University of California, San Diego

UCSD-CER-06-09

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6 December 2006

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A comparison of Hyades and Cretin for modeling laser absorption in underdense plasmas

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Abstract. In a laser produced plasma (LPP), the temperature and density profile and history are determined by the laser energy absorbed by the plasma. Therefore, it is extremely important that the absorption coefficients are calculated accurately when modeling LPP's. We have compared the inverse bremsstrahlung absorption coefficients of the radiation-hydrodynamic code Hyades [1] with the non-LTE atomic kinetics / radiation transfer code Cretin [2]. We found that the absorption coefficients disagree at relatively low electron temperatures (1-100 eV), and then begin to converge as the temperature rises above 100 eV. These discrepancies lead to a dramatically different temperature and density evolution of the LPP.

1. INTRODUCTION

It is difficult to model LPP's due to their rapid evolution and sharp spatial gradients. In addition, these plasmas are often non-LTE so that textbook equations for the ionization balance, radiation field, and velocity distribution no longer apply. Instead, detailed tracking of populations, through rate equations, is necessary to model LPP's. Several codes have been developed in an attempt to model non-LTE plasmas, but there is uncertainty in the codes' ability to predict radiative properties of non-LTE plasmas. In order to validate the modeling, experimental data must be collected from a clean, well characterized plasma for comparison.

The experimental design calls for SiO_2 aerogel targets with 3 at% Ti to be volumetrically heated by a laser [3]. The density of the targets is 3 mg/cc. The density was made as low as possible so that the laser could penetrate to the center of the target, and so that the plasma would be optically thin to the radiation produced from the plasma.

Hyades [1], a radiation-hydrodynamics code, simulations were used to guide the experimental activities. Simulations were performed to predict the electron temperature, T_e, achieved for various laser intensities. Temperatures of a few hundred eV are needed to create L-shell emission from Ti, which is the emission to be studied in this project. The Hyades results showed large temperature gradients that were not expected with the laser intensity and target design. This led to an investigation of the laser absorption model in Hyades and a comparison with the model in Cretin [2], a non-LTE atomic kinetics / radiation transfer code.

2. HYADES LPP RESULTS

The target is 2 mm thick, with 0.5 mm thick outer regions, which contain no Ti, as shown in

Figure 1. Figure 2 shows the electron temperature profile for a prospective target. A laser, with an intensity of 2.3×10^{12} W/cm^2, is incident on each side of the target to allow for uniform heating. The much lower temperature in the central region is an indication that the laser is only heating the outer portion of the target, and that reradiation and conduction provide the heating for the doped region. This is confirmed in Figure 3 where the laser absorption is plotted as a function of position. If this is true, then the experiment cannot provide useful data for benchmarking the non-LTE codes. However, it has been demonstrated that the laser penetrates an arogel target to heat volumetrically [4,5]. The fact that the laser was fully absorbed in the first 0.5 mm of the target suggests that the absorption model is over predicting the inverse bremsstrahlung absorption (IBA) coefficient.

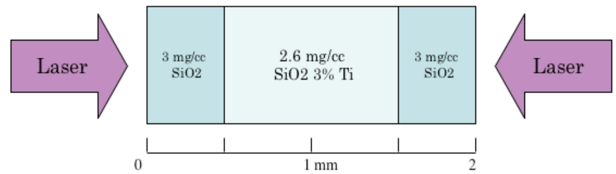

Figure 1. The target geometry is a doped core with an undoped tamping layer on the outside.

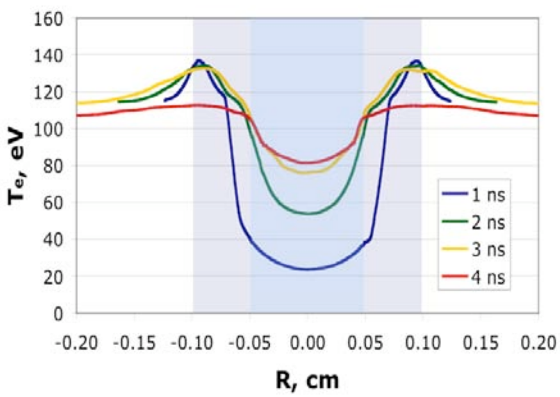

Figure 2. The temperature profile of the target showing the outer undoped region getting hot while the central doped region remains too cool.

