GENERATION OF HIGH SHOCK PRESSURES BY LASER PULSES

J. Romain

JOURNAL DE PHYSIQUE
Colloque C8, supplément au n°11, Tome 45, novembre 1984 page C8-281

GENERATION OF HIGH SHOCK PRESSURES BY LASER PULSES

J.P. Romain

GRECO ILM, Laboratoire d'Energétique et Détonique[+], *E.N.S.M.A., rue Guillaume VII, 86034 Poitiers, France*

Résumé : Les caractéristiques d'ondes de choc de très haute pression induites par impulsion laser et les résultats obtenus au cours des dernières années sont examinés. Les pressions déduites de mesures de la vitesse de choc atteignent 5 TPa. L'influence de la longueur d'onde et du flux laser ainsi que les effets de l'expansion bidimensionnelle du plasma sur la pression de choc sont étudiés. Le rendement hydrodynamique déterminé à partir des données incluant de nouveaux résultats à 0,26 μm de longueur d'onde met en évidence l'avantage des courtes longueurs d'onde pour obtenir de très hautes pressions. La possibilité d'obtenir des pressions de l'ordre de 10 TPa par la méthode des impédances de choc est examinée.

Abstract : Aspects of laser generated high shock pressures and results obtained over the last years are reviewed. Shock pressures up to 5 TPa inferred from shock velocity measurements are reported. Effects of laser wavelength, intensity and 2-D plasma expansion on the generated shock pressure are discussed. The hydrodynamic efficiency determined from various data including new results at 0,26 μm wavelength outlines the advantage of short wavelengths for producing very high pressures. The possibility of achieving shock pressures in the 10 TPa range with the use of the impedance match technique is examined.

INTRODUCTION

The use of high intensity lasers for producing ultrahigh pressure shock waves has been developed in the last few years essentially in concern with inertial confinement fusion experiments, and also as a possible application to equation of state research. Pressures in excess of 10 TPa were expected for a plane wave configuration. But until recently, the maximum pressure inferred from shock velocity measurements at high laser intensity was 3.5 TPa /1/. Most of the experiments have been done at 1.06 μm laser wavelength, a few experiments at 0.35 μm wavelength and recently the first experiments at 0.26 μm wavelength.

In this paper, we present a review and a discussion of these various results with emphasis on laser wavelength effects and 2-D plasma expansion effects on shock pressure and hydrodynamic efficiency.

I - LASER SHOCK PROPERTIES

The mechanism of shock generation by laser pulses of high intensity is well known and has been described in various papers /2-4/. A shock wave is generated in a solid target by ablation of material at the irradiated surface. The ablation is produced by energy absorbed in the low density regions of the expanding plasma and transported by thermal conduction through the dense plasma region up to the solid surface. From the incident energy (E_{inc}), only part is absorbed in the plasma below or at

[+] L.A. CNRS 193

critical density (E_{abs}) and again part of this absorbed energy, called efficient energy (E_{eff}) is used for the shock compression (Fig.1).

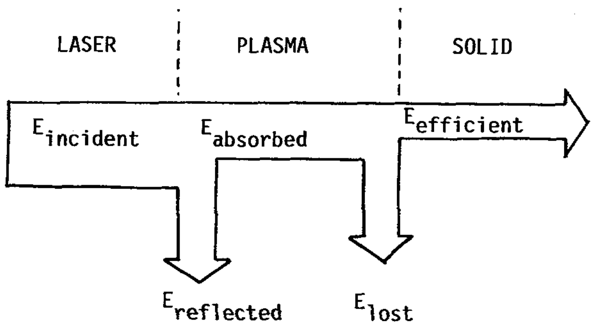


FIG.1 - Schematic representation of energy distribution during an interaction experiment. The efficient energy is the part of incident energy used for the shock compression of the solid target.

The absorption ration E_{abs}/E_{inc} determined from measurements on plasma expansion /5/ is about 30 % at 1.06 µm wavelength and 90 % at 0.26 µm wavelength, for 500 ps laser pulses in the 10^{14} - 10^{15} W/cm^2 intensity range. The increased absorption at 0.26 µm is a first advantage of using short wavelength for producing high pressures. Experiments at 1.06 µm and 0.35 µm wavelength /6/ have confirmed this advantage. The measurement of shock pressures provides one means for evaluating the total interaction balance E_{eff}/E_{inc} and the part of absorbed energy lost in the plasma expansion (E_{lost}).

