Further enhancement of the Xe LPP 11-nm radiation source efficiency – a study of the laser energy absorption at varied parameters of the gas-target irradiation

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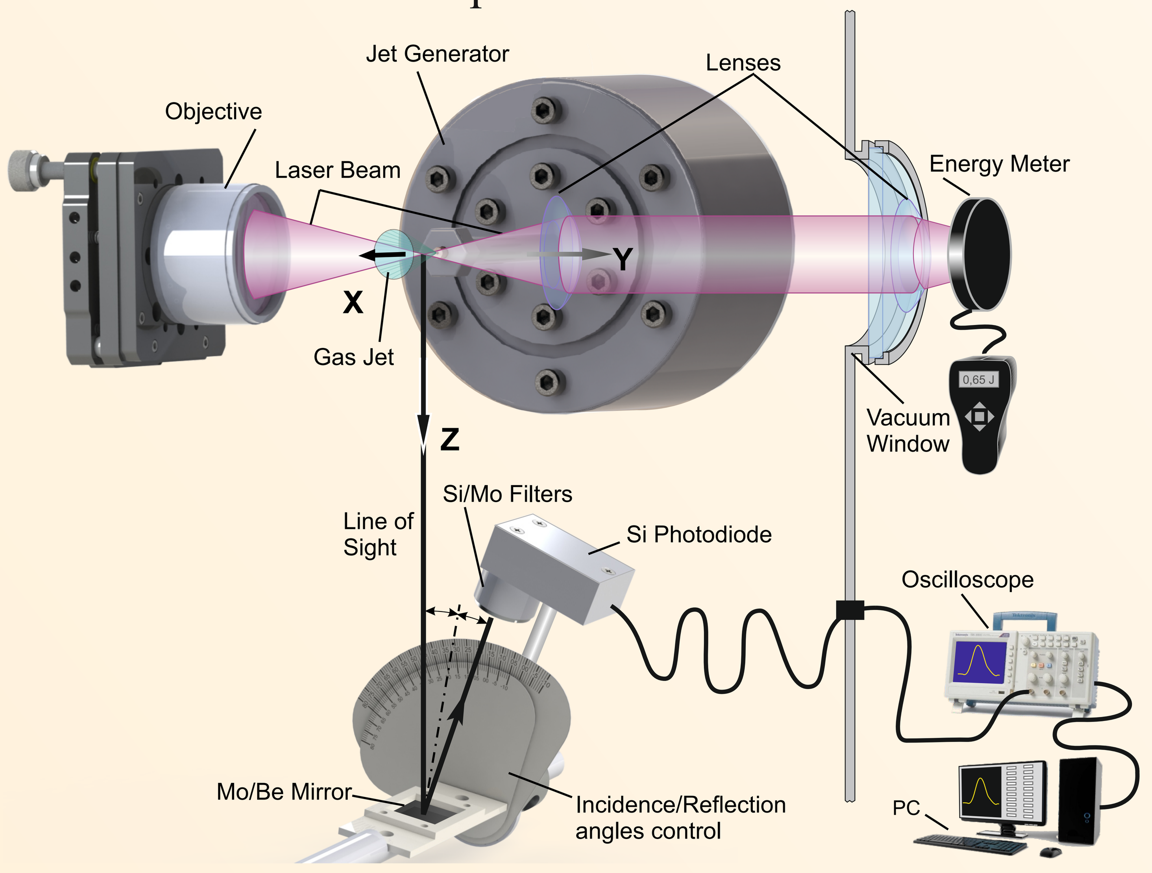
Motivation

At the Ioffe Institute, studies of the Xe laser plasma considered a promising $\lambda \approx 11$nm radiation source for the EUV lithography are ongoing. CE = 3.9% at $\lambda = 11.2$ nm attained by now [3] stimulates to a further source optimization effort.

Experiment details



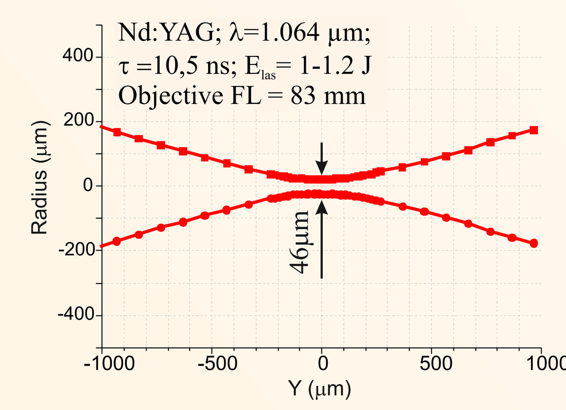


Fig.1. Measured geometry of the laser beam.

