TEMPORAL ANALYSIS AND SHAPE CONTROL OF UV HIGH ENERGY LASER PULSES FOR PHOTOINJECTORS*

D. Garzella†, O. Gobert, Ph. Hollander, F. Lepetit, M. Perdrix
Commissariat à l´Energie Atomique (CEA-France)
T. Oksenhendler
FASTLITE, Ecole Polytechnique, Palaiseau (France).

Abstract

This work shows a survey of the studies conceived for obtaining Ultraviolet, high energy laser pulses, totally controlled and characterized in shape, on the kHz, Chirped Pulse Amplification (CPA)-based Ti:Sa laser system PLFA at CEA-Saclay. The pulse shaping deals with the amplitude and phase control of the stretched laser pulses issued from an amplifier before entering the compressor and the tripling unit. The work presents the theoretical background and the proposed experimental setup, before showing the preliminary promising results.

INTRODUCTION

In order to generate high power, subpicosecond XUV radiation by following the classical Self Amplified Spontaneous Emission (SASE) scheme [1, 2] and/or seeded FELs [3, 4, 5, 6, 7], tight specifications on the electron bunch are required, noteworthy in terms of highly reduced emittance, both for achieving very short wavelength or high average power, thus high duty cycle continuous electron beams (repetition rates ≥ 1 kHz). Even though emittance compensation schemes [8] are used, or ”RF-focusing” ones [9] for superconducting RF photo-injectors, for obtaining high brightness electron bunches, the laser pulses impinging onto the photocathode must meet special requirements not only in terms of wavelength and delivered energy per pulse. High repetition rate systems like the one retained for photo-injector operation at Arc-en-Ciel [10] will have to fulfil the following requirements:

- Up to 50 μJ pulse energy in the UV (following the cathode material work function, between 240 and 300 nm), for a 1 nC electron bunch production on a photocathode with $\rho \approx 0.1 - 1\%$ quantum efficiency (QE) (as in the case of the most commonly used semiconductor Cs_2Te). This calls, before a very highly efficient third harmonic generation, for laser amplifiers delivering at least 1 mJ in the IR (800 nm), and, for high repetition rates, on Chirped Pulse Amplified (CPA), Ti:Sa based systems.

- A final duration in the UV, before the cathode, between 5 and 20 ps [10].

- A precise measurement and control of longitudinal and transverse features (dimensions and shape) in order to prevent non-linear contribution to the emittance increase.

Indeed, it has been shown [11, 12] that in order to minimize the bunch emittance at the issue of the electron gun, temporally and spatially shaped UV pulses are needed to prevent non linear space charge forces and then minimize the electron emittance. Shaping techniques for ultrashort laser pulses (in the sub-ps range) are well known. In transverse space an homogeneous energy distribution with a circular symmetry is needed. This can be obtained by use of mask filters or deformable mirrors and lenses. In longitudinal space, shaping techniques are mostly based on the utilisation of spatial masks, in some cases by using programmable liquid crystals structures at the fourier plane of a $4f$ zero-dispersion line [13], or by using an Acousto-Optic Programmable Dispersive Filter (AOPDF), or DAZZLER [14]. Both techniques have been already used in the framework of accelerator and FEL studies [15, 16]. In the EUROFEL program framework, our goal is to obtain a few picosecond, 100 μJ laser pulses in the UV (266 nm) with a totally controlled and characterized longitudinal and transversal shape. This work presents the experimental setup and the main diagnostics designed to obtain every desired pulse shape from the ”beer can” profile (corresponding to a cylindrical bunch in the 3D-space) to a parabolic one (”waterbag” bunch distribution) starting from the IR ultrashort pulse issued by the kHz, Chirped Pulse Amplification (CPA)-based Ti:Sa laser system PLFA (French acronym for Tunable Laser Femtosecond Platform) [17] at CEA-Saclay. The pulse manipulation is based on the amplitude and phase control of the stretched laser pulses issued from the amplifier, which is performed by the DAZZLER before entering the compressor and the tripling unit.

