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The plasma medium as a source for intense attosecond pulses

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The advent of attosecond pulse generation has had a tremendous impact on the temporal measurement technology. It has provided the means of temporally resolving dynamic processes evolving at atomic time scales. The technique for the attosecond pulse generation relies on the production of phase-locked harmonics in a non-linear medium using short laser pulses. In the time-domain this leads to attosecond temporal localization. A number of attosecond spectroscopic measurements have been performed using attosecond sources based on high-harmonic generation in atomic gases. The span of experiments that can be performed with this source is though rather limited because of the low number of photons available. Since the first observation of harmonic generation from solid targets using a tabletop laser system [1-3] it became apparent that the interaction of an intense laser pulse with an overdense plasma constitutes an alternative route for the efficient production of phase-locked harmonics leading to attosecond light bunching [4]. The main advantage over the process of harmonic generation in rarefied gases is that the plasma medium allows the use of higher laser intensities and in addition, it exhibits higher conversion efficiencies. Given the rapid technological advancements in laser technology, tabletop lasers based on the Optical Parametric Chirped Pulse Amplification (OPCPA) technique [5-8] delivering several tens of TW power with kHz repetition rate appears to be within our reach.
Motivated by the prospects offered by the rapidly evolving laser technology, we have used the one-dimensional Particle-In-Cell (PIC) code LPIC and looked into the possibility of producing single attosecond pulses using the harmonic emission emanating from the interaction of intense few-cycle laser pulses with overdense plasmas [9].

The method to generate a train or single attosecond pulse is schematically depicted in Fig. 1. The reflection of a high intensity pulse off a planar target is highly distorted and consequently rich in harmonic content. A very useful model that provides insight into the mechanism of high harmonic generation in solid targets is the so called *oscillating mirror* model. [10,11]. More recently, using this model Gordienko et al. [12], have deduced in rather general terms a universal power law scaling for the roll-off of the harmonic spectrum. They also showed that the harmonic spectrum extends up to a maximum cut-off frequency that depends on the maximum velocity at which the mirror moves towards the incoming light. It corresponds to the maximum Doppler shift of the Compton backscattered light on the relativistic mirror.

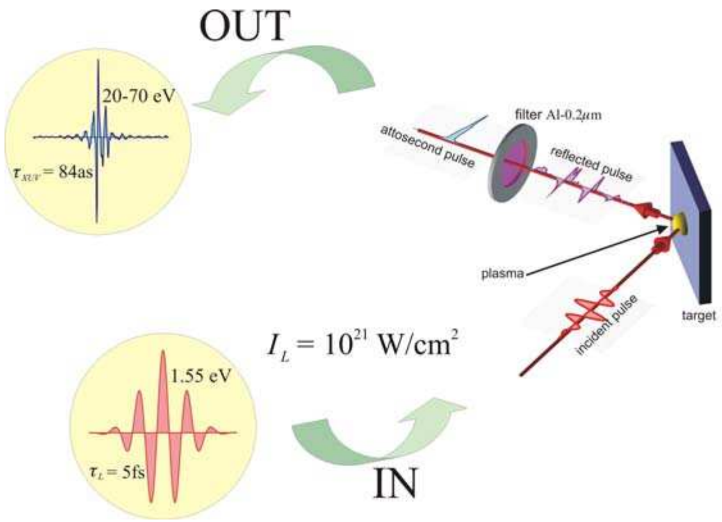

Fig. 1: Schematic showing the technique of attosecond pulse generation from the interaction of high-intensity laser pulse with solid targets.

In our simulations [9], a two-cycle (Gaussian-FWHM) p-polarized laser pulse is incident at 45^0 onto a planar target consisting of ~80 times overdense plasma for the λ = 0.8μm laser wavelength. The most important parameter pertaining to this interaction is the normalized field amplitude or normalized vector potential a_L, which in terms of the laser intensity I_L and wavelength λ_L is given as $a_L^2 = I_L \lambda_L^2 / (1.37\times10^{18}\ \text{W}\ \mu\text{m}^2/\text{cm}^2)$. It was varied between $a_L = 3-100$ corresponding to a laser intensity range of $I_L = 2\times10^{19} - 2\times10^{22}\ \text{W/cm}^2$ thus covering the present day capabilities in laser technology as well as those envisaged for the near future. The common procedure to generate shorter pulses from this interaction is to exclude the dominating low frequency harmonics by filtering the power spectrum generated using a high-pass filter. In Fig. 2, the efficiency η_{XUV} with which attosecond pulses in the indicated spectral range are produced is given as a function of the normalized field amplitude and for three commonly used filters of $0.2\ \mu\text{m}$ thickness.

A laser system delivering pulses of $E_L = 1\,\text{J}$ energy in $\tau_L = 5\,\text{fs}$ and focusable to a $10\,\mu\text{m}$ spot produces intensities of $2.5\times10^{20}\ \text{W/cm}^2$, i.e., $a_L \approx 11$. For this intensity and using a $0.2\ \mu\text{m}$ thickness Al filter, this laser system is capable of generating attosecond pulses with duration of ~84 as in the 20-70 eV spectral range with 10^{15} number of photons per pulse.

