A Study On Hydrodynamics Of Melt Expulsion In Pulsed Nd: Yag Laser Drilling Of Titanium

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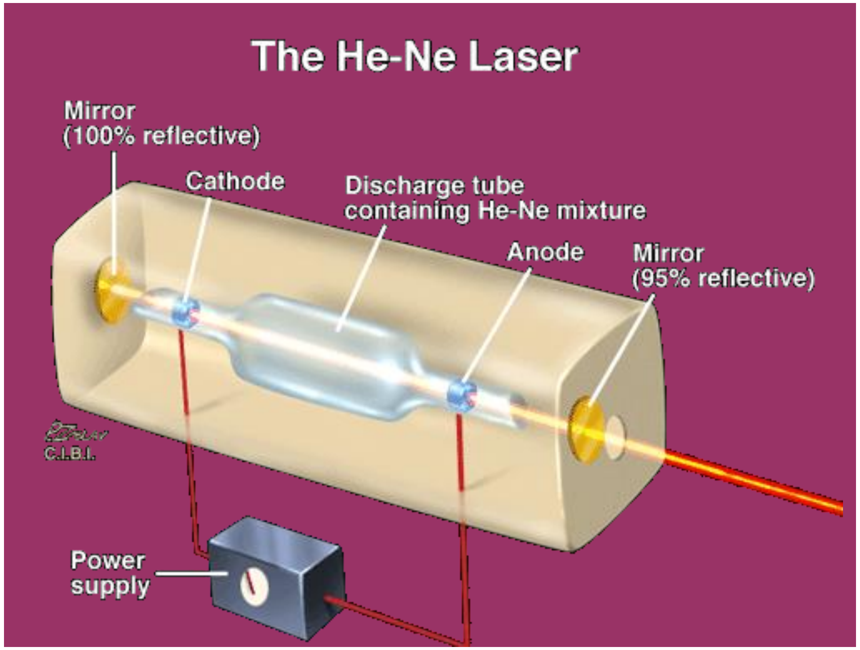
Introduction to lasers

System

- Active/gain medium
- Pump source
- Optical resonator/cavity
- Output coupler

Properties

- Monochromatic
- Coherent
- Directional
- CW : constant power for more than 250ms
- Pulsed



Source:http://www.research.usf.edu/cs/rad/LASERS.ppt

Types of Lasers and their wavelengths

Solid State Laser
- Nd:Yag Laser

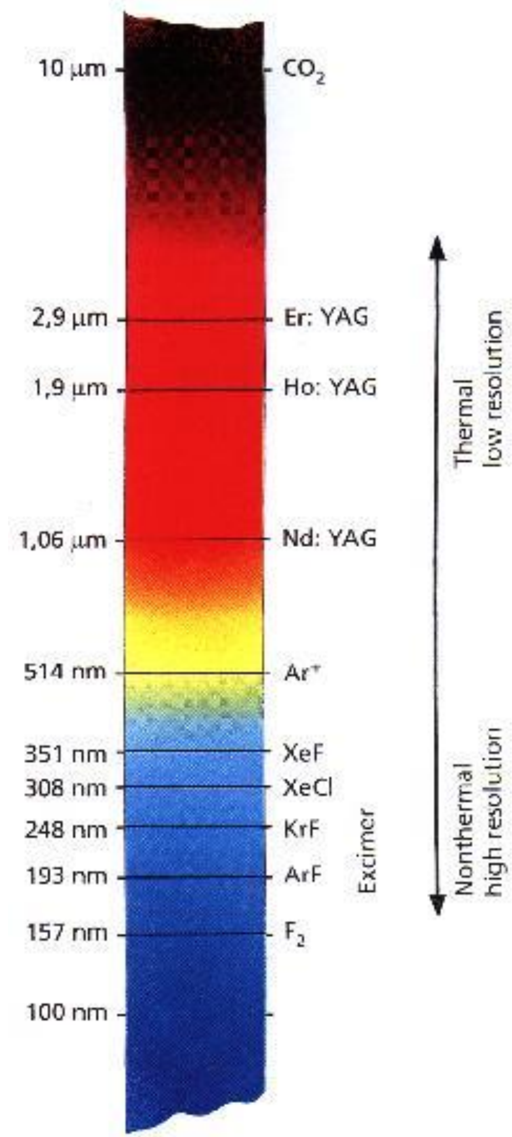
Liquid Laser
- Dye Laser

Gas Laser
- Excimer Laser
- HeNe Laser

Semiconductor Laser
- Diode Laser

Wavelength → Photon energy
Wavelength → Absorptivity
Wavelength → Feature resolution

10600 nm:	CO2 Laser	
1064 nm:	Fundamental Nd-YAG Laser	
632 nm:	Red He-Ne Laser (Continuous Wave)	
532 nm:	Frequency Doubled Nd-YAG Laser	
351 nm:	XeF	(Pulsed Excimer Gas Laser)
248 nm:	KrF	(Pulsed Excimer Gas Laser)
193 nm:	ArF	(Pulsed Excimer Gas Laser)
157 nm:	F2	(Pulsed Excimer Gas Laser)



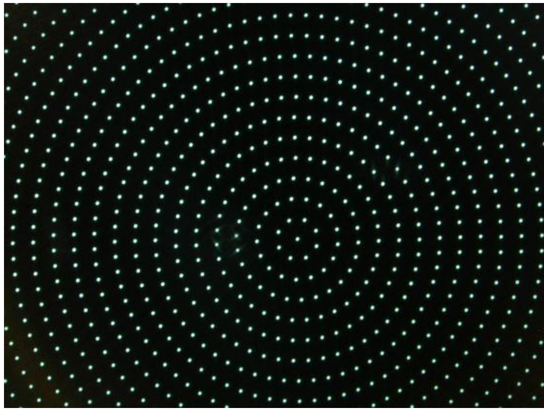
Why Laser drilling of titanium ?

Titanium : Aerospace material

- Corrosion resistance
- High strength to weight ratio
- High fatigue and crack resistance
- Ability to withstand high temperature

Laser Drilling

- Selective removal of material
- High accuracy & speed
- Able to drill holes at normal to extreme angles to the surface
- Variety of shape



