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Dependence of the yield of hard incoherent X-rays from femtosecond laser plasma on the atomic number of target material

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Abstract. The yield of hard incoherent X-rays emitted by a dense femtosecond laser plasma is studied as a function of the atomic number Z of target material. It is shown that for Z values in the range from 14 (Si) to 73 (Ta), the efficiency of laser radiation conversion to X-rays with quantum energy exceeding 8 keV varies as $Z^{3/2}$. The temperature of hot electrons formed in the plasma weakly depends on the atomic number of the target material and is equal to ~ 4 keV for both Si ($Z = 14$) and Ta ($Z = 73$) targets for laser radiation intensities $\sim 10^{16}$ W/cm^2.

The search for ways to increase the yield of hard X-rays from a dense high-temperature femtosecond laser plasma evokes much interest in view of efficient generation of ultrashort pulses of incoherent X-rays. Such pulses are required for X-ray spectroscopy with high temporal resolution, excitation of low-lying nuclear levels in a dense plasma, and for solving various problems in nonlinear X-ray optics.

An increase in the efficiency of X-ray generation is feasible both via optimization of laser radiation characteristics (such as intensity, duration, contrast) on the target surface and by an optimum selection of the atomic number of the target material.

The investigations of laser radiation conversion into soft X-rays (with quantum energy up to 1.2 keV) as a function of the atomic number Z of the target material were reported in Refs [1, 2]. It was found that the soft X-ray pulse duration weakly depends on the target material and is about 4 – 6 ps [1]. The plasma X-ray emission in the energy range from 0.8 to 1.2 keV also weakly depends on the target material, whereas the efficiency of energy conversion into the spectral interval 200 – 300 eV can vary by a factor of 3 to 5. This is explained by the fact that the maximum spectral radiance of the plasma was observed for elements whose electronic shells had ionization potentials equal to 200 – 300 eV [3].

It is natural to expect an increase in the yield of X-rays emitted by a femtosecond laser plasma in a shorter-wavelength spectral range with increasing atomic number of the target material. Emission of hard incoherent X-rays in a femtosecond laser plasma appears primarily due to inelastic scattering of 'hot' electrons by atoms. The hot electrons emerging in the skin layer penetrate inside the target and emit X-ray quanta with energy as high as hundreds of kiloelectronvolts. The pulse duration of hard X-ray plasma emission is comparable to laser pulse duration and is determined in fact by the lifetime of hot electrons.

The purpose of this work is to study experimentally the dependences of the hard X-ray yield from a dense femtosecond plasma and of the temperature of the hot electronic component on the atomic number of the target material.

1. Experimental

In our experiments, we studied the radiation of the femtosecond laser system described elsewhere [4]. Fig. 1 shows schematically the experimental setup for measuring the yield of X-rays emitted by a plasma. The p-polarised laser radiation was focused on the target surface using an aberration-free objective oriented at an angle of 45° to the normal and having a focal distance of 6 cm (3-μm beam waist). The intensity of up to 5×10^{16} W cm^{-2} at a pulse duration of 200 fs was thus attained.

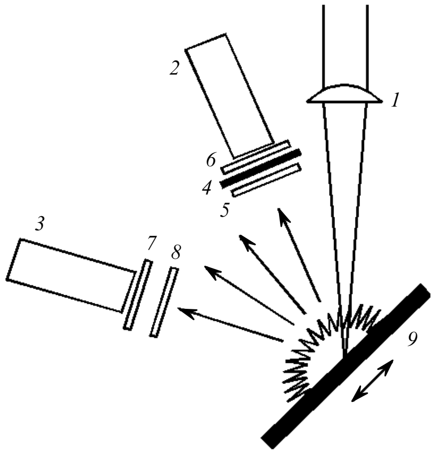

Figure 1. Schematic diagram of the experiment setup for measuring the yield of X-rays from a target:
(*1*) objective; (*2*, *3*) scintillation detectors; (*4*) plug-in additional filter; (*5* – *8*) 100-μm-thick beryllium filters; (*9*) target.

For detection of hard X-rays in the time-integration mode, two X-ray detectors *2* and *3* were used, each consisting

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of a FEU-119 photomultiplier and a NaI (Tl) scintillator and located outside the interaction chamber. The detectors were calibrated using radiation from a ^{55}Fe X-ray source emitting quanta with energy of 5.9 keV.