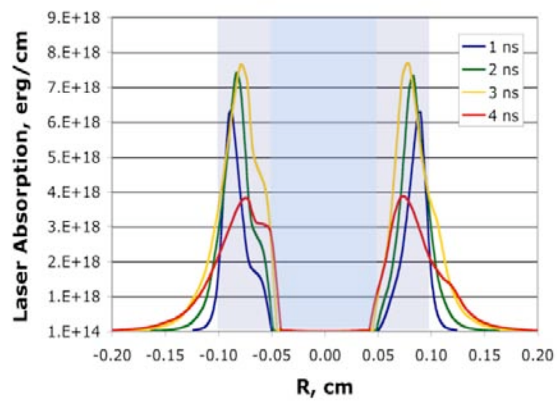

Figure 3. Showing that the laser only penetrates the outer layers of the target.

To determine if the IBA coefficient in Hyades was really the problem, a comparison case between Hyades and Cretin was made. A test case was constructed by turning off any physics in the codes that could have an affect on the temperature and absorption, fixing the temperature to a value relevant to the experimental studies, 700 eV, and introducing a laser of the appropriate intensity, 5×10^{12} W/cm^2. The modeled target was composed of four, 25 micron thick SiO_2 zones. The mass density was set to 3 mg/cc. Four zones were designated since this is the minimal number of zones allowed in Hyades. The targets were made thin so that each region would see nearly the same laser intensity. We then compared the laser energy absorbed in each code, shown in Figure 4. It is obvious here that there is a disagreement in the IBA between Hyades and Cretin.

The discrepancies in the IBA in the test case led to a more thorough investigation to compare the temperature dependence for the absorption coefficients. Similar cases to the test case were run for the range of temperatures that would be encountered in the experimental campaign. In Figure 5, it can be seen that Hyades has a much higher absorption than Cretin at low temperatures. The difference reduces as the temperature increases, but is still a factor of two even at 1 keV. The most dramatic difference occurs around 6 eV were Hyades is 20 times higher than Cretin. Additionally, Hyades shows an increase in the absorption with temperature from 1 to 6 eV. It should be mentioned that Hyades was not intended to work in the temperature and density ranges in question, and that there is little question of it's accuracy in the regime where it was intended to work.

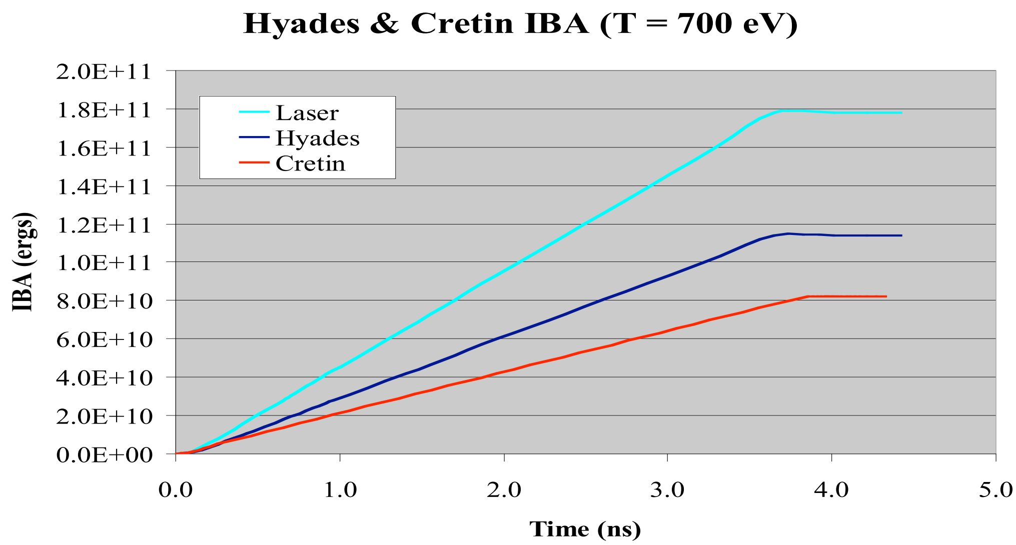

Figure 4. A comparison of Hyades and Cretin IBA for a underdense SiO_2 aerogel target at 700 eV

