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Optimization of plasma uniformity in laser-irradiated underdense targets*

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Abstract. We used the Hyades [1] and Helios [2] radiation-hydrodynamic simulation tools, and the Cretin atomic kinetics code [3] to model low-density SiO_2 aerogel carriers doped with trace amounts of Ti and subjected to high-energy pulsed laser irradiation. Underdense targets are expected to respond to laser irradiation more uniformly as compared with solid targets, and therefore provide a better platform upon which to perform measurements of the properties of warm dense matter. We report modeling results for several cases of interest, with laser intensities in the range of $5x10^{12}$–$6x10^{13}$ W/cm^2, SiO_2 densities in the range of 2–8 mg/cm^3 and Ti doping in the range of 0–6%. Recommendations are given for the conditions under which relatively uniform temperature and density can be obtained.

1. INTRODUCTION

Studies of the properties of warm dense matter using lasers are complicated in part due to difficulties interpreting data from targets that evolve rapidly and contain large spatial gradients during irradiation. This is especially true in non-LTE plasmas, whose emissions depend on the complex time-dependent evolution of excited states. Clean, well-characterized benchmark data are needed in order to validate models of atomic processes in these plasmas.

Analyses were performed to help guide experimental studies of the radiative properties of non-LTE laser plasma such as those described in [4]. In that work, Ti L-shell spectra were measured in order to help resolve discrepancies between data and models of plasmas in recombination. Two experimental cases were considered: a "low-fluence" case at $4.6x10^{12}$ W/cm^2 using a 1-mm thick target containing 2.5 mg/cc of SiO_2+6 at% Ti, and a "high-fluence" case at $5.7x10^{13}$ W/cm^2 using a 2.2-mm thick target containing 2.7 mg/cc of SiO_2+3 at% Ti. In all modeling cases, the laser wavelength was 248 nm and the intensity ramped from zero to full intensity in 0.2 ns, remained flat for 3.6 ns and then ramped down to zero in 0.2 ns.

In order to isolate individual effects, we first examined a base case with pure SiO_2 at 2.5 mg/cc and laser intensity of $4.6x10^{12}$ W/cm^2, and then individually explored the effect of doping and laser intensity. Different models of radiation transport and ionization were evaluated. Finally, alternative target designs were analyzed using 2-sided illumination with and without end caps.

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2. PHYSICS MODELS

In underdense targets, inverse bremsstrahlung is the primary mechanism for energy absorption. Figure 1 shows the absorption length for several electrron densities and temperatures. Limitations in target fabrication prevent us from fielding targets with thickness less than ~1 mm and density below ~2 mg/cc, which corresponds to about $5x10^{20}$ cm^{-3} in SiO_2. Under these conditions, plasma temperatures below 300 eV are difficult to heat entirely by direct illumination.

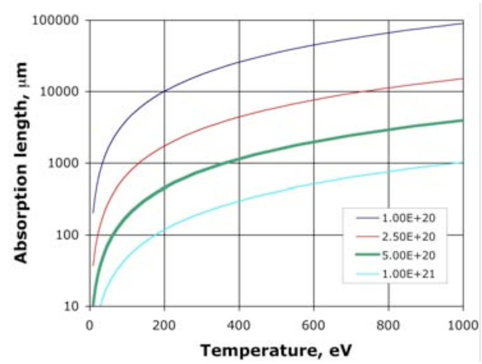

Figure 1. Inverse bremsstrahlung absorption length for underdense SiO_2

In any case, radiation emission plays an important role in the energy balance. These plasmas are fully non-LTE, as verified by the McWhirter condition and results of modeling, which indicate much slower electron-ion collision frequency as compared with mean radiative transition rates. Hyades [1] and Helios [2] were used to examine radiation trasport; these are commercially available 1D Lagrangean radiation hydrodynamic simulation tools. In both cases, multi-group radiation transport was used; Helios utilizes spectrally resolved opacity data (from the PROPACEOS code), whereas Hyades employs a hydrogenic model of the atoms.

Obtaning uniform density in underdense targets is significantly easier than obtaining uniform temperature. Non-LTE Cretin simulations show that Z_{eff}~8 at 100 eV, indicating SiO_2 has been stripped to the K-shell. Above this temperature, the average charge state gradually increases to 10. For laser intensities below 10^{14} W/cm^2, simulations show that hydrodynamic expansion during the laser pulse is small enough that the density is determined by the charge state. Above 10^{14} W/cm^2 the hydrodynamic expansion is so rapid that uniform densities can not be maintained.

Figure 2 highlights one of the primary difficulties in non-LTE modeling of underdense targets. The retained internal energy (including electrons, ions, radiation and kinetic energy) is plotted together with the energy escaped by radiation for several different cases using pure SiO_2. Hyades and Helios predict substantially different amounts of retained energy when multi-group transport is used. In general, Helios plasmas retain more energy, leading to higher observed electron temperatures.

