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Integrated Implicit Particle-In-Cell (PIC) Simulations of PetaWatt Laser Heating of Compressed Cores for Fast Ignition.[1]

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Abstract

There has been much interest in the fast heating of compressed matter by short pulse petawatt lasers [1]. Some time ago, we studied the heating process as applied to the GEKKO/PW experiments at Osaka [2] with a 3D hybrid electromagnetic implicit PIC code [3]. One limitation of our analysis was that we legislated the distribution of hot electrons entering the high density region. While the ansantz for the hot electron energy and angular distribution was consistent with experimental data, it clearly lacked rigor. We have now removed that limitation and will present integrated simulations which include the self-consistent laser plasma interaction with the blowoff plasma, as well as the electron transport through the pedestal and deposition in the core. For GEKKO/PW and FIREX [4] phase I scale experiments, the scaling of core temperature with increasing laser energy is nearly linear, and does not appear to have any saturation up to the highest we have considered, a laser energy of 2kJ. The heating profiles in the core show localized heating on the density gradient. Higher laser intensity does create higher energy electrons in the simulations, in agreement with ponderomotive scaling, but this higher mean energy does not appear to directly impact the location of the heating zone at the core edge. From the integrated results of these simulations, a method for igniting a half-moon shaped shell of material and subsequently the entire core is suggested.

I. INTRODUCTION

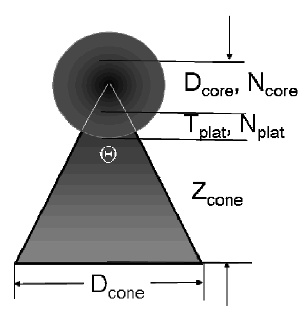
This brief paper serves as a progress report in our effort to simulate in an integrated fashion the important elements of cone-focused fast ignition coupling. The simulations include the laser/plasma interaction, transport of hot laser generated particles through the blow off plasma, and final energy deposition in the dense, compressed fast ignition core.

The simulations are performed with the LSP code in 3D, implicit hybrid mode [5]. It is assumed that the initial density profiles are given, that is, the simulations are not integrated to the level that the hydrodynamic compression is also included, although it would not be very difficult to include that phase in the future as a separate initial calculation.

The gold cone geometry is modeled in a manner reminiscent of the GEKKO/PW experiments. It is of interest to study the scaling of core temperature as a function of delivered energy to the core, since the coupling should eventually get weaker as the core becomes hotter, assuming the deposition scales classically. While the majority of the simulations discussed will be of the GEKKO-class compressed core, we will also introduce some simulations in progress of the ignition-class, using initial conditions reflecting optimum (near minimum energy requirement for ignition) parameters of DT core size, density, laser intensity and pulse length as described by Atzeni [6].

II. COMPRESSED CORE GEOMETRY

We start the integrated simulation with an assumed cone/blowoff/core geometry and plasma parameters. Figure 1 shows this configuration in terms of the major variables. Here, D_{core} and N_{core} are the core diameter and core peak electron density, respectively. The spatial density profile in the core is approximately Gaussian, with a width one half the radius of the core. T_{plat} and N_{plat} are the thickness and electron density in plateau blowoff region. The gold cone is characterized by the entrance diameter, D_{cone}, and the cone height, $Z_{cone} + T_{plat} + ½ D_{core}$. Note that the cone full angle, Θ, is a derived quantity and is provided for convenience. The plasma, laid in initially in the cone interior, has a density gradient perpendicular to the cone surface (at solid density) and drops at the cone centerline to below the critical density at 1 micron wavelength of about $1x10^{21}$ cm^{-3}.



[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Figure 1—Cone geometry and major variable definitions.

III. GEKKO/PW-LIKE SIMULATION

We have performed GEKKO-class simulations with basic characteristics of the initial state listed in Table 1. The peak 100-g/cc CD mass density and 300eV initial plasma temperature are consistent with estimates from the original experiments as a post isochoric compression state. We irradiate the cone entrance with a one micron laser with a pulse width of about 700 fsec, with a total energy of 300J as a baseline case.

Table 1. Gekko initial conditions

Parameter	Value
D_{core} (micron)	40
T_{plat} (micron)	25
D_{cone} (micron)	60
Θ (degree)	60
N_{core} (10^{23} cm^{-3})	400
N_{plat} (10^{23} cm^{-3})	2

Figure 2 shows the result for the core ion temperature at 3.3psec. (carbon and deuterium are in thermal equilibrium at these densities).

