Analysis of Silicon Emission in Rayleigh–Taylor Unstable Imploded Layered Targets

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Summer High School Research Program 2003

1. Abstract

The Rayleigh-Taylor instability occurs at the interface between two fluids, where one fluid is significantly denser than the other and the lighter fluid is being accelerated into the heavier one. The presence of this instability affects the various processes that occur in the target during laser implosion. This instability occurs at the surface at which material is ablated by the laser in targets imploded with the OMEGA laser, and has been analyzed using post-processing files from the 2-D simulation code DRACO and various Fortran programs. The time history of the emission of radiation from a silicon-doped plastic layer placed beneath a non-doped outer plastic layer has been calculated and found to agree qualitatively with experimental results.

2. Introduction to the Rayleigh-Taylor Instability

The Rayleigh-Taylor instability is a fluid instability which can break-up the shell of an imploding inertial confinement target. It occurs when a light fluid is being accelerated into a heavy fluid. An everyday example of this instability is a container that has water and oil in it. The oil, being less dense than the water, will naturally settle in a distinct layer on top of the water. Yet when the layers are reversed, that is, when the water is placed on top of the oil, the Rayleigh-Taylor instability occurs at the interface between the two layers as they attempt to resume their natural positions. It should be noted that if the interface between the two layers were perfectly uniform, the instability would not occur. In other words, the instability does not cause perturbations to form, but it amplifies any existing perturbations.

The same phenomenon that occurs between water and oil also occurs at the surface at which the material is ablated by the laser (the ablation surface) in targets used on OMEGA. The lighter ablated region outside the ablation surface is accelerated into the heavier solid shell by the laser (see Fig. 1). Non-uniformities in the laser beams cause tiny perturbations at the ablation surface[2]. These perturbations grow exponentially as a result of the instability[2]. The shapes formed by the instability are referred to as "bubbles and "spikes" (see Fig. 2). In the layered target of Fig. 1 the bubbles of CH are pushed through the CHSi layer, forcing the material to flow around them such that most of the mass is concentrated in the spikes (see Fig. 2). The CHSi then flows from the tip of the spike into the laser-heated heated plasma.

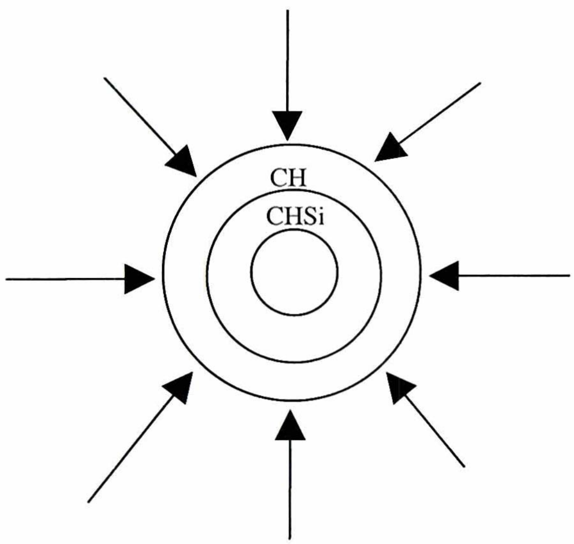

Figure 1. A schematic of the target is shown with a layer of Si-doped plastic (CHSi) surrounded by a layer of un-doped plastic (CH). The arrows indicate the directions the laser beams are coming from.

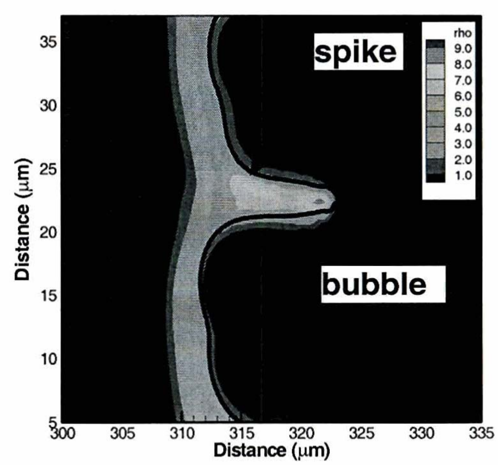

Figure 2. Density contours of part of the target shell is shown. The dark black lines indicate the shape of the CHSi layer in the target. The laser beams are incident from the right. This contour plot was generated using post-processing files from the 2-D code DRACO.

