DESIGN OF A TWO-STAGE LASER PULSE SHAPING SYSTEM FOR FEL PHOTOINJECTORS*

M. B. Danailov, A. Demidovich, R. Ivanov (ELETTRA, Basovizza, Trieste).

Abstract

This paper presents an approach for photoinjector laser pulse shaping which combines the two main pulse shaping techniques, namely acousto-optic dispersive filter (DAZZLER) and Fourier-based 4-f system. The DAZZLER is inserted between the seed mode-locked oscillator and the amplifier and is used for preliminary shaping in the infrared, while the final pulse shape and duration are determined by a 4-f dispersive system positioned after the harmonic conversion to UV.

INTRODUCTION

Temporal pulse shaping is one of the most important requirements to photoinjector lasers needed in the majority of FEL projects. The laser pulses commonly requested for excitation of the photocathode are in the UV (around 260 nm) and have flat-top shape of duration in the 5-10 ps range. Recently, more complex pulse shapes like ramps have been shown to be advantageous and proposed for implementation [1,3], indicating that the pulse shaping scheme must offer flexibility in generating different shapes. In principle, there are two main ultrashort pulse shaping techniques, namely 4-f type Fourie shaping [4] and acousto-optic dispersive modulator (DAZZLER) based [5] shaping. As it will be shown below, the use of one of these only is unlikely to allow reaching the required performance. The main complication comes from the fact, that the pulse shape is needed in the UV, and the required pulse energy is quite high, while pulse shaping is easy to do at low pulse energy in the IR. In the paper we describe a hybrid scheme proposed for the FERMI photoinjector, which utilizes both methods, one in the infrared and the other in UV. The paper starts with brief introduction to the ultrashort pulse shaping basics and notation, which is important for understanding the analysis and results presented later on. The specific problems related to photoinjector laser pulse shaping and the proposed optical scheme are discussed in the next section, followed by simulations and preliminary experimental results of flat-top and increasing ramp pulse generation.

PULSE SHAPING BASICS

As mentioned above, there are different laser pulse shapes that can be used to optimize the photoinjector (and overall FEL) performance. Here we will mostly refer to two of them, namely flat-top and increasing ramp, however the techniques used allow in principle to generate any desired pulse shape. To make the discussion of the pulse shaping schemes clearer, we will very briefly introduce some basics of the pulse shaping theory.

Assuming that the light field can be factorized into spatial and time dependent part, the electric field of the latter can be written as:

$$E(t)=1/2\,[I(t)]^{1/2}\,exp\{i[\omega_0 t-\varphi(t)]\}+\text{c.c.}\,, \qquad (1)$$

where ω_0 is the central frequency , $I(t)^{1/2}$ and $\varphi(t)$ are the time dependent temporal amplitude and phase. For simplicity in the following equations the c.c. part will be omitted. The quantity

$$E(t)= I(t)^{1/2}\,exp[-i\varphi(t)] \qquad (2)$$

is referred to as the complex amplitude in the time domain. In the frequency domain, the pulse field can be represented in a similar manner:

$$E(\omega)=1/2\,[S(\omega)]^{1/2}\,exp[-i\psi(\omega)]\,, \qquad (3)$$

where $S(\omega)$ is the spectral intensity of the light pulse. As it is known, the time and frequency domain field representations are linked by a Fourier transform relation:

$$E(t)=(1/2\pi)\int_{-\infty}^{\infty} E(\omega)\,exp\,(i\omega t)\,d\omega \qquad (4).$$

Most of the known methods for shaping of ultrashort pulses are based on this relation, they implement manipulation of the spectral amplitude or phase (or both) of the pulse, which in turn leads to the required modulation in the time domain. The output pulse shape is given by the convolution of the input pulse and the impulse response function of the modulating function:

$$E_{out}(t)=\int_{-\infty}^{\infty} E_{in}(t`)\,h(t-t`)\,dt`\,, \qquad (5)$$

where h(t) can be calculated from its complex frequency transfer function by:

$$h(t)=(1/2\pi)\int_{-\infty}^{\infty} M(\omega)\,exp\,(i\omega t)\,d\omega. \qquad (6)$$

