Further development of the Xe laser plasma 11-nm radiation source – new data on laser energy absorption and spectroscopy

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Abstract. Absorption of the laser pulse energy in the plasma has been shown to change from 8.5% at irradiation of a gas-puff target with a beam narrow-focused onto a near-central area of the jet up to 65% at the wide defocused irradiation. An analysis of this phenomenon is based on a hypothesis that plasma density decays significantly during the 10ns laser pulse due to hydrodynamic expansion of the hot plasma. A similarity of the EUV (Extreme UltraViolet) intensity and the laser light absorption as functions of the laser beam diameter suggests a revision of the conventional idea of a strong EUV radiation self-absorption in a cold peripheral shell of the laser plasma whereas the high absorptivity of the laser radiation by the plasma looks like a major feature to gain high efficiency of an EUV source.

1. Introduction
Since the early 2000s, the term of "EUV lithography" has been meaning a lithography with the working wavelength of \(\lambda = 13.5\) nm. This happened due to a general agreement to use, in the lithographer optical system, Si/Mo interference mirrors which reflect the radiation within a range around that wavelength [1, 2]. In those times, laser-produced plasmas (LPP) with a Xe gas microjet as a target believed to be a suitable radiation source [3-6].

But later, about 2005-06, researchers were forced to replace the Xe gas with Sn droplets because of much higher emissivity of tin at the wavelength used [7-9]. However, it turned out that the gain in the EUV radiation intensity should be paid with a high price – a huge flux of tin ions and clusters to the first collector mirror in the source has required a development of complex and expensive protective measures [10]. This struggle against Sn pollutions and for increasing the power of the source has been going on for about 15 last years.

In 2013, a proposal of a new extension of the EUV lithography with \(\lambda \approx 11.2\) nm and Be/Mo or Be/Ru reflection optics had been made in the IPhM (Institute for Physics of Microstructures, Nizhniy Novgorod, Russia) [11]. Along with the change in the wavelength, it was proposed to return to the “debrisless” Xe LPP source of the working radiation since its emissivity at \(\lambda \approx 11.2\) nm was believed to be several times higher than at \(\lambda \approx 13.5\) nm (see, e. g., [12, 13]). Thus, interest in the Xe LPP EUV radiation source has arisen again. First results on the 11-nm Xe LPP source have been published in [14-18]. It was reported there that a laser-energy-to-EUV conversion efficiency CE reached approximately 4% – a rather encouraging value.
In [16-18], an experiment has been described, when the Xe gas-jet target was irradiated with a laser beam of a variable diameter – from $\theta_{\text{beam}} = 40\text{-}50 \, \mu\text{m}$ (a sharply focused beam) up to $\theta_{\text{beam}} = 350\text{-}400 \, \mu\text{m}$ (widened, defocused beam). At that, the EUV radiation output from the plasma increased by 4-11 times depending on the wavelength. Since in plasmas of many-electron atoms, the introduced energy is almost completely lost in the form of radiation, a natural question arises concerning variations in absorption of the laser energy by the plasma in the above mentioned experiment. The present work is devoted to this question. As well, some spectral measurements have been carried out to clarify the above-mentioned dependence of the EUV output on the wavelength. A preliminary information on results of this work has been presented at the 2019 EUV Source Workshop in Amsterdam [19].

2. Description of the experiment

Both absorption and spectral measurements were performed on the same experimental setup, a scheme of which is shown in Figure 1.

The target jet flowed out from the Laval nozzle with diameters of critical and exit cross sections of 0.2 mm and 1.1 mm, respectively, and with a length of 13 mm. All experiments in this work were carried out at the stagnation pressure (the pressure before the nozzle entry) $P_0 = 13 \, \text{atm}$. Gas parameters in the jet were calculated by means of a fluid dynamics numerical simulation [20].

A laser spark was excited in the jet with a focused IR (InfraRed) beam of the Nd:YAG laser. The laser pulse parameters were as follows: the wavelength $\lambda = 1.064 \, \mu\text{m}$, the pulse duration $\tau_{\text{pulse}} \approx 8\text{-}10 \, \text{ns}$ (at half magnitude, and 15 ns at the base), and the pulse energy delivered to the plasma $E_{\text{las}} \leq 1 \, \text{J}$. The beam and the jet axis intersected at right angles at a point located at a distance $\Delta X = 1 \, \text{mm}$ from the nozzle outlet. A spatial distribution of Xe atoms at that point taken from [21] is shown in (Figure 2a)

2.1. Measurements of the laser energy absorption

In the experiments described, the focus point was held at a fixed position, $Y = Z = 0$, and $\Delta X = 1 \, \text{mm}$, but the jet generator was displaced, from pulse to pulse, along a direction parallel to the laser beam, so that the gas target moved along the beam axis, $Y$. Therefore, diameter of the beam illuminating the target jet varied depending on $Y$ (Figure 2b), and the plasma diameter changed accordingly.
The part of the laser energy remaining unabsorbed in the plasma was measured as shown in Figure 1. The results are presented in Figure 3a. In parallel to the absorption, measurements of the EUV radiation from the plasma were carried out also (Figure 3b).