3. Introduction to Burn-through Experiments

This type of layered target is used in burn-through experiments, which are carried out to test improvements in the laser illumination uniformity. The signature layer, in this case, the CHSi layer, is used to indicate the extent of the penetration of the heat front generated by the ablation process[2]. When the emission from the silicon ions is detected, burn-through has occurred. In other words, the outer CH layer has passed through the heat front and the CHSi layer has moved into it. The time at which burn-through occurs depends on a number of variables. The Rayleigh-Taylor instability causes the burn-through time to vary based on the uniformity of the target and the uniformity of the laser irradiation[2]. The less uniform the irradiation, the greater the initial perturbations on the target and the faster the R-T instability will cause these perturbations to grow. Since the spikes caused by the instability are growing faster, the CHSi concentrated in these spikes will be pushed into the heat front earlier, causing an earlier burn-through time[2]. Thus, burn-through experiments can be used to measure the uniformity of the laser[2].

4. Introduction to Silicon Emission

During implosion, the outside of the target is heated to extremely high temperatures. As the material is heated, it ionizes, i.e. it loses electrons. The ions of most importance in this project are the hydrogen-like silicon ions, which are silicon atoms that have lost all but one of their electrons. Emission occurs when this one remaining electron becomes excited, or when it jumps to an energy level higher than the ground state. When the electron returns to the ground state, a photon is emitted. The frequency of this photon is proportional to the energy difference of the ground state and the excited state as illustrated in the equation:

$$\Delta E = E_{excited} - E_{ground} = h\upsilon$$

where v is the frequency of the photon and h is Planck's constant.

5. Calculations

The first step in calculating the silicon emission (i.e. the amount of energy released in the form of photon emission) was to determine the ion populations, particularly the population of the hydrogen-like species. This was done using the Saha equation[1]:

$$\frac{N_{r+1}N_e}{N_r} = \frac{g_{r+1}g_e}{g_r}\frac{(2\pi m_e kT)^{3/2}}{h^3}e^{-\chi_r/kT}$$

where N_{r+1}, N_r, and N_e are the number densities of the r+1 times ionized species, the r times ionized species and the free electrons respectively, m_e is the mass of an electron, k is the Boltzmann constant, h is Planck's constant, and T is the temperature. The terms g_{r+1}, g_r, and g_e are statistical weights, or the number of possible states for the r+1 times ionized species, the r times ionized species, and an electron respectively. An electron can be in one of two possible states, which correspond to two different directions of spin, therefore its statistical weight is 2 or $g_e = 2$. The other two statistical terms, g_{r+1} and g_r are normally expressed as partition functions, which are infinite sums that take into account all the possible excited states for the ions. For the sake of simplicity, the excited states of the ions were ignored and only the ground states were taken into account when the statistical weights were calculated.

Solving the Saha equation for all the combinations of adjacent ion species of silicon yields a series of population ratios. If the total ion population is known, then the ratios can be used to determine the individual populations. The population of most interest is that of the hydrogen-like ion, the ion in which only one electron remains. Once this population has been determined, the next step in calculating the emission is to determine the population of the excited state of this ion. This is done using the equation:

$$\frac{N_{exc}}{N_{grnd}} = \frac{g_{exc}}{g_{grnd}} e^{-E_{21}/kT}$$

where N_{exc} is the number density of the excited state, N_{grnd} is the number density of the ground state, g_{exc} and g_{grnd} are the statistical weights of the excited and ground states respectively, E_{21} is the energy difference between the second principal energy level (excited state) and the first principal energy level (ground state), k is the Boltzmann constant, and T is the Kelvin temperature.

