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Study of Radiative Blast Waves Generated on the Z-Beamlet Laser

Aaron D. Edens and Jens Schwarz

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Aaron D. Edens
Z Operations Department

Jens Schwarz
Z-Backlighter Laser Facility Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1193

Abstract

This document describes the original goals of the project to study the Vishniac Overstability on blast waves produced using the Z-Beamlet laser facility as well as the actual results. The proposed work was to build on earlier work on the facility and result in the best characterized set of data for such phenomena in the laboratory. To accomplish the goals it was necessary to modify the existing probe laser at the facility so that it could take multiple images over the course of 1-2 microseconds. Troubles with modifying the probe laser are detailed as well as the work that went into said modifications. The probe laser modification ended up taking the entire length of the project and were the major accomplishment of the research.

Our proposed work was motivated by a desire to probe various hydrodynamic theories and simulations forwarded in the astrophysical literature which predict the growth of instabilities on shock fronts in strongly radiating blast waves. These instabilities are thought to give rise to much of the spectacular structure observed around supernovae remnants. In particular, we wanted to examine the Vishniac overstability. This instability was originally proposed by Vishniac and Ryu[1] in 1987 and the theory was refined over the next several years[2]. The theory describes an oscillating perturbation on a supernova remnant surface that can grow in time. This oscillating perturbation was thought to potentially have a role in star formation[3]. The theoretical predictions of the Vishniac overstability state that its evolution should be determined by two main parameters, the wavelength of perturbations compared to the radius of the supernova remnant and the polytropic index of the gas in which the supernova remnant is traveling. There have been several studies done on radiating blast waves such as those that may be susceptible to the Vishniac overstability[4].

Radiative blast waves have primarily been studied using laser based experimental platforms. In most experiments, a laser has been used to illuminate a solid target immersed in a gas or the gas itself and create a point or line explosion that then travels into the surrounding medium creating a radiating blast wave. Different gasses will radiate different amounts and thus have different polytropic indices. For experiments specifically looking at the Vishniac overstability, perturbations can then either be allowed to grow from noise or can be induced by means of placing an object in the path of the blast wave. Inducing perturbations allows study of a wider variety of wavelengths of perturbation and allows for large initial perturbations to be induced, making them easier to measure. By varying the wavelength of the induced perturbation and the gas in which the blast wave travels one can explore the two primary parameters of the Vishniac overstability.

Previous experiments on this topic at the Z-Beamlet (ZBL) facility were done as part of a collaboration with the University of Texas[5]. In these experiments the ZBL laser was used to illuminate a solid target and create a blast wave inside a vacuum chamber that was filled with a small amount of gas (~1% of an atmosphere by pressure). During each experiment, a single image of the evolution of the created blast was taken using a probe laser. By performing multiple experiments with a given induced perturbation wavelength and gas type in the chamber, a data set could be built that described the evolution of a blast wave. Using this approach, we built data sets for several different wavelengths of induced perturbations in several different gasses. We then compared the results of our experiments to published theoretical predictions[2]. The exact results can be seen in previous publications[6]. While the basic premises of the astrophysical theory were confirmed by this research, several questions still remained about the overstability that could not be solved with the previous experimental platform.

When designing the new set of experiments, there were three primary questions that we sought to resolve. As described above, the Vishniac overstability involves an oscillating perturbation. In the previous experiments, only decaying perturbations were examined and no oscillations were seen. Therefore, our first goal was to observe the oscillation of a perturbation on a blast wave surface, as this is a key component of the theory that has never been observed experimentally. In a similar vein, while only decaying perturbations were previously definitively seen, there were indications of a slightly growing perturbation for one set of conditions. Therefore our second objective was to obtain a definitive measurement of a growing perturbation. Finally, one complication of studying the evolution of radiating blast waves is that as the blast wave radiates, it loses energy and thus the hydrodynamic conditions of the blast wave, and consequently its polytropic index, change in time. Because we had no means of directly measuring these changing hydrodynamic conditions, we used computer simulations to estimate the conditions at a given point in time. The changing hydrodynamic conditions made the comparison to theory, where a constant polytropic index was assumed, more difficult. To combat this problem, we set out to develop a direct measurement of the density and temperature across the shock front to more accurately gauge the polytropic index of the blast waves as a function of time. If successful, this set of measurements would have resulted in a new level of quantitative understanding of these astrophysically relevant radiative shocks.

