Pulse-Shaping Effects in Optical Parametric Amplifications

George Dahl

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George E. Dahl

Allendale Columbia School

Rochester New York

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Abstract:

An optical parametric amplifier (OPA) can provide laser amplification over a much larger spectral bandwidth than current amplifiers used in the OMEGA laser system. The OMEGA laser system is located at the University of Rochester Laboratory for Laser Energetics (LLE) which is where the work for this project was performed. Wider spectral bandwidth is advantageous for laser pulse smoothing techniques such as smoothing by spectral dispersion (SSD)[1]. An OPA could replace an OMEGA regenerative amplifier and possibly a Large Aperture Ring Amplifier (LARA), both of which are used in the "front end" of the OMEGA laser system, if its output pulse shape and stability were suitable for injection into the main OMEGA laser chain. In the optical parametric amplification process, a "pump" laser pulse transfers its energy to a "seed" laser pulse through a nonlinear interaction in a crystalline material. A numerical computer model was used to determine the input pulse shapes required to obtain a specific desired output pulse shape (the shape that after going through the main OMEGA laser chain would produce the "alpha308" shape). A two-crystal system that can create the desired output pulse shape is presented. To the best of my knowledge, this is the first time an OPA has been shown to be able to produce the highly shaped pulses necessary for Inertial Confinement Fusion lasers. A tradeoff between output pulse stability and input pulse contrast ratio is described.

I. Introduction

Inertial Confinement Fusion (ICF) could be a clean and essentially unlimited energy source. The fuel is made of deuterium and tritium, which are both readily available, and the main byproduct of ICF is helium, an inert gas. Deuterium naturally occurs in water, and tritium can be produced from lithium in a reaction induced by the fusion process.[2] Inertial Confinement Fusion can be achieved by using a high intensity laser pulse to uniformly illuminate a spherical target composed of deuterium and tritium fuel. The illumination causes ablation of the spherical target shell, which in turn produces an equal and opposite reactive force that implodes the fuel at the center of the target.

An optical parametric amplifier is being considered as a possible replacement for the regenerative amplifier and the large aperture ring amplifier (LARA) in the front end of the OMEGA laser system at the University of Rochester Laboratory for Laser Energetics (LLE), one of the major laboratories studying inertial confinement fusion. The National Ignition Facility at Lawrence Livermore National Laboratory might also directly benefit from greater understanding of the pulse shaping capabilities of an OPA.

The primary advantage of the replacement would be that an OPA can provide broadband amplification, whereas the current system only amplifies a narrow spectral bandwidth. Greater bandwidth would allow the bulk phase modulators currently in use to be replaced with integrated phase modulators. Integrated phase modulators simplify and add flexibility to smoothing by spectral dispersion (SSD)[1] bandwidth generation. Another key advantage of integrated phase modulators is that they can be commercially purchased and do not need to be specially built at LLE or another research facility. Using an OPA would also result in a reduction in the number of optical surfaces used, thus reducing the complexity and improving the reliability of the SSD system.

In order to replace the regenerative amplifier and large aperture ring amplifier with an OPA, the OPA must be able to produce the pulse shape required by the main OMEGA laser chain. The main OMEGA laser chain requires a specific input pulse shape that, after emerging from the chain, will be what is known as the alpha308 shape. The pulse shape required as input to the OMEGA laser chain in order to produce the alpha308 pulse shape will hereafter be referred to as the pre-compensated alpha308 pulse shape (the pre-compensated alpha308 pulse shape is shown as the dashed line in Fig. 6). A computer simulation was used to determine the input pulse shapes to an OPA that are necessary to produce the pre-compensated alpha308 pulse shape at the output of the OPA. The computer model used a two-crystal OPA design[3] that is currently implemented as a prototype laser system at LLE.

Using an OPA for front end amplification in OMEGA also requires that the output pulse of the OPA remains stable against input pulse intensity fluctuations. After the input shapes required to produce the pre-compensated alpha308 pulse shape were determined, the output stability was calculated and examined. When possible, changes were made to the input pulse shapes to improve output stability while still producing the pre-compensated alpha308 pulse shape. The methodology used to determine the input pulse shapes and to improve output intensity stability is quite general, and can be used for any OPA output pulse shape.

II. Introduction to OPA

The optical parametric amplifier used in all simulations consisted of two lithium triborate (LBO) crystals. The dimensions of the crystals were 5 mm x 5 mm x 29.75 mm with the largest dimension equal to the length of the crystal in the propagation direction of the laser beam. A seed beam was amplified by a pump beam through a nonlinear interaction in the crystalline material. In the OPA process, a third beam, called the idler, is generated as a result of the nonlinear mixing of the pump and seed waves. A type 1 process was simulated, where the pump was an extraordinary wave (e-wave) and the signal (i.e. amplified seed) and idler were both ordinary waves (o-waves). The model[3] simulated the propagation of the input pump and seed beams through the two crystals and produced a depleted pump beam, an amplified signal beam, and an idler beam that was ignored. Spatially, the pump was a 10^{th} –order super Gaussian with a full width at half maximum (FWHM) of 3.5 mm and the seed was a Gaussian with a FWHM of 3.18 mm.

