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Authors: O.GOBERT, S.GRABIELLE, D.GARZELLA

(CEA/DSM/DRECAM/SPAM CEA SACLAY)

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This work was done at CEA SACLAY (CEA/DSM/DRECAM/SPAM/SLIC)
The people who participated in this work (LUCA/PLFA team), apart from the authors of the report, are the following:

P.Hollander,O.Tcherbakoff, J.F.Hergott, F.Lepetit, M.Perdrix, D.Jourdain, R.Maksimenka.

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Contents :

I) Introduction.

The minimization of the emittance of electron bunches is an extremely important issue for photoinjectors. It was demonstrated that an isodensity cylinder photoelectron bunch can lead to a far better emittance than the one obtained with a standard gaussian spatial distribution [1]. We assume the photo-electrons emission time to be short enough that the cylinder electron pulse shape will come directly from the laser pulse. So the generation of an isodensity cylinder photon bunch (also called "beer can") is the goal of this work. An interesting feature is that it allows us to decouple the spatial and temporal parts of the field (i.e. E(x,y,t) = g(x,y).E(t)).

The parameters of the beam should be the following:

λ ~ 266 nm,

Pulse duration: 5 ps,

Rise time/Fall time < 1ps,

Fluctuation of the intensity in the plateau (temporal or spatial profile) < 5 %

Energy per pulse: 500 µJ on the photocathode (Copper photocathode)

This report presents the study of the longitudinal (temporal) shaping we carried out at CEA Saclay.

Obtaining a cylindrical isodensity photoelectron bunch is a first important step towards improving the emittance of a phoinjector beamline. The optimum photo-electron distribution from the cathode of an RF photoinjector producing a space charge dominated beam is an isodensity ellipsoid [2]. Generating an isodensity ellipsoid photon bunch is a far more complicated task, since we can not decouple the spatial and temporal part of the electric field. (i.e. E(x,y,t) cannot be written as g(x,y).E(t) as for the isodensity photon cylinder).

II) Longitudinal Beam Shaping.

II.1) Longitudinal beam shaping with a linear or a combination of linear systems.

Among the different approaches which can be used to shape the beam in the temporal domain, we chose to use one based on a linear or a combination of linear systems. Pioneering work in this field was carried out by Weiner and Heritage [3,4,5].

In this work, we suppose that the electric field corresponding to the laser beam can be written as follows:

$$E(x,y,t) = g(x,y).E(t) \tag{1}$$

so that the temporal and spatial part of the field are decoupled and we deal only with the temporal part of the field.

The use of a linear or a combination of linear systems can be represented in the following mathematical form:

$$E_{out}(\omega) = H(\omega).E_{in}(\omega) = |H(\omega)|.e^{i\varphi(\omega)}.E_{in}(\omega) \tag{2}$$

where $E_{in}(\omega)$ ($E_{out}(\omega)$) is the Fourier transform of E(t) at the input (output) of the system and $H(\omega)$ is the transfer function of the system or the combination of systems. $H(\omega)$ is a complex function.

In this work, when dealing with a combination of linear systems, we use a programmable linear system and a compressor or stretcher system. In this case, the previous relation can be rewritten in the following form:

$$E_{out}(\omega) = H_{prog}(\omega).H_{comp}(\omega).E_{in}(\omega) \propto |H_{prog}(\omega)|.e^{i\varphi_{prog}(\omega)}.e^{i.\varphi^{(2)}_{comp}.\frac{(\omega-\omega_c)^2}{2}}.E_{in}(\omega) \tag{3}$$

The effect of the compressor or stretcher system is to provide a quadratic phase factor (depending on the sign, one speaks of a compressor or a stretcher). The programmable system can provide amplitude and phase modulation. The interest of using this combination is linked to the fact that, in our case, the programmable system cannot usually give a sufficiently high second order spectral phase.

II.2) Theoretical studies.

Before presenting the different linear systems which can be used, we will discuss the different ways of generating a quasi-top hat temporal profile with a duration in the 10 ps range from a pulse with a duration in the tens of femtoseconds. This is typically what has to be done with our experimental system since our laser system is a CPA TiS laser. One important parameter here is the ratio of the pulse duration at the output to the pulse duration at the input which is of the order of 100.

The only constraint is to generate a temporal intensity with a quasi top hat profile which means that the temporal phase of the field at the output of the system is a free parameter. Looking again at the formula (2),

$$E_{out}(\omega) = H(\omega).E_{in}(\omega) = |H(\omega)|.e^{i\varphi(\omega)}.E_{in}(\omega) \tag{2.bis}$$

This means that the field at the input being known, there is no single solution for the transfer function. The number of solutions being infinite, we will now detail our approach to find useful solutions from an experimental point of view. We will split the different methods into three types. Without loss of general applicability, we will suppose that the input beam is Fourier Transform Limited.

II.2.1) Amplitude modulation only.

This means that the transfer function is purely real. It is well known that the Fourier transform of a rectangle function is a sinc function. So this sinc function has to be generated from the input field by amplitude modulation in the spectral domain. A detailed study was presented in [6].

This method has very serious drawbacks.

Obtaining a good rectangular intensity profile requires the generation of a certain number of lobes for the sinc function with a good accuracy. Thus a high dynamic of the pulse shaper is necessary. The pulse duration to reach is 5 ps. It is easy to show, then, that the spectral resolution of the pulse shaper has to be better than 5 10^{-3} nm (which can be a problem for some pulse shapers). Lastly, the transmission of the system can be very low which disqualifies this method if no saturated amplification of the beam is done before the photocathode. In this case, the problem is no longer linear (we discuss this point later).

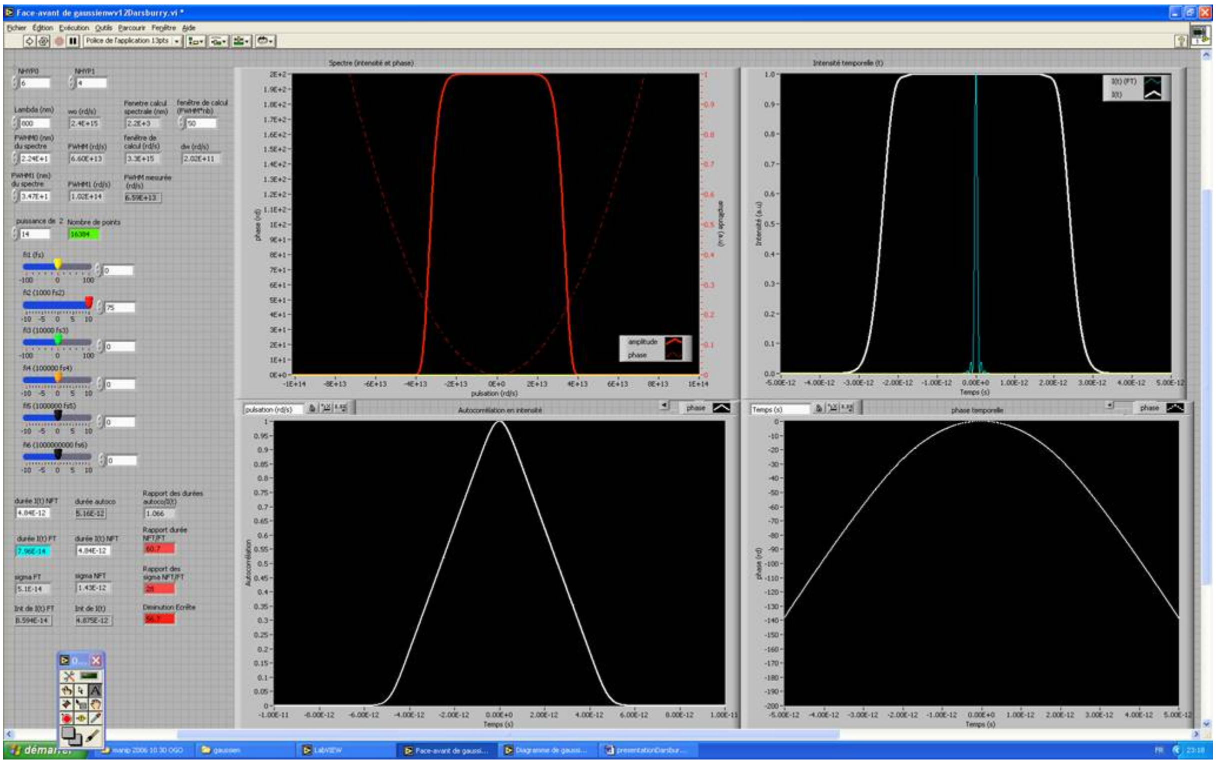
II.2.2) Amplitude and phase modulation.

