Angle-Dependent X-Ray Emission and Resonance Absorption in a Laser-Produced Plasma Generated by a High Intensity Ultrashort Pulse

U. Teubner, J. Bergmann, B. van Wonterghem,[a] and F. P. Schäfer
Abteilung Laserphysik, Max-Planck-Institut für biophysikalische Chemie, Postfach 28 41, Am Fassberg, D-3400 Göttingen, Germany

R. Sauerbrey
Rice Quantum Institute and Department of Electrical & Computer Engineering, Rice University, P.O. Box 1892, Houston, Texas 77251-1892
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Plasmas were generated by 400 fs KrF laser pulses at intensities of $\sim 10^{17}$ W cm^{-2} on aluminum targets. Reflectivity and x-ray emission were measured as a function of laser polarization, angle of incidence, and intensity. For the same absorbed intensity, *p*-polarized laser light is up to a factor of 5 more efficient in generating x rays (>0.5 keV) than *s*-polarized light. These results show the importance of an additional absorption process, besides collisional absorption, for short scale length plasmas that is effective for *p*-polarized light only and has the characteristics of resonance absorption.

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Plasmas produced by ultrashort laser pulses of pulse durations below 1 ps and intensities in excess of 10^{14} W cm^{-2} constitute a novel form of extremely hot, dense matter. Since the plasma has little time to expand during the laser pulse, the extension of the plasma characterized by its scale length is typically considerably smaller than the laser wavelength representing an entirely new situation for the description of laser-plasma interaction. Several experimental investigations that study the interaction of laser radiation with such plasmas for intensities up to $\sim 10^{16}$ W cm^{-2} have been reported [1-3]. The observation of x rays emitted from plasmas produced by ultrashort laser pulses has led to a number of very interesting results [4-9]. For example, the emission of spontaneous x rays up to energies exceeding 1 MeV has been observed [9]. Furthermore, short pulse laser-produced plasmas show considerable promise as new sources for time-resolved x-ray microscopy [10] or as novel active media for x-ray lasers [11,12].

Initially, experimental results for plasmas generated by ultrashort laser pulses at intensities in the range of 10^{15} W cm^{-2} suggested that inverse bremsstrahlung is the dominant absorption mechanism for the laser radiation [1-3]. Recently, however, new evidence based on x-ray emission [9,13] at intensities of 10^{16} to 10^{18} W cm^{-2}, second harmonic generation [14], as well as theory [15,16], has suggested that other absorption processes such as resonance absorption which describes the energy transfer from an electromagnetic wave to an electron plasma wave could play an important role even for plasmas with a scale length considerably shorter than the laser wavelength. If this is the case, the x-ray yield of ultrashort laser pulse generated plasmas could be increased by optimizing the total absorption consisting of collisional and resonance absorption in the laser target. Conversely, the investigation of x-ray emission as a function of laser intensity, angle of incidence, and polarization should provide information on the laser-plasma interaction and the plasma conditions.

In this work we (1) extend the studies of ultrashort pulse ultraviolet laser absorption in solid targets up to laser intensities of 10^{17} W cm^{-2} and (2) investigate the dependence of the x-ray emission on the incident and absorbed laser intensity between 10^{15} and 10^{17} W cm^{-2}. To our knowledge, these are the first experiments that relate the absorbed laser intensity of a short scale length plasma with its x-ray emission and provide strong evidence for efficient noncollisional absorption processes in such plasmas.

In the present experiments solid, polished aluminum targets were irradiated in vacuum ($<10^{-5}$ mbar) by a KrF laser system (248 nm) [17]. It emitted 30 mJ pulses of 400 fs (FWHM) length at a repetition rate of 1 Hz with a shot-to-shot energy fluctuation of about 10%. The reflected laser light and the x-ray emission were measured as a function of laser intensity, angle of incidence, and laser polarization. The KrF laser radiation, was focused to a diffraction limited spot size of 7.0 ± 0.5 μm diameter (FWHM). The focal beam profile was carefully characterized by a microscope with CaF_2 optics, which imaged the focal spot of the attenuated beam at the target position onto a charge-coupled device camera. For this measurement the target was removed from the beam path. For the determination of the intensity, the $1/e$ width of the bell-shaped beam profile was used. The maximum intensity on the target for perpendicular incidence was $I_{0\perp} = (1.0 \pm 0.2) \times 10^{17}$ W cm^{-2}. For the angle-dependent measurements, all input intensities I_0 were corrected for the angle of incidence: $I_0 = I_{0\perp} \cos\alpha$. The ratio between the short pulse intensity I_0 and the ~ 15 ns long amplified spontaneous emission (ASE) background intensity I_{ASE} from the excimer amplifiers was experimentally determined to be $I_0/I_{\mathrm{ASE}} > 10^{10}$ on the target. This high contrast results from an improved amplifier arrangement [17]. Consequently, no preplasma was formed by the ASE pulse in our experiments. The polarization of the KrF laser could be changed by varying the polarization of the seed pulse injected into the amplifier and was either in the s or p direction with respect to the target surface. The degree of polarization exceeded 95% at the entrance window of the target chamber. The target was mounted on an xyz-translation stage driven by stepper motors and moved along the focal plane between two consecutive shots. The reflected laser radiation was measured in the specular direction by a calorimeter whose acceptance aperture was 4 times larger than the reflected beam. Investigation of the scattered beam profile at this position indicated, however, that the laser was scattered essentially in the specular direction, in agreement with earlier observations at lower intensities and similar pulse lengths [3,4].

