

Experimental and numerical investigations on the density profile of CO₂ laser-produced Sn plasma for an EUVL source

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ABSTRACT

Experimentally observed density profile of CO₂ laser-produced Sn plasma was compared with that predicted by one dimensional hydrodynamic radiation numerical code. Experimental showed a much smaller corona and a much shorter shift distance of the critical density from the initial target surface as compared with those predicted by the numerical simulation. The possible reason may come from thin localized laser deposition region, less energy transport into the corona and into the dense region beyond the critical density. This research suggests that more efforts to understand the fundamental dominating the interaction of CO₂ laser with high Z plasma is necessary to form a more solid foundation for the application of numerical method to the development of the EUVL source.

Keywords: laser-produced Sn plasma, density profile, EUV emission

1. INTRODUCTION

A powerful, efficient, long-lifetime, and cost-effective extreme ultraviolet (EUV) source is one of the most critical issues in the development of EUV lithography (EUVL), which is being expected to be the next generation lithography tool used in semiconductor industry to produce microchips with a feature size down to 22 nm or smaller ^[1]. The availability of optics with a high reflectivity at normal incidence in EUV range limits the EUVL source's wavelength and bandwidth to 13.5 nm and 2 % (in-band) respectively. Until now, hot plasma with temperature from 30 to 60 eV provides the only possible EUV source used in high volume manufacturing (HVM) EUVL. Electric discharge and high power pulsed laser are the two main techniques to produce the EUV plasma. Compared with electric discharge method, laser-produced plasma (LPP) has several advantages for HVM EUVL source, including high conversion efficiency (CE), remote plasma, high collecting efficiency, and scalable power etc. Especially, the use of CO₂ laser ensures the LPP EUV source to reach the requirement of HVM EUVL ^[2,3]. Even though, industries are trying to deliver CO₂ laser driven EUVL source for the starting application of EUVL, further efforts are still necessary to increase the output power, improve efficiency, reduce the footprint, and lower the cost of the EUVL source for real application and further improvement of EUVL system.

Even the interaction of a CO₂ laser with plasmas has been studied for more than 40 years mostly motivated by laser fusion and laser fabrication, mysteries are still remaining in the fundamentals of the generation of in-band 13.5 nm EUV emission from CO₂ laser-produced Sn plasma. To name a few,

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(1). It is well-known that in order to efficiently emit 13.5 nm EUV light Sn plasma has to be heated up to a temperature of ~ 30 eV. For Nd:YAG laser, laser intensity above 5×10^{10} W/cm² is required to generate efficient in-band 13.5 nm EUV emission; however, for a CO₂ laser, it has been shown that the optimum laser intensity, i.e., 3×10^9 W/cm², is one order lower than that of Nd:YAG laser.

(2). Even with a much lower laser intensity, ions generated from CO₂ laser-produced Sn plasma have the similar kinetic energy, i.e., several to tens keV, as compared with that of Nd:YAG laser with much higher intensity.

(3). It has been shown that almost constant in-band CE is obtained with a CO₂ laser with pulse durations from 10 to 200 ns [4,5]. This is hard to understand based on classical isothermal model, in which a long scale length plasma density profile resulted from the long pulse could block laser pulse to reach the critical density and the long scale plasma also re-absorbs the EUV light, resulting in a lower CE with a long pulse as compared with that of short pulse. This is reason why the existing EUVL source uses a CO₂ laser with pulse duration of 20 ns as a laser driver.

The reasons for the existing mysteries come from the lack of understanding of fundamentals dominating the generation and transport of in-band EUV emission in high Z plasma at the CO₂ laser intensity of interest to efficient EUV emission. Previous research related to laser fusion requires high laser intensity, i.e., higher than 10^{12} W/cm². At the same time, low intensity is used in laser fabrication. There has been very little research on the interaction of CO₂ laser with plasma at the intensities from 10^9 to 10^{11} W/cm². And high Z materials, like Sn and Xe, used in EUVL source, makes it more complicate to account for the transitions contributing to the in-band.

