EQUATION OF STATE MEASUREMENTS IN THE MEGABAR REGIME WITH
LASER-DRIVEN SHOCK WAVES

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Introduction
The study of Equation of State (EOS) at high pressures is of interest for several fields of
physics, in particular astrophysics and inertial confinement fusion. Presently, no model of
material behaviour above 10 Mbar has been experimentally validated and, although in the
limiting case of extremely high pressure, EOS are expected to follow a Thomas-Fermi-Dirac
model, the regimes of applicability and approach to this limit are not known. One reason is
that experimental EOS data are sparse because of the difficulty in producing very high
pressures and measuring the relevant parameters at the same time. Indeed while pressures
1 Mbar can be obtained with static methods (diamond anvil cell), higher ones can be only
obtained dynamically for short times by generating shock waves in the material.

In the past, only a few EOS measurements in the tens of Mbar domain were performed by
nuclear explosions. This, because of reproducibility, environmental, economic and
proliferation considerations, was certainly not a good experimental method. Nowadays it is
possible to reach very high pressures in laboratory by using laser-generated shocks, i.e. by
focusing intense beams onto solid targets. This creates a hot, rapidly expanding plasma on
the laser side of the target (the plasma corona) and, owing to momentum conservation, a
shock travelling into the material. Recently pressures up to 0.75 Gbar have been obtained in
these experiments at the Livermore Laboratory [1].

Laser experiments can bring information on the interior of stars. The theory of stellar
evolution is affected by uncertainties in EOS in a few areas. One is white dwarfs. Through
most of the white dwarfs, the pressure of degenerate electrons supports the material against
gravity, but near the surface the electrons become less degenerate and the ions become
important setting the specific heat and thus the rate at which the white dwarf cools. Another
kind of dwarf stars, the brown dwarf, is poorly understood due in part to our imperfect
knowledge of EOS. After being predicted, brown dwarfs have recently been observed
experimentally [2]. Their internal structure and cooling time depend on the details of the
equation of state at densities approaching solid density at a temperature of a few eV,
conditions easily reachable in laser experiments.

The other main field of physics interested to EOS is ICF. Here a target containing deuterium
and tritium is illuminated by intense laser or ion beams and implodes reaching gigabar
pressures. The thermodynamics and hydrodynamics of these systems cannot be predicted without a knowledge of the EOS which describes how a material reacts to pressure.

**Shock production and Determination of Equation of State**

EOS experiments with shock waves are based on the so-called Hugoniot-Rankine relations which, in the simplest case of "strong" shocks, read [3]:

\[
\rho_0 D = \rho (D-u) \\
P - P_0 = \rho_0 D u \\
E - E_0 = \frac{u^2}{2}
\]

where \(u, \rho, p, D\) and \(E\) are respectively the fluid velocity, the mass density, the pressure, the shock velocity and the specific internal energy of the material (after shock passage), while with "0" we indicate the values in the un-perturbed material (i.e. before shock passage). Being a system of 3 equations with 5 unknowns, Hugoniot-Rankine relations allow one point on the EOS of the material to be found once two parameters are experimentally measured.

Now, although it was well known that lasers could produce shocks with pressures up to 100 Mbar [4], there has always been reluctance from the EOS community to use them as a quantitative tool. This was due to the "bad" quality of produced shocks concerning the flatness of the shock fronts (in direct drive experiments the laser intensity distribution in the focal spot is not flat but, in first approximation, gaussian and with many speckles or hot spots) and the problem of preheating. Indeed hot electrons or hard X-rays can be produced in the plasma corona and penetrate into the material ahead of the shock and "preheat" it. In this case, the shock travels in a non-unperturbed material and the Hugoniot-Rankine relations are useless.

In recent experiments, we have shown the possibility of creating very uniform shocks with negligible preheating by using two different methods. The first one consists in producing shock waves by direct laser drive with optically smoothed laser beams [5]; the second method uses thermal X-rays from laser heated cavities to generate shocks ("indirect" laser drive [6]). Here the laser beam is focused into a small cavity through an entrance hole: an isotropic X-ray radiation is then created whose temperature depends upon the cavity size and the laser power. For the generation of intense shocks, direct drive allows higher pressures for the same incident laser energy, since no energy is lost in the intermediate step of X-ray conversion. The shock pressure (in Mbar) is of the order of [7]

\[
P \approx 8.6 (I_L / 10^{14})^{2/3} \lambda^{-2/3}
\]

Here \(I_L\) is the intensity on target (in W/cm²) and \(\lambda\) the laser wavelength (in µm). To solve the uniformity problem we used the Phase Zone Plates smoothing technique [8]. PZPs are made of a Fresnel lens array, each with a random dephasing of 0 or \(\pi\) to break the laser
beam spatial coherence and give smoothing effects like in more common techniques of optical smoothing (e.g. Random Phase Plates). But unlike RPPs, they allow a top-hat distribution to be obtained in the focal spot. As a result, 2D effects are almost completely eliminated (around the centre of the focal spot) and high quality flat shocks are generated. This also allows high pressures (> 10 Mbar) to be reached with relatively small lasers (100 J).

**Experimental set-up**

We present some results on Fe obtained with the laser Phebus, at CEA, Limeil, France.

![Fig.1: Schematic of the experimental set-up. Double step targets were used to measure the shock velocities in the two materials shot by shot with a visible streak camera. The laser beam was smoothed with PZP.](image)

The diagnostic used to detect the shock breakout was based on the detection of the emissivity, in the visible region, of the target rear face, illuminated on the other side by the laser beam. The arrival of the shock causes a sudden variation in temperature and hence of emissivity. A visible streak camera recorded such variations in time.

![Fig.2: Rear side shock breakthrough for an Al-Fe target. The laser shot energy was 0.6 kJ. Shock break-out from the Al step on the left and from the Fe step on the right.](image)

Finally, instead of measuring 2 parameters in order to find the EOS, in our experiment we used the impedance-matching technique with two-step, two-material targets. Here a "relative" EOS point of one "unknown" material is obtained if the EOS of a "reference" material is known. In our case, the target is made of an aluminium base (chosen as reference material), which supports two steps, one of Al and the other of the material to be investigated. This geometry allows the shock velocities to be experimentally determined in the two materials on the same shot. By knowing the aluminium EOS and using the laws of
shock transmission at the interface between the two materials (the impedance-matching conditions) we then find the unknown EOS points. We have recently proved the reliability of this method, used in the past in nuclear experiments, in laser shock experiments [10]. Fig. 2 shows a "flat" shock breakthrough obtained with PZPs and a stepped target. Shock velocity is determined with high precision by measuring the shock breakout time from the base and the step of the target.

Results and discussion

Fig. 3 shows our nine experimental points for iron EOS, in a ($\rho/\rho_o$, P) diagram where $\rho_o$ is the density of cold iron ($\rho_o = 7.85$ g/cm$^3$). The experimental pressure range is 10 - 45 Mbar.

![Fig. 3. Experimental results for iron EOS in the ($\rho/\rho_o$,P) plane. The continuous curves correspond to QEOS (blue) [10], SESAME (green) [11] and the semi-empirical fit by Trunin (red) [12].](image)

The errors on pressure and on fluid velocity are about 10%, while the error on compression is about 20%; these error bars have been estimated by calculating the propagation of the experimental error on the shock velocity (5%) on the quantities determined by the mismatch method. The error on shock velocity is instead determined from the experimentally measured uncertainties on step thickness and by streak-camera temporal resolutions.

As can be seen from Fig. 3 all our points are above the SESAME curves, and the agreement is much better with QEOS model and the semi-empirical fit by Trunin.

References