EOS measurements of pressure standard materials using laser-driven ramp-wave compression technique

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Abstract. To study the EOS of the pressure standard materials using the ramp-wave compression technique as a novel approach different from shock compression has been proposed. Laser-driven ramp-wave compression technique was used to shocklessly (or quasi-isentropically) compress platinum samples to peak longitudinal stress up to 40 GPa. Platinum stress-density data along the ramp-compression path was determined up to 20 GPa from free-surface velocity data of different thickness samples.

1. Introduction
Static compression methods such as diamond anvil cell and multi anvil apparatus are widely used in high-pressure sciences including earth, planetary and material sciences. In static compression experiments, characterizing thermodynamic quantities is of intrinsic importance. Pressure calibration standards are commonly used to know the thermodynamic quantities. The materials proposed for the pressure standards (pressure scale) are Pt[¹], Au[², ³], Al, Cu, Ta, W[⁴] and NaCl[⁵], for instance.

Pressure standard developed by dynamic shock compression experimental data is now one of outstanding questions in the over all-high pressure sciences, because pressures obtained in static compression experiments strongly depend on the pressure standard materials. A large discrepancy between the pressures, which each standard shows, has been revealed [⁶]. A discrepancy between Au and Pt pressure scale is more than 10 % in Mbar (100 GPa) pressure regime, between the pressures which Au and Pt standard shows, and demonstrates the urgent need to refine the pressure standard immediately.

One of dominant contributions to the pressure scale’s uncertainty is the uncertainty of the Grüneisen parameter volume dependency [⁵]. The Grüneisen parameter is used to reduce the high pressure and
high temperature shock Hugoniot data to \( P-V-T \) surface. In this procedure, higher temperature has more negative effect on accuracy of the reduced low temperature isotherm. It can be realized by high pressure and lower temperature compression that to suppress the effect of the Grüneisen parameter uncertainty.

Laser-driven ramp-wave compression (RWC) techniques, which are sometimes called quasi-isentropic compression, have been developed recently\(^\text{[7]}\)\(^\text{[8]}\). The RWC techniques provide high pressure (up to 1.4 TPa to date) and relatively low temperature compression. We have proposed to study the EOS of the pressure standard materials using the RWC technique as a novel approach different from shock compression. Ramp-compression \( P-V-E \) data are potentially used not only to obtain precise room temperature isotherm (most commonly used) but also a constrain condition to determine all over \( P-V-T \) surface.

2. Experiments

The experiments were conducted on the LULI2000 laser facility in the Laboratoire pour l’Utilisation des Lasers Intenses (LULI), Ecole Polytechnique, a neodymium-doped glass system operating with frequency-doubled 527 nm light. A schematic of the target package and experimental arrangement are shown in figure 1. The laser-driven ramp-compression target consists of a 75 \( \mu \)m polyimide foil as a reservoir which is a source of expansion plasma, a 200 \( \mu \)m vacuum gap, and the 10 or 24 \( \mu \)m Pt target with a purity of better than 99.98 \%. One beam from the LULI2000 laser was focused onto the polyimide foil with a 1 mm spot diameter, 4 ns pulse duration, and 378 or 374 J pulse energy. A hybrid phase plate was installed to achieve a uniform irradiation pattern.

A strong laser-driven shock wave is used to pressurize the polyimide and turn it into weakly ionized plasma. After shock breakout from the rear surface, the polyimide rarefies across the vacuum gap and a smooth momentum gradient of the polyimide plasma is generated. This plasma with momentum gradient loads up against the Pt sample, and launches a ramp compression wave into it. As the compression wave reached the rear surface of the platinum, it begins to accelerate into free space.

The two line-imaging VISARs\(^\text{[9]}\) were employed to measure the free-surface velocity, \( u_{fs} \), of the platinum. These VISARs had different velocity sensitivities in order to resolve \( 2\pi \) -phase shift ambiguities in case of shock formation. The sensitivities of the two VISARs were 0.28 and 0.938 km/s/fringe, respectively. The temporal resolution was 490 ps over a 20 ns time window. We detected fringe position to 7 \% of a fringe.

