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Heat and fluid flow modeling of keyhole formation in laser welding

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I – Introduction
- Physics of laser welding

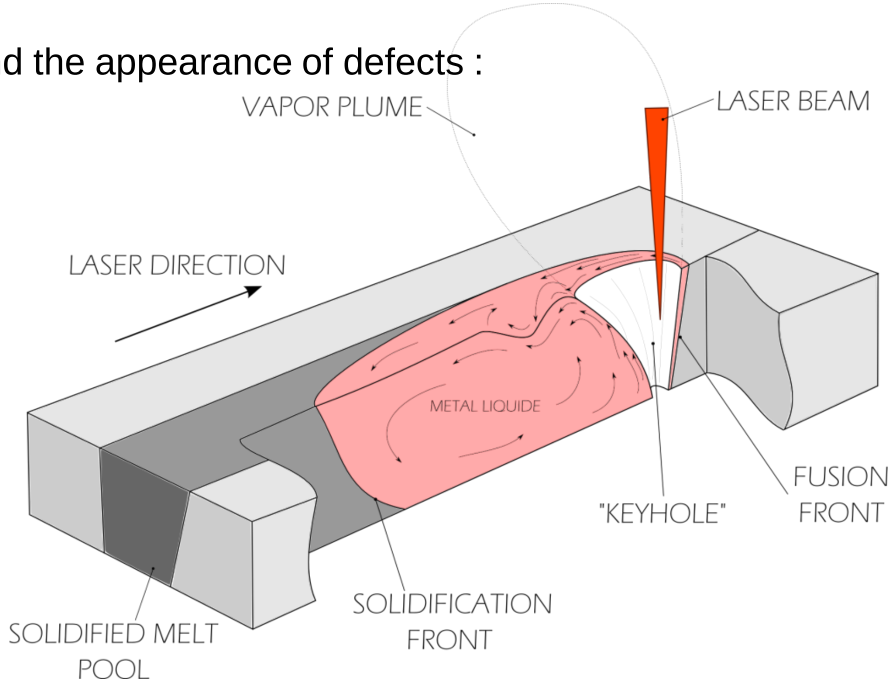
II – Definition of the heat and fluid flow model
- Equations
- Level-set method

III – Results and discussion
- 2D axisymmetric model

IV – Conclusion and future work
- 3D model ?

Keyhole laser welding

Mains phenomena influencing the melt pool geometry and the appearance of defects :

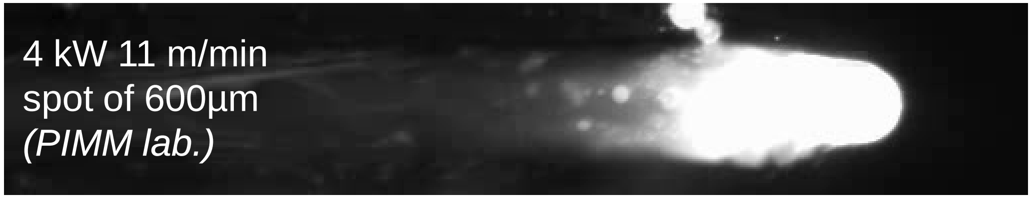


Energy:

- Conduction
- Convection
- Radiation

Fluid mechanic:

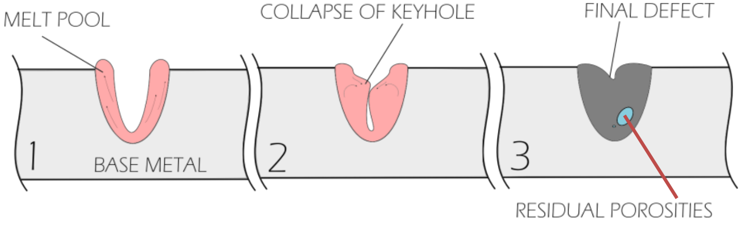
- Liquid and gas flows
- Vaporization
- Recoil pressure
- Surface tension
- Marangoni effect



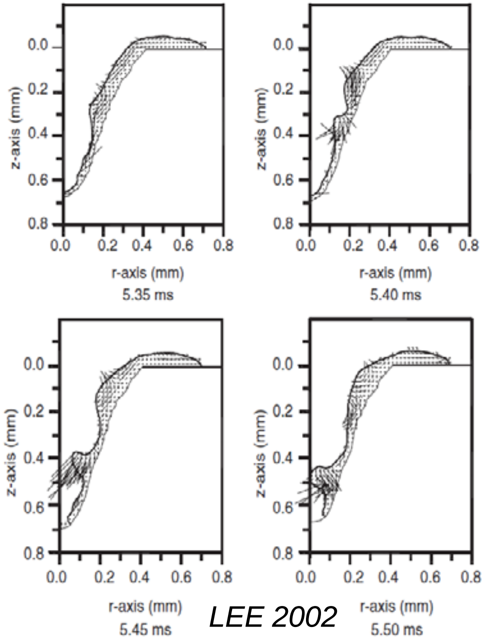
4 kW 11 m/min
spot of 600µm
(PIMM lab.)

