Formation of quasi-monochromatic soft x-ray radiation from laser-produced plasmas

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ABSTRACT

This paper describes a simple method for formation of quasi-monochromatic soft x-ray radiation from laser-produced plasmas. The method uses a special combination of laser target materials and x-ray filters. Targets with middle atomic numbers Z_a~10-25 are chosen, so hydrogen- and helium-like ions ([H]- and [He]-like ions) are excited in the laser-produced plasmas. The x-ray *K*-absorption filters isolate only a few lines in the spectrum: resonance lines and corresponding satellites of [H]- and [He]-like ions. These lines occupy a narrow spectral band $\lambda/\delta\lambda$ = 10–100. The contribution of continuum radiation out of the separated spectral band is studied theoretically and experimentally. It is shown that the continuum radiation contribution does not exceed 20% of the line radiation intensity. The method of formation of quasi-monochromatic soft x-ray radiation is used for reflectometry (measurements of crystal reflectivity, calibration of crystal spectrometers and x-ray detectors) and for radiometry (absolute radiation yield measurements) of laser-produced plasmas.

Keywords: laser plasma x-ray sources, linear and continuum x-ray radiation, reflectometry, radiometry

1. INTRODUCTION

A formation of wide aperture (large solid angle) monochromatic x-ray radiation is important for many practical applications. Among them we could emphasize reflectometry, which includes the study of transmission of large aperture x-ray filters and calibration of focusing crystal spectrometers. Monochromatic radiation is needed for proximity print absorption because the absorption coefficient has strong wavelength dependence $\mu = \mu(\lambda) \sim \lambda^3$. Quasi-point monochromatic x-ray sources could be used in x-ray tomography of high spatial resolution.

In this work we describe some monochromatization methods of laboratory-based plasma x-ray sources such as laser-produced plasmas, plasma focus, micropinch, etc. These sources have small sizes and can be considered as quasi-point sources with radiation as defined by x-ray spectra of highly charged ions. Due to the importance of both monochromatization and solid angle, we will further characterize the source by the product of (Spectral resolving power) and (Solid angle) = $\lambda/\delta\lambda \cdot \Omega$.

A high degree of monochromatization could be achieved by crystal-monochromator techniques: $\lambda/\delta\lambda \sim \tan\theta/\delta\theta \sim 10^3$–$10^5$. However, in this case the acceptance angle is defined by rocking curve width $\delta\theta$ of the crystal and is very small $\Omega \sim \delta\theta$. Parameter $(\lambda/\delta\lambda)\times\Omega$ is equal to ~ $(\tan\theta/\delta\theta)\times\delta\theta \sim \tan\theta \sim 1$ (or, more accurately, ~0.1–10, $\tan\theta$~10 at θ~85°).

The simplest method of monochromatization is by single-filter techniques.[1] Radiation with wavelengths longer than *K* (or L_{III}) absorption edge $\lambda > \lambda_0$ is transmitted through the thin filter. All radiation of the shorter wavelength $\lambda < \lambda_0$ is strongly absorbed. For white or continuum radiation, a small degree of monochromatization is observed $\lambda/\delta\lambda$~10 but at large acceptance angle $\Omega \sim 2\pi$. Parameter $(\lambda/\delta\lambda)\times\Omega$ is equal to ~ $10\times 2\pi \sim 100$. The further increase in the monochromatization degree could be achieved by using line spectra.
In this work we describe a simple formation method of quasi-monochromatic soft x-ray radiation from laser-produced plasmas. The method uses a special combination of laser target materials and x-ray filters. The important question for the method motivation is the contribution of continuum radiation out of the separated spectral band. This contribution defines

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the contract ratio: filtered line radiation/filtered continuum radiation. The goal of this work is the theoretical and experimental study of the contrast ratio to characterize the method.

2. METHOD OF MONOCHROMATIZATION AND CONTRAST MEASUREMENT

A special combination of K absorption filters and laser target material is used for the monochromatization method (see Fig. 1). Targets with middle atomic numbers Z_a are chosen, so hydrogen- and helium-like ions ([H]- and [He]-like ions) were excited in the laser-produced plasmas. The x-ray K-absorption filter isolates a narrow spectral band with only a few lines and continuum radiation. The few lines are resonance lines with corresponding satellites of [H]- and [He]-like ions. All other lines of the principal series are completely absorbed by the filter. The lines of lower ionization stages (e.g., [Li]-like ions) occupy the spectral band with much longer wavelengths and are also completely absorbed by the filter. This method of monochromatization was successfully used for calibration of focusing crystal von Hamos spectrometers[2,3] and for measurement of quantum efficiency and sensitivity of CCD linear array[4,5] as an x-ray detector.

