



# Design of absolute equation of state measurements in optically thick materials by laser-driven shock waves

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## Abstract

Some aspects of the design of a target for the absolute measurement of Equation-of-State data at pressure of tens of Mbar, in optically thick materials are discussed. In the proposed experiment, a shock wave is generated in a laser-irradiated sample, and the shock velocity and the material velocity behind the shock are simultaneously measured by the optical and X-ray diagnostics. Accurate measurements require the generation of a steady, planar shock, and the detection of the motion of a shocked fluid interface by transverse radiography. One- and two-dimensional numerical fluid simulations have been performed to optimize beam and target design, in order to fulfil such requirements. © 1998 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Powerful and flexible laser facilities allow to generate shock waves in matter with pressure as high as 100 Mbar [1,2], and to perform experiments [3–5] aiming to measure Equation-of-State (EOS) data. These could be helpful in validating theoretical models and in providing data of interest to many scientific areas, including Inertial Confinement Fusion (ICF).

Equation-of-State (EOS) data of the shocked material can be evaluated from the Hugoniot equations [6], expressing the conservation of mass, momentum and energy, at the shock front. For a high-pressure shock they read

$$\rho = \rho_0 \frac{D}{D - u}, \quad P = P_0 + \rho_0 D u, \quad E = E_0 + \frac{u^2}{2}, \quad (1)$$

and relate the pressure  $P$ , internal energy  $E$  and density  $\rho$  of the shocked material to the respective pre-shock values (subscripts 0). Use of Eq. (1) requires measuring two unknown quantities, such

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as, e.g. the shock velocity ( $D$ ) and the fluid velocity ( $u$ ).

Recently, laser-generated shocks have been used to perform absolute EOS measurements of transparent low  $Z$  materials [3,5]. As for opaque metallic materials, so far in experiments with laser drive, only *relative EOS data* have been obtained by measuring the shock velocity in two different materials; EOS data of one of the materials were obtained by taking the EOS of the other one as a reference (see, e.g. Refs. [7,8]).

An experiment aiming at *absolute EOS measurements* at  $P \leq 50$  Mbar has been recently proposed [9] and will be performed with the laser Phebus

[10] (Nd:glass  $E_L = 2.5$  kJ;  $\Delta t = 2.5$  ns;  $2\omega$ , i.e.  $\lambda = 0.53 \mu\text{m}$ ) of the CEA-Limeil Laboratory. A direct drive approach [7,11] will be employed, which is more efficient [8] than the indirect drive. Kinoform Phase Plates (KPP) [12] will be used to provide uniform irradiation over a laser spot size of  $\approx 300 \mu\text{m}$  [13]. This experiment aims to generate a shock wave in a target made of two layers (see Fig. 1). A secondary laser beam will be focused onto a Fe target to produce a X-ray source, with a k-shell spectrum above 6.7 keV, used to perform a transverse X-ray radiography, in order to measure the fluid velocity  $u$ . Our target geometry shows two main zones: the

