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Graded-density reservoirs for accessing high pressure low temperature material states

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In recently developed laser-driven shockless compression experiments an ablatively driven shock in a primary target is transformed into a ramp compression wave in a secondary target via unloading followed by stagnation across an intermediate vacuum gap. Current limitations on the achievable peak pressures are limited by the ability of shaping the temporal profile of the ramp compression pulse. We report on new techniques using graded density reservoirs for shaping the loading profile and extending these techniques to high peak pressures.

Understanding high pressure-low temperature compressive states is relevant to the study of planetary interiors [1]. Traditionally high pressure multi-Mbar states have been accessed by launching a near instantaneous compressive shock into the material. Shock waves are associated with large jumps in temperature which greatly increases the thermal contribution to the pressure, and can cause melting of the material under study. In aluminum, shock pressures above 1.4Mbar produce temperatures above ~4000K and melting of the sample [2]. Recent laser-driven shockless compression techniques [3-6] have demonstrated near quasi-isentropic compression (ICE) in an aluminum sample to peak pressures of over 1 Mbar [3] and at estimated temperatures of 500K. The isentrope generally lies to the compressive side of the Hugoniot in P-V space. Since the Al melt temperature is measured to increase with compression, isentropic loading from room temperature to multi-Mbar pressures will stay below the melt line. The smaller amount of internal energy imparted into the material within the ICE platform allows for greater compression for comparable pressures on shock experiments. The technique has been demonstrated with several drivers such as the magnetic pulse loading of the Sandia Z-machine [7], pillow impactors in gas guns facilities [8] and the chemical energy of high explosives [9]. The time scales for these experimental platforms range from 100's of ns to several microseconds. In the case of the gas-gun driven ICE platform the ~mm thick impactor is constructed using a graded density layered-plate approach that initially produces a series of small steps in the loading, which subsequently transition to smooth compression as a result of wave interactions in the layer plates [8].

In laser-driven ICE experiments the loading time is over tens of nanoseconds. Laser-driven ramp compression experiments have recently been used to measure material strength [10] and the kinetics of polymorphic phase transformations [11]. Currently the highest pressure achieved on laser-driven ICE targets is 2 Mbar [5]. With current laser ICE target designs the ramp compression rise time scales inversely with peak pressure, which for high pressures results in hydrodynamic steepening of the ramp compression wave into a shock over short distances. For a given target thickness this places a limit on the maximum pressure that can be applied to a sample while still ensuring shockless compression. Within this paper we describe new techniques which incorporate graded densities into the standard laser ICE target design for increasing the rise time within laser-driven ramp compression experiments. The developments of these techniques are important for realizing the potential of shockless compression to peak pressures over 10 Mbar on the National Ignition Facility (NIF) [1, 4].

The target design for the laser-driven shockless compression consists of a low-Z reservoir foil followed by a vacuum gap and the target to be shocklessly compressed (as shown in Fig. 1(a)). In the experiments described here one beam of the Janus laser at 527 nm delivered a maximum of 380J in a 4ns square pulse onto the front surface of the reservoir material. A kinoform phase plate (KPP), inserted into the beamline to spatially smooth and shape the laser focal spot, generated a ~1mm square planar ($\Delta I/I \sim 5\%$) region at the focal plane which contained an estimated 80% of the total drive energy, giving a maximum on-target intensity of $\sim 5\times10^{12}$ W/cm^2. The focused laser beam launches an ablatively driven shock through the reservoir. Reservoir materials typically consist of a plastic foil (< 300μm thick) doped with a higher Z material (e.g. Br) in order to absorb x-rays generated in the laser corona. After breakout from the rear surface shock heating and momentum cause the reservoir material to dissociate and unload across a vacuum gap. Transit across the vacuum gap causes the mass density gradients along the target axis to relax as a function of distance from the original reservoir / vacuum gap interface. The unloading reservoir material monotonically loads up against the sample and the imparted momentum launches a ramp stress wave through the material. The temporal profile of the compression wave may be shaped to a limited extent by varying the size of the vacuum gap, the density of the reservoir or by controlling the laser energy [5]. In the experiments described here we apply the ramp compression pulse to a Al/LiF target. As the ramp stress wave reaches the back surface of the Al, the sample begins to accelerate into a 500μm thick LiF window material. The time history of the Al/LiF interface acceleration is recorded with a line imaging velocity interferometer (VISAR) with two channels set at different sensitivities [12] (Fig. 1(b)). The output of the VISAR is recorded by a fast optical streak camera. Fringe movement is linearly proportional to the velocity of the Al/LiF interface. This allows for accurate measurement of the interface velocity (after taking into account the refractive index of the window [13]) as a function of time. As Al and LiF are well impedence matched the VISAR effectively records the Al particle velocity history. This information allows for the compression source to be determined via a back-integration technique where the time dependent particle velocity at the rear surface is used as an input [14]. Due to increase of sound speed with increasing pressure the ramp compression wave will eventually steepen up into a shock within the Al sample. This would result in a near instantaneous jump in entropy and off-isentropic compression (and possible target melting) would ensue. The maximum Al thickness is therefore designed to be less than the calculated shock-up thickness.

