Brandon Corbett
University of Rochester Laboratory for Laser Energetics
Advisors:
Dr. P. B. Radha
Dr. T. J. B. Collins
2/28/06

Maximization of Inertial Confinement Fusion Yields through Laser Pulse Optimization

Abstract

A method has been developed for the optimization of high-gain inertial confinement fusion targets. Using this method, software simulations have yielded pulse shapes that produce high fusion gain and demonstrate good target stability using a 1 megaJoule (MJ) laser source. These pulse shapes could help attain ignition on the National Ignition Facility inertial confinement fusion system.

Introduction

For many years Inertial Confinement Fusion (ICF) has been of interest as a source of clean energy. ICF is a technology that uses high-powered laser pulses to implode a small target containing deuterium and tritium fuel, compressing it to high enough densities and temperatures to initiate a self-sustaining thermonuclear burn wave resulting in ignition. The goal of this technology is power production. ICF is, in principle, capable of greater efficiencies than nuclear fission and uses fuels that are plentiful without the dangerous by-products of fission. Experimental and theoretical results at the University of Rochester's Laboratory for Laser Energetics and elsewhere have demonstrated that ICF may be feasible in practice as well.

The National Ignition Facility (NIF), currently under construction at Lawrence Livermore National Laboratory in California, is a project of particular importance for ICF development. It will be capable of energies believed to be sufficient to achieve ignition, where the energy produced is greater than the laser energy incident on the target. The NIF will be able to provide increased energy on targets three times as large as the targets in use today. In order for this project to succeed, however, targets must be designed and manufactured that are stable and produce high gain. We describe here promising new targets designed for the NIF. Key measures of a target design are its gain—the ratio of energy produced to the incident laser energy—and stability during the implosion (described below). A program has been written that systematically varies pulse shapes in order to improve the ease and efficiency of designing these targets. The targets analyzed using this program have demonstrated high gain and good stability, indicating a very high likelihood of ignition on the NIF using these designs. We will describe here an ICF target designed and optimized for the NIF using this program.

Targets and Pulse Shape Design

An ICF target design consists of both the target pellet structure and the laser pulse used to implode it. The target pellet is a spherical structure about 3 millimeters in diameter, composed of a number of layers of materials, the most important of which is the deuterium-tritium (DT) fusion fuel. The simplest target consists of an outer DT ice shell containing DT vapor, with a thin outer polymer shell used in the fabrication process. It has been shown that the absorption efficiency of targets can be enhanced by replacing the outer portion of the DT ice layer with a layer of *wetted foam* – a polymer foam saturated with DT ice.[1] The foam layer is located just inside the spherical plastic shell; its bubbles are filled with the DT ice. In our designs, the thickness of each layer was determined by scaling another target design,[2] intended for a 1.5 MJ ignition pulse, to 1 MJ - the planned initial energy of the NIF. The resulting target has an inner shell radius of 1300 microns, a 280-micron DT ice layer, a 90-micron wetted foam layer and a 3-micron plastic layer. This structure is the same for all the designs discussed here.

An ICF implosion has three stages - acceleration, coasting and deceleration. When the laser pulse begins, the target is imploded by laser ablation of material from its outer surface. The laser illumination rapidly heats the pellet. This causes the material at the surface of the target to ablate outward, forcing the shell inward. When this process is taking place the implosion is in the acceleration phase. An acceleration phase for a typical target lasts around 10 nanoseconds (ns). After the laser pulse terminates, the shell material "coasts" toward the center with the inertia imparted by the acceleration phase. Finally, deceleration occurs when the pressure of the vapor inside the shell is sufficient to decelerate the imploding shell material. A critical part of the design process is determination of the laser pulse power as a function of time to optimize this sequence. This laser pulse power function can be varied to produce different implosion characteristics.

A typical ICF laser pulse sequence is shown in Figure 1. This pulse sequence consists of a picket pulse (the small-amplitude pulse at 0 – 1 ns), a foot-pulse (the pulse roughly between 1 ns and 4 ns), and a drive-pulse (the large-amplitude pulse at 4 – 8 ns.) More complex pulse sequences may have additional “picket” pulses and relaxation periods (the time between the picket and the main pulse).