From 1-D models of plasma blow-off, scaling laws relating pressure to absorbed intensity and laser wavelength can be derived /7/

$$P = 1.2\ I_{abs}^{2/3} \qquad \text{at } \lambda = 1.06\ \mu m \qquad (1)$$

$$P = 1.5\ I_{abs}^{3/4} \qquad \text{at } \lambda = 0.26\ \mu m \qquad (2)$$

where units are TPa for P and 10^{14} W/cm^2 for I_{abs}.

These relations indicate that pressure is an increasing function of absorbed intensity and a decreasing function of wavelength. They also predict that pressures produced by laser irradiation are relatively insentitive to target material. In the range 10^{14} - 10^{15} W/cm^2 absorbed intensity, theoretical pressures are 1 to 3 TPa at 1.06 µm and 1.5 to 8 TPa at 0.26 µm. Conditions of 10^{14} - 10^{15} W/cm^2 are easy of access to lasers used in fusion experiments. However difficulties are encountered for achieving such extreme pressures involving much energy, short laser pulses and small focal spots.

- A short pulse duration (≈ 1 ns) implies a rapid decay of shock amplitude due to rarefaction waves propagating into the target and overtaking the shock front /8-9/. The pressure is maintained over a small distance in the target and the useful target thickness is only a few tens of microns.

- A consequence of small focal spots, typically of the order of 100 μm diameter, is a 2-D plasma expansion /10/ resulting in a strong reduction of efficient energy and consequently in pressure.

- Suprathermal electrons generated by resonant absorption with long mean-free-paths can produce a preheat of the target. Their temperature is a decreasing function of wavelength and their penetration depth at 10^{15} W/cm^2 is estimated to be ∿ 10 μm at 1.06 μm wavelength and only ∿ 0.5 μm at 0.26 μm wavelength. These values point out another advantage of short wavelengths : negligible electron preheat even at very high intensity.

- X-rays produced in the plasma during the interaction are another possible source of target preheat. This effect is enhanced at short wavelength and in high Z materials.

- Finally, the existence of spatial inhomogeneities or so called "hot spots" in the laser beam can disturb the shock planarity. Generally, at long wavelength, intensity variations are smoothed out by thermal conduction. But, at short wavelength, owing to energy deposition at a smaller distance from the ablation surface, strong effects of beam profile non uniformities may be observed on the shock planarity.

II - DETERMINATION OF SHOCK PRESSURE FROM SHOCK VELOCITY MEASUREMENTS

Technique :

In a material of known equation of state, pressure is usually determined from shock velocity measurements. The first results at high intensity in the Mbar range were obtained by Van Kessel and Sigel (1974) /11/ and by Billon et al. (1975) /12/. Since 1978, more extensive measurements have been performed using an optical technique of shock detection /13-14/. The laser pulse is focused on the front and flat face of a solid target stepped on its rear side, which is imaged on the slit of a streak camera recording the luminosity produced by the shock break out at both step levels. The shock velocity and the shock pressure are then inferred from the shock transit time accross the step.

Results at 1.06 μm wavelength. Estimation of 2-D effects

Nearly all experiments have been done on aluminum targets, standart material for shock studies, with strong temperature elevation under shock, facilitating the shock detection with the use of a streak camera. Experimental results are reported in table I. Pressures between 0.2 and 1.8 TPa have been obtained in the 10^{14} - 10^{15} W/cm^2 intensity range. Large error bars are due to the difficulty of accurate time and distance measurements as a consequence of the small space scale (steps of∿10μm) and time scale (shock transit times of a few 100 ps).

Analysis of these results reveals that finite spot sizes produce a significant decrease in the generated pressure as compared to 1-D estimates from eq.1.

