Analyzing x-ray emission of target impurities to determine the parameters of recombining laser plasma

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Abstract. In this work, the possibility of the implementation of impurities in the compositions of solid thick targets irradiated by intense lasers is discussed in order to solve problems of optically-thick plasma diagnostics. Calculations were conducted for relative intensities of oxygen resonance lines (H-like—3p–1s, 4p–1s, 5p–1s, 6p–1s, 7p–1s transitions) in a recombination quasi-stationary model to obtain plasma parameters. In the experiment with 0.6 ns, 40 J laser pulses focused to 600 $\mu$m focal spot at solid polyvinylidene chloride target the parameters of plasma jet stopped by solid oxidized Teflon obstacle were studied by means of spatially-resolved x-ray spectroscopy.

1. Introduction
X-ray diagnostics is one of the most demanded techniques, to date, to determine parameters of the test object. It found applications in biology and medicine [1], chemistry [2], crystallography [3] and of course in plasma physics [4, 5]. X-ray spectroscopy is used in high energy density physics to research charge state of plasma object, its electron temperature, density and even velocity. However, certain complexities can be appeared creating such dense object associated with its optical thickness. In this case, the absorption in resonance lines of multicharged ions can lead to a wrong evaluation of plasma parameters. Often plasma consists of ions of different chemical elements, especially when it comes to irradiation of solid thick targets by intense lasers in contemporary facilities. The focus of the paper is to demonstrate the possibility of use the impurities inside these targets, for example oxygen layer on the target surface, to receive the dynamics and parameters of plasma flows expanded into vacuum.
2. Experimental setup

Experiments in creation of laser-induced plasma flows were performed in France, at the Ecole Polytechnique in laboratory LULI on the ELFIE facility. A laser beam with a basic frequency ($\lambda = 1.057 \, \mu m$), energy $\approx 40$ J and pulse duration 0.6 ns was directed at $10^\circ$ to the normal to the front surface of the solid PVDC target (polyvinylidene chloride—chemical formula $[C_2H_2Cl_2]_n$) into a focal spot about 600 $\mu m$ size. Achieved intensity on the target at these conditions was $2 \times 10^{13}$ W/cm$^2$. The experimental scheme is given in figure 1. The generated plasma flow was expanded into the vacuum with velocity about 500 km/s and then collimated by the large-scale magnetic field 20 T [6] by means of the Helmholtz coil [7]. Almost constant values of electron temperature and density [8] as well as a diameter of the plasma flow (about 1 mm) allow to use this experimental platform [6] to simulate various astrophysical phenomena. Here the collimated plasma flow was collided with a solid obstacle manufactured from another material—Teflon (CF$_2$)—to simulate accreting columns valid for the Young Stellar Objects (YSO). Plasma emission close to the obstacle is investigated. The cornerstones and astrophysical interpretation of experiment are discussed in details in paper [9].

Emission spectra are registered by focusing spectrometer with 1D (one-dimensional) spatial resolution (FSSR) along expansion axis of laser-induced plasma jet. FSSR was equipped with a spherically bent mica crystal with a lattice spacing $2d = 19.9376 \, \AA$ and curvature radius of $R = 150 \, \text{mm}$. The crystal was aligned to operate at $m = 1$ order of reflection to record
the emission spectra of multicharged fluorine ions in 13–16 Å wavelength range (800–950 eV corresponding energy range). By the way, obstacle target was oxidized, that is why oxygen has been detected within the same wavelength range with hydrogen-like transitions 4p–1s, 5p–1s, 6p–1s 7p–1s of corresponding ion (O H-like). Typical spectrum with visible lines in experiment is given in figure 2. Spectra were recorded on fluorescence detector Fujifilm Image Plate which was situated in a cassette holder shielded from the optical radiation. The aperture of the cassette was covered by two layers of filters made of polycarbonate (2 µm) coated with aluminum (7 nm). The spatial resolution along expansion direction ≈ 100 µm was achieved.

