Contrast Enhancement of Femtosecond Terawatt Laser Pulses by Preamplification and Temporal Pulse Cleaning

Master's Thesis
by
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Abstract

In this report the building of a multipass amplifier with pulse cleaning is summarized. The aim was to improve the temporal contrast of a femtosecond multi-terawatt laser system based on Chirped Pulse Amplification (CPA) in titanium sapphire at the Lund Laser Centre (LLC). The contrast of the system before this project was normally[1] about 10^{-8}, meaning that if the pulses produced by the system have a focused intensity of 10^{20} W/cm^2 the background light has an intensity of 10^{12} W/cm^2. This high background level causes problems during experiments by interfering with the target before the main pulse arrives. By seeding the regenerative amplifier with a higher energy the amplification can be lowered and thereby also lowering the production of Amplified Spontaneous Emission (ASE) which constitutes the majority of the background noise.

[1]The highest achieved contrast for the old system is $\sim 5 \cdot 10^{-9}$.

Contents

Chapter 1

Introduction

As the focused intensities of femtosecond Ti:sapphire lasers increase it becomes more and more important that the produced pulses are extremely clean from noise. The ratio between the background, consisting of a nanosecond pedestal and pre- and postpulses, and the peak of the pulse is called the temporal contrast. A large part of the effort in high-intensity femtosecond lasers is now also made on the area of contrast enhancement instead of increasing the pulse intensity. The reason for this is that the intensities available today can not yet be fully taken advantage of in all kinds of experiments because of the poor contrast [1].

The introduction of Chirped Pulse Amplification (CPA) in combination with Ti:sapphire lasers made it possible and affordable for university laboratories to keep up with the advances in the otherwise very expensive high-field science. With rather modest energies it is possible to reach focused intensities of over 10^{20} W/cm^2. The research areas possible in gas targets include, among others, high-harmonic generation, electron acceleration and high-energy ions from exploding clusters. On solid targets interesting experiments such as ultrafast X-ray sources, high-harmonic generation and ion acceleration have become possible [2].

1.1 The Multi-Terawatt Laser System in Lund

The multi-terawatt laser system at the Lund Laser Centre (LLC) is based on chirped-pulse amplification in Ti:sapphire and was officially established in 1992 [3]. Since then the system has been upgraded many times and it is currently one of the largest high-power 10 Hz systems in Europe. A rather accurate schematic illustration of the system can be seen in figure 1.1. A pulse duration of less than 35 fs and a peak power of more than 30 TW can be achieved. The LLC is a European Large Scale Facility and part of Laserlab-Europe and Lasernet Europe.

An Ar-ion pumped Ti:sapphire oscillator produces 20 fs long pulses with an energy of 5 nJ at 80 MHz repetition rate and with a spectral width of 50 nm at the central wavelength of 800 nm. The pulses are then stretched to 350 ps in the following stretcher where the pulse energy is reduced to less than 1 nJ and thereafter sent to the regenerative amplifier (regen) on the next table. The Ti:sapphire-crystal in the regen is pumped by 65 mJ from Nd:YAG #1, see figure 1.1. Here the signal is amplified to 5 mJ and a pulse picker selects pulses at a rate of 10 Hz, discarding the rest. The chosen pulses then continue to the five-pass amplifier. Nd:YAG lasers #1 and #2 are used to longitudinally pump the crystal in the amplifier from both sides with a total of 1.2 J. After the multipass amplifier the pulses hit a beam splitter that divides them into two beams, one of which contains about 230 mJ that is compressed and sent into a target room resulting in a peak power of about 2 TW. The other beam is spatially filtered and then once again amplified in a multipass amplifier pumped by Nd:YAG lasers #3–#7 with a total of 5 J. After four passes through the crystal the pulse energy is about 1.7–2 J. The pulses are then sent into a target room where they are compressed in vacuum to about 35 fs. Then the 30 TW pulses are ready to be used in experiments. The diameter of the focal spot is less than 10 μm giving light intensities exceeding 10^{19} W/cm^2. Temporal contrast today is normally 10^8 on the ps scale.

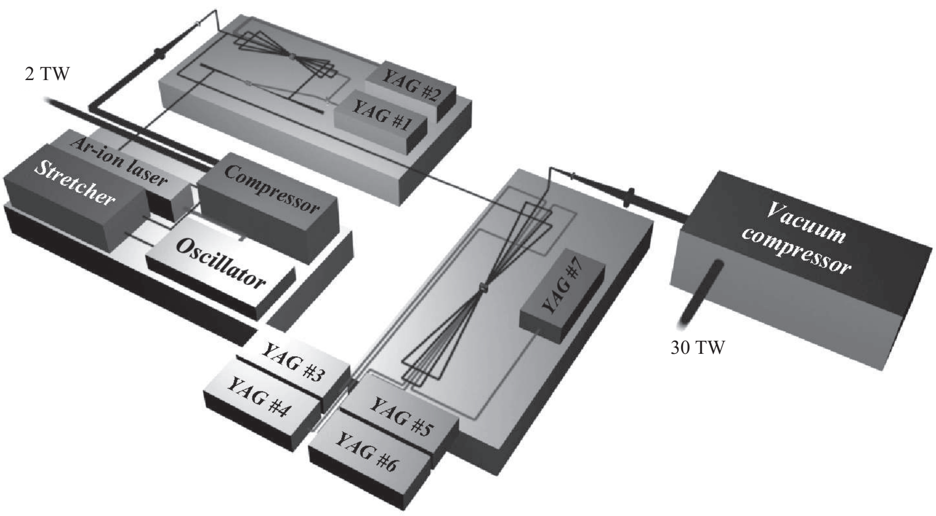


Figure 1.1: *Schematic illustration over the terawatt laser system [4].*

1.2 The Project

This project is a step in the continuous upgrade of the LLC multi-terawatt laser system and aims at increasing the temporal contrast. The idea is also to do it in a non-expensive way with a robust setup that requires little daily adjustment. The setup is planned to be inserted between the oscillator and the stretcher in the system, see figure 1.1.

Earlier investigations [5] indicate that the production of Amplified Spontaneous Emission (ASE) scales linearly with the gain factor, meaning scaling inversely with the energy of the clean pulses seeded into the regenerative amplifier. Therefore, a preamplifier that partly replaces some of the amplification in the regen by increasing the seed energy is a possible way to accomplish contrast enhancement. This also requires that the preamplified pulses still remain rather clean. Today most of the spectral narrowing and ASE production of the system take place in the regen where the main part of the amplification also takes part.

1.3 Outline

Chapter 2 contains, among other things, the background theory for temporal stretching and compression of pulses, laser amplification, ASE and prepulses and non-linear filtering. The theory in this chapter is primarily aimed at describing Ti:sapphire-based systems and the components adjusted for them. In chapter 3 the optical setup built during this master's thesis is described in detail. The report ends with chapter 4 that includes results and conclusions as well as a comparison between the amplifier and simulations made on a computer.

Chapter 2

Theory

To produce femtosecond laser pulses that can be focused to intensities over 10^{20} W/cm^2 with a high temporal contrast a wide range of theory is needed. Some of it is presented in this chapter.

2.1 Titanium Sapphire Lasers

The self-mode-locked Ti:sapphire (Ti:Al_2O_3) laser is the most frequently used laser for generating femtosecond pulses. To obtain these pulses mode-locking is necessary. Because of the wide emission spectrum of Ti:sapphire, see figure 2.1, pulses with a large bandwidth can be produced. With one of the largest bandwidths of any laser it can be operated over a broad wavelength range, $\Delta\lambda \cong$400 nm. For a pulse with a Gaussian shaped spectrum the duration (FWHM[1]) of the pulse, $\Delta\tau_p$, can be expressed as

$$\Delta\tau_p \cong \frac{0.441}{\Delta\nu_L} \tag{2.1}$$

where $\Delta\nu_L$ is the total oscillating bandwidth. A pulse for which this is true is said to be transform-limited [6]. To create a Gaussian pulse of 10 fs duration centered at 800 nm a bandwidth of 94 nm is needed [7]. For pumping of a Ti:sapphire oscillator a continuous wave (cw) laser is used. The absorption spectrum of Ti:sapphire has its peak slightly above 500 nm and this makes it suitable to pump the crystal with the cw green output of Argon-Ion lasers at λ=514.5 nm or frequency doubled Nd:YAG lasers at 532 nm. Required pump powers usually lie between 3–10 W and are determined by the stimulated emission cross section and upper state lifetime [6].

The Ti:sapphire crystal can also be used to amplify femtosecond pulses. When such short pulses are amplified in Ti:sapphire they are severely reduced in bandwidth despite the broad gain bandwidth of the material, lead-

[1] Full Width at Half Maximum is applied to compare measurements on durations or spectral widths of pulses.

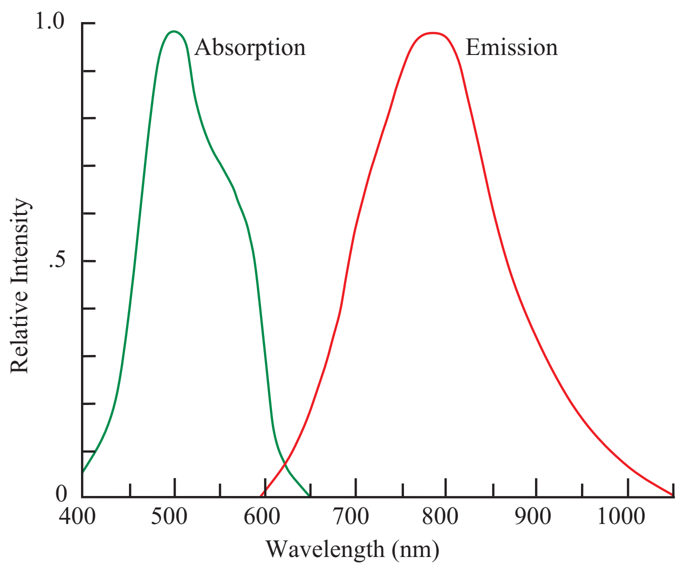


Figure 2.1: *Absorption and emission spectrum for Ti:sapphire [8].*

ing to longer pulse durations. Shifting of the central wavelength may also occur if it does not coincide with the peak of the emission spectrum [9]. For the crystal to obtain its properties Al_2O_3 is doped with Ti_2O_3 in concentrations between 0.1–0.5%. The excited state has an approximate lifetime of τ=3.2 μs. For amplification of already existing pulses the pulsed frequency-doubled output from Nd:YAG or Nd:YLF (λ=527 nm) lasers can be used to pump the crystal [6].