FEMTOSECOND LASER PULSES

Direct temporal manipulation of an ultrashort laser pulse is rather complicated. Thanks to Fourier Analysis, every temporal feature of a laser pulse has its corresponding one in the frequency domain. Thus, an ultrashort pulse in time space exhibits a very broadband spectrum (several tens of nm). The electric field $\widetilde{E}(\omega,\phi)$ can be described in terms of the spectral components of amplitude $E_0(\omega)$ and phase $\phi(\omega)$:

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† david.garzella@cea.fr

$$\widetilde{E}(\omega,\phi) = E_0(\omega)\cdot e^{i(\omega_0 t+\phi(\omega))} \tag{1}$$

$$\phi(\omega) = \phi_0 + (\omega-\omega_0)\cdot\left.\frac{\delta\phi}{\delta\omega}\right|_{\omega_0} + \frac{(\omega-\omega_0)^2}{2}\cdot\left.\frac{\delta^2\phi}{\delta\omega^2}\right|_{\omega_0} \dots + \frac{(\omega-\omega_0)^n}{n!}\cdot\left.\frac{\delta^n\phi}{\delta\omega^n}\right|_{\omega_0} \tag{2}$$

In the polynomial approximation of the phase term (eq. 2), the constant and the first order term coefficient, called respectively the ”absolute” phase and the group delay, are not crucial for the propagation of the pulse, as they account respectively for the position of the peak amplitude of the field in the phase and the delay undertaken by the central frequency component $E_0(\omega_0)$ propagating between two reference planes [18]. The second-order term coefficient becomes extremely interesting for pulse manipulation as it accounts, for example, for the different response of the frequency components to the propagation of the pulse in a ”dispersive” medium. Thus, an original transform-limited laser pulse will be stretched by a factor $\propto \left.\frac{\delta^2\phi}{\delta\omega^2}\right|_{\omega_0}$. Higher order terms account for symetric and antisymetric distortion terms of the pulse shape.

EXPERIMENT

Pulse Shaping Technique

The principle of the AOPDF [14] is based on the coupling between the laser pulse and an acoustic wave in a birefringent crystal. For IR laser pulses, around $800\ n$m, a TeO_2 crystal is cut in such a way that the acoustic wave energy and the optical waves energy travel along the same axis. The incident optical pulse polarized on the ordinary axis is diffracted by the Bragg grating made by the acoustic wave onto the extraordinary axis. Shaping the pulse is equivalent to programmming the associated suite of acoustic grating, so that the spectral amplitude and phase of the laser pulse is directly linked to the acoustic wave ones.

Target, Filter and Correction Loop

Defining a ”target” pulse here means defining ”target” spectral amplitude and phase. As the DAZZLER is a linear filter, the output optical pulse is the product of the input pulse by the filter response in the spectral domain:

$$\widetilde{E}_{out}(\omega,\phi) = \widetilde{E}_{in}(\omega,\phi)\cdot\widetilde{S}(\omega,\phi) \tag{3}$$

where $\widetilde{S}(\omega,\phi)$ is the filter response.

Therefore, knowing the input pulse, the target pulse is directly obtained by fitting the filter response (see fig. 1). The spectral amplitude and phase shapings can be separated as they are independently measured and controlled.

In practice, amplitude loop preceeds phase loop because of bandwidth limitation. The complete procedure can be described as the following steps:

1. The user builds the target amplitude and phase terms.
2. Amplitude loop:
    - Initial filter amplitude.
    - spectrum measurement.
    - Modification of the filter by dividing the ”target” amplitude by the measured amplitude.
    - spectrum measurement ... loop until the measurement fits the ”target”.
3. Phase Loop: Analog process is made on the ”target” phase.
4. Experimental amplitude and phase are acquired and an initial check in the time domain is made by IFT on the experimental data, thus retrieving the temporal duration and shape (fig. 2).

