High-order harmonic generation (HHG) from the interaction of an intense laser field and a gas target is attracting a lot of attention, since it provides an interesting table-top coherent extreme ultraviolet (XUV) radiation source, and since it is becoming a reliable source with pulse duration in attosecond regime. However, one major problem is that the efficiency of HHG is extremely low, which limits its further application. To meet the demanding of different kinds of applications, the pulse energy needs to be improved, the beam properties need to be fully characterized and better controlled. The OHIO project was devoted to optimize this interesting light source and to explore some of its applications.

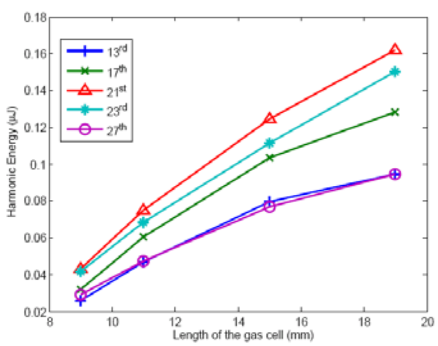

Fig. 1. Harmonic energy as a function of cell length for different orders.

The harmonic pulse energy was optimized by considering both collective and single atom responses. Collective effects were optimized by a careful study of phase matching for different medium lengths. To check the output harmonic energy, a calibrated XUV photodiode was used and the absolute energy was measured for each order. The optimized media length was found to be approximately 20 mm for argon as shown in Fig. 1. The laser beam in this experiment was focus by a 2 m focal length spherical mirror into a gas cell with changeable length. With such a very loose focus, the transverse volume of the generation area was increased, which led to increased pulse energy. The best pulse energy around 40 nm was 160 nJ.

The spectrum of harmonics could be broadened by increasing the intensity of the driving laser field. This effect is due to fundamental reshaping leading to an efficient phase matching of both short- and long-trajectory contributions. The short- and long-trajectory contributions interfere in the far field, leading to double and even triple peaks in the spectrum. This effect provides an easy way for covering a larger spectral range, which is very important for seeding applications.

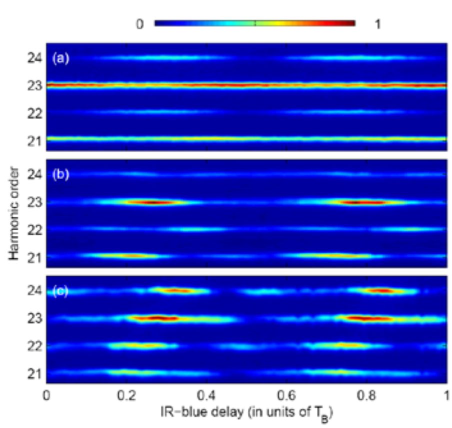

Fig. 2: 21st to 24th harmonic spectra as a function of the relative delay between the IR and blue fields for different intensity ratios, increasing from about half a percent in (a) to a few percent in (b) and (c).

To improve the single atom response, harmonic generation driven by an intense infrared laser field and a small fraction of its second harmonic was studied. A two-color interferometer was built and the harmonic spectrum was measured as a function of the relative phase and intensity ratio between the two fields. Both odd and even harmonics were detected. The intensity and divergence of the emitted harmonics were found being strongly modulated as a function of the relative delay between the two fields and the modulation depends on the relative intensity shown in Fig. 2. By using a semi-classical model we provided a detailed analysis of the underlying physics. By changing the delay between the two fields, harmonics in different spectral range could be selectively enhanced and the beam divergence could be controlled as shown in Fig. 3. This could be useful for a range of applications. Depending on the parameters, five times to one order of magnitude enhancement could be gained compared with the one color case.

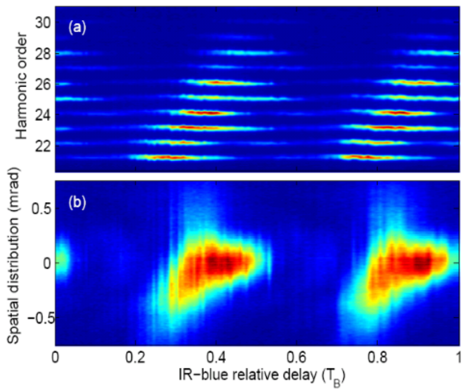

Fig. 3: Harmonic spectra as a function of the relative delay between the IR and blue fields for strong blue field (a) and corresponding spatial distribution for 23rd harmonic (b).

The high-order harmonic beam was also completely characterized. The beam profile was measured by sending the harmonics directly to the sensor and the beam divergence was estimated to be 0.7 mrad. The focus property of the beam was examined by focusing it with a Schwarzschild objective. With 27 mm focal length 1.4 µm spot size was obtained. Considering the pulse energy the harmonic intensity at focus spot is of the order of 10^{14} W/cm^2, which is enough for studying nonlinear optics in this wavelength regime. With the optimized source, single-shot digital in-line holography with ultra-short XUV pulses from harmonic generation was demonstrated. The optimized harmonics were focused by the Schwarzschild objective, which is coated for reflecting the spectrum around 38 nm. An hologram of a deformed microscopic tip was recorded (Fig. 4). A numerical algorithm was used to reconstruct the image from the hologram, giving a. 4-µm resolution. This is a very important step for future time-resolved holography experiments, showing the reliability of the source.

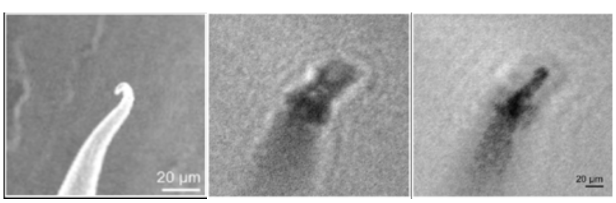

Fig. 4. Images of a deformed microscope tip, (a) STM-image,(b) single shot hologram and (c) object after reconstruction.

In summary, high order harmonic generation has been optimized considering both collective and single atom effects. A pulse energy close to a micro-Joule was obtained. The harmonic beam was fully calibrated including pulse energy, pulse duration, beam profile and focus property. The intensity at focus is enough for nonlinear optics applicatiosn. The control of spectrum and beam divergence was demonstrated. A single shot hologram was realized by using a 38 nm harmonic beam. Femtosecond time resolved holography is within reach.