We will detail the two methods we used, which are a subset of what can be done.

II.2.2.1) Amplitude and quadratic phase modulation.

We have, in this problem, a stretching ratio of the order of 100. For this value, it can be easily shown that a second order spectral phase can be used to generate a temporal intensity which is an image of the spectrum (we have a one-to-one mapping between the spectral domain and the time domain). So we have to create a rectangular function for the spectrum and by application of the right second order phase we obtain a rectangular function for the temporal intensity (the amplitude modulation can be made by the programmable linear system and the second order phase by a compressor or a stretcher).

This is illustrated on the figure below:



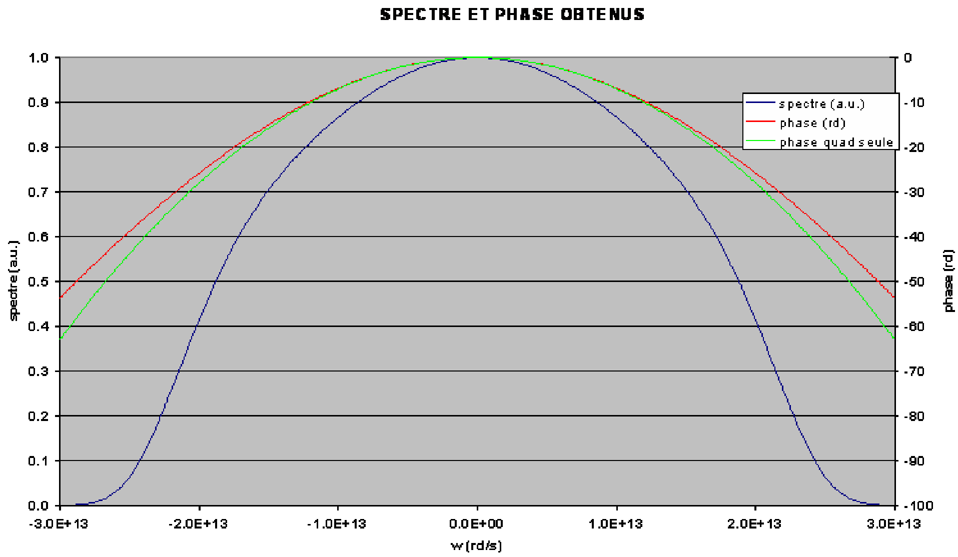
The top left figure gives the spectral amplitude (full line) and quadratic phase (dashed line) of the output pulse. The top right figure gives the temporal intensity in the presence (white) or in the absence of the quadratic spectral phase (blue). The bottom right figure shows the temporal phase of the pulse which is mainly quadratic (the pulse is not Fourier Transform Limited). The bottom left figure gives the temporal intensity autocorrelation which is without surprise a nearly triangular function.

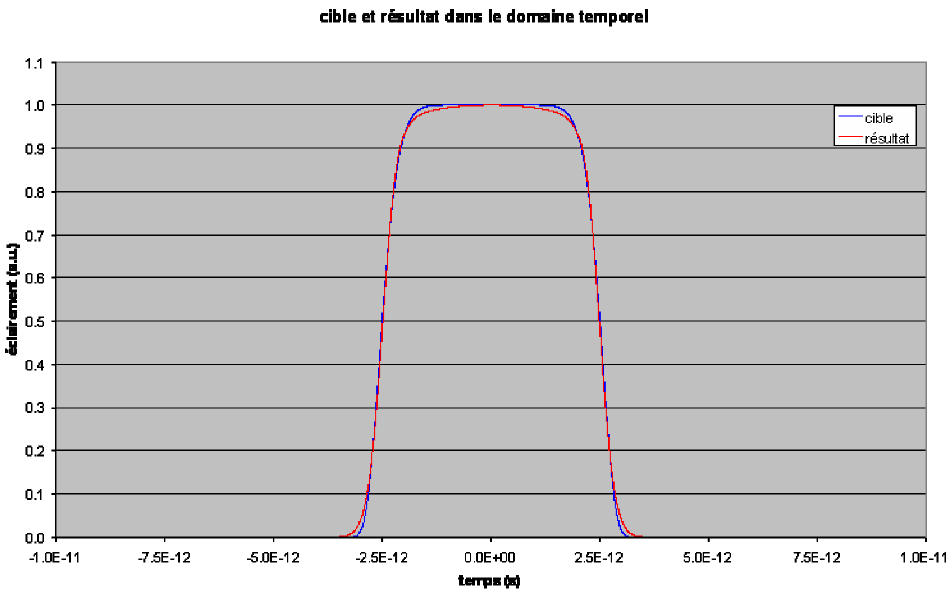
II.2.2.2) Amplitude and more complex phase modulation.

Usually the spectrum of the input pulse is closer to a gaussian or a product of gaussian and supergaussian functions than to a square function. Thus the transmission of the system can be increased if we choose to shape the spectrum of the output beam to these kinds of functions. In this case, we have to calculate the phase to obtain a quasi top hat intensity profile. This problem is solved by an optimization program in which the parameters are the polynomial coefficients of the spectral phase (we limit ourselves to a sixth order polynomial function).

An example of calculation is given on the two figures below. On the first one, which gives the output field in the spectral domain, the blue curve is the shaped output spectrum (product of a gaussian and a supergaussian function). On the second figure (time domain), the blue curve is the temporal intensity target we chose. The spectral phase obtained from the optimization program is given in red on the first figure. The second order phase part is given in green to illustrate the difference with the previous method using rectangular functions spectrum. The temporal intensity obtained with this optimization is shown on the second figure (red curve).

The optimization program was also used to generate more complex temporal shapes which are not discussed here.



