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SIMPLIFIED SCHEME FOR UV TIME PULSE SHAPING

C. Vicario *(INFN/LNF)*, M. Petrarca. *(INFN/Roma1)*, S. Cialdi *(INFN/Milano)* P. Musumeci *(UCLA).*

Abstract

We present a method to generate high-energy flat-top UV laser pulses such as the ones needed to optimally drive high brightness radio frequency photo-injectors. In this novel scheme the longitudinal profile of a laser pulse from a Ti:Sa master oscillator power amplifier system is controlled using a mechanical mask in the Fourier plane of a 4f-stretcher located after the harmonic conversion crystals. Such scheme allows overcoming many of the difficulties faced by current state-of-the-art pulse shaping designs. These are in fact based on various versions of pre-amplifier infrared shapers, and hence suffer from the limitations set by the non-linearities of CPA amplification and harmonic conversion. Beyond the clear advantages of simplicity and robustness, the proposed solution offers the possibility to deliver a pulse with very short rise and fall times and to freely change the output pulse length. We also note that, after proper calibration between spectral and temporal profiles, the shaper optical setup offers the possibility to retrieve the longitudinal profile of the laser pulse on a shot-to-shot basis.

1 INTRODUCTION

The shaping of ultra-fast laser pulses is of increasing interest in a wide variety of optical applications, including quantum and optimal control, high speed communications and material characterization.

The promise of increasing the brightness of electron beams from RF (radio frequency) photoinjectors by using a flat top UV laser pulse to illuminate the cathode is the application inspiring the work presented here. For optimum driving a photocathode of a S-band RF cavity, one desires ideally a relatively high energy (>100 μJ) UV laser pulse 5 to 10 picoseconds long, with a flat top temporal profile having fast (about 1 ps) rise and fall [1,2,3]. Current state of the art designs employ various kinds of shapers in the IR, usually located after the oscillator and before the amplifier thus suffering from deleterious non-linear effects introduced mostly in the harmonic [4,5]. Another option that has been studied [6] is the use of a pulse stacker obtained successive splitting and differentially delaying fractions of an incoming laser pulse. While these different schemes promise to achieve relatively flat-top laser profiles, the major problem has been to satisfy at the same time also the other tight requirements on the pulse shape to drive a photoinjector, such as very short rise and fall times and the pulse to pulse stability.

In a previous paper [7] we analyzed a simple approach to the problem based on the possibility of transferring the spectral profile into the temporal profile using a paired grating stretcher in the UV. The required spectral profile in the third harmonic was generated using a programmable acousto-optic filter (DAZZLER) [5] on the IR beam just after the laser oscillator and before the amplifier. This scheme though presents a drawback since, as we showed, the harmonic generation strongly affects the spectral shape. Also, due to the finite bandwidth of the non-linear crystals, the steepness of the rise and fall time of the resulting flat-top pulses, is not extremely fast (about 3 ps).

Building on our previous experience we show here how it is possible to solve this problem by using a properly designed pulse shaper directly in the third harmonic [8]. The interesting point here is that it is found that a Gaussian spectrum like the one naturally produced by the laser system is actually ideal if one aims at a flat-top longitudinal profile, thus removing the need of expensive and complex shaper systems in the IR.

In the following we first illustrate in detail the optical setup used for shaping the UV pulse and then we discuss the experimental results. This work was performed using the SPARC laser system [2] which is based on an amplified Ti:Sa laser system that delivers 100 fs pulse with energy up to 50 mJ at 800 nm at 10 Hz. The amplified pulse is frequency-tripled at central wavelength of 266.7 nm, using two BBO crystals of 0.5 mm and 0.3 mm, for more details see [7].

2 UV TIME PULSE SHAPER

After the third harmonic generation the beam is sent through a specially built optical system in order to shape the longitudinal pulse profile. Basically it is a particular version of the classical 4f optical scheme with two anti-parallel gratings and two lenses of focal distance f respectively separated by a distance f Fig. (1) [8]. A collimated beam is sent onto a diffraction grating having 4350 lines/mm at an incidence angle θ_i = 43°, close to the Littrow angle. The dispersed spectral components of the pulse are then focused using a f =500mm lens located at a distance f from the grating.