The remaining mysteries of the interaction of CO₂ laser with plasma slow the further improvement of the EUV source. As well known, numerical simulation is a convenient and cost-effective way to explore new ideas to optimize laser plasma interaction. However, the remaining mysteries make even the up-to-date numerical code not accurate enough to provide meaningful guidance to the experiment and mostly only follow and explain experimental phenomena in the development of EUVL source. In order to benchmark hydrodynamic radiation numerical models, fine laser and plasma conditions equipped, and fine plasma diagnostics are greatly desired.

In this report, we present experimental efforts to diagnose CO₂ laser-produced plasma density profile and its comparison with the results of numerical simulation with 1-D hydrodynamic radiation code. This research shows that there are big differences between experimental and simulation results. The effect of energy transport from the region of laser deposition to corona and to the dense region beyond the critical density on the plasma density profile is discussed.

2. EXPERIMENTAL ARRANGEMENT AND NUMERICAL CODES

A home-built master oscillator and power amplifier (MOPA) CO₂ laser is used as the pumping laser in present experiments [6]. The MOPA laser consists of an oscillator, a plasma shutter, a pre-amplifier, a power amplifier, and electronic synchronization system. The oscillator, pre- and power amplifiers are transverse excited atmosphere CO₂ lasers. In fact, the gas pressure in the oscillator and the pre-amplifier is lower than atmosphere to get a glow discharge. In present experiments, the CO₂ laser pulse durations are varied from 25 to 85 ns. The laser is focused with a meniscus ZnSe F/5 lens onto a planar target surface at normal incidence. The diameter of the laser focal spot is 100 μ m. Laser intensities on the target for various pulse durations are almost constant at 1×10^{10} W/cm². A high-purity Sn slab with thickness of 2 mm is always used as the target in present experiments.

A Nomarski interferometer with an IR (1064 nm) probe beam is used to diagnose the plasma density profile. A Nd:YAG laser with a 0.13 ns pulse duration is used as the probe beam. The purpose of the use of long wavelength probe beam is to provide a more sensitivity to low-density corona in CO₂ laser-produced plasma. The probe beam passes through the EUV plasma along the target surface, i.e., at an angle of 90 degrees with respect to the target normal. The probe beam is relayed to a CCD camera by a F/5 lens with a 10 $\times$ magnification. Spatial resolution of the interferometer is better than 10 μ m. The probe beam is synchronized with the pumping laser using a pulse generator/delay unit (SRS DG535). The jitter is better than 5 ns. The time waveforms of the pumping beam and the probe beam are monitored with photodiodes equipped with a 500 MHz digital oscilloscope for each shot.

The numerical hydrodynamic radiation code used here is HYADES from Cascade Applied Science Inc. [7] The HYADES code is a one-dimensional, three-temperature, three-geometry, Lagrangean hydrodynamics and energy transport code. The electron and ion components are treated separately in a fluid approximation and are loosely coupled to each other, each in thermodynamic equilibrium and described by Maxwell-Boltzmann statistics. Radiative energy transport is treated in a multi-group prescription. The radiation is coupled only to the electron fluid. The diffusion

approximation is used for modeling all energy transport phenomena. The degree of ionization is determined by a time-dependent nonLTE average-atom. The thermodynamic and equation of state quantities are derived from realistic Sesame tables. The tabular Rosseland mean opacity is used in the gray radiation transport model.