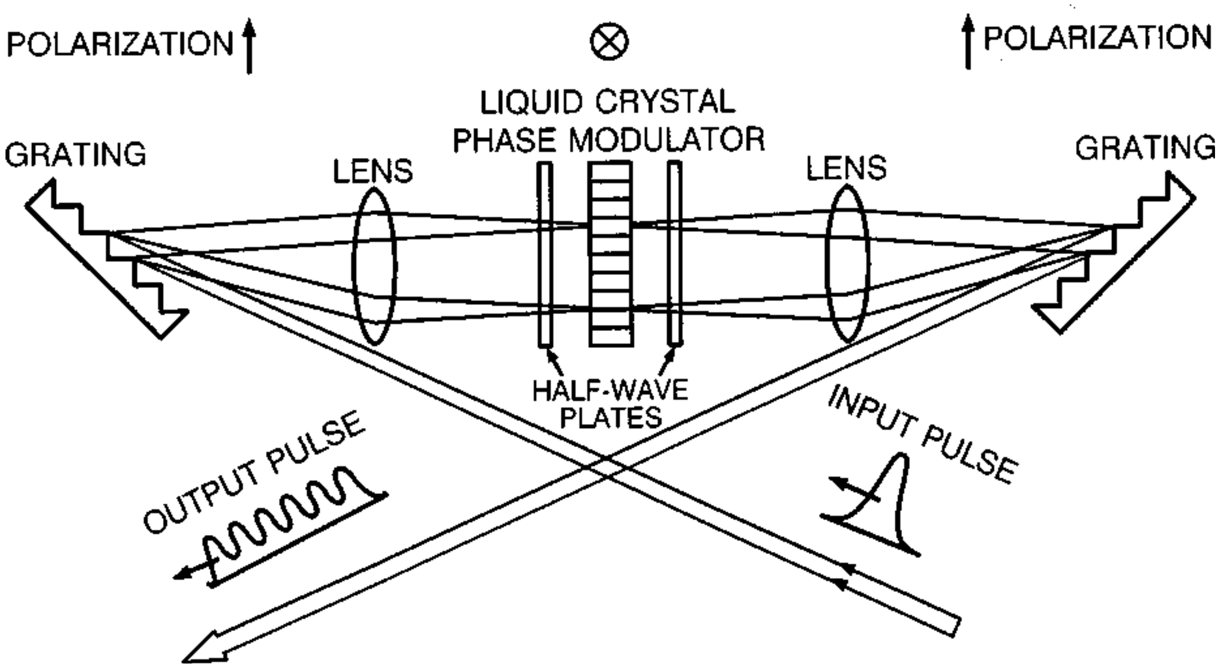


II.2.2.3) Phase modulation only.

This method has a main advantage: the transmission is equal to unity (from a mathematical point of view, real systems introduce loss and, for some systems, the loss can depend on the transfer function to be generated). The main drawback of this method is a more stringent requirement on dynamic and spectral resolution of the pulse shaper than with amplitude and phase modulation.

II.3) Linear systems: principle and limitations.

We restrict ourselves to the most common systems available for pulse shaping. The most well-known system was proposed by Weiner and Heritage and is called a 4f system. In this system, (see figure below), the first grating is separated from the first lens by a distance equal to the focal length f. In the back focal plane of the lens we find a modulator (here a liquid crystal phase modulator). In this plane, the Fourier plane of the system (at each transverse position corresponds a frequency) the modulator is able to apply different optical paths (phase) to the different frequencies. A more complex modulator can allow amplitude and phase modulation. After the modulator, there is another lens at a distance f, then a second grating at a distance f. The output beam is shaped in time.

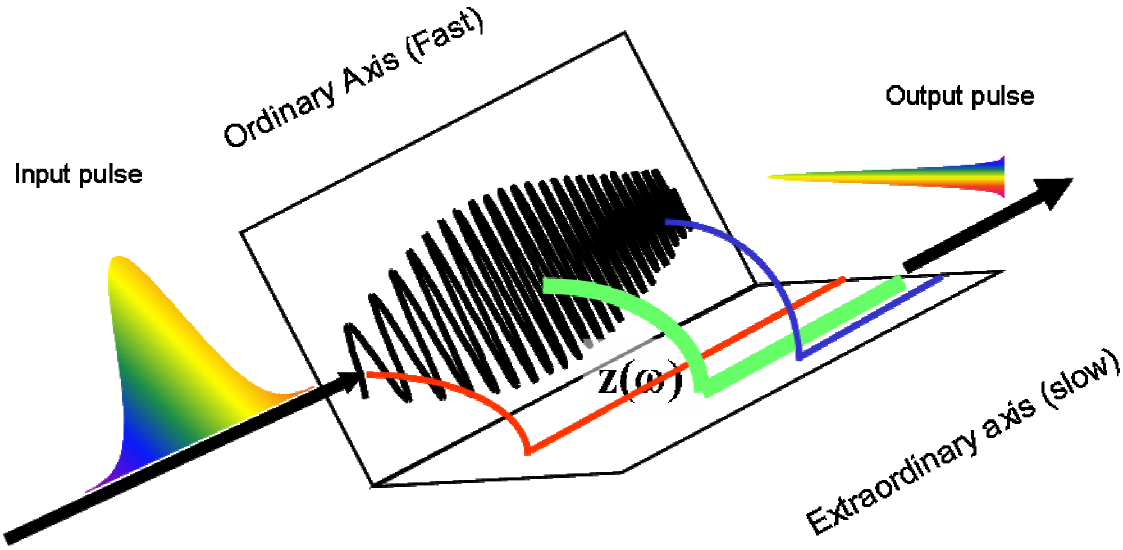


The limitations of the system are linked to the efficiency of the gratings (which will introduce some losses) and to the modulator. High resolution and a good dynamic can be obtained but many modulators do not allow UV light use or high intensity pulses. Some solutions were found to deal with this problem like the use of an array of silica plate able to sustain UV high intensity pulses [7].

The system we chose to use is an acousto-optic programmable dispersive filter proposed and patented by P.Tournois [8]**.** The commercial name of this system is Dazzler (Fastlite Company). The basic principle of the system is given on the figure below.

It is based on the use of a shaped acoustic wave packet. This shear acoustic wave generates a rotation of the polarization of the optical field at a place z where Bragg condition is verified for the optical and acoustic wave frequency components. The amplitude of the acoustic wave allows control of the amplitude, the position z at which the rotation of the polarization takes place allows control of the phase. The transfer function can be written in the following form:

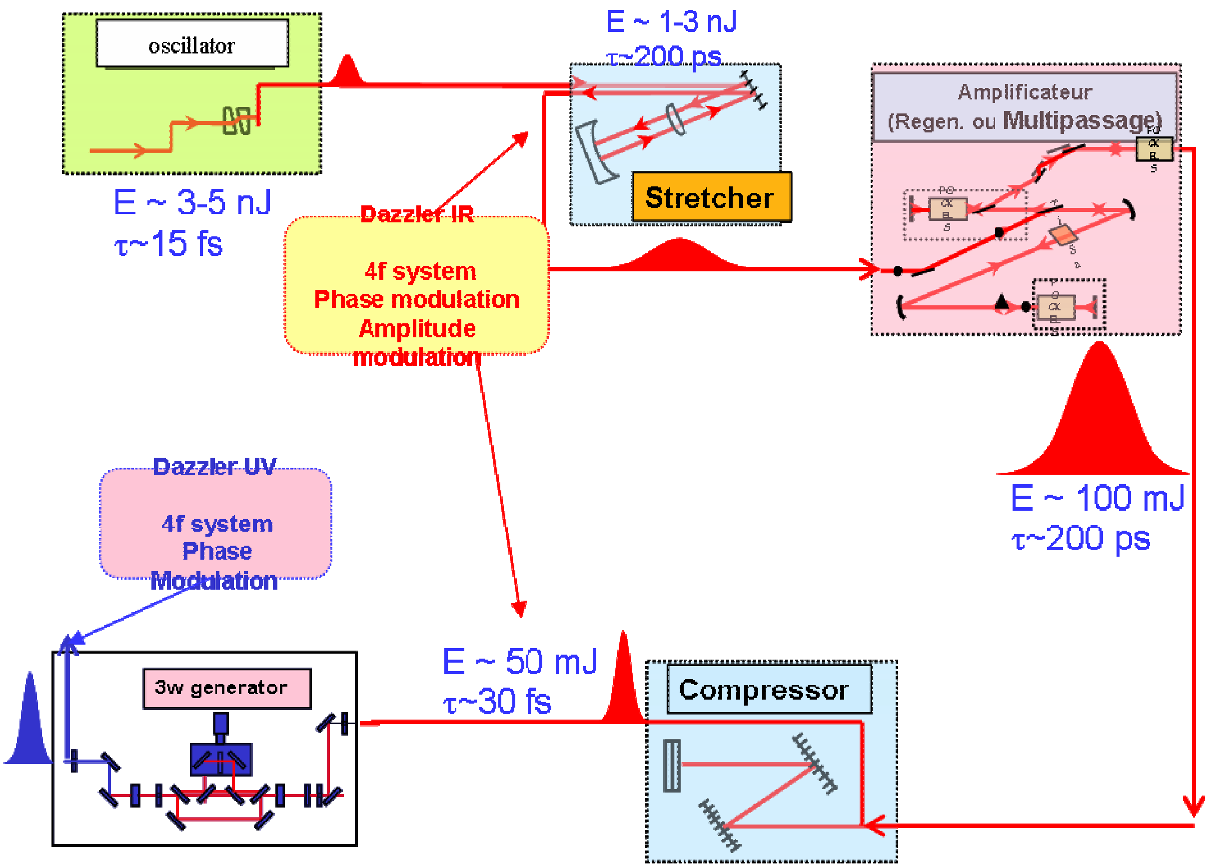
$E_{out}(\omega) = S(\alpha.\omega).E_{in}(\omega) \qquad \alpha \approx 10^{-7}$ (S corresponding to the acoustic wave).



There are also limitations with this system. An important one for our application is the maximum intensity allowed which is 100 MW/cm^2 for the IR version (TeO_2 crystal) and 1 GW/cm^2 for the UV system (KDP crystal). This is not a fundamental limitation as discussed further.

II.4) Considerations on how to do longitudinal beam shaping with a CPA TiS laser system.

We saw in the previous paragraph that the use of a linear system can be submitted to serious limitations. We now discuss how it can be used in a CPA TiS system and present the approach we chose.



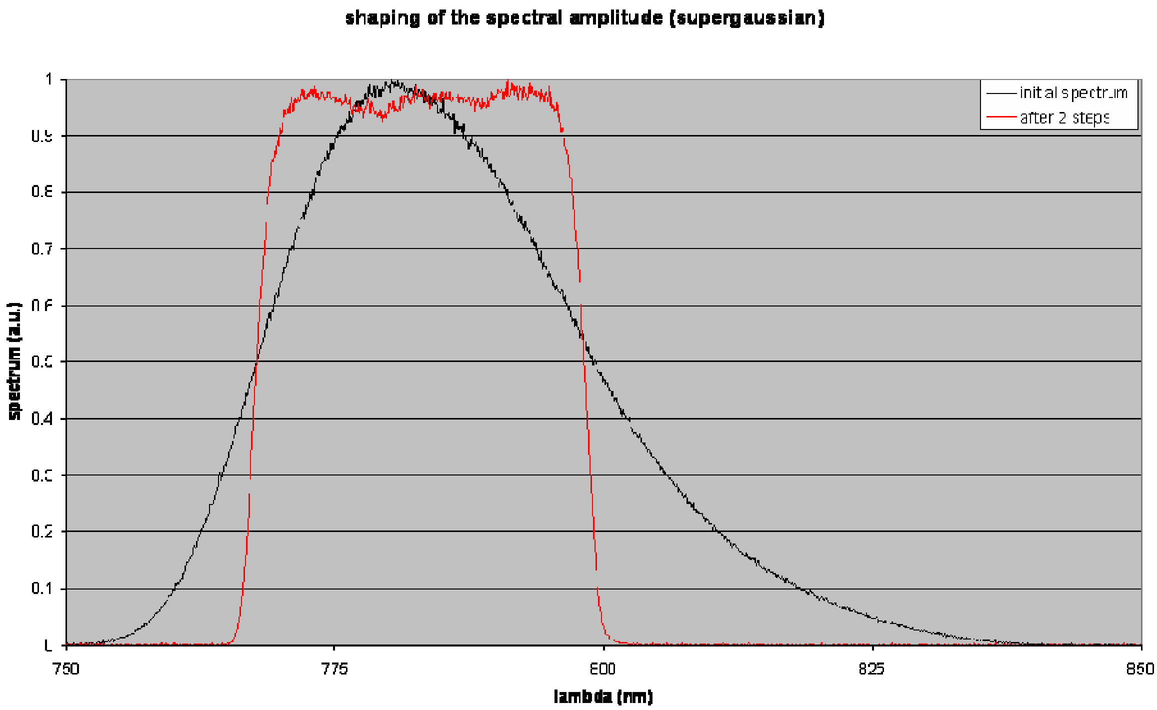
In the CPA TiS system, the Dazzler or 4f system is usually placed after the oscillator and before the amplifier. In this case, the wavelength is λ=800 nm and the intensity is lower than a value which could lead to self phase modulation or optical damage. With this configuration, it is quite easy to correct the spectral phase to obtain a Fourier Transform Limited pulse at the output of the system, if the spectral phase to correct is measured [9]. It is more complicated to shape the amplitude at the output because saturated amplification is used. This can be done in an iterative way. Our goal is to shape the UV beam at the output of the system. Unfortunately, to the nonlinearity in the amplifier, we have to add nonlinearity in the 3ω generator. Constraints linked to the efficiency of the 3ω generation also make the problem more complex. The best solution should evidently lay in the use of a shaper after the 3ω generator.

