DESY Summer Student Project

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Nationality:

German

Construction and Simulation of a Femtosecond X-ray Pulse Shaper for use at FLASH

Area of research:

Femtosecond Photon Physics

Time frame:

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1. Introduction

During the DESY summer students program it was my task to help with the construction and simulation of a femtosecond soft X-ray pulse shaper. The shaping of soft X-ray FEL pulses is quite important for research, as FEL pulses are usually not Fourier limited but longer. One of the tasks of a pulse shaper is compressing a linearly chirped pulse down to the Fourier limit. This allows for experiments with higher time resolution that will help further progress in medical research, chemistry, biology and physics.

My work here consisted of two parts: participating in the assembling of the soft X-ray pulse shaper and simulating its performances using Wolfram Mathematica™.

2. Theory

2.1. Free Electron Laser

A FEL consists of a particle accelerator and special magnets called undulators. In the particle accelerator electrons are accelerated to the speed of light, reaching energies in the order of 1GeV. These high energy electrons are then sent into undulators, magnets made of a series of small dipoles with alternate polarity. In the undulators the electrons are deflected into a sinusoidal trajectory due to the alternating perpendicular magnetic field due to Lorentz force interaction.

This interaction also leads to deceleration, i.e. loss of energy. This energy is then emitted as photons, their energy depending on the magnetic field strength and the geometry of the undulator, as well as the angle Θ in which the photon comes from the undulator, where 0 is parallel to the electron beam. The radiation wavelength λ is given by the equation:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + (\Theta\gamma)^2\right)$$

Where:

$$K = \frac{eB\lambda_u}{2\pi mc}$$

Here λ_u the undulator wavelength (thickness of two magnets), γ Einstein's γ-factor and B the magnetic field strength, c the velocity of light, e the electric charge, and m is the electron mass. These FEL pulses have only a very short duration, as the electrons are ultra-relativistic and contained in a bunch which is just about 1ps long. As the electrons interact with their emitted photons, more so the ones with very small Θ, the microbunching process takes place, where the electrons form subgroups within the electron bunch, which are spatially separated by λ. Under ideal circumstances this process could lead to emission of coherent light (when a seeding scheme e.g. HGHG is used) in the form of a Fourier limited Gaussian pulse. In practice though, this is not quite the case. To compress a pulse down to its Fourier limit a pulse shaper with special mask is needed.

2.2. Ultrashort Pulses

Ultrashort pulses are pulses with only a few femtoseconds time duration. Such pulses can be expressed in either angular frequency ω or in time and phase domain. These two representations are equivalent and can be transformed into one another using a Fourier transform:

$$\boldsymbol{E}(t) = A(t)e^{i\phi(t)} = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} \boldsymbol{E}(\omega)e^{i\omega t}$$

Where:

$$\boldsymbol{E}(\omega) = A(\omega)e^{i\phi(\omega)}$$

is the electric field in frequency domain and **E**(t) in time domain.

The product of time duration and energy bandwidth cannot be lower than the Fourier limit, which reads for a Gaussian pulse:

$$\Delta E[eV]\Delta t[fs] \geq 1.825.$$

2.3. Fourier Limited Pulse and Chirped Pulse

A Fourier limited pulse is defined by its constant phase, such that

$$\phi_{FL} \propto Cos(\omega_0 t)$$

A linearly chirped pulse is a little more complex. Here the instantaneous frequency $\omega(t) = \frac{d\phi}{dt}$ changes with time, therefore the chirp $\frac{d^2\phi}{dt^2} \neq 0$.

This lets us expand the phase around ω_0:

$$\phi(\omega) = \phi(\omega_0) + \frac{d\phi}{dt}(\omega_0)(\omega - \omega_0) + \frac{1}{2}\frac{d^2\phi}{dt^2}(\omega_0)(\omega - \omega_0)^2 + O(\omega^3)$$

Here $\phi(\omega_0)$ is the absolute phase, $\frac{d\phi}{dt}(\omega_0)$ a delay between pulse and an arbitrary origin and $\frac{d^2\phi}{dt^2}$ the chirp of the phase. In the experiment the chirp can be determined using the HWHM of the incoming and outgoing pulse. The chirp can be expressed by [Leslie's Book, Fundaments of Photonics, B.E.A. Saleh and M.C. Teich]:

$$\frac{d^2\phi}{dt^2} = \frac{1}{{\sigma_{in}}^2} \sqrt[2]{\frac{{\sigma_{in}}^2}{{\sigma_{out}}^2} - 1}$$