In parallel with the theoretical investigations, experiments for the temporal characterization of the frequency spectrum produced by irradiation of solid targets are in progress.

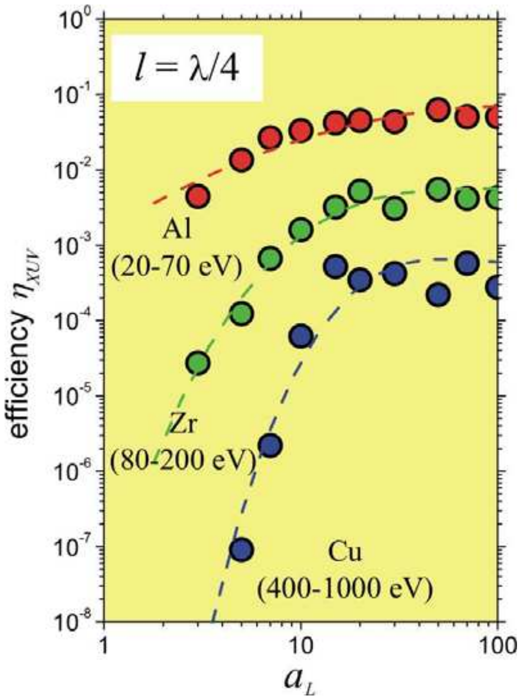

Fig. 2: The efficiency of the laser to attosecond XUV pulse conversion as a function of the normalized field amplitude for three different filter materials(1D-PIC simulations).

To date, the generation mechanism of harmonics from solid targets using short pulses from table-top laser systems has been demonstrated and some properties of the emitted spectrum have been studied. However, no measurement in the time-domain to demonstrate the formation of attosecond pulses has been performed. Using the ATLAS-Upgrade laser system at MPQ (300 mJ, 50 fs), we have generated up to 17th harmonic of the fundamental frequency at moderate intensities (~10^{18} W/cm^2). The experimental setup is similar to the one shown in Fig. 1 with Quartz substrates as targets. A typical spectrum is shown in Fig. 3a. The corresponding frequency spectrum is given in Fig. 3b without corrections for the spectral sensitivity of the spectrometer. Assuming that the harmonics between 7th and 17th are coherent (no phase difference) the experimentally obtained frequency spectrum would produce in time domain a train of attosecond pulses with ~400 as duration and period that of the fundamental laser frequency (see Fig. 3c).

The near future experimental goal is to fully characterize and optimize the harmonic generation from solid targets using short (<10fs) laser pulses. The next step is to demonstrate the formation of single attosecond pulses using similar techniques already developed for harmonics from atomic gases [13-15]. The issue of spatial coherence of the emitted spectrum has to be clarified. Some recent three-dimensional PIC simulations indicate that the emitted spectrum preserves its coherence even if the target surface does not remain planar during the interaction.

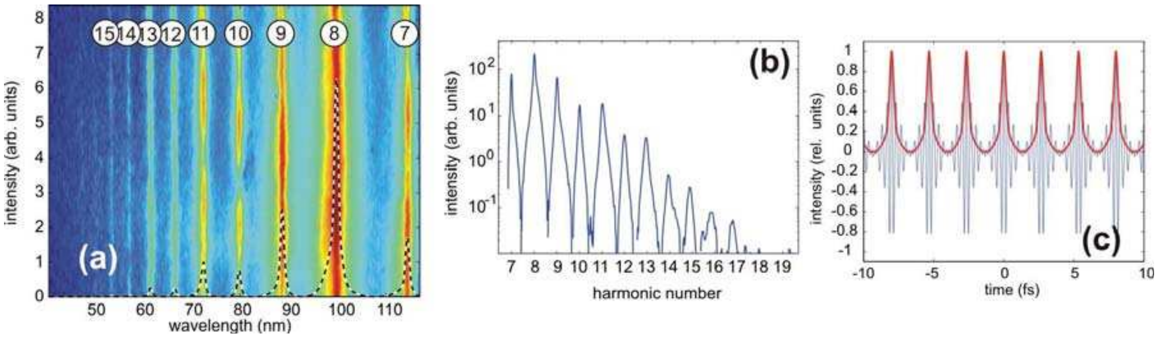

Fig. 3: (a) experimentally produced harmonic spectrum using Quartz targets. (b) the harmonic comb in frequency domain. (c) the train of attosecond pulses (~400 as) assuming that the frequency comb in (b) is coherent.

The objective would be to experimentally verify some of the theoretical predictions on pulse duration and number of photons. The ultimate goal is the focusing of the attosecond pulses using grazing incidence optical systems to create unprecedented intensities in the XUV spectral range. In view of the prospects for table-top, high-repetition rate, PW laser systems within the next decade, this would constitute the dawn of an implement with exceptional properties appropriate for a host of applications like inner-shell non-linear optics, relativistic atomic physics, of electron transfer processes at interfaces and real-time observation of electron dynamics in atoms, molecules, and high density plasmas.

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