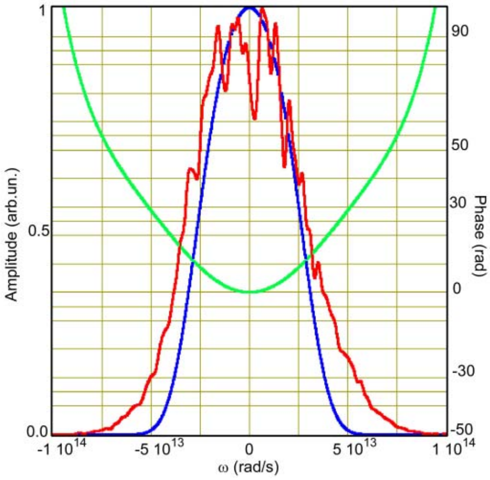

Figure 1: Blue curve : computed target spectral intensity; Red curve: experimental spectral intensity; Green curve: target spectral phase.

Spectral Interferometry

The crucial point in the laser pulse analysis is the retrieval of the spectral phase. Indeed, the spectrum intensity acquisition is not enough to characterise a non Fourier-limited pulse (i.e when its phase is not flat over all the spectral range). In our experiment, we want to measure the spectral phase on a single shot, simple, sensitive and extendable to UV range measurement. Spectral interferometry [21] between a reference pulse and the unknown pulse gives directly, through Fourier transform, access to the phase difference between these two pulses (cf. fig. 3). In our case, the reference pulse is the input pulse and the measurement confirms only the phase shaping. For complete phase shaping, the phase of the reference pulse is needed. As the reference pulse is close to Fourier transform pulse, any self-referenced measurement (SPIDER [19],

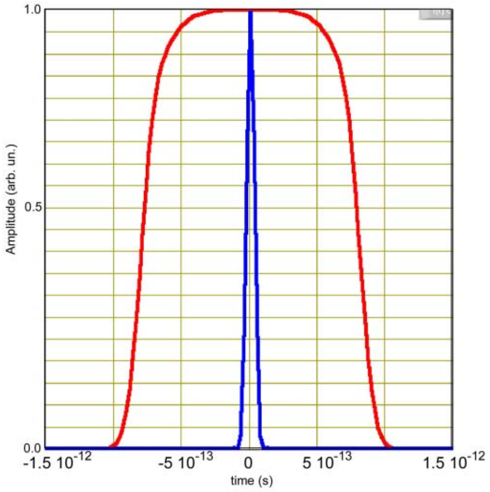

Figure 2: Blue curve : Fourier Limited laser pulse taking into account only the target spectral amplitude; Red curve: target temporal shape taking into account the target spectral phase.

FROG [20]...) is able to measure the residual phase of this pulse. This phase is then added to the measured one by spectral interferometry.

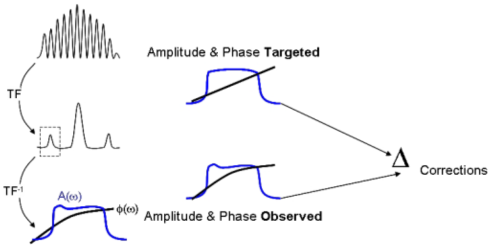

Figure 3: Layout of the Interferogram retrieving protocol.

Experimental Setup

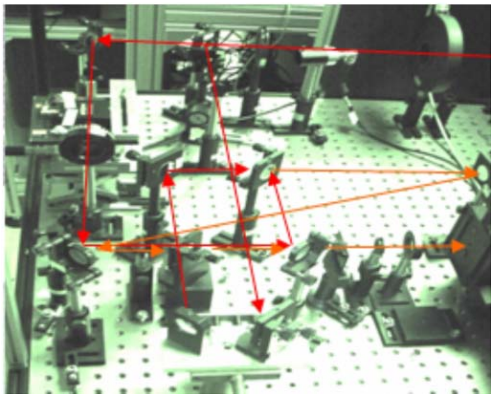

Figure 4: Experimental set-up for spectral interferometry. The red line shows the path for the two arms of the interferometer.

First studies are being performed on the laser facility LUCA (Tunable Ultra Short Laser) which delivers 50 fs long, 800 nm laser pulses, with an energy of up to 100 mJ, at a 20 Hz repetition rate. The pulse is split into the two arms of the interferometer (cf. fig. 4). On the first arm the laser passes through the acousto-optical device, thus undergoing a phase and/or amplitude manipulation. The second one travels through a delay line and it is then superposed on the first one. The two recombined beams enter the spectrometer where they interfere on the sensor. Single-shot interferograms are then collected on a personal computer. This latter also handles the transfer of the target or reference amplitude and phase files, as well as the associated reconstruction process. In practice the difficulty is to isolate the secondary lobe without information losses when the contrast is not very high. Also, to correctly recover the spectrum, a great care should be taken with the spectrometer calibration, and the signal processing to convert from the wavelength to the frequency space.

