XUV radiation from gaseous nitrogen and argon target laser plasmas

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Abstract. Laser plasma created in gaseous target is studied as a source of radiation in the “water window” wavelength range. Plasma is created by focusing an 800 mJ/7 ns Nd:YAG laser pulse into the gas-puff target. Using nitrogen gas results in emission of an intense quasi-monochromatic radiation with the wavelength 2.88 nm, corresponding to the quantum transition $1s^2p \rightarrow 1s^2$ of helium–like nitrogen ion. The emission spectrum with argon target covers all the water window range. Laboratory and computer experiments have been performed for both target gases. The spatial distributions of emitted energy in the water window spectral range were compared. The total emitted energy with argon was one order higher than with nitrogen.

1. Introduction
We intend to develop a new laboratory source of XUV radiation appropriate for university biological research laboratory. Namely, a source of intensive monochromatic radiation in the “water window” spectral region (2.33 – 4.37 nm) may be useful for imaging of small biological objects in water environment and as a source emitting continuous spectra in the vicinity of carbon K absorption edge may be used to study carbon molecular bonds via absorption spectroscopy. Such sources are not readily available today outside synchrotron facilities. We have decided to extend our previous research activities and to develop a source of XUV radiation based on laboratory plasmas properly heated either by capillary pinching discharge or by focused infrared laser radiation [1, 2].

Results of our study accomplished with nitrogen and argon plasma laboratory radiation source made by Laser-Laboratorium Göttingen (LLG) [3] are presented here. Recently, we have measured XUV emission spectra and proved the quasi-monochromatic emission at wavelength 2.88 nm with nitrogen and quasi-continuous emission spectrum with argon target. Here we pay attention to time profiles of emitted XUV radiation intensity and spatial distribution of emitted XUV energy. Results of computer simulations and experiments are summarized and compared.
2. Experiment

The experimental setup is shown in Figure 1. The target material - nitrogen and argon gas, respectively - is injected in short bursts through a conical tungsten nozzle into a vacuum chamber using a piezoelectric needle valve. The valve assembly is located at the top of the vacuum chamber. The plasma is generated by the impact of high energy pulses from an Nd:YAG laser focused onto the gaseous target by a 100 mm focal length plan-convex lens. The laser beam enters the chamber from a side, perpendicular to the direction of gas injection. The diameter of the focal spot is approx. 60 µm.

The wavelength of the laser output is 1064 nm. The energy of the pulses is 0.8 J and the pulse width 7 ns. The source was operated at 2 Hz repetition rate. For both temporal and imaging measurements, a 0.8 µm thick titanium foil filter was employed to block radiation outside the spectral region of interest.

2.1. Measured time dependences of emitted power

The waveforms were recorded using InfiniiVision DSO7104A digital storage oscilloscope (Agilent, USA) with an analogue bandwidth of 1 GHz and a sampling rate of 4 GSamples/s. The temporal profile of the infrared excitation pulses was measured using a biased InGaAs photodiode DET01CFC (Thorlabs GmbH, Germany) with a 1.2 GHz bandwidth. The photodiode was placed to detect the excitation radiation scattered from the focusing lens. The temporal profile of the infrared pulse presented in Figure 2 is an average of 100 recorded waveforms.

Time dependencies of emitted power in the XUV spectral region were recorded using a fast XUV-sensitive photodiode AXUV20HS1 (IRD Inc., USA) placed at the 250 mm distance from the source. A reverse bias voltage of 90 V was applied. The inbound radiation power was reduced by a pinhole aperture with 20 µm diameter placed 3 mm from the source. An additional titanium foil filter with 0.4 µm thickness was used to ensure the spectral purity of the detected radiation. The measured time profiles of infrared pulses from the excitation laser and XUV pulses generated from the plasma are shown in Figure 2.
2.2. Spatial profiles of emitted energy

Spatial distribution of energy emitted in the XUV region by the laser generated plasma was recorded in a pinhole imaging setup [5]. A 30 µm pinhole aperture was placed 34 mm from the object (plasma), followed by the titanium filter. The object-screen distance was 996 mm, thus the resulting magnification of the imaging setup was approx. 30 times. A hybrid semiconductor pixel device Timepix was used as the screen. The resolution of the Timepix chip is 256×256 pixels with pixel size 55 µm. The details and advantages of using Timepix device for detection of soft X-rays are given in [6].

