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New method of comparison for electron temperature measurements in plasmas using X-ray spectra of heavy elements

A.P. Shevelko

Abstract. **Conditions and applicability limits of a new X-ray spectroscopy method for electron temperature measurements in plasmas of heavy elements are considered. The method is based on comparison of spectra under study with those of well diagnosed laser-produced plasmas. To apply the method for diagnosing tungsten plasmas a thorough analysis of laser-produced plasma spectra has been performed. The analysis included investigation of spectrum peculiarities and determination of electron temperatures. Quantitative data were obtained for determining electron temperatures in tungsten plasmas using relative intensities of spectral peaks in the spectral range $\lambda = 3 - 6$ nm.**

Keywords: *diagnostics of high-temperature plasmas, multiply-charged ions, X-ray spectra.*

1. Introduction

X-ray spectroscopy of multiply-charged ions is a most efficient method for studying high-temperature plasmas, which is widely used for diagnosing laboratory and astrophysical plasmas. Presently, the most developed methods are based on diagnosing the spectra of hydrogen- and helium-like (H- and He-like) multiply-charged ions [1, 2]. In particular, the electron temperature T_e is determined from the ratio of dielectronic satellite intensities to that of a reference resonance line. The resonance lines and the corresponding dielectronic satellites are excited from the same ion states; hence, the lines are emitted from the same plasma domains, and the ionisation state does not affect the measured temperature T_e.

X-ray spectra of heavy-element plasma (of elements with large atomic weights A_Z) usually exhibit a complicated structure distinct from that of H- and He-like ions. They also include many spectral lines originated from ions of different ionisation stages. The overlapping lines in the spectra result in a quasi-continuum. This noticeably hinders spectral diagnostics of such plasma. Nevertheless, these spectra are often of great interest in scientific investigations, for example, molybdenum and tungsten spectra in tokamak plasmas (materials of a divertor [3]), tungsten spectra in high power Z-pinch plasmas (a material for wire arrays [4]), stannum spectra in plasma sources for projection EUV lithography [5].

In most cases, the coronal equilibrium is valid for multiply-charged ions [6]. In the coronal model, unlike the thermodynamic equilibrium, the degree of ionisation is independent of the electron density N_e. In this model, the spectrum structure and ionisation composition of a stationary plasma are described by a single parameter, namely, the electron temperature T_e, which allows one to compare spectra of different plasma sources by this parameter.

In [7], a new method was proposed for determining the electron temperature of iron plasma. This is based on a comparison of the spectra under study with those of well-studied laser-produced plasma. The method is successfully employed for diagnosing iron plasmas produced in a final anode – cathode gap of the high-current pulsed Z-Machine generator (Sandia National Laboratories, USA) [7]. Further development of the method, expansion it to other elements and a wider temperature range are worthwhile. The present work is aimed at developing the method for diagnosing tungsten plasma. With this purpose, tungsten spectra in laser-produced plasmas were thoroughly analysed and the spectral ranges were found sensitive to the electron temperature; quantitative data were obtained for determining the plasma temperature.

2. Description of the method and conditions of applicability

In the new method for determining the electron temperature T_e of heavy-element plasmas it is proposed to compare the studied spectra with those of well-diagnosed laser-produced plasmas [8] (see Fig. 1). In this approach, the important property of laser-produced plasmas is used: at moderate flux densities of laser nanosecond pulsed radiation on a target, the electron temperature of a hot plasma core mainly depends on the flux magnitude and only weakly depends on the atomic weight of a target material [9, 10]. This is explained by mutual compensation of the two factors: at fixed temperature T_e, the ionisation losses increase with an increase in A_Z; however, they are compensated by an increase in the absorbed energy of laser radiation per ion [9, 10].

Diagnostics of laser-produced plasmas is performed by spectra of light elements whose structure is similar to that of H- and He-like ions, for which the corresponding methods of temperature measurements are well developed (see, e.g., [1, 2]). The spectral structure and intensity distribution of heavy-element plasmas are very sensitive to T_e, this fact is

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A.P. Shevelko P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia;
e-mail: shevelko@rambler.ru

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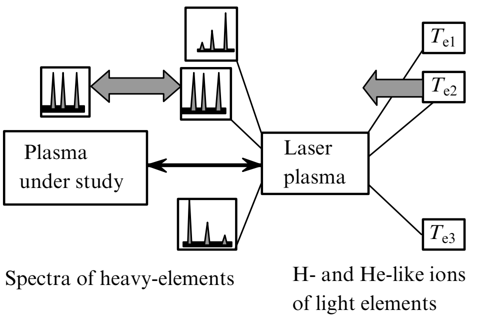

Figure 1. Scheme of measuring the heavy-element plasma temperature.

used for plasma diagnostics. The spectra of heavy elements are studied at the same laser intensities on a target as in the case of light elements. Thus, we may ascribe a certain temperature to each spectrum. A comparison of spectra 'calibrated' by T_e with those of the source under study makes it possible to estimate the temperature of the source (see Fig. 1).

