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Spectroscopic VUV diagnostics of high-temperature iron plasmas using the comparison method

A.P. Shevelko

Abstract. **We report the development of a new comparison method used to estimate the electron temperature T_e of heavy-element plasmas and high-temperature iron laser-produced plasmas. To this end, two laser-produced plasmas – magnesium plasmas and iron plasmas – were studied at identical laser radiation fluxes on the target. Plasma diagnostics was performed using X-ray spectra of H- and He-like Mg ions. VUV spectra of Fe ions were recorded in the wavelength range 15–150 Å. As a result, the change in the structure of the VUV spectra of Fe ions as a function of T_e in the range of 100–400 eV was studied. These data are necessary for diagnosing plasma sources containing the iron element.**

Keywords: *X-ray and VUV spectroscopy and plasma diagnostics, laser-produced plasmas, multiply charged ions, X-ray spectrometers.*

1. Introduction

Considerable recent interest has been shown in the study of plasmas of heavy elements, which is mainly associated with the program of controlled thermonuclear fusion (CTF) and the development of new high-intensity X-ray sources. Heavy elements (elements with a large atomic weight A_Z) are the most difficult atomic systems for spectroscopic study. Spectroscopic diagnostics, the most informative method for studying high-temperature plasmas, is very difficult in this case due to the complex structure of the spectra. However, these spectra are especially important for scientific research: the case in point are the spectra of W and Bi ions in the plasmas of high-power Z-pinches (material of wire arrays), the spectra of Au ions for a laser inertial CTF (the material of hollow cylindrical hohlraum-type targets), the spectra of Mo and W ions in tokamak plasmas (divertor materials), Sn ion spectra in plasma sources intended for projection nanolithography (see, for example, Refs [1–6] and references therein). Considerable interest is also shown in the study of iron plasmas, the main element of stainless steel, the structural material of almost all laboratory facilities. When carrying out experiments, it is necessary to take into account a variety of effects: the interaction of plasmas with the walls of vacuum chambers, sputtering of wall material, closing of interelectrode gaps, etc. Usually, Fe is not the main element of plasma sources; therefore, spectroscopic data on iron plasmas are required at moderate electron temperatures (T_e < 500 eV), i.e., in the VUV region of the spectrum. Obtaining new experimental and theoretical data on iron plasma assumes considerable significance.

To study the plasmas of heavy elements, in Refs [7–12], we came up with a new comparison method, which involved comparing the spectra under study with the spectra of well-diagnosed laser-produced plasmas. Plasma diagnostics is carried out using the X-ray spectra of light elements with the structure of hydrogen- and helium-like (H- and He-like) ions. The method has been successfully used to diagnose tungsten [7, 9] and molybdenum [10, 11] laser-produced plasmas as well as iron [8] plasmas. In the present work, this method was further developed and employed to diagnose high-temperature iron laser-produced plasmas. The aim of this work is to study the structure of the VUV spectra of Fe ions as a function of T_e in a range of 100–400 eV. These data are necessary for diagnosing plasma sources containing the Fe element, which is part of the structural materials of almost all laboratory facilities.

2. Brief description of the comparison method

X-ray spectroscopy methods are widely used for diagnosing laboratory and astrophysical plasmas. To date, methods of spectroscopic diagnostics based on the spectra of H- and He-like multiply charged ions have been elaborated in most detail. The spectra of such ions for elements with atomic numbers $A_N = 6–30$ have been adequately studied and are widely used to measure the electron temperature T_e in plasmas from ~100 eV to several keV (see, for example, Refs [13–15]).

The X-ray and VUV spectra of plasmas of heavy elements usually have a complex structure, which is different from that of H- and He-like ions, and the superimposition of a huge number of lines in these spectra leads to the appearance of a quasi-continuum. This circumstance greatly complicates the spectroscopic diagnostics of such plasmas. Nevertheless, the structure and intensity distribution in the spectra are highly sensitive to T_e. It is this circumstance that is used in the new comparison method for estimating the T_e of the plasmas of heavy elements.

In the new comparison method [7–12] for determining the electron temperature T_e of the plasmas of heavy elements, it is proposed to compare the spectra under study with the spectra of a well-diagnosed laser-produced plasmas. Plasma diagnostics is carried out by the spectra of light elements having the structure of H- and He-like ions. In this case, the spectra of light and heavy elements are investigated for the same laser radiation intensities on the target. The applicability conditions and limitations of the method are considered in detail in Ref. [7]. In particular, the main conditions are the presence of

A.P. Shevelko P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: apshev51@gmail.com

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coronal equilibrium and a weak or known dependence of T_e on the atomic weight A_Z of the laser target material ($T_e \sim A_Z^{2/9}$, see, for example, Refs [16, 17]).