III. Methodology

For each temporal point in an input pulse there is a corresponding local intensity value. Each combination of a pump and a seed local intensity produces a single local output intensity. Output intensity is a function of input seed intensity and input pump intensity. A look-up table of pump and seed input intensity combinations and corresponding output intensities was constructed. To find the input needed for an arbitrary temporal shape, the following steps were performed:

1. The look-up table was filled with input and output intensity data that was calculated using a computer simulation[3] of the two-crystal OPA in section II. Flat-topped seed pulses of different total energies and a single linearly-ramped pump were used as input in order to systematically calculate many possible combinations of input intensities.
2. Output stability was calculated at each temporal point in the output pulse shape and added to the look-up table.
3. The look-up table was used to specify the input pulse shapes required to obtain the pre-compensated alpha308 pulse shape. The computer simulation was used to verify

that the predicted input shapes actually produced the required output and to further optimize the pulse shape design and stability.

1. Simulation of an OPA with linearly-ramped pump and flat-top seed pulses

The simulation program was run many times with the same input pump and with seeds of different total energies. As shown in Fig. 1, the pump was a simple linear ramp. As shown in Fig. 2, the seeds were all flat. The only difference between successive runs in this stage of the simulation process was the energy of the seed. The local output intensities for all of the runs were recorded in the look-up table. Each run filled up one row of the table. Figure 3 shows typical corresponding output.

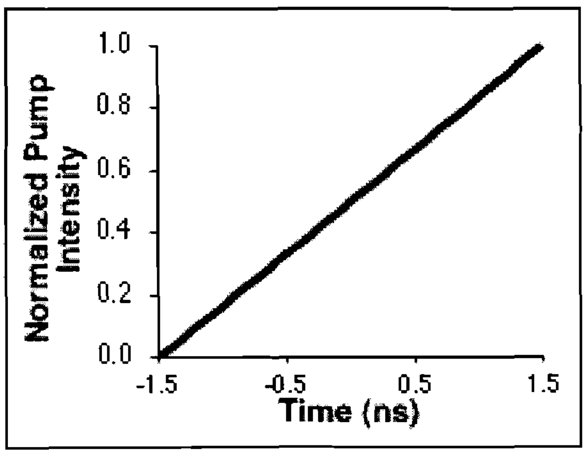

Figure 1: Plot of the normalized temporal pump shape used to gather output data. This pump shape was used in all the flat-top seed runs.

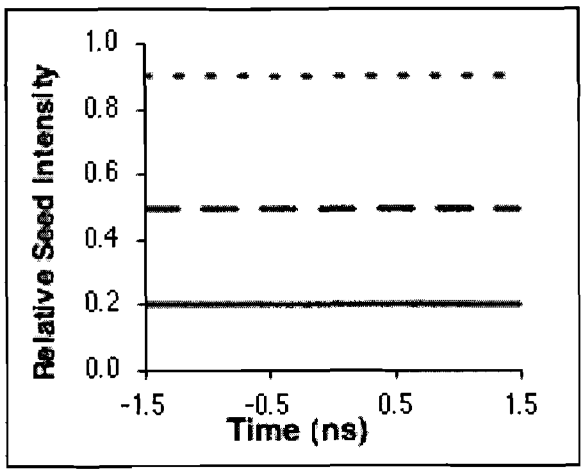

Figure 2: Plot of temporally flat seed pulses of different relative energies used with the ramped pulse of Fig. 1

At the foot of the output pulse in Fig. 3, the signal experienced exponential gain. At the peak of the output pulse (i.e., the peak saturation point), the pump beam was depleted and had no more energy to transfer to the signal. The peak saturation point marks the beginning of the reconversion regime where the signal begins to amplify the pump. The effect of increasing the seed energy is to change the point where reconversion begins. Increasing the seed energy moves the saturation point backward temporally and decreases the intensity of the peak of the output.

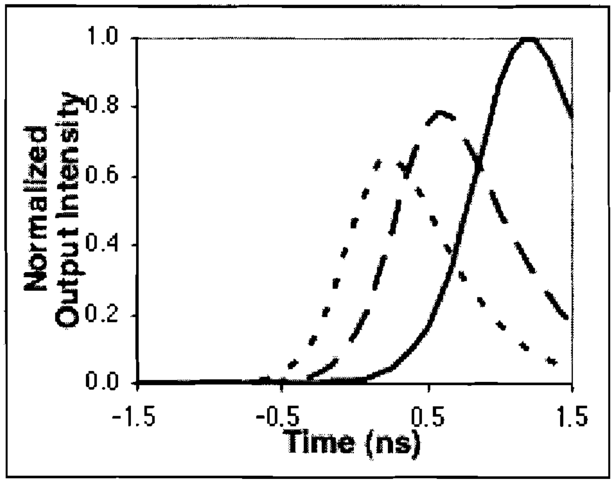

Figure 3: The output temporal pulse shape produced by the three sample seeds in Fig. 2 when combined with the pump shape shown in Fig. 1. The plot shows that as the seed energy is increased, peak saturation occurs at earlier times and at lower relative intensity values. Relative seed energies: 0.2 – solid, 0.5 – dashed , 0.9 – dotted.

