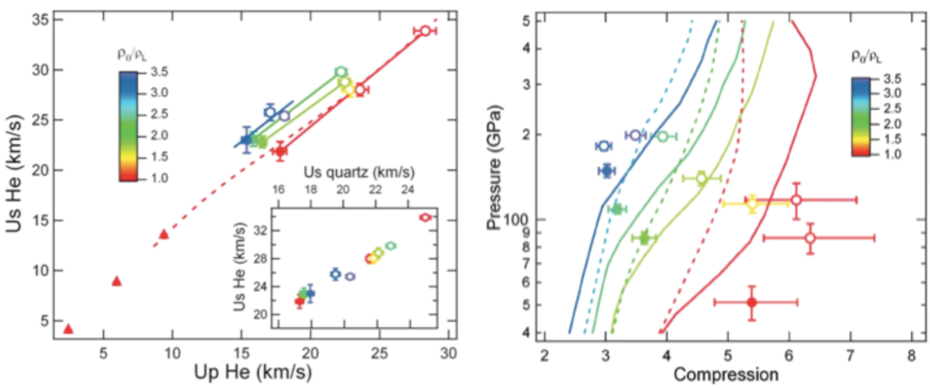

FIGURE 7. Helium Hugoniots for different pre-compressed initial densities. The full lines are the SCVH model and the dashed line the *ab initio* PIMC calculations.

ACKNOWLEDGMENTS

This work performed under the auspices of the U.S. DOE by LLNL under Contract DE-AC52-07NA27344.

REFERENCES

1. P. Loubeyre, P. M. Celliers, D. G. Hicks, E. Henry, A. Dewaele, J. Pasley, J. Eggert, M. Koenig, F. Occelli, K. M. Lee, R. Jeanloz, D. Neely, A. Benuzzi-Mounaix, D. Bradley, M. Bastea, S. Moon, and G. W. Collins, "Coupling Static and Dynamic Compressions: First Measurements in Dense Hydrogen," *High Pres. Res.* **24**, 25-31 (2004).
2. Raymond Jeanloz, Peter M. Celliers, Gilbert W. Collins, Jon H. Eggert, Kanani K. M. Lee, R. Stewart McWilliams, Stephanie Brygoo , and Paul Loubeyre, "Achieving high-density states through shock-wave loading of precompressed samples," *Proc. Nat. Acad. Sci.* **104**, 9172-9177 (2007).
3. J. Eggert, S. Brygoo, P. Loubeyre, R. S. McWilliams, P. M. Celliers, D. G. Hicks, T. R. Boehly, R. Jeanloz, and G.W. Collins, "Hugoniot Data for Helium in the Ionization Regime," *Phys. Rev. Lett.* **100**, 124503 (2008).
4. P. M. Celliers, D. K. Bradley, G. W. Collins, D. G. Hicks, T. R. Boehly, and W. J. Armstrong, "Line-imaging velocimeter for shock diagnostics at the OMEGA laser facility," *Rev. Sci. Instrum.* **75**, 4916-4929 (2004).
5. D. G. Hicks, T. R. Boehly, P. M. Celliers, J. H. Eggert, E. Vianello, D. D. Meyerhofer, and G. W. Collins, "Shock compression of quartz in the high-pressure fluid regime," *Phys. of Plasmas* **12**, 082702 (2005).
6. D. G. Hicks, T. R. Boehly, J. H. Eggert, J. E. Miller, P. M. Celliers, and G.W. Collins, "Dissociation of Liquid Silica at High Pressures and Temperatures," *Phys. Rev. Lett.* **97**, 025502 (2006).
7. P. M. Celliers and et al., (To be published).
8. D. Saumon, G. Chabrier, and H. M. Van Horn, "An Equation of State for Low-Mass Stars and Giant Planets," *Astrophys. J.* **99**, 713-741 (1995).
9. B. Militzer, "First Principles Calculations of Shock Compressed Fluid Helium," *Phys. Rev. Lett.* **97**, 175501 (2006).