![Figure 1. Schematic diagram of the target configuration.](image)

3. Results

Figure 2 (a) and (b) shows the VISAR raw images for 10 \( \mu \)m and 24 \( \mu \)m Pt targets and inferred free-surface velocities from the images, respectively. We estimated from 24 \( \mu \)m sample data and SESAME EOS that the ramp-compressed platinum reached a peak pressure of up to 40 GPa.

The energies between shots on 10 \( \mu \)m and 24 \( \mu \)m were very close. We determined lagrangian sound velocity from these different thickness sample data, assuming stepped target. The lagrangian
analysis method [10] was used to determine the lagrangian sound velocity, \( C_L(u_p) \) and stress, \( P_x \) and density, \( \rho \) from \( u_p(t) \) and \( u_p(t) = \frac{u_f(t)}{2} \) approximation, where \( u_p \) is the particle velocity. \( C_L(u_p) \) and its uncertainty \( \sigma_{C_L}(u_p) \) are obtained from thickness and velocity history data by our measurement accuracies: \( u_p \) (0.066 km/s), time (490 ps), and step height (1 µm). \( C_L \) and \( \sigma_{C_L} \) are integrated to obtain \( P_x, \rho \), their uncertainties \( \sigma_{P_x} \) and \( \sigma_{\rho} \), using expressions below [8, 11]

\[
\begin{align*}
P_x &= \rho_0 \int_0^{u_p} C_L u_p \, du_p \\
\rho &= \rho_0 \left( 1 - \int_0^{u_p} \frac{du_p}{C_L} \right)^{-1} \\
\sigma_{P_x} &= \rho_0 \int_0^{u_p} \sigma_{C_L} u_p \, du_p \\
\sigma_{\rho} &= \frac{\rho^2}{\rho_0} \int_0^{u_p} \frac{\sigma_{C_L}}{C_L^2} u_p \, du_p,
\end{align*}
\]

where \( \rho_0 \) is initial density.

**Figure 2.** (a) VISAR raw images for ramp-compressed 10 µm and 24 µm Pt samples. (b) Inferred free-surface velocities from the figure 2 (a).

**Figure 3.** Lagrangian sound velocity versus particle velocity (solid line) together with a calculated lagrangian sound velocity form SESAME 3730 EOS (dashed line). Where \( u_p = u_p/2 \) approximation was used.

**Figure 4.** Ramp-compressed stress versus density data presented here (solid line). Also shown are Hugoniot [12] (circle) and a calculated isentrope from the SESAME 3730 EOS (dashed line).
In 10 µm Pt data, a reverberation wave, which went back and forth within the sample, reached rear surface at about 26 ns. Thus, $C_L$ could be determined as long as $u_s$ is less than 0.5 km/s (corresponding to the time 26 ns). Determined $C_L$ from the experimental data, calculated $C_L$ from SESAME EOS, bulk sound velocity by Holmes et. al.[1] and longitudinal sound velocity[12] are shown in figure 3. Due to velocity measurement accuracy, 0.066 km/s, obtained $C_L$, where $u_s$ is less than 0.033 km/s, is meaningless. Hence, we determined $P_x$-$\rho$ relation using $C_L$ data, where $u_s$ is over 0.033 km/s, and extrapolated $C_L$ by linear regression, where up is less than 0.033 km/s. Figure 4 shows obtained $P_x$-$\rho$ data up to ~20 GPa. Experimental data is in good agreement with SESAME EOS although uncertainties in $P_x$ and $\rho$ are large. The large errors in $C_L$, $P_x$ and $\rho$ were due to large uncertainty of thickness measurement and VISAR record quality. By developing target fabrication and VISAR diagnostics, measurement accuracies are potentially refined to $u_s$ (0.005 km/s), time (10 ps), and step height (50 nm).

4. Summary
In summary, we have proposed to study the EOS of the pressure standard materials using the ramp-wave compression technique as a novel approach different from shock compression (Hugoniot). Platinum was ramp-compressed up to a pressure of 40 GPa, and a stress-density relation along the ramp compression path was determined up to 20 GPa from $u_s$ data of different thickness samples. Applying recently developed pulse-shaped-laser-driven RWC technique with improved diagnostics EOS measurements of pressure standard materials in the multi-Mbar regime with higher accuracy will be potentially realized.

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