Abstract

The main subject of this thesis is a theoretical study of the generation of high harmonics by interaction of ultrashort laser pulses with condensed matter at intensities $I\lambda^2 = 10^{17} \ldots 10^{20}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2$, where λ is the laser wavelength. At these intensities, solid targets are rapidly ionized, and short pulses interact with sharp boundaries of overdense plasmas of electron densities on the order of the electron density in solids. The fact that electrons are driven to relativistic energies at intensities $I\lambda^2 \gtrsim 10^{18}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2$ is the most prominent feature of this new type of laser–plasma–interaction that can be approached by new short-pulse high-power lasers using the technique of Chirped–Pulse-Amplification.

The basic numerical tool for studying the interaction of intense laser light with fully ionized collisionless plasma are kinetic simulations that reveal the selfconsistent, collective and relativistic evolution of plasma and fields. Here, a one-dimensional relativistic Particle–In–Cell (PIC) Code is used that has been developed within the framework of this thesis. This code allows for arbitrary polarization of incident and generated light, but restricts the emission of light to the specular direction. In order to interprete the simulation results, the interaction is also described analytically by hydrodynamic equations treating the plasma as a cold relativistic fluid.

The simulations show that harmonics of high order (≈ 100) and high intensity (conversion 10^{-7}) can be obtained if the the incident intensity is significantly higher than the relativistic threshold intensity $I\lambda^2 \approx 10^{18}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2$. A substantial part of the present work deals with the *mechanism* that leads to high harmonic generation (HHG) at plasma surfaces and involves comparisons between simulation results and simple model calculations. On the other hand, the dependence of HHG on incident intensity, angle of incidence, plasma density (steplike profiles) and the surface shape (linear density profiles) is studied in detail numerically.

It turns out, that the mechanism of HHG can be traced back to oscillations of the electron density at the plasma surface that are excited by the laser pulse. Depending on the polarization of the incident light, the driving force is given by the ponderomotive force (the light pressure) or a combination of the ponderomotive force and the force that corresponds to the component of the laser's electric field perpendicular to the surface. These forces lead to surface modes oscillating at twice the laser frequency 2ω and the laser frequency ω, respectively.

Based on these observations and the fluid equations mentioned above, a simple mo-

del is derived explaining the harmonic spectra by reflection of the laser light from the oscillating surface. Quantitative agreement between PIC and model spectra is obtained when the amplitudes of a few (up to three) surface modes are adjusted. The simulations show that general selection rules with respect to parity (odd/even harmonics) and polarization (s/p) of harmonics exist depending on the polarization of the incident light: At normal incidence, linearly polarized light generates only odd harmonics, while circularly polarized light does not generate any harmonic. At oblique incidence, s-polarized incident light generates even p-polarized harmonics and odd s-polarized harmonics, while p-polarized incident light generates odd and even p-polarized harmonics. These rules are confirmed by inspection of the fluid equations and are valid only under the assumption that the laser pulse interacts with a plane plasma layer.

High harmonics can also be observed in the light transmitted through the plasma layer. This holds for harmonic frequencies above a cutoff, which is defined by the dispersion for transverse waves in plasmas and depends on the bulk plasma frequency ω_p and angle of incidence. This cutoff can be used experimentally to estimate the electron plasma density.

In experiments, the plasma (ion density profile) will generally expand during the time of interaction. To account for these situations, plasma density profiles are considered that rise linearly over a certain length L and are kept constant beyond. The intensity of emitted harmonics rises with increasing length L according to the fact that the laser light interacts essentially with softer plasma and drives larger surface oscillations. For lenghts L, small compared to the laser wavelength, harmonics with frequencies below the bulk plasma frequency ω_p can be enhanced because of resonant excitation of plasma waves in the ramp region, so that the reflected spectrum shows a cutoff at ω_p. This effect can be used in experiments to estimate the bulk plasma density or the density scale length at the plasma surface.

Finally, it is observed that the interaction of p-polarized obliquely incident intense short laser pulses with sharply bound overdense plasmas leads to emission of light at harmonics of the bulk plasma frequency ω_p. Its origin is of kinetic nature: Bunches of fast relativistic electrons (jets) are generated periodically at the plasma surface and injected into the material. Inside the bulk plasma, these jets excite large amplitude plasma waves with fundamental frequency ω_p. Convective, ponderomotive and relativistic nonlinearities of these longitudinal waves couple to the transverse fields and lead to emission at harmonics of ω_p, which can be interpreted as the decay of two (or more) plasmons into one photon. These processes are a new aspect of laser interaction with matter that is developed here for the first time.