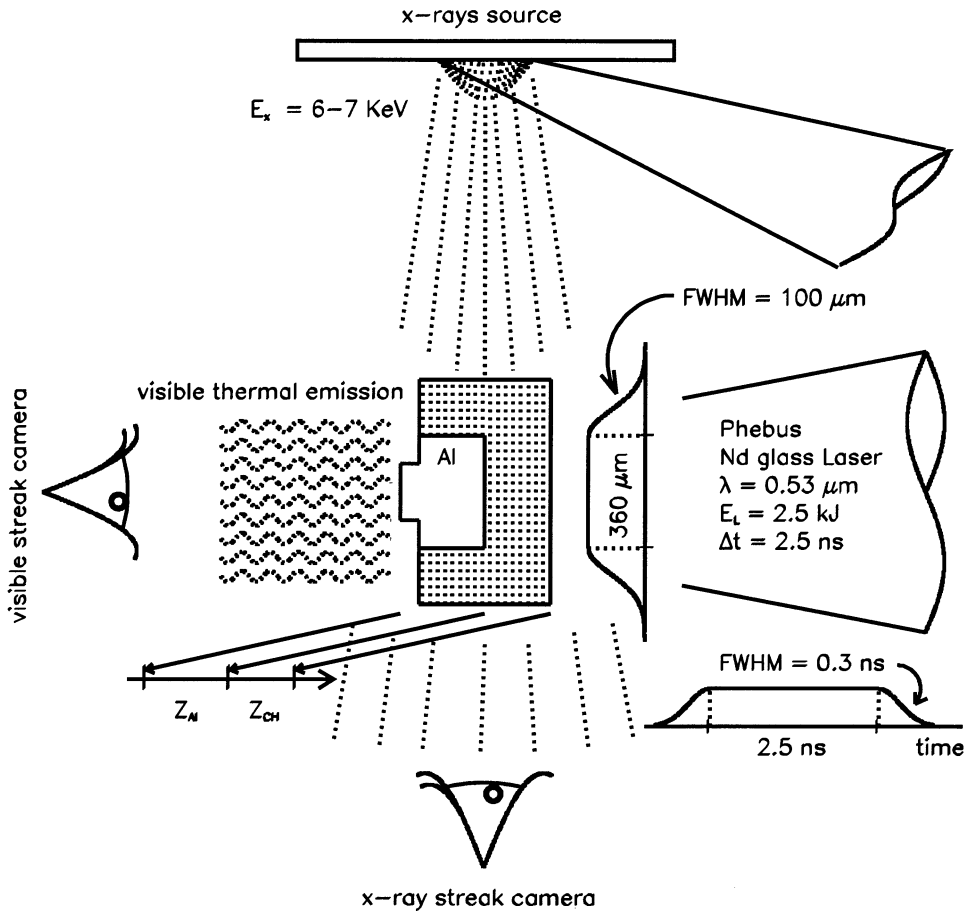


Fig. 1. Sketch of the experimental setup.

plastic support, which is optically transparent to the X-rays, and the “true” target made of Al, which is X-ray opaque. The radiographic image will thus discriminate the interface between Al and plastic, allowing the measurement of its velocity  $u$ . The shock velocity  $D$  will instead be measured by a well tested method, using a visible streak camera (with estimated resolution of  $10\ \mu\text{m}$  in space and  $10\ \text{ps}$  in time) detecting the light emitted when the shock breaks out of the target rear side, thus allowing to measure the shock transit time. (Here, to test the potentiality of the proposed method we consider a target made of aluminium supported by a plastic layer, but of course the method could be applied as well to measure EOS data of other optically thick materials.)

In a previous paper [14] we have analysed two-dimensional hydrodynamic effects which could spoil the measurement of  $u$  and  $D$ . In this work a target with fixed aluminium ( $\Delta Z_{\text{Al}} = 100\ \mu\text{m}$ ) and plastic ( $\Delta Z_{\text{CH}} = 40\ \mu\text{m}$ ) thickness was considered; it was found that an appropriate geometry (such as shown in Fig. 1) must be adopted in order to allow the shock generated in the central zone to be detected by X-radiography. A non-uniform shock front due to the laser profile (see Section 2), was found to hinder the X-ray diagnostics.

In this paper we analyze other important issues for the success of the proposed method, namely that shock and fluid velocities have to refer to the same matter state. This means that the matter conditions behind the shock front must be uniform. Furthermore, since absolute EOS measurements require the simultaneous determination of the shock and fluid velocities, the generation of a stationary shock wave is an essential requirement to allow the use of the Hugoniot relations with the data provided by the envisaged diagnostics. In particular, we analyse how the thickness of the two layers affects the shock propagation; we also aim at determining how long the interface can move with a constant velocity. The hydrodynamic evolution of the target has been simulated by using the Lagrangian code DUEED [15–17] and an adhoc developed post-processor [14] was used to simulate the X-ray image.

## 2. Shock propagation

As a preliminary step in the design of our experiment, we performed 1-D numerical simulations of the hydrodynamic evolution of the targets of the type shown in Fig. 1. In Fig. 2 the time evolution of the Lagrangian cells is shown for a typical case. The laser intensity was  $I_0 = 100\ \text{TW}/\text{cm}^2$  with a  $2.5\ \text{ns}$  flat temporal profile, preceded and followed by Gaussian tails (FWHM =  $300\ \text{ps}$ ). The target was made of a layer of aluminium ( $\rho = 2.7\ \text{g}/\text{cm}^3$ ), with a thickness of  $60\ \mu\text{m}$ , supported by a plastic ( $\rho = 1.0\ \text{g}/\text{cm}^3$ ) layer with a thickness of  $40\ \mu\text{m}$ .

Around time  $t_s = 1.25\ \text{ns}$ , the shock generated in the plastic reaches the interface between Al and plastic (point S), initially located at  $Z = 60\ \mu\text{m}$ . The impedance mismatch [6] between the two materials generates a shock in the Al and a reflected shock in the plastic. In this case, at time  $t_R = 1.56\ \text{ns}$ , the reflected shock meets the ablation front (point R) and the rarefaction wave will penetrate in the already shocked plastic. The interaction of this rarefaction wave (faster than the primary shock) with the interface (for  $t \geq t_I \approx 1.83\ \text{ns}$ , point I in the figure) and with the primary shock results in a reduction of the fluid and shock velocities.

