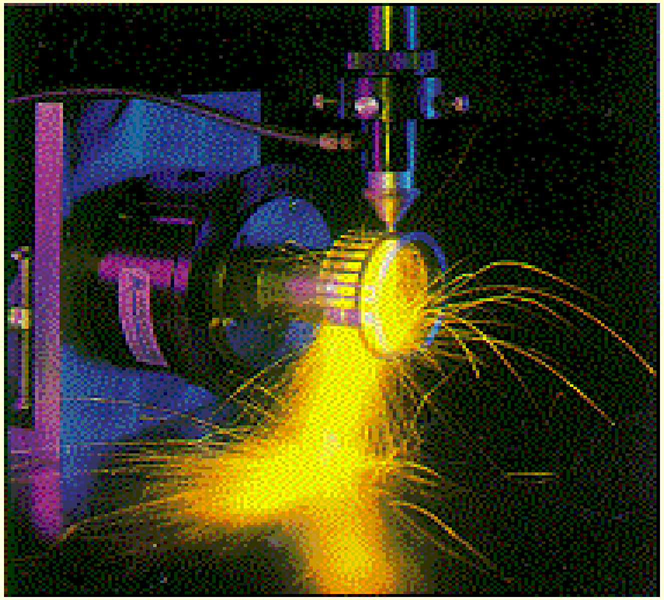
A Numerical Investigation of Laser Heating Including the Phase Change Process in Relation to Laser Drilling



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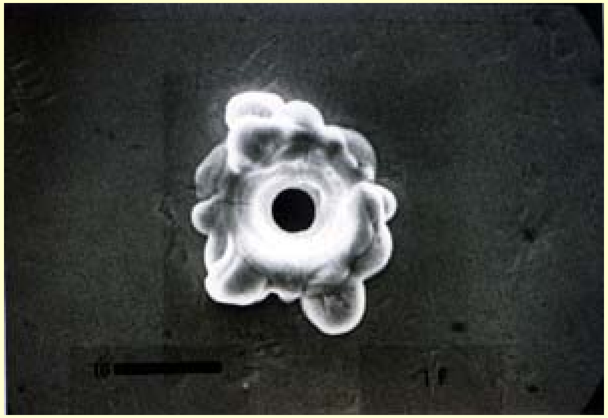
Overview:

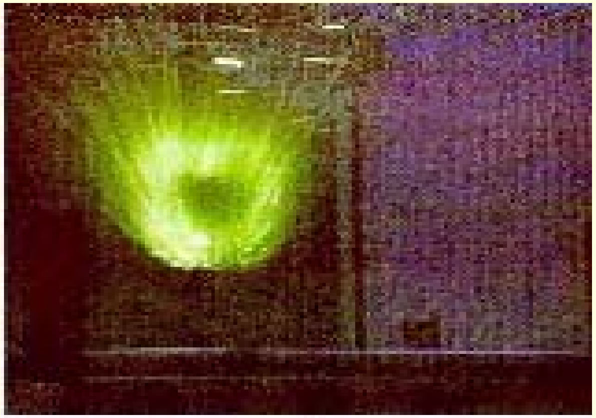
- **Introduction**
- **Laser material interaction**
- **Mathematical modeling**
- **Numerical solution**
- **Results & discussion**
- **Conclusions**

Why Laser Drilling?