3. RESULTS AND DISCUSSIONS

Typical interferograms of CO₂ laser-produced Sn plasma obtained at various times with respect to the peak of the pumping laser pulse are shown in Fig.1. Laser is incident from the right hand as shown in Fig.1. Laser intensity is 1×10^{10} W/cm². Laser pulse duration is 85 ns. Zero point is the peak of the pumping laser pulse. Fringe shift induced by the plasma is obvious starting from the rising slope of the pumping laser pulse. The initial target surface is determined by the straight part of the first fringe on the left side, as shown by the red dashed lines in Fig.1. Black region with a maximum width along the line of laser incidence between the initial target surface and shifted fringe is due to the fact that the probe beam can only propagate in the plasma with a density less than the critical density as a function of the wavelength of the probe beam, i.e., for 1064 nm probe beam the critical density is 1.1×10^{21} cm⁻³ and the effect of refraction induced by the plasma density gradient that deviates the probe beam toward vacuum.

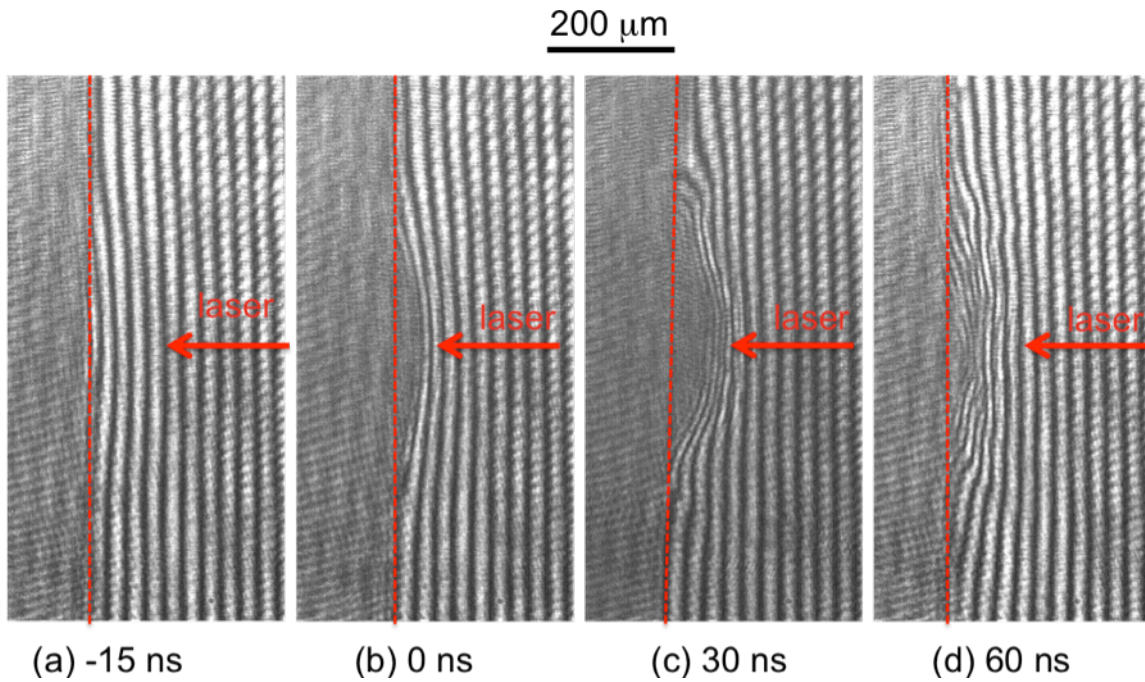


Figure 1. Interferograms of CO₂ laser-produced Sn plasma obtained at various times of (a) -15, (b) 0, (c) 30, and (d) 60 ns with respect to the peak of laser pulse.

Phase shift map induced by the plasma is extracted from the interferograms shown in Fig.1 and their reference interferograms taken at the same times before laser irradiation (without plasma) with a mathematic process based on Fast Fourier transform. By assuming that CO₂ laser-produced Sn plasma obeys cylindrical symmetry, Abel inversion (AI) is applied to get density map from the phase shift map. During the AI process, the profile of phase shift along lateral direction is smoothed and fit with a polynomial function to reduce the error induced by the background.