When amplifying high-energy pulses large dimensions of the amplifier crystal are required. For the last amplifier stage in a multi-terawatt laser system the diameter needed of the crystal, in order not to damage it[2], can be several centimeters. Uniformly doped crystals in these dimensions without any imperfections are hard to grow and therefore very expensive.

2.2 Stretching and Compression of Pulses

When a short laser pulse is sent through a dispersive material, such as glass, the different wavelengths travel at different velocities resulting in a stretched pulse with the frequency components separated in time. Usually materials introduce a positive chirp which means that the lower frequencies are ahead of the higher. To compensate for this dispersion a prism compressor or a grating compressor can be used [7].

A simple ordinary prism compressor can consist of two prisms arranged

[2]Ti:Sapphire crystals have a high damage threshold of ~8–10 J/cm^2 [9].

as in figure 2.2. When the pulses travel through the first prism the frequencies are angularly spread. In the second prism the red frequencies must travel through more glass than the blue frequencies and are thereby delayed by the higher index of refraction in glass than in air. At the same time the blue frequencies travel a longer distance in air. By moving the second prism in or out of the beam and varying the distance between the two prisms it is possible to cancel or at least almost cancel the different lower orders of dispersion [10].

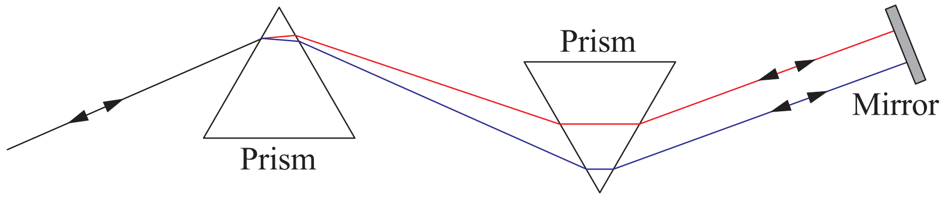


Figure 2.2: *One of many possible prism compressor arrangements.*

A grating compressor utilizes the same principle, by delaying some frequencies in relation to others, see figure 2.3. Here the different orders of dispersion can be adjusted for by changing the angle, α, and the distance, L, between the gratings. Of course both prisms and gratings can also be used to stretch short pulses in time [9].

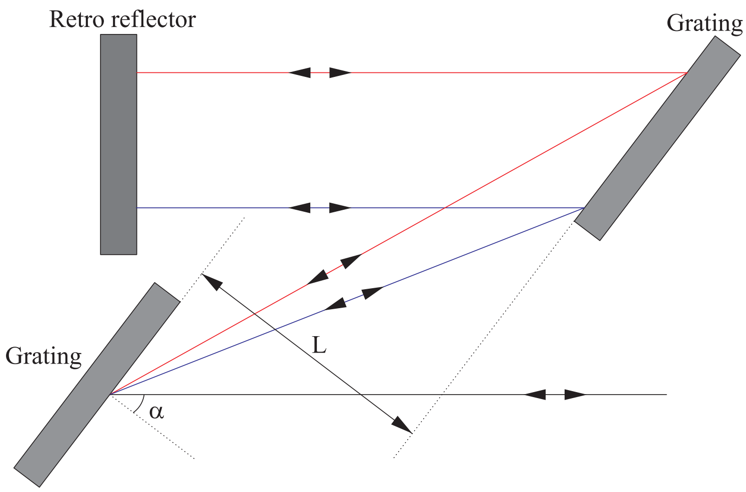


Figure 2.3: *A typical grating compressor where the retro reflector sends back the output beam parallel to, but separated from, the input beam.*

Prism compressors have a few advantages over grating compressors. First, a prism compressor can be made almost free of loss by cutting the prisms in such a way that the minimum deviation[3] of the central wavelength is at the Brewster angle of the incoming and outgoing light [7]. Second, the third-order-dispersion (TOD) in prism compressors is negative while it is positive in most grating compressors. Most materials have positive TOD that can be compensated for by a prism compressor but not by a grating compressor, except in some cases [10]. Stretching and recompression with gratings thus allow large and reversible stretch factors [9].

One drawback with the prism compressor is the large dimensions required since the spatial, and thereby also the temporal, separation of the frequencies is dependent on the distance between the two prisms [10].

2.2.1 Dispersion Calculations

For a femtosecond laser pulse with a bandwidth as large as 100 THz the dispersion in the material that the pulse passes through can cause large duration broadening of the compressed pulse. The propagation constant, β, for a transparent medium is generally dependent on the angular frequency, ω. $\beta(\omega)$ is called the dispersion relation of a medium. For a plane wave propagating through such a medium the velocity, v_{ph}, at which the phase front moves can be written as

$$v_{ph} = \frac{\omega}{\beta} \tag{2.2}$$

and is referred to as the phase velocity. If it is assumed that the dispersion relation, over the bandwidth of the pulse $\Delta\omega_L$, can be approximated to be linear, the velocity at which a pulse propagates without changing its shape is referred to as the group velocity and is given by

$$v_g = \left(\frac{d\omega}{d\beta}\right)_{\beta=\beta_L} \tag{2.3}$$

for a pulse with the center frequency ω_L and where β_L is the propagation constant corresponding to that frequency.

The time delay, τ_g, introduced by a propagation of the pulse through a medium of length l is

$$\tau_g = l\left(\frac{d\beta}{d\omega}\right)_{\omega_L} \tag{2.4}$$

and is referred to as the group delay of the medium at the frequency ω_L. If a pulse has a bandwidth that is very large the dispersion relation can no longer be approximated with a linear function. If such a pulse propagates through a medium the different spectral regions of the pulse travel at different group velocities and thereby the pulse is broadened. If the dispersion relation

[3] I.e. the incidence angle is equal to the exiting angle.

within the bandwidth, $\Delta\omega_L$, instead can be approximated by a parabolic curve the pulse broadening, $\Delta\tau_d$, can be described by:

$$\Delta\tau_d \cong l \left| \left(\frac{d^2\beta}{d\omega^2} \right)_{\omega_L} \right| \Delta\omega_L \tag{2.5}$$

For pulses shorter than ∼30 fs the next term, i.e. the third order dispersion where the third derivative is taken, must also be calculated and considered [6]. As an example it can be mentioned that a 20 fs pulse at 800 nm is approximately doubled in duration if passing through 0.9 cm fused silica because of group velocity dispersion [11].

2.3 Amplification

To be able to produce laser pulses with high energies the pulses from the oscillator have to be amplified. There are several ways to do this. Often a combination of different amplifiers are used in several steps. Several different factors determine which configuration that is best suited in each case. Some of the factors to have in mind are first of all the wanted amplification and cost, but also the saturation and gain properties of the amplifier medium. Saturation of the amplifier medium is reached when the number of photons extracted is comparable to the number of excited atoms [12]. For Ti:sapphire saturation is reached at fluences of ∼1 J/cm^2 [13].

Although it is desirable to reach gain saturation in order to stabilize the pulse-to-pulse fluctuations, too deep saturation leads to higher gain of the leading edge of the amplified pulse than of the trailing edge. If the pulse is chirped this leads to a shifting of the central wavelength toward longer wavelengths and that the final pulse duration after compression is broadened [14].

The gain depends on the amount of pump light absorbed by the crystal, i.e. the concentration of excited atoms in the amplification volume, and the stimulated cross section [6].

If the total amplification is high problems can occur with non-linear effects and damage of optical components. This can be solved with a very clever technique introduced by D. Strickland and G. Mourou [15], see section 2.3.3.

Often the amplifier crystal is cut at Brewster angle for the signal beam wavelength so that the incident p-polarized light is almost totally transmitted and propagates along the crystal rod. The Brewster angle, θ_B, is calculated through

$$\theta_B = \arctan\left(\frac{n_t}{n_i}\right) \tag{2.6}$$

where θ_B is measured from the normal and n_t and n_i are the indices of refraction for the crystal and the surrounding medium respectively [16].

To calculate the angle of refraction, θ_t, for a beam with incident angle θ_i, Snell's law is applied.

$$n_i \sin(\theta_i) = n_t \sin(\theta_t) \tag{2.7}$$

To obtain a gain as high as possible it is important to maximize the overlap between the pump and signal beams. Because of the high index of refraction for Ti:sapphire the angle between the incident signal and the pump beam is greatly reduced inside the crystal. Still, to include the passes of the signal beam inside the pumped volume a larger diameter of the pump than of the signal is often needed.

2.3.1 Regenerative Amplifier

The regen is used to obtain high amplification of short pulses. A pulse is trapped inside a cavity bouncing back and forth through the pumped Ti:sapphire crystal. An electro-optical device is used to force the pulse to stay in the regen where the pulse can make many round trips, usually until saturation, and thereafter the same electro-optical device opens the path out of the amplifier by changing the polarization, see figure 2.4. This way it is possible to obtain high energies with a rather moderate sized amplifier. Due to the many passes and the high amplification the bandwidth of the pulse may decrease causing an increase in pulse duration [7, 17].

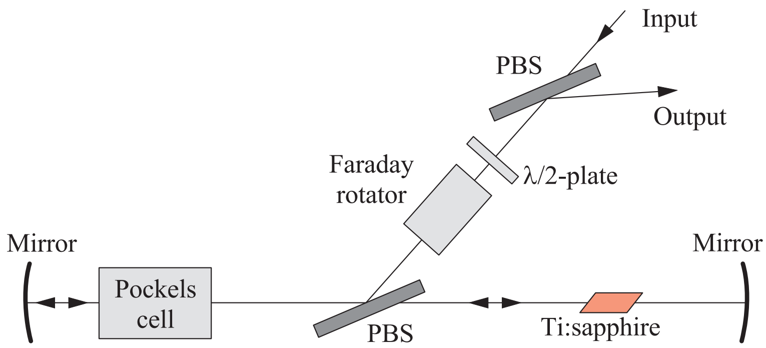


Figure 2.4: *A scheme for regenerative amplification. PBS is a polarizing beam splitter.*

When the laser pulses are amplified a lot of ASE will also be produced in the gain medium, see section 2.4.1. Because of the existence of a cavity in a regenerative amplifier the ASE can grow to high levels, causing problems later on in the amplifier chain. Also prepulses caused by reflections in surfaces inside the cavity will be amplified [18].

