Diagnostics of recombining laser plasma parameters based on He-like ion resonance lines intensity ratios

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Abstract. While the plasma created by powerful laser expands from the target surface it becomes overcooled, i.e. recombining one. Improving of diagnostic methods applicable for such plasma is rather important problem in laboratory astrophysics nowadays because laser produced jets are fully scalable to young stellar objects. Such scaling is possible because of the plasma hydrodynamic equations invariance under some transformations. In this paper it is shown that relative intensities of the resonance transitions in He-like ions can be used to measure the parameters of recombining plasma. Intensity of the spectral lines corresponding to these transitions is sensitive to the density in the range of 10^{16}–10^{20} cm^{-3} while the temperature ranges from 10 to 100 eV for ions with nuclear charge $Z_n \sim 10$. Calculations were carried out for F VIII ion and allowed to determine parameters of plasma jets created by nanosecond laser system ELFIE (Ecole Polytechnique, France) for astrophysical phenomenon modelling. Obtained dependencies are quite universal and can be used for any recombining plasma containing He-like fluorine ions.

1. Introduction

General idea of x-ray plasma diagnostics is associated with the fact that parameters of radiated x-ray spectrum, such as line width or intensity ratios of several spectral lines, depends on plasma parameters. Diagnostics is provided by obtaining an agreement between parameters of calculated and observed spectra. Such diagnostics is successfully applied for plasma observed both in different laboratory experiments and in astrophysical objects (e.g. [1–6]).

It should be noted that the most of methods based on x-ray spectra analysis use the assumption that the ionization state of the plasma is close to the steady state for a given electron temperature. However, in many instances, including the case of expanding laser plasma, ionization state of a plasma is definitely non-stationary. However, in many instances, including the case of expanding laser plasma, ionization state of a plasma is definitely non-stationary. For example, plasma expanding from the laser irradiated target surface has ionization state that corresponds to the temperature of electrons which is higher than its real electron temperature. Such plasma is called recombining. The condition $T_e \ll T_z$ (ionization temperature T_z is the temperature of stationary plasma with the same ionization state as given) is sufficient to consider the plasma as recombining. In fact, it means that plasma can be recombining at arbitrarily high temperature if the temperature T_z is high enough. Rising tide of interest to such plasma is associated with laboratory astrophysics because it is fully scalable to young stellar objects (YSOs) [7–10]. The scaling is possible because of the invariance of the plasma hydrodynamic equations under a set of transformations [11]. The type of transformation depends on the type of plasma [12–15]. So to improve diagnostic methods applicable for such plasma is rather important problem in laboratory astrophysics.

In this paper it is shown that relative intensities of transitions $1snp\,^1P_1$–$1s^2\,^1S_0$ where $n = 3$–7 in multiple charged He-like ions (He$_\beta$, Heγ, He$_\delta$, He$_\varepsilon$, He$_\xi$ lines correspondingly), can be used for recombining plasma diagnostics. Such lines are sensitive to the density in the range of 10^{16}–10^{20} cm^{-3} when the temperature ranged from 10 to 100 eV for ions with nuclear charge $Z_n \sim 10$. Calculations were carried out for F VIII ion and can be used for any recombining plasma containing such ions. Example of the proposed diagnostic method application for determining of the plasma jets parameters produced at laser facility ELFIE (Ecole Polytechnique, France) is also provided.

2. Intensity ratios calculations for resonance series lines of He-like ion in case of recombining plasma

Intensity ratios as well as intensities of spectral lines are proportional to populations of an excited ion levels, which can be obtained from the set of kinetic equations:

$$\frac{\mathrm{d}N_i^Z}{\mathrm{d}t} = \sum_{i',Z'} K_{ii'}^{ZZ'} N_{i'}^{Z'}, \tag{1}$$

where N_i^Z is a population of level with index i (levels are numbered in the order of increasing energy) for ion with spectroscopic symbol Z, and $K_{ii'}^{ZZ'}$ is a kinetic matrix. Off-diagonal elements of the kinetic matrix equals to probabilities of transition between i', Z' and i, Z by all possible atomic processes. Diagonal elements multiplied by -1 equals to the sum of probabilities of transitions from state i, Z to all others. In case of non-stationary plasma approach the calculation of excited level populations should take into account non-stationary distribution of ions throughout the ionization stages [16–18]. This approach can be based on so called quasi steady-state approximation.