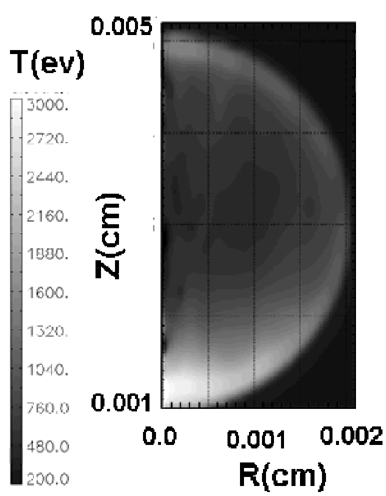


Figure 2—Half space contour plot of core ion temperature at 3.3 psec. The laser is introduced through the cone at the bottom (not shown). While there is a localized region of high temperature at lower density, the high density core is heated to 600-700eV.

Note that there is a region of high temperature at the injection side of the core, at a density of about 10^{25} cm^{-3}, a full factor of four below peak density and 20 microns from the center of the core. The bulk of the core is however around 600-700eV, in reasonable agreement with the experimental data.

Figure 3 shows time histories of the total energy and energy error (absolute measure of energy conservation) contained in the system. As can be seen, the laser is on for approximately 700 fsec, at which time it is shut off. Of the 300J delivered, approximately 200J are deposited into plasma species, distributed between cone, blowoff and core regions. It is also worth noting the good energy conservation in these implicit hybrid simulations for multiple picoseconds, a particularly difficult achievement in explicit simulations with such a wide disparity of densities and timescales. From this graph, we see that energy is conserved to better than 16%.

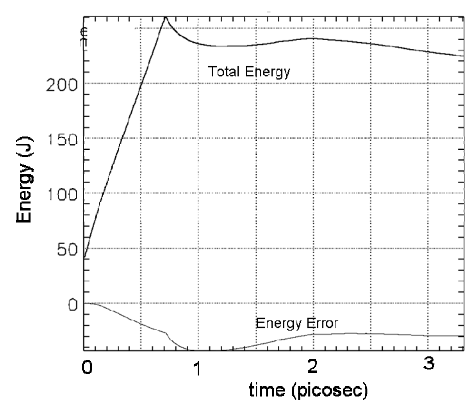


Figure 3 – Time history of system energy and energy error for the baseline 300J case.

IV. LASER ENERGY SCALING FOR GEKKO/PW SCALE CORES

It is now of interest to examine the scaling of core ion temperature as a function of delivered laser energy. There are two ways (or combinations thereof) to provide this increased energy. The first method involves lengthening the pulse while fixing the laser intensity; the second involves increasing the intensity at constant pulse length. Since there was appreciable energy deposition at lower densities, it was judged that the dense core heating could benefit from a higher mean energy of laser produced electrons since they would have a greater penetration potential. Since higher laser intensity results in hotter electrons, we chose the latter method for increasing the pulse energy.

Figure 4 shows the scaling of the dense core temperature as a function of laser energy, from the nominal 300J to 2kJ. The 2kJ point corresponds to the single beam configuration of FIREX [4] expected to operate in late 2007, although the simulation laser here operates at higher intensity than that proposed 10psec system. The energy conservation profiles for each case, in percentage terms, are similar to that shown in Figure 3. For the energy range examined, the core energy content scales approximately linearly with the increased laser energy. This result should be encouraging in that if there is a saturation of the ion temperature as core temperature and laser energy is increased, it apparently does not appear upt to the 2kJ level at these core densities. Work is underway to investigate higher energy levels.

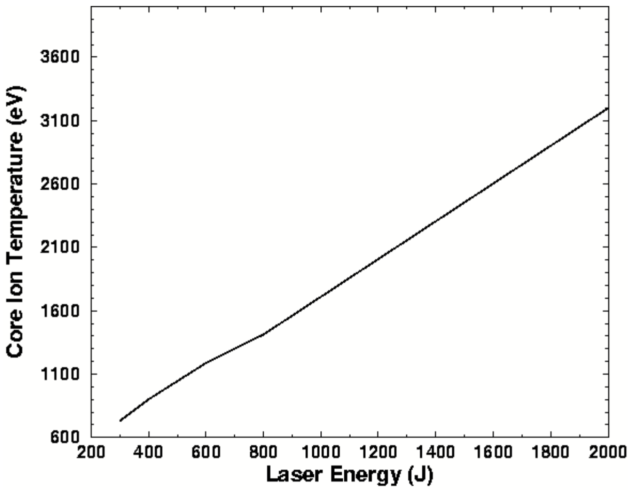


Figure 4—Core ion (CD) temperature as a function of delivered laser energy.

One interesting aspect of the simulations at the higher intensities is that the expected change in the location of energy deposition for the higher energy electrons from lower density to higher density of the core did not materialize. There was some trend to deposit marginally higher on the ‘hill’, but one that was not considered significant.

To confirm that the generated electrons have the proper energy scaling from the simulation, Figure 5 shows the peak hot electron kinetic energy in the plateau region at 10 times critical density, for several delivered laser energy levels (equivalent to intensity at constant spot size and pulse length).

