Limits on the Level of Fast Electron Preheat In Direct-Drive Ignition Designs

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1. Abstract

Inertial confinement ignition designs are characterized by their gains (energy produced over energy input), which can be reduced by preheat of the fuel. High intensity lasers like the ones used in direct-drive ignition create plasma instabilities, producing fast electrons. When fast electrons penetrate the cold fuel shell, they preheat the target, increasing the adiabat (a measure of the preheat) and decreasing the gain. The one-dimensional hydrodynamic code LILAC was used to simulate target implosions affected by the fast electrons. The optimizing code TELIOS adjusted the picket timings and levels in the laser pulse for the implosions in an attempt to decrease the preheat and counteract the decrease in gain caused by fast electrons. Optimization with TELIOS was able to partially recover the gain by varying the picket timings and powers.

2. Introduction

Direct-drive ignition is one of two ways that inertial confinement fusion (ICF) is carried out.[1] Direct-drive ICF uses high intensity lasers focused directly on the surface of a target, which contains the fuel used in fusion, in order to compress it. The laser energy heats up the outside shell of the target, usually composed of a carbon-hydrogen compound, which then ablates outwards and compresses the fuel in the center of the target. The energy of this compression triggers fusion, which releases energy. The DT fuel is composed of a mix of deuterium and tritium, two isotopes of hydrogen. Deuterium contains one neutron and tritium contains two, whereas normal hydrogen atoms have none. When deuterium and tritium are combined, an atom of helium is produced along with a neutron, accompanied by a release of energy. This released energy, divided by the energy input by the laser, is known as the gain. A high gain is required for fusion to be an efficient energy source.

One of the methods used to improve the gain is using cryogenic targets. While normal targets contain DT gas only, cryogenic targets contain a layer of frozen DT ice with a low-density DT gas inside. The frozen DT is denser than the DT gas, so it is possible to fit more fuel into the target. In the simulations used in this project, a high-gain target designed for the National Ignition Facility (NIF), composed of a 1,338 μm layer of DT gas, a 199 μm layer of DT ice, and a 39 μm layer of CH plastic [Fig. 1] was irradiated with a 1.6 MJ laser pulse [Fig. 2]. This target requires low preheat of the fuel before implosion, as preheat reduces the fuel compressibility and the energy gained from fusion.

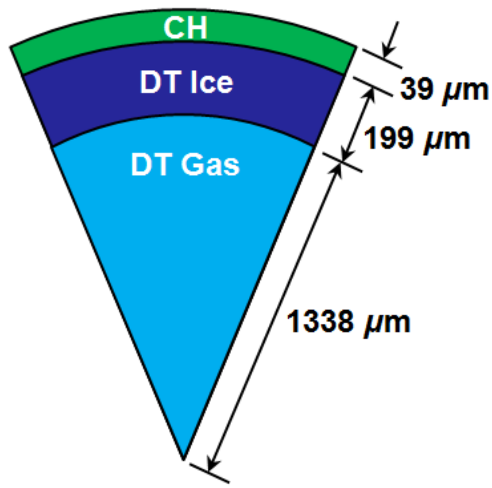

Figure 1: Structure of a typical high gain cryogenic target. The ice layer is much thinner than the gas layer, and is deposited inside the CH shell.