For employing the method, equal conditions are required for the investigated and laser-produced plasmas (the reference diagnosed plasma). These conditions are a coronal equilibrium, equilibrium ionisation, and quasi-stationary state of both plasmas. There is an additional condition for laser-produced plasmas – weak or known dependence of T_e on the atomic weight A_Z of the target material. An experimental condition of the method is employment of calibrated or the same spectrometers in studying the spectra of heavy elements in laser-produced plasmas and in the plasma source under investigation. An optical thickness, spatial and time inhomogeneity of plasma sources require separate consideration.

The conditions of method applicability impose limitations on the laser intensity q and temperature T_e of laser-produced plasma [8]. Equilibrium ionisation and weak dependence of T_e on A_Z occur in nanosecond laser plasma at $q < 10^{14}$ W cm^{-2}. A limitation on q in measuring the electron temperature by the spectra of H- and He-like ions is as follows: $q > 10^{12}$ W cm^{-2}. Thus, in the case of nanosecond laser plasma, the method may be applied in the range of laser intensities $10^{12} \leqslant q \leqslant 10^{14}$ W cm^{-2}, which corresponds to the electron temperature range $100 \leqslant T_e \leqslant 1000$ eV. These are the conditions that limit employment of the method.

As it was mentioned, the new method proposed for diagnosing plasmas of heavy elements is based on the weak dependence of the electron temperature T_e on the atomic weight of the target material A_Z. In [9], a review is given of the results of numerous experimental works on measuring the temperature T_e in laser-produced plasmas over a wide range of laser intensities on a target q ($q = 10^9 - 10^{14}$ W cm^{-2}). It was shown that the temperature is well described by the formula $T_e \sim q^{4/9}$, and is almost the same for different targets from hydrogen to tungsten. A theoretical model for a quasi-stationary model and inverse Bremsstrahlung absorption in plasmas in the case of nanosecond pulses gives the following dependence of the temperature T_e on q, A_Z, and ion charge Z [10, 11]:

$$T_e \propto q^{4/9} A_Z^{2/9} \left(\frac{Z}{Z+1}\right)^{2/3}. \tag{1}$$

This model predicts that the weak dependence of T_e on the atomic weight of the target material ($T_e \sim A_Z^{2/9}$) should hold up to $q \sim 10^{14}$ W cm^{-2}.

3. Analysis of tungsten spectra

Spectra of tungsten laser plasma were recorded at Brigham Young University (BYU), USA [12, 13]. The laser-produced plasmas were created by radiation of an Infinity Nd:YAG laser (0.53 µm, 200 mJ, 3 ns, 10 Hz) with the maximal laser intensity $q = 5 \times 10^{12}$ W cm^{-2} focused onto a massive tungsten target. The spectra in the wavelength range $\lambda = 2 - 20$ nm were studied by means of a calibrated spectrometer with a transmitting diffraction grating. The spectra were independently analysed at the P.N. Lebedev Physics Institute of the Russian Academy of Sciences (LPI, Moscow, Russia) [8]. The analysis of tungsten laser-produced plasma spectra obtained at BYU included the estimation of T_e by spectra of H- and He-like magnesium ions, correction of tungsten plasma temperature, and finding the spectral ranges in which the intensities are sensitive to T_e.

In diagnosing laser-produced plasmas, the X-ray spectra of H- and He-like magnesium ions were used [14, 15], which were studied by means of a high-luminosity focusing crystal spectrometer [16, 17]. At a maximal laser intensity $q \sim 5 \times 10^{12}$ W cm^{-2} the measurements give the value of temperature$T_e = 240 \pm 20$ eV, which well agrees with the results of measuring T_e by a continuum [14]. Then the temperature T_e was made lower by reducing the laser pulse energy, assuming the variation of T_e obeys (1).

The electron temperature T_e^{Mg} was determined in magnesium laser-produced plasmas. In accordance with the dependence $T_e \sim A_Z^{2/9}$, the temperature should be corrected to tungsten laser plasmas and the corrected electron temperature should be ascribed to each of the spectra: $T_e^W = 1.57 T_e^{Mg}$. Examples of the tungsten spectra at various temperatures T_e^W are presented in Fig. 2. One can see a characteristic structure of the spectra – the peaks in the ranges of 2.5–4.2 nm (peak 1) and 4.5–6.5 nm (peak 2), which are identified [3] as transitions 4–5 in tungsten ions XXII–XXIX and 4–4 in tungsten ions XXVIII–XXX, respectively. Note that the intensity 'fall' in the spectra at $\lambda \geqslant 20$ nm is, seemingly, related to a reduction of the efficiency of the employed spectrometer. The structure of spectra and intensities in the mentioned spectral ranges (peaks) are sensitive to the electron temperature, which was used for T_e measurements.