2.3.2 Multipass Amplifier

In the multipass amplifier the ASE is not amplified to the same extent as in the regen due to the absence of a cavity [6]. The multipass amplifier on the other hand becomes impractical when many passages are made through the gain medium.

Mirrors are arranged so that the input beam makes several passages through the gain medium. A typical bow-tie configuration can be seen in figure 2.5 and a three-mirror ring configuration in figure 2.6. During each pass through the gain medium the beam enters at a slightly different angle but still passes through the optically pumped volume. The number of passes is determined by the gain per pass and the desired overall gain [12].

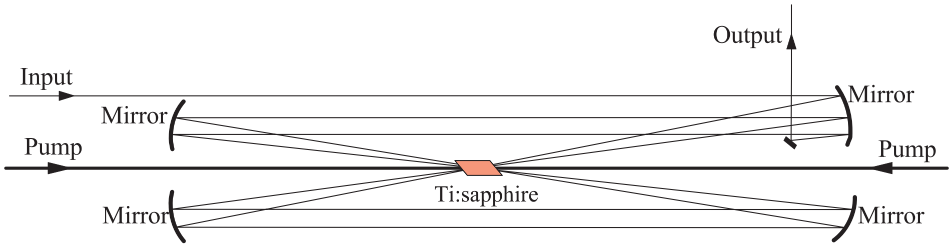


Figure 2.5: *The configuration of a typical multipass setup longitudinally pumped from both directions.*

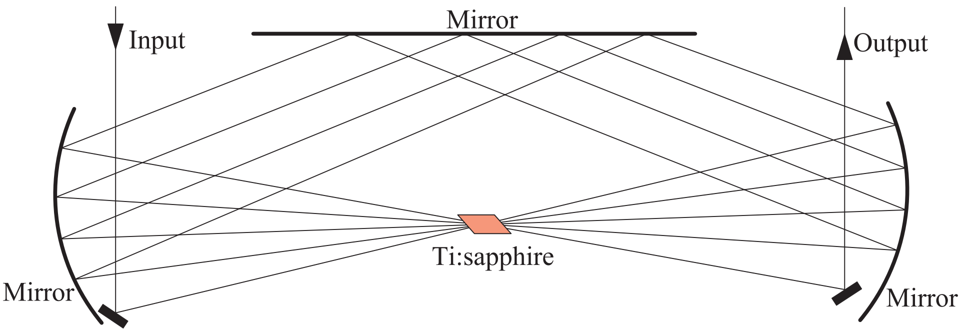


Figure 2.6: *A 3-mirror multipass amplifier ring. The crystal can be pumped through holes in the two curved mirrors.*

Due to the higher gain in multipass amplifiers compared to regenerative amplifiers less passages through the amplification medium need to be done and as a result of that less high-order dispersion is introduced in the short signal pulses. This makes it easier to obtain shorter pulses after compression [9].

Another advantage with multipass amplifiers, compared to regenerative ones, is that they, with proper alignment, can be made to not emit pre-pulses [19].

2.3.3 Chirped Pulse Amplification

With the discovery of chirped pulse amplification in the late 80's it became possible to amplify femtosecond laser pulses and create compact terawatt laser systems with modest pulse energies and repetition rates $\geq$10 Hz. CPA is based on the principle of stretching the short laser pulses from the oscillator in time and thereby reducing the peak power by a few orders of magnitude. This allows an increase in energy of the pulses without damaging the amplifier medium or other optical components. After amplification the beam is expanded spatially with a telescope and thereafter temporally compressed again, see figure 2.7. Very short pulses must contain a broad frequency distribution according to equation 2.1. To stretch these pulses temporally prisms or gratings are used. This process is reversed later on in the compressor. Usually the amplification of the pulses is achieved by a combination of the above mentioned regenerative and multipass amplifiers [17].

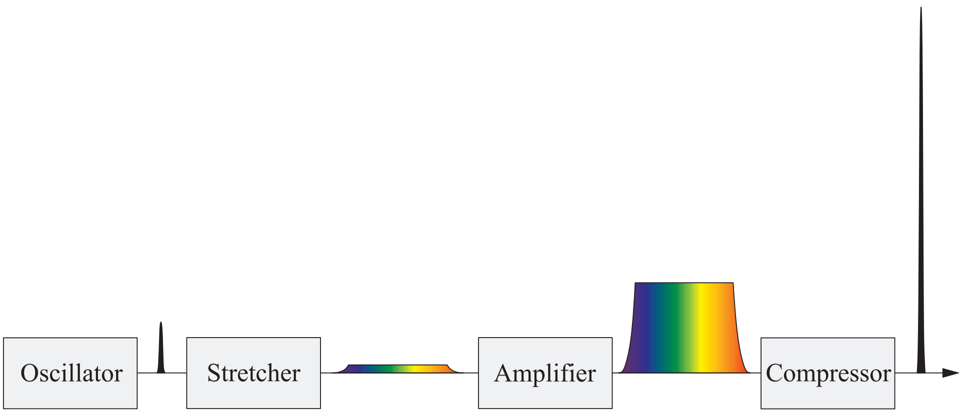


Figure 2.7: *The principal of Chirped Pulse Amplification.*

2.4 Temporal Contrast

Before and after each laser pulse there exist a certain level of background light, dominantly consisting of ASE [20]. In terawatt systems this background noise, combined with prepulses, can be strong enough to create plasma in front of the experimental target area before the main pulse reaches there. The intensity required to ionize a solid target depends on the interaction time [2]. The different time-domains of interaction between femtosecond laser pulses and solid-state targets can bee seen in figure 2.8. At an optimized interaction between an intense femtosecond pulse and a solid target the pulse intensity must remain inside the green-shaded area of the figure [21]. A commonly used limit for plasma formation is 10^{11}–10^{12} W/cm^2 [22], though some reports have shown that intensities as low as 10^8–10^9 W/cm^2 are sufficient to alter high intensity laser-solid interactions and that the contrast of the system is not the most important parameter to describe the preplasma formation. Instead, the energy density on the target surface at the time when the rising edge of the pulse arrives is more interesting [23]. The presence of ASE also reduces the amplification gain of the signal especially in saturated amplifiers where the extracted energy is comparable to the pump energy [20].

The temporal contrast is defined as the intensity ratio between the ASE or prepulses and the main femtosecond pulse. It is often stated both on the nano- and picosecond timescale.

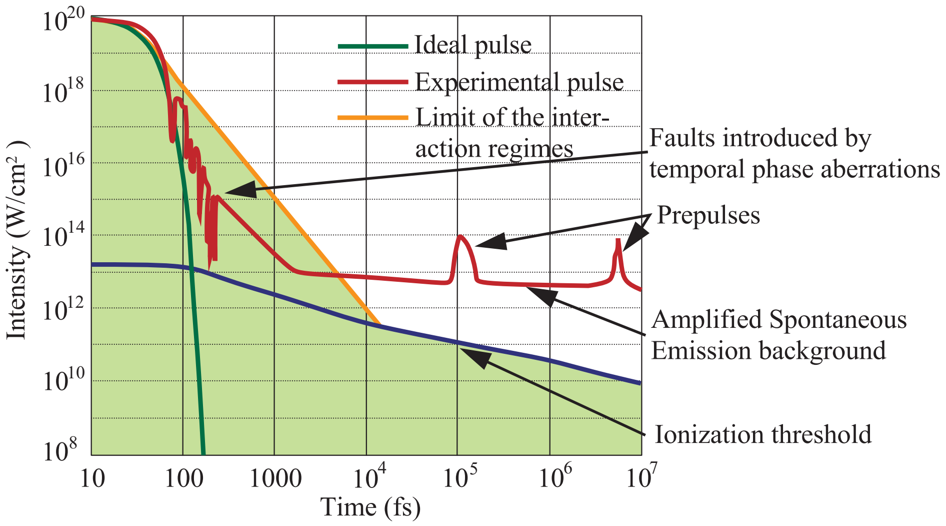


Figure 2.8: *Different domains of interaction between laser and solid-state targets [21].*

2.4.1 ASE and Prepulses

ASE is, as the name implies, created when spontaneous emission within the gain medium[4] is amplified by stimulated emission. The level of ASE in the output is determined for example by the population inversion and the dimensions of the crystal. A higher population inversion results in a larger amount of spontaneous emission and also a larger gain of the ASE. If the ASE intensity becomes comparable to the saturation intensity the population inversion and therefore also the gain is affected [24]. If the ASE experiences a high gain inside the crystal the ASE may start to oscillate. For this reason it is very important to have anti-reflective coatings on the front and rear end crystal surfaces. In saturated or nearly saturated large-aperture amplifiers a way to suppress the transverse parasitic oscillation is to add an index-matched absorbing material on the periphery of the crystal to increase the oscillation threshold [25]. If an amplifier is run too deep into saturation it results in an increased level of ASE because the ASE still experiences gain [26].

The spontaneous emission is distributed in a 4π solid angle and the divergence of the ASE is directly related to the diameter, D, of the pump beam and inversely dependent on the length, L, of the gain medium. The solid angle that contributes to ASE is proportional to D/L which means that a long gain medium and a narrow pump beam helps suppress the ASE [20].

Prepulses can, for example in a multipass amplifier, be created by reflections or scatterings in coatings or inside the amplifier crystal if these reflected or scattered signals take a shortcut in the amplifier and end up a few nanoseconds[5] or more ahead of the main pulse [27]. Because of this it is very important to have high quality materials and anti-reflective coatings on surfaces inside the amplifier.

