AMERICAN UNIVERSITY OF BEIRUT
الجامعة الأميركية في بيروت

NUMERICAL SIMULATION OF METALLIC SURFACES DURING PULSED LASER ABLATION FOR MICROTHRUSTERS

PRESENTED BY: CARL TAMERIAN – AUB
SUPERVISED BY: CHRISTOPHER NAHED – CEA, GHASSAN ANTAR - AUB

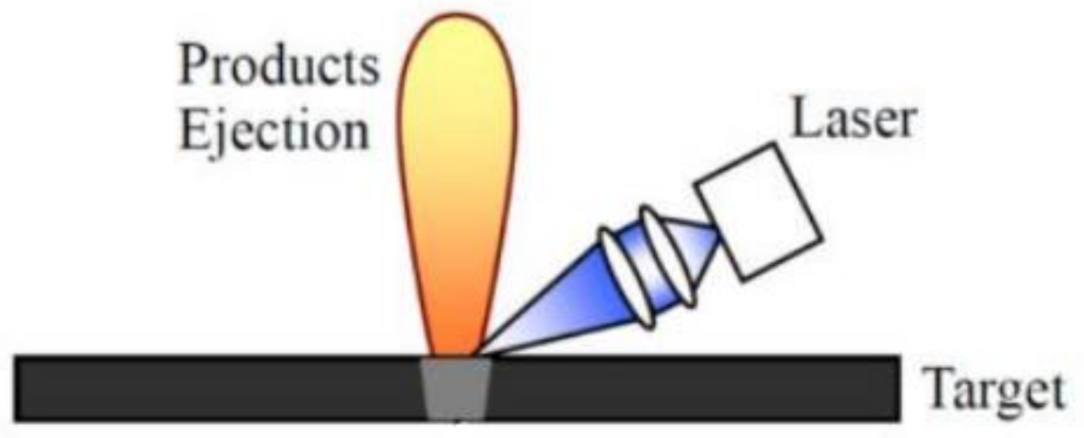
CLUB CAST3M - NOVEMBER 25, 2022

CONTENT

AMERICAN UNIVERSITY OF BEIRUT

1.1 OVERVIEW OF LASER ABLATION

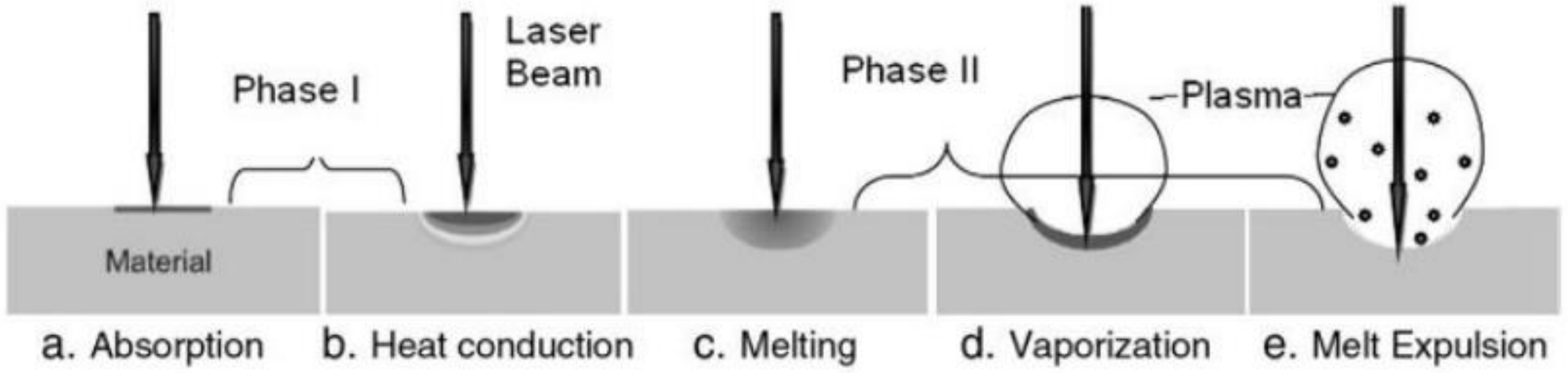
- Laser-induced mass removal from an irradiated zone of a target material.
- Causes rapid heating and phase change from solid to liquid to gas.
- Laser pulses are classified into ultrashort and nanosecond pulses.
- Used in various manufacturing fields including surface processing, welding applications; and aerospace propulsion technologies.



1.2 MICROTHRUSTERS BASED ON PULSED LASER ABLATION

- Microthrusters can provide very small and accurate thrust forces to maneuver microsatellites
- They are characterized by their small volume and mass, low power requirements, and high specific impulse
- Working principle:

- Energy from the laser photons heats up the irradiation zone causing rapid phase change from solid to liquid to gas.
- The gas transforms into plasma once the ionization energy is exceeded.
- The recoil force at the surface propels the system as per the momentum conservation principle.



2.1 GOVERNING EQUATIONS

- For nanosecond pulsed lasers, continuum heat transfer theories apply at this scale.
- Heat flux equation over a constant control volume **Ω**: $\rho(T)C_p(T)\frac{\partial T(x,y,z,t)}{\partial t} - \nabla \cdot [k(T)\nabla T(x,y,z,t)] = Q(x,y,z,t)$
- Heat input absorbed by the material: $Q(x,y,z,t) = \alpha(1-R)I_s(x,y,t)e^{-\alpha z}$
- Boundary conditions:

- Initial condition: $T(x,y,z,0)_{\Omega} = T_0$

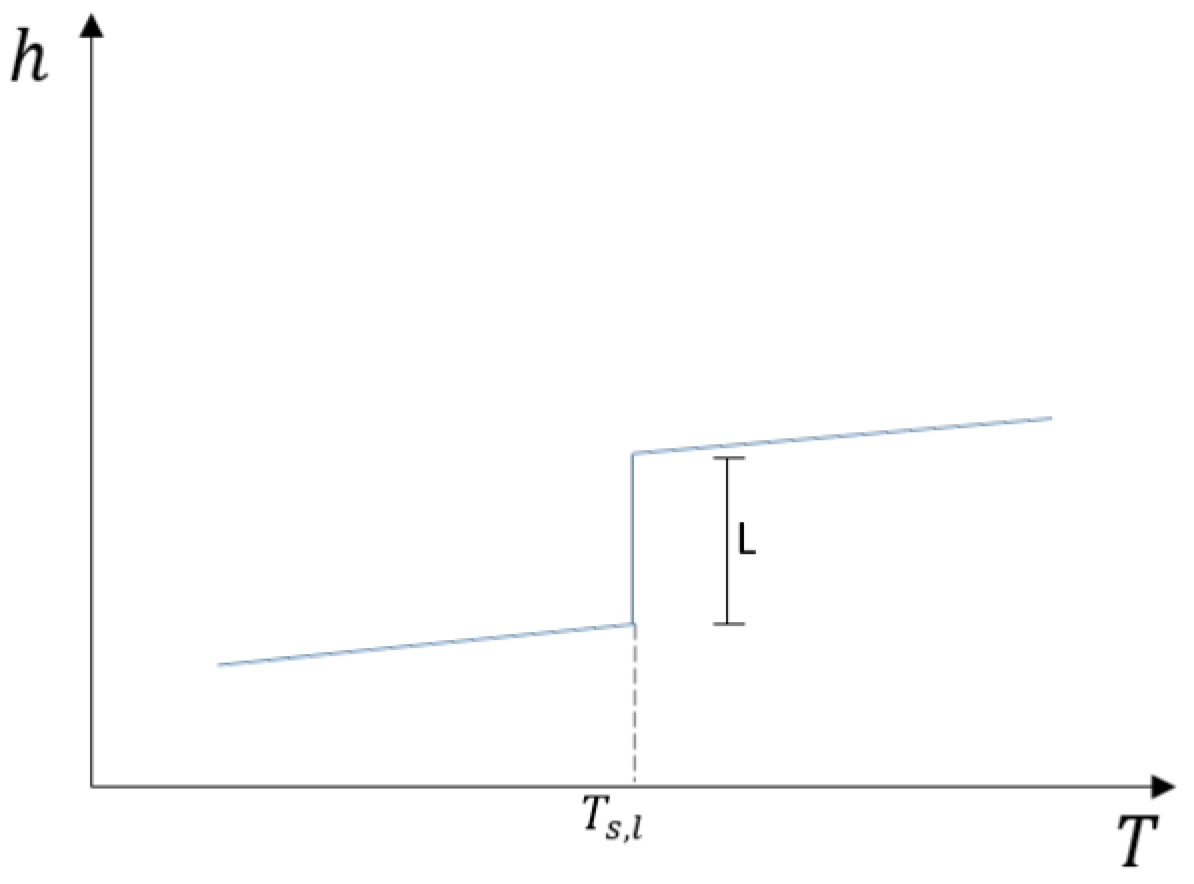
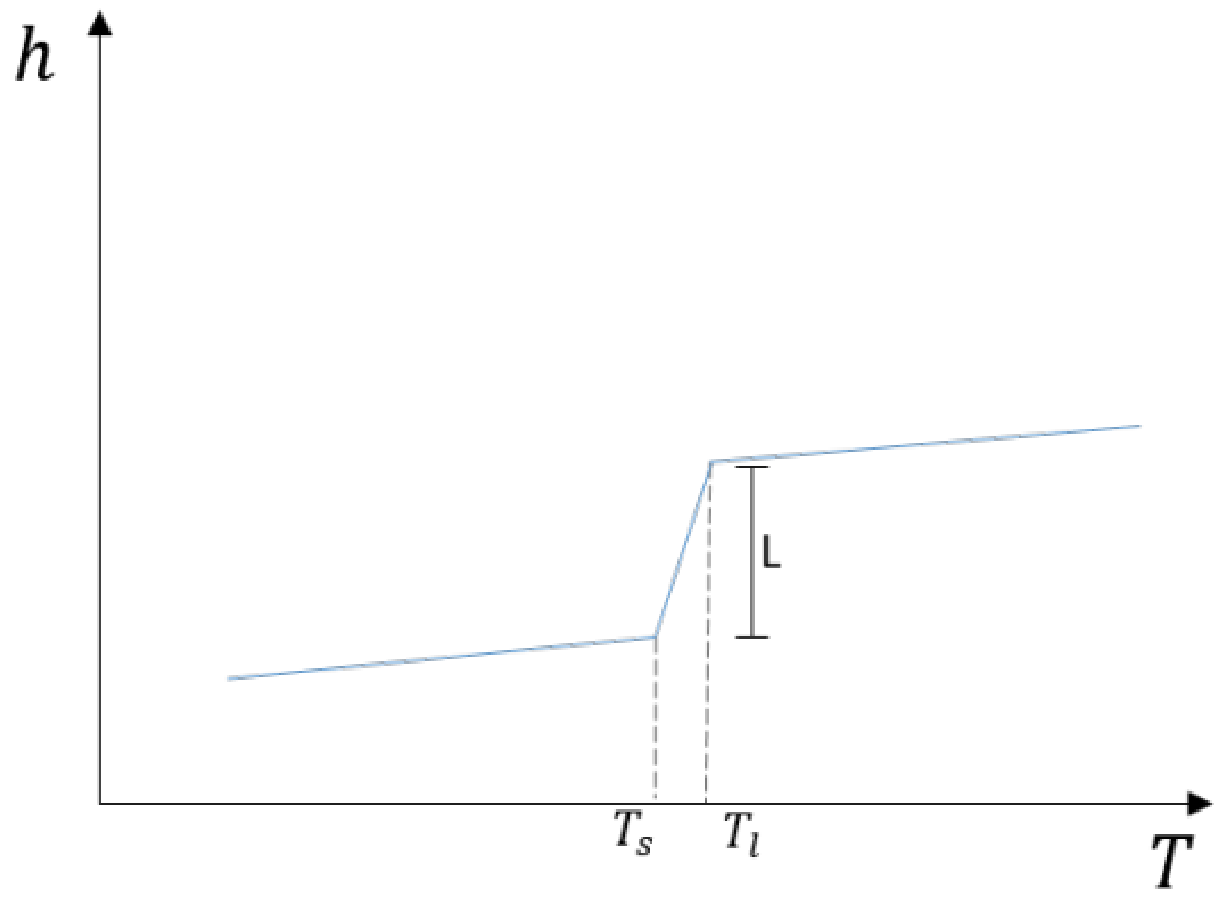
- Radiation at upper surface: $(-\lambda\nabla T \cdot n)_{\partial\Omega} = \epsilon(T)\sigma(T^4 - T_{\infty}^4)$

- Adiabatic at other surfaces: $(-\lambda\nabla T \cdot n)_{\partial\Omega} = 0$

- OR isothermal at other surfaces: $T(x,y,z,t)_{\partial\Omega} = T_0$

AMERICAN UNIVERSITY OF BEIRUT

2.2 SOLID – LIQUID PHASE CHANGE

Isothermal Phase Change	Phase Change over Mushy Zone
	
For idealized materials and pure metals	For metals with impurities or alloys
$h(T) = \begin{cases} \int_{T_0}^{T_{s,l}} C_{p,s}(T)dT, & \text{for } T < T_{s,l} \\ \int_{T_0}^{T_{s,l}} C_{p,s}(T)dT + L_f + \int_{T_{s,l}}^{T} C_{p,l}(T)dT & \text{for } T \geq T_{s,l} \end{cases}$	$h(T) = \begin{cases} \int_{T_0}^{T_s} C_{p,s}(T)dT, & \text{for } T \leq T_s \\ \int_{T_0}^{T_s} C_{p,s}(T)dT + \int_{-\infty}^{T} \frac{dL_f}{dT}dT & \text{for } T_l < T < T_s \\ \int_{T_0}^{T_s} C_{p,s}(T)dT + L_f + \int_{T_l}^{T} C_{p,l}(T)dT & \text{for } T > T_l \end{cases}$

AMERICAN UNIVERSITY OF BEIRUT

2.3 ONCE ABLATION IS INITIATED

- Once the boiling point of the material is exceeded, ablation is initiated, and surface material is removed.
- Depending on the laser intensity, ablation might be due to surface evaporation alone or coupled with phase explosion.
- The ablation rate (recession velocity) due to surface evaporation is represented by the Hertz-Knudsen relation:

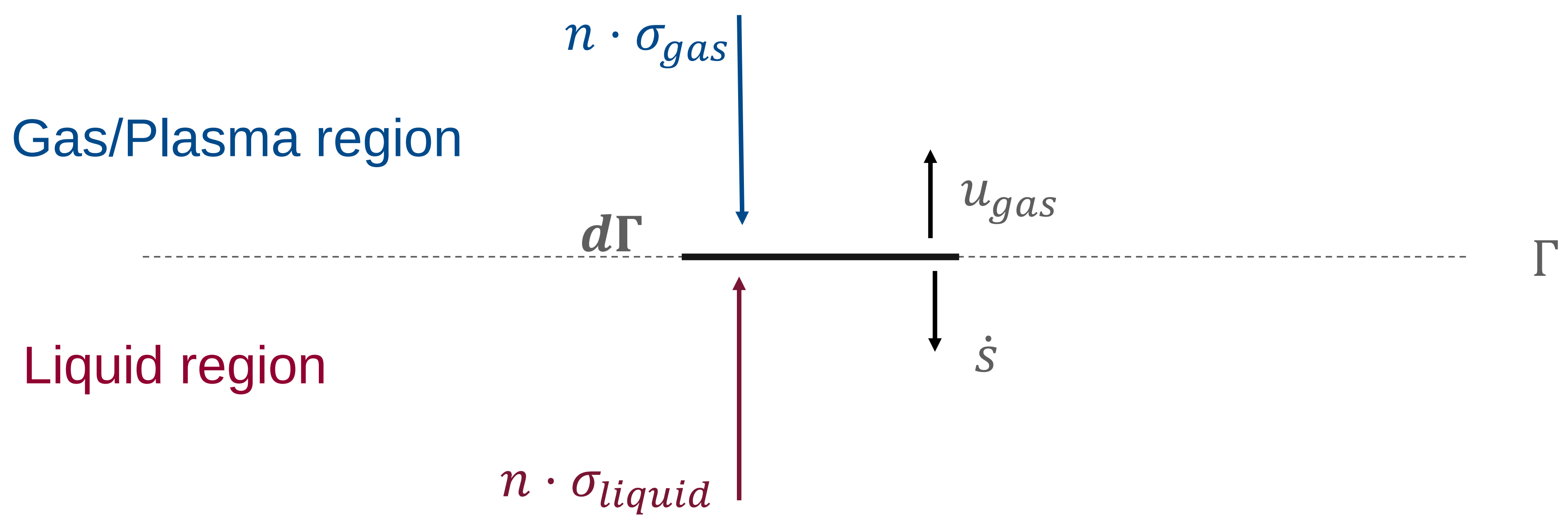
$$\dot{s} = \frac{\beta}{\rho}\sqrt{\frac{m}{2\pi k_b T_s}} p_{vap}$$

$$p_{vap} = P_b \exp\left[\frac{m L_v}{k_b}\left(\frac{1}{T_b} - \frac{1}{T_s}\right)\right]$$

- Ablation depth is calculated by integrating the ablation rate over time

AMERICAN UNIVERSITY OF BEIRUT

2.4 RECOIL FORCES



- The total recoil momentum is due to two contributions: pressure exerted by gas/plasma plume on the material and the pressure at the gas/liquid interface.

$$M_{rec} = \int \int P_{rec}\, dAdt, \text{ where } P_{rec} = P_v + P_{ev} - P_\infty$$

- The pressure is discontinuous at the liquid-gas interface
- Using the momentum conservation equation across $d\Gamma$:

$$\left(\rho.u.(u.n)\right)_{gas} - \left(\rho.u.(u.n)\right)_{liquid} = (\sigma_{gas} - \sigma_{liquid}).n$$

$$where\ \sigma = -P\mathbb{I} + \mu\left(\nabla u + \nabla^T u - \frac{2}{3}\nabla \cdot u\right)$$

$$\sigma_{gas} = -P_{gas}\mathbb{I} \quad (\mu \approx 0)$$

$$\sigma_{liquid} = -P_{liquid}\mathbb{I} \quad (u \approx 0)$$

$$\therefore F_{rec,ev} = \rho_{gas} u_{gas}^2$$

- Applying the mass conservation equation along $d\Gamma$: $u_{gas} = \frac{\rho_{liquid}\dot{s}}{\rho_{gas}}$

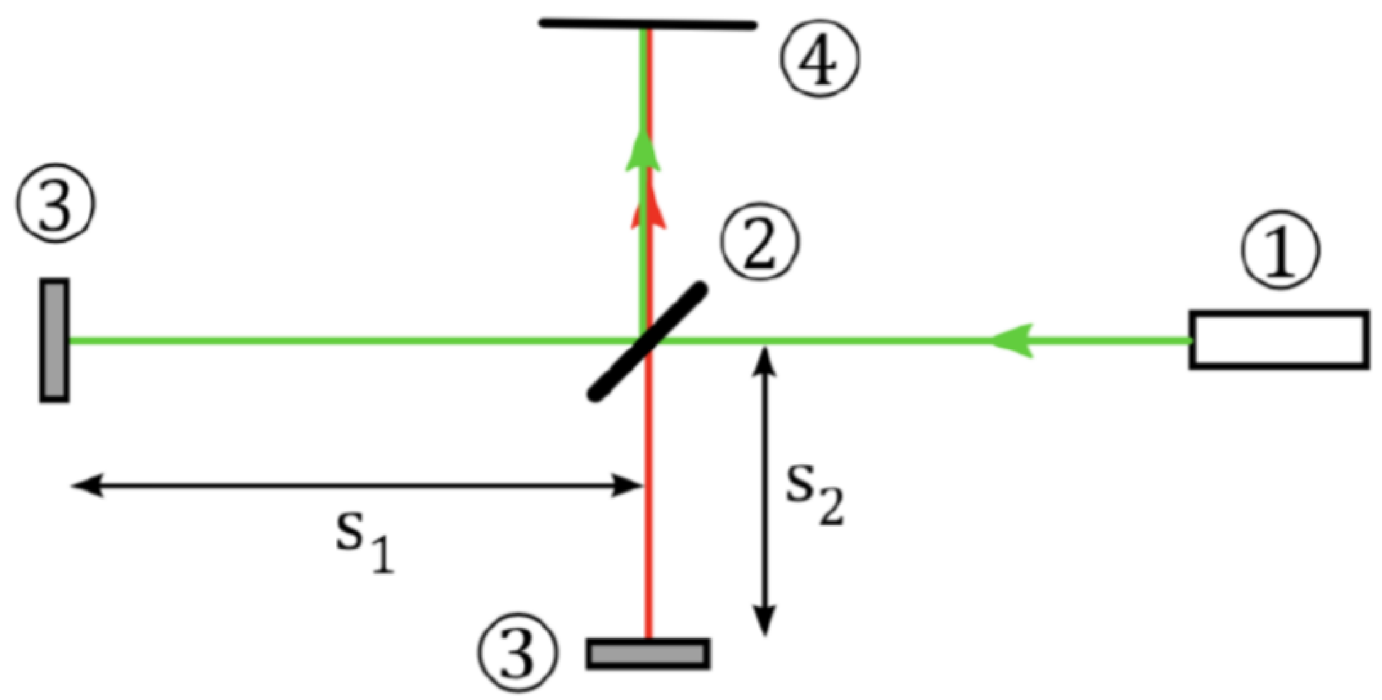
3.1 INTRODUCTION TO NUMERICAL METHODS

- Difficulty obtaining analytical solutions of our heat transfer model due to:
- Complex material – laser – plasma interactions
- Phase change
- Thermophysical properties of the material are temperature dependent
- Use of FEM to discretize the heat equation in space and time

4.1 OVERVIEW OF OUR PROJECT

- Goals: Compute the ablation depth, the recoil force at the interface, and select the optimal material.
- Numerical model: Simulate the ablation phenomenon on *CAST3M*
  - Obtain the temperature evolution profiles at critical points while accounting for phase change
  - Account for material removal once ablation is initiated
  - Compute the ablation depth and recoil force
  - Compare the performance of three metals: lead, copper, and aluminum
- Experimental model: Conduct the PLA experiment at AUB Physics department – Fluid dynamics & Plasma lab
  - Measure the crater size to validate the numerical model
  - Measure the recoil force using an interferometer