Obviously, with an increase in T_e in the plasmas of heavy elements, the ion charge state increases. This leads both to a change in the structure of the spectra and to a shift of the spectrum to the short wavelength region. Both of these circumstances can be used for plasma diagnostics. In this work, we study the dependence of the structure of Fe ion spectra on the temperature T_e. The shift of the centre of gravity in the intensity distribution of the spectra of Fe ions was used to estimate T_e in the plasmas generated in the finite anode–cathode gap of a high-current pulsed generator Z-Machine (Sandia National Laboratories) [8].

The heart of the comparison method is the study of the T_e-dependence of the structure and intensity distribution in the spectra. This permits 'ascribe' a specific temperature to each spectrum. Comparison of such T_e-'calibrated' spectra with the spectra of the plasma sources under study makes it possible to estimate the T_e of these sources. Note that T_e is estimated using only the structural features of the spectra and their intensity distribution in the experimental method of comparison. In this case, neither identification of transitions nor knowledge of the ion charge state distribution is required.

3. Experiment

The experiment for studying laser-produced plasmas is schematised in Fig. 1. The plasmas were produced using a neodymium glass laser whose radiation ($\lambda = 0.53$ μm, $E_{las} = 1$ J, $\Delta t = 2$ ns) was focused on a massive iron or magnesium target (Fe or Mg target) by a lens with a focal length $f = 300$ mm. Two spectrometers were used simultaneously: an X-ray focusing crystal spectrometer (XRS-1) and a VUV grazing incidence spectrometer (GIS-1).

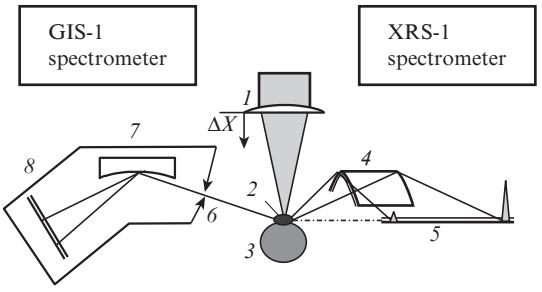

Figure 1. Schematic of the experiment:
(*1*) focusing lens; (ΔX) lens displacement relative to the position of optimal focusing; (*2*) laser-produced plasmas; (*3*) Mg or Fe target; (*4*) cylindrical mica crystal with a bending radius of 20 mm; (*5*) radiation detector (CCD line array); (*6*) entrance slit; (*7*) spherical diffraction grating; (*8*) radiation detector (UF-4 photographic film).

The electron temperature of the laser-produced plasmas was varied by changing the laser radiation intensity on the targets. To do this, the distance ΔX between the lens and the target was varied at a constant energy of laser pulses $E_{las} = 1$ J. Under conditions of optimal focusing, the spot diameter ϕ was ~20 μm, which corresponded to a laser intensity $\sim 10^{14}$ W cm^{-2} on the target. In this case, the electron temperature of the laser-produced plasmas T_e could be as high as ~600 eV [18]. To reduce it, it was necessary to significantly lower the intensity q at the target. This was done by increasing the size of the focal spot on the target at a fixed energy of the laser pulse $E_{las} = 1$ J. The size of the focal spot changed as a result of a decrease in the distance between the focusing lens and the target and varied from ~50 to ~750 μm when the lens displaced from the optimal focusing position by distances ΔX ranging from 0.6 to 7.6 mm. A linear dependence $\phi \sim \Delta X$ was experimentally observed.

The electron temperature was determined by X-ray spectroscopy techniques. X-ray spectra of H- and He-like Mg ions were studied using a focusing crystal spectrometer [19, 20] designed according to the von Hamos scheme [21]. In this scheme, the crystal is bent in the shape of a cylinder surface, and the X-ray source (laser-produced plasmas) and the detector plane are located on the axis of the cylinder. When reflected from the bent crystal, the radiation at each wavelength is focused to a point on the axis of the spectrometer (Fig. 1). Due to this focusing geometry, the device has a high efficiency in a wide spectral range [19, 20]. The dispersing element in the spectrometer was a mica crystal ($2d = 19.84$ Å) with a bending radius of 20 mm. X-ray spectra were recorded using a linear CCD array (Toshiba TCD 1304 AP) consisting of 3724 cells with a width of 8 μm and a height of 200 μm.