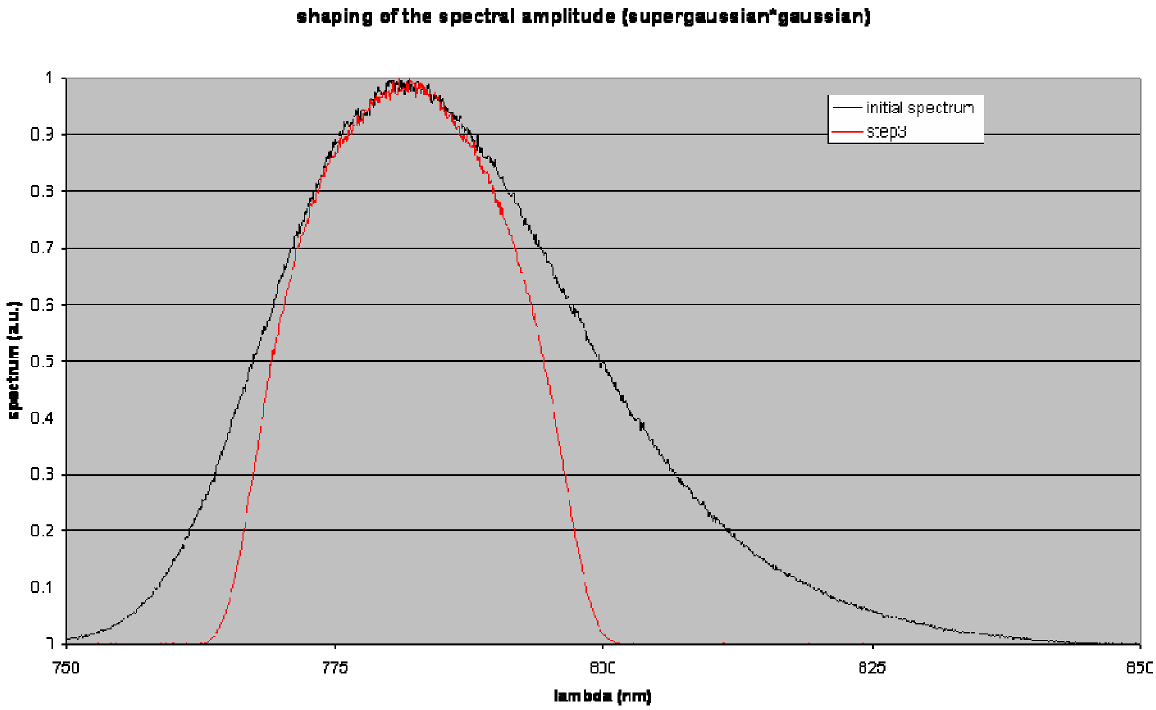
Our approach was to study the pulse shaping with a Dazzler system and to avoid, at least initially, dealing with an overly complicated physical situation. When the studies began, the UV Dazzler was not available. We planned to do our experiment at 800 nm where it was also easier to characterize and manipulate the pulse. The results obtained were then used when the UV Dazzler was available.

II.5) Experimental studies.

II.5.1 Test of the amplitude shaping in the IR.

To test the quality of the amplitude shaping, we used the beam directly at the output of the oscillator. We tried to generate a supergaussian spectrum and then a product of gaussian and supergaussian spectrum. The results are given on the following two figures. The black curves correspond to the input spectrum and the red curves to the shaped spectrum.



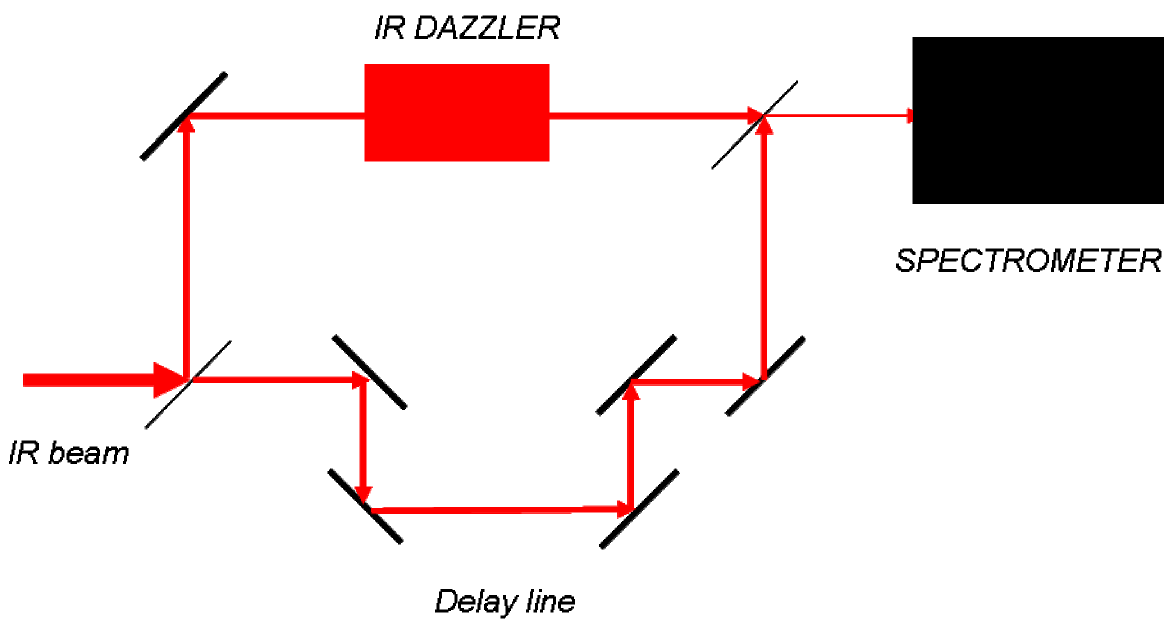


The results are good with a low noise level. For the supergaussian beam, the fluctuations are less than +/-3% in the plateau and the edges are steep enough for the application planned.

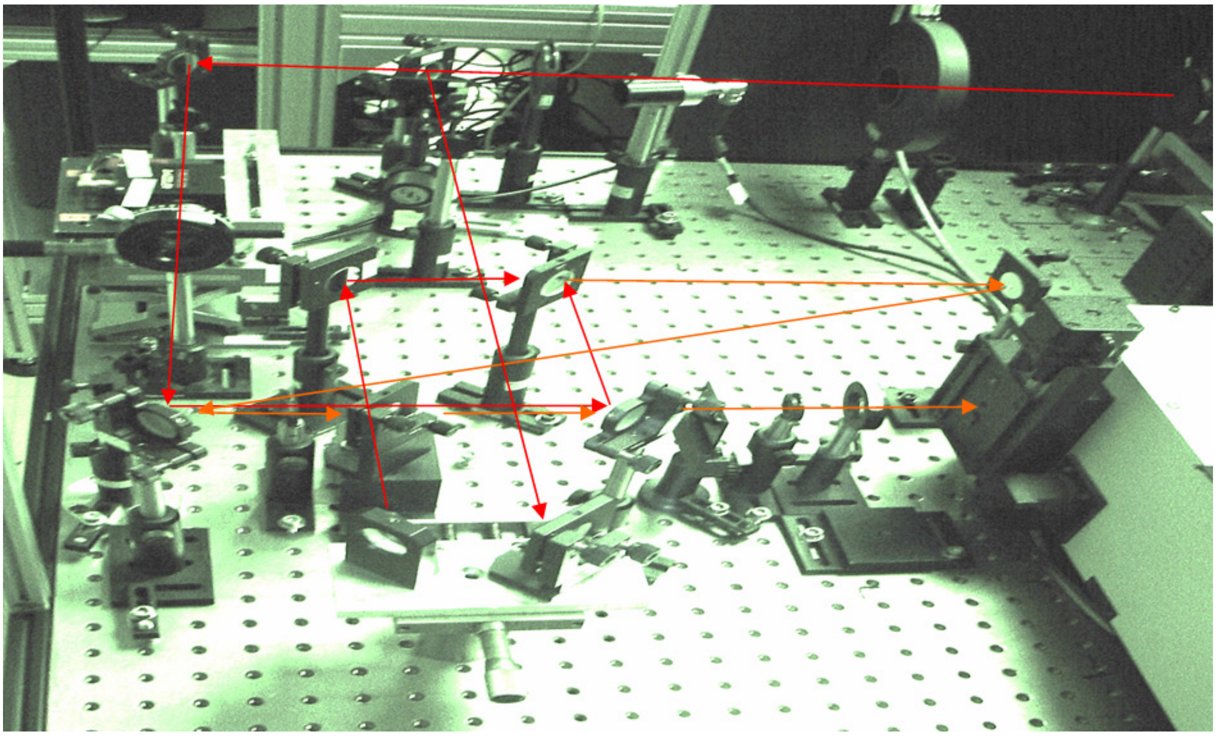
II.5.2 Amplitude and Phase Modulation in the IR.