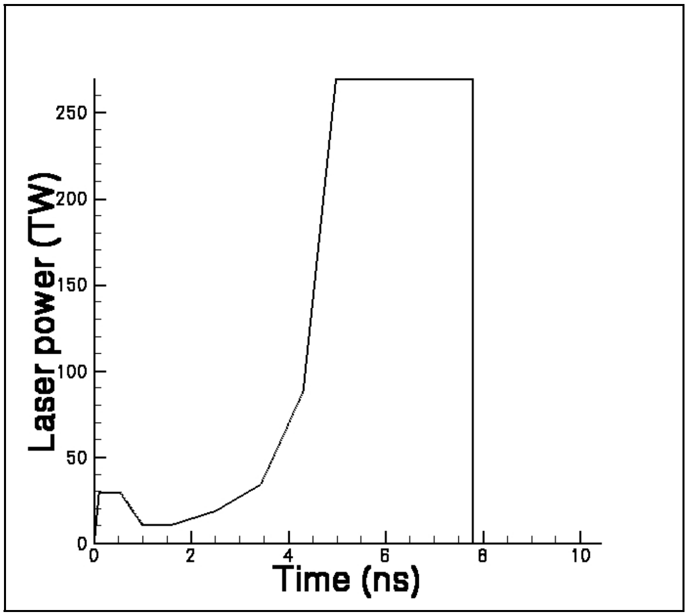

Figure 1: A sample laser pulse shape.

A shock wave propagates into the shell whenever the laser power increases rapidly. A shock is a wave of abrupt compression that propagates through a target. Shocks are significant because as they pass through a target they concentrate energy, increasing the temperature of the target. As the DT fuel becomes hotter it becomes harder to compress. The lower the density of the fuel remaining after the laser has turned off, the lower the fusion rate, and the lower the energy released by the implosion. In order to minimize the loss in gain that is caused by a series of shocks, pulse shapes must be designed to time shocks to heat specific parts of a target. This timing is accomplished by varying aspects of pulse shapes such as foot-pulse length or drive-pulse height. For this pulse shape, shocks are launched at the start of the pulse, and during the rise in power from the foot-pulse to the drive-pulse.

Instability

Imploding targets are subject to a phenomenon called the Rayleigh-Taylor instability. This instability occurs when a light fluid accelerates a heavier one. A simple example of this phenomenon is an inverted glass of water, as shown in Figure 2. When a glass of water is inverted, the pressure in the atmosphere is sufficient to hold the water at the top of the glass. However, any small perturbations in the water's surface result in pressure perturbations. These perturbations grow exponentially in time, causing bubbles of air to rise into the water and "fingers" of water to fall into the air at the bottom of the glass, eventually resulting in the air and water changing places.

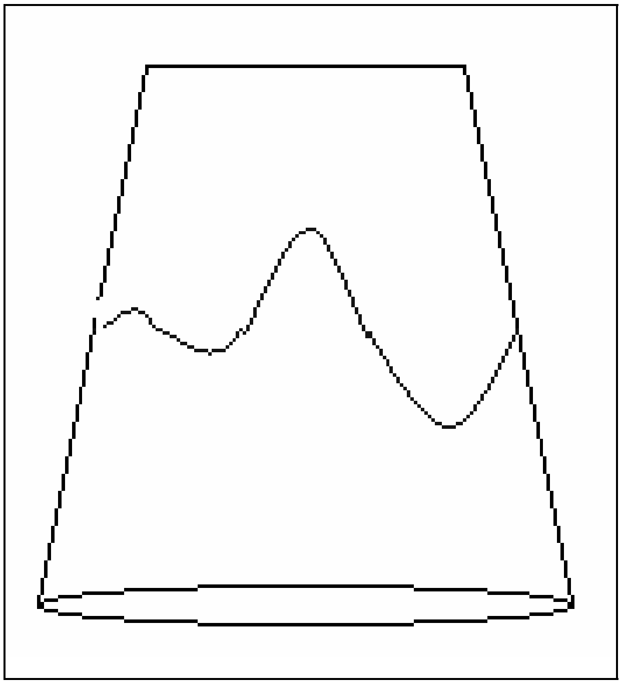

Figure 2: Rayleigh-Taylor instability demonstrated in an inverted glass of water

The Rayleigh-Taylor instability occurs in two places during the implosion of a target - first within the ablated material at the outer surface of the shell during the acceleration phase, and later between the DT vapor and the interior of the shell during the deceleration phase. Although other instabilities exist, the Rayleigh-Taylor instability is the most significant because its growth is exponential. When the bubbles and fingers caused by the Rayleigh-Taylor instability grow too large, holes are punched through the shell of the target, preventing it from achieving ignition.