2.5 Non-Linear Filtering

All ASE and every prepulse can not be prevented when building the amplifier stages. There will always exist a background level to some extent. A Pockels cell can be inserted to block the beam between the pulses. It is although limited by a typical rise and fall time of at least 1 ns[6] and the part of the pedestal possible to remove decreases further for a chirped pulse because of the temporal overlap between the stretched pulse and the pedestal. The solution to this problem lies in non-linear filtering. By introducing a loss that is higher for low-intensity noise than for the high-intensity amplified pulse the ASE and prepulses can be suppressed by a few orders of magnitude [28].

[4] The medium of interest here is Ti:sapphire crystal.

[5] Depending on the length of the amplifier arms.

[6] There are Pockels cells available with a rise and fall time of about 0.2 ns but the cost is several times higher.

There exists several ways to perform non-linear filtering of laser pulses. A few of the methods, most interesting for this project, are discussed below.

2.5.1 Saturable Absorber

The most simple way to filter the pulses is by inserting a Saturable Absorber (SA) in the beam path. The absorber can be a cell with a liquid dye or a colored glass filter. The filter is bleached by high energies and for a short while thereafter it is more or less transparent.

Dyes often suffer from degradation and a great deal of them are chemicals that are not very pleasant to work with. Also solid saturable absorbers can degrade but not as easily. Before Kerr-lens mode-locking was discovered saturable absorbers were commonly used as a way to passively accomplish mode-locking [29]. Passive Q-switching can also be accomplished by inserting a saturable absorber in the laser cavity. The laser action begins when the gain in the active medium is high enough to at least compensate for the losses in the saturable absorber plus the cavity losses [6].

There are some important terms needed to describe the performance of a saturable absorber. Perhaps the most important is the transmission curve that determines where the material absorbs and transmits light. The modulation depth of a saturable absorber describes the maximum possible change in optical loss due to saturation. There is always some absorption of the light that passes through the absorber even if it is saturated, this part is called the unsaturable losses. For a saturated absorber it takes some time to recover, this time is called the dynamic response or the recovery time. The saturation fluence is the fluence required to reduce the initial absorption by a factor 1/e. In order not to damage a solid saturable absorber it is also important to know its damage threshold, given in intensity or fluence [30].

For pulsed lasers a saturable absorber is said to be fast if it has a dynamic response that is much shorter than the pulse duration and slow if it is much longer than the pulse duration [31].

Figure 2.9 shows an example of the transmission through a saturable absorber as a function of the intensity where the ASE experiences a factor 10^2 lower transmission than the peak pulse.

2.5.2 SESAM

SESAM stands for SEmiconductor Saturable Absorber Mirror and as the name implies it is based on a thin semiconductor quantum well absorber in front of a Bragg mirror structure. A Bragg mirror consists of many alternating layers of two materials with different indices of refraction, each layer with an optical thickness corresponding to one quarter of the wavelength for which the mirror is designed. The semiconductor saturable absorber looses its absorption when the incident light excites the carriers and accumulates

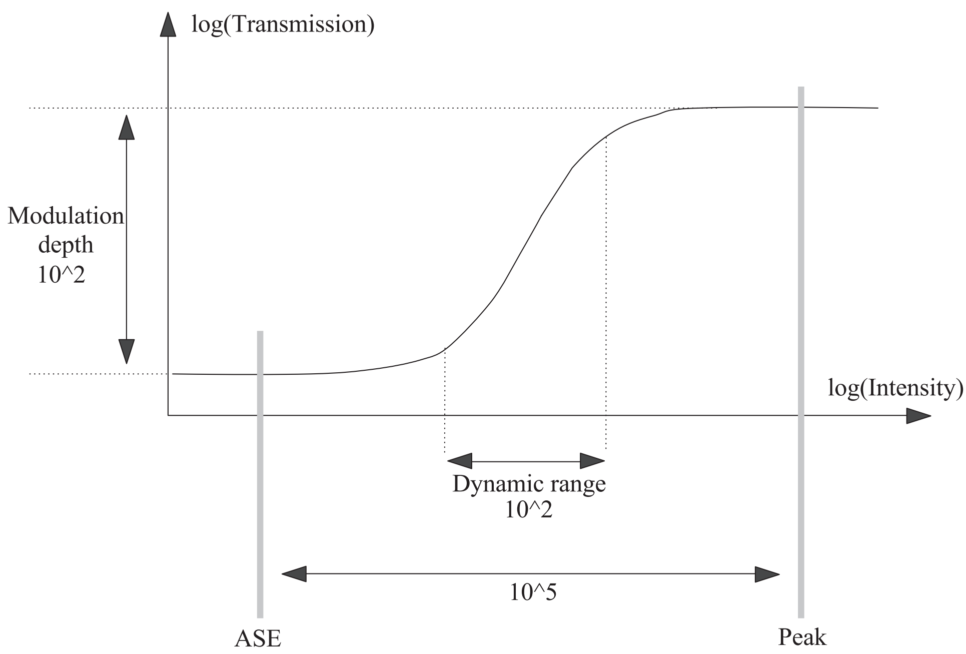


Figure 2.9: *Example of dynamic range and modulation depth of a saturable absorber [32].*

them in the conduction band and thereby depleting the valence band. A partial recovery of the absorption typically occurs within 50–100 fs after the saturating pulse. A complete recovery takes from a few picoseconds to a few nanoseconds. The SESAM works in reflection and the modulation depth is consequently the change in reflectivity between high and low intensities in the incoming light. The most common use for SESAMs is to passively mode-lock lasers. An ordinary SESAM only has a few percent in modulation depth requiring many reflections to get a high total modulation depth. Many reflections will introduce high dispersion on a pulse with large bandwidth [31]. For these two reasons SESAM is less suited for removal of ASE in femtosecond pulses.

2.5.3 Sagnac

A non-linear Sagnac interferometer, as shown in figure 2.10, uses a non-linear medium to introduce a phase shift between the two different beams created by a 50:50 beam splitter. The two beams travel the same path but in different directions. This automatically compensates for dispersion and makes the alignment of the interferometer easier even if some non-linear medium is introduced in the path. On one side of the non-linear medium something that changes the intensity of the pulses is inserted, it can be an attenuation filter or some chirped mirror to stretch the pulses in time. The beam that travels one way through the interferometer will first pass the item that lowers the intensity and then pass through the non-linear medium experiencing a certain phase shift. The low ASE-level will not be phase shifted in the medium. The beam that travels the other way through the interferometer first passes the non-linear medium, and thereby experiences a larger phase shift, and thereafter passes through the intensity-lowering item. If there is not any phase difference between the two beams the energy goes back to the direction of the laser. Hopefully this is the case for the low-intensity ASE. The femtosecond pulses however have different phases creating an output depending on the phase shift [28].

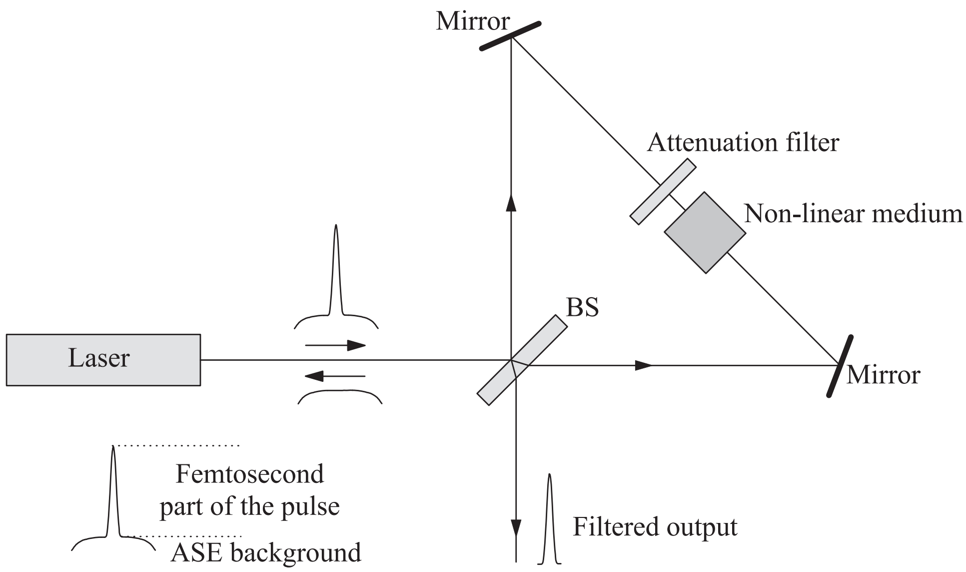


Figure 2.10: *Non-linear Sagnac interferometer [28]. BS is a 50:50 beam splitter.*

For a Gaussian pulse the non-linear phase shift will not be the same at the center of the spatial profile as at the edges because of the intensity distribution. This leads to a spatially narrower output pulse [33]. ASE-suppression by four orders of magnitude have been accomplished but the setup has a low transmission [28]. Another drawback is the difficult alignment of the setup and the spatial deformation of the output pulse making it less suitable for further amplification. The deformation is due to the fact that the two beams have different phases, amplitudes and, often also, mode sizes [28, 34].

2.5.4 Non-Linear Polarization Rotation

There are several ways to perform non-linear polarization rotation; in air, in hollow waveguides filled with xenon or in crystals. The latter option is probably the most promising although it is rather new and untried. It also requires energies near the mJ level.

One crystal material that has been tested is BaF_2 that is placed between two crossed polarizers. The polarization of the high-intensity pulse is rotated in the crystal while the lower ASE and prepulses are not. The second polarizer then transmits some part of the rotated pulse but not the background. The contrast enhancement is limited by the extinction ratio of the polarization discrimination devices. Improvement of the temporal contrast by more than 4 orders of magnitude can be obtained. The filter also acts as a spatial filter of the pulses. An energy transmission above 10% has been shown [35].

Chapter 3

The Optical Setup

3.1 General Description

The arrangement of the components in the new setup, the preamplifier and pulse cleaner, can be seen in figure 3.1. A photo of the setup is attached in Appendix A, figure A.1. The area occupied on the optical table by the new setup, built during this project, is about 0.6 m · 1.4 m. The input to the setup comes directly from the oscillator and the pulses out from the setup go into the grating stretcher and then continue as they did in the old system, figure 1.1. Switching between using the new setup or not is done by a few mirrors on flip mounts between the oscillator and stretcher. Some changes have been made on the regenerative amplifier to lower its amplification since it is partly replaced by the new 4-pass amplifier. The amplification in the regen is lowered by reducing the number of times the pulses go through the amplifier crystal, from 15 to 11, before they are switched out. It is also possible to vary the pumping of the crystal inside the regen.

