Laser Induced Shock Pressure Multiplication in Multi Layer Thin Foil Targets

Mayank Shukla 1), Yogesh Kashyap 1), P. S. Sarkar 1), A. Sinha 1), H. C. Pant 2), R.S.Rao 1), N.K.Gupta 1), B.K.Godwal 1)

1) High Pressure Physics Division, Bhabha Atomic Research Center, Mumbai, India.
2) Hon. Visitor, Homi Bhabha Centre for Science Education, Mumbai, India.

email: mayank@apsara.barc.ernet.in

Abstract. The *impedance mismatch technique* has been used for shock pressure amplification in two and three layer thin planar foil targets. Numerical simulation results using one dimensional radiation hydrocode MULTI in two layer targets consisting of Al-Au & Al-Cu and three layer target consisting of Plastic - Al -Au & Foam-Al-Au respectively are presented. These results show a pressure enhancement up to 25 & 29Mbar Plastic-Al-Au and Foam-Al-Au target respectively from initial pressure of 7Mbar in the reference material using laser intensity of $5x10^{13}$ W/cm^2 at 1.064µm. This enhancement is more as compared to 18 & 22Mbar found in Plastic-Au and Foam-Au two-layer targets respectively . Results of laser driven shock wave experiments for equation of state (EOS) studies of Au and Cu in two-layer target are also presented. A Nd:YAG laser chain (2 Joule, 1.06 µm wavelength, 200 ps pulse FWHM) is used for generating shocks in the planar Al foils and Al-Au (or Al-Cu) layered targets. EOS of Au and Cu in the pressure range of 9-14 Mbar obtained shows remarkable agreement with the simulation results and with experimental data of other laboratories and SESAME data.

1. Introduction

The study of matter in high-pressure conditions (10-100Mbar) is a subject of great interest for several branches of physics. In particular, it is important in the context of inertial confinement fusion, EOS studies, laboratory astrophysics and material science [1-3]. Various techniques of static and dynamic high pressure generation are in use viz. diamond anvil cells, two stage gas guns, chemical explosives, exploding foils, magnetic compression, nuclear explosions and high power lasers. Except nuclear explosions and high power lasers, all the other methods have been used to generate pressure up to 10Mbar. In the past, EOS measurements in tens of Mbar domain could only be performed using nuclear explosions. However, the high cost and configurations of such experiments has limited their utility for generation of data.

High power lasers, advented to realize inertial confinement fusion in the laboratory, was first demonstrated to produce pressure of 2Mbar in solid hydrogen 10J, 5ns, Nd:YAG laser pulse [4]. Nowadays, it is possible to reach very high pressures (more than 100Mbar) under laboratory using advance lasers that produces high intensity (~10^{14} W/cm^2) at the focal plane of the target utilizing both direct and indirect drive schemes. The experiments performed so far have shown the possibility of producing shock waves with pressures up to 100Mbar in a laser-irradiated solid [5] and in a target foil impacted by laser-accelerated foil [6]. Pressures as high as 750Mbar have been achieved using laser pulses of 25kJ (at a wavelength λ = 0.53µm) and a radiatively foil impact technique [7]. In all such published work, the EOS was determined either indirectly from the measurement of the shock velocity and with the use of known EOS of a given reference material or directly from simultaneous measurement [8] of shock velocity (u_s) and particle velocity (u_p) related to Rankine-Hugoniot relations [9], as carried out in nuclear explosion driven shock-wave experiments [10]. An intermediate route between indirect and direct methods of determining EOS is the *impedance mismatch technique*, which consists of measuring the shock velocity simultaneously in two different materials. This makes it possible to achieve a relative determination of one EOS point of one material (test material) by taking the EOS material of another material as reference. The reliability of this method, used in the past in nuclear experiments, has also been proven in laser driven shock experiments [11,12]. This technique has been applied to EOS measurements between 10-20Mbar for Cu [13], Au [14] and low-density foams [15]. However, the planarity and the stationarity of the shock fronts as well as the low preheating of the material ahead of the shock waves are essential to obtain accurate measurements of the EOS with minimum possible errors in these experiments. Infact, EOS of many materials between 10-20Mbar has also been determined employing this technique with in ±3% errors in indirectly heated Hohlraum cavity [16]. Besides this, the technique is also useful for generating high pressures (10-50Mbar) using lasers of relatively small size. This regime is important from the point of view of EOS studies as well as studying phase transitions, pressure ionization effects etc. The pressures that are produced using high power lasers depend on the absorbed intensity at the target surface under study. However, generation of one-dimensional planar shock that requires large focal spot puts an upper limit to the pressure. On the other hand, even if large laser systems are available to obtain a bigger focal spot, the laser intensity on target cannot be increased indefinitely. Indeed, higher intensity (>10^{14} Watts/cm^2) leads to higher plasma temperature, and hence a larger x-ray generation in the corona. This also leads to growth of instabilities like parametric decay instability, stimulated Raman scattering and two-plasmon decay. These instabilities produce hot electrons and hard x-rays causing pre-heat of the target material. This in turn inhibits any meaningful measurement of EOS. To mitigate these effects, the absorbed laser intensity (I in W/cm^2) and the wavelength (λ in μm) product ($I\lambda^2$) is desired to be $\leq 10^{14}$, where the laser plasma interaction remains in the collisional absorption regime. A novel target consisting of low Z ablator (plastic or polymer foams) is used to inhibit generation of hard x-rays in experiments related to laser shock studies. Interestingly, this also helps in producing high pressure (up to 50Mbar) using moderate intensity laser pulse (~5×10^{13}W/cm^2) in two or more layer targets and add helps in mitigating illumination nonuniformities.