Table 1. Composition and spectral characteristics of filters.

Filter number	Filter composition	ΔE/keV
I	200 μm Be + 300 μm Al	Over 8.7
II	200 μm Be + 1 μm Al	Over13.1
III	200 μm Be +13 μm Ta	9.0 – 9.8 and over 15.5
IV	200 μm Be + 26 μm Ta	Over 20.2
V	200 μm Be	Over 2.5

Note: ΔE is the transmission bandwidth at the 0.05 level.

To determine the efficiency of conversion of laser energy to different X-ray spectral ranges, X-ray band filters were placed in front of detector *2*. The characteristics of the filters are summarized in the Table 1 and shown in Fig. 2. Detector *3* measured the integrated efficiency of conversion into X-rays with quantum energy over 2.5 keV. Signals from the detectors were fed to the inputs of charge-sensitive amplifiers of a multichannel analog-to-digital converter and then processed using a computer.

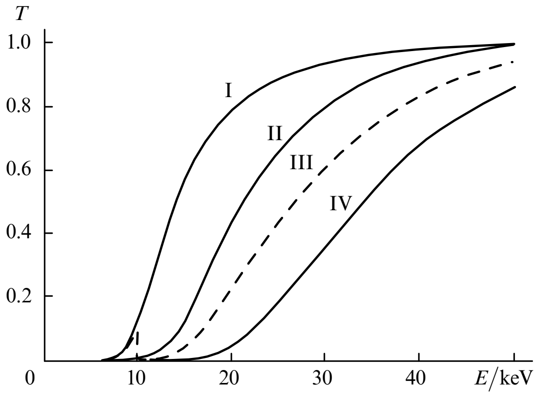

Figure 2. Transmission coefficients T of filters as functions of the X-ray quantum energy E (the digits at curves correspond to filter numbers from the Table 1).

The target located in a vacuum chamber at pressures of $10^{-2} - 10^{-3}$ Torr was displaced after each flash. Accurate focusing of laser radiation on the target surface was attained by maximizing the yield of hard X-rays.

2. Experimental Results

To measure the relative efficiency of laser energy conversion into different spectral X-ray ranges, a series of experiments was carried out on comparison of parameters of plasma containing Si ($Z = 14$) and heavier materials, such as Fe ($Z = 26$), GaAs ($Z = 31, 33$), Pd ($Z = 46$) and Ta ($Z = 73$).

The plasma emission intensity in the investigated spectral ranges turned out to be substantially dependent on the atomic number Z of the target material (see Fig. 3). By fitting experimental dependences of the hard X-ray yield Y by a power function of Z, we found that the exponent is the same (within the experimental error) for all X-ray regions and equal to 3/2 ($Y \sim Z^{3/2}$).

Let us compare the experimental results with theoretical estimates. Two models were proposed [5 – 7] to calculate the efficiency of X-ray continuum generation. In the first model [5, 6], a thin layer of substance is considered through which an electron beam passes. In this case, the reverse bremsstrahlung takes place and the electron velocity changes insignificantly. This model predicts a quadratic dependence of X-ray yield on the atomic number of a substance ($Y \sim Z^2$).