Given our three desired measurements, we designed a new experimental platform . The core of the layout was the same as in the previous experiments at the ZBL facility [REF], with two primary changes. In order to achieve our goal of a direct experimental measurement of the hydrodynamic conditions of the gas, the first change we made was the addition of a spectroscopic diagnostic to look at Stark broadening of spectral lines in the gas. Since the polytropic index of a gas can be determined by looking at the density jump across the shock front of the blast wave, what we wanted from this diagnostic was a relative density measurement across the shock front that was time resolved. As an added positive, a relative measurement is somewhat easier to analyze and more robust than an absolute measurement with this type of diagnostic. A similar diagnostic has been previously successfully fielded by other groups looking at blast waves traveling in nitrogen gas[7].

Our plan involved a two staged approach to the spectrometer. At first, we planned on taking a single snapshot per experiment of the hydrodynamic conditions on either side of the shock front utilizing a spectrometer system previously fielded on the Z machine. This system uses a micro-channel plate detector attached to a spectrometer to obtain time gated spectra with one dimension of spatial resolution. By using this system and imaging across our blast front, we could get a time resolved snapshot of the hydrodynamic conditions in our experiment. We planned later upgrade that system with a multi-frame channel plate to allow for multiple images. Since our previous experiments indicated that blast waves in a mixture of nitrogen and xenon held promise for producing a growing blast wave, and there were published results for looking a nitrogen lines in blast waves, we planned on studying the same nitrogen lines in our experiment. We therefore purchased gratings for the spectrometer system appropriate for the nitrogen lines of interest.

In order to aid in satisfying our other two goals, the second change to our experimental system was to upgrade the probe laser at the ZBL facility previously known as NLS and now known as HALO. The lifetime of our blast waves was noted to be a few microseconds in previous experiments. Obtaining multiple images of a single blast wave over this time frame would allow us to correlate spatial features better, leading to a more definitive measurement of both oscillation and growth. Therefore we set out to upgrade the laser to allow us to obtain multiple images of a single blast wave evolution. An additional benefit of this upgrade would be to quadruple the data output of an experiment compared to the previous incarnation.

In researching the options for detectors that could capture multiple images over the course of a couple of microseconds, it was discovered there was an available camera at Sandia that we could borrow that took 4 images with 250ns spacing between them, ideal for our purposes. We therefore set our requirements on the upgrade of the laser to be compatible with this camera. In addition, based on previous experiments, we knew laser energy of order 70mJ was necessary in the probe beam to be seen over scattered laser light from the Z-Beamlet laser. When proposing the research it was thought that this upgrade should be relatively simple to implement, and should be able to be completed in the first year, enabling multiple years of experiments to satisfy the experimental goals. Upon more detailed examination, this regime of time and energy proved to be challenging to reach. In order to reach the experimental requirements, the former NLS laser was heavily modified and is now called the HALO laser. Design and implementation of the upgrade ended up taking well over 2 years, with determination of initial specification taking several months on the front end, meaning the laser upgrade project ended up consuming all the available time for the project. As such, the original experimental objectives of the proposal were not met. However, the laser upgrade was completed and enhances the capabilities of the ZBL facility. The rest of this report will detail the upgrade to the HALO laser.

THE HALO LASER SYSTEM

Overview

The HALO Laser consists of three subsystems: A Master Oscillator/pulse shaping front end, a Regenerative Amplifier (regen), and the Main Amplifiers. The front end is a commercial Novawave SFL-1064PM 2W continuous wave solid state class IV laser, that is pulse shaped using two electro-optic modulators (EOM). Pulse shaping is necessary to account for the temporal pulse distortions in successive amplifiers. The Regenerative Amplifier is a custom design that allows a maximum output energy of 10mJ in a pulse width less than 8ns at a repetition rate of 10Hz with a burst mode capability of 4 frames at 4MHz. The Main Amplifiers consist of a custom commercial six Rod laser system, (Continuum Model SG518 Solid State Glass Amplifiers) and one Nd:YAG 6mm rod. The repetition rate of the Main Amplifiers is laser head dependent. The 6mm amplifier repetition rate is 10Hz. The 9mm repetition rate is 1 ppm (pulse per minute), 16mm repetition rate is 0.5ppm, 25mm v rate is 0.25ppm, 45mm repetition rate is 0.125ppm, and the 64mm repetition rate is 0.05 ppm. The System is the then frequency doubled from 1064nm to 532nm using a KDP type I, followed by a KDP type II doubling crystal.