2.4. Pulse Shaping

Using gratings and some specific kinds of mask, it is possible to shape ultrashort pulses in time and frequency domain. For doing so a common device is a 4f pulse shaper, where two identical lenses or mirrors are used in conjunction with two identical gratings and the mask. Each optical device is a focal length apart from one another, such that the length of the whole system is four times the focal length. It is also very important that the optical path length is the same for all frequencies. This yields a focused and wavelength dispersed beam in the so-called Fourier plane where the mask is located (an LCD modulator in Figure 1).

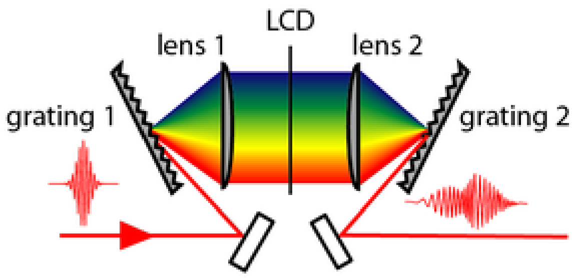

Figure 1: Sketch of the 4f-Steup. An LCD modulator used as mask, and it is located in the Fourier plane. The distance between grating and lens, as well as lens and focal plane is the lenses focal length respectively.

When the mask is applied to the signal, the calculation can be done in the frequency space, such that the outgoing pulse can be calculated as:

$$\boldsymbol{E}_{out}(\omega) = \boldsymbol{M}(\omega)\, \boldsymbol{E}_{in}(\omega)$$

$$\boldsymbol{M}(\omega) = A_{Mask}(\omega) e^{i\phi_{Mask}(\omega)}$$

with *M(ω)* being the mask in frequency space. This yields the following equations:

$$A_{out}(\omega) = A_{Mask}(\omega)\, A_{in}(\omega)$$

$$\phi_{out}(\omega) = \phi_{Mask}(\omega) + \phi_{in}(\omega)$$

So for a known input pulse and a desired output pulse one can easily calculate the function the mask is supposed to have.

For this particular case, a Gaussian shaped linearly chirped input pulse was used to form a Gaussian Fourier limited output.

3. The Experiment

3.1. Experimental Setup

The pulse shaper consists of a 4f-setup within vacuum chambers. It consists of concave mirrors instead of lenses for focusing the beam, as soft X-rays are absorbed by any kind of matter. The mask is a micro mirror array consisting of many small mirrors next to one another having a width of 45µm and a separation of 5µm. Each of those mirrors can be tuned in height separately from one another. This enables very fine tuning of the masks phase shift in frequency space.

The geometry of this setup dictates a slightly nonlinear dispersion of the frequency in position space:

$$x(\omega) = f\ (Tan\left[\frac{\pi}{2} - \gamma\right] - Tan[\frac{\pi}{2} - \gamma + ArcSin\{\frac{2\,\pi\,c}{d\,\omega} - Sin\{\Theta_i\}\}])$$

where f is the lenses focal length, γ the angle between focal plane and grating normal, d the distance between two grating lines and c is the speed of light.

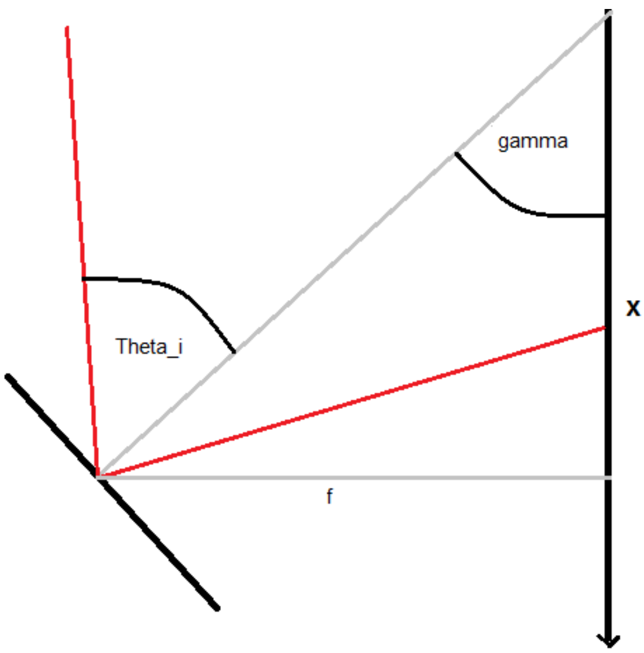

Figure 2: Sketch of the setups geometry.

