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Harmonic emission from the rear side of thin overdense foils irradiated with intense ultrashort laser pulses

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Current sub-picosecond laser systems allow the study of laser plasma interaction in a new regime of large values of $I\lambda_0^2$ up to $\approx 10^{20}$ (W/cm^2)μm^2, where I is the laser intensity and λ_0 the wavelength [1]. One of the new processes occurring at these intensities is the generation of high harmonics from solid targets [2]. This type of harmonic emission has the potential for bright coherent XUV light sources including the possibility to generate atto-second pulses [3]. In addition, they are of interest for studying the complex laser-plasma interaction at high intensities [4].

Harmonics from solid targets have been mainly observed in reflection from the front side of massive solid targets. Here we report harmonic emission from the rear side of thin foils with thicknesses of a fraction of λ_0=395 nm in a "modest" intensity range below the relativistic limit $a_0 = 1$, with $a_0^2 = I\lambda_0^2/1.37 \times 10^{18}$ (W/cm^2)μm^2 the normalized field amplitude [5]. The interesting issue is that the low order harmonics below the plasma frequency are emitted from the rear of strongly overdense foils. Thus, we can exclude that harmonics generated at the laser irradiated front side are transmitted through the foil[6]. The rear side harmonics are denoted in the following as reemitted harmonics.

The experimental setup is schematically shown in Fig. 1a. We have used a 10 Hz Ti:sapphire laser system emitting 180 fs laser pulses of 200 mJ energy at a wavelength of 790 nm. To avoid early expansion of the thin foils by preplasma formation, the laser light was frequency doubled to λ_0 = 395 nm. From the measurement of the prepulse intensity performed at 790 nm we expect at λ_0 = 395 nm a contrast ratio $\leq$1:10^{10} at t >2 ns and $\leq$1:10^8 at 2 ns> t >1 ps, where t is the time before the pulse maximum. After a set of four multilayer mirrors that reduce the remaining unconverted laser light by a factor of $> 10^7$, the blue light was focussed by an f/2.5 off-axis multilayer-coated parabolic mirror to a focal spot of 5 μm diameter containing 50% of the energy. This yields an average intensity of $1.5 \cdot 10^{18}$ W/cm^2 while the peak intensity at the center was $\approx 5 \cdot 10^{18}$ W/cm^2.

The laser pulses were incident p-polarized under an angle $\alpha = 45°$ on thin foils of aluminum or carbon 50 nm up to 450 nm thick. The emitted harmonic spectra from single shots were recorded by a transmission grating spectrograph. A 100 nm thick aluminum filter was mounted in front of the transmission grating spectrograph to avoid damage by fundamental laser light. In some shots this filter was removed to detect the low order harmonics emitted from the rear side of the foil. In addition to the transmission grating spectrometer, an optical spectrometer with high spectral resolution has been used to measure the spectra of the reemitted 1st (the fundamental) and 2nd harmonic. An absolute value of the conversion efficiency into the total solid angle of the 1st and 2nd harmonic has been measured by a calibrated diode (reemitted pulse energy monitor).

Our experimental results are displayed in Fig. 1b - 1f. Fig 1b shows the efficiency of the harmonics. Reflected and reemitted harmonics are shown, but in the following we will discuss only the reemitted harmonics. They are observed up to the 10th order. From the 9th to the 10th harmonic a strong cutoff is visible. Higher reemitted harmonics than the 10th order are below the noise level. The spectrum in Fig. 1b was measured at the maximum intensity with a 0.62 nm thick carbon foil. We also observed rear harmonics with thicker foils (Fig 1c) up to a foil thickness of 450 nm. While the fundamental decreases only weakly with foil thickness, the higher harmonics show a more rapid decrease. The fundamental was also observed when we reduced the intensity by more than one order of magnitude (Fig. 1d). The spectra of the reemitted fundamental are strongly broadened compared to the incident