For all reported Laser ICE experiments the laser pulse duration is designed to be less than the shock transit time through the reservoir. Therefore by the time the shock reaches the reservoir-vacuum interface the initial steady shock has transformed into a blast wave which contains no information about the temporal history of the laser drive. For a fixed target design higher ramp pressures may be achieved in the sample by increasing the input laser energy. This results in increased peak pressures in the blast wave exiting the reservoir and increased velocities of the material unloading across the vacuum gap. Increased peak pressures are then launched into the sample material but over increasingly shorter timescales. Using this technique peak pressures of 0.1 Mbar and 2Mbar have ramp compression rise times of ~30ns [11] and ~5ns [5], respectively. The dynamics of the unloading solid reservoir produces a shaped ramp compression profile which tends to shock up at low pressures. There is a need therefore to develop techniques for shaping the time history of the compression wave which will firstly increase the loading up time for a given peak pressure and secondly soften the gradient in the ramp wave such that eventual steeping into a shock will tend to occur at the top of the loading profile. The net effect in both cases, for a given peak pressure, is to increase the shock up distance and hence for a fixed target thickness higher levels of shockless compression may be obtained.

In the experiments reported here we use two different techniques for applying a density gradient onto the gap side of the reservoir material. The expectation is that the density gradient slows the rate at which momentum is imparted into the target and by customizing this gradient we can ultimately customize the shape of the pressure profile. The first reservoir design used consists of a 110 μm thick 1% Br/CH laser ablator with 60μm of SU8 ($CH_6O_4N_5$) photopolymer glued onto the vacuum side. Recently developed phase contrast lithographic techniques [15] are used to produce 3D nanostructures which reduce in size with increasing depth within an 60μm thick SU8 photopolymer (see Fig. 2(a) insert). The resultant density gradient is characterized with transmission x-ray radiography, with a spatial resolution of ~0.3μm, to go from full density to 19% density over 60μm (Fig. 2(a)). Using the target conditions described in Fig. 1(a) data is taken for solid density and graded density SU8. The time history of the ramp pressure profiles are shown in Fig. 2(b). It is observed that for the same peak pressure the rise time of the ramp compression wave is ~30% longer for the graded density reservoir case. Importantly the slope of the ramp compression wave associated with the graded density reservoir is noticeable reduced in the pressure range over which shocks typically develop within solid density reservoirs. Approximately 30% more laser energy was required in the graded density target to reach the same peak pressures as for the solid density reservoir. The peak pressure is related to the total amount of momentum imparted by the impacting reservoir material into the Al sample. The higher amount of laser energy is therefore needed for the graded density material to match the momentum associated with the solid density reservoir. Also shown are the calculated pressure profiles from the LASNEX plasma physics code [16] which as an approximation used a linear density gradient from full density to 19% density over the 60μm SU8 layer. The simulations show some disagreement in the gradient of the pressure profiles but qualitatively agree with the experimental observations of increased compression rise time with the use of a density gradient. Further improvements are expected in the compression rise time through customization of the density gradient profile.