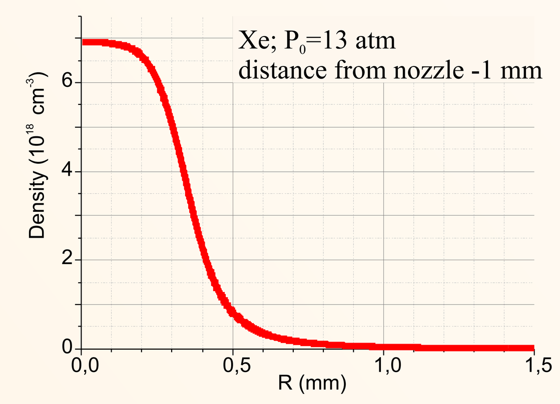


Fig.2. Gas-jet density under the experimental conditions (numerical simulation in [4])

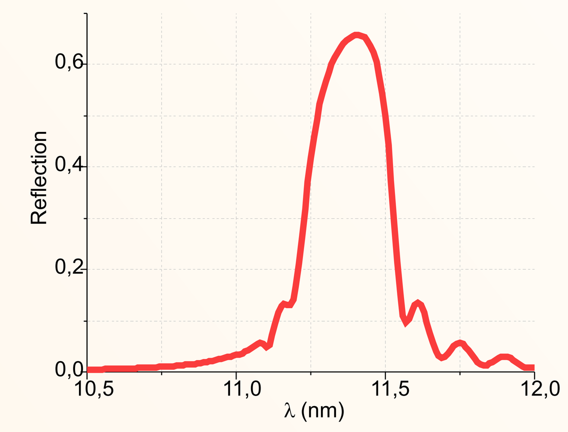


Fig.3. Reflection of the Mo/Be mirror at 76° vs. wavelength

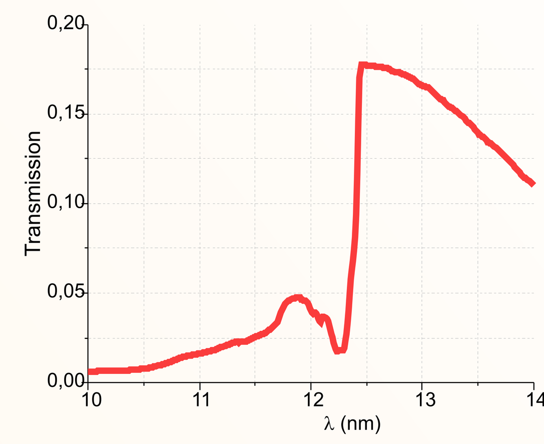


Fig.4. Transmission of Si/Mo spectral filter vs. wavelength.

Experimental results and analisis

Absorption measurements: The laser energy absorption in the plasma has been measured at 5 laser pulse energies – 1.0, 0.65, 0.56, 0.36 and 0.17 Joules. Along with variations of the laser beam diameter these cover more than two orders of magnitude of laser light intensities variations – from 5×10^{10} to 4×10^{12} W/cm^2 (Figs. 5 and 6).

The absorption cœfficient, μ , was derived from the experimental data on the assumption that an effective absorption length was L_{eff} = 500 μm (Fig. 7, black squares).

$$\mu = \frac{16\,\pi^2\,\Lambda\,e^6\,Z^3\,n_i^2}{(3\,m_e\,k_b\,T_i)^{3/2}\,c\,\omega_{las}} \qquad (1),$$

where Λ – Coulomb logarithm, e and m_e - electron charge and mass , Z - ion charge, k_B - Boltzmann constant, c - light speed, ω_{las} - laser light frequency, n_i and T - ion density and temperature.

The plasma temperature, T, was deduced from the values of μ with the help of (1) supposing Z = 10= const. The supposition has been based on the experimental fact that Xe XI spectral lines were strongly emitted in all of our experiments, and the consideration that the ionization time for $Xe^{10+} \rightarrow Xe^{11+}$ was longer (under our experimental conditions) than the laser pulse time.