The spectra of the emitted x rays were measured by a grazing incidence spectrometer in the wavelength range between 25 Å (~500 eV) and 250 Å (~50 eV) [8]. The spectrum was dominated by a broad continuum that extended beyond the short wavelength cutoff of the spectrometer. The x-ray yield measurements reported here were obtained using a Schottky type GaAsP photodiode behind a 1.6 μm thick Al filter. This detector-filter combination is sensitive for photon energies exceeding $E=0.5$ keV with a slowly decreasing sensitivity for $E>4$ keV [18]. The x-ray detector viewed the target surface under an angle of 25° from normal.

A fast x-ray streak camera also equipped with a 2 μm aluminum filter was used to measure the temporal duration of the x-ray emissions. For an aluminum target irradiated at an angle of incidence of $\alpha=45°$ with p-polarized light at an intensity of $I_0=2\times10^{16}$ W cm^{-2}, the temporal duration of the x-ray emission for $E>0.5$ keV is below the 2 ps temporal resolution of the camera, in agreement with earlier experiments using visible laser wavelengths and other target materials [4].

The reflected laser energy and the x-ray yield were measured for s- and p-polarized KrF laser radiation as a function of intensity on target for three different angles of incidence. The result of this experiment is shown in Fig. 1. For each angle of incidence and both polarizations, the reflectivity $R(\alpha,I_0)$ shows a weak increase with increasing intensity. In each case the reflectivity is significantly higher for s-polarized than for p-polarized light. For p-polarized laser light, the maximum total absorption $A_p=1-R_p$ of the laser radiation in the plasma exceeds $A_p=0.7$, even at an intensity above 10^{16} W cm^{-2}. For $\alpha=45°$ and 5×10^{15} W cm$^{-2}<I_0<5\times10^{16}$ W cm^{-2}, the difference in absorption between p- and s-polarized light is constant at about $A_p-A_s\approx0.3$.

For all angles of incidence, the spectrally integrated x-ray emission increases strongly with increasing intensity (Fig. 1). Within the experimental errors the intensity scaling of the x-ray signal X is, however, independent of the angle of incidence α and the polarization of the laser light. For the absorbed intensity

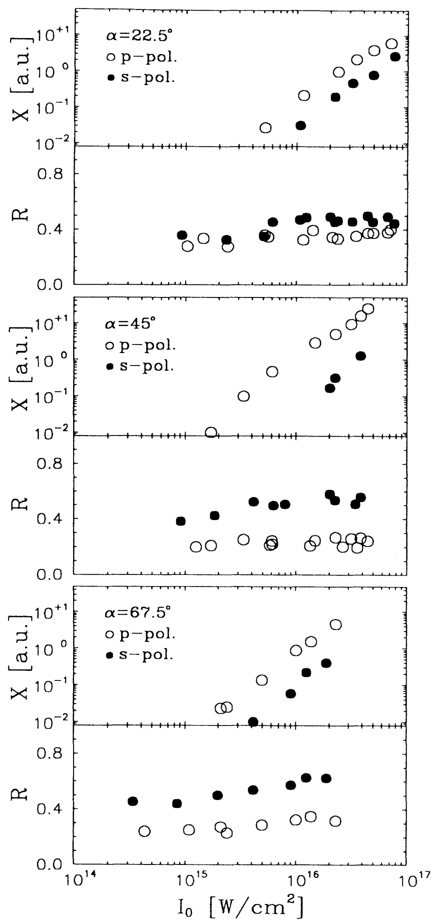

FIG. 1. Reflectivity R and integrated x-ray emission X from a polished aluminum target as a function of input intensity I_0 of a 400 fs KrF (248 nm) laser for s- and p-polarized light and three angles of incidence α. The focal spot diameter was 7 μm (FWHM). The experimental data are averaged over 25 shots. The size of the symbols indicates the statistical error. The relative systematic error is estimated to be less than 10% for the reflectivity measurements.

$$I_{abs}=[1-R(\alpha,I_0)]I_0\,, \tag{1}$$

a power-law dependence of

$$X\propto I_{abs}^{\gamma} \tag{2}$$

with $\gamma=2.2\pm0.2$ is obtained from the experimental data for 10^{15} W cm$^{-2}<I_{abs}<5\times10^{16}$ W cm^{-2} (Fig. 2).