TABLE I - Experimental results at 1.06 μm laser wavelength

References	Intensity (W/cm^2)	Focal spot (μm)	Pressure (TPa)
Veeser and Solem /13/	3.10^{14}	100	0.2
Trainor et al. /14/	8.10^{13}	600	0.6 ± 0.2
	3.10^{14}	600	$1.8\ ^{+0.3}_{-0.4}$
Trainor et al. /6/	3.10^{14}	240	0.6 ± 0.2
Cottet et al. /15/	$1.2\ 10^{14}$	300	0.3 ± 0.1
	$3.5\ 10^{15}$	60	0.6 ± 0.1

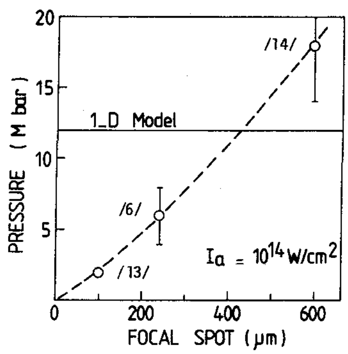


Fig.2 - Pressure dependence on focal spot diameter at fixed intensity.

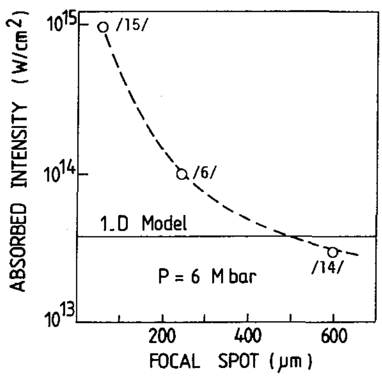


Fig.3 - Dependence on focal spot diameter of absorbed intensity necessary for generating a shock of 6 Mbar.

Figure 2 shows that the pressure generated at 10^{14} W/cm^2 absorbed intensity is lower than expected from the 1-D model for spot diameters $\lesssim$ 500 μm. Figure 3 shows that absorbed intensity required for generating a pressure of 0.6 TPa is higher than predicted from the 1-D model also for spot diameters $\lesssim$ 500 μm. Both evolutions lead to a critical value of $\sim$ 500 μm above which 2-D effects of plasma expansion on pressure reduction become negligible. This value determined from shock pressure measurements at 1.06 μm wavelength and for $\sim$ 500 ps laser pulses is in good agreement with the value inferred from considerations on plasma expansion /16/ and also from hydrodynamic code calculations /10/.

Results at 0.26 μm wavelength

Series of experiments were recently performed by Cottet et al. /17,18/ at 0.26 μm wavelength using the laser of the GRECO ILM (Groupement de Recherches Coordonnées Interaction Laser Matière). The technique used is similar to that described above with exception of steps in the foils. The shock transit-time through thin and flat foils was measured with reference to a signal synchronized with the arrival of the laser pulse on the front face of the target. The pressure was then determined from the best fit between experimental points and the 1-D calculated shock trajectory in a space time diagram where the maximum generated pressure is a free parameter. Example is given on fig.4, showing also that at fixed irradiation conditions the same pressure is generated in Al and Mo targets as expected from theory. This behaviour has been verified with various target materials and at various pressures /17,18/.

Experimental results on the pressure dependence on laser intensity are reported in table II.

TABLE II - Experimental results on laser induced pressure at 0.26 μm wavelength in aluminum targets.

I_{inc} (W/cm^2)	I_{abs} (W/cm^2)	focal spot (μm)	measured pressure (TPa)	theoretical pressure eq.2 (TPa)
$1.3\ 10^{13}$	$1.2\ 10^{13}$	300	0.5 ± 0.1	0.3
$2.5\ 10^{14}$	$2.2\ 10^{14}$	35	1.8 ± 0.3	2.7
$4.0\ 10^{14}$	$3.7\ 10^{14}$	50	3.0 ± 0.5	4.0
$1.4\ 10^{15}$	$1.2\ 10^{15}$	35	5.0 ± 1.0	10.0