These experiments were done with an amplified pulse in order to be able to do single shot measurements. The spectral bandwidth is 20 nm after amplification instead of 40 nm at the output of the oscillator. For this experiment, we used a HR IR Dazzler which has twice the resolution of the wide band Dazzler used for the amplitude shaping at the output of the oscillator.

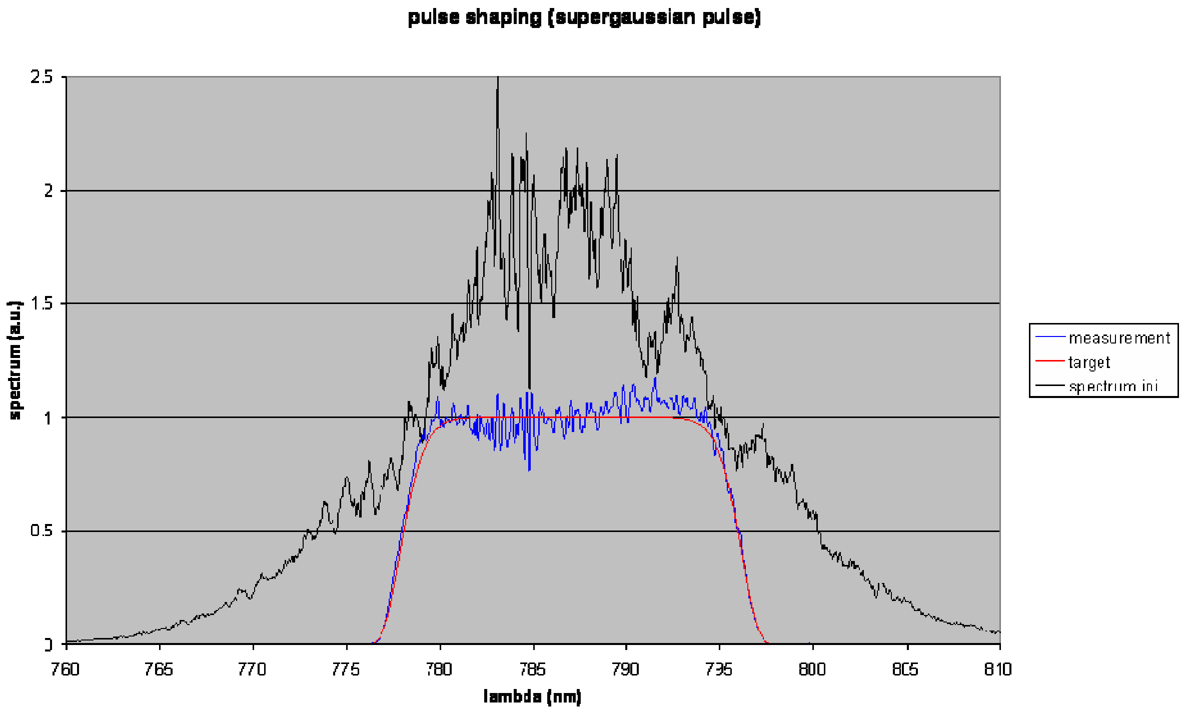
The schematic layout of the experiment in the IR is given on the figure below.

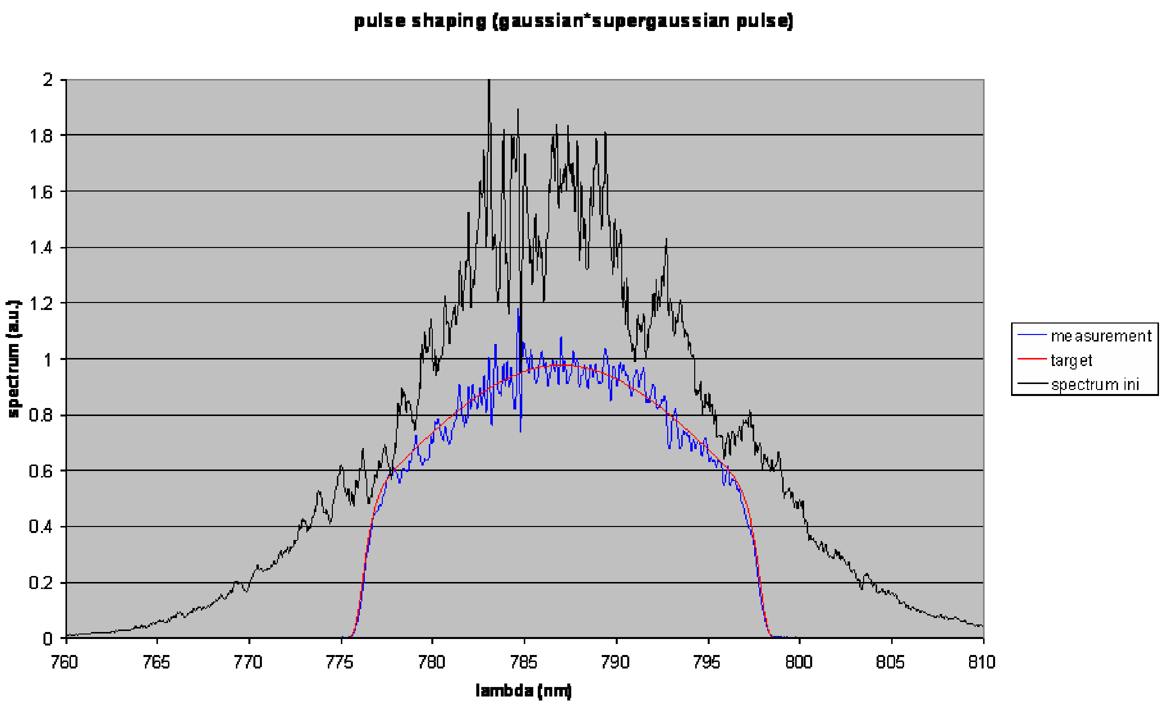


The photograph of the experiment is given below. The Dazzler is in one arm of the Mach-Zehnder interferometer. We can see the entrance slit of the spectrometer which is used with a 16 bit CCD camera (512*1024 pixels). The electro mechanical shutter is used to lower the repetition rate in order to be able to do single shot measurements.

