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Recent results on Laser ablation and crater formation in laser- plasma interaction

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Abstract: We have experimentally studied laser ablation and crater formation using high power laser interaction with solid Copper target. Experiments were performed using a laser system of 10 Hz delivering up to 100 mJ in 40 ps and the flux on targets surface was F≤ 5000 J/cm^2. Crater dimensions were measured using optical microscopy or SEM (Scanning Electron Microscopy). In order to understand the process of crater formation, we considered various models present in the literature and revised them taking into account the occurrence of plasma phenomena, which are important at the intensities used in this experiment. We also compared our experimental results with other results obtained at the PALS laboratory, using a different laser wavelength and much higher laser intensities. Finally we explore the possibility of extending the information derived from laser produced craters to other craters.

Introduction: Laser ablation[1-2] and crater formation[3-4] is a complex process. Although a lot of study has been reported on this topic, still several aspects are unclear. Information can be still derived and extrapolated for further studies for other branches of physics.

Under the influence of an energetic radiation like lasers, electrons oscillate to the incident electric field and generate plasma[1-2]. When ions acquire energy much higher than their binding energy, they escape from the target surface causing ablation of material.

The purpose of the work reported in this paper was the experimental study to understand the physics of laser ablation at higher flux F ≈ 5000 J/cm^2, undisclosed in the literature. To our knowledge such discussion is not reported though a lot of study exists on laser ablation and crater formation. We have irradiated the target materials of industrial interest and also commonly used in the laboratories like copper. Experiments were performed in vacuum (>10^{-4} mbar of pressure) and also in atmospheric pressure. Laser radiation was focussed normal to the target surface and X-ray emission spectra were recorded at 45° to target normal during the experiment using a flat crystal Bragg's spectrometer (RbAp crystal, 2d = 2.6121nm). Such X-ray measurement was necessary to realize the plasma properties during laser ablation. Each time, a fresh target surface was irradiated with five consecutive shots to estimate the ablation depth per pulse. Optical microscope and SEM were used to measure the crater diameter and depth.

Results: Fig.1 shows spectrally resolved X-ray intensity (arb. units) as a function of X-ray wavelength from Copper plasma. It is clearly seen that the spectral emission corresponding to ions with charge Z*=20-21.

Fig.2 shows typical craters formed in Cu targets observed with optical (a) and SEM (b). The crater in fig.21 was obtained with a high number of shots (N), enough to drill a clear hole in a Cu plate of thickness d=1 mm. This is of course another method to measure laser ablation depth per shot (≈ d/N).

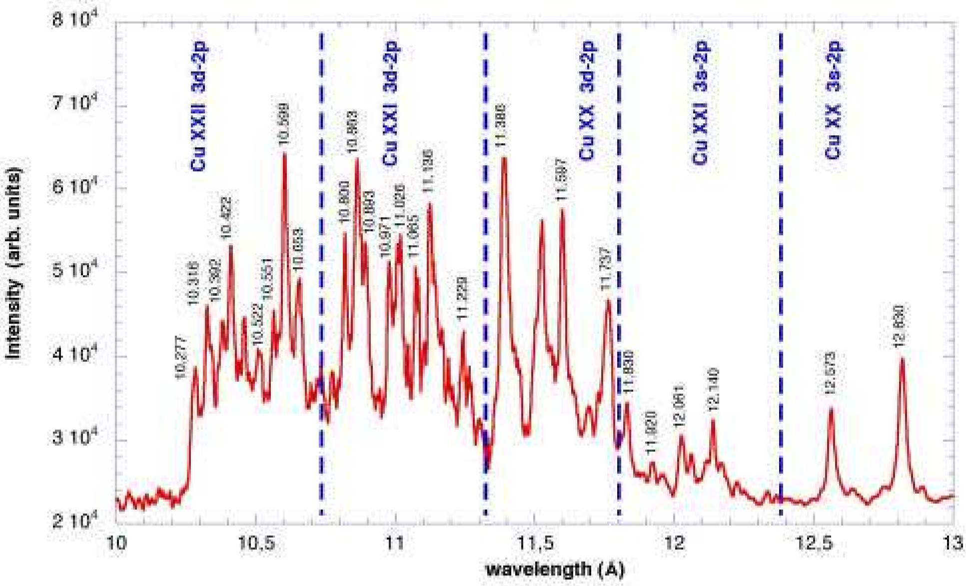

Fig.1. X-ray emission spectra as a function of X-ray wavelength from Copper target.