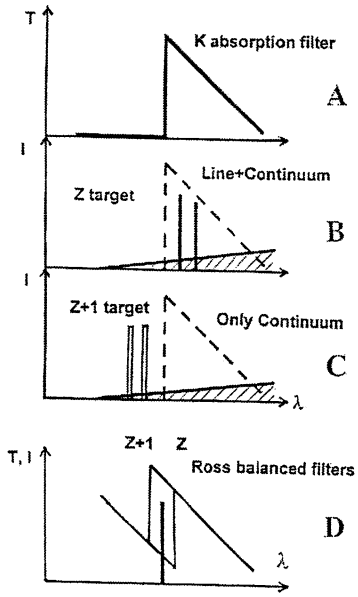


Fig. 1. Method of contract ratio measurement: A – transmission of K-edge filter; B – intensity of line and continuum radiation passed through the filter from target Z; C – intensity of continuum radiation passed through the filter from Z+1 target, line radiation is completely absorbed by the filter. D – Ross balanced filter scheme.

The important question regarding the method motivation is the contribution of continuum radiation from the separated spectral band. This contribution defines the contract ratio: filtered line radiation/ filtered continuum radiation. We suggest a new method for investigating the contrast ratio using a special combination of K absorption filters and laser target material of neighboring elements (Z and Z+1 atomic numbers) (Fig. 1). For the Z target the x-ray K-absorption filter works as described above. For the Z+1 target the filter completely absorbs the line radiation and transmits only continuum radiation. Due to the neighboring targets of Z and Z+1 the continuum radiation is practically the same for both targets so the intensity ratio of the Z and Z+1 targets gives the contract ratio. This method of contrast measurement has some analogy with the Ross balanced filter method[1] (Fig.1). In the Ross method a combination of characteristic line radiation (one target) and two filter materials of neighboring elements (Z and Z+1 atomic numbers) is used. Our method uses a combination of two targets of neighboring elements (Z and Z+1) and one filter.

3. THEORY

The intensity ratio of the resonance line of the He-like ion (w) to the integral intensity of recombination continuum (dN_r/dE_r , E_r is energy of the resulting photon) passed through x-ray filters is

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$$r(Te)=I_w \cdot T(\lambda_w)/\int \frac{dN_r}{dE_r} T(E_r)dE_r \ , \qquad (1)$$

where $T(\lambda)$ is filter transmission, dN_r/dE_r is recombination emission per unit energy/volume unit/second, and N_e is electron density. We consider the recombination process of the [He]-like ion

$$[He] + e = [Li] + h\omega \ . \qquad (2)$$

The intensity of the resonance line is given by $N_{He} \cdot N_e <v\sigma>$, where N_e is electron density and N_{He} is the density of the corresponding [He]-like ions. The rate coefficient $<v\sigma>$ of the resonance line excitation can be fitted by the formula[6,7]

$$\langle v\sigma \rangle = \frac{10^{-8}}{Z^3}\left[cm^3/s\right] A \frac{\beta+1+D}{\beta+\chi}\sqrt{\beta}e^{-\Delta E/kT}; \quad \beta = \frac{Z^2 Ry}{kT}; \qquad (3)$$

where Z is the spectroscopic symbol, ΔE is the excitation potential, and the adjusted A, χ, D parameters are given in Table 1.

Table 1. Adjusted parameters for calculation of the rate coefficient $<v\sigma>$.

Ions	ΔE eV	A	χ	D
MgXI	1350	2.54	0.3	1.6
TiXXI	4740	2.98	0.3	1.5

We now consider the recombination process of the [He]-like ion (Eq. 2). The recombination cross-section in the Kramers approximation can be written as[6,7]

$$\sigma_r = \frac{32}{3\sqrt{3}}\alpha^3 \frac{\left(Z^2 Ry\right)^2}{E\left(E-I_n\right)}\frac{\pi a_0^2}{n^3} \ , \qquad (4)$$

where E is energy of the recombining electron, Z, n, I_n are spectroscopic symbol, principal quantum number and ionization potential of the resulting ([Li]-like) ion, E- I_n is photon energy, α = 1/137 is the fine structure constant, and v_0, a_0 are the atomic units of velocity and length, respectively.