4.2 EXPERIMENTAL MODEL

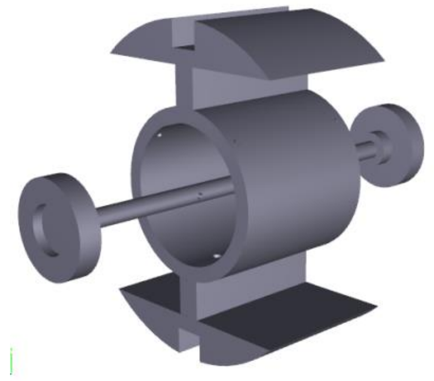


➢ Interferometer:

- Sensor that measures micronewton thrust by measuring the speed or displacement of the target.
- The splitting and recombination of beams results in an interference pattern.
- A high-speed camera captures the interference pattern to analyze the central fringe intensity and direction in which the fringes are moving.
- The absolute displacement could be calculated from the phase shift of the sinusoidal mapping of the intensity.

➢ Setup:

- Vacuum chamber: lower tube connected to vacuum pump; right tube holds the pendulum with the target at the center; other tubes for observation purposes.
- Pendulum stand which holds the mirror on one end and the target material is on the other.



4.3.1 NUMERICAL MODEL: CONDITIONS

- The material has a volume of 1mm * 1mm * 10μm
- 2D simulation in x and z with material size of 0.5mm * 10μm
- Mesh size: 1.25μm along the horizontal, variable 10nm – 500 nm along the vertical
- Timesteps: 5e-12 s
- Initial Boundary condition: $\boldsymbol{T(x,z,0) = T_0}$
- Adiabatic boundary conditions:

$$\begin{cases} -k \left.\dfrac{\partial T}{\partial x}\right|_{x=l} = 0 \\ -k \left.\dfrac{\partial T}{\partial x}\right|_{x=0} = 0 \\ -k \left.\dfrac{\partial T}{\partial x}\right|_{z=0} = 0 \end{cases}$$

