Pulse compression below 40fs at 1µm: the first step towards a short-pulse, high-energy beam line at LULI

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Abstract. We present the upgrading project ELFIE (Equipement Laser de Forte Intensité et Energie) based on the “100TW” mixed Nd:glass CPA laser system at 1µm at LULI, which includes an energy enhancement and the development of a short-pulse, high-energy, good temporal contrast beam line (50fs/5J). We report the first experimental step towards the short-pulse, high-energy beam line: spectral broadening above 60nm from 7nm and temporal pulse compression below 40fs from 300fs at 1µm through a Krypton-filled hollow fiber compressor.

1. ELFIE project
The goal of the ELFIE project is to upgrade the 100TW laser facility \cite{1} at LULI which consists of a Ti:sai and Nd:mixed-glass CPA laser system. In order to support different plasma experiments, this laser facility provides a main laser beam of 30J/300fs optically synchronized with a 60J/500ps uncompressed (chirped) beam, an auxiliary 10J/300fs beam and a 100 ml/few ps tuneable probe beam. High laser operation efficiency has been demonstrated since its commissioning in 1997, and the laser quality and performance have been improved constantly. With the dynamic wavefront control, the laser system can fire a full energy shot every 20 minutes while keeping excellent beam focusing ability on target.

The ELFIE project was initiated in order to increase the laser intensity available on target and to provide a more versatile laser tool for plasma physics research. Fig.1 shows a schematic of the ELFIE system design that mainly includes a boost in energy of the original mixed Nd:glass laser chain based on CPA technique, and the development of a new short-pulse, high-energy, good temporal contrast beam line based on OPCPA technique. The total amplified pulse energy delivered by the upgraded mixed Nd:glass laser system will be up to 200J, providing the synchronized pump source for the last OPCPA stage of the short-pulse beam line, a 50J/500ps laser beam for plasma creation and two 30J/300fs compressed laser beams. The high-energy short-pulse good contrast beam line aims at achieving 50fs laser pulses with the energy of 5J to be used as probe beam with a good temporal resolution in the plasma physics experiments. This versatile laser facility will enable the use of a variety of secondary sources of particles or radiation in order to study high-energy density matter (e.g. fusion or astrophysical plasmas) or fast evolving plasmas.
2. 50fs/5J beam line
The development of the short-pulse high-energy good temporal contrast beam line will consist of five stages, as highlighted by the orange parts in Fig.1:
1) An OPCPA pre-amplifier boosting the stretched nJ pulses up to several mJ at 10Hz without spectral narrowing, achieving 1mJ/100fs pulses after compression.
2) Spectral broadening from ~15nm to above 60nm by a noble gas-filled hollow fiber followed by temporal compression below 50fs using chirped mirrors, with an overall energy efficiency of ~50%.
3) Temporal contrast enhancement of the >0.4mJ/<50fs pulses by a nonlinear cross-polarized wave generation (XPWG) filter [2, 3] for 3~4 orders, with a typical throughput >20% for Gaussian input beams using a two-crystal arrangement. XPWG also has the advantage of broadening and smoothing the incident laser spectrum. We expect to seed the booster OPCPA stages with high temporal quality broadband pulses [4].
4) Boosting of the temporally filtered pulses from the µJ level up to 7J by two broadband high-energy OPCPA stages while preserving the 60nm spectral bandwidth.
5) Pulse compression using a new high-efficiency broadband grating compressor enabling the delivery of 50fs/5J pulses on target.
This beam line will provide new opportunities for high-field plasma physics research.

3. Spectral broadening and pulse compression through gas-filled hollow fiber technique

3.1. Pulse compression in hollow fibers
Because the laser source we plan to use is in 100fs level, spectral broadening is necessary in order to achieve pulse duration below 50fs. Nonlinear propagation through a noble gas-filled hollow fiber is a widely used technique to obtain efficient spectral broadening in the VIS-IR spectral range [5, 6]. Moreover, the confinement of the dielectric waveguide ensures spatially uniform broadening and an excellent output beam profile. However, as far as we know, few experiments have been carried out in nJ level in 1µm range till now. In order to demonstrate the affectivity of this technique in 1 µm region, we tested it on the front-end regenerative amplifier of the current LULI 100TW laser system. Here, we report the high spatial quality spectral broadening from 7nm to >60nm and temporal pulse compression down to 38fs by using a Krypton-filled hollow fiber compressor. This work is a key step in development of our 50fs/5J beam line.