The paper presents laser induced pressure enhancement studies in two and three layered targets using impedance mismatch technique. In the first part we describe the numerical simulations result of pressure induced at the interface of two layer targets consisting of Al-Au & Al-Cu and three layer target consisting of Plastic-Al-Au & Foam-Al-Au respectively using one dimensional radiation hydrocode MULTI [17]. The results show a pressure enhancement of ~2 and ~1.66 in case of Al-Au and Al-Cu targets respectively for an initial pressure of 6-7Mbar in the reference material (Al) at absorbed laser intensity of ~5×10^{13}W/cm^2. The simulations performed for three layer target consisting of Plastic(954mg/cc)-Al-Au or Foam(400mg/cc)-Al-Au show induced pressures of 25Mbar or 29Mbar respectively at the second interface for an initial pressure of 7Mbar in the first material at absorbed laser intensity of ~5×10^{13}W/cm^2. This pressure enhancement is more as compared 18 & 22 Mbar found in Plastic-Au or Foam-Au targets. The second part describes the experimental results of laser driven shock wave experiments for equation of state (EOS) studies of Au and Cu in two-layer target. A Nd:YAG laser chain (2 Joule, 1.06 μm wavelength, 200 ps pulse FWHM) is used for generating shocks in the planar Al

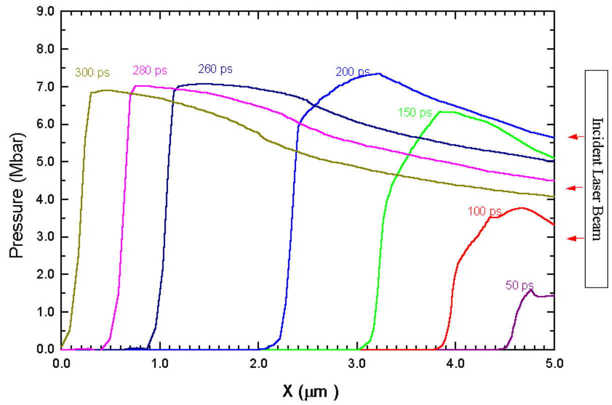

Fig1. Steady state shock propagation in 5μm A l

foils and Al-Au (or Al-Cu) layered targets. EOS of Au and Cu in the pressure range of 9-14Mbar obtained using *impedance mismatch technique* shows remarkable agreement with the simulation results and with experimental data of other laboratories and SESAME data, with the first principle calculations [18].