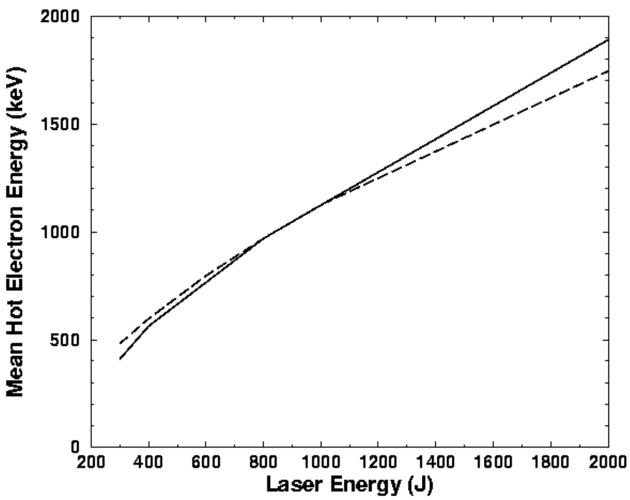


Figure 5-- Mean Hot Electron Energy as a function of delivered laser energy, equivalent to laser intensity for these constraints. The dashed line is ponderomotive scaling, normalized to the 800J point.

To within 20%, the energy scales as the well known ponderomotive scaling, suggesting that the deposition location is governed by a process not strongly driven by the electrons that represent the mean energy of the distribution. The exact reason for this behavior is a topic that we are currently investigating, especially the interaction that occurs at the tip of the gold cone with the outer boundary of the dense core.

V. IGNITION SCALE SIMULATION

We have begun to look at of ignition scale core fast ignition heating. The core and laser parameters were derived from the work of Atzeni, who looked at systems of minimum delivered energy to achieve ignition. The parameters that were varied to achieve minimum energy in that work were heating beam power, pulse length, core size and peak density. Table 2 shows the core parameters

Parameter	Value
D_{core} (micron)	40
T_{plat} (micron)	25
D_{cone} (micron)	80
Θ (degree)	60
N_{core} (10^{23} cm^{-3})	1600
N_{plat} (10^{23} cm^{-3})	2

The peak core DT density is about 650 g/cc, corresponding to an average density of about 300 g/cc. The pulse length is 20psec, at an intensity of 1 micron light of $8.84x10^{19}$ W/cm^2 . The total laser energy incident is taken to be about 85kJ, based on an estimated 20% core absorption efficiency to yield the 17kJ absorbed from the Atzeni analysis. At these core densities and pulse lengths, we have seen some numerical instabilities that we are working through presently to overcome. One possible way to avoid these instabilities is to use 3D Cartesian coordinates rather than the 3D cylindrical system we are using presently, since we believe the presence of an axis is introducing some noise problems. The disadvantage of such an approach is that the problem becomes larger, both in cell count and particle count, since we need to finely resolve all three dimensions.

Nevertheless, up to about 5kJ of energy absorbed into the cone/blowoff/core system, there is good energy accounting, and we can provide some observations/insights. First, after 5kJ was delivered, DT temperature profiles similar to those shown in Figure 2 were generated. This is reasonable, since the density and applied energy was each scaled up a factor of ten at that point in time. The temperature peaked on the density gradient at about ρ=300 g/cc, with width of about 15 microns. The average hot electron energy at 10 times critical density was around 1.5MeV.

The behavior of both the GEKKO/PW and ignition class cores and lasers suggests a possible way to facilitate the lighting of the entire core by only lighting a relatively thin shell of material. If the product of density and heating region width can be made to exceed a value characteristic of a tamped (lower than bare) system, then the shell can be ignited, and the rest of the compressed core can be bootstrapped through an ellipsoidal, nearly radially directed wave of plasma energy flow and non-local alpha particle heating. The present case for the ignition class system at least as far as we have simulated (to 5kJ), does not have the requisite mass density heating layer thickness product. More work is necessary to first get the entire complement of laser energy delivered (by eliminating the presently observed numerical instabilities), and then propose laser scenarios and isochoric compression schemes to get the width of the heating zone acceptably large.

VI. SUMMARY AND CONCLUSIONS

In this brief paper, we have provided a progress report on the integrated simulations of cone focused fast ignition heating using a 3D implicit hybrid PIC code. For GEKKO/PW and FIREX phase I scale experiments, the scaling of core temperature with increasing laser energy is nearly linear, and does not appear to have any saturation up to the highest we have considered, a laser energy of 2kJ. The heating profiles in the core show localized heating on the density gradient. Higher laser intensity does create higher energy electrons in the simulations, in agreement with ponderomotive scaling, but this higher mean energy does not appear to directly impact the location of the heating zone at the core edge.

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VII. REFERENCES

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