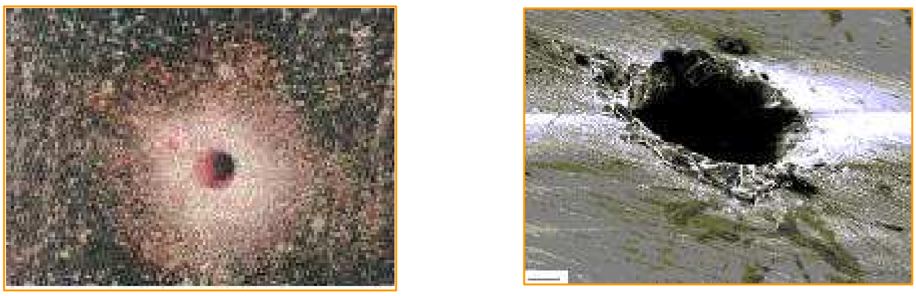

Fig.2. a) Clear hole in 1mm thick Copper target, diameter ≈100 μm seen by optical microscopy; b) Crater on the Copper target, target, diameter ≈100 μm observed with SEM.

Ablation depth per pulse from copper target in vacuum and atmospheric air is shown in fig.2. It is clearly seen that the ablation depth decreases by about 40 % in the ambient atmosphere as compared to vacuum. Effect of ambient pressure in reducing the ablation depth is discussed in our earlier work[5].

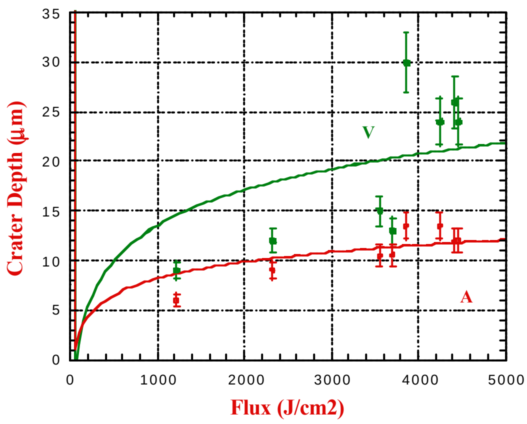

Fig.3. Experimental ablation depth per pulse from Cu target in air (A) and vacuum (V).

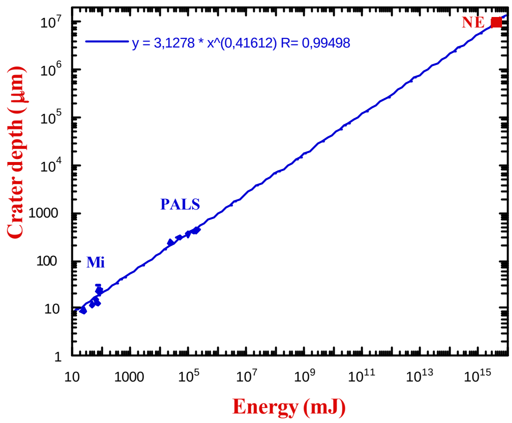

Fig.4. Crater depth: Our data (Mi), PALS [7] and nuclear explosion[8].

Analysis of the experimental results: We compare our experimental results with the well-known theoretical model for the ablation discussed by Nolte[6]. The model describes the behavior of electrons from the conduction zone in metallic targets like Cu (where electron density N_e=8.5×10^{22}/cm^3). These electrons have Fermi energy [E_F=7eV=0.5$m_e(V_F)^2$] and their motion is described with Fermi velocity (V_F). Material ablation[4] can take place due to Optical penetration depth or due to electron heat conduction at higher flux. This gives a typical scale length for energy penetration $l = (D\tau_a)^{1/2}$ where D = Electron Diffusivity ≈ $[(V_F)^2\tau_e / 3]$, and τ_e is electron relaxation time. Finally this provides an ablation depth per pulse, L= l ln(F / F_{th}) where and F_{th} = [ñÙl/A] is threshold flux required for ablation, ñ, Ù, and A are respectively material density, evaporation This model is in good agreement with the experimental results at low laser flux limit.

Table-1

Noltes 'model	Our model E_L = 20 mJ
Z^*= 1	Z^*= 19-20
N_e = 8.5x10^{22} cm^{-3}	N_e = 17x10^{23} cm^{-3}
E_F = 7 eV (=Fermi energy)	KT = 7.18 KeV (=Thermal energy)
$V_e = V_F$ =1.57x10^8 cm/s	V_{th} =1.57x10^9 cm/s
τ_e = a/ V_F= 2.2 x10^{-16} s, (a=Interatomic dist)	τ_e (Spitzer) = 1.2 x10^{-15} s
D = $(V_F)^2 \tau_e$ /3 =1.8 cm^2/s	D = $(V_{th})^2 \tau_e$(Spitzer) /3 ≥ 1000 cm^2/s
l = 0.085 µm	l = 6.3 µm
F_{th}= $(\rho\Omega l)/A$ = 1.2 J/cm ^{2}	F_{th}= $(\rho\Omega l)/A$ = 70 J/cm^2

Presently several types of lasers (ns to fs duration) at much higher flux are being used for the study. Obviously this creates a debate on the suitability of Nolte's model at higher flux. In the present work we have addressed to this theoretical aspect and suggest modification based on plasma phenomenon. The model shows a good agreement with our experimental results.