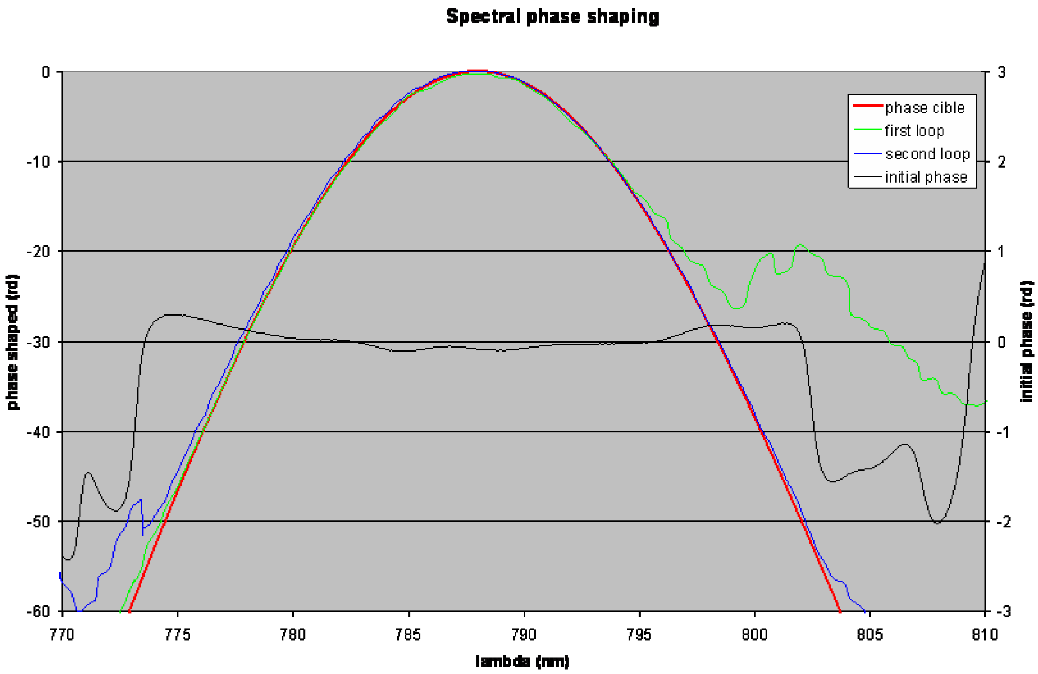


The results obtained for amplitude shaping (supergaussian and product of gaussian and supergaussian spectra) are given on the two figures below. The initial spectrum is strongly modulated. This is due to the presence of optical defects in the Offner type stretcher. We planned to change the optics and redo the measurement. We have been unable to do this so far, due to time constraints and because it is not of fundamental interest, except to show that this type of problem can be present and the cause of strong fluctuations on the temporal intensity. Once again, the detection of this problem will depend on the diagnostic used. However, the shaped spectra obtained are very close to the targets except for the fast modulations which we were not able to correct perfectly.

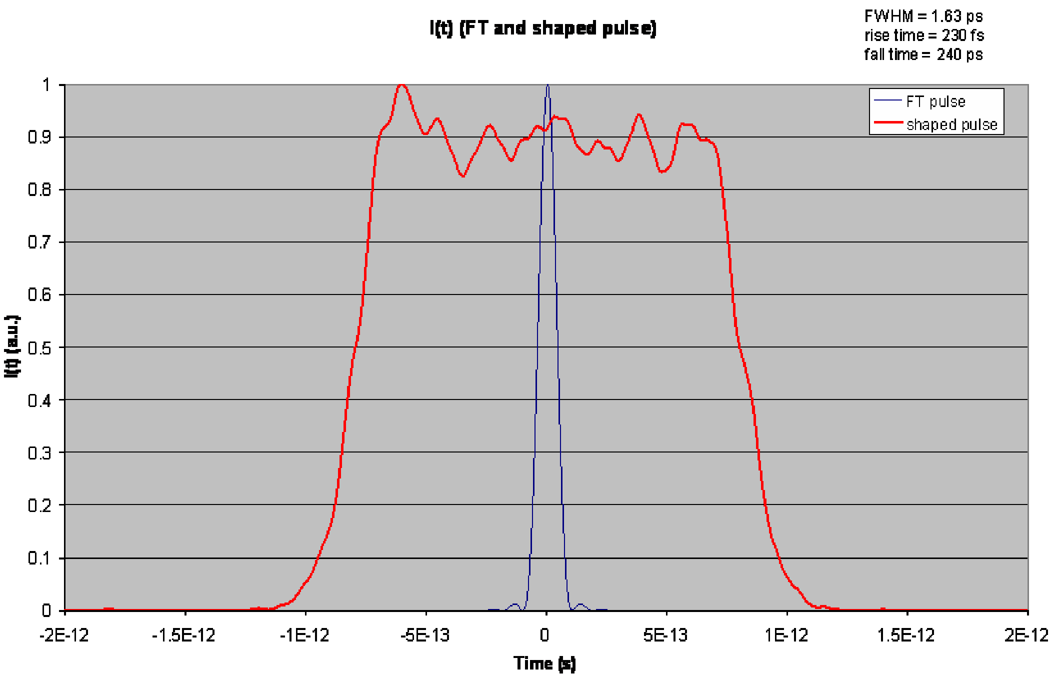




The next step was to generate the proper spectral phase to obtain the target intensity profile. One case is presented on the figure below. The black curve corresponds to the phase at the input of the Dazzler. The red curve corresponds to the target phase. The green curve corresponds to the results obtained after one correction; the blue curve corresponds to a second correction (to remove residual errors).



With the shaped spectrum and phase, we obtained the temporal intensity given on the figure below.

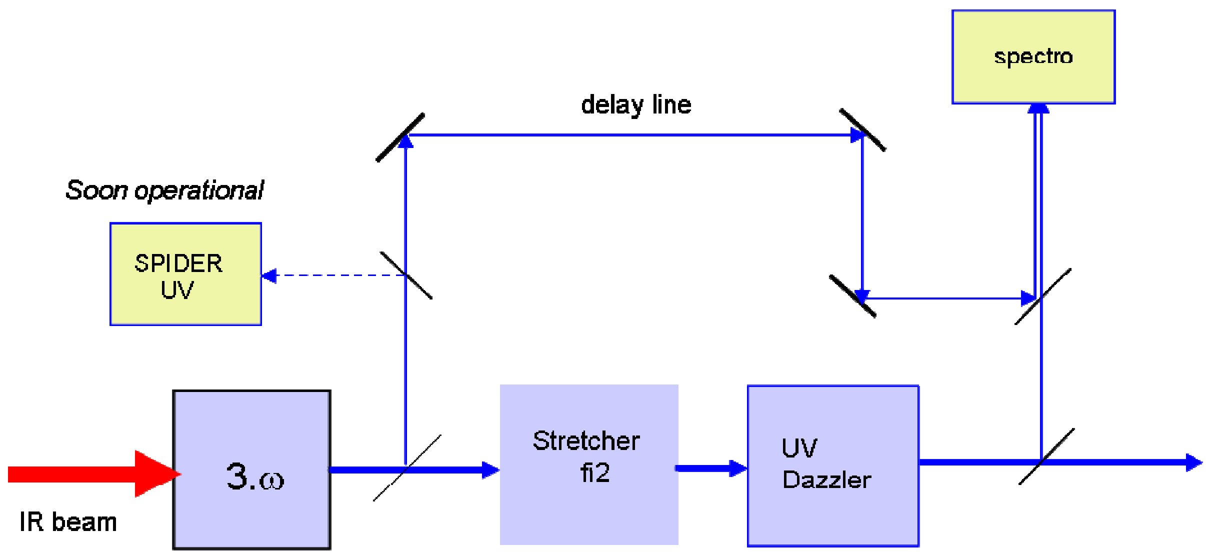


We deliberately chose pulse duration of 1.6 ps in order to make the phase measurement easier. This is linked to the fact that the spectral phase is determined by spectral interferometry between the shaped pulse and the nearly Fourier transform-limited pulse; that leads, for the chirp value used, to a strong variation of the fringes spacing from one side to the other side of the spectrum. This can be solved and longer pulses can be measured with a slight experimental setup modification. As this does not change the quality of the result (with respect to the ratio of the rise time and fall time over the pulse duration) we did not do it.