2. Numerical Simulation:

In laser shock experiments aimed at measurement of EOS, the pressure generated can be obtained from scaling law [19] as

$$P = 12.3(I_L/10^{14})^{2/3}\lambda^{-2/3}(A/2Z)^{1/3} \quad (1)$$

where I_L is the laser intensity (W/cm^2) , λ is the laser wavelength (μm), A & Z are the atomic mass and number. It is essential to ensure that planar shock wave fronts propagate in a steady state condition through the reference material as well as through the test material(s). This requires a proper choice of target thickness. In case of very thin targets, the shock breakout occurs much earlier to the laser pulse peak time leading to unsteady shock propagation since shock waves are in the acceleration phase. On the other hand, rarefaction wave from the laser irradiation side can interact with the shock wave for a very thick target. Thus for steady state shock propagation the target should satisfy the condition [20]

$$d \leq 2u_s\tau \quad (2)$$

where d is target thickness, u_s the shock velocity in the material and τ is the laser pulse duration (FWHM). Further the laser focal spot diameter should be much larger than the target thickness to minimize two- dimensional (2D) effects and hence to ensure a planar shock [21]. The thickness of the target should be kept larger than the range of supra-thermal electrons and hard x-rays to avoid pre-heat reaching ahead of the shock wave on the rear side of the target.

A proper radiation hydrodynamic simulation serves as an important tool in predicting proper target thickness that can avoid the effects of preheating and also ensure steady state shock wave propagation conditions. The multilayered target has been studied in detail using one-dimensional radiation hydro code MULTI. This code uses a multi group method of radiation transport coupled with Lagrangian hydrodynamics based on fully implicit numerical scheme. Material properties like EOS, Planck and Rosseland opacities and non-LTE properties (for Au) are used in tabulated form, which are generated externally. The simulation performed initially for a single layer Al target for absorbed laser irradiation of 5×10^{13} W/cm^2 (λ= 1.064 μm; pulse FWHM = 200 ps), suggests that the base material must be thicker than 3.4μm to reach stationary

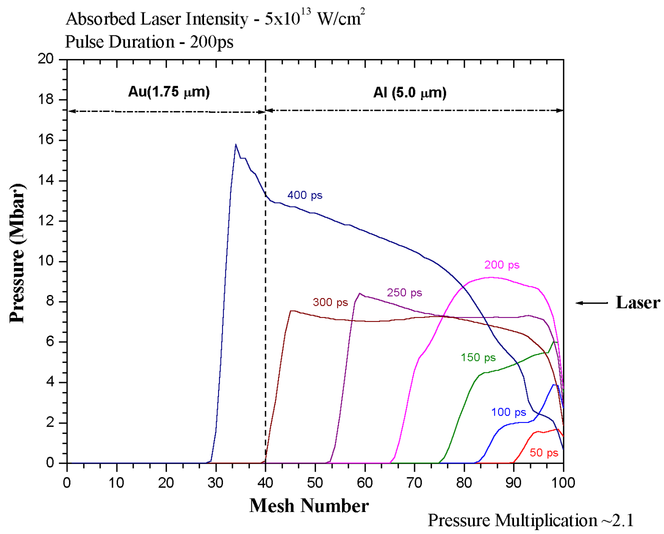

Fig2. Pressure enhancement in Al-Au target

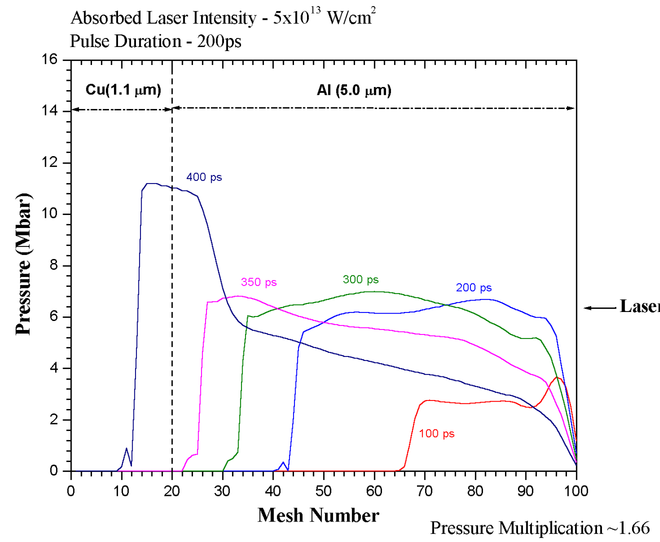

Fig3 Pressure enhancement in Al-Cu target

condition with a maximum thickness up to 8μm for steady state shock propagation. This agrees well with the criteria that the target thickness should be less than $2u_s\tau$. The pressure profiles shown in *Fig1* for 5μm Al target (used as reference material in two-layered target) infers that the shock reaches a steady state after 300ps. The peak pressure and shock velocity observed to be 7Mbar and 2.06×10^6cm/sec is in close agreement with the experimental observation where the shock pressure and velocity are observed to be 6.6Mbar and 2.09×10^6cm/sec respectively.