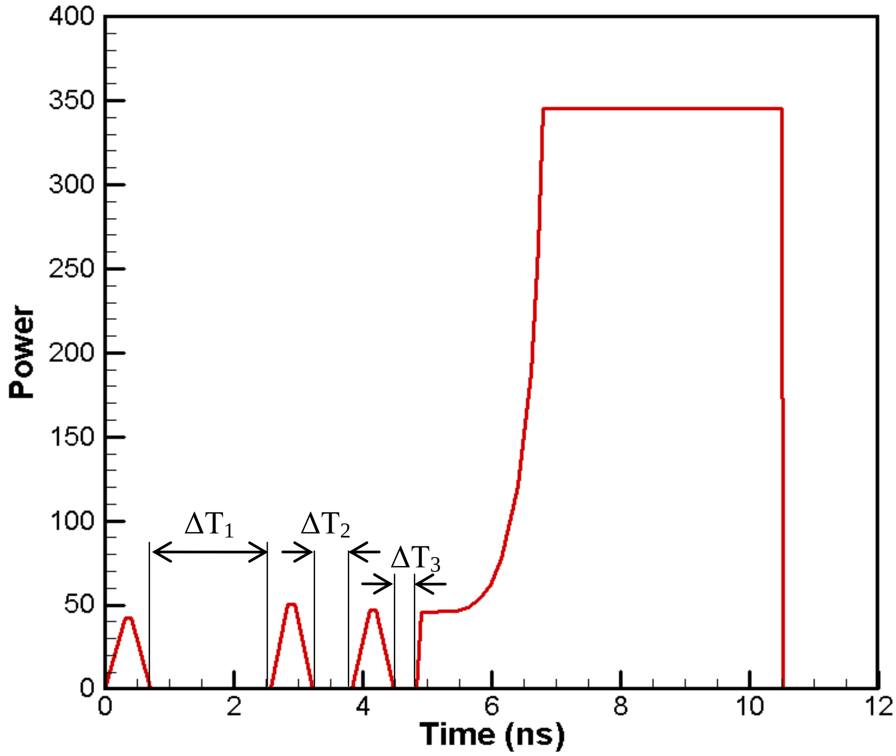

Figure 2: Typical laser pulse (power in TW) used in an ICF high gain design. The three small spikes are the pickets, and the much larger shape is the main pulse, which contains the majority of the laser's energy.

A primary cause of preheat in the targets is from the fast electrons that are created by laser-plasma instabilities. When the natural plasma frequency is resonant with (typically) half the laser frequency, instabilities occur which produce fast electrons. They can reach temperatures of 60 keV, compared to 3 keV in the corona of the target. These fast electrons penetrate the cold fuel and lose their energy, heating up the fuel. This preheat can prevent the fuel from being compressed to a sufficiently high density to reach ignition. Preheat was measured in this project as the percentage of the laser energy that is deposited by the fast electrons into the cold fuel shell. The gain was plotted in Fig. 3 as a function of preheat. As a result of density changes, increases in preheat result in a steep drop-off in the gain.

The compressibility of the fuel can be measured using the concept of adiabat (defined as the electron pressure divided by the pressure that the shell would have at a temperature of absolute zero). Lower adiabat values correspond to low preheat and higher levels of compressibility. The adiabat of the target must have a value under around 3 before the target is compressed by the main pulse in order for the implosion to reach high gains. But, when the target experiences high enough levels of preheat, the adiabat before compression becomes too large for effective fusion reactions [Fig. 4].

