Invited Paper

Laser light coupling physics in high repetition rate laser-plasma droplet-target x-ray point sources

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Abstract

The droplet laser plasma source has previously been shown to have many attractive features as a continuous, almost debris-free source for EUV and X-ray applications. In a combined experimental and theoretical study, we analyze the interaction physics between the laser light and the target over a range of conditions.

Keywords: Laser plasma, EUV lithography, water droplet target

1.0 Introduction

With the advancing need for bright, clean x-ray point sources for applications such as lithography, the water droplet laser target has received considerable attention. The cryogenic water droplet target was first proposed as a debris-free mass-limited laser plasma target source of EUV radiation in 1993[1,2]. One of the advantages to using the water droplet target is that the target material is easily delivered to the laser focal region. Also, the water droplet target is a mass limited target, meaning that the dimensions of the target are closely matched to the laser focal spot size.[3,4] This is important because it has previously been shown that mass limited targets will be necessary for EUV lithography to minimize debris produced from the plasma.[5] Another advantage to using a fluid target is the evaporation and subsequent evacuation of any large material ejected from the target before it can reach nearby optics.[6]

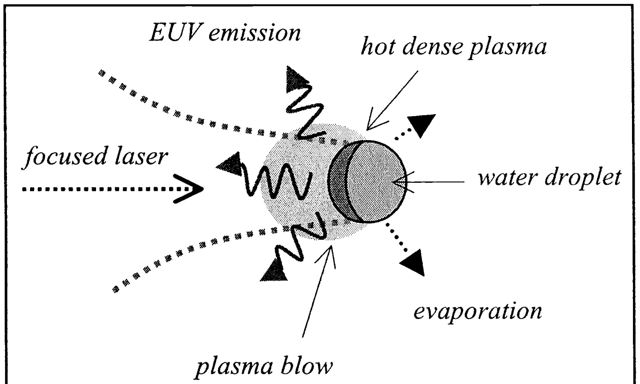

Figure 1. Principle of the water droplet laser plasma

Figure 1 indicates the working principle of the water droplet as a laser plasma point source. A high intensity laser pulse is focused onto a water droplet causing the formation of a hot dense plasma. The drops are produced by a jet capillary at frequencies of 20-200 kHz having diameters in the range of 30-80μm. Previous studies of the water droplet plasma have focused on the spectral emission and debris characterization. Spectra of the oxygen emission in the 13nm region were recorded using a flat field spectrograph;[7,8] the resulting spectrum is shown in Figure 2.[9] This spectrum indicates that there is strong 13nm line emission from the 4d-2p transition in Li like oxygen. The shaded region represents the mirror bandpass of the Mo/Si mirrors that are to be used on EUV lithography steppers. As seen in this spectrum there is complete overlap of the mirror bandpass and the oxygen 13nm line. The maximum conversion efficiency recorded for the water droplet target was 0.63 %/4π sr.[9] To characterize the debris production of the water droplet plasma the reflectivity of a Mo/Si mirror placed at 32mm from the plasma was monitored as a function of the number of laser pulses. This was completed for the case of no debris interdiction technique and for the case of an electric repeller field created by placing the mirror housing at +100V.[9] These results are shown in Figure 3. The oscillations of the reflectivity indicate sputtering away of alternating layers of Mo and Si. To ascertain the benefit of the repeller field the number of MoSi layers sputtered for both cases was counted. It was concluded that the application of the electric field increased the lifetime by a factor of 7 as compared to the case with no repeller field.

To attain a more comprehensive understanding of the plasma dynamics, emission and debris characteristics of the water droplet plasma, theoretical simulations and optical diagnostics of the laser plasma are being made.