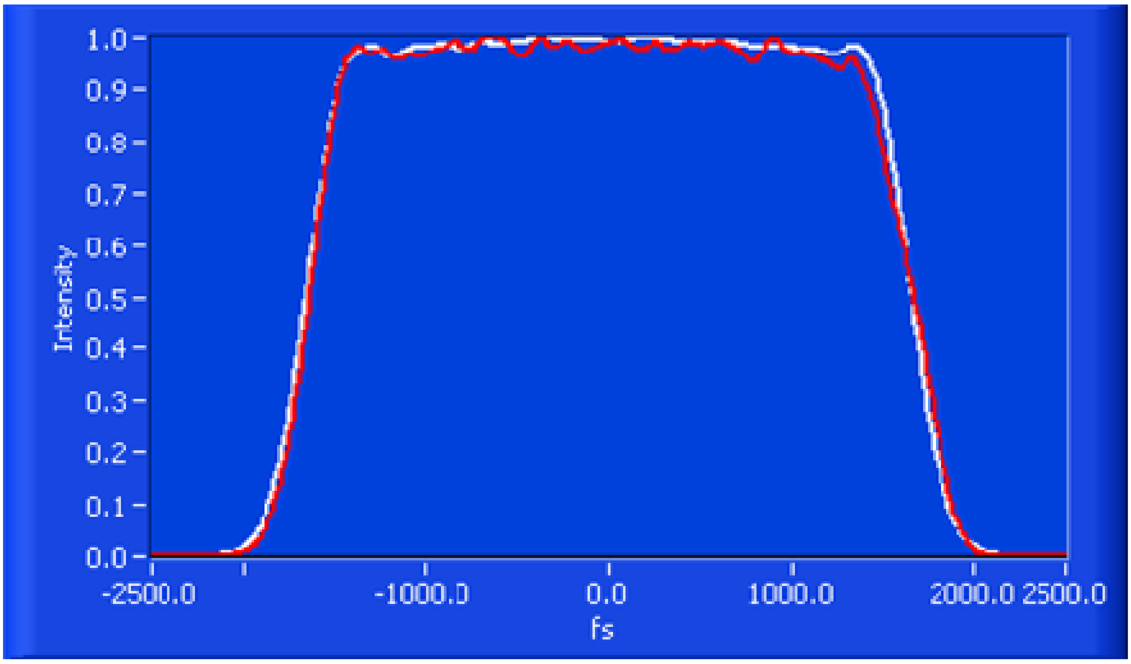
II.5.3 Amplitude and Phase Modulation in the UV.

When the UV Dazzler was available, we did the same kind of experiment at λ = 266 nm. This work was presented at CLEO 2007 (see [10] for details). The schematic layout of the experimental setup we planned to use is shown on the following figure. Unfortunately, the UV SPIDER was not operational at that time; so, the reference phase taken into account is the spectral phase of the 3ω pulse at the output of the 3ω generator. This is of no importance to demonstrate the generation of 3ps square UV pulse.

Pulse shaping : UV experiment setup



The temporal intensity profile obtained is given on the figure below. The FWHM of the pulse is 3 ps and the rise time and fall time of the order of 400 ps. The detail of the signal processing used is discussed in [10].



II.6) Considerations about the energy available at the output of the system.

In the previous paragraphs, we have detailed our approach for the study of the longitudinal beam shaping. We based our work on the use of a linear system (DAZZLER) to shape the λ=266 nm pulse. From the point of view of beam shaping, we consider our results as satisfactory. The most difficult parameter to reach is the energy which has to be sent on the photocathode (a value of 500 µJ is required for a copper photocathode).

The new version of the UV Dazzler has a useable acoustic column of 3*3 mm^2. The KDP crystal used has a nonlinear index n_2 of the order of 10^{-15} cm^2/W. The crystal length is 70 mm.

A quick estimation of the energy which can go through the system while keeping the non linear phase below a value of $\pi/2$ can be done. We recall the definition of the B integral:

$$B = \frac{2.\pi}{\lambda}.\int_0^L n_2.I(z).dz \qquad (4)$$

Where I is the temporal intensity which can be expressed in the following form:

$$I(z) = k.\frac{E}{\tau_p(z).S_0} \qquad (5)$$

where k is a constant close to 1 whose value depends on the temporal shape of the beam. τ_p is the pulse FWHM at z. For a gaussian temporal profile:

$$k = 1/\sqrt{\frac{\pi}{4.Ln(2)}} \cong 0.939 \qquad (6)$$

S_0 is the beam effective area depending on the spatial beam distribution.

For a gaussian beam of waist ω_0 :

$$S_0 = \frac{\pi.\omega_0^2}{2} \qquad (7)$$

For a square temporal profile of radius r_0:

$$S_0 = \pi.r_0^2 \qquad (8)$$

The value of the beam waist for the gaussian beam has to be taken equal or below the third of the size of the acoustic column (ω_0 = 1mm). In the case of a square spatial profile, r_0=1.5 mm. The numerical values obtained are:

$$S_0^{gaussian} \cong 0.0157 cm^2 \quad S_0^{square} \cong 0.0707 cm^2$$

A square spatial profile would allow pulse energy 4.5 times higher than a gaussian one using a spatial beam shaping before the UV Dazzler.
In the most favourable case, the pulse duration inside the Dazzler crystal should be approximately higher than 15 ps (we took a transmission of 50% for the UV Dazzler). Unfortunately, this value is higher than the 5 ps required.
That does not mean that it is not possible to reach the target parameters but, to do so, we need to stretch the pulse before the Dazzler and compress the beam after (instead of just stretching the pulse once). The main drawback of this method is the transmission of the compressor.

One solution could be the use of loss free systems for compression and dispersion (prism compressor and bulk material). In this case, the constraint is put on the spectral width of the 266 nm pulse.

Another solution could be to use a Dazzler with an acoustic column of a bigger size which is not planned to be made soon.

III) Summary of our study of longitudinal beam shaping.

Our study of the longitudinal pulse shaping was based on the use of a linear system (UV Dazzler) at the output of the 3ω generator of a TiS CPA laser. Before the UV Dazzler was available, we did our experiments with IR Dazzler and beam. This step enabled us to validate our calculations and experimental methods. Once the UV Dazzler was available, we applied the same methods and were able to generate high quality quasi top hat intensity profile at λ=266 nm. Emphasis should be put on the use of powerful diagnostics (spectral interferometry, spectral shearing interferometry,…) that allowed us to do single shot measurements. To our knowledge, we are the only group that has used UV Dazzler and spectral interferometry.

The parameter which is not easy to reach with our method, is the energy at the output of the system (500 µJ on the copper photocathode, we estimate to be able to reach at least 100 µJ with a high quality beam). There are no fundamental limitations for this and we suggested different solutions which we still have to investigate thoroughly.

Our study is complementary to others which use longitudinal beam shaping before chirped pulse amplification and third harmonic generation [11-12]. In this case, the generation of a very high quality profile is quite difficult due to the different nonlinear stages between the linear pulse shaper and the photocathode.

IV) References.

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