Source: www.wikipedia.com

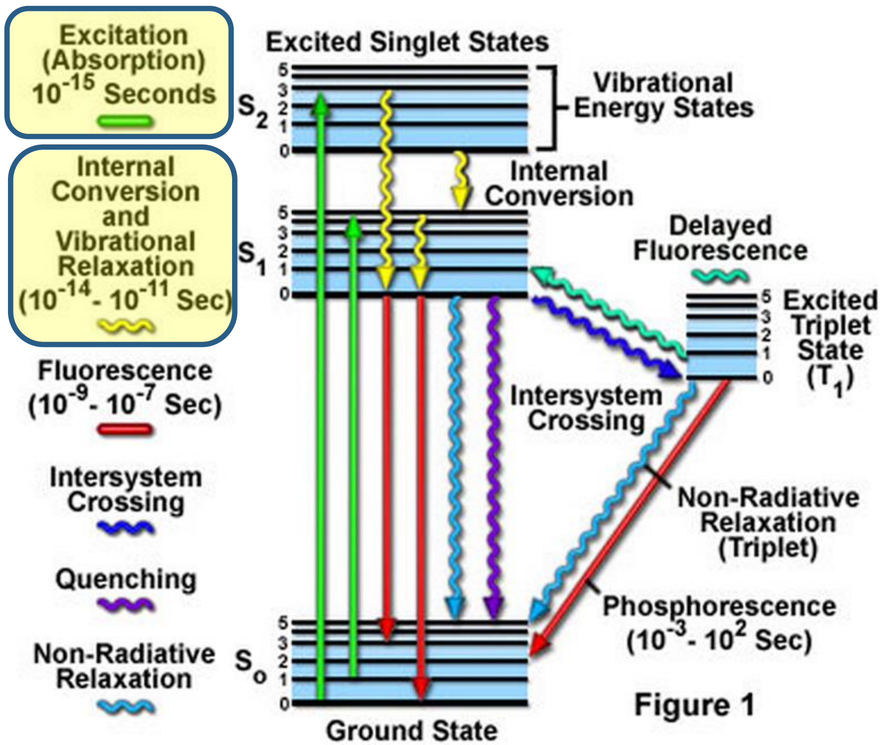
Laser Matter Interaction

- Transfer of Photon energy to lattice
- Melting and vaporization
- Interference from vapor plume

Characteristic times

$$|\langle \mathbf{S} \rangle_t| = \frac{c}{8\pi} |\mathcal{E} \times \mathcal{H}^*| = \frac{c}{8\pi} \sqrt{\frac{\epsilon}{\mu}} |\mathcal{E}_0|^2 e^{-4\pi n_i z/\lambda}$$

Electric Field — Magnetic field — Absorption coefficient



Jablonski energy diagram. (Source: www.olympusmicro.com/primer/techniques/confocal/fluoroexciteemit.html)

Photon absorption time

t_a	~ 1 fs

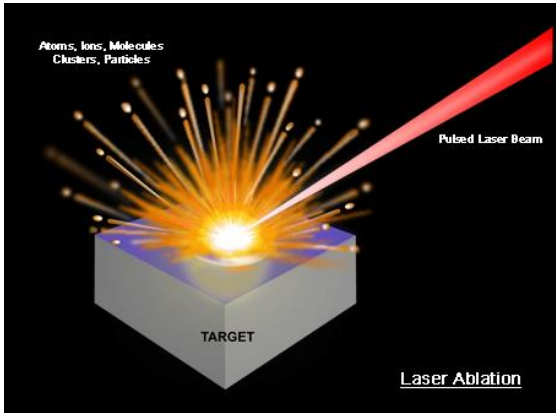
Electron relaxation time

t_e	~ 1 ps

Conversion into lattice energy

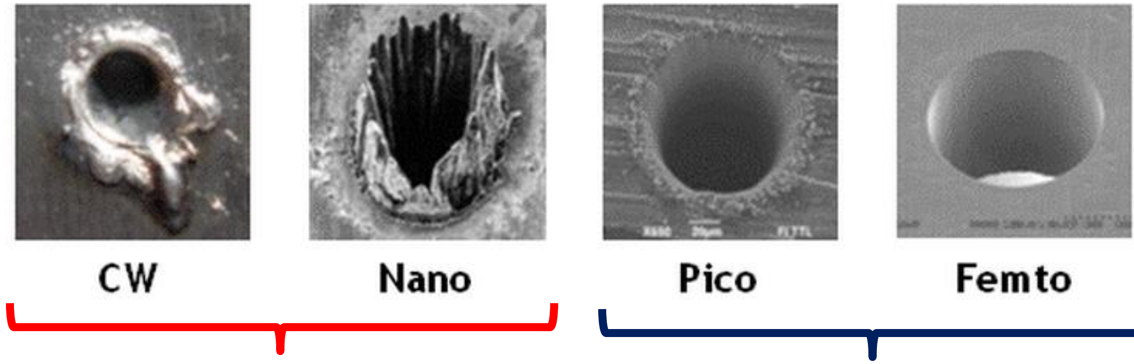
time	> 1 ps

Laser ablation



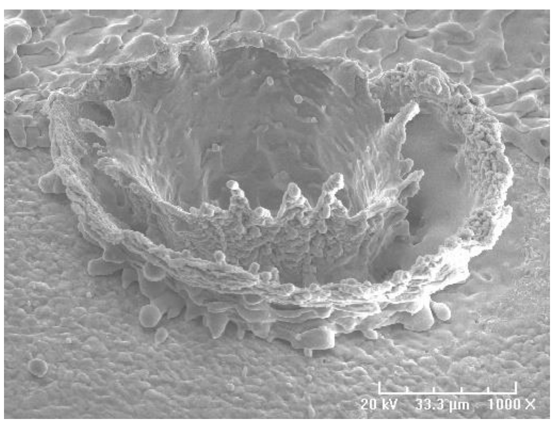
Laser ablation
(Source: www.astrobio.net/pressrelease/4605/green-laser-spectroscopy)

Source: http://info.raydiance.com/blog/?Tag=cold%20ablation

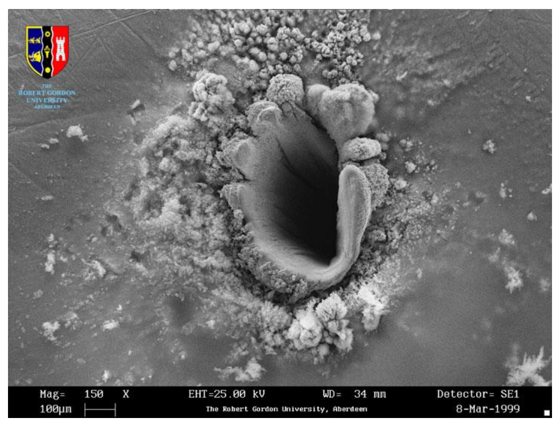


Melt- Vaporization

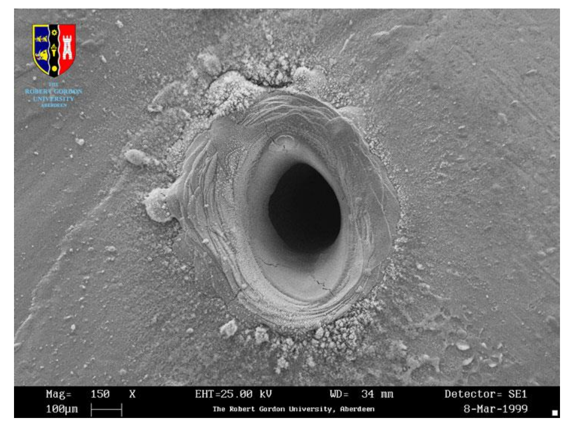
Cold Ablation



Metal ablation
(Source: http://www.orslabs.com/LaserAblation.php)