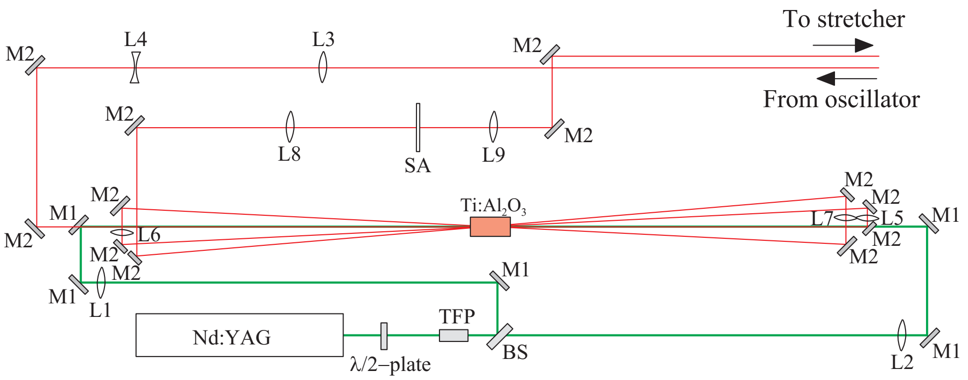
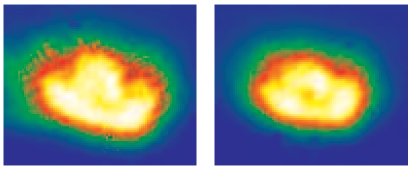


Figure 3.1: *Schematic picture of the setup with the abbreviations explained in Appendix B, table B.1 and B.2.*

3.2 The Pump Laser

To pump the Ti:sapphire crystal a frequency doubled Nd:YAG (Quantel, Brilliant 10) able to produce pulses of 180 mJ at 10 Hz and 5 ns duration is used. The pump laser is set to work at maximum power in order to minimize its pulse energy fluctuations that still are up to 5%. A $\lambda/2$-plate and a thin film polarizer are set to lower the pulse energy to 85 mJ. The pulses are then split in two by a 50:50 beam splitter to pump the Ti:sapphire crystal longitudinally from both sides. The two beams overlap in the crystal. Of the incident 85 mJ about 72 mJ is absorbed in the crystal. If the pump pulses reach the crystal long before the oscillator pulse does, an unnecessary large amount of ASE is produced. To suppress this the pump laser is trigged and delayed so that the pumping of the crystal is performed as late as possible before the oscillator pulse arrives for its first pass. This is also the reason why the beam splitter is placed so that the two created beams propagate an equal length before reaching the crystal.

The spatial mode from the laser is too big so lenses are used to focus the pulses slightly behind the crystal creating a spot size on the crystal of about 0.022 cm^2. As can be seen in figure 3.2 the mode is not perfect. However this should not be a problem since there are two pump beams overlapping in the crystal and the four passes of the signal beam through the crystal even the amplification. The average pump fluence on the crystal is totally $\sim$3.8 J/cm^2.



(a) **(b)**

Figure 3.2: *Profiles of the two pump beams at the crystal, a) left arm and b) right arm.*

3.3 Multipass Amplifier

In the multipass preamplifier the signal pulse does four passes through the amplifier crystal. It is possible to obtain the same level of amplification in three passes if the pump fluence is increased. Simulations in Lab2 [36], however, show a slightly more stable amplification if it is done in four passes instead.

Because of the wavelength dependence of the refraction index of sapphire the signal and pump beams have different angles of refraction. To optimize the overlap inside the crystal between the signal beam and the two pump beams they have to have different angles of incidence as seen in figure 3.3. Since the crystal is Brewster cut for 800 nm the angle of incidence, $\theta_i\left(800nm\right)$, for the signal beam should, according to equation 2.6, be:

$$\theta_i\left(800nm\right) = \theta_B\left(800nm\right) = \arctan\left(\frac{1.76013}{1}\right) = 60.40^\circ \tag{3.1}$$

n_t is taken as the value of $n_o\left(800nm\right)^1$ for sapphire and comes from [37] and n_i is said to be 1. The internal angle of refraction, θ_t, at 800 nm can be calculated from Snell's law in equation 2.7

$$\sin\left(60.40\right) = 1.76013\sin\left(\theta_t\left(800nm\right)\right) \Rightarrow \theta_t\left(800nm\right) = 29.60^\circ \tag{3.2}$$

The pump beams at 532 nm overlap with the signal beam inside the crystal if

$$\theta_t\left(800nm\right) = \theta_t\left(532nm\right) \tag{3.3}$$

This makes it possible to use Snell's law again, this time to calculate the angle of incidence for the pump beams, $\theta_i\left(532nm\right)$

$$\sin\left(\theta_i\left(532nm\right)\right) = 1.77170\sin\left(29.60\right) \Rightarrow \theta_i\left(532nm\right) = 61.07^\circ \tag{3.4}$$

where $n_t\left(532nm\right)$ is taken from [37]. The difference in angles of incidence between the incoming beams, $\Delta\theta_i$, is thereby:

$$\Delta\theta_i = \theta_i\left(532nm\right) - \theta_i\left(800nm\right) = 61.07^\circ - 60.40^\circ = 0.67^\circ \tag{3.5}$$

The overlap is only true for the first pass of the signal beam through the crystal in the multipass amplifier. The other three passes are arranged so that the angular differences between the beams inside the crystal are minimized. This is done by taking advantage of the Brewster cutting of the crystal by keeping the passes of the signal beam in a horizontal plane and tilting the pump beams slightly vertically. This means that the pump beams are not in the way when placing the multipass mirrors. By doing this the width of the amplifier can be made very compact and, as stated earlier, the angular separations of the beams can be minimized.

The largest angle between the pump beams and a pass of the signal beam is about 3° and happens for the fourth pass. Because of the high refractive index of Ti:sapphire this angle is roughly halved inside the crystal. Two beams, overlapping, at one of the surfaces of the crystal, are then separated by 300 μm after passing through the 12 mm long crystal. With an average

[1] The o stands for the ordinary axis in a birefringent crystal.

pump beam diameter of about 1.7 mm the signal beam can easily be made smaller to entirely pass through the pumped volume.

Both the signal and pump beams are vertically polarized to make the setup easier since the mirrors are better at reflecting s-polarized light and the easiest design of the multipass amplifier is when all beams are held in one horizontal plane. The orientation of the Ti:sapphire amplifier crystal can be seen in figure 3.3.

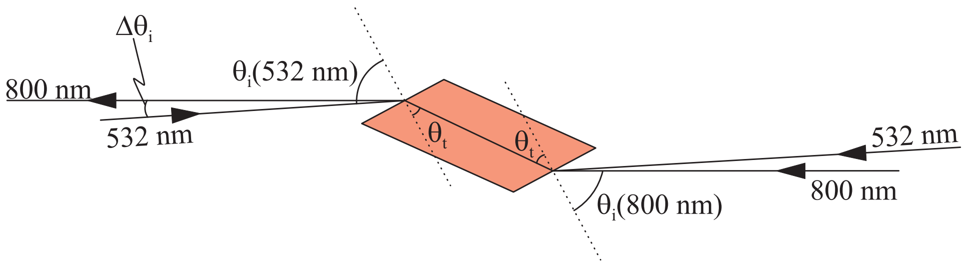


Figure 3.3: *Angles of incidence and refraction of the beams entering and leaving the Ti:sapphire crystal, viewed from the side.*

Because none of the lenses in the setup are anti-reflection coated the passive losses are high, roughly 60–70%. This means that a factor 3 of the achieved amplification in the setup is needed for compensating the losses.

A long train of pulses comes from the oscillator into the preamplifier. This means that the first pulses to arrive at the Ti:sapphire after pumping will be amplified the most and thereafter the amplification will be lower and lower as the upper state relaxes into the ground state or stimulated emission partly empties it. The output from the preamplifier will therefore consist of pulses with very varying pulse energies and it is important to set the timings of the Pockels cells in the regen to pick one of the most amplified pulses.

3.4 Pulse Cleaning

The pulse cleaning part of the setup consists of a Schott RG850 solid-state saturable absorber filter with an unbleached transmission profile that can be seen in figure 3.4. The filter is located near the focus of a telescope.

A few other filters were also tested, among others a Schott RG1000 and some neutral density filters. None of them were bleachable, at least not at 800 nm and with the pulse energies used. The pulses are still rather short when they reach the SA, according to simulations made in Lab2 [36] the pulses are stretched to about 350 fs when passing through the lenses and the crystal in the setup. For this reason the saturable absorber is mounted on an x- and y-translator so that the position of the beam on the filter easily can be moved if the filter is damaged by fluctuations in pulse energy.

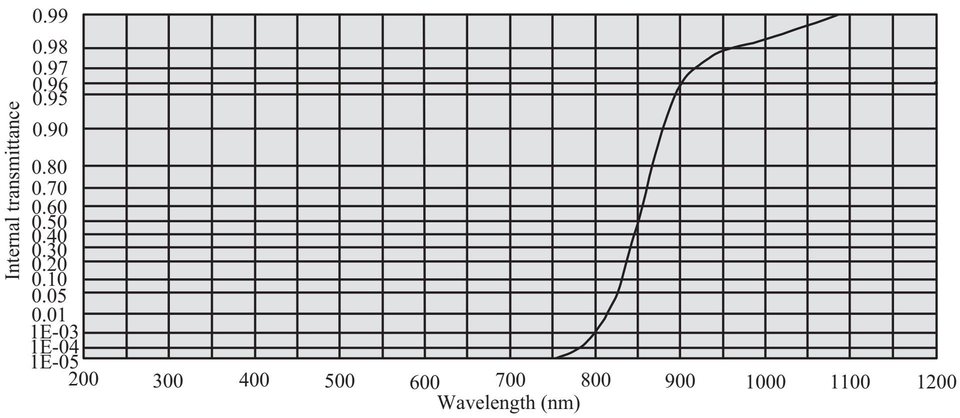


Figure 3.4: *Internal transmittance of a 3 mm thick Schott RG850 filter [38].*

A saturable absorber inserted in the setup also helps to prevent backscattered light from components later in the system from reaching all the way back to the oscillator and disturb the mode-locking.