Axisymmetric approach ➡ Stationary spot laser welding

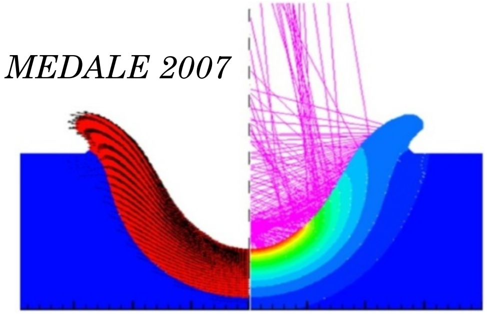
Goal: model the keyhole formation in order to improve understanding



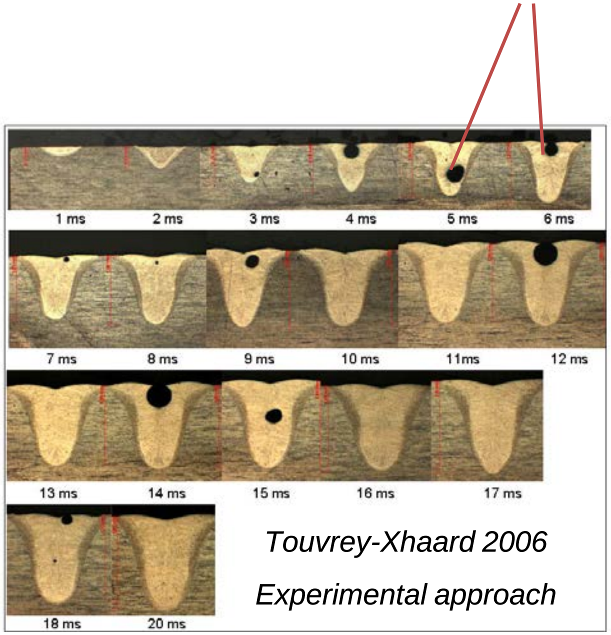
- ➢ Taking into account of:
  - recoil pressure
  - gravity
  - surface tension
  - Marangoni effect
  - Multiple reflection of laser rays



LEE 2002



MEDALE 2007



Touvrey-Xhaard 2006

Experimental approach

Setting up the model

Assumptions:

- Axisymmetric geometry
- Incompressible Newtonian fluids
- Laminar flows
- Constant thermophysical properties
- Gaussian distribution of energy

Equations solved:

- Energy conservation
- Momentum conservation
- Mass conservation
- Transport equation of Level Set variable

Taking into account of:

- gravity
- surface tension
- solid phase (Darcy condition)
- recoil pressure
- vapor plume

Neglected (here)**:**

- Marangoni effect
- Latent heats
- Laser reflections

Code: Comsol Multiphysics® v4.3 (+ CFD module)

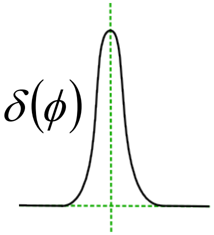
Conservation equations for each phase

Mass conservation:

$$\nabla .u = \boxed{\dot{m}\,\delta(\phi)\left[\frac{\rho_l-\rho_v}{\rho^2}\right]}$$

→ *Away from the interface*

$$\nabla .u = 0$$



Momentum conservation: Navier-Stokes equations

$$\rho\left(\frac{\partial u}{\partial t}+u.(\nabla u)\right)=\nabla .\left[-PI+\mu\left(\nabla u+(\nabla u)^T\right)\right]-\rho\left(1-\beta\left(T-T_{fusion}\right)\right)g+K(T)u+F_{ts}$$

buoyancy

Darcy condition

With: $F_{ts}=\left(\gamma .n\,\kappa-\nabla_s\gamma .t\right)\delta(\phi)$

surface tension

Marangoni effect (here = 0)

Energy conservation:

$$\rho\, cp\left[\frac{\partial T}{\partial t}+\nabla .(u\,T)\right]=\nabla .(\lambda\nabla T)+I(r)$$

with

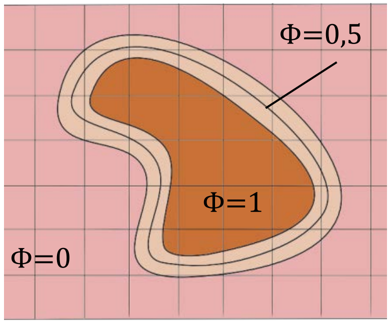
$$I(r)=\frac{P_{\max}}{\pi R_g^2}\exp\left(\frac{-r^2}{R_g^2}\right)\delta(\phi)$$