3. Diagnostics of recombining plasma
A plasma stream at significant distance from the laser-irradiated target usually is characterized by a non-stationary distribution and plasma is in a recombination mode [8]. Typically, the unique quasi-stationary approach, described in details in [10, 11], is used to measure electron density and temperature. The method is based on the calculation of relative intensities of the resonance transitions in He-like and H-like ions and also takes into account recombining plasma with “frozen” ion charge. It was shown the method is sensitive when the electron density is in the range of $10^{16} – 10^{20}$ cm$^{-3}$ while the temperature ranges from 10 to 100 eV for ions with nuclear charge $Z_n \sim 10$. In this paper the calculations were carried out the same way as in [10] but for O VIII ions and are presented in figure 3.

Here the resonance line Ly$\gamma$ (4p–1s transitions) was chosen as a normalization factor mainly due to its reasonable values and more successful location than for Ly$\beta$ line—the latter is close to the end of the range where distortion effects can play a major role. Obviously, two any ratios are enough to describe clearly plasma parameters, but the additional ratios can improve
The experimental approach allows to observe the parameters of the recombining plasma shocked by the obstacle and propagating back from it [9]. Note, the emission of the incoming plasma flow before putting the solid obstacle is negligible. Table 1 demonstrates observed parameters of plasma flow close to the obstacle surface. Electron density close to the obstacle was about $3 \times 10^{18}$ cm$^{-3}$, which is consistent with data derived by the optical interferometry in the experiment. Electron temperature was $\approx 45$ eV and actually corresponds to values obtained using a basic element of the target material—fluorine. As a result the plasma parameters obtained by impurity emission spectra confirms the strong influence of the solid obstacle on the dynamics of the plasma flow as well as the generation of a plasma region with increased electron density and temperature [9].

We note here that use of this method requires the investigated plasma to be optically thin, i.e. self-absorption effects are negligible. For example, the utilization of resonance fluorine lines Lyα or Heβ gives here 10–15% of self-absorption at measured plasma parameters. As a result it leads
Table 1. Values of electron density and temperature according to the distance from the solid obstacle surface. Zero value corresponds to the point close to obstacle surface. All values are mean values by 500 µm to avoid noise issues.

| Distance, mm | Density, cm⁻³ | Temperature, eV |
|-------------|---------------|----------------|
| 0           | 3.5 × 10¹⁸    | 45             |
| 0.5         | 2.2 × 10¹⁸    | 32             |
| 1           | 1.7 × 10¹⁸    | 26             |
| 1.5         | 1.0 × 10¹⁸    | 19             |
| 2           | 6.0 × 10¹⁷    | 19             |
| 2.5         | 4.0 × 10¹⁷    | 13             |

to iterative corrections in intensity ratios and plasma parameters making it more difficult. By the way, close to the laser-irradiated target and using more dense plasma objects, self-absorption effects are therefore stronger. However, the application of an impurity substance allows to receive significantly less optical thickness since the ion density of impurities are less than for the basic material. It makes possible to investigate the plasma parameters more accurately. For sure, it is necessary to note and negative side. In case of impurities the x-ray yield is very low at huge distances from laser-irradiated surfaces or obstacles hampering the description of relative intensity ratios and consequently plasma parameters. However, combined application of both materials assists to significantly clarify characteristics.

4. Conclusions
The described above method demonstrated the possibility of use the impurities inside and on solid targets to receive the dynamics and parameters of plasma flows expanded into vacuum. Particularly, it can be useful to obtain the electron temperature and density more accurately in case of optically thick plasma in an experiment. By the way, the calculation of relative intensities for H-like oxygen resonance lines (3p–1s, 4p–1s, 5p–1s, 6p–1s, 7p–1s transitions) in a recombination quasi-stationary model is conducted making possible to use them for oxidized targets.

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