Another approach for incorporating an effective integrated density gradient into a solid density reservoir is by direct micro-machining three dimensional features into the gap side of the reservoir material. In these experiments, a sawtooth feature was diamond turned into one side of a 225μm Polyimide [$C_{22}H_{10}N_2O_5$] foil. This feature was machined in one dimension and was characterized with high resolution imaging to have a period of 10μm and a depth of 8μm (insert of Fig. 3). Pressure profiles measured from identical target and irradiation conditions for polyimide reservoirs with and without the sawtooth feature are shown in Fig. 3. The target without the micro-machined feature exhibits a smooth ramp up to a peak pressure of ~190 kbar. The rise time of the graded density reservoir has increased over the solid density case. The target with the density gradient shows a more structured rise with two mini-plateaus which is due to local softening followed by steepening of the ramp gradients when compared to the solid density case. Locally there is expected to be a lot of turbulence as the pressure profile breaks out of the sawtooth reservoir but experimentally this is observed to be annealed out at the distance of the vacuum gap. Future experiments will concentrate on varying the structure of the machined feature in order to extend the rise time and smooth out the gradients within the ramp profile.

Increasing the rise time for a given peak pressure in laser driven quasi-isentropic compression experiments is necessary to drive these technique into the multi-Mbar pressure regime where low temperature compressive material states relevant to planetary interiors may be accessed. Using two separate techniques to introduce a graded density in the gap side of the reservoir it has been shown that the rise time of the compression wave in laser-driven ICE is increased. Further improvements are expected by customizing the shape of the density gradient which will facilitate shockless compression experiments on NIF to peak pressures over 10 Mbar.

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References

[1] B.A. Remington, R.M. Cavallo, M.J. Edwards, D.D.-M. Ho, K.T. Lorenz, H.E. Lorenzana, B.F. Lasinski, J.M. McNaney, S.M. Pollaine, R.F. Smith, "Accessing high pressure states relevant to core conditions in the giant planets", Astrophysics and Space Science 298 (1-2), (2005).

[2] C.A. Hall, J.R. Asay, W.M. Trott, M. Knudson, K.J. Fleming, M.A. Bernard, B.F. Clark, A. Hauer, G. Kyrala, AIP Conference Proceedings of Shock Compression of Condensed Matter, no.505 (2), p.1171-4 (2000); R. G. McQueen, J. N. Fritz, and C. E. Morris, in *Shock Waves in Condensed Matter-1983*, edited by J. R. Asay, R. A. Graham, and G. K. Straub (Elsevier, Amsterdam, 1984), pp. 95–98; A.D. Chijioke, W.J. Nellis, I.F. Silvera, J. App. Phys. 98, 073526 (2005).

[3] R.F. Smith et al., "Laser-driven shockless compression technique for measuring stress-strain in Aluminum to 120 GPa", Submitted to Phys. Rev. Letts (2006).

[4] M.J. Edwards, K.T. Lorenz, B.A. Remington, S. Pollaine, J. Colvin, D. Braun, B.F. Lasinski, D. Reisman, J.M. McNaney, J.A. Greenough, R. Wallace, H. Louis, D. Kalantar, Phys. Rev. Lett., **92** (7), pp.075002/1-4 (2004).

[5] K.T. Lorenz, M.J. Edwards, A.F. Jankowski, S.M. Pollaine, R.F. Smith, B.A. Remington, "Laser Driven Shockless Loading in Aluminum to 200Gpa", Submitted to Journal of High Energy Density Physics (2006).

[6] D.C. Swift, R.P. Johnson, Physical Review E, **71**, p.066401 (2005).

[7] J.R. Asay, "Isentropic compression experiments on the Z Accelerator", in Shock Compression of Condensed Matter – 1999, AIP Conf. Proceedings, NY, ed. by M.D. Furnish, L.C. Chhabildas, and R.S. Hixson; D.B. Reisman, A. Toor, R.C. Cauble, C.A. Hall, J.R. Asay, M.D. Knudson, M.D. Furnish, J. Appl. Phys, 89 (3), pp.1625-33 (2001); C.A. Hall, J.R. Asay, M.D. Knudson, W.A. Stygar, R. Spielman, T.D. Pointon, D.B. Reisman, A. Toor, and R.C. Cauble, Rev. Sci. Instrum. **72**, 3587 (2001).

[8] L.C. Chhabildas and L.M. Barker, Sandia Report SAND86-1888 (1986); J.R. Asay, Int. J. Impact Engng. **20**, 27 (1997).