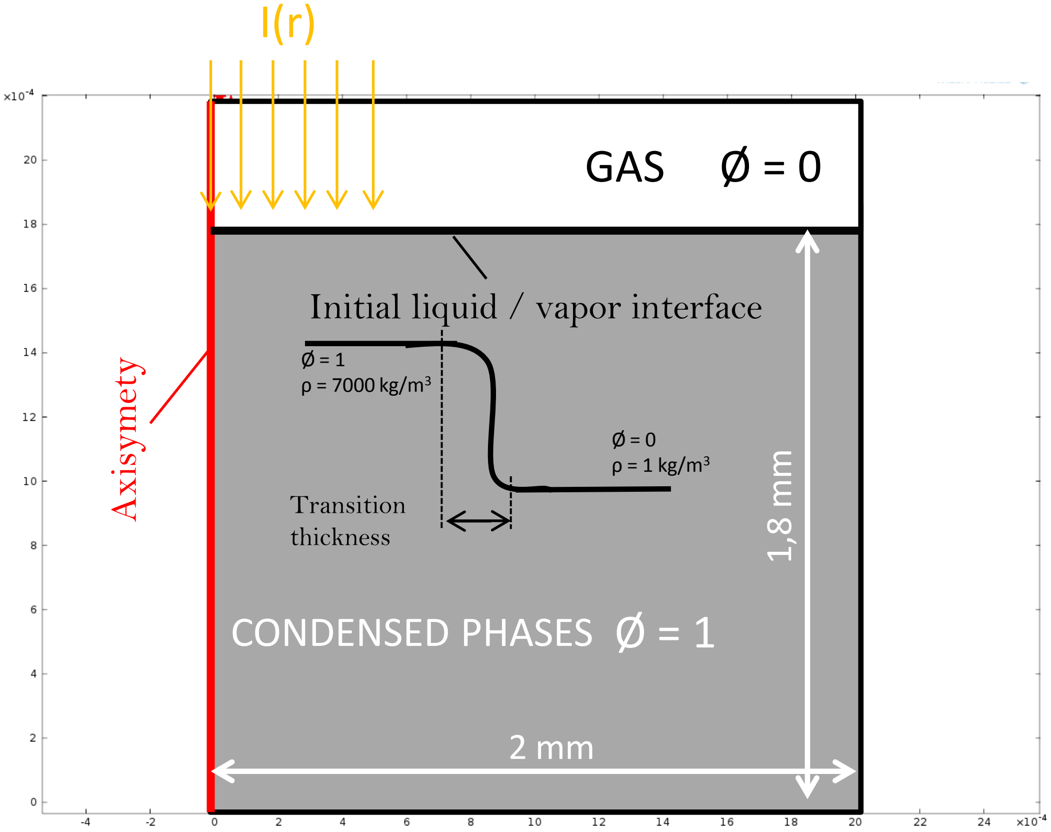
Level Set method

Fixed mesh

Definition of a variable ϕ in all the elements

Transport of this variable using the fluid flow calculation





Engine: Laser energy at liquid / vapor interface:

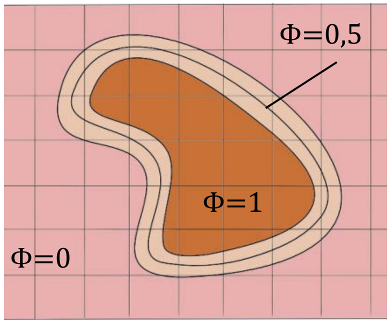
$$I(r) = \frac{P_{\max}}{\pi R_g^2} \exp\left(\frac{-r^2}{R_g^2} \right) \delta(\phi)$$

