

## Optimized XUV source at 100 kHz repetition rate

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**Abstract.** Fiber based laser systems at high repetition rate are becoming very attractive for high-order harmonics generation as they allow to reach high intensities. Their characteristics (central wavelength, energy and pulse duration) require specific optimizing conditions. We analyse how the harmonic efficiency with such a system is influenced by several parameters (atomic gas media, pressure, interaction geometry (a jet or a cell)). This study allows us to define optimal conditions for HHG appropriate to this new type of laser and experimentally, a photon flux higher than  $10^{12}$  photons/s is measured.

### 1 Introduction

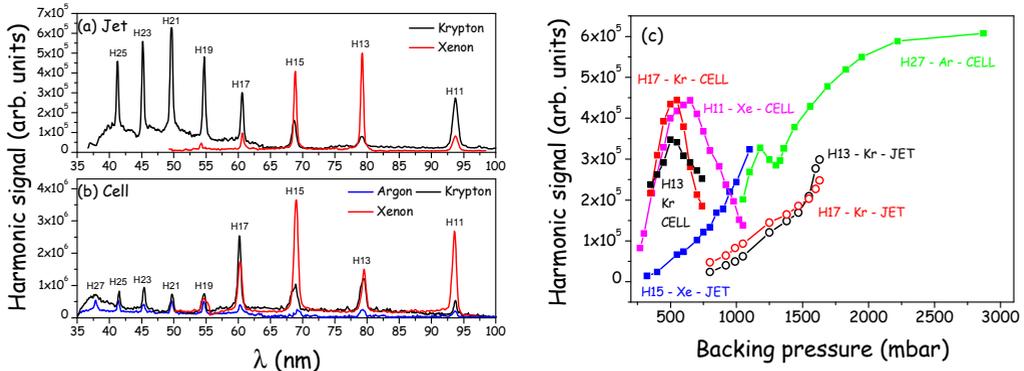
High harmonic generation (HHG) in gas is a well-established technique used to produce extreme ultraviolet (XUV) pulses on the picosecond, femtosecond or attosecond timescale. High repetition rate and high average power laser systems are now very attractive to push further this field and are a promising tool for new understanding of HHG physics [1, 2]. The moderate energy and long duration of the pulses delivered by these systems require tight focusing geometry leading to a reduced harmonic efficiency. Nevertheless, few groups reported the observation of high-order harmonics at very high repetition rate in such geometry [3-5]. In first experiment, HHG at repetition rates of up to one MHz has been reported using a 1030 nm fibre chirped-pulse amplification (FCPA) system [3]. By considering a  $10^{-6}$  typical conversion efficiency,  $3 \times 10^{11}$  photons/s/harmonic has been estimated. A similar FCPA system has led to a measured conversion efficiency of  $1.2 \times 10^{-9}$  [4]. Nonlinear compression of their pulses has increased the conversion efficiency of  $1.2 \times 10^{-7}$  but the reduced pulse energy led to  $7.9 \times 10^{11}$  photons/s. Using a 100 kHz laser, centred at 800 nm, system with a laser pulse energy of only a few  $\mu$ J, Heyl *et al.* generates HHG in different gas species with a photon flux up to  $3 \times 10^9$  photons/s (conversion efficiency  $10^{-8}$ ) [5]. Several groups have also recently demonstrated the promising approach of cavity-enhanced HHG and the optimization of the efficiency of HHG in the tight focusing regime is of prime importance.

In this work, we focus on the generation and on the optimization of high-order harmonics with a high repetition rate ultrafast Yb fiber laser (1030 nm) by studying the influence of atomic gas media (Ar, Kr or Xe), gas pressure and interaction gas geometry (gas jet or gas cell) in a tight focusing geometry. We achieve optimization of emission with a XUV photon flux up to  $10^{12}$  photons/s in Xe at 100 kHz using a finite gas cell. To obtain a controlled and useful XUV source, we designed a compact XUV spectrometer compatible with the imaging of the XUV source on an experiment (with spectral or temporal control) with an additional probe beam and compatible with the high thermal load of this type of laser. This led to a tabletop controlled XUV source operating at 100 kHz repetition rate well fitted for pump probe experiments.

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## 2 Experiment & Simulation

