Quantum Electronics **46** (9) 845–847 (2016)

DOI: 10.1070/QEL16166

Method for formation of quasi-monochromatic divergent X-ray fluxes from laser-produced plasmas

A.P. Shevelko

Abstract. **Conditions and applicability limits of a new method for formation of quasi-monochromatic, with a large solid angle of divergence, linear X-ray fluxes from laser-produced plasmas are considered. The method is based on a special combination of laser target elements and *K*-absorption filters, when the spectra of [H]- and [He]-like ions are excited in laser-produced plasma and *K*-absorption filters select only the resonance lines of these ions from the linear spectrum. Experimental and theoretical studies have shown that, in the fluxes formed, the degree of monochromatisation $\lambda/\Delta\lambda$ may reach $\sim$100 at the radiation contrast ratio of 5–10 and angular divergence of $\sim\pi$ sr.**

Keywords: *multiply charged ions, X-ray spectroscopy, reflectometry and radiometry, high-temperature plasma diagnostics.*

Scientific research and various practical applications, such as X-ray reflectometry, microscopy, projection X-ray lithography, etc. (see, for example, [1]) require monochromatisation of X-ray radiation from various sources in a large solid angle. Below, we will characterise such radiation by the parameter $\eta = (\lambda/\Delta\lambda)\Omega$ equal to the product of the spectral selectivity (monochromatisation) $\lambda/\Delta\lambda$ by the solid angle Ω (radiation divergence angle) measured in steradians. A high degree of monochromatisation, $\lambda/\Delta\lambda \sim \tan\theta/\delta\theta \sim 10^3-10^5$ (θ is the Bragg angle), can be achieved with the use of crystal monochromators (see, for example, [2, 3]). However, the solid angle of radiation, which is determined by the width $\delta\theta$ of crystal reflection, is small: $\Omega \sim \delta\theta$ ($\delta\theta$ is the angle in the plane of crystal dispersion, and the angle of $\sim$1 rad in the perpendicular plane is defined by the angular width of the crystal). In this case, $\eta \sim \tan\theta \sim 1$. The simplest monochromatisation method is based on the use of absorption filters (see, for example, [2]). The filter transmits radiation at wavelengths $\lambda > \lambda_0$ beyond the corresponding *K*, *L*, or *M* absorption edge (λ_0), while the short-wavelength radiation with $\lambda < \lambda_0$ turns out almost completely absorbed. For continuum (white) radiation, the degree of monochromatisation is not large, $\lambda/\Delta\lambda \sim 10$, but radiation may be formed in a large ($\Omega \sim \pi$) solid angle, and in this case the parameter $\eta \sim 10\pi \sim 30$. The aim of this work is to achieve a higher (10–100) monochromatisation degree in divergent fluxes ($\Omega \sim \pi$) through the use of linear X-ray radiation from plasma. The parameter η in this case may reach $\sim$300.

To form a quasi-monochromatic, with a large solid angle of divergence, X-ray fluxes from laser-produced plasmas, we have used a method based on a special combination of the laser target elements and *K*-absorption filters. The laser targets with average atomic numbers $Z_a \approx 10-20$ are selected to ensure the excitation of hydrogen- ([H]) and/or helium-like ([He]) ions (spectral range λ = 0.2–1 nm) in laser-produced plasmas. The selected *K*-absorption filters transmit light in a narrow spectral range which only contains the resonance lines of [H]- and [He]-like ions (Fig. 1a). Other spectral lines of these ions are located beyond the *K*-edge and completely absorbed by the filter (Fig. 1b). The resonance lines of ions with a lower ionisation degree ([Li] and others) occupy the long-wavelength range and are also completely absorbed by the filter. This monochromatisation method was first used for calibration of a focusing crystal spectrometer [4] in the spectral range $\lambda \approx 0.8-0.9$ nm for a Mg/Al pair (laser target/*K*-filter).