2. Calculation of output intensity stability

Relative stability is defined as:

$$(\Delta I_{signal} / I_{signal}) / (\Delta I_{pump}/I_{pump}) \qquad (1)$$

Where $(\Delta I_{signal} / I_{signal})$ is the relative change in output intensity and $(\Delta I_{pump}/I_{pump})$ is the relative change in input pump intensity. The relative stability factor is a measure of the effect input pump intensity fluctuations have on output intensity. The closer the relative stability factor is to zero, the less the output intensity is affected by fluctuations in pump intensity. To find the relative stability factor for all the temporal points in a given run, the simulation was repeated with a +1% and a –1% total pump energy variation. At each temporal point, the difference in output signal intensity between the +1% pump energy run and the - 1% pump energy run was divided by the output intensity of the original run. That quantity was then divided by the relative change in pump energy (2%) to obtain the relative stability value. The relative stability factor was calculated for each temporal point in each run of the simulation and recorded with the corresponding output intensity in the look-up table. Sample relative stability curves appear in Fig. 4. Note from Figs. 3 and 4 that relative stability is best at the peak of the pulse and reduced at the foot of the pulse. The most stable region of the pulse is where the signal is saturated and reconversion begins.[3,4] For a temporally flat seed, and a linearly ramped pump, there is a unique pump local intensity value that produces the most stable output, and this point corresponds to the start of reconversion. The zeros of the stability curves in Fig. 4 are the points of maximum stability and they correspond to the peaks of the output curves in Fig. 3.

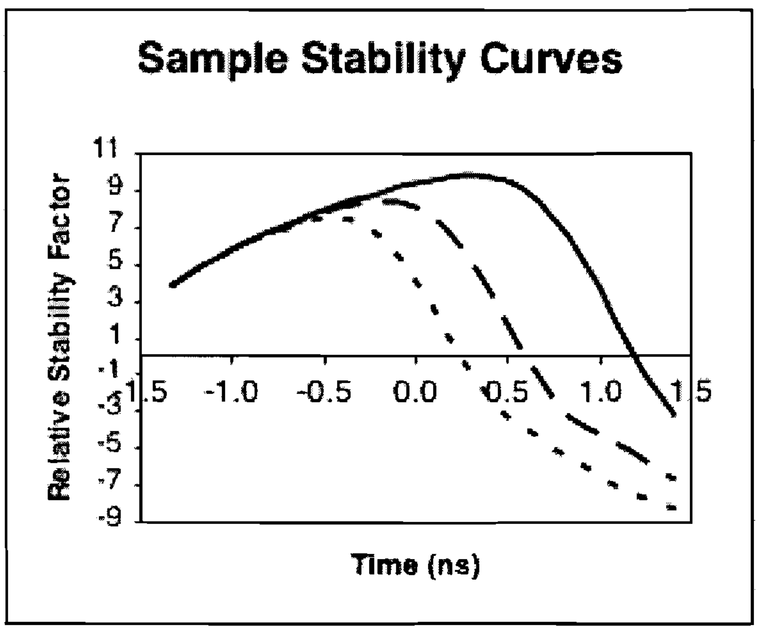

Figure 4: Plot of Eq. (1) vs. time. Since peak output intensity moves backward temporally as seed energy increases, the point of best stability (relative stability factor=0) does also. Relative seed energies: 0.2 – solid, 0.5 – dashed , 0.9 – dotted.

3. Design of input pulse shapes

The input and output intensity and relative stability data were collected into a look-up table so that input intensity values could be chosen to make the pre-compensated alpha308 pulse shape. Looking up a desired output intensity in the table gives input pump and seed intensities that will produce the desired value. Each combination of input pump and seed intensities also gives an estimate of what the relative stability will be. Although there is only one output value and relative stability for any given combination of input pump and seed values, there are many combinations of input pump and seed values that produce a given output value. This fact provides flexibility in choosing input intensity values to make an arbitrary output pulse shape. Since there are many combinations of input pump and seed values that will produce the same local output intensity value, additional criteria for either input or output pulses can be imposed. Points can be chosen to produce input pulse shapes that are smoother or have lower contrast ratios. Contrast ratio (CR) is defined as the ratio of the largest local intensity value in the pulse to the smallest local intensity value in the pulse. Avoiding discontinuities in the input shapes was a high priority in choosing points. Points were chosen to make relatively smooth curves while curves with many relative maxima or minima were avoided. Flexibility in choosing points for the input shapes makes it possible to create the pre-compensated alpha308 pulse shape with better relative stability than if such flexibility were not present.

IV. Results

The first successful attempt to specify input shapes that produced an output shape close to the pre-compensated alpha308 pulse shape was performed with a flat seed and the pump shape shown in Fig. 5 (below). The total energy of the flat seed pulse was 100 pJ. The total energy of