Fig2 and *Fig3* shows the pressure profiles of two layer Al-Au(5 +1.75μm) and Al-Cu(5+1.1μm) targets. The targets are chosen such that the total thickness does not exceed 8μm satisfying relation 2. The impedance mismatch at the interface of the Al-Au and Al-Cu targets shows a pressure multiplication of ~2.1 and 1.66 which also matches well with the ideal gas formula given by

$$P_2/P_2 = 4\rho_2 /[(\rho_2)^{1/2} + (\rho_1)^{1/2}]^2 \qquad (3)$$

Here, P_1 and P_2 are the pressures in the first and the second material of density ρ_1 and ρ_2

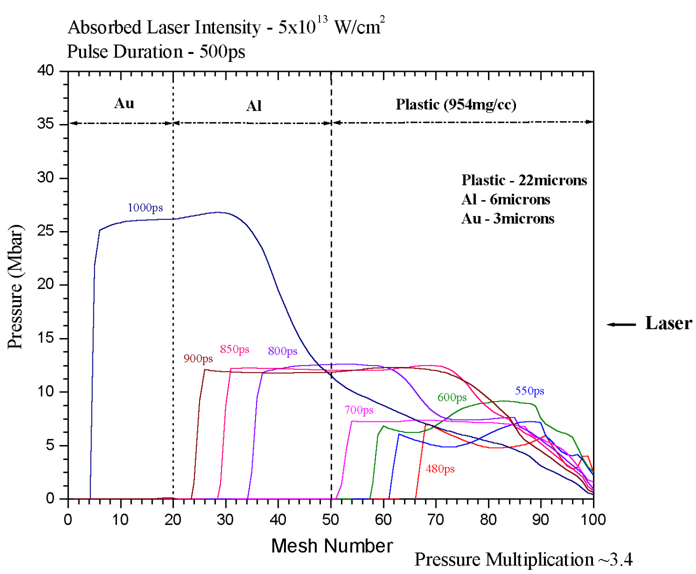

Fig4a. Pressure enhancement in Plastic-Al-Au target

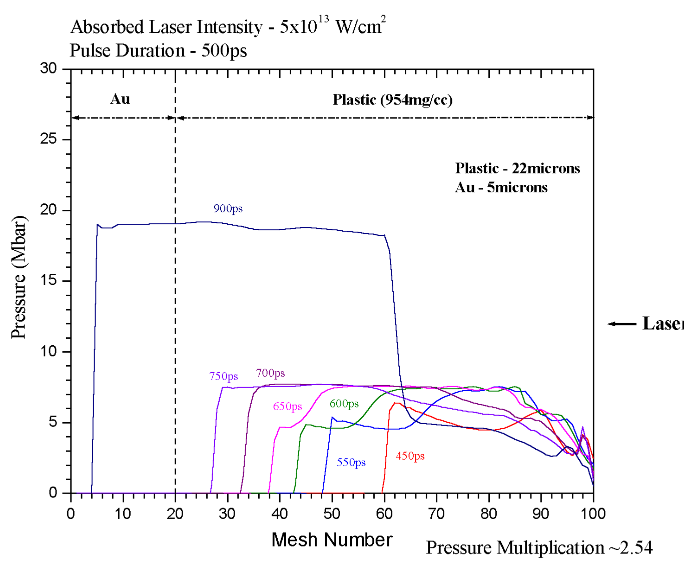

Fig4b . Pressure enhancement in Plastic-Au target respectively. The rear side temperature before the shock breakout in these targets is found to be around 0.02ev which rises to 2.0ev the moment shock breaks out. These result compare well with experimental results obtained as discussed in the later section of the paper.