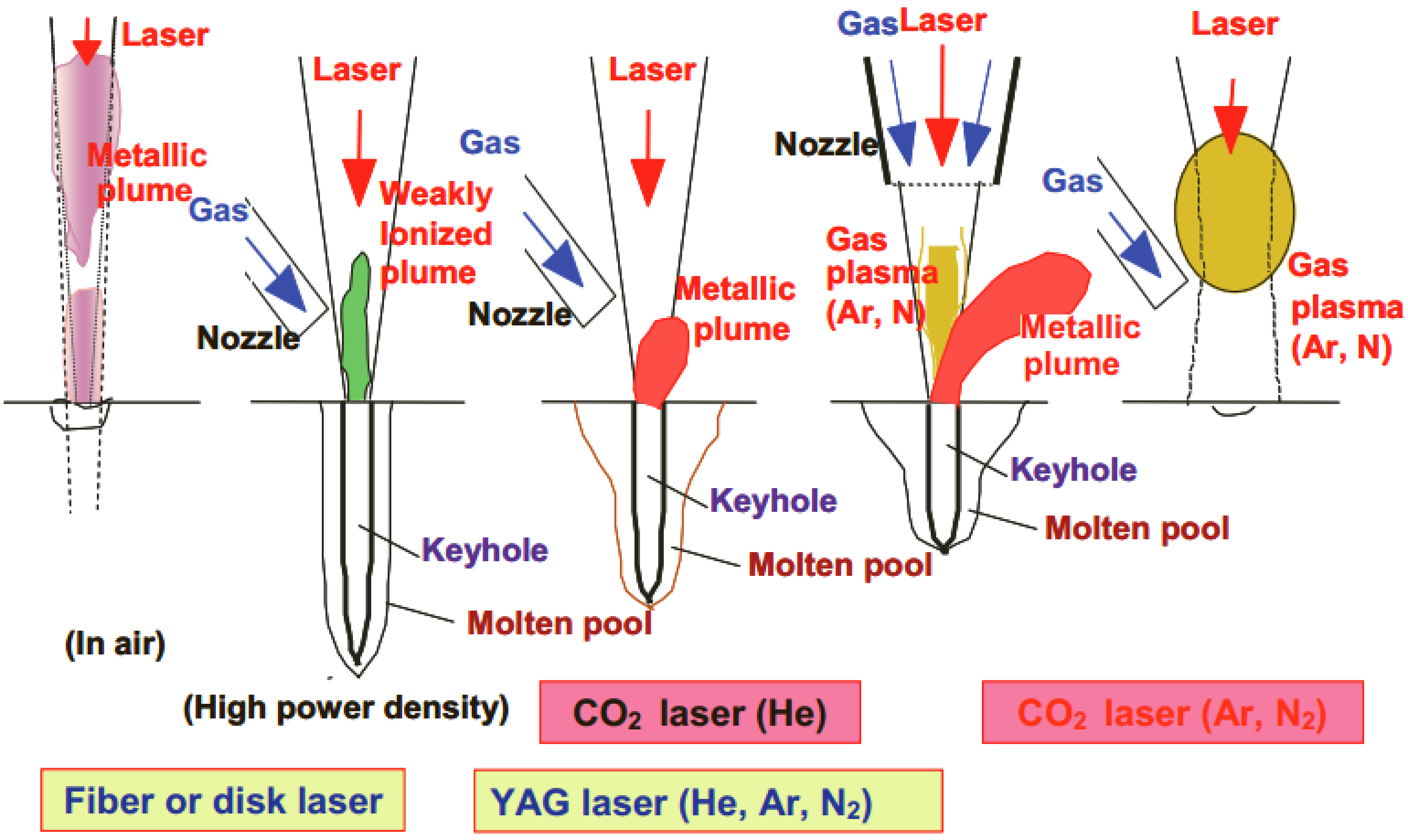


Ablated steel
(Source:www2.rgu.ac.uk/life_semweb/engimages/ablationimg2.jpg)



Ablated steel
(Source:www2.rgu.ac.uk/life_semweb/engimages/ablationimg1.jpg)

Laser Drilling/Welding

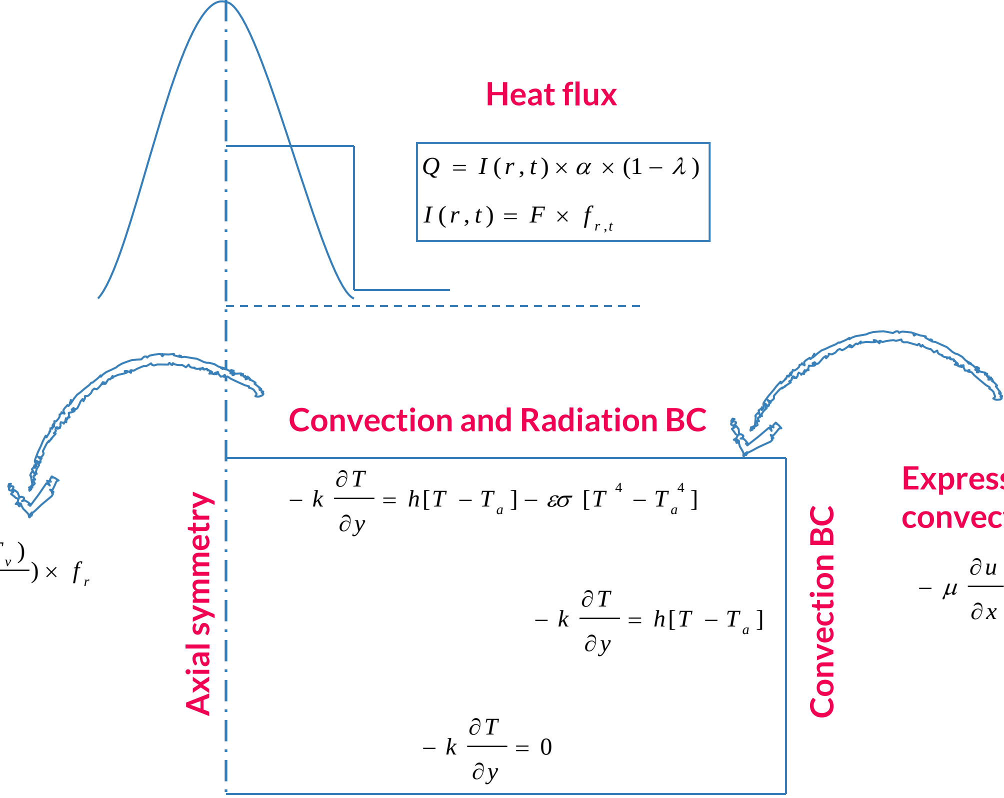


Katayama, S., Kawahito, Y., & Mizutani, M. (2010). Elucidation of laser welding phenomena and factors affecting weld penetration and welding defects.Physics procedia, 5, 9-17.