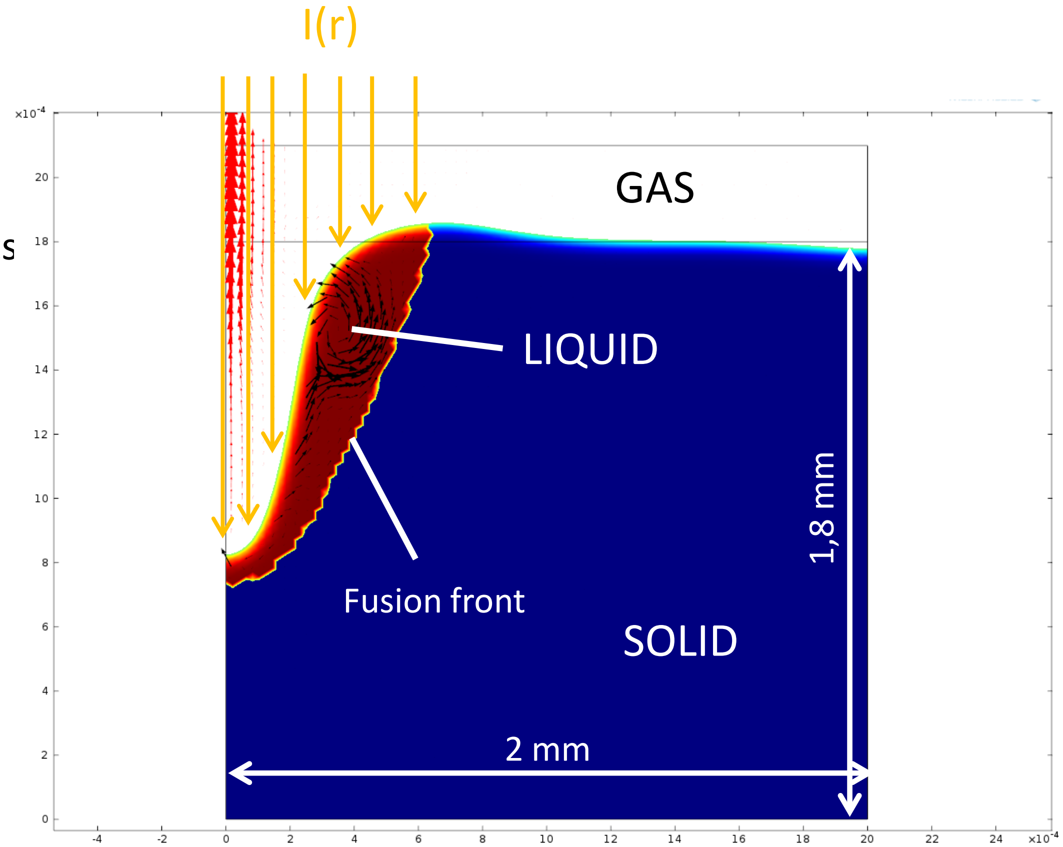
Level Set method

Fixed mesh

Definition of a variable ϕ in all the elements

Transport of this variable thanks to fluid mechanic calculation





Engine: Energy application on liquid / vapor interface

$$I(r) = \frac{P_{\max}}{\pi R_g^2} \exp\left(\frac{-r^2}{R_g^2}\right) \delta(\phi)$$

Operating parameters:

P = variable

Øfocal = 600 µm

Heating time = 20 ms

Cooling time = 5 ms

Increase power with the drilling velocity
$P_{laser} < 800$ W => no porosity

Thermophysical properties

$\rho_{liquid} = 7000\ kg.m^{-3}$

$\lambda_{liquid} = 40\ W.m^{-1}.K^{-1}$

$Cp_{liquid} = 400\ J.kg^{-1}.K^{-1}$

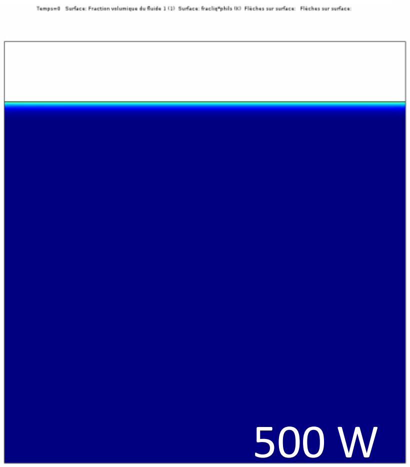
$\mu_{liquid} = 5.10^{-3}\ Pa.s^{-1}$

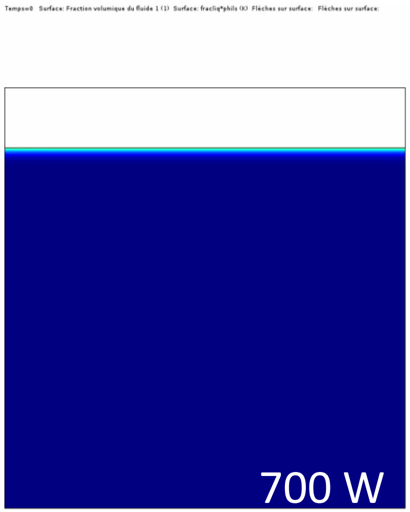
$\rho_{vapor} = 10\ kg.m^{-3}$

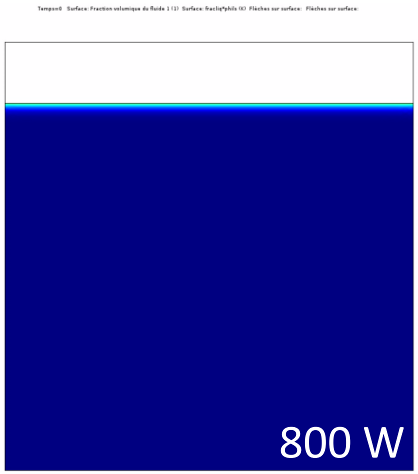
$\lambda_{vapor} = 10\ W.m^{-1}.K^{-1}$ ⚠