Three layer target consisting of Plastic-Al-Au and Foam-Al-Au were studied for pressure amplification at the two interfaces for absorbed laser intensity of 5×10^{13} W/cm^2 (λ= 1.064 μm; pulse FWHM= 500 ps). In these targets, plastic (954mg/cc) and foam (400mg/cc) provide a large shock impedance mismatch at the plastic(foam)-Al(or Au) interface and low Z ablator inhibits generation of significant x-rays. *Fig4a & Fig4b* show the simulation results obtained for Plastic-Al-Au and Plastic-Au targets, where the thickness of the plastic is taken to be 22μm. A total pressure multiplication of ~ 3.4 is observed in three layered Plastic-Al-Au as compared to ~2.54 in two layered Plastic-Au targets. The shock velocity deduced from the pressure profiles in plastic is found to be 3.4×10^6cm/sec and gives a maximum thickness of 34μm for steady shock propagation. This velocity is in close agreement with the LASL data [22]. The final pressure in Plastic-Al-Au target is found to be ~25Mbar as compared to 18Mbar in Plastic-Au target. *Fig5a* and *Fig5b* shows the observed pressure profiles in Foam-Al-Au target for a foam thickness of 33μm. An over all Pressure enhancement of ~4.25 is observed in case of foam-Al-Au as compared to ~3.28 for Foam-Au target which is in close agreement with relation 3. The shock velocity of ~5×10^6cm/sec deduced from the pressure profiles also matches well with the reported results [15] and gives a maximum thickness of 50μm. Final pressure is observed to be 29Mbar for Foam-Al-Au target as compared to 22Mbar for Foam-Au target.

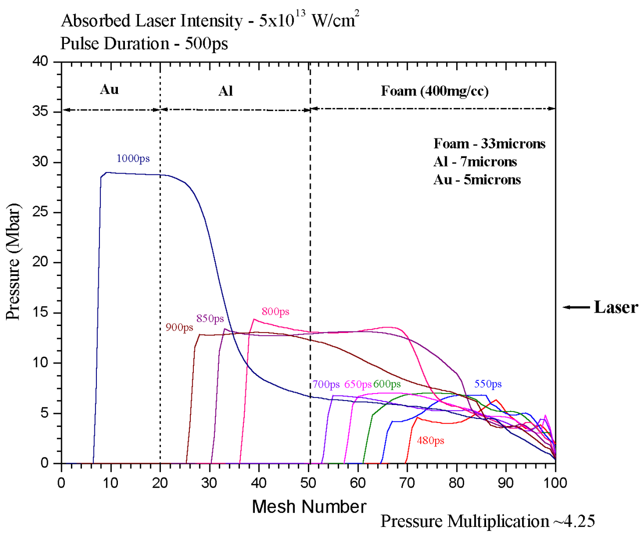

Fig5a. Pressure enhancement in foam-Al-Au target

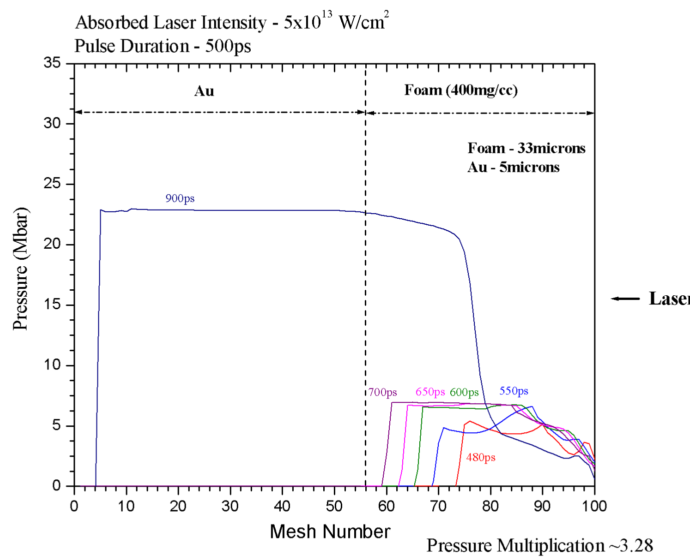

Fig5b. Pressure enhancement in foam-Al-Au target

3. Experimental studies:

EOS measurement of Au and Cu in the pressure range of 9-14Mbar was done in two layered Al-Au and Al-Cu targets using impedance mismatch technique. A 2J/200ps(FWHM) Nd:Glass laser (λ= 1.064μm), focussed at 100μm at the target surface, was used as driver [18]. The absorbed laser intensity was varied from 5×10^{13} W/cm^2 to 3×10^{13} W/cm^2 for different targets. Shock luminosity signal at the rear surface of the target, kept in vacuum (10^{-3} torr), was recorded with a