X-ray spectra of multiply charged Mg ions were recorded in the first order of reflection from a mica crystal in one laser shot. Spectral resolving power $\lambda/\delta\lambda = 500–1000$. By way of example, Fig. 2 shows the spectra of magnesium in the vicinity of H- and He-like ion resonance lines (Ly_α and w, respectively) for different distances ΔX.

The VUV spectra of iron ions were studied using a GIS-1 grazing incidence spectrometer with a diffraction grating of 300 lines mm^{-1} (radius 1 m, grazing incidence angle 4°, W/Re coating) [22, 23]. The spectrometer used an off-Rowland scheme, when the spectrum is recorded on a plane perpendicular to the diffracted rays (see Fig. 1). Accurate focusing was realised only for the centre wavelength λ_0, which corresponded to the intersection point of the recording plane with the Rowland circle. However, due to the small angular aperture of the spectrometer, it was possible to record the spectrum in a fairly wide spectral range, $\lambda_0 \pm \Delta\lambda$. Due to the use of the off-Rowland recording scheme, it was possible to significantly simplify the assembly and alignment of the instrument.

A UV-4 film was used as a radiation detector in the GIS-1 spectrometer. The film was located at a distance of 90 mm from the centre of the diffraction grating, which corresponded to the central wavelength $\lambda_0 \sim 55$ Å. A 1.5-mm wide diaphragm was placed between the entrance slit and the grating. The 15-μm wide entrance slit of GIS-1 was located at a distance of 20 mm from the laser-produced plasmas generated on the surface of the Fe target.

The densitometric characteristics of the UV-4 film were determined for the spectral range 50–200 Å using a VUV source based on capillary discharge plasmas [24]. The VUV spectra recorded on the photographic film were scanned using a pre-calibrated scanner (Epson Perfection 4990 Photo) and digitised using a special 8-bit program (Scion Image for Windows) [25]. The conversion of the optical density scale D into the relative intensity scale was carried out according to the UV-4 film calibration data for $\lambda = 49$ Å. The wavelength scale was reconstructed from the reference lines of H- and He-like carbon ions (in this case, a polyethylene CH_2 target was used). The digitised VUV spectra of Fe ions at different positions ΔX of the focusing lens are shown in Fig. 3.