3.2. Simulating the Experiment with Mathematica

It was my task to write a program for simulating the micro mirror array with Mathematica. The incoming pulse is a Gaussian one with a linearly chirped phase and the outgoing one is desired to be as close at possible to a Fourier limited Gaussian pulse. To simulate the behavior of this setup the incoming and desired output pulse in time domain were sampled and transformed into frequency domain using the Mathematica FFT routine. The micro mirror array was moved in order to compensate the phase delay of the frequency in the middle of the mirror. Therefore the position of the mirrors can be written as:

$$y(\omega) = \frac{c}{\omega}\ [\phi_{out}(\omega)\text{-}\ \phi_{in}(\omega)]$$

where c is the velocity of light and y is the height of the corresponding mirror inducing a phase shift from ϕ_{in} to ϕ_{out}.

This height of the mirrors is used further to simulate a mask, that is applied all points of the sampled incoming pulse in frequency space.

This should yield something similar to the desired outgoing pulse in frequency space, which then can be transformed back into the time domain. This should then yield the desired outgoing pulse in time domain.

3.2.1. Results of the Simulation

The simulated chirped incoming Pulse has FWHM of 118fs, the outgoing Fourier limited pulse a FWHM duration of 11.2 fs. This yields a chirp of 1.748×10^{29} for a bandwidth of 0.5% at 38nm.

The incoming pulse had a Gaussian intensity distribution in the time domain with a linear chirp.

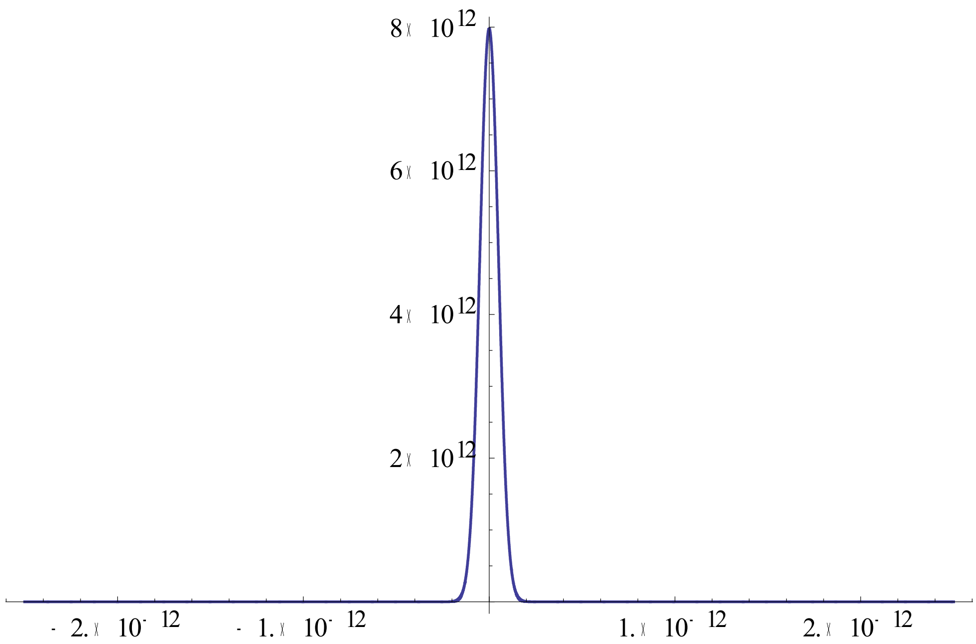

Figure 3: Temporal intensity profile in arbitrary units of the incoming pulse with respect to time in s.