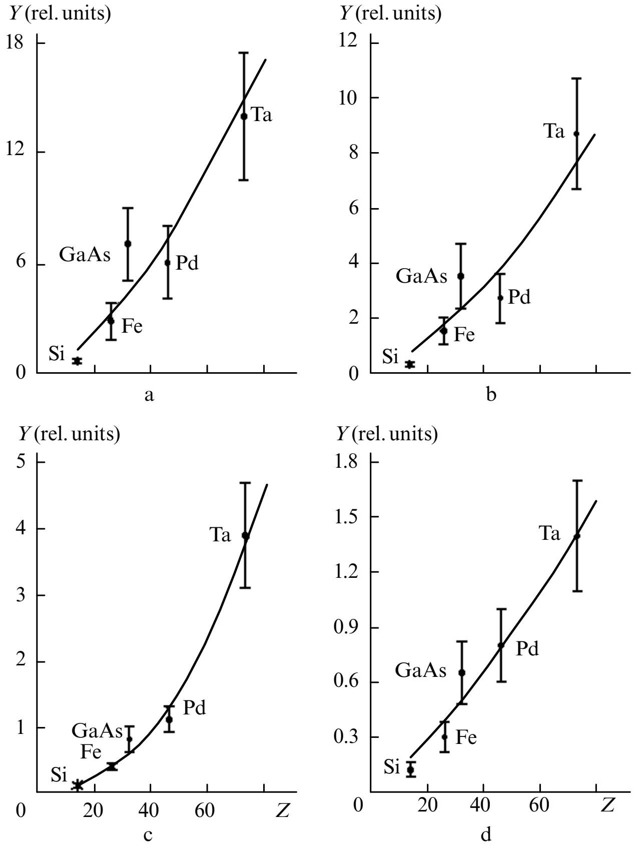

Figure 3. Yields Y of X-rays as functions of the atomic number Z of the target material obtained in different spectral intervals for laser radiation intensity on the target surface $\sim 2 \times 10^{16}$ W cm^{-2} and using filters I (a), II (b), III (c), and IV (d). Solid curves show approximation functions $Y \sim Z^{\alpha}$, where $\alpha = 1.5$ (a, b), 1.7 (c), and 1.2 (d). The uncertainty of determination of α is ± 0.3.

In the second model [5 – 7], the absorbing layer is assumed to be thicker, so that the electron energy losses cannot be neglected. In this case, the energy emitted by the X-ray continuum of a plasma is directly proportional to the atomic number of the absorbing substance ($Y \sim Z$).

Under conditions of our experiment, the free path length of a hot electron with a temperature of about 4 keV can be estimated as $L_{\text{fp}} \simeq V_{\text{e}}/\nu_{\text{ei}} \simeq 50$ nm, where $\nu_{\text{ei}} \sim 7 \times 10^{-7} \times n_{\text{e}}/T_{\text{h}}^{3/2}$ is the frequency of electron-ion collisions measured in s^{-1}; $V_{\text{e}} \sim 2 \times 10^9 \sqrt{T_{\text{h}}}$ is the velocity of electrons in cm s^{-1}; T_{h} is the temperature of hot electrons in keV; $n_{\text{e}} \sim 10^{22}$ cm^{-3} is the concentration of electrons. One cannot therefore neglect the electron energy losses, and consequently the yield of hard X-rays should be directly proportional to the atomic number of the target material ($Y \sim Z$).

It is important to note that this model describes the X-ray continuum generation excited by a monoenergetic electron beam. To describe the hard X-ray bremsstrahlung in a plasma, it is necessary to take into account the generation of hot electrons. Since the degree k of ionisation of the laser plasma depends on the atomic number of a substance ($k \sim f(Z)$), other plasma parameters, such as the skin layer thickness, the free electron concentration n_e, the ionisation energy of a single atom, the electron temperature T_h, etc, are also dependent on Z. Thus, the dependence of the yield of incoherent X-rays on the atomic number of a substance is determined by the influence of atomic composition of the target on generation and scattering of hot electrons in the femtosecond laser plasma and therefore can be written as $Y \sim n_e(Z)T_h(Z)Z \sim Z^{\alpha}$.

The experimentally found exponent $\alpha = 3/2$ can be apparently explained by the increase in the temperature and the number of hot electrons generated in the plasma with increasing atomic number of the target material.

At the same time, according to the known theoretical concepts [8, 9], the hot electron temperature depends only on the intensity and wavelength of laser radiation. For experimental verification of this hypothesis, we developed a method to evaluate the temperature of hot electrons using simultaneous measurements of the hard X-ray yields in two different spectral intervals.

3. The hot electron temperature evaluation

The standard method for measuring the temperature of hot electrons is based on the measurement of the line plasma spectrum (the intensity of the K_α emission line) [10–12]. Another approach is based on the measurement of the continuous X-ray radiation spectrum of a laser plasma (the method of absorbers [13, 14]). This method consists in the following. First, a series of experimental measurements of the relative efficiency of the laser radiation conversion into different spectral X-ray ranges is performed. Then, on the basis of the known emission spectrum of the laser plasma and filter transmissions, the temperature is selected at which the theoretical curve coincides with experimental data to within a constant factor.

The main drawback of such an approach is an arbitrary selection of the plasma temperature because it is necessary to vary two or more parameters, namely, the temperature and fitting coefficients. In this case, the electron temperature has to be calculated from a set of experiments, and consequently, a high reproducibility of experimental results should be ensured.

The interpretation of experimental results calls for a fast method for determining the temperature of hot electronic component in each individual experiment. For this purpose, we modified the above method of absorbers. The basic feature of the modified method is the use of two X-ray detectors with a linear response within the measurement spectral range and with equal sensitivities (or the known ratio of sensitivities).

