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Polarization and Propagation Properties of High Harmonics for $10^{17} W/cm^2$ Intensities

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High harmonics as coherent short wavelength radiation can be generated in interactions of femtosecond laser pulses with steep gradient plasmas generated on solid surfaces even for nonrelativistic laser intensities. Polarization properties and propagation direction of harmonics as function of the polarization of the incoming laser beam are essential to the understanding of the generation mechanism. In our previous low intensity ($5 \cdot 10^{15} W/cm^2$) experiments 2nd and 3rd harmonics were detected. The harmonics kept the polarization of the incoming laser beam and propagated into specular direction in all cases [1]. Harmonics were also generated by the TITANIA KrF laser system of RAL with a strong prepulse. 2ω-4ω were generated up to the intensity $10^{19} W/cm^2$ [2]. A transition from specular harmonic emission to diffuse emission occured between 10^{16} and $10^{17} W/cm^2$. Our aim was to generate harmonics and to investigate their propagation and polarization properties as a function of the incoming beam polarization in case of a practically prepulse-free laser at $10^{17} W/cm^2$.

The experiments were carried out using a KrF-dye excimer laser system. The $600 fs$ dye laser pulse is frequency doubled and then led through the KrF amplifier. The laser emits $15 mJ$ energy in a $600 fs$ pulse on the $248 nm$ wavelength. The polarization of the laser can be changed by rotating a $\lambda/2$ phase-plate built into the laser. The $20 \times 30 mm$ beam was focused by an F/2 off-axis parabolic mirror ($f = 10 cm$). In order to measure the diameter of the focal spot it was magnified by a special CaF_2 microscope objective ($56\times$) to a CCD camera. The diameter of the focal spot was found to be $2.5 \mu m$ FWHM and approximately $50 - 55\%$ of the laser energy was inside this spot which corresponds to $5 \cdot 10^{17} W/cm^2$ intensity. The laser intensity on target surface reached $3 \cdot 10^{17} W/cm^2$

for 45^o angle of incidence. This value was more than 50-times higher then in our previous experiments. The diameter of the ASE in the focus was measured and its intensity was found to be less than $10^7 W/cm^2$.

As shown in Fig. 1 a VUV spectrometer was built by using a Jobin-Yvon toroidal grating ($550 l/mm$) and an MCP detector with a phosphor screen.

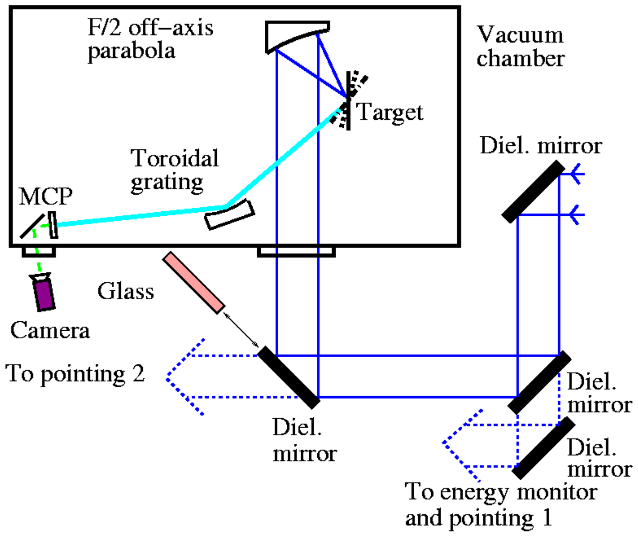
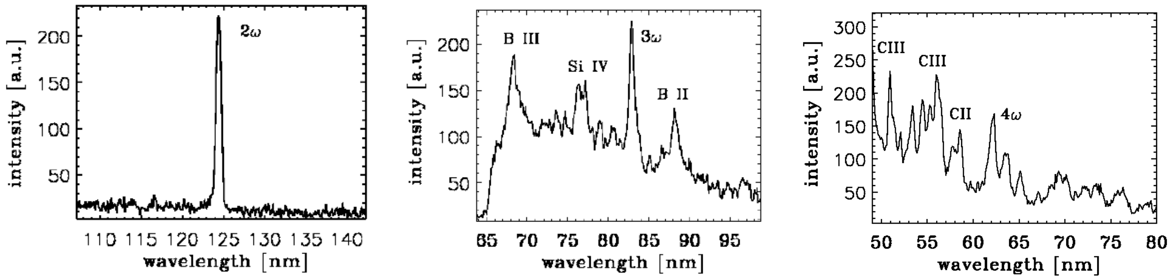


Figure 1: *Experimental setup*

The P- or S-polarized incoming beam always hits a fresh target element. The angles of incidence were set to be $45^o, 39^o$ and 27^o with observation angles of 45^o, 51^o and 63^o, respectively. Several targets were used such as $500nm$ thick Al, B or $270nm$ thick C layers evaporated onto glass plates.