The complex transmission function $M(\omega)$ can be presented as:

$$M(\omega)=[M_I(\omega)]^{1/2}\,exp[-i\Phi(\omega)]\quad , \qquad (7)$$

and the phase transmission is commonly expanded in Taylor series :

$$\Phi(\omega)=\Phi(\omega_0)+\Phi^{(1)}\Delta\omega+(1/2!)\Phi^{(2)}\Delta\omega^2+ +(1/3!)\Phi^{(3)}\Delta\omega^3+\ldots \qquad (8)$$

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where $\Phi^{(i)}$ is the i-th derivative of the phase evaluated at ω_0 and are usually called i-th order dispersion. While the first and second terms in (9) represent only a constant and an overall time shift of the pulse, the third and higher order terms may lead to significant pulse shape changes even if the spectral amplitude $[M_I(\omega)]^{1/2}$ remains constant. In principle, if one could design a frequency filter with a prescribed optical frequency transmission function, any desired pulse shape (with temporal resolution limited by the inverse bandwidth of the input pulse $E_{in}(t)$) can be generated. In reality, it is quite difficult to produce optical filters with complex frequency transmission functions defined with high precision. As will be shown later, some specific shapes, like flat-tops, however, can be produced by use of interference filter.

The first technique which solves in a general way the pulse shaping has been known for more than a decade [4] : the spectral components of the input pulse are spatially separated by a dispersive element (e.g. diffraction grating) , and then manipulated in the spatial domain by using a modulator with spatially dependent transmission, placed in the Fourier (focal) plane of a lens, as shown on Fig.1. A second lens and grating recollimated the pulse spectral components, so the output pulse has again a spatially independent pulse shape that can be calculated using Eq.6. By proper choice of the modulator the technique allows to use both amplitude and phase modulation. It is worth noting that large second order phase terms (i.e large linear chirp) can be produced even without the use of modulator in this scheme, by just shifting the grating with respect to the focal plane of the lens.

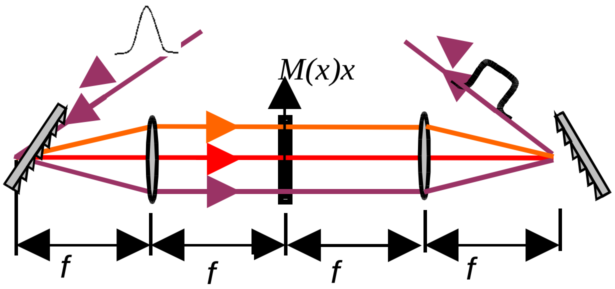

Figure 1: 4-f Fourier shaping system

A newer and very powerful technique for pulse shaping is the so called DAZZLER introduced by P.Tournois [5] and commercially available from Fastlite (France). In this method, also based on Eq.6, the spectral components are not separated spatially, the optical pulse travels in an acousto-optic modulator where a longitudinal acoustic wave is present. By shaping the acoustic wave frequency and amplitude, the spectral components of the optical pulse are diffracted out of the crystal at different positions (and therefore with different delay) and with different efficiency. In this way, the deviated part of the incoming pulse can be time modulated with very good precision.

DISCUSSION

The basic gun laser specs in the case of Copper photocathode are relatively well agreed. It is usually accepted that about 0.5 mJ of pulse energy in the UV (wavelength around 260 nm) has to be provided in order to obtain about 1 nC of charge.