The Master Oscillator Front End

The initial laser light is provided by a 2W continuous wave, 1064nm, solid state laser. This seed is used to create an arbitrary input pulse shape for the successive regenerative amplifier. This is accomplished using two EOM's (Electro-optic modulators). The first free space EOM is used to lower the input power by slicing out rectangular light packets of 1ms FWHM (Full width at half maximum). The resulting low average power beam is then fiber coupled and pulse shaped using an arbitrary waveform generator (AWG) in conjunction with the second fiber EOM. Using this technique one can generate pulses as short as 300ps FWHM and as wide as 10ns FWHM. Furthermore, within a time interval of 10ns, multiple pulses of arbitrary shape and amplitude can be created. Figure shows a fully amplified two pulse sequence where the first pulse is less than 500ps FWHM and the main pulse is 1ns FWHM.

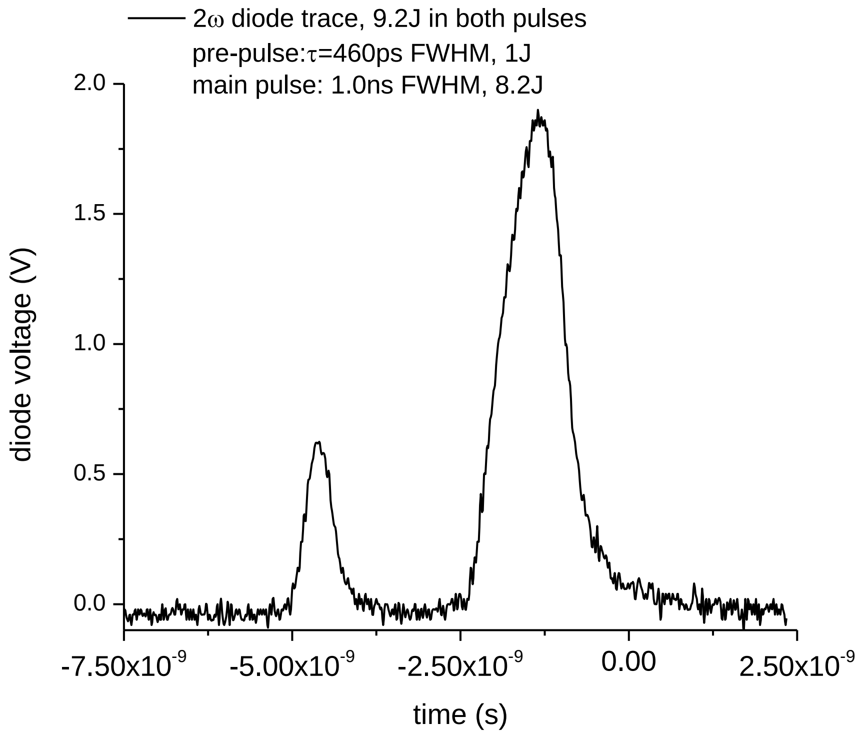

Figure 1: Photodiode trace of an amplified frequency doubled two pulse sequence, demonstrating our arbitrary pulse shape capability.

The Regenerative Amplifier (Regen)

Once the desired pulse shape is created, the sub nJ energy pulse is injected into the ring regen cavity (see Fig.).

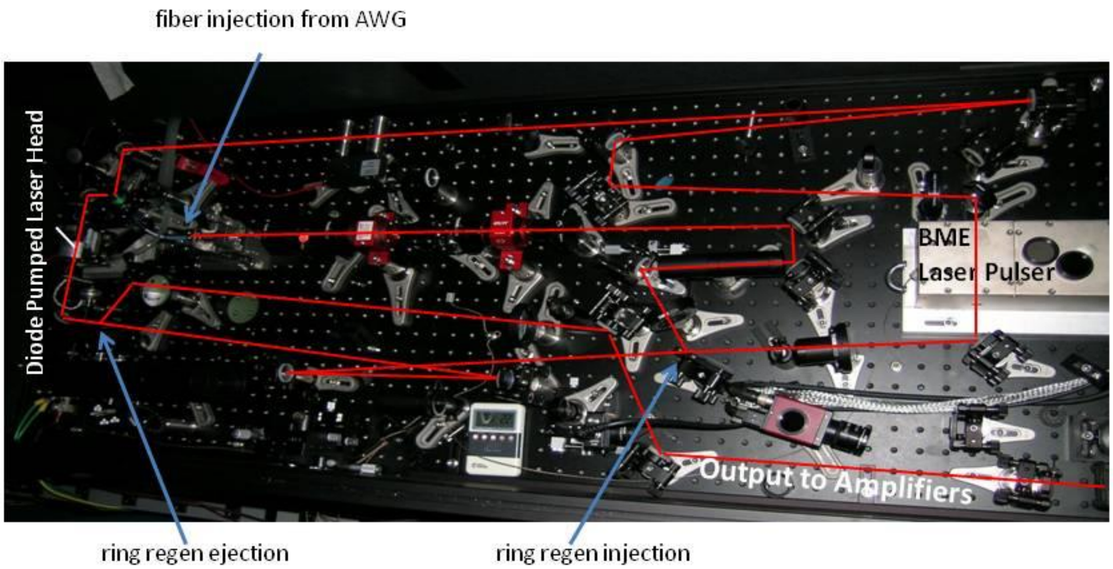

Figure 2: HALO ring regen.