The population of the excited state can be used in the equation below to calculate the power in ergs/cm^{3}sec.

$$P_{21} = N_{exc} E_{21} A_{21}$$

E_{21} should be in ergs when used in this equation. A_{21} is the rate at which excited electrons in the second energy level return to the ground state (units are sec^{-1}). Summing all the powers (P_{21}) for a given area yields the total emission from the hydrogen-like silicon ions.

6. Results

A program was written in Fortran to perform the calculations described above. Input variables from DRACO post-processing files were used. These variables included total mass density, mass density of the CHSi, electron temperature, average ionization, and x-y variables corresponding to relative locations. These variables were used to calculate the total ion density, and the density of free electrons, values that were needed to perform the ion population calculations.

Three separate simulations were analyzed using this program. The first, shot 21133, shows that most of the emission occurs at the tips of the spikes. Figure 3 shows a contour plot of the emission with line contours of temperatures superimposed. The 500eV isotherm goes through the areas of high emission, indicating that most of the emission occurs at this temperature. When this plot is compared to one of a uniform case taken at the same time (where the instability is nonexistent as shown in Figure 4) it is clear that no emission occurs in the uniform case because the CHSi does not become hot enough.

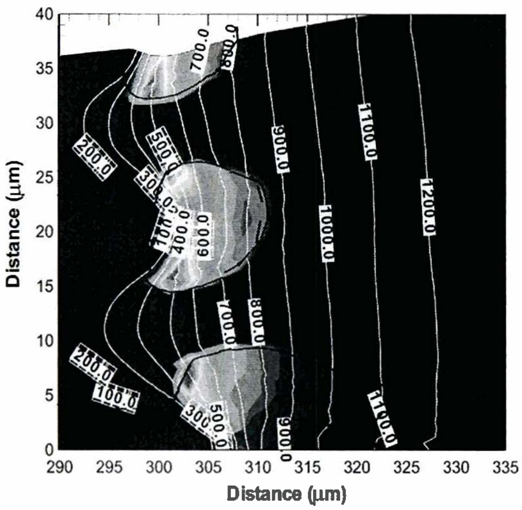

Figure 3. The shaded contours of shot 21133 show the level of emission from Si ions while the line contours superimposed over it shows the temperature in eV. The heavy black line indicates the border of the CHSi plastic layer. The laser beams are incident from the right.

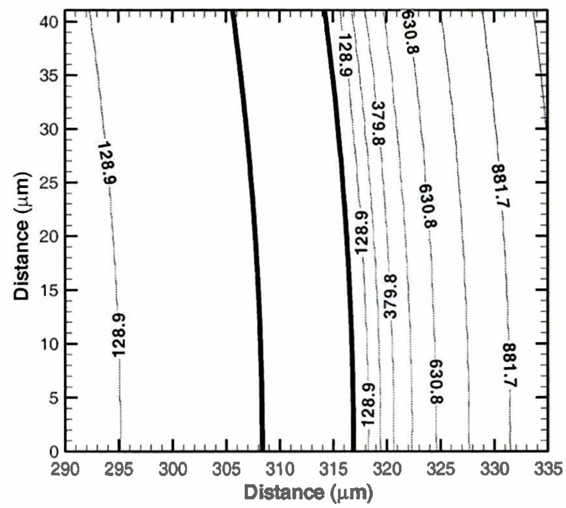

Figure 4. This temperature contour (in eV) of a uniform case illustrates that the CHSi layer (indicated by the region between the heavy black lines) does not reach the temperatures needed in order for emission to occur.

Two other simulations of actual target shots, both full quarter spheres (see Figure 6) as opposed to smaller portions of spheres, were analyzed. Shot 21144 was done without SSD, a technique of smoothing the laser beam to increase uniformity and shot 21146 was done with SSD. Figure 5 shows a graph of emission as a function of time for each of these two simulations. It is clear from the graph that emission occurs later with the more uniform illumination (dashed line). The early emission in the non-SSD case occurs because the less uniform laser beam creates larger initial perturbations in the surface of the target. These larger perturbations grow quickly due to the R-T instability. As a result, the silicon-doped plastic is pushed into the heat front earlier than in the more uniform illumination case.

