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Soft-x-ray radiation from plasmas produced by obliquely incident subpicosecond laser pulses

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Soft-x-ray spectra (< 0.5 keV) from subpicosecond-laser-pulse-produced Al plasmas have been measured at a series of intensities up to 10^{17} W/cm^2 and different angles of incidence. It was found that the spectra depended strongly on these parameters. Comparison of the spectra produced by p- and s-polarized 248 nm radiation showed that not only collisional but also other absorption mechanisms were present. These additional processes affected only the total amount of the generated *soft*-x-ray radiation but not the spectral shape and not the electron temperature.

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The generation of x rays from hot dense laser produced plasmas is a topic of much current interest [1–8]. It offers the opportunity to study the interaction of laser pulses with plasmas of near solid state density under extreme conditions. The interaction is characterized by both the nature of the absorption mechanism and the conversion efficiency of the absorbed laser energy into x rays [7,8]. The relative importance of the different absorption processes depends strongly on the experimental conditions [9]. The second important feature, namely, the conversion of the *absorbed energy* into x rays, has received little detailed attention until now. It has been found that the x-ray yield depends not only on the amount of absorbed energy but on other parameters as well [7]. Spectra of the emitted radiation, not available for that previous work, provide further information on the laser plasma interaction. In the present work we relate the subpicosecond laser pulse absorption and the x-ray production, in particular in the *soft*-x-ray range. Some aspects of this work, carried out in a lower x-ray energy region (<0.5 keV), complement previous investigations of the keV radiation [7,8].

The experimental setup was similar to that in Ref. [7]. The laser pulses were generated by a combined dye-excimer laser system which was a modified version of that described in Ref. [10]. It delivered 5 mJ pulses with duration of 400 fs at a repetition rate of 1 Hz. In some of the measurements a two pass off-axis amplifier was included, giving an additional amplification factor of 8. The 248 nm pulses were focused onto a highly polished target of solid aluminum. The target was mounted on an xyz-translation unit and was moved between consecutive shots to always present a fresh surface. The laser radiation was focused with a spherical mirror (f number=7) to a 1.5 times diffraction limited spot size of 5 μm [full width at half maximum (FWHM)] at normal incidence. Since the pulse broadened and suffered transmission losses in windows and lenses, the pulse length on the target was increased to 0.7 ps (FWHM) and the pulse energy was reduced. The maximum intensity for normal incidence was $I_{0\perp}=3\times10^{17}$ W/cm^2 with the additional amplifier. The shot-to-shot fluctuation of the intensity was 20%.

For the angle dependent measurements all intensities on the target surface I_0 were corrected with respect to the angle of incidence α, i.e., $I_0=I_{0\perp}\cos\alpha$. By exploiting this dependence and placing dielectric attenuators in the beam path, the intensity I_0 could be adjusted between 3×10^{14} and 3×10^{17} W/cm^2. The intensity ratio between the short pulse and the amplified spontaneous emission exceeded 10^{10} on the target [7] and so preplasma formation could be avoided [4,11]. The angle of incidence was varied between 10° and 70°. The polarization of the pumping pulse could be adjusted either to the p or s direction with respect to the plane of incidence and with a degree of polarization exceeding 95% [7].

The soft-x-ray emission from the plasma was measured with a novel spectrograph [12] which was capable of detecting single shot spectra in the wavelength range from 15 to 150 Å with a resolution of about 2 Å. In order to reduce the fluctuations caused by the pump pulses, ten single shot spectra were averaged for each measurement and the corresponding errors calculated (standard deviation typically between 6% and 13%). A series of spectra was measured at 8 different angles of incidence between 10° and 70°, each at 7 different intensities and for p- and s-polarized pump pulses. Thus it was possible to compare spectra with *only one* changed parameter, and all the others were kept constant.