In case of Al, B and C targets intensive 2ω and 3ω light was detected regarding both P- and S-polarized incoming laser beam (Fig. 2(a),(b)). For C target 4ω radiation at the wavelength of $62nm$ was detected having a near-threshold behaviour (in Fig. 2(c)).

The angular intensity distribution of the harmonics was investigated both for Al and B targets. In contrast to the low intensity experiments strong diffuse harmonics components were seen. In order to study the angular distribution the angle of incidence was changed keeping the position of the spectrometer fix. The measurements were realized for different beam diameters and intensities by varying the beam diameter. Fig. 3 shows the angular distribution for the full beam. The two dotted parallel vertical lines represent the horizontal beam width, which was calculated from geometrical optics at



(a) 2ω on Al target in case of P-polarized incoming laser.

(b) 3ω on B target in case of S-polarized incoming laser.

(c) 4ω on C target in case of P-polarized incoming laser

Figure 2: *Single shot harmonics spectra*

the position of observation. The small thick horizontal lines above the X-axis show the position of the VUV spectrometer aperture at different angle of incidence. Intense 2ω and 3ω radiation was detected even well outside the original light cone, i.e. for 27^o, in good agreement with the cited previous results [2]. The rippling of the critical surface can be an explanation for this feature. As in the present experiment the contrast of the laser was high, we conclude that this is an intrinsic effect occuring during the short-pulse laser plasma.

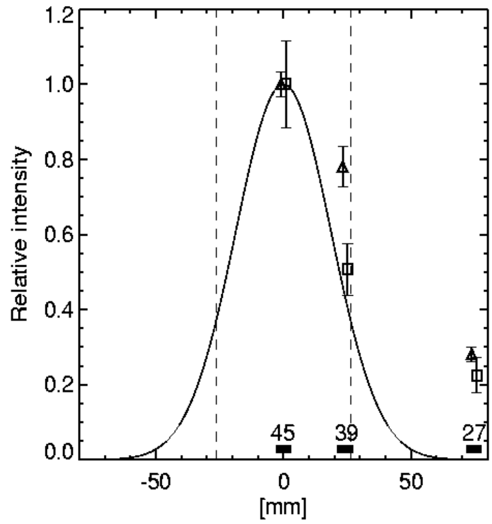


Figure 3: *Angular distribution of the generated harmonics. B target, (the $\triangle$ and $\square$ correspond to 2ω and 3ω, respectively.)*

The efficiency of harmonics generation was determined as well. The results show that the intensity of harmonics was independent of the polarization of the incoming laser pulse for laser intensities above $10^{16} W/cm^2$. The surface rippling effect would explain these results as well.

The polarization of harmonics was investigated at maximum laser intensity using Al targets. Both P- and S-polarized 2ω and 3ω radiation were detected both for P- and S-polarized incoming laser beam. Again, rippling of the critical surface may cause the mixing of polarizations of harmonics.

1D PIC simulations have been carried out by the code of Lichters et. al. [3]. For a P-polarized laser it shows 2ω – 5ω generation with P-polarized harmonics. In case of S-polarized laser the simulations gave only weak P-polarized 2ω and S-polarized 3ω radiation in contrast to our observations. The code calculations revealed that the light pressure slows down plasma expansion with increasing intensity, therefore the plasma profile remains steep. This can be the origin of critical surface rippling.

Summarising, intense 2ω, 3ω, 4ω were detected for P- and S-polarized radiation using a $3 \cdot 10^{17} W/cm^2$ KrF excimer laser. Diffuse behaviour of harmonics propagation was observed. The rippling of the critical surface even mixes the polarization, thus resulting both P- and S-polarized harmonics components.

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