Density profiles along the line of laser incidence extracted from density map are shown in Fig.2. The data at times of -15, 0, 30, and 60 ns are represented by black squares, red dots, green up-triangles, and blue down-triangles respectively. It is seen that the critical density shifts towards vacuum from -15 to 30 ns. However, it returns towards the initial target surface at 60 ns. The data in corona in the case of -15, 0, 30, and 60 ns can be fitted by an exponential decay function, $f(x) = \exp(-x/l_s)$, with a scale length l_s and are shown by black, red, green, and blue lines respectively. The scale length of the plasma at various times of -15, 0, 30, and 60 ns are 80, 60, 35, and 55 μm respectively and are plotted in Fig.3.

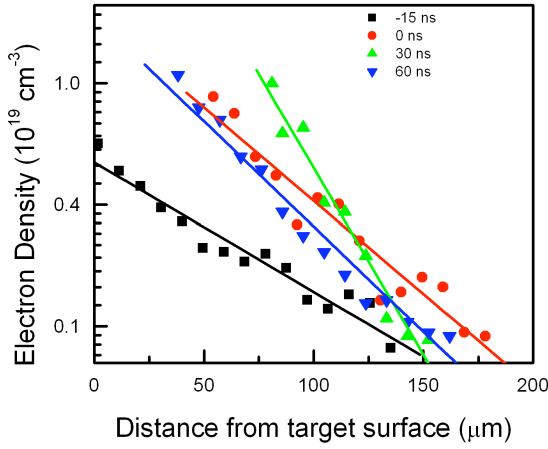


Figure 2. Experimentally observed electron density profiles of CO₂ laser-produced Sn plasma.

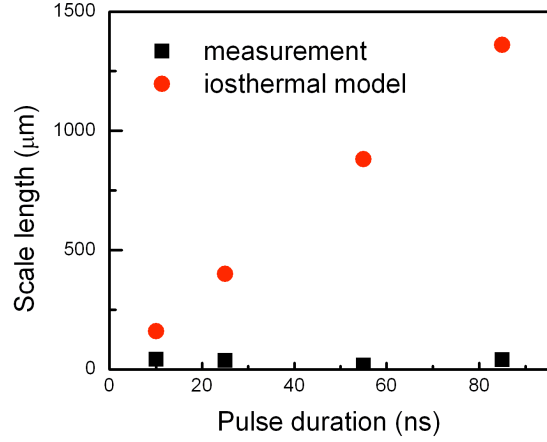


Figure 3. Scale length of plasma density profile of CO₂ laser-produced Sn plasma.

The in-band 13.5 nm EUV emission mainly comes from the unresolved transition array (UTA) from the 4d-4f transitions of Sn⁸⁺ to Sn¹³⁺. The optimum plasma temperature to let Sn⁸⁺ to Sn¹³⁺ dominate the population of Sn ions is 30-60 eV^[8]. High in-band CE has been obtained under identical conditions with various pulse durations from 25 to 110 ns as described in our previous work^[4]. Since it has been shown that in-band 13.5 nm EUV light just follows the shape of laser pulse^[4], it is reasonable to assume that at all of the times of -15, 0, 30, and 60 ns plasma temperature are around the optimum value. The high CEs indicate that the plasma temperatures at the times of -15, 0, 30, and 60 ns should be close to the optimum value of 30 eV. The expansion of hot plasma into vacuum can be described with a speed determined by the temperature of the electrons (T_e) and the mass of the ions. In the corona, isothermal expansion is a good approximation for laser-produced plasma during the laser pulse^[9] and provides a solution for the plasma density profile in corona as, $n = n_c \exp(-x/l_s)$, where $l_s = c_s \tau$ is the scale length, $C_s = (ZT_e / M)^{1/2}$ is the sound speed, τ is the pulse duration, Z is the average charge state, and M is the mass of Sn ion. Therefore, with the plasma temperature to be ~ 30 eV, the plasma scale length given by the isothermal model are 240, 400, 880, and 1360 μm at the times of -15, 0, 30, and 60 ns respectively. The results are shown in Fig.3.

