Ten-femtosecond laser pulse compression apparatus for Astra target areas

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Introduction

Academic research is conducted in Target Areas 1 and 2 (TA1 and TA2) of the Astra Laser especially in the field of ultrafast phenomena and ultra-intense laser-matter interactions. Astra provides ultrafast, 35fs, laser pulses for science with ultra-high intensity laser pulses. However, there is a need for probe pulses with much shorter pulse durations in the region of 10fs and below. Such probe-pulses are essential for scientific investigations in atomic and molecular physics and materials and surface science (TA1) as well as in relativistic plasmas (TA2). Ten-femtosecond laser pulses can be provided by using a simple add-on device to the main 30-40 fs laser[1, 2]. Such a ten-femtosecond laser pulse-compressor has recently been commissioned in Astra TA1.

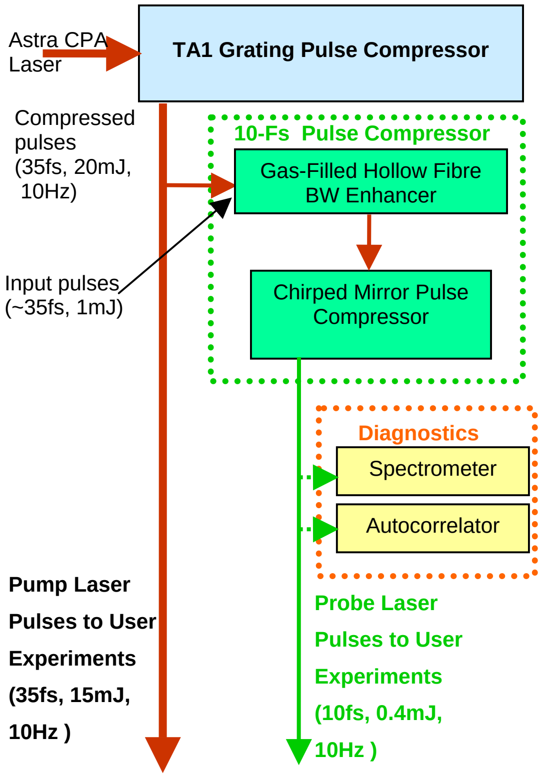


Figure 1. Schematic of the laser pulses available for user experiments in Astra TA1: 35fs laser-pump pulse and 10fs laser-probe pulse.

TA1 layout for pump and probe experiments

Figure 1 shows a diagram of the new configuration of laser beams available for user experiments in Astra TA1: 10fs probe-beam and 35fs pump-beam. Figure 2 shows an image of the new system. The Astra CPA laser pulse is compressed in the TA1 grating compressor. The 35fs, 20mJ, pulse from the grating compressor is split in two by a mirror with a 9mm central hole: up to 5 mJ passes through the mirror hole of which 1mJ can be used for further compression to yield the 10fs laser-probe pulse while the remaining 15mJ is reflected to produce the 35fs laser-pump pulse.

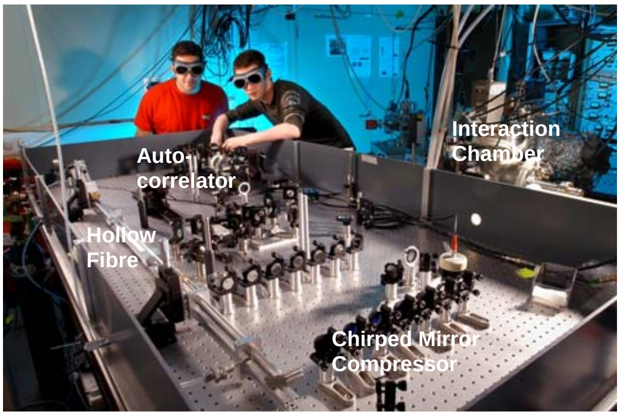


Figure 2. Image of the ten-femtosecond hollow-fibre pulse compressor in Astra TA1. An interaction chamber can be seen to the right of the compressor box.

