Generation of Short 1.7 keV X-Ray Radiation from Laser-Produced Plasmas

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Abstract – Measurements of a x-ray radiation from well-collimated jets by interaction of laser pulse with a metallic target in vacuum have been done by means of picosecond x-ray streak camera. Short x-ray pulse with a duration of 100ps in spectral range of 1.1–1.7 keV has been detected in small space angle of 10°. Interferometric measurements with high temporal and spatial resolution confirm the formation of plasma channel in plasma corona in the first 100 ps after ignition.

1. Introduction

X-ray generation from laser produced plasmas has received increasing attention in the past years and is developing into important application area [1, 2, 3].

When a sufficiently intense laser pulse of sufficiently short duration is focused onto surface of a solid, the electrons within an optical skin depth of the surface absorb energy from the laser and heat rapidly to temperatures of several hundred electron volts. The hot electrons subsequently ionize the much cooler atoms and form a high-temperature, x-ray emitting plasma spark at the surface of the solid. Theoretically a very high conversion efficiency can be reached for laser pulse widths less than a few hundred femtoseconds. In this case the laser energy will couple directly into the free electrons in the solid. During and after the excitation laser pulse, rapid thermal conduction and plasma expansion will cool and reduced the density of the x-ray emitting region, and result in a short x-ray pulse width from the plasma source. But experiments [2] performed with a commercially available femtosecond-laser systems showed a low conversion coefficient for x-ray emission in keV-range for this short pulse length.

The discrepancy can be only explained by formation of a plasma prior to the arrival of the main laser pulse due to long prepulse stadium with an intensity well above the threshold intensity for plasma generation. The resulting lower-temperature, lower-density plasma will yield smaller x-ray conversion efficiencies for short x-ray radiation.

The aim of our present experiment is to investigate the behavior of a preformed plasma by an interaction of a short laser pulse solid target in vacuum and to find out an influence of a nonlinear plasma behavior on conversion efficiency of x-ray radiation.

2. Experimental Equipment

The experiments have been carried out with a 100 ps, 90 mJ laser pulse at $\lambda = 1064$ nm. By using a lens ($f = 25$ cm) the short pulse was focused onto solid target in vacuum ($P \approx 10^{-7}$ mBar). The vacuum incident angle of the short pulse was varied in the range of 90°, 60°, 45°, 30°, 23°, 19°. As target was used Cu, W, Ta, Ag. The spot diameter of the short pulse at the best focus position was 20 µm in vacuum giving a peak intensities of $3 \cdot 10^{14}$ W/cm^2. Interferometric measuring technique has been used to obtaine two dimentional distribution of electron density for different delay time between the probe beam at $\lambda = 532$ nm and main pulse at $\lambda = 1064$ nm [4, 5]. The radiation emitted from the region of laser-produced plasmas was registred by X-ray streak camera with an Au photo-cathode and set of foil filters: Al (1.5, 3, 4.5, 6, 7, 7.5, 9, 12, 14, 21, 500 µm Fe (1.8 µm), Be (70, 140 µm), which allowed to select a different spectral ranges of emitting photons in the spectral range of 0.1–10 keV. According to Ref. [6], the temporal resolution is as small as 10 ps, and generally is determined by the dispersion time-of-flight for photoelectrons moving from different parts of the photocathode to the deflecting plates of the steak tube (temporal dispersion due to photo-electron energy distribution).

A sweep time of about 3ns or 30 ns was used to investigate plasma radiation close to the ignition by the laser pulse, as well as in later state. A Peltier-cooled charge-coupled-device camera (Cordin CCD), which permitted image analysis with 14 bit depth, and a specially designed computer system (Cordin CCD Readout System) were used to record the streak-camera output. The experimental set-up is shown in Fig. 1.