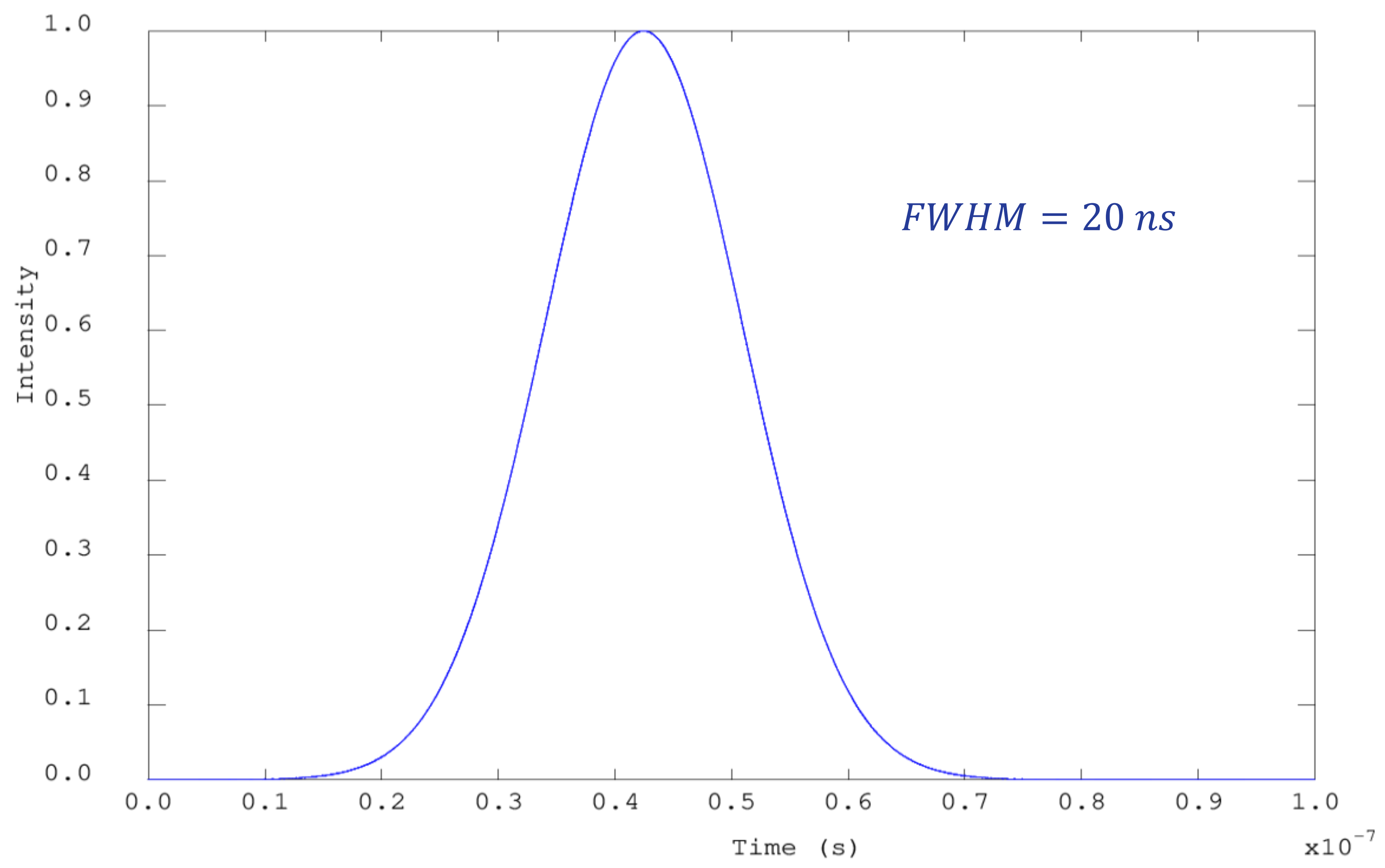
4.3.2 LASER PROFILE

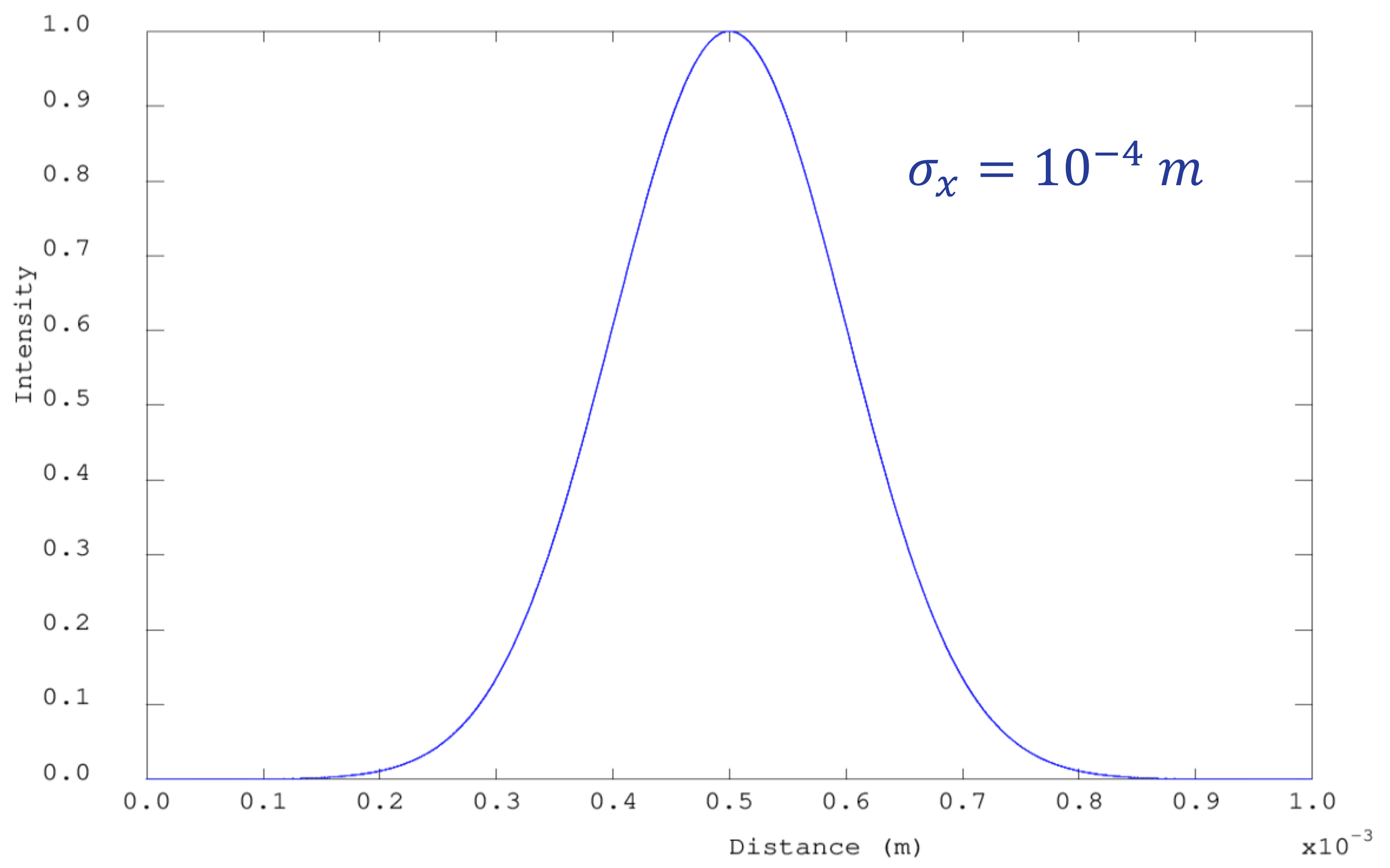
$$Q(x,y,z,t) = \alpha(1-R)I_s(x,y,t)e^{-\alpha z}$$

- Assuming that the laser irradiance is equivalent to the laser intensity
- UV laser with $\lambda = 308\ nm$
- The laser intensity can be fitted into a Gaussian distribution which varies exponentially in space and time

$$I_s(x,y,t) = I_0 e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} e^{-\frac{(y-y_0)^2}{2\sigma_y^2}} e^{-\frac{(t-t_0)^2}{2\sigma_t^2}}$$

- Given the energy per pulse: $I_0 = \frac{E}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_t}$
- A laser with a smaller irradiation radius or smaller FWHM results in a larger intensity