[9] J.F. Barnes, P.J. Blewett, R.G. McQueen, K.A. Meyer and D. Venable, J. Appl. Phys. 45, 727 (1974); D.G. Tasker, J.H. Goforth, H. Oona, C.M. Fowler, J.C. King, D. Herrera, and D. Torres, Shock Compression of condensed Matter- AIP Conference Proceedings, 706, pp. 1239-1242 (2004).

[10] K. T. Lorenz, M. J. Edwards, S. G. Glendinning, A. F. Jankowski, J. McNaney, S. M. Pollaine, B. A. Remington, Phys. Plasmas **12**, 056309 (2005).

[11] R.F. Smith et al., "Ultra-fast dynamic compression technique to study time kinetics of phase transitions in Bismuth", submitted to Phys. Rev. Letts (2006).

[12] P.M. Celliers, D.K. Bradley, G.W. Collins, D.G. Hicks, T.R. Boehly, W.J. Armstrong, Rev. Sci. Instrum. **75**, 4916 (2004).

[13] J.L. Wise and L.C. Chhabildas, Shock waves in condensed matter – 1985, Y.M. Gupta, ed., pp. 441-454, Plenum, New York, 1986.

[14] D.B. Hayes, Backward Integration of Equations of Motion to Correct for Free Surface Perturbations, Sandia Report SAND2001-1440 (2001); D. B. Hayes, C. A. Hall, J. R. Asay, and M. D. Knudson, J. Appl. Phys, **94** (4), (2003); D.B. Hayes, C. A. Hall, J. R. Asay, and M. D. Knudson, J. Appl. Phys.. **96** (10), (2004).

[15] S. Jeon, J-U Park, R. Cirelli, S. Yang, C.E. Heitzman, P.V. Braun, P. J.A. Kenis, J.A. Rogers, PNAS **101** (34) 12428–12433 (2004).

[16] G.B Zimmerman and W.L. Kruer, Comments on Plasma Physics for Controlled Thermonuclear Fusion **2**, 51-61 (1975).

