High-order harmonic generation using a multi-jet gas puff target

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Abstract–Results on high-order harmonics generation (HHG) by focusing a high power femtosecond laser pulse onto a multi-jet gas puff target with modulated gas density are presented. The use of this target makes it possible to increase efficiency of HHG by quasi-phase matching (QPM). Preliminary measurements of high-order harmonics in the extreme ultraviolet range for various experimental parameters are presented. Some improvement of the emission characteristics was observed.

High-order harmonic generation (HHG) resulting from the interaction of ultra-short laser pulses with gases is one of the most promising methods to obtain coherent radiation in the soft x-ray (SXR) and extreme ultraviolet (EUV) regions [1-2]. Pulses of such radiation with femtosecond to attosecond duration are highly attractive for applications in various areas, including ultrafast science [3] nanoscale coherent imaging [4], interferometry [5], seeding of a free electron laser (FEL) [6].
However, the possibility of using high-order harmonics strongly depends on the improvement of harmonic generation efficiency.

To obtain efficient generation of a harmonic field, phase matching is required between the laser fundamental beam and the harmonics, generated by the coherent emission of photons from a large number of atoms. This type of phase matching has been presented, using targets in the form of hollow-core fibers filled with gas [7-8] or elongated gas jets [9-11]. However, in this approach, HHG efficiency is limited by the ionization of the gaseous medium.

It was theoretically demonstrated that quasi-phase-matching (QPM) of high-order harmonic generation in gases with modulated density may strongly increase harmonic generation efficiency [12-15]. This approach has been proved experimentally using a gas-filled hollow-core fiber with a modulated inner diameter [16] and coherent superposition of harmonics generated in two successive sources by the same laser pulse [17]. The strong enhancement of HHG has been observed for an array of gas jets [18] and dual-gas multi-jet arrays [19].

In this paper we present the first results of HHG experiments with the use of a newly developed multi-jet gas puff target. The details of the target design and the results of its characterization measurements using EUV shadowgraphy were previously published in [20]. The results of the studies should be useful for the development of an efficient source of coherent EUV radiation.

A multi-jet gas puff target is formed by the injection of gas to the laser interaction region through a custom made nozzle in the form of an array of small orifices, arranged equidistantly in-line over a distance of 9mm. The diameter of a single orifice is 0.5mm. In the experiments we have used the nozzles with 5-, 7-, and 9-orifices. The nozzle was coupled to a fast-acting electromagnetic valve developed in the Institute of Optoelectronics, MUT. Argon was used as a working gas. The system to produce multi-jet gas puff targets and gas density distribution for the nozzle are shown in Figs. 1a and 1b respectively.

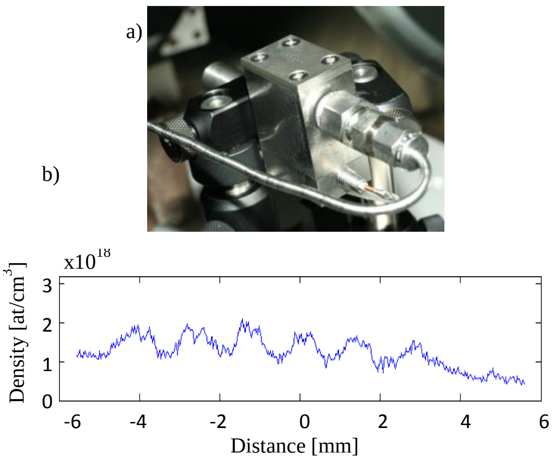

Fig. 1. The valve to produce a multi-jet gas puff target (a) and gas density distribution for the target produced with a 7- orifice nozzle (b) (measured at 2 bar backing pressure and 1.5mm above the nozzle).

The experiment was performed at the PALS center (Prague Asterix Laser System). To irradiate the multi-jet gas puff targets we used a Ti:Sapphire femtosecond laser chain operating at a fundamental wavelength of 810nm and 40fs pulse duration. All spectra were obtained for single femtosecond laser pulses, each with energy ~1mJ. Laser radiation was focused onto the target by an *f*=750mm focal length lens. To measure high-order harmonic radiation in the extreme ultraviolet (EUV) range the flat field spectrograph was used. The angle of the reflective diffraction grating (1200 groves/mm) was set to

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3 degrees and signal was collected by a back-illuminated CCD camera, sensitive to the EUV radiation (Andor, model DX440-BN). The long wavelength radiation was filtered by an aluminum filter with a thickness of 160nm. The scheme of the experimental setup is presented in Fig. 2.

