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X-ray emission from high-intensity interaction of picosecond and subnanosecond laser pulses with solid targets

Jan Badziak, Sławomir Jabłoński, Józef Makowski, Piotr Parys, Leszek Ryć, Aleksander B. Vankov, Jerzy Wołowski, Eugeniusz Woryna

Institute of Plasma Physics and Laser Microfusion, ul. Hery 23, 00–908 Warszawa, Poland.

Libor Juha, Josef Krása

Institute of Physics ASCR, Prague, Czech Republic.

The results of comparison of X-ray emission from plasmas produced by 1-ps and 0.5-ns laser pulses from massive and foil targets are reported. The measurements were performed for the soft (0.8–1.6 keV) and hard (4–30 keV) X-rays with the use of filtered p-i-n Si photodiodes at laser intensities of up to 10^{17} W/cm^2 for ps pulses and up to 3×10^{14} W/cm^2 for sub-ns ones. The effect of the laser pulse duration on the X-ray yields for various laser beam focal spots, laser pulse energies and atomic numbers of the targets were investigated.

1. Introduction

X-rays from laser-produced plasma are an important source of information on physical properties and parameters of the plasma. Besides, they find many unique applications, for example, in microscopy, lithography, materials science or micro biology. For these reasons, laser-driven X-ray emission has been studied intensively for years with the use of nano- and subnanosecond laser pulses and, more recently, with pico- and femtosecond ones. In spite of a huge amount of papers related to this subject only a very limited number of them have been devoted to the comparison of X-ray emission from plasmas produced under the same experimental conditions by laser pulses of essentially different duration [1]–[6]. Moreover, most of the comparisons were focused on the emission in a soft X-ray region [2]–[4], [6].

In this paper we report first, to our knowledge, the direct comparison of X-ray yields in the soft (0.8–1.6 keV) and hard (4–30 keV) X-ray regions from plasmas produced by 1-ps and 0.5-ns laser pulses. Both massive (thick) and thin foil targets were used for the comparison. The measurements were performed under the same experimental conditions (geometry, targets, beam quality, *etc.*) for similar ranges of energies of the laser pulses but significantly different laser pulse intensities: up to 3×10^{14} W/cm^2 for 0.5-ns pulse and up to 10^{17} W/cm^2 for 1-ps pulse.

2. Experimental arrangement

The experiment was performed with the use of terawatt chirped-pulse-amplification (CPA) Nd:glass laser [7], generating a 1-ps pulse of short-time-scale (<1 ns) intensity contrast ratio $\sim 10^4$ at $\lambda = 1.05$ μm. By removing the grating pulse compressor from the optical path of the laser system, the laser could deliver 0.5-ns pulse of the wavelength, energy and beam divergence close to those of 1-ps pulse. Both in the case of 1-ps and 0.5-ns pulses a laser beam was transmitted towards the target along the same path and through the same optical components, including focusing optics. Such geometry of the experiment ensured similar conditions of laser-target interaction for both cases.

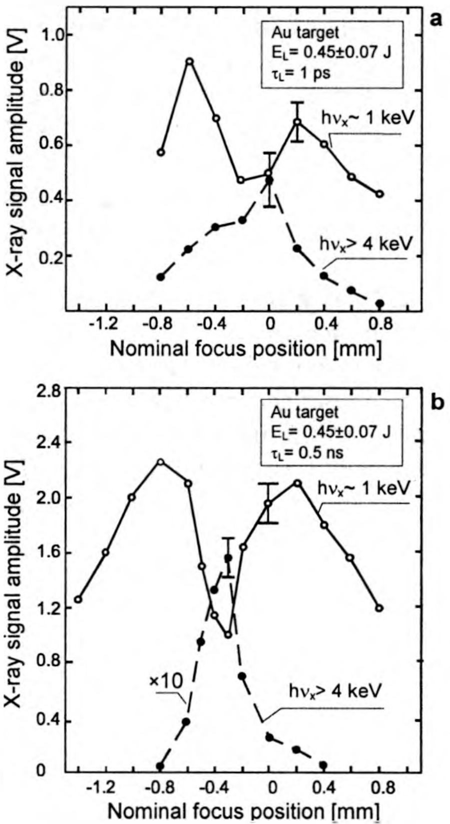
The investigations were carried out with the use of massive Au targets and thin foil targets. Both single-layer and double-layer foil targets were applied. Namely, polystyrene (PS) and Al foils as well as double-layer targets containing PS foil covered with Au or Cu layer were used. Further on we will use the symbols identifying particular foil targets which will comprise the letter symbol of the layer and the number marking the thickness of the layer in micrometers (*e.g.*, Al0.75, Au0.05/PS2).

The massive Au targets were irradiated by the laser beam with the use of on-axis parabolic mirror ($f = 27$ cm) and X-rays were recorded *in front of the target* at an angle of about 30° with respect to the optical axis. The foil targets were irradiated by the beam with the use of an aspheric lens ($f = 7.5$ cm) and X-rays were measured *behind the target* at the same angle. In both cases the laser beam was perpendicular to the target surface. The maximum intensity of laser light focused by the mirror reached 8×10^{16} W/cm^2 for 1-ps pulse and 2×10^{14} W/cm^2 for 0.5-ns pulse. In the case of laser light focused by the lens these intensities were 1.5×10^{17} W/cm^2 and 3×10^{14} W/cm^2, respectively.