Fig.4 shows the density profiles of CO₂ laser-produced Sn plasma at various times with respect to the peak of laser pulse from the simulation with the numerical code. Real laser pulse waveform, i.e., a smooth profile with periodical modulations (period is $\sim 7-8$ ns) due to multi-mode beat, is used in the simulation. Laser intensity is $1 \times 10^{10} \text{ W/cm}^2$. For comparison, the experimental are plotted again in Fig.4 represented with color dots.

In addition to the deviation of scale length of corona between the experimental data and prediction by an isothermal model, the big difference of shift distance of the critical density away from the initial target surface between the experimental and simulation data is noted in Fig.4. It is seen in Fig.4 that experimental data showed that even for a long pulse duration, like 85 ns, the critical density surface is located near the initial surface, i.e., within 100 μm . However, simulations show that the shift distance of the critical density is proportional to time. It is seen in Fig.4 at 60 ns, the critical density is located at a distance of 700 μm from the initial target surface.

Now we can conclude that CO₂ laser-produced Sn plasma doesn't obey isothermal expansion at all even during the laser pulse. The smaller scale length of the corona and the short shift distance of the critical density may come from the laser deposition, energy transport into the corona and into the dense region with density above the critical density.

We follow the reference 10 to analysis the laser absorption in plasma. The absorption length of laser light in plasma can

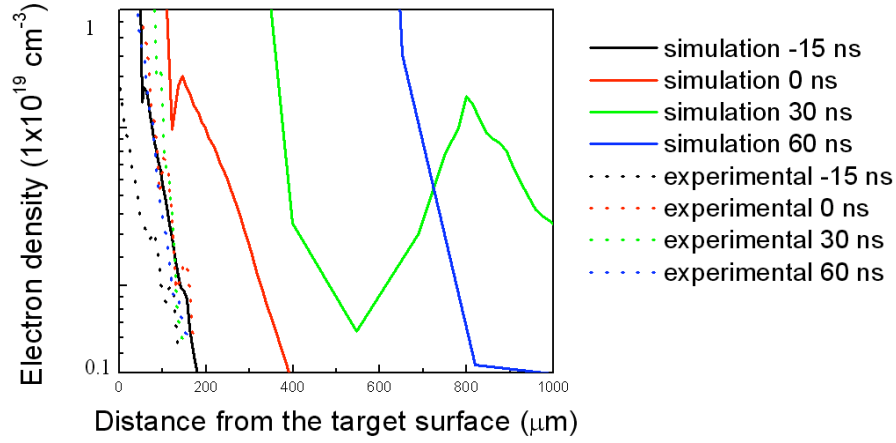


Figure 4. Experimentally observed (color dots) and numerically simulated (color lines) electron density profiles of CO₂ laser-produced Sn plasma at various times of -15 (black), 0 (red), 30 (green), and 60 ns (blue).

be described as, $l_{abs} = \frac{n_c}{n_e} \frac{v_g}{v_{ei}}$, where $v_g = c \sqrt{1 - \frac{n_e}{n_c}}$ is group velocity of light wave in plasma,

$v_{ei} = \frac{e^4 Z n_e \ln \Lambda}{3(2\pi)^{3/2} \epsilon_0^2 m^{1/2} (kT_e)^{3/2}}$ is electron-ion collision frequency, $\Lambda = b_{max} / b_{min}$ is the ratio of the impact

parameters corresponding to the Debye length ($b_{max} = \lambda_D = \sqrt{\frac{\epsilon_0 kT_e}{e^2 n_e}}$) and the classic distance of the closest approach,

the later can be determined by equating the energy in Coulomb field at the closest approach, $\frac{e^2 Z}{4\pi \epsilon_0 b_{min}}$, to the average

electron thermal energy, $\frac{3}{2} m v_e^2$, $v_e = \sqrt{\frac{kT_e}{m}}$ is the electron thermal velocity. The favorable temperature for efficient

13.5 nm EUV is 30 eV, and the charge state is 10. The absorption length of laser light in plasma with various densities generated by Nd:YAG (1.06 μm), and CO₂ (10.6 μm) lasers are listed in Table 1.

