GENERAL EXPERIMENTAL TECHNIQUES

Focusing of X-Rays with a Photon Energy of 9.5 keV by an Ellipsoid with a HOPG Crystal

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Abstract—The arrangement and results of full-power experiments on the Iskra-5 laser facility (the laser energy is 150 J, the pulse length is 0.3 ns, and the laser-radiation intensity on the target is 1.6×10^{15} W/cm²) on focusing of hard X rays from a laser-plasma source with a Ga target using an ellipsoid with a HOPG crystal are described. The design of an ellipsoid focus pointer is described that made it possible to create an X-ray source at the focus of the ellipsoid with an accuracy of no worse than 100 μm. Focusing X-ray radiation into a 1-mm-diameter spot in full-power experiments was achieved at a distance of 250 mm. An eighty-fold increase in the X-ray flux density with a photon energy of 9.5 keV was attained.

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INTRODUCTION

The rapid development of lasers with pico- and femtosecond laser-pulse durations in recent decades has made it possible to create compact laser-plasma sources of pulsed X-ray radiation (XR) with equally short pulse durations, which are based on laser plasma. Due to their compactness and short pulses, such sources proved to be in demand for a large number of applied studies, such as studies of dense and high-temperature plasma [1], phase transitions in materials under extreme conditions [2], and rapid processes of molecular dynamics [3], and also contributed to the development of imaging methods in medicine [4, 5].

The beginning of research using an X-ray free-electron laser (XFEL) poses a new important task of preliminary certification of the optical properties and radiation strength of X-ray optics elements, which will be used to control and form high-energy-density X-ray fluxes in a wide spectral range. To preserve the short duration of X-ray pulses from XFEL and, most importantly, their coherence, high-intensity x-rays are required for certification. The effect of such fluxes may cause thermal surface changes in both smooth (with a surface roughness of several angstroms) substrates of grazing-reflection mirrors and Au or Pt monolayer coatings with a thickness of ~100 nm, or multilayer interference structures for the X-ray range. In addition, such fluxes may cause volumetric phase modifications of mirrors [6, 7]. The necessary densities of X-ray fluxes can be achieved by using laser-plasma sources of X rays in combination with adequate focusing components of X-ray optics.

When intense laser radiation interacts with matter due to such processes as, for example, the resonant absorption or parametric instabilities, so-called “hot electrons” arise in laser plasma, whose energy may reach hundreds of kiloelectronvolts or even several megaelectronvolts. While propagating in the target, these electrons cause bremsstrahlung, as well as characteristic radiation of the cold or partially ionized target material via ionization of the *K*-shell of the target substance with subsequent radiative de-excitation [8–10]. The duration of this radiation is mainly determined by the duration of the electron acceleration, i.e., approximately the duration of a laser pulse and the average time of the electron movement inside the target, which is on the order of several picoseconds [11].

Despite the progress that has been achieved in the development of laser-plasma sources of X rays, research continues on the mechanisms of interaction of intense laser radiation with matter in order to optimize the characteristics of these sources to achieve the necessary parameters. Depending mainly on the parameters of both laser radiation (the incident intensity, contrast ratio, pulse duration, and polarization) and the target, the efficiency of generating characteristic K_α radiation varies from 10^{-6} to 10^{-4} [12–15]. However, in order to be in demand in applied experiments, the sources that are created with the help of lasers must be isotropic and use X-ray optics with a large aperture that collects a maximum number of photons of focused X-rays. Focusing and monochromatization of X rays can be achieved using two-dimensional curved perfect crystals, such as quartz,

Fig. 1. A schematic of the experiments on studying the focusing properties of the ellipsoid: (1) ellipsoid body; (2) HOPG crystal; (3) focus pointer case; (4) needle; (5) target substrate; (6) Ga target; (7) laser radiation beam; (8) 200- μm -thick Lavsan filter; (9) Al filter with a thickness of 50 μm ; (10) Ta disk with a thickness of 2 mm; (11) cassette case; (12) spacers of various thicknesses; (13) set of X-ray films; (14) 50- μm -thick Lavsan filter; (15) 12- μm -thick Ta filter; and (16) LiF-crystal-based spectrograph of X-ray line emission.

silicon, or GaAs [16–18]. Such crystals make it possible to obtain a focal spot of $\sim 50\ \mu\text{m}$, but their efficiency is limited to $\sim 10^{-4}$.