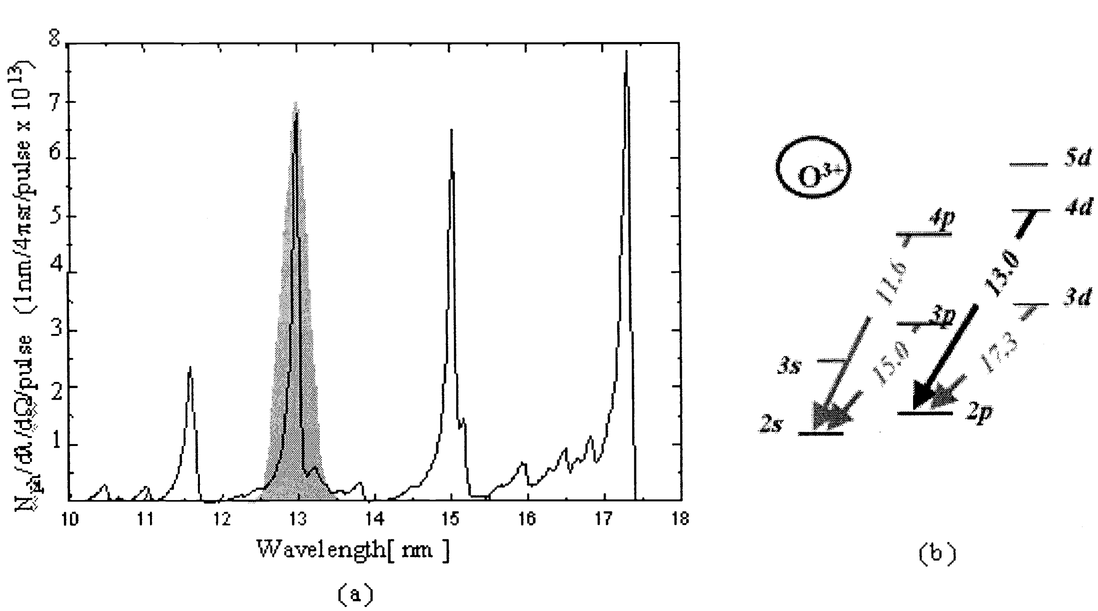

Figure 2. (a) O^{3+} spectra from water droplet plasma. (b) Energy level structure of O^{3+}.

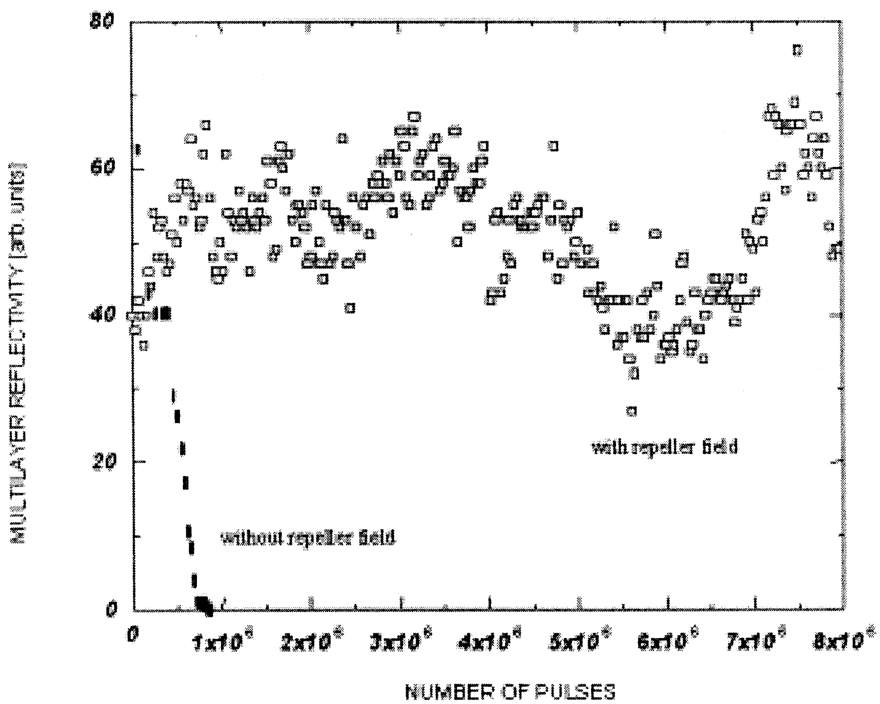

Figure 3. Multilayer mirror reflectivity as a function of the number of laser pulses

2.0 Theoretical Simulations

Computer aided laser plasma simulations are useful in ascertaining information concerning the plasma heating and can therefore provide insight into the wavelength and intensity of the radiation emitted from the plasma. MEDUSA is a 1-D hydrodynamic simulation code that allows one to specify the parameters of a laser plasma interactions: these parameters include the laser pulse length, intensity, wavelength and pulse shape as well as the target geometry and composition.[10] Based on these input parameters and a number of parameters to specify the physics of the interaction the code yields the plasma density, temperature, average charge state, and plasma velocity as a function of time and space. Figure 4 shows the simulation results for the plasma expansion and heating as a function of time relative to the peak of the laser pulse for our experimental conditions, which include the following: $I = 5x10^{11}$ W/cm^2, pulse length = 9ns, a laser spot size = 80 μm and a water droplet radius = 15 um.