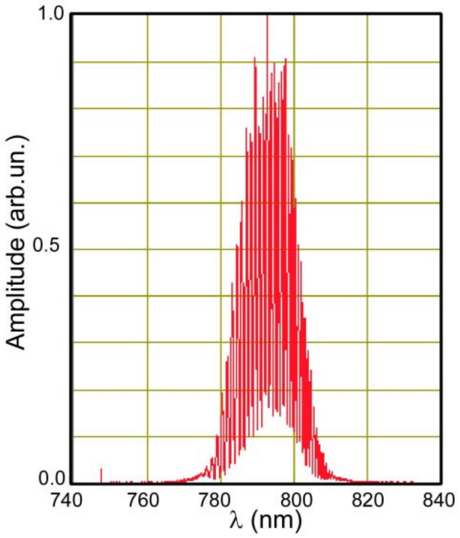

Figure 5: Typical interferogram acquired on the spectrometer.

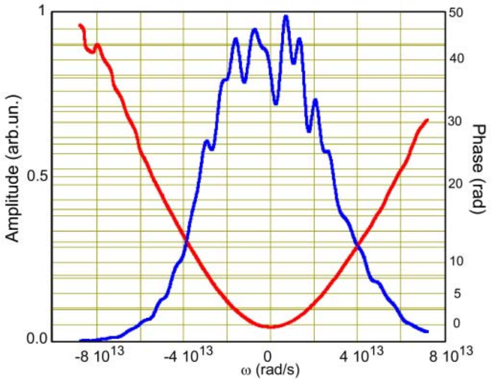

Figure 6: Retrieved Spectral Amplitude (blue curve) and Phase (red curve).

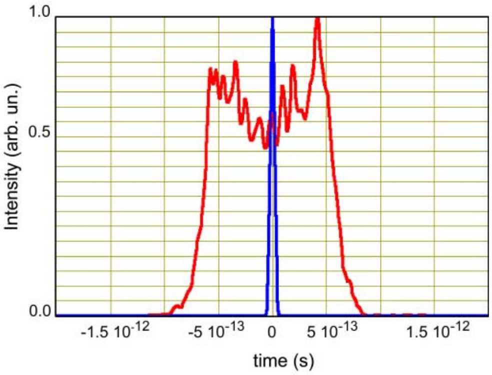

Figure 7: Temporal shape computed with IFT of the experimental data. Blue curve : Fourier Limited laser pulse taking into account only the target spectral amplitude; Red curve: with the target spectral phase.

PRELIMINARY RESULTS

The experiment has been implemented on the LUCA laser facility. Very low energy IR pulses ($\approx 10\ \mu$J) have been processed up to now. The few obtained preliminary results are very encouraging. A first example for a rectangular laser shape has been performed. Fig. 6 shows the retrieved amplitude and spectral phase behaviours, this latter without the constant and first order terms, whereas in fig. 7 the computed temporal shape, obtained with only one iteration, highlights the difference between the gaussian shape pulse which is obtained when only the spectral amplitude is taken into account, and the rectangular shape, when the spectral phase is inserted. The obtained pulse has a duration of $1.3\ p$s $FWHM$, with leading and trailing edges lasting around $170\ f$s. In order to get rid of the observed modulation on the top of the pulse, a higher signal-to-noise ratio should be achieved, always in a single shot configuration.

CONCLUSIONS

The spectral interferometry setup has been implemented on LUCA. Future steps will deal with the improvement of the laser beam spatial profile, the completion of the corrective loop for several different longitudinal shapes, a big increase of the pulse energy injected in the Dazzler, up to $1\ m$J before compression. Afterwards the grating compressor will be installed on the beamline, together with a third harmonic generation stage and a further prisms stretcher, in order to obtain shaped pulse in the UV at 266 nm, with an energy of several tens of μJ.

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