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Terawatt Post compression of high energy fs pulses using ionization: A way to overcome the conventional limitation in energy of few optical cycle pulses

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Abstract. By using optical-field-ionization of helium we postcompress 50 fs pulses to 8 fs with a pulse energy of 8,7 mJ. Hence few cycle pulses were obtained with TW peak power and a good shot-to-shot stability.

1 Introduction

High energy femtosecond laser pulses can be used to generate high energy isolated attosecond (1 as = 10^{-18}s) pulse via high harmonic generation in gases [1] or on plasmas [2]. High energy single attosecond pulses will open the door to nonlinear processes in XUV spectral region with attosecond resolution in the perturbative domain. Generating such pulses requires high energy ultra-short duration laser pulses with a high quality beam spatial profile. These characteristics can be fulfilled separately but it is very difficult to obtain both simultaneously. Post compression techniques using hollow core capillary filled with noble gas have already demonstrated their potential [3]. Kerr induced self-phase modulation (SPM) is often used to broaden the spectrum to achieve post compression of short pulses. However, the pulse output energy is limited by the critical power that is relatively low in high gas pressure required with this approach. Similar limit exist with filament based post compression [4].

To overcome this limit, we developed a post compression technique using optical-field-ionization induced spectral broadening at low gas pressure in a guided geometry [5]. It shows several advantages compared to Kerr based post compression technique. First, the ionization is the key to broaden the spectrum, making this technique favourable for high energy pulses. Second, requiring high intensity implies that short focal length can be used to inject the beam into the capillary. Third, no complex differential pumping is necessary to use the pulses under vacuum because few milibars of Helium are sufficient to get a large spectral broadening with reasonable propagation lengths.

In the experiment presented in this paper the ultrashort pulse ionizes helium in a hollow core capillary causing rapid variation of the refractive index. This process results in a blue shifted spectral broadening associated to a quadratic spectral phase allowing pulse-compression by chirped mirrors located under vacuum as all the experiment.

2 Experimental setup

We used a conventional high-energy Ti:Sapphire chirped pulse amplification laser giving pulses of 75 mJ in 50 fs at a repetition rate of 10 Hz with a 30 mm diameter super Gaussian spatial beam profile. A 3 m focusing mirror is used to couple the beam in the fundamental mode [6] in a 420 μm internal diameter 40 cm long (4,5 Rayleigh length) capillary. This laser beam propagates in the capillary filled

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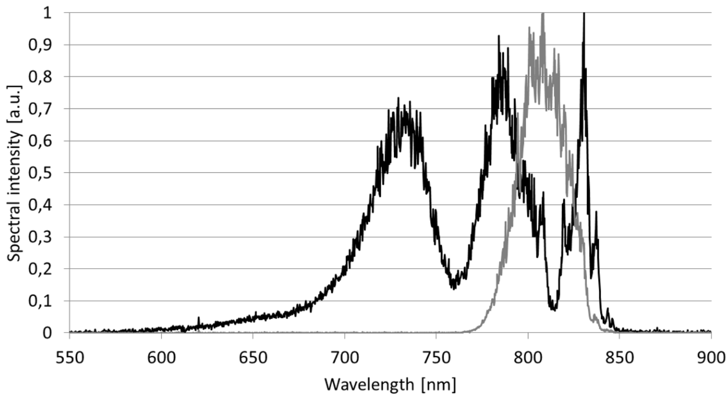

Fig. 1. Comparison of the normalized experimental spectra obtained by a beam blocker diffusion in vacuum without (clear gray) and with (black) the Helium gas in the capillary. The FWHM are 28 nm and 115 nm respectively. The latter spectrum was obtained with 74,4 mJ injected in the capillary containing 7 mbar of Helium inside.

with helium gas. After exiting the capillary the beam diverges and is collimated by a 5 m focal length mirror. 4 chirped mirrors (-50 fs^2 each) compensate spectral dispersion induced by propagation in the ionized Helium. A beam sampler reflects 10 % of the beam out of the vacuum chamber to get characterized by a single-shot autocorrelator. There are four chirped mirrors (-50 fs^2 each) in front of the autocorrelator to compensate dispersion of exit window (4 mm thick SiO_2 plate) and 2 meters of air (21 fs^2/m [7]). Note that, from input of the compressor to the end of the beam line in an interaction chamber designed for high harmonic generation the beam propagates under high vacuum and only reflective optics is used. This is critical to avoid unwanted nonlinear effects in material, and to avoid chromatic dispersion. These effects become very important for TW, 10 fs laser pulses.