An important condition for the applicability of this method is a small contribution of the intensity of continuum radiation, which can lead to a decrease in the monochromatisation degree. We characterise this contribution by the radiation contrast γ, i.e. the ratio of intensities of the linear and

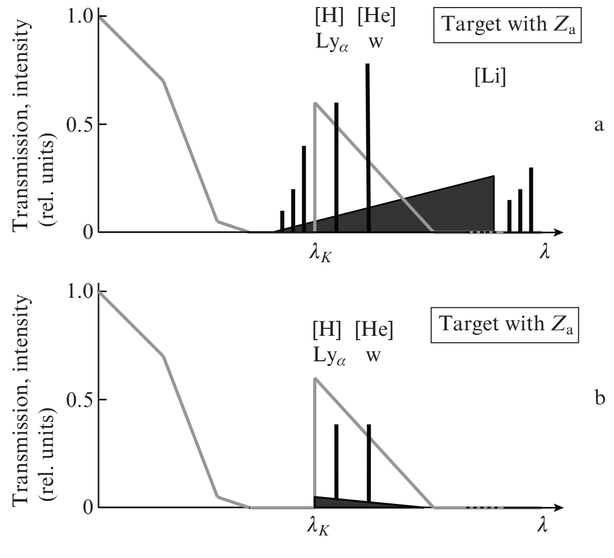

Figure 1. Scheme of the method for monochromatisation and selection of the linear and continuum spectra of the targets – linear (columns) and continuum (black triangle) spectra of an ion with Z_a (a) and the same in the case of passage through the *K*-filter (b); the grey curve shows the *K*-filter transmission; λ_K is the wavelength of the absorption *K*-edge of the filter.

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

Received 23 June 2016; revision received 20 August 2016
Kvantovaya Elektronika **46** (9) 845–847 (2016)
Translated by M.A. Monastyrskiy

continuum radiations passed through the filter: the higher the contrast ratio, the smaller the contribution of the continuum spectrum. For experimental evaluation of the radiation contrast ratio, a new method is developed, which also employs a special combination of the K-absorption filters and two laser target elements with adjacent atomic numbers: Z_a and $Z_a + 1$ (see Figs 1, 2). For a target with the atomic number Z_a, the method works in the way described above (see Fig. 1). For a target with $Z_a + 1$, the K-filter completely absorbs all the linear radiation and only transmits the continuum radiation (Fig. 2). Due to the proximity of the atomic numbers of the targets, their intensity of continuum radiation is virtually the same. Thus, the measurement of intensity ratios for the targets with Z_a and $Z_a + 1$ provides information about the value of the contrast ratio γ (Figs 1b and 2b).

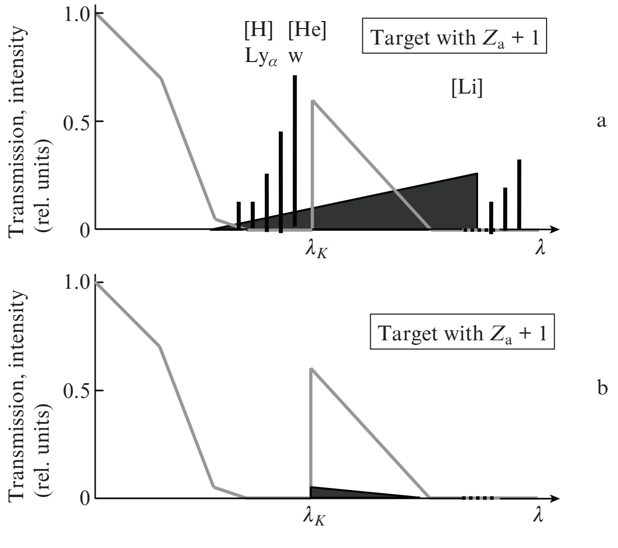

Figure 2. Selection scheme of only continuum spectrum of the target with $Z_a + 1$ – linear (columns) and continuum (black triangle) ion spectra (a) and the same in the case of passage through the K-filter (b); the grey curve shows the K-filter transmittance.