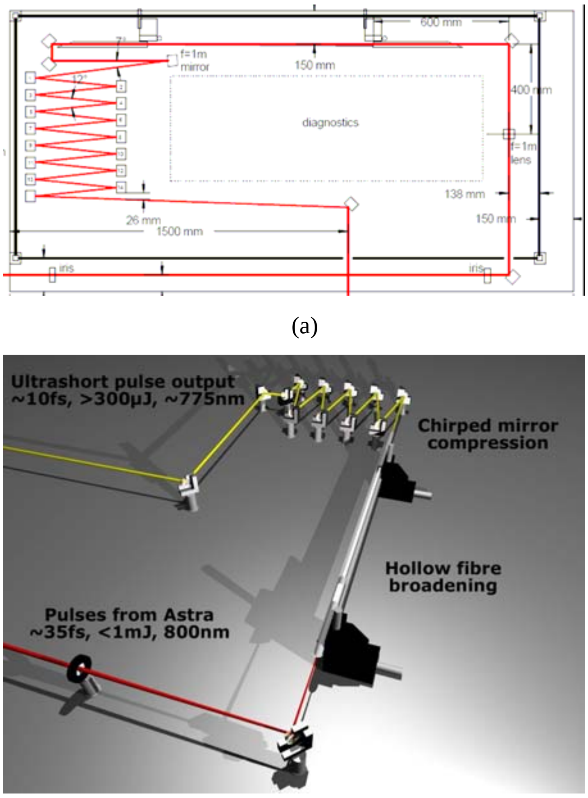
The ten-femtosecond laser pulse compressor consists of two main components: a gas filled hollow-fibre for bandwidth enhancement and a pulse-compressor with chirped mirrors. Only 1mJ, 35fs is focused in the hollow fibre. The 10fs, 0.4mJ output pulse of the compressor provides the laser-probe pulse for experiments.

The system has on-line diagnostics: an all reflective autocorrelator with a 20μm thick BBO SHG crystal, spectrometer and pulse energy meter.

The ten-femtosecond laser pulse compression apparatus was successfully installed and commissioned in TA1 in March 2005. Immediately after installation, the new system was used in scheduled experiments in atomic and molecular physics by the UCL/QUB collaboration.

Ten-femtosecond system description

The ten-femtosecond compressor requires a 35fs, 1mJ/pulse, 800nm, transform and diffraction limited pump beam. In order to meet these requirements, a central 9mm diameter was selected from the 22mm diameter of the Astra beam in TA1, as described in the previous section. This beam was measured to be near-diffraction limited in the far-field of a 5m focal length lens. This beam is expanded to 15mm diameter before being focused into the fibre by the 1m lens. The TA1 pulses were also measured to be near-transform limited. The pulse duration was measured to be 35fs by means of the TA1 all-reflective autocorrelator with a 100µm BBO SHG crystal. The spectral bandwidth (BW) was measured to be >30nm (Figure 4 a) with a dedicated on-line spectrometer.



(a)

(b)

Figure 3. Schematic of the hollow-fibre laser pulse compressor in Astra TA1. (a) Laser beam path and 2-D system layout on the optical bench (b) Detail showing novel glass hollow fibre support and chirped mirror compressor.

Figure 3 shows a 2-D schematic (Figure 3a) and a 3-D detail (Figure 3b) of the hollow-fibre laser pulse compressor installed in TA1. The 35fs laser beam (red) is aligned through the two irises at the bottom of the diagram. The beam is focused into the hollow-fibre by the f=1m lens on the right of the diagram. The hollow fibre is at the top of the diagram between the two x-z translation stages.

The spectrally broadened pulse emerging from the fibre is re-collimated by the f=1m mirror and then temporally re-compressed by the two rows of chirped mirrors on the right of the diagram. The compressed beam is then reflected out of the system enclosure towards the user experiment. The last turning mirror is a flip-mirror which when lowered allows the beam to propagate to the autocorrelator placed in the diagnostic area.

Pulse spectral broadening is achieved by self-phase modulation through propagation along the hollow-core fused silica waveguide filled with noble gas[1)].

The amount of broadening achieved in the fibre, Δω, obeys the following relationship:

$$\Delta\omega \propto Ep\eta_2/\tau^2$$

where E~1mJ and τ~35fs are the energy and duration of the input pulse, respectively, η_2 is the nonlinear refractive index (n_2/bar) and p is the gas pressure. When filled with 0.2Bar of Argon gas, the fibre provides >100nm spectral broadening as shown in Figure 4b.