3 Stages of Pulsed Laser Drilling

- Initial Melting resulting in marangoni convection
- Melt Vaporization and melt expulsion due to recoil pressure
- Retraction of melt inside the cavity when laser pulse is off

Mathematical Modeling



Heat flux

$$Q = I(r,t) \times \alpha \times (1-\lambda)$$

$$I(r,t) = F \times f_{r,t}$$

Convection and Radiation BC

$$-k\frac{\partial T}{\partial y} = h[T - T_a] - \varepsilon\sigma[T^4 - T_a^4]$$

Convection BC

$$-k\frac{\partial T}{\partial y} = h[T - T_a]$$

Insulation BC

$$-k\frac{\partial T}{\partial y} = 0$$

Expression for Recoil pressure

$$R_p = 0.54 \times P_a \times \exp\left(\frac{L_v(T - T_v)}{RTT_v}\right) \times f_r$$

Expression for marangoni convection

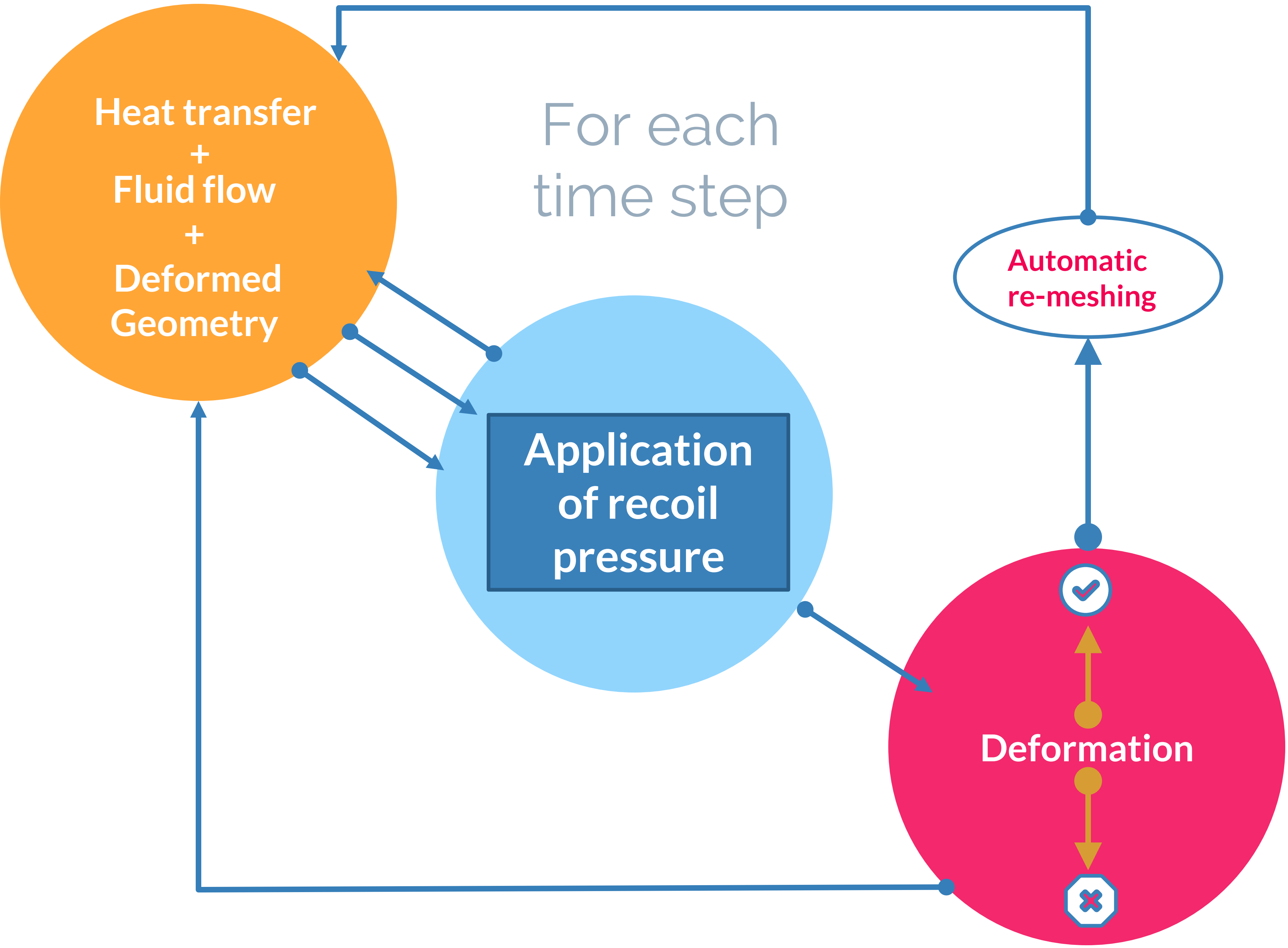
$$-\mu\frac{\partial u}{\partial x} = \frac{\partial T}{\partial y}\frac{\partial \gamma}{\partial T}$$

Governing Equations

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0$$

$$\rho\frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.[-pI + \mu(\overrightarrow{\nabla u} + (\overrightarrow{\nabla u})^T)] - \rho(1 - \beta(T - T_m))\vec{g} + \vec{F}$$

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u\nabla T = \nabla.(k\nabla T)$$



Heat transfer
+
Fluid flow
+
Deformed
Geometry
For each
time step
Automatic
re-meshing
Application
of recoil
pressure
Deformation

Numerical Aspects

Thermo-physical Parameters

▹Temperature dependent parameters are chosen with suitable transtion values at melting and boiling points.

Meshing

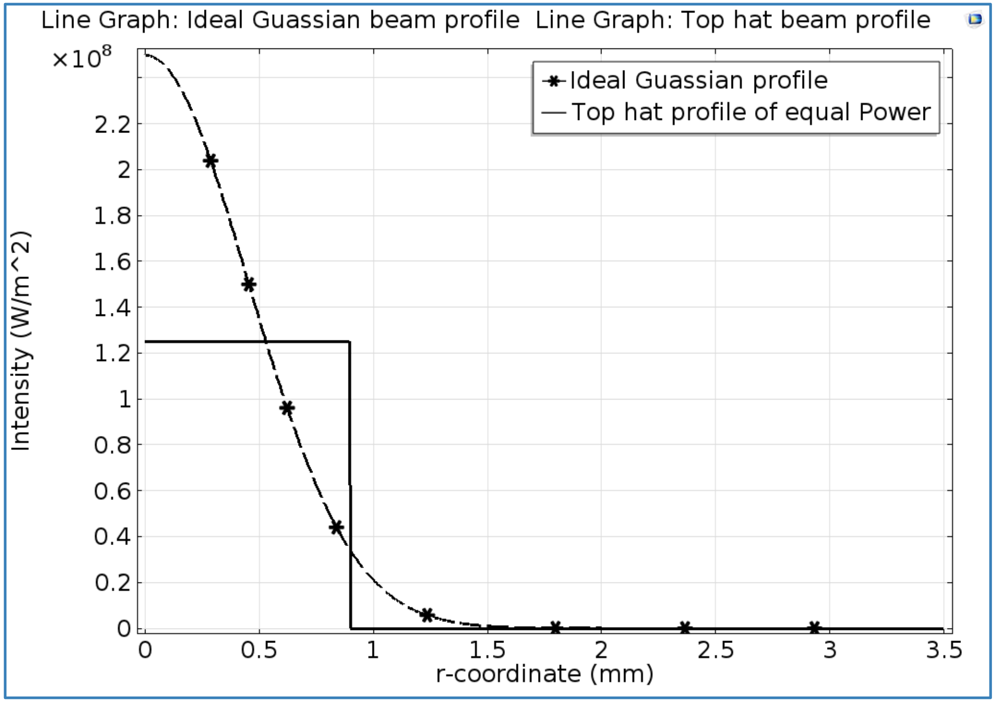
▹A uniform triangular mesh with minimum element size of 0.8 μm is generated for the whole domain.

