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Investigating the Heating of a Potassium-Doped Aluminosilicate Ion Source Using a 1 Micron Laser

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Introduction

The heavy ion fusion (HIF) program is interested in developing a high brightness ion source for high energy density physics (HEDP) experiments. One possible approach to obtaining higher brightness may be to raise the surface temperature of the ion source just prior to extraction. The current ion source material being studied is a layer of potassium-doped aluminosilicate bonded to a tungsten substrate. It is speculated that if the surface temperature of the source is raised above 1200 ^{o}C (from a steady-state temperature of 900 ^{o}C) for time periods on the order of 100's of nanoseconds, current densities of greater than 100 mA/cm^2 of ions may be achievable. Typical aluminosilicate sources produce ion current densities (either K^+ or Na^+ ions) of ~10 mA/cm^2 (at 1100 ^{o}C). A number of heating methods might be possible, including lasers, diode arrays, and flash lamps. Here we assume laser heating. In this preliminary study, we used the LLNL RadHeat code to model the time-temperature history of the surface when hit by laser pulses and illustrate how RadHeat can be used to optimize the surface temperature response. Also of interest is the temperature history of the interface temperature between the ceramic and the metal layers. This is also investigated.

Material Properties

Potassium-doped aluminosilicate is a material for which the properties are not well understood for a large range of temperatures. From reference [1] and www.azom.com some properties were found for this material. The density was given as 2.6-3.2 g/cm^3. For this study, an average of 2.9 g/cm^3 was used. A constant value of 50 J/kg-K was used for the specific heat. The thermal conductivity was given to be 0.5-7 W/m-K at 20

^{o}C. This is quite a large range, and may be due to the inconsistencies in manufacturing this material. For this study, a constant value of 3 W/m-K was assumed, but could be easily changed for further analysis. Later in the report, we look at varying the thermal conductivity in this range, and the effects it has on the heating of the surface layer of the ceramic. Photon opacity data was obtained by using the TART code from LLNL [2]. A 1-D monte-carlo code was run for both materials used (K^{+}- doped aluminosilicate and tungsten) in order to find the energy-dependent mean free paths for photons incident on the material. The photon opacity data is derived from the output of the TART calculations. Energy-dependent photon opacity data is available from the code for energies of 100 eV up to 1 GeV. Even though these energies are well above the energies of the laser photons, we can assume an opacity which allows the photons to deposit their energy in a shallow surface (roughly 1 angstrom). [3]

Code Input and Results

In order to scope the heat source requirements, the RadHeat code (LLNL) was used to model a heat source incident on a layer of potassium-doped aluminosilicate that is 0.5 mm. thick bonded to a layer of tungsten with thickness of 3 mm. A model of laser pulses at 1 micron light was modeled to be incident upon a 5.25 cm radius plate of the material. The total energy incident on the plate was calculated to be 1.065 J. RadHeat modeled the surface temperature of the source versus time. Figure 1.1 below shows a plot of this time-temperature history for this laser pulse. Note that convection and radiation cooling methods were “turned off” in RadHeat for these runs. This is an acceptable assumption due to two reasons. First, the radiation heat loss will be very small over the time periods of interest (100’s of nanoseconds). Also, the convection can be ignored because we assume the source is in vacuum. In reality, some active cooling of the back surface may be needed to cool the sample after heating from multiple pulses, but this is not modeled here. Also not modeled is any contact resistance between the two materials. We find that this may not be very important for single shot effects, as the heat has more than enough time to conduct away from the surface before the next laser pulse would be incident on the material.