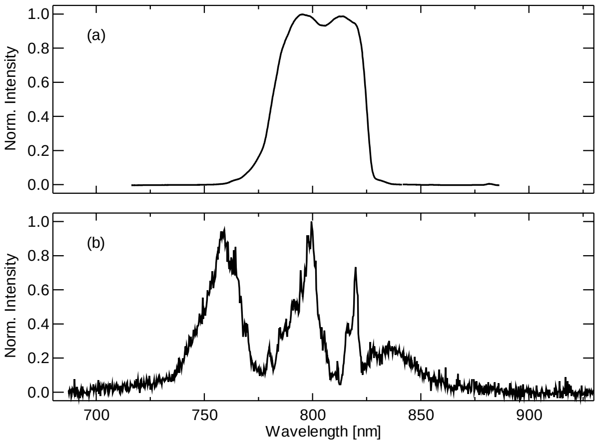


Figure 4. Typical spectrum measurement of the: (a) 35fs pump laser with a bandwidth of >30nm and (b) 10fs laser pulse with a bandwidth of >100nm. The pulse is generated by the hollow fibre compressor. The fibre is filled with Argon gas at 0.22Bar absolute pressure. The two spectra are obtained with two dedicated spectrometers.

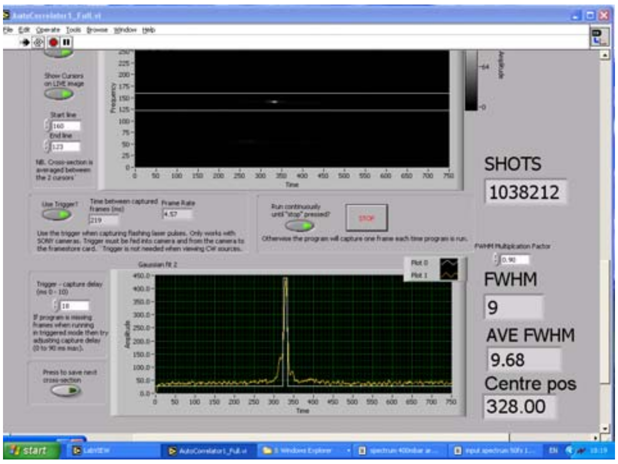
Wave propagation along hollow waveguides can be thought as occurring through grazing incidence reflections at the dielectric inner surface. Since the losses caused by these multiple reflections greatly discriminate against higher order modes, only the fundamental mode can propagate in sufficiently long channels. For fused silica hollow fibres the lowest loss mode is the EH_{11} hybrid mode. Our fibre is 1m long and has 250µm inner channel diameter. Optimal coupling into the fundamental mode is achieved when the laser is focused into the fibre input to a focal diameter equal to 0.65 times the inner channel diameter. In our case this corresponds to a focal spot of 160µm. Additional features of the hollow fibre system are: differential pumping of the input end of the fibre to avoid gas breakdown and provide shot-to-shot pulse stability; x-z translation stages at both ends of the fibre providing improved fibre alignment capability; CCD camera imaging of the focal spot at the input of the fibre also facilitating user-friendly fibre alignment.

The bandwidth-enhanced laser pulse emerging from the hollow fibre is compressed by a system of chirped mirrors (Figures 2 and 3). Each chirped mirror imposes a ~45fs^2 group delay dispersion (GDD). Thus one bounce compensates for approximately 1mm of fused silica or 1m of air path. Seven chirped mirrors are needed to compress the pulse. An additional three chirped mirrors are needed in order to compensate for the 3mm thick fused silica input window of the UHV interaction chambers. Therefore the compressor has a total of ten chirped mirrors.

Ten-femtosecond system performance

The pulse duration after the 10fs pulse compressor is measured with the TA1 all reflective autocorrelator with a 20µm thick BBO crystal. A 3mm fused-silica window, identical to the one used on the UHV interaction chambers, is placed in front of the autocorrelator. This ensures that the autocorrelator measures the correct pulse duration inside the interaction chamber. Immediately after installation, the pulse duration was ~12-15fs. After further optimization of the input laser beam focusing into the fibre, the compressor provides 9-11fs pulse duration with and energy of ~0.4mJ/pulse and ~40% transmission efficiency.

Figure 5 shows a typical Lab-View screenshot of the autocorrelator display monitor in Astra TA1 during the May –June 2005 experiments. The temporal FWHM of the pulse is calculated from the measured temporal calibration of the autocorrelator and assuming a Gaussian pulse-shape. A reduction of 7% in pulse duration would result if we assumed a Sech^2 shape.



Start line 160

End line 123

NB. Cross-section is averaged between the 2 cursors

Time between captured frames (ms) 219

Frame Rate 4.57

Use the trigger when capturing flashing laser pulses. Only works with SONY cameras. Trigger must be fed into camera and from the camera to the framestore card. Trigger is not needed when viewing CW sources.

Otherwise the program will capture one frame each time program is run.