In the most of cases, especially for multicharged ions' plasma, the relaxation time $\tau_i^Z \sim (K_{ii'}^{ZZ'})^{-1}$ of ground states is greater (often by some orders) than the relaxation time of excited states, in particular such difference results in widely known "frozen" charge states effect. Also, it should be noted that populations of excited states are very low and reach stationary values rather fast. This facts forms the core of mentioned quasi steady-state approximation, which allows to set left-side of (1) to zero for excited states and reduce it to algebraic set of equations instead of differential ones. Populations in such approach can be expressed with the help of population coefficients.

$$N_i^Z = \beta_i^Z N_e N_1^{Z+1} + S_i^Z N_1^Z, \tag{2}$$

where index 1 is used for the ground state, β_i^Z is a recombination population coefficient and S_i^Z is excitation population coefficient. The first member in (3) dominates for recombining plasma [16]. The possibility of such neglecting depends not only on T_e but also on the ratio N_1^{Z+1}/N_1^Z. If $T_e \ll T_z$ then the first term in (2) is greater the second one. Of So in terms of quasi steady-state approximation set of equations (1) transforms into algebraic system for β_i^Z:

$$\sum_{i'} K_{ii'}^{ZZ} \beta_{i'}^Z = -\frac{K_{i1}^{Z,Z+1}}{N_e}, \quad i > 1. \tag{3}$$