The recombination emission for Maxwellian electron distribution with temperature T can be written

$$\begin{aligned} \frac{dN_r}{dE}dE &= N_{He} \cdot N_e \ \frac{64}{3\sqrt{3\pi}}\frac{v_0 \pi a_0^2}{n^3}\alpha^3 Z^4 \left(\frac{Ry}{kT}\right)^{3/2}\frac{dE}{E}e^{-(E-I_n)/kT} \\ &= 5.2\cdot 10^{-14}[cm^3/s] N_{He} \cdot N_e \frac{Z^4}{n^3}\left(\frac{Ry}{kT}\right)^{3/2}\frac{dE}{E}e^{-(E-I_n)/kT}; \ E \geq I_n \end{aligned} \qquad (5)$$

The ratio of recombination intensity to bremsstrahlung intensity from the corresponding ion is equal to

$$\frac{N_r}{N_b} \approx \frac{2}{n^3}\frac{Z^2 Ry}{kT}e^{I_n/kT} \ . \qquad (6)$$

There are actually some small contributions from the bremsstrahlung on [Li]- and [H]- like ions, but we do not consider them.

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Filter transmission $T(E) = exp(-c_k(E_k/E)^k)$ near the K-threshold can be written

$$T(E)/\,T(E_k) \approx exp(-k \cdot c_k(E-E_k)/E_k)\,, \tag{7}$$

where E_k is K-threshold energy and k is the index. This approximation is justified if $k \cdot c_k \gg 1$. Coefficients k and c_k are fitted using calculations.[8] Therefore, the recombination emission passed through a filter can be approximated by

$$\int \frac{dN_r}{dE} T(E) dE \approx \left.\frac{dN_r}{dE}\right|_{E=E_k} \frac{E_k}{c_k k} T(E_k)$$
$$= 5.2 \cdot 10^{-14} [cm^3/s] \mathrm{N_{He}} \cdot \mathrm{N_e} \frac{(Z_{He}-1)^4}{n^3} \left(\frac{Ry}{kT}\right)^{3/2} \frac{E_k}{c_k k} e^{-c_k - (E_k - I_n)/kT}\,; \tag{8}$$

The ratio of the recombination signals for two neighboring ions is equal to $((Z-1)/Z)^4 \exp(-\delta I_n/kT)$, i.e., is practically equal to 1. Note that calculations of continuum radiation passed through foils of different materials and thickness were also performed in [9].

The ratio of the recombination photon number to resonance line photons can be presented as

$$\frac{N_{rec}}{N_{res}} = 5.2 \cdot 10^{-6} [cm^3/s] \frac{(Z-1)^4}{n^3 \cdot k \cdot c_k} \frac{\beta(\beta+\chi)}{A(\beta+1+D)} e^{I_n/kT}\,. \tag{9}$$

(We neglected the difference between the filter threshold E_k and the resonance line excitation potential.)
The results of the intensity ratio calculations versus electron temperature are shown in Figs. 2 and 3. The calculations were performed for Mg and Ti ions and K filters of different thickness (Al, 10 and 20 μm; Ti, 16 and 32 μm, correspondingly). In the case of the Ti ion, the total line intensity emission – the sum of resonance, intercombination and satellite lines – was considered using the data. [10,11]

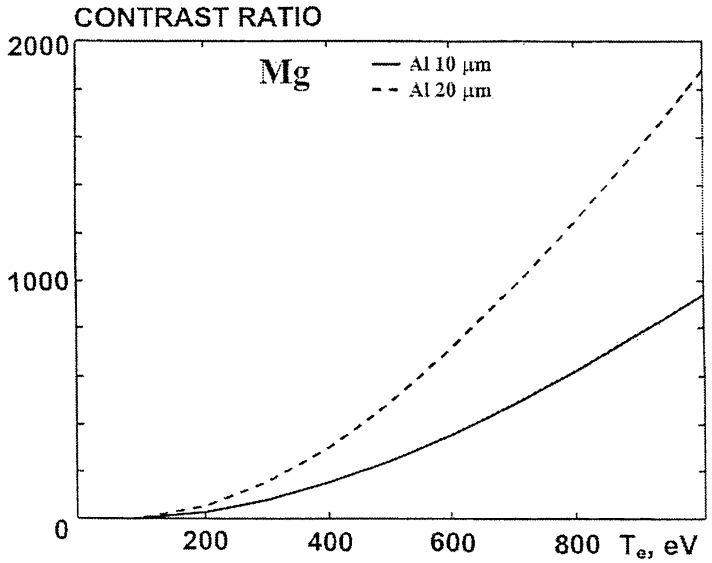


Fig. 2. Contrast ratio for Mg ions (intensity ratio of [He]-like ion resonance line to recombination emission) for Al filters of different thickness (10 and 20 μm).