This cavity consists mainly of a diode pumped amplifier head with a gain of 4, and a Pockels cell that is used to trap the laser pulse for about 40-50 round trips.

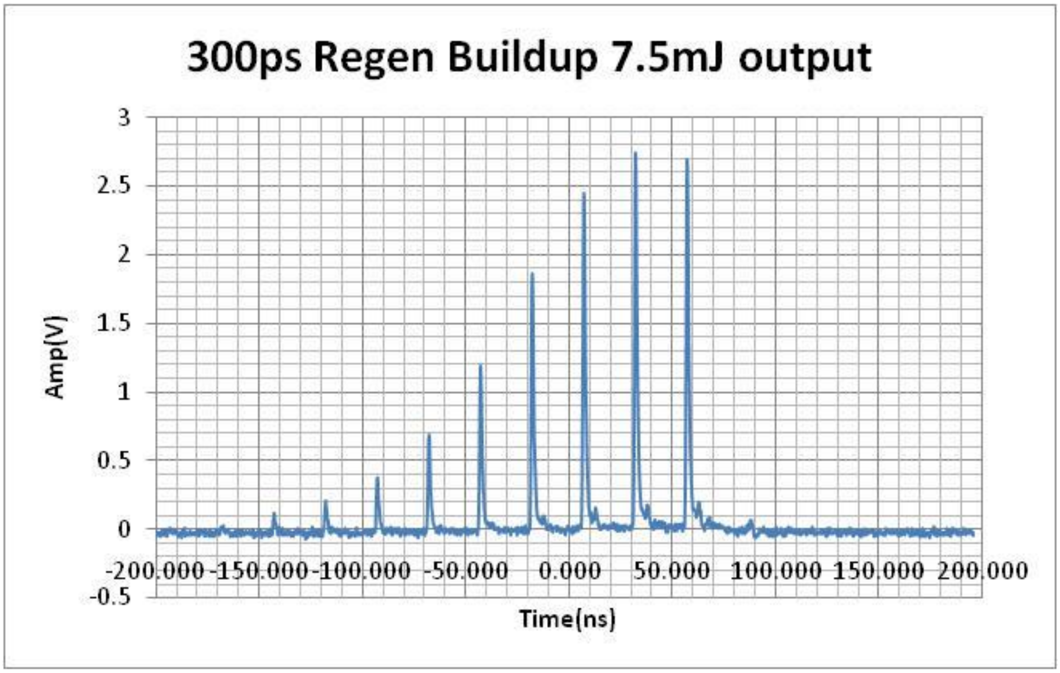

Figure 3: Regen buildup after 41 round trips.

Figure shows the pulse buildup in the cavity for a 300ps FWHM seed pulse with an output energy of 7.5mJ after 41 round trips. The regen has a round trip time of 12.5ns and operates at 10Hz repetition rate. In order to achieve the desired four pulse sequence at 4MHz, a special optical modulator (and driver) had to be identified (see Appendix A). After long and thorough testing, we decided to implement Pockels cells from BME Bergmann which can generate 4MHz burst pulses at a 10Hz repetition rate. Figure shows such a burst sequence where the Pockels cell is used to chop light out of a continuous wave beam.

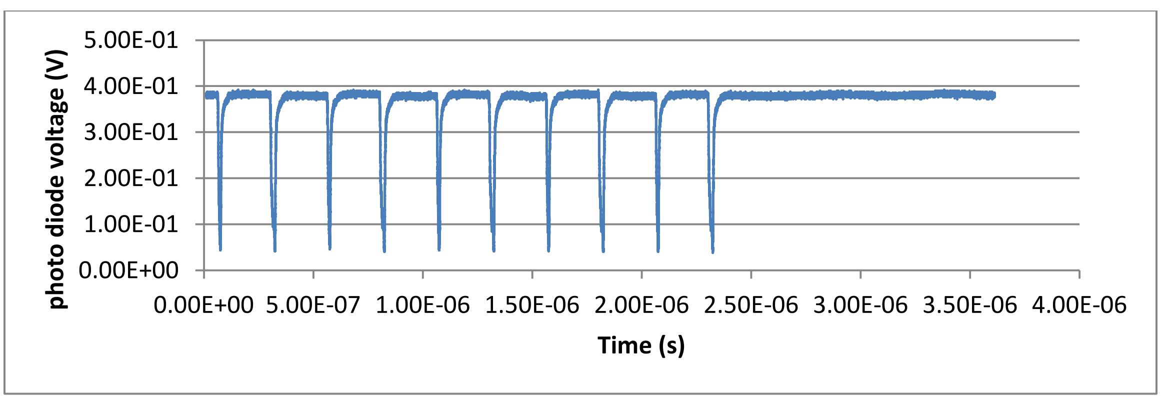

Figure 4: Initial off-line test of BME Pockels cell 4MHz burst capability.