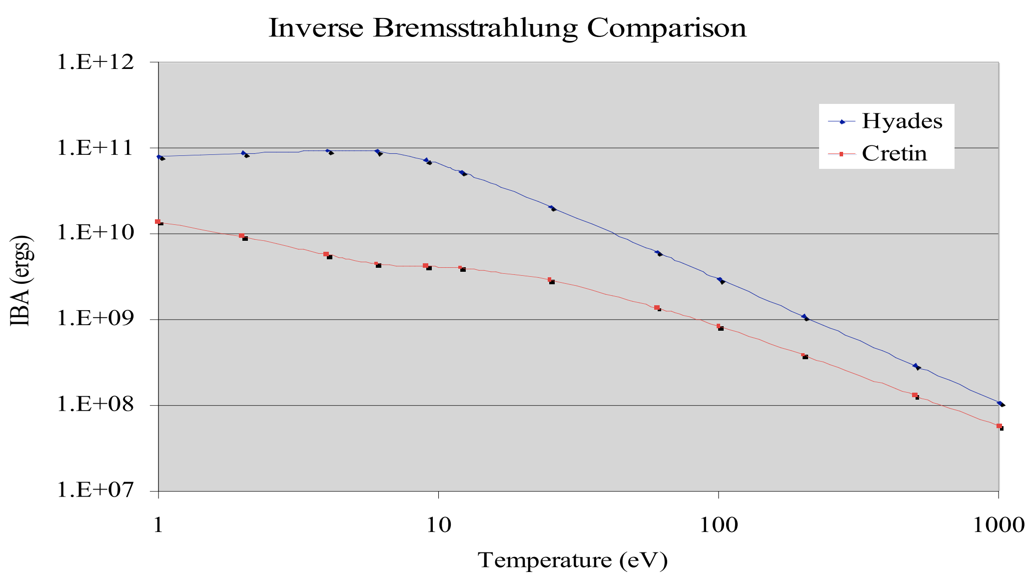

Figure 5. The temperature dependence of the IBA for Hyades and Cretin

3. HYADES IBA prescription

There are two reasons for the higher absorption in Hyades. The first is related to an approximation made to the stimulated emission term in the IBA calculation. Equation (1) is the prescription used in Hyades. The $T_e^{3/2}$ dependence comes from an approximation that is only valid for $kT_e >> h\nu$. Equation (2) indicates how the IBA could be calculated if this approximation was not used. This approximation leads to the narrowing differences between the two codes at T_e increases, and the relatively large differences at low T_e.

$$\alpha = const * \frac{\left\langle n_i \left(Z^*\right)^2 \right\rangle n_e}{T_e^{3/2} \omega_0^2 \sqrt{\varepsilon'}} \ln \Lambda_{ei} \tag{1}$$

$$\alpha = const * \left(1 - \exp\left(\frac{-h\nu}{kT}\right)\right) \frac{\left\langle n_i \left(Z^*\right)^2 \right\rangle n_e}{h\nu T_e^{1/2} \omega_0^2 \sqrt{\varepsilon'}} \ln \Lambda_{ei} \tag{2}$$

$$\ln \Lambda_{ei} = \frac{1}{2} \ln \left[\max\left\{2.,1 + \frac{b_{\max}^2}{b_{\min}^2}\right\}\right] \tag{3}$$

$$b_{\max}^2 = \max\left\{\lambda_D^2, R_o^2\right\} \qquad b_{\min}^2 = \frac{h^2}{48\pi^2 m_e k T_e} \tag{4}$$

$$\ln \Lambda_{ei} = \frac{1}{2} \ln \left[1 + \frac{b_{\max}^2}{b_{\min}^2}\right] \tag{5}$$

The second problem lies in the calculation of the Coulomb logarithm, $\ln \Lambda_{ei}$, for which the Hyades formula is given in equation (3-4). Calculating the Coulomb logarithm this way leads to an over estimate for lower temperatures. This compounds the over estimation already caused by the stimulated emission approximation. In contrast, Cretin calculates the Coulomb logarithm using equation (4-5).

4. Summary and Conclusions

We have shown that Hyades predicts higher than expected laser absorption. This results in over heating of the outer zones of the illuminated target, while the inner zones are only heated by conduction and reradiation. The reason Hyades over predicts the laser absorption is that an approximation is made for the stimulated emission and an error in the Coulomb logarithm. However, at high values of T_e, the IBA in Hyades will be accurate since these affects are only important below about 2 keV.

The plasma uniformity and peak temperatures were of key importance for the modeling of laser irradiated aerogels. The overestimate of the IBA makes Hyades inaccurate for these low density and temperature conditions. Cretin was used, instead of using Hyades to calculate the temperature and density profiles. The ability to do Hydrodynamic calculations was added to Cretin in order to account for plasma expansion.

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