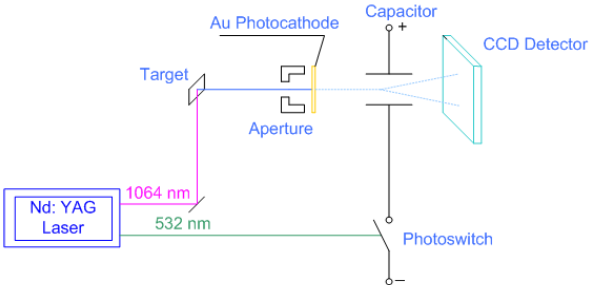
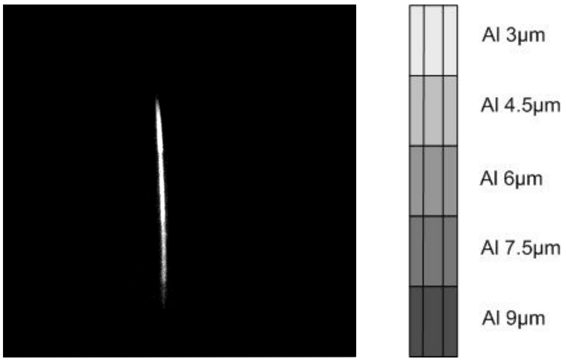


Fig. 1. Schematic diagram of set-up for recording of X-ray radiation

The synchronization of the streak camera recording with the plasma ignition was realized with an optical signal from second harmonic radiation of the laser pulse from – 9 ns. A minus means that the trigger signal prepares the streak camera for recording before the initiation by means of an IR-laser pulse.

3. Experimental Results and Discussion

The interaction of Nd:YAG-laser with various flat target has been investigated by studying the x-ray continuum radiation and interferometric diagnostics. X-ray emission spectra of laser-produced plasmas yield valuable information about thermal transport and the generation of superthermal electrons. The experiments described here allowed a determination of time-resolved electron temperature from the relative intensities of x-ray continuum spectrum.



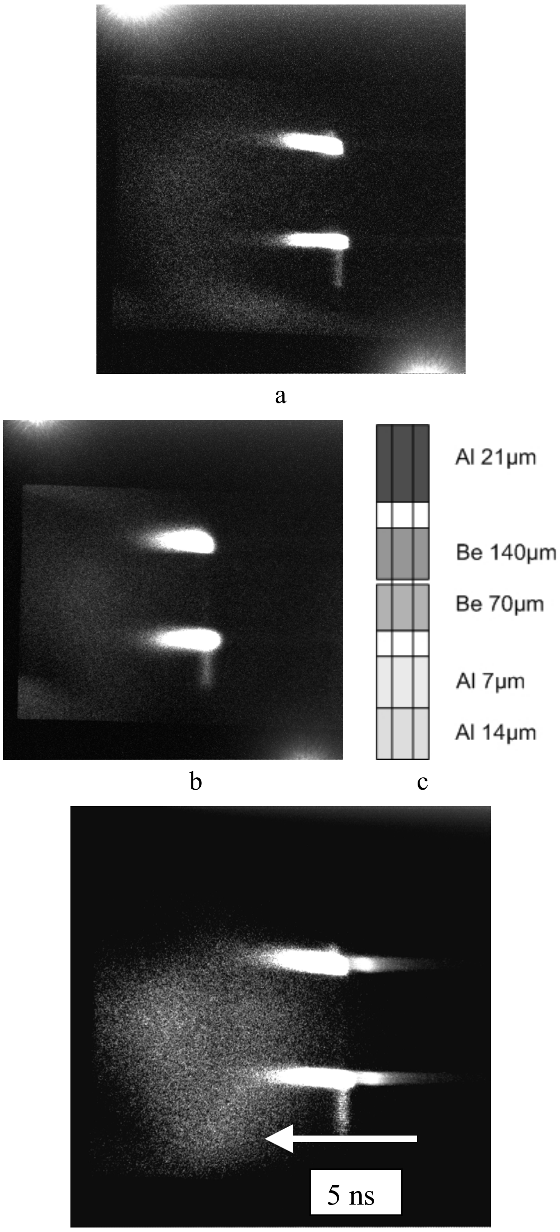
a b

Fig. 2. Integrated in time image of camera slit (a). Cu-target, $\alpha = 90^\circ$, pulse energy 85–90 mJ. Position of absorbing filters on the slit (b)

Figure 2. shows an integrated in time slit image of streak camera with a set of foil filter for laser pulse at normal incidence onto planar Cu-target. An average electron temperature of 400–500 eV was determined by absorption method. Time-resolved measurements for Cu-targets have shown more higher electron temperatures and a strongly temperature dependence on the incident angle of laser beam on target. Fig. 3 shows a streak photographs of x-ray continuum radiation transmitted through the set of absorbing filter (filter position on streak camera slit is schematically indicated right from the streak images) for different angles of incidence.