Let us assume that the plasma emission is simultaneously detected by two detectors equipped with two different band filters having transmission coefficients $T_1(E)$ and $T_2(E)$ for X-ray quanta of the energy E. Then, the detector signal amplitudes can be written as

$$S_{1,2} = G(T_h, Z, n_e)\int T_{1,2}(E)F(T_h, E)\mathrm{d}E,$$

where $F(T_h, E)$ is the spectral density of radiation power of the laser plasma in a specific experiment and $G(T_h, Z, n_e)$ is the function describing the plasma condition. The ratio of signals from these detectors is

$$r(T_e) = \frac{S_1}{S_2} = A\frac{\int T_1(E)F(T_h, E)\mathrm{d}E}{\int T_2(E)F(T_h, E)\mathrm{d}E},$$

where the coefficient A is determined by the ratios of sensitivities of the detectors and solid angles of detection.

The method of measuring the electronic temperature described above requires *a priori* information on the spectral density of plasma radiation power $F(T_h, E)$. According to Ref. [15], the spectral power densities of bremsstrahlung and recombination radiation for free-free (F_{ff}) and free-bonded (F_{fb}) transitions for the quantum energy $E > E_1$ (E_1 is the energy of recombination of a free electron on the ion with the maximum degree of ionisation) are well described for the Maxwell distribution of hot electrons by the expression:

$$F_{ff,fb}(T_h, E) \sim C_{ff,fb}(T_h)\mathrm{e}^{-E/T_h},$$

where C_{ff} and C_{fb} are the coefficients that are independent of the X-ray quantum energy. If the radiation with the quantum energy corresponding to the recombination edge of the substance ($E < E_1$) falls within the transmission bands of one of the filters, it becomes necessary to allow for this energy and possibly for the energies corresponding to the subsequent recombination edges E_2, E_3... . In this case, the spectral densities of radiation power can be written in the form

$$F_{ff,fb}(T_h, E) \sim C_{ff,fb}(T_h)\Big[\mathrm{e}^{-(E-E_1)/T_h} + \alpha_2(T_h)\mathrm{e}^{-(E-E_2)/T_h} + \alpha_3(T_h)\mathrm{e}^{-(E-E_3)/T_h} + ...\Big],$$

where α_i is the ratio of maximum quantum energies corresponding to the ith and first recombination edges. The constants α_i depend substantially on the plasma parameters. Since the measured energy interval of hard X-ray quanta corresponds to the recombination K- and L-edges, it is sufficient to take into account only two or three terms in the above sum. The use of two and more pairs of different band filters in the above method allows one to determine fitting parameters to match the electron temperatures obtained for different pairs of filters in each experiment.

In the experimental series with silicon targets (34 measurements) and tantalum targets (50 measurements), we measured the hot electron component temperatures for the laser radiation intensity $\sim 2 \times 10^{16}$ W cm^{-2} (Fig. 4). The scatter of temperatures is primarily due to the low reproducibility of the spatial mode, energy and duration of laser pulses in different experiments. From the constructed histograms, we determined the most probable temperatures of hot electrons equal to 4.0 ± 0.8 keV for Si ($Z = 14$) and 4.2 ± 0.6 keV for Ta ($Z = 73$). Thus, the temperatures of hot electron component for Si and Ta targets coincide within the experimental error.

