

# SIMLI Programme: Scientific report

Compression of ultrashort laser pulses at the 100 mJ energy level to the few-optical-cycle regime using planar hollow waveguides

## Purpose of the visit

In this project we propose the temporal compression of very energetic ultrashort laser pulses via nonlinear propagation in gas-filled planar hollow waveguides (PWGs). Such pulses with duration of few- to single-optical cycles are indispensable tools to advance many applications in nonlinear optics, attosecond science [Krausz and Ivanov, *Rev. Mod. Phys.*, **81**:163 (2009)], and high-field physics [Esaraya *et al.*, *Rev. Mod. Phys.*, **81**:1229 (2009)], such as generation of high-order harmonic radiation [L'Huillier *et al.*, *J. Nonlinear Opt. Phys.*, **4**:647 (1995)] and single attosecond pulses [Goulielmakis *et al.*, *Science* **320**:1614 (2008)], as well as acceleration of particles [Schmid *et al.*, *Phys. Rev. Lett.*, **102**:124801 (2009)]. All of these applications are within the scientific scope of the two partners Laboratoire d'Optique Appliquée (LOA) and Lund Laser Centre (LLC) and also of particular importance for the SIMLI Programme.

The technique of applying PWGs for temporal compression of very energetic laser pulses was recently essentially advanced at LOA by the applicants, one of which is now located in Lund. Compression of pulses exceeding 10 mJ energy was demonstrated [OL **34**:1462 (2009)] and the scalability to much higher energy was discussed in several articles [Arnold *et al.*, *OE* **17**:11122 (2009), *NJP* **12**:073015 (2010)]. Currently there is no other pulse compression method with such a promising scaling to higher energy.

The present project focuses on adapting the technique to the 100 mJ energy level and on transferring the technology from the research level to an actual implementation in the Lund high-order harmonic beam line, dedicated to high energy attosecond science. The technique developed in this joint experimental campaign can potentially become a key technology for LOA and LLC. The project will also shine light on the potential of applying PWGs to energy levels exceeding 100 mJ. The technique is potentially interesting for all partners in the programme with TW level lasers to easily and conveniently reach down to the few-cycle regime.

## Description of the work carried out during the visit

The PWG compression setup was installed on the terawatt laser facility of Lund delivering 45fs pulses, with a maximal energy of 100 mJ, a central wavelength at 800 nm at a repetition rate of 10 Hz. The energy of the laser can be varied continuously with an attenuator placed before the compression and the chirp of the pulse can be adjusted to maximize intensity at the waveguide input by detuning the compressor. The experimental setup is described in figure 1. The waveguide dimension is 500\*40\*15 mm with a spacing of 128  $\mu$ m between the two glass plates. The waveguide spacing is chosen to match the beam size at the focus of the 2 m cylindrical focusing mirror. It is placed inside a long PET gas cell with anti-reflexion glass windows at both ends. The length of the gas cell was adjusted to minimize the laser fluence on the windows.