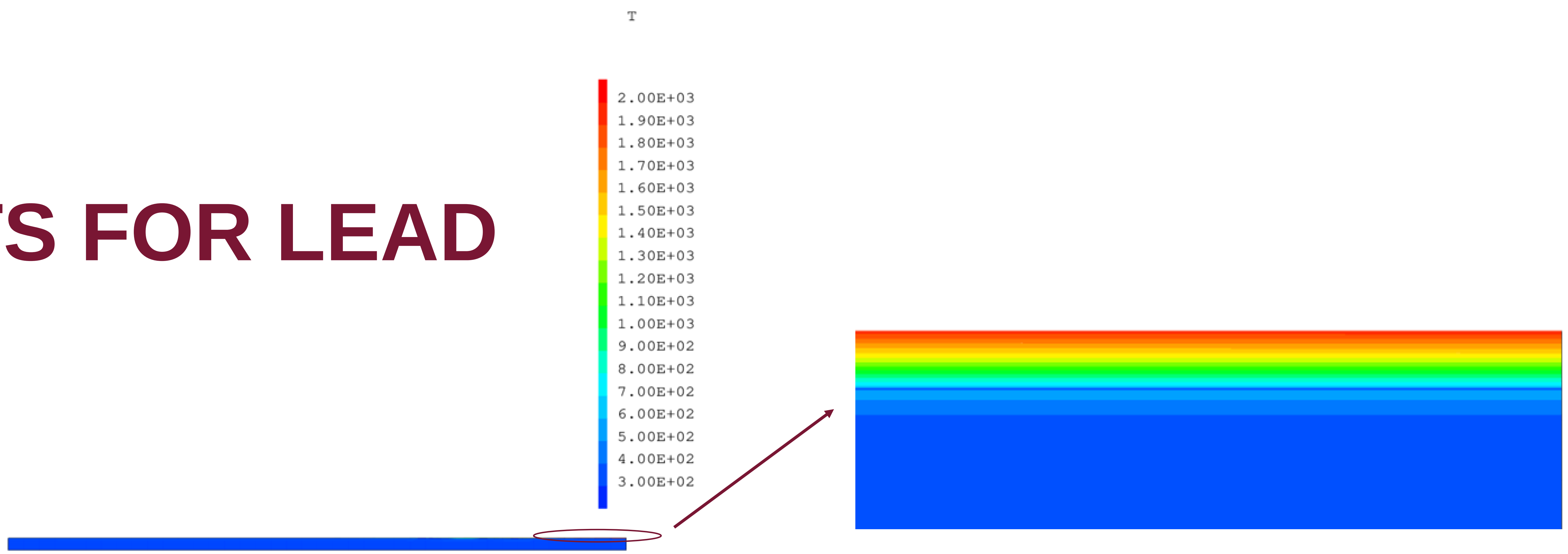


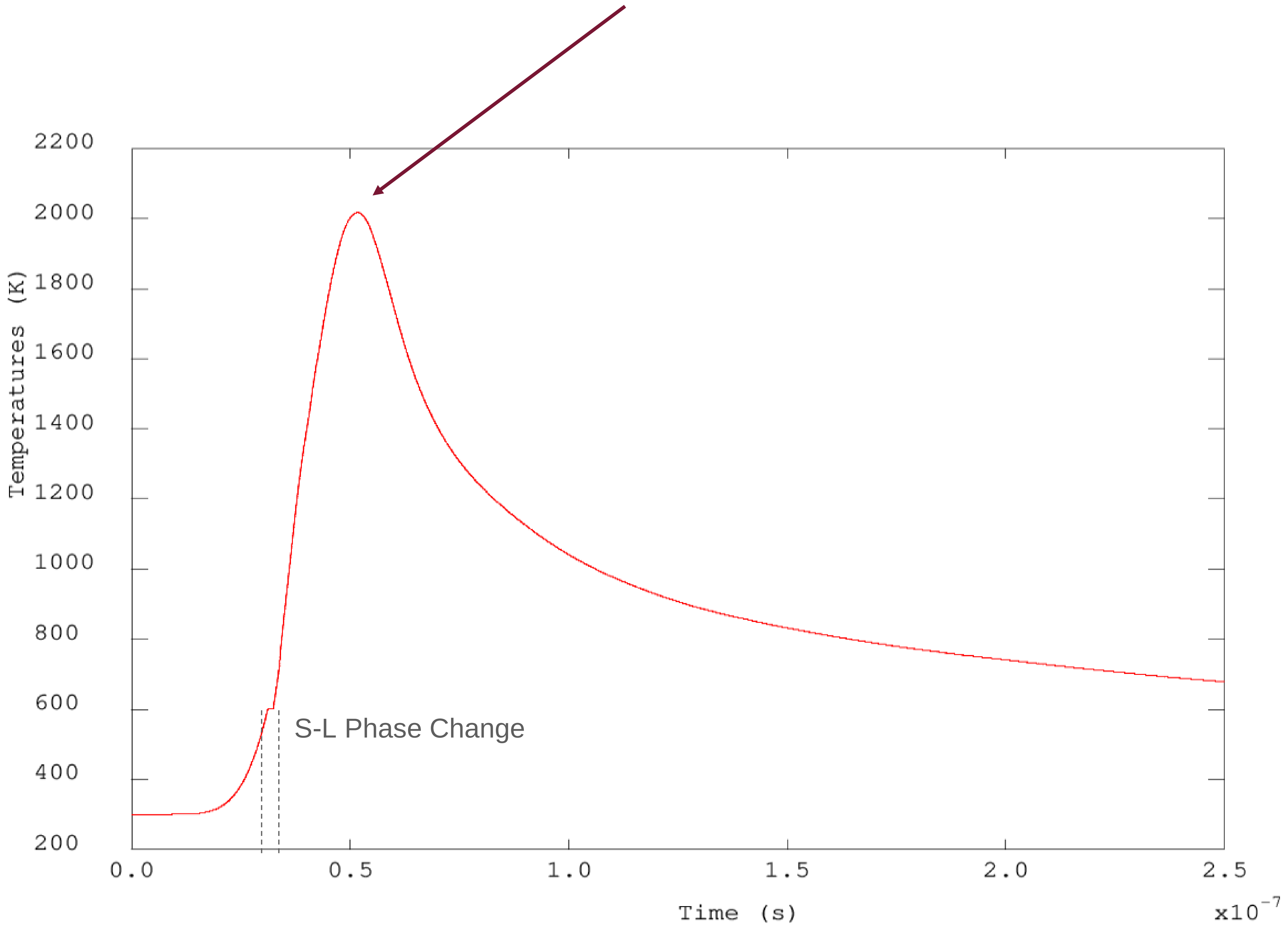


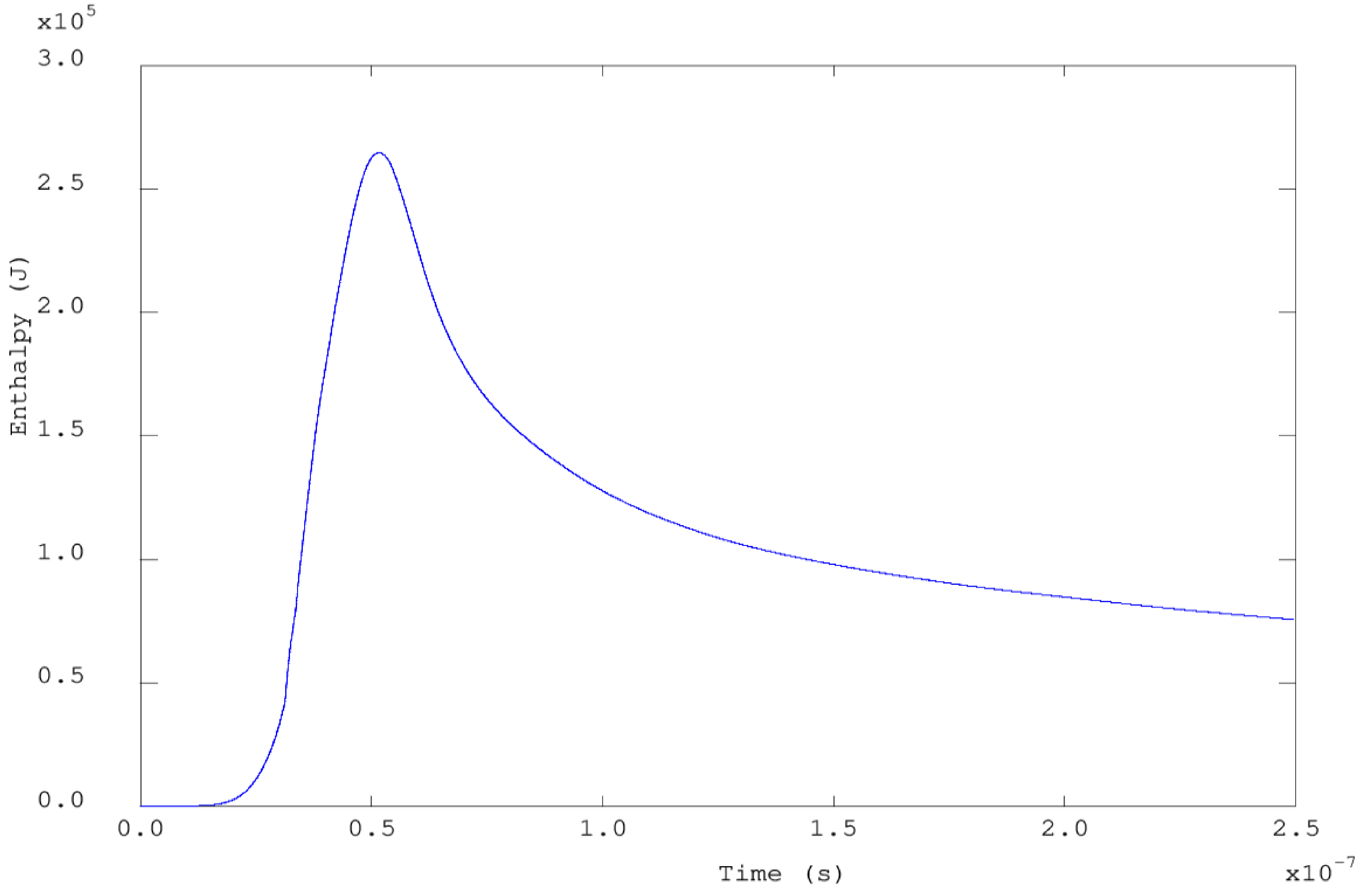
4.3.3 THERMOPHYSICAL AND OPTICAL PROPERTIES OF DIFFERENT METALS

	LEAD	ALUMINUM	COPPER
$\alpha\ (m^{-1})$	$1.148 * 10^{-8}$	$1.5025 * 10^{-8}$	$1.0168 * 10^{-8}$
R	0.8917	0.927	0.522
$T_m\ (K)$	600.61	933.61	1357.77
L_m (J)	$2.32 * 10^4$	$3.96 * 10^5$	$2.04 * 10^5$
$\rho\ (kg.m^{-3})$	$\begin{cases} 11345 - 0.959(T - 293.15) - 3.715 * 10^{-5}(T - 293.15)^2, & T < T_m \\ 10651 - 1.262(T - T_m) + 4.62(T - T_m)^2, & T > T_m \end{cases}$	$\begin{cases} 2700, & T < 600 \\ 2648 + 0.332\,T - 4.99 * 10^{-4}T^2, & 600 < T < T_m \\ 2670 - 0.267 * T, & T_m < T < 2000 \end{cases}$	$\begin{cases} 8810 - 0.428(T - 293) - 6.12 * 10^{-5}(T - 293)^3, & T < T_m \\ 9109.7077 - 0.8194 * T, & T > T_m \end{cases}$
$C_p(J.kg^{-1}.K^{-1})$	$\begin{cases} 116.41 + 4.24 * 10^{-2}\,T - 3.32 * 10^{-5}\,T^2, & T < T_m \\ 167.72 - 3.92 * 10^{-2}\,T + 1.307 * 10^{-5}T^2, & T_m < T < 1500 \\ 210.367 - 9.609 * 10^{-2}T + 3.203 * 10^{-5}T^2, & 1500 < T < 2400 \end{cases}$	$\begin{cases} 643.9 + 0.5203 * T, & T < T_m \\ 1160, & T > T_m \end{cases}$	$\begin{cases} 370.87 + 0.108 * T - 4.649 * 10^{-5}T^2 + 2.8045T^3, & T < T_m \\ 527.872, & T > T_m \end{cases}$
$k(W.m^{-1}.K^{-1})$	$\begin{cases} 35.49 - 1.82 * 10^{-2}(T - 293.15), & T < T_m \\ 9.2 + 0.011 * T, & T > T_m \end{cases}$	$\begin{cases} 226.67 + 0.033 * T, & T < 400 \\ 226.67 - 0.055 * T, & 400 < T < T_m \\ \frac{1}{12.47 + (1.36 * 10^{-2} * T)} * 2.45 * T, & T > T_m \end{cases}$	$\begin{cases} 418.775 - 0.075 * T, & T < T_m \\ 89.7 + 0.04976 * T, & T > T_m \end{cases}$