Both techniques presented above allow in principle to obtain pulses with the required shape for the photoinjector. When flat-top is concerned, some experimental results with Dazzler have been presented in [6].The Dazzler has the obvious advantage of flexibility and compactness. It is provided with computer control allowing both amplitude and phase modulation. However, it has the following limitations:

- wavelength resolution of the high resolution model is about 0.3 nm. For this reason the bandwidth of the input pulse should be about 10 nm or higher in order to obtain high fidelity amplitude shaping;
- if a single pass is used, the maximum second order dispersion that can be provided by the Dazzler allows to generate pulses of up to 4 ps, which is not enough in most cases. A two pass geometry can be used for having ~10 ps long pulses, however in this case the insertion loss , even at maximum diffraction efficiency, is above 90% which does not seem to be practical;
- the Dazzler can be used only in IR. Fastlite announced recently a UV version, however it is not suitable for the task considered here (allowed power levels and wavelength resolution can not be met)
- maximum peak power limitation in the IR does not allow to use the Dazzler after the amplifier. For this reason it has to be placed between the seed oscillator and laser amplifier.

On the other hand, the 4-f based shaping can be used directly in UV, if a proper modulator is found. At present, the only available option is a piezo-deformable mirror [7] with a dielectric coating. Liquid crystal modulators like are only available down to 350 nm, which is not enough for our photoinjector case. There are two main limitations to be taken into account:

- the use of deformable mirror allows to obtain only phase modulation
- the obtainable phase curvature is limited by the limit of about 8 micron for maximum mirror deformation, so the deformable mirror alone will not be enough for obtaining large phase gradients, it can rather be used as a tool for compensating slow phase curvature errors.

PROPOSED LAYOUT

Fig.2 presents a layout of the hybrid shaping setup proposed for the FERMI photoinjector. Input seed pulses with a bandwidth of about 12 nm at 780 nm are generated by a mode-locked Ti:Sapphire laser. The IR pulse shaping is done by a DAZZLER inserted before the amplifier stages. The Dazzler is implemented primarily for producing the desired spectral amplitude shape (e.g. super-gaussian like) , and in addition for compensation of

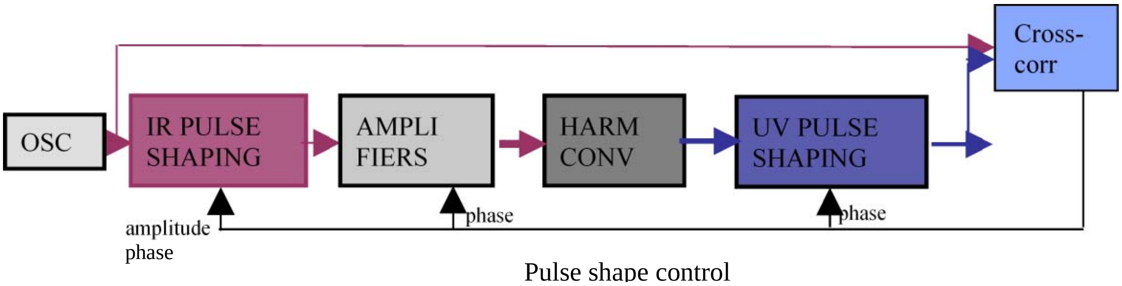

Figure 2: Proposed two-step shaping setup

third-order phase distortions due to the grating compressor of the amplifier. Usually this compressor is used for exact compensation of the chirp introduced by the stretcher. In our scheme it is also used for adding a second order dispersion by detuning with respect to maximum compression point. In this way, the pulse duration at the entrance at the harmonic generation crystals can be adjusted to an optimum value which allows to have high enough harmonic efficiency while still keeping high order nonlinear effects (e.g. self-phase modulation) at low. Such a safe peak power level is reported to be in the order of 10-20 GW/cm^2 for BBO. We note that our approach gives an additional degree of freedom for adjusting this level.

The final pulse duration and shape is then controlled by a dispersion based system working in the UV. Two version of this system are under consideration. The simpler one is just a two-pass grating stretcher used for adding a second-order phase needed to obtain the exact pulse duration (see the simulation later on). This version will be used in case the DAZZLER alone allows good enough compensation of all phase distortions. If it appears that an additional high order spectral phase compensation is needed after the harmonic generation, the UV shaping will include also a deformable mirror in a modified 4-f arrangement.