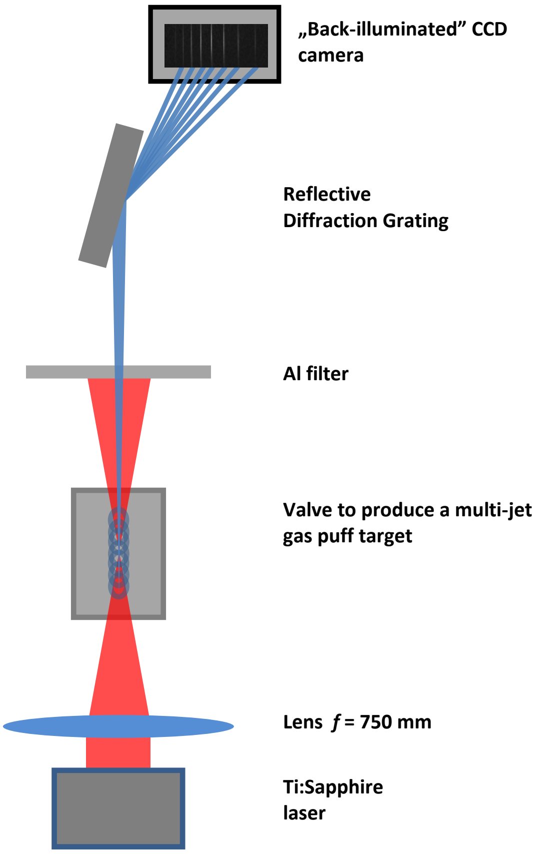

Fig. 2. Scheme of the HHG experiment.

An additional CCD camera in the visible range with a microscopic objective was used to determine the diameter of the focus position relative to the gas puff target. The diameter of the focus at FWHM was 91µm, giving the laser intensity in the focus of about 10^{14}W/cm^2. The calculated Rayleigh length was 14mm. The experiment was conducted in a tandem of vacuum chambers with the pressure of few 10^{-5}mbar.

The goal of the research was to find optimal conditions for HHG generation using a new multi-jet gas puff target. We changed the laser focus position along the optical axis and the distance between the focus and the nozzle. It was made by changing the gas puff target position using a 3-axis motorized translation stage. EUV spectra were obtained for different nozzles and two backing pressures of working gas (1 and 2 bar).

We collected nearly 1000 spectra during the course of our investigations. The most promising results were obtained for the nozzle with 7 orifices. Figure 4 shows the typical spectra (scaled in arbitrary units and averaged over the measurement series) with optimal conditions for high harmonics generation. The red line depicts the spectrum for the argon backing pressure of 1 bar, the laser focus height above the nozzle of 1.5mm and the laser waist position of 1mm into the gas puff target. The blue line represents the spectrum at the argon backing pressure of 2 bar, the laser focus 2.5mm above the nozzle and the laser focus position of 1mm upstream the gas puff target.

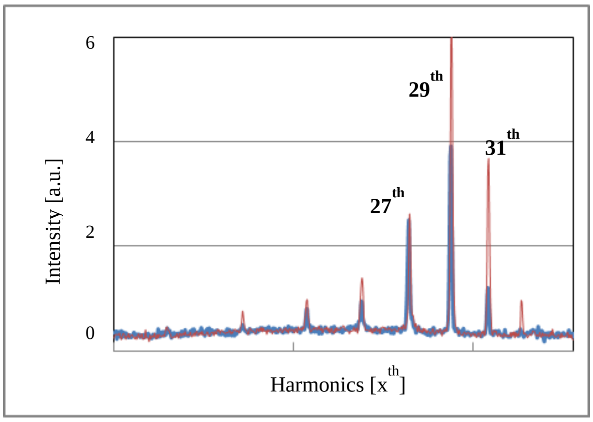

Fig. 4. The example of spectra for a 7-orifice nozzle at the optimal conditions for HHG: - red line: 1 bar Ar, focus height 1.5mm, focus position 1mm; - blue line: 2 bar Ar, focus height 2.5 mm, focus position -1 mm.

The most prominent lines in the spectrum correspond to the 27th (λ=30nm), 29th (λ=27.9nm) and 31st (λ=26.1nm) harmonics. As can be seen, to obtain relative high intensity at higher backing pressure, we had to place the laser beam focus far above the nozzle. We concluded that the optimal value of gas density should be similar for each backing pressure with a precisely defined spatial distribution of the interaction region with high (~ 2×10^{18} at/cm^3) and low (~ 1×10^{18} at/cm^3) gas densities. With subtle control of the parameters (near 1 bar Ar backing pressure, focus position ~1mm into the gas puff target and laser beam focus height 1.7mm above the nozzle), we successfully obtained energy transfer between 27th and 29th harmonics, while keeping the other harmonics at a relatively low level. The results give us an opportunity to develop a tunable quasimonochromatic coherent source of radiation in the EUV range.

In summary, we performed the preliminary experiments on generation of high-order harmonics using a newly developed multi-jet puff target with a modulated density of gas. EUV spectra of harmonics for various conditions have been measured. The results show increased monochromaticity of the high harmonic spectra, suggesting a possibility to develop an efficient, temporarily coherent EUV source. In order to verify the effectiveness of the high-order harmonics generation process using a new technique and further quantitative measurements are required.

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