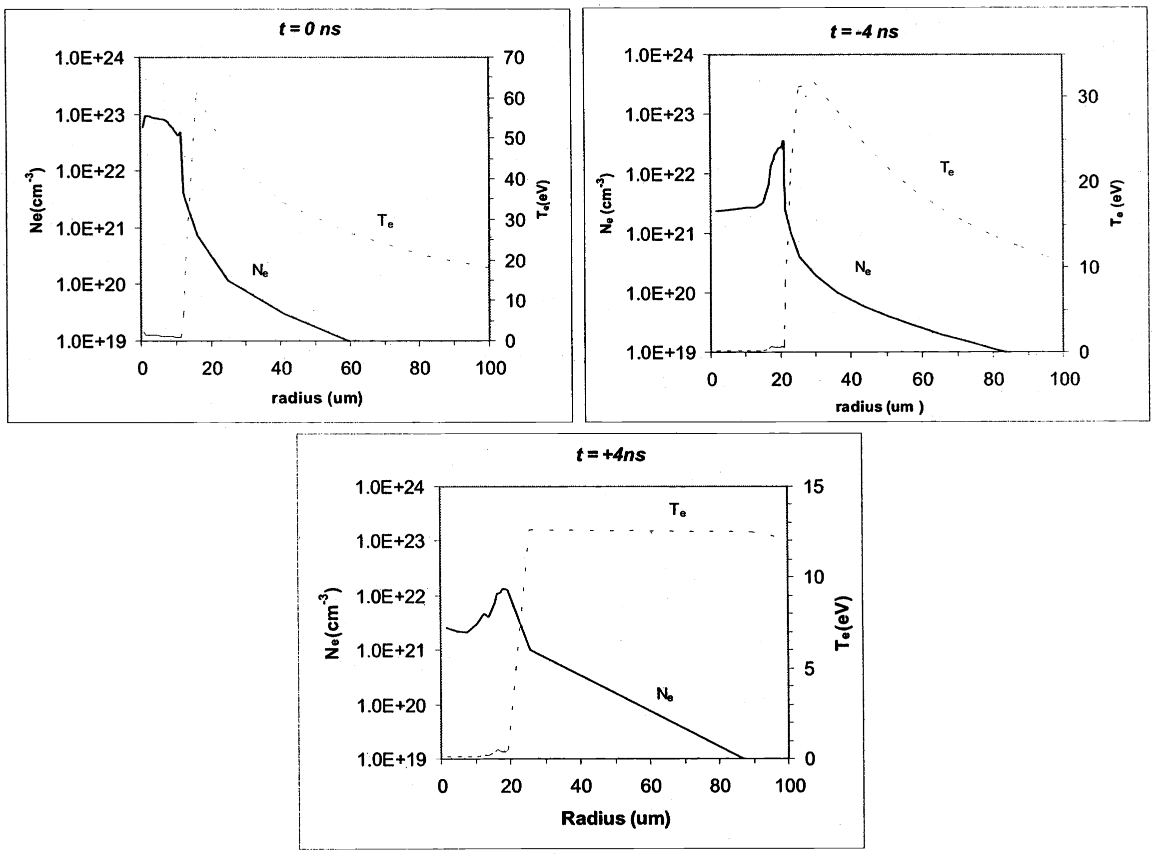

Figure 4. MEDUSA simulations shown at times relative to the laser pulse peak

Characteristic of nanosecond laser plasmas, most of the x-ray emission occurs near critical density where the laser beam is reflected and has most of its energy absorbed. For a 1μm ionizing laser pulse the critical density is ~ 10^{21} cm^{-3}. Previous simulations with the spectral simulation code RATION have indicated that the optimum plasma temperature for populating the 4d level of O^{3+} at critical density is about 28 eV.[3] It is seen at the peak of the laser pulse, at 0ns, the temperature at critical density is about 35eV. One can therefore expect strong 13nm line emission from the water droplet target under these irradiation conditions. An important aspect of the plasma expansion to note for the discussion of the optical diagnostics is the strong density gradient just beyond the critical density.