Figure 1 shows aluminum spectra measured with p-polarized light at *different intensities* for a *fixed angle of incidence* ($\alpha=45°$). Line emission is visible sitting on a continuum in a range of about 20 to 90 Å. However, the spectra are convoluted with higher orders. In particular, comparison with high resolution Rowland spectra measured under similar experimental conditions [11] showed that there is only weak emission for wavelengths longer than 130 Å. The background noise from the detector in the spectra of Fig. 1 could be neglected. Several groups of lines could be easily identified, e.g., the Balmer series of hydrogenlike aluminum at about 20 Å and two emission bands at 33 Å and at 40 Å. However, the latter are not emitted by the aluminum plasma but instead by carbon particles from the polishing process used for the targets. From Fig. 1 it is obvious that the soft-x-ray emission increases strongly with the intensity. In com-

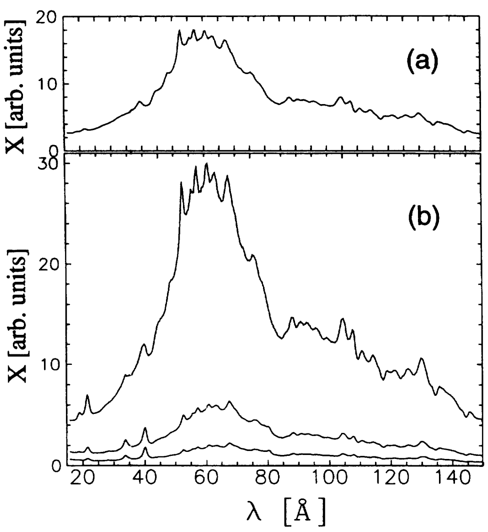

FIG. 1. (a) Aluminum spectrum at an intensity $I_0=2\times10^{17}$ W/cm^2 for p-polarized light at fixed angle of incidence of $\alpha=45°$. (b) Similar to (a) but measured with a different detector gain [13] and at $I_0=2\times10^{16}$ W/cm^2, 1×10^{16} W/cm^2, and 5×10^{15} W/cm^2 (from top to bottom). The scale for the x-ray emission is in arbitrary units in (a) and (b), and the proportional constants of scaling are different in both cases.

parison with the overall soft-x-ray signal $X_{p,\mathrm{soft}}$ (integral over the wavelength from 20 to 150 Å) the Balmer series radiation increased *relatively* less with intensity.

In contrast to this Fig. 2 illustrates the x-ray emission per unit emission area at a *fixed intensity* and measured at *different angles of incidence*. The error bars include both the fluctuations of the laser pulse and the systematic error of each spectrum due to the detector gain [13]. From Fig. 2(a) it can be seen that while for s-polarized pump light and constant intensity on the target surface ($I_0=6\times10^{15}$ W/cm^2) $X_{s,\mathrm{soft}}$ decreases steadily with α, this is not the case if the pump pulse has p-polarization: $X_{p,\mathrm{soft}}$ increases with α, reaches a distinct maximum in the vicinity of 40°, and afterwards decreases relatively quickly.

A much more interesting case than that of constant incident intensity I_0 is to study the angular dependence of the x-ray yield for constant absorbed intensity I_A in the plasma. Such spectra provide information about the x-ray conversion efficiency. Taking the absorption values A from our previous measurements, the absorbed intensity $I_A=A(\alpha,I_0,$ polarization) I_0 [7] could be calculated for each measured spectrum. In Fig. 2(b) the corresponding measurements are shown for a constant absorbed intensity $I_A=4\times10^{15}$ W/cm^2. Although Fig. 2(b) does not show more than a rough angular dependence for the soft-x-ray yield one can recognize that (1) the overall soft-x-ray emission decreases steadily to zero at large α and (2) $X_{p,\mathrm{soft}}$ is larger than the corresponding value produced by s-polarized pump light, namely $X_{s,\mathrm{soft}}$, in particular at intermediate angles.

Figure 3 shows soft-x-ray spectra for a constant absorbed intensity ($I_A=4\times10^{15}$ W/cm^2) normalized to the overall soft-x-ray emission. It may be seen that the x-ray emission is very similar for both polarizations at all angles of incidence. The maximum shifts distinctly to longer wavelengths with increasing α. At the same time the large x-ray emission band in the vicinity of 60 Å (lines due to Al IX–Al XI) disappears totally and the Balmer series at about 20 Å is significantly reduced. Additionally it should be mentioned that the strength of the spectra at large α is much smaller than that of spectra at small angles (e.g., the spectrum at $\alpha=70°$ is 2 to 3 orders of magnitude weaker than that measured at 10°; compare Fig. 2). The angle of incidence affects the the spectral shape much more than the intensity (compare Figs. 1 and 3; in Fig. 1 the intensity is varied more than one order or magnitude).