The proposed, but not as of yet realized, four pulse scheme is as follows: A seed pulse from the fiber front end is injected into the ring regen cavity and makes 250ns/12.5ns=20 round trips. At this point, the Pockels cell switches and 95% of the beam is ejected. The remaining 5% of the pulse experience gain during the following 20 round trips until this pulse is ejected as well, and so on. In order to prevent pre-pulses from entering the main amplifier chain, a second 4MHz burst capable Pockels cell has been purchased and is ready to be implemented. Figure shows the operation of the current second Pockels cell for a single pulse coming from the regen cavity.

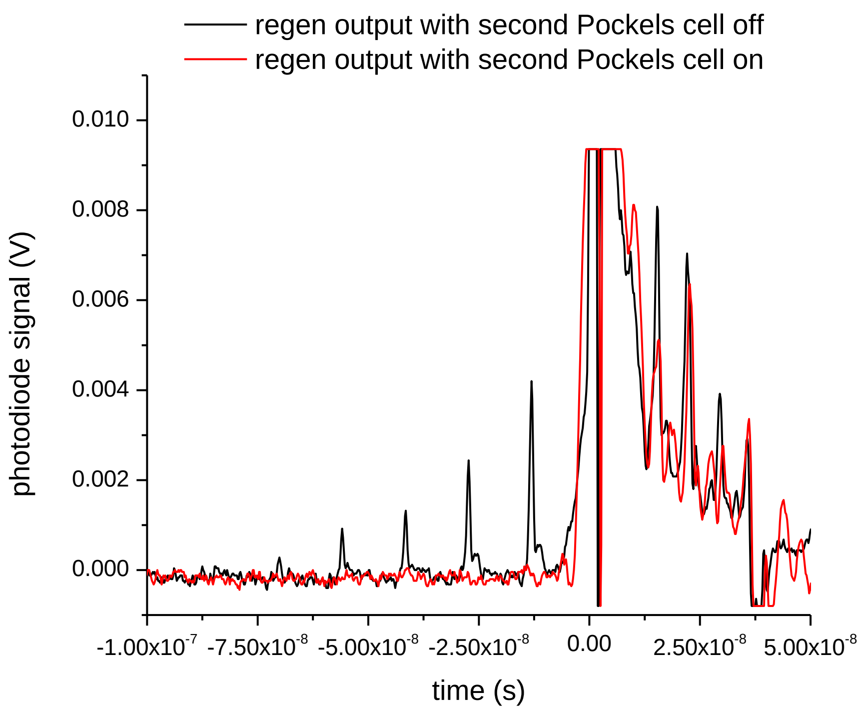

Figure 5: Photodiode signal of the regen output beam after the second Pockels cell. A train of equally spaced pre-pulses is visible when the second Pockels cell is turned off (black trace). Once the Pockels cell becomes operational, these pulses vanish and the rise-time of the main pulse decreases as well (red trace).

One can see that several pre-pulses are present when the second Pockels cell is turned off. Theses pulses are due to leakage from the regen cavity and are spaced 12.5 ns, the roundtrip time of the regen cavity.

So far only single pulse operation has been demonstrated. The four pulse operation upgrade is scheduled for October 2011.

The main amplifier chain

The main amplifier chain consists of five single shot rod amplifiers (see Table) and one 6mm diameter pre-amplifier at 10Hz.

Rod Amplifier Parameters						
Diameter (mm)	**Length (mm)**	**Glass Type**	**Max Rep Rate (ppm)**	**Output Energy (J)**	**Fluence (J/cm^2)**	**Gain/pass**
9	115	Silicate	1	0.1	0.096042	6.666667
16	235	Silicate	0.5	0.768	0.284557	7.68
25	235	Silicate	0.25	1.79	0.187649	2.330729
45	235	Silicate	0.125	5	0.279268	2.793296
64	235	Silicate	0.05	14	0.781951	2.8

Table 1: List of various amplifier heads and their respective size, glass type, repetition rate, and gain.