3.2. Experimental setup
The laser source consists of a Ti:sapphire oscillator operating at 1057nm, an Offner-type stretcher and a Ti:sapphire regenerative amplifier working at 10Hz. The bandwidth of the seed pulses is decreased from
15nm to 7nm due to the spectral gain narrowing effect after ~100 roundtrips inside the regenerative amplifier. After amplification >1mJ pulses are sent to a temporary grating compressor yielding 0.7mJ/300fs compressed pulses. These pulses are then coupled into a hollow fiber (Femtolasers GmbH) by an f=80cm focusing lens. The hollow fiber is 1-m-long with an inner diameter of 250µm and rests inside a glass tube filled with Krypton. The experimental setup is shown in Fig.2. The dispersion of the output pulses from the hollow fiber is then carefully compensated using six commercial broadband chirped mirrors with -50fs²/bounce (Layertech) and a pair of fused silica wedges to get the shortest compressed pulses. The compressed pulses are finally characterized by a fiber spectrometer (Ocean Optics), a CCD camera, a home-made autocorrelator, and an energy meter.

Fig.2 Krypton-filled hollow fiber pulse post-compressor setup.

3.3. Experimental results and analysis

In the experiment, we gradually increase the Krypton pressure while monitoring the measured output. Spectra at different gas pressures are shown in Fig.3a. We observe the characteristic spectral broadening due to self-phase modulation (SPM) because of the higher nonlinear refractive index of the gas. The spectral clipping at the gas pressures of 3bar and 3.5bar comes from the bandwidth limitation of the spectrometer. Comprehensive numerical simulations of nonlinear pulse propagation inside the fiber have also been done, in which a Gaussian pulse was assumed and all the pulse, hollow fiber and gas parameters were set according to the experimental condition. The 2D+1 simulation code is based on the nonlinear envelope equation (NEE) and typical nonlinear effects such as Kerr effect, self-steepening and gas ionization were considered. Fig.3b shows a calculated spectral profile and spectral phase of the output pulses from the fibre at a Krypton pressure of 3.5bar. Except the fast modulations observed around the central wavelength, the simulation shows qualitative agreement with the experimental measurement on the spectral broadening. The simulation results confirm that SPM is the dominant broadening process in our experimental conditions. In Fig.3b, the deep spectral modulations and the ripple shape of the spectral phase both stem from typical SPM effects. This ripple-shape spectral phase includes high-order phase terms which are difficult to compensate simply by using chirped mirrors. However, the frequency chirp is relatively linear across the whole bandwidth, ensuring efficient pulse compression. At a Krypton pressure of ~3.5bar, the pulse duration can be compressed below 40fs after fine compensation of spectral chirp. A typical measured autocorrelation trace of the compressed pulses is shown in Fig.4b, corresponding to a pulse duration of 38fs (FWHM). For comparison, the measured autocorrelation trace of the input laser pulses is also shown in Fig.4a. Thanks to the mode confinement of the hollow fiber, the generated 38fs laser beam has an excellent spatial profile, which is measured by a CCD camera in the experiment, as shown by the colourful insert figure in Fig.4b. In addition, the energy stability of the compressed pulses has been preserved quite well, only slightly decreased from ~3% to ~5% due to the nonlinear propagation in the hollow fiber.
Fig. 3 (a) Experimental spectrum evolution of the output pulses from the hollow fiber at different Krypton pressures. (b) Simulated spectral profile and phase of the output pulses from the hollow fiber at the gas pressure of 3.5bar, in which the input pulses are assumed as 0.7mJ/300fs.

Fig. 4 Measured autocorrelation trace of the compressed 38fs pulses (b), compared with that of the 300fs input laser pulses (a). The insert shows the measured spatial profile of the compressed laser beam.

4. Conclusion and prospects
In conclusion, we demonstrate pulse compression by a factor of 7.5 at 1 µm wavelength with an overall energy efficiency close to 60% using a Krypton-filled hollow fiber compressor. The mode confinement of the waveguide ensures spatially uniform broadening and an excellent output beam profile. These pulses can then be efficiently temporally filtered by using XPWG technique before seeding the high-energy OPCPA stages. This work is currently underway as a significant step towards completion of 50fs/5J beam line for ELFIE project.

Since the residual phase of the laser pulses affects a lot the XPWG energy efficiency as well as the pulse spectral profile, fine dispersion compensation is one of the important issues for the following XPW stage in the development of 50fs/5J beam line. Broader and less modulated spectrum can be expected by seeding the hollow fiber with shorter input pulses with higher energy, which is feasible under the broadband OPCPA front-end configuration.

References
[1] J. P. Zou et al., 3rd IFSA, 7-12 June 1998, Monterey, CA, USA, SPIE 3492, 94 (1998).
[2] A. Jullien et al., Opt. Lett. 30, 920 (2005).
[3] A. Cotel et al., Applied Phys. B 83, 7 (2006).
[4] V. Chvykov et al., Opt. Lett. 31, 1456 (2006).
[5] M. Nisoli et al., Appl. Phys. Lett. 68, 2793 (1996).
[6] X. Chen et al., Opt. Lett. 34, 1588 (2009).