$Cp_{vapor} = 373\ J.kg^{-1}.K^{-1}$

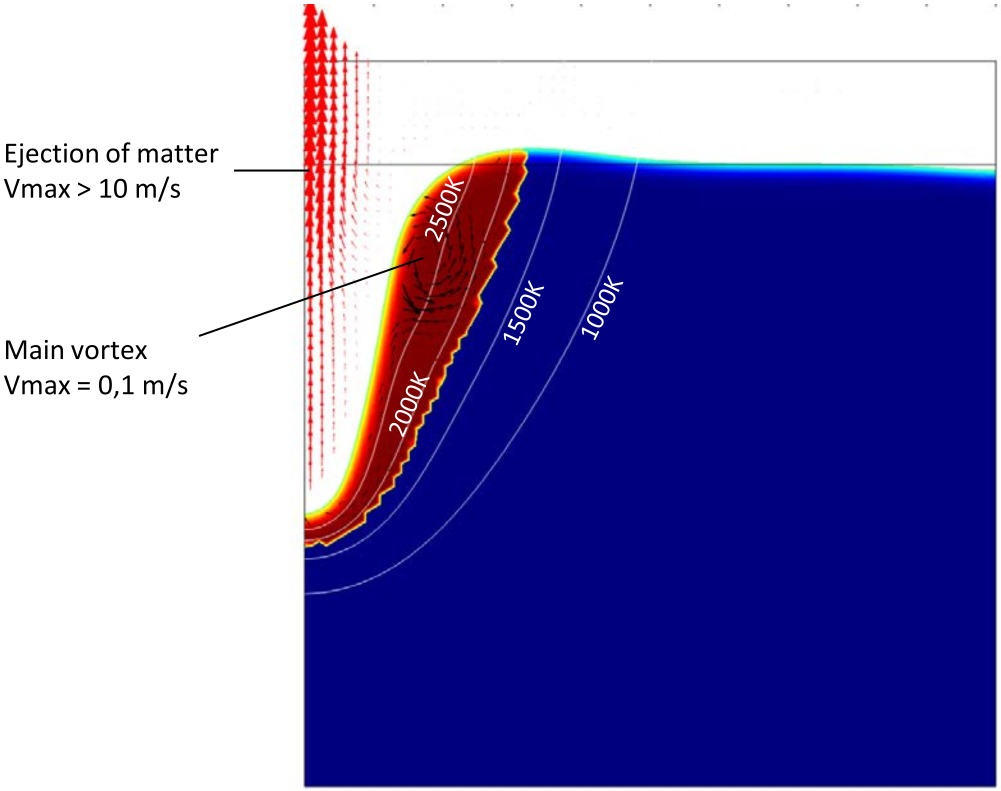
$\mu_{vapor} = 1.10^{-5}\ Pa.s^{-1}$



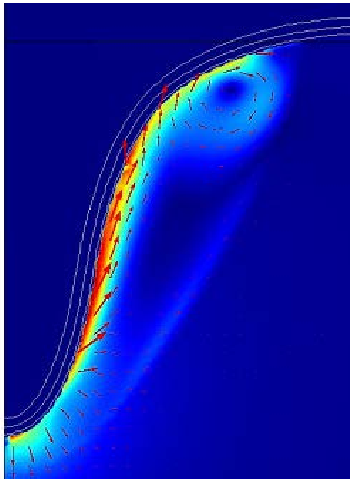




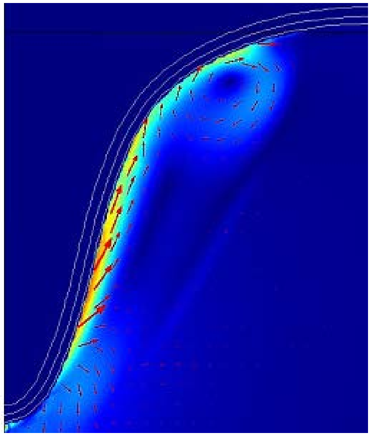
Velocity fields



Velocity field **with** buoyancy (no Marangoni)



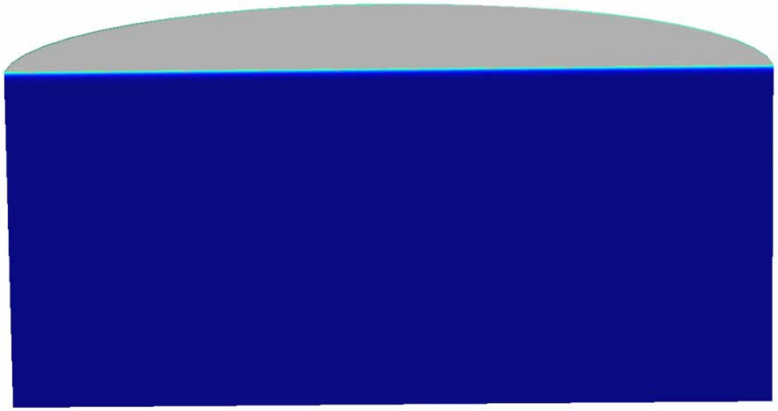
Velocity field **without** buoyancy (no Marangoni)