The wavelength at which the ASE, produced in the multipass preamplifier, is centered varies with the pump energy on the crystal. At 85 mJ pump energy the ASE is centered somewhere between 775–780 nm, see figure 3.5, but with 50 mJ pumping the center wavelength is instead around 750 nm. The fact that the ASE is centered at lower wavelengths than the oscillator pulses is good because it then has a lower transmission through the SA.

If the counts collected by the spectrometer are summed up for the different filter thicknesses used and then compared to the ASE output without any filter inserted it can be seen that the 1 mm thick RG850 filter transmits ~8%, the 2 mm filter ~6% and the 3 mm thick filter ~3%. The peak of the ASE spectra is shifted towards longer wavelengths, as can be seen in figure 3.5 b), c) and d), due to the transmission profile of the RG850 filter.

The dip at 840 nm that clearly can be seen in figure 3.5 b), c) and d) is present also in a) but then not as obvious. If the hight of the bump at 850 nm is studied it is observed that the filters only have a little effect on it. The reason for this is the high transmission of the filter at 850 nm as can be seen in figure 3.4.

At the same time the amplified pulses are also partly absorbed in the SA. If the filter is placed as close to the telescope focus as possible without being damaged, the transmission is about 70%, 60% and 40% for the filter thicknesses 1, 2 and 3 mm respectively. The recovery time of the RG850 filter seems to be shorter than the time between the pulses, ~12 ns, because no variation in transmission can be seen in the pulse train.

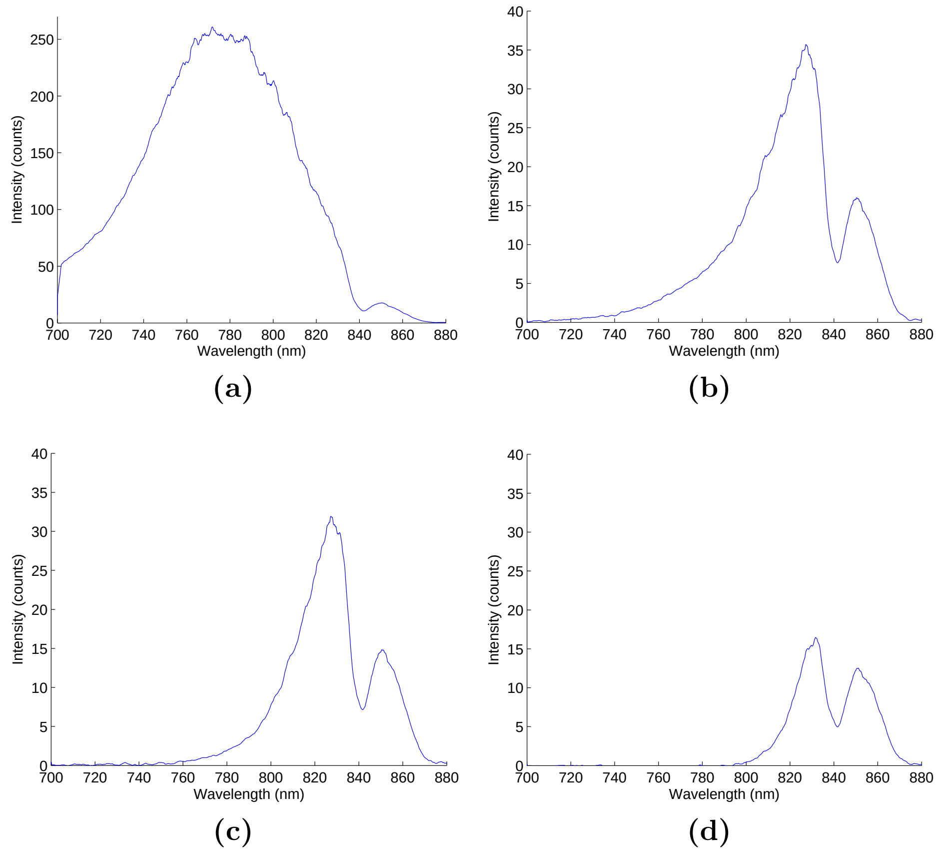


Figure 3.5: *Spectra over the ASE that comes out from the multipass preamplifier when no oscillator pulses are present. a) ASE output without any filter, b) ASE output after 1 mm RG850, c) ASE output after 2 mm RG850 and d) ASE output after 3 mm RG850. (Observe the different scales on the y-axis.)*

Chapter 4

Results & Conclusions

Measurements made with a third order auto-correlator (Sequoia, Amplitude Technologies) after pulse compression show that the temporal contrast is enhanced for times larger than ∼20 ps before the pulse peak if the new preamplification and pulse cleaning setup is used, see figure 4.1. This is further discussed in section 4.2.

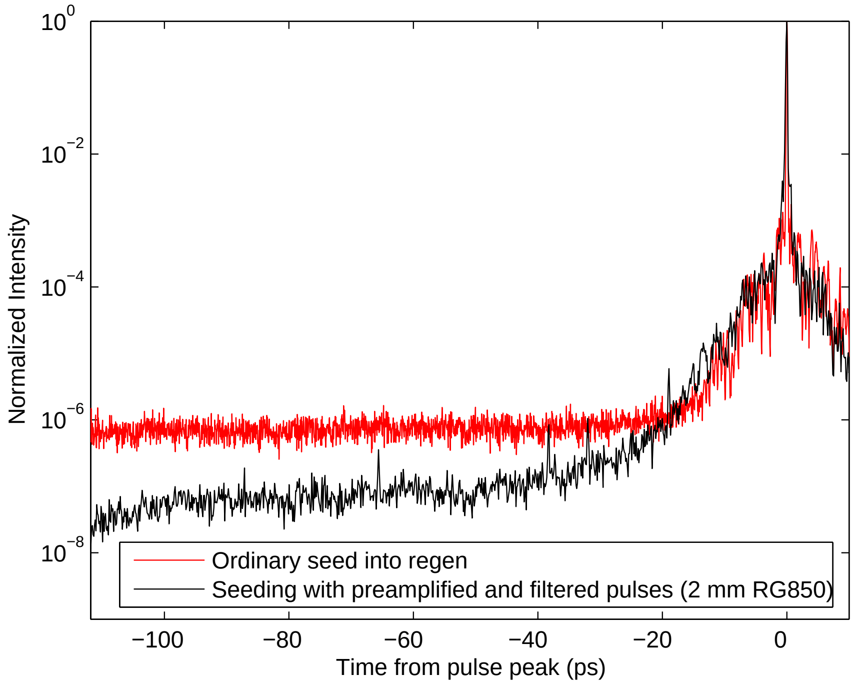
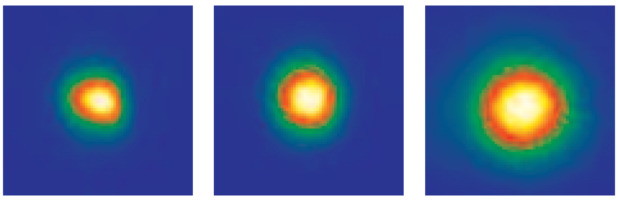


Figure 4.1: *Comparison between seeding the regen with ordinary pulses and with preamplified and cleaned pulses.*

4.1 Pulse Characteristics

The pulses out from the new setup are approximately a factor 200 more energetic than the input pulses from the oscillator if the 2 mm RG850 filter is used. The amplification in the amplifier is around 2000 but the large passive losses mentioned in section 3.3 and the absorption in the filters mentioned in section 3.4 reduce the effective amplification. Because the amplifier is not run into saturation the shot-to-shot energy fluctuations of the amplified pulses are rather high. If the maximum received amplification is divided by the minimum received amplification, on a minute time scale, a factor of 2 is obtained. Behind this fluctuation stands mainly the 5% variation of the pump laser output. Simulations in Lab2 [36] show that 5% variation in pump energy results in 80% variation of the amplification. The pointing stability of the oscillator and the pump laser probably creates the rest of the fluctuations in output pulse energy.

If looking at the beam profile of the signal beam after passing through the preamplifier and SA it can be seen that it is spatially very clean. Figure 4.2 compares the profile of the signal beam at different stages in the setup. If a distorted signal beam is sent into the setup the output will still look similar to the one in figure 4.2 c).



(a) **(b)** **(c)**

Figure 4.2: *Beam profiles for a) the incoming signal, b) the amplified signal and c) the filtered signal.*

Also spectrally the pulses will be affected, both by the multipass amplifier and by the saturable absorber. In figure 4.3 the spectrum at different stages in the setup can be seen. The spectrometer had a minimum integration time of 3 ms and it was triggered to start its measurement directly after the pumping of the amplifier crystal in the multipass preamlifier. This means that the most amplified pulses were collected by the spectrometer but also pulses with lower or no amplification. If a filter was present in the setup before the spectrometer both pulses with energies high enough to bleach the filter and pulses with too low energy to bleach the filter were collected. This of course means that the two amplified spectra in figure 4.3 are wider than what the pulse spectra of interest are in reality. Measurements in the figure can therefore only say something about the upper boundary of the bandwidth. The input has a FWHM of ∼43 nm, after amplification it is ∼38 nm and finally after filtering it is ∼24 nm according to figure 4.3.