- **Precision**
- **Robustness**
- **Versatility**
- **No physical contact**

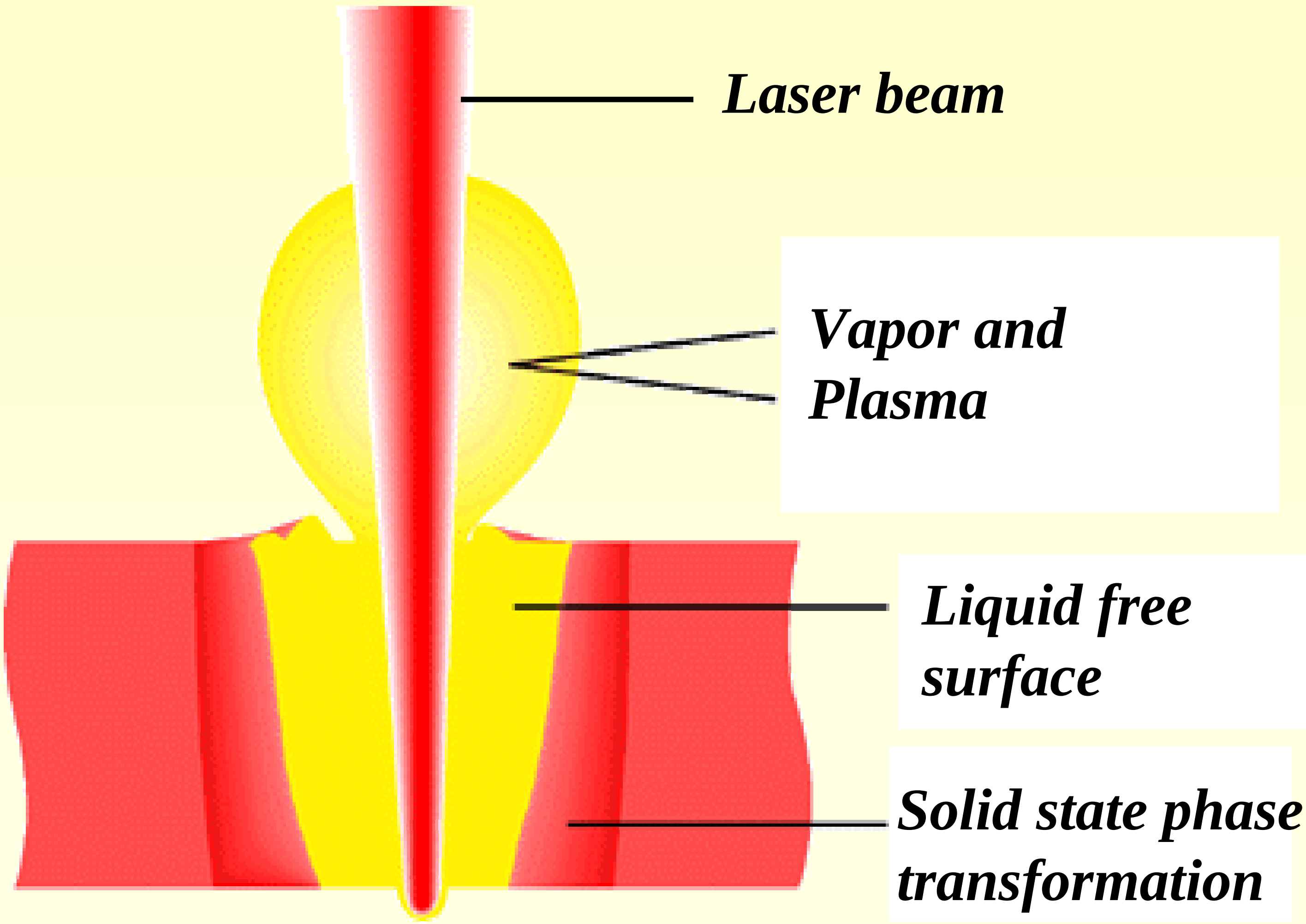


A 7μm dia. hole drilled by Laser



6 in. dia. hole with high energy Laser beam

Laser Material Interaction:



Schematic view of laser material interaction

Interaction Physics:

- **When a laser strikes the material, electrons in the near surface region absorb the energy.**
- **Electrons collide with the lattice and transfer this energy to the bulk of the material (electron relaxation).**
- **The temperature of the bulk starts rising.**
- **If the laser has enough energy the temperature can reach to the melting or even the boiling point.**