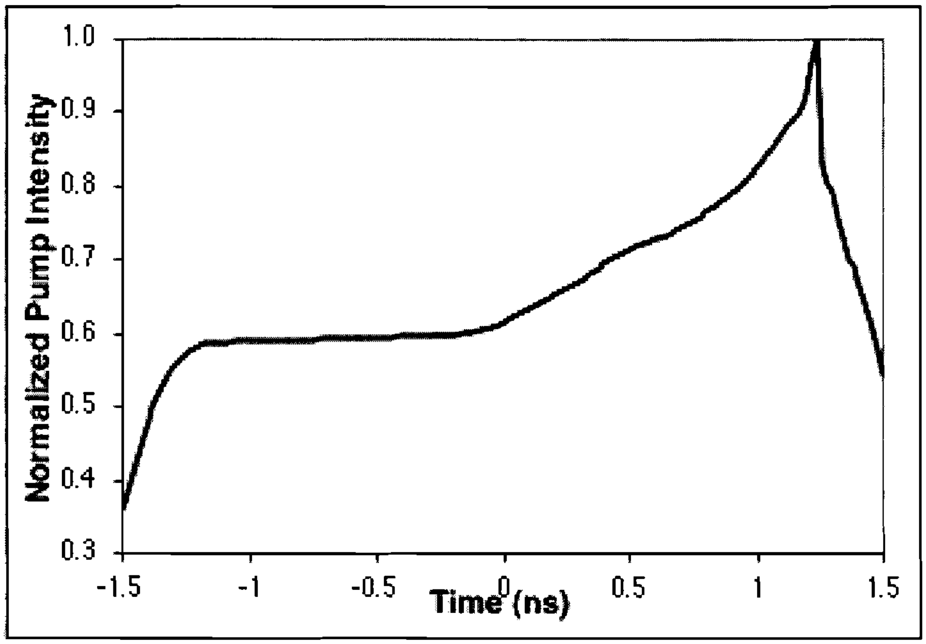

Figure 5: Plot of the normalized temporal pump shape that, when combined with a 100 pJ flat-top seed produced the pre-compensated alpha308 pulse shape.

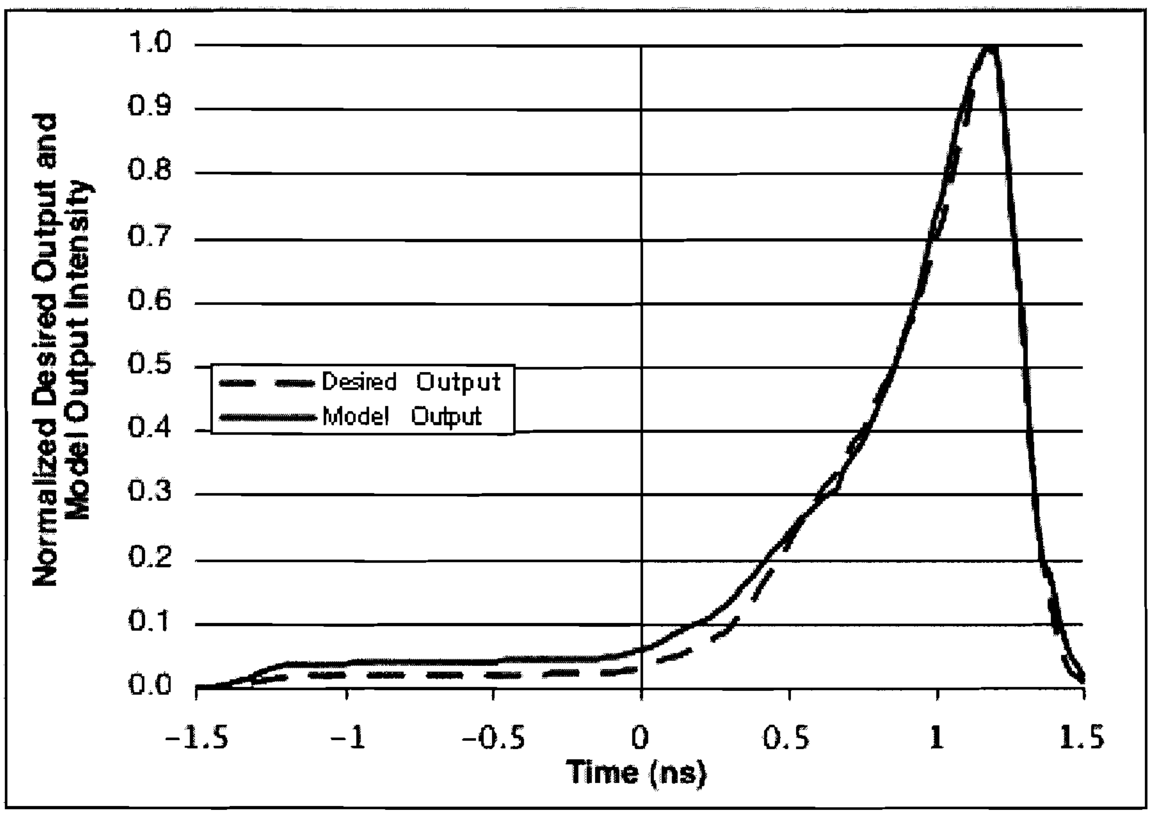

Figure 6: Plot of normalized temporal shapes for the desired output and the output produced by Fig. 5 and a 100 pJ flat-top seed.

the pump pulse was 0.250 J. The output shape produced by the input pump shape in Fig. 5 and a 100 pJ flat-top seed closely matched the pre-compensated alpha308 shape. Figure 6 shows the model output and desired output. The area of the pulse where the most noticeable discrepancy between the desired output and the model output shape occurs is at the foot of the pulse close to 1.5 ns into the pulse. A better fit of model output to desired output could have been achieved, but was not deemed worthwhile because of poor relative stability. The output stability at the foot of the pulse in this case was about 10 times that of the pump stability. Although it is useful to know that the output shape can be produced using a flat seed, the stability of such a shape is very poor at the foot of the pulse due to little saturation in this region.