Besides, in the calculations, hydrodynamic variations of the plasma density were taking into account as well:

$$n(t) = n_0\,e^{-t/\tau_p}\,, \qquad \tau_p = \frac{n\,[\text{plasma volume}]}{[nV_s(T)][\text{plasma surface}]} = \frac{R_{pl}}{2\,V_s(T)\,[1+R_{pl}/L_{eff}]}\,, \qquad \langle n\rangle_t = n_0\,[\tau_p/\tau_{pulse}][1-e^{-\tau_{pulse}/\tau_p}] = F(T)$$

Time-averaged values of n and T as deduced from μ are depicted in Fig. 7.

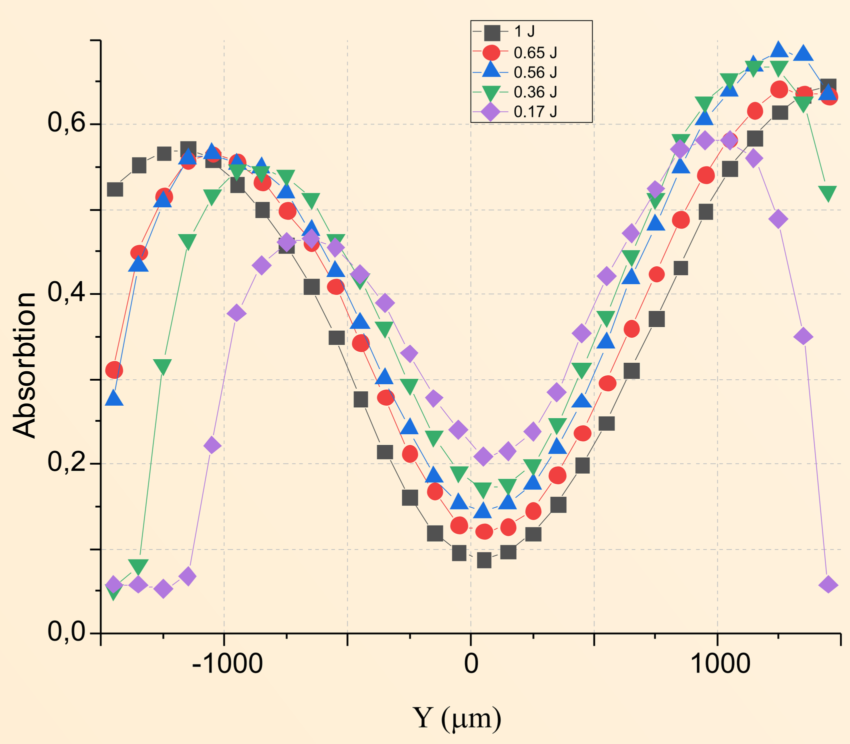


Fig.5. Measured laser beam absorption vs. jet-focus relative position for 5 cases of laser energy.