To predict the effect of the Rayleigh-Taylor instability during the acceleration phase, the ratio Q of the root-mean-square (RMS) bubble amplitude to the shell thickness ratio at the end of the acceleration phase is calculated. To gauge the degree of instability during the deceleration phase, the peak implosion velocity of the shell is calculated. This can be related to the degree of growth the inner-surface perturbations will experience. The growth rate of the Rayleigh-Taylor instability of each mode number was used to calculate of the bubble amplitude using the Betti formula, [3]and taking into account non-linear effects through Haan saturation.[4]

One of the factors that affects the stability of the shell during the acceleration phase is the amount by which the shell has been preheated and the area in which it has been preheated. This preheating can be changed by shocks that travel through the shell. Preheating on the exterior of the shell allows for material to ablate more easily, effectively reducing instability; preheating on the interior of the shell makes the target harder to compress, reducing the effectiveness of the target. In order to create this gradient of preheating from the inside to the outside of the shell a power spike or “picket” is added as seen in Figure 1. Another factor that affects stability is ablation velocity. As the ablation velocity increases a target becomes more stable. This is the case because the fingers that form on the target receive more heat flux than the bubbles. Because of this they ablate faster and are thus minimized. Another important thing to note is the presence of Haan saturation. Haan saturation essentially levels off the exponential growth that occurs when a target is imploded.

There are trade offs between the amount of stability at different points within a given target and the gain that a given target will produce. For example, as the stability on the inside of the target during the deceleration phase increases there may be a loss of stability on the exterior of the target. This occurs because to increase stability on the inside of the shell the implosion velocity must be high. To attain a high implosion velocity the shell must be accelerated faster meaning more force must be exerted on the shell and thus the outer surface has a lower stability. Other such tradeoffs also exist between stability on either surface and gain. This is indicated by the fact that perfect shock timing indicated by high gain is usually not the best solution for good stability.

Optimization and results

A program has been written that allows the user to vary the parameters of the pulse shape over specified ranges. For each point in the variation a 1-D simulation of the implosion is performed and the gain and stability properties calculated. The program is capable of varying either one variable at a time, or two simultaneously. (To improve simulation efficiency, 1-D simulations may be performed simultaneously up to a system limit the of number of concurrent jobs.) First, based on laser system restrictions, the program creates a pulse using the Kidder model.[5] The Kidder model is based on the concept of a pulse shape that sends an infinite number of infinitely small shocks through the target. Once a pulse shape is created, certain parameters of it are varied based on user inputs such as foot-pulse length and drive-pulse height. The results of the simulations are written to a final output file in a format that can be plotted graphically. Ratios of the RMS bubble amplitude to shell thickness of less than 20% (or 0.2) were sought to maintain sufficient acceleration-phase stability. In order to maintain sufficient deceleration-phase stability, we generated designs for which the implosion velocity must be comparable to or greater than 430 microns per nanosecond (μm/ns).

Three basic designs have been tuned to produce the highest gain possible with acceptable stability. First, a simple Kidder pulse constrained by NIF laser system requirements was tuned. This pulse shape demonstrated a highest gain of 80, but the variation that produced the highest gain had a low implosion velocity, indicating greater susceptibility to deceleration-phase growth and therefore the likelihood of failure. However, slight variations in drive-pulse height brought implosion velocities up to the marginal speed of 410 μm/ns. For this design the bubble amplitude to shell thickness ratio was 0.4.