Using a more extensively shaped seed offers an improvement in stability over using a flat seed. Highly shaped seed and pump temporal profiles that produced the pre-compensated alpha308 pulse shape are shown in Figures 7 and 8. The output produced by these input shapes is a better fit to the desired output than the output of the flat seed attempt because more time was spent making small adjustments to the input shapes. The output is shown as the grayed line in Fig. 9.

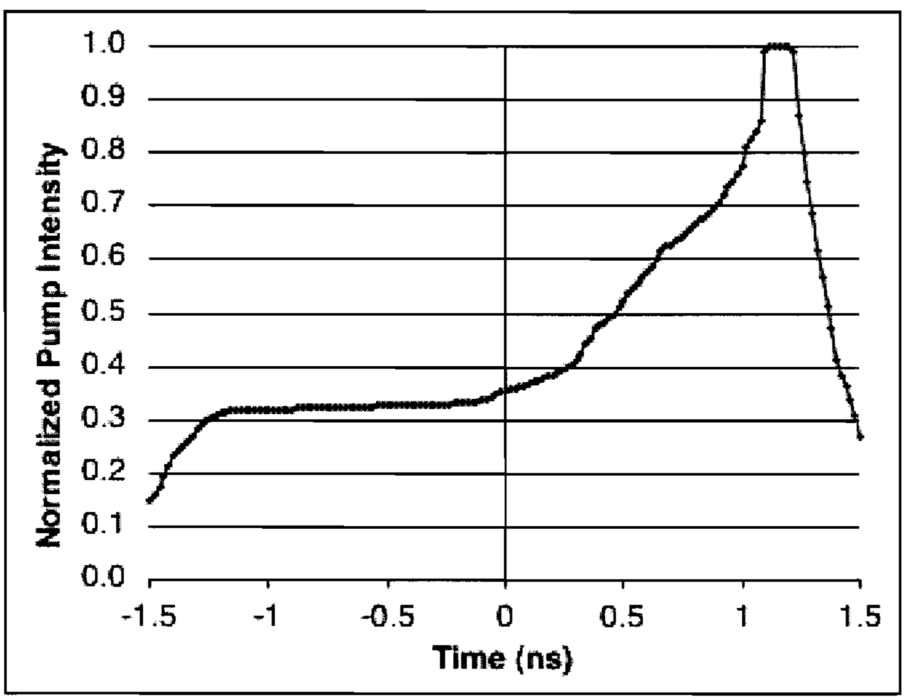

Figure 7: Plot of the normalized temporal pump shape that, when combined with the seed in Fig. 8, produced the pre-compensated alpha308 pulse shape.

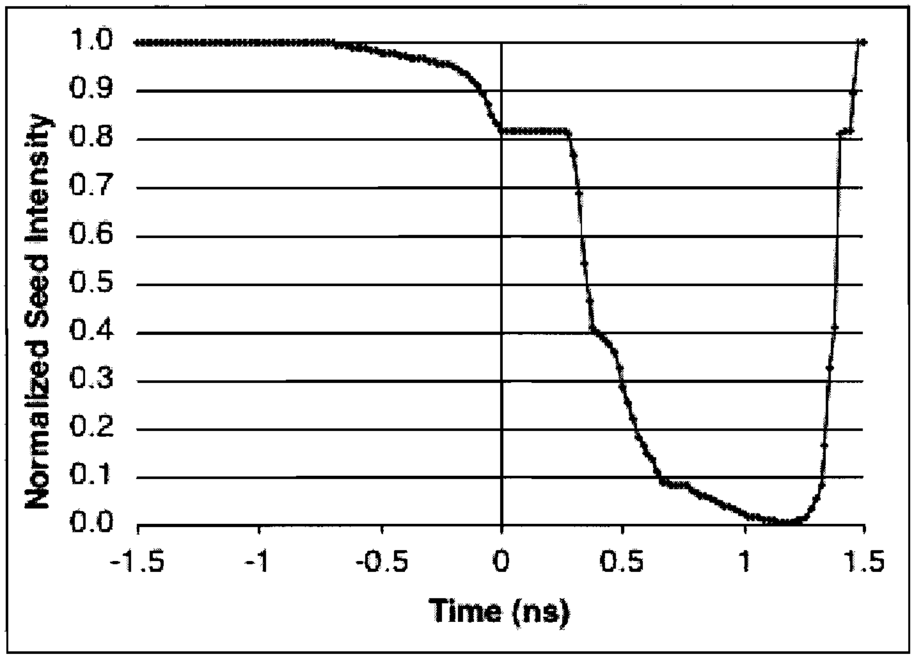

Figure 8: Plot of the normalized temporal seed shape that, when amplified by the pump in Fig. 7, produced the pre-compensated alpha308 pulse shape.