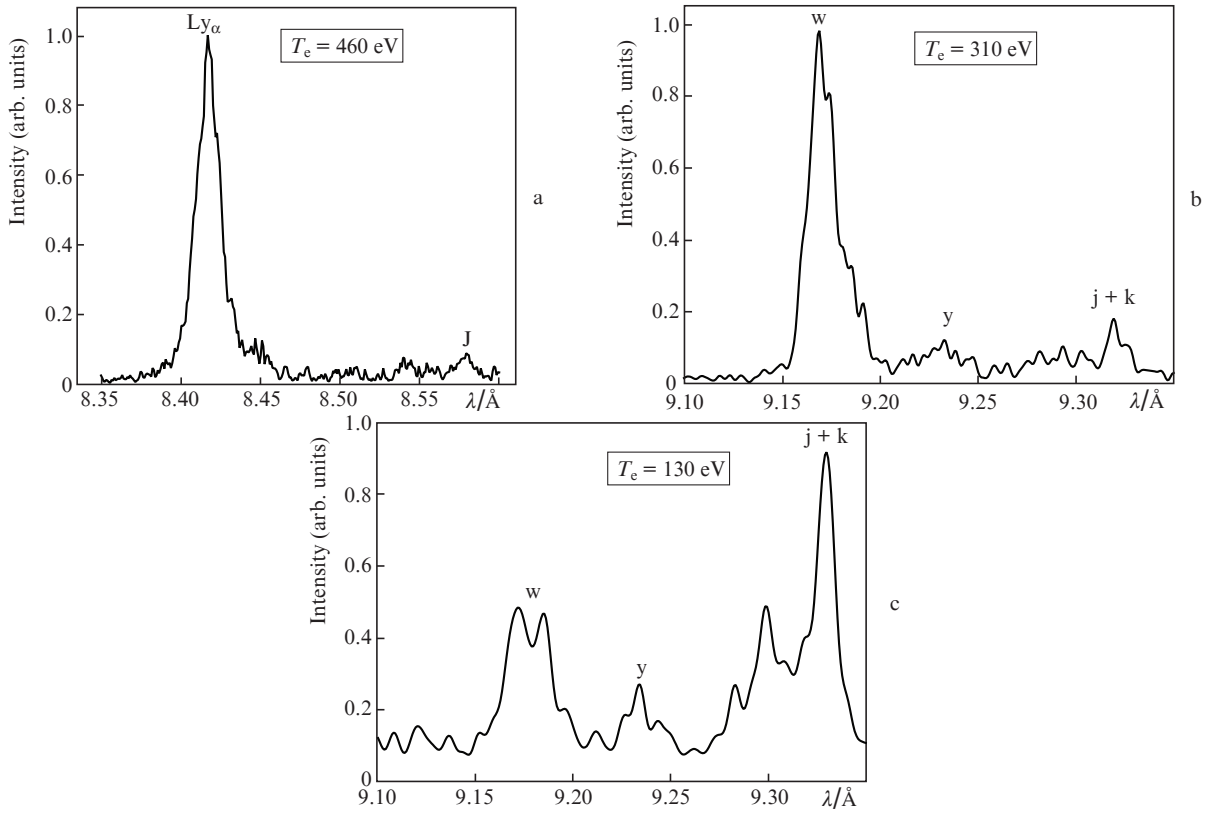

Figure 2. Examples of the X-ray spectra of Mg ions at different temperatures T_e: (a) in the vicinity of the Ly$_\alpha$ resonance line of H-like Mg ions for $\Delta X = 0.8$ mm; (b, c) in the vicinity of the resonance line w of He-like Mg ions for $\Delta X = 1.6$ and 5.6 mm, respectively.