There are the following features in tungsten spectra (see Fig. 2). At low temperatures ($T_e^W \sim 250$ eV), the intensity has maxima at the wavelengths $\lambda_{max} \sim 5.0$ nm (peak 2), 12.5 and 17 nm, the intensities of the last two peaks exceeding that of peak 2. At higher T_e^W, the relative intensity of peak 2 increases and at $T_e^W \sim 400$ eV it is approximately twice that of the long-wavelength peaks. This fact may be used in taking measurements at relatively low temperatures. Starting from $T_e^W \geqslant 250$ eV, the spectra exhibit a short-wavelength peak 1 at $\lambda_{max} \sim 4$ nm, whose intensity I_1 relative to the intensity I_2 of peak 2 increases with T_e^W. The corresponding spectral range is shown in Fig. 2, and the temperature T_e^W versus the intensity ratio I_1/I_2 is presented in Fig. 3.

The dependence of temperature T_e^W (in eV) versus the intensity ratio of peak 1 to peak 2 is well approximated by the expression (see Fig. 3)

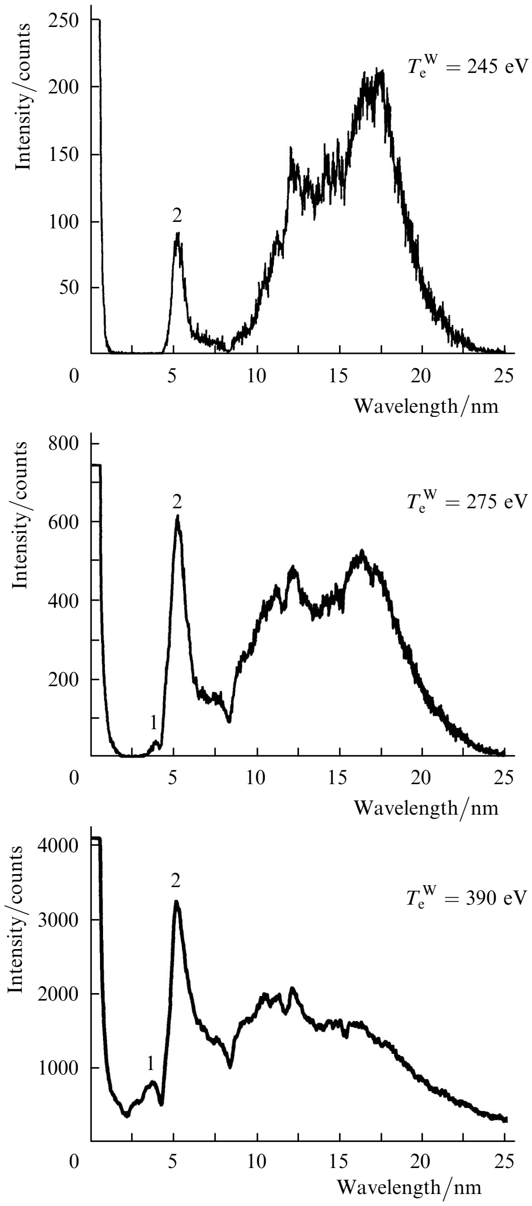

Figure 2. Spectra of tungsten laser-produced plasmas obtained at various electron temperatures T_e^W. Numeral 1 denotes the peaks corresponding to transitions 4–5 in tungsten ions XXII–XXIX, numeral 2 refers to the peaks corresponding to 4–4 transitions in tungsten ions XXVIII–XXX.

$$T_e^W = A\left(\frac{I_1}{I_2}\right)^{\alpha} \tag{2}$$

with the constants $\alpha = 0.3$ and $A = 700$.

Similar investigations of tungsten spectra were performed at the LPI [18]. The tungsten spectra were recorded using another laser facility (0.53 μ, 1 J, 2 ns) under different experimental conditions. The laser-produced plasmas were diagnosed by the spectra of H- and He-like magnesium ions as well. The spectra were recorded at the temperature $T_e^{Mg} = 200$ eV, which corresponds to $T_e^W = 315$ eV. The ratio of peak intensities I_1/I_2 was 0.1. These data are also shown in Fig. 3. A comparison of the data with those obtained at BYU allows one to estimate the experimental error of determining T_e^W (not exceeding 10 %) due to different experimental conditions.

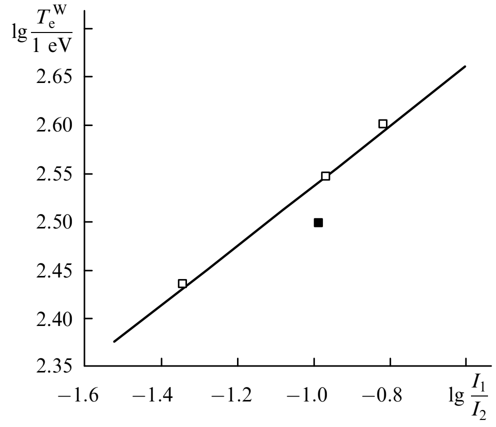

Figure 3. Temperature T_e^W (in eV) as a function of intensity ratio I_1/I_2. Solid line is the calculation by formula (2), points correspond to the experimental results obtained at BYU (□) and LPI (■).

The new X-ray spectral method of comparison may be used for estimating an electron temperature of heavy-element plasmas in various plasma sources including high-power Z-pinch plasmas based on multi-wire tungsten arrays.

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