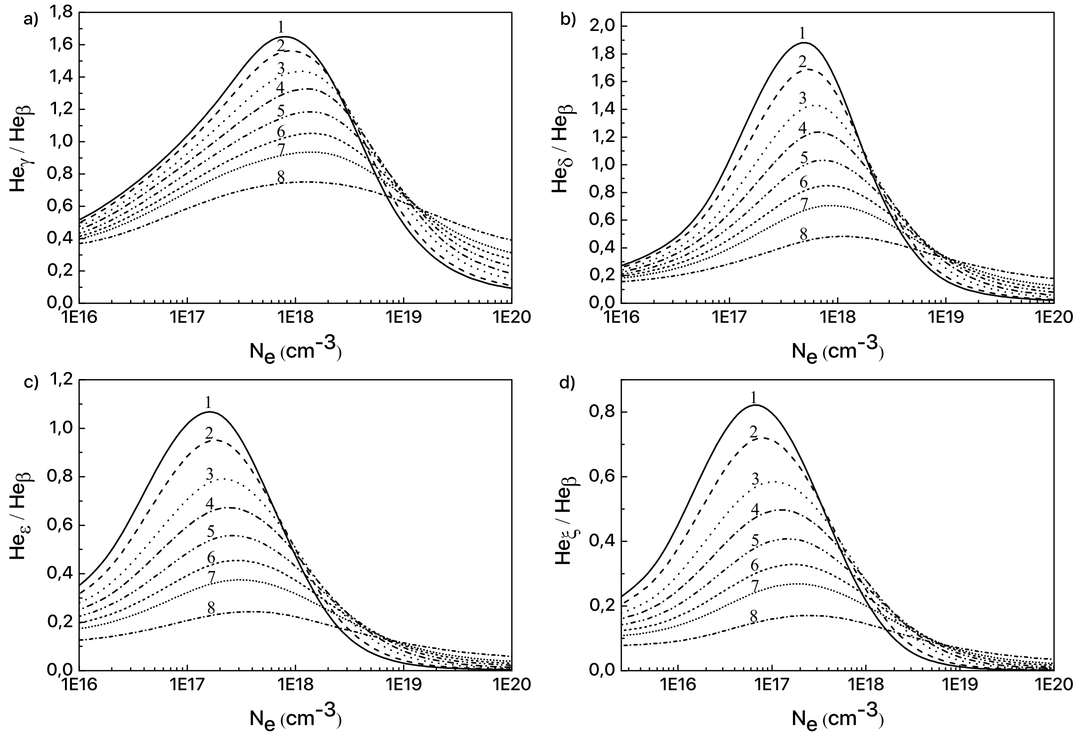

Figure 1. Intensity ratios: (a) $\mathrm{He}_\gamma(1s4p\,^1P_1\text{–}1s^2)$ and $\mathrm{He}_\beta(1s3p\,^1P_1\text{–}1s^2)$; (b) $\mathrm{He}_\gamma(1s5p\,^1P_1\text{–}1s^2)$ and He_β; (c) $\mathrm{He}_\gamma(1s6p\,^1P_1\text{–}1s^2)$ and He_β; (d) $\mathrm{He}_\gamma(1s7p\,^1P_1\text{–}1s^2)$ and He_β. Different curves correspond to temperatures: 1—9.6 eV, 2—12.8 eV, 3—19.2 eV, 4—25.6 eV, 5—35.2 eV, 6—44.8 eV, 7—64 eV, 8—128 eV.

Obtaining of β_i^Z values from (3) is one of the main aims of our work. It should be noted that in the case when the second term can not be neglected (for example ionizing plasma) it is necessary to solve a similar to (3) system for the coefficient S_i^Z [19]. The solution of (3) can be solved only numerically. It is impossible to write the analytical expression for it. For solving (3) we took into account all the transitions between $1snl$ levels with $n < 20$ during following processes: electron-impact excitation and deexcitation, electron-impact ionization, three-body recombination, radiative decay and photorecombination. Levels with $n > 20$ were divided into two groups (triplets and singlets) and they were considered in terms of single-quantum approximation [17]. The fine structure is taken into account for $1s2l$ levels, $1snl\,^{(2S+1)}L_J$ levels with $n = 3$–5 were considered as levels with total angular momentum degeneracy; levels with $n > 5$ were considered as levels with both total angular momentum and orbital momentum degeneracy.

In accordance with (2) intesity ratio equals to ratio of calculated β_i^Z coefficients multiplied by corresponding probabilities of radiative transitions. Probabilities were taken from [20–22]. Calculations were held for F VIII ion in wide ranges of density and temperature of plasma. Dependency of intensity ratios on electron density is shown on figure 1 for different temperatures.

For recombining plasma the intensity ratios of fluorine ion's lines are sensitive to plasma's electron density only in the range of 10^{16}–10^{20} cm^{-3} when the temperature ranges from 10 to 100 eV. Out of the mentioned density range relative intensities for F VIII ions are quite constant so it is impossible to use them for plasma's parameters determination. But the density values,

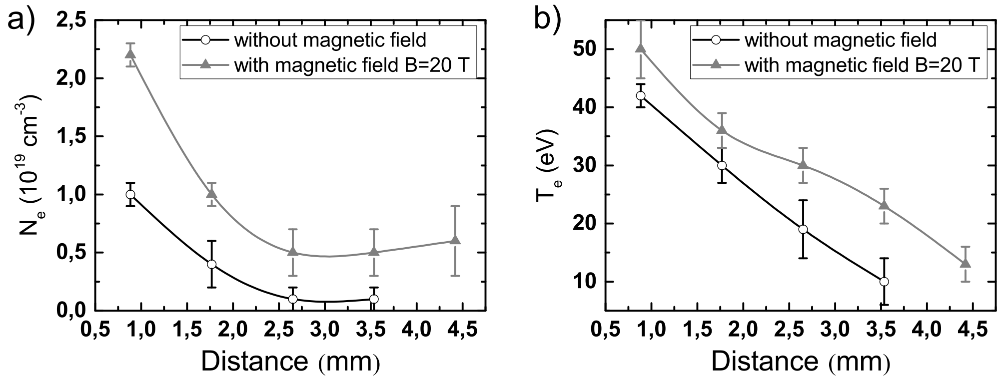

Figure 2. Plasma parameters obtained with help of intensity raios: (a)—electron density, (b)—electron temperature.

which are usual for laboratory astrophysics' experiments and, in particular, for experiments carried out on ELFIE experimental setup, lie inside the mentioned range. It is confirmed by interferometry measurements [8, 10, 23]. Spectral lines of another He-like ions can be used in case of different density range.