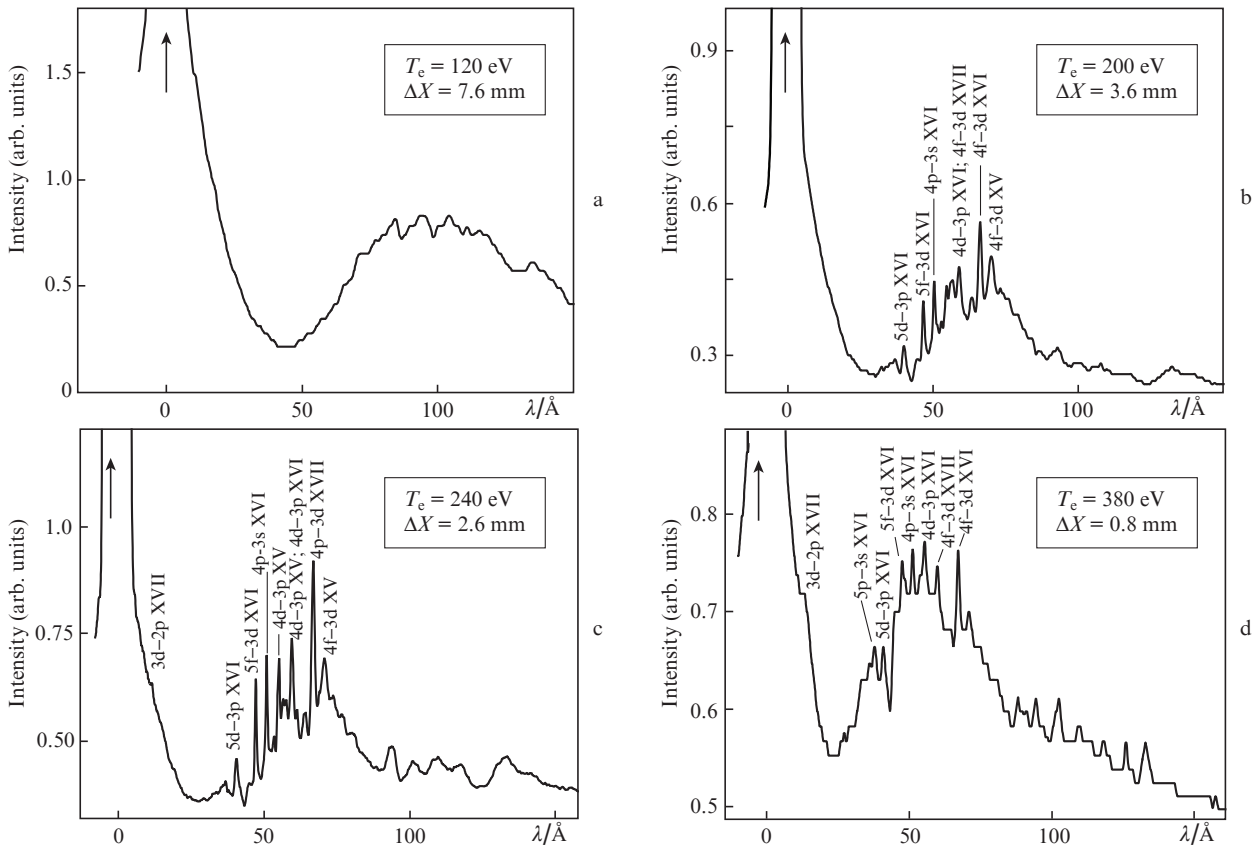

Figure 3. VUV spectra of iron laser-produced plasmas at various positions of the focusing lens ΔX and various electron temperatures T_e. Positions of the zero order ($\lambda = 0$) are indicated with vertical arrows.

4. Results and their discussion

The X-ray spectra of Mg ions were used to measure the electron temperature (see Fig. 2). The electron temperature of He-like ions T_{eHe} was measured from the ratio of the intensities of the dielectronic satellites j + k and the resonance line w (the notation is borrowed from Refs [13–15]). The temperature T_{eH} of H-like ions was measured from the ratio of the intensities of the dielectronic satellite J and the resonance line Ly_α. In both cases, T_e was found using data from theoretical calculations [15]. The electron density N_e was determined from the ratio of the intensities of the intercombination (y) and resonance (w) lines of the He-like Mg ion [26]. The measured dependences of $1/T_{eH}$ and $1/T_{eHe}$ on the position ΔX of the focusing lens are shown in Fig. 4. They are nicely approximated by the linear function

$$1/T_e = a + b(\Delta X), \tag{1}$$

where $a = 1.92 \pm 0.13$, $b = 0.87 \pm 0.05$ (Fig. 4); T_e is measured in keV and ΔX in mm. The error in determining the coefficients a and b (~6% in terms of root-mean-square spread) underlies the temperature T_e measurement accuracy, which is approximately 6%. The electron density N_e, measured from the ratio of the intensities of the resonance and intercombination lines of He-like Mg ions [26] (see Fig. 2), was $(1–2) \times 10^{20}$ cm^{-3} for all values of ΔX.

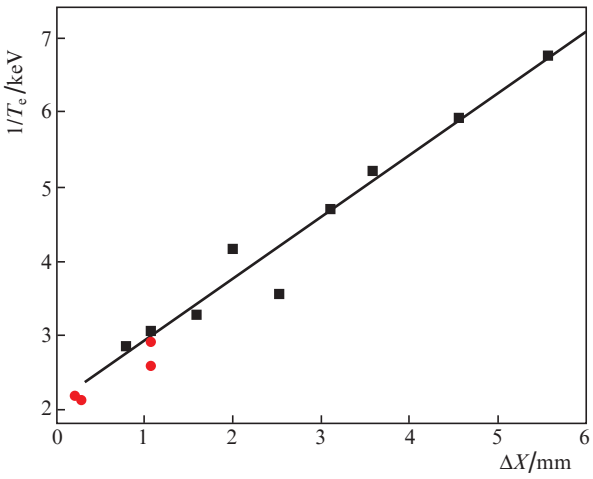

Figure 4. Measured $1/T_e$ values for (squares) He-like and (circles) H-like Mg ions as a function of the focusing lens ΔX. The straight line stands for the approximation by formula $1/T_e = a + b(\Delta X)$.

The method of changing the intensity q of laser radiation on the target by its defocusing at a fixed laser pulse energy ($E_{las} = 1$ J) offers a number of advantages. The linear approximation by formula (1) at large values of ΔX is in excellent agreement with the canonical dependence $T_e \sim q^{4/9}$ [16]:

$$1/T_e \sim 1/q^{4/9} \sim \phi^{8/9} \sim \Delta X^{8/9}. \tag{2}$$

This suggests that this method of changing the intensity q makes it possible to minimise the effect of laser radiation divergence and plasma expansion on q, as was observed in Refs [12, 19]. Measurement of the dependence $T_e(\Delta X)$ in a broad range of ΔX makes it possible, ultimately, to improve the accuracy of the experimental data.