3 Results

Significant spectral broadening of more than 100 nm FWHM and spectral blue-shift were obtained when increasing laser energy and pressure. For a fixed input pulse energy, the spectral width increases and the output pulse energy decreases with increasing pressure in the capillary. To obtain high energy in short output pulses one should use high input energy and relatively low pressure as recently investigated theoretically [8]. For example 115 nm of spectral bandwidth (Fig. 1) was obtained with 74,4 mJ and 7 mbar of Helium in the capillary. This supports pulse duration lower than 10 fs.

We performed a single shot autocorrelation (Fig. 3) to ensure that the broad spectrum can be recompressed below 10 fs. The results show that with proper chirp compensation it is possible to obtain pulses with a duration of 8 fs FWHM ($sech^2$ pulse assumed) and 8.7 mJ of energy that gives more than 1 TW of peak power which remains unusual at these pulse duration [9]. The stability of the technique was also tested by single shot measurements of shot-to-shot pulse duration during long time interval. Fluctuation smaller than 7 % RMS were observed as shown on Fig. 2.

Moreover, low gas pressure used here results in critical power higher than the pulse peak power and permits to conserve a good spatial profile for the output beam.

4 Conclusion and discussion

From a conventional CPA Ti:sapphire laser chain providing 75 mJ in 50 fs pulses, we demonstrate generation of 8 fs sup 1 TW peak power pulses. The pressure of 12 mbar of helium was optimal to generate sub 8 fs pulses keeping more than 8 mJ of energy. In this regime the shot-to-shot pulse length stability is less than 7 % RMS. The beam spatial profile was also very good. As an additional proof

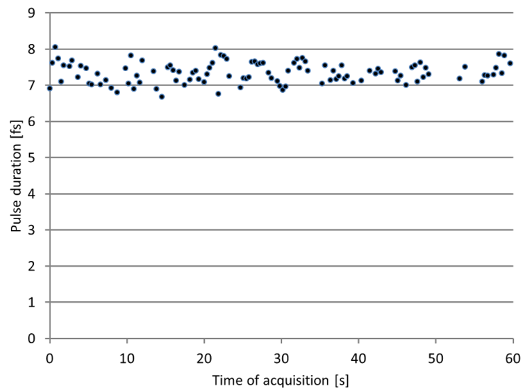

Fig. 2. Shot-to-shot pulse duration fluctuation

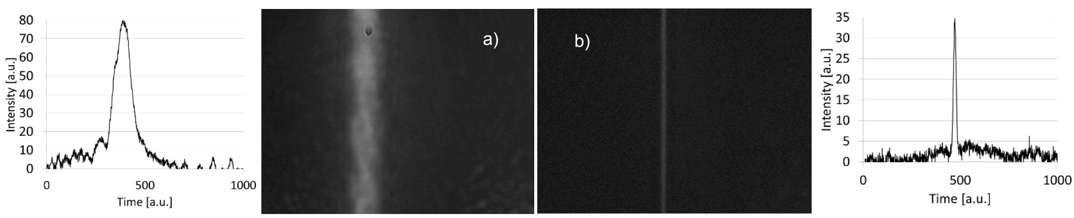

Fig. 3. Single-shot autocorrelation traces for a) 0 mbar of Helium, 28,6 mJ in 50 fs on the capillary exit, b) 10 mbar of Helium, 8.7 mJ in 8 fs at the capillary exit

of the laser beam quality, high order harmonics have been generated and large XUV spectrum has been observed in single shot acquisition. In conclusion our approach allows us to reach the terawatt peak power level in the 8 fs range under vacuum providing a stable and reliable laser source useful for applications. We observe its high suitability for high order harmonic generation obtaining XUV spectra not accessible with longer TW femtosecond pulses.

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