Figure 3 shows the x-ray signal ratio for p- and s-polarized pump light as a function of angle of incidence. The upper curve corresponds to a constant input intensity. The relative increase of the x-ray yield for p-polarized over s-polarized light has a distinct maximum at intermediate angles of $\alpha\approx45°$. For this angle, p-

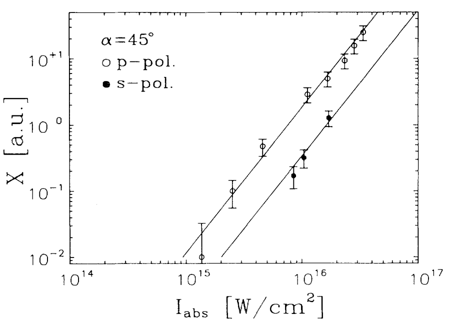

FIG. 2. X-ray emission from a polished aluminum target as a function of the absorbed intensity I_{abs} for an angle of incidence of $\alpha=45°$ and s- and p-polarized 248 nm, 400 fs laser pulses. The error bars give the statistical error based on 25 individual measurements for each point, including the statistical error in I_{abs}. The systematic error in the absorbed intensity is 12%. The same straight lines with the identical angle- and polarization-independent slope of $\gamma=2.2\pm0.2$ were obtained for all angles shown in Fig. 1.

polarized light produces 15 times more x rays than s-polarized light at the same input intensity. When the experimentally determined angle- and polarization-dependent reflectivities and Eqs. (1) and (2) are taken into account, the ratio of x-ray emission for s- and p-polarization can be obtained as a function of the absorbed intensity. The lower curve in Fig. 3 shows that for *constant absorbed* intensity p-polarized pump light incident under $\alpha=45°$ is still a factor of 5 more efficient in producing x rays than s-polarized light.

These present experiments show that the absorption of ultrashort pulse high intensity ultraviolet laser radiation in the intensity range between 10^{15} and 10^{16} W cm^{-2} (Fig. 1) is significantly higher than for 1 ps, 1 μm laser light [2]. The absorption at 10^{15} W cm^{-2} given in Fig. 1

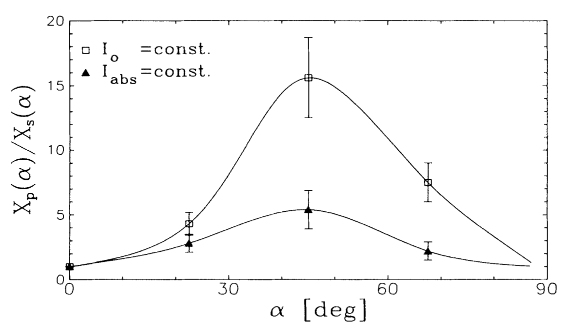

FIG. 3. Ratio of integrated x-ray emission X_p/X_s as function of angle of incidence for p- and s-polarized, 400 fs KrF laser irradiation. The upper curve (squares) corresponds to constant input intensity $I_0=10^{16}$ W cm^{-2}, while the lower curve (triangles) gives the x-ray emission ratio X_p/X_s for any constant absorbed intensity in the range of 10^{16} W cm^{-2}. At intermediate angles the x-ray yield for p-polarized light in each case is significantly higher than for s-polarized light. The solid lines are spline interpolations through the experimental data points.

is also slightly higher than that given by Milchberg *et al.* [1], using an aluminum target and the same angle of incidence, but a laser wavelength of 308 nm, and that obtained by Fedosejevs *et al.* [3] for 248 nm. While for most of the measurements reported in Refs. [1–3] the prepulse levels exceeded the plasma generation threshold on target, this was not the case in the present experiments.

The scaling of the x-ray signal with intensity (Fig. 2) differs considerably from the scalings observed by Stearns *et al.* [5], who found $X\propto I_0^{4.3}$ for laser intensities in the vicinity of 10^{14} W cm^{-2} using visible wavelengths and Kmetec *et al.* [9], who observed $X\propto I_0^{1.5}$ for 807 nm pulses of 10^{18} W cm^{-2}. In order to establish, however, a systematic trend for a decreasing γ with increasing intensity, more experiments will be required.