Table.1 Absorption length of laser light in plasma

Density	Nd:YAG	CO ₂
$n_c/20$	100	10000
$n_c/10$	25	2500
$n_c/2$	1	100

It is seen in Table 1 that for Nd:YAG laser the laser energy can be significantly absorbed in a corona region with a length of 100 μm. This simple estimation confirms that distributed absorption in corona for short wavelength driving laser.

The absorption length decreases rapidly with the increasing of electron density. It is seen in Table 1, for CO₂, it needs very large size low-density plasma to damp laser significantly. It means that for CO₂ laser most of the laser light is always locally deposited around the critical density. Recalling the short scale length of CO₂ laser-produced Sn plasma shown in Fig.2, the corona is too small to affect CO₂ laser absorption. So most of the absorbed CO₂ laser energy is deposited in a very thin layer localized at the critical density.

Isothermal expansion requires energy and materials compensation from the laser absorption region. The thin absorption layer of CO₂ laser-produced Sn plasma might not provide enough energy and material into corona to maintain an isothermal expansion, especially for a long pulse laser. The reason for the deviation from the classical expansion model may come from the limited material ablated for CO₂ laser, since the energy required to keep isothermal expansion valid can be compensated by the continuous energy absorption during the laser pulse. In order to estimate the ablation-mass for a CO₂ laser, interferograms of Sn plasmas irradiated by Nd:YAG and CO₂ lasers are shown in Fig.5 (a) and (b) respectively. Both cases are under the optimized conditions for efficient 13.5 nm EUV emission. The initial target surfaces are marked with the dashed white lines. For the Nd:YAG laser case, the laser intensity is 2×10^{11} W/cm², and the pulse duration are 7 ns. For the CO₂ laser case, these are 1×10^{10} W/cm² and 85 ns. Laser pulse energies are similar ~ 140 mJ for both cases. Both of the inteferograms were taken at the peak of the pumping laser pulses with a 532 nm probe beam. It is seen in Fig.5 (a) and (b) that the fringe shift at the identical locations marked by the red lines are ~ 1 fringe and above the nc of 532nm light respectively. So the corresponding plasma densities are $\sim 1 \times 10^{19}$ and $> 4 \times 10^{21}$ cm⁻³ for CO₂ and Nd:YAG lasers respectively. Since in both cases, the average charge state should be close to 10 for efficient 13.5 EUV emission, the difference of the ablation ions mass should be roughly similar with that of the electron density. This results in 2 orders of magnitude less ablation-mass for a CO₂ laser than that of a Nd:YAG laser. It has been shown that Nd:YAG laser-produced Sn plasma can be well described by isothermal model ^[11].

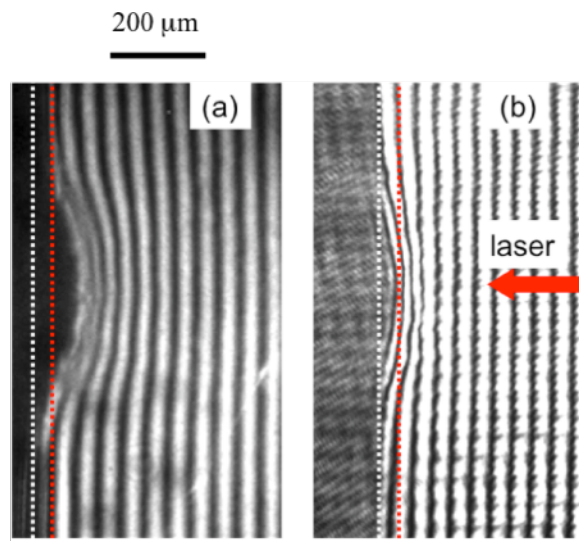


Figure 5. Interferograms of Sn plasmas irradiated with (a) a CO₂ laser and (b) Nd:YAG with the same pulse energy.