- **When material starts ablating from the surface a cavity is formed.**

Mathematical Modeling:

- **If the laser pulse length or the heating period is more than the electron relaxation time a Fourier heating model is applicable.**
- **The laser acts as a source term in the heating model.**
- **Because of the phase change it is a moving boundary problem.**
- **The model also needs to accommodate the shape change of the domain with surface ablation.**

Heating Models:

1. **Classical Phase Change Model-Stefan Problem.**

   Good for analytical solution.

   Cannot account for ablation.

2. **Energy method.**

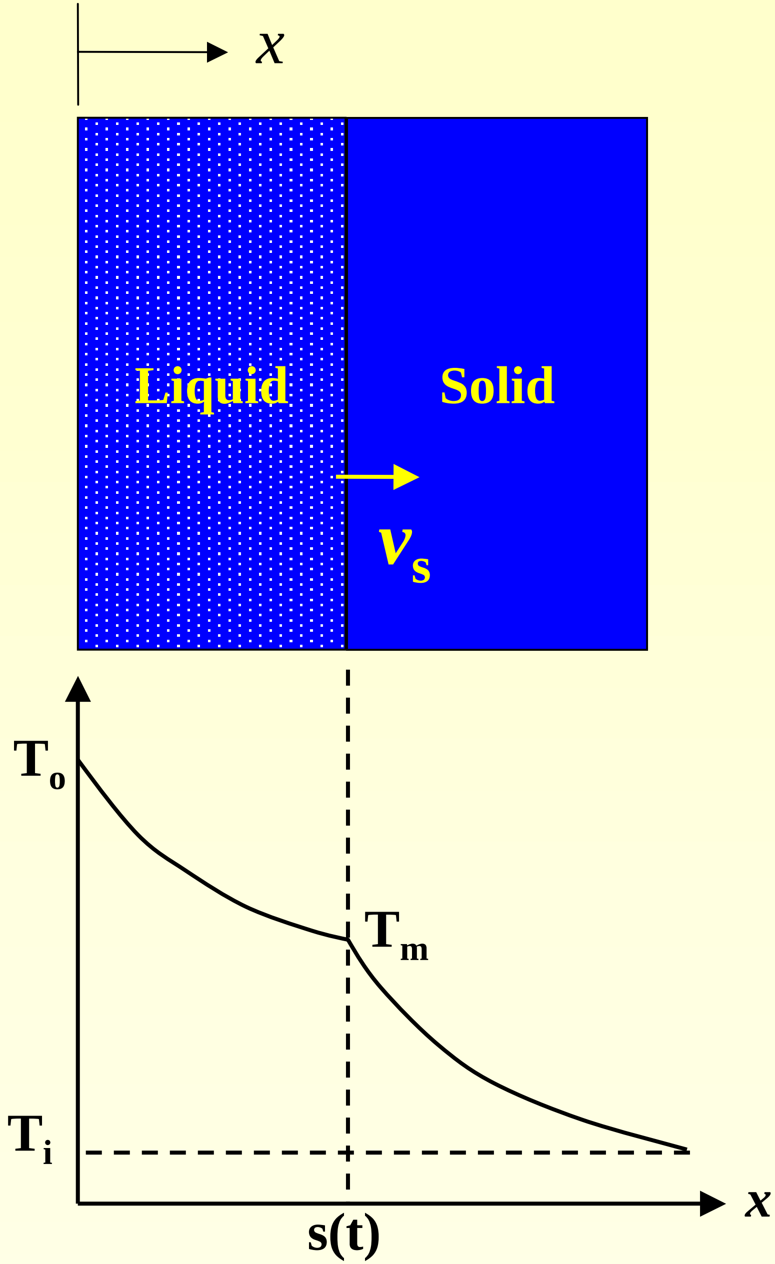
   Good for numerical solution.