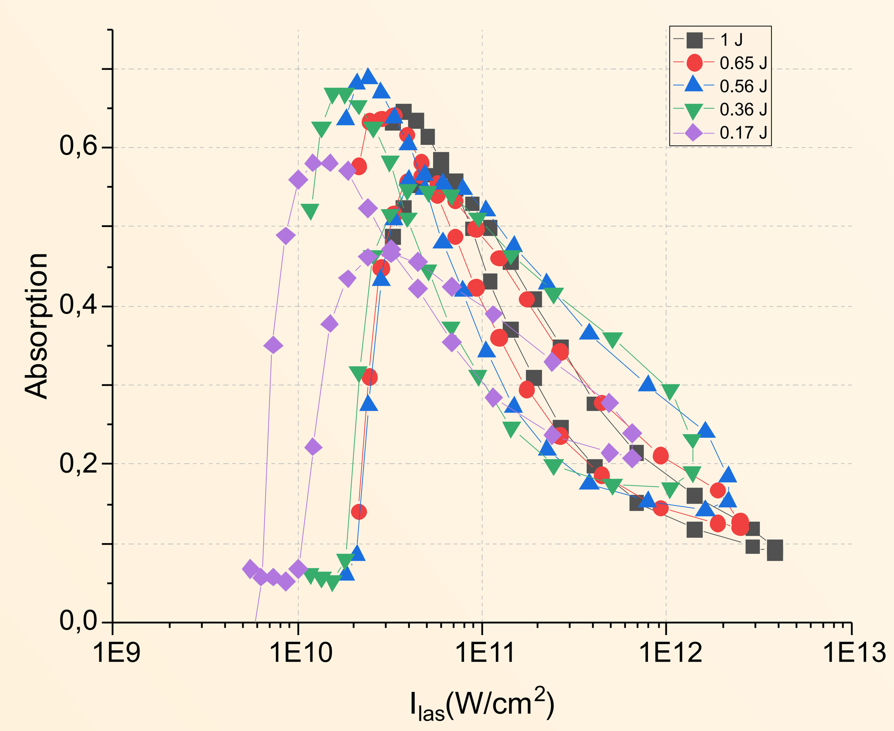


Fig.6. Absorption of laser energy vs. laser power density.

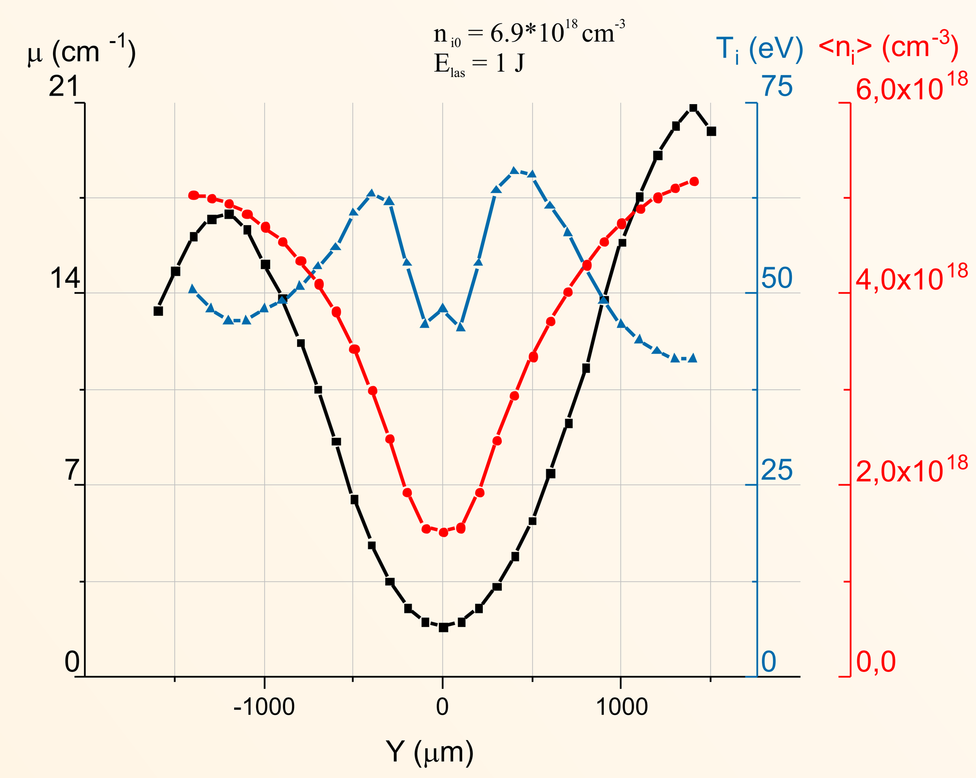


Fig.7. Absorption coefficient (black squares) and corresponding ion temperature (blue curve) and time-averaged ion density (red curve) vs. jet-focus relative position.

EUV measurements: Analogous to absorption measurements, the EUV radiation was measured as a function of the relative position of the nozzle axis and the laser focus (Fig.8). A ratio of the EUV radiation output to the absorbed laser energy was calculated (Fig. 9).