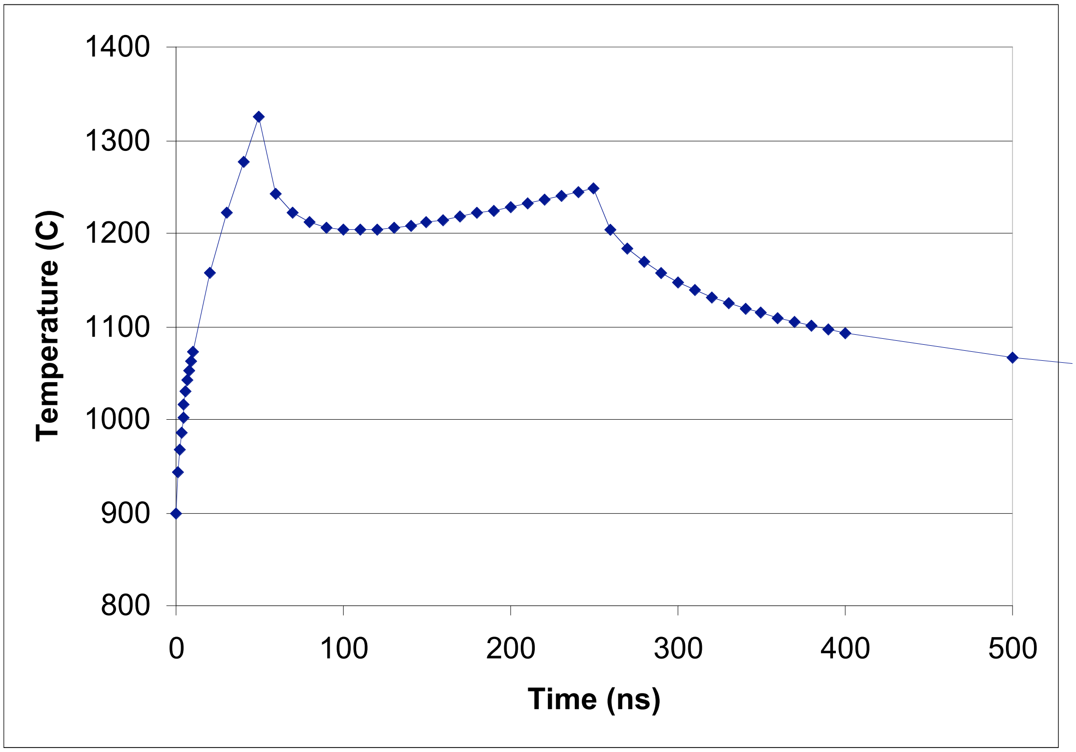

Figure 1.1 - Time-temperature history for surface of potassium-doped aluminosilicate.

By varying the intensity and pulse duration of the laser inputs, we can control the time-temperature history of the front surface of the aluminosilicate. Noting that the requirement from colleagues in the HIF program is to raise the temperature of the surface to approximately 1200 ^{o}C for a few hundred nanoseconds, we ran multiple cases of RadHeat until a sufficient case was found. As shown in the graph above, the surface temperature is raised to a temperature of 1360 ^{o}C in only 50 ns. The temperature then falls to approximately 1200 ^{o}C. Just after the first laser turns off, a second laser (or the first laser is turned down in intensity) is fired at the surface, which allows the temperature to be held above 1200 ^{o}C for roughly 200 ns. longer. Figure 1.2 shows the laser pulse profiles. The first laser pulse is a pulse with power density of 1.2 GW/m^2. This pulse is started at time 0 and held constant for 50 ns. At exactly 50 ns the pulse power density is turned down to 0.45 GW/m^2 and held on for duration of 150 ns. This is a total heating time of 200 ns. This laser profile allows for a much more constant temperature profile.

If a larger initial temperature spike is acceptable, and keeping the temperature nearly constant at 1200 ^oC is not an important feature (i.e. we can allow the temperature of the surface to vary by approximately 100 degrees over the 200 ns. time period), the heating could be done by only one laser pulse.