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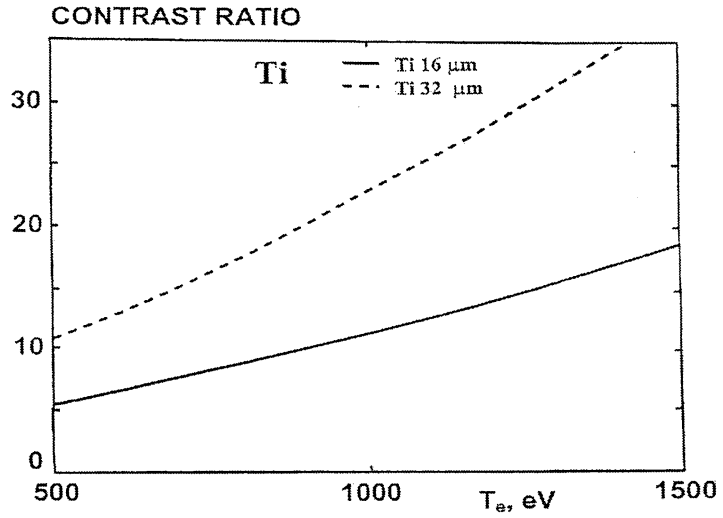


Fig. 3. Contrast ratio for Ti ions (intensity ratio of total intensity of [He]-like ion resonance line, intercombination line and satellite lines to recombination emission) toTi filters of different thickness (16 and 32 μm).

It is clear from Figs. 2 and 3 that the contrast ratio (CR) is very high for electron temperatures needed for the excitation of [He]-like ions. The calculations show that the method works very effectively.

The calculated contrast ratio is high when the intensity ratio of the resonance line of the [He]-like ion to integral intensity of the recombination continuum is considered. The contribution of [Li]-like ion emission is negligible due to large differences in ionization potential: I_{He}/I_{Li} = 4.2-4.5. In this case the [Li]-like ion emission is effectively absorbed by the *K* filter. For another ion configuration (*L* shell/*M* shell or *M* shell/*N* shell) the situation will be worse ($I_{L\ shell}/I_{M\ shell}$ = 2.1 and $I_{M\ shell}/I_{N\ shell}$ = 1.6). Nevertheless, in each case it is necessary to make theoretical estimations or experimental measurements using the same experimental method.

4. EXPERIMENT

The experiment scheme is shown in Fig. 4. Laser-produced plasmas were created using two laser facilities: The "Phoenix" *Nd* glass laser (0.53 μm/10 J/2 ns) at the Lebedev Physical Institute and the "Infinity," a high-repetition rate *Nd-YAG* laser (0.53 μm/200 mJ/3 ns/10 Hz) at Brigham Young University. The laser beam was focused onto massive solid targets (see Table 2). The focal spot diameter was equal to ~15 μm for the Phoenix and ~40 μm for the Infinity laser.

Table 2. The targets used in the experiment, observed ions, filtered spectral range, and *K* absorption filters.

Z+1 target	*Z* target	Ions	λ, Å	*K* filters
Al	Mg	[H] [He]	8.4-9.2	Al 12.5μm
Si	Al	[H] [He]	7.2-7.8	Si 9.5μm
V	Ti	[He]	2.61-2.64	Ti 15.9 μm
Mn	Cr	[He]	2.18-2.2	Cr 15 μm

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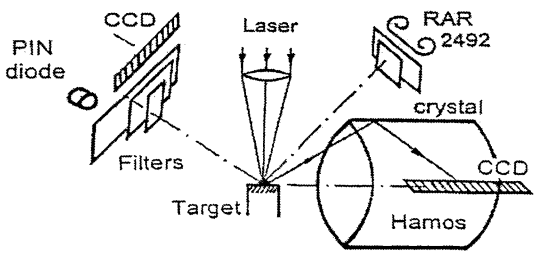


Fig. 4. The experiment scheme.