The VUV spectra of iron were recorded at different positions ΔX of the focusing lens and, consequently, at different temperatures T_e. For each ΔX value, the electron temperature was determined from measurements in the X-ray range of the spectrum (Fig. 4, formula (1)). The VUV spectra of iron laser-produced plasmas in a broad range of wavelengths and for $T_e = 120–380$ eV are shown in Fig. 3. With an increase in T_e, we observed a structural change of the spectrum and a shift of the highest intensity region to the short-wavelength domain of the spectrum. As was pointed out in Section 2, in the experimental method of comparison, T_e can be estimated using only the structural features and intensity distribution of the spectra. In this case, neither identification of transitions nor knowledge of the ion charge state distribution is required. Nevertheless, in order to determine the limitations of the method in the case of studying iron plasmas, the identification of spectral lines in the spectrum was carried out. In this case, advantage was taken of the data of Refs [8, 27].

The spectral lines observed in the range $\lambda = 35–85$ Å were identified as $4 \to 3$ and $5 \to 3$ transitions with a change in the principal quantum numbers in FeXIV–FeXVII ions (see Fig. 3). With an increase in temperature, the iron ion charge state increases, which leads to a shift of the experimental spectra to the short-wavelength domain. The wavelength λ_{max} corresponding to the highest intensity of the spectrum is also sensitive to the electron temperature T_e. This circumstance was used to estimate T_e in iron plasmas generated in the final anode-cathode gap of the high-current pulsed generator Z-Machine (Sandia National Laboratories) [8]. Another distinctive feature of the VUV spectra of Fe ions is the zero-order diffraction structure. At low temperatures, the zero order is a smooth peak. At $T_e \geqslant 250$ eV, a feature appears in the zero-order structure near $\lambda \sim 15$ Å. This wavelength may correspond to a resonance transition in the Ne-like FeXVII ion. The presence of radiation from these ions imposes a limitation on the comparison method in the VUV region of the spectrum: the use of this method for VUV plasma diagnostics is probably limited by the temperature $T_e \leqslant 300$ eV. At higher temperatures, a sharp increase in the soft X-ray yield was observed in the region $\lambda = 10$ Å. This spectral region corresponds to the L spectra of iron ions. The spectral lines of the principal series of these ions fill the range of 6–15 Å. In this case, the spectrum is a superposition of a huge number of lines. A more effective diagnostics can be based on X-ray spectroscopy methods.

As a result of experimental studies of iron laser-produced plasmas, three features of the spectrum that are sensitive to temperature T_e (Fig. 5) can therefore be distinguished: the structure of the spectrum (spectral range $\lambda \sim 30–90$ Å), the wavelength λ_{max} of the intensity distribution maximum, and the structure of the zero order. The latter is used to find high-temperature limitations on the application of the method. The structure of the spectrum (this work) and the wavelength λ_{max} [8] can be used to diagnose iron plasmas.

5. Conclusions

The comparison method was used to estimate the electron temperature of high-temperature Fe plasmas. The experiments included the study of two laser-produced plasmas created at the same laser radiation fluxes on Mg and Fe targets.

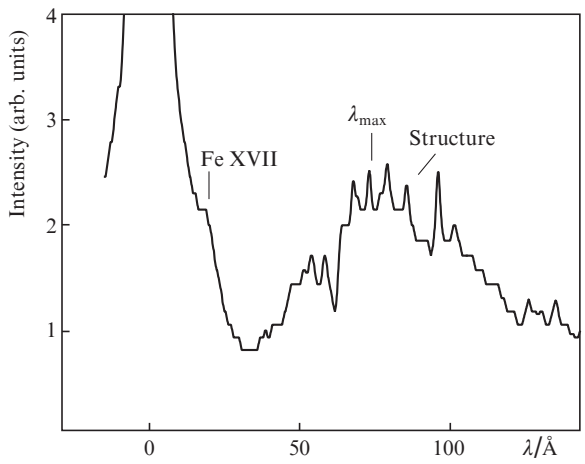

Figure 5. Temperature-sensitive features of the VUV spectrum of Fe ions.

X-ray spectra of H- and He-like Mg ions were used to measure T_e. Spectra in the range $\lambda = 8-10$ Å were recorded using an X-ray focusing crystal spectrometer, and the VUV spectra of Fe in the region $\lambda \leqslant 150$ Å were recorded using a grazing incidence spectrometer. As a result, the change in the structure of the VUV spectra of Fe ions was studied as a function of T_e, which made it possible to estimate the electron temperature for each spectrum in the range of 100–400 eV.