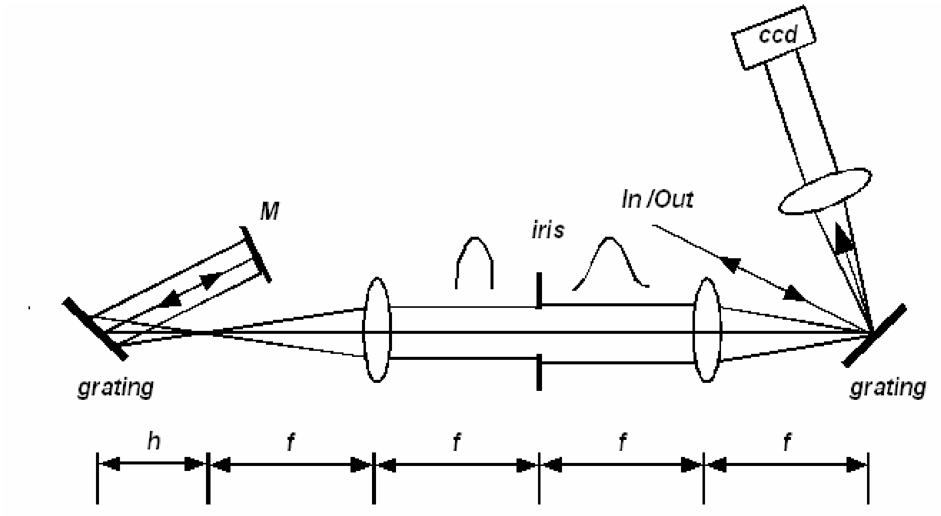

Figure 1. Schematics of the UV pulse shaper. The iris plane is the Fourier plane where the spectral cut is operated. The CCD and the lens on the beam reflect reflected composed an high resolution spectrometer.

On the lens focal plane each spectral component will reach a focus in a different spot. In other words on this plane (henceforth named Fourier plane) there is full correlation between wavelength and transverse position. This allows any desired amplitude modulation on the spectrum simply placing a filter or mask at this plane. The beam is then re-collimated by a second lens and sent to another grating which compared to a classical 4f system is shifted from the symmetry position (which would be at a distance f from the second lens) by a distance h. The spectral components are then retro-reflected by the mirror M and retrace back their path through the system. The shift h of the second grating introduces a chirp on the outgoing beam $\frac{1}{2}\beta\omega^2$ where ω is the shift from the frequency corresponding to the central wavelength ω_0, and β given by:

$$\beta = \left(\frac{\lambda_0^3 h}{\pi c^2 d^2}\right) \frac{1}{1-\left(\frac{\lambda_0}{d} - \sin\left(\theta_i\right)\right)^2} \qquad \textbf{(1)}$$

where d is the grating step, and θ_i is the incident angle. In our implementation of the UV pulse shaping (see Fig. (1)) after the second pass the fraction of the beam reflected by the grating is focalized by a 30 cm lens onto the plane of a CCD camera. In this way a high-resolution ($\approx$ 0.05 nm) spectrometer is integrated in the shaping system.

Simulation has been carried out using the Zemax optical design code [9]. In Fig 2 is reported the transverse distribution along the beam path as function of the different laser wavelengths represented by different colours. At the input, Fig. 2a), all the wavelengths perfectly overlap, on the first lens, Fig. 2b), the frequencies are partially dispersed, at the Fourier plane, Fig. 2c), the different wavelengths are well distinguished. Here it is possible to operate a selection of the spectral components. On the second lens the laser spot is shown in Fig. 2d), after the first pass the spot present a spatial chirp Fig. 2e). A frequency position correlation in the laser beam means a correlation of the time intensity profile respect to the position. This is an unwanted effect that greatly complicates the control of optimal pulse shape to drive the SPARC photoinjector. This residual chirp can be completely compensated by a second pass in the UV stretcher as reported in Fig. 2f) at a price of higher energy losses.