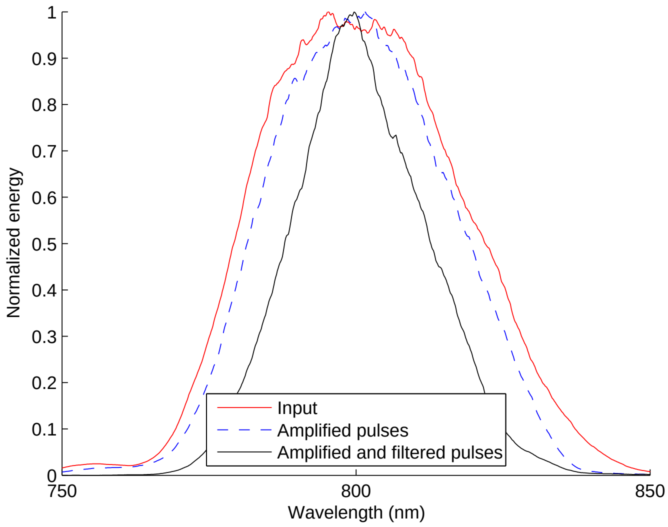


Figure 4.3: *Spectral profile of the signal pulses at different stages in the setup. The amplification is around a factor 2000 and the filter used is a 2 mm RG850.*

If the spectrometer is placed after the regen the measured pulses are amplified once more. There the bandwidth of the preamplified and filtered pulses are ∼15 nm, compared to 24 nm with the old system. This makes it obvious that the pulses in the end cannot be compressed to the same short durations as before. Where the most of the spectral clipping occurs is hard to say. It is natural that the bandwidth is lowered during amplification in the multipass amplifier. Simulations made in Lab2 [36] predict a narrowing from the input 43 nm to a 31 nm output[1]. It seems as if most of the spectral narrowing occurs in the filtering stage.

If the pulses from the oscillator are sent through the setup but without any amplification or filter present the spectrum is still narrowed by more than 5 nm. The mirrors used are specified for 750–850 nm so even with the large number of mirrors used the bandwidth should not really be affected.

The minimum pulse duration obtained after compression was around 50 fs. This should be compared to the 35 fs that is possible to get with the old system. In some experiments the preferred pulse duration is not the shortest possible and perhaps the setup can then be used.

Lab2 calculates a shifting of the central wavelength to 804 nm after

[1] Filtering not included.

amplification. This has been hard to measure, but as long as it is that small it does not matter very much.

4.2 Achieved Contrast Enhancement

For times larger than ∼50 ps before the peak pulse in figure 4.1 the contrast enhancement is more than a factor 10 and for times around 120 ps before the pulse the enhancement is a factor ∼50. Contrast measurements earlier than 160 ps before the main pulse are not possible at this time. As can be seen in the figure there are more prepulses in the new setup. Where these prepulses come from is so far unknown. They are hardly reflections that have taken shortcuts in the multipass amplifier, as mentioned as a possibility in section 2.4.1, because of the small separation in time from the peak pulse. If any of the visible prepulse in the figure had been represented in both of the curves that had meant that they were produced somewhere in the old jointly used system. The prepulses that have a lower intensity than the noise level of the old system can exist there as well but may be hidden in the noise. For the prepulses that reach above the noise level of the old system this is probably not the case though. Prepulses are easily created in the regenerative amplifier that has a high total gain, a cavity and lots of surfaces in the beam path. Here reflections can end up almost anywhere in time compared to the main pulse.

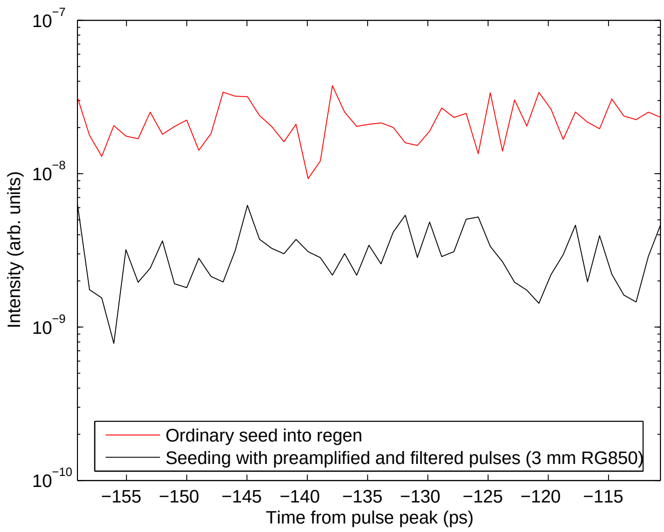
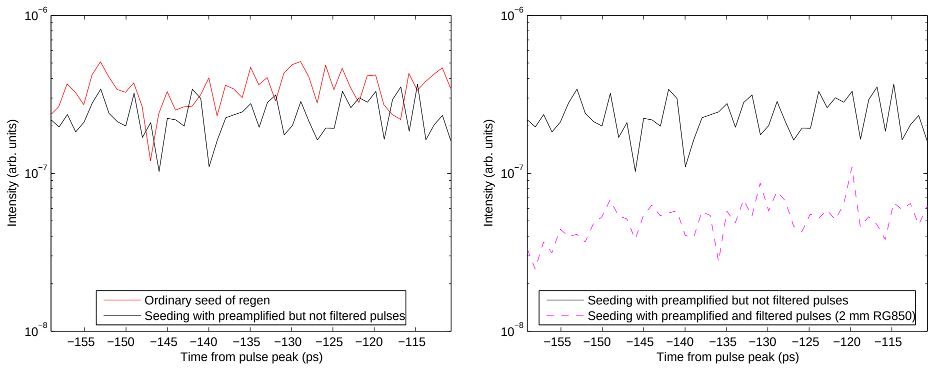


Figure 4.4: *Plot over the best achieved contrast between 160–110 ps before the peak pulse.*

The contrasts in the figures in this section can seem poor compared to the earlier mentioned 10^{-8}, and the reason for this is that the whole system was not optimized. It can also be seen that the contrast of the normally seeded system varies between the figures and this is because the measurements were performed on different days.

So what contrast that is possible to achieve with the new setup cannot be determined without spending more time on optimizing the complete system. The best contrast measured with the new setup is $3 \cdot 10^{-9}$ at the same time as the ordinary system had a contrast of less than $2 \cdot 10^{-8}$, see figure 4.4.

In plot a) in figure 4.5 the seeding with preamplified pulses without filter is compared to normal seeding of the regen. As can be seen the preamplifier produces slightly better contrast then the regen does, in agreement with the theory in section 2.3.2. If the contrast with preamplification and a 2 mm RG850 filter inserted is plotted in the same figure as when the filter is removed, plot b) in figure 4.5, the effect of the filter can be seen. A thicker filter blocks more of the low intensity noise but on the other hand it also lowers the pulse energy and therefore decreases the seed energy into the regen.



(a) (b)

Figure 4.5: *Comparison between seeding the regen with preamplified, but not filtered, pulses and in a) the ordinary seeding and in b) with preamplification including filtering with a 2 mm RG850 filter.*

In figure 4.6 comparisons have been made between different thicknesses of the filter. In the first, 4.6 a), the filters are inserted in the setup and for compensating the lowered seeding into the regen, because of the filters, the pumping of the regen is increased. When the pump power is increased the production of ASE is also increased. In the second, 4.6 b), the pumping is kept constant and instead the number of passes through the crystal inside the regen is increased for the thicker filters.

The fact that the peak of the ASE spectrum is pushed toward longer

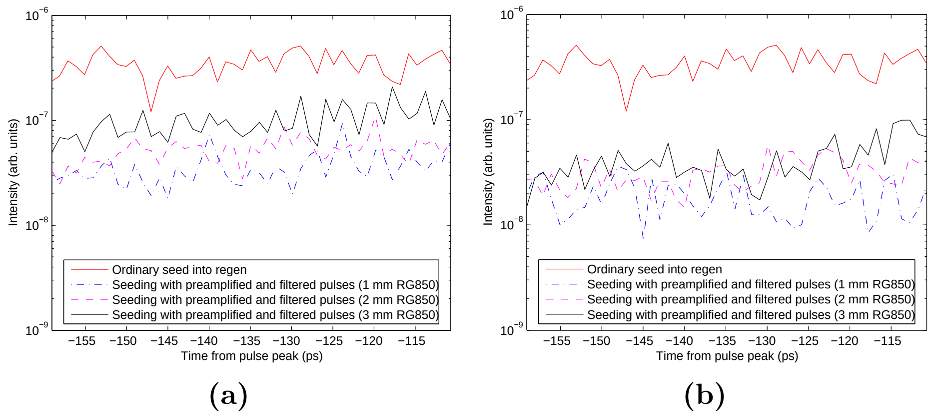


Figure 4.6: *A comparison between how the final contrast varies depending on if the amplification in the regen is adjusted by a) varying the pumppower of the regen or b) if the number of passes in the regen is adjusted.*

wavelengths by the SA also helps to suppress the total ASE because the amplification in Ti:sapphire is highest around 800 nm. The stretcher is built in such a way that only wavelengths between ∼750–850 nm can pass through it, meaning that wavelengths longer than ∼850 nm are blocked. This slightly increases the suppression of the ASE.

The noise level after the main pulse is of less interest for the experiments made at the LLC and therefore no measurements have been made on the contrast there.

4.3 Comparison with Simulations of Amplification

Simulations of amplification have been made with Lab2 [36] in LabView. The simulations are based on the example *tutorial amplifier 4pass.vi* that comes with the program. A dispersive element representing the lenses in the setup has been added as well as a detector to measure the final pulse duration. The block diagram can be seen in Appendix C, figure C.1, together with a view over the control panel, figure C.2.

Table 4.1 shows the results from simulations where the pump fluence on the crystal and the number of passes in the amplifier are varied. The values that are varied in the simulations are shown in the table except for the thickness of the dispersive element. The thickness was set to be 2.5 mm times the number of lenses needed for a certain number of passes. There are two telescopes outside the multipass amplifier with two lenses each and one lens is also needed for every pass inside the amplifier except for the first pass. The other values are fixed and can be seen in the view over the control panel in Appendix C figure C.2.

The diameter set in the control panel is not exactly true for all passes. As long as the amplifier is not saturated the value is only relevant for intensity measurements. The value of the doping concentration of the Ti:sapphire crystal is an educated guess and the total gain does not vary very much with this value since most of the pump light is absorbed by the crystal. BK7 is chosen as the dispersive material. What materials the lenses are made of are unknown for many of them but BK7 is common and affects the pulses in a quite similar way compared to other materials. The Ti:sapphire crystal stands for most of the pulse broadening since it is 12 mm thick.