A 6mm pre- amplifier was later added to boost the energy into the main amplifier chain. Figure shows a schematic of the HALO laser system, including the main amplifier section.

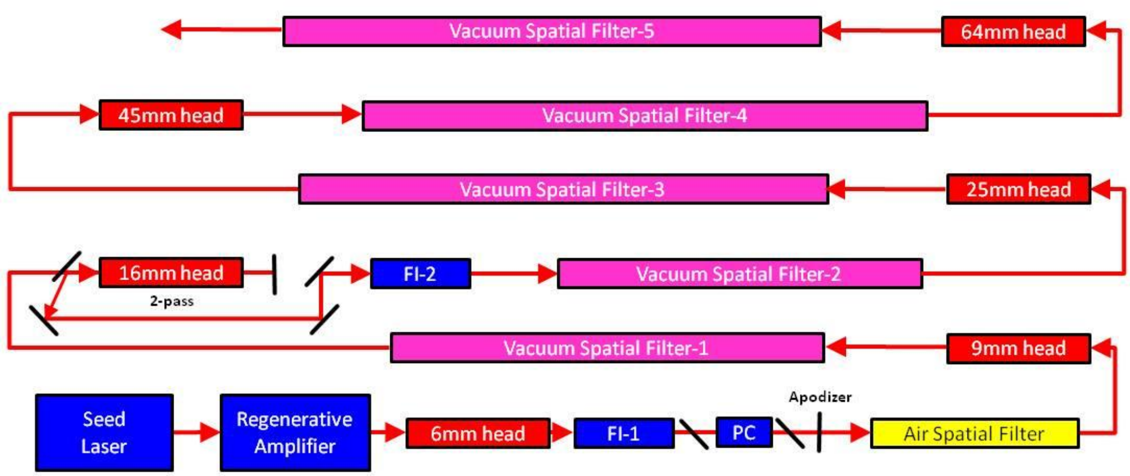

Figure 6: Amplifier table with its successively larger amplifier heads. FI-1 and FI-2 are the Faraday Isolators that provide back-reflection protection for the system. PC is the Pockels cell that chops out the pre-pulses.

As the beam traverses each amplifier it is image relayed by vacuum spatial filters. A diagnostic leakage mirror is used at each stage to measure the beam profile/near field and energy (not shown). An extensive diagnostic suite (temporal pulsewidth, energy, near field, far field and wavefront sensor) has been added at the end of the amplifier chain, just before frequency doubling occurs. This is essential for system performance measurements, and machine safety considerations. Figure shows the amplified beam profile (near field NF6) at the output of the main amplifier chain, before frequency conversion occurs.