   Can take care of ablation.

Stefan Problem:

Assumptions:

- **Unsteady heat transfer.**
- **Solid and liquid phases are separated by a sharp interface.**
- **The Fourier equation is applicable on the solid and liquid phases separately.**
- **The energy balance is being applied at the interface.**



T_m = Melting temperature

v_s = Interface velocity

T_o = Boundary temperature

T_i = Initial temperature

s(t) = Interface position

Phase change from solid to liquid with sharp interface

In solid phase:

$$\rho_s c_{ps} \frac{\partial T_s}{\partial t} = k_s \frac{\partial^2 T_s}{\partial x^2} \qquad 0 \le x \le s(t)$$

In liquid phase:

$$\rho_l c_{pl} \frac{\partial T_l}{\partial t} = k_l \frac{\partial^2 T_l}{\partial x^2} \qquad s(t) \le x \le \infty$$

At the interface:

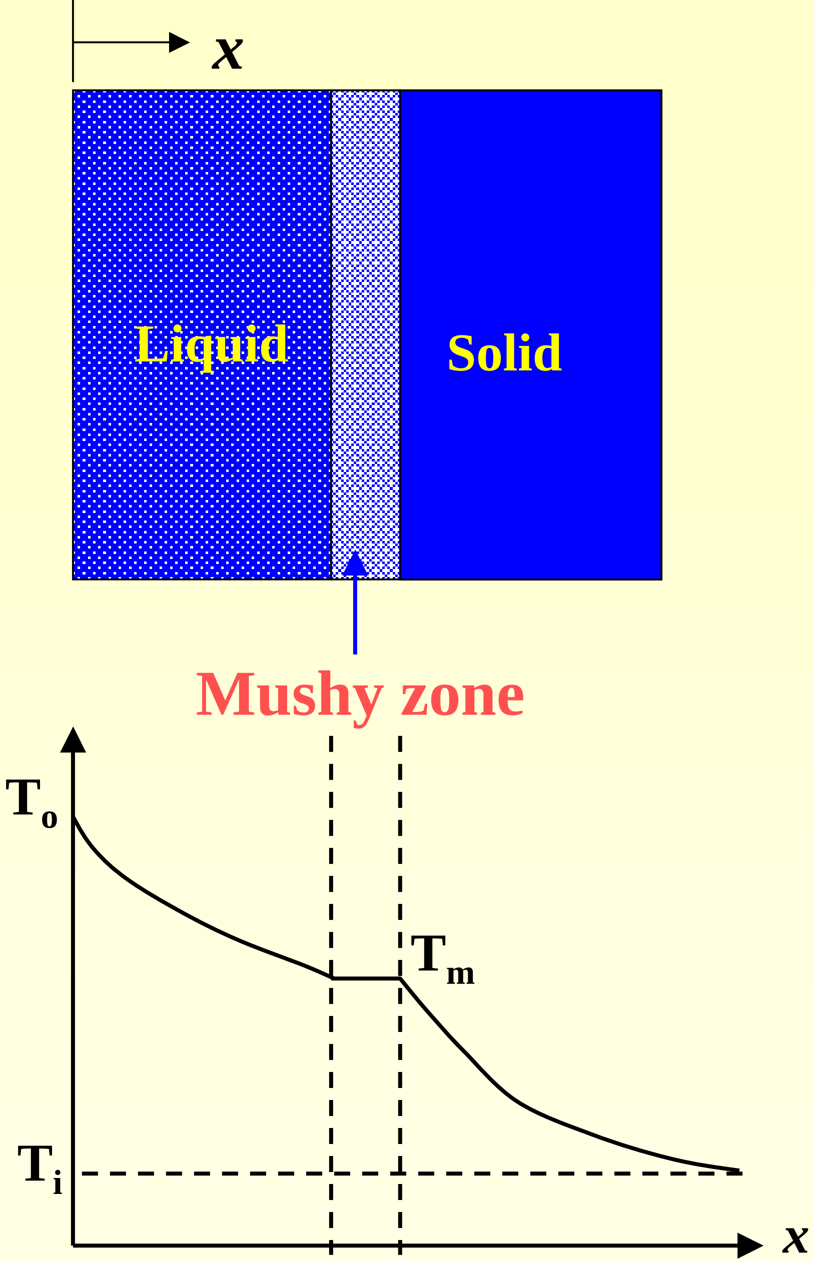
$$\begin{bmatrix} \text{Conduction heat} \\ \text{flux in positive } x \\ \text{direction through} \\ \text{liquid phase.} \end{bmatrix} + \begin{bmatrix} \text{Rate of heat} \\ \text{addition during} \\ \text{melting per unit} \\ \text{area of Interface.} \end{bmatrix} = \begin{bmatrix} \text{Conduction heat} \\ \text{flux in positive } x \\ \text{direction through} \\ \text{solid phase.} \end{bmatrix}$$

or $$k_s \frac{\partial T_s}{\partial x} - k_l \frac{\partial T_l}{\partial x} = \rho_s L v_s \quad \text{at} \quad x = s(t), \quad t > 0$$