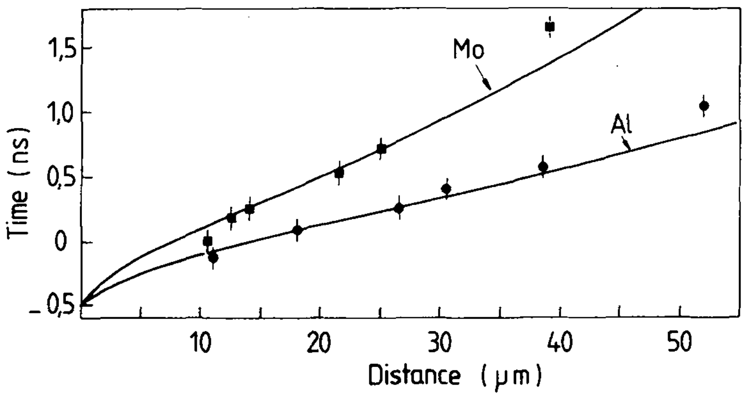


Fig.4 - Experimental points of shock transit time versus target thickness in Al and Mo irradiated at 10^{15} W/cm^2 incident intensity, laser pulse length 500 ps, focal spot diameter 35 μm. Best fit curves to the experimental points are calculated for the same driving pressure of 4.5 TPa in Mo and Al.

In the intensity range 10^{13} - 10^{15} W/cm^2, measured pressure extends from 0.5 TPa to 5 TPa uppermost pressure actually achieved for a plane shock wave in a laboratory experiment. The pressure reduction due to 2-D plasma expansion is evaluated by comparison with theoretical values from eq.2. The hydrodynamic efficiency is estimated from the value of ratios E_{lost}/E_{abs}, E_{eff}/E_{abs} and E_{eff}/E_{inc} reported in table III and compared with the results at 1.06 μm wavelength.

TABLE III - Hydrodynamic efficiency dependence on laser wavelength, irradiance and focal spot diameter.

λ (μm)	I_{abs} (W/cm^2)	focal spot (μm)	E_{lost}/E_{abs}	E_{eff}/E_{abs}	absorption ratio	E_{ff}/E_{inc}
0.26	10^{13}	300	0 %	100 %	0.9	90 %
	10^{15}	35	60 %	40 %		35 %
1.06	10^{14}	300	50 %	50 %	0.3	15 %
	10^{15}	50	97 %	3 %		1 %

Particularly significant are the results at 10^{15} W/cm^2 absorbed intensity for small focal spots, showing that 40 % of absorbed energy are converted into efficient energy at 0.26 μm wavelength and only 3 % at 1.06 μm wavelength in similar irradiation conditions. These values give evidence of a strong reduction of 2-D plasma expansion effects at short wavelength, which, in addition to the increase of absorption ratio, gives a considerable advantage to short wavelengths for generating high pressures. Typically, at 10^{15} W/cm^2 incident intensity, with focal spots of $\sim$ 50 μm, the pressure is ten times higher at 0.26 μm wavelength (5 TPa) than at 1.06 μm wavelength (0.5 TPa).

III - DETERMINATION OF PRESSURE BY DOUBLE-FOIL EXPERIMENTS

Laser induced shocks produce an acceleration of thin foil targets to high velocities. The pressure P and the foil velocity V are related by momentum conservation (rocket model) :

$$\rho e V = P \tau \qquad (3)$$

where ρ is the foil density, e its thickness and τ the pulse duration. In the double foil technique /19/, the foil velocity is measured by observation of the shock generated in a second foil placed at a known distance, by impact of the first foil. Effects of non homogeneous density profile of the accelerated foil and on velocity measurements have been recently mentionned by Fabbro et al. /20/. In the case of very small impact foil thickness the detected shock at the rear face of the second foil is due to the low density part of the accelerated foil mooving faster than the high density part. The impact foil must be thick enough to ensure an increase of shock amplitude up to the maximum value during the transit time of the shock front through the foil. This behaviour is illustrated by the following result /20/: at 0.26 m wavelength, 10^{15} W/cm^2 absorbed intensity and accelerated foils of

27 µm, the measured velocity was 65 km/s with impact foils of 6 µm and 45 km/s with impact foils of 18 µm. The corresponding pressures inferred from the rocket model, eq.3, are respectively 6 TPa and 4.8 TPa. In same irradiation conditions, the pressure inferred from shock velocity measurements was 4.5 TPa indicating that foil velocity measurements are correct with impact foils of 18 µm thickness but not with 6 µm thickness.