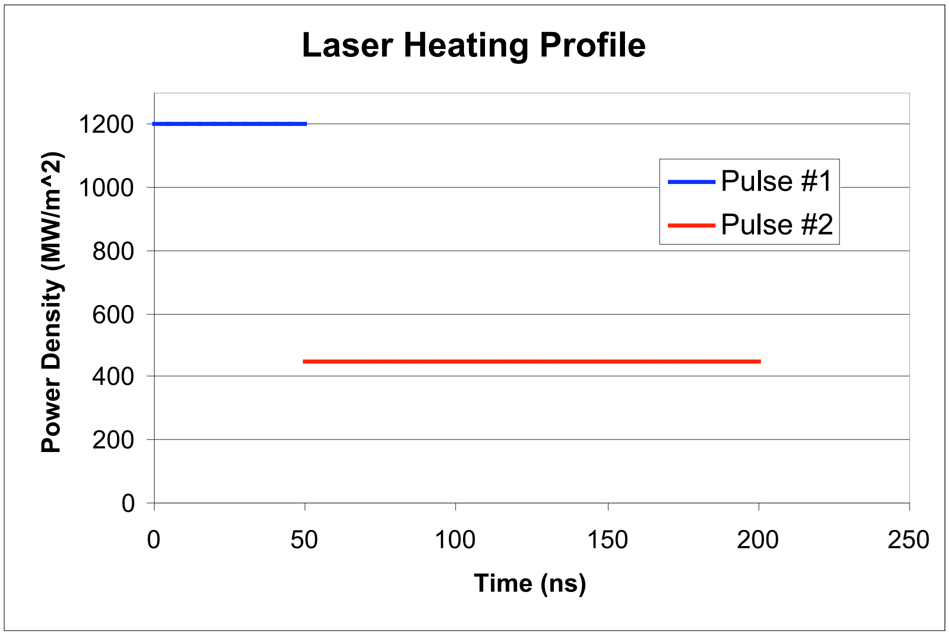

Figure 1.2 – Heating profile for the two laser pulses.

It is also of great interest to understand the temperature profile of the ceramic/metal interface. This is of importance so that material bonding issues can be discussed and studied. Obviously, a small temperature difference at the boundary is desired to allow for little expansion of the materials, and less probability of debonding and failure. Figure 1.3 shows the temperature of the materials as a function of depth into the surface. Notice that the temperature of the ceramic is back to the original 900 ^oC at a depth of only ~5000 nm. This is only 1/100th the distance to the ceramic/metal interface. This is due to the heat not having conducted back to this distance in the time frame studied in this graph. Note that this snapshot was taken at 50 ns.

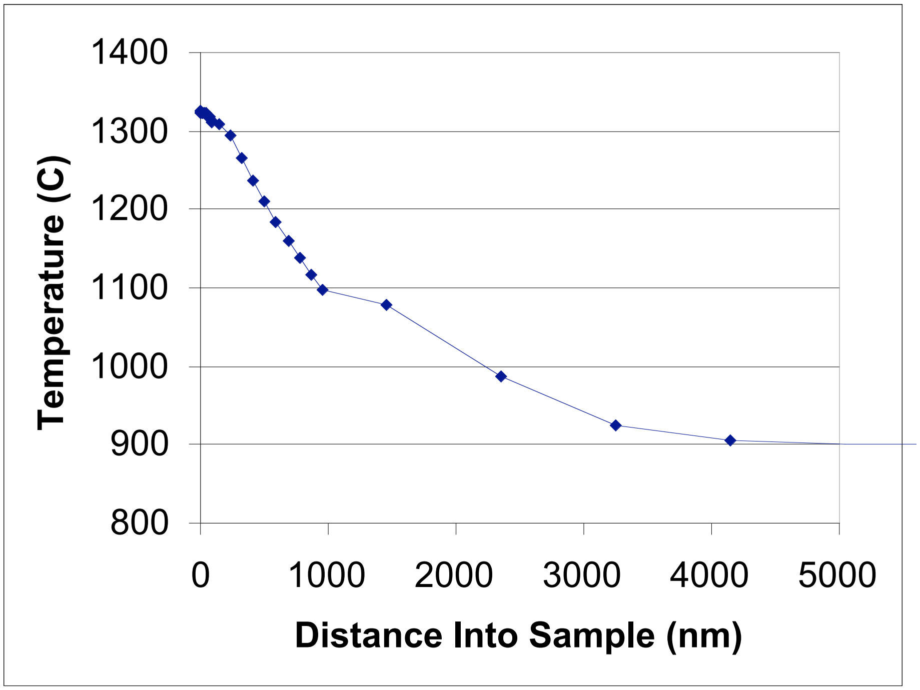

Figure 1.3 – Temperature versus distance profile for the time at which the largest surface temperature is observed. Snapshot is taken at 50 ns after the laser pulse was initially turned on.