Energy Method:

Assumptions:

- **Unsteady heat transfer.**
- **Solid-liquid or liquid-gas phases are separated by a region of considerable thickness called the ‘mushy zone’.**
- **The mushy zone is the mixture of two phases at the melting or boiling temperature.**
- **The energy balance is being applied on the mushy zone.**



Phase change from solid to liquid for energy method.

Laser drilling is axisymmetric heating.

For solid and liquid phases;

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r} \right) + k \frac{\partial^2 T}{\partial z^2} + S_o$$

Where;

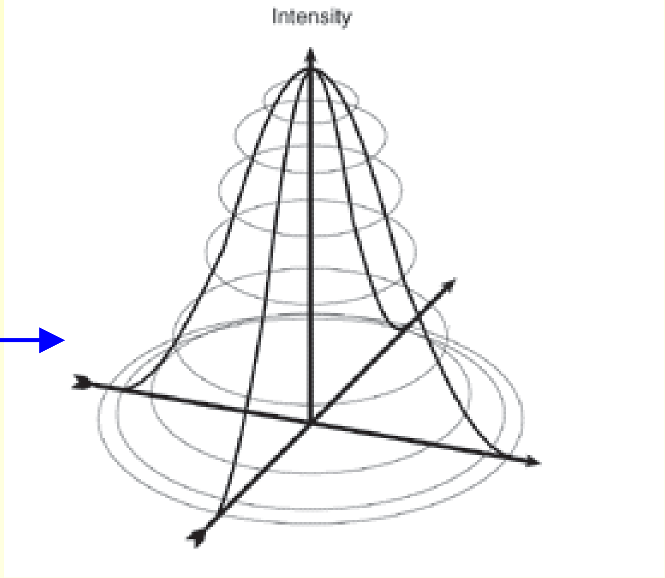
$$S_o = I_o \delta (1 - r_f) exp(-\delta z) exp\left(-\frac{r^2}{a^2} \right)$$

$I_o = Intensity$

$\delta = Absorption\ depth$

$r_f = Surface\ reflectivity$

$a = Gaussian\ parameter$



Laser intensity distribution

Energy balance for solid-liquid mushy zone;

$$\rho L_m \frac{\partial x_m}{\partial t} = \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + k\frac{\partial^2 T}{\partial z^2} + S_o$$

Energy balance for liquid-gas mushy zone;

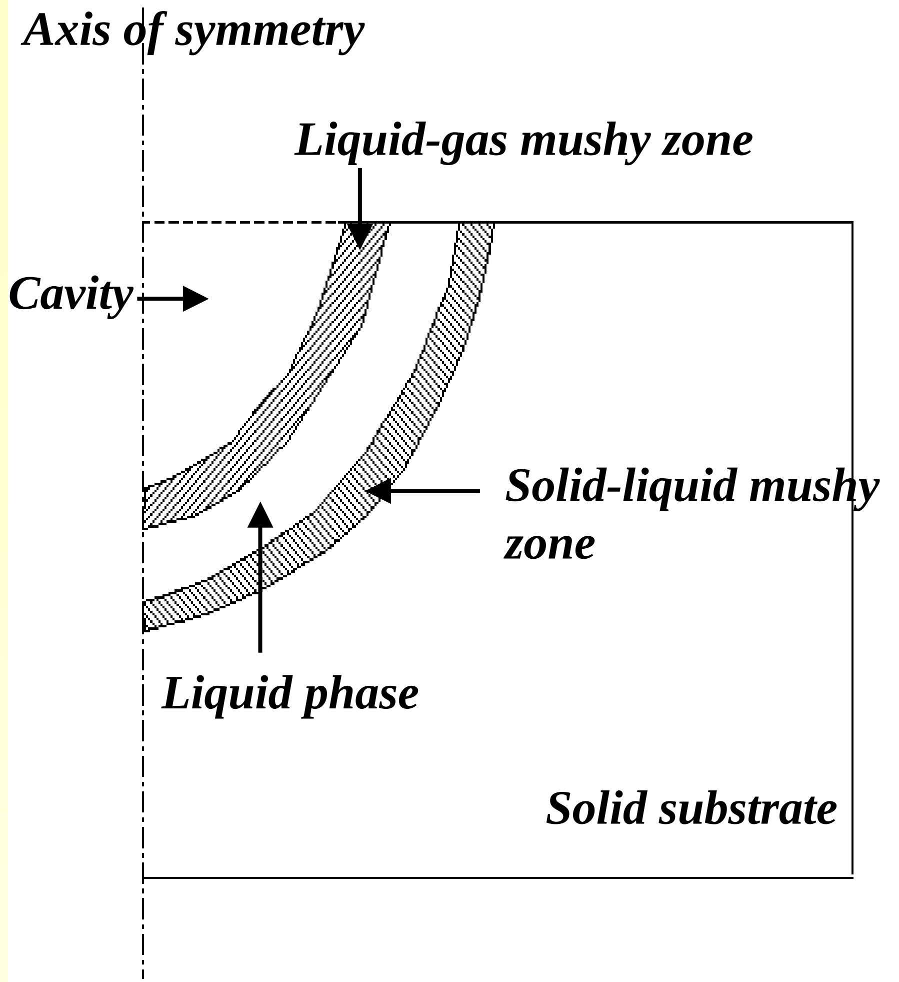
$$\rho L_b \frac{\partial x_b}{\partial t} = \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + k\frac{\partial^2 T}{\partial z^2} + S_o$$