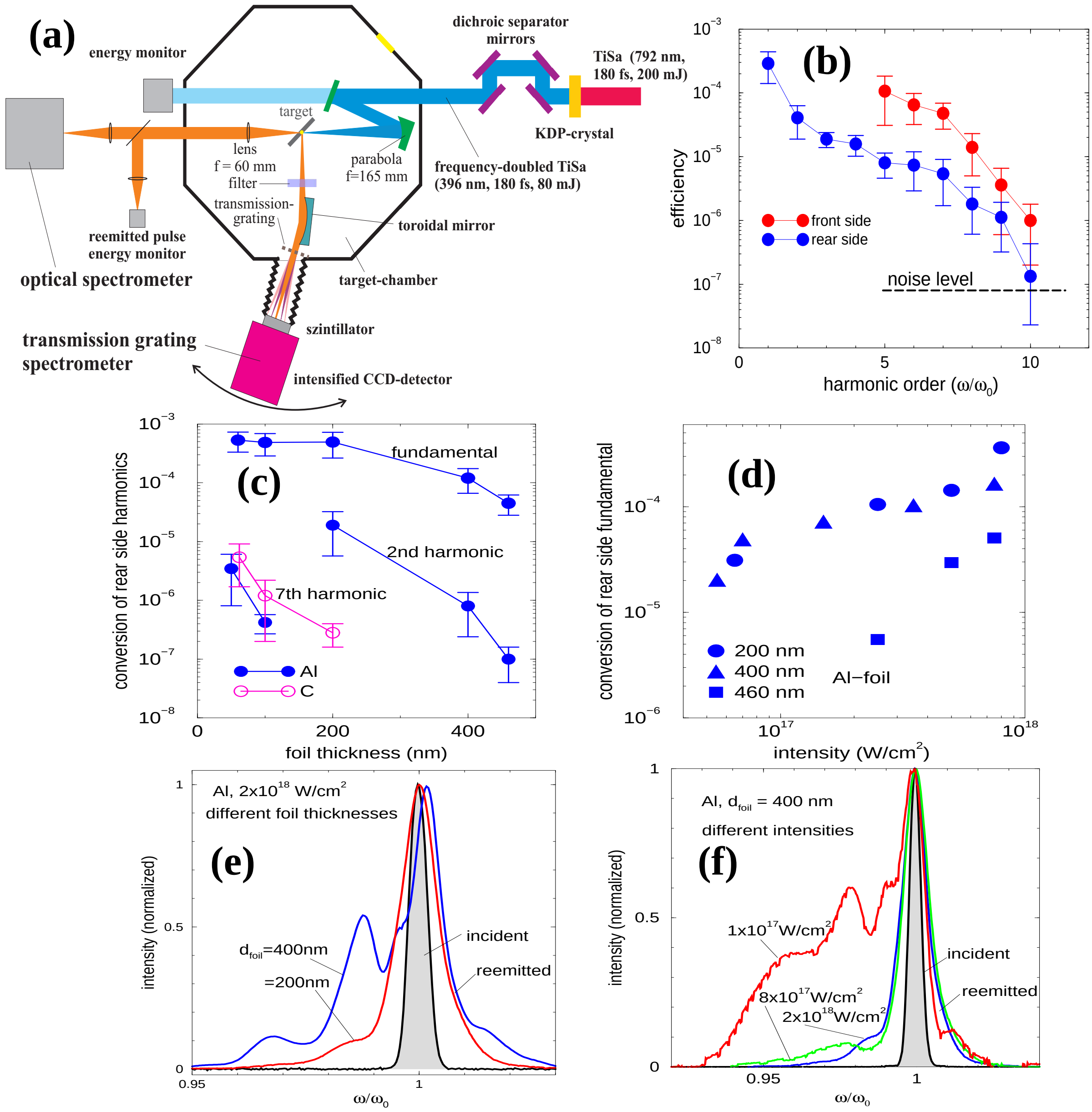

Figure 1: Experimental results. a) experimental setup. The harmonics have been measured by a transmission grating spectrometer for the high harmonics and an optical spectrometer for the reemitted fundamental and the 2nd harmonic. Absolute conversion efficiency of the 1st and 2nd harmonic is measured by the reemitted pulse energy monitor. b) Efficiencies of harmonics emitted from the rear and front side of a 62 nm thick carbon foil. c) Conversion efficiency of the fundamental, the 2nd and 7th harmonic versus foil thickness at maximum intensity. d) Conversion efficiency of the fundamental of different thick Al foils versus intensity. e and f) Spectra of reemitted fundamental at different foil thicknesses (in e) and different intensities (in f) together with the spectrum of the incident laser pulse.