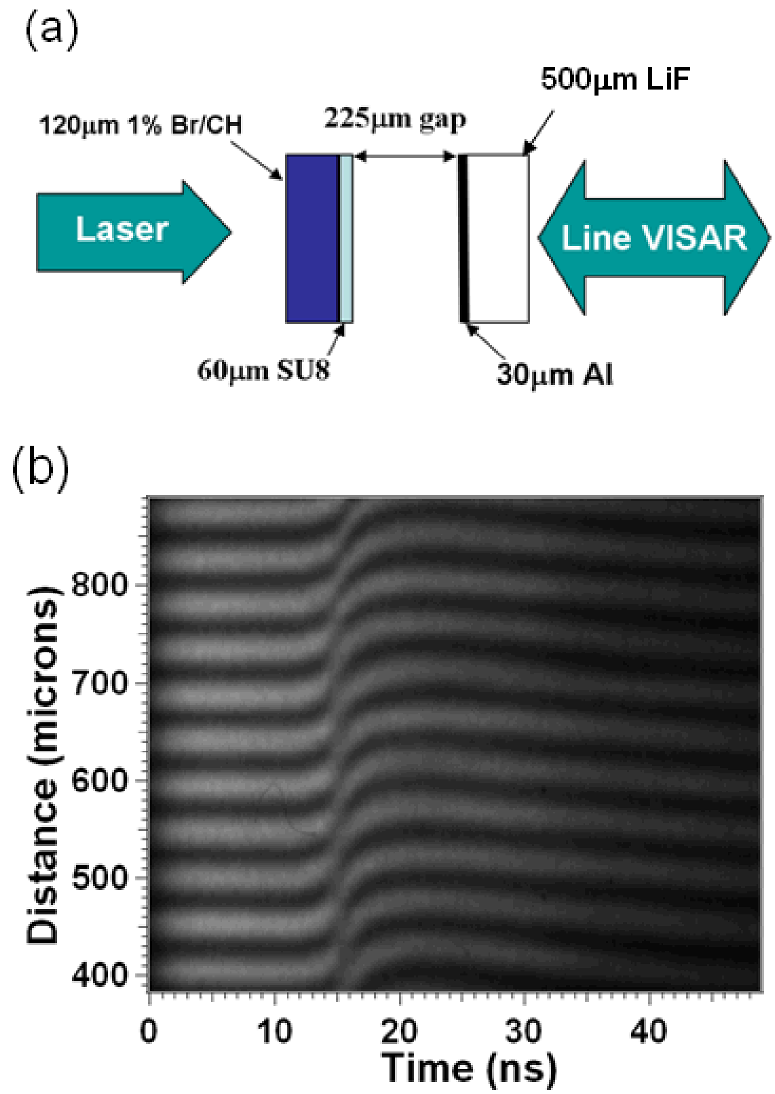
Figure Captions

Fig. 1 - (a) Schematic of Laser ICE target. (b) The output of the VISAR as recorded with a streak camera gives a temporal history of Al particle veocity and a spatial record of the applied pressure wave. Fringe movement is linearly proportional to the Al/LiF interface velocity.

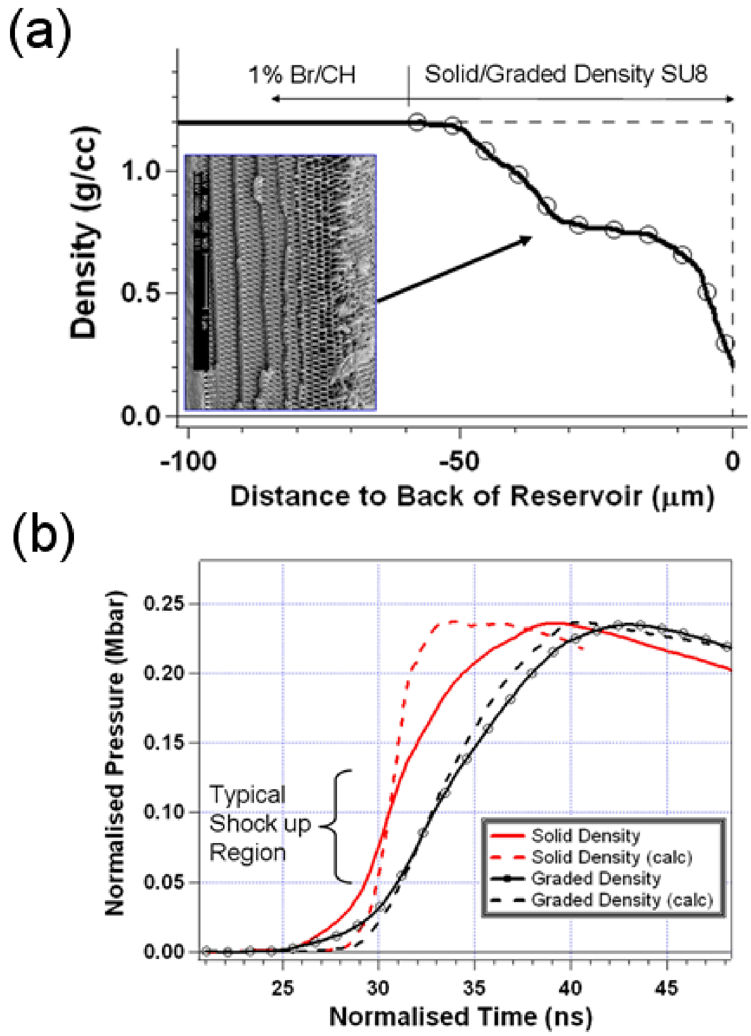
Fig. 2 - (a) Novel phase contrast lithographic techniques [13] produce 3D nanostructures which reduce in size with increasing depth within an 60μm thick SU8 photopolymer (see insert). The resultant density gradient is characterized with x-ray radiography to go from full density to 19% density over 60μm. (b) Using the target conditions described in Fig. 1(a) the time history of the ramp pressure profile with and without a density gradient in the SU8 is shown. Also shown are the calculated pressure profiles from the LASNEX plasma physics code [14]. The pressure and time axes have been normalized to make comparisons easier.

Fig. 3 - An average graded density is produced within a 225μm thick polyimide foil by machining of a sawtooth feature into the vacuum gap side. A Scanning Electron Microscope (SEM) image (insert) reveals the diamond turned feature to have a depth of 8μm and a period of 10μm. The resultant ramp compression profiles with and without the sawtooth feature are shown.

Smith *et al.* – Fig. 1



Smith *et al.* – Fig. 2



Smith *et al.* – Fig. 3