Using the Fourier transform of the incoming Pulse (Figure 3) and the Fourier transform of the desired outgoing pulse (Figure 8), one can obtain the phase difference of both pulses.

From this information, the program can calculate the height of the mirrors in m of the MMA, which are shown in Figure 4.

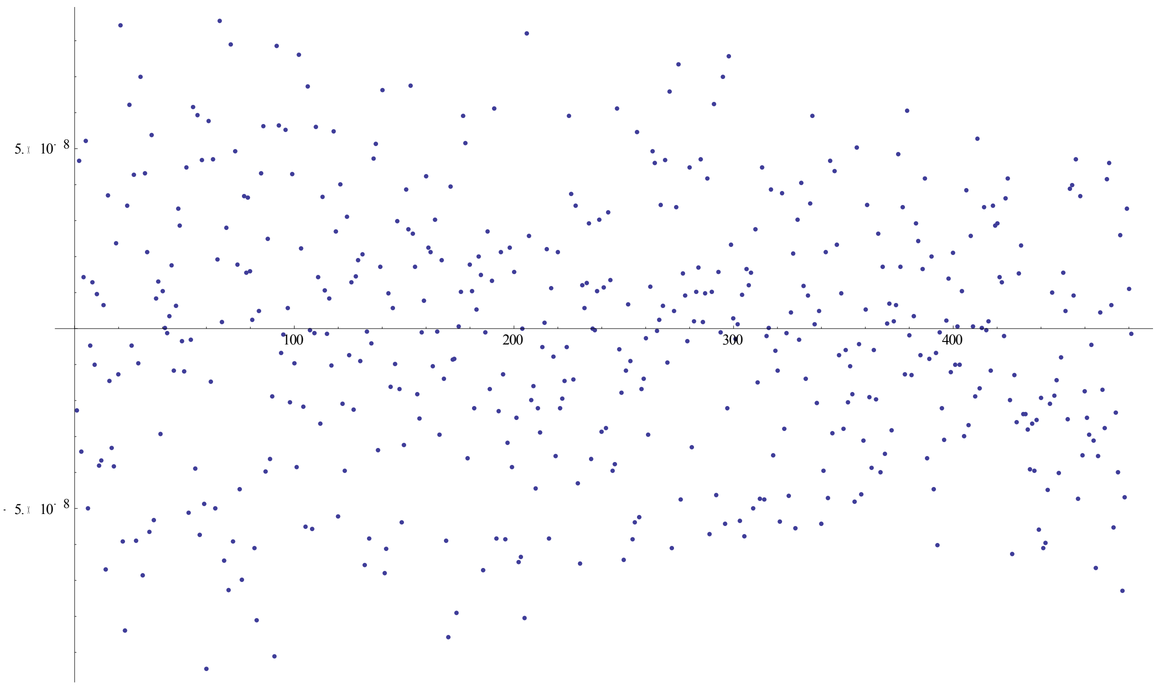

Figure 4: Displacement of the respective micro mirror in the MMA to obtain the desired phase shift.

Applying this mask to the incoming pulse as shown in Figure 5 one gets the shaped pulse in frequency space as shown in Figure 6.