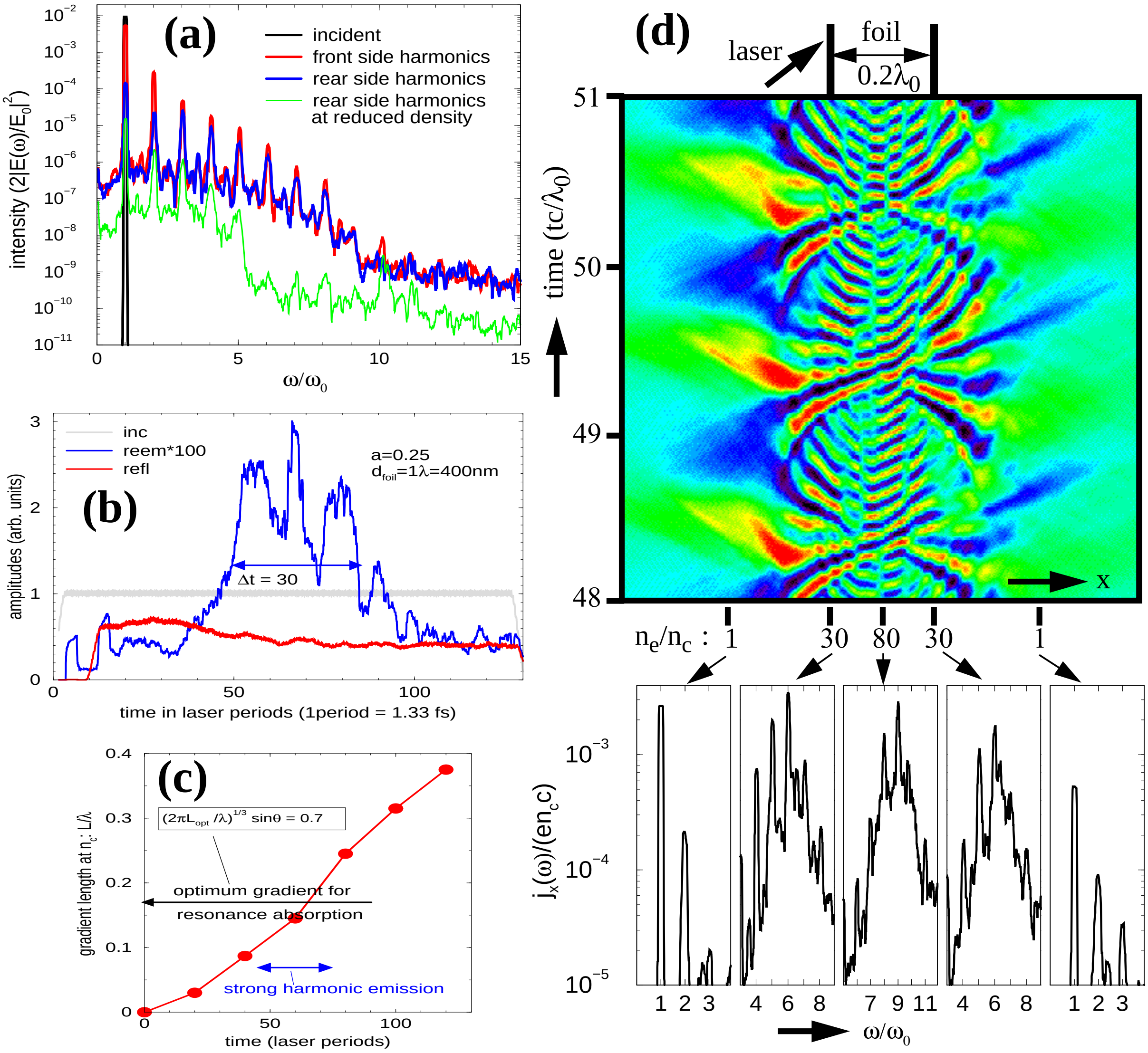

Figure 2: Result of simulation with LPIC. a) Simulated spectrum (incident = black, reflected = red, reemitted=blue). Input parameters are close to the experimental conditions: a_0=0.5 (corresponding to an intensity 2×10^{18} W/cm^2), angle of incidence = 45° at p-polarization, pulse duration = 100 periods (at λ_0 = 400 nm one period is 1.33 fs long), foil thickness = $0.2\lambda_0$ and $n_e/n_c = 84$ (corresponding to 10 times ionized Al or nearly fully ionized C at solid density). Green line (for clearness it is shifted down by a factor of 10) shows the rear side spectrum at lower density $n_e/n_c = 27$, but the same areal mass (thickness = 0.6λ), while the other parameters correspond to the standard ones. The cutoff of the reemitted spectrum (given by (n_e/n_c) is shifted from ≈ 9 for the blue curve to ≈ 5 for the green curve. b) Time dependence of the reemitted and reflected intensity for an incident pulse, which is constant in time. c) Temporal development of the density scale length at $n_e = n_c$. During significant reemission the scale length is optimal for resonance absorption. d) Current density j_x along the target normal for standard parameters. At the top the space-time mapping of j_x (in the laboratory frame) is shown. Red corresponds to maximum positive, blue to maximum negative values, green to zero. The thick bars indicate the unperturbed foil at t=0. At a few positions the density at the time of the laser pulse maximum is given. The diagram at the bottom shows the Fourier spectrum of j_x at these positions with peaks at $\omega/\omega_0 \approx \sqrt{n_e/n_c}$.