In order to illustrate better the described scheme, on Figs.3 and 4 we present the results of a simple simulation of pulseshaping which generates the pulse shape (increasing ramp) requested for the FERMI ‘long bunch case’ [3].

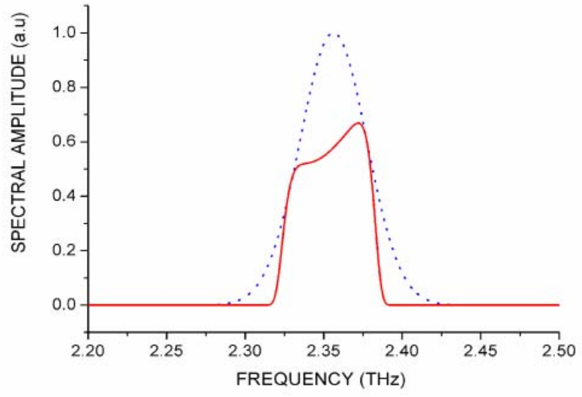

Figure 3: Input spectrum for the simulation (blue dots) and modulated spectrum after Dazzler (red solid line).

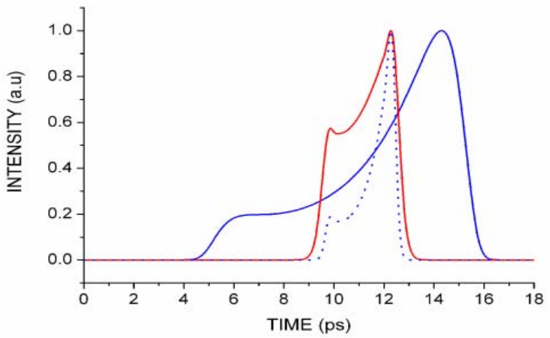

Figure 4: Pulse profiles after compressor in the IR(red solid line), after THG (blue dots), after UV stretcher (blue solid).

The simulation is done starting with a transform-limited Gaussian pulse at 800 nm having 12 nm of FWHM bandwidth (dashed blue line on Fig.3). The spectrum shown in red line is obtained after amplitude filtering by the Dazzler. In addition, it is assumed that the latter completely compensates the residual third-order dispersion of the system. The pulse shape shown by blue line on Fig.4 corresponds to the amplifier output, where a second order dispersion of about 60000 fs^2 has been introduced by detuning the compressor. Assuming that the third harmonic generation is performed in sufficiently thin BBO crystals , so GVM and spectral acceptance effects can be neglected, the UV pulse shape (dashed blue line) is proportional to the third power of the IR one. The final shape and duration, shown by solid blue line are obtained by adding only an additional second order dispersion from the UV grating stretcher. We note that this stretcher will inevitably add also a third order dispersion term on the order of 100 000 fs^3 , which is in principle possible to compensate in advance by the Dazzler, so it has not been taken into account into the above presented simulation. As mentioned above, in case the DAZZLER compensation is not sufficient the odd dispersion terms will be cancelled by the use of deformable mirror.

PRELIMINARY EXPERIMENTAL RESULTS

Most of the components of the above presented setup have already been tested at Elettra. Here we will briefly summarise some of the results. The DAZZLER has been installed and tested using a femtosecond Ti:Sapphire oscillator at 780 nm. On Figure 5, two typical flattop pulse shapes are presented: phase only polynomial modulation (blue line) and amplitude super-gaussian modulation. In both cases, the pulses were additionally stretched by the use of grating stretcher. The pulse measurement is done by cross-correlating the shaped pulse with a part of the input 100 fs long pulse.