Relatively low power => stable keyhole, steady state establishment

Vapor plume => interaction with the melt pool

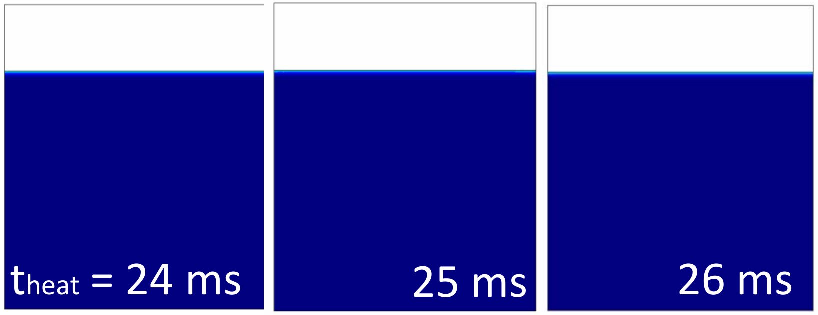
Creation of porosity possible with the level set method



Computation performed in 6 h *(8 cores X5690 and 8 gb ram)*

Presence of porosities from 900 W

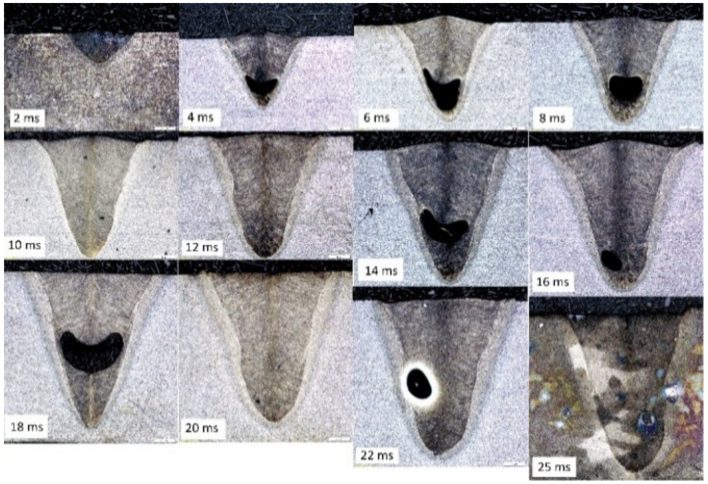
Important sensibility to the heating time:



↑ P_{laser} → ↑ vaporization → ↑ depth & inclination of liquid → ↑ porosities presence probability

Experimental validation

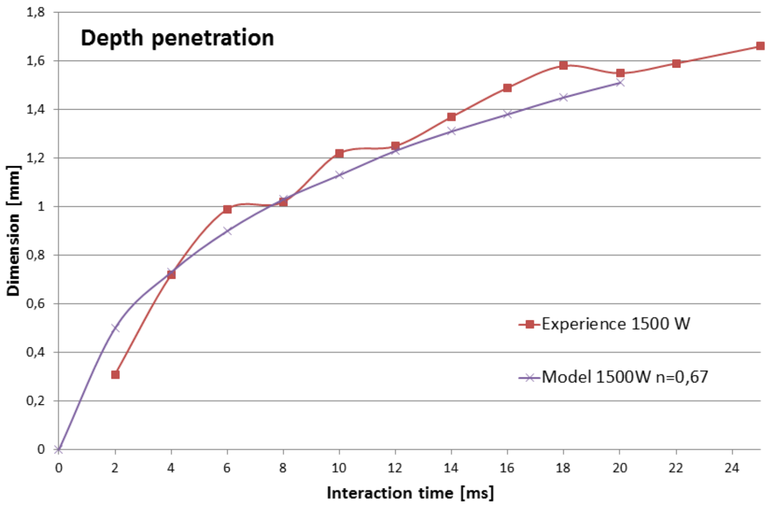
Disk Laser λ=1,06 µm , D_{focus} = 600 µm , DP 600 steel, thickness 1,8 mm

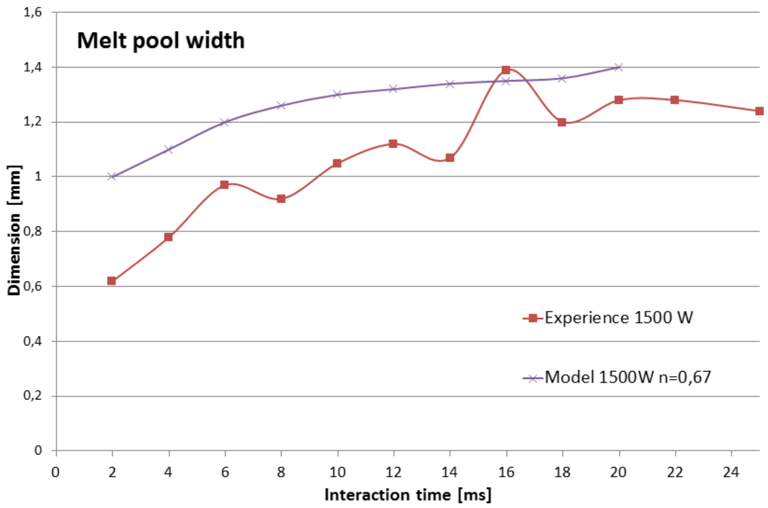


P_{laser} = 1500 W

- Rate of porosity > 50 %
- Axisymmetric shape well verified (except porosities)

- Depth penetration of model is satisfying
- Width over-estimated but with good tends





Conclusion 2D axisymmetric model

- Promising approach, possibility to take into account many phenomena and configurations:
  - Recoil pressure, gravity effects, vapor plume…
  - Liquid collapsing, porosity capturing…

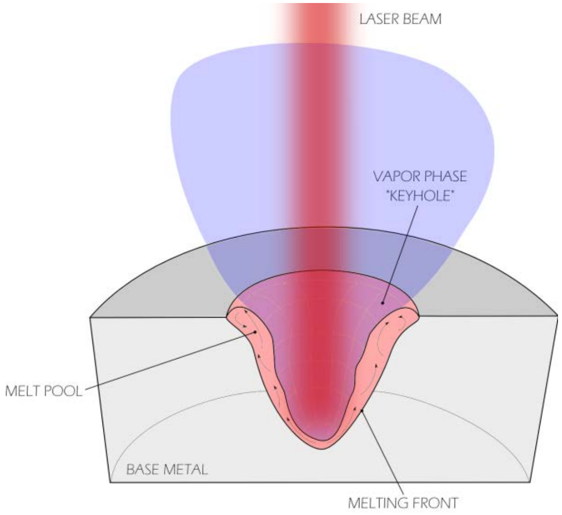
Medium term objectives

- Considering:
  - latent heats
  - Marangoni effect
  - Laser beam reflections and energy concentration

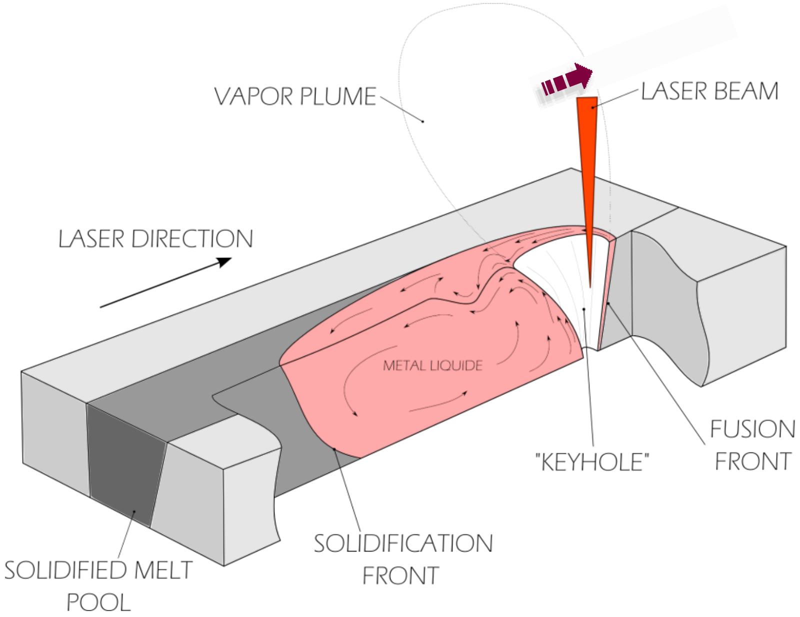
Long term outlook ? 3D?

Main goal of the project → 3D configuration with laser movement

Is that the transition to 3D is possible (with reasonable computation time)?

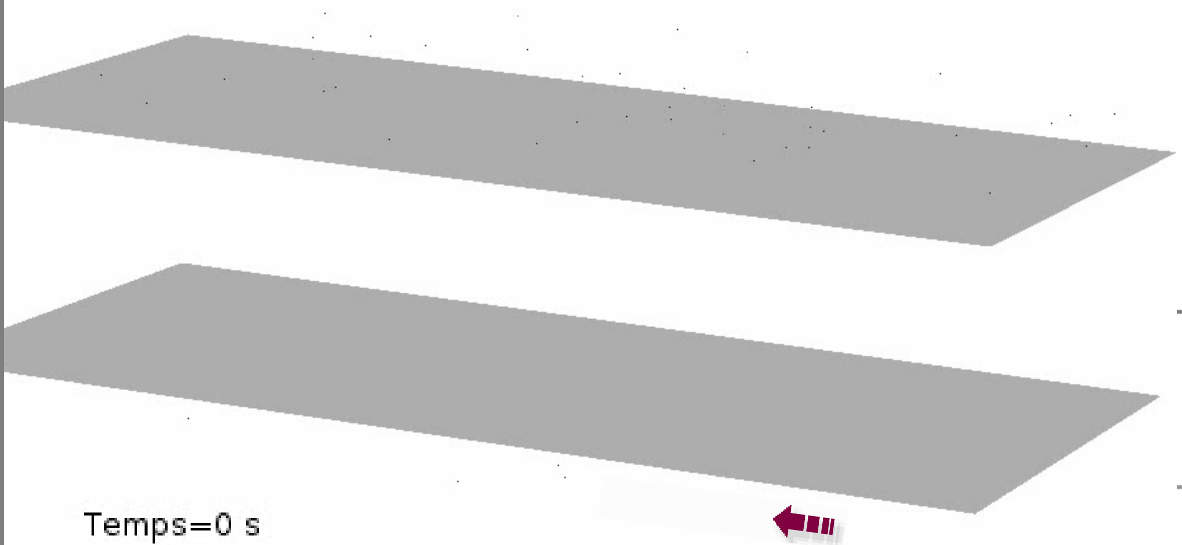


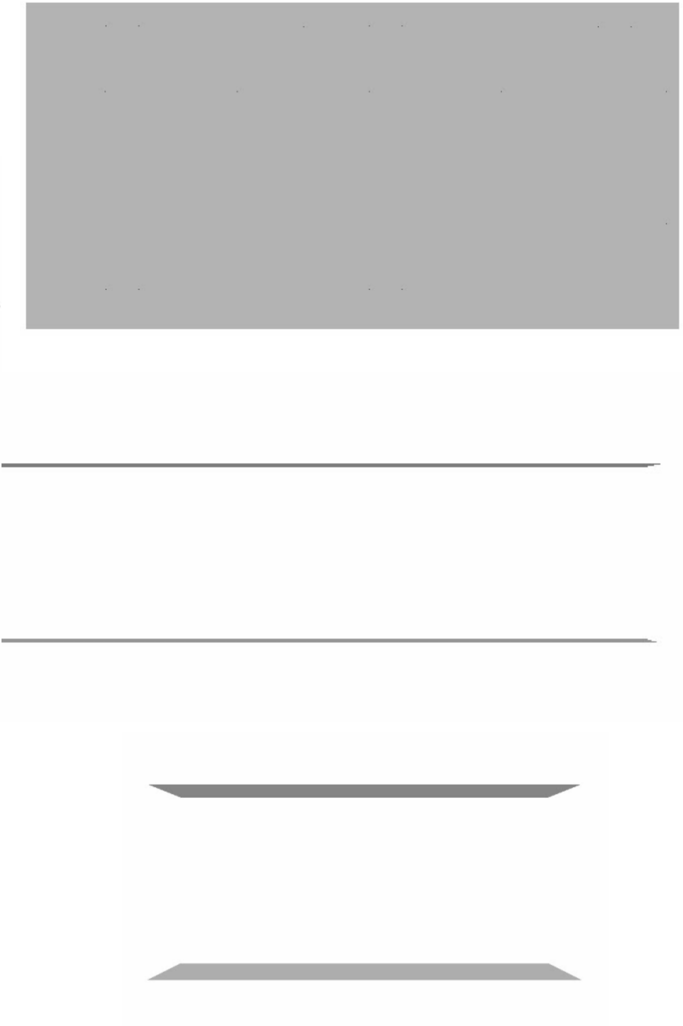
Static laser – 2D (axi.)



Laser in movement – 3D

3D configuration -> material sustainability ok ✓





Scrolling materiel direction
(Fixed Laser)

- P_{laser} = 1000 W
- Thikness = 0,9 mm
- V_{laser} = 6 m/min

400 000 DDL; 63 000 cells; Calculation on 33 ms
Calculation time 4 days
(around 8 cores & 15 gb ram)

General conclusion

- Promising approach:
  - Mains physical phenomena treated
  - Prediction of different defects possible (porosities, collapsing, partial penetration…)
  - large number of possible configurations (tailored blanks with gap, by transparency…)

Medium and long term objectives

- Finish to improve 2D axisymmetric model (laser reflections…)
- Transpose to 3D, use the model in industrial configurations

… Thanks for your attention …