![Image of Timepix setup and XUV radiation profiles](image)

**Figure 2.** Temporal profiles of measured emitted XUV radiation power from nitrogen (solid line), argon (dashed), and IR power from the excitation laser (solid grey).

![Image of XUV radiation distributions](image)

**Figure 3.** The spatial distributions of XUV radiation energy recorded using Timepix detector in a pinhole imaging setup for nitrogen (left) and argon (right) gas target.

The spatial profiles of XUV radiation emission recorded for nitrogen and argon gas targets, respectively, are shown in Figure 3. Both profiles were acquired by integration of 100 consecutive single-shot images recorded at 2 Hz repetition rate. The energy emitted from the nitrogen plasma is clearly smaller than that from argon plasma. Metal mesh supporting the titanium foil filter can be recognized as it is superimposed on the plasma images.
3. Computer modeling

The spatial development of plasma created by the laser beam was simulated using 2D RMHD (Radiation-Magneto-Hydro-Dynamic) code Z* [4]. The non-stationary, non-equilibrium radiation physics are introduced in this code for modeling the transient laser plasma properties in 2D geometry. The axis of symmetry of the simulations coincides with the laser beam axis.

For the purpose of calculation, the gas stream cone is approximated by a plasma disk target [5] (2D object) with axial symmetry along the laser beam (see Figure 4). The z-coordinate is oriented in the opposite direction to the laser beam propagation. Note that the laser beam is propagating horizontally in our experimental setup.

Figure 4. Gas puff laser plasma source geometry.

3.1. Input data for the Z* code

The input laser pulse time profile is presumed to be Gaussian with the peak position at 10 ns and the calculation begins at -15 ns. The main input parameters are listed in table 1.

Table 1. Laser and target parameters.

| Nd:YAG laser | Target |
|--------------|--------|
| Wavelength   | Thickness 0.2 nm |
| Laser energy | Focus position 2.5 mm |
| Pulse FWHM   | Radius 2.5 mm |
| Focal length | Focal spot diameter 0.05 mm |
| Pressure N₂  | Pressure Ar 10 bar |

3.2. Spatial distributions of plasma quantities

The Z* code allows to determine all plasma field quantities at given temporal and spatial coordinates; plasma mass density $\rho$, longitudinal and radial velocities $v_z$ and $v_r$, electron density $N_e$, electron and ion temperatures $T_e$ and $T_i$ during the laser pulse. The spatial distributions of selected field quantities with nitrogen initial pressure 10 bar at three different times (at 4 ns – corresponding to the laser pulse leading edge, 8 ns – peak of laser power and 18 ns- after the laser pulse) are shown in Figure 5.

At the very beginning of the laser pulse (~ 1 ns) a deep crater is formed and the gas target is “drilled through” at ~ 4 ns. The mass density compression wave moves in the radial direction in the gas layer. After the end of the laser pulse the compression wave vanishes (see the 1st row of figure 5). The created plasma moves in the opposite direction to the laser beam reaching the highest value of longitudinal velocity $v_{z,max} = -180 \text{ km.s}^{-1}$ at the time ~ 4 ns. When the crater is formed, the plasma starts moving in both directions. The peak value of electron plasma density is achieved at ~8 ns i.e. in the region of the compression wave (see the 2nd row of Figure 5).