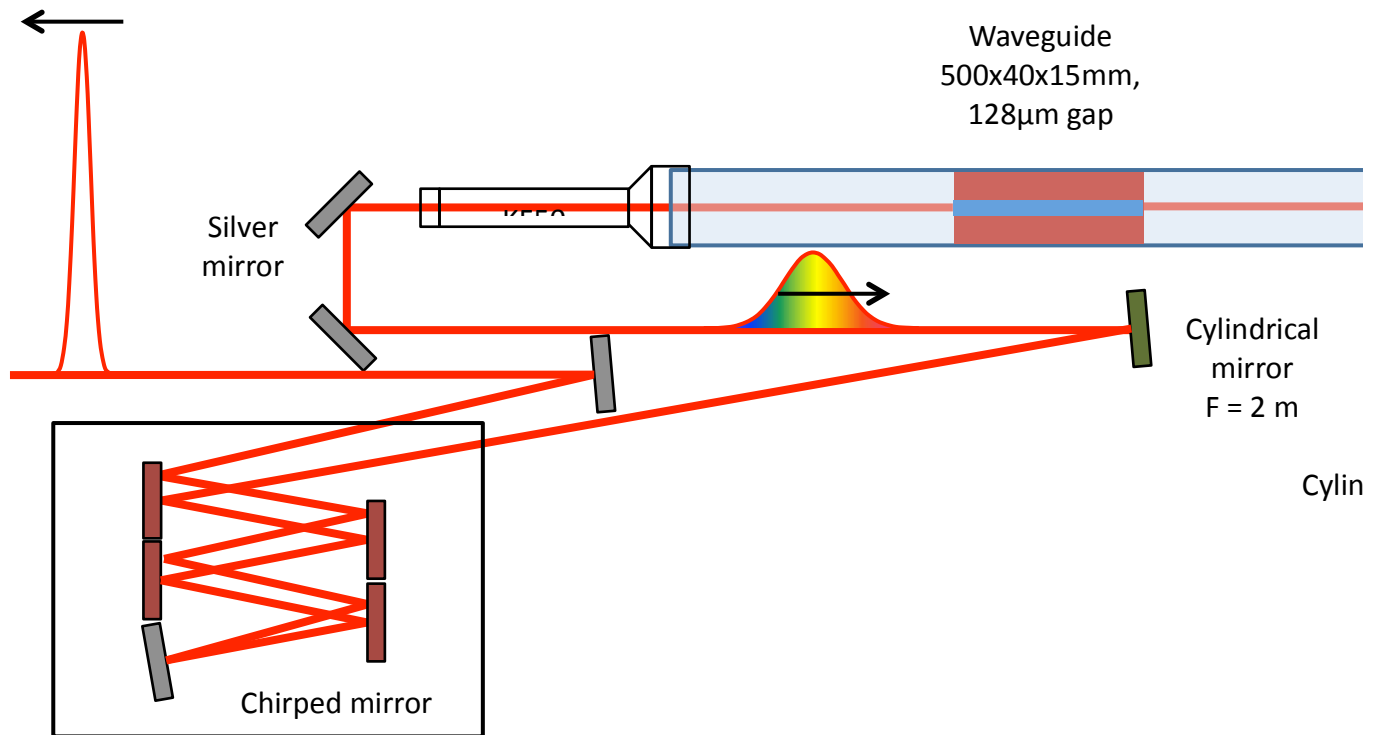


Figure 1: Experimental setup.

The compression was tested in Argon and Neon but most results were obtained with Argon, since only a small quantity of Neon was available during the campaign.

### Description of the main results obtained

We first measured the energy coupling efficiency in the waveguide as a function of the gas pressure in the cell. An efficiency  $> 80\%$  was found up to an input energy of 100 mJ.

We then measured the beam profile and the spectral broadening at the output of the gas cell (after the collimating mirror) for different input energies and gas pressures, using a CCD camera. The output beam profile in the case of vacuum is shown in figure 2 for an input energy of 50 mJ. When the pressure is increased the beam quality is progressively degraded while the spectrum width is increased. We determined that in Argon and for an input energy of 50 mJ the spectrum broadening is maximal for 400 mbar. At this pressure the beam profile presents some modulations in the transverse direction but is still sufficiently good (see figures below). At higher pressure Filamentation starts to appear in the waveguide, degrading significantly the mode quality.

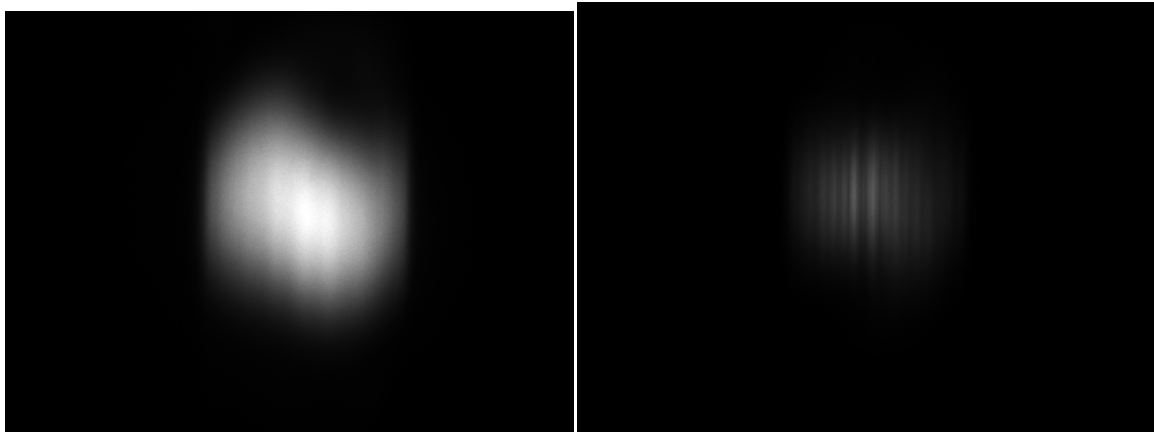


Figure 2: Beam profile at the output of the cell containing the waveguides. Left: vacuum 50 mJ, Right: 400 mbar 50 mJ.