To measure the radiation contrast using the method described above, experiments with laser-produced plasmas were performed. The plasma was produced by focusing the radiation from a 'Phoenix' Nd : glass laser (0.53 μm, 5 J, 2 ns) onto solid targets. For recording the X-ray spectra of [H]- and [He]-like ions and measuring the monochromatisation degree, von Hamos focusing crystal spectrometer equipped with a CCD linear array (Toshiba TCD 1304 AP) [5] or a photographic film (Kodak RAR 2492) [6] was used as a radiation detector. The electron temperature was measured from the ratio of the intensities of resonance lines of [He]-like ions and dielectronic satellites $j + k$ or j (notations of satellites and data on intensities are given in [7]); the contrast ratio was measured using a pin-diode (Siemens BPX-66) [4]. Table 1 characterises the targets with adjacent atomic numbers Z_a and $Z_a + 1$ used in the experiment, excited ions, spectral intervals $\Delta\lambda$, thicknesses of the K-absorption filters and the wavelengths λ_K at the absorption K-edge, and also the results of experimental measurements of the monochromatisation degree $\lambda/\Delta\lambda$, values of the contrast ratio γ and electron temperature T_e.

Theoretical calculations of the linear spectrum intensities of the radiation passed through an absorption filter (the resonance lines of [H]- and [He]-like ions), and of the continuum (recombination) spectrum intensities, are conducted in our work [8]. The process [He] + e = [Li] + $\hbar\omega$ has been considered for the recombination spectrum. The resonance line intensities were calculated using the approximate formulas [9, 10], the recombination radiation intensities – using the Kramers approximation [9, 10], while the data of the work [11] were used to calculate the K-filter transmission. Omitting numerous formulas, we only give here the dependence of the radiation contrast ratio γ on the Z, i.e.spectroscopic symbol of [He]-like ions, and on the electron temperature T_e:

$$\gamma \sim \frac{kT_e}{Z^2(Z-1)^4}\exp\left(-\frac{I}{kT_e}\right), \qquad (1)$$

where I is the ionisation potential of [Li]-like ions.

It follows from this dependence that γ increases with increasing T_e and decreases strongly with increasing Z. These dependences are qualitatively confirmed by the experimental data shown in Table 1. The contrast increases with increasing thickness.

Quantitative calculations are performed for the Ti-target and K-absorption filters of different thicknesses (16 and 32 μm). In this case, the total intensity of the resonance, intercombination, and satellite lines of the linear spectrum was calculated using the data published in [7]. The results of the radiation contrast calculations for the laser Ti plasma versus the electron temperature are shown in Fig. 3. A satisfactory agreement with experiment is observed at T_e = 750 eV. It is also seen from Fig. 3 that the radiation contrast is large enough for electron temperatures required for excitation of [He]-like ions. The calculations confirm the high efficiency of the proposed monochromatisation method. In addition, the contrast ratio measurement for two adjacent elements may become a simple method for the electron temperature measurements without the use of a high-resolution X-ray spectrometer. Because of the strong dependence of γ on Z, the measurement error of this method is estimated at 20%–30%.

The monochromatisation degree $\lambda/\Delta\lambda$ depends on the ionisation composition of laser-produced plasmas. If [H]- and [He]-like ions are excited in plasmas, the value of $\lambda/\Delta\lambda$ is defined by the spectral interval between the resonance lines and amounts to ~10. If only [He]-like ions and associated

Table 1.

Z_a	$Z_a + 1$	Ions	$\Delta\lambda$/nm	K-filter thickness/μm	λ_K/nm	$\lambda/\Delta\lambda$	γ	T_e/eV
Al		[H], [He]	0.72–0.78	9.5 (Si)	0.6745	12.5	20	260 ± 25
	Si	[H], [He]	0.62–0.67			–	–	–
Ti		[He], [Li]	0.261–0.264	15.9 (Ti)	0.2497	100	6	730 ± 80
	V	[He], [Li]	0.238–0.242			–	–	–

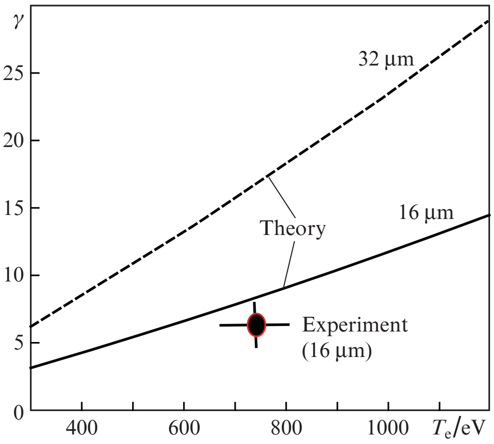

Figure 3. Contrast ratio γ vs. electron temperature T_e for Ti laser-produced plasmas at a thicknesses of titanium *K*-filters of 16 and 32 µm.

dielectronic satellites are excited in plasma, the value of $\lambda/\Delta\lambda$ is defined by the spectral interval between the resonance line and dielectronic satellite j, thus reaching the maximal values of ~100. With a further increase in Z near the resonance lines, the peaks corresponding to satellite lines with lower ionisation degrees ([Be], [B], …-like ions) appear, and the monochromatisation degree falls again.