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References

1. Matzen M.Keith., Sweeney M.A., Adams R.G., et al. *Phys. Plasmas,* **12**, 055503 (2005).
2. Grabovski E.V., Sasorov P.V., Shevelko A.P., et al. *Matter Radiat. Extrem.*, **2**, 129 (2017).
3. Aleksandrov V.V., Volkov G.S., Grabovskii E.V., et al. *Fiz. Plasmy*, **42**, 978 (2016).
4. Campbell E.M., Goncharov V.N., Sangster T.C., et al. *Matter Radiat. Extrem.*, **2**, 37 (2017).
5. Chowdhuri M.B., Morita S., Goto M., et al. *Plasma Fus. Res.*, **2**, S1060 (2007).
6. Bakshi V. (Ed.) *EUV Sources for Lithography* (Billingham: USA SPIE Press, 2006).
7. Shevelko A.P. *Quantum Electron.*, **41**, 726 (2011) [*Kvantovaya Elektron.*, **41**, 726 (2011)].
8. Shevelko A.P., Bliss D.E., Kazakov E.D., et al. *Plasma Phys. Rep.*, **34**, 944 (2008) [*Fiz. Plasmy*, **34**, 1021 (2008)].
9. Andreev S.N., Shevelko A.P., Tolstikhina I.Yu., et al. *EPJ Web Conf.*, **132**, 02022 (2017).
10. Shevelko A.P., Yakushev O.F., Vainshtein L.A., et al. *Phys. Plasmas*, **25**, 073306 (2018).
11. Shevelko A.P., Andreev S.N., Tolstikhina I.Yu. *J. Quant. Spectrosc. Radiat. Transfer*, **265**, 107565 (2021).
12. Shevelko A.P. *Quantum Electron.*, **51**, 453 (2021) [*Kvantovaya Elektron.*, **51**, 453 (2021)].
13. Gabriel A.H. *Mon. Not. R. Astron. Soc.*, **160**, 99 (1972).
14. Presnyakov L.P. *Sov. Phys. Usp*. **19**, 387 (1976) [*Usp. Fiz. Nauk*, **19**, 49 (1976)].
15. Vainshtein L.A., Safronova U.I., Urnov A.M. *Proc. Lebedev Phys. Inst.*, **119**, 13 (1980) [*Trudy FIAN*, **119**, 13 (1980)].
16. Anan'in O.B., Afanas'ev Yu.V., Bykovskii Yu.A., Krokhin O.N. *Lazernaya plazma. Fizika i primenenie* (Laser Plasma. Physics and Application) (Moscow: Izd. MEPhI, 2003).
17. Bykovskii Yu.A., Degtyarenko N.N., et al. *J. Exp. Theor. Phys.*, **33**, 706 (1971) [*Zh. Eksp. Teor. Fiz.*, **60**, 1306 (1971)].
18. Shevelko A.P. *Quantum Electron.*, **49**, 839 (2019) [*Kvantovaya Elektron.*, **49**, 839 (2019)].
19. Shevelko A.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **3406**, 91 (1998).
20. Shevelko A.P., Kasyanov Yu.S., Yakushev O.F., Knight L.V. *Rev. Sci. Instrum.*, **73**, 3458 (2002).
21. Von Hámos L. *Ann. Phys.*, **17**, 716 (1933).
22. Shevelko A.P. *IOP Conf. Ser.: J. Phys.: Conf. Ser.,* **1115**, 022042 (2018).
23. Shevelko A.P., Yakushev O.F. *Poverkhnost'*, (2), 51 (2003).
24. Kazakov E.D., Shevelko A.P., Yakushev O.F. *VANT. Ser. Termoyadernyi Sintez*, **40**, 63 (2017).
25. Kazakov E.D., Shevelko A.P. *VANT. Ser. Termoyadernyi Sintez*, **37**, 71 (2014).
26. Vinogradov A.V., Skobelev I.Yu., Yukov E.A. *Sov. J. Quantum Electron.*, **5**, 630 (1975) [*Kvantovaya Elektron.*, **2**, 1165 (1975)].
27. Kelly R.L. *J. Phys. Chem. Ref. Data*, **16**, Suppl. 1 (1987).