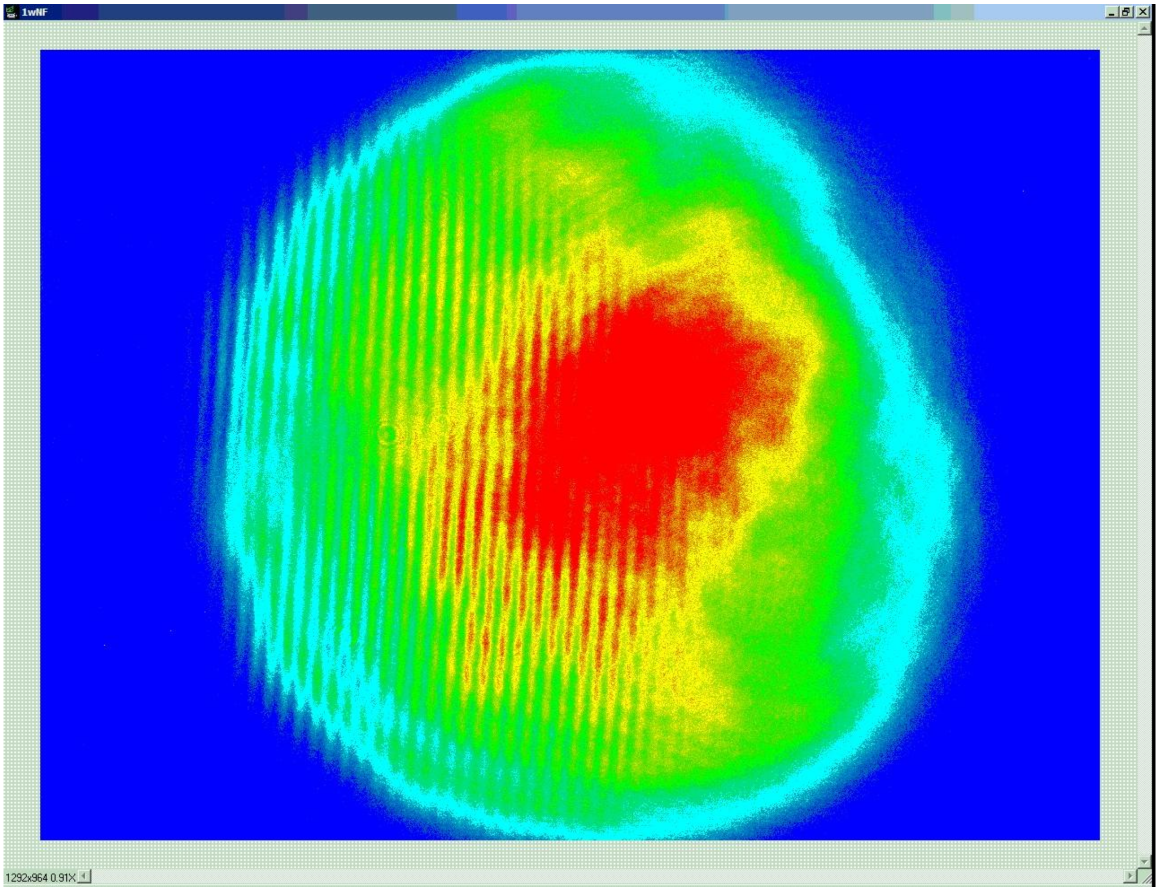

Figure 7: Amplified beam profile at the end of the main amplifier chain. The fringe pattern is due to beam interference at the neutral density filter on the diagnostic camera. It does not exist in the actual beam profile.

Since this beam will be used for interferometry and frequency doubling it is important to consider wavefront aberrations during and after amplification. Due to the cylindrical symmetry of the rod amplifiers, the main source of aberration is “defocus”. Defocus can accumulate if the amplifiers don’t have enough time to cool down between shots. Hence we have measured the “defocus” term versus time for every amplifier after it has been fired. Figure shows the cool down time for each amplifier.

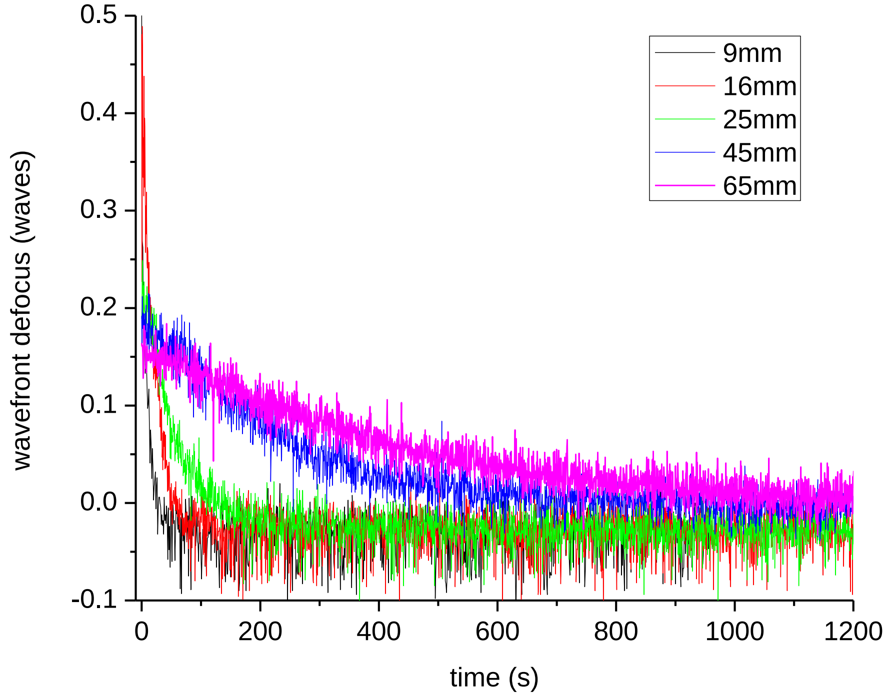

Figure 8: Wavefront defocus versus time for all single shot amplifiers.

As one can see, the cool down time for the first three amplifiers is less than five minutes whereas the last two amplifiers should not be fired faster than once every twelve minutes.

Frequency conversion

Before the beam can be used as a probe beam, it has to be frequency doubled from 1064nm to 532nm. This is achieved by appropriate doubling crystals. It was believed that the existing doubling crystal from the former NLS laser (which had similar performance parameters) would be adequate. However, closer investigation showed that this was not the case. Currently, an additional crystal has been used to extend the effective crystal length at the cost of added complexity and additional energy losses (up to 15%) due to uncoated surfaces. Nonetheless, conversion efficiencies up to 70% have been achieved so far. In order to optimize frequency conversion, we have modeled the conversion process (using SNLO) for various input energies, temporal pulsewidths, and crystal types (see Fig.).