In this paper, we experimentally demonstrate the possibility of high-efficiency focusing of hard X rays using a single-component X-ray optical device in the form of an ellipsoid with a HOPG (highly oriented pyrolytic graphite) crystal.

THE DESIGN

An ellipsoid with a HOPG crystal was manufactured according to the technology described in [19], but its half axes are larger: $a = 126.85\ \text{mm}$ and $b = 24.5\ \text{mm}$, thus corresponding to a focal length of $f = 124.5\ \text{mm}$. The 50-mm-long ellipsoid itself was made symmetrically with respect to the foci. In the ellipsoid, the HOPG crystal with a thickness of 100 μm was fixed on the reflecting surface.

In accordance with the dimensions of the semi-axes of the ellipsoid and the doubled interplanar distance of the HOPG crystal ($2d = 6.708\ \text{\AA}$), the energy of X-ray photons that is reflected from the ellipsoid surface and focused into its focus varies from $\sim 9.389\ \text{keV}$ at the ends of the ellipsoid to $9.570\ \text{keV}$ at its center.

It should be noted that there are no X-ray tubes with such a photon energy. A number of components of the X-ray line emission of gallium ions in laser plasma have suitable photon energy. The energies of the $K_{\alpha 2}$ - and $K_{\alpha 1}$ emission lines, the resonance, and intercombination lines of a helium-like gallium ion are, respectively: 9.22482, 9.25174, 9.62781, and 9.57413 keV. As a rule, the laser-plasma spectrum, apart from the intense $K_{\alpha 1,2}$ and resonance lines of a helium-like ion, contains weaker lines of ions with a lower degree of ionization [20].

THE ARRANGEMENT AND RESULTS OF THE EXPERIMENTS

For experiments with the ellipsoid, a precision ellipsoid focus pointer (hereinafter, referred to as the focus pointer) was made in the form of a cylindrical cup with a thin-walled bottom, on which a stepped rod was cut along the cup axis, turning into a truncated cone. Inside the cup, two steps were cut along the circumference with such a diameter that the ellipsoid could be easily inserted into the cup, although there was no backlash. Four windows were cut out in the bottom of the glass to allow for the passage of X rays, and narrow but quite rigid radial ribs were left. A hole with a diameter of 1 mm was drilled in the truncated cone along its axis, into which a needle was inserted. The length of the needle was such that its tip that was completely inserted into the hole coincided with the focus of the ellipsoid. The diameter of the needle was reduced to a size at which it was easily inserted into the hole without a backlash.

The target substrate was a 0.4-mm-thick steel plate with a hole with a diameter slightly larger than 1 mm, so that the needle could be easily removed through it. On the side of the incident laser radiation, the hole was coredrilled to a diameter of 1.5 mm. When conducting the experiment, the target holder was placed in such a way that the needle tip was located in the plane of the back surface of the target holder, being at the center of the hole with an accuracy of at least 100 μm . Then, after removing the needle through the hole, a Ga-plate was glued to the back surface of the holder. In the experiments, the laser radiation was focused to the center of the hole with an accuracy of no worse than 100 μm .

Inside the ellipsoid, a HOPG crystal with a thickness of 100 μm was fixed on the reflecting surface.

Studies of the focusing properties of the ellipsoid were performed in full-scale experiments in one of the channels of the Iskra-5 laser facility [21] according to the scheme that is shown in Fig. 1.

The relative intensities of the XR lines depend on the laser-radiation intensity in the irradiated spot and on the laser wavelength. Thus, when targets are irradiated with shorter-wavelength radiation of the second harmonic, the number of “hot electrons” in laser plasma is low; therefore, the lines of helium-like ions dominate in the emission spectrum and the $K_{\alpha 1,2}$ radiation is much weaker or almost absent. Therefore, in order to obtain a narrower spectrum of the XR source in the experiments, the targets were irradiated with second-harmonic laser radiation with $\lambda = 0.6575\ \mu\text{m}$. To obtain a small XR source, laser radiation was focused into a spot with a diameter of $\sim 100\ \mu\text{m}$. The energy of second-harmonic laser radiation that was supplied to the target was 150 J; accordingly, at a laser-pulse duration of 0.3 ns, the laser radiation intensity at the focal spot reached $1.6 \times 10^{15}\ \text{W/cm}^2$, thus making it possible

Fig. 2. (a) The spectrogram and (b) the spectrum of X-ray line emission for gallium.

to generate intense and comparatively hard X-ray line emission with a photon energy higher than 9.5 keV.