Our model: During laser-matter interaction, laser energy is initially deposited in the conduction band electrons. This produces plasma and thereby increasing electron density. In this paper we specifically consider our experimental parameters for the ease of analysis and understanding. As a specific case, the laser energy deposited in to the target surface was 20 mJ. As per our spectral record shown in fig.1, the peak ionization of the copper plasma was 20, implies an electron density, N_e= 17x10^{23} cm^{-3}. Such electrons oscillate with a frequency ω_P. The incident radiation will evanesce in the high density plasma over a distance δ (skin depth) = $c(\omega_P)^{-1}$. Therefore the electrons in the cylindrical volume, $V=\delta\pi R^2$ share the laser energy. After subtracting the ionization energy E_i from the total energy acquired by the electron we obtain the average thermal energy associated with individual electron. Motion of such electron can be appropriately described by Spitzer conductivity. Thus we enter a new regime of electron penetration depth at higher laser flux. Table-1 shows the laser ablation related values at low flux according to Nolte's model and the respective values at higher flux according to our model where plasma effects are taken in to account. In our case, ablation region may not be really in thermal equilibrium but in the first approximation we consider $E_{th} = (m_e V_{th}^2)/2$ and calculate thermal velocity, V_{th} of the electron. According to our calculation for 20 mJ of incident laser energy, electron conduction length l = 6.3 µm. For comparison, the fit of the experimental data in fig.3 obtained in vacuum gives l =5.2 μm. This is not too far from theoretical prediction considering the large experimental range, and in complete disagreement with Nolte's model.

Fig.4 shows along with our results, the experimental data[7] obtained using PALS system of duration 400 ps and wavelength = 438 nm at higher laser energy regime 25-250 J. This data has been valuable for corroborating the trend of our results at higher flux.

The shape of the crater, the scaling laws of ablation depth with energy provide an insight on the possibility of extending the present study to other types of craters. Fig. 5 shows the crater structure of a nuclear explosion crater, and a Lunar crater due to meteorite impact as recorded by Apollo spacecraft in 1969. A large number of meteorites, volcano craters have a circular shape and well-defined depths.

Fig.5 a). Crater formed during a nuclear explosion of 1.7 kiloton energy release (TNT equivalent) fired on 19th Sept. 1957; b). Moltke Crater on Lunar surface, 7-Km diameter and 1.4 Km. depth. *(Apollo 10 photographs AS10-29-4324.)*

Nuclear explosions conducted at various underground depths have been documented[8] and crater depth scales with energy as $E^{1/3}$. For 1 kiloton ($E= 4.2\times10^{15}$ mJ) device, explosion conducted on earth surface shows a crater depth of 10 meter (10^7 μm). This very well fits along the extrapolation of the scaling law obtained from laser produced craters from our results and that from ref.7 giving a scaling of depth vs energy $\propto E^{0.41}$. It seems there is a universal scaling law governing the crater formation. Further detail study is necessary.

Conclusion: We have performed experiments to study laser ablation and crater formation at high flux regime 1000-5000 J/cm^2. Results were analyzed taking in to account the ionization effects and thermal electron motion governed by Spitzer conductivity. Electron conduction length l according to our model is 6.3 μm, which agrees with the experiment. Results also provide a clue on the extension of the information from laser produced craters to other types of craters including nuclear explosion, meteorite, volcano craters etc.

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References:

1. W.L.Kruer, "The Physics of Laser plasma Interactions" Westview Press (2001)
2. C.E.Max, Physics of Laser Fusion, Vol. 1UCRL-53107 (1982)
3. C.Momma et al., Optics communication 129, (1996)
4. S.Borodziuk et al., Czechoslovak J. of Physics, Vol. 53, (2003)
5. A. di Bernardo et al., Laser and Particle beams, 21(1), 59-64, (2003).
6. S.Nolte et al., J. opt. Soc. Am B. Vol. 10, (1997)
7. L.Torrisi et al., Czechoslovak J. of Physics, Vol. 52, Suppl. D (2002)
8. Effects of Nuclear weapons by S. Glasstone and P. Dolan. Published by United States Department of Defense and the Energy Research and Develop. Adm. P-257 (1977).