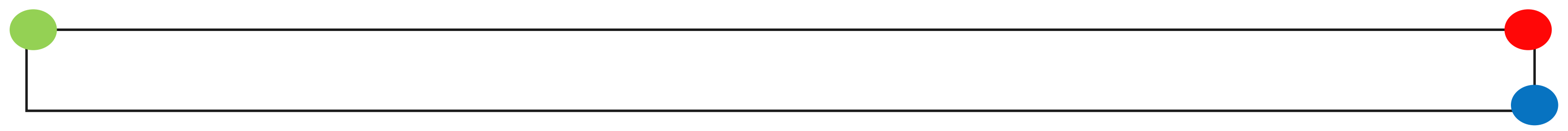
5.1 RESULTS FOR LEAD

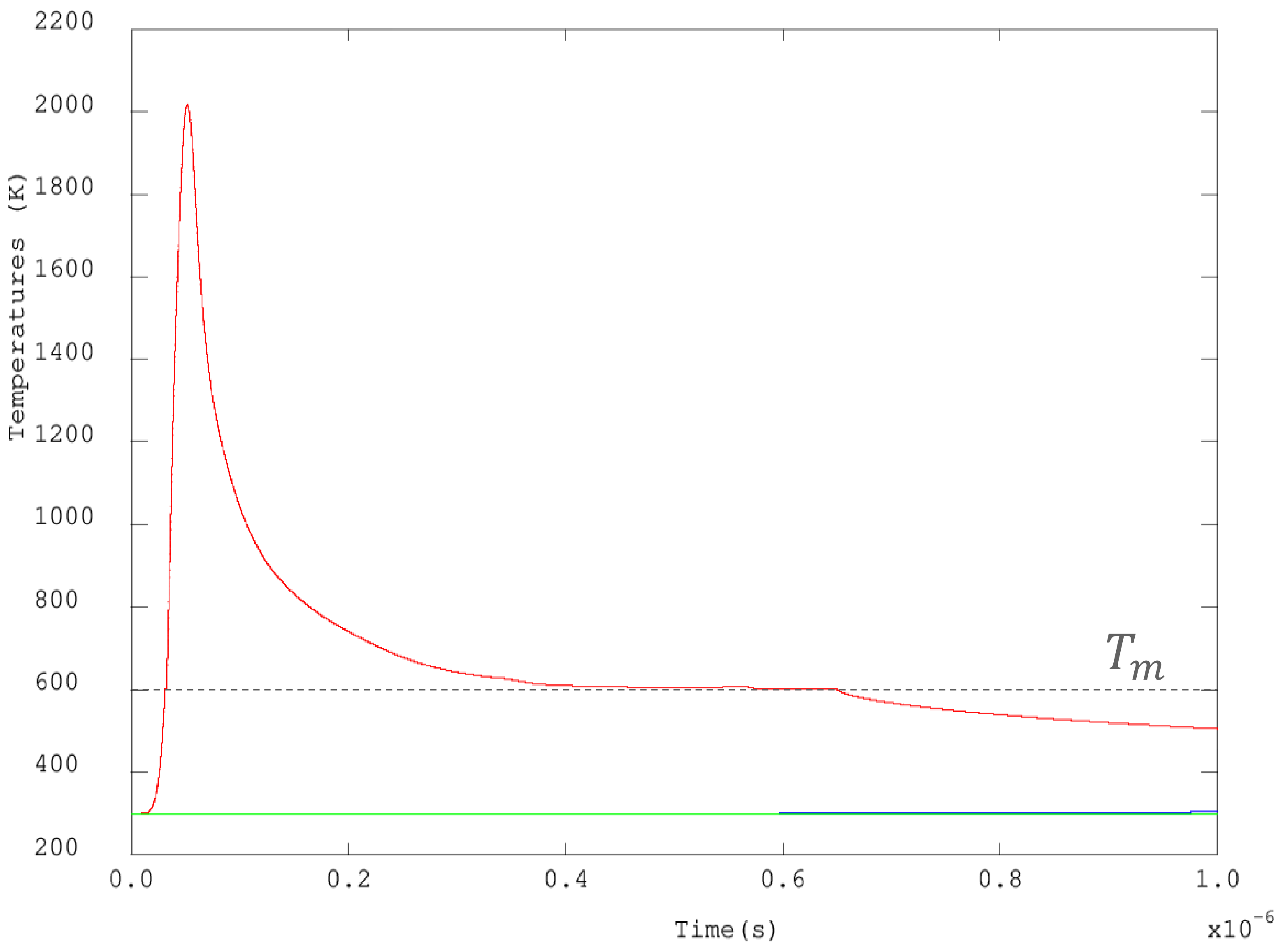




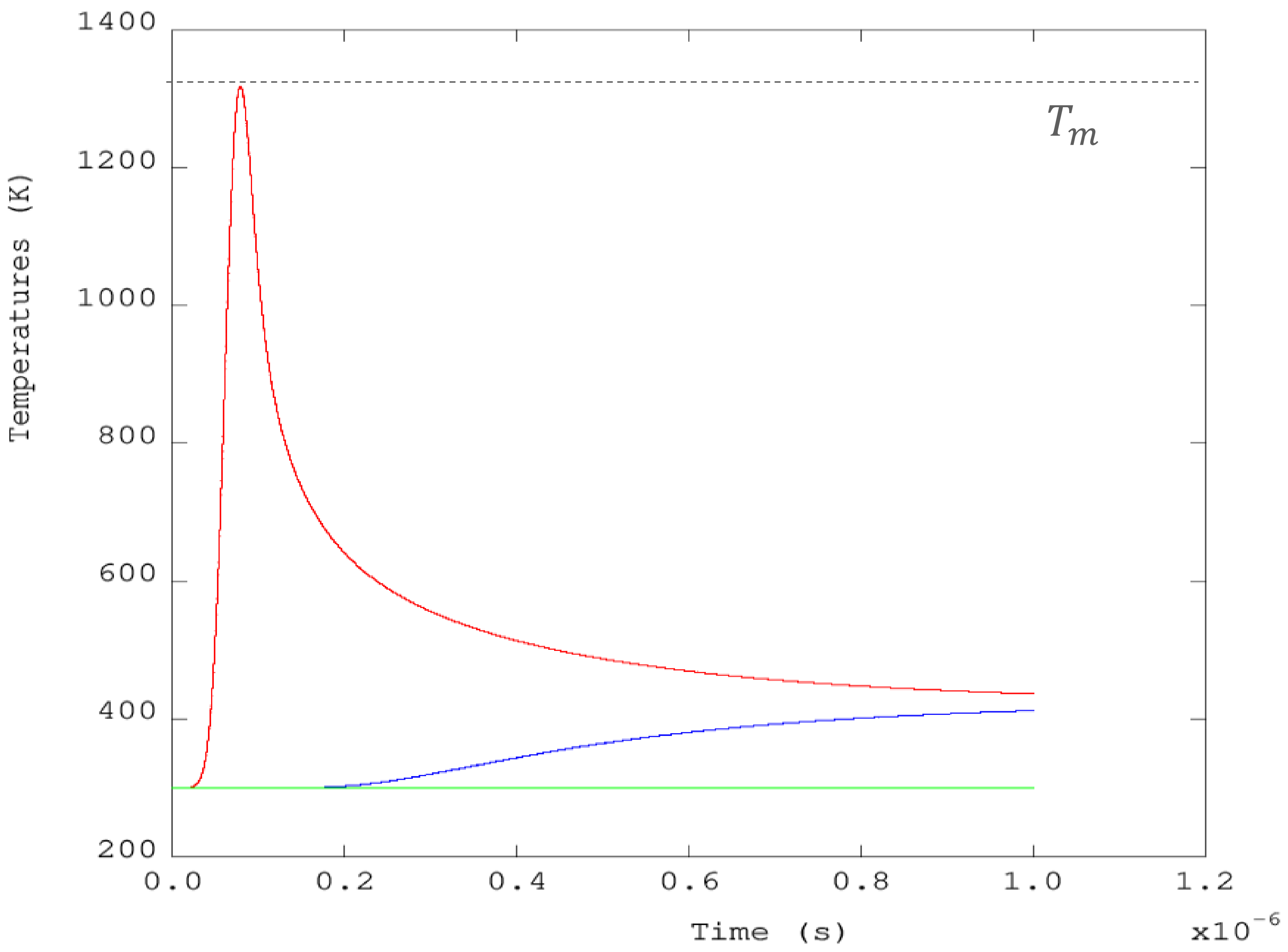


5.2 COMPARISON OF TEMPERATURE CURVES OF LEAD, COPPER, AND ALUMINUM

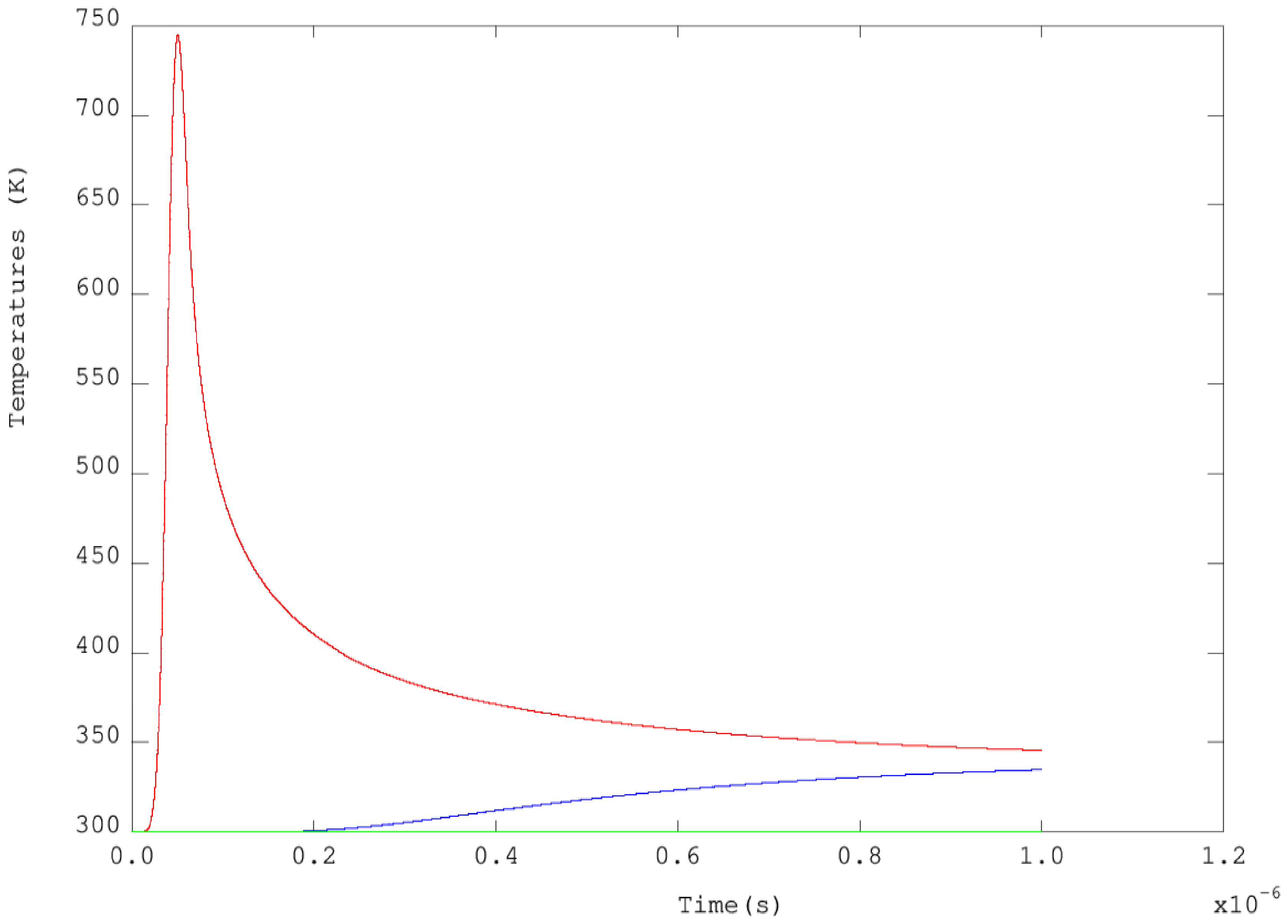




LEAD



COPPER



ALUMINUM

6.1 CONCLUSIONS

- Lead proves to have the optimal performance among copper and aluminum.
- Thermal Response:

- $T_{m,Pb} < T_{m,,Al} < T_{m,,Cu}$
- $L_{m,Pb} < L_{m,Cu} < L_{m,Al}$
- $k_{Pb} < k_{Al} < k_{Cu}$
- $(Fo)_{Pb} < (Fo)_{Al} < (Fo)_{Cu}$, where $Fo = \frac{\alpha t}{L_c^2}$ represents the heat conduction through the material relative to the heat stored

- Recoil Force and Ablation Rate:

- $\rho_{Pb,gas}$ is the largest which results in a larger recoil force at the interface
- m_{Pb} is the largest which results in the greater ablation rate

6.2 FUTURE WORK

- Verifying the results obtained via comparison with other time-integrator programs
- Adding radiation as a boundary condition on the upper surface
- Accounting for the gas phase and material removal
- Calculating the instantaneous ablation rate to compute the ablation depth
- Computing the recoil force at the interface
- Comparing the simulation results with the experimental outcomes
- Level-set method to capture the solid, liquid, and gas/plasma phases simultaneously

THANK YOU