Changes of electron temperature $T_e$ are seen from the 5th row of Figure 5. During a short period before the deep crater is formed the increase of temperature is remarkable in front of the gas target. The peak value of electron temperature is $T_e \sim 130 \text{ eV}$ is achieved at the peak of laser pulse. Spatial distribution of electron temperature is almost the same on both sides of the target sheet and fades away with increasing time. The plasma is non-isothermal in the central part of the plasma cloud.
Figure 5. Spatial distribution of selected plasma quantities at various times for initial nitrogen pressure 10 bar: 1 - Mass plasma density \( \rho \), 2 - Longitudinal velocity \( v_z \), 3 - Radial velocity \( v_r \), 4 - Electron density \( N_e \) (in Av units), 5 - Electron temperature \( T_e \).
3.3. Spatial distributions of emitted energy
The code Z* enables us also to determine the spatial development of plasma radiation, together with all its spectral characteristics. The integrated power emitted in the 2.88 nm helium – like nitrogen spectral line at ~ 4, ~ 8 and ~ 20 ns, evaluated for the above used parameters, is seen from Figure 6. At the very beginning of the pulse \( t < 1 \) ns the volume of radiation is very small. In the radial direction its radius is practically the same as the laser beam radius 25 \( \mu m \) \( \) and in the longitudinal direction it is \( \sim 45 \mu m \). The volume of the luminous region and the local amplitude of the emitted radiation grow up to the time of the peak value of the laser power and are stable later on.

![Figure 6](image)

**Figure 6.** Spatial distributions of integrated power emitted in wavelength band 2.876 - 2.886 nm at various times; for nitrogen target initial pressure 10 bar.

3.4. Pressure dependence of emitted energy
We have performed repetitive simulations for various initial nitrogen gas pressures and the above used other parameters. The dependence of the spatially integrated emitted energy in the three selected bands is seen from Figure 7. In the pressure region from 1 bar to 50 bar the emitted energy is increasing with increasing initial pressure. If the pressure is about 50 bar the highest expected energy in the quasi-monochromatic spectral line is about 1.5 mJ whereas for the pressure about 5 bars the estimated output is one order lower, corresponding to \( 10^{11} - 10^{12} \) photons/steradian.

![Figure 7](image)

**Figure 7.** Pressure dependences of radiation energy emitted in selected spectral bands.

4. Comparison of simulated results for argon and nitrogen
We have compared the evaluated results for nitrogen and argon performed under identical initial conditions. The initial pressure of 10 bars has been presumed. The output emission in the spectral wavelength region limited by the transmission of the titanium foil was taken into account. For nitrogen
4.1. Evaluated time dependences of absorbed laser power and emitted radiation power
Spatial integration over the laser plasma cloud provides the information about total absorbed laser power and total emitted power in selected spectral bands, see Figure 8. The peak value of absorbed power is almost two times higher with the argon gas than with the nitrogen one. The peak value of the emitted radiation in the whole radiation spectrum is more than 4 times higher with argon gas than with nitrogen. The peak value of emitted power in the single 2.88 nm line of helium-like nitrogen is about $8 \times 10^4$ watts, whereas the power emitted by the argon plasma, when filtered by the titanium foil, is estimated to be $3 \times 10^6$ watts.

![Figure 8](Image)

**Figure 8.** Time dependences of laser power (blue filling), absorbed power (green filling), emitted radiation power (orange filling) and XUV radiation power (yellow filling) from nitrogen and argon targets at pressures 10 bar (XUV output power for nitrogen is 10 times magnified).

4.2. Evaluated spatial profiles of emitted energy in selected spectral bands
The evaluated spatial distributions of energy emitted in selected spectral bands by the plasma cloud are shown as Figure 9. The plasma source may be roughly approximated by a cylinder 450 $\mu$m long with diameter of 150 $\mu$m if nitrogen is considered and by a cylinder 850 $\mu$m long with diameter of 400 $\mu$m with argon. The estimated peak value of the emission is roughly one order higher with argon than with nitrogen.

5. Conclusions
We have studied laser plasma as a source of XUV radiation and compared the results of computer and laboratory experiments for nitrogen and argon. The calculated time profiles of XUV radiation power and spatial distributions of luminous areas are in a good agreement with the experimentally recorded data. The initial density of the gas target during the experiment was not known. Therefore, an estimated value had to be used for the simulations. Performed computer simulations show strong increase of emitted XUV energy with pressure in the range from 1 to 50 bars. Thus, to achieve higher output energy of XUV radiation, higher gas density in the jet is needed.
Figure 9. Estimated XUV radiation energy spatial distributions emitted by nitrogen and argon targets when observed behind the titanium foil; initial pressures are the same for both gases.

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