The measurements of X-rays were performed with the use of two p-i-n Si photodiodes [8]. The first photodiode, shielded by a 7-μm Al filter, recorded soft X-rays in the range 0.8 – 1.6 keV. The second one, with 7-μm Al and 1200-μm Be filters, measured hard X-rays in the range 4 – 30 keV.

3. Results and discussion

Figures 1 and 2 present the results of the X-ray emission measurements performed for the case of a massive Au target. The dependencies of the soft and hard X-ray signal amplitudes on the laser focus position with respect to the target surface (FP) are illustrated in Fig. 1. FP = 0 indicates that the target surface is in the nominal in-focus position, the sign "+" means that the laser beam focus is inside the target, and the sign "–" that the focus is in front of the target. The nominal in-focus position was determined with the use of an auxiliary red beam (from He-Ne laser) of angle divergence adjusted to the divergence of picosecond laser beam. To determine the real in-focus position the X-ray measurements were supplemented with the measurements of the target reflectivity [9]. Because intensity of laser light



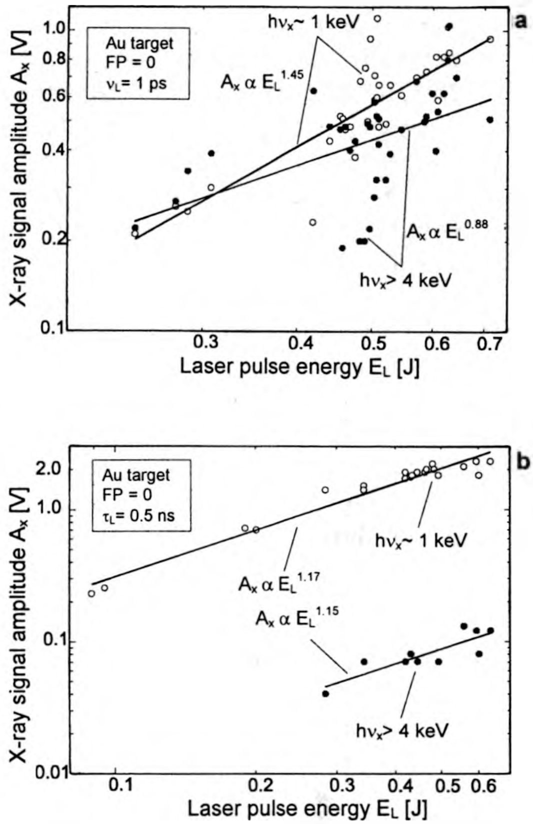


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Fig 1. Soft and hard X-ray signal amplitudes for 1-ps and 0.5-ns pulses as a function of the laser focus position with respect to the Au taget surface (a — $\tau_L = 1$ ps, b — $\tau_L = 0.5$ ns).

Fig. 2. Soft and hard X-ray signal amplitudes for 1-ps and 0.5 ns laser pulses irradiating Au target as a function of the laser pulse energy (a — $\tau_L = 1$ ps, b — 0.5 ns).

on the target surface is the highest when the surface is placed in the real focus, both the temperature of plasma on the surface and the production of hot electrons should be the highest as well. As a result, the target reflectivity and the yield of hard X-rays produced by hot electrons (see further) should attain maximum values at such a focus position [9]. From the analysis of the correlation between the hard X-ray yield and the target reflectivity measured for ps and sub-ns pulses, it follows that the real in-focus position corresponds to FP = 0 for ps pulses and to FP = −0.3 mm for sub-ns pulses.

We can see that dependencies of the soft and hard X-ray yields on FP for ps and sub-ns pulses are qualitatively similar. For both cases the dependencies for soft X-rays are strongly nonmonotonic functions with minima at real in-focus positions, which, in turn, correspond to maxima of hard X-ray yield. There can be at least two reasons for such behaviour. First, at real in-focus position the volume of plasma and amount of particles emitting soft X-rays are the smallest. Second, as mentioned above, at the best focusing the laser intensity is the highest and considerable part of laser energy is transferred to hot electrons, being the main source of hard X-rays [10]. In spite of qualitative similarity there are significant quantitative differences in X-ray emission for ps and sub-ns pulses. For ps pulses maximum hard X-ray yield is 3 – 4 times higher and maximum soft X-ray yield is 2 – 3 times lower than the ones for sub-ns pulses at the same laser energy. This implies that in the case of ps pulses the amount of laser energy transferred to hot electrons is several times as much as in the case of sub-ns pulses.