Smaller flux limiters have been at high intensity of interest to laser fusion. From 0.266 to 1.06 μm, the scaling law of ablation-mass rate described as ^[12], $m(kg/scm^2) \approx 110[I(W/cm^2)/10^{14}]^{1/3} \lambda(\mu m)^{-4/3}$, where I and λ are laser intensity and wavelength respectively, has been experimentally confirmed with laser intensities of interest to laser fusion. Considering the different pulse durations, it predicts only ~ 4 times less ablation mass for a CO₂ laser as compared with that of a Nd:YAG laser. Ablation-mass is closely connected with the thermal conduction between the hot nc and the cold ablation surface. The cold material between these two surfaces is heated up and expands into the region below the nc, and significantly contributes to the total ablation-mass. Strong inhibition of heat transport has been found in laser-produced plasma with flux limiters of 0.01-0.04 at laser intensities above 10^{14} W/cm². This much less hydrodynamic efficiency suggests a much smaller flux limiter for CO₂ laser-produced Sn plasma as compared with that of short wavelength laser. Even though the flux limiter has been claimed to be comparable for visible and near IR lasers,

more attention is necessary to be paid to the velocity distribution function of plasma electrons used in hydrodynamic code to explain the much less ablation-mass observed with a CO₂ laser.

This much less hydrodynamic efficiency of CO₂ laser-produced Sn plasma may provide explanations for several unclear phenomena in the development of EUVL source. First, the high in-band conversion efficiency from CO₂ laser to EUV emission despite the less laser absorption due to longer wavelength can be attributed to the steep density profile, which reduce the re-absorption of EUV emission induced by the outer layer cold plasma. And less hydrodynamic efficiency is helpful to enhance conversion efficiency from laser into plasma radiation, like 13.5 nm EUV emission.

Another mystery is the weak dependence of the in-band CE on pulse duration within a wide range. It has been shown in our previous work that a constant in-band CE, i.e., 2.6 to 3 %, is obtained with CO₂ laser with pulse durations from 25 to 100 ns. And the pulse durations to keep the constant in-band CE were successfully extended down to 10, and up to 200 ns with a special experimental arrangement using dual master oscillators. Since the small scale length outer layer cold plasma could neither significantly block the laser beam nor re-absorb the EUV light, laser absorption and EUV transport are always good for any laser pulse duration. Small lateral expansion makes sure that no significant laser energy is wasted even with a long laser pulse. In this case, the effect of laser pulse duration on in-band conversion efficiency should be very weak.

But the smaller plasma density scale length due to the lower hydrodynamic efficiency could produce ions with higher kinetic energy, since the ion acceleration electric field built up during the plasma expansion depends on initial plasma density profile, described as $E = k_b T_e / e l_s$ ^[13], where k_b is Boltzmann constant. Ions with kinetic energy of ~ several keV were observed in Sn plasma irradiated with a CO₂ laser with intensity of 1×10^{10} W/cm². This ions kinetic energy is similar with that observed with Nd:YAG laser with a much higher intensity, i.e., 2×10^{11} W/cm².

4. SUMMARY

In summary, experimental and numerical efforts were carried out to understand the dynamics of CO₂ laser-produced Sn plasma. It was found that the experimentally measured scale length and the shift distance of the critical density from the initial target surface are much shorter than those predicted by hydrodynamic radiation numerical simulation. The shorter shift of the critical density surface revealed less energy transported into the dense region with density above the critical density, which has important consequential impacts on the generation and transport of radiation and ion acceleration. . More efforts to fine laser and plasma conditions, and fine diagnostics

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