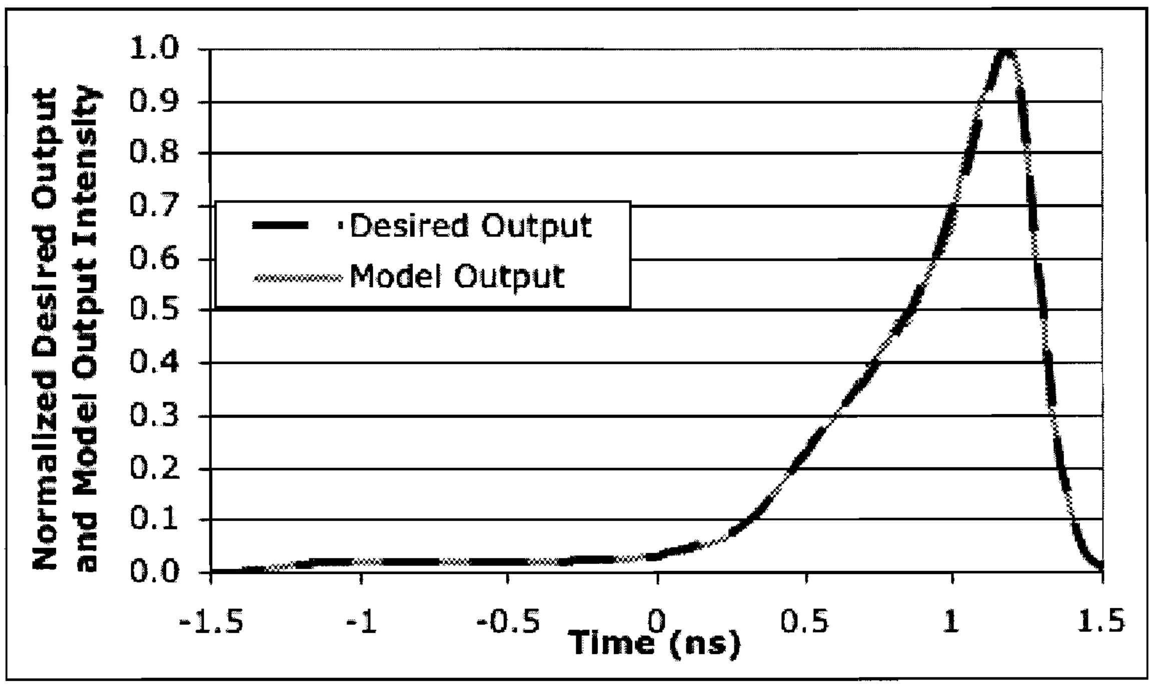

Figure 9: Plot of the temporal pulse shapes of the model output and the desired output. The model output was produced by the non-flat seed in Fig. 8 and the shaped pump in Fig. 7.

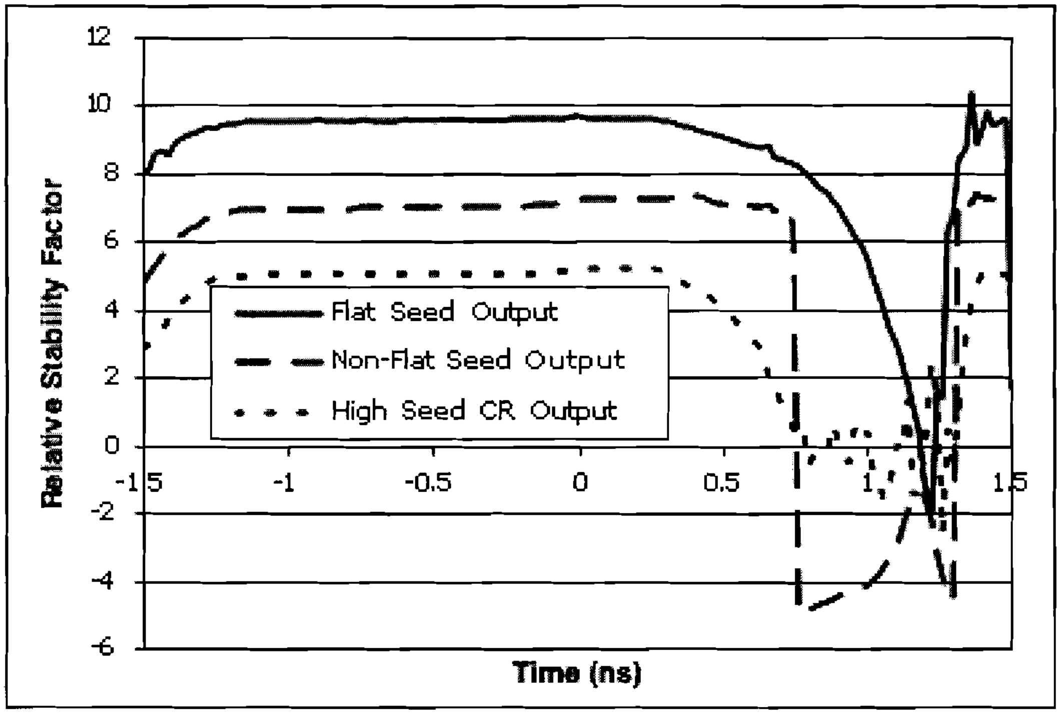

Figure 10: Relative stability factor vs. time for three different pulse shape combinations. The solid line is a plot of the relative stability factor of the output produced by a 100 pJ flat-top seed and the pump shape shown in Fig. 5. The dashed line is a plot of the relative stability factor of the output produced by the seed in Fig. 8 and the pump in Fig. 7. The fine dashed line is a plot of the relative stability factor of the output produced by the high contrast ratio pump in Fig. 11 and the high contrast ratio seed in Fig. 12.