A self-consistent calculation of the initial plasma temperature [4,11] gives values between 100 eV (for $I_A=10^{14}$ W/cm^2) and several keV (for $I_A=10^{17}$ W/cm^2). This is consistent with calculations [14] using the one-dimensional (1D) time dependent hydrodynamic code FILM [15], which has been extended for subpicosecond laser pulses [16]. The scale length of the plasmas of the present experiment can be estimated from the angle of maximum absorption [4] and is of the order of one-tenth of the laser vacuum wavelength [7]. The electron temperature and the average ionization state of the plasma increase strongly with the laser intensity as can be seen from Fig. 1. As expected at higher absorbed intensities not only does the overall x-ray yield increase strongly but the shape of the spectrum changes, too. In particular, the shorter wavelength emission from 40 to 80 Å corresponding to higher ionization and excitation states is enhanced. Conversely, in the present experiment the population of the highest ionization states has increased less as can be seen from the *relative* reduction of the Balmer lines. This is most pronounced at the highest intensity [2×10^{17} W/cm^2, Fig. 1(a)]. This effect is significant and is caused by the quenching of

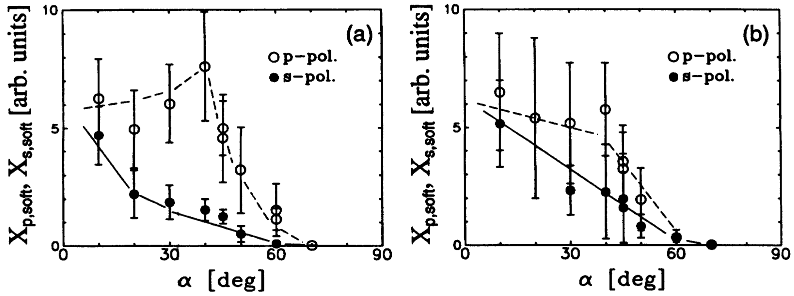

FIG. 2. Overall x-ray emission $X_{p,\mathrm{soft}}$ for p-(open circles) and $X_{s,\mathrm{soft}}$ for s-polarized (closed circles) pump pulses respectively measured at different angles of incidence: (a) at constant intensity on the target surface ($I_0=6\times10^{15}$ W/cm^2), (b) at constant absorbed intensity ($I_A=4\times10^{15}$ W/cm^2).

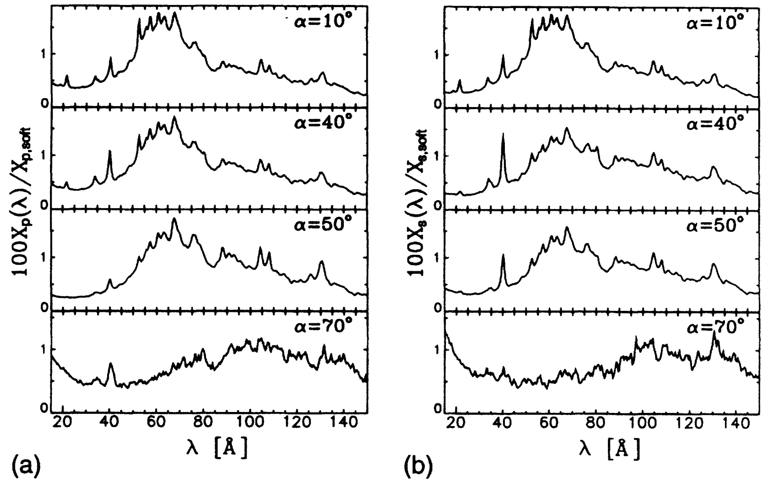

FIG. 3. Aluminum spectra measured at constant absorbed intensity (4×10^{15} W/cm^2) with p-polarized light (a) and s-polarized light (b) respectively at different angles of incidence. All spectra are normalized to the corresponding overall x-ray emission. The emission bands at 33 and 40 Å are not Al lines but are emitted instead by carbon particles from the polishing process used for the targets. The increase of the emission below 25 Å at large angles is caused by the zeroth order of the spectra.

the short wavelength radiation from the highest ionization states due to collisional deexcitation [5].