As a result, the maximum measured value of the parameter η constituted ~300. This indicates the advantage of the proposed monochromatisation method (we should note that $\eta \sim 1$ in the case of a crystal monochromator). Another advantage of this method is its simplicity: the tuning of the working wavelength requires only a change of the laser target and *K*-filter. Such a change can be made without vacuum violation in the chamber. Finally, the use of absolutely calibrated detectors, for example, pin-diodes [12, 13] for measuring the radiation intensity in fluxes makes this method indispensable for absolute calibration at different wavelengths and very promising for many practical applications. In particular, the focusing crystal spectrometers have a large angular aperture. For example, the input aperture of a spectrometer designed according to the von Hamos scheme may reach ~π sr [6]. The use of this method ensures absolute *in situ* calibration of these spectrometers at different wavelengths. Such a calibration is required for large-area X-ray detectors, such as CCD linear arrays and CCD matrixes. This method can also be used in X-ray tomography and microscopy [1]. A simple change of the wavelength allows investigation of various absorption effects in different spectral ranges. The source size (in our case 50–100 µm) can be greatly reduced by employing a shorter pulse duration. The method application in the contact X-ray lithography (see, for example, [1]) allows optimisation of the spectral range. The method has two aspects – monochromatisation of radiation and a large solid angle. The first aspect, monochromatisation, can be used for plasma diagnostics – measuring the radiation output in different spectral ranges. In this case, the method may be extended to other plasma sources, such as plasma of high-power *Z*-pinches, based on multiwire arrays. For aluminium arrays, silicon *K*-filters can be used (see Table 1 below), for tungsten arrays – *L*-filters made of Zr, Nb, Mo. This technique will allow quantitative measurements of the X-ray radiation output and study its spatial structure in the lines of multiply charged ions.

Acknowledgements. This work was partially supported by the Russian Foundation for Basic Research (Grant No. 15-02-04411).

References

1. Attwood D. *Soft X-Rays and Extreme Ultraviolet Radiation. Principles and Applications* (Berkeley: Cambridge Univ. Press, 2000).
2. Van Grieken R.E., Markowics A.A. (Eds) *Handbook of X-Ray Spectrometry, Methods and Techniques* (New York: Marcel Dekker, 1993).
3. Gilfrich J.V., Brown D.B., Burkhalter P.G. *Appl. Spectrosc.*, **29**, 322 (1975).
4. Bijkerk F., Louis E., van Dorssen G.E., Shevelko A.P., Vasiliev A.A. *Appl. Opt.*, **32**, 4247 (1993).
5. Shevelko A.P., Kasyanov Yu.S., Yakushev O.F., Knight L.V. *Rev. Sci. Instrum.*, **73**, 3458 (2002).
6. Shevelko A.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **3406**, 91 (1998).
7. Vainshtein L.A., Safronova U.I., Urnov A.M. *Trudy FIAN*, **119**, 13 (1980).
8. Shevelko A., Beigman I., Knight L.V. *Proc. SPIE Int. Soc. Opt. Eng.*, **4781**, 10 (2002).
9. Sobel'man I.I. *Atomic Spectra and Radiative Transitions* (Berlin, Heidelberg: Springer-Verlag, 1992).
10. Sobel'man I.I., Vainshtein L.A., Yukov E.A. *Excitation of Atoms and Broadening of Spectral Lines* (Berlin: Springer-Verlag, 1981; Moscow: Nauka, 1979).
11. Henke B.L., Gullikson E.M., Davis J.C. *Atomic Data Nucl. Tables*, **54** (2), 1 (1993).
12. http://www.ird-inc.com.
13. Aruev P.N., Zabrodskii V.V., Kolokol'nikov Yu.M., et al. *Poverkhnost'*, (2), 19 (2010).