The experimental setup combines both the HHG-based XUV techniques and the high-energy FCPA technology. At 100 kHz and 1030 nm, the laser system delivers 500 fs pulse duration with 10 W of average power, resulting in 100  $\mu\text{J}$  pulse energy. High-order harmonics are generated by focusing the laser beam with a 100-mm focal length lens inside a vacuum chamber leading to an estimated peak intensity of  $6 \times 10^{13} \text{ W/cm}^2$  onto several gas target (a jet or a cell). The emitted XUV beam is characterized by a spectrometer consisting in a 100  $\mu\text{m}$  entrance slit, a gold coated grazing incidence grating and a microchannel plate detector (MCP + phosphor screen and camera). With a gas jet ( $\Phi=200 \mu\text{m}$ ), odd harmonics have been produced in Kr and in Xe (Figure 1-a). We measure a maximum photon flux of  $3 \times 10^{11} \text{ s}^{-1}$  in Xe (conversion efficiency =  $3.6 \times 10^{-8}$  per harmonic) by placing an aluminium filter and a XUV photodiode before the spectrometer slit. The XUV photon flux was further increased by using a gas cell ( $L=1 \text{ mm}$ ). This geometry offers a longer interaction length in comparison with a gas nozzle and confines the gas in the volume where the laser intensity is high enough for HHG ( $Z_R = 305 \mu\text{m}$ ). Odd harmonics have been produced in Kr, Xe and in Ar (Figure 1- a and b). The measured emitted photon flux increased up to  $10^{12} \text{ s}^{-1}$  in Xe (conversion efficiency =  $1.6 \times 10^{-7}$  per harmonic). Figure 1 (c) shows the detected harmonic signal. With a gas jet, we observe a constant increase with backing pressure. We could not reach any optimum pressure before being limited by the pumping cavity (turbo pump 500 l/s). With a gas cell, the gas load decreases sufficiently to reach the optimal pressure at lower backing pressure. The XUV signal was roughly ten times higher than the highest signal obtained with the jet. With Ar, the signal also evolved strongly with the pressure and showed interesting features that can also be explained by phase matching considerations [6]. Our numerical simulations have shown that the first maximum is attributed to a perfect phase matching and the following minimum corresponds to destructive interferences on axis.



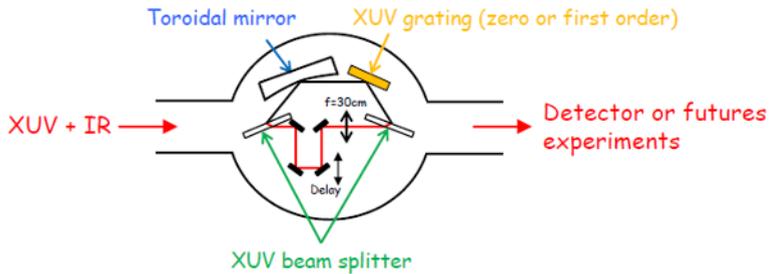
**Fig. 1.** (a) XUV spectra obtained at 100 kHz with (a) a gas jet, (b) with a gas cell. (c) Experimental results of harmonic signal as function of pressure for different gas species and harmonic orders.

In conclusion, we have performed an experiment designed to study HHG at very high repetition rate. The XUV photon flux has been optimized by using a gas cell with a measured photon flux up to  $10^{12} \text{ s}^{-1}$  (conversion efficiency of  $10^{-7}$  per harmonic). With this setup, harmonics can be characterized but cannot be used. We redesigned the XUV spectrometer to cope with the high thermal load and to image the full XUV beam on a sample with possible spectral or temporal resolution.

## 3 An XUV spectrometer for spectral / temporal control and high thermal load.

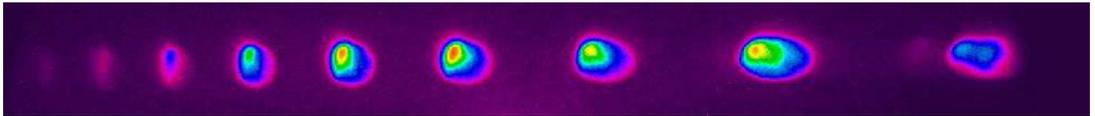
With the optimized and reliable XUV source, the XUV spectrometer was redesigned to create a real XUV beam line (Figure 2). The XUV beam gets now reflected on a first XUV beam splitter that

transmits most of the fundamental IR. After this reflection, the XUV beam is reflected by a toroidal mirror ( $f = 30$  cm) toward a grating that can be used at zeroth order (for temporal resolution) or at first order (for spectral resolution). Finally, a second beam splitter reflects the XUV toward the detector (or experiment) where it is focused. It also enables to recombine IR and XUV beams for pump probe experiments. Indeed, to fully use the possibilities of this source, we will refocus the IR beam onto the XUV focus. With this compact setup, one can control the IR intensity at focus and control the XUV-IR delay with high resolution.



**Fig. 2.** XUV spectrometer and IR-XUV delay control

With a second FCPA laser (1030 nm, 100 kHz, 46 W, 460  $\mu$ J, 570 fs), we generated high-order harmonics with this new setup in several gases. The laser beam is focused with a 200-mm focal lens leading to a peak intensity of  $7 \times 10^{13}$  W/cm<sup>2</sup>. We measure at the end of the setup  $5 \times 10^{10}$  photon/s, which corresponds to  $2 \times 10^{12}$  photons/s exiting the gas cell.



**Fig. 3.** Spectrum of high harmonic emitted in Kr with orders ranging from 13 to 29 for a  $P = 500$  mbar

In conclusion, we have studied the optimization of a XUV source based on a 100 kHz repetition rate system 1030 nm laser in function of gas species, pressure and interaction geometries. The development of a new XUV spectrometer has lead to a tabletop high repetition rate XUV beam line with a high photon flux of  $5 \times 10^{10}$  photons/s in the detection zone ( $2 \times 10^{12}$  emitted). The combination of the high average power fiber laser and the optimized XUV source provides a unique source of controlled coherent and ultrashort XUV light at very high repetition rate.

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