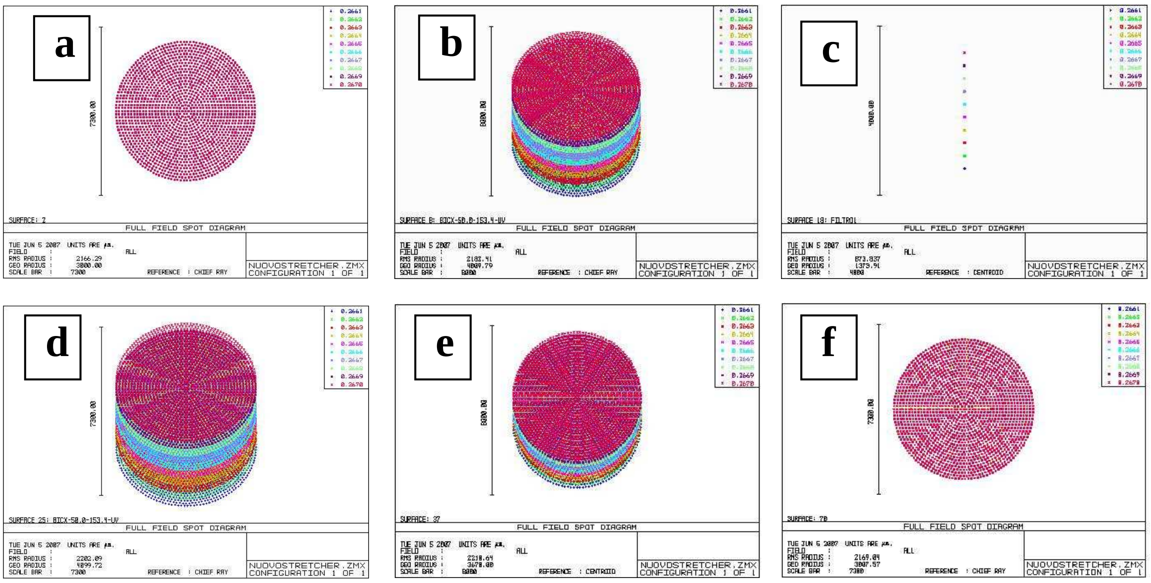

Figure 2. Zemax simulations of the laser spot at the input a), on the first lens b), at the Fourier plane c), on the second lens d). The beam transverse profiles after the first pass in the stretcher e), and the second pass are also reported.

Summarizing, the functions of the described optical system are: i) introduction of a frequency chirp in order to change the pulse length; ii) introduction of a amplitude modulation on the spectrum by placing a mask at the Fourier plane; iii) single shot measurement of the spectrum of the output pulse.

3 EXPERIMENTAL RESULTS

The simple idea at the basis of the described shaper is to eliminate the spectral tails of a natural bell-shaped spectrum of the lasers, by using a mechanical beam block –an iris– located on the Fourier plane. In Fig. (3), we show simulations of the effect of the cut of the spectral tails when the input pulse has a Gaussian spectrum. In the top left corner (a1) we report different laser spectra obtained for different apertures of the blocking iris. In the bottom left corner (a2) we show the temporal profiles relative to such spectra, when the second grating is shifted by the symmetric position by a distance h = 16 cm and a chirp of 10.4 ps/nm is applied by the stretcher. As it is immediately evident, a sharp cut of the spectral tails induces overshoots in the temporal profile of the pulse, which could be used to balance the curvature of the Gaussian spectrum. In this simple way it would be possible to obtain a flat top laser pulse starting from a Gaussian-like spectrum. Moving away from the Fourier plane the iris, one can in fact change the sharpness of the applied cut to adjust for the required curvature compensation. In our implementation of the shaper we can pass from a resolution of 0.005 nm (on the Fourier plane) to a resolution of 0.05 nm moving the iris by about 1 cm. In the top-right corner of Fig. (3), we report Gaussian spectra cut with increased sharpness going from top to bottom. In the bottom right corner we show the corresponding temporal profiles.

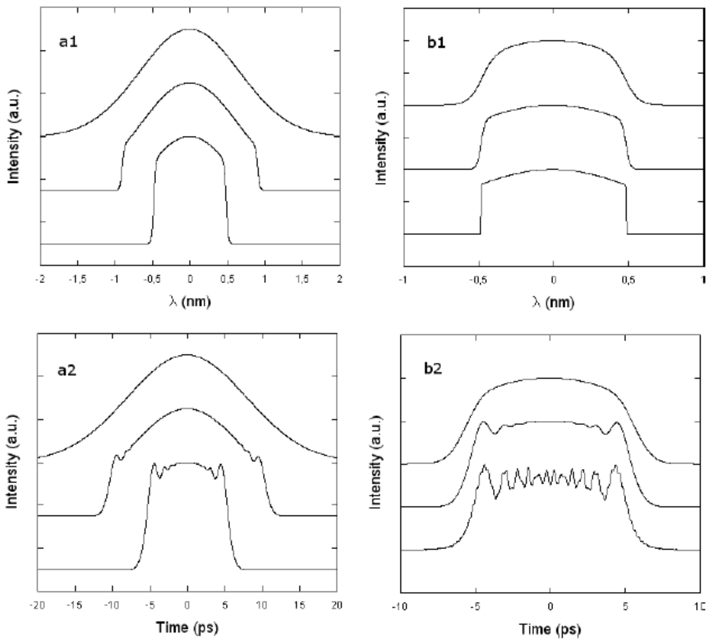

Figure 3. Simulated time intensity profile, a2) for different spectral cuts a1). On the right side we show the effects on the time distribution of changing the sharpness of the spectral cut.