Figure 2 presents the hard and soft X-ray yields as a function of laser pulse energy. The scaling laws shown were obtained with the use of the least-squares method. The scaling laws for sub-ns pulses are similar – both the X-ray yields grow slightly faster than linearly with laser energy. For ps pulses the increase of the hard X-ray yield with laser energy is remarkably slower than the increase of soft X-ray yield and production of hard X-rays slightly saturates (exponent lower than 1). However, the spread of the measurement point is large in the case of ps pulses, so the level of certainty of the scaling laws obtained is rather low.

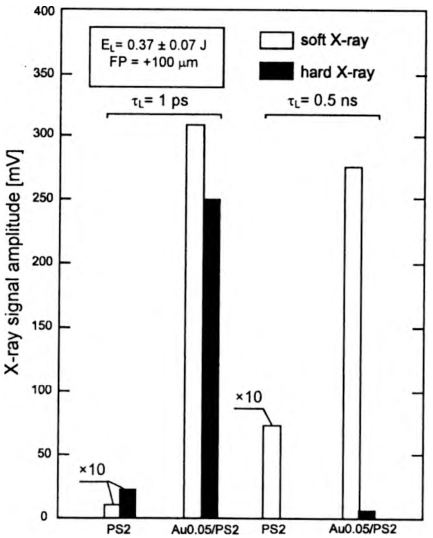

Fig. 3. Amplitudes of soft and hard X-rays produced by 1-ps and 0.5-ns laser pulses from thin polystyrene and double-layer (polstyrene covered with gold – Au/PS) foil targets.

The measurements of X-ray emission from thin foil targets give results considerably different from those for massive targets. This can be seen from Fig. 3, where amplitudes of hard and soft X-ray signals from single-layer PS2 and double-layer Au0.05/PS2 targets irradiated by 1-ps or 0.5-ns pulses are presented. For a sub-ns pulse hard X-rays were recorded only for a target of a high atomic number Z and, moreover, the hard X-ray yield was over 20 times lower than in the case of a ps pulse. This can be understood if we realise that due to short time of the interaction, practically the whole ps pulse interacts with sufficiently dense plasma (of the density near the critical ones) and, as a result, hot electrons produced by the pulse propagate in high-density media (dense plasma and a solid), which is a necessary condition for efficient transfer of hot electron energy to hard X-rays. In the case of a sub-ns pulse, a significant part of the pulse interacts with relatively low-density plasma produced by the leading edge of the pulse and expanding during its interaction with the target. As a result, most of the hot electrons propagate in a medium of low density. In addition to the lower level of the hot electrons production (because of the lower intensity of a sub-ns pulse) this leads to a remarkably lower hard X-ray yield in comparison with the case of a ps pulse.

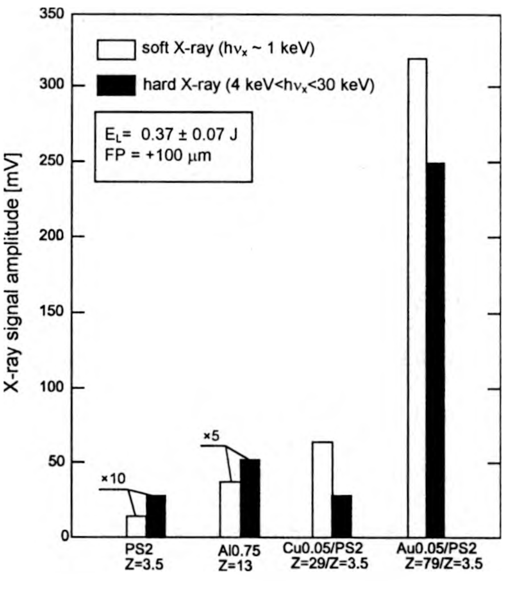

Fig. 4. Amplitudes of soft and hard X-rays produced by 1-ps laser pulse from various thin foil targets.

Comparing the amplitudes of soft X-rays generated from the foil targets (Fig. 3), we can notice that the influence of the target Z-number on soft X-ray yield in the case of a ps pulse is stronger than in the case of a sub-ns pulse. The effect of the Z-number on X-rays produced by ps pulses is shown in more detail in Fig. 4, where soft and hard X-ray yields for the four foil targets are presented.

4. Conclusions

The comparison of soft and hard X-ray emission from plasmas produced by ps and sub-ns laser pulses interacting with massive or foil targets has been presented. It has been found that:

– Both for ps and sub-ns pulses, the dependence of soft X-ray yield on the laser beam focus position (FP) reaches minimum when the real focus of the beam is near the target surface.

– Both for ps and sub-ns pulses, the dependence of hard X-ray yield on FP reaches maximum when the focus is near the target surface.

– In the case of a thick Au target the maximum soft X-ray yield is higher for sub-ns pulses (2 – 3 times) and, vice versa, the maximum hard X-ray yield is higher for ps pulses (3 – 4 times).

– Hard X-ray yield depends more strongly on a laser pulse duration for thin foil targets than in the case of thick targets.

– Both soft and hard X-ray yields depend strongly on atomic number and on the structure of a thin foil target.

It is believed that the observed distinctions are mainly due to the fact that in the case of ps pulses, more laser energy is transferred to hot electrons, which play dominant role in a hard X-ray production.

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