LASER-PRODUCED PLASMAS AS UNIQUE X-RAY SOURCES FOR INDUSTRY AND ASTROPHTISICS

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Abstract. Laser produced plasma is one of the brilliant x-ray source that has unique capabilities for use in a wide range of science. Here we describe two examples of laser-produced plasma x-ray source application: one is for the semiconductor device industry and the other is for the astronomy. Extreme ultraviolet (EUV) light sources for micro lithography are receiving much attention as an industrial application of laser-produced x-ray source. High power and clean EUV light source, 13.4 nm of wavelength, is developed for mass-production of next generation semiconductor devices. Highest EUV conversion efficiency of 4% has been attained by using low-density and minimum mass tin targets produced by laser-driven explosion of micro-droplet. In addition, it was recently demonstrated that laser-produced x-ray source is very useful to simulate x-ray astronomical phenomena in the laboratory. A 0.5-keV Planckian x-ray source was created with laser driven implosion for producing non-local-thermodynamical-equilibrium (non-LTE) photoionized plasmas, which is a key to understand astronomical compact objects. Laboratory experiment of non-LTE photoionized plasma offers novel test bed for validation and verification of computational codes used in x-ray astronomy.

1. Introduction
A laser-produced plasma is an attractive radiation source since it has high brightness and is compact. Generating high-intensity radiation from laser-produced plasmas is one of the fundamental and long-term research objectives for several applications including use as a probe for experiments in high-energy-density physics, and a compact x-ray source for nondestructive
inspection, radiotherapy, and nanofabrication [1]. Laser-produced x-ray source has unique capabilities for use in a wide range of interdisciplinary research tools and has great potential also in industrial production field. Application of laser-produced x-ray source have yet to be widely explored, because no intense x-ray sources have been available other than the synchrotron radiation sources.

Out of those applications, an extreme ultraviolet (EUV) light source for lithography is receiving considerable attention and is being investigated intensively as an attractive application for laser-produced plasmas in industry [2]. EUV lithography is a developing technology expected to be used in mass production of the next-generation semiconductor devices, which have a node size of less than 32 nm. Moore’s law, the famous scaling law for the feature size of semiconductor devices, requires EUV lithography to be implemented in the manufacturing stage by 2011 [3]. 13.5 nm-wavelength radiation within a 2% bandwidth has been selected as suitable EUV radiation for lithography because a Mo/Si multilayer mirror has the highest reflectivity (∼70%) for in-band light. Laser-produced tin (Sn) plasma has a high-intensity emission peak at 13.5 nm, thus much effort is being devoted to developing a Sn-based EUV light source [4] [5] [6] [7] [8] [9] [10] [11] [12] [13]. Some critical issues in the development of a Sn-based EUV source include achieving a high CE of incident laser energy into in-band light, reducing debris emanating from light source plasmas, and suppressing out-of-band light in the vacuum ultraviolet region. One of the ways to achieve these goals is to use a minimum-mass target [14] [15], which contains the minimum number of Sn atoms required for EUV radiant energy. Using a minimum-mass target substantially reduces debris [14] [15] [16] [17] and out-of-band radiation [18].

The other application to be described in this paper is the laboratory x-ray astrophysics. In a high-mass x-ray binary, a compact object sweeps up material as it orbits through the stellar wind of its companion star. As material is accreted onto the compact object, a fraction of its gravitational potential energy is converted into thermal energy, and some of this thermal energy is released as x-ray radiation, whose mean radiation temperature is on the order of 1 keV, which ionizes the surrounding stellar wind. X-ray astronomers rely on non local-thermodynamic-equilibrium (non-LTE) physics of photoionized plasma generated in such the stellar wind. Theoretical models have been developed on the basis of observed spectra [19] [20] [21] [22] and complex computer codes are written to analyze them [23] [24] [25] [26] [27] [28]. Verification and validation of photoionized plasma models and codes are difficult, because laboratory experiments of photoionized plasma are rare [29] [30], mainly owing to the lack of high flux x-ray sources. The novelty of the present experiment is to use laser-driven implosion for x-ray source production that emits a flash of brilliant, continuum x-rays which simulate those produced by an astronomical compact object. This brilliant x-ray source offers a novel test bed for validation and verification of computational codes used in x-ray astronomy.

2. Laser-driven explosion of micro-droplet for efficient and clean EUV light source generation

An EUV power of 180 W is required at the IF point to achieve EUV lithography [2]. About 33% of the EUV radiation emitted from the source plasma can be transported to the IF point [2]. Thus, a practical EUV light source requires 545 W of EUV power in 2π sr. Assuming a repetition rate of 50 kHz for EUV light radiation generation, the in-band radiant energy must be 10.9 mJ/pulse, which corresponds to 7.4 × 10¹⁴ photons/pulse. In a laser-produced plasma, Sn ions emit in-band photons while traveling from the target surface through the high-temperature, low-density corona region. The number of in-band photons emitted per Sn ion was measured to be in the range of 5 to 10 [31]. Therefore, the minimum number of Sn atoms for the required EUV radiant energy is evaluated to be in the range of 7.4 × 10¹³ to 1.5 × 10¹⁴. This number of Sn atoms is contained in a pure Sn microdroplet with a diameter of 20 μm. A CO₂ laser (wavelength: 10.6 μm) is a practical driver for efficient EUV light source production [9,32].
Figure 1. (a) Energy CEs of the main CO\textsubscript{2} laser beam to 13.5-nm-wavelength light within a 2% bandwidth. The CEs were measured by varying the temporal separation between the main CO\textsubscript{2} pulse and the Nd:YAG pre-pulse. An EUV-CE of 4\% was attained by this scheme. (b) Schematic of a practical EUV light source based on laser-driven explosion of pure tin microdroplet.