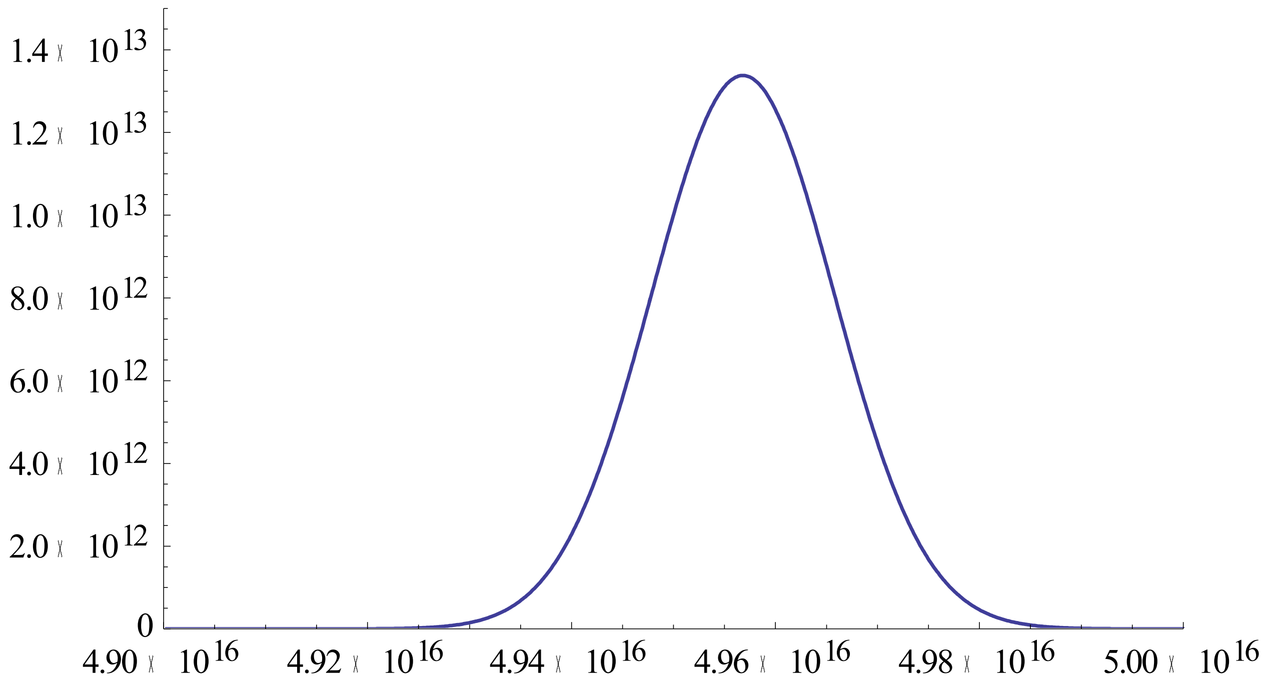

Figure 5: Shape of the Intensity profile in arbitrary units of the incoming pulse in frequency space in rad/s.