L_m = *Latent heat of fusion*

x_m = *Liquid mass fraction*

L_b = *Latent heat of boiling*

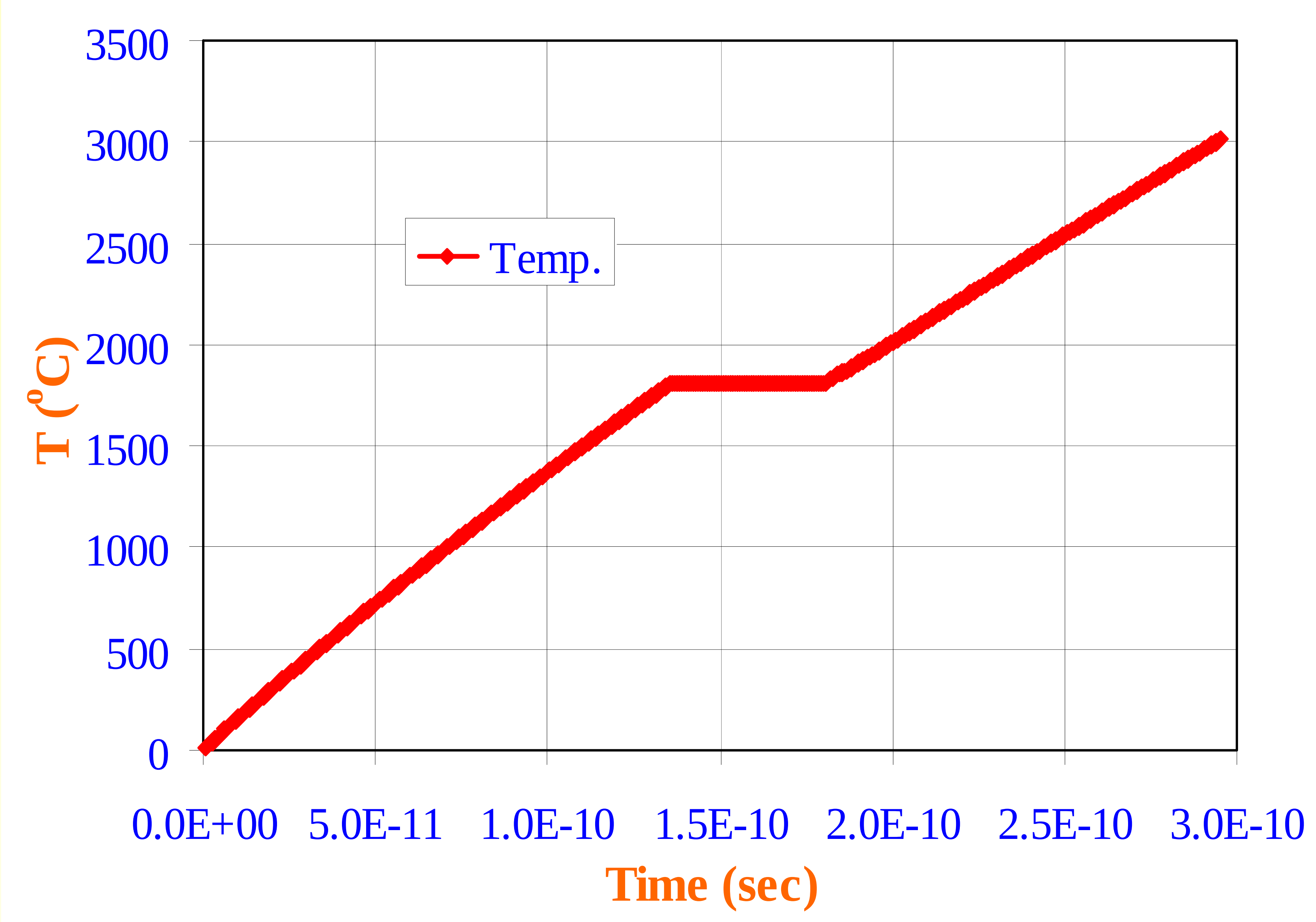
x_b = *Vapor mass fraction*



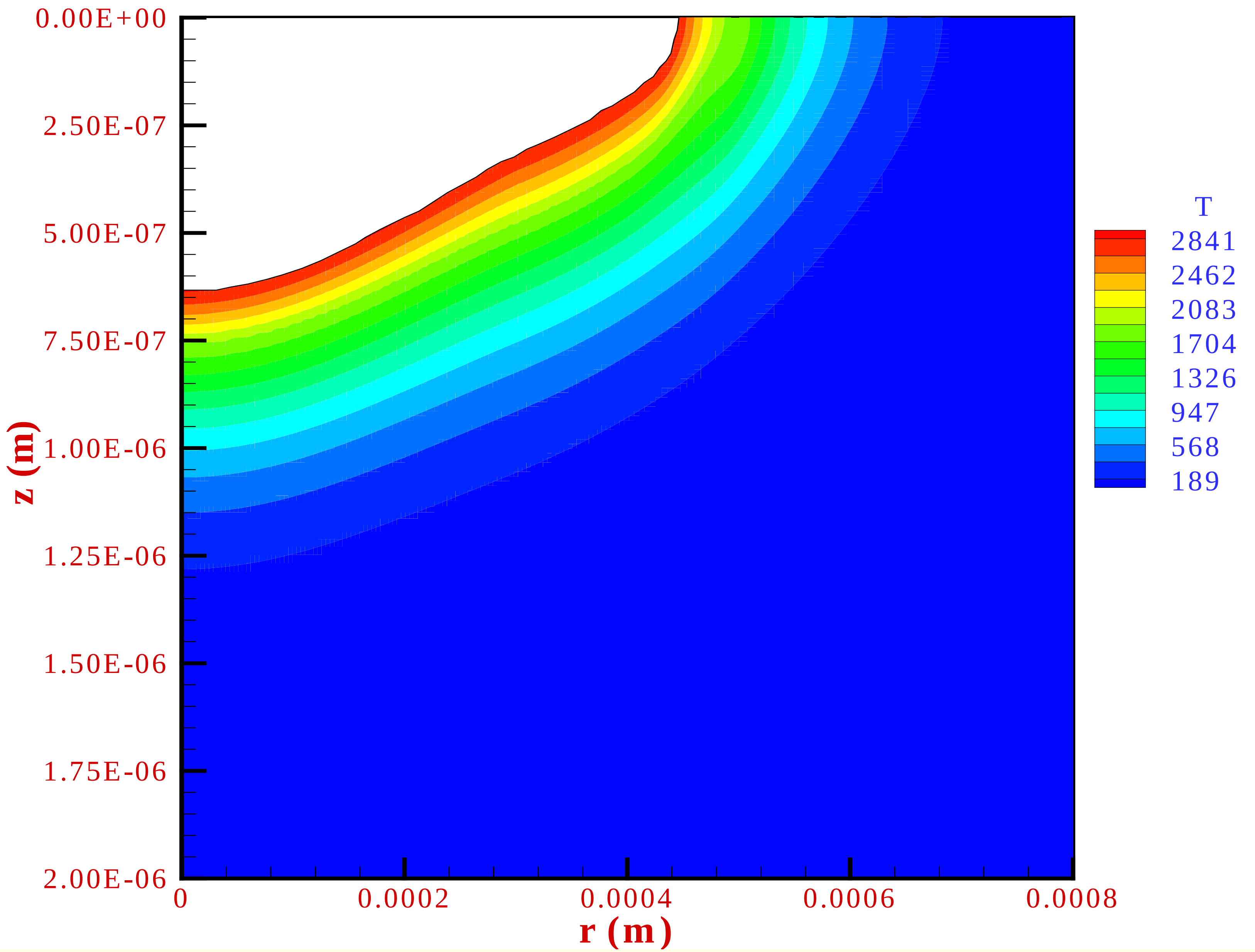
Axisymmetric heating and surface ablation with two mushy zones

Numerical Solution:

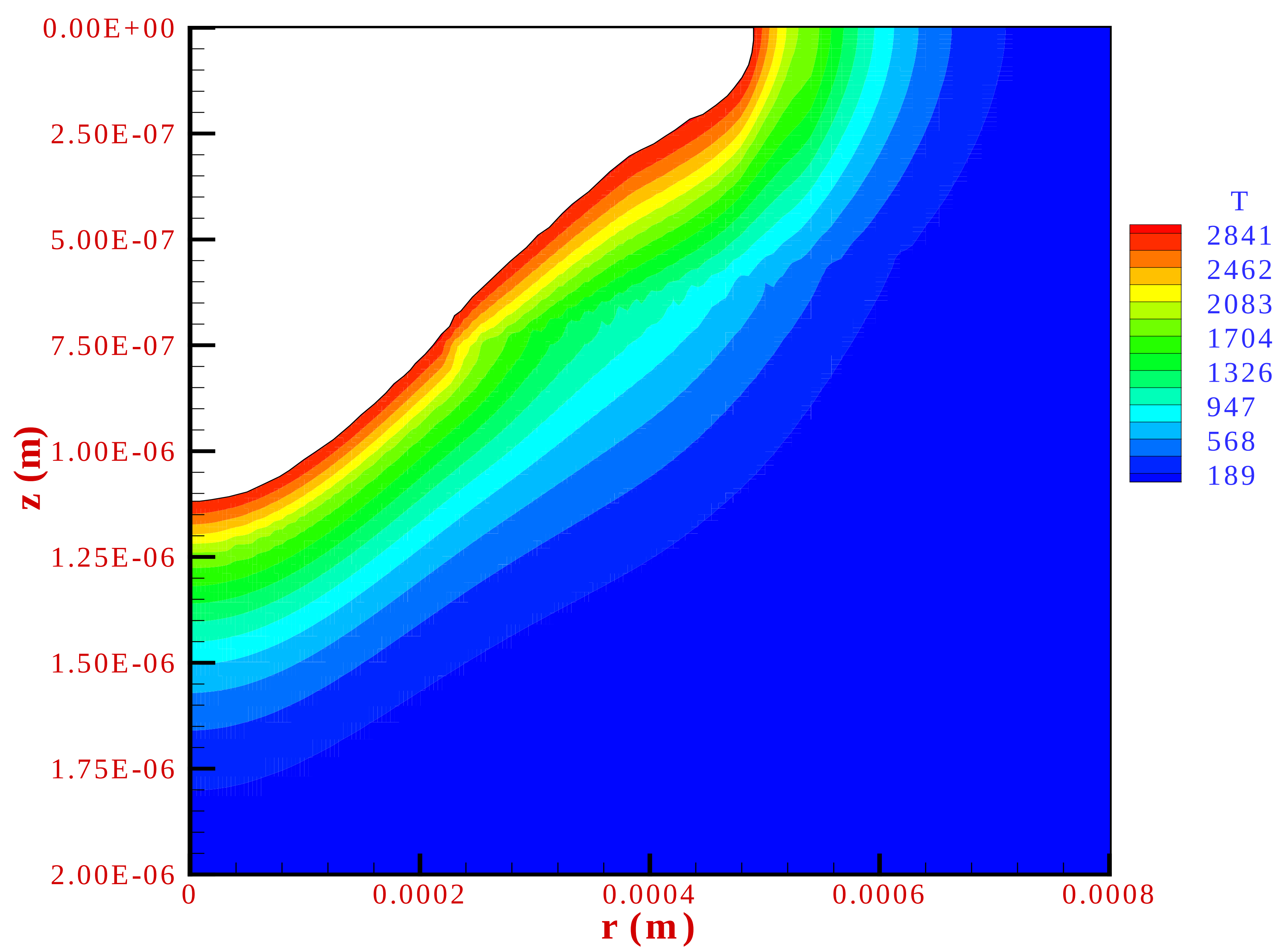
- **The model equations are discretized using a finite volume approach and solved in explicit time marching fashion.**
- **Liquid-gas mushy zone equation also determines the change in the domain shape with the ablation.**



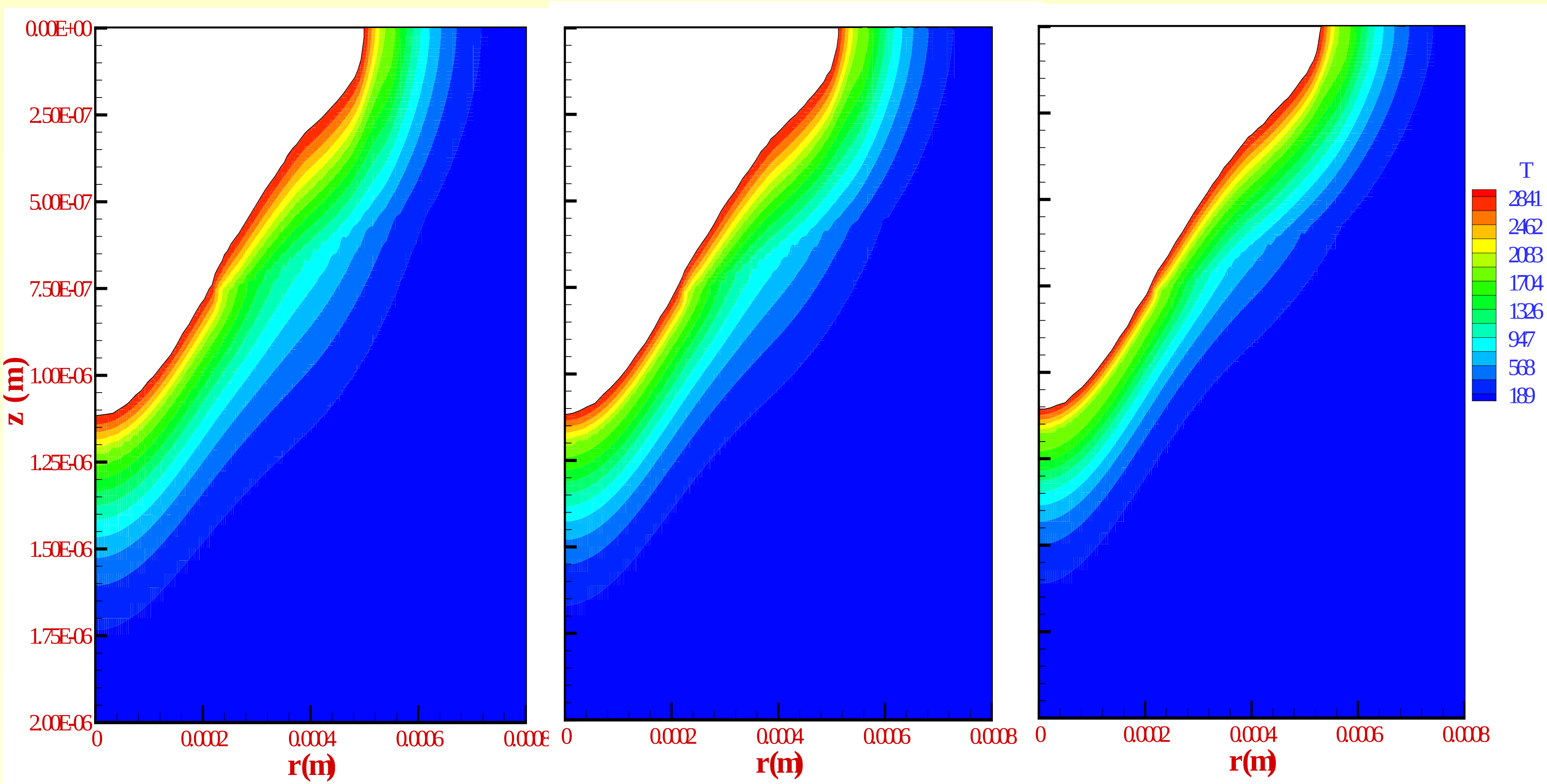
Temporal variation of temperature at the beam centre