The relative stability of the output produced by the pump shape in Fig. 7 and the non-flat seed shape in Fig. 8 was better than the relative stability of the output produced by a 100 pJ flat-top seed and the pump from Fig. 5. The relative stability factors for both attempts are plotted in Fig. 10. The stability near the peak of the output pulse (1.2 ns) is very good in both output pulses. There is a significant improvement in stability at the foot of the output pulse between the output produced by the 100 pJ flat-top seed and the non-flat seed. In order to get maximally stable output at the foot of the pulse (i.e. stability like that at the peak), only local input intensity values that produce a local output intensity value very close to saturation can be used. As previously discussed, increasing the seed local intensity means that a smaller pump local intensity is required for saturation and reconversion to occur and that the signal intensity at the point of greatest stability is reduced. Although it is possible to use only highly stable points

(points near saturation) to make the input shapes that produce the pre-compensated alpha308 shape, an extremely large range of local seed intensities would be required to obtain a sufficiently large range of output intensities.

A large range of seed local intensities requires that the input seed pulse have a large contrast ratio. Input pulses with high contrast ratios are more difficult to produce than input pulses with lower contrast ratios. The pre-compensated alpha308 shape has a contrast ratio of about 50:1. The pump that together with a flat 100 pJ seed was able to produce the pre-compensated alpha308 shape had a contrast ratio of 2.8:1. The more highly shaped pump and seed pulses of Figs. 7 and 8 had higher contrast ratios of 7:1 and 146:1, respectively.

Additional runs were performed in order to improve the output stability beyond that shown in Fig. 10 by further increasing the contrast ratios of the input pulses. It was necessary to do additional runs of flat-top seeds and a linearly ramped pump in order to generate more data for the look-up table. The flat-top seeds had significantly higher total energies than when the same procedure was performed earlier (see Methodology: Section 1). The seed and pump input shapes that produced a highly stable pre-compensated alpha308 pulse shape in this case had significantly higher contrast ratios of 5760:1 and 17:1 respectively. The higher contrast ratio pump shape is shown in Fig. 11 juxtaposed with the pump used previously (Fig. 7). Figure 12 shows the higher contrast ratio seed shape along with the seed from Fig. 8.

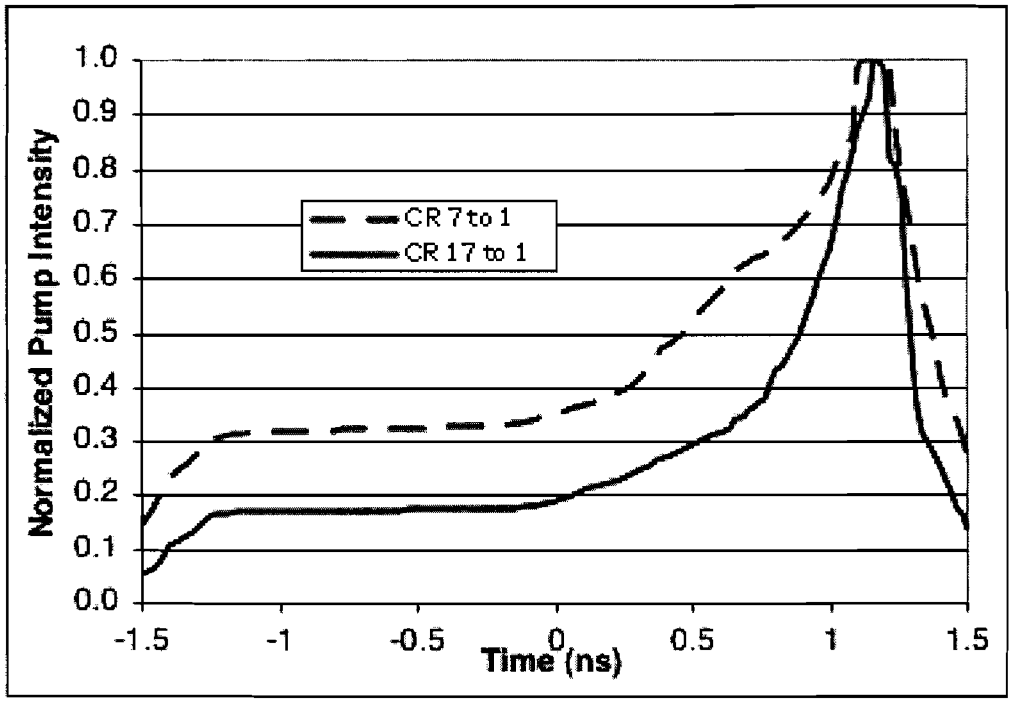

Figure 11: Plot of the higher contrast ratio pump shape and the pump shape from Fig. 7.