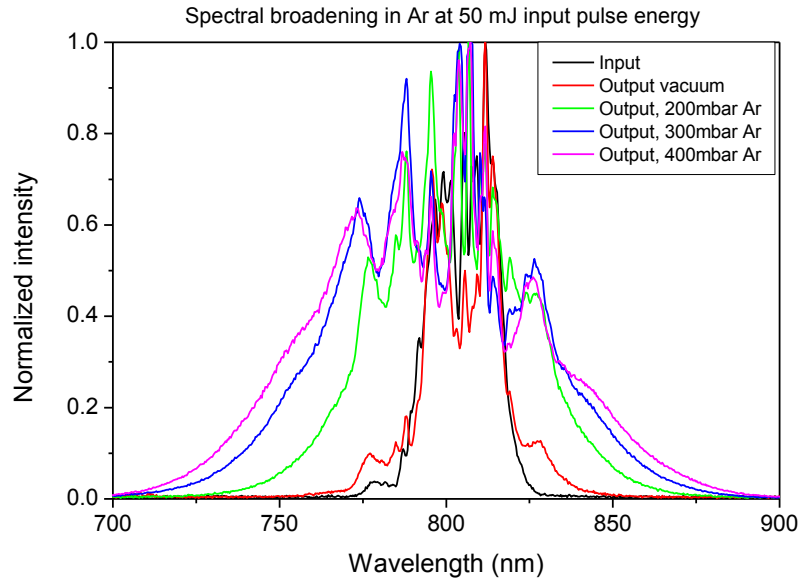


Figure 3: Input laser spectrum (black curve) and output laser spectrum for different Ar gas pressure in the cell. The input pulse has energy of 50 mJ and duration of  $\sim 45$  fs.

We then measured the beam focusability after the cell. One can see in Figure 4 that the focusability does not change significantly as we increase the Ar pressure. With increasing Ar pressure, i.e. increasing nonlinearity in the waveguide, the beam develops an astigmatism. This is due to 1-dimensional self-focusing in the waveguide and can easily be corrected by the position of the collimating cylindrical mirror.

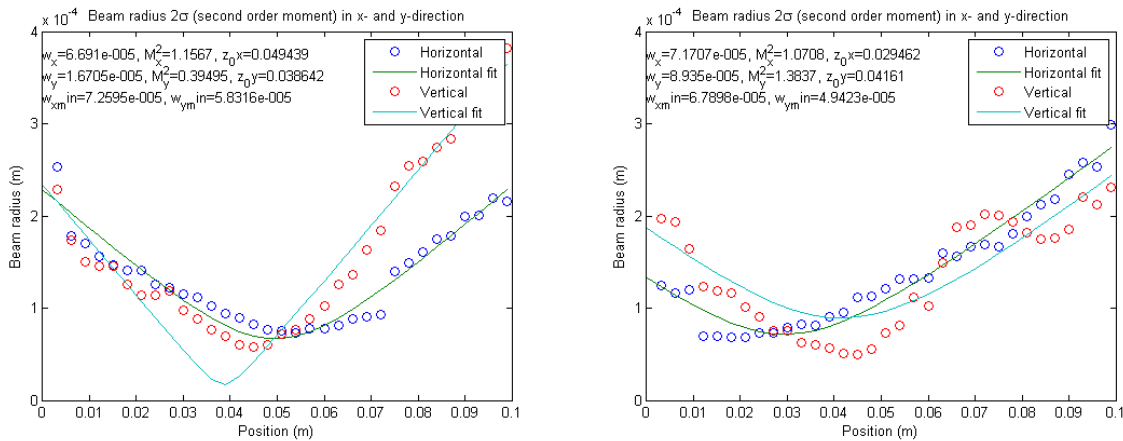


Figure 4: Measurement of the beam M2 for the case of vacuum (left) and for 400 mbar (right). The input pulse has energy of 50 mJ and duration of  $\sim 45$  fs.

Finally the compression was achieved by means of chirped mirrors placed after the collimating mirror. The number of bounces on the chirped mirror was adjusted to obtain the shortest pulse and a commercial Spider was used to measure the pulse duration. With 400 mbar Argon and input energy of 50 to 100 mJ we achieved to compress the pulse down to 15-17fs in Argon. Note that the output

energy after the chirped mirrors was reduced by 20% due to the size of the mirrors and to their reflectivity. These losses could be significantly reduced using larger chirped mirrors with a better coating.

As a conclusion the experiments were very successful. We demonstrated a coupling into the PWG with efficiency up to 80% for input pulse energy of 50 to 100 mJ. Input pulses with 45 fs duration could be compressed down to 15 fs using 400 mbar of Argon. The global efficiency of the PWG compression setup (including the chirp mirror) was found to be higher than 30 % and could reach 60 or 70 % with better dispersive mirrors.

**Future collaboration with host institution (if applicable)**

A second experimental campaign in Lund is scheduled for May 2013. This campaign will be focused on the characterization of the harmonics generated by the compressed pulse.

**Projected publications/articles resulting or to result from your grant**

An article will be written on these results demonstrating the scalability of the PWG compression at the 50-100 mJ level.

**Other comments**