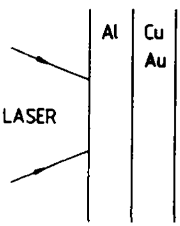
IV - TECHNIQUES OF PRESSURE ENHANCEMENT

Double foil experiments

The double foil technique can be used to produce an amplification of pressure by collision of the first foil on the second. This effect, similar to that of the flyer plate technique used in conventional shock experiments has been observed by Rosen et al. /21/ : a pressure of 2 TPa was measured in an aluminum impact foil, while the laser induced pressure in the first foil was only 0.5 TPa. In recent preliminary experiments performed at the GRECO ILM /22/ pressures in excess of 20 TPa were estimated from shock velocity measurements in aluminum foils impacted by aluminum accelerated foils at 10^{15} W/cm^2 intensity and 0.26 µm wavelength.

Impedance-match experiments

Using the advantage that laser generated shock pressure is independent of target material, enhancement of shock amplitude can be obtained by transmission of the laser induced shock from a low impedance material (Al) into a high impedance material (Cu, Au), Fig.5.



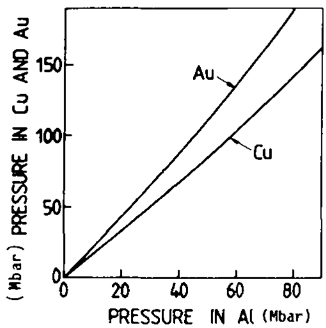


Fig.5 - Impedance match experiments on Al-Cu or Al-Au targets. Pressure transmitted in Cu and Au versus laser generated shock pressure in Al.

The curves of fig. 5 show that transmitted pressure in Cu or Au is about twice the incident pressure in Al. Experiments on Al-Cu targets in the range 5 10^{13} - 4.10^{14} W/cm^2 incident intensity at 1.06 µm wavelength have confirmed this effect /23/ : measured presures extended from 0.2 to 0.6 TPa in Al and from 0.4 to 0.8 TPa in Cu. In recent experiments made by our group on Al-Au targets irradiated at 0.26 µm wavelength and 10^{15} W/cm^2 incident intensity, pressures of 4.5 TPa were generated in Al and transmitted pressures of the order of 9 TPa in Au were inferred from shock velocity measurements. The results of these preliminary experiments are in good agreement with the theoretical impedance-match values from the curves of fig.5.

V - SHOCK TEMPERATURE MEASUREMENTS

Attempts to temperature measurements at very high shock pressure (4.5 TPa) have been recently presented by Fabbro et al. /20/. The technique used consists in measuring the rear face temperature of thin irradiated foils at shock emergence by optical pyrometry in the visible range (4230 Å) or by soft X-ray pyrometry. From SESAME equation of state data /24/, the temperature in aluminum is about 20 eV at 4.5 TPa.

Difficulties in these experiments are due to the non uniform density and temperature of the expanding foil after shock break out. As mentionned for double-foil experiments, the observed edge of the accelerated foil at low density and low temperature moves faster and screens the emission of the high density part at peak temperature T_M. For this reason, the measured temperature is a brightness temperature T_V by optical pyrometry and T_X by soft X-ray pyrometry, being expected to be smaller than T_M. However because of the larger penetration capacity of X-rays, $T_X > T_V$. For Al foils of thickness larger than 10 μm, experimental results of Fabbro et al. /20/ are in accordance with these predictions. But for thicknesses smaller than 10 m, the measured temperature ($T_X \sim$ 35 eV for Al foils of 6 μm) is higher than the predicted shock temperature, indicating another heating process. A preheat of the target proceeding from hard X-rays generated in the plasma and penetrating ahead of the shock could be at the origin of these observed high temperatures.

CONCLUSION

From actual results in laser shock studies it appears that the main advantage of the laser technique is the possibility to achieve very high pressures in laboratory experiments. Short wavelengths are prooved to be much more efficient than long wavelengths, because of better absorption ratio and reduced 2-D effects of plasma expansion. Actually, pressures up to 5 TPa have been measured in simple foil targets and plane wave configuration. Shock pressure enhancement near 10 TPa in impedance match experiments and beyond 20 TPa by foil collision are announced. These extreme pressures are obtained with very small irradiated areas. The short space and time scales are the major difficulties of laser shock experiments and an actual limit to accurate measurements. However, presently, the unique alternative method for generating shocks in the 10 TPa range is the use of nuclear explosive drivers, therefore high power pulsed lasers provide a simple and useful technique for exploring this ultra high pressure regime.