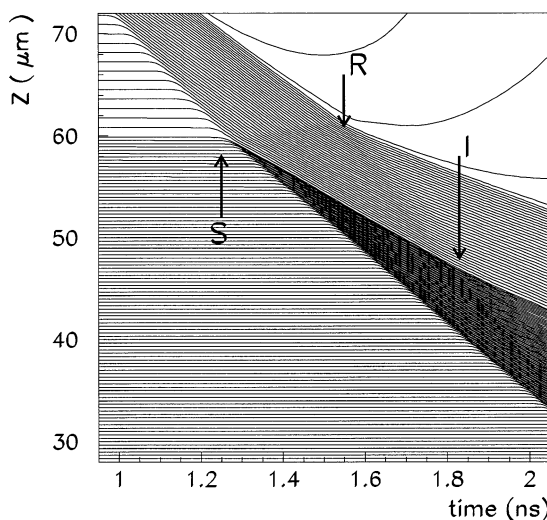


Fig. 2. 1-D numerical simulation. Time evolution of the Lagrangian grid.

It is then apparent that only in the interval  $t_s \leq t \leq t_b$ , which we could call the *open window* for our method, a shocked material with constant and uniform parameters exists. For a meaningful use of the Hugoniot relations the shock and fluid velocities must be measured simultaneously inside such an open window. Given the available instrumental resolution, we need an open window  $\Delta t_o = t_b - t_s \geq 1$  ns, longer than that obtained in the case of Fig. 2 (indeed the estimated resolution of the X-ray radiography diagnostics will be  $7 \mu\text{m}$  spatially and  $14$  ps in time). By means of simulations we have found, as expected, that  $\Delta t_o$  grows with the thickness of the plastic layer; on the other hand a too thick layer would result in nonuniform laser deposition, due to defocusing effects. It turned out that a thickness of  $100 \mu\text{m}$  is a good compromise between the above quoted requirements. E.g., for a target made of  $60 \mu\text{m}$  of Al supported by  $100 \mu\text{m}$  of plastic (the laser characteristics are unchanged)  $t_s \approx 2.8$  ns,  $t_b \approx 4.2$  ns, resulting in an interval  $\Delta t_o = 1.4$  ns during which  $u$  is nearly constant.

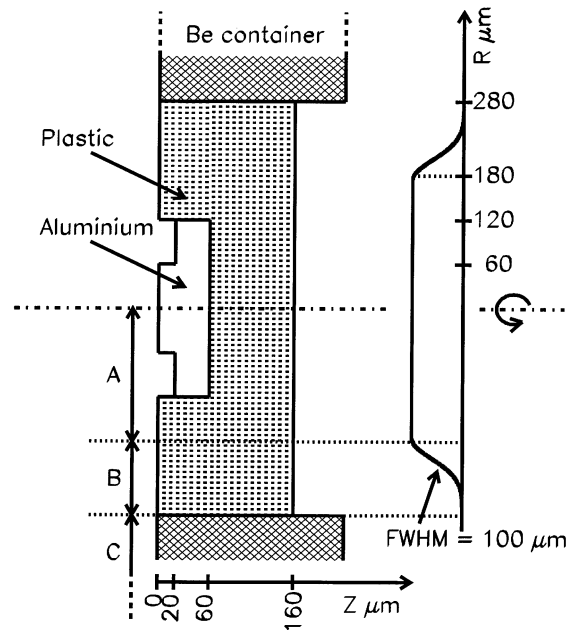


Fig. 3. Target design. Zones: (A) plane shock region; (B) zone for the transit of the spurious shock generated by the laser edges; (C) cylinder of optically thin Be to contain the lateral plasma expansion.

### 3. Target design and experiment simulation

Taking into account the results of the previous section and those of Ref. [14] we propose the target design shown in Fig. 3. The target has been subdivided along the radius in three zones: A, B and C.

**Zone A:** The aluminium target with thickness  $\Delta Z_{\text{Al}} = 60 \mu\text{m}$  and radius  $\Delta r_{\text{Al}} = 120 \mu\text{m}$  with, on its rear side, a step of  $20 \mu\text{m} \times 60 \mu\text{m}$ . The Al target is supported by a plastic layer with a thickness  $\Delta Z_{\text{CH}} = 100 \mu\text{m}$  and radius  $\Delta r_{\text{CH}} = 180 \mu\text{m}$ .

**Zone B:** Hollow plastic cylinder,  $r_{\text{P}} = 180 \mu\text{m} \leq r \leq r_{\text{L}} = 280 \mu\text{m}$ . Previous analyses have shown that, if the radius of the Al target is larger than  $r_{\text{P}}$ , then the shocks generated by the laser beam edges ran more slowly than the shock in the central zone A. This resulted in a “shadow” on the radiography that did not allow the detection of the interface motion. Including the zone B, the shock coming from the laser beam edges, must move faster than the shock in Al, thus overcoming the above problem.