If we look further along in time, we can plot the same data again. Figure 1.4 shows the temperature versus distance profile again, but this time for a time snapshot at 500 ns. Notice that the temperature reaches 900 ^{o}C at a distance of approximately 10 microns. This is obviously because conduction has had proper time to move the heat from the surface through the sample further. Yet, even at these time scales, the heat has not had time to raise the temperature of the ceramic/tungsten interface.

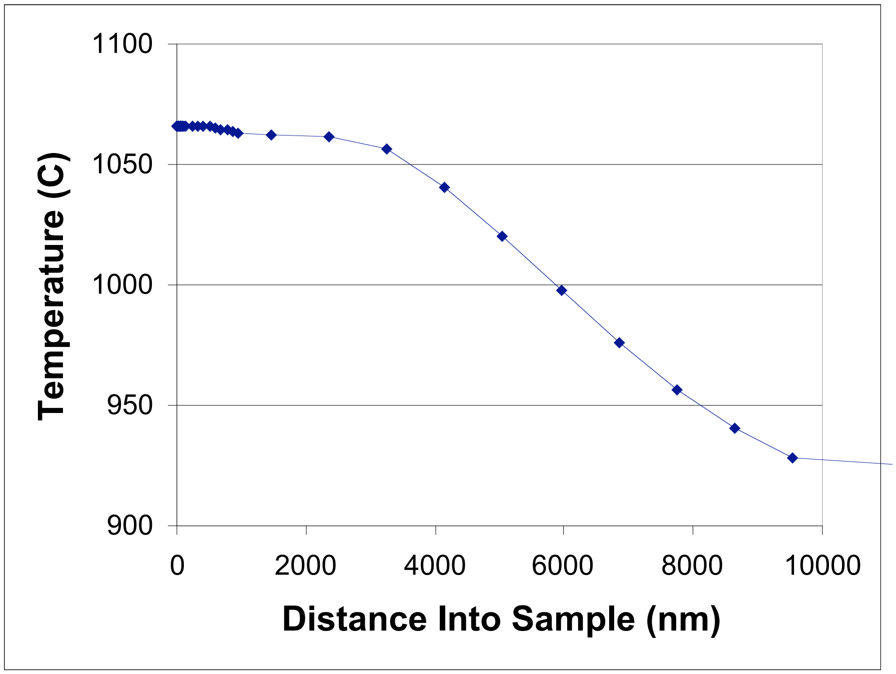

Figure 1.4 – Temperature profile versus distance into the sample for a time snapshot at 500 ns.

Because of the uncertainties in the material property data for potassium-doped aluminosilicate, it was decided to do some scoping studies into what effect changing the material properties has on the thermal response of the surface layer. A major property with large uncertainty is the thermal conductivity of the material. From the reference, a thermal conductivity was given to be 0.5-7 W/m-K at 20 ^{o}C. As an assumption, a value was chosen to be 3 W/m-K for this study. However, the values of 0.5 and 7 W/m-K were studied as bounding situations on the thermal conductivity. Starting with a thermal conductivity of 0.5 W/m-K, we assume the laser profile stays the same as the 3 W/m-K case. When this case is run with the RadHeat code, it is found that the surface layer melts in approximately 26.5 ns. (Using an assumed melting temperature of 1550 ^{o}C) Obviously, this would not be a desired case, as the material needs to not melt during the ion extraction period. This means that the laser pulse would need to be modified to accommodate the low thermal conductivity. This analysis is not done in this report, but note that changing the laser input profile is easily done and also easily modeled in the RadHeat code. For the second case, the material was run with a thermal conductivity of 7

W/m-K. Figure 1.5 below shows the results from this run. Notice that the temperature of the surface never reaches the desired 1200 ^{o}C. Obviously, this is due to the large thermal conductivity removing the heat from the surface layer before the laser can heat the surface to above the desired temperature. Again, the laser pulse amplitude can be tuned in order to reach the desired temperature for the range of times interested, but this exercise is simple, and not done in this analysis.