2.2. Spectral measurements

A spectral analysis of the plasma radiation within the narrow 11-14-nm wavelength band has been realized with use of two interchangeable (Mo/Be and Si/Mo) and turnable interference mirrors. It was based on the Bragg law, $\lambda = 2d \sin(\alpha)$, as it was described in [14, 18]. The result is presented in Figure 4. It can be seen that the spectrum for the case of the wide-beam illumination looks more "long-wave" one. However, this can hardly evidence in favor of lower temperatures in this case because of a nonequilibrium of the plasma due to its too short life time.

3. An analysis of data on the absorption

The absorption coefficient $\mu$ was deduced from the experimental data shown in Figure 3a. To describe the dependence of the absorption coefficient on plasma parameters, a well-known expression taken from the classical theory of propagation of electromagnetic waves in the plasma...
Figure 4. Comparison of the spectra obtained with two geometries of laser radiation in absolute units: a solid line and black circles represent the spectrum in the case of sharp focusing, black triangles are the spectrum at the defocused beam.

A plasma density decay due to an outflow from a hot, laser-illuminated core was taken into account. In general, this phenomenon is complex enough. At the beginning, the hot plasma expansion into the peripheral gas produces a shock wave. Then, during expansion into the vacuum, two processes occur simultaneously: transformation of the particle heat energy into that of the directional outflux and ion acceleration & electron deceleration in the electric field of the front double layer. But the plasma outflux velocity just at crossing the hot plasma core boundary seems to be close to the ion thermal one, \( V_i \). The plasma body was considered to be a cylinder of \( L_{pl} \) length and \( R_{pl} \) radius. Then a momentary value of the plasma density should be

\[
n(t) = n_0 e^{-t/\tau_p}, \quad \text{where a particle lifetime, } \tau_p, \text{ is } \tau_p = \frac{n_{[\text{plasma volume}]} }{n_{[\text{plasma surface}]} V_i(T) [1 + R_{pl}/L_{pl}]}.
\]

Averaged over the pulse time plasma parameter values are used everywhere in the formulas, so the time averaged plasma density is:

\[
\langle n \rangle_t \equiv n = n_0 \left[ \frac{\tau_p}{\tau_{\text{pulse}}} \right] \left[ 1 - e^{-\tau_{\text{pulse}}/\tau_p} \right], \quad (2)
\]

with \( n_0 \) being an initial density value. The laser spark length which was defined by thickness of the gas-jet target (see Figure 2) has been supposed to be \( L_{pl} = 500 \mu m \). Note also that all three plasma parameters in expressions (1) and (2) are averaged over the plasma volume.

Then, it was assumed that \( Z = 10 - \text{const.} \). This follows from the experimental fact that the Xe XI spectral lines emitted strongly in all our experiments, and also from what the ionization time for the transition Xe10+ → Xe11+ was close and longer (under our experimental conditions) than the laser pulse time.
Thus, the described consideration resulted in a system of two equations, (1) and (2), with respect to two unknowns, \( n \) and \( T \), which was solved for each point on the Y-axis (i.e. at different values of the geometric parameter, \( R_{pl} \)) separately with step-by-step approach (or with trial-and-error method). The obtained results are depicted in Figure 5.

![Figure 5](image)

**Figure 5.** Absorption coefficient (black squares), plasma temperature derived from it (blue triangles) and ion density (red circles) as functions of the jet-focus relative position at the laser pulse energy \( E_{las} = 1 \) J.

4. **Discussion and conclusion**

The way to deduce the plasma parameters from only the laser energy absorption looks like another method of the plasma diagnostics. However, it is unlikely can pretend for a universality. The ion charge can be indeterminable in plasmas with longer life time (or/and with lower temperatures and densities). Therefore, the absorption coefficient turns out to be a function of two unknowns.

The strong variability of the laser light absorption in the plasma (from 10 to 70%) subject to the mode of gas-jet illumination provides some options for optimization of the EUV source.

And finally, a similarity of the laser light absorption and the EUV emission as functions of the laser beam diameter needs a further research.

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