laser pulse (Fig. 1e and f). The broadening increases and a red wing appears when we increase the foil thickness (Fig. 1e) and also when we reduce the intensity (Fig. 1f). It is very important to note that we could observe harmonics only with p-polarized incident light. With s-polarized incident laser light no reemitted fundamental light was visible above the detection limit. Also, the polarization of the reemitted harmonics did not change as was observed for the fundamental.

To understand these experimental observations, we have performed PIC calculations with the one-dimensional LPIC code [7]. The ions are assumed to be mobile and an initially sharp boundary between foil and vacuum has been used. We not that due to the low prepulse level the thin foil is still dense when the main pulse arrives. This has been seen in hydrodynamic calculations with the MULTI-fs code [8] using as input the temporal shape of the laser pulse corresponding to our experimental conditions, i.e., including the weak pedestal.

A simulated harmonic spectrum is shown in Fig. 2a. As seen, the LPIC simulations reproduce the main features of the experiment. Intense rear side harmonic emission is observed at low harmonic orders including the fundamental. Furthermore, around the 9th harmonic a sharp cutoff is seen where still higher harmonics have intensities close to the numerical noise limit. The cutoff position coincides with the plasma frequency of the dense foil: $\omega_p/\omega_0 = \sqrt{84} \approx 9.2$. In fact, when we change the initial density we observe a shift of the cutoff, as seen by the green curve in Fig. 3.

The harmonics appear only when the density gradient at $n_e = n_c$ is optimal for resonance absorption, as illustrated by Figs. 2b and c. Thus strong reemission occurs during a shorter time (during about 30 periods in Fig. 2b) than the duration of the laser pulse. This results in spectra of the reemitted fundamental, which are broader than the incident light spectra as has also been observed in the experiment (Fig. 1e and f).

We assume that the excitation of the reemitted light occurs by the electrons generated by resonance absorption. These electrons propagate into the dense foil and excite plasma oscillations at positions, where the local plasma frequency coincides with multiples of the laser frequency (i.e., at positions where $\omega_p(x_q) = q\omega_0$ with $q = 1, 2, ...$). The excitations of such resonance layers is demonstrated in Fig. 2d, in terms of j_x (electron current along the target normal) plotted in the x, t plane for three laser oscillations during the pulse maximum. The maximum density in the foil determines the maximum frequency at which plasma oscillations can be excited. This explains the strong cutoff of the spectra at $\omega \approx n_{e,max}/n_c$. For more details of these investigations we refer to reference [5] and a longer paper which is in preparation.

References

[1] S. V. Bulanov *et al.*, Phys. Plasmas **1**, 745 (1994)

[2] N. H. Burnett *et al.*, Appl. Phys. Lett. **31**, 172 (1977); R. L. Carman *et al.*, Phys. Rev. Lett. **46**, 29 (1981); S. Kohlweyer, *et al.*, Optics Comm. **177**, 431 (1995); D. von der Linde, *et al.*, Phys. Rev. A **52**, R25 (1995); P. A. Norreys *et al.*, Phys. Rev. Lett. **76**, 1832 (1996); R. Hässner *et al.*, Opt. Lett. **22**, 1491 (1997); M. Zepf *et al.*, Phys. Rev. E **58**, R5253 (1998);A. Tarasevitch *et al.*, Phys. Rev. A **62**, 023816-1 (2000); I. Watts *et al.*, Phys. Rev. Lett. **88**, 155001 (2002); U. Teubner *et al.*, Phys. Rev. A **67**, 013816 (2003).

[3] L. Plaja, *et al.*, J. Opt. Soc. Am. B **15**, 1904 (1998).

[4] W. Theobald *et al.*, Phys. Rev. Lett. **77**, 298 (1996).

[5] U. Teubner, K. Eidmann *et al.*, Phys. Rev. Lett. **92**, 185001 (1996).

[6] P. Gibbon *et al.*, Phys. Rev. E **55**, R6352 (1997).

[7] R. Lichters, *et al.*, Phys. of Plasmas **3**, 3425 (1996).

[8] K. Eidmann, *et al.*, Phys. Rev. E **62**, 1202 (2000).