From Figs. 1–3 it is evident that both the intensity and the angle of incidence have a strong influence on the generation of soft-x-ray spectra. It is obvious that this influence is due not only to the amount of energy deposition but also to the absorption itself [in Fig. 2(b) $I_A=$const at all α]. The main absorption process particularly at low intensities is collisional absorption [2,4]. In the case of p-polarized light obliquely incident on the target, resonance absorption [7] and collisionless absorption processes like vacuum heating [17] can in addition contribute quite efficiently to the absorption at intermediate angles α. The presence of these additional absorption mechanisms is supported by Fig. 2(b), where it can be seen that for constant absorbed intensity at intermediate α, p-polarized pump light is more efficient in producing soft-x-ray radiation than s-polarized light.

On the other hand, the shape of the soft-x-ray spectra at constant absorbed intensity is the same for both polarizations (Fig. 3). This differs from the result of Meyerhofer *et al.* [8], who found a strong influence of the polarization degree on hard-x-ray radiation (keV energies and beyond) and high energy particle generation. The difference is explained as follows. Resonance absorption and vacuum heating play an important role for intensities exceeding 10^{15} W/cm^2 in the generation of *hard*-x-ray radiation and high energy electrons and ions [3,7,8,17]. These particles which were scarcely found with s-polarized pump light can carry quite a large fraction of the resonantly deposited energy [3,6,8,18]. This energy is rapidly transported from the original interaction region at the critical surface to the overdense plasma where it is converted into hard-x-ray radiation (mainly inner-shell radiation and keV bremsstrahlung) [8,17,18].

On the other hand, *soft*-x-ray radiation is produced by both collisional absorption and resonance absorption, but at a different electron density than hard-x-ray radiation. Collisional absorbed energy leads to rapid ionization of the atoms in the original absorption volume on time scales of the order of the laser pulse duration [19]. Some of the absorbed intensity is transported into denser plasma regions via nonlinear heat transport [1,4,5] and causes ionization there as well. However, most of the *soft*-x-ray radiation comes from the vicinity of the originally heated region [5]. In the case of p-polarized light a second channel of soft-x-ray production arises from that fraction of resonantly absorbed light that remains in the vicinity of the critical density and is not converted into high energy particles. This is most pronounced for p-polarized light at $\alpha=40°$ (compare Fig. 2).

The decrease of the soft-x-ray emission with increasing angle of incidence [Fig. 2(b)] is the result of the lower conversion efficiency. At normal incidence collisional absorption takes place mainly in the vicinity of the critical density, even more so in the overdense region and at times before significant plasma expansion occurs [1,3,4,14]. With increasing α the absorption volume becomes larger due to both the longer propagation length in the plasma and the larger area of illuminated surface. The result will be a lower electron temperature in this volume as can be seen from Fig. 3, where the emission from the highest ionization stages, e.g., the Balmer series, is generally reduced although the amount of absorbed intensity in the plasma is the same. For subpicosecond pulses the ionization rate decreases with decreasing electron temperature and electron density [19]. If α is increased the absorption volume and the emission volume both shift to regions with lower electron density [9] where the ionization rate is lower and thus the conversion efficiency into *soft*-x-ray radiation reduced [Fig. 2(b)]. The additional contribution from resonance absorption at intermediate angles always takes place in the vicinity of the critical density. It only affects the total amount of soft-x-ray radiation but not the electron temperature which is the same for both polarizations (see Fig. 3).

In conclusion, we have found that the generation of soft-x-ray spectra by obliquely incident laser light is strongly dependent on the polarization, the intensity, and even more so on the angle of incidence. While for s-polarized light collisional absorption is the dominant absorption process, p-polarized light is absorbed by resonance absorption as well. It was found that the additional absorption affects only the total amount of the *soft*-x-ray radiation but not the spectral shape and the electron temperature. The origin of the x-ray radiation is at least partly different for soft and hard x rays: soft x rays are mainly generated in the original heated absorption volume. Hard x rays are produced by high energy particles and in more dense regions [8].

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