**Zone C:** Cylinder of beryllium with indicative thickness of  $100 \mu\text{m}$ . It serves to reduce the lateral expansion of the plasma, that could defocus the laser beam, with consequent decrease of the laser intensity.

In Ref. [14] we used 2-D simulations to find means to reduce the negative effects due to the finite laser spot size, and hence to the unavoidable shock-wave edge effects. Here, being mostly interested in verifying the existence of a sufficiently long, nearly steady stage of shock propagation, we have only considered the central zone A, taking a sliding boundary condition so that no lateral radial expansion occurs. Such simplifications are justified by the fact that the shock in zone B moves faster than the shock in zone A.

The simulated X-ray radiography is shown for a typical case in Fig. 4 (the transmitted intensity is normalized: black indicates maximum transparency and white total absorption of the X-rays), together with the shock and interface trajectories

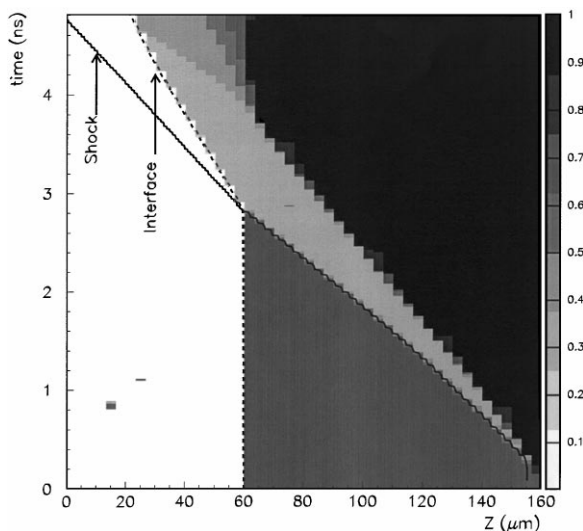


Fig. 4. Simulated radiography, generated by a postprocessor acting on the DUED output data. Also plotted are the shock front (continuous curve) and interface (dashed curve) position as computed by DUED along the  $Z$ -axis.

on axis as evaluated by the code DUED. It is found that the radiographic signal follows quite well the interface motion, thus allowing the evaluation of the fluid velocity  $u$ .

In Fig. 5 we analyze the data from the radiography: the interface and shock positions are shown with the respective error bars. The points before  $t = t_s$ , when the shock reaches the interface, represent the shock motion through the plastic. At  $t = t_s$  the interface starts moving and the contrast due to the different opacities of the shocked plastic (optically thin) and that of the shocked Al (optically thick) allows X-radiography to detect the interface position as a function of time. By interpolation and subsequent differentiation of these data we have obtained the shock velocity for  $t \leq t_s$ , and the interface velocity for  $t \geq t_s$ . We get a fluid velocity  $u = 20.5 \mu\text{m/ns}$  and a shock velocity  $D = 31 \mu\text{m/ns}$ . Such values correspond, by Eq. (1), to pressure  $P \approx 17 \text{ Mbar}$  and density  $\rho \approx 8 \text{ g/cm}^3$ . Very good agreement is observed with the data computed by the fluid code DUED (dashed curves).

In conclusion, by means of an analysis based on 1-D and 2-D simulations, we have designed a target for absolute EOS measurements at pressures in

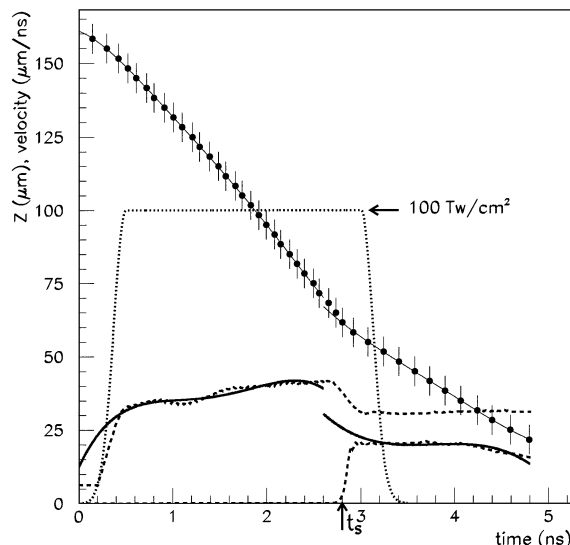


Fig. 5. Interface and shock position as evaluated by the radiography (with respective error bar). The polynomial fit of such points has provided, by differencing, the interface velocity for  $t \geq t_s$  and the shock velocity for  $t \leq t_s$ . Shock and fluid velocities on the axis as computed by DUED (dashed line) are also shown.

excess of 10 Mbar. We have found a design which allows to minimize effects due to the finite size of the laser spot. In addition, we have found that the requirement of a sufficiently long stage of stationary shock propagation can be fulfilled by an appropriate choice of the thickness of the aluminum and plastic layers.

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