▹The stop condition for automatic re-meshing are mesh quality and peak temperature, meaning whenever deformation happens, a newer mesh will be generated for the deformed geometry.

Simulation Time

▹The pulse train used for heating operates in the time interval of 2s, with pulse on and off time of 50 ms.

Input Parameters

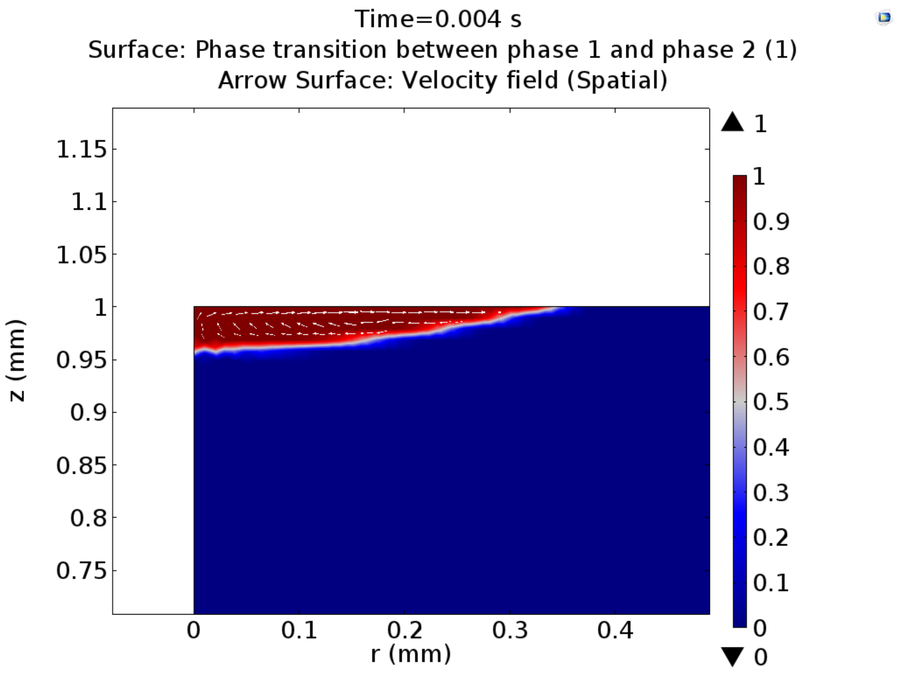


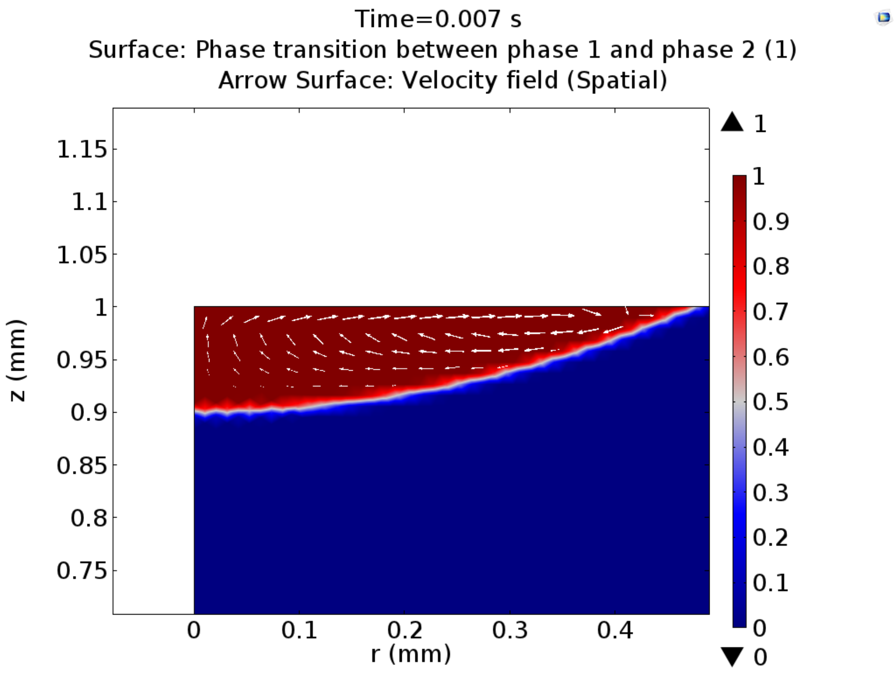
Thermo-physical properties	Value
Melting Temperature (K)	1923
Thermal expansion coefficient (1/K)	8e-6
Vaporization Temperature (K)	3315
Density (kg/m3)	4200 (0-1923K) 3780 (1923-5000K)
Thermal Conductivity (W/(mK))	7.5(0K) 34.1(1923K 37(3315K)
Specific heat(J/(kgK))	550(0K) 850(1923-5000K)
Latent heat of melting (J/kg)	2.86e5
Latent heat of evaporation (J/kg)	9.83e6
Temperature derivative of the surface tension (N/m*K)	-0.28e-3
Dynamic viscosity(Pas)	3.25e-3 (1923K) 3.03e-3 (1973K) 2.66e-3 (2073K) 2.36e-3 (2173K)
Universal gas constant (J/(kg*K))	8.314
Emissivity	0.1536+1.8377e-4×(T-300K)