Hyades provides several options for the ionization model. These include Saha, LTE average atom and non-LTE average atom. Figure 3 shows the electron temperature profile for several combinations of opacity and ionization models for the low-fluence case (the target is originally between 0 and 1 mm). Direct experimental measurements of temperature are not available, but the spectroscopic data suggest that a temperature of ~200 eV is appropriate for the low-fluence experimental conditions. More data are needed in order to better understand the model results. At this time, we are continuing to explore the sensitivities of the results to the models in order to help design the next set of experiments.

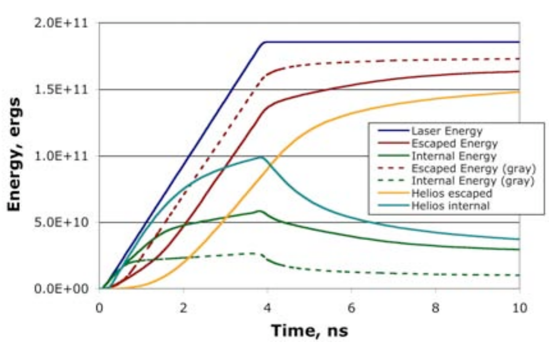

Figure 2. Energy balance for low-fluence cases

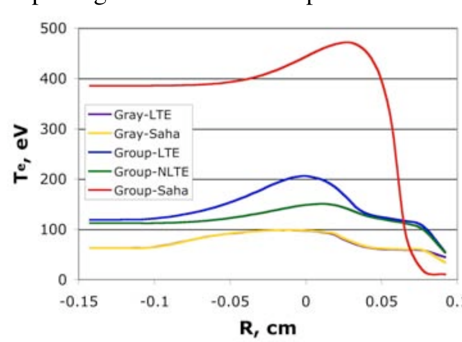

Figure 3. Hyades temperatures obtained using different physics models at 2 ns

3. EFFECT OF DOPING, LASER INTENSITY AND ALTERNATIVE TARGET DESIGNS

As seen in Figure 4, the addition of a dopant, even at the relatively low levels used here, results in significant reductions in temperature, and the spatial gradients become larger. The spectrally resolved opacity shows differences primarily for photon energies around 800 eV. In most cases we observe that higher opacity degrades the temperature uniformity. Since opacity generally decreases with temperature, we might expect that the high fluence case would have more uniform profiles. Figure 5 shows temperature profiles at 2.5 ns (high-fluence case with 2.2 mm target), and tends to confirm this.

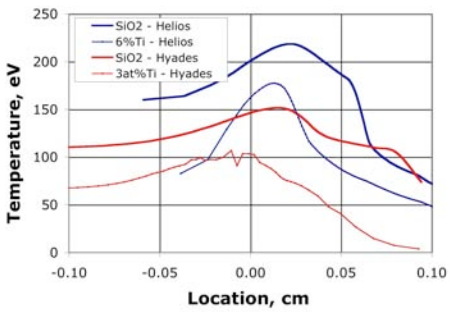

Figure 4. Effect of doping on temperature at 2.5 ns

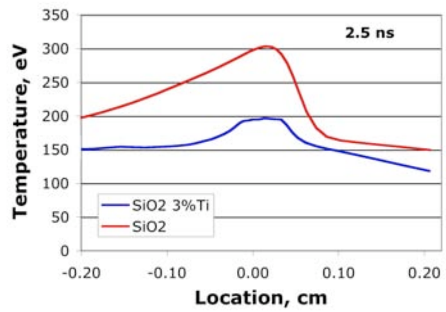

Figure 5. Hyades result at 5.7×10^{13} W/cm^2

As shown above, uniform heating of targets is possible when the temperature is sufficiently high to reduce the optical depth at the laser wavelength, but achieving uniform temperatures becomes increasingly difficult at lower intensities when the electron temperature remains below 300-400 eV. A straightforward technique to improve the uniformity is to use 2-sided irradiation. We explored two such geometries. First we divided the energy of the low-fluence case into two equal counterpropagating parts striking a 1-mm SiO_2 target (Fig. 6). In the second example (Fig. 7) we used a 3% doped core surrounded by 0.5-mm undoped side regions. In both of these geometries the profiles improved.

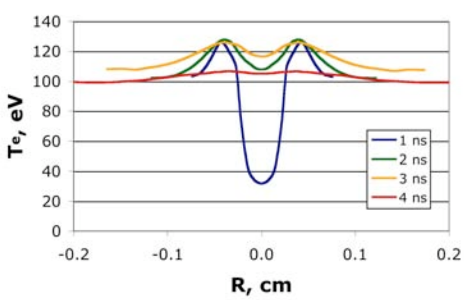

Figure 6. Electron tempertaure with double-sided illumination

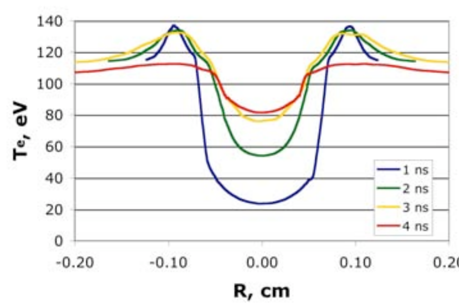

Figure 7. Electron temperature for the "pillbox" target

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