There was evident the following facts: very short emission of x-ray radiation behind the Al 7 µm-filter for incident angle of 30°, 45°, 67°. Positions of laser beam, target and slit of x-ray camera are schematically shown in Fig. 4. This behavior may be connected with nonhomogenous distribution of x-ray emission in space.

In addition a fast increase in x-ray emission versus time is also observed. Fig. 5 represents time evolution of electron temperature calculated by absorption method for different incidence angles. From analysis of these curves it follows that the central part of plasma emits



a

b c

d

Fig. 3. Streak phtograph of x-ray emission for Cu-target: a – $\alpha = 30^\circ$, b – $\alpha = 45^\circ$, d – $\alpha = 60^\circ$; c – position of absorbing filter on the slit

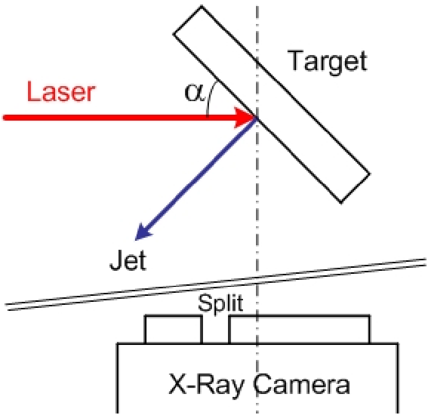


Fig. 4. Target position related to incident laser beam

soft x-ray quanta. In this region we have a plasma corona with the electron temperature of 400–500 eV. The diameter of emitting corona, which was determined from interferometric measurements, is approximately equal 400–500 µm. An increasing of electron temperature to 2.5 keV during 250 ps may be connected with a self-channeling of laser radiation in preformed laser-produced plasmas and excitation of parametric two-plasmon instability in the region of Ncr./4. The absorption of laser radiation then occurs not only due to inverse bremsstrahlung uniformity distributed in space, but also in small channels due to resonant absorption, or in region with strong density and temperature gradients leading to a high x-ray emission.

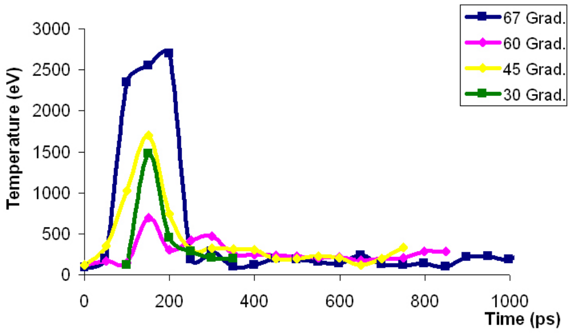
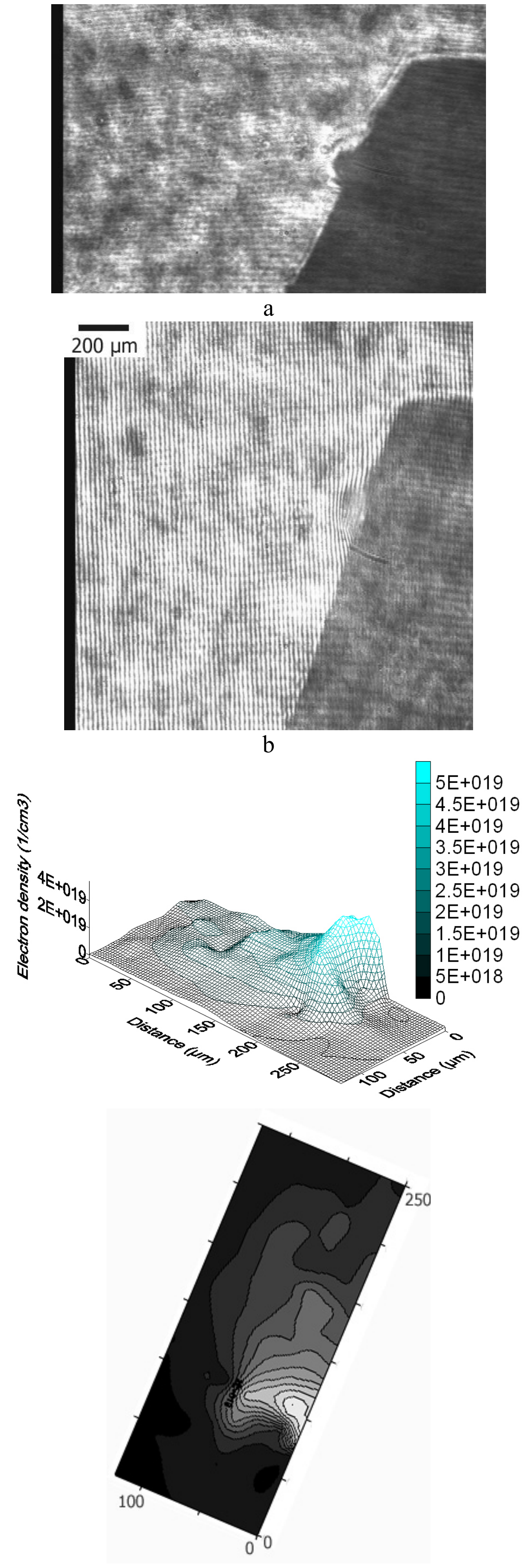