A final scan of both drive-pulse power and foot-pulse duration is shown in Fig. 3. In this plot the grayscale contours show the gain, while the contour lines give the values of Q. The same plot, but with the contour lines marking the implosion velocity, is shown in Fig. 4. Note from these two figures that while the peak gain corresponds to a foot-pulse length of 2.4 ns and a drive-pulse height of about 185 TW, the highest gain which can be achieved while maintaining the desired implosion velocity and bubble amplitude is in the neighborhood of 2.4 ns and 200 TW. It is interesting to note the way in which gain, bubble amplitude, and implosion velocity vary with drive-pulse height and foot-pulse length. As seen in Fig. 3, there is a large drop off of gain for each drive-pulse height as the foot-pulse length is increased. This is because as foot-pulse length increases past a certain point the shocks become poorly timed. It is also interesting to note that the contours of minimum implosion velocity on Fig. 4 run roughly parallel to the horizontal axis. This indicates that as the drive-pulse power increases the implosion velocity increases and is relatively independent of foot-pulse length.

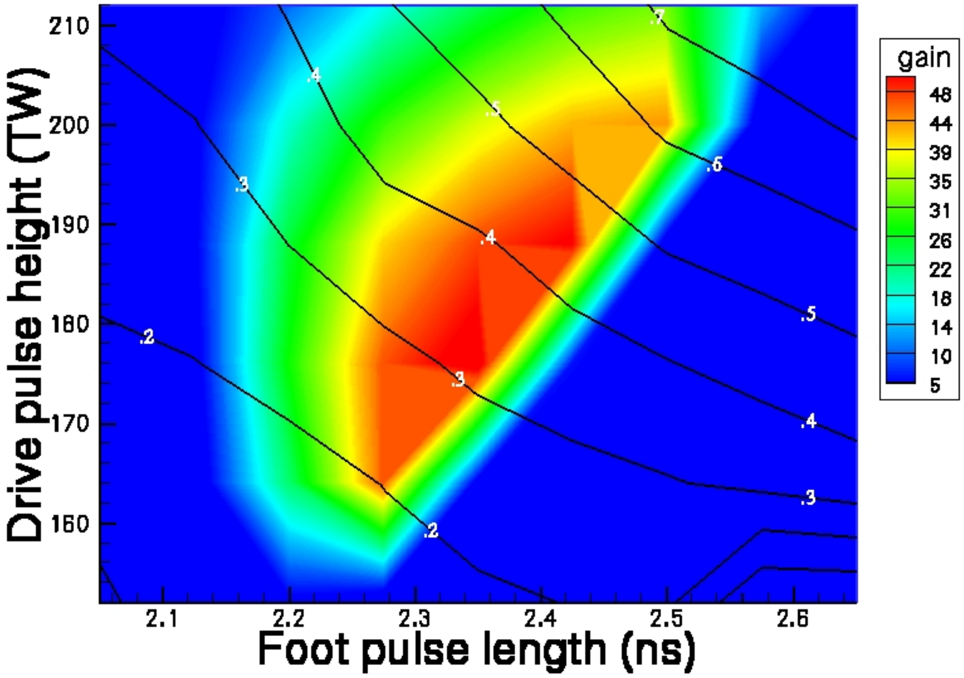

Figure 3: Plot of simulations of a picket-less design showing gain in color contours and bubble amplitude ratio Q in line contours as they vary with changes in foot-pulse length and drive-pulse power. Each simulation has the same input laser energy (1 MJ).