The time at which the CHSi layer burns through the CH layer can be roughly predicted using this graph as the time at which the total emission reaches one tenth of its maximum level. These two shots were part of an experiment conducted using OMEGA during which their actual burn-through times were recorded. Figure 5 shows that the predicted burn-through times qualitatively agree with the experimental burn-through times.

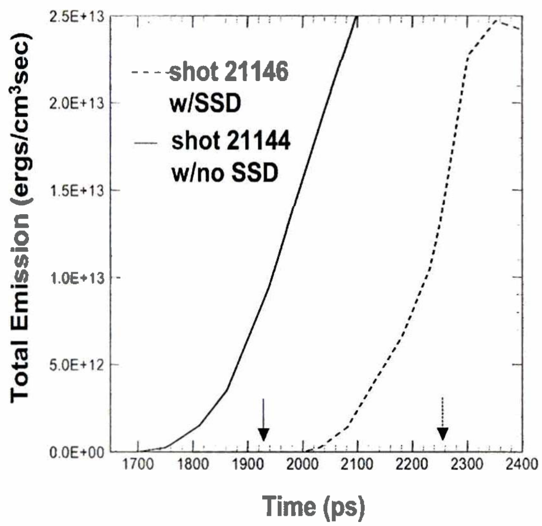

Figure 5. Total emission as a function of time is shown for a case with SSD (more uniform) and a case without SSD. The corresponding arrows indicate the times when burn-through of the CHSi layer occurred in the experimental shots.

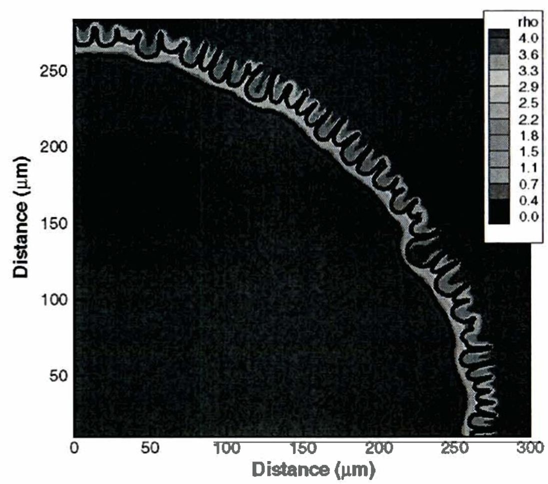

Figure 6. A density contour plot of shot 21146 with SSD.

7. Conclusion

The analysis of the DRACO post-processing files showed that the Rayleigh-Taylor instability causes the CHSi plastic layer to flow into spikes. By forcing the CHSi into the spikes, the R-T instability pushes the CHSi layer farther into the heat front of the ablation plasma causing it to become hotter faster. As a result, most of the emission from hydrogen-like silicon ions occurs in the spikes. The analysis of data from simulations of two experimental shots (21144 and 21146) showed that more emission occurs under less uniform laser irradiation. This occurs because in less uniform targets, the instability grows faster and creates larger spikes, thus pushing more of the CHSi layer into the hot plasma and causing more emission. The results of this analysis qualitatively agreed with the actual experimental results.

8. Acknowledgements

First of all I would like to thank my supervisor, Dr. Jacques Delettrez, for guiding me through this project and teaching me almost everything I needed to know in order to complete it. I would also like to thank Dr. Reuben Epstein for taking the time to explain Saha's equation to me and showing me how to calculate the emission. His help was invaluable to the completion of this project. Finally, I thank Dr. Stephen Craxton and the Laboratory for Laser Energetics for allowing me the opportunity to work at the laser lab and to gain the experience of completing a real scientific investigation.

9. References

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