Several detectors were used to monitor the absolute intensity of the laser plasma x-ray emission. The contrast ratio was measured by a p-i-n diode (Siemens BPX 66: p-type top layer thickness 0.3 μm, intrinsic layer thickness 100 μm).[2] The diode's quantum efficiency was close to unity in the photon energy range 1–10 keV. Corrections connected with absorption in the dead layer and incomplete absorption in the intrinsic layer were taken into account and were not larger than 20%. The absolute calibrated x-ray photographic film Kodak RAR 2492[12] was used for calibration of the CCD linear array (Toshiba TCD 1304 AP) as x-ray detector.[4,5]

The focusing crystal von Hamos spectrometer was used for recording x-ray spectra and for measuring monochromatization degree. Mica crystal ($2d$ = 19.84 Å) with radius of curvature R = 20 mm was installed in the spectrometer. Spectra were recorded using x-ray photographic film Kodak RAR 2492[12] or CCD linear array as x-ray detectors.[4,5] As an example the x-ray spectra of highly charged Mg and Ti ions are shown in Fig. 5.

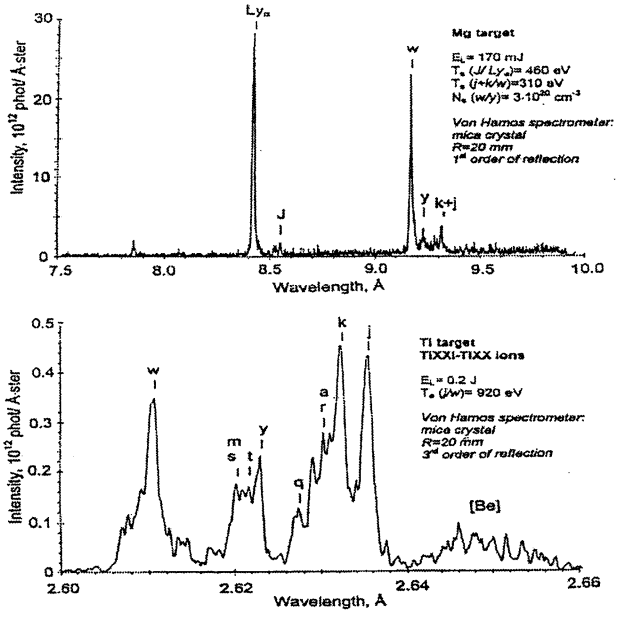


Fig. 5. Examples of x-ray spectra: [H]- and [He]-like magnesium ions (top) and [He]-like Ti ion (bottom).

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The targets used in the experiment, observed ions, filtered spectral range, and K absorption filters are shown in Table 2. Experimental results (contrast ratio and monochromatization degree $\lambda/\delta\lambda$) are presented in Table 3. The contrast ratio was equal to 5–20. These values are the low limit of the measuring values when the experimental errors are defined by the unreproducibility of laser pulse energy from shot to shot. For this reason the experimental contrast ratios are somewhat lower than the theoretical ones. The monochromatization degree $\lambda/\delta\lambda$ was dependent on the ionization stage as observed in laser-produced plasmas. If both [H]- and [He]-like ions were excited, then $\lambda/\delta\lambda$~10. If only [He]-like ions were observed, the monochromatization degree was higher $\lambda/\delta\lambda$~100. As a result the measured parameter (Monochromatization) × (Solid angle) = $\lambda/\delta\lambda\times\Omega$ = 100–1000. This value indicates the advantage of the method of monochromatization (compared with the values $\lambda/\delta\lambda\times\Omega$~1 for crystal-monochromator techniques) and makes this method very effective for numerous practical applications. The method was used for calibration of the focusing crystal von Hamos spectrometer (the needed Ω~1 ster) [2,3], for calibration of the CCD linear array as x-ray detector,[4,5] and to study the laser plasma–wall interaction in monochromatic x-ray emission.[13] Color (at many wavelengths) x-ray absorption and tomography are interesting applications for the future.

Table 3. Contrast ratio and monochromatization degree measured in the experiment.

Targets $Z/Z+1$	Contrast Ratio	$\lambda/\delta\lambda$
Mg/Al	5	11
Al/Si	20	12.5
Ti/V	5	100
Cr/Mn	5	80

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