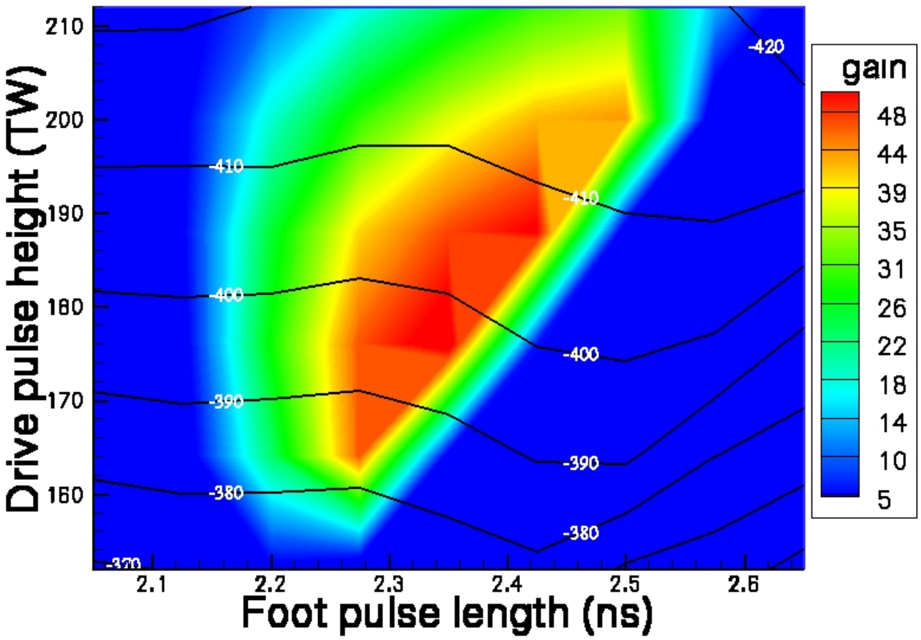

Figure 4: Plot of simulations of a picket-less design showing gain in color contours and implosion velocity (μm/ns) in line contours as they vary with changes in foot-pulse length and drive-pulse power

Second, a pulse was tuned which included a picket at the start of the pulse. A series of variations were made, varying the foot-pulse length, drive-pulse power, and picket height. These yielded a number of promising targets. Maximum gains peaked around 60 but had implosion velocities of around 400 μm/ns. Values of *Q* for these designs were all below 0.40. One pulse shape in particular produced a gain of near 50 with an implosion velocity of around 440 μm/ns and bubble amplitude ratio of 0.15. Since this is a promising result, future investigations may focus on further optimizing this target.

Third, a pulse was tuned which was preceded by a picket, followed by a period of relaxation during which the laser power was zero. An initial pulse shape was provided[6] that combined a Kidder pulse with an extremely short picket, a relaxation period, and a foot-pulse. This pulse shape successfully ignited fusion in a wetted-foam target design. With variations of picket power and relaxation time, a pulse shape was arrived at that produced a gain of 80 with a reasonable bubble amplitude to shell thickness ratio. However, the implosion velocity was too low. In order to increase the velocity, the drive-pulse power was varied over a large range using the pulse shape with the maximum gain as a starting point. From this variation a pulse shape was chosen with an implosion velocity of 406 μm/ns. Variation of relaxation time and drive-pulse height of these pulse shapes produced high gain with good implosion velocity, but the ratio of bubble amplitude to shell thickness was extremely high (approaching 1).

Next, a pulse from the initial variation set was chosen with a gain of 60 but with better stability. Using this pulse drive, the pulse power and foot-pulse length were varied. In this variation a maximum gain of 64 was found but the stability was moderate. After three more variations the grid of targets shown in Figures 5 and 6 was created. Within this grid, at a foot-pulse length of around 1.5 ns and a drive-pulse height of around 220 TW, there are pulse shapes that produce gains in the 50's, implosion velocities around 440 μm/ns and bubble amplitude to shell thickness ratios of around 0.14. With slight modifications, this pulse shape could prove very stable and productive for use on the NIF.

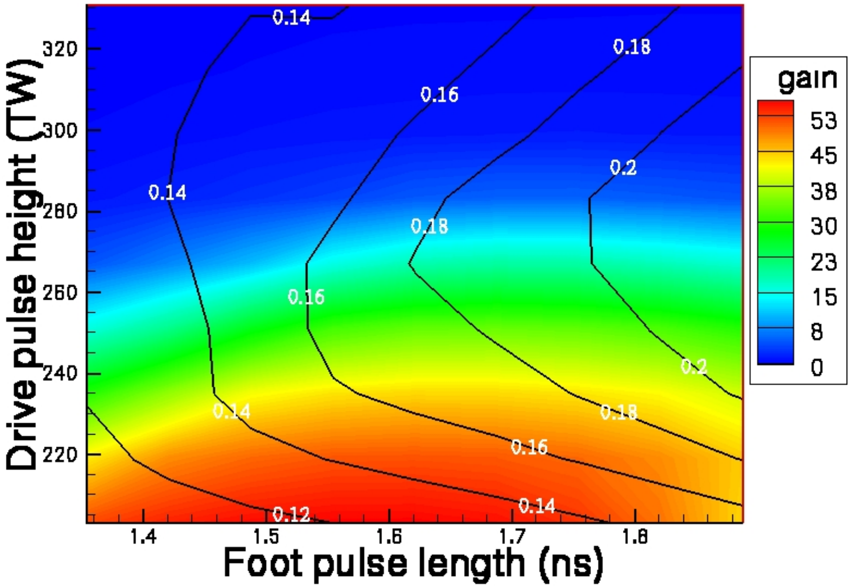

Figure 5: Plot of simulations of a picket design showing gain in color contours and bubble amplitude ratio Q in line contours as they vary with changes in foot-pulse length and drive-pulse power.

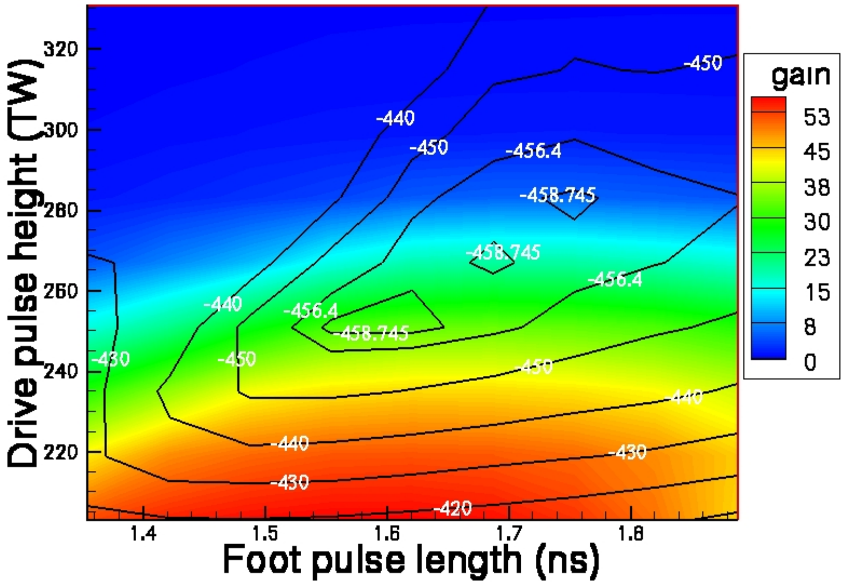

Figure 6: Plot of simulations of a picket design showing gain in color contours and implosion velocity (μm/ns) in line contours as they vary with changes in foot-pulse length and drive-pulse power.

Conclusions

Targets and laser pulse shapes have been designed that show very good likelihood of ignition on the National Ignition Facility (NIF). These designs demonstrate possible starting points from which highly efficient, finely tuned pulse shapes can be designed. These improved pulse profiles may provide the basis for demonstrating high-yield fusion on the NIF, proving the concept of Inertial Confinement Fusion. This would be a first step towards proving the viability of Inertial Confinement Fusion as an energy resource.

References

---

[1] Sacks, R. A. and Darling, D. H., *Nuclear Fusion*, **27**, 447 (1987)
[2] P. W. McKenty et al., *Physics of Plasmas*, **8**, 2315 (2001)
[3] Betti, R., et al., *Physics of Plasmas*, **5**, 1446 (1998)
[4] Haan, S. W., *Physical Review*, **A39**, 5812 (1989)
[5] Kidder, R. E., Nuclear Fusion, **14**, 797 (1974)
[6] Anderson, K., private communication (2005)

Acknowledgements

I would like, first and foremost, to thank my advisors, Tim Collins and Radha Bahukutumb, for their guidance and support of my project. I can not say enough to thank Tim and Radha for everything; from the hours spent teaching me to program in FORTRAN to the Saturday they spent with me at the lab while I ran my final sets of variations. I could not have had two better advisors and I certainly could not have completed my project without them.

I would also like to thank Dr. Steve Craxton for accepting me into the U of R Laser Lab's summer internship program. It was the experience of a lifetime and one that I could not have gotten in any other setting.

Finally, I would like to thank all of the Laser Lab staff who took time from their own work to instruct, guide, and encourage me throughout the summer.