A very sharp cut induces large overshoots in the temporal shape. When the iris is too far from the Fourier plane, and the cut is more smooth, we obtain again a temporal profile which resembles the Gaussian-like initial spectrum. An optimal cut resolution (that in our particular case is 0.05 nm) is needed to obtain the best flat top pulse. The resolution can be set by monitoring on the spectrometer the effect of small shifts of the iris from the Fourier plane. It is important to stress the fact that the quality of the beam transverse profile is not significantly affected by the cut of the spectral tails.

In Fig. (4) we report the experimental results obtained with this pulse shaper. In the top-left corner (a1) we show the initial spectrum. It is a bell-shaped spectrum with a bandwidth similar to the one used in the simulations. In the bottom left picture (a2) we report the corresponding temporal profile measured with a cross-correlation Ref [10] between the UV pulse and the infrared pulse which has a length of 750fs (probe pulse). The dotted line represents the theoretical cross-correlation obtained from the measured spectrum taking into account the chirp introduced by the stretcher and the finite length of the probe pulse. In the top-right corner (b1) we show the spectrum after the tails have been removed. In (b2) we display the corresponding measured cross-correlation and the theoretical one. As shown in Fig. (4) the experimental cross-correlation presents ripples that are absent in the simulated profiles. In fact the experimental cross-correlation profile is a multi-shot measurement that suffers from the pulse to pulse laser fluctuations. Since in this shaping scheme it is required to block only the spectral tails, the fraction of the laser pulse which is transmitted through the blocking iris is in fact greater than 40 %. The overall efficiency of the shaper was on the other hand limited to < 40% due to the high diffraction losses of UV gratings (< 80% per pass).

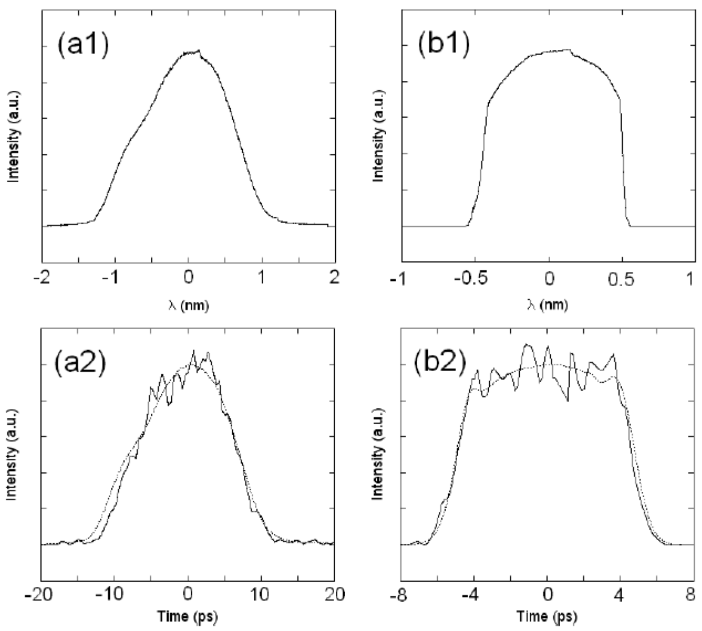

Figure 4. Initial spectrum (a1) and spectrum after the mask (b1) and relative measured cross-correlations (a2 and b2). The dotted lines represent the theorethical cross-correlations obtained taking into account that the probe pulse is used for the measurement is actually 750 fs long.

In our measure a pulse with energy of about 2mJ is sent to the shaping system and the resulting output rectangular pulse has energy greater than 300μJ.

From these measurements we deduce two main results: 1) cutting the spectrum tails with the iris we obtained a rise time of 1.55 ps as measured by the cross-correlation. Since the latter has been obtained with a 750 fs long IR gate pulse which actually adds in quadrature, the real rise time is only 1.4ps (the result is satisfactory because simulations [11] show that the change in the emittance value obtained within (1 − 1.4) ps rise and fall time pulses is still acceptable); 2) if the applied chirp is known with a single shot measurement of the spectrum one can calculate with a good approximation the final temporal profile of the pulse. In practice one obtains the longitudinal pulse shape from the spectrum simply by a Fourier transformation (Eq.(2)):

$$I(t) = \left| \int \sqrt{\tilde{I}(\omega)}\, e^{i\left(\frac{\beta\omega^2}{2} - \omega t\right)}\, d\omega \right| \qquad \textbf{(2)}$$

where $\tilde{I}(\omega)$ is the measured power spectrum of the output pulse and β is the chirp coefficient introduced by the stretcher Eq.(1).