Most interesting is the much higher efficiency for x-ray generation by p-polarized KrF laser light as compared to that for s-polarized light for constant *absorbed* intensity (Fig. 3). In the present experiment the x-ray yield may be higher for three reasons: (1) The spectral shape of the x-ray emission remains constant but the total intensity increases; (2) the intensity remains constant but the spectrum shifts to higher x-ray energies; (3) a combination of (1) and (2). In each of these cases either more x-ray photons, higher energy x-ray photons, or both are emitted. This is only possible when the p-polarized KrF laser light generates, for constant *absorbed* intensity, plasma conditions that favor the generation of harder x rays and/or x rays of higher intensity. If the absorption of the laser radiation were due to collisional absorption only [1–3], the x-ray signal would be expected to be a function of the absorbed intensity only and independent of the angle of incidence and polarization for constant absorption. Since this is not observed (Fig. 3), noncollisional, angle- and polarization-dependent absorption processes such as resonance absorption must contribute to the total absorption.

If the angular dependence of absorption (Fig. 1) is treated according to classical resonance absorption theory, as suggested in Ref. [19], the plasma scale length $L=n_e/\nabla n_e$ (n_e is the electron density in the vicinity of the critical density) and the plasma expansion velocity c_s are estimated to $L\approx 50$ nm $\approx 0.2\lambda$ and $c_s\approx 10^7$ cm/s. These values are in good agreement with other experiments for similar laser and plasma conditions [7,8,20].

Resonance absorption at high intensities can lead to a plasma profile steepening, and localized electron plasma oscillations are a source for hot electrons [21] which could explain the observed increased x-ray yield for p polarization. A process similar to resonance absorption, in the sense that it would operate for p-polarized light only, was proposed by Brunel [15]. Somewhat simplified, Ref. [15] states that the electric field component perpendicular to the plasma surface pulls electrons from the plasma in one half cycle and accelerates them during the next half cycle into the dense plasma, where they deposit their energy through collisions. Simple estimates give $A \approx 0.02$ to 0.06 total absorption at $I_0 = 10^{16}$ to 10^{17} W cm^{-2}, $\alpha = 45°$ and 248 nm [15]. More detailed calculations by Gibbon and Bell [16] that include both resonance absorption and the Brunel process show that the noncollisional absorption component of a laser produced plasma for p-polarized light in the same intensity range can reach values of $A = 0.35 \pm 0.10$ for a scale length of $L/\lambda = 0.2$, in good agreement with the present results (Fig. 1). The calculated absorption for short scale length ($L/\lambda \approx 0.1$) can be higher than for long scale length ($L/\lambda = 2$). These calculations also predict a maximum noncollisional absorption component for angles of incidence between 40° and 50° and $L/\lambda \approx 0.1$. We observe the maximum difference in absorption between s- and p-polarized light (Fig. 1) and the maximum x-ray production (Fig. 3) for $\alpha \simeq 45°$. In addition, these calculations show that for $I_0\lambda^2 \geq 10^{15}$ W cm$^{-2}\mu$m^2, electrons with energies in excess of 10 keV are produced by p-polarized light. Such electrons should generate an energetic x-ray continuum by bremsstrahlung in the solid target [9], and thus contribute to the increased x-ray emission observed for p-polarized light (Fig. 3).

Investigations of the second harmonic generated in plasmas of short scale length also show evidence for an absorption process that is effective for p-polarized pump light only and that relies on the resonant enhancement of the electric field at the critical density [14]. The measured and calculated resonance of the electric field at scale lengths of $L/\lambda \approx 0.1$ [14] should give rise to strong ponderomotive potentials accelerating electrons from the undercritical plasma region into denser regions of the plasma. Ponderomotive acceleration processes, as well as the Brunel process, are effective only during the laser pulse, and are thus consistent with the short temporal duration (< 2 ps) of the observed x-ray pulse.

In summary, we have observed that for the same absorbed intensity, p-polarized light is significantly more efficient in producing x rays than s-polarized light. Based on these results and their good agreement with theory [16], we conclude that an additional absorption process, besides collisional absorption, is important for the interaction of laser radiation with short scale length plasmas produced by ultrashort laser pulses. This second absorption process is effective only for p-polarized light and has the characteristics of classical resonance absorption and the Brunel process [15,16]. The present experiments, however, cannot isolate these two mechanisms independently or distinguish between them. Since the x-ray emission from ultrashort pulse laser-produced plasmas exhibits a strongly nonlinear intensity and angle dependence, it can be enhanced considerably by optimizing the plasma excitation parameters.

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[a]Present address: Lawrence Livermore National Laboratories, P.O. Box 5508, Livermore, CA 94551-9900.

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