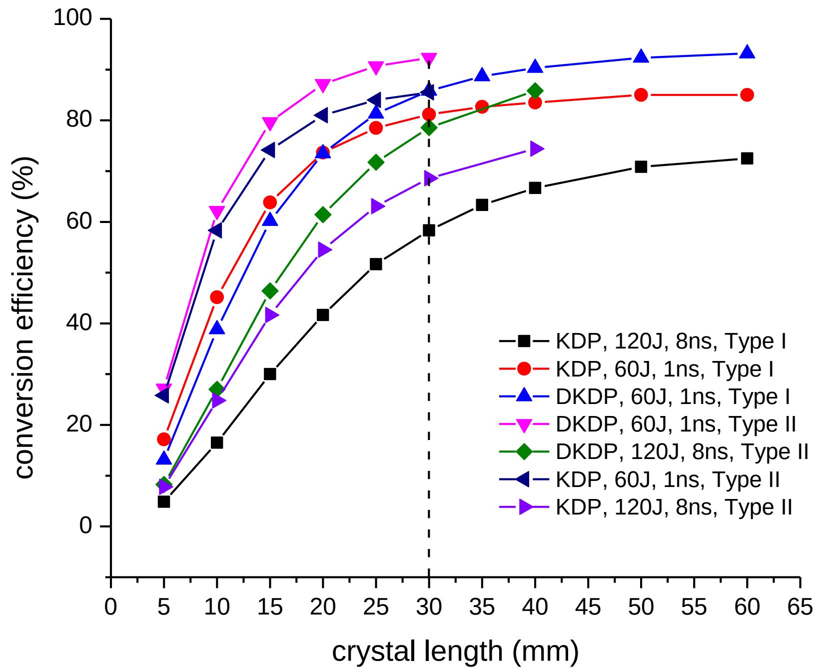

Figure 9: Doubling conversion efficiency versus crystal length for various crystal materials, lengths, and conversion types.

Based on Fig. , a 60mm diameter, 30mm long, type II DKDP crystal has been ordered and is scheduled to ship by mid October 2011. This crystal should increase conversion efficiency and should also reduce losses to less than 5%.

CONCLUSION

At this point, all parts for the laser upgrade and the spectroscopic diagnostic have been procured, and thus with appropriate laser and personnel time, the original scientific goals of the proposal could be carried out with minimal additional hardware purchase necessary.

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APPENDIX A

Project time delay due to identifying appropriate optical modulators

In investigating available technologies for 4MHz optical modulators, two possible solutions stood out.

1. Fast Pockels cell electro-optic modulators (EOMs) in general can handle the energy requirements we desire, but are marginal for achieving the switching times necessary.
2. In contrast, acousto-optic modulators (AOMs) can more easily reach the speeds but are marginal for handling the intensity necessary for our probe beam.

These two technologies seemed the most suitable and so they were investigated in detail. Initially, a quote was obtained from InterAction for a AOM unit with a several month promised lead time, originally due July of 2009. As this time grew closer, the vendor was unable to meet the deadline, but still believed they could provide the product. The deadline was moved back a couple of times by a few months, but eventually it became apparent that this vendor could not supply the requested part. Alternate options were explored during the delays, resulting in a quote from Gooch and Housego for another AOM being obtained in December of 2009. The contract with InterAction was terminated and a order placed with Gooch and Housego in February of 2010. This part was delivered in April of 2010 and tested.

During this time period, as part of our collaboration with the University of Texas, experiments were conducted there looking at multi frame imaging of blast waves in a cylindrical geometry. The laser there fired much lower energy pulses and thus the life time of the blast waves it produced was only 10s of ns. Given this, there inter-frame time on images was only on order of a few ns, and thus they could use the physical pulse stacking techniques with beamsplitters mentioned earlier.

The new AOM was installed and was successful at low energies, but at higher energies the crystal inside the AOM was damaged (the electrodes on the crystal in the AOM cavity were blown off by the energy flux). The part was repaired and tested again with similar results. With two failed attempts at securing an AOM solution, it was decided to instead investigate EOM possibilities. Two potential vendors for EOM solutions were found and parts ordered from each.

One of the chosen vendors was a German manufacturer of Pockels cells, BME Bergmann, and a single pulser was ordered and delivered in October of 2010. At the same time a second unit was ordered from a Canadian vendor, AVTech. The single pulser from BME was tested and met our needs. The second pulser encountered legal issues involving export control and this second pulser was dropped.

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