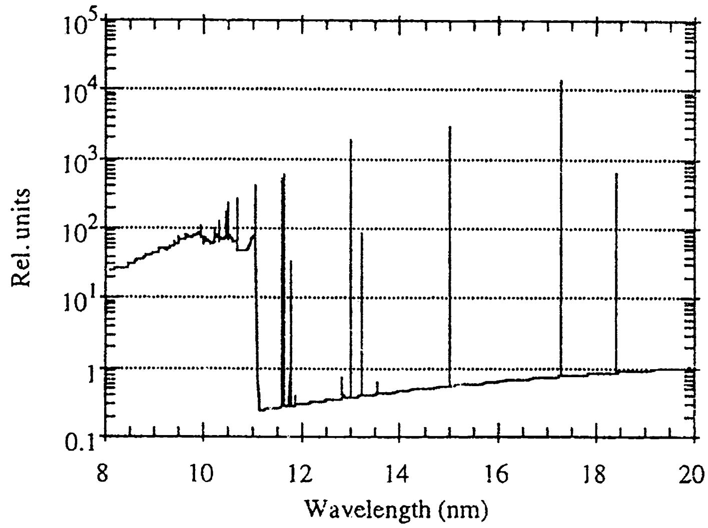

Figure 5. RATION spectra calculated for the water droplet plasma

The simulation code RATION has been used to model the spectral emission of the oxygen from the water droplet plasma.[11] RATION calculates the radiation emission of H, He, and Li like ions as a function of electron density and plasma temperature given the atomic number of the plasma atomic species. Figure 5 shows the spectra produced by RATION. It is seen that there is strong line emission at 13nm just as was recorded with the flat field spectrograph.

3.0 Optical Diagnostics

Schlieren photography and optical shadowgraphy are well-known time-resolved optical probe techniques that can provide much information on the plasma expansion. Schlieren imaging produces a high contrast image of the plasma by imaging the refracted probe rays while blocking non-refracted probe rays. Probe rays that enter the region of steep density gradient below critical density are refracted away from the high density region. An image of these refracted rays is captured by a high resolution imaging system that includes a focal point stop to block most of the unrefracted probe light. In the image plane the strongly refracted rays are able to interfere with rays that scatter from the pin stop to form interference fringes that are normal to the density gradient. The contrast is sensitive to the first derivative of the index of refraction and therefore to the electron density.[12]

With shadowgraphic imaging the plasma is simply backlit by the probe beam. In this case the refracted rays can interfere with unrefracted rays to form interference fringes normal to the density gradient.

Figure 6 illustrates the experimental set up being used for the optical diagnostic experiments. The ionizing laser beam is produced by a Spectra Physics Q-switched Nd:YAG laser operating at 100Hz, having 9ns duration (FWHM), 320 mJ pulses that are focused to 5 x 10^{11} W/cm^2 by a f/2 lens. A 2.5ns, 532nm probe beam is generated by passing the Nd:YAG fundamental beam through a second harmonic generator. The plasma was imaged by a f/3 lens with a magnification of 18 and a spatial resolution of about 5μm. A HeNe laser beam collinear with the Nd:YAG 1μm beam is used in conjunction with a photodiode to monitor the stability of the droplets.

Figure 7 shows a Schlieren image and a shadowgram recorded at the peak of the laser pulse. In each image the 1μm heating pulse is incident on the droplet from the left side of the image. In both images there are several crescent shaped fringes on the left side of the image just beyond the large bright crescent shaped fringe. These symmetric fringes indicate a spherical symmetry in the plasma expansion. This confirms that the plasma expansion on the side of the target struck by the laser is undergoing a 1 dimensional expansion and therefore, to first order, validates the use of the 1-D MEDUSA code to model the laser plasma interaction. Further analysis of the fringe spacing will lead to a measurement of the electron density gradient.[13,14]

This diagnostic identified a feature of the droplet system not previously seen., namely the presence of satellite droplets. The additional drops increase the mass in the laser focal volume and can therefore increase the debris from the laser plasma. Careful control of the operating conditions can eliminate these secondary droplets.