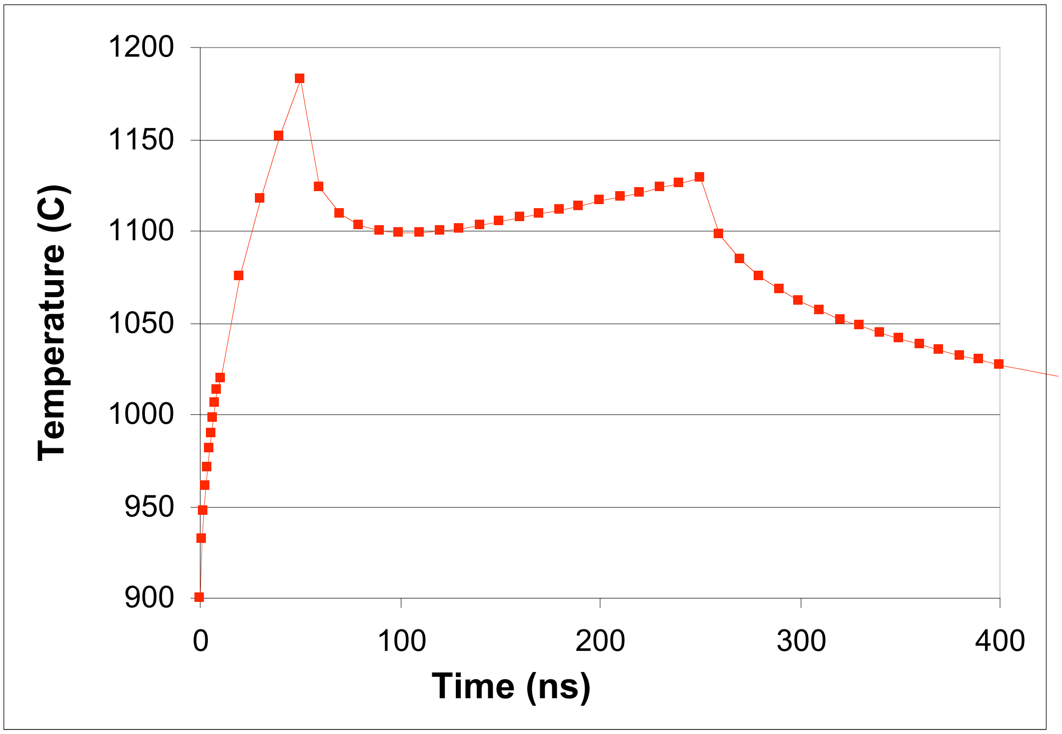

Figure 1.5 – Temperature versus time history of the ceramic surface with a thermal conductivity of the ceramic set to 7 W/m-K.

Conclusions

A study has been conducted at LLNL to understand the thermal response of a potassium-doped aluminosilicate layer mounted on a thick tungsten plate when hit with a laser pulse. It has been proposed that the brightness of the ion source could be increased with flash heating of the surface of the ceramic. The RadHeat code that was developed at LLNL allows us to accurately model the effects of the photon deposition on the temperature of the ceramic layer. Using total laser energy of ~1 J on a spot of radius ~ 5 cm we can raise the temperature of the surface above 1200 ^{o}C for a few hundred nanoseconds. These energies are easily obtained with lasers currently available. Also, the temperature of the interface between the ceramic and the tungsten layer was examined. Results from the RadHeat code show that the interface temperature is raised only a fraction of a degree for a single pulse. Also, using varying material properties, we can show that the surface temperature of the ceramic layer can be changed dramatically. This tells us that if we wish to accurately model this situation using a code such as the RadHeat code, we need to more accurately understand the thermal properties of potassium-doped aluminosilicate.

Acknowledgements

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References:

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[2] D. E. Cullen, TART98*: A Coupled Neutron Photon, 3-D, Combinatorial Geometry, Time Dependent, Monte Carlo Transport Code*, UCRL-ID-126455, Rev. 2, Lawrence Livermore National Laboratory (1998).

[3] Private conversation with Dr. Jeffrey Latkowski, LLNL.