REFERENCES

/1/ - R.J. Trainor, N.C. Holmes and R.A. Anderson, in Shock Waves in Condensed Matter, AIP Conference Proceedings (1982) 145.
/2/ - R.E. Kidder, Nucl. Fusion, 8 (1968) 3.
/3/ - C. Fauquignon and F. Floux, Phys. Fluids, 13 (1970) 3.
/4/ - R.J. Trainor, H.C. Graboske, K.S. Long and J.W. Shaner, UCRL report 52562 (1978).
/5/ - C. Garban-Labaune, E. Fabre, C.E. Max, R. Fabbro, F. Amiranoff, J. Virmont, M. Weinfeld and A. Michard, Phys. Rev. Lett. 48 (1982) 1018.
/6/ - R.J. Trainor, N.C. Holmes, R.A. Anderson, E.M. Campbell, W.C. Mead, R.J. Olness, R.E. Turner and F.E. Ze, Appl. Phys. Lett. 43 (1983) 542.
/7/ - R. Fabbro, thesis, University of Paris XI, (1982).
/8/ - F. Cottet and J.P. Romain, Phys. Rev. 1 25 (1982) 576.
/9/ - R.J. Trainor and Y.T. Lee, Phys. Fluids, 25 (1982) 1898.
/10/ - P.C. Thompson and P.D. Roberts, Laser and Particle Beams, 2 (1984) 13.
/11/ - C.G.M. Van Kessel and R. Sigel, Phys. Rev. Lett. 33 (1974) 1020.
/12/ - D. Billon, D. Cognard, J. Launspack, C. Patou, D. Redon and D. Schirmann, Opt. Commun. 15 (1975) 108.

/13/ - L.R. Veeser and J.C. Solem, Phys. Rev. Lett. 40 (1978) 1391.
/14/ - R.J. Trainor, J.W. Shaner, J.M. Auerbach and N.C. Homes, Phys. Rev. Lett. 42 (1979) 1154.
/15/ - F. Cottet, J.P. Romain, R. Fabbro and B. Faral, J. Appl. Phys. 55 (1984) 4125.
/16/ - M.H. Key, W.T. Toner, T.J. Goldsack, J.D. Kilnenny, S.A. Veats, P.F. Cunnigham and C.L.S. Lewis, phys. Fluids, 26 (1983) 2011.
/17/ - F. Cottet, J.P. Romain, R. Fabbro and B. Faral, Phys. Rev. Lett. 52 (1984) 1884.
/18/ - F. Cottet, M. Hallouin, J.P. Romain, R. Fabbro and B. Faral, this Conference.
/19/ - J. Grün, S.P. Obenschain, B.H. Ripin, R.R. Whitlock, E.A. Mc Lean, J. Gardner M.J. Herbst and J.A. Stamper, Phys. Fluids, 26 (1983) 588.
/20/ - R. Fabbro, b. Faral, H. Pepin, F. Cottet and J.P. Romain, Communication at the 14th Annual Anomalous Absorption Conference, Charlottesville, U.S.A. May 6-11 (1984).
/21/ - M.D. Rosen, D.W. Phillion, R.H. Price, E.M. Campbell, S.P. Obenschain, R.R.Whitlock, E.A.Mc Lean and B.H. Ripin, in Shock Waves in Condensed Matter (1984) 323.
/22/ - E. Fabre, C. Labaune, R. Fabbro, B. Faral, A. Michard, A. Poquerusse, J. Virmont, F. Briand, J. Briand, P. Mora, J.F. Luciani, R. Pellat, H. Baldis, F. Cottet and J.P. Romain, Communication at the 10th International Conference on Plasma physics and Research on Controled Nuclear Fusion, London September 12-19 (1984).
/23/ - N.C. Holmes, R.J. Trainor, R.A. Anderson, L.R. Veeser and G.A. Reeves, in Shock Waves in Condensed Matter, AIP Conference proceedings (1982) 160.
/24/ - J. Abdallah, R.C. Albers, B.I. Bennet, F. Dowell, B.L. Helion, W.F. Huelner, J.D. Johnson, D.A. Liberman, S.P. Lyon, G.K. Straub and K.S. Trainor, L.A.N.L. Report n°834 (1983).