because CO\textsubscript{2} laser-produced Sn plasma is optically thin for the in-band radiation so that self-absorption of the in-band radiation is negligibly small in the plasma [8]. The optimal intensity and pulse duration of a CO\textsubscript{2} laser were assumed to be 1 \times 10^{10} W/cm\textsuperscript{2} and 40 ns, respectively, and the EUV-CE was taken to be 4\% (details are discussed below), so that the energy in a single laser pulse will be 273 mJ/pulse. To obtain this optimal laser intensity, the laser spot diameter must be 295 µm. This simple evaluation indicates that the diameter (20 µm) of the minimum-mass droplet is too small to be irradiated by the optimal laser intensity (1 \times 10^{10} W/cm\textsuperscript{2}) and required laser energy (273 mJ). To resolve this considerable mismatch between the optimal laser spot size (295 µm) and droplet diameter (20 µm), the droplet must be expanded prior to laser irradiation by the main pulse. To achieve this we used instantaneous heating by a laser pre-pulse to expand a small microdroplet.

The expansion behavior of pre-pulse irradiated Sn microdroplets was observed using a laser shadowgraph technique [31]. The diameter of the droplets was 36 µm, and the droplets were supported by a 6 µm-diameter carbon fiber. The laser pre-pulse used to expand the droplets was the fundamental output of a Q-switched Nd:YAG laser. The pre-pulses were Gaussian with a pulse width of 8 ns and their intensities were in the range of 5 \times 10^{10} to 4 \times 10^{11} W/cm\textsuperscript{2}. The second-harmonic of a Nd:YAG laser was used as the probe laser pulse (Gaussian with a 10-ns pulse width). The expansion of the laser-heated droplet changed drastically when the laser intensity was increased and the expansion diameter approaches the optimal laser spot diameter. To expand the microdroplet, the intensity of the Nd:YAG laser pre-pulse must exceed 3 \times 10^{11} W/cm\textsuperscript{2}. The flying velocity of the expanded target was 0.5 - 1 km/s for 2 - 4 \times 10^{11} W/cm\textsuperscript{2}.

The expanded pure Sn droplet was irradiated with a CO\textsubscript{2} laser pulse. The incident angle of the pre-pulse was 20 degrees, from the incident axis of the CO\textsubscript{2} laser beam. The laser pre-pulse was the fundamental of a Q-switched Nd:YAG laser, whose output was a Gaussian with a pulse width of 8 ns, a focal spot size of 50 µm, and an intensity of 4 \times 10^{11} W/cm\textsuperscript{2}. The main laser pulses was from a CO\textsubscript{2} laser, and was Gaussian with a pulse width in the range 30 - 50 ns, a focal spot diameter of 250 µm, and an intensity of 1 \times 10^{10} W/cm\textsuperscript{2}. An in-band EUV microscope [33] coupled with a back-illuminated x-ray CCD camera was installed at 90 degrees with respect to the incident axis of the CO\textsubscript{2} laser beam.

The dependence of EUV-CE on the delay time between the pre-pulse and the main pulse is shown in Fig. 1. The EUV-CEs are in the range of 2.0 to 2.5 \% for Sn plates irradiated with a single CO\textsubscript{2} pulse. This value is almost equal to that reported by Ueno \textit{et al.} [32]. The highest
CE (4%) was obtained for a delay of 1 $\mu$s. The dependence of the EUV-CE on laser intensity was also measured, and the optimal laser intensity was found to be $1 \times 10^{10}$ W/cm$^2$ for a 1-$\mu$s delay.

An example of a practical EUV light source system design is described. The droplet diameter is assumed to be 20 $\mu$m, the feasibility of which has been demonstrated at a repetition rate of 500 kHz [34, 35]. A Nd:YAG laser is selected to generate the pre-pulses. The intensity of the laser pre-pulses is $4 \times 10^{11}$ W/cm$^2$, the pulse width is 10 ns, the wavelength is 1.064 $\mu$m, and the spot diameter is 20 $\mu$m. Thus, the pre-pulse energy is 12.6 mJ/pulse and its power is 628 W. The intensity of the laser pre-pulse is sufficiently high to generate EUV light, and an EUV-CE of 1.5% was obtained in the above experiment. Thus, the EUV radiant energy due to pre-pulse irradiation is about 0.2 mJ/pulse. The residual radiant energy (10.7 mJ/pulse) must be generated by the main CO$_2$ laser irradiation. The intensity of the main pulse is $1 \times 10^{10}$ W/cm$^2$, the pulse width is 40 ns, and the EUV-CE was 4%. Thus, the laser energy is 268 mJ/pulse and the spot size is 292 $\mu$m. In this manner, a practical EUV light source can be designed with a 50 kHz-0.63 kW Nd:YAG laser system and a 50 kHz-13.4 kW CO$_2$ using a 20-$\mu$m-diameter droplet. The total EUV-CE of the system is calculated to be 3.9%.