Using this equation it is immediate to understand how to further improve the rise time. In Fig. (4) we show the simulation results of the rise time variation as a function of the bandwidth of the spectrum after the cut as calculated using Eq. 2. This simulation assumes that the chirp introduced by the stretcher has to be adjusted to maintain the same final pulse length (10 ps). For a wider (smaller) spectral bandwidth the applied chirp is decreased (increased). Note that with a spectral bandwidth > 1.7 nm it is possible to obtain very fast rise times (< 1 ps). A simple way to broaden the bandwidth in the third harmonic is found reconsidering Eq. 5 in Ref [7]. In order to obtain a wider UV bell-shaped spectrum one could in fact introduce a chirp on the IR pulse before the non-linear conversion crystals, for example simply detuning the final amplifier compressor. In our case, in order to increase the UV pulse bandwidth (from 0.9 nm to 1.5 nm), we increased the length of the IR pulse from 100 fs to 750 fs pulse. For further increase of the bandwidth and reduction of rise-time, in our set-up, thinner non-linear crystals in the harmonic generation are necessary. In order to keep the same third harmonic generation efficiency with thinner crystals, we estimate that it is possible to reduce the laser spot; this will be the goal of further work.

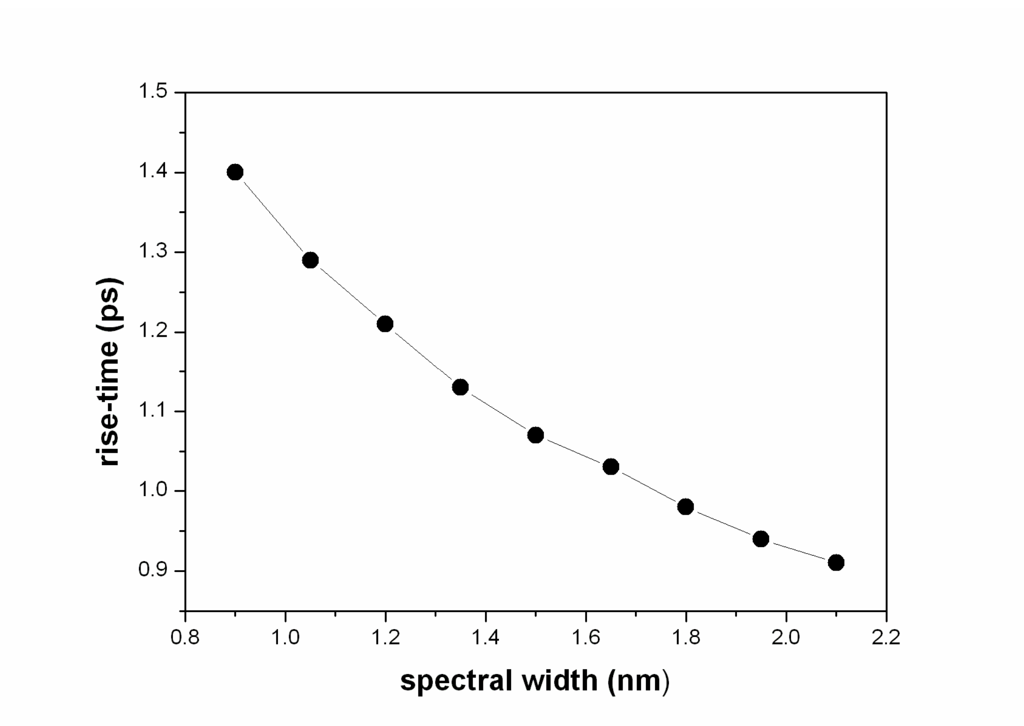

Figure 5. Simulated rise time as a function of spectral bandwidth $\Delta\lambda$ after the cut.

4 CONCLUSIONS

In conclusion with this shaper scheme we are able to achieve flat top laser pulses with very good rise-time suitable to drive optimally the next generation photoguns. With the same optical setup, the temporal profile of the pulse can be monitored with a single shot measurement of the spectrum easily integrated in the shaper design. Finally, the proposed scheme proved to be robust, very low-cost and easy to implement thus it can also serve different pulse shaping applications, as for instance the generation of a multi-peaked pulse. The main drawback is the insertion loss of the described optical system. The losses can be mitigated if a square-like pulse, premodulated by the DAZZLER or by a liquid crystal mask, is sent to the UV shaper. In this conditions the losses at the Fourier plane are 20% lower than the case when a Gaussian spectrum is used.

4 ACKNOWLEDGMENTS

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