Temperature contours in the substrate at 4 ns

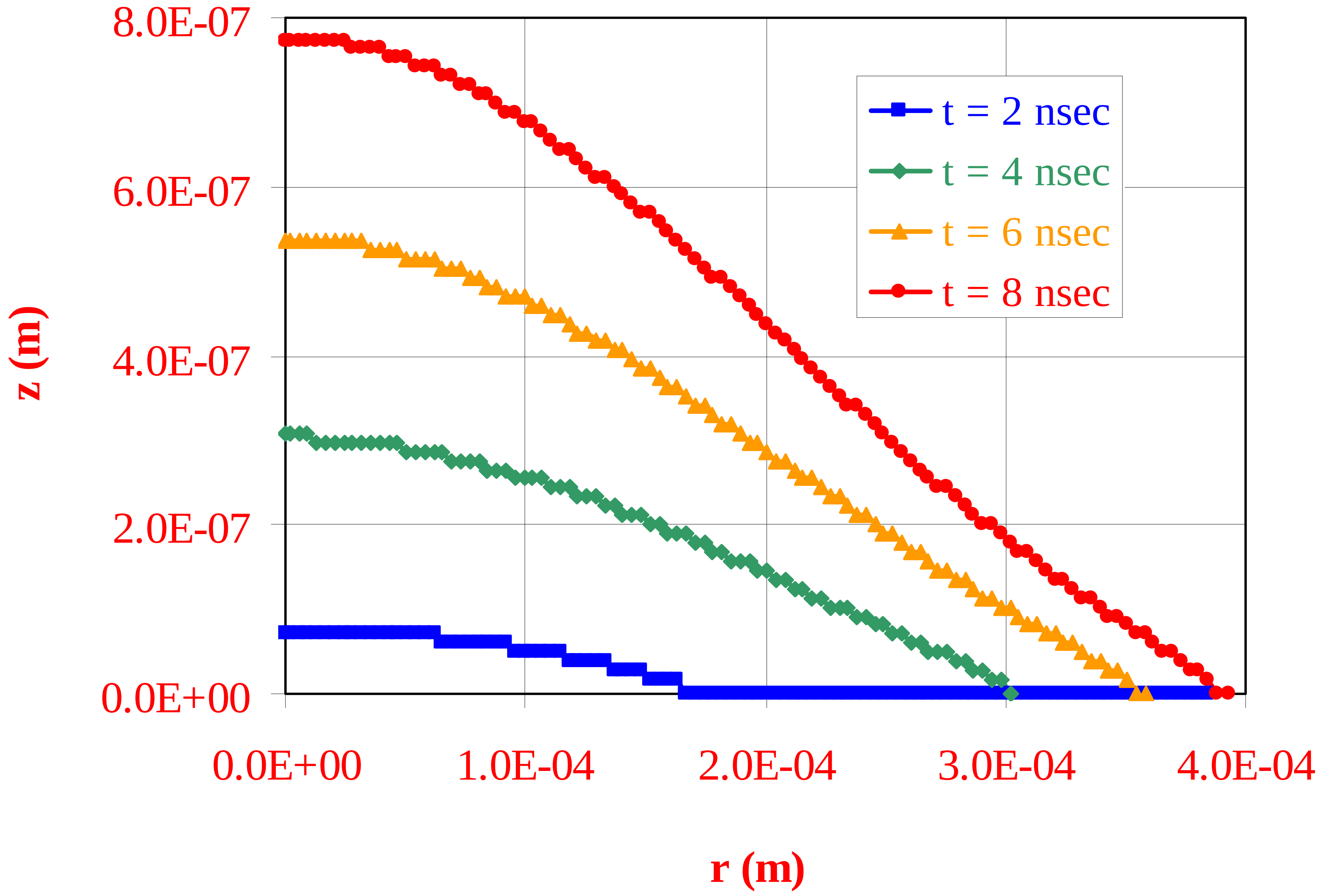


Temperature contours in the substrate at 8 ns



$9.3\times10^{12}\,{W}/{m^2},\ 6\,ns$ $14\times10^{12}\,{W}/{m^2},\ 4\,ns$ $28\times10^{12}\,{W}/{m^2},\ 2\,ns$

Effect of beam intensity on the heat-affected zone



Development of the drilled hole geometry

Conclusions:

- **The energy method can capture the phase change process.**
- **With high energy input only a very small amount of heat diffuses in the substrate because of the ablations.**
- **The depth of the heat-affected zone is independent of the pulse length.**
- **The heat-affected zone can be reduced by using a higher pulse intensity.**

Thank you