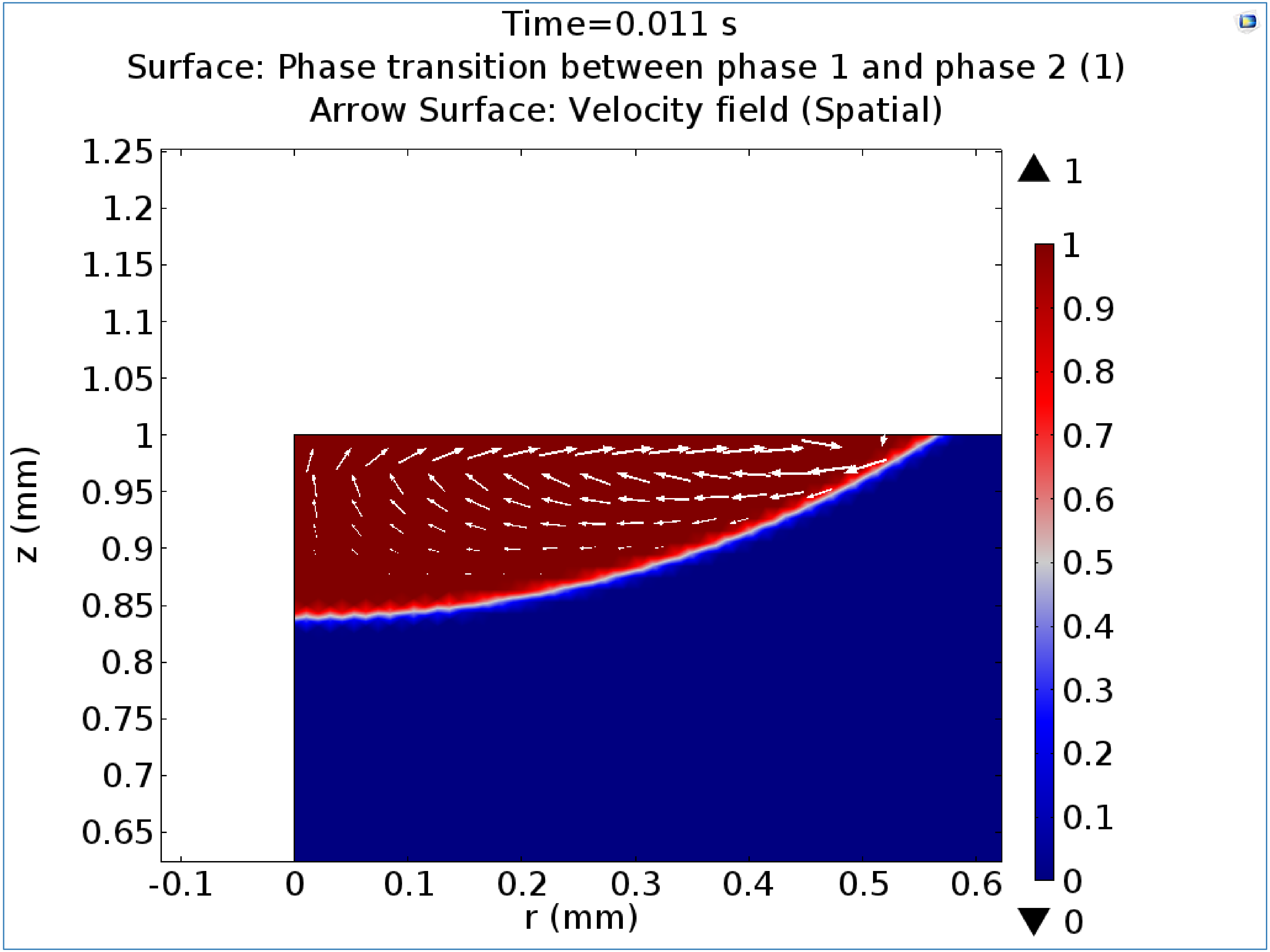
Simulation Results

3 Stages of Pulsed Laser Drilling

Initial Melting resulting in marangoni convection







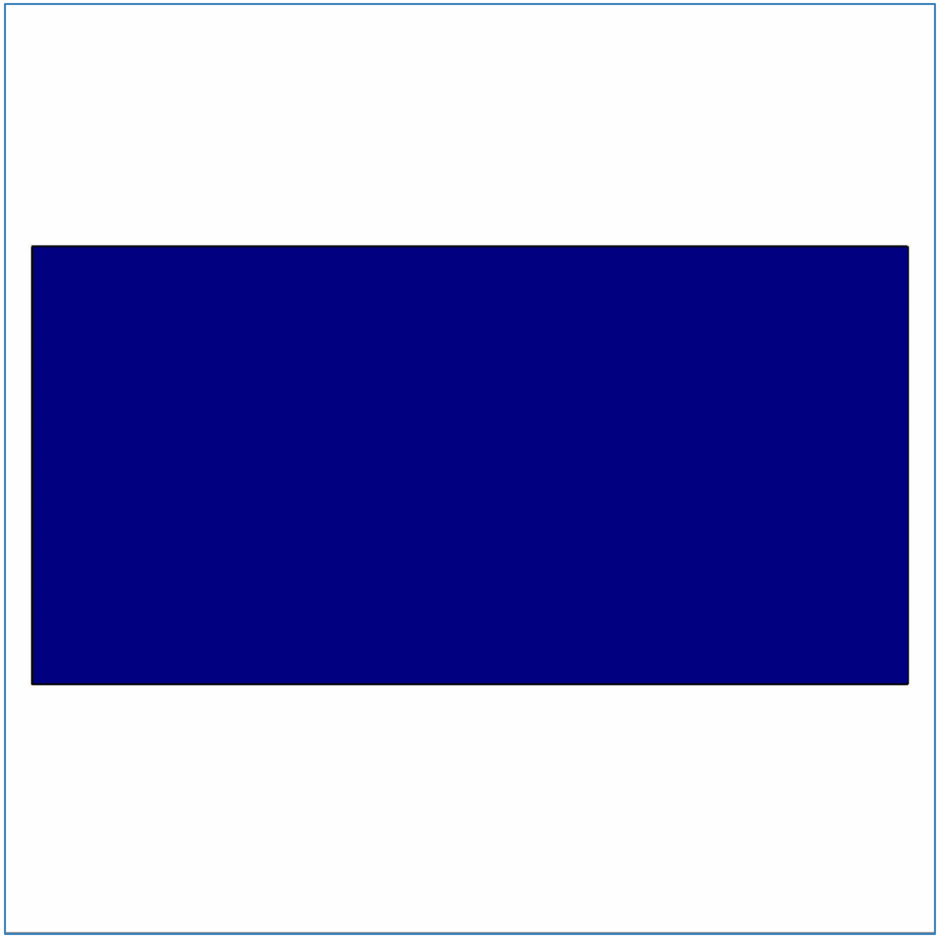
Time=0.011 s
Surface: Phase transition between phase 1 and phase 2 (1)
Arrow Surface: Velocity field (Spatial)
z (mm)
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
r (mm)
▲ 1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
▼ 0