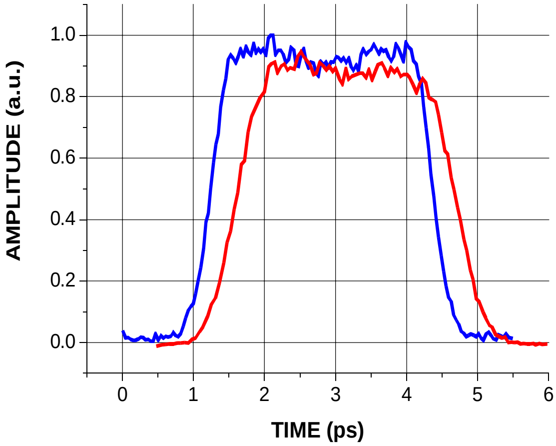

Figure 5: Flat-top pulses generated by the Dazzler; blue line: phase modulation, red line: amplitude modulation

It is important to mention here that the fact that amplitude filtering plus stretcher added second order dispersion works well indicates a simpler method. The amplitude filtering can be performed by the use of an interference filter. Indeed, we demonstrated this by the use of a commercial filter (Spectrogon), centered at 780 nm. There is some freedom to detune the filter transmission curve position and shape by tilting and to obtain a nearly perfect super-Gaussian spectrum. As a result, after stretching , a flat-top pulse can also be obtained, as shown on Fig.6.The price to pay for the simplicity is that there is no control on phase, this might not be a problem if the UV part contains the deformable mirror.

On Fig. 7 we show a ramp type pulse profile [3] obtained on the same setup by using the Dazzler in amplitude modulation mode. We note that the cross-correlator scanning in this setup was starting from the back of the pulse, so the pulse front is on the right of graph and the ramp is increasing, as requested.

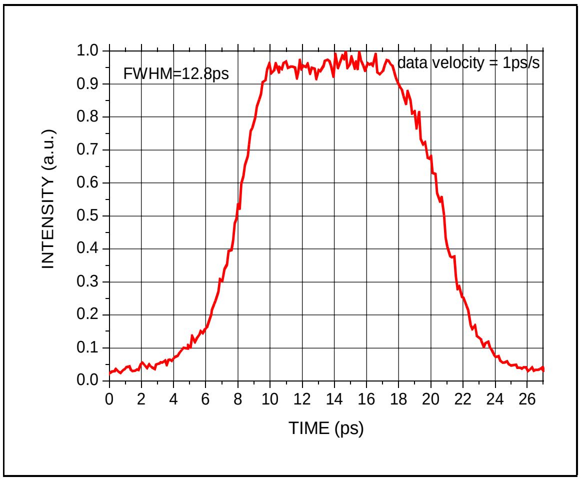

Figure 6: Flat-top pulse generated by the use of interference filter as an amplitude filter.

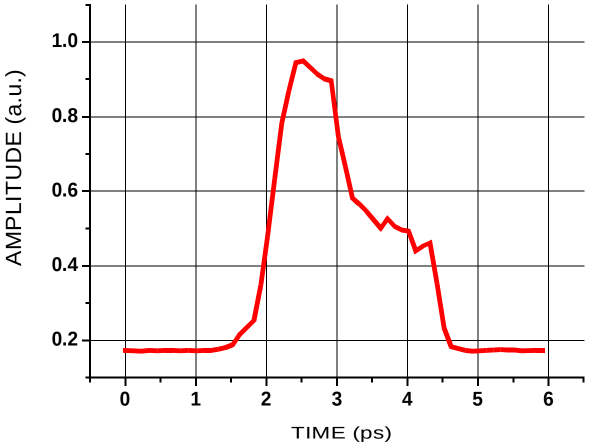

Figure 7: Increasing ramp generated by the Dazzler with pure amplitude modulation

CONCLUSIONS

The setup described above is in principle capable of producing arbitrary pulse shapes in UV, especially in the version containing deformable mirror. The two basic techniques have been already tested at low power at Elettra, and a high energy version including the UV part is to be completed and tested in a few months time. There is still some freedom to choose the exact system and laser pulse parameters in order to obtain the required shapes with high fidelity.

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