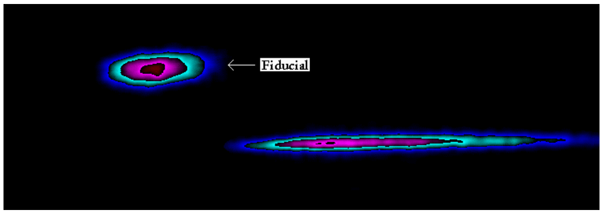

Fig6a. Shock luminosity signal in Al target

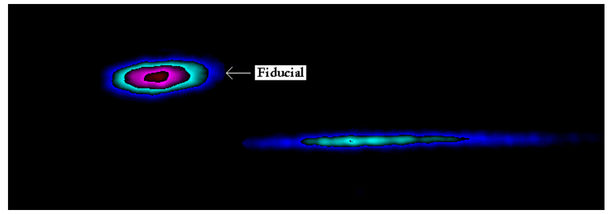

Fig6b Shock Luminosity signal in Al-Au Target

high speed S-20 photocathode streak camera of temporal resolution 5ps. A time fiducial signal, generated by converting 4% laser energy to green light, was recorded simultaneously along with the shock luminosity signal with the help of optical fiber in each laser shot as shown in *Fig6a* and *Fig6b*. The shock transit time for a given target thickness was determined from the peak of the laser signal. The total target thickness was chosen so as to satisfy the steady state shock propagation given by relation 2. Shock velocity in Al, used as reference material, was determined using set of thin foils of varying thickness from 3.2μm to 8μm for each different absorbed laser intensities as shown in Table-1. The particle velocity and the pressure is calculated using Rankine-Hugoniot relations

$$u_s = a + bu_p \tag{4}$$

and

$$P = \rho_0 u_s u_p \tag{5}$$

where a, b and ρ_0 for Al, Cu and Au are

	a	B	ρ_0
Al	0.5386	1.339	2.7
Cu	0.3933	1.510	8.924
Au	0.3120	1.488	19.25

Table-I represents the observed shock transit time in Al-Au and Al-Cu targets along with the measured shock and particle velocities. As shown the maximum pressure in Al at 5×10^{13} W/cm^2 laser intensity is found to be 6.6Mbar. This is in close agreement with the simulation results. The pressure in the test material (Au or Cu) was determined using impedance mismatch technique by drawing Hugoniot and reflected Hugoniot for Al and Hugoniot for Au and Cu using Rankine-Hugoniot relations as shown in *Fig7* and *Fig8*. The intersection of the reflected Hugoniot of reference material with the Hugoniot of test material gives the final state in Au (or Cu). Final pressure reached in Au is 13.47 Mbar and 9.01 Mbar at absorbed laser intensities of 5×10^{13} W/cm^2 and 3x10^{13} W/cm^2 respectively. Similarly, the final pressure in Cu is 10.38Mbar & 8.90Mbar at absorbed laser intensities of 4.4 x10^{13} Watts/cm^2 and 3.9x10^{13} Watts/cm^2 respectively.

4. Results and Discussion

The simulation results performed using the radiation hydrocode MULTI for two and three layered targets, show a pressure enhancement at the interface(s) due to impedance mismatch. For two layer Al-Au and Al-Cu targets this enhancement is found to be ~2.1 and 1.66 respectively. The simulation and the experimental results are in close agreement with the reported results from the other laboratories, LASL data and SESAME data with in a pressure accuracy of ±7% and ±9% for Au and Cu respectively [22,23]. Simulation results of three layer Plastic-Al-Au and

Table-1

	Target	Absorbed Laser intensity W/cm^2 ($\times10^{13}$)	Reference (ref.) material (μm)	Test material (μm)	Shock Transit time in ref. material (ps)	Shock Transit time in test material (ps)	Shock Velocity ($\times10^6$ cm/s) $u_{s\text{-}ref}$	$u_{s\text{-}test}$	Particle Velocity ($\times10^6$ cm/s) $u_{p\text{-}ref}$	$u_{p\text{-}test}$	Pressure in ref. material (Mbar)	Pressure in test material (Mbar)
1.	Al-Au	5	5 ±0.1	1.75 ±0.05	220 ±3.2	147 ±3.2	2.09 ±0.05	1.19 ±0.04	1.16 ±0.03	0.59 ±0.02	6.58 ±0.33	13.46 ±0.83
2.	Al-Au	3	5 ±0.1	1.5±0.05	280 ±3.2	147 ±3.2	1.78 ±0.04	1.02 ±0.04	0.93 ±0.02	0.47 ±0.02	4.46 ±0.21	9.01 ±0.55
3.	Al-Cu	4.4	5 ±0.1	1 ±0.05	243 ±3.2	66 ±3.2	2.06±0.05	1.54 ±0.12	1.13±0.03	0.76 ±0.05	6.24±0.30	10.38 ±0.87
4.	Al-Cu	3.9	5 ±0.1	1 ±0.05	257 ±3.2	75 ±3.2	1.94 ±0.04	1.45 ±0.09	1.04 ±0.02	0.70 ±0.04	5.44 ±0.25	8.90 ±0.71