Trigger - capture delay (ms 0 - 100) 18

If program is missing frames when running in triggered mode then try adjusting capture delay (0 to 90 ms max).

FWHM Multiplication Factor 0.90

SHOTS 1038212

FWHM 9

AVE FWHM 9.68

Centre pos 328.00

Figure 5. Lab-view screenshot of the autocorrelator display monitor showing a typical pulse measurement in Astra TA1 during the May –June 2005 experimental session. Top: CCD camera autocorrelation trace; bottom: densitometry of the trace; bottom-right: 9fs FWHM current pulse duration and 9.68fs AVE FWHM multi-shot average of the pulse duration, in femtoseconds. The de-convolution assumes a Gaussian pulse shape.

The laser beam diameter is ~7mm. The beam is diffraction limited. There is good shot-to-shot reproducibility. The system appears to have good long term stability over hours of operation, although we recommend checking the pulse duration every 20 minutes by engaging the flip-mirror to the on-line autocorrelator.

The hollow fibre compression system was also tested by the Imperial College Attosecond Group before installation in TA1. Figure 6 shows a typical 11.3 fs pulse measured by the SHG-FROG. Argon gas pressure was 0.5 Bar, optimized for that particular input laser pulse.

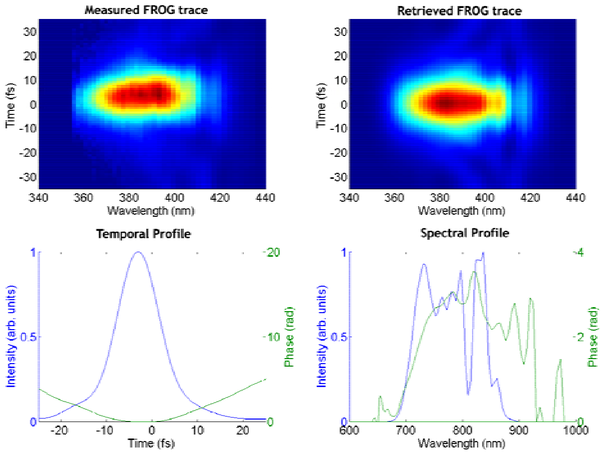


Figure 6. Typical 11.3 fs pulse measured by SHG-FROG before the installation of the hollow fibre compressor in Astra TA1. Measurement performed at the Imperial College Attosecond Group who supplied the system. Argon gas pressure was 0.5 Bar.

Future directions

A number of experiments, especially in atomic and molecular physics and material and surface science require large number of laser-pulses for scanning and statistical analysis. We have the opportunity of upgrading the 10-fs compressor from 10Hz to 1kHz operation. This is made possible by the installation of the new Astra front-end laser during the autumn of 2005. The new front-end incorporates a "Compact-Pro" amplifier[3)] manufactured by Femtolasers. The shorter, 30fs, pulses from this new laser will also allow compression to sub-10fs, few-cycle laser pulses by using the existing fibre compressor. The stabilisation of the carrier envelope phase (CEP) becomes essential when using few cycle laser pulses for research into light-matter interaction. The new Astra front-end laser can be upgraded to provide CEP stabilisation[3)]. The existing hollow fibre compressor, together with the new Astra front end could therefore provide in the near future: CEP stabilized few cycle (~7fs) pulses, 0.2mJ energy and 1 kHz repetition rate, for user experiments.

Other experiments require 10fs pulses with larger pulse energy but at relatively low, 10Hz repetition rate. Such higher energy pulses are now becoming possible. A recent paper[2)] has demonstrated 10fs pulses with 5mJ pulse energy, obtained with a hollow fibre compressor pumped by 8mJ pulses. The implementation of such a system in TA1 would require further development of the present hollow fibre compressor. The system could provide laser pulses with 5mJ energy, 10fs pulse duration and 10Hz repetition rate.

We plan to install an additional hollow-fibre compressor dedicated to Astra Target Area 2. It will provide 10fs probe pulses for laser-driven relativistic plasmas. We will use the know-how acquired in developing the TA1 10fs compressor to make this possible.

References

1. M Nisoli, S De Silvestri, O Svelto,
Appl. Phys. Lett. 68 2793, (1996)

2. A Suda, M Hatayama, K Nagasaka, K Midorikawa,
Appl. Phys. Lett. 86 111116, (2005)

3. The "Femtopower-Compact-Pro" laser amplifier is
described on the web-page:
http://www.femtolasers.com/