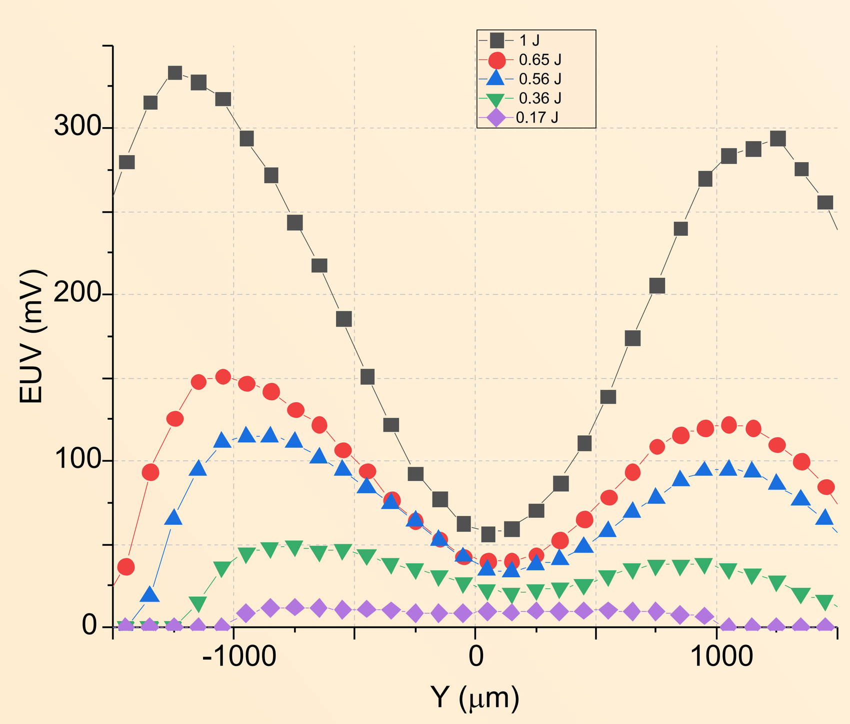


Fig.8. Measured EUV signal vs. jet-focus relative position

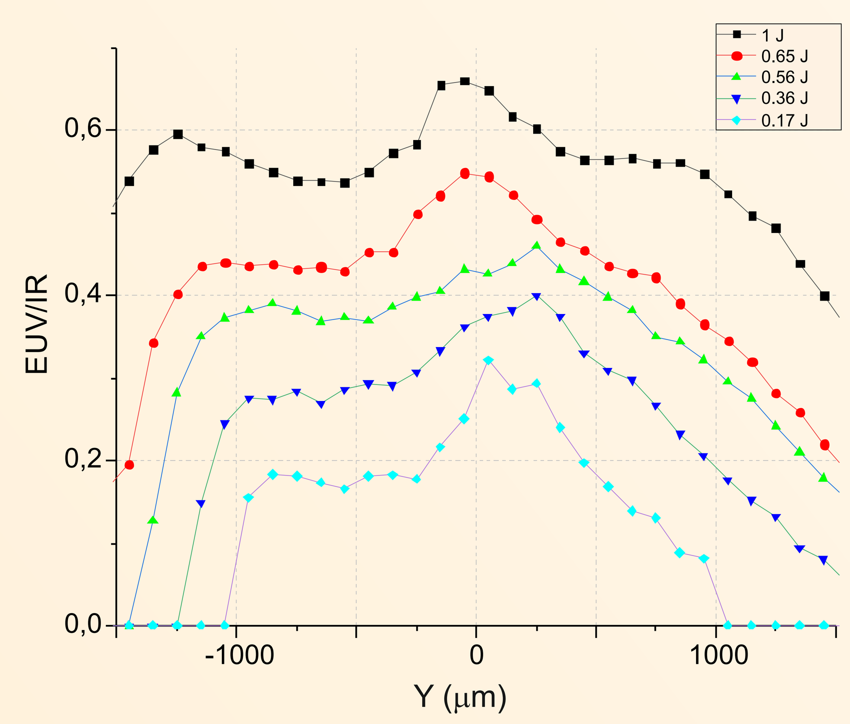


Fig.9. Calculated ratio of the EUV radiation output to the absorbed laser energy.

Findings

1. A strong dependence of the laser energy absorption in the plasma (10 to 70 %) on the laser irradiation geometry has been found. This provides a large spectrum of possibilities to optimize the EUV source efficiency.
2. A rough estimate of plasma parameters (density and temperature) has been deduced from the laser light absorption measurements. So, experiments of this sort can be considered as another method of the laser plasma diagnostics.

Acknowledgment

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References:

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[3] *S.G. Kalmykov, P.S. Butorin and M.E. Sasin* // J. Appl. Phys. 126, 103301 (2019)

[4] *A. V. Garbaruk, et al..* // J. Phys. D: Appl. Phys.. 2017. V. 50. 025201