The spectrum of the line X-ray emission was recorded using a spectrograph based on a flat absolutely calibrated LiF crystal. To obtain a spectral label, a narrow Hf filter strip with a thickness of 5 μm was installed at the entrance to the spectrograph. The absorption jump on L_{III} Hf with an energy of 9.561 keV was used as the spectral label [22].

A typical spectrum of the line X-ray emission from Ga that was recorded in one of the experiments is shown in Fig. 2. According to this figure, three comparatively bright components of a He-like ion are clearly seen in the hard segment of the spectrogram: the resonance $\text{He}_{\alpha}(\text{R})$, intercombination $\text{He}_{\alpha}(\text{I})$, and satellite $\text{He}_{\alpha}(\text{sat})$ lines. In the soft spectral region, weaker components of $K_{\alpha 1,2}$ radiation of the cold material can be seen, as well as the components of ions of low degrees of ionization. An L_{III} edge of the Hf absorption coefficient is observed in the spectrogram between the resonance and intercombination lines on the Hf filter strip.

Images of focused X-ray at different distances behind the ellipsoid, as well as spectrograms of X-ray line emission, were recorded in the spectrograph on Fuji X-ray film with a low fog level and sufficient sensitivity. In order to minimize errors when processing the results, the filters on the focus pointer and the cassette with films were selected so as to provide close optical densities on the spectrogram and photographic films in cassette. The characteristic curve of a photographic film was reconstructed from the spectrogram, one half of which was recorded behind a 100- μm Al filter, while the other half was recorded without a filter. The transmission of the 100- μm -thick Al filter at the most intense intercombination line with an energy of 9.57413 keV was 0.469, which is suitable for reconstructing the characteristic curve. The thus-obtained characteristic curve of the photographic film was used for processing the spectrogram (see Fig. 2) and image of the spot with the highest focusing.

Figure 3 shows the images of the cross section of focused X-ray that were recorded in one of the experiments on several X-ray films, which were installed at different distances z from the focal plane. An image of the spot with the highest focusing and the intensity distribution in it are presented in Fig. 4.

The focusing-spot-averaged X-ray flux density in the focal plane of the ellipsoid was compared to the flux density directly from the laser plasma, which was obtained as a result of processing the spectrogram according to the experimental characteristic curve of the used photographic film. In this case, the absolutely measured integral reflectivity of the LiF crystal, as well as the recording geometry and the transmission coefficients of all filters, was taken into consideration. It has been found that the use of an ellipsoid allows an increase in the focal-spot-averaged X-ray flux density in the focal plane of the ellipsoid, i.e., at a distance of ~ 250 mm from the radiation source, by a factor of ~ 80 and, moreover, a factor of ~ 1.5 at the center of the spot.

CONCLUSIONS

Full-scale experiments on the Iskra-5 laser facility (the laser energy is 150 J in a pulse of 0.3-ns duration, the laser-radiation flux density on the target is $1.6 \times 10^{15} \text{ W/cm}^2$) on focusing hard X-ray from a laser-plasma source using an ellipsoid with a HOPG crystal have been developed.

A design of the ellipsoid focus pointer was developed that allows the creation in the experiments of an X-ray source at the focus of the ellipsoid with an accuracy of no worse than 100 μm .

Full-power experiments with a Ga target were conducted. At a distance of 250 mm, focusing of X-rays into a spot with a diameter of 1 mm was achieved. An approximately eighty-fold increase in the X-ray flux density with a photon energy of 9.5 keV was obtained.

It has been shown experimentally that using an ellipsoid with a HOPG crystal manufactured via high-

Fig. 3. Images of the cross section of focused XR that were recorded in an experiment on several X-ray photographic films installed at various distances z from the focal plane of the ellipsoid.

Fig. 4. (a) An image of the spot of the highest focusing and (b) the intensity distribution in the spot.

precision turning, an almost eighty-fold increase in the flux density of X-ray photons with an energy of ~ 10 keV can be achieved at the focus of the ellipsoid.

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