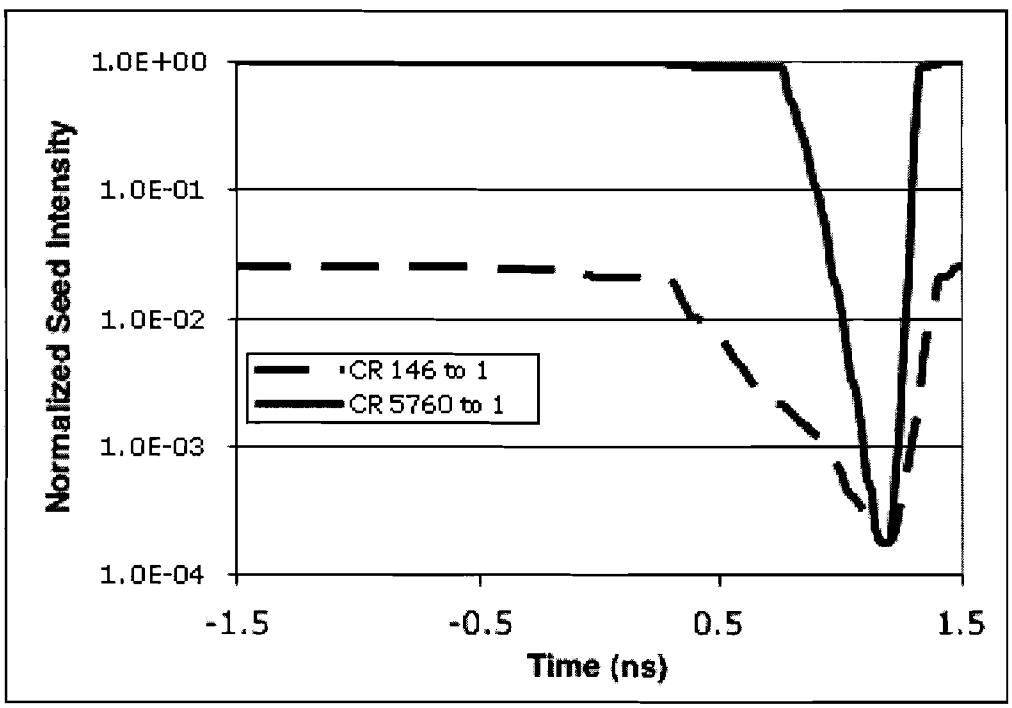

Figure 12: Plot of the higher contrast ratio seed shape (solid line) that corresponds to the higher contrast ratio pump shape of Fig. 11. The seed shape from Fig. 8 is also shown.

The high contrast pump and seed shapes produced a pre-compensated alpha308 pulse shape with better relative intensity stability than in any previous attempts. The relative stability was approximately a factor of 5 at the foot of the pulse (seed Fig. 10, fine dashed line). A relative stability of a factor of 2 or better was predicted based on the relative stabilities of the points used to make the shape. The reason for the difference between the predicted stability and the actual stability is that there was a difference between the predicted output intensities and the actual output intensities. Although visually, the model output pulse shape and the desired output pulse shape look practically identical, there is as much as a 20% error at points at the foot of the output pulse. The percentage error is largest at the foot of the pulse because the local intensity values in this region are small. Percentage error is very low (less than 5%) at the peak of the output pulse. Since input values were specified by matching the peak local intensity of output produced by a flat-top seed and a linearly ramped pump with a desired local output intensity, a 20% error could mean that the local intensity actually produced is not the peak local intensity and not at the beginning of the reconversion regime. A closer match between predicted local intensities and actual intensities can be achieved by increasing the resolution of the pulse shapes used to determine the input shapes needed. Making numerous small adjustments to individual points at the foot of the output pulse would also be necessary. Time constraints on this project precluded attempts to increase the resolution or adjust the points.

V. Directions for Future Research

A third crystal may provide the flexibility needed to improve stability in the foot of the output pulse with lower contrast ratio input pulses. Adding a third crystal will also allow scaling to higher output energies since it can be configured as a separate amplification stage using a pump beam with higher input energy than used with the first stage of amplification. The output energy obtained from the two-crystal system is intermediate between the energy obtained from the OMEGA regenerative amplifier and that obtained from the LARA. Thus the two-crystal system could replace the current regenerative amplifier. However, the third crystal would be necessary if the LARA replacement were also desired. In addition, since a different pump beam can be used with the third crystal, greater flexibility is allowed in defining input pulse shape requirements than with a single stage alone.

VI. Conclusion

A numerical computer model has been used to determine the input pulse shapes required to obtain the pre-compensated alpha308 pulse shape. A general methodology for determining input shapes applicable to any desired output pulse shape, not just the specific shape required by OMEGA, was described. Three sets of input shapes that produce the pre-compensated alpha308 pulse shape were presented. The first set contained a flat seed and a shaped pump, the second set contained a highly shaped seed as well as a shaped pump, and the third set contained very high contrast ratio seed and pump shapes. To my knowledge, this was the first time an OPA has been shown to be able to produce the highly shaped pulses necessary for Inertial Confinement Fusion lasers. A tradeoff between output pulse intensity stability and input pulse contrast ratio was discussed. The broadband amplification at the front end of OMEGA provided by an OPA can improve pulse smoothing techniques and therefore improve the uniformity of the target implosion. Improved target implosion uniformity will help improve the efficiency of ICF and potentially make fusion a viable energy source.

References

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