Due to the curves for intensity ratios are nonmonotonic there are two different solutions which correspond to lower and higher density. In order to avoid such ambiguity, four different ratios are used simultaneously to determine two parameters of plasma.

3. Determination of plasma parameters for jets generated by ns laser pulse focused at teflon targets

The described method was applied to interpret the data obtained in laboratory astrophysics experiment [10]. This experiment was carried out on ELFIE experimental setup in Ecole Polytechnique. Density and electron temperature were determined for plasma jets immersed in external magnetic field created by pulsed coil. Plasma jet was created by laser beam with wavelength $\lambda = 1.053$ nm with pulse duration of ~ 0.5–1 ns and energy from 5 to 50 J focused on a $(C_2F_4)_n$ target in spot with diameter of 750 μm. The main motivation for such experiments was to reproduce a plasma jet evolution appeared near the polar region of YSOs where an intense poloidal magnetic fields (with force lines parallel to the star rotation axis) are assumed to be acting and inside the external magnetic field. Spectra were recorded using focusing spectrometer with spatial resolution (FSSR), equipped with spherically bent mica crystal with a lattice spacing $2d = 19.9376$ Å and a radius of curvature $R = 150$ mm. The crystal was aligned to operate at $m = 1$ order of reflection to record emission spectra of multicharged fluorine ions in 13–16 $\AA$ wavelength range which corresponds to 800–950 eV energy range. Spectra were recorded on fluorescence detector Fujifilm Image Plate TR which was situated in the light-tight cassette. The aperture of the plate holder was covered by two layers of filters made of polycarbonate (2 μm) evaporated by aluminum (40 nm). The recorded x-ray spectrum were adjusted with help of a spectrometer instrument function which is determined by a method of numerical calculation calculations of x-rays traced within dispersion scheme [24].

Electron temperature and density profiles of the plasma were defined with the spatial resolution along the jet axis, on the base of He_β, $He\gamma$, He_δ, He_ε, He_ξ lines' relative intensities which are shown on figure 1. $N_e(x)$ and $T_e(x)$ profiles for two different cases are shown on figure 2.

As one can see from the figure 2, the method allowed to determine plasma parameters far from the target surface (up to 4.5 mm). Sensitivity of the method is enough to demonstrate the difference between parameters of plasma jets expanded with and without external magnetic field. For determined plasma parameters optical depth of the plasma was calculated for all spectral lines considered for plasma diagnostics. It was confirmed that the plasma is optically thin in all lines which allow using it without any restrictions.

The main source of errors in plasma parameters' definition is inhomogeneity of plasma in the direction across the jet propagation. Generally, such errors can be minimized by using the spectrometer setup with two-dimensional spatial resolution.

4. Conclusion

Characteristics of x-ray spectrum, e.g. the spectral widths of one or several lines or the ratios of the intensities of several pairs of clearly observed lines emitted by the plasma, depends on the plasma parameters. Sensitivity of He-like ion resonance lines intensity ratios to the density in the range of 10^{16}–10^{20} cm^{-3} while the temperature ranges from 10 to 100 eV for F VIII ions is shown as example. The method based on the fact of such sensitivity was applied to successfully interpret the spectra of F VIII ions emitted by laser plasma jet created from CF_2 solid target irradiated by nanosecond 10–60 J laser pulses. For diagnostics in a different density range, the spectral lines of other He-like ions can be used. The probabilities of atomic transitions in He-like ions with $Z_n \sim 10$ should be scaled along the isoelectronic sequences according to the same laws as for H-like ions. In this case, the regions of sensitivity of the relative intensities to the temperature and plasma density will be shifted approximately by $(Z_n - 1)^2$ and $(Z_n - 1)^7$, respectively. Method allowed determining plasma parameters rather far from the target surface. Sensitivity of the method was proved to be enough to distinguish the difference between parameters of plasma jets for various geometries in the experiment.

Acknowledgments

This work was supported by the Russian Science Foundation (project No. 14-50-00124).

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