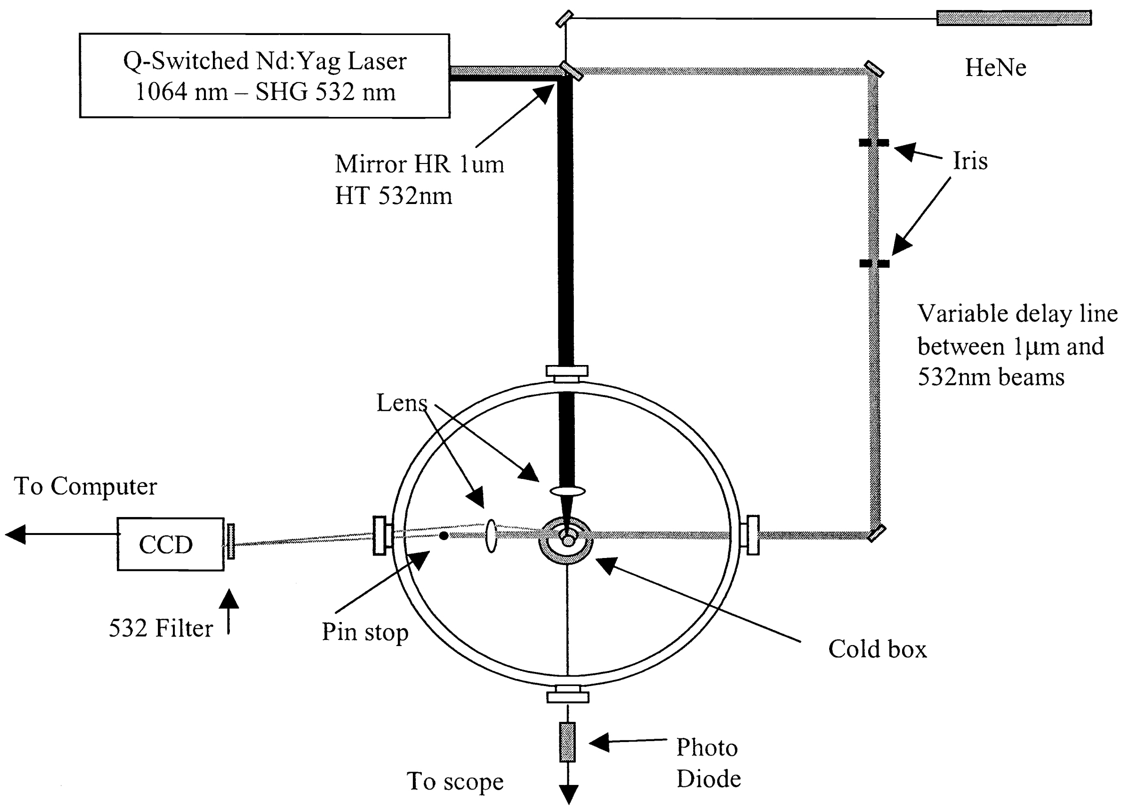

Figure 6 Experimental set up for optical diagnostics

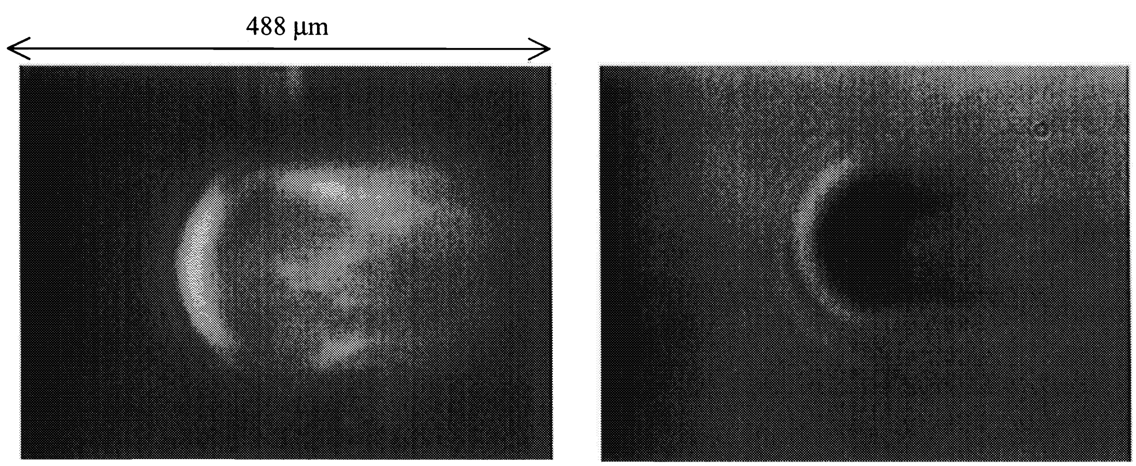

Figure 7 (a) Schlieren image, (b) Shadowgram, Both images are recorded at the peak of the laser pulse.

4.0 Summary

Having a number of favorable qualities the laser produced water droplet plasma is a strong candidate for a point source of EUV radiation. Lithium-like oxygen has strong line emission well within the band pass of conventional Mo/Si mirrors. The debris emission is minimized by the mass limited target and can be further reduced through the use of an electric repeller field. Application of the 1-D laser-plasma simulation code MEDUSA in conjunction with the synthetic spectra code RATION indicate that there should be strong 13 nm line emission at laser intensities of $5x10^{11}$ W/cm^2 in agreement with the recorded spectra. For the first time optical diagnostics have been used to image the laser produced water droplet plasma. Preliminary optical diagnostic studies indicate that the plasma expansion is spherically symmetric, and therefore, to first order, validates the use of MEDUSA to model the laser plasma interaction.

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