3. Laboratory x-ray astrophysics with a high-power laser facility

We report a novel laboratory simulation of photoionized plasma generated at a high-power laser facility [36]. An example of photoionized plasma is the stellar wind around compact objects. The novelty of the present experiment is a laser-driven implosion that creates a flash of brilliant, continuum x-rays which simulate those produced by an astronomical compact object. As demonstrated below, an imploded core plasma emits a nearly blackbody continuum x-ray pulse of sub-keV mean radiation temperature ($T_R$). It irradiates a low-density ($n_e = 1 \times 10^{20}$ cm$^{-3}$) and low-temperature ($T_e = 30$ eV) silicon plasma. Silicon is highly abundant in the universe. In fact, characteristic line emissions from silicon ions are observed in CYGNUS X-3 [37, 38] and VELA X-1 [39–42].

X-ray emission from the imploded core plasma was characterized with two types of spectrometers, an absolutely calibrated transmission-grating (TG) spectrometer and a filtered-pinhole-array (FPA) device. These were coupled to cooled x-ray CCD cameras, whose spectral response and analog-to-digital gain were calibrated with two radioisotopes ($^{55}$Fe and $^{109}$Cd) which emit 3, 6, and 22 keV x-rays. The TG spectrometer was designed to measure the absolute
Figure 3. (a) X-ray spectrum from the core plasma measured with a transmission grating spectrometer. (b) Temporal profile of the x-ray pulse measured with an x-ray streak camera.

Figure 4. Comparison between the experimental x-ray spectra of photoionized Si plasma (a) and x-ray spectrum observed from VELA-X1 with the on-board Chandra spectrometer (b).

intensity and spectral shape from a core plasma in the 1 to 6 keV photon-energy range, and the FPA spectrometer measures the two-dimensional (2D) distribution of the radiation temperature \( T_R \) with nine x-ray filters in the 1 to 8 keV photon-energy range. Figure 3 (a) plots the x-ray spectrum from the core plasma measured with the TG spectrometer, along with Planck spectra at various radiation temperatures \( T_R = 400, 500, \) and 600 eV. The spectral response of the grating, x-ray filters, x-ray CCD camera, and source size were all taken into account. The spectrum for \( T_R = 500 \) eV best agrees with the experiment. The maximum temperature is 810 eV, and the core has the shape of a rugby ball, with long and short axes of, respectively, 35 and 63 \( \mu \)m FWHM. Both the TG and FPA spectrometers give a consistent temporal- and spatial-averaged temperature of \( T_R = 480 \pm 20 \) eV. The duration of the blackbody x-ray pulse was measured to be 160 \( \pm 20 \) ps FWHM with an x-ray streak camera as shown in Fig. 3 (b), whose temporal resolution and spectral window were 20 ps and 1 to 5 keV (10 \( \mu \)m aluminum filter and 300 \( \AA \)-thick gold cathode), respectively.

In the astrophysical literature [19, 29], the ionization parameter is defined as \( \xi = 16\pi^2 J/n_e \) (with units of erg cm/s) to measure the importance of photoionization in a plasma. Here \( J \) and \( n_e \) are the mean x-ray intensity (erg/s/cm\(^2\)) and the electron number density in the plasma (cm\(^{-3}\)), respectively. UV and x-ray satellites observed characteristic x-ray emission of highly-ionized ions from the region of photoionized plasmas with \( \xi = 10 \times 10^4 \) ergs cm/s. For example, the ionization parameter for VELA X-1, a neutron star binary system, peaks around \( \xi = 300 \) [39]. In our laboratory plasma, the ionization parameter is \( \xi = 5.9 \pm 3.8 \), which is slightly below the lower limit of the astrophysical value. Figures 4 (a) and (b) are x-ray spectra from the laboratory plasma and from VELA X-1, respectively. Detailed analysis of the experimental results, astronomical observation, and model are described in the reference [36, 43].
4. Summary
We have demonstrated two distinguished applications of laser-produced x-ray source for industry and basic science. High efficiency of laser produced EUV light source generated from microdroplet and dual laser pulses ensures to provide ongoingly us high performance computer devices at reasonable cost. A brilliant flash of keV Planckian x-ray produced by laser-driven implosion offers a novel test bed for understanding non-LTE photoionized plasma physics relevant to x-ray astronomy. Unique capabilities of laser produced x-ray source will be continuously explored and open new horizon in the wide field of science.

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