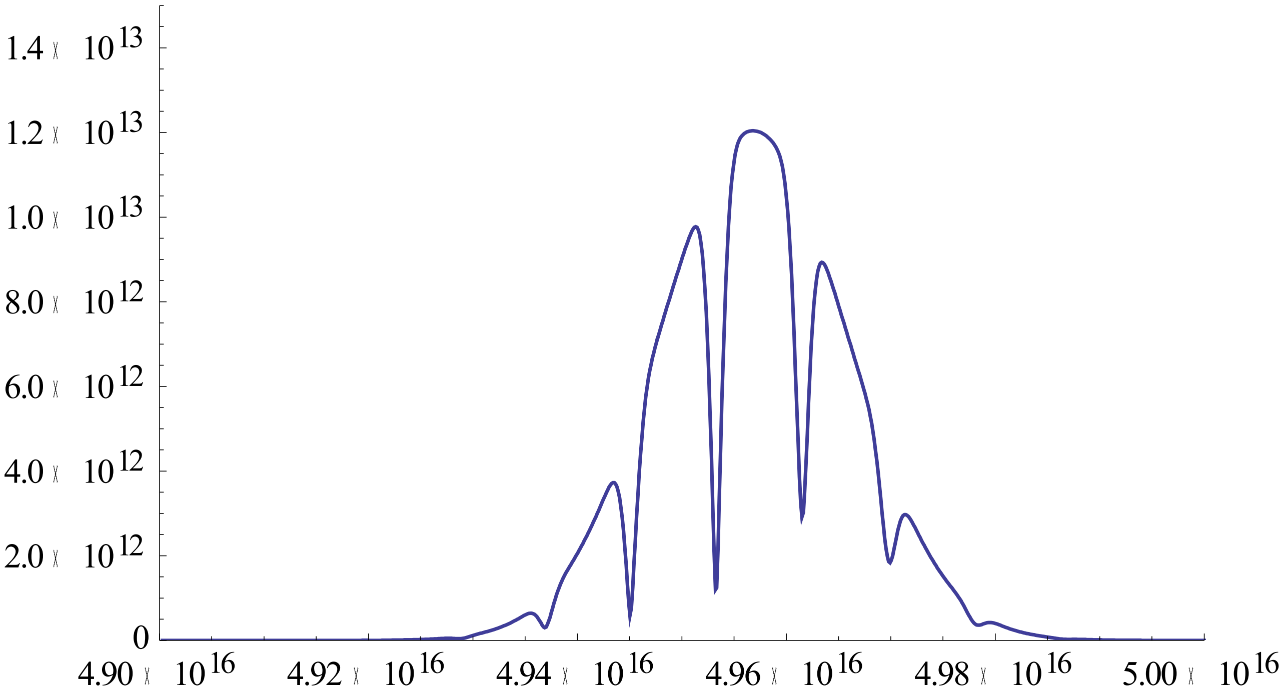

Figure 6: Shape of the Intensity profile in arbitrary units of the incoming pulse in angular frequency in rad/s space after applying the mask.

As one can see in Figure 6, there are several dents in the Gaussian pulse. This is due to the distance between the micro mirrors. In this picture one can see that there are only seven micro mirrors actively shaping the pulse.

The Fourier transform of this pulse yields the temporal distribution of the shaped pulse, which can be seen in Figure 7. Comparing this result to the desired outgoing pulse shown in Figure 8, one can see big discrepancies. The intensity distribution is not Gaussian anymore and the phase is not as well defined as desired.

Also the temporal length of the shaped pulse is way bigger than desired. The pulses FWHM is 116fs, which is slightly shorter than the 118fs long incoming, chirped pulse.

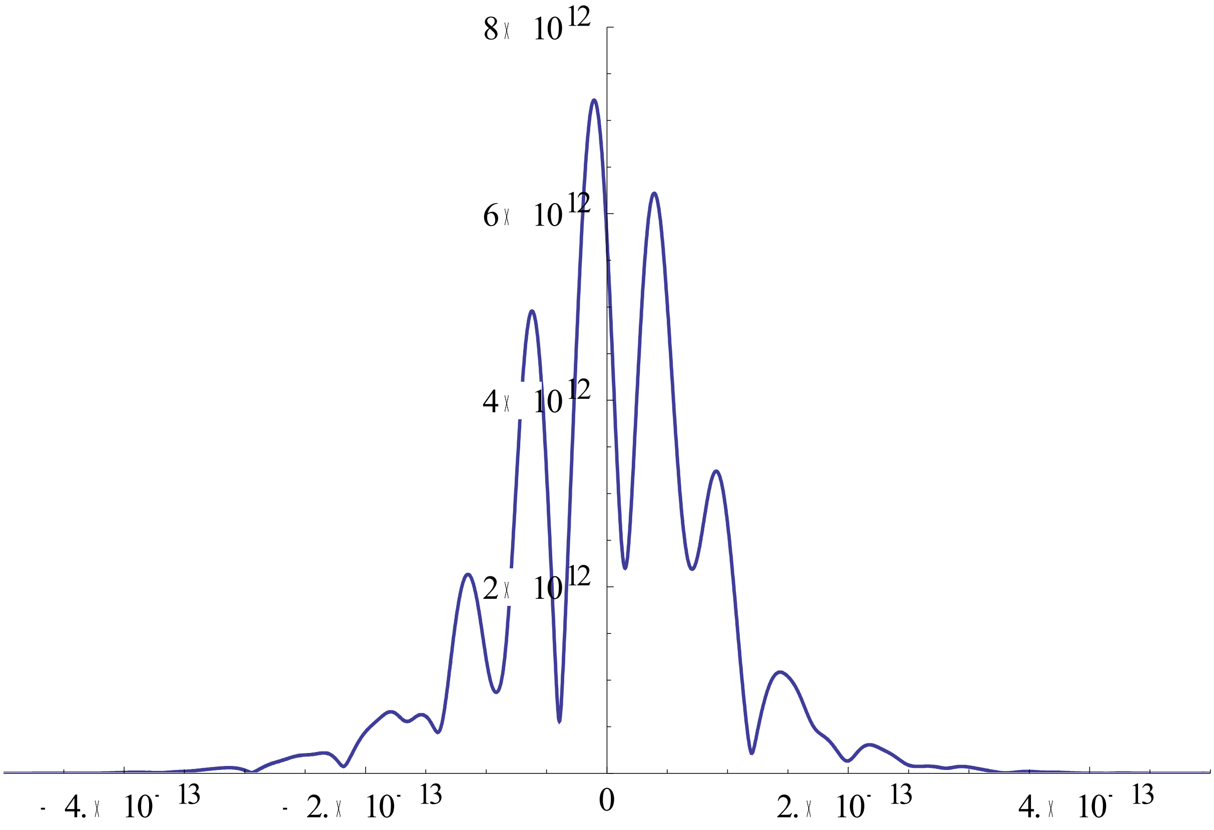

Figure 7: Temporal envelope incoming pulse after applying the mask in arbitrary units vs. time in s.