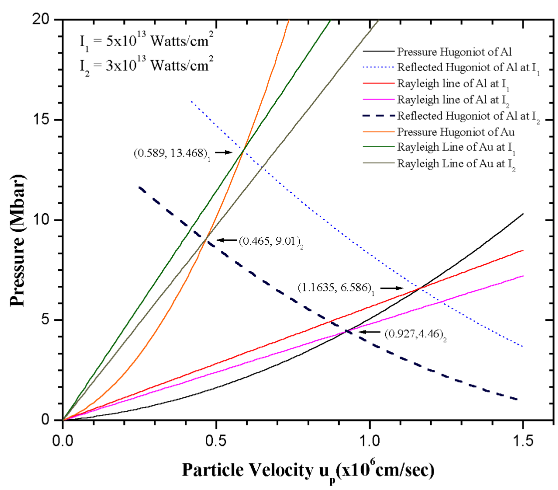

Fig7. Hugoniot curves for Al-Au target

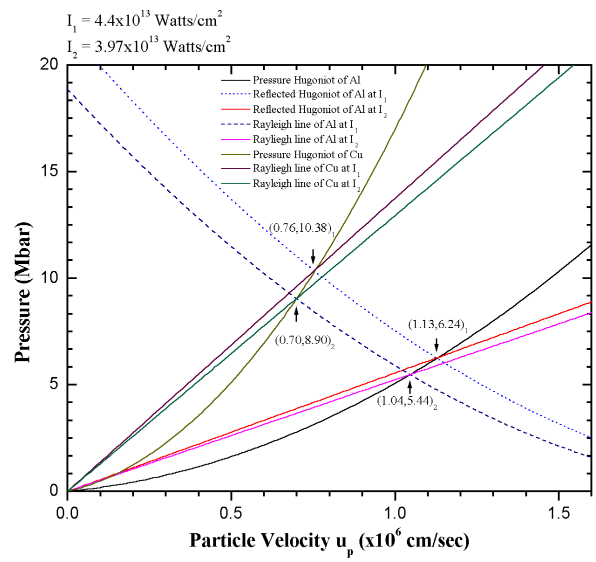

Fig8. Hugoniot curves for Al-Cu target

Foam-Al-Au targets show pressure amplification of ~3.4 and ~4.25 as compared to two layer Plastic-Au and Foam-Au where the pressure amplification is found to be 2.54 and 3.28 respectively. The shock velocity in plastic and foam for the absorbed laser intensity of 5×10^{13} W/cm^2 is found to be 3.4×10^6 cm/sec and 5×10^6 cm/sec. This matches well with the reported results of LASL data and other laboratories. Simulation results also show that for steady state shock propagation, the maximum thickness of the plastic and foam should be 34μm and 50μm. Total thickness of the three layer targets is kept lower than these values. However, the thickness of the first material in these targets is chosen such that the shock reaches the first boundary after the peak of the laser pulse i.e 500ps. The final pressures reached in three layer targets, viz. Plastic-Al-Au and Foam-Al-Au were found to be 25 and 29Mbar respectively.

5. Conclusions

In conclusion, we say that high pressure in the range of 10-30Mbar can be generated in multilayered targets using a modest intensity laser beam employing impedance mismatch technique. Selection of target material layers in increasing order of shock impedance and an optimized thickness of layers target thickness for steady state shock propagation leads to generation of high pressure. This pressure regime is useful in studies related to EOS, phase transitions, pressure ionization effects etc. It is also concluded that if the initial pressure in the reference material can be increased to 10-12Mbar, then this technique can be used for pressure generation up to 50Mbar. This can be achieved by using laser light at 0.53μm or lower, since in this case the absorption of laser is dominated by collisional process and also produces initial high ablation pressure[19]. Use of low-density foam has been shown to help in removing the laser non-uniformities as well as reducing the x-ray pre heat effects.

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