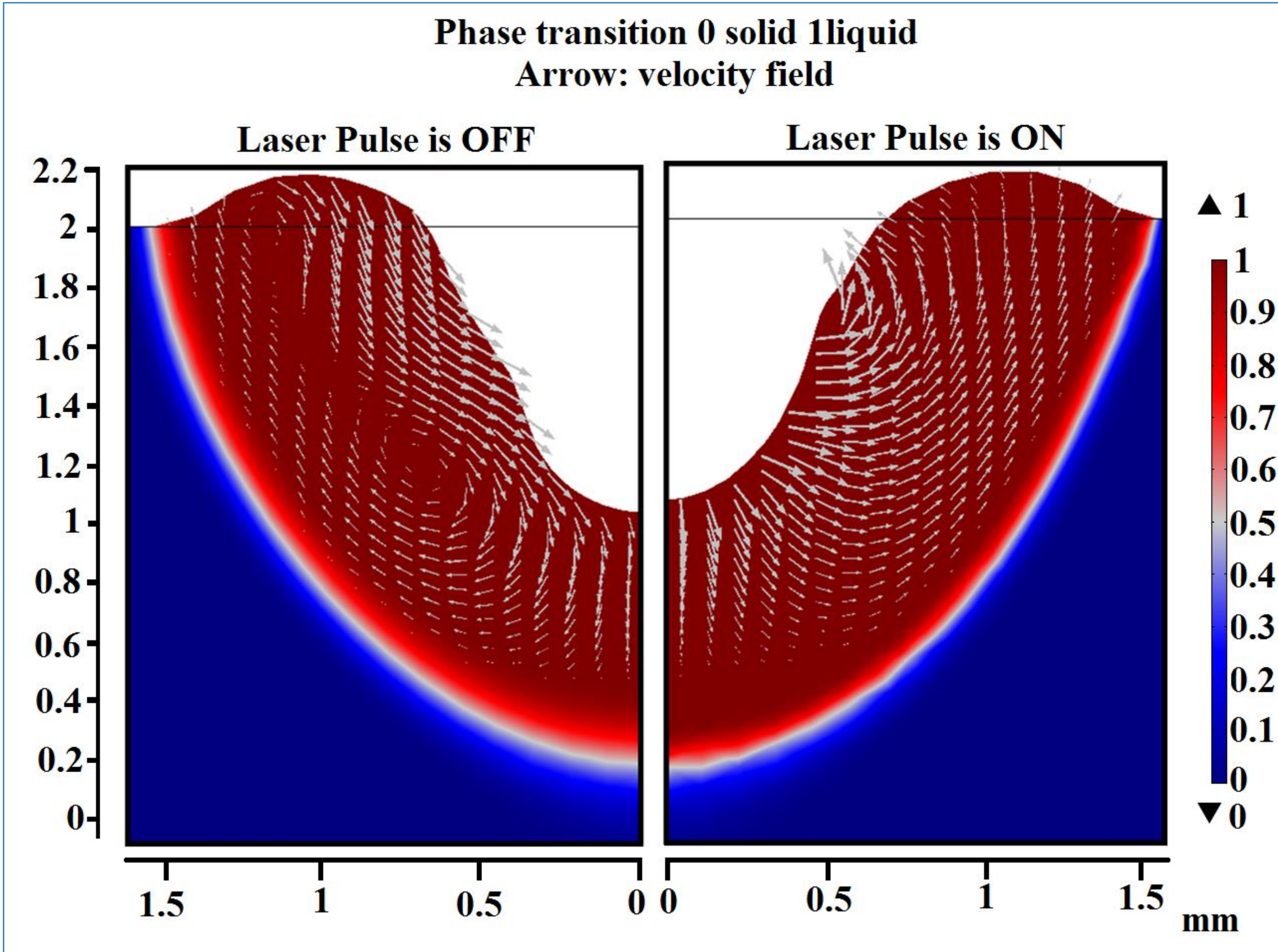
3 Stages of Pulsed Laser Drilling

Initial Melting resulting in marangoni convection

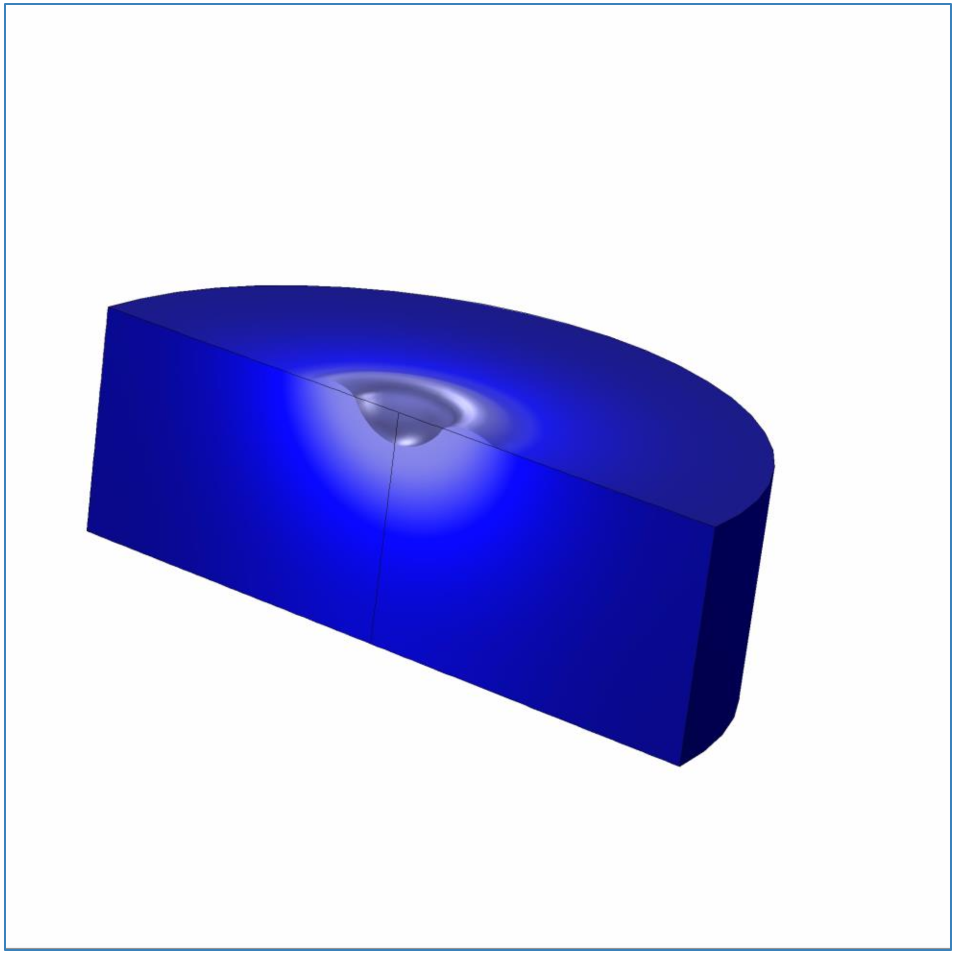
Melt Vaporization and melt expulsion due to recoil pressure

Retraction of melt inside the cavity when laser pulse is off




Phase transition 0 solid 1liquid
Arrow: velocity field
Laser Pulse is OFF
Laser Pulse is ON
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.5
1
0.5
0
0
0.5
1
1.5
mm
▲ 1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
▼ 0