According to table 4.1 the expected amplification in the preamplifier for its present values[2] is ~35000. Currently the amplification is around a factor 2000, but it has been ~12000 for the same pump fluence. This reduction shows the importance of mode matching.

Table 4.1: *Simulations of amplification in Lab2*

Pump fluence [J/cm^2]	Nbr. of passes	Final FWHM [fs]	Tot. gain
2	1	140	3
3	1	140	7
3.8	1	130	13
4	1	130	16
2	2	220	12
3	2	210	55
3.8	2	210	183
4	2	200	248
2	3	300	43
3	3	280	415
3.8	3	270	2540
4	3	270	4000
2	4	370	154
3	4	340	3150
3.8	4	330	34900
4	4	330	62800
2	5	440	548
3	5	400	23700
3.8	5	420	381000
4	5	440	660000

[2] 3.8 J/cm^2 and 4 passes.

4.4 Possible Future Improvements of the Setup

Even if the contrast is enhanced with the new setup built during this project there are still many things in it that can be improved or investigated.

The most crucial part to be changed is the increased pulse duration due to the spectral narrowing caused by the preamplifier and the RG850 filter. The easiest way to decrease the pulse duration may be to adjust the Dazzler[3] located directly after the oscillator and by this broaden the final bandwidth. It is also possible to adjust for spectral shifting of the pulse spectrum. Adjustments of the Dazzler are, however, not likely to compensate for all the loss in bandwidth. This way the real reason for why such a large part of the spectrum is cut off is not found. Perhaps the pulses when arriving at the SA need to be fully compressed so that the different wavelengths are not separated in time and thereby affected differently by the filter. There is then a risk that the intensity on the filter at its current location will be too high and therefore necessary to increase the spot size on it. This on the other hand may lower the fluence too much for the filter to be fully saturated. The solution may also be to stretch the pulses before they reach the SA and in this way the filter can be placed in the focus of the telescope and therefore a smaller area need to be bleached. Bleaching of a smaller area means less absorbed photons and perhaps a better transmitted spectrum.

Small things to reduce the passive losses are to put anti reflection coatings for 800 nm on the lenses and place the SA in Brewster angle, or add a coating to it. The reason why the SA is not already at Brewster angle is the fact that if a beam propagates through a plate of some thickness it is displaced with a distance depending on the thickness of the plate. During the measurements the SA was often changed or removed and with a normal angle of incidence there was no displacement that needed to be compensated for.

If a SA that has a lower transmission at 800 nm could be found the ASE would be suppressed even further. For the Schott RG850 filter the difference in transmission between a non-saturated and a saturated filter is just a little more than a factor of 10. The SA can also be exchanged for a completely different pulse cleaning technique, for example from section 2.5. A combination of techniques can also be used.

The mode matching in the regen between the pump and the preamplified seed pulses are not perfect, this contributes to a need for higher pumping or a larger number of passes than with perfectly matched modes. This of course also affects the competition with the ASE build-up in the regen. The mode matching can be improved if the telescopes and lenses, jointly

[3] An ultrafast pulse shaping system that simultaneously and independently can perform both spectral phase and amplitude programing.

used by the old and the new systems, are adjusted to fit the preamplified pulses. Then on the other hand the switching between the two would be more complicated.

Due to some rebuilding of the system the spatial profile of the pulses sent into the preamplifier changed. As not enough lenses with right focal lengths were available the matching of the modes, of all four passes, with the pump beams did not reach the same quality as before. This resulted in a reduced total amplification after the four pass preamplifier from $\sim$12000 to 2000 and also a less stable amplification on a day-to-day basis since the size of the signal beam is now larger and harder to keep inside the pumped volume.

In the beginning of this project the need for a Pockels cell early in the setup was discussed so that only one pulse was amplified at a time. But because of the compact design of the preamplifier one pulse has managed to complete all its four passes before the next pulse arrives at the crystal. Even if the next pulse would enter the preamplifier before the preceding one is finished the energies are so low that no reduction in amplification is noticeable. The main advantage of the Pockels cell would probably be that the energy absorbed by the SA and therefore also the heating of it is considerably lower. The Faraday isolator now present just before the regen, to block back reflexions, could also be removed and this would increase the seeding into the regen since the isolator has a transmission of around 20–30%.

As mentioned before, the biggest problem that needs to be solved is the large spectral narrowing.

Acknowledgements

First of all I would like to thank my supervisor Anders Persson for always taking his time to help me or answer my questions. Not only did he seem interested, he also always had the knowledge. I think he spent so many hours on helping me that it would have been faster for him to do it all by himself.

Filip Lindau and Olle Lundh also deserves to be thanked for showing interest in my work and answering my questions.

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Appendix A

The Experimental Setup

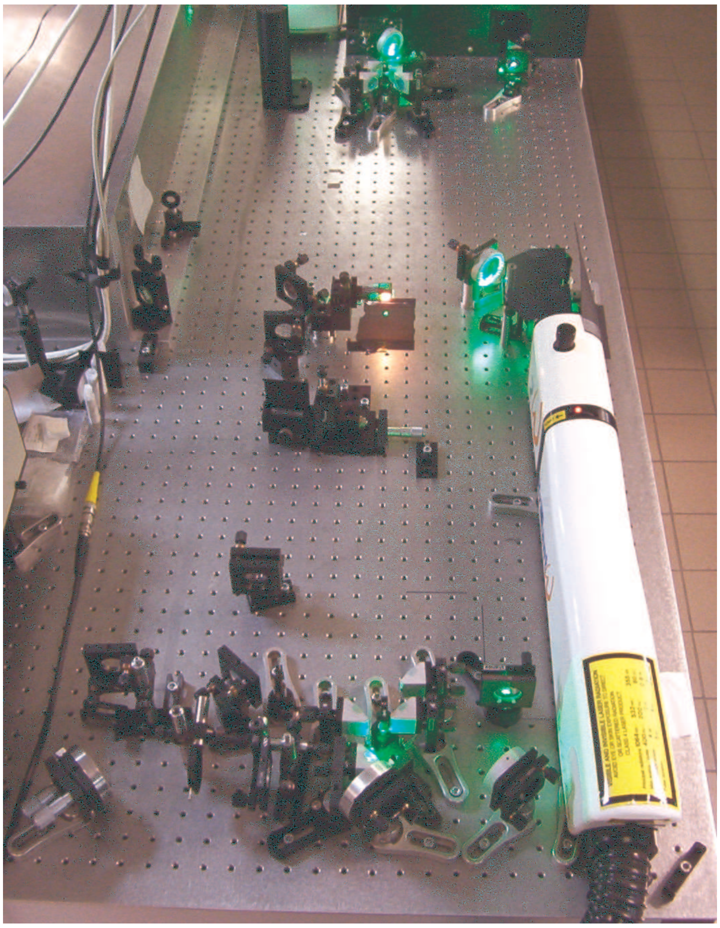

Figure A.1: *Photo of the new preamplifier and pulse cleaner.*

Appendix B

List and Description of Optical Components

Table B.1: *Lenses*

Item	focal length f [mm]
L1	1000
L2	1000
L3	300
L4	-100
L5	300
L6	350
L7	254
L8	200
L9	102

Table B.2: *Misc components*

Item	Description & Specification
M1	532 nm, 45°
M2	750–850 nm, 45°, dielectric
BS	Beam splitter, 50:50, 45°, non-polarizing, coated
TFP	Thin Film Plate, BK7 glass, center wavelength: 532 nm
$\lambda/2$-plate	Multiorder
Nd:YAG	Brilliant 10Hz, Quantel, 532 nm, 5 ns
SA	Saturable Absorber, Schott RG850, 1, 2 or 3 mm
Ti:Al_2O_3	Ti:sapphire, Brewster cut, dia.: 7 mm, length: 12 mm

Appendix C

Simulations in Lab2

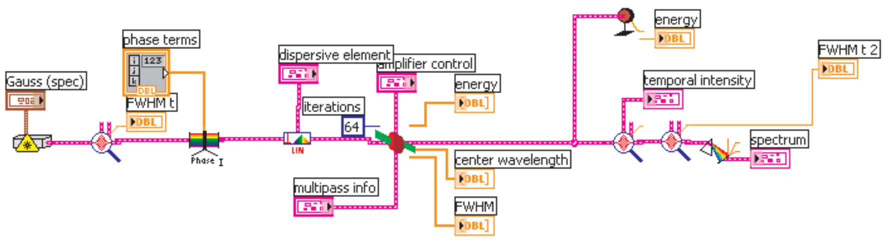

Figure C.1: *The block diagram in Lab2.*

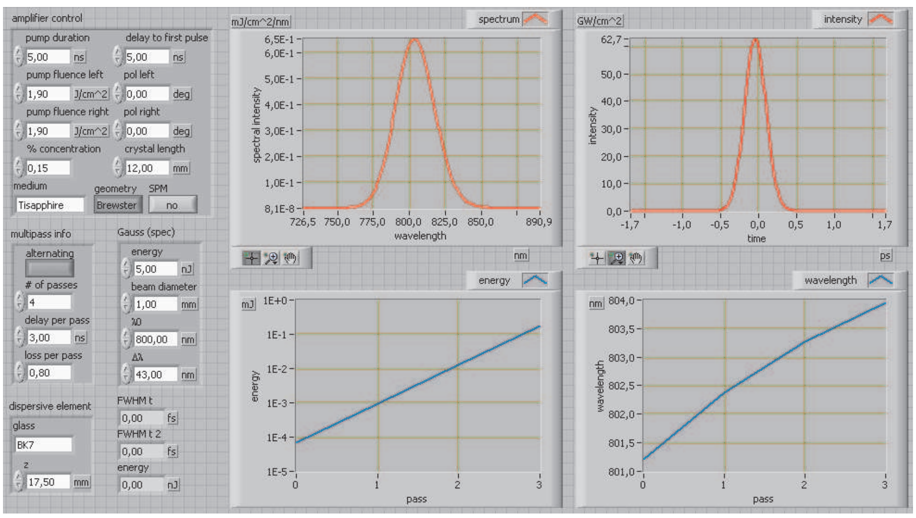

Figure C.2: *A view over the control panel.*