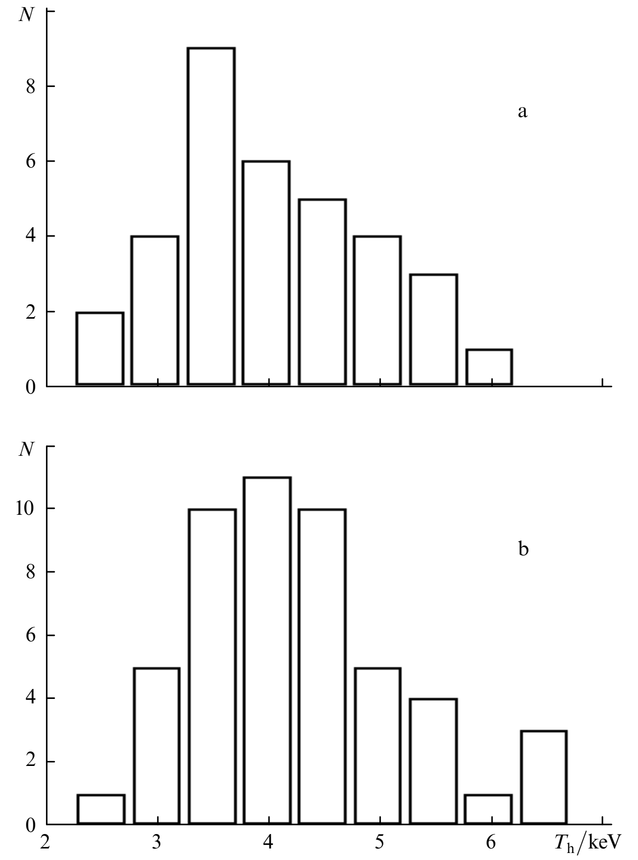

Figure 4. Histograms of temperature T_h of hot electron component in Si (a) and Ta (b) plasmas for the laser radiation intensity of 2×10^{16} W cm^{-2}.

Note that in Ref. [16], the hot electron temperature was apparently estimated in a similar way, although the technique used was not described. Moreover, the authors [16] obtained a stronger dependence of the hot electron temperature on the laser radiation intensity $T_h \sim I^{\beta}$, (where $\beta = 1 - 1.5$) as compared with known theoretical and experimental dependences [8, 9], which, in our opinion, points to an inaccurate calibration of the detection system in these experiments.

The temperature of the hot electron component of the plasma can also be approximately estimated from the X-ray yield in various spectral ranges (Fig. 5). Because the spectral distribution of this plasma emission obeys the law $Y \sim \exp(-E/T_h)$ [15], the integrated radiance of the plasma is characterized by the same exponential dependence throughout the entire range of hard X-rays. Therefore, the slope of the curves in Fig. 5 allows one to determine the hot electron temperature. For a silicon target, $T_h = 3.9$ keV and for a tantalum target, 4.0 keV. The main drawback of this method for estimating the electron temperature is that the transmission band of the filters used in experiments has broad wings so that the choice of their level can be arbitrary (0.05, in our case). The good agreement was nevertheless obtained with the above hot electron temperature estimated by the method of band filters.

4. Conclusions

Thus, the efficiency of conversion of laser energy to hard X-rays is proportional to $Z^{3/2}$, and consequently the yield of hard X-rays from a plasma increases by an order of magnitude with increasing atomic number of the target material from $Z = 14$ (Si) to $Z = 73$ (Ta).

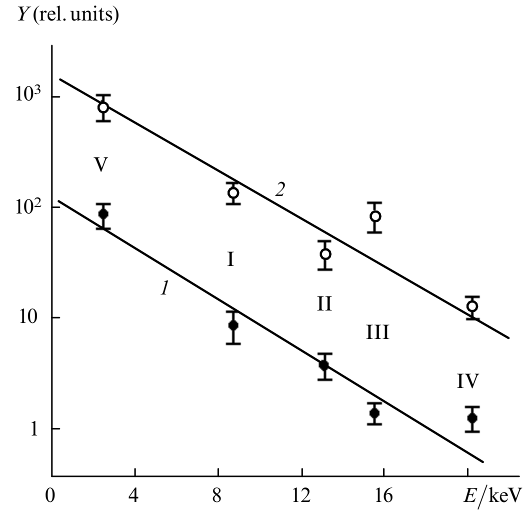

Figure 5. The yield Y of X-rays in the ranges with quantum energies exceeding E, which are determined by transmissions of filters I – V (see the Table 1) at the 0.05 level for Si targets (*1*, ●) and Ta targets (*2*, ○) for the laser radiation intensity $\sim 2 \times 10^{16}$ W cm^{-2}. Solid curves are exponential approximations of experimental data with hot electron temperatures T_h = 3.9 (*1*) and 4.0 keV (*2*).

The temperature of the hot electron component formed in a plasma weakly depends on the atomic number of the target material and is of about 4 keV for the laser radiation intensity $\sim 10^{16}$ W cm^{-2} for both silicon and tantalum targets. Since under our experimental conditions, the energy of the X-ray bremsstrahlung Y should be proportional to Z, the experimentally observed dependence $Y \sim Z^{3/2}$ can be explained by an increase in the concentration of hot electrons generated in a plasma, which is proportional to $\sqrt{Z}$.

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