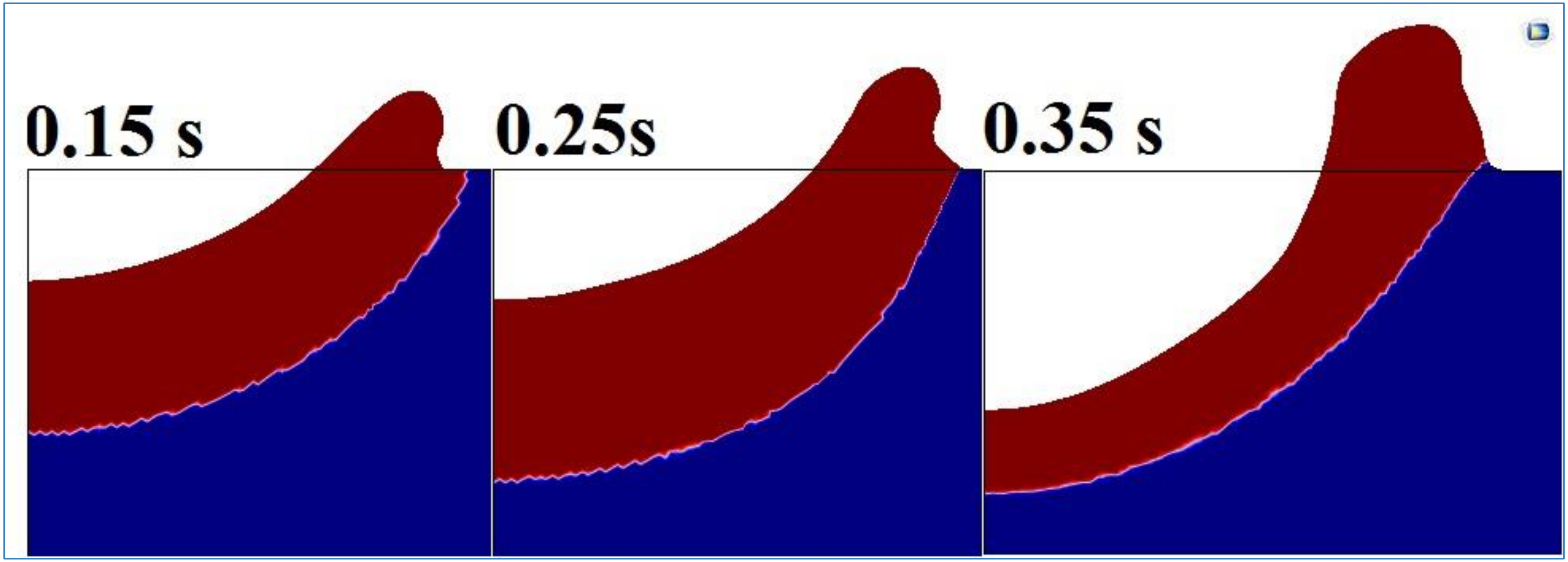
Evolution of Keyhole cavity

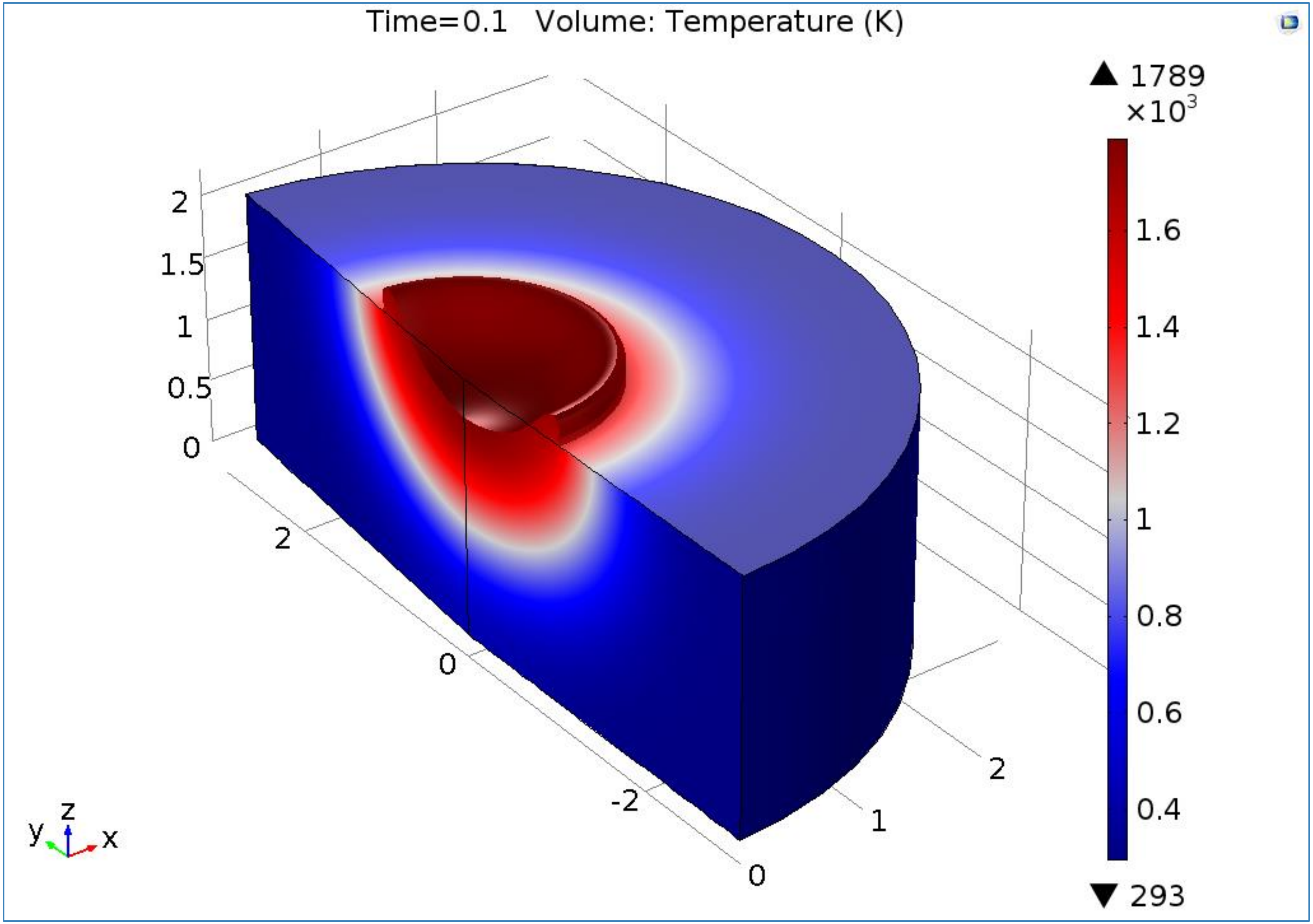


Top- Hat beam profile

- The tapered nature of the cavity is obviated.

- Due to uniform geometry of the cavity there is no obstruction for splashing molten metal and the size of molten hump near the edge of the cavity is more in the case of top hat laser intensity.




Time=0.1 Volume: Temperature (K)
▲ 1789
×10³
1.6
1.4
1.2
1
0.8
0.6
0.4
▼ 293
2
1.5
1
0.5
0
2
0
-2
2
1
0
y
z
x

Conclusions

- Comprehensive model with different spatial laser intensity profiles.

- Deformation and cavity formation due to recoil pressure is simulated.

- Gaussian intensity results in tapered shape cavity similar to keyhole.

- Top hat intensity profile results in uniform shape cavity.

Scope of improvement in simulated results

- The loss of laser intensity due to plume interaction should be incorporated in the simulation to improve the results.

- Multiple reflection inside the keyhole should be simulated and its effects should be studied.

Thanks!

Any questions?

You can find me at:

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