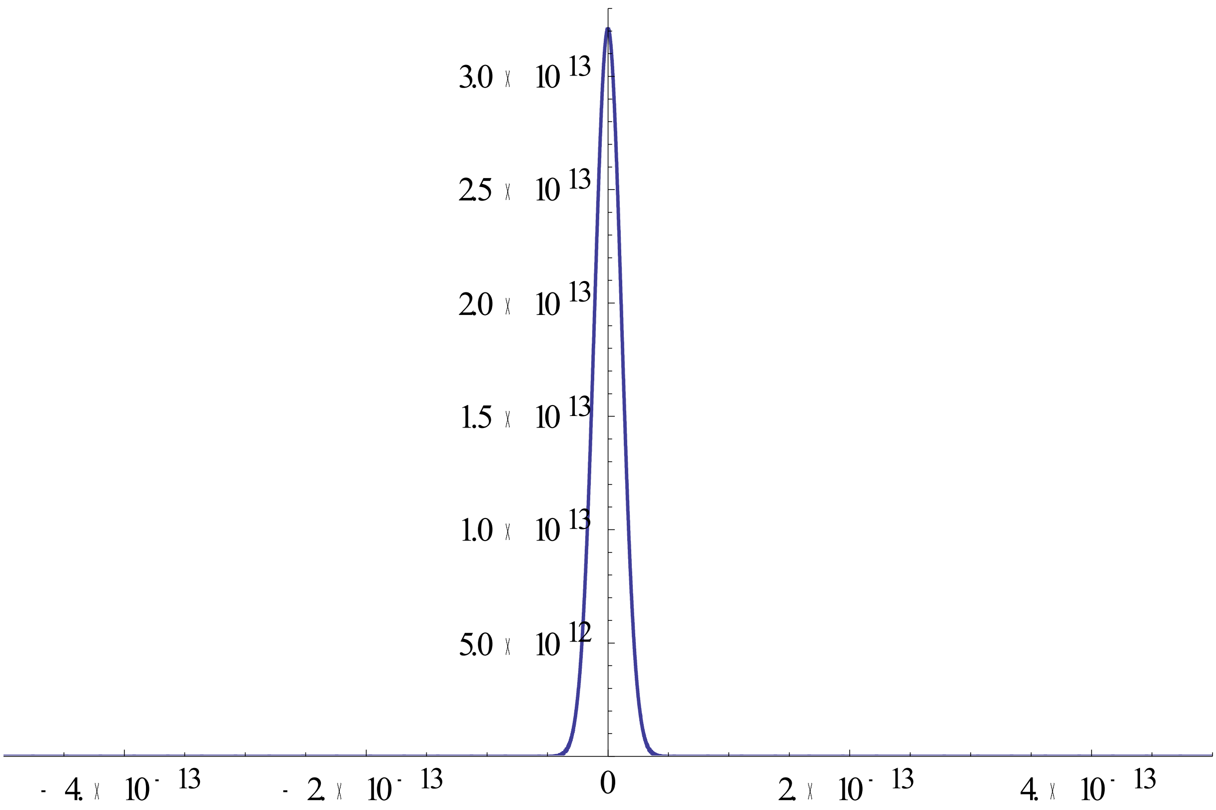

Figure 8: Temporal envelope of the desired outgoing pulse in arbitrary units vs. time in s.

5. Conclusion and Outlook

In my time as a summer student I managed to create the first version of a simulation program for simulating a MMA pulse shaper. This program needs to be optimized further to yield good results though. As it stands the program still has some bugs and needs further optimization for calculating the mirror positions.

It is important to note, that the first, basic version of the program is working and only a few minor adjustments need to be done to make this project a full success and to simulate a real pulse shaper.