Fig. 5. Time evolution of electron temperature for laser-produced plasmas for different incidence angles α. Cu-target

Time resolved interferometric and shadowgraphic measurements have been made to investigate plasma evolution during interaction of ignition pulse with plasma. Temporal resolution of interferometric diagnostics was equal 100 ps, so allowed us to reveal a plasma density distribution for selected delay time between probe pulse and ignition pulse in the first interaction stadium. To study an influence of plasma distribution on an nonhomogenous x-ray emission in corona region we varied an incident angle between laser beam and planar target from 15° to 70°. Two delay time 0 and 250 ps were selected to investigate time history of density distributions. Fig. 6 illustrates an interferogram, shadowgram and electron density distribution for delay time $t = 250$ ps after ignition for Cu-target and an incident angle α = 67°. High density gradient and formation of channel with a diameter of 20 µm and length of 70 µm can be seen. Analogous behavior was estimated also for incident angle of 30°. Channel formation occurs on the time scale between 100 ps an 250 ps fter ignition. It well correlates with an increasing of electron temperature for this incident angle, that is shown in Fig. 5.

The self-channeled propagation of laser radiation in preformed plasma can be efficiently used for amplification of x-ray radiation. The most important and most effective mechanism for generation of stimulated x-ray radiation is a traditional three-body recombination of electron and high charged ions in plasma filament.



a

b

c

Fig. 6. a) Shadowgram, b) interferogram, c) electron density distribution of laser-produced plasma for delay time $t = 250$ ps after ignition by IR-laser beam. Cu-target. α = 67°

Another important feature is a generation of strong magnetic field in the regime of the laser pulse self-channeled propagation, which allowed us to create Z-pinched plasma channel. Due to combination of a powerful pondermotive and coulomb forces each electron traces in self-channeled regime out a closed trajectory with a radius of approximately (2–3)λ. The total current created in channel may be obtained as a sum of all the elementary currents inside the area occupied by the laser beam. It had been shown by Sudan [7] that the physical origin of the dc magnetic field must be strongly coupled with electron dynamics, which can be expelled in Z-direction by the pondermotive force of the laser pulse. So long as the laser pulse increases in amplitude the pondermotive force generates an average electron current in Z-direction.

Time resolved measurements of self-generated magnetic field in channeled regime by means of Faraday rotation [8] have revealed a toroidal nature of magnetic field in channel with a value of 7–8 MG. In such magnetized channel x-ray radiation may be produced similar to a free electron laser or due to resonance transition radiation from electron beam in channel [9, 10].

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