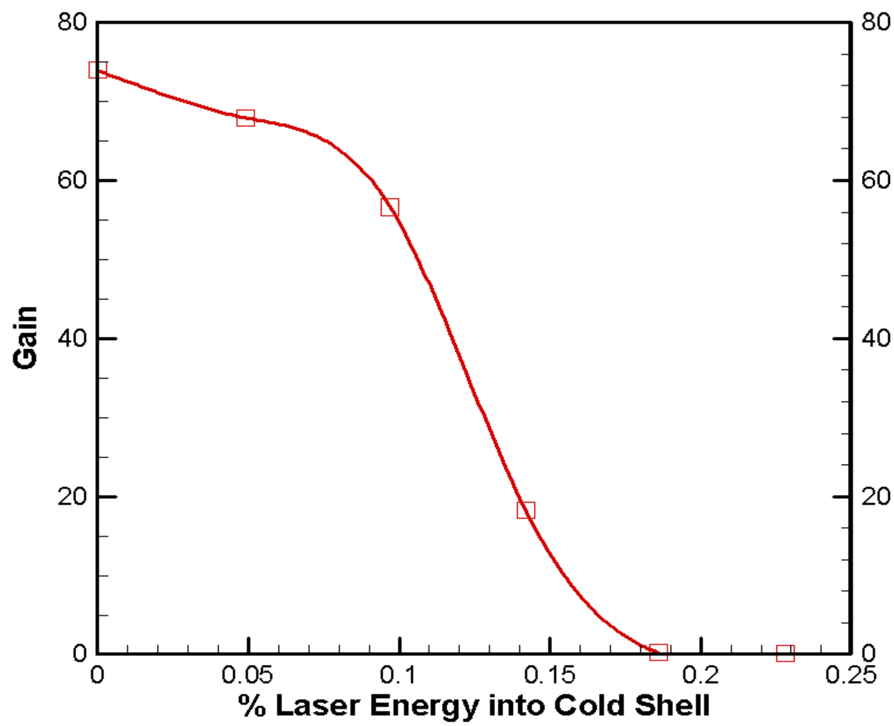

Figure 3: The effect of preheat on gain in ICF. Preheat is measured by the percentage of laser energy deposited in the cold fuel shell.

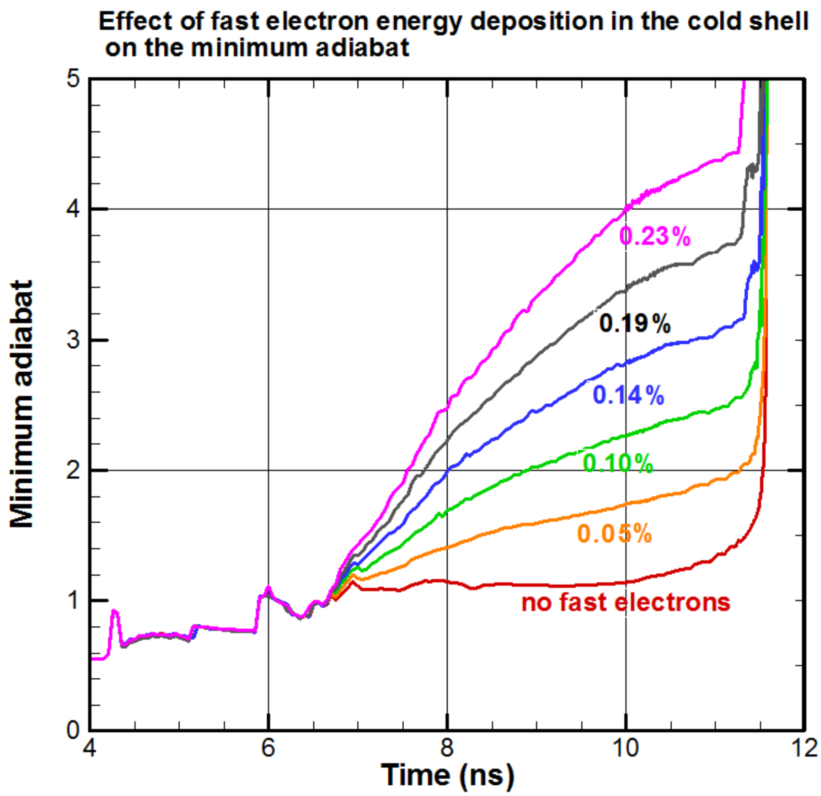

Figure 4: Effect of fast electron energy deposition in the cold shell on the minimum adiabat. The six lines correspond to the six preheat conditions in Fig. 3.

Because the NIF is normally able to fire its laser only one to three times a day, this study would have been impossible to conduct using an actual laser and target. Instead, the one-dimensional hydrodynamic code LILAC[2] was used to simulate the implosions. LILAC takes input decks including the parameters of the shot and runs through the implosion, computing conditions in the target for each time step.

In this project, the amount of preheat was manipulated by changing the parameters of the laser pulse. The laser pulse (Fig. 2) is composed of a main pulse preceded by three “pickets,” which are smaller laser pulses that deliver small shocks to the target and prepare it for the main pulse. The times between pickets and the powers of the pickets were the six variables used to adjust the level of preheat.

Since there were an unlimited number of possible combinations of different parameters for the pickets, an optimizer was used to find the right set of parameters which resulted in the highest gain. The optimizing code TELIOS[3] was used to find the picket timings and powers that gave the highest gain, and therefore were affected the least by preheating. The code required an input of all the laser pulse and target parameters for the basic simulation. Then TELIOS modified each picket parameter slightly using a downhill simplex method (Nelder-Mead method) until it found the highest possible gain. This saved the time that would have been required to enter new input decks and manually decide how to adjust the variables.

3. Initial Attempts

At first, only the timings of the pickets were adjusted in an attempt to reduce the effects of preheat on the gain. TELIOS was given an input deck for the LILAC simulation discussed previously, and was allowed to manipulate only the time between the first and second picket, the time between the second and third picket, and the time between the third picket and the main pulse. From this initial "guess," it ran subsequent LILAC simulations in an attempt to obtain the maximum possible gain. TELIOS was given input decks with the six preheat conditions presented above to optimize, each with an increasing amount of preheat. The goal was to reduce the steep drop-off in gain that occurs once the percentage of laser energy into the cold fuel shell reaches about 0.1% (see Fig. 3). But TELIOS was unable to recover the gain in any significant manner when more than 0.1% of the laser energy entered the cold shell [Fig. 5]. At around 0.14% of laser energy into the cold shell, TELIOS was able to recover the gain by about 8, but it was not enough to create a significant amount of leeway in the percentage of laser energy in the cold shell tolerable to the gain. For all five other conditions of preheat, TELIOS was unable to recover the gain by more than 5.

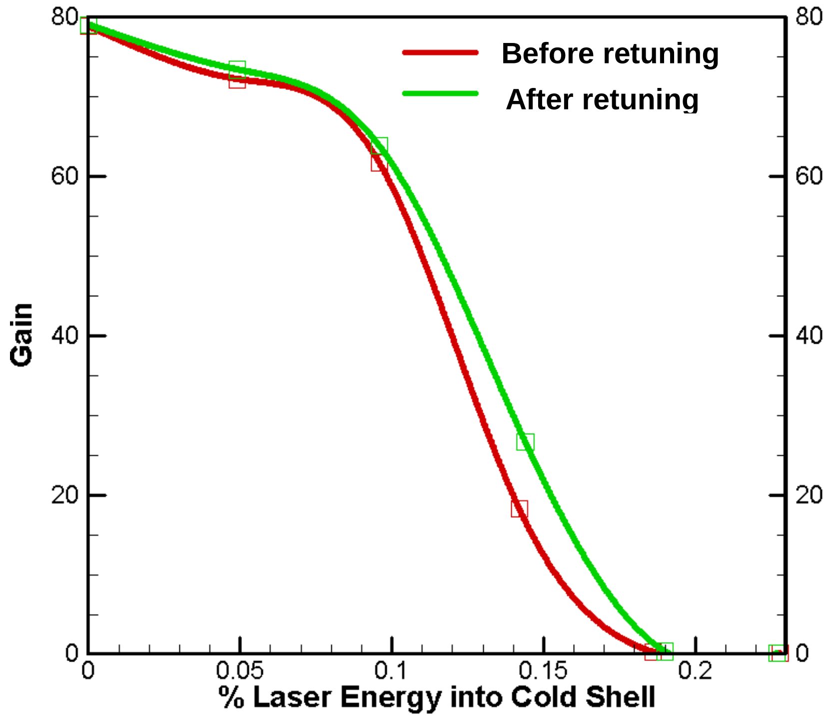

Figure 5: Effects on gain of retuning the picket timings. The curves are fitted to data points from the six different conditions of preheat that TELIOS retuned.

The initial retuning attempts were done with a straight-line model for fast electron transport. Under this model, the fast electrons are simulated as single particles that travel in straight lines and bounce off the outer edges of the target. The modeled electrons bounce inside the cold shell until they deposit all of their energy. Another model for electron transport in LILAC is the diffusion model, in which the electrons slowly diffuse throughout the cold shell, depositing energy as they move through it. It is unknown which model presents the more accurate picture of what actually occurs during fusion reactions, and the reality is most likely a combination of both. So, the diffusion model was also used in TELIOS retunings in order to see whether there was a difference in results between the two models. The results for the TELIOS runs using the diffusion model saw more improvement than the runs with the straight line model [Fig. 6]. The fourth condition of preheat, where around 0.23% of the laser energy went into the cold shell, showed the most significant improvement. The retunings at 0.17% and 0.29% were also more successful than the retunings using the straight line electron transport model. But the retuning still gave less than 0.05% of leeway for the amount of laser energy into the cold shell permitted without severely damaging the gain. It was clear that retuning the three picket timings alone was not enough to significantly recover the gain from the effects of fast electron preheat.

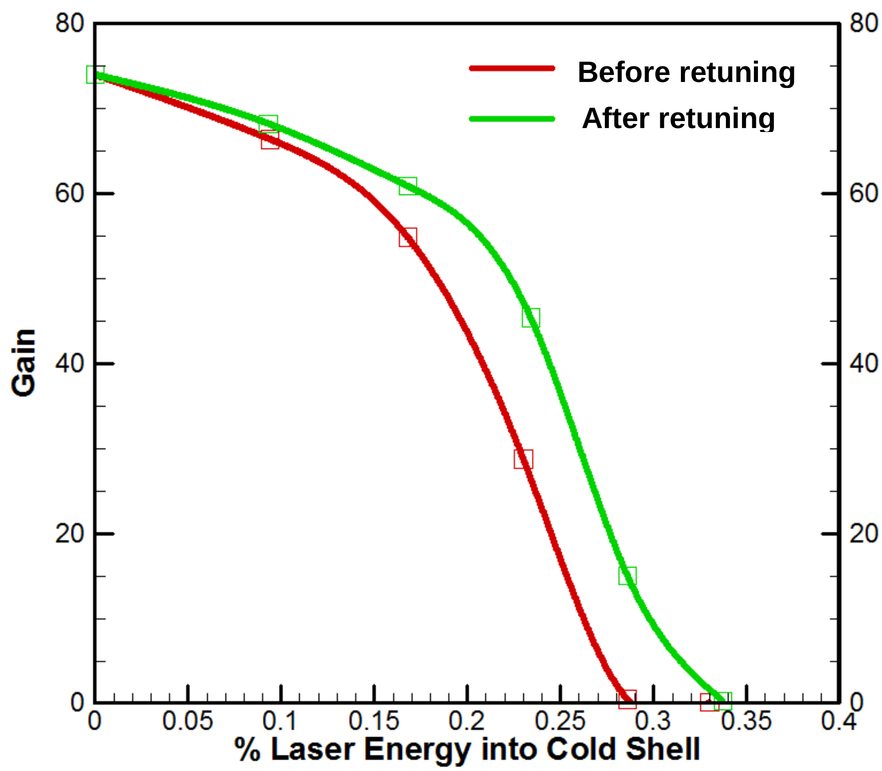

Figure 6: TELIOS retunings using the diffusion model of fast electron transport. These retunings showed much greater improvements, including an increase in gain of almost 20 when about 0.23% of the laser energy went into the cold shell.

4. Picket timing and power retunings

The next logical step was to retune the picket powers as well as the timings. TELIOS was therefore allowed to adjust the three picket timings as well as the three picket powers, for the same six conditions of preheat. This produced slightly better results [Fig. 7]. Figure 8 gives the change in the picket pulse parameters from the original setting to the one that produced the best improvement in gain. Several conditions of preheat saw larger recoveries in gain than when only the picket timings were retuned. The most dramatic improvement was seen in the fourth condition of preheat, with around 0.14% of the laser energy deposited into the cold shell. In this case, TELIOS was able to more than double the gain, giving about 0.03% more tolerance of laser energy into the cold shell. Although this was an improvement over the retuning using only the picket timings, it is not enough to significantly reduce the effects of fast electron preheat. Other factors will need to be explored to determine if it is possible to cancel out its effects on the gain.

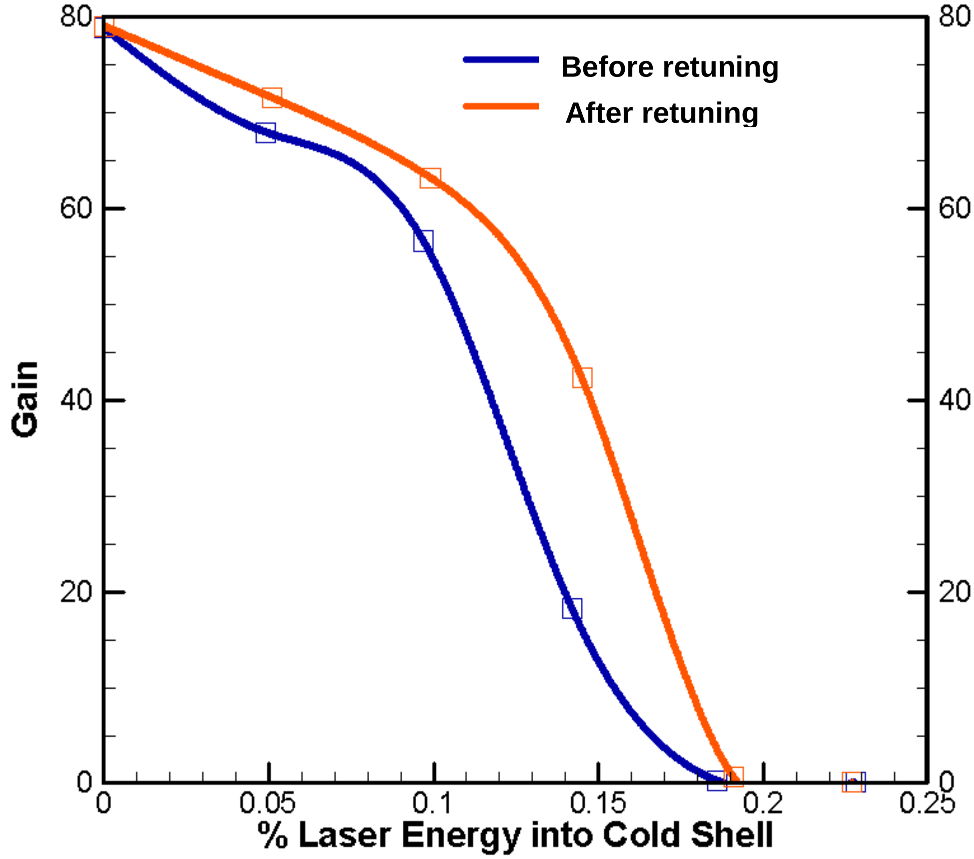

Figure 7: Results of TELIOS retuning of both picket timings and powers (straight line model).

	ΔT_1	**ΔT_2**	**ΔT_3**
Original	**1.87**	**0.61**	**0.35**
Optimized	**2.17**	**0.65**	**0.32**
	P_1 (Power in TW)	**P_2 (Power in TW)**	**P_3 (Power in TW)**
Original	**42.02**	**50.40**	**47.00**
Optimized	**34.56**	**48.91**	**47.10**

Figure 8: Parameters before and after TELIOS optimization for the fourth case of preheat. ΔT_1 is the time from the end of the first picket to the beginning of the second picket, ΔT_2 is the time from the end of the second picket to the beginning of the third picket, and ΔT_3 is the time from the end of the third picket to the beginning of the main pulse.

5. Conclusion

Fast electron preheat greatly reduces the gain of inertial confinement ignition designs by reducing the density and compressibility of the fuel. The optimizing code TELIOS was used to improve the gains of these designs by retuning the picket timings over a range of preheat conditions. It was unable to achieve significant improvements with either the straight-line model or the diffusion model of fast electron transport. Later tests where TELIOS was allowed to adjust both the picket timings and the picket powers yielded better results. However, these improvements were not significant enough to substantially counteract the effects of fast electron